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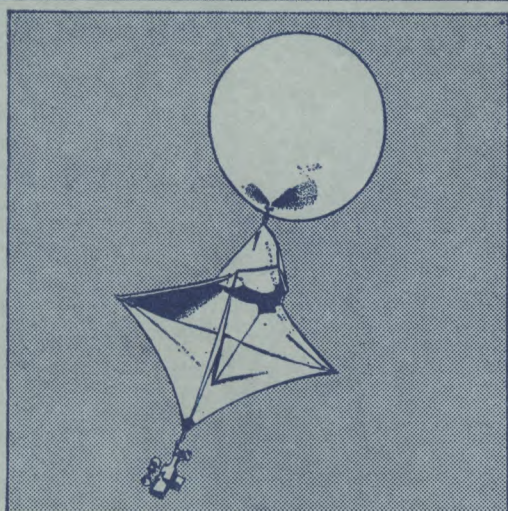
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THE FORECASTING OF SHOWER ACTIVITY IN AIRSTREAMS FROM THE NORTH-WEST QUARTER OVER SOUTH-WEST ENGLAND AND SOUTH WALES IN SUMMERTIME

By C. A. S. LOWNDES

Introduction.—In an earlier paper¹ a study was made of the shower activity in airstreams from the north-west quarter over south-east England in summertime and the relative usefulness of a number of predictors for forecasting shower activity, thunder and hail was evaluated. The present work deals in the same way with the problem of forecasting shower activity over south-west England and south Wales in summertime. The investigation was again restricted to airstreams which approached the British Isles from the north-west quarter. This was achieved by including only those days when the surface isobars over south-west England and south Wales at midday showed a flow from between west and north-west inclusive and the polar front lay to the south of the British Isles or had cleared south-west England by 0600 GMT. Occasions were not included if a front was situated over south-west England or south Wales between 0900 and 2100 GMT or if the precipitation was not mainly showery. The classification of the intensity of shower activity was based on reports from eight stations in the months May to September during the 10-year period from 1954 to 1963. From 1956, the stations were Ross-on-Wye, Bristol, Aberporth, Plymouth, Chivenor, St. Mawgan, Culdrose and Scilly. Before 1956, St. Eval was used instead of St. Mawgan. From the Beaufort letters in the *Daily Weather Report** the total number of mentions of slight, moderate and heavy showers at the eight stations during the period 0900 to 2100 GMT was obtained for each day. From these figures, the intensity of shower activity was classified as follows :

- A Widespread showers with a good proportion of moderate or heavy showers (8 or more mentions of showers ; more than 25 per cent moderate or heavy showers).
- B Widespread showers with few moderate or heavy showers (8 or more mentions of showers ; 25 per cent or less of moderate or heavy showers).
- C Few showers (Less than 8 mentions of showers).
- D No showers.

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

A note was made of thunder or hail reported between 0900 and 2100 GMT at any station in south-west England or south Wales included in the *Daily Weather Report*. Surface reports were supplemented by sferic (atmospherics) observations during the same hours of the day.

The factors which were considered.—It is reasonable to associate the degree of shower activity primarily with the degree of instability of the lower troposphere as indicated by the dry-bulb temperatures. Instability can be assessed in a simple fashion in various ways, of which seven were chosen for this investigation*, (1) the 1000–500 mb thickness anomaly, (2) the 1000–700 mb thickness anomaly, (3) the 700 mb temperature anomaly, (4) the Boyden instability index,² (5) the Rackliff instability index,³ (6) the Jefferson instability index⁴ and (7) the modified Jefferson instability index.⁵

The thickness anomalies are departures from a climatological normal of thickness values and are closely related to the general excess or deficiency of air temperature which in turn is related to the degree of instability resulting from surface heating. The anomaly of 700 mb temperature is a fair measure of the instability attainable between the ground and the freezing-level. The instability indices, which were all devised for thunderstorm forecasting, are measures of instability which dispense with climatic normals. Apart from the humidity measurements inherent in the Rackliff and Jefferson indices, humidities in the troposphere were not considered because the variations in space and with time are large and difficult to forecast and because a high relative humidity may be simply the consequence of the evaporation of raindrops from a shower and may not be representative of the airmass. However, it became clear that the level of surface pressure was a useful predictor in association with the thickness and temperature anomalies, probably because of the well-known association between high surface pressure and relatively dry air aloft.

Other factors considered included the position of the associated depression and the curvature of the surface isobars over south-west England and south Wales.

Association with surface synoptic features.—

The position of the associated depression at midday.—Table I shows for each class of shower activity the number of occasions when the depression with which the polar air was associated was situated in a particular locality.

On 82 per cent of occasions when the depression was situated over Scotland there were widespread showers over south-west England and south Wales (classes *A* and *B*). On 71 per cent of occasions when the depression was situated over the Norwegian Sea or the Arctic there were few showers or no showers (classes *C* and *D*). In general, the nearer the depression was to the British Isles, the more intense was the shower activity in south-west England and south Wales. This suggests that the isobaric curvature and the level of surface pressure over the British Isles might be useful predictors.

The curvature of the surface isobars.—On many days of widespread showers, a surface trough moved eastwards or southwards across south-west England. Of

* For the years 1954 and 1955, solar radiation and lag corrections have been applied to the upper air temperatures and thicknesses to make them comparable with the data for 1956 to 1963 to which the corrections had already been applied.

TABLE I—SHOWER ACTIVITY RELATED TO POSITION OF ASSOCIATED DEPRESSION
AT MIDDAY (MAY–SEPTEMBER 1954–63)

Position of depression	Class of shower activity			
	A	B	C	D
	<i>Number of occasions</i>			
Arctic	0	0	2	0
Iceland region	1	1	3	1
Norwegian Sea	4	2	10	3
Scandinavia	11	2	17	6
North of Scotland	7	5	8	2
West of Scotland	1	1	0	0
Scotland	12	2	3	0
North Sea	16	8	11	2
Irish Sea	2	0	0	0
England	1	0	1	0
Denmark	0	1	6	1
Germany	0	0	1	0
All areas	55	22	62	15

the troughs which moved eastwards, 50 per cent were major features with the trough axis some 600 to 1000 miles in length and 50 per cent were minor perturbations with the trough axis some 200 to 600 miles in length. Of the troughs which moved southwards, 20 per cent were major features and 80 per cent were minor perturbations. Table II shows the number of these occasions for each class of shower activity.

TABLE II—SHOWER ACTIVITY RELATED TO THE CURVATURE OF THE SURFACE
ISOBARS OVER SOUTH-WEST ENGLAND (MAY–SEPTEMBER 1954–63)

	Class of shower activity			
	A	B	C	D
	<i>Number of occasions</i>			
Surface trough moved eastwards across south-west England	22	2	3	0
Surface trough moved southwards across south-west England	10	1	2	0
Uniform cyclonic isobars over south-west England	11	6	3	0
Neither surface trough nor cyclonic isobars	12	13	54	15
Total	55	22	62	15

On 58 per cent of occasions of widespread showers with a good proportion of moderate or heavy showers (class A) a surface trough moved eastwards or southwards across south-west England. Of the 15 days on which a major surface trough moved across south-west England, 13 (87 per cent) were associated with widespread showers with a good proportion of moderate or heavy showers and 7 (47 per cent) with thunder. Of the 25 days on which a minor perturbation moved across south-west England, 19 (76 per cent) were associated with widespread showers with a good proportion of moderate or heavy showers and 13 (52 per cent) with thunder. Of the 20 days with uniform cyclonic isobars over south-west England, 17 (85 per cent) were associated with widespread showers (classes A and B) and 8 (40 per cent) with thunder. There were no occasions of widespread showers when the isobars over south-west England were anticyclonic. On 90 per cent of occasions of few showers or no showers (classes C and D) there were neither surface troughs nor uniform cyclonic isobars. On 29 per cent of occasions of few showers or no showers, the isobars over south-west England were anticyclonic.

Association with 700 mb temperature and surface pressure.—The following data were extracted :

- (i) The 700 mb temperature anomaly at Camborne for 1200 GMT (1500 GMT before 1957). The anomaly was based on the 5-day mean temperatures given in Table III.
- (ii) The mean sea level pressure at Chivenor for 1200 GMT.

TABLE III—5-DAY MEAN 700 MB TEMPERATURE AT CAMBORNE* IN °C

Period	Mean	Period	Mean	Period	Mean
1-5 May	-5	30 June- 4 July	0	29 Aug- 2 Sept	0
6-10	-5	5- 9 July	0	3- 7	0
11-15	-5	10-14	+1	8-12	0
16-20	-4	15-19	+1	13-17	-1
21-25	-4	20-24	+1	18-22	-1
26-30	-3	25-29	+1	23-27	-1
				28 Sept- 2 Oct	-1
31 May- 4 June	-3	30 July- 3 Aug	+1		
5- 9 June	-2	4- 8 Aug	+1		
10-14	-2	9-13	+1		
15-19	-1	14-18	+1		
20-24	-1	19-23	+1		
25-29	0	24-28	0		

*Obtained from 5-year monthly means for the period 1951-55. The monthly mean values were based on midday and midnight ascents and were corrected for radiation and lag errors.

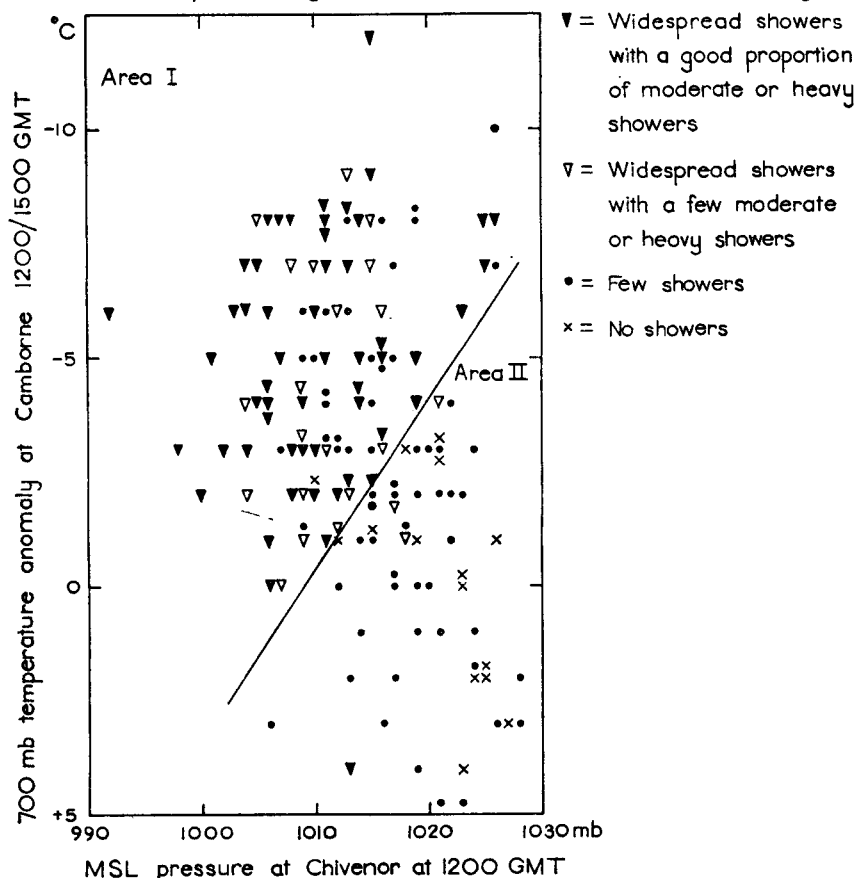


FIGURE 1—SHOWER ACTIVITY IN SOUTH-WEST ENGLAND AND SOUTH WALES ASSOCIATED WITH SURFACE PRESSURE AND THE 700 MB TEMPERATURE ANOMALY. The line divides the diagram into area I containing most of the occasions of widespread showers and area II containing most of the occasions of few or no showers.

Rain showers.—A diagram was plotted (Figure 1) of the 700 mb temperature anomaly at Camborne against the mean sea level pressure at Chivenor. The various intensities of shower activity are indicated by symbols, class *A* by a black triangle, class *B* by an open triangle, class *C* by a dot and class *D* by a cross. The diagram can be divided into two areas as indicated. If the diagram were used to forecast either widespread showers or few showers/no showers, a 'skill score' of 0.62 would be obtained. The skill score S^6 is defined by

$$S = \frac{\text{number of correct forecasts} - \text{number correct by chance}}{\text{total number of forecasts} - \text{number correct by chance}}$$

It ranges from 0 for no success to 1 for complete accuracy.

Rainfall amount.—A similar diagram (Figure 2) was plotted, the symbols representing the average rainfall between 0900 and 2100 GMT for the eight

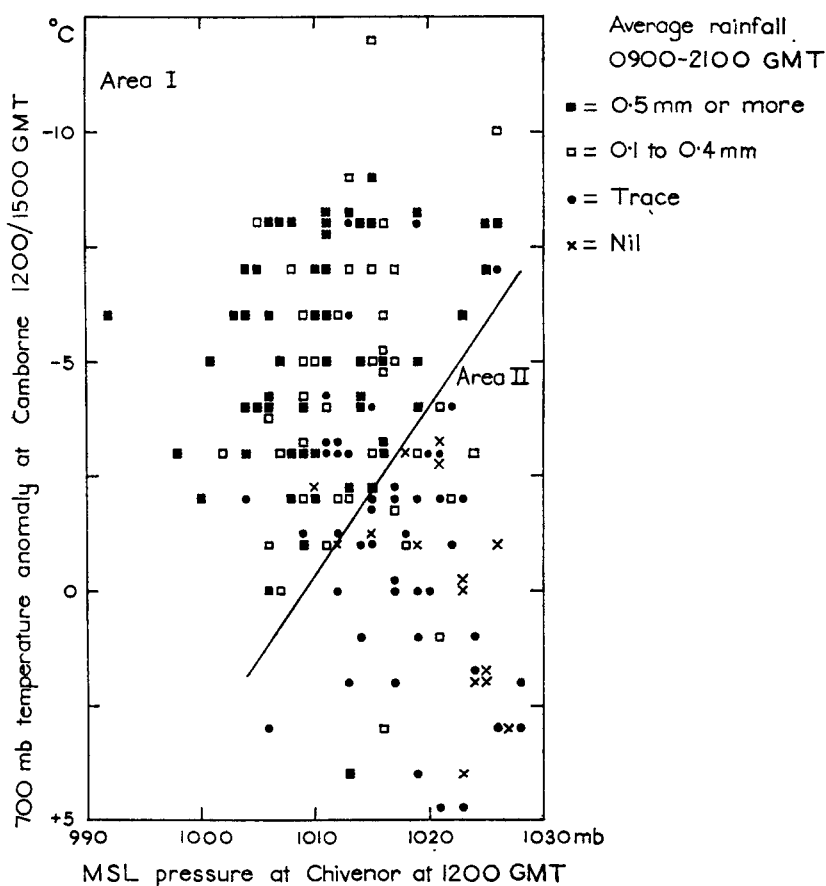


FIGURE 2—AVERAGE RAINFALL FOR EIGHT STATIONS IN SOUTH-WEST ENGLAND AND SOUTH WALES FOR EACH INDIVIDUAL DAY ASSOCIATED WITH SURFACE PRESSURE AND THE 700 MB TEMPERATURE ANOMALY

Areas I and II are the same areas as in Figure 1.

stations in south-west England and south Wales for each day examined. The diagram can be divided into the same two areas which were used in Figure 1. If the diagram were used to indicate an average rainfall of either 0.1 mm or more, or less than 0.1 mm, a skill score of 0.67 would be obtained.

If it were used to indicate an average rainfall of either 0.5 mm or more, or less than 0.5 mm, a skill score of 0.44 would be obtained.

Figure 3 shows the highest and lowest rainfall amounts plotted against the average amount for the eight stations in south-west England and south Wales for each day examined. For an average value of up to 0.5 mm, the highest value is likely to be about five times the average and for an average value of more than 0.5 mm, about four times the average. For an average value of up to 1 mm, the lowest value was nil or a trace and for an average value above 1 mm the lowest value varied between nil and 2 mm. It is clear

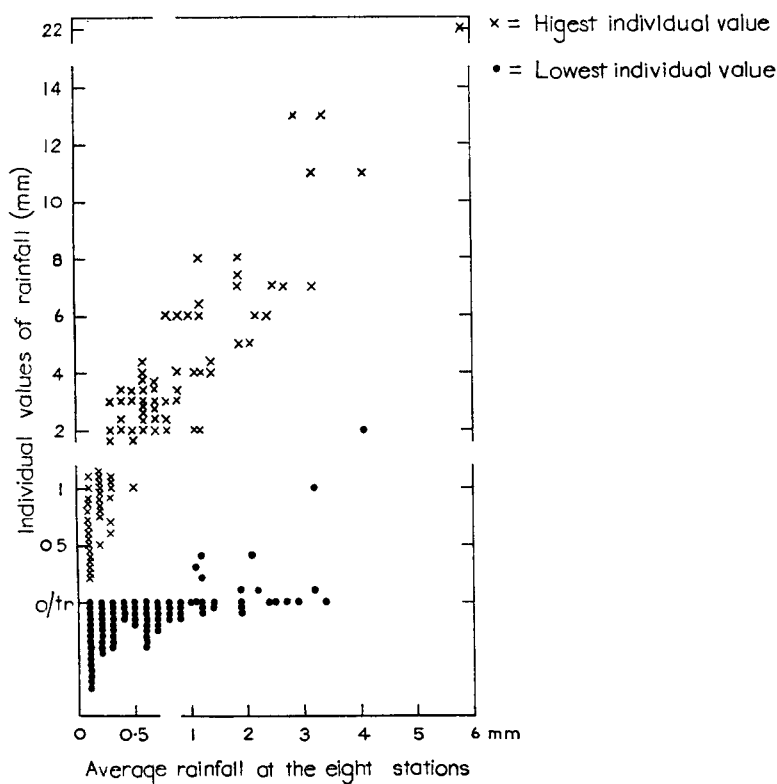


FIGURE 3—THE HIGHEST AND LOWEST RAINFALL AMOUNTS (0900–2100 GMT) ASSOCIATED WITH AVERAGE VALUES FOR EIGHT STATIONS IN SOUTH-WEST ENGLAND AND SOUTH WALES

For some values of the average rainfall the lowest amount was zero on several occasions and such occasions are plotted below the axis.

that however widespread the showers, some places are likely to escape with little or no rain.

Thunder and hail.—A diagram was plotted (Figure 4) of the 700 mb temperature anomaly against mean sea level pressure with symbols representing thunder or hail. If no thunder or hail was reported, a cross was plotted. The diagram can be divided into two areas as indicated. If the diagram were used to indicate thunder or no thunder, a skill score of 0.31 would be obtained.

For an indication of hail or no hail, a skill score of 0.15 would be obtained.

On all but one occasion of thunder and on all occasions of hail, the negative temperature anomaly was 2 deg C or more.

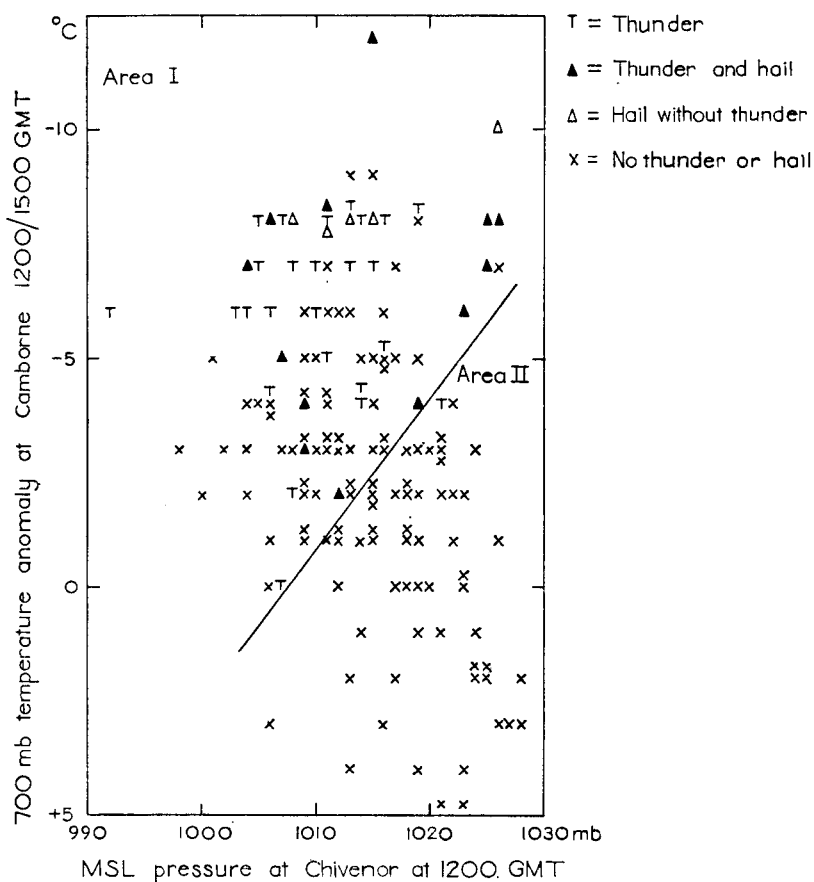


FIGURE 4—THUNDER AND HAIL IN SOUTH-WEST ENGLAND AND SOUTH WALES ASSOCIATED WITH SURFACE PRESSURE AND THE 700 MB TEMPERATURE ANOMALY

Sunshine.—A study of the average duration of sunshine for the eight stations in south-west England and south Wales for each day examined revealed no evidence of any association between the intensity of shower activity and the duration of sunshine.

Association with 1000–500 mb thickness and surface pressure.—The 1000–500 mb thickness anomaly at Camborne for 1200 GMT (1500 GMT before 1957) was extracted. Anomalies were measured from 5-day mean thickness values for Camborne given in Table IV.

An analysis was carried out with the 1000–500 mb thickness anomaly in place of the 700 mb temperature anomaly and statistics were extracted to construct Figures 5, 6 and 7. The corresponding skill scores are shown in Table V.

An analysis was also carried out with the 1000–700 mb thickness anomaly in place of the 700 mb temperature anomaly and similar statistics extracted. The corresponding skill scores are also shown in Table V.

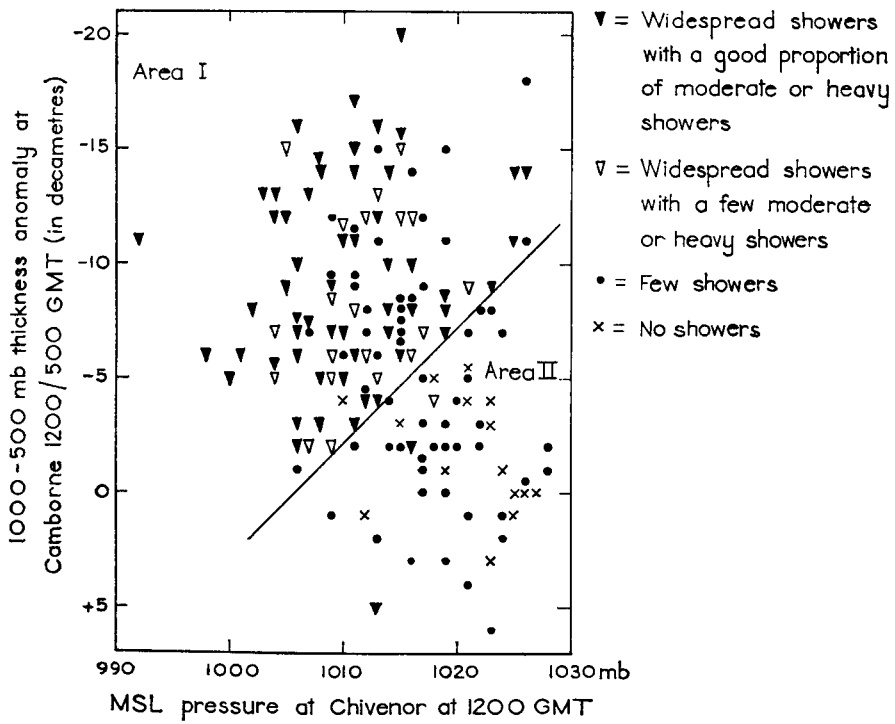


FIGURE 5—SHOWER ACTIVITY IN SOUTH-WEST ENGLAND AND SOUTH WALES ASSOCIATED WITH SURFACE PRESSURE AND THE 1000–500 MB THICKNESS ANOMALY The line divides the diagram into area I containing most of the occasions of widespread showers and area II containing most of the occasions of few or no showers.

TABLE IV—5-DAY MEAN 1000-500 MB THICKNESS AT CAMBORNE* IN DECAMETRES

Period	Mean	Period	Mean	Period	Mean
1-5 May	544	30 June-4 July	555	29 Aug-2 Sept	555
6-10	544	5-9 July	556	3-7 Sept	555
11-15	545	10-14	557	8-12	554
16-20	546	15-19	557	13-17	554
21-25	547	20-24	557	18-22	553
26-30	548	25-29	557	23-27	553
				28 Sept-2 Oct	552
31 May-4 June	549	30 July-3 Aug	557		
5-9 June	550	4-8 Aug	556		
10-14	551	9-13	556		
15-19	552	14-18	556		
20-24	553	19-23	556		
25-29	554	24-28	555		

*Obtained from 5-year monthly means for the period 1951-55. The monthly mean values were based on midday and midnight ascents and were corrected for radiation and lag errors.

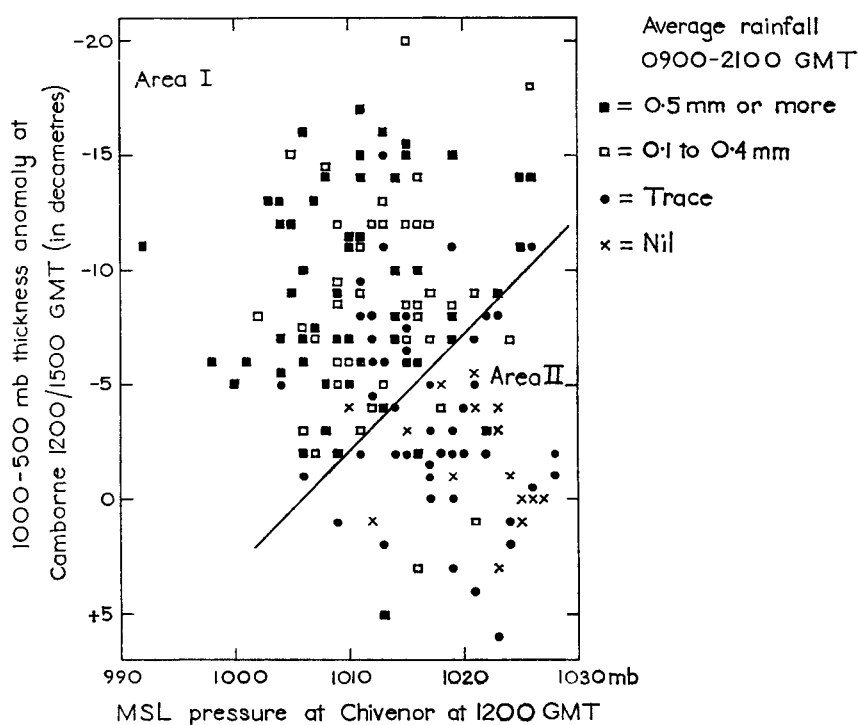


FIGURE 6—AVERAGE RAINFALL FOR EIGHT STATIONS IN SOUTH-WEST ENGLAND AND SOUTH WALES FOR EACH INDIVIDUAL DAY ASSOCIATED WITH SURFACE PRESSURE AND THE 1000-500 MB THICKNESS ANOMALY

Areas I and II are the same areas as in Figure 5.

Association with the instability indices.—The Boyden instability index,² the Rackliff instability index,³ the Jefferson instability index⁴ and the

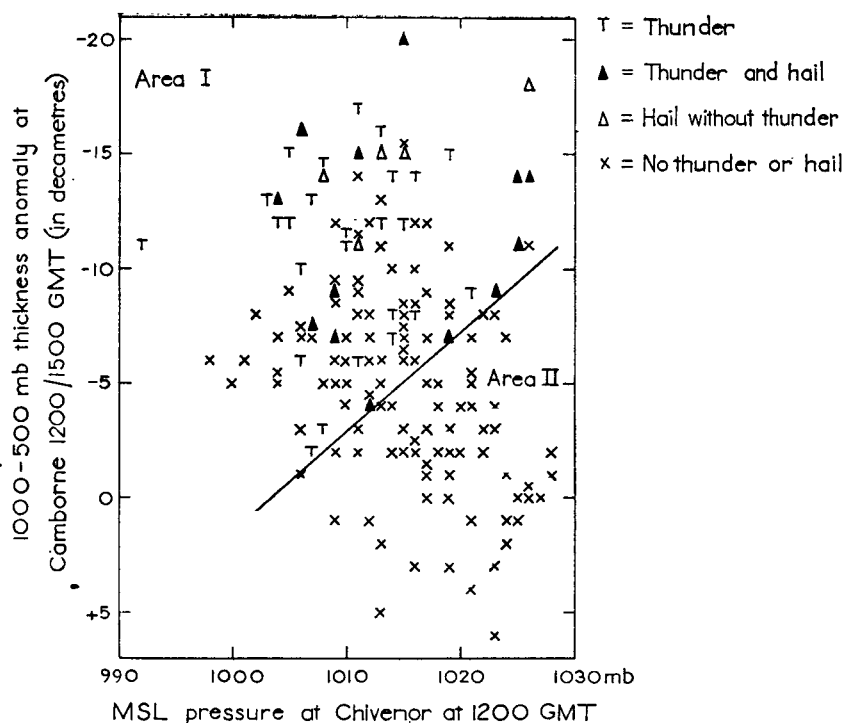


FIGURE 7—THUNDER AND HAIL IN SOUTH-WEST ENGLAND AND SOUTH WALES ASSOCIATED WITH SURFACE PRESSURE AND THE 1000-500 MB THICKNESS ANOMALY

modified Jefferson index⁵ were calculated for the Camborne 1200 GMT ascents (1500 GMT before 1957). The critical values of the indices which gave the highest skill scores in forecasting either widespread showers or few showers/no showers were obtained. A similar procedure was carried out for rainfall amount, thunder and hail. The skill scores and critical values of the indices are given in Table V.

The relative usefulness of the predictors.—Assuming that the predictors can be forecast, their relative usefulness in forecasting shower activity, rainfall amount, thunder and hail can be assessed by a comparison of skill scores. Table V shows the skill scores obtained and the critical values of the instability indices.

The highest scores for the forecasting of shower activity and the lower rainfall amounts are obtained by the 700 mb temperature and the 1000-500 mb thickness predictors. The 1000-700 mb thickness predictor is rather less successful than the 1000-500 mb thickness predictor. The highest scores for the forecasting of the higher rainfall amounts and thunder are obtained by the Boyden instability index. None of the predictors provide a useful indication of the likelihood of hail.

TABLE V—A COMPARISON OF SKILL SCORES

Predictors	Shower activity	Rainfall (limit 0.1 mm)	Rainfall (limit 0.5 mm)	Thunder	Hail
700 mb temperature anomaly and surface pressure	0.62	0.67	0.44	0.31	0.15
1000-500 mb thickness anomaly and surface pressure	0.59	0.67	0.37	0.31	0.14
1000-700 mb thickness anomaly and surface pressure	0.52	0.57	0.33	0.25	0.10
Boyden instability index (critical values)	0.36 (93/94)	0.46 (91/92)	0.50 (93/94)	0.50 (94/95)	0.21 (94/95)
Rackliff instability index (critical values)	0.39 (25/26)	0.48 (25/26)	0.34 (30/31)	0.40 (31/32)	0.15 (31/32)
Jefferson instability index (critical values)	0.46 (21/22)	0.52 (21/22)	0.44 (22/23)	0.45 (24/25)	0.04 (24/25)
Modified Jefferson instability index (critical values)	0.43 (17/18)	0.54 (17/18)	0.47 (21/22)	0.43 (24/25)	0.06 (24/25)

The geographical distribution of the showers.—Of the 8 stations used in the analysis, half are situated on the windward coast, that is, Aberporth, Chivenor, St. Mawgan (St. Eval) and Scilly, whilst Culdrose is not far from the windward coast (see Figure 8). One would expect a rather narrow coastal

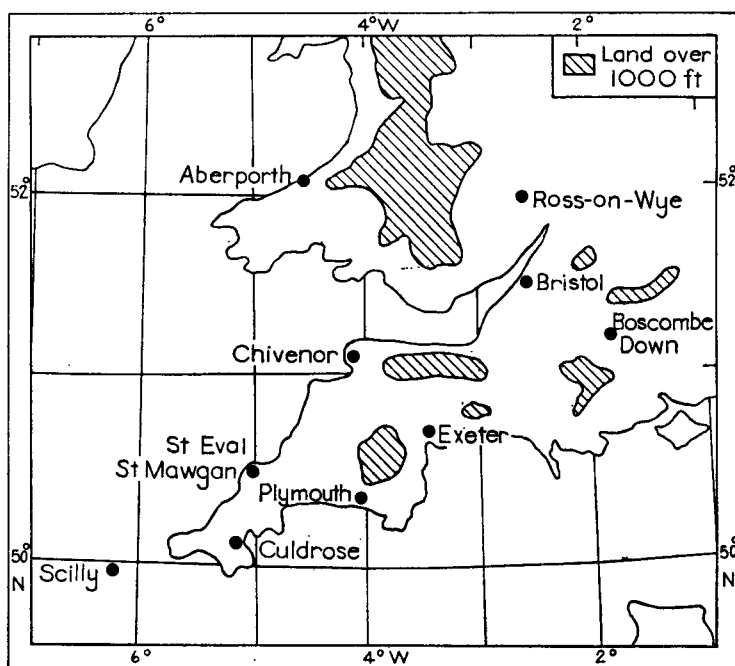


FIGURE 8—THE POSITIONS OF THE STATIONS USED

strip in which showers would be absent or weak on days when showers would not be initiated at sea and these stations might not be representative of south-west England as a whole. An indication of the variation of shower activity over the area was obtained by an analysis of the rainfall at each of the 8 stations and also at Exeter and Boscombe Down, stations some distance from the windward coast.

TABLE VI—RAINFALL FROM SHOWERS AT EACH INDIVIDUAL STATION
(MAY – SEPTEMBER 1954–63)

Station	Average rainfall (mm)	Percentage of days with 0.5 mm or more	Percentage of days with nil or trace
Boscombe Down	1.0	34	54
Ross-on-Wye	0.9	27	60
Bristol	0.9	28	62
Exeter	0.7	27	60
Plymouth	0.5	23	61
Aberporth	0.5	21	71
Chivenor	0.4	21	67
St. Mawgan (St. Eval)	0.4	19	67
Culdrose	0.3	18	77
Scilly	0.2	16	71

Table VI shows that the stations on or near the windward coast had the lowest average rainfall from showers ranging from 0.2 mm at Scilly to 0.5 mm at Aberporth. The average rainfall at the other stations ranged from 0.5 mm at Plymouth to 1.0 mm at Boscombe Down. The windward coast stations also had the lowest percentage of days with a total rainfall of 0.5 mm or more, averaging 19 per cent compared with 28 per cent for the other stations. The percentage of days with nil or a trace of rain averaged 71 per cent for the windward coast stations compared with 59 per cent for the other stations.

It is clear that stations on or near the windward coasts have rather less rainfall from showers than inland stations, the percentage of days with 0.5 mm or more of rain being on average about 10 per cent less at the coastal stations and the percentage of days with a trace or less about 10 per cent higher.

A comparison with the forecasting of shower activity in south-east England.—In an earlier paper¹ the problem of forecasting shower activity in south-east England was examined in a similar way. The forecast skill scores obtained by the various predictors are all lower for south-west England compared with those for south-east England. In particular, the 700 mb temperature anomaly predictor which provides a useful indication of thunder for south-east England (skill score 0.62) is of little use for south-west England (skill score 0.31). For both areas, the 700 mb temperature anomaly predictor is the best indicator of shower activity and the Boyden instability index the best indicator of thunder. It seems likely that the lower skill scores for south-west England are associated with the relative proximity of this area to the windward coast and the consequent motion of air across the area which is less subjected to heating from the land.

Conclusions.—This investigation was concerned with polar airstreams from the north-west quarter affecting south-west England and south Wales in summertime and was restricted to days when no fronts were situated over this area. Widespread showers are likely if the associated depression is

situated over Scotland, west of Scotland or over the Irish Sea at midday. Few showers are likely if the depression is situated over the Norwegian Sea or the Arctic. Widespread showers with a good proportion of moderate or heavy showers are likely if a major surface trough or minor perturbation moves across south-west England with thunder likely to occur on about half the occasions. Widespread showers are also likely on days with uniform cyclonic isobars over south-west England. Few showers or no showers are likely if the isobars are anticyclonic.

Places on or near the windward coasts have rather less rainfall from showers than inland stations, the percentage of days with a trace or less of precipitation being about 10 per cent higher at windward coast stations.

The best indication of the intensity of shower activity can be obtained from (1) the 700 mb temperature anomaly at Camborne and the surface pressure at Chivenor and (2) the 1000–500 mb thickness anomaly at Camborne and the surface pressure at Chivenor. The Boyden instability index gives the best indication of the likelihood of thunder. None of the predictors provides a useful indication of the likelihood of hail.

The relative usefulness of the predictors has been evaluated ; which is to be preferred in forecasting depends largely on how successfully each can be forecast.

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LOW MINIMUM TEMPERATURES AT SANTON DOWNHAM, NORFOLK

By J. OLIVER

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Local climatic contrasts occasionally reveal extremes which are more striking than regional differences. These local characteristics are most often associated with topographical conditions. Human modification of the surface or of the lower part of the atmosphere may also have a significant effect. Some of the most marked local meteorological features are experienced in frost hollows. An interesting example of the development of low temperature minima due to local factors is provided by the record available for Santon Downham from 1958.

Although the record is a short one, it is sufficient to place Santon Downham amongst those stations, below 1000 feet above MSL, which have a high frequency of air and ground frosts and low night temperature minima. The data tabulated in Table I (a), (b) and (c) show that, out of over 300 stations below

1000 feet listed in the *Monthly Weather Report** (see Table II), Santon Downham quite frequently records the lowest monthly extreme.

TABLE I—FROSTS AND EXTREME MINIMUM TEMPERATURES AT SANTON DOWNHAM, NORFOLK, DURING 1958–64

(a) Number of stations, below 1000 feet, in England, Wales and Northern Ireland with more air frosts than Santon Downham.							
	1958	1959	1960	1961	1962	1963	1964
	4	2	3	2	1	0	1
(b) Number of stations, below 1000 feet, in England, Wales and Northern Ireland with more grass minimum temperatures below 0.0°C (−0.9°C or below for 1960 and earlier) than Santon Downham.							
	1958	1959	1960	1961	1962	1963	1964
	4	0	1	1	1	1	2
(c) Number of stations, below 1000 feet, in England, Wales and Northern Ireland with lower extreme minimum temperatures than Santon Downham in June, July and August.							
	1958	1959	1960	1961	1962	1963	1964
June	0	0	0	0	0	17	4
July	4	0	0	0	0	0	1
August	0	2	0	2	0	4	1

TABLE II—NUMBER OF STATIONS, EXCLUDING THOSE IN SCOTLAND, BELOW 1000 FEET REPORTING MINIMUM TEMPERATURES IN THE MONTHLY WEATHER REPORT

1958	1959	1960	1961	1962	1963	1964
316	327	332	333	344	348	303

The meteorological station at Santon Downham is located about one mile north of the Valley of the Little Ouse at Grime's Graves (National Grid Reference 813901), 80 feet above MSL, in the Breckland of west Norfolk (see Figure 1). The site is on a small shelf on a gentle slope with a southerly aspect and in a clearing in the 52,000-acre Thetford Forest. The vegetation of the clearing is short grass-heath, whilst the nearest trees are some 150 feet away towards the west. The light sandy soils, which characterize much of the Breckland, are free-draining and dry out readily, particularly since the mean annual rainfall of the area is only about 24 inches. The station is located sufficiently far away from the coast, being 26 miles from the Wash and 45 miles from the nearest eastern coast, for the ameliorating effects of the sea on nocturnal or winter temperatures to be significantly limited. Diurnal variations of temperature are considerable in this area.

The comparison between Santon Downham and other British stations (excluding Scotland) for the period 1958–64 is interesting. Although at Santon Downham January is the month with the greatest incidence of frost on average, a particular feature of the site is that there are low night minima in the period June to August. There is, in fact, no month in the year when frost has not been recorded at Santon Downham. Table I (c) shows that few other stations have recorded lower monthly extreme minima in June, July and August. Where other stations have been colder they have not been consistently the same ones so that Santon Downham is the coldest station on the greatest number of occasions compared with any other single station. The station has recorded the lowest known June temperature in Britain of -5.6°C .¹ This was on 1 June 1962 when the next coldest station was Lincoln with -4.4°C .¹ June, in general, is a month in which, in the Breckland, frosts can

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

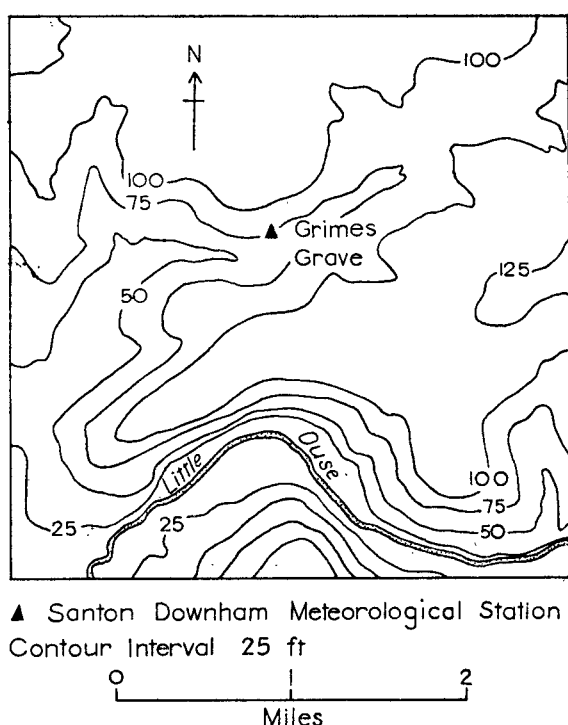


FIGURE 1—MAP SHOWING THE TOPOGRAPHY OF THE AREA SURROUNDING SANTON DOWNHAM

Note: the spelling Grime's Graves is preferred.

occasionally be severe. Over the period 1958–64, Santon Downham recorded air frosts 12 times in June, 4 times in July and 4 times in August. The comparable totals for ground frosts (see note to Table III) were 37, 17 and 21. No other East Anglian station experienced air frosts in July, August or September during 1958–64. In July 1961 and again in July 1963, Santon Downham recorded an air frost and 5 days with a grass minimum temperature below 0.0°C , whilst in August 1964 there were two air frosts (one with a minimum of -1.7°C) and 6 days with grass minimum below 0.0°C .

TABLE III—AVERAGE ANNUAL NUMBER OF AIR FROSTS AND GROUND FROSTS AT EAST ANGLIAN STATIONS DURING 1958–64

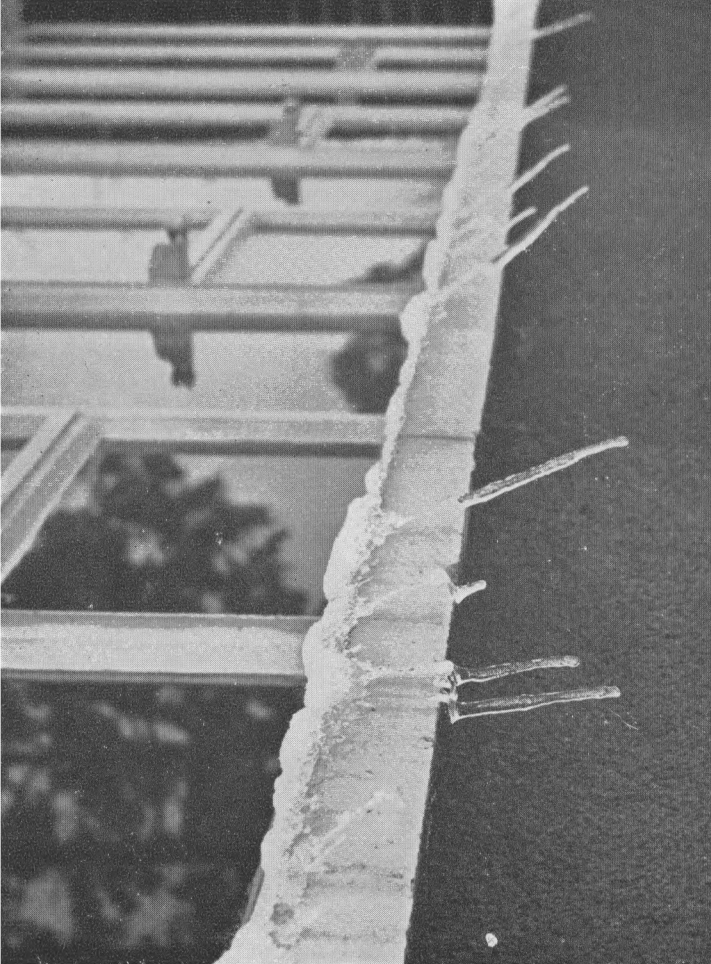
Station	Number of frosts		Station	Number of frosts	
	air	ground		air	ground
Terrington St. Clement	60	91	Gorleston	33	55
Marham	63	88	Mildenhall	56	91
West Raynham	63	99	Lowestoft	55	64
Cromer	37	74	Cambridge Botanic Gardens	66	123
Sprowston	59	115	Santon Downham (see note (ii))	103	156
Burlingham	49	84			

Notes:—

- (i) Ground frosts before 1961 were defined as days with grass minimum -0.9°C or below; for 1961 and after, days with grass minimum below 0.0°C have been used. For comparative purposes this does not raise any difficulty but the absolute figures are affected by the change of definition.
- (ii) The minimum temperatures at Santon Downham are recorded at 0900 GMT. The total of air frosts at Santon Downham for 1958 has been estimated. No total for February 1958 was available.

The other information in Tables I and III illustrates in different ways the tendency for low night temperatures at Santon Downham. It is clear from Table III that local circumstances may make a station unrepresentative of the larger area in which it is situated. A station sited in a forest clearing under conditions of radiation cooling may well be affected by colder air draining from the canopy level, which would be the active heat-exchange surface, and accumulating in the clearing. Extremes of cold at night are thus more likely than in open sites outside the forest, and even lower temperatures could be expected in inversion hollows such as the floor of the Little Ouse valley nearby. The meteorological records at the Forestry Commission District Office at Santon Downham, nearer the river, do not show quite such a degree of night cold as Grime's Graves, although the extremes are more marked than at other meteorological stations in East Anglia. Sandy soils contribute further to such conditions. The poorer conductivity of sands with a coarser texture and lower moisture content, in contrast with heavier and wetter clays, would limit the upward transfer of heat to replenish surface losses. These factors would operate in a clearing, but under a tree cover soil qualities would become much less important. For instance, in the Thetford area on 4 July 1965, when a screen minimum of -0.5°C (at 4 feet) was recorded at Grime's Graves, readings taken over grass at a height of 6 inches in the centre of a large clearing on the same morning fell to -5.4°C . In five other clearings readings of -3°C or lower were recorded at 6 inches above the surface (information kindly supplied by Mr. J. M. B. Brown of the Forestry Commission Research Station). In addition to such local circumstances, there are other reasons for low night temperatures. The Breckland area, as a whole, is particularly liable to experience low night temperatures as other investigators have indicated (Day,² Manley,³ and Hawke⁴). Distance from the sea and exposure to cold easterly winds play a part. The extreme minimum of -9.4°C for May in Britain occurred near Thetford, close to Santon Downham on 4 May 1941 (Manley⁵). This temperature was equalled at Fort Augustus on 15 May 1951. Cambridge and other stations in East Anglia have, on average, a high total of ground and air frosts (see Table III) but Santon Downham stands out clearly from amongst these.

Local climates are usually looked upon as aberrations from the normal climate of an area and, on occasions, there is an inclination to exclude or discount the local features as abnormalities or oddities when assessing the climatic environment. When the climatic relationships of agriculture (especially horticulture), forestry or even studies of human health are under consideration, full attention should be paid to the varying characteristics of different localities. Information on frost risk in the forest area of the Breckland is clearly of great importance especially from the viewpoint of establishing frost-sensitive species, and the Forestry Commission have an investigation in progress on frost incidence. At Santon Downham, for instance, the average annual number of days with a grass minimum temperature below 0.0°C over the period 1961-64 has been 175. If one is trying to select a 'representative' station considerable care is needed, as other unusual sites have shown, for example the frost hollow at Rickmansworth in the Chilterns (Hawke⁴,⁶). For many practical purposes, however, actual rather than representative conditions are what matter.



Photograph by N. R. Watson

PLATE I — UNUSUAL ICICLES

This photograph was taken in early March 1965 at the Meteorological Research Flight, Farnborough. The most probable explanation seems to be as follows : The icicles originally formed vertically as heat from the interior of the building gradually melted a portion of the snow cap on the window-sill. The melting was greatest near the metal window frame and least near the edge of the ledge. The snow cap on the ledge was frozen to the pendant icicle and the whole slowly pivoted about the edge of the window-sill.



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PLATE II—AIR MARSHAL SIR CHRISTOPHER HARTLEY INTRODUCING MAJOR K. J. GROVES AND MRS. GROVES AT THE PRESENTATION OF THE L. G. GROVES MEMORIAL PRIZES AND AWARDS ON 8 NOVEMBER 1965

See p. 26.



Crown Copyright

PLATE III—MAJOR K. J. GROVES PRESENTING THE MEMORIAL PRIZE FOR METEOR-
OLOGY TO MR. L. P. SMITH
See p. 26.



Crown Copyright

PLATE IV—MR. A. SANDLAND RECEIVING THE METEOROLOGICAL OBSERVER'S
AWARD FROM MAJOR GROVES
See p. 27.



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PLATE V—DR. B. J. MASON, DIRECTOR-GENERAL OF THE METEOROLOGICAL OFFICE, ADDRESSING A PRESS CONFERENCE HELD AT THE METEOROLOGICAL OFFICE BRACKNELL ON 2 NOVEMBER 1965

Left to right seated: Mr. V. R. Coles, Mr. T. N. S. Harrower, Mr. J. K. Bannon and Mr. N. Bradbury (Assistant Directors) and Mr. E. Knighing (Deputy Director) (see p. 28).

Acknowledgements.—The data used in this discussion have been based upon the *Monthly Weather Report* and on unpublished information, for earlier periods, supplied by the Meteorological Office. Acknowledgement should be made also for details kindly supplied by the Santon Downham District Office and by Mr. J. M. B. Brown of the Forestry Commission.

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551.558.21:629.13

SEVERE TURBULENCE AT LOW LEVELS OVER THE UNITED KINGDOM

By R. A. CASHMORE

Förchtgott's observations on turbulence in rotor-streaming at low levels made in rugged mountainous terrain in Central Europe are well known. There is an excellent summary in the WMO *Technical Note* on "The airflow over mountains"¹ which indicates that the requirements for rotor-streaming appear to be "high static stability and strong winds confined to a limited layer no more than about $1\frac{1}{2}$ times the height of the hills". The text continues : "Förchtgott's work contains some well-documented cases of this particular variety of turbulence, but the sparsity of similar observations from elsewhere suggests that the phenomenon is rare, presumably because of the lack of suitable airstreams in other regions". Before Förchtgott's paper appeared in 1949, the phenomenon was unrecognized. By that time civil and military aircraft were flying, at any rate in the United Kingdom, at heights well above $1\frac{1}{2}$ times the height of the hills ; but, now that low-level flying by high-speed military aircraft and by light aircraft is increasing, severe turbulence in rotor-streaming may well become more frequently experienced than it has been in the past.

A period of severe turbulence in the lee of the Pennines lasting more than two days in an easterly régime has been described by Dent and Dyson², and an example of rotor-streaming at Acklington in a westerly airstream has been described by Gray and Stewart.³ The object of this note is to present three more cases, two over Yorkshire to the lee of the Pennines and one over Scotland downwind of Ben Nevis ; these cases are particularly interesting because the measurements recorded in the aircraft give some idea of the vertical gusts involved.

Case 1.—At 1450 GMT on 5 January 1965 a four-jet aircraft flying at 1500 feet above sea level, airspeed 250 kt, on a south-easterly heading, was passing over the Nidd valley over Pateley Bridge, about 11 miles north-west of Harrogate. A stratocumulus sheet, base 3000 feet, was continuous over the Pennines but broken over the Vale of York with a clear lane adjacent to the flight path of the aircraft. Approaching the Nidd valley the pilot observed a small dome-shaped cloud ahead, base 1500 feet, top 2000 feet, lateral dimension

about 2500 feet ; the top of the cloud was smooth, the base ragged. Just as the aircraft was entering this cloud, sudden violent short-period pitching oscillations were experienced, and the registered accelerations ranged from $-0.75g$ to $+2.1g$. The pilot climbed to clear the turbulence which continued in some degree until the level of the stratocumulus top was reached at 4500 feet. Aughton, the nearest radiosonde station upwind, reported winds from 290° at 1200 GMT, the wind thus being roughly at right angles to the ridge, and a marked inversion at about 880 mb, in good agreement with the observed position of the stratocumulus top. The maximum vertical acceleration produced an effect on this aircraft equivalent to vertical sharp-edged gusts of 37 ft/s upwards and over 60 ft/s downwards in rapid succession.⁴ (The meter in undisturbed level flight records $+1g$).

Case 2.—At 1530 GMT on 26 February 1965 a similar aircraft at 1000 feet above sea level on an easterly heading was flying at 240 kt over Loch Leven, south of Ben Nevis, in relatively smooth conditions when sudden severe turbulence was experienced. The main upwind ridges all lie east-west. The Stornoway radiosonde ascent for 1200 GMT showed a stable layer at 800 mb and a northerly wind constant in direction with speed increasing with height. Vertical accelerations of between 0.0 and $+2.0g$ were recorded.

Case 3.—This example also involved a similar aircraft flying to the lee of the Pennines but the inversion in this case was provided by an active warm front. The aircraft was at 2000 feet on route from Ouston to Lindholme, between 0001 and 0100 GMT on 18 June. The course lay parallel to and 100 n. miles ahead of the front. Continuous moderate to severe turbulence was experienced ; at one stage the pilot climbed to 6000 feet, but the turbulence did not decrease. The aircraft flew in and out of cloud, mostly between layers ; some turbulence existed all the time, but it was most severe at the cloud boundaries, as in Case 1. The Aughton radiosonde ascent for midnight was made 50 n. miles ahead of the front and a similar distance upwind of the aircraft track ; it showed an inversion at about 850 mb and wind speeds increasing with height. At Aughton the wind veered with height in the lower layers, but from this information alone it is difficult to say exactly what the wind direction was over east Yorkshire. Recorded vertical accelerations ranged between 0.0 and $+2.0g$.

Summary.—This note suggests that severe low-level turbulence may be more common than the published literature has hitherto established. It also indicates the nature and magnitude of the effect. Turbulence of this severity under a warm front at low level⁵ does not appear to have been documented previously and although Wallington,⁶ for example, mentions the possibility of lee waves ahead of a warm front, he makes no mention of the possibility of severe turbulence.

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METEOROLOGICAL OFFICE PARTICIPATION IN SEVERE STORM INVESTIGATIONS IN THE U.S.A. IN 1965

By T. W. HARROLD

During May and June 1965, a team of 29 persons (and also the writer) from the Royal Aircraft Establishments at Bedford and Farnborough was detached to the National Severe Storms Laboratory (NSSL), Norman, Oklahoma, to collaborate with the United States Weather Bureau in the investigation of the severe thunderstorms that occur in the area. The main objectives of the United Kingdom team were to obtain data on the operational and handling problems involved in flying aircraft through and near severe storms, and to obtain measurements of gusts. An additional aim was to attempt to use the data obtained to derive a model (or models) of the airflow in and around the storms and in connexion with this it was decided that a meteorologist should accompany the team.

Oklahoma was chosen as the location of the project because of the high probability of severe thunderstorms in the State during spring, and because of the excellent ground radar facilities at the NSSL. Radar is an essential tool in any investigation of the storms since it provides detailed information on their structure, and it can be used to guide aircraft to suitable locations. During past seasons the Weather Bureau has acquired considerable experience in using weather reconnaissance aircraft, in conjunction with radar, to investigate the structure and physical processes associated with thunderstorms, and this experience was of great value to the British team.

Three British aircraft were taken on the project. A Scimitar FI, a single-engine jet fighter, was used to fly through storms, usually at altitudes between 30,000 and 38,000 feet, depending on the height of the storm tops. It was equipped with instrumentation for measuring the vertical component of turbulence. During the 5 weeks the aircraft was in Oklahoma, 65 storm penetrations on 19 days were made. Generally the Scimitar worked in conjunction with an American F-100 aircraft, each penetrating a particular storm in turn. Two Canberras, a B 6 and a PR 9 flew around and over the storms. Both of these made gust and temperature measurements and were equipped with a Doppler navigator system which provided wind measurements. In addition, the PR 9 carried an airborne radar, while the B 6 had equipment for producing smoke trails, which gave an additional indicator of air motion. The Canberras flew at altitudes mostly between 40,000 and 45,000 feet.

At Norman, a WSR-57 radar, which has a 2-degree pencil beam and a wavelength of 10 cm, showed the location of storms to a range of 250 nautical miles on a Plan Position Indicator (PPI). A calibrated attenuator enabled the reflectivity to be measured, and the aerial was programmed to scan at a series of elevations, thus providing information of the three-dimensional structure of the storms. As well as a conventional PPI display there was a contoured display on which the reflectivity of a storm was shown as a series of light and dark contour bands. Dr. Lhermitte of the NSSL is also developing an *integrated* contour display which is an improvement on earlier displays in that it integrates a sufficient number of radar pulses to remove the fuzziness which normally occurs at the edges of echo because of the noise-like nature

of the signal. In addition to the WSR-57 radar, a MPS-4 4.7-cm radar provided range-height data on storms out to 80 n. miles. This radar was operated by the writer. Aircraft movements were observed on a PPI display from a 10-cm CPN-18 air traffic control radar at the laboratory. This radar provided a continuous record of the position of the aircraft relative to the storms to a range of 110 n. miles.

After a quiet period at the beginning of the detachment, thunderstorms, sometimes with hail and tornadoes, occurred on several days within 150 n. miles of Norman. These storms often developed into extensive squall lines, sometimes extending several hundred miles with cumulonimbus tops between 40,000 and 50,000 feet. Cloud tops over 60,000 feet have been observed in previous years but the highest during our detachment was 55,000 feet. On other occasions storms were more isolated but some of these were also severe, with strong winds, hail and tornadoes. One of the most interesting meteorological situations was on 27 May 1965, when two storms developed less than 20 n. miles apart. One of these, with a top around 40,000 feet, moved north-north-east at about 25 knots whilst the other, with a top over 50,000 feet, moved east-south-east at 20 knots. Three hours after their formation these storms were over 100 n. miles apart. A Canberra flying at 43,000 feet around the larger of these storms encountered a temperature change of 12 deg C in a little over 1 n. mile. The occurrence of storms close to Norman was rather disappointing, with only four storms passing overhead, three of these at night. However these were active storms by British standards, one of them producing about an inch of rain in 15 minutes and another wind gusts of 75 knots.

The writer found it exhilarating to participate in a project of this magnitude and to co-operate with people from a variety of disciplines. The first-hand experience of some of the effects of severe weather, both in the air and on the ground, was also very interesting. The detailed analysis of all the data acquired on this detachment will be a lengthy task but work is proceeding. It is a pleasure to record the excellent co-operation received from Dr. E. Kessler, Director of the NSSL and all of his staff.

551.509.313:551.511.3:061.3

INTERNATIONAL SYMPOSIUM ON DYNAMICS OF LARGE-SCALE PROCESSES IN THE ATMOSPHERE, MOSCOW, 23-30 JUNE 1965

The International Symposium on Dynamics of Large-Scale Processes in the Atmosphere held at the University, Moscow, from 23-30 June 1965, was jointly sponsored by the International Association of Meteorology and Atmospheric Physics and the World Meteorological Organization. Its purpose was to provide a forum for papers and discussion on the scientific aspects of global weather processes and to describe the most important problems that require solving before further progress can be made in large-scale weather forecasting.

There are three main types of problem. First, the problem of how to express the physical ideas in a simplified form in mathematical terms, then, that of actually solving the mathematical equations which have been evolved and finally the problem of obtaining the necessary data to enable one to use

the mathematical formulation. The first two problems are often treated together as a single problem because the people who formulate the equations are also the people who solve them. There is a danger here of the advantages of the most recent advances in mathematical techniques being lost owing to lack of communication between mathematicians and meteorologists. The mathematical techniques are usually the least discussed aspects of the problem and the papers that dealt specifically with methods of representing and integrating the equations were very welcome.

The papers dealing with actual integration of the equations of motion over short and long periods were a reminder that the solution of the problems of carrying out such computations is now at a more advanced stage than seemed possible only five years ago. There is now good qualitative agreement between the climatology of some of the models and the observed climatology, although in some cases it is perhaps difficult to be sure that the initial assumptions, sometimes expressed empirically, are not responsible for the good agreement. Almost everyone in the field would agree that there is still a very long way to go, but that progress so far has been most encouraging. It is perhaps worth noting that some of these computations are among the largest ever undertaken by man and make use of the most advanced giant computers.

The interest aroused by the discovery of the 26-month cycle has led to much research both on the tropical cycle itself and parallel cycles in extra-tropical zones. There were a number of fascinating papers concerned with this problem, dealing with the dynamics as well as relating the cycle to the circulation patterns in mid-latitudes, to the winter stratospheric warming, and so on. Perhaps the general opinion at the end of the conference was that the cause of the cycle remains as mysterious as when the cycle was first discovered.

Probably the greatest interest at the symposium was aroused by the problem of the data required in order to make longer-term predictions. It is well recognized that observations on a global scale are necessary, but are available in sufficient quantities only in the well-populated areas in the mid-latitudes of the northern hemisphere. The oceanic areas in each hemisphere are singularly lacking in data, despite the provision of weather ships. It seems that the traditional methods of making atmospheric observations are too expensive to allow a global coverage and that new and cheaper methods of obtaining the data are necessary. Such methods might include the use of buoys and constant-pressure balloons carrying instruments of new type and the use of satellites both to probe the atmosphere and to act as collectors and distributors of data. Experiments are about to be carried out, by both the U.S.A. and France, to establish the use of constant-pressure balloons and the next decade could well see a revolution in the methods of obtaining data and a vast increase in the amount available over the surface of the earth.

The symposium gave us the opportunity to discuss more easily with our Russian colleagues the problems that are of interest to all meteorologists. Our hosts were charming and provided all the facilities needed for a very successful meeting.

E. KNIGHTING

EVAPORATION FROM A RESERVOIR NEAR LONDON

By D. J. HOLLAND

Readers expecting reviews here to be of works by meteorologists might at first be surprised that this is a review of a paper* from an engineer in an engineers' publication. If so, however, they are perhaps also a little surprised — and perturbed — that the mean loss of water by evaporation from a reservoir near London is just about as large as the top-up received from the rainfall.

Not that this is news. It is not, in fact, the paper's main point. G. J. Symons, founder of the *Meteorological Magazine* and pioneer of the standard evaporation tank (*British Rainfall*¹), had already collected, in *British Rainfall* 1869,² many studies of evaporation, one of which in particular — from C. Greaves, M.Inst.C.E., Engineer-in-Chief to the East London Water Works — actually indicated from a site near London a 10-year total evaporation amounting to more than 200 inches. And although the relevance of French data to London might be questioned at first, there undoubtedly was some relevance in an adjoining résumé (*British Rainfall* 1869,² p. 160) of data culled many years earlier from Dijon, and obtained with the aid of 8-foot square water-filled zinc-lined tanks which would seem to have been forerunners of the 6-foot square tank introduced by Symons. The Dijon annual mean evaporation for 1846–52 was apparently 26.1 inches, almost exactly balancing the 26.9-inch rainfall, and it is worth remarking that an annual mean evaporation of 26.1 inches is the very figure for 1956–62 now published in Mr. Lapworth's paper for the reservoir near London; 24 inches had meanwhile been registered by a tank of Symons' pattern while the rainfall was 25 inches. Nearly a century later, in a well-known paper,³ Penman estimated what he described as the hypothetical open-water evaporation, remarking that it might be of direct use in estimating losses from reservoirs. The annual totals of his estimates for stations in southern England all lay between about 23 and 30 inches. The value computed by him from data of Kew Observatory, in particular, namely about 28 inches, proved to be highly pertinent to Mr. Lapworth's work, not only because the reservoir under discussion was not far from Kew, but also because Dr. Penman himself, serving on the Evaporation Subcommittee which had been convened by the Hydrological Research Group of the Institution of Water Engineers for the express purpose of investigating the evaporation of this particular reservoir, proceeded to work out a fresh estimate based on data for the relevant period 1956–62. The final table of the Appendix to Mr. Lapworth's paper is actually a worked example of the present-day scheme of 'Penman' evaporation computation, from the hand of Dr. Penman himself. Worked examples which are as authoritative as this are seldom seen in print, and this one therefore has notable scarcity value.

What was special about the body of water under discussion, rendering it unique for the purpose in hand, and possibly raising the investigation into the ranks of the classics, was simply that no piped water passed in or out

* *Evaporation from a reservoir near London*, by C. F. Lapworth. 8½ in × 5½ in, pp. 18, *illus.*, reprinted from *J. Instn wat. Engr, London*, 19, No. 2, 1965, Institution of Water Engineers, 11 Pall Mall, London SW 1. Price: 5s.

at any time in a long term of years, the reservoir being nearly full but entirely untapped. Water level was thus governed solely—or almost solely—by rainfall and evaporation, on much the same principle as in the Symons type of tank and in well-known variants on the same basic scheme of gauging (e.g. the 'Class A' pan). The adventitious evenness of the natural balancing of those two factors in that particular locality duly kept the reservoir nearly full all the time ; and by recording the day-to-day fluctuations of water level along with the day-to-day rainfalls it was possible to get a long series of what were effectively direct measurements of daily, monthly and yearly evaporation from more than 40 acres of open water, and to test the tank and pan and other methods against them.

A test combining such size with such directness had never been achieved in this country before. Direct checks of the Penman type of estimate of open-water evaporation had hitherto been almost unobtainable, too, as Penman had said in his 1950 paper.³ Admittedly wide acceptance had already been gained by Penman's method as applied to potential evaporation of vegetated ground, provided that nobody rated its accuracy very high. And although some high hopes were pinned on the 'Class A' pans that were going to be tried in Britain there had of course been generations of users of standard evaporation tanks, who, even if lacking an absolute accuracy test, had probably been quite happy to note the unfailing station-to-station coherence displayed by their data in the long run.

But the tanks had long been the subject of misgivings in certain quarters. Symons' original one, though seemingly keeping in quite good shape, had always read curiously low for London (it was at Camden Square until 1955) ; the much newer one at Kew read higher, and other fairly new ones in various places behaved like Kew's. A tank like Kew's was sited, at Kempton, alongside the reservoir, together with such rain-gauges and other instruments as were favoured by the Subcommittee in general and by the Meteorological Office and Metropolitan Water Board (MWB) members of it in particular ; and a programme of regular measurements was duly carried out—largely by the local MWB staff—from 1955 onwards. A 'Class A' pan, too, was installed when available, somewhat as was done at Kew Observatory at the time of the International Geophysical Year. The reservoir evaporation measurements ceased early in 1963 when everything froze ; but the pan and tank and rain-gauge readings went on afterwards and are going on still. The Subcommittee's report, in the form of Mr. Lapworth's paper, covers the 7 complete years 1956-62. The project ran into some problems, the solving of which indirectly involved organizations as far afield as the National Institute of Oceanography. Then there slowly emerged fairly clear-cut results, and whilst the discussion of them in the report is largely confined to the observations at Kew and Kempton the present review takes the opportunity to link them with what has meanwhile been found elsewhere in Britain.

The Kempton reservoir's evaporation, in brief, has been well matched by Penman's estimate when a physically rational allowance has been made for the deep water's albedo and heat-storage properties ; and it has been nearly—though not quite—matched (again after allowance for heat storage) by evaporation from Kempton's standard tank, which in turn has matched

Kew's almost perfectly on the average and has been in good accord with such tanks elsewhere as have been similar in all essentials *including freedom from major windbreaks*. (This last is now held to be a key requirement—key to why many of the older tanks read low.) All such tanks seem concordant, and moreover by a recent scheme of co-ordination of data from many sources in Britain, the Meteorological Office has indicated that every such tank has been registering what is approximately the potential evaporation of grass-land. (That this should be a little less than from deep water, of course, makes sense in terms of albedo, though admittedly the albedo of water-filled tanks is still a moot point). These tank findings have allayed former misgivings and have at least restored the tank technique to its original favour, if not indeed brought it into as high a favour as Penman's method, subject to the need to watch out for signs of over-shadowing of sites by windbreaks such as must have inhibited evaporation from Symons' tank at Camden Square.

Evaporation from Kempton's 'Class A' pan, on the average, was about 1.5 times its tank counterpart, or 1.4 times the evaporation of the reservoir. The scaling factor of 0.7 from pan to reservoir accords more or less with textbook ideas, and if other stations with pan-tank comparisons had had pan-tank evaporation ratios likewise averaging about 1.5 then all pan data would in effect have been parallelling the tank data. The 'Class A' type of pan — a United States Weather Bureau standard — had long had a reputation for being rather handier than the Symons invention, and so any such parallelling might well have permitted the pan to oust the tank as Britain's standard evaporation gauge. But in fact other stations have given ratios markedly different from 1.5, even after averaging over several years. Kew's figure, for instance, has been about 1.3. Each of several stations in Britain, having 'Class A' pan and adjacent standard tank exposed conventionally, has displayed its own characteristic pan-tank evaporation ratio, year after year ; but, although a station-to-station comparison has shown a lot of 'tank' coherence and some 'pan' coherence, it has shown striking incoherence among the ratios. Mr. Lapworth touches upon the Kew-Kempton disparity but does not dwell upon it, and readers in Britain might thereby have been lulled into too ready an acceptance of the idea of simply using a 'Class A' pan and multiplying the answer by about 0.7. Even the American recommended procedures for refining this rule, notwithstanding their textbook status, are clearly inadequate in Britain, and the whole technique has been falling from favour, at least in Meteorological Office circles.

Incidentally, readers of Mr. Lapworth's graphs of reservoir evaporation against "monthly evaporation using Tank" and against "monthly evaporation using Pan", will find that they have been left to think out for themselves, in the light of the paper's text, how to interpret the phrases "using Tank" and "using Pan". Scaling-factors and heat-storage terms have been quietly built into these graphs' construction, though the captions do not make this clear ; and anyone who is impressed by the overall matching of the estimates to the observations should bear in mind that the scaling factors were so designed as to achieve just this. The same can be said of yet another of the graphs, the one which shows reservoir evaporation against "monthly evaporation using Walker's method". Walker's method, by the way, a superficially attractive simplification of Penman's, emerges here from comparative

obscurity, virtually with Dr. Penman's blessing. Readers seeking to use it equally effectively elsewhere, however, should think twice. The simplifications which underlie it are to some extent just a happy accident.

The final item of Mr. Lapworth's own summary is salutary: "Values for individual months estimated by any of the four methods (tank, pan, Penman, and Walker) can vary from reservoir evaporation by as much as $\pm \frac{1}{2}$ inch".

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REVIEW

Die Tagebücher Franz de Paula Haslingers. Witterung und Klima von Linz: Anhang Band 1 1796–1817, Anhang Band 2 1818–1833, edited by Georg Wacha. $9\frac{1}{2}$ in \times $7\frac{1}{2}$ in, pp. 259 and 212, Stadtmuseum, Linz, 1962 and 1964. Price : not available.

The first two sections of *Witterung und Klima von Linz*, a work published by the Stadtmuseum, Linz, in collaboration with the Zentralamt für Meteorologie und Geophysik, Vienna, were published in Linz in 1959. Section I by Georg Wacha, *Zur Wetterchronik des Linzer Raumes*, dealt in 80 pages with records from Linz and its surroundings from the Middle Ages down to about 1850, including tabular summaries of the daily observations of Haslinger from 1796 to 1833 now published *in extenso* in the volumes under review, which have also been worked up by Georg Wacha — Band 1 1796–1817, Band 2 1818–1833. Other interesting material in section I included brief daily weather notes from the observations of the astronomer Kepler at Linz from 1617 to 1626, tables giving daily values of temperature for the years 1760 and 1767 and a full list of the dry and wet spells of the period 1796–1833. Section II by Maria Roller, *Die 105-jährigen meteorologischen Beobachtungen in Linz von 1852 bis 1956*, also published in 1959, gave in 76 pages not only serial values of monthly mean temperatures, etc. for each year, but tables of overall averages and frequencies of almost every imaginable aspect of the local climate.

This work makes Linz, which lies on the Danube in Upper Austria, surely the city in all the world with the most accessible climatic history and about the most comprehensively summarized modern climatic data — just as Vienna, by another series of publications produced jointly by a city council and the Austrian weather service (*Klima und Bioklima von Wien*, Volumes I, II and III published in 1955, 1957 and 1959 respectively) can claim the most thoroughly investigated and documented study of local climates and microclimatic effects within a city.

Franz de Paula Haslinger (1765–1833), assistant priest in Hörsching on the south-west environs of Linz from 1789, pastor in Gallneukirchen a few miles north-east of Linz from 1797, and holder of various appointments at the Cathedral of Linz from 1806, was a devoted priest who recorded not only the weather (mostly with three temperature observations daily) but also visitations of the sick, etc. His 38-year record is the more effective as a

climatological document because he spent his working life within about 10 miles of Linz. His journals have survived *in toto*, apparently preserved till 1844 by relatives in the book trade, thereafter in the Oberösterreichische Landesarchiv at Linz. These volumes contain only the daily weather observations but at the end of Band 2 there is an 11-page glossary of the abbreviations used.

It may be doubted whether there is much of a market for such a complete reproduction in print of a weather diary of long ago. However, these two small volumes make a worth-while addition to the documented weather of the times before daily weather maps and should be available in the archives of meteorological institutions concerned with the functioning of our climate over the longest period for which it can be accurately known. Microfilm might have been more appropriate as the method of publication, to reduce bulk in storage, but these books produced by a lithographic process are better for the reader. The years contained happen to be of special interest being a harsh period of the Little Ice-age cold epoch, especially in north-west Europe, although possibly less marked in central Europe which escaped the rigours of 1816 and where the summers of 1826 and 1822 were notably hot, but still with many severe winters.

H. H. LAMB

AWARDS

L. G. Groves Memorial Prizes and Awards

The presentation of the L. G. Groves Memorial Prizes and Awards for 1965 was made by Major K. J. Groves in the Historic Room at the Ministry of Defence, Main Building, Whitehall on 8 November 1965. The presentation was presided over by Air Marshal Sir Christopher Hartley and attended by the Director-General of the Meteorological Office, Dr. B. J. Mason (see Plates II, III and IV).

The Memorial Prize for Aircraft Safety was awarded to Mr. M. J. Forrest of Loughborough, Leics., for designing an illuminated aid — simple, accurate, completely self-contained and easily portable in the field — to help visual landing by helicopters at night in difficult terrain. The equipment is adjustable to enable a helicopter to clear surrounding obstacles and land in a small open space which could previously only be used in daylight. Above all, it is virtually fool-proof, both to set up on the ground and for the pilot to follow. The 'Nightlight' approach and landing aid, to give it its correct name, is, says the citation, a "valuable contribution to aircraft safety".

The Memorial Prize for Meteorology was presented to Mr. L. P. Smith, B.A., a Senior Principal Scientific Officer at the Meteorological Office, Bracknell, for his work over 15 years as a pioneer in the investigation of meteorological factors affecting problems of agriculture, horticulture and forestry. The prize is given for the most important contribution to the science of meteorology or its application to aviation. Mr. Smith has discovered several relationships of practical value between meteorological parameters and animal and plant diseases or crop yields. The citation says: "He has also investigated the influence of climate on the distribution of grass and other crops, and devised techniques of forecasting milk production from weather observations. Recently

he has devoted attention to climatic change and its consequences for agriculture, which he has shown to be of considerable economic significance”.

The Meteorological Observer's Award went to Mr. A. Sandland of Birmingham, for his work in Weather Ships over more than 12 years. When he returned to Britain recently in the *Weather Monitor* he had just made his 99th voyage. “His long experience and expert leadership”, says his citation, “have proved invaluable in the training of new meteorological staff on Ocean Weather Ships, in their sometimes dangerous duties in rough weather. He helps them to accustom themselves to the unfamiliar conditions of life at sea, and encourages them to share his own pride in the tradition that the observing programme must be maintained in all weathers”.

Chief Technician D. B. Parry of RAF Waddington, received the Second Memorial Award. He has designed a slim, light-weight back parachute pack which can be worn during flight, and does not impede exit, by navigators in B(I)8 Canberra aircraft. If they are above average size, navigators have hitherto experienced difficulty in leaving the aircraft in emergency because of the bulky chest parachute pack.

METEOROLOGICAL OFFICE NEWS

Forecasting for non-aviation purposes is increasing year by year, not only through the establishment of weather centres in large towns but also because outstations which were set up to meet aviation needs are dealing more and more with enquiries of a more general nature. A tribute to the work of one of these stations is the subject of the following letter which was sent to the Prime Minister.

NATIONAL FARMERS' UNION—LINCOLNSHIRE BRANCH
ISLE OF AXHOLME BRANCH

N.F.U. Office,
Temperance Hall,
Epworth,
Doncaster.
25th September, 1965.

Sir,

I feel I should like to draw your attention to the splendid work which the Meteorological Office at Bawtry has performed during the last season.

As representative of the farmers in this district who have, as you are no doubt aware, been faced with a long and difficult cereal harvest, I would like to pay tribute to the unflinching courtesy, technical knowledge, accuracy and — not least — the good humour of the officers who man this particular and important service.

I have personally utilised this “free” service as perhaps it has never been used before. I have rung them up at all hours. And, perhaps quite unknown to the officers who man this service, they have unwittingly saved us many thousands of pounds in the effective manner in which they have enabled us to deploy our labour to the best advantage.

The harvest, Sir, is nearly accomplished. And it would be quite easy for the Met. Service to be forgotten. Their usefulness is taken for granted. If I knew their superior officers I would write to them and express our gratitude.

But, I feel sure that you will do this for us, and let them know that the farming community owe them a debt of gratitude.

I am, Sir,

Yours faithfully,

R. B. KITSON
Branch Secretary

The Right Hon. Harold Wilson, P.C., M.P.,
10, Downing Street,
London, S.W.1.

Press Conference

The Director-General held a Press Conference at Bracknell on 2 November, 1965 to mark the introduction of routine numerical forecasts in the Meteorological Office. The Conference was attended by a wide cross-section of the national and technical Press, the BBC, and a large corps of photographers.

An introductory talk by the Director-General was followed by 45 minutes of lively questioning. The Press were then invited to watch the production of the first routine chart on the line printer, each correspondent receiving a souvenir copy. There followed visits to the Central Forecasting Office and informal discussions with senior members of the staff.

The Conference was reported on radio and television, produced leading articles in *The Times* and the *Financial Times* and was extensively reported in the national and local Press. The substance of the Director-General's talk is given below:

Ladies and gentlemen, it gives me great pleasure to welcome such a large and distinguished gathering of the Press to the Meteorological Office. Today is a landmark in the history of forecasting in the Office — a history which goes back more than a century — because this afternoon you will see the production of our first routine numerical weather forecast by the computer. But first I should like to introduce some of my colleagues (see Plate V) who are involved in this important project, and then take a few minutes to explain how the machine forecast is produced, its significance, its limitations, and something of our plans and hopes for the future.

As many of you will know, the traditional techniques of weather analysis and forecasting involve the preparation, at regular three- or six-hour intervals, of maps that give a two-dimensional representation of weather conditions at the earth's surface and at a number of levels in the upper air. Observations of pressure, temperature, humidity, wind and so on, made simultaneously at fixed hours at hundreds of stations all over the world are transmitted as quickly as possible to all countries on an internationally agreed basis. When these data are plotted on the maps the forecaster draws lines (for example isobars connecting places recording the same pressure and isotherms connecting places at the same temperature) which emerge as recognizable patterns that reveal the position, structure and evolution of weather systems. After careful study of these patterns in relation to similar charts for earlier times, the forecaster can extrapolate for some hours ahead the tracks of the main depressions and anticyclones and the movements of such features as troughs, ridges, fronts and rain areas. Here the forecaster relies upon a number of well-tested rules, his understanding of the physical processes, his experience of how similar situations have developed in the past, and his intuitive feeling for how the atmosphere works. This judicious combination of knowledge, experience, intuition, judgement and flair introduces a subjective element into the forecast. Nevertheless, even under the difficult conditions experienced in the British Isles, the main features of the daily forecast are correct on about 85 per cent of occasions ; not unnaturally the public tends to remember only the mistakes which, by the way, are usually errors of timing.

But over the years it has become apparent that the traditional techniques have been pushed nearly as far as seems profitable ; at any rate there is no

real hope of further major improvements. The objective is, of course, more comprehensive, detailed and accurate forecasts that will remain reliable for longer periods ahead. Among other things, this will require many more observational data from larger regions of the atmosphere. Now clearly there is a limit to the quantity of data that a human forecaster can assemble, assimilate, analyse and interpret in the short time allowed by the fact that he has to keep well ahead of the actual weather. This is where the big computers come to the rescue. They are able to handle huge quantities of data and perform vast numbers of mathematical calculations at very high speed. For example, our KDF9 computer, named COMET, can make an addition or subtraction in one millionth of a second. We have, of course, to tell it exactly what to do and how to do it.

I shall now try to explain, in simple terms, the procedure for making a numerical forecast. We work with a large section of the atmosphere stretching from Hawaii to Malaya, from the North Pole to central Africa, and extending up to a height of about 40,000 feet, and we concentrate on developments at three levels — at the surface, at 20,000 and at 40,000 feet. We subdivide this huge region by a grid, similar to lines of latitude and longitude, that provides 1300 regularly-spaced grid points. Fed with weather observations made simultaneously from 1200 land stations, 300 ships, and 600 radio-sounding balloons that transmit information on pressure, temperature, humidity and wind up to heights of 100,000 feet, the computer assigns a value for the pressure and temperature at each grid point at a convenient 'zero' hour. We also supply the computer with a very simplified mathematical description of the atmosphere — a set of differential equations to describe the gross behaviour of the air in our region and to allow the machine to compute how the pressure and temperature will change at each grid point during the next hour. (In practice it is more convenient to work in terms of two parameters called contour heights and thickness patterns, but these are closely related to pressure and temperature.) Using these new values the computer then carries the calculation forward in steps of one hour until, eventually, we have a forecast, for 12 or 24 hours ahead, of the distribution of pressure and temperature at the three levels. In addition, the machine calculates the large-scale vertical motions of the air which indicate regions of widespread cloud and rain and of dry settled weather. The whole operation takes less than one and a half hours.

Here I must emphasize that, because we are using only a very simplified model of the real atmosphere, the computer at present calculates only the gross features of the pressure and temperature field — the position and movement of the large weather systems such as the depressions and anti-cyclones. It does not attempt to deal with the detailed weather such as the occurrence of showers, thunderstorms and fog; these are added by conventional methods. Some progress along these lines is possible, at least in principle, but you will appreciate the magnitude of the problem when I tell you that one of our current research investigations on the development of a simple pair of fronts taxes the largest computer available in this country.

We show here a series of computed charts forecasting the conditions at midnight tonight; for comparison we also show the corresponding charts drawn by the human forecaster. I think that you will agree that, as far as

the positions and magnitudes of the main pressure centres are concerned, the correspondence is very good. Such agreement is fairly typical in that, during the research trials, the computed forecasts of surface conditions were, on average, about as good as those produced by an experienced forecaster, while the computed upper air charts were consistently a little better. This degree of reliability in the numerical prognosis of the large-scale pressure field, essential to the production of a good weather forecast, is most encouraging. So, from today, the computed charts will serve as an additional aid to the forecaster. For a time he will continue to draw his conventional maps and use the machine forecast as a strong second opinion, but we hope and expect that, within a few months, he will acquire sufficient confidence in the computed charts to accept them unchanged. Since the machine actually prints the predicted values of pressure and temperature at each of the grid points on the chart, and will shortly be drawing the isopleths automatically, the forecaster may look forward to being relieved of much donkey work and to having more time for analysis and interpretation of his data and for presentation of his forecast to the customer.

Looking into the future, to more accurate forecasts for three, four or more days ahead, we shall need a number of things : a deeper understanding of how the atmosphere works on a global scale ; a more sophisticated mathematical description of the atmosphere ; many more observational data, particularly from the oceans and tropical regions and, perhaps, from the southern hemisphere; faster methods of communication to transmit these data; and bigger and faster computers. Given all of these and satellites too, we may look forward to gradual rather than dramatic improvements in the quality and range of the weather forecast. The atmosphere is an infinitely complex, subtle machine that will tax not only the largest computers, but more important, the best of our physicists and mathematicians for many years to come. Therein lies the challenge.

Dr. K. H. Stewart — special merit promotion to Senior Principal Scientific Officer

Dr. K. H. Stewart joined the Meteorological Office in 1949 following four years postgraduate research at Cambridge University on ferromagnetism. Apart from the usual training in synoptic meteorology, Dr. Stewart's career in the Meteorological Office has been devoted entirely to research in the physics of the atmosphere. From 1951 to 1960 his main interest was in the physics of fog and poor visibility. This work was pursued first at Headquarters and later at Kew Observatory where Dr. Stewart was promoted to become Superintendent in 1957. Dr. Stewart's interpretation and analysis of the special observations of fog made at Cardington under his guidance has done much to bring out the complexities of the physical processes of fog formation and point the way to a more realistic understanding.

In 1960 Dr. Stewart was transferred to the newly-formed branch for the study of the high atmosphere, and he has been largely responsible for the design and execution of novel experiments made from the Anglo-U.S. satellite Ariel II and from the rockets fired at Woomera. For such experiments new instruments have to be designed to make observations of quantities previously

unmeasured, under conditions far removed from laboratory experience. Their success calls for deep physical insight into the behaviour of both instruments and atmosphere. It is particularly appropriate that Dr. Stewart's achievements in this field should be acknowledged by his promotion to Senior Principal Scientific Officer under the scheme for the promotion of officers of special merit.

J.S.S.

NOTES AND NEWS

New Zealand Meteorological Service

Dr. J. F. Gabites succeeded Dr. R. G. Simmers as Director, New Zealand Meteorological Service on 15 October 1965.

International Antarctic Meteorological Research Centre

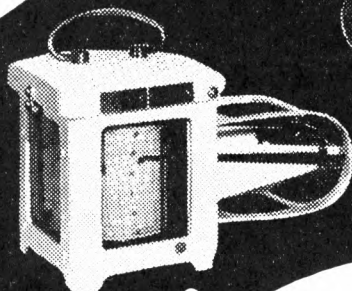
The following is an extract from a letter received by the Royal Society from the Secretary of the Scientific Committee for Antarctic Research (SCAR) of the International Council of Scientific Unions :

The Director of Meteorology in Australia has asked me to inform you that the International Antarctic Analysis Centre (IAAC) will in future be known as the International Antarctic Meteorological Research Centre (IAMRC). The change of title reflects a change in the type of work to be undertaken. Due to the establishment in Melbourne of a World Centre of the World Weather Watch, the IAAC has been relieved of the work of routine data and chart analysis, and the newly-oriented Centre is now free to concentrate on research related to Antarctic meteorology.

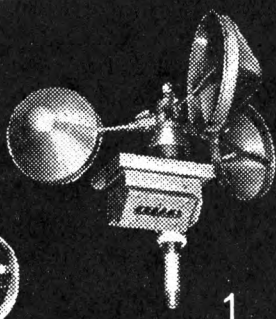
Under the new arrangements, research meteorologists will be free to pursue the lines of their individual interest, but it is emphasized that facilities will be available for overseas meteorologists attached to IAMRC to work in the Southern Hemisphere Analysis Centre if they wish to develop and extend their synoptic analysis experience. Mr. H. R. Phillpot, formerly leader of the IAAC, will be in charge of the new Centre. A full account of these developments and the present structure of IAMRC will be published in the January issue of SCAR Bulletin.

Meteorological Service of Portugal Retirement of Professor H. Amorim Ferreira

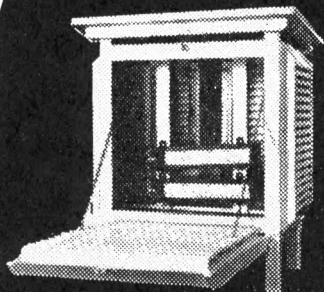
We have been informed that Professor H. Amorim Ferreira, former Director of the Meteorological Service of Portugal, retired from his post on 22 October 1965. Mr. José B. Blanc de Portugal will be responsible for the directorship until Professor Ferreira's successor is appointed.



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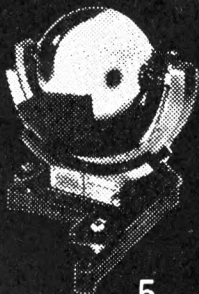
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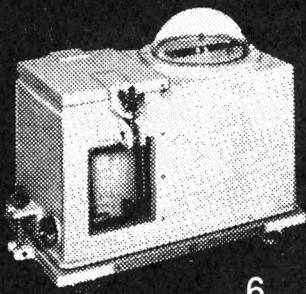
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CONTENTS

	<i>Page</i>
The forecasting of shower activity in airstreams from the north-west quarter over south-west England and South Wales in summertime. C. A. S. Lowndes	1
Low minimum temperatures at Santon Downham, Norfolk. J. Oliver	13
Severe turbulence at low levels over the United Kingdom. R. A. Cashmore	17
Meteorological Office participation in severe storm investigation in the U.S.A. in 1965. T. W. Harrold	19
International Symposium on Dynamics of large scale processes in the Atmosphere, Moscow, 23-30 June 1965. E. Knighting	20
Evaporation from a reservoir near London. D. J. Holland ...	22
Review	
Die Tagebücher Franz de Paula Haslingers. Witterung und Klima von Linz. Edited by G. Wacha. <i>H. H. Lamb</i>	25
Awards	
L. G. Groves Memorial Prizes and Awards	26
Meteorological Office News	
Press Conference	28
Special merit promotion to Senior Principal Scientific Officer	30
Notes and news.	
New Zealand Meteorological Service	31
International Antarctic Meteorological Research Centre ...	31
Retirement of Professor H. Amorim Ferreira	31

NOTICES

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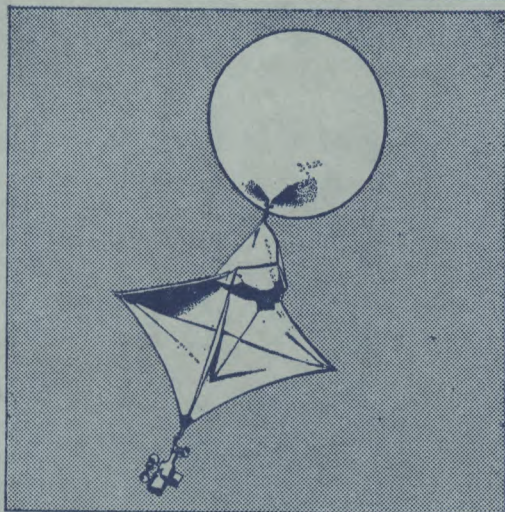
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THE METEOROLOGICAL MAGAZINE

Vol. 95, No. 1123, February 1966

551.513.1:517.512.2:532.59

THE BEHAVIOUR OF THE FIRST SIX ZONAL WAVE NUMBERS AT 50 AND 500 MILLIBARS DURING SOME WINTER MONTHS IN 1958 AND 1959

By G. R. R. BENWELL

Summary.—Results are presented of zonal harmonic analysis applied to the 50 and 500 mb height fields around the three latitude circles 40°N, 50°N and 60°N, during the two winter periods, 1 January 1958 to 28 February 1958 inclusive and 1 December 1958 to 28 February 1959 inclusive. The analysis was carried out on a daily basis since adequate data at 50 mb were available owing to the increased observations made during the International Geophysical Year 1958 and the International Geophysical Co-operation 1959.

The behaviour of wave number one at 50 mb was markedly dissimilar to the behaviour of wave number one at 500 mb; wave number two showed some correlation between the two levels, whilst wave numbers three to six showed closely paralleled behaviour over quite long periods of time at the two levels, even though there were marked differences in the overall behaviour of these wave numbers from one winter period to the next.

Introduction.—The scales of motion present in the atmosphere vary from the large-scale systems recognized by synoptic meteorologists as long waves in the flow pattern to the smallest eddies which can be detected by micro-meteorologists. Harmonic analysis applied to upper air charts permits the examination of the long-wave part of the motion.

The variation of a meteorological parameter, x , around a latitude circle, φ , of the northern hemisphere can be expressed in the harmonic form

$$x = A_0(x) + \sum_{n=1}^{\infty} A_n(x) \cos \left(n\lambda - \psi_n(x) \right)$$

where $A_0(x)$ is the mean value of x around the latitude circle, $A_n(x)$ and $\psi_n(x)$ are the amplitude and phase angle of the n th harmonic and λ is the longitude, increasing eastwards from $\lambda=0$ at the Greenwich meridian. The ridges of the n th harmonic are located at the longitudes

$$\lambda = \frac{\psi_n(x) + 2k\pi}{n} \quad (k = 0, 1, 2, \dots, n-1).$$

The fluctuations of x about its mean value $A_0(x)$ around the latitude circle are regarded as being composed of sinusoidal oscillations the wavelengths of which represent the scales of the motion systems present. Each harmonic gives an integral number of complete wave forms around a latitude circle and this number is referred to as the zonal wave number. The low wave numbers correspond to the large-scale motion systems. The amplitude $A_n(x)$ gives the amplitude of the sinusoidal oscillations representing wave number

n , and the phase angle $\psi_n(x)$ defines the position of the oscillation with respect to the Greenwich meridian. For example if the variation of x was almost entirely represented by wave number four the amplitudes of all the other wave numbers would be effectively zero and there would be four equal maxima and corresponding minima distributed equidistantly around the latitude circle.

It may also be noted that the zonal wave number one is the only wave number which permits flow over the pole, and it can therefore be accepted as giving a measure of the eccentricity of the flow. All the other wave numbers represent flow which is symmetric with respect to the earth's axis. The maximum wave number which can meaningfully be extracted by harmonic analysis is about 15 because of sparse data in some sectors and the inevitable smoothing of the data.

Van Mieghem¹ has dealt very fully with the representation by zonal harmonic analysis of the northern-hemisphere geostrophic wind field, and has appealed for more universal study of the general circulation by means of zonal harmonic analysis.

Teweles² presented some interesting diagrams showing the behaviour of wave numbers one to eight at 50 and 500 mb during January 1958, and mentioned one or two features of the behaviour pattern which required explanation and merited further study.

This paper presents the results of a somewhat similar investigation using data for two winter periods in 1958 and 1959. These winter periods were chosen since there were more complete data at high levels of the atmosphere than were available in earlier years : the increase of data was due to the extra meteorological observations made during the International Geophysical Year (IGY), 1958 and the International Geophysical Co-operation (IGC), 1959. The basic data consisted of the variation of contour height of the 50 and 500 mb surfaces around the three latitude circles 40°N, 50°N and 60°N : the heights were taken at intervals of 10 degrees of longitude and the harmonic analysis was carried out on the Meteorological Office computer, METEOR.

The purpose of the investigation was to determine whether there was any indication of coupling between the stratospheric and tropospheric flow patterns, as represented by the 50 and 500 mb pressure fields respectively. As far as possible it was decided to use data which had already been assembled on tape within the Meteorological Office, even though these data originated from different sources. In some ways this was an advantage since any similar behaviour noted between wave numbers at 50 and 500 mb would be a real effect and would not have arisen from the way in which the analysis at the two levels had been carried out. In the event the data for the five months used in the investigation, January, February and December 1958, and January and February 1959, were obtained from the following sources :

- (i) The 500 mb data for January 1958, February 1958 and December 1958 were largely extracted from data tapes held by the Synoptic Climatology Branch of the Meteorological Office ; these were made from punched cards received from the *Deutscher Wetterdienst*. The gaps in the data at 40°N, over the sector 160°E–180–130°W, and at 50°N, over the sector 180°–160°W, were filled in from the *Sinoptičeskij Bjulleten* issued by the Central'nyj Institut Prognozov, Moscow.

- (ii) The 500 mb data for January 1959 were extracted from the *Daily Series, Synoptic Weather Maps, Part 1, Northern Hemisphere Sea Level and 500 millibar Charts*, published by the U.S. Department of Commerce, Weather Bureau.
- (iii) The 500 mb data for February 1959 were extracted from the *Sinoptičeskij Bjulleten* issued by the Central'nyj Institut Prognozov, Moscow.
- (iv) The 50 mb data for January, February and December 1958 were extracted from *Daily 100-millibar and 50-millibar and three times monthly 30-millibar synoptic weather charts of the IGY period*, published by the U.S. Department of Commerce, Weather Bureau and the 50 mb data for January and February 1959 were extracted from the similar series of the IGC period, published by the same authority.

It was realized that the use of this rather hybrid set of data incurred the risk that some real effects might become blurred or obliterated since Barrett³ had shown that the use of contour charts drawn by different agencies resulted in different values of amplitude and phase angle for the harmonics, because of the subjective nature of the analysis over the areas of the chart where the observations were sparse. This subjectivity was expected to have considerable effects in the higher wave numbers. Attention was therefore confined to the study of the behaviour of the first six wave numbers. The amplitudes of each harmonic are given in units of geopotential metres, and ridge positions have been used to indicate the orientation of each harmonic in preference to the phase angle.

The daily changes in the first six zonal wave numbers.—Figures 1 to 6 show the daily changes in the ridge positions and amplitudes of each of the zonal wave numbers one to six for the two winter periods, 1 January to 28 February 1958 and 1 December 1958 to 28 February 1959. The harmonic analysis was carried out once daily for these periods, but for convenience the daily values have been connected together, by a continuous line as far as the 50 mb surface is concerned and by a broken line for the 500 mb surface. By this means it was hoped to show more clearly the day-to-day variation. No ambiguity arises in the case of amplitude, but some convention has to be adopted if it is desired to show the sequence of ridge positions in this way. The convention used in this paper was to select the ridge position as that which required the smallest longitudinal shift from the previous day's position. If the shift was exactly equivalent to half a wavelength, then the progressive or retrogressive shift was chosen to agree with the shift over the preceding few days. Generally on Figures 2 to 6, only one of the possible 50 mb ridges has been indicated for these wave numbers two to six, but in order to illustrate the movement of the 500 mb wave relative to the 50 mb wave it was necessary to present more than one 500 mb ridge. For convenience on the diagrams the tracks of the various 500 mb ridges which travelled through the 50 mb ridge are marked as a series of broken tracks. Each track lasts for such period as is required for comparison with the 50 mb ridge.

One further comment is required concerning the apparent movement of the ridges, as indicated on these Figures. Most of the large shifts in ridge position occurred when the amplitude of the wave in question was very small. Such shifts therefore should not be given too much prominence and, in some

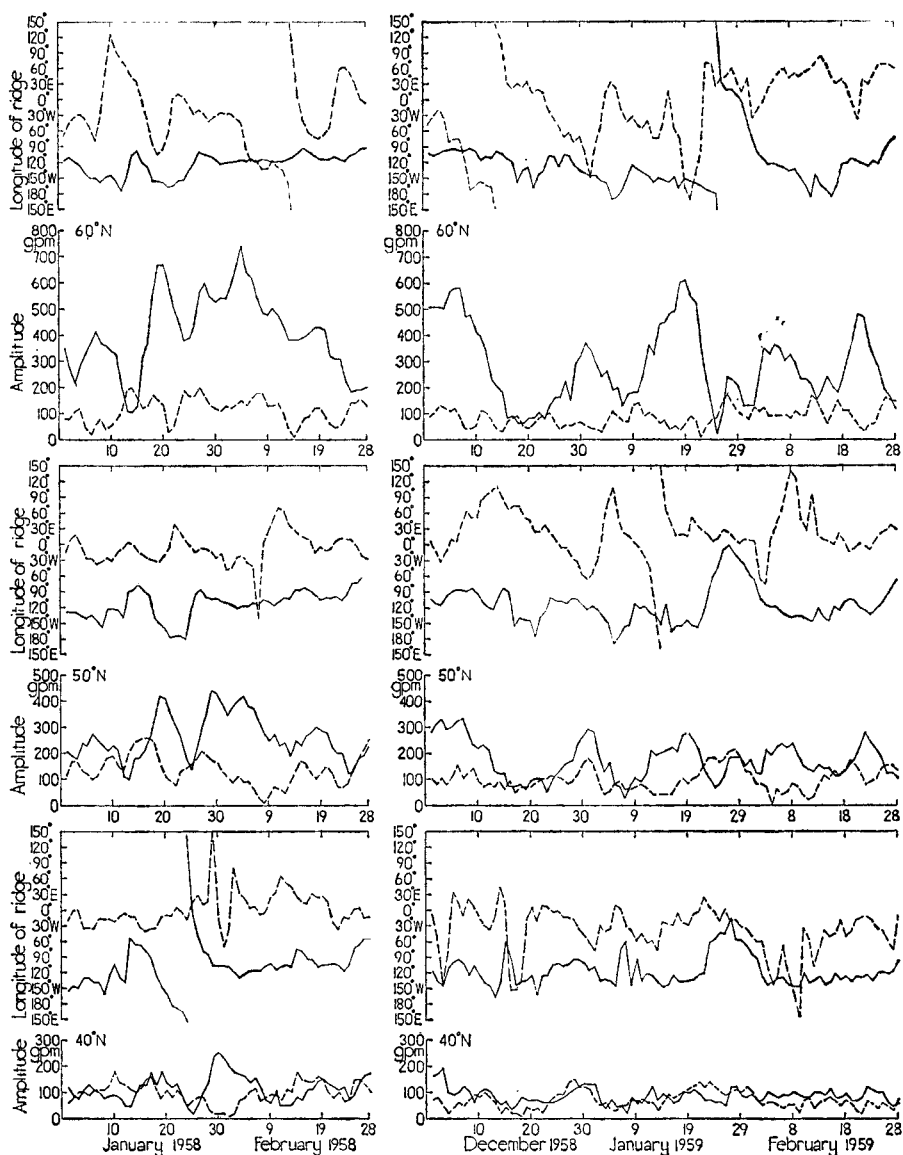


FIGURE 1—DAILY CHANGES IN RIDGE POSITION AND AMPLITUDE OF ZONAL WAVE NUMBER ONE AT 50 AND 500 MILLIBARS IN THE TWO WINTER PERIODS

— 50 millibars
 - - - 500 millibars

ways, it would appear better to confine the study of the behaviour patterns to those periods when the amplitudes are sufficiently large (possibly employing some kind of significance test to determine this). However, as Teweles² has noted, even when the amplitudes of some of the higher wave numbers were low, there often appeared to be a coherent and consistent movement of the wave in question.

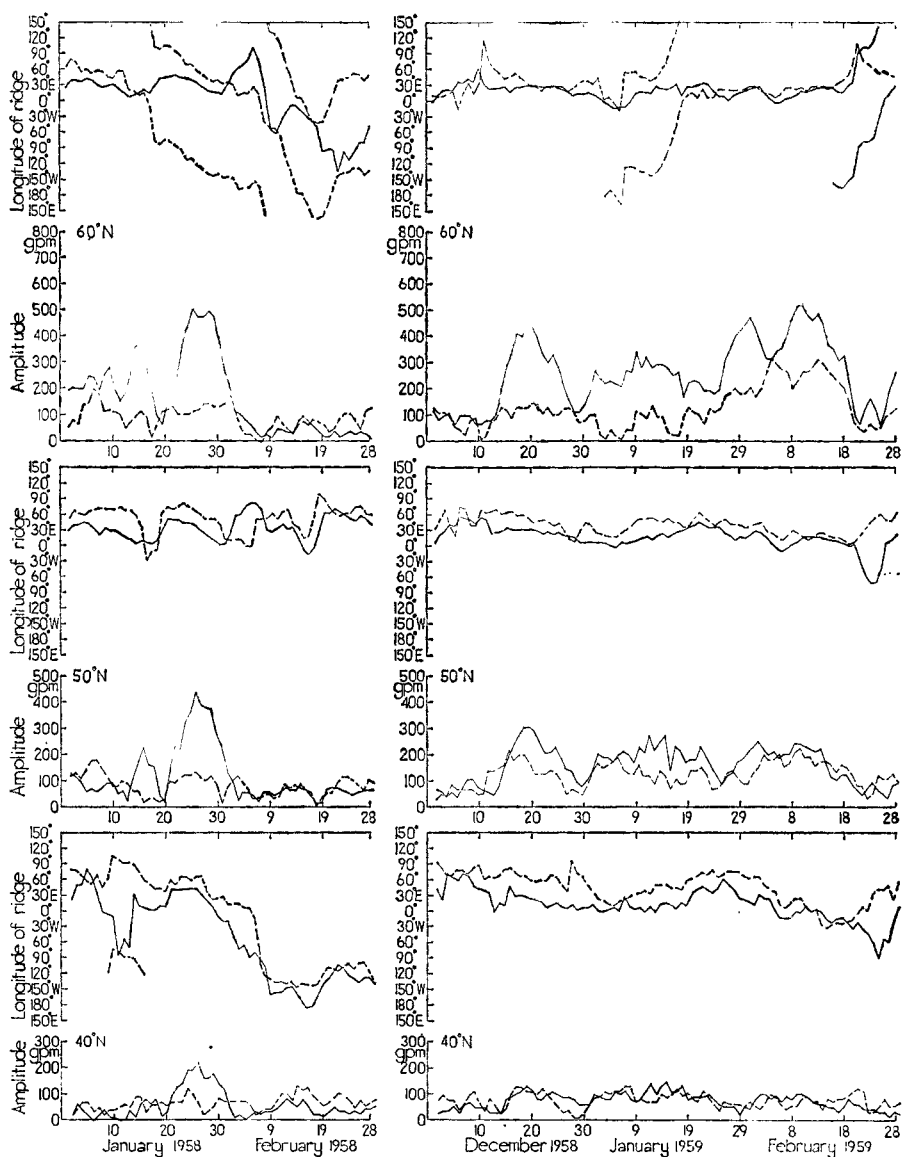


FIGURE 2—DAILY CHANGES IN RIDGE POSITION AND AMPLITUDE OF ZONAL WAVE NUMBER TWO AT 50 AND 500 MILLIBARS IN THE TWO WINTER PERIODS

———— 50 millibars
 - - - 500 millibars

The main features concerning the behaviour of the individual zonal wave numbers can be summarized briefly as follows.

(a) *Zonal wave number one* (Figure 1).—The stratospheric and tropospheric waves are almost always out of phase, with the amplitudes of the stratospheric wave being considerably larger than those of the tropospheric wave on most occasions. The amplitudes of this wave number at both 50 mb and 500 mb

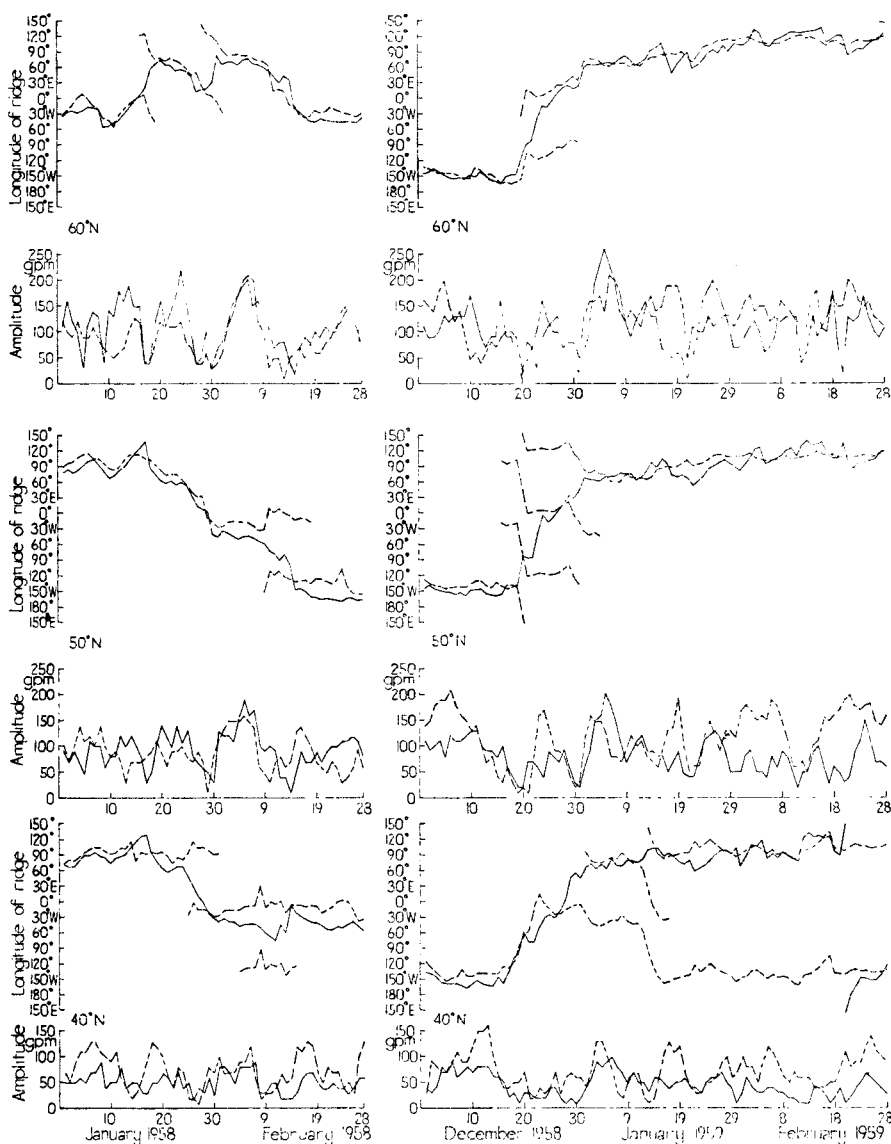


FIGURE 3—DAILY CHANGES IN RIDGE POSITION AND AMPLITUDE OF ZONAL WAVE NUMBER THREE AT 50 AND 500 MILLIBARS IN THE TWO WINTER PERIODS

———— 50 millibars
 - - - - 500 millibars

usually decrease with decrease of latitude. The wave at 50 mb is quasi-stationary and pulsatory with the pulsatory behaviour being rather similar at all these latitudes. The 500 mb wave, though also quasi-stationary and pulsatory in character, shows less connected behaviour at the three latitudes and the movement of this wave about its mean position at each latitude appears to be slightly greater than the oscillations of the 50 mb wave.

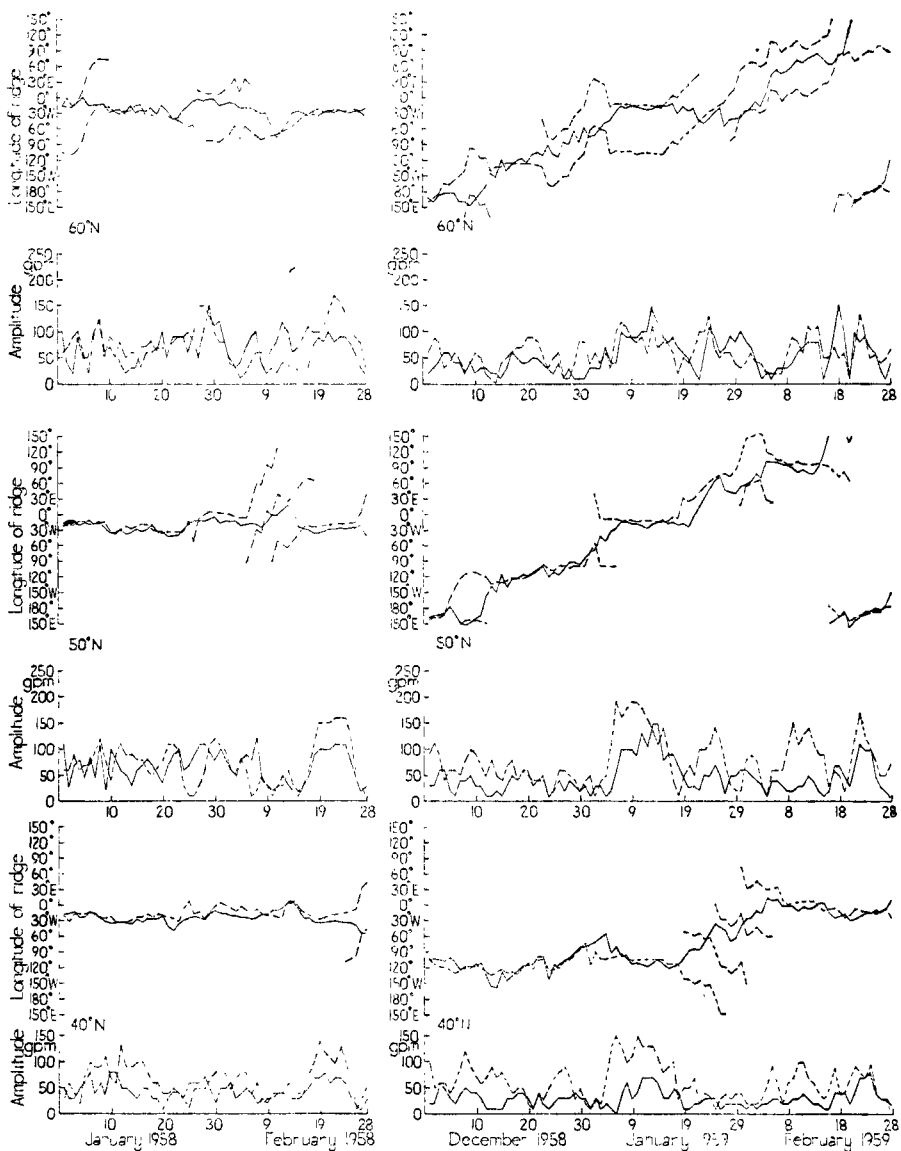


FIGURE 4—DAILY CHANGES IN RIDGE POSITION AND AMPLITUDE OF ZONAL WAVE NUMBER FOUR AT 50 AND 500 MILLIBARS IN THE TWO WINTER PERIODS

— 50 millibars
 --- 500 millibars

(b) *Zonal wave number two* (Figure 2).—The waves at the two pressure levels behave in a rather similar way, though there is usually a phase difference. For the greater part of the time the waves are pulsatory and quasi-stationary, with the waves during the second period being particularly steady. The changes in amplitude at the two pressure levels are not closely connected but there

are periods when the changes at the two levels are similar. The amplitudes at 50 mb are in general larger than those at 500 mb and show a decrease with decrease of latitude, but the mean values of the amplitudes of this wave at both 50 mb and 500 mb are smaller than those of wave number one.

(c) *Zonal wave number three (Figure 3).*—For long periods the stratospheric and tropospheric waves behave similarly. The amplitudes are of the same order at the two levels and there is not such marked variation of amplitude with latitude as occurs with the first two zonal wave numbers. The marked retrogression of the 50 mb wave, which occurs at all three latitudes for some part of the first winter period has no parallel during the second winter period when, apart from a period of progression in the second half of December 1958, the wave is quasi-stationary. In general the closest connexion between the two pressure levels occurs when the 50 mb wave is quasi-stationary since then the 500 mb wave is also quasi-stationary. When the 50 mb wave is retrogressive in the first period, the 500 mb wave is retrogressive (at 50°N and 60°N) or quasi-stationary (at 40°N and 50°N) ; when the 50 mb wave is progressive, as in the second period, the 500 mb wave is progressive (at 40°N), retrogressive (at 50°N) or quasi-stationary or only slightly progressive (at 60°N).

(d) *Zonal wave number four (Figure 4).*—There is closely paralleled behaviour at 50 mb and 500 mb at each of the three latitudes for quite long periods, though the overall character of the wave behaviour is different in the two winter periods. The 50 mb wave, and also the 500 mb wave for much of the time, are extremely steady in January and February 1958. In the second winter period, however, there are only brief intervals when the 50 mb wave is quasi-stationary and the dominant movement is a progressive one, especially at 50°N and 60°N. The variation of amplitude with latitude is not particularly marked, either at 50 mb or 500 mb, whilst the amplitudes of the tropospheric wave are usually larger than those of the stratospheric wave.

(e) *Zonal wave number five (Figure 5).*—For long periods, especially in the second winter period, the waves at 50 mb and 500 mb move in a similar manner. Over the first period, however, the overall shift of the 500 mb wave at 40°N and 60°N is about 290 and 230 degrees of longitude respectively, whilst the overall shift of the 50 mb wave at these two latitudes is very small. At 50°N the difference between the overall shift of the 500 mb wave and that of the 50 mb wave is not very great. During the second winter period there is closer agreement between the overall shifts of the 500 mb and 50 mb waves ; the shift is almost identical at 40°N and 50°N at the two pressure levels, whilst at 60°N, the 500 mb wave makes a slightly larger progressive shift during the three months than the 50 mb wave. The amplitudes of the 50 mb wave are markedly smaller than those of the 500 mb wave.

(f) *Zonal wave number six (Figure 6).*—The shift in ridge position over periods of the order of a week or so is often about the same at 500 mb and 50 mb. The overall shifts during each of the two periods at the three latitudes show considerable differences however. Whilst the 500 mb wave moves eastward about 150 degrees of longitude at 60°N and between 250 and 300 degrees of longitude at 50°N and 40°N during the first winter period, the 50 mb wave only moves about 90 degrees eastward at 60°N and 40°N and

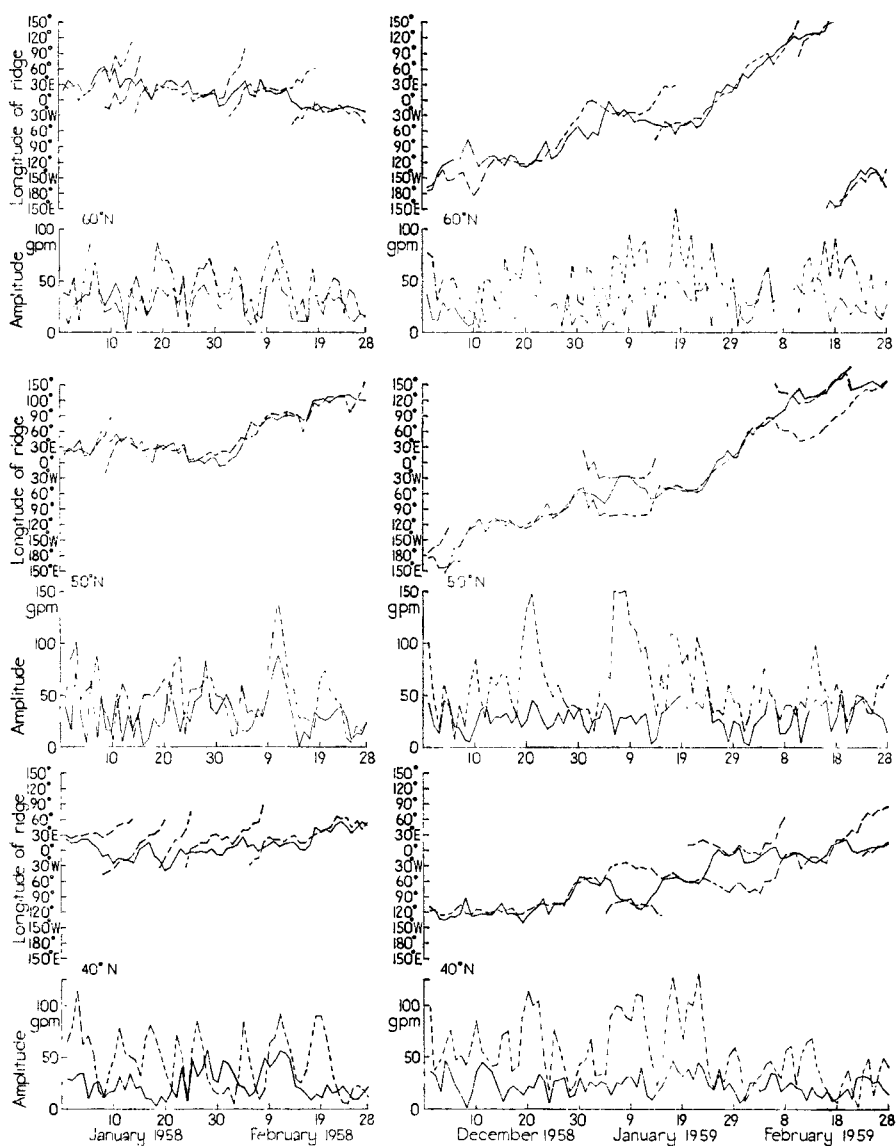


FIGURE 5—DAILY CHANGES IN RIDGE POSITION AND AMPLITUDE OF ZONAL WAVE NUMBER FIVE AT 50 AND 500 MILLIBARS IN THE TWO WINTER PERIODS

———— 50 millibars
 - - - - 500 millibars

about 180 degrees at 50°N. During the second winter period whereas the 500 mb wave moves eastward about 500/550 degrees at all three latitudes, the 50 mb wave moves about 300 degrees eastward at 60°N, about 50 degrees westward at 50°N and 300 to 350 degrees eastward at 40°N. As with zonal wave number five there is a tendency for the long-period movement of the

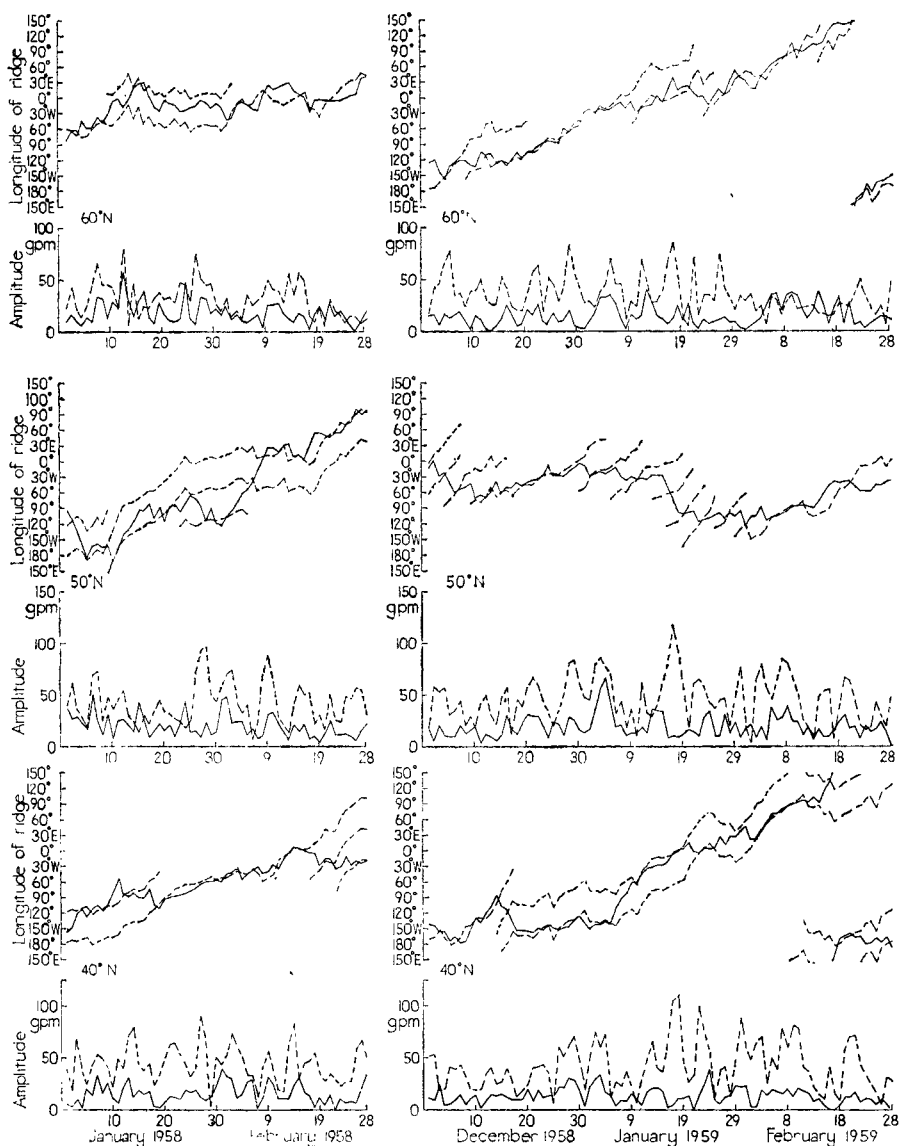


FIGURE 6—DAILY CHANGES IN RIDGE POSITION AND AMPLITUDE OF ZONAL WAVE NUMBER SIX AT 50 AND 500 MILLIBARS IN THE TWO WINTER PERIODS
 ——— 50 millibars
 - - - 500 millibars

stratospheric wave to lag behind that of the eastward moving tropospheric wave and, in fact, the shift of the stratospheric wave may be a retrogressive one. With few exceptions the daily amplitudes of the 50 mb wave are smaller at each of the three latitudes than the amplitudes of the 500 mb wave.

(g) *Zonal wave numbers greater than six.*—No attempt was made to follow diagrammatically the daily behaviour of the zonal wave numbers greater

than six. However Table I, which gives comparative values of the mean daily amplitude at 50 and 500 mb throughout each of the five months at 40°N, 50°N and 60°N, contains information relating to zonal wave numbers seven to ten in addition to the first six wave numbers. This table shows that for the first two wave numbers, the stratospheric waves have considerably larger amplitudes than the tropospheric waves in each month, except for wave number two in February 1958. For wave number three, the amplitudes at the two levels are much the same, but for wave numbers four to ten, the amplitudes of the tropospheric waves are greater than those of the stratospheric waves.

TABLE I—MEAN DAILY AMPLITUDE OF THE FIRST TEN ZONAL WAVE NUMBERS FOR EACH MONTH AT 50 AND 500 MILLIBARS AT SPECIFIED LATITUDES

		Zonal wave number									
		1	2	3	4	5	6	7	8	9	10
		<i>geopotential metres</i>									
January 1958	60°N	397	287	116	78	27	19	14	10	9	9
		(115	119	106	76	43	33	22	17	10	10)
	50°N	259	180	89	46	33	21	17	12	11	10
		(164	103	87	75	54	41	32	25	18	15)
February 1958	40°N	115	86	52	47	25	15	10	9	7	6
		(94	69	76	66	50	45	34	28	23	18)
	60°N	423	54	107	54	27	14	9	6	5	3
		(110	70	99	81	41	25	22	18	15	12)
December 1958	50°N	265	61	97	63	33	16	13	7	5	4
		(105	77	90	70	45	42	30	29	21	18)
	40°N	114	44	50	44	26	16	10	7	4	4
		(102	80	72	64	41	43	33	30	20	17)
January 1959	60°N	287	201	95	33	22	12	9	7	6	6
		(72	97	99	51	44	41	25	20	12	11)
	50°N	188	145	79	32	27	16	8	6	6	5
		(97	108	102	60	59	43	26	34	19	15)
February 1959	40°N	92	71	44	29	24	13	10	5	6	3
		(66	73	70	59	58	36	24	33	19	15)
	60°N	292	274	126	74	30	16	13	9	6	6
		(80	94	141	69	55	40	25	23	14	14)
January 1959	50°N	159	191	98	65	29	21	13	8	8	5
		(104	123	111	97	72	53	42	27	24	16)
	40°N	80	87	55	30	26	15	10	6	5	3
		(84	84	69	70	68	49	46	37	24	16)
February 1959	60°N	271	313	115	54	33	20	9	8	6	5
		(102	187	133	60	46	26	19	22	11	11)
	50°N	169	146	68	41	30	19	11	8	5	4
		(91	145	145	83	48	44	30	28	18	16)
January 1959	40°N	85	60	32	30	20	12	9	8	5	4
		(57	69	78	56	34	43	29	24	17	13)

Note : Rows in brackets refer to 500 mb.

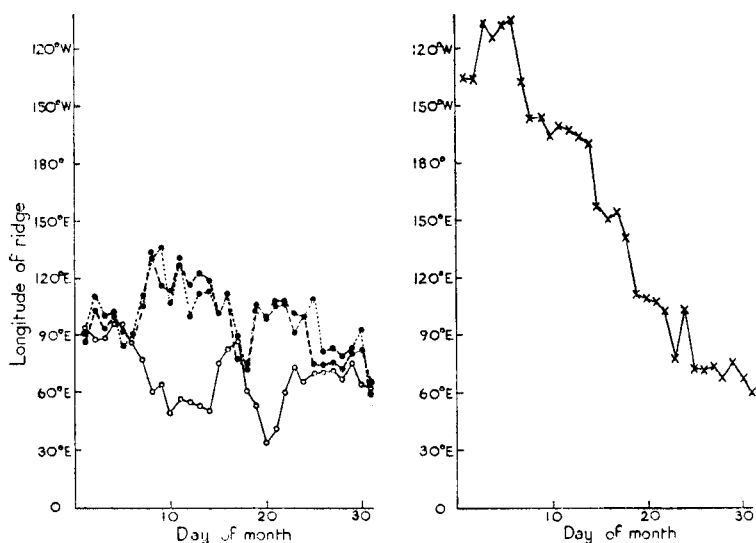
Discussion.—Van Mieghem¹ commenting upon the quasi-stationary behaviour of the ultra-long waves (zonal wave numbers one to three) at 500 mb in the northern hemisphere, concludes tentatively that 'component $n=3$ of the normal circumpolar circulation is mainly of orographic origin, the component $n=2$ is mainly under direct thermal control ; as for the component $n=1$ there is a certain orographic effect without apparently any direct thermal steering'. It is interesting to see how these three wave numbers at 500 mb are positioned during the specific five months of this investigation in relation to their normal position. The normal ridge positions for these waves are given in Table II for the months of January, February and December, taking as normal the period 1949 to 1958.

TABLE II—NORMAL RIDGE POSITIONS OF 500 MILLIBARS ZONAL WAVE NUMBER

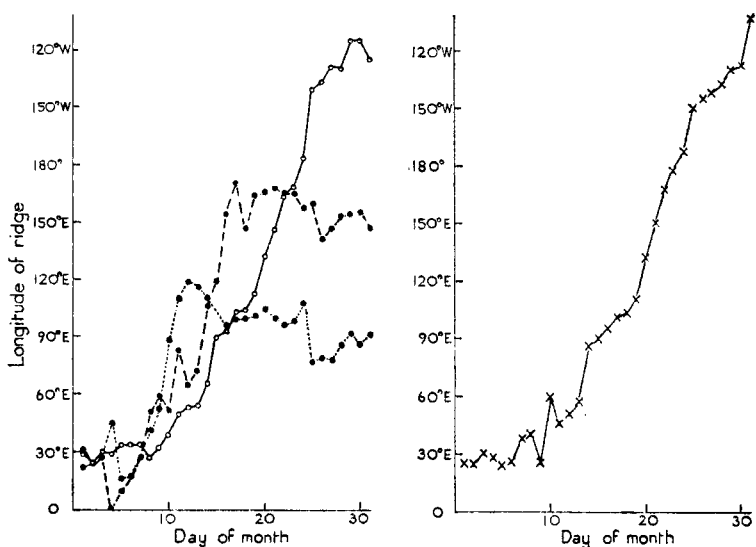
		Wave one	Wave two	Wave three
January	60°N	10°E	26°E, 154°W	26°W, 146°W, 94°E
	50°N	18°E	33°E, 147°W	24°W, 144°W, 96°E
	40°N	46°W	46°E, 134°W	23°W, 143°W, 97°E
February	60°N	22°E	24°E, 156°W	26°W, 146°W, 94°E
	50°N	22°W	38°E, 142°W	23°W, 143°W, 97°E
	40°N	46°W	49°E, 131°W	23°W, 143°W, 97°E
December	60°N	14°E	33°E, 147°W	30°W, 150°W, 90°E
	50°N	7°W	38°E, 142°W	26°W, 146°W, 94°E
	40°N	33°W	45°E, 135°W	27°W, 147°W, 93°E

From a comparison with the details given in Figure 1 and Table II, it will be noted that wave number one at 500 mb varies considerably from its normal position though during January 1958 the wave is quasi-stationary close to its normal position at both 40°N and 50°N. From Figure 2 it will be seen that there are reasonably long periods when wave number two maintains its ridge position close to the normal, more particularly in the second winter period at 50°N. From Figure 3 it is seen that wave number three has ridge positions fairly close to normal when it is quasi-stationary: however, throughout most of February 1959 the ridges are on average about 20 degrees of longitude east of the normal position, whereas in January 1959 the ridges are on average about 20 degrees west of the normal position. These differences may be important.

The daily behaviour of wave numbers one to six during January 1958 was compared with the behaviour of these waves at 45°N and 65°N given by Teweles.² There is fairly close agreement between the results of this investigation and Teweles's results, but the difference in behaviour of wave number five requires further mention as the behaviour of this wave number was the subject of a special comment by Teweles. Figure 7(a) shows the comparison between the behaviour at 40°N, 50°N and 60°N as found in this investigation and that at 45°N as given by Teweles for the 50 mb pressure level and Figure 7(b) shows the comparison for 500 mb. There is not too much difference at 500 mb though wave number five progresses more at 45°N than at 40°N or 50°N. It will be noted in Figure 7(a) that whereas this wave at 50 mb steadily retrogresses throughout the month at 45°N, the behaviour at 40°N and 50°N shows progressive shifts as well as retrogression with the result that there is only a slight overall retrogression during the month. The difference in the two behaviour patterns is largely accounted for by the retrogressive shifts at 45°N which are shown between the 6th and 7th and between the 14th and 15th day of the month when the shift in each case is almost half a wavelength. Teweles² had noted that when the daily movement of a wave is about half a wavelength, the direction becomes arbitrary and, in fact, when the amplitude is small, quite slight differences in the original data, giving a relatively slight change of ridge position, could result in progressive shifts being indicated instead of retrogressive shifts. This comparison suggests that when comparing wave behaviour at two pressure levels attention should be focused on those periods when the amplitudes are sufficiently large and that big progressive or retrogressive shifts which occur when amplitudes are small should be ignored. Despite these comments, however, it does appear that there is a tendency, as noted earlier, for the stratospheric wave numbers five and six to be considerably less progressive than their eastward-moving tropospheric counterparts.



(a) 50 millibars



(b) 500 millibars

FIGURE 7—DAILY CHANGES IN RIDGE POSITION OF ZONAL WAVE NUMBER FIVE DURING JANUARY 1958

o — — — — — 40°N 50°N - - - - - 60°N
x — — — — — 45°N (after Teweles²)

Though this investigation is concerned chiefly with the relative movement of the waves in the troposphere and stratosphere it is as well to keep in mind the character of the periods used in the investigation. The chief comment about the stratospheric behaviour is that whereas in the first period there

was marked stratospheric warming in the latter part of January 1958 (Teweles and Finger⁴), in the second period no stratospheric warmings of any significance affected the 50 mb surface. As far as the troposphere is concerned the first period was one with generally low zonal index with the jet stream displaced far south of its normal position over the American sector of the northern hemisphere (O'Connor⁵). In contrast, during the second winter period the zonal index was higher and the belt of maximum winds was located considerably further north (Green,⁶ Stark,⁷ O'Connor⁸). Despite the completely different character of the two periods examined, the similarity noted earlier in the behaviour of zonal wave numbers four, five and six at the two pressure levels suggests that these stratospheric waves are reduced tropospheric effects. The behaviour of zonal wave number three at 50 mb may also be largely of tropospheric origin.

It would have been interesting to have been able to examine more closely the pulsations of the ultra-long waves in order to determine whether these are periodic. Chu Pao-Chen⁹ put forward the view that the amplitude of the ultra-long waves varies periodically with a period of 10–30 days and, in support of this suggestion, he gave a diagram showing the variation of the amplitude of zonal wave number two at 50°N during January and February 1958. The diagram is very similar to the amplitude graph for the first winter period at 50°N in Figure 2 for 500 mb. Before it is possible to determine whether these long wave pulsations are periodic, however, considerably more results of this present form of analysis are required.

Conclusions.—The results presented in this paper possibly pose more questions than are answered but the following conclusions are tentatively put forward.

The behaviour of zonal wave numbers four, five and six, as shown during the two winter periods examined, suggests that these waves at 50 mb are reduced or damped tropospheric waves. However, the retrogressive shifts which affect the movement of wave numbers five and six in the stratosphere over the middle latitudes whilst the equivalent tropospheric waves progress relatively steadily eastward, cannot be easily explained or dismissed.

Zonal wave number three at 50 mb may also be of tropospheric origin since it behaves similarly to wave number three at 500 mb for most of the time, especially when it is quasi-stationary.

There also appears to be some associated behaviour between zonal wave number two in the stratosphere and its counterpart in the troposphere, but zonal wave number one at 50 mb, far from behaving similarly to wave number one at 500 mb, is at times almost in anti-phase with this tropospheric wave.

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551.552 (672.2)

LOW-LEVEL WIND FLOW AT NAIROBI

By B. RAMSEY

Summary.—The monthly averages of hourly surface wind and the 0000 and 1200 GMT (GMT+3 hours=local time) winds at 800 and 700 millibars at Nairobi Airport (01°19'S, 36°55'E, 5329 feet (1624 metres) above mean sea level — see Figure 1) provide a unique opportunity to present monthly and diurnal changes in the wind régime at a high-level equatorial station on the western fringe of the great Indian Ocean monsoon system. The north-east and south-east monsoons are clearly impressed on the data, but additional

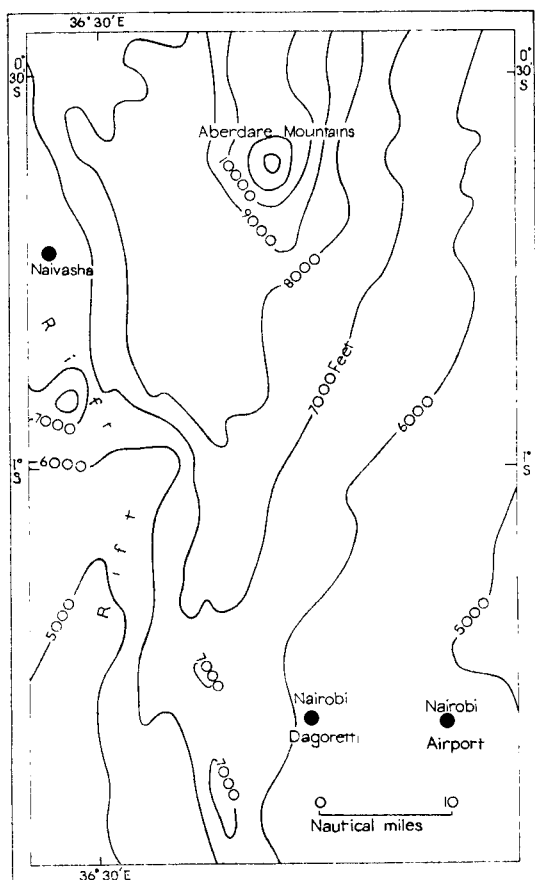


FIGURE 1—SMOOTHED TOPOGRAPHY IN THE NAIROBI AREA

TABLE I—VECTOR MEAN WINDS FOR EACH HOUR AND MONTH AT NAIROBI
AIRPORT (1959-63)

Approximate placing of events on the time scale	Time GMT	January <i>deg kt</i>	February <i>deg kt</i>	March <i>deg kt</i>	April <i>deg kt</i>	May <i>deg kt</i>	June <i>deg kt</i>
Sunrise	0000	007 2.3 (2.9)	346 2.0 (3.1)	012 2.0 (3.3)	048 1.4 (2.9)	127 0.2 (2.7)	258 1.5 (3.6)
	0100	360 1.7 (2.6)	337 1.5 (3.1)	028 2.4 (3.6)	046 1.4 (2.8)	215 0.2 (2.1)	241 1.6 (3.1)
	0200	010 1.5 (2.3)	340 1.5 (3.1)	040 1.7 (3.1)	050 1.4 (2.9)	194 0.4 (2.1)	233 1.6 (2.9)
	0300	355 1.2 (2.1)	342 1.2 (2.9)	040 1.4 (3.0)	058 1.3 (3.0)	209 0.6 (2.0)	220 1.6 (2.9)
	0400	013 0.8 (2.0)	352 0.6 (2.7)	031 1.8 (3.0)	060 1.2 (2.7)	200 1.2 (2.1)	221 1.8 (2.8)
	0500	025 2.2 (3.0)	019 1.0 (2.7)	042 2.5 (3.9)	062 1.7 (3.7)	184 1.7 (2.9)	200 2.0 (3.0)
	0600	045 5.0 (6.0)	036 2.4 (5.3)	048 4.6 (6.2)	072 2.5 (4.5)	170 2.2 (3.8)	178 2.4 (3.7)
Sun zenith	0700	038 8.0 (8.8)	032 7.0 (7.6)	044 6.2 (6.9)	069 3.4 (5.5)	164 2.6 (4.3)	170 3.0 (4.3)
	0800	045 9.5 (10.1)	040 9.0 (9.5)	044 7.8 (8.8)	066 4.2 (6.3)	160 2.9 (4.6)	163 3.0 (5.1)
	0900	046 10.0 (10.6)	043 10.0 (10.4)	044 9.0 (9.7)	069 5.5 (7.3)	151 3.1 (5.1)	156 3.5 (5.2)
	1000	048 9.8 (10.4)	048 10.5 (11.3)	049 10.3 (11.2)	068 6.4 (8.5)	146 3.0 (5.4)	144 3.4 (5.4)
	1100	057 10.2 (10.9)	050 11.0 (12.0)	053 10.6 (11.2)	071 7.0 (8.9)	132 3.9 (6.6)	138 3.9 (5.9)
	1200	058 10.8 (11.5)	055 11.5 (12.7)	057 10.9 (11.9)	075 7.5 (9.8)	115 3.7 (6.9)	120 4.0 (6.6)
	1300	062 11.0 (11.6)	062 11.6 (12.7)	062 11.2 (12.6)	073 8.4 (10.5)	107 4.9 (8.1)	111 5.1 (7.0)
Maximum temperature	1400	063 11.8 (12.3)	063 12.7 (13.5)	064 12.5 (13.3)	074 9.2 (11.2)	102 6.1 (8.5)	105 5.8 (7.7)
	1500	065 11.9 (12.8)	062 14.0 (14.4)	065 12.7 (13.6)	073 8.9 (10.4)	100 5.9 (8.0)	097 7.0 (7.8)
	1600	062 9.4 (10.0)	057 10.5 (11.1)	061 9.2 (10.2)	074 7.0 (8.1)	096 4.2 (5.9)	095 5.7 (6.5)
	1700	053 7.8 (8.6)	054 8.0 (8.8)	058 7.1 (8.4)	072 5.2 (6.4)	092 2.7 (5.3)	104 4.1 (5.3)
	1800	045 6.5 (7.1)	048 6.3 (7.3)	056 6.4 (7.5)	065 4.1 (5.4)	081 2.1 (4.4)	104 2.0 (4.3)
	1900	035 5.5 (5.9)	043 5.4 (6.3)	048 5.2 (6.2)	055 4.3 (4.9)	052 1.3 (3.9)	077 0.9 (3.4)
	2000	027 4.9 (5.0)	031 4.5 (5.5)	034 4.0 (5.1)	047 2.5 (4.0)	038 1.3 (3.9)	360 0.6 (3.7)
Sunset	2100	020 4.0 (4.3)	024 4.2 (4.6)	025 3.6 (5.0)	036 2.0 (4.2)	028 1.1 (3.7)	293 1.4 (4.3)
	2200	020 3.0 (3.6)	013 3.0 (3.9)	019 3.1 (4.6)	038 2.0 (4.1)	031 0.6 (3.8)	272 1.9 (4.5)
	2300	010 2.4 (3.1)	358 2.4 (3.7)	013 2.7 (4.0)	043 2.0 (3.4)	022 0.6 (3.3)	271 1.7 (4.1)

Note: Values in brackets are scalar mean speeds.

effects are present and become more apparent when surface winds are compared with the flow at 800 and 700 mb. In addition, the diurnal variations in anemometer-level wind speeds and screen temperatures show correlations common to all seasons.

Data.—As monthly diurnal temperature curves for the period 1959 to 1963 had already been extracted as an aid to forecasting take-off temperatures at Nairobi Airport, it was decided to undertake a similar analysis of hourly surface winds (vector mean and scalar speed) by the month, for the same period, as an additional forecasting aid. In all, over 42,000 observations were averaged manually. Additionally, from rawin and rawinsonde ascents at 0000 and 1200 GMT, average monthly vector means and scalar speeds were found for the 800 and 700 mb levels. These levels are about 1300 ft (400 m) and 5000 ft (1500 m) respectively above airfield height. The results are presented in Tables I and II.

TABLE 1—*contd*

Approximate placing of events on the time scale	Time GMT	July		August		September		October		November		December	
		deg	kt	deg	kt	deg	kt	deg	kt	deg	kt	deg	kt
Sunrise	0000	228	2.4 (3.8)	234	1.8 (3.7)	360	0.9 (3.7)	043	2.8 (4.5)	039	3.6 (4.8)	029	2.6 (3.1)
	0100	220	2.5 (3.1)	232	2.1 (3.6)	180	0.5 (3.0)	045	3.0 (3.3)	042	3.0 (4.0)	029	2.3 (2.7)
	0200	220	2.6 (3.2)	228	1.9 (3.1)	225	0.6 (2.7)	047	2.3 (2.8)	043	2.8 (3.8)	027	2.0 (2.7)
	0300	217	2.7 (3.3)	207	2.0 (3.3)	208	0.7 (2.4)	050	2.2 (2.8)	043	2.6 (3.5)	029	2.6 (2.8)
	0400	209	2.7 (3.1)	206	1.9 (3.1)	205	1.2 (2.4)	054	2.2 (2.6)	049	2.8 (3.6)	027	1.6 (2.3)
	0500	196	2.7 (3.4)	192	1.9 (3.1)	171	1.4 (2.6)	055	2.6 (3.2)	051	2.9 (4.7)	031	3.1 (3.9)
Sun zenith	0600	173	3.8 (4.7)	166	2.4 (3.5)	150	1.9 (3.3)	065	3.1 (4.0)	050	5.1 (6.2)	036	5.3 (6.5)
	0700	170	3.5 (4.7)	160	2.9 (3.9)	138	2.3 (3.7)	062	3.7 (4.8)	046	5.4 (6.9)	042	2.8 (8.8)
	0800	168	4.4 (5.3)	158	2.9 (4.4)	133	2.5 (4.1)	066	4.7 (5.8)	049	6.4 (8.1)	042	8.9 (10.2)
	0900	158	4.2 (5.1)	144	3.1 (4.9)	124	2.8 (4.5)	069	6.2 (7.2)	049	6.9 (8.7)	045	9.3 (10.7)
	1000	154	4.3 (5.9)	145	3.2 (4.8)	116	3.6 (5.1)	073	6.8 (8.2)	055	8.1 (9.5)	050	9.7 (11.0)
	1100	146	4.4 (6.0)	130	3.5 (5.6)	117	4.2 (6.2)	076	7.4 (8.7)	061	8.4 (9.7)	053	10.1 (11.7)
Maximum temperature	1200	142	4.8 (6.5)	118	4.2 (6.3)	096	5.2 (6.7)	080	7.8 (8.7)	064	8.6 (9.9)	059	10.2 (11.9)
	1300	136	5.4 (7.0)	106	5.0 (6.8)	098	6.2 (7.9)	083	9.3 (10.1)	068	9.6 (11.2)	062	11.0 (12.5)
	1400	122	5.8 (7.0)	097	6.8 (8.3)	094	8.2 (9.3)	081	9.8 (10.7)	070	9.5 (11.2)	062	11.3 (13.2)
	1500	114	6.4 (7.6)	094	7.3 (8.6)	093	9.1 (10.2)	083	10.0 (10.6)	068	9.8 (11.2)	061	10.7 (12.1)
	1600	106	5.6 (6.3)	091	6.1 (7.3)	094	8.0 (8.3)	083	7.8 (8.6)	064	6.6 (8.0)	056	8.2 (9.2)
	1700	114	4.5 (5.4)	093	5.1 (6.2)	095	6.2 (6.8)	081	6.2 (7.2)	053	6.0 (7.0)	048	6.6 (7.3)
Sunset	1800	119	2.9 (4.3)	092	3.4 (4.8)	091	4.4 (5.1)	078	5.8 (6.6)	052	5.6 (6.5)	041	5.8 (6.4)
	1900	143	1.5 (3.7)	074	2.3 (4.2)	078	3.0 (3.9)	068	4.9 (5.6)	044	4.9 (5.6)	035	5.0 (5.4)
	2000	198	1.2 (4.0)	060	0.8 (4.2)	035	1.7 (3.7)	052	3.9 (4.8)	035	4.2 (4.9)	031	4.1 (4.4)
	2100	233	2.6 (4.3)	280	0.5 (4.3)	027	1.8 (4.1)	038	4.4 (5.4)	028	3.8 (4.8)	026	3.7 (4.1)
	2200	237	2.5 (4.1)	256	1.2 (4.6)	344	1.5 (3.9)	041	4.9 (5.6)	030	3.3 (4.5)	027	3.3 (3.7)
	2300	238	2.5 (3.8)	252	1.6 (3.9)	352	1.4 (4.2)	042	4.4 (5.0)	034	3.5 (4.4)	026	2.8 (3.1)

Note: Values in brackets are scalar mean speeds.

To find the depth of the turbulent mixing layer at the time of maximum heating, the mean monthly convective condensation level (CCL) was found by dividing the difference between the average dry-bulb and dew-point temperatures ($^{\circ}\text{C}$) at 1200 GMT by three, to give an approximation to the cloud base.¹ The monthly average rainfall over this period was also found as well as the monthly vector difference between the average component of wind flow from the ground to 700 mb in the early morning and that in the afternoon. The difference in direction between these morning and afternoon winds, together with the rainfall and CCL is shown on Figure 2.

Figure 3 was compiled from the annual hourly scalar wind speeds at the surface and the hourly surface temperatures, together with the curves for the hottest (February), and the coldest (July) months.

TABLE II—COMPARISON OF MORNING AND AFTERNOON VECTOR MEAN WINDS AT NAIROBI FROM GROUND LEVEL TO 700 MB
(1959-63)

	January	February	March	April	May	June	July	August	September	October	November	December
0300 GMT												
Surface	355	342	040	058	209	220	217	207	208	050	043	029
wind	1.2 (2.1)	1.2 (2.9)	1.4 (3.0)	1.3 (3.0)	0.6 (2.0)	1.6 (2.9)	2.7 (3.3)	2.0 (2.3)	0.7 (2.4)	2.2 (2.8)	2.6 (3.5)	2.0 (2.8)
0000 GMT												
800 mb	050	050	052	078	091	117	153	144	097	068	058	048
wind	11.1 (11.6)	14.1 (14.4)	11.9 (14.6)	9.9 (11.3)	4.9 (7.8)	4.2 (7.4)	5.5 (8.2)	4.4 (7.4)	5.5 (7.9)	11.4 (12.0)	11.6 (14.3)	12.4 (13.6)
700 mb	049	044	055	079	083	074	205	241	114	085	073	053
wind	11.5 (13.0)	13.4 (14.2)	14.2 (15.1)	11.6 (13.0)	4.5 (8.6)	2.5 (7.6)	3.9 (8.7)	4.6 (8.4)	2.9 (7.8)	9.5 (11.0)	12.0 (13.4)	11.7 (13.5)
1500 GMT												
Surface	065	062	065	074	102	097	114	094	093	083	068	062
wind	11.9 (12.8)	14.0 (14.4)	12.7 (13.6)	9.2 (11.2)	6.1 (8.5)	7.0 (7.8)	6.4 (7.6)	7.3 (8.6)	9.1 (10.2)	10.0 (10.6)	9.8 (11.2)	11.3 (13.2)
1200 GMT												
800 mb	062	061	064	079	115	125	141	134	111	081	070	063
wind	9.8 (10.9)	12.1 (12.6)	12.3 (12.7)	9.4 (10.5)	5.8 (7.7)	6.5 (7.8)	6.8 (8.6)	6.2 (8.0)	7.9 (8.9)	11.2 (12.2)	11.5 (12.7)	11.5 (12.3)
700 mb	062	057	062	080	088	097	144	158	110	088	076	064
wind	10.3 (11.6)	12.0 (12.4)	13.0 (13.8)	11.2 (12.0)	6.3 (9.2)	5.6 (8.3)	3.8 (8.8)	3.7 (7.0)	7.0 (9.2)	10.9 (11.7)	11.7 (12.6)	11.0 (12.1)
Vector difference												
between morning												
and after-	093	092	097	099	117	102	091	092	101	104	108	102
noon wind (mean												
from surface	4.1	4.4	4.4	2.6	3.0	4.4	3.9	5.3	5.2	3.5	3.2	3.5
to 700 mb).												

Note : Values in brackets are scalar mean speeds.

Local time = GMT + 3 hours.

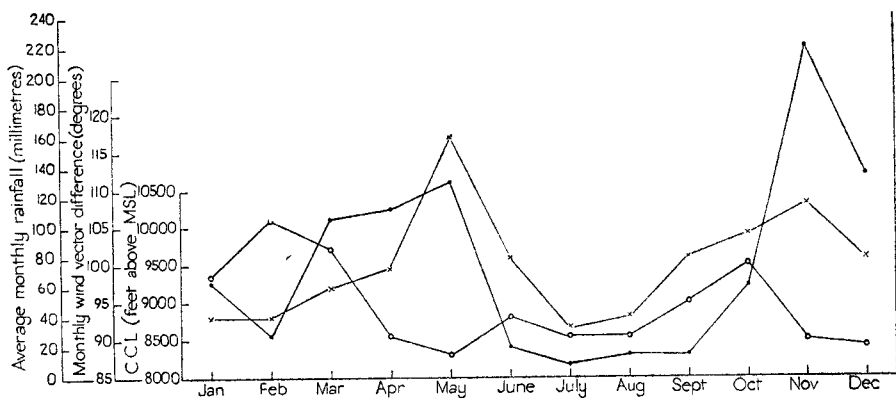


FIGURE 2—AVERAGE MONTHLY RAINFALL AND CCL AND MONTHLY VECTOR DIFFERENCE BETWEEN AVERAGE WIND COMPONENTS FROM SURFACE TO 700 MB IN THE MORNING AND AFTERNOON, 1959-63

—•—•— Average monthly rainfall
 —○—○— Average monthly CCL
 —x—x— Monthly wind vector difference

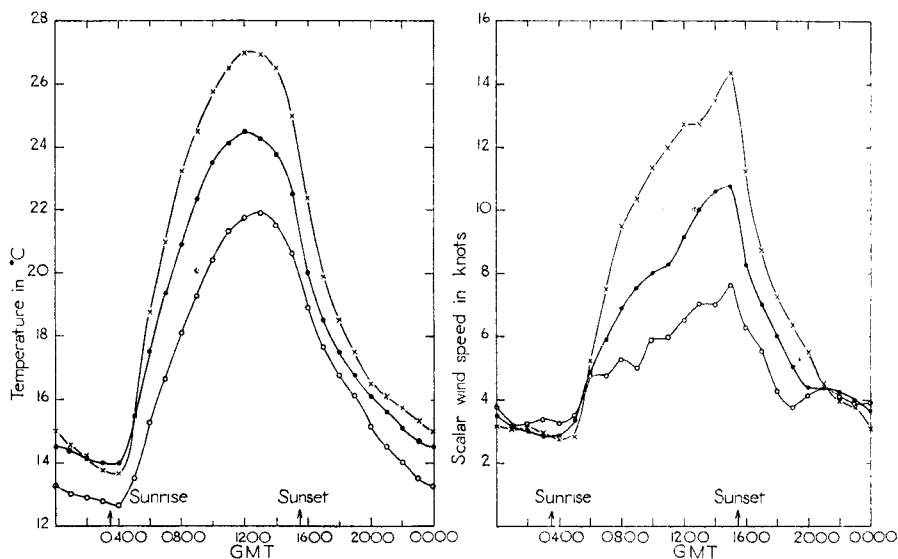


FIGURE 3—HOURLY SCALAR WIND SPEEDS AND SURFACE TEMPERATURES FOR FEBRUARY, JULY AND THE YEAR, 1959-63

x—x—x February —○—○— July
 —•—•— Year

Surface wind.—

North-east monsoon season.—The north-east monsoon begins in October and continues until the end of April. The extreme months, October and April, exhibit rather more zonal flow, as can be seen from Table I and Figure 4, than do the other north-easterly months November to the end of March.

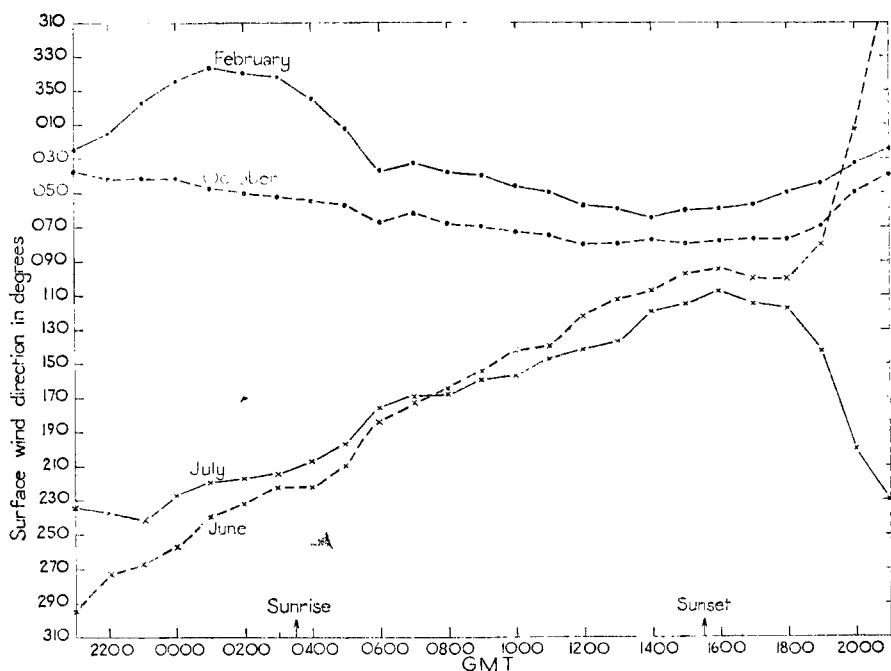


FIGURE 4—DIURNAL VARIATIONS OF SURFACE WIND DIRECTION AT NAIROBI AIRPORT 1959-63

Winds throughout the day at the beginning and end of this monsoon are both more easterly and less strong than in the remainder of the period. The direction of the maximum wind (1500 GMT) from November to the end of March (see Table II) is remarkably consistent. However, in the early part of the day the wind is backed from this direction by a lesser amount in the wetter cloudy months of November and December than in the drier months of January and February. Daily temperature curves reveal more or less the same pattern throughout the year, and the scalar wind speed profile follows these curves faithfully until the period between maximum temperature and sunset (1530 GMT) during which time the winds continue to increase. The greatest increase in wind speed is coincident with the greatest hourly temperature rise from 0500 to 0600 GMT. Similarly, the greatest fall in temperature from 1500 to 1600 GMT (about sunset) coincides with the most rapid fall in wind speeds. As mentioned above, this is not peculiar to the north-east monsoon and applies all the year. It may be noted that the steady progression of the wind direction throughout the forenoon is interrupted on the average each day between about 0600 and 0700 GMT. This is a feature of all north-east monsoon months, although it occurs between 0700 and 0800 GMT in April, and in December there is merely a halt in the gradual veering at this time.

South-east monsoon season.—This monsoon, which lasts from May to the end of September, is marked by a diurnal cycle rather different from that in the north-east season. Only one month, July, the mid-season month,

shows an equal and opposite régime in the backing and increasing surface wind as the day warms up, followed by a veering and decreasing after sunset (Table I). All the other south-easterly months show a rotation through the full 360° with light south-westerly winds in the early morning gradually backing and increasing until sunset and then continuing to back through north round to south-west again by next morning. This variation is shown in Figure 4. However, the vector mean speed is very light compared with the scalar speed during the dark hours, especially in May. The constancy ' q '² of a set of vector winds is defined as $q=100V_R/V_s$ where V_R is the modulus of the vector mean wind and V_s is the scalar mean wind. From Table IV it may be noted that in the annual breakdown of constancy q , the hour of least q in the whole year is 0000 GMT (or 0300 local time) in May.

A feature of the wind speed at this season is the comparative weakness of the flow in the afternoon as compared with the north-east season. However, the south-east monsoon occurs during the local winter and, as may be seen from the July temperature curve, there is a good deal less heating in spite of the loss of only about 3° of sun elevation as compared with January. The season is very much more cloudy, although, as indicated in Figure 2, very dry.

Upper winds at 800 mb.—The 800 mb level is equivalent to a height of 700 ft (200 m) above the release point Dagoretti Corner which is about 10 miles to the west of the Airport (see Figure 1).

North-east monsoon season.—The wind at 800 mb shows a steady annual change at both 0000 and 1200 GMT (Table II). The early morning direction varies as the surface wind from a more easterly point at the beginning and end of the season, to a maximum northerly component in December, almost equalled in January and February. The speed shows a seasonal rise and fall with a maximum in February of 14.1 kt (14.4 kt scalar). By 1200 GMT daily, the 800 mb wind has undergone a rather similar change in direction to the surface wind, a veer towards east and, in general, a decrease.

South-east monsoon season.—There is a southerly component in May to the end of September with, as may be expected, a maximum in the mid-season month of July. This month shows the maximum speed also. By afternoon a rather different picture presents itself. May, June and September show a continuing tendency to veer, whereas in July and August, when the southerly component is greater, the tendency is to show backing at this level. However, a notable difference from the north-east monsoon is the increase in speed at this time, rather than a decrease.

Upper winds at 700 mb.—The 700 mb level is equivalent to 4200 ft (1280 m) above release point.

North-east monsoon season.—At 0000 GMT the north-east monsoon is extended over a longer period than at lower levels (Table II). Northerly components are apparent in all months except July, August and September. Also, apart from October, November and June, the direction is fairly well in phase with the flow at 800 mb. Speeds do not show such a steady progression as those at lower levels and reach a maximum in March (14.2 kt vector mean and 15.1 kt scalar).

Directions, however, do show a steady progression throughout, from well to the east (085° in October), back to north-east (044° in February) and

veering again towards east (083° in May). The steady seasonal progression from northerly to southerly components is interrupted in June when the mean direction at 0000 GMT is 074° . The vector mean speed, however, is very low (2.5 kt) compared with the scalar speed (7.6 kt).

By 1200 GMT, southerly components from May to September, have reduced the north-east season to the same length as at lower levels. All winds from November to the end of April have veered and decreased compared with 0000 GMT as may be expected from the exchange of momentum with lower winds in the turbulent mixing layer. At this time of day the wind flow below 700 mb is extremely uniform in direction, as may be seen from October to the end of April, and December is markedly so.

South-east monsoon season.—At 0000 GMT there is no true south-east monsoon season as such at 700 mb and it may be described as a shorter season with southerly components, July and August showing a good deal of westerly influence, and only September having an easterly as well as a southerly component. The difference between the vector mean and the scalar speeds indicates a large variation about the mean.

By 1200 GMT daily, 700 mb winds have all resumed their easterly components and, as indicated above, a southerly component is apparent at this level from June to the end of September. Again, as opposed to the north-east monsoon season, speeds have increased rather than decreased. Also this applies to May and October at this level ; with a direction of 088° in both months, the season could be called transitional at these times.

Discussion.—

Surface wind.—The overall picture provided by Tables I and II confirms what may be expected from a station on the western fringe of the Indian Ocean monsoon system. There is a well-defined north-east season from October to the end of April, and a southerly or south-easterly season from May to the end of September. However, there are some variations in time and space which are of interest.

Figure 1 shows the line of the contours near Nairobi, and also the position of the Rift Valley and its west-facing escarpment wall. As indicated earlier, the time of maximum wind follows the time of maximum temperature at the Airport by about three hours. Figure 3 shows how the wind speed curve departs from the average temperature curve between the hours of 1200 and 1500 GMT. Several factors may combine to give this late maximum wind speed. Table III shows the average daily maximum temperature for each month at the rawin release point at Dagoretti, 5900 ft above MSL, and at Naivasha,

TABLE III—AVERAGE DAILY MAXIMUM TEMPERATURES FOR EACH MONTH AT DAGORETTI AND NAIVASHA

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
	<i>degrees Celsius</i>												
Dagoretti (5900 ft)	24.6	25.7	25.6	24.2	22.9	22.2	20.9	21.9	23.7	24.8	23.2	23.3	23.6
Naivasha (6234 ft)	27.7	28.3	27.3	25.1	23.8	23.0	22.5	22.9	24.5	25.6	24.7	25.8	25.6
Excess of Naivasha over Dagoretti	3.1	2.6	1.6	0.9	0.9	0.8	1.6	1.0	0.8	0.8	1.5	2.5	2.0

6234 ft above MSL (Figure 1), in the Rift Valley about 50 miles to the north-west. In spite of the excess 300-ft elevation of Naivasha, maximum temperatures throughout the year are higher than at Nairobi. This may help to increase the already established anabatic flow from the land configuration in the Nairobi area, and this may be further augmented by the excess late afternoon heating on the steep west-facing wall of the Rift Valley about 15 miles west of the city. Thus, this late and also greater heating, together with the fact that in the late afternoon the gentle eastward slope at Nairobi is losing its heat, may be the cause of the late maximum of surface wind at the Airport. A rather interesting feature of the anabatic effect on the wind flow over Nairobi is brought out in Table II. The components of the 800 and 700 mb winds at 0000 GMT were combined with the components of the 0300 GMT surface winds and averaged over each month. An average was also obtained for each month for the components of the 800 and 700 mb winds at 1200 GMT along with the 1500 GMT surface winds. The difference between the averaged components for the morning and afternoon times was then taken to represent the vector difference between the mean flow from surface to 700 mb in the morning and that in the afternoon. Over the whole year the vector difference was $100^{\circ} 4$ kt. This may be seen to be almost perpendicular to the average contour line near Nairobi, and the fact that the monthly vector differences were between 091 and 117° indicates a fairly steady component added to the wind flow each day. These monthly directions are shown on Figure 2 and it may be seen that the dry months tend to have a daily component more near to east than the wetter periods, when anabatic effects might be expected to be weaker.

A feature of the daily veering of the surface wind in the north-east monsoon season is the halt in the daily swing each morning between about 0600 and 0800 GMT. This feature is missing from the south-east season although June, August and September have this tendency earlier on, between 0300 and 0400 GMT, about sunrise. Otherwise, the diurnal cycle in the north-east monsoon and July call for little comment, but the rotation of wind directions through the full 360° in May, June, August and September is rather unexpected. Humphreys³ explains a complete daily cycle in the observations from Blue Hill Observatory as the tendency for winds to blow towards the region of maximum heating. At this season, in East Africa, on the macro-scale, the area of maximum heating is far to the north in the summer hemisphere. However, on the meso-scale the situation is rather different. Referring to Figure 1 it may be seen that the contours will allow considerable cold air drainage from the Aberdare Mountains to flow to an area over the flat plains north-north-east of Nairobi Airport. This would create a north-south gradient until the plains were uniformly filled with colder air at the surface, and only then would the weaker katabatic effect of the local gentle slope to the east become effective. That this does not happen in July is probably due to the stronger monsoon flow of mid-season dominating the situation.

Attention is drawn to Table IV which is a summary of constancy q of the surface winds at Nairobi Airport. Hourly values vary widely from a low of 7 at 0000 GMT in May to a maximum of 98 at 2000 GMT in January. These figures fit very well with January as the month of steadiest flow (88) and

TABLE IV—MONTHLY AND ANNUAL CONSTANCY q OF SURFACE WIND AT NAIROBI
AIRPORT 1959-63

Time GMT	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual mean
0000 ...	79	65	60	48	7	42	64	48	24	62	75	84	55
0100 ...	65	48	56	50	9	52	63	58	16	91	75	85	56
0200 ...	65	48	55	48	19	55	81	61	22	82	74	74	57
0300 ...	57	41	47	43	30	55	81	61	29	79	74	71	56
0400 ...	40	22	60	44	57	64	82	61	50	85	77	70	58
0500 ...	73	37	64	46	58	66	87	45	54	81	62	80	62
0600 ...	83	45	68	55	58	65	88	70	58	63	82	82	68
0700 ...	91	91	90	62	60	70	81	76	62	77	78	89	77
0800 ...	94	95	89	67	63	59	74	66	61	81	79	87	76
0900 ...	94	96	93	75	61	67	83	63	62	86	79	87	79
1000 ...	94	93	92	75	56	63	82	66	71	83	85	88	79
1100 ...	94	92	95	79	59	66	68	62	73	85	84	86	79
1200 ...	94	90	92	77	53	70	73	66	78	90	87	86	80
1300 ...	95	91	90	80	60	77	74	73	78	92	86	88	82
1400 ...	96	94	94	82	72	75	77	82	88	92	85	86	85
1500 ...	93	97	94	86	74	89	83	85	89	94	87	88	88*
1600 ...	94	95	90	86	73	88	84	83	96	91	82	89	87
1700 ...	91	91	85	81	51	77	89	82	91	86	90	86	83
1800 ...	91	86	85	76	48	65	83	71	86	88	86	91	80
1900 ...	93	86	88	88	33	27	41	55	77	87	88	93	70
2000 ...	98	82	78	62	33	16	30	19	46	81	86	93	60
2100 ...	94	91	72	48	30	33	60	12	44	82	79	90	61
2200 ...	83	77	68	49	16	42	60	26	38	88	73	90	60
2300 ...	77	65	67	59	19	41	66	41	33	88	80	90	60
Mean ...	88†	76	79	81	46	59	73	60	59	84	80	86	72

* Maximum annual hourly mean.

† Maximum monthly mean.

May as the month of least steady flow (46). The hour of least constant flow throughout the year is 0000 GMT (0300 local time) although there is little difference between that time and sunrise (about 0630 local time or 0330 GMT). The hour of greatest constancy is coincident with the time of maximum wind speed (1500 GMT) just before sunset, again emphasizing the strong effect of the superimposed anabatic flow at all seasons. Seasonally the north-east monsoon is steadier than the south-east, the constancy of January winds being quite remarkable. July stands out among the south-easterly months as the one with highest constancy, which might have been expected from the mid-season month.

Upper winds.—There is little to comment on in the monthly changes at these levels, apart from the peculiar backing of the 700 mb wind in June at 0000 GMT against the seasonal veering.

The diurnal changes in direction show, both at 800 mb and 700 mb the effect of the deepening of the turbulent mixing layer as evidenced by the height of the CCL in the various months (Figure 2). There are fairly significant changes from 0000 to 1200 GMT in each month as the flow between the surface and 700 mb obeys the influence of the upslope wind, although these changes are least in evidence when the season is more transitional than otherwise such as in April and September. The depth of the mixing layer at the time of maximum heating is further evidenced by the organization of the afternoon flow between the surface and 700 mb in most months. The north-east season shows this organization best; apart from November and December, a homogeneous flow exists from 800 to 700 mb in the morning, and from the surface upwards in the afternoon. The south-east monsoon is not so well

organized, probably because this monsoon is shallower than its counterpart, and does not extend to the 700 mb level. In July and August especially, there are considerable differences between the 800 and 700 mb winds at 0000 GMT. However, by 1200 GMT such are the combined effects of the mixing and anabatic influence, that the morning difference has been largely eliminated and the flow regularized to a considerable degree. The early and late months of the south-east season (May and September) which are more transitional, do show a great homogeneity, especially September. Diurnal changes in speed at 800 and 700 mb do not call for much comment in the greater part of the year. In most months, the maximum surface wind scalar speed is greater than that at 800 mb. The exceptions are July, October and November. This may indicate that the anabatic component which is in the direction of the general circulation, is of considerable magnitude.

Conclusion.—The results are what might have been expected in this part of the world with one notable exception. In this latitude just south of the equator it might have been anticipated that instead of a north-east monsoon, there would have been the beginnings of a north-west monsoon, as applies from about 45°E to New Guinea. That there is a north-east monsoon is because of the presence of the large heated land mass to the south and south-west with its resultant large heat low into which the local stream is drawn. The daily superimposition of a local topographic effect on the two monsoons is very clear from all the observations; just how far it extends upward is not known as winds above 700 mb were not investigated. The survey was started originally as applying to surface winds only.

Acknowledgements.—This article is published by permission of the Director, East African Meteorological Department, and grateful acknowledgement is made to Mr. J. Findlater, RAF Eastleigh, and Dr. Mörth, EAMD, for help and advice.

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MAJOR STORMS IN WEST PAKISTAN IN SEPTEMBER IN RELATION TO THE MANGLA DAM PROJECT

By R. FROST

Summary.—As a part of the Mangla Dam project it was planned to divert the River Jhelum in September 1965 and the mean date of the recession of the south-west monsoon was taken as a provisional date for the diversion. Occasionally at the end of the monsoon in September (most often between the 16th and 20th of the month) there are major storms and floods in West Pakistan, and a long-term study which was made of these storms suggested that their frequency, which was low at the turn of the century, reached a maximum in the period 1945–50 and is now declining. The storm pattern appears to be linked with a secular change of sea temperature in the Bay of Bengal where the depressions originate as developments in the Northern Equatorial Trough. The depressions favour a track towards West Pakistan if the 300 mb ridge over East Pakistan extends west of its mean position. Synoptic studies were used to check the suitability of the date for the diversion.

The Mangla Dam Project.—When the Indian subcontinent was partitioned in 1947 the new international frontier between West Pakistan and India cut across the vast irrigation complex of the Indus Basin which had been developed over the past century, and it became necessary, therefore, for some arrangements to be worked out between India and Pakistan for access to and disposal of the waters of the Indus and its tributaries. By the Indus Waters Treaty of 1960 it was agreed that—in return for exclusive use by India of all waters flowing into the three eastern tributaries of the Indus, namely the Sutlej, Ravi and Beas—two major dams would be constructed, one at Mangla on the Jhelum, and the other at Tarbela on the upper reaches of the Indus. These dams, together with a system of canals, would transfer water from the rivers to which Pakistan would have exclusive rights, namely the Indus itself and its two other tributaries, the Jhelum and the Chenab, to the lower parts of the three eastern tributaries the Sutlej, Ravi and Beas (see Figure 1). All the Indus Water Treaty Works have been entrusted for execution to the West Pakistan Water and Power Development Authority by the Government of Pakistan.

A time clause in this treaty made it clear that India's right to the water of the three eastern tributaries would be recognized in 1970 but for three years thereafter Pakistan could demand the continuance of certain flows to her canals on payment of certain royalties. The scale of these however would increase from year to year until 1973 when India's proprietary rights would become all-embracing. It can be seen therefore that it is a matter of urgency for Pakistan for all replacement works and in particular the Mangla dam to be ready by the dates laid down by the Indus Waters Treaty.

On the design side the main consultants for the Mangla scheme are Binnie and Partners of London and the contract for the Mangla Dam which was awarded to a consortium of eight American firms is believed to be the largest-ever civil engineering contract. The estimate of the cost of this dam amounts to £425 million, based on 1963 costs, and the target date for its completion is July 1968.

In 1959 Dr. Tucker of the Meteorological Office assisted Binnie and Partners in carrying out maximum flood studies for the Mangla project and an account of his work is given in *Weather*.¹

The Mangla dam is now under construction and in order to complete the work of carrying the main dam across the final gap in the river Jhelum the contractors planned to carry out the critical diversion of the river immediately following the present south-west monsoon season, approximately one year ahead of schedule. For this to be successful it was necessary that the diversion should take place as early as possible in order that the dam could reach certain specified heights before the floods of the winter and the next summer monsoon. On the other hand as the consequences of a large flood immediately after the river diversion could be very serious the selection of the suitable date for the diversion was a matter of some importance. The provisional date of 10 September was selected for the commencement of the diversion and the Meteorological Office was asked if it could carry out studies of historic storms causing flooding in September and of the recession of the south-west monsoon, in order to assist in the interpretation of meteorological forecasts made on or immediately prior to 10 September. The Meteorological

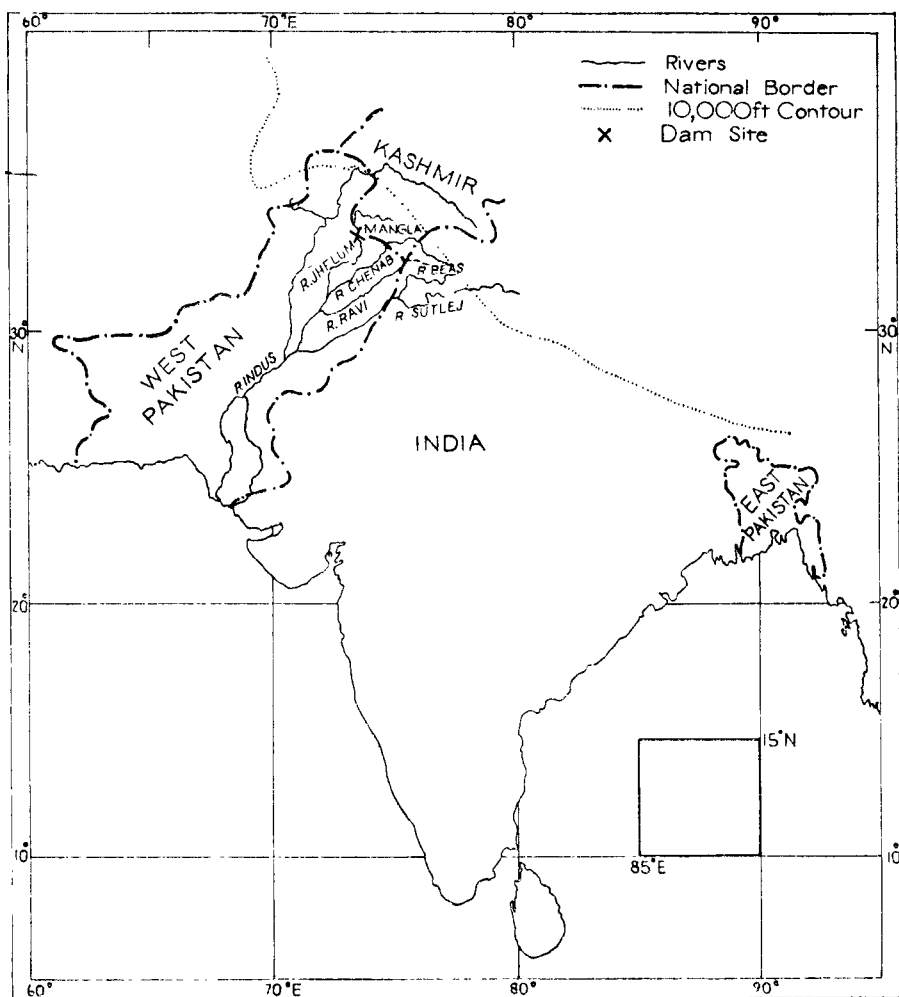


FIGURE 1—INDUS BASIN AND MANGLA DAM

Office was also asked if the writer, who had been closely associated with the present studies, could visit Lahore in early September to act as meteorological consultant on the project.

The mission in Pakistan was marred by the war which broke out between India and Pakistan on 6 September, and the imposition of meteorological security upon all weather reports made life somewhat difficult for the meteorological consultant. Fortunately, as indicated by the long-range weather forecasts based on the present studies and issued prior to 6 September in conjunction with the Pakistan Meteorological Service, no major storms affected West Pakistan during the critical phase of the river diversion and the work was carried out satisfactorily.

The recession of the south-west monsoon.—According to the *Climatological Atlas for Airmen* published (in Poona) by the India Meteorological Department in 1943, the mean date of the recession of the monsoon from that

part of India which is now Pakistan is 10 September and this was the provisional date selected for the diversion of the River Jhelum. Naqvi² however, using a longer series of observations, listed all dates of the recession of the monsoon from 1878 to 1960 and obtained as the average date of the recession 13 September with 31 August and 2 October as the earliest and latest dates respectively. The method of arriving at the dates of recession differed in the two cases. The India Meteorological Department in deriving their dates of recession used only 5-day normals of accumulated rainfall and selected the middle date of the period in which the characteristic fall occurred whereas Naqvi used all climatological data irrespective of rainfall amounts to determine when the monsoon current actually withdrew from West Pakistan.

Although the recession of the monsoon is less spectacular than the onset and has correspondingly received less study the floods which occur in West Pakistan in September at the end of the monsoon are in general more severe than those which occur at any other time.

Historic storms affecting West Pakistan.—From studies made by Naqvi³ and an examination of the September synoptic charts of the Indian sub-continent, it is clear that all major floods in West Pakistan during this month are caused by depressions which form over the north Bay of Bengal in the Northern Equatorial Trough (NET), more commonly known as the Intertropical Front (ITF), and move west-north-west across the Indian sub-continent curving northwards when at a line extending from about 24°N 70°E to 20°N 80°E. These depressions which do not in general reach beyond the 300 mb level have a life of about eight days from the time they form till the time they reach West Pakistan.

Approximately one in seven of all depressions which form over the Bay of Bengal in September and move over India curve northwards in this manner to affect West Pakistan and the main problems are to forecast the development of such depressions and to predict their tracks.

Table I lists the dates of all major storms which have affected West Pakistan in September during the period 1890–1964.

TABLE I—DATES OF MAJOR STORMS IN SEPTEMBER IN WEST PAKISTAN DURING THE PERIOD 1890–1964

Year	September	Year	September
1893	19	1945	14
1902	6	1945	25
1905	19	1947	26
1914	20	1949	19
1928	2	1950	19
1933	19	1954	25
1933	27	1955	25
1937	16	1959	16
1941	12	1961	16

Table II, which is derived from Table I, gives the number of major storms in West Pakistan for each 5-day period in September during the period 1890 to 1964.

TABLE II—NUMBER OF MAJOR STORMS IN EACH PENTAD OF SEPTEMBER DURING THE PERIOD 1890–1964

Pentad	1 – 5	6 – 10	11 – 15	16 – 20	21 – 25	26 – 30
Number of storms	1	1	2	9	3	3

Inspection of Table II suggests that if a major storm affects West Pakistan in September the most likely time for this to occur is between the 16th and 20th of the month.

The somewhat striking peak occurrence in the storm frequency over West Pakistan between the 16th and 20th of the month appears to be associated with the increased convectivity which develops in the NET as it moves southwards from over the land to over the north Bay of Bengal during the first week of September.

TABLE III—NUMBER OF STORMS PER DECADE IN SEPTEMBER

Decade	1890-99	1900-09	1910-19	1920-29	1930-39	1940-49	1950-59	(1960-64)
Number in decade	1	2	1	1	3	5	4	(1)

In Table III the storms listed in Table I are grouped within decades. It can be seen from the table that for the 50 years from 1890 to 1939 there were only 8 major storms in West Pakistan in September whereas in the 20 years from 1940-59 there were 9. There is a suggestion in Table I that the storm activity reached its peak in the period 1945-50 and is now declining. Since these storms all form over the sea it was a logical first step to investigate whether the decadal variation in storm frequency was associated with a secular change in sea temperature in the Bay of Bengal similar to that found by Brown⁴ in the tropical Atlantic between the decades 1910-19 and 1940-49. This is discussed in the following section.

Storm frequency and sea surface temperatures.—It is known that tropical cyclones form only over warm tropical areas and that, with other factors remaining the same, the frequency of formation is greatest during the months when the sea surface temperatures are the highest.

Palmén,⁵ from a consideration of the release of latent heat energy with normal lapse rates in the tropics, found that sea temperatures in excess of 26-27°C were necessary for the type of deep convection which always accompanied tropical cyclones, whilst Fisher,⁶ from an examination of hurricanes in the tropical Atlantic, concluded that temperatures of 28°C were necessary to initiate hurricane formation. Table IV shows the mean sea temperature since 1900 in the five-degree sea square bounded by 10-15°N and 85-90°E. Observations on punched cards were unfortunately not available for the decade 1890-99.

TABLE IV—MEAN SEA SURFACE TEMPERATURES IN SEPTEMBER FOR EACH DECADE DURING THE PERIOD 1900-64

Decade	1900-09	1910-19	1920-29	1930-39	1940-49	1950-59	(1960-64)
Temperature degrees C	28.0	27.9	27.9	28.6	28.7	28.5	(28.0)

It can be seen from Table IV that the change in sea temperature between 1910-19 and 1940-49 is 0.8 degC which is of the same order of magnitude as the change found by Brown.⁴

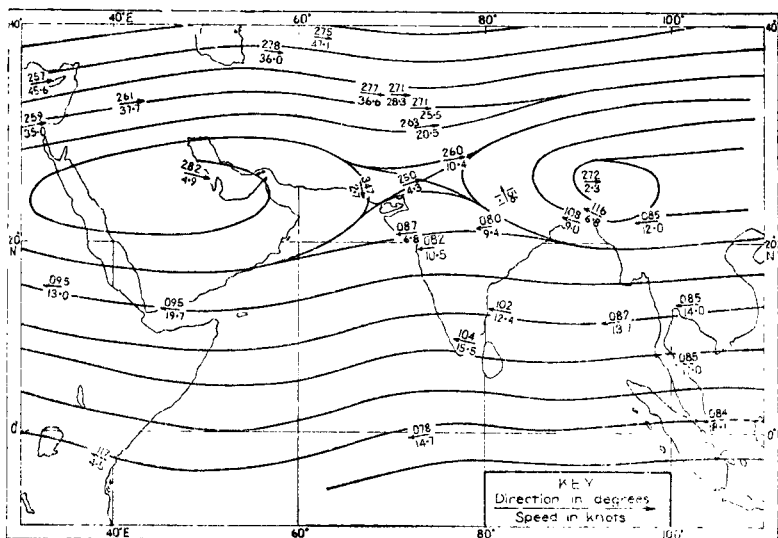
Comparison of Tables III and IV indicates that the frequency of depressions over West Pakistan in September increases with increase of sea temperature above 28°C in the Bay of Bengal. This suggests that a sea temperature of 28°C is the critical temperature not only for the vigorous tropical cyclones discussed by Fisher but also for the tropical depressions in the Bay of Bengal. (Note.—Few tropical depressions over the Bay of Bengal develop into tropical cyclones in September, probably because the temperature at 200 mb is too

high and the necessary deep convection from the surface to 200 mb cannot take place. The temperature at 200 mb over the north of the Bay of Bengal reaches its maximum in July and does not in general fall below a critical value of -51°C until October).

Tracks of depressions originating over the Bay of Bengal.—

Various studies have been made of the tracks of depressions originating over the Bay of Bengal and the present studies support the conclusion that the flow pattern at 300 mb is the crucial pattern for forecasting the movement of storms over the Indian sub-continent, see for example Chelam.⁷

Figure 2, which is based mainly on data made available by Mr. C. V. Raman of the International Meteorological Centre, Bombay, shows the mean flow pattern at 300 mb in September over India and the adjacent land masses.



Binnie and Partners for permission to publish this paper. The author also wishes to acknowledge with thanks the help and co-operation which he received from Dr. Naqvi, Director of the Pakistan Meteorological Service, whilst in West Pakistan.

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OBITUARY

Mr. L. H. G. Dines, M.A.—Lewin Henry George Dines died on 6 October 1965 at his home in Teddington, less than three weeks before his 82nd birthday. He joined the staff of the Meteorological Office in 1912, and served as Chief Assistant at Eskdalemuir Observatory and Valentia Observatory, and as Superintendent at Valentia from 1920 to 1922. After a year at Benson—the Observatory of those days, not the airfield—he came in 1923 to Kew Observatory where he remained until his retirement in 1947 at the age of 64.

He was the son of W. H. Dines, and his life's work was guided by his father's interests ; at Eskdalemuir he was a contemporary of L. F. Richardson. As a scientist he did not compare with these two great men, but he was for many years their loyal and diligent helper, and would be content to be so remembered. Though his publications include notes on wind structure and on the dynamics of cyclones he was mainly concerned with instrumentation and the exploration of the upper air in the days before the radiosonde. Before he joined the Meteorological Office he spent some time in the locomotive workshops of the Great Western Railway at Swindon and this experience may have contributed something to the strength and durability of even the lightest of his balloon-borne instruments. Perhaps his most ingenious device was that flown in the 1930's to obtain samples of stratospheric air subsequently analysed for water vapour and helium in Professor Paneth's laboratory at Durham. He did not solve the problem of how to exclude extraneous water vapour from the sample, but he may have come nearer to a solution than others working twenty years later. He was in charge of the first radiosonde flights made by the Meteorological Office.

His retirement was devoted to Church administration and the spirited companionship of the four daughters who survive him.

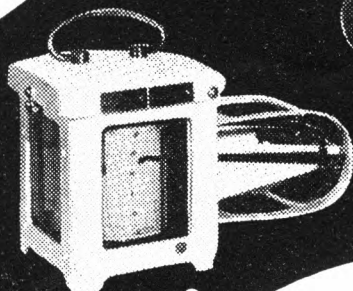
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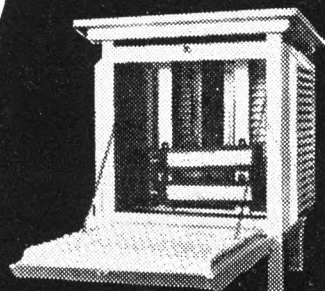
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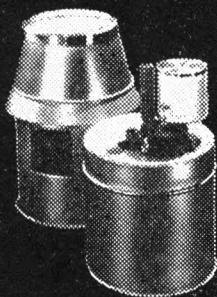
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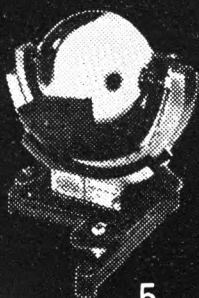
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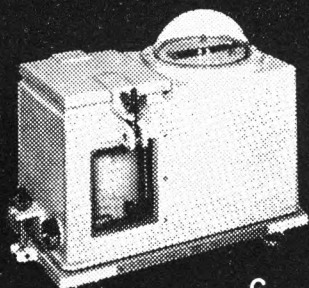
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CONTENTS

	<i>Page</i>
The behaviour of the first six zonal wave numbers at 50 and 500 millibars during some winter months in 1958 and 1959. G. R. R. Benwell	33
Low-level wind flow at Nairobi. B. Ramsey	47
Major storms in West Pakistan in September in relation to the Mangla Dam Project. R. Frost	57
Obituary	63
Corrigendum	63

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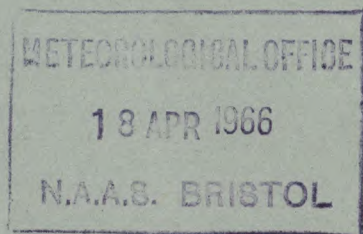
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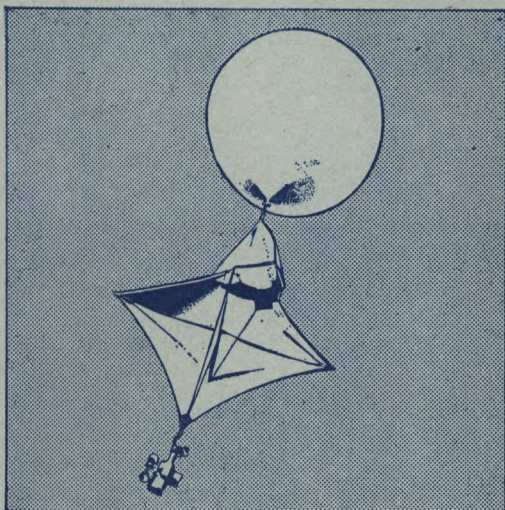
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CLOUD TOPS OVER MALAYA DURING THE SOUTH-WEST MONSOON SEASON

By R. F. ZOBEL, O.B.E. and S. G. CORNFORD

The project.—The Canberra aircraft of the Meteorological Research Flight was sent to RAF Station, Changi, Singapore, in order to obtain a general survey of the high-level cloud distribution, i.e. cirrus and cumulonimbus, in the Malaysian area during a period of south-west monsoon over south-east Asia. The survey took place during the period 8–21 July 1965.

In view of the unknown, but almost certainly severe, nature of turbulence inside cumulonimbus clouds in the area and the possibility of encountering cumulonimbus clouds invisibly embedded in cirrus, it was not the intention to enter cloud for the purpose of measuring vertical velocities because although the aircraft used is instrumented for such a purpose it is structurally unsuitable for use in cumulonimbus clouds and it has no forward-looking radar to assist in avoiding the precipitation cores.

Observational procedure.—Since the object was merely a survey of the highest clouds to be found on about 20 flights over a limited part of south-east Asia during part of a single south-west monsoon season, there was no point in attempting to measure cloud tops with great accuracy. Consequently estimation of cloud top height by the meteorological observer was intended to be used as the main basis of measurement.

The aircraft was however fitted with three fixed cameras which can take photographs horizontally to port and starboard, and vertically downwards. It was therefore possible from a sequence of shots at known intervals and a knowledge of the camera dimensions to calculate the height of the cloud and its distance from the aircraft.

The main difficulty in interpreting the photographs is that they frequently do not show the horizon. The position of the horizon on the photographs depends mainly on the angle of roll of the aircraft but there are also difficulties due to yawing and pitching of the aircraft as well as to inadvertent changes of course. Records of the rolling, yawing and pitching were made on the aircraft but the desired accuracy in cloud height to within 2000 feet could be expected to be realized by simple eye estimation, so that the labour involved in measuring photographs and trace recordings was not justified. A few photographs of cumulonimbus tops have however been measured and these confirm that the eye estimates were reliable. It is, of course, necessary to rely on the latter for the cirrus heights, as cirrus lacks distinctive features

of shape. All heights in this report are on the ICAO (International Civil Aviation Organization) scale. True heights prevailing were approximately 2000 ft greater. Distances between cumulonimbus clouds are entirely the observer's eye estimates.

The flights.—A total of 20 flights had been hoped for but only 9 were successfully made, all over Malaya and adjacent waters ; other flights planned were abandoned because of unserviceability of the aircraft and because it was found impossible to avoid cloud penetrations during which turbulence occurred of sufficient degree to constitute a hazard to the aircraft which was already flying near its ceiling. It is thought that some of the aircraft faults which developed were in fact caused by turbulence during inadvertent cloud penetrations.

The ceiling of the aircraft is limited to 48,000 ft for operational reasons but in the low temperature conditions prevailing, safety and all-up weight considerations led to a ceiling, in several instances, well short of this value. This meant that the aircraft often did not reach the cloud tops until late in the sortie, if at all. These limitations led to a number of unavoidable cloud penetrations. Such penetrations were never intentionally made into cloud other than cirrus. On at least one occasion however the turbulence was so violent that it seems likely that cumulonimbus clouds may have been embedded in the cirrus.

The cloud conditions.—The overall picture of the cloud conditions is one of large amounts of cirrus, mainly associated with cumulonimbus tops, but only rather infrequently penetrated by cumulonimbus.

Details of this general impression may be seen in Tables I – III. During the 9 flights observations were made at five-minute intervals. Of the total number of these, 167 in all, only 3 showed cirrus to be absent. Table I shows that on the 56 occasions when the observer had confidence in his observations 41, or about three-quarters, show the cirrus to have been, to at least some extent, associated with cumulonimbus tops. Table II shows that on some occasions cirrus was present above the main sheet. Again on two-thirds (20 out of 30) of the occasions the cirrus was associated with cumulonimbus tops. There were however 18 occasions when cumulonimbus clouds penetrated the main cirrus sheet without further cirrus formation. Such differences may indicate different stages of development of the cumulonimbus clouds.

TABLE I—NUMBER OF OBSERVATIONS OF CIRRUS SHEETS OF 6/8 OR MORE AND THEIR ASSOCIATION WITH CUMULONIMBUS

Association of cirrus sheets and cumulonimbus				Cirrus sheets without cumulonimbus	Total number of observations
Entirely associated	Mostly associated	Partly associated	Not at all associated		
9	17	15	6	9	56

TABLE II—NUMBER OF OBSERVATIONS OF CIRRUS ABOVE THE MAIN CIRRUS SHEET AND THE ASSOCIATION WITH CUMULONIMBUS PENETRATING THE MAIN SHEET

Association of 'cirrus above' and cumulonimbus penetrating the main cirrus sheet				'Cirrus above' without cumulonimbus	Total number of observations
Entirely associated	Mostly associated	Partly associated	Not at all associated		
6	11	3	9	1	30

Note : there were also 18 occasions when cumulonimbus penetrated the main sheet but there was no cirrus above the sheet.

TABLE III—NUMBER OF OBSERVATIONS OF CIRRUS FROM DIFFERENT AIRCRAFT

Aircraft altitude	ALTITUDES							
	Cirrus top below aircraft			Aircraft in cirrus cloud		Cirrus base above aircraft		
	No cloud	1/8-5/8 cloud	6/8-8/8 cloud	1/8-5/8 cloud	6/8-8/8 cloud	No cloud	1/8-5/8 cloud	6/8-8/8 cloud
	<i>number of observations</i>							
<i>feet</i>								
≤ 35,000	18	7	0	2	2	4	6	15
36-40,000	0	8	3	1	13	4	5	2
41-45,000	4	9	14	12	28	21	5	1
46,000	0	2	21	1	4	23	0	0
47,000	0	3	9	0	2	7	5	0
48,000	0	1	0	0	1	0	1	0
49,000	0	1	1	0	0	1	1	0

In Table III are shown the amounts of cirrus observed from different levels. It will be seen that there were usually only small amounts of cirrus above about 46,000 ft. The base of cirrus was observed mostly to be located between 25,000 and 35,000 ft. The highest cirrus observed was estimated to be 1/8 at 55,000 ft and about 1000 ft thick.

Several examples of cumulonimbus clouds with cirrus streamers of estimated lengths of over 100 miles were observed, particularly striking examples being seen during the outward journey between Madras and Malaya. A photograph of one of these is shown as Plate I. Such clouds have been described earlier by Frost.¹ On this occasion however cirrus streamers of great length were still attached to the parent cumulonimbus, indicating a life for the cloud of several hours.

On many occasions the presence of cirrus prevented observation of other cloud formations. There is however no doubt, as shown earlier, that much of the cirrus was engendered by cumulonimbus clouds. Indeed cumulonimbus clouds were often observed to be 'feeding' the cirrus which obviously contained embedded cumulonimbus tops. On the other hand on one flight there were unusually small amounts of cirrus, whilst only one cumulonimbus was to be seen over the whole southern half of Malaya. It was occasionally observed that some extensive sheets of cirrus were unaccompanied by cumulonimbus development and the same may be true in a number of other flights when observation was difficult.

The cumulonimbus tops were usually associated with large amounts of cirrus and were thus not visible. Along the 6000 miles flown above 40,000 ft on the 9 flights, which were in areas selected as most likely to produce cumulonimbus clouds, only 26 cumulonimbus tops were encountered. These were clouds which had penetrated the cirrus sheet, or were not surrounded by cirrus and which it was possible to approach within about 30 miles.

The main features of the cumulonimbus observations may be briefly summarized :

- (i) Cumulonimbus tops were mostly associated with large amounts of cirrus which obscured them ;
- (ii) Cumulonimbus tops infrequently penetrated the cirrus veil ;
- (iii) The average height of cumulonimbus tops was 46,000 ft ;
- (iv) The maximum height of cumulonimbus tops was 51,000 ft ;
- (v) The separation of cumulonimbus tops at heights above 40,000 ft exceeded 100 miles on 75 per cent of occasions and was never less than 20 miles ;

- (vi) It was not possible to arrive, with reasonable certainty, at any conclusions regarding the distribution of cumulonimbus clouds with orographic features, but the general impression was that the distribution was largely random.

These results are in substantial agreement with those of Deshpande,² who collected a much greater volume of observations relating to India and Pakistan over six south-west monsoon seasons. He found less than 1 per cent of tops reaching above 52,500 ft (true).

Relationship of cloud tops to the tropopause.—There was inevitably a degree of subjectivity in assessing the tropopause level from the sparse network of radiosondes over the routes flown. However on 4 of the 9 flights there is little doubt that cloud was below the tropopause by amounts between about 2000 and 9000 ft. On 3 flights cumulonimbus tops were found at tropopause level, whilst on the other two, cloud was found about 5000 ft within a diffuse tropopause zone. This cloud was observed to be cirrus, but the turbulence within it suggests that cumulonimbus may also have been present. It seems probable that these observations were of cumulonimbus in the glaciated, degenerating phase.

Conclusion.—The present observations are too few to be able to draw firm conclusions from them in isolation. However they agree well with Deshpande's results and the two sets of results taken together suggest that the distribution of maximum height of cloud top may be fairly uniform over a wide area of south-east Asia during the south-west monsoon season. At 50,000 ft the chance is high that a pilot will be on top of all cloud or cloud amounts will be small, but at lower heights the chance of encountering cumulonimbus clouds or cirrus concealing cumulonimbus increases rapidly.

Acknowledgements.—The authors' thanks are due to Mr. B. W. Butler and Mr. D. M. Pusey who made the observations, as well as to the Royal Air Force crews who flew the aircraft under difficult conditions.

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A SIMPLIFIED CALCULATION OF MAXIMUM VERTICAL VELOCITIES IN MOUNTAIN LEE WAVES

By S. A. CASSWELL

Introduction.—The general conditions most favourable for the occurrence of waves to the lee of mountains, and the conditions for lee waves to be associated with large vertical velocities are well known, mainly as a result of theoretical studies by Scorer.¹ However, the application of the theory in practical cases is difficult, especially in the assessment of vertical velocities, a problem of considerable importance in aviation.

In the theory, the occurrence and properties of lee waves are shown to depend on the vertical variation of the parameter l where, neglecting the rate of change of wind shear with height,

$$l^2 = \frac{g}{U^2} \frac{1}{\theta} \frac{\partial \theta}{\partial z} = \frac{S}{U^2} \quad \dots (1)$$

where g = acceleration due to gravity
 U = horizontal wind speed
 θ = potential temperature
 z = height
 S = static stability.

If one considers a given airstream in detail, computation of the wavelength(s) and other properties of the flow is a formidable undertaking, necessitating the use of an electronic computer. For this reason Foldvik² proposed that an approximation to the profile of l should be obtained from an exponential function uniquely determined by two parameters only. Thus he put

$$l = l_0 e^{-cz} \quad \dots (2)$$

and found values of l_0 and c to give a best fit to the observed profile of l computed using 100-mb layers. The advantage of this scheme is that the variation of l is reduced to two parameters and the lee wavelengths, etc., can then be calculated in a straightforward manner. Foldvik showed that results so obtained compare favourably with observations, and with those from more elaborate calculations. His method, however, is still too time-consuming for application in routine forecasting, taking perhaps 20 minutes for one upper air sounding. In this paper additional simplifications are proposed to speed up the calculations still further so that the results can be obtained in about 2 minutes. Basically, the present method makes a simplification by obtaining l in terms of two parameters at an early stage of the work, instead of after the rather lengthy process of calculation of the l -profile.

The simplified method.—In lee-wave conditions there is typically a stable layer located somewhere in the lower troposphere, with less stable air above. It is therefore proposed to represent the atmosphere approximately by two layers only, namely 1000 to 700 mb and 700 to 300 mb, and to obtain an approximation to the profile of l by using the exponential equation (2) made to fit the observed values of l found for the layers centred at 850 and 500 mb.

The static stability S can be obtained from the equation :

$$S = \frac{g}{\theta} \frac{\partial \theta}{\partial z} = - \frac{g^2 \rho}{\theta} \frac{\partial \theta}{\partial p} = \frac{g^2}{RT} \left(K - \frac{p}{T} \frac{\partial T}{\partial p} \right) \quad \dots (3)$$

where $K = R/c_p$ and T, p, ρ, R, c_p have their usual meanings.

By taking finite differences in the vertical and inserting values for the constants,

$$S = \frac{0.366}{T_m} \left(0.288 - \frac{p_m}{T_m} \frac{\Delta T}{\Delta p} \right) \text{ in terms of (seconds)}^{-2} \quad \dots (4)$$

where T_m and p_m are means over the layer.

This expression can be evaluated for the lower and upper layers by using appropriate values for $T_m, p_m, \Delta T$ and Δp as follows :

	T_m °K	p_m millibars	Δp	ΔT
Lower layer ...	273	850	300	$T_{1000} - T_{700}$
Upper layer ...	250	500	400	$T_{700} - T_{300}$

A smoothed temperature curve is used, as in Foldvik's method, to obtain ΔT . If the tropopause is below 300 mb the tropospheric curve is extended to 300 mb to obtain ΔT ; in such examples the stratospheric temperatures are ignored because they are not representative of the layers examined.

From equation (1), $l = S/U$. . . (5)

where U is the component of the wind across the mountain range for the particular layer used for l and S . Graphs to obtain l_{850} and l_{500} , the values

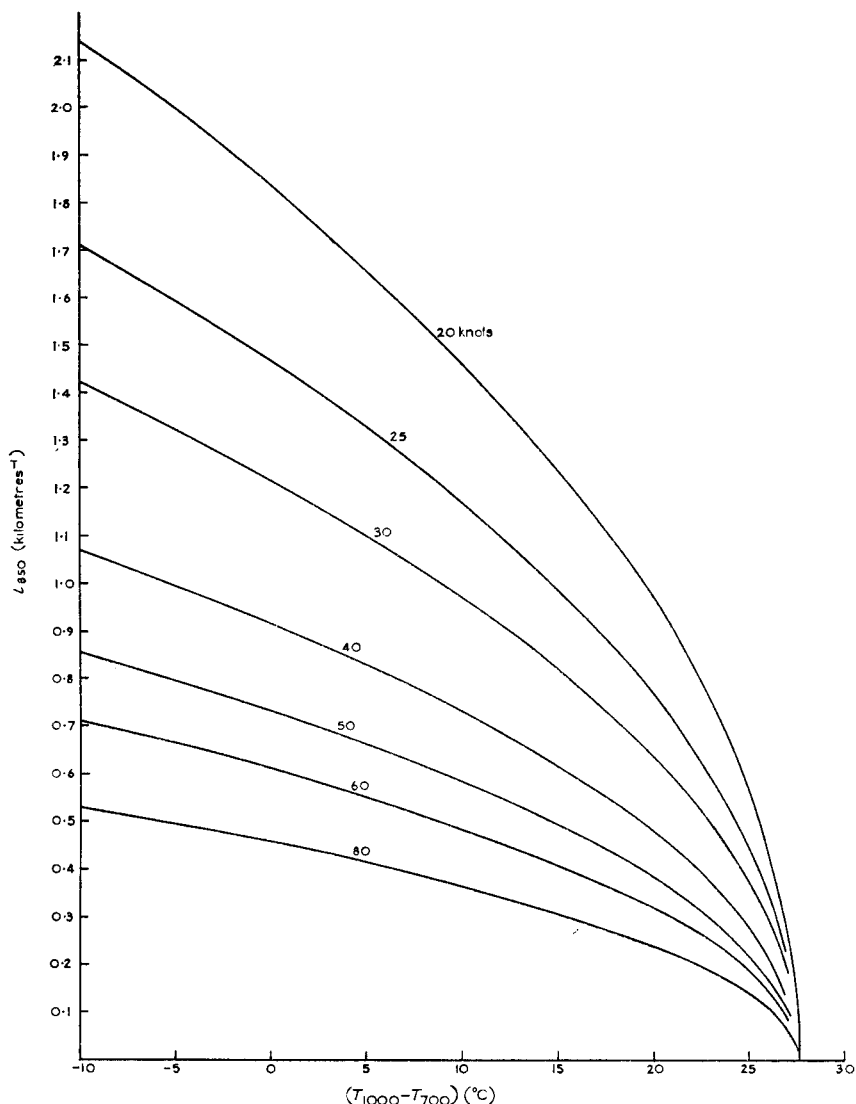


FIGURE 1—GRAPHS USED TO OBTAIN l_{850} FROM $(T_{1000} - T_{700})$ AND U_{850}

of l at 850 mb and 500 mb, are shown in Figures 1 and 2 which have been computed from equations (4) and (5) using the values of S obtained for the lower and upper layers.

Substituting l_{850} and l_{500} in turn in Foldvik's exponential formula (2), values of l_0 and c can be obtained.

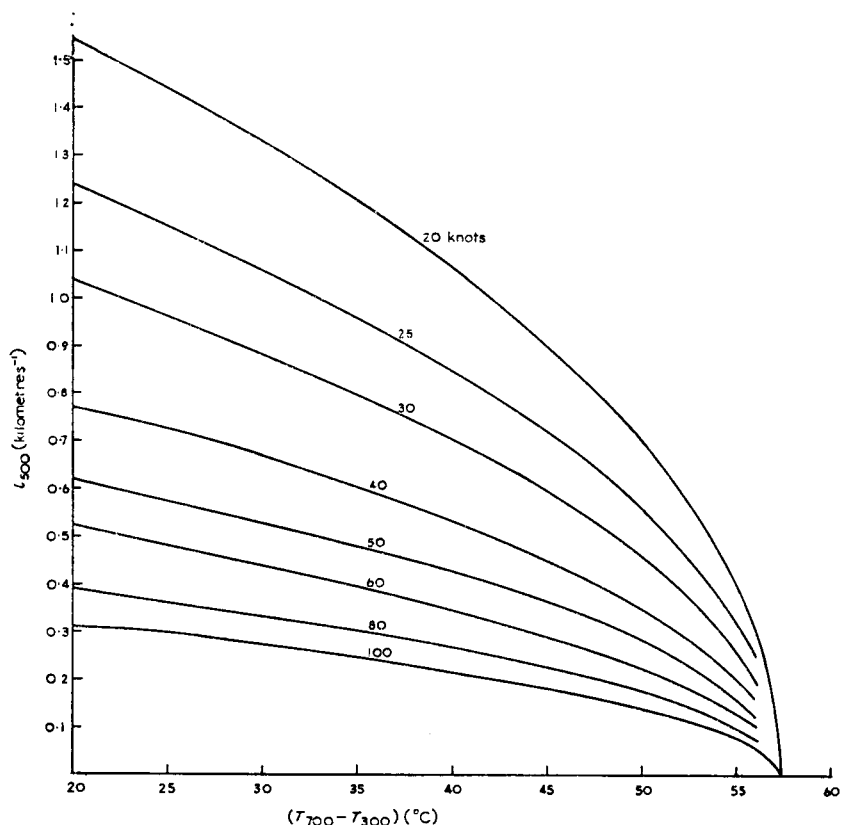


FIGURE 2—GRAPHS USED TO OBTAIN l_{500} FROM $(T_{700} - T_{300})$ AND U_{500}

From Foldvik's method the heights h_1, h_2 , at which the vertical velocities w_1, w_2 of the primary and secondary trains of waves reach their maximum values, are given by :

$$h_1 = c^{-1} \ln \frac{l_0}{l_0 - 2.2c} \quad \text{and} \quad h_2 = c^{-1} \ln \frac{l_0}{l_0 - 5.5c} \quad \dots (6) \text{ and } (7)$$

The corresponding wavelengths L_1, L_2 can be obtained from l_0 and c using Foldvik's graph of the appropriate Bessel function.

The values of the maximum vertical velocities can then be obtained from his approximations, thus :

$$(w_1)_{\max} = \left(2.5 + \frac{0.7}{cL_1} \right) HcU_0 \left(\frac{\rho_0}{\rho_1} \right)^{\frac{1}{2}} \quad \dots (8)$$

$$\text{and } (w_2)_{\max} = 3.2 HcU_0 \left(\frac{\rho_0}{\rho_2} \right)^{\frac{1}{2}} \quad \dots (9)$$

where H is the height of the mountain barrier and for practical purposes U_0 can be taken as the wind velocity at about the level of H in the free air, and ρ_0 , ρ_1 and ρ_2 refer to the density at heights 0, h_1 and h_2 .

$$\text{Let } \left(2.5 + \frac{0.7}{cL_1}\right) c \left(\frac{\rho_0}{\rho_1}\right)^{\frac{1}{2}} = C_1 \quad \dots (10)$$

$$\text{and } 3.2c \left(\frac{\rho_0}{\rho_2}\right)^{\frac{1}{2}} = C_2. \quad \dots (11)$$

$$\text{Then } (w_1)_{\max} = HU_0C_1 \quad \dots (12)$$

$$(w_2)_{\max} = HU_0C_2. \quad \dots (13)$$

Values of the parameters C_1 and C_2 can be obtained graphically from equations (10) and (11) with l_{850} and l_{500} as the variables. Thus the values of L_1 , h_1 , C_1 , L_2 , h_2 and C_2 can be obtained from l_{850} and l_{500} and are shown in Figures 3 and 4. These were drawn by taking a grid of points on the $l_{850}-l_{500}$ diagram and first calculating for each point the values of l_0 and c , next from these determining L_1 , L_2 , h_1 and h_2 , and finally calculating C_1 and C_2 . Isopleths of the required six items were then drawn freehand, dividing them into two groups, each of three items for convenience.

The vertical velocity.—It will be seen that wavelengths and the heights of the maximum vertical components depend only on the airstream, and are independent of the mountain height, but that the value of the vertical component is proportional to this height.

It is generally recognized that the lee slope is the important factor of the mountain profile, so it is not the mountain peak elevation above mean sea level that should be used for H but the difference between the general height of the mountain barrier in the vicinity of the lee slope and the height of the ground to its lee. Most of the various factors that cannot easily be taken into account tend to reduce the vertical component, e.g. friction effect, possible separation of the flow from the surface (say with cold air over the lower ground), though some factors such as overlapping effects from two or more ridges of mountains could either increase or decrease the values. A general figure of 300 metres was taken by Foldvik for the value of H in the neighbourhood of Leuchars. It is suggested that this value be used generally within the British Isles and the result taken as a general figure that might be expected over an appreciable area on a particular occasion, but it cannot be expected to give extreme local values.

Use in forecasting.—The mountains of the British Isles have lee slopes in most directions, so for general forecasting of lee waves the gradient wind can be taken as the horizontal wind speed U_0 at the ridge height and the upper-level winds should be resolved along the gradient wind direction. The effects calculated will then be for the region that lies directly to the lee of the mountain range, with, usually, smaller effects where the lee slope is not perpendicular to the wind direction. In forecasting for a specific small area components perpendicular to the specified ridge would be used at all levels required.

Limits and limitations.—There are various requirements before lee waves can be expected, and some limitations of the present method of calculation.

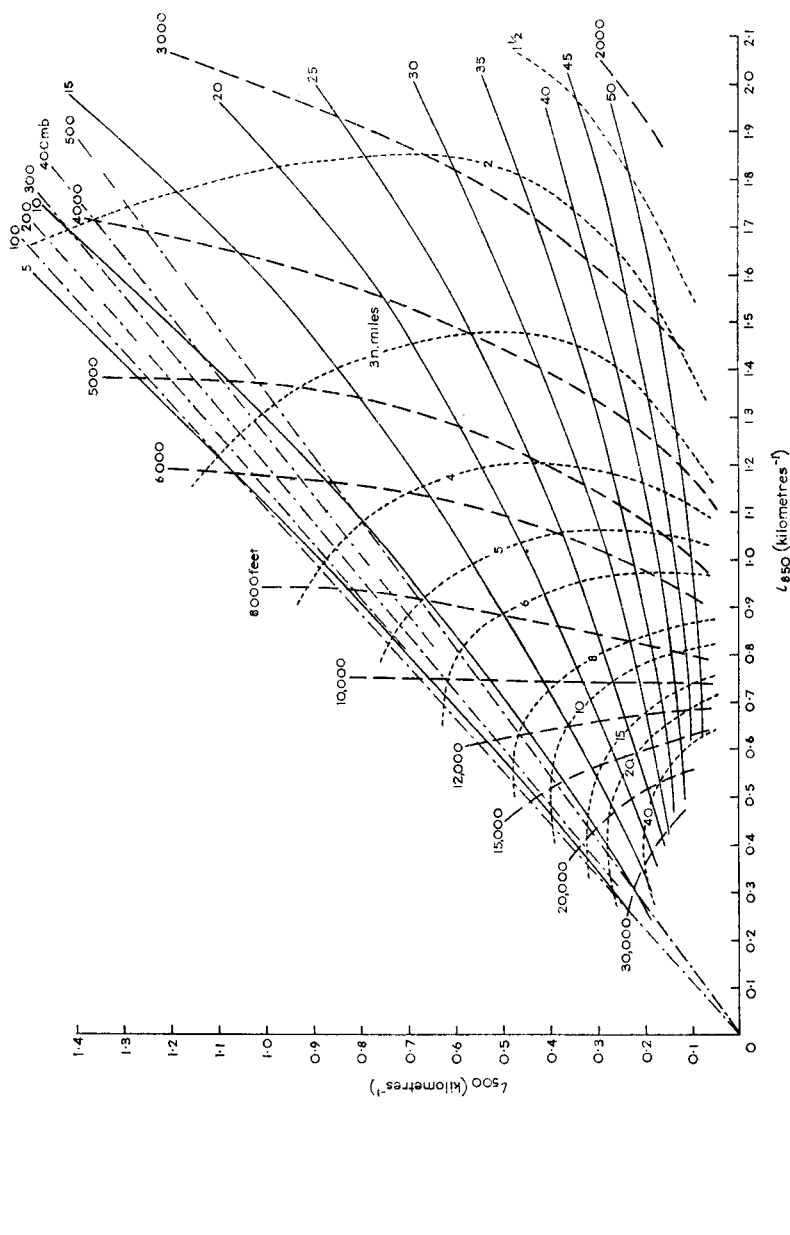


FIGURE 3—GRAPHS USED TO OBTAIN L_1 , h_1 AND C_1

— Values of C_1 (see text) --- Values of h_1 (feet)
 - - - - - Values of L_1 (nautical miles) - - - - - Level of tropopause (millibars) for limiting value of L_{850}/L_{500}

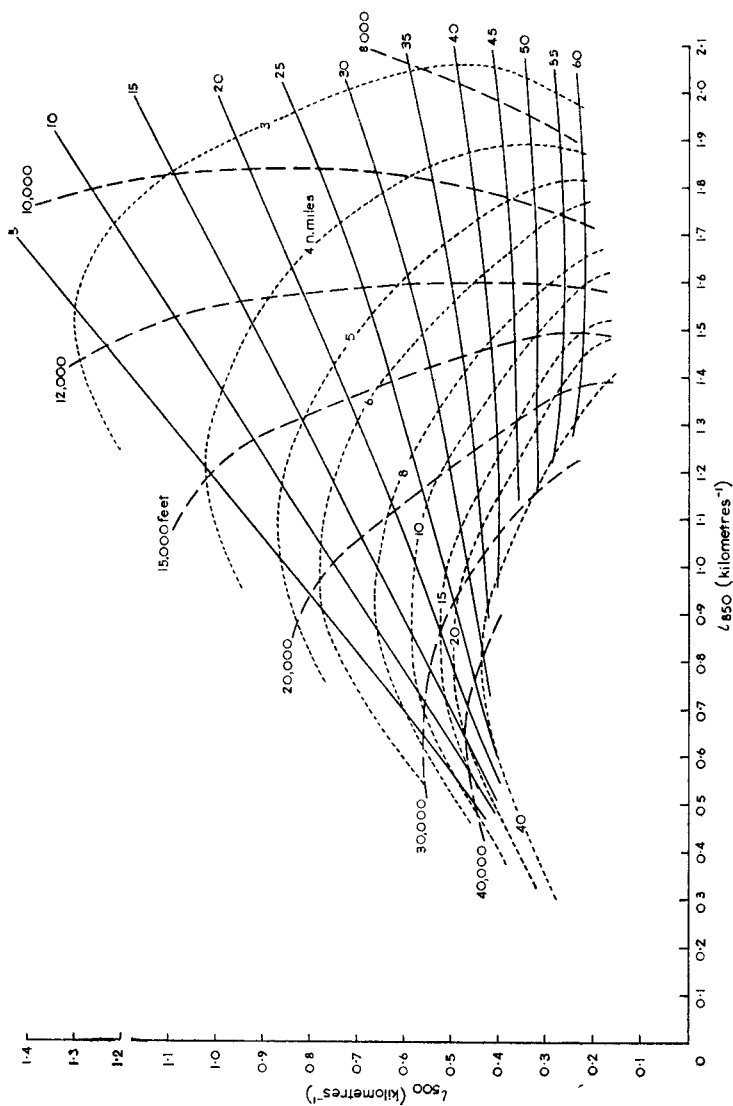


FIGURE 4—GRAPHS USED TO OBTAIN L_2 , h_2 AND C_2

— Values of C_2 (see text) - - - Values of L_2 (nautical miles) . . . Values of h_2 (feet)

A minimum wind component across the mountain barrier of between 7 and 15 metres/second is generally considered necessary for small mountains and the wind direction should be within about 30 degrees of the perpendicular to the line of the lee ridge, and should change little with height (*WMO Tech. Note No. 34*, pp. 29, 42, 48, 119³). A marked decrease, with height, of the component across the ridge will limit the wave activity to below this level. (*WMO Tech. Note No. 34*, Figure 46 *b*).

No marked waves will occur unless l decreases appreciably with height. One of Foldvik's approximations requires that l_0 should be greater than 1.5 times the minimum value of l . If this requirement is not fulfilled the calculations are invalid. It seems likely however that marked waves should not be expected in these cases and this is allowed for in Figure 3 by the straight lines through the origin, marked 100, 200, etc. mb, which are drawn on the assumption, generally true, that the minimum value of l is at the tropopause. The line corresponding to the tropopause level should be noted, and if the plot of l_{500} against l_{850} lies above this then marked waves are not expected.

No use is made of stratospheric winds and temperatures in the present method, which is concerned chiefly with waves in the lower levels. Any waves calculated to have a maximum vertical velocity above the tropopause are not likely to be real, and if the maximum is near the tropopause the values obtained may be appreciably in error. Waves at lower levels however are little affected by the marked change in value of l at the tropopause (Corby and Sawyer⁴).

Comparison with other methods.—When marked waves occur, large vertical velocities extend over only short distances perpendicular to the line of the mountains, but over much longer distances parallel to this line. The effect on an aircraft can be very serious if it should be flying at the appropriate height, place and course, whilst other aircraft flying across the same area may experience little effect. Thus few aircraft observations are available giving details sufficient to allow comparison with calculated values of vertical motion.

However, another characteristic of the motion, the wavelength, would not be expected to vary so greatly with height as does the vertical velocity. One of the best series of observations available is that of Corby⁵ who calculated the wavelengths of lee waves from the changes in vertical motion found in routine radiosonde ascents from Leuchars. This series has been used by Foldvik² and by Wallington and Portnall.⁶ A comparison with the present method is given in Table I. In the comparison with the observed wavelength, there is the complication that the temperatures are measured in the airstream that is already disturbed by the wave motion. Both the suggested method and the full exponential one are somewhat subjective, so that some appreciable differences are to be expected. Generally, however, these differences are not found to be large.

The calculated maximum vertical velocity in the primary wave train is within 20 per cent of that obtained by the full exponential method except for the following four examples (the numbering is taken from Table I) :

- (i) No. 3. — The l -trace has an unusual shape due to a marked decrease of wind above 800 mb, followed by an increase above 650 mb. The

TABLE I—COMPARISON BETWEEN OBSERVED AND VARIOUSLY COMPUTED LEE-

Example No.	Date Time (GMT)	WAVE CHARACTERISTICS											
		Observed λ (Corby)	Computed λ (Wallington and Portnall)	COMPUTED VALUES—FOLDVIK					COMPUTED VALUES—PRESENT METHOD				
				λ vertical velocity	Maximum Height of max.	l_0	c	λ vertical velocity	Maximum Height of max.	l_0	c		
		kilometres		km	m/s	km	km ⁻¹	km ⁻¹	km	m/s	km	km ⁻¹	km ⁻¹
1	4.11.53 1400	13.3	14.6	15.0	3.0	2.7	1.06	0.21	17	2.5	3.2	0.90	0.17
2	18.11.53 0400	13.3	15.0	13.6	2.7	2.6	1.05	0.17	14	3.2	2.8	1.08	0.19
3	20.11.53 0400	8.9	4.5	6.3	3.2	1.4	1.75	0.19	9	2.5	2.0	1.26	0.14
4	30.11.53 0200	26.7	—	13.4	3.8	4.8	—	—	20	3.7	7.3	—	—
	Aldergrove 21.12.53 1400	10.0	13.0	23.0	4.9	2.9	1.15	0.31	24	4.9	3.3	1.07	0.29
6	3.1.54 0300	18.5	17.0	13.2	4.0	2.3	1.23	0.24	17	4.2	2.8	1.09	0.25
7	3.1.54 1500	18.5	17.9	19.3	4.6	2.9	1.05	0.25	17	4.4	2.9	1.07	0.23
8	4.1.54 0200	10.0	10.0	10.9	3.4	2.0	1.35	0.23	9	3.7	1.8	1.50	0.23
9	11.1.54 0200	12.0	8.9	8.6	1.7	2.0	1.23	0.13	39	5.5	8.5	—	—
10	11.1.54 1400	5.9	7.6	17.4	2.2	6.7	—	—	11	2.0	2.2	1.17	0.15
11	12.1.54 1600	8.9	11.0	15.5	—	—	—	—	32	3.0	8.5	—	—
			12.0*	15.9	2.6	5.9	1.45	0.16	8	1.7	1.9	1.33	0.12
			11.0	12.9	1.5	3.3	0.75	0.062	15	2.2	6.1	—	—
				21.4	2.0	9.8	—	—	12	1.0†	3.4	0.68	0.032
				44.0	—	—	—	—	15	1.0†	9.2	—	—
12	14.1.54 0200	10.4	—	16.2	1.4	3.6	0.70	0.082	18	1.2	4.3	0.61	0.07
13	Stornoway 23.1.54 1400	5.6	5.7	15.0	1.4	3.2	0.84	0.12	17	1.4	3.7	0.78	0.12
			7.4*	5.1	0.8	1.4	1.74	0.11	5	1.1	1.3	1.85	0.13
			8.3*	7.3	0.8	3.9	—	—	7	1.1	3.7	—	—
14	24.1.54 1400	4.8	9.1*	11.2	1.1	7.9	—	—	—	—	—	—	—
			11.8*	12.4	2.8	2.3	1.20	0.21	11	2.2	2.3	1.14	0.15
15	Aldergrove 21.3.54 0200	8.7	—	15.3	2.1	4.8	0.71	0.078	18	2.4	4.0	0.70	0.102
				22.2	3.8	3.2	1.00	0.25	30	3.4	4.1	0.86	0.23
16	Aldergrove 11.4.54 1400	8.7	7.8	12.0	4.0	2.0	1.50	0.32	12	3.8	2.1	1.41	0.30
			10.6*	8.4	1.7	2.0	1.21	0.11	9	1.8	2.1	1.18	0.11
17	14.4.54 1500	24.1	—	14.4	2.0	6.3	—	—	17	2.3	6.7	—	—
				25.9	2.6	4.7	0.60	0.11	31	2.9	5.5	0.59	0.13
18	15.4.54 0200	18.7	23.4	23.3	2.8	4.1	0.70	0.14	31	2.3	5.5	0.55	0.11
19	15.4.54 1400	14.4	11.5	13.7	2.6	2.4	1.20	0.23	12	2.6	2.1	1.36	0.26

Computations are from Leuchars radiosonde ascents except where otherwise stated. More than one wave system is shown on some dates. λ =Wavelength. * Accuracy doubtful. † Accuracy doubtful, see text

values from the full exponential method are very subjective, see Figure 5, 20.11.53. The present calculation gives a more accurate wavelength, according to the observed value.

- (ii) No. 11. — This is an example where the exponential method is not valid owing to the slow decrease of l with height. The plot on Figure 3 falls just outside the limit since the tropopause is at 200 mb, so that marked waves would not be expected. Both calculations do show the vertical motion to be relatively slight.
- (iii) No. 13. — The values are very small.
- (iv) No. 14. — Winds decrease above 600 mb. None of the methods is successful in obtaining the observed wavelength.

The other important characteristic concerning aviation is the height of the maximum vertical component. This differs according to the method used and the difference is more than 0.5 km (1600 feet) in the following examples :

- (a) No. 3. — See (i) above.
- (b) No. 12 (Leuchars). — The numerical calculation of Wallington and Portnall⁶ using a computer, failed to give a result in this case.
- (c) No. 14 (Aldergrove). — See (iv) above.
- (d) Nos. 15 and 17. — These are also examples for which the computer failed to give a result.

(e) No. 18. — Values with the full exponential method are rather subjective, see Figure 5, 15.4.54.

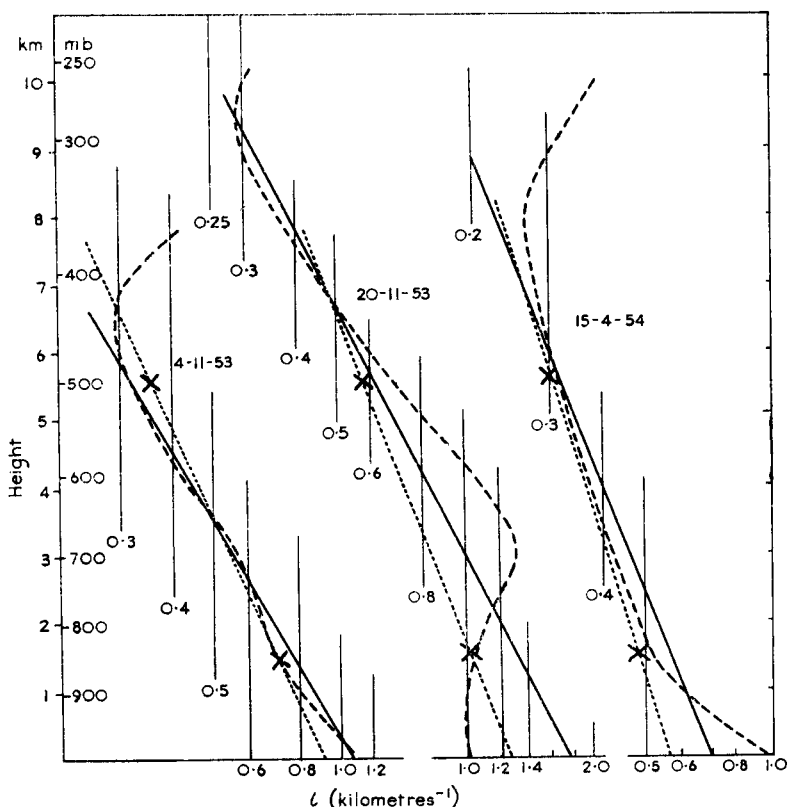


FIGURE 5—COMPARISONS OF THREE METHODS OF PRODUCING l -CURVES
 ——— Exponential approximation of Foldvik - - - l -curves
 x Values at 850 and 500 mb calculated by the present method.
 These points are joined by a dotted line for comparison.

Units.—In the calculations and for comparisons metric units have been used, but for practical use in Figures 1 to 4 they have been converted to the more usual aviation units of nautical miles and feet, with horizontal speeds in knots and vertical speeds in feet per minute, but l is simply transferred from figure to figure in units of km^{-1} .

Use of the diagrams.—From a smoothed sounding or estimate in the appropriate air mass, obtain the temperature differences :

$T_{1000} - T_{700}$, temperature lapse between 1000 and 700 mb.

$T_{700} - T_{300}$, temperature lapse between 700 and 300 mb.

If the tropopause is below 300 mb extend the tropospheric curve to 300 mb to obtain T_{300} .

Note the pressure at the tropopause.

From upper wind data or charts obtain :

U_0 , the wind speed across the mountains, say the gradient wind or 2000-ft wind for mountain heights such as those of the British Isles ;

U_{850} , the wind speed at 850 mb, or preferably the mean between the mountain top and 700 mb ;

U_{500} , the wind speed at 500 mb, or preferably the mean between 700 and 300 mb.

If U_0 is less than about 20 kt then no marked waves can be expected. They should not be expected where the direction of U_0 is at an angle greater than about 30 degrees from the perpendicular to the ridge line nearest to the lee slope.

If waves are not ruled out by the above conditions, then

from $T_{1000} - T_{700}$ and U_{850} use Figure 1 to obtain l_{850} ,

from $T_{700} - T_{300}$ and U_{500} use Figure 2 to obtain l_{500} .

Using in Figure 3 the values just obtained for l_{850} and l_{500} , read off the wavelength and the height of the maximum vertical velocity together with a value from the third set of lines, which when multiplied by U_0 will give the maximum vertical velocity.

If the point on the graph lies above the pressure line corresponding to the level of the tropopause then no waves are expected. If the height of the maximum vertical component is higher than the level of the tropopause then the values are not reliable but marked waves in the lower levels are not to be expected. If this level is near the tropopause then the values may be appreciably in error, but again, marked waves in the lower levels are not expected.

If there is a marked decrease of wind speed at any level, or a marked change in direction, say more than 30 degrees, then wave activity is not likely to extend above this level.

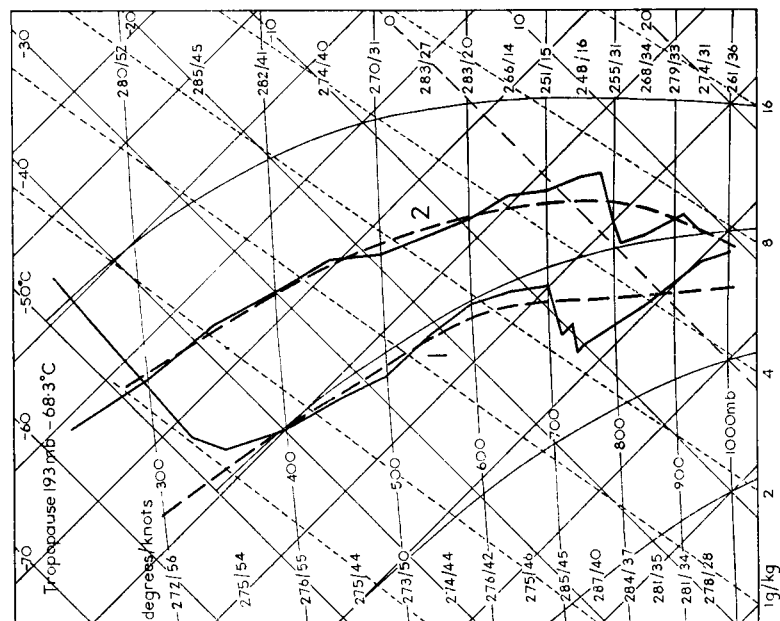
From Figure 4, values for a further series of waves at a higher level may be found in certain cases. The limitations mentioned above also apply to these.

The wavelength of the lee wave and the height of maximum vertical velocity do not vary with the ridge height, i.e. the height of the mountain above the surrounding country. The vertical velocities are proportional to this height. In Figures 3 and 4 the factors are for a ridge height of 1000 feet and give vertical velocities in feet per minute if wind speeds are in knots.

Examples.—Figures 6 (a) and (b) give examples of the smoothing process. The details extracted and the computed values are given in Table II.

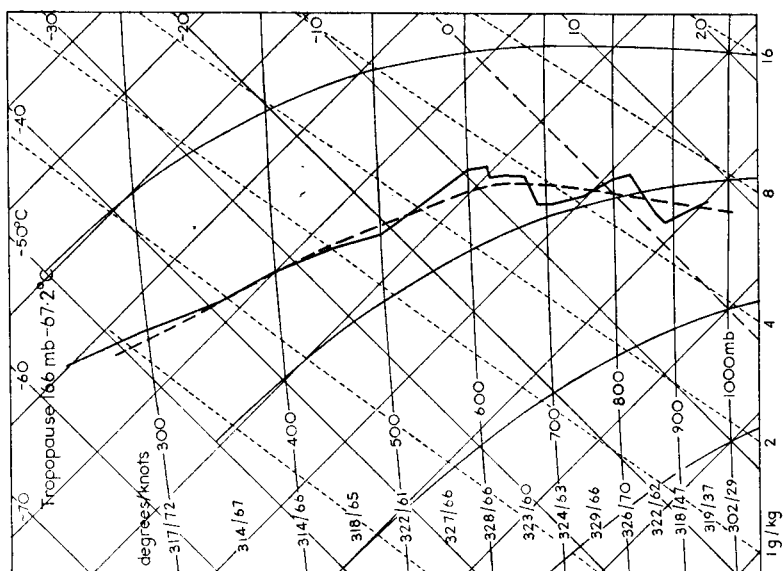
TABLE II—THREE EXAMPLES BASED ON THE LEUCHARS RADIOSONDE ASCENTS

IN FIGURE 5				
Date	4.11.53	20.11.53	15.4.54	
Time (GMT) ...	1400	0400	0200	
$T_{1000} - T_{700}$ (°C) ...	15	11	12	
$T_{700} - T_{300}$ (°C) ...	46.5	45	43	
U_0 (knots)	28	33	37	
U_{850} (knots)	35	28	60	
U_{500} (knots)	48	33	64	
l_{850} (km ⁻¹)	0.71	1.01	0.47	
l_{500} (km ⁻¹)	0.36	0.57	0.30	
L_1 (km)	17	9	32	
(n. miles)	9	5	18	
h_1 (km)	3.2	2.0	5.5	
(feet)	10,700	7000	18,000	
C_1	17.5	15	12.5	
w_1 (m/s)	2.5	2.5	2.3	
(ft/min)	490	500	460	



(a) 1400 GMT on 4 November 1953 - curves (1)
0400 GMT on 20 November 1953 - curves (2)

FIGURE 6—LEUCHARS RADIOSONDE OBSERVATIONS AND SMOOTHED TEMPERATURE CURVES
—— Observed temperatures
--- Smoothed curves



(b) 0200 GMT on 15 April 1954

Acknowledgement.—Thanks are expressed to Mr. G. A. Corby for very valuable help.

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THE FORECASTING OF SHOWER ACTIVITY IN AIRSTREAMS FROM THE NORTH-WEST QUARTER OVER NORTH-WEST ENGLAND IN SUMMERTIME

By C. A. S. LOWNDES

Introduction. — In earlier papers ^{1,2} a study was made of the shower activity in airstreams from the north-west quarter over south-east England and south-west England in summertime and the relative usefulness of a number of predictors for forecasting shower activity, thunder and hail was evaluated. This paper deals in the same way with the problem of forecasting shower activity over north-west England in summertime. The investigation was again restricted to airstreams which approached the British Isles from the north-west quarter. This was achieved by including only those days when the surface isobars over north-west England and the northern Irish Sea at midday showed a flow from between west and north-west inclusive and the polar front lay to the south of the area or had cleared it by 0600 GMT. Occasions were not included if a front was situated over north-west England between 0900 and 2100 GMT or if the precipitation was not mainly showery. The classification of the intensity of shower activity was based on reports from six stations in the months May to September during the period 1953–63, excluding 1961 when data from one of the stations was not available. From 1953–60 the stations were Silloth, Ronaldsway, Squires Gate, Manchester, Valley and Shawbury. For 1962 and 1963, Carlisle was used instead of Silloth. From the Beaufort letters in the *Daily Weather Report* the total number of mentions of slight, moderate and heavy showers at the six stations during the period 0900 to 2100 GMT was obtained for each day. From these figures, the intensity of shower activity was classified as follows :

- A Widespread showers with a good proportion of moderate or heavy showers. (6 or more mentions of showers ; more than 25 per cent moderate or heavy showers).
- B Widespread showers with few moderate or heavy showers. (6 or more mentions of showers ; 25 per cent or less of moderate or heavy showers).
- C Few showers (less than 6 mentions of showers).
- D No showers.



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PLATE I—CUMULONIMBUS WITH CIRRUS STREAMER BETWEEN MADRAS AND MALAYA

See page 67.



Photograph by P. L. Baylis

(a) Damage in the orchard.



Photograph by P. L. Baylis

(b) Damage in the orchard.

PLATE II (a)-(d)—DAMAGE CAUSED BY THE TORNADO AT WISLEY ON 21 JULY
1965

See page 92.



Photograph by P. L. Baylis

(c) Damage in the orchard.



Photograph by P. L. Baylis

(d) Damage to a tree close to the Portsmouth road.



Photograph by R. K. Pilsbury

PLATE III—FROST PATTERNS ON A GLASS DOOR ON 29 DECEMBER 1965



Photograph by R. K. Pilsbury

PLATE IV—FROST PATTERNS ON A GLASS DOOR ON 29 DECEMBER 1965

See page 94.

A note was made of thunder or hail reported between 0900 and 2100 GMT at any of the stations. Surface reports were supplemented by sferic (atmospheris) observations during the same hours of the day.

The factors which were considered were essentially the same as in the two previous investigations.^{1,2}

Association with surface synoptic features.—

The position of the associated depression at midday.—Table I shows for each class of shower activity the number of occasions when the depression with which the polar air was associated was situated in a particular locality.

TABLE I—SHOWER ACTIVITY RELATED TO POSITION OF ASSOCIATED DEPRESSION AT MIDDAY (MAY TO SEPTEMBER 1953–60, 1962–63)

Position of depression	Class of shower activity			
	A	B	C	D
		number of occasions		
Arctic	0	1	5	1
Iceland region	0	2	4	0
Norwegian Sea	4	9	11	2
Scandinavia	9	16	11	1
North of Scotland	12	7	8	2
West of Scotland	0	0	3	0
Scotland... ..	3	4	0	0
North Sea	10	7	6	0
Denmark	1	1	2	2
Poland	0	0	1	0
All areas	39	47	51	8

On all 7 occasions when the depression was situated over Scotland and on 74 per cent of occasions when the depression was over the North Sea there were widespread showers (classes *A* and *B*) over north-west England. When the depression was situated north of Scotland or over Scandinavia, there were widespread showers on about 67 per cent of occasions. With the depression situated over the Norwegian Sea there were widespread showers (classes *A* and *B*) on 50 per cent of occasions and few showers or no showers (classes *C* and *D*) on the other 50 per cent of occasions. In general, the nearer the depression was to the British Isles, the more intense was the shower activity in north-west England. This suggests that the isobaric curvature and the level of surface pressure over the British Isles might be useful predictors.

The curvature of the surface isobars.—On a number of days with widespread showers, a surface trough moved eastwards or southwards across north-west England. Of the troughs which moved eastwards, about half were major features with the trough axis some 600 to 1000 miles in length and about half were minor perturbations with the trough axis some 200 to 600 miles in length. All the troughs which moved southwards were minor perturbations. Table II shows the number of these occasions for each class of shower activity.

TABLE II—SHOWER ACTIVITY RELATED TO THE CURVATURE OF THE SURFACE ISOBARS OVER NORTH-WEST ENGLAND (MAY TO SEPTEMBER 1953–60, 1962–63)

	Class of shower activity			
	A	B	C	D
		number of occasions		
Surface trough moved eastwards across north-west England	11	4	1	0
Surface trough moved southwards across north-west England	7	3	2	0
Uniform cyclonic isobars over north-west England	8	10	1	0
Neither surface trough nor uniform cyclonic isobars	13	30	47	8
Total	39	47	51	8

On 46 per cent of occasions of widespread showers with a good proportion of moderate or heavy showers (class *A*) a surface trough moved eastwards or southwards across north-west England. Of the 8 days on which a major surface trough moved across north-west England, 7 were associated with widespread showers (classes *A* and *B*) and 5 with thunder. Of the 20 days on which a minor perturbation moved across north-west England, 18 (90 per cent) were associated with widespread showers and 16 (80 per cent) with thunder. Of the 19 days with uniform cyclonic isobars over north-west England, 18 (95 per cent) were associated with widespread showers and 6 (32 per cent) with thunder. There was only one occasion of widespread showers when the isobars over north-west England were anticyclonic. On 93 per cent of occasions of few showers or no showers (classes *C* and *D*) there were neither surface troughs nor uniform cyclonic isobars. On 29 per cent of occasions of few showers or no showers, the isobars over north-west England were anticyclonic.

Association with 700 mb temperature and surface pressure.—The following data were extracted :

- (i) The 700 mb temperature anomaly at Liverpool for 1200 GMT (1500 GMT before 1957). The anomaly was based on the 5-day mean temperatures given in Table III.
- (ii) The mean sea level pressure at Squires Gate for 1200 GMT.

TABLE III—FIVE-DAY MEAN 700 MB TEMPERATURE AT LIVERPOOL* (FAZAKERLEY)
IN °C

Period	Mean	Period	Mean	Period	Mean
1-5 May	-7	30 June-4 July	-1	29 Aug.-2 Sep.	-2
6-10	-6	5-9 July	-1	3-7 Sep.	-2
11-15	-6	10-14	-1	8-12	-2
16-20	-5	15-19	-1	13-17	-3
21-25	-5	20-24	-1	18-22	-3
26-30	-4	25-29	-1	23-27	-3
31 May-4 June	-4	30 July-3 Aug.	-1	28 Sep.-2 Oct.	-3
5-9 June	-4	4-8 Aug.	-1		
10-14	-3	9-13	-1		
15-19	-3	14-18	-1		
20-24	-2	19-23	-1		
25-29	-2	24-28	-1		

* Obtained from 5-year monthly means for the period 1951-55. The monthly mean values were based on midday and midnight ascents and were corrected for radiation and lag errors.

Rain showers.—A diagram was plotted (Figure 1) of the 700 mb temperature anomaly at Liverpool against the mean sea level pressure at Squires Gate. The various intensities of shower activity are indicated by symbols, class *A* by a black triangle, class *B* by an open triangle, class *C* by a dot and class *D* by a cross. The diagram can be divided into two areas as indicated, area I containing most of the occasions of widespread showers and area II most of the occasions of few showers or no showers. If the diagram were used to forecast either widespread showers or few showers/no showers, a 'skill score' of 0.55 would be obtained. The skill score S^7 is defined by

$$S = \frac{\text{number of correct forecasts} - \text{number correct by chance}}{\text{total number of forecasts} - \text{number correct by chance}}$$

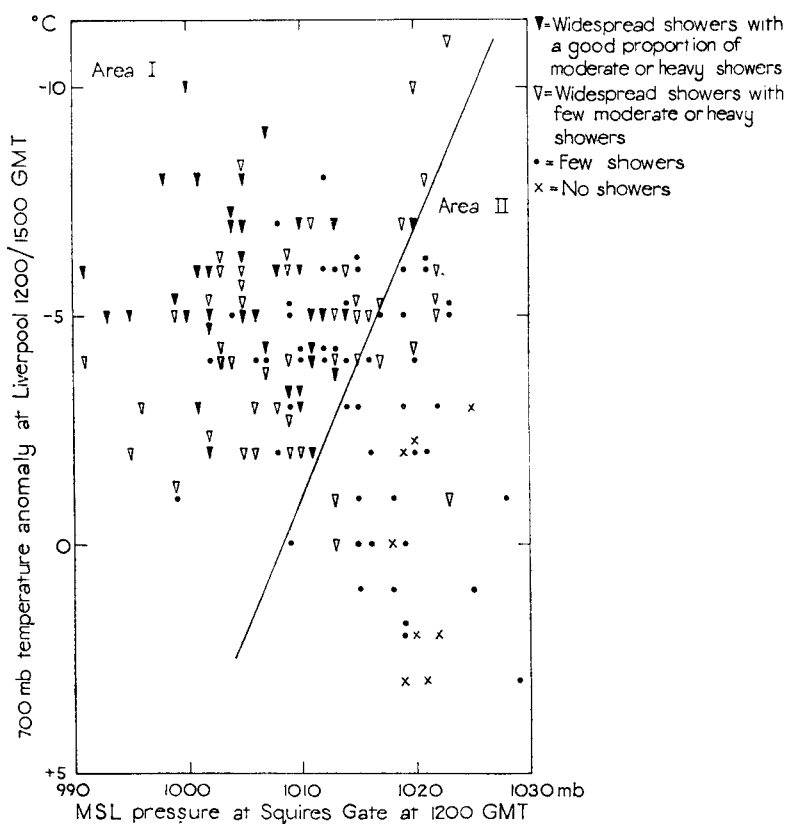


FIGURE 1—SHOWER ACTIVITY IN NORTH-WEST ENGLAND ASSOCIATED WITH SURFACE PRESSURE AND THE 700 MB TEMPERATURE ANOMALY

The line divides the diagram into area I containing most of the occasions of widespread showers and area II containing most of the occasions of few or no showers.

It ranges from 0 for no success to 1 for complete accuracy.

Rainfall amount.—A similar diagram (Figure 2) was plotted with symbols representing the average rainfall between 0900 and 2100 GMT for the six stations in north-west England for each day examined. The diagram is divided into the same two areas which were used in Figure 1. If the diagram were used to indicate an average rainfall of either 0.1 mm or more, or less than 0.1 mm, a skill score of 0.52 would be obtained. If it were used to indicate an average rainfall of either 0.5 mm or more, or less than 0.5 mm, a skill score of 0.41 would be obtained.

Figure 3 shows the highest and lowest rainfall amounts plotted against the average amount for the six stations in north-west England for each day examined. For an average value of up to 1 mm the highest value is likely

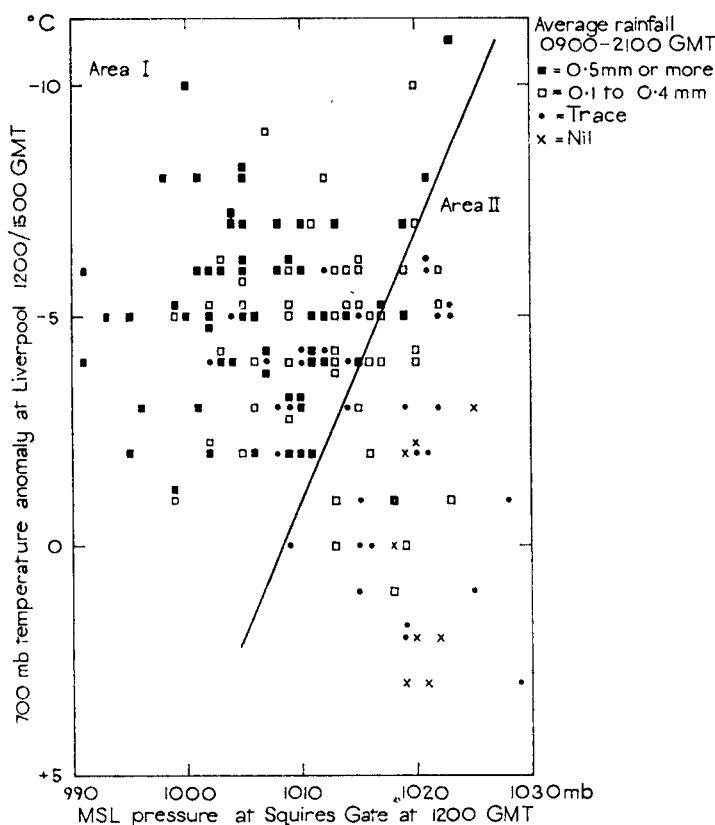


FIGURE 2—AVERAGE RAINFALL FOR SIX STATIONS IN NORTH-WEST ENGLAND FOR EACH INDIVIDUAL DAY ASSOCIATED WITH SURFACE PRESSURE AND THE 700 MB TEMPERATURE ANOMALY

Areas I and II are the same areas as in Figure 1.

to be about four times the average, and for average values of 2 mm or more about three times the average. For an average value of up to 1.3 mm the lowest value was nil or a trace, and for an average value above 1.3 mm the lowest value varied between nil and 1 mm. It is clear that however widespread the showers, some places are likely to escape with little or no rain.

Thunder and hail.—A diagram was plotted (Figure 4) of the 700 mb temperature anomaly against mean sea level pressure with symbols representing thunder or hail. If no thunder or hail was reported, a cross was plotted. The diagram was again divided into the same two areas. If the diagram were used to indicate thunder or 'no thunder', a skill score of 0.33 would be obtained. For an indication of hail or 'no hail', a skill score of 0.11 would be obtained.

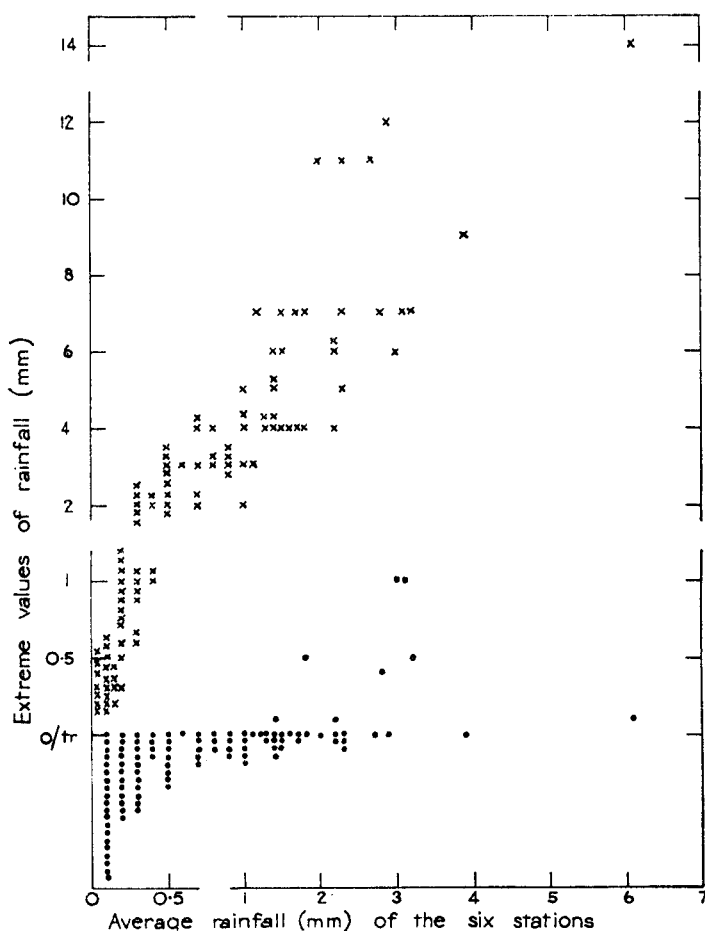


FIGURE 3—THE HIGHEST AND LOWEST RAINFALL AMOUNTS (0900–2100 GMT) ASSOCIATED WITH AVERAGE VALUES FOR SIX STATIONS IN NORTH-WEST ENGLAND
 x Highest individual values . Lowest individual values

For some values of the average rainfall the lowest amount was zero on several occasions and such occasions are plotted below the 0/tr line.

On all but two occasions, reports of thunder were associated with negative temperature anomalies of 3°C or more. On all but one occasion of hail, the negative temperature anomaly was 5°C or more.

Sunshine.—A study of the average duration of sunshine for the six stations in north-west England for each day examined revealed no evidence of any association between the intensity of shower activity and the duration of sunshine.

Association with 1000–500 mb thickness and surface pressure.—The 1000–500 mb thickness anomaly at Liverpool for 1200 GMT (1500 GMT before 1957) was extracted. Anomalies were measured from the 5-day mean 1000–500 mb thickness values for Liverpool given in Table IV.

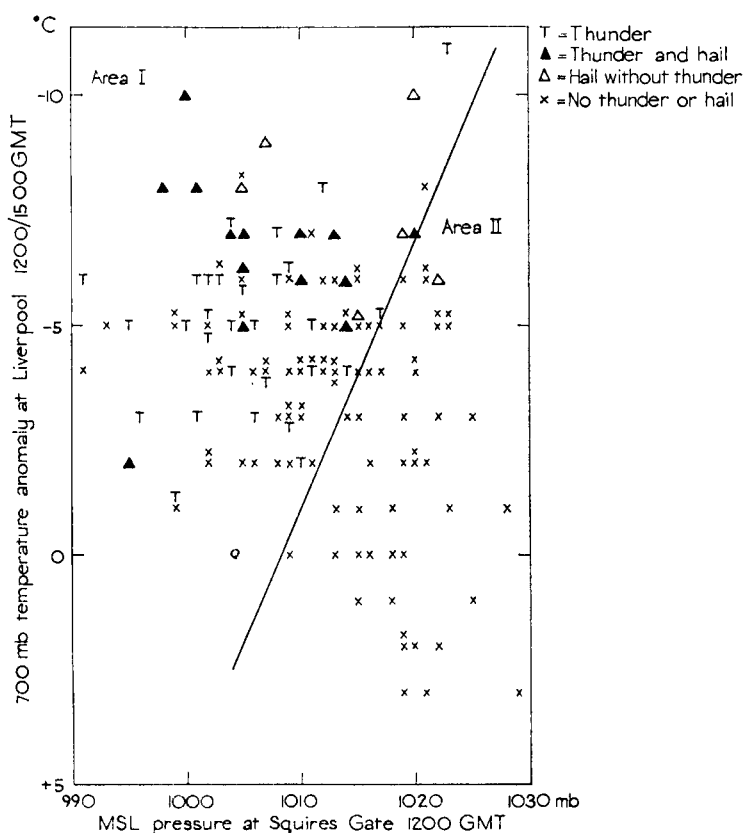


FIGURE 4—THUNDER AND HAIL IN NORTH-WEST ENGLAND ASSOCIATED WITH SURFACE PRESSURE AND THE 700 MB TEMPERATURE ANOMALY
Areas I and II are the same areas as in Figure 1.

TABLE IV—FIVE-DAY MEAN 1000–500 MB THICKNESS AT LIVERPOOL*
(FAZAKERLEY) IN DECAMETRES

Period	Mean	Period	Mean	Period	Mean
1–5 May	541	30 June–4 July	552	29 Aug.–2 Sep.	552
6–10	542	5–9 July	553	3–7 Sep.	551
11–15	543	10–14	554	8–12	551
16–20	544	15–19	554	13–17	550
21–25	545	20–24	554	18–22	550
26–30	546	25–29	554	23–27	549
31 May–4 June	547	30 July–3 Aug.	553	28 Sep.–2 Oct.	549
5–9 June	548	4–8 Aug.	553		
10–14	549	9–13	553		
15–19	550	14–18	553		
20–24	551	19–23	552		
25–29	552	24–28	552		

* Obtained from 5-year monthly means for the period 1951–55. The monthly mean values were based on midday and midnight ascents and were corrected for radiation and lag errors.

Analyses were carried out with the 1000–500 mb thickness anomaly in place of the 700 mb temperature anomaly and statistics were extracted to construct Figures 5, 6 and 7. The corresponding skill scores are shown in Table V.

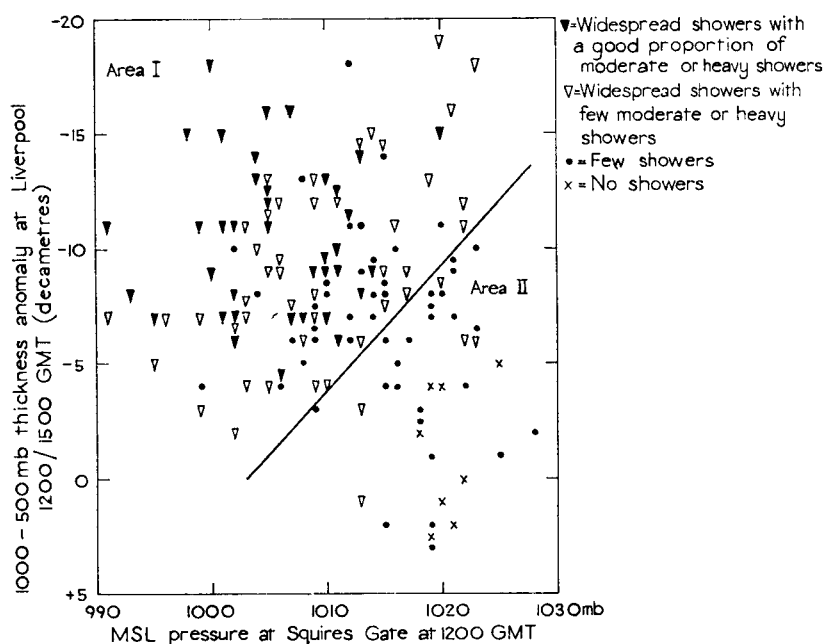


FIGURE 5—SHOWER ACTIVITY IN NORTH-WEST ENGLAND ASSOCIATED WITH SURFACE PRESSURE AND THE 1000-500 MB THICKNESS ANOMALY

The line divides the diagram into area I containing most of the occasions of widespread showers and area II containing most of the occasions of few or no showers.

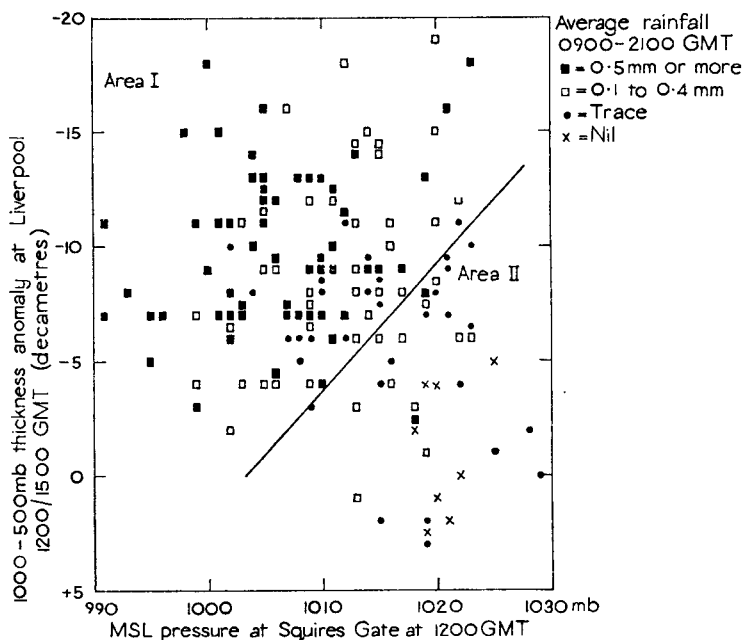


FIGURE 6—AVERAGE RAINFALL FOR SIX STATIONS IN NORTH-WEST ENGLAND FOR EACH INDIVIDUAL DAY ASSOCIATED WITH SURFACE PRESSURE AND THE 1000-500 MB THICKNESS ANOMALY

Areas I and II are the same areas as in Figure 5.

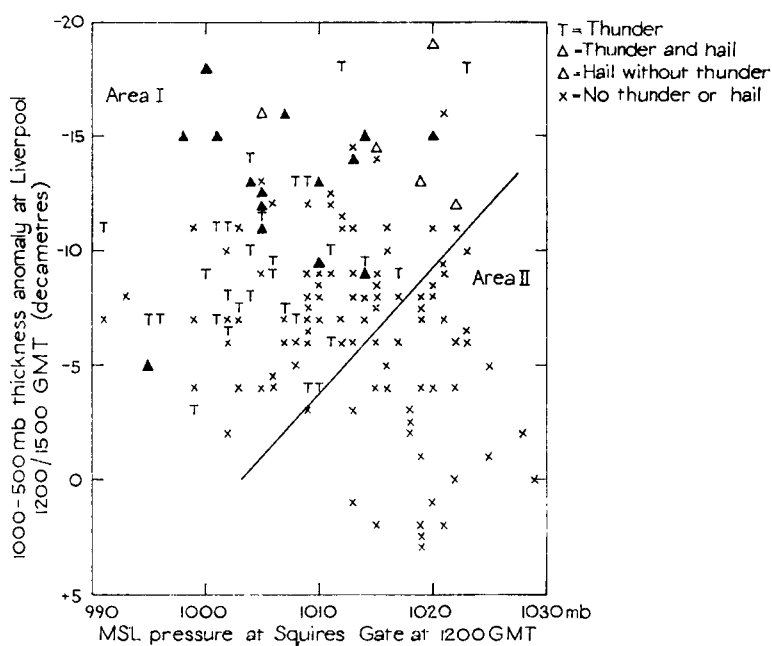


FIGURE 7—THUNDER AND HAIL IN NORTH-WEST ENGLAND ASSOCIATED WITH SURFACE PRESSURE AND THE 1000-500 MB THICKNESS ANOMALY

Areas I and II are the same areas as in Figure 5.

Note: occasions of thunder and hail are represented by a black triangle.

An analysis was also carried out with the 1000-700 mb thickness anomaly in place of the 700 mb temperature anomaly and similar statistics extracted. The corresponding skill scores are also shown in Table V.

Association with the instability indices.—The Boyden instability index,³ the Rackliff instability index,⁴ the Jefferson instability index⁵ and the modified Jefferson instability index⁶ were calculated for the Liverpool 1200 GMT ascents (1500 GMT before 1957). The critical values of the indices which gave the highest skill scores in forecasting either widespread showers or few showers/no showers were obtained. A similar procedure was carried out for rainfall amount, thunder and hail. The skill scores and critical values of the indices are given in Table V.

The relative usefulness of the predictors.—Assuming that the predictors can be forecast, their relative usefulness in forecasting shower activity, rainfall amount, thunder and hail can be assessed by a comparison of skill scores. Table V shows the skill scores obtained and the critical values of the instability indices.

The highest scores for the forecasting of shower activity and the lower rainfall amounts are obtained by the 700 mb temperature predictor, the 1000-500 mb thickness predictor and the modified Jefferson instability index. The highest scores for the forecasting of the higher rainfall amounts and thunder are obtained by the two Jefferson indices and the Rackliff index. None of the predictors provide a useful indication of the likelihood of hail.

TABLE V—A COMPARISON OF SKILL SCORES

Predictors	Shower activity	Rainfall (limit 0.1 mm)	Rainfall (limit 0.5 mm)	Thunder	Hail
700 mb temperature anomaly and surface pressure	0.55	0.52	0.41	0.33	0.11
1000-500 mb thickness anomaly and surface pressure	0.53	0.51	0.33	0.27	0.11
1000-700 mb thickness anomaly and surface pressure	0.46	0.43	0.37	0.30	0.09
Boyden instability index (critical values)	0.35 (92/93)	0.44 (91/92)	0.39 (93/94)	0.46 (94/95)	0.21 (94/95)
Rackliff instability index (critical values)	0.44 (28/29)	0.45 (27/28)	0.44 (32/33)	0.59 (32/33)	0.38 (32/33)
Jefferson instability index (critical values)	0.44 (22/23)	0.49 (22/23)	0.48 (26/27)	0.66 (26/27)	0.29 (27/28)
Modified Jefferson instability index (critical values)	0.51 (20/21)	0.52 (20/21)	0.57 (25/26)	0.66 (27/28)	0.27 (27/28)

The geographical distribution of the showers.—Of the 6 stations used in the analysis, half are situated on or near the exposed windward coast, that is, Ronaldsway, Squires Gate and Valley (see Figure 8). One would expect a rather narrow coastal strip in which showers would be absent or weak on days when showers would not be initiated at sea and these stations might not be representative of north-west England as a whole. An indication of the variation of shower activity over the area was obtained by an analysis of the rainfall at each of the 6 stations.

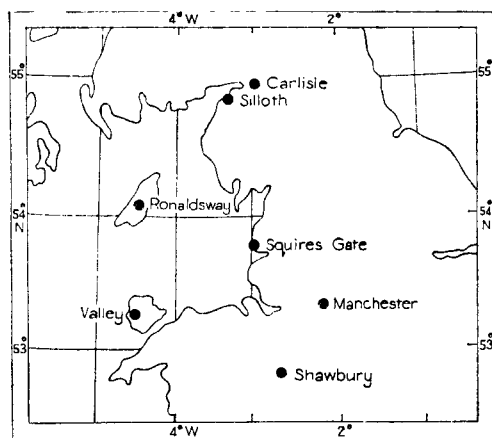


FIGURE 8—THE POSITIONS OF THE STATIONS USED

Table VI shows that the stations on or near the windward coast had the lowest average rainfall ranging from 0.4 mm at Squires Gate to 0.6 mm at Ronaldsway. The average rainfall at the other stations ranged from 0.7 mm at Silloth to 1.3 mm at Manchester. The windward coast stations also had the lowest percentage of days with a total rainfall of 0.5 mm or more, averaging

TABLE VI—RAINFALL FROM SHOWERS AT EACH INDIVIDUAL STATION (MAY TO SEPTEMBER 1953-60)

Station	Average rainfall	Percentage of days with 0.5 mm or more	Percentage of days with nil or trace
Manchester	1.3	33	51
Shawbury	0.8	30	57
Silloth	0.7	33	52
Ronaldsway	0.6	26	62
Valley	0.4	14	68
Squires Gate	0.4	15	72

18 per cent compared with 32 per cent for the other stations. The percentage of days with nil or a trace of rain averaged 67 per cent for the windward coast stations compared with 53 per cent for the other stations.

It is clear that stations on or near the windward coasts have rather less rainfall from showers than inland stations, the percentage of days with 0.5 mm or more being on average 14 per cent less at the coastal stations and the percentage of days with a trace or less about 14 per cent higher.

An analysis of rainfall from showers in south-west England² showed a similar effect.

A comparison with the forecasting of shower activity in south-east and south-west England.—In earlier papers ^{1,2} the problem of forecasting shower activity in south-east and south-west England was examined in a similar way. The best forecast skill scores obtained are all lower for south-west England than those for south-east England. The best skill scores for the forecasting of shower activity and the lower rainfall amounts are even lower for north-west England than for south-west England. It seems likely that the lower skill scores for the south-west and north-west compared with the south-east are associated with the relative proximity of the two western areas to the windward coast and the consequent motion across these areas of air which is less subjected to heating from the land. However, for the higher rainfall amounts and thunder, the best skill scores obtained for the north-west are comparable with those obtained for the south-east.

For all three areas, the highest skill scores for forecasting shower activity and the lower rainfall amounts are in general obtained by the 700 mb temperature indicator and the 1000-500 mb thickness indicator but the highest skill scores for forecasting the higher rainfall amounts and thunder are in general obtained by the instability indices.

It is interesting to note that the Boyden index, which obtains the highest skill score for the forecasting of thunder in the south-east and south-west, obtains a relatively low value for the north-west for which the Jefferson and Rackliff indices obtain quite high values. None of the predictors provide a useful indication of hail for the south-west or north-west. However, for the south-east, the Rackliff and Jefferson indices obtain a value of about 0.5 if the freezing level is included as a further predictor.

Conclusions.—This investigation was concerned with polar airstreams from the north-west quarter affecting north-west England in summertime and was restricted to days when no fronts were situated over north-west

England. Widespread showers are likely if the associated depression is situated over Scotland or the North Sea at midday. If the depression is situated north of Scotland or over Scandinavia widespread showers are rather more likely than few or no showers. If the depression is over the Norwegian Sea, few or no showers are just as likely as widespread showers. Widespread showers with thunder are likely if a major trough or minor perturbation moves across north-west England. Widespread showers are also likely on days with uniform cyclonic isobars over north-west England, with thunder likely to occur on about one day in three. Few or no showers are likely if the isobars are anticyclonic. Places on or near the windward coasts have rather less rainfall from showers than inland stations, the percentage of days with a trace or less of precipitation being on average about 14 per cent higher at windward coast stations.

The best indication of the intensity of shower activity and the lower rainfall amounts can be obtained from (1) the 700 mb temperature anomaly at Liverpool and the surface pressure at Squires Gate, (2) 1000-500 mb thickness anomaly at Liverpool and the surface pressure at Squires Gate and (3) the modified Jefferson instability index. The best indication of the higher rainfall amounts can be obtained from the modified Jefferson index. The two Jefferson indices and the Rackliff index provide the best indication of the likelihood of thunder. None of the predictors provides a useful indication of the likelihood of hail.

The relative usefulness of the predictors has been evaluated ; which is to be preferred in forecasting depends largely on how successfully each can be forecast.

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TORNADO AT THE ROYAL HORTICULTURAL SOCIETY'S GARDEN, WISLEY

By T. W. VERNON JONES

At 1540 GMT on 21 July 1965, a tornado crossed the Royal Horticultural Society's garden at Wisley, Surrey. The tornado appears to have formed about a mile to the west of the garden in the vicinity of the River Wey. It then travelled very nearly in an easterly direction, mainly over open land as far as the Society's experimental fruit collection. It swept through the collection and went on again over open land, or land planted with very small trees, until it reached the Portsmouth Road, about half a mile away to the east.

This road is fringed with trees on both sides. About 10 trees, some of them quite large, were brought down by the tornado, and the road was blocked for an hour or so. The disturbance then travelled a short distance further, on to the nearby aerodrome where it ended its life. Some slight damage was caused on the aerodrome.

Broadly speaking the track of the tornado appears to have had a width of about 70 to 100 yards ; but in the fruit collection where the major damage was caused, the extreme width of the tornado path was more of the order of 130 to 140 yards.

The fruit trees, (mainly apples, plums and peaches), were planted symmetrically, with a space of five yards between each tree. Most of the trees were about 18 years old, and in all there were rather more than 1200 in the orchard. Of these about 140 were uprooted, and another 150 or so badly damaged. Many of the remaining trees suffered considerable root damage. It is interesting to note that the agro-meteorological station, situated just north-east of the fruit collection, was completely undamaged although within literally a few yards of uprooted or damaged trees.

For some days previous to 21 July the British Isles had been covered by a complex system of slow-moving shallow depressions. On the 21st some showers and thunderstorms had occurred. The midday upper air ascent at Crawley on the 21st is fairly typical of disturbances of this sort showing latent instability in the lower layers and convective instability around 700 millibars.

Plates II, (a), (b) and (c) illustrate some of the damage caused in the orchard ; and Plate II (d) is a picture taken close to the Portsmouth Road.

REVIEWS

Physics of the boundary layer of the atmosphere, by D. L. Laikhtman. 9½ in × 7 in, pp. vii + 200, (translated from the Russian by the Israel Program for Scientific Translations, Jerusalem), Oldbourne Press, 1 - 5 Portpool, London, EC 1, 1964. Price : 72s.

This is a most interesting monograph which appeared in the original Russian form in 1961. Its availability now in English translation will provide a wider audience of micrometeorologists with a first-hand indication of the lines of thought which have evolved in their field at the Main Geophysical Observatory at Leningrad. This is one of the foremost Russian institutes publishing research in micrometeorology and, as it is one which appears to have had little communication with the 'West' in this field, the event is particularly welcome.

The monograph is expressly intended for the specialist and the classical introduction to the dynamics of atmospheric flow (Chapter 1) is kept to a minimum. Thereafter the main substance emerges quite logically in four chapters dealing with the basic properties of the vertical profiles in stationary and horizontally uniform conditions, the temporal and especially the diurnal variation in these properties, the advective transformation of the properties as a result of a sudden change in the surface conditions, and finally the variety of applications of human and economic interest (including such uncommon aspects as wind drift of ice floes and heat transfer from buildings).

The whole work carries the stamp of a thorough and sophisticated mathematical approach. For all major aspects the essential equations and solutions are set out, though frequently with greater attention to the formalities and less consideration of the physics of the problem than might be expected from the title. This is particularly evident in two of the applications which occupy the interests of micrometeorologists the world over, namely the determination of natural evaporation and estimation of the dispersion of air pollutants. Despite the foundation provided by the well-known Monin-Obukhov theory of the surface layer, there does not appear to be any realistic appraisal here of the accuracy with which vertical fluxes can be determined or estimated. In considering the diffusion from a point source the attitude is rightly taken that lateral diffusion cannot be satisfactorily treated by the K approach, but no explanation is given, nor is it made clear that by the same token vertical diffusion from an elevated source also cannot be so treated. Furthermore, although the need for a statistical approach is recognized, no indication is given of how this might be applied in practice, other than in the plainest empirical sense. It is also in the field of diffusion from sources that one is immediately struck with the apparent lack of contact with other Russian work. The more novel aspects of Monin's work in this context, well known in the 'West', receive no mention.

However the foregoing are special criticisms which are not intended to reflect on the general value of this work as a whole, and most micrometeorologists will find it informative and interesting in one feature or another. In the translated edition the symbols tend to be rather small for comfortable reading, which is a pity in view of the emphasis on the mathematical development, but otherwise the production is adequate.

F. PASQUILL

Meteorological and radiation régime of Antarctica, by N. P. Rusin. 9½ in × 7 in, pp. iv + 355, *illus.*, (translated from the Russian by the Israel Program for Scientific Translations, Jerusalem), Oldbourne Press, 1-5 Portpool Lane, London EC 1, 1965. Price : £6 15s.

This is a valuable book, the most convenient and fully up-to-date regional text on the surface meteorology and climatology of Antarctica since Meinardus' *Klimakunde der Antarktis*, published in 1938, with the addition of a neat systematic treatment in the last 160 pages of the text of what is now known of the heat balance of the surface of Antarctica. A terse style, with short sentences and brief paragraphs, makes it possible to compress a massive amount of information into a reasonably small book. The reviewer's only complaint is the absence of any index.

Since the International Geophysical Year, the only roughly equivalent works have been compendia of research papers, mostly publishing the papers read at this or that scientific meeting. The nature of such books is to illumine more or less deeply this or that aspect without attempting to cover the whole field. In these circumstances, this Russian production seems likely to become the standard reference for a decade or so — and more if it is revised at that sort of interval. There is room for similar works on the upper atmosphere over Antarctica and on other branches of geophysics. The one weakness of

this type of presentation, which points to where others may produce competitive works, is the need to set Antarctica — and preferably the sub-Antarctic zone, too, with its great ocean and the islands — into their proper context in the meteorology of the southern hemisphere, as Meinardus did to some extent in his pioneer work. This demands treatment of the whole circulation of the atmosphere in depth and of the ocean circulation likewise.

A selection of chapter and section headings will give a closer look at the actual content of the present work. The one-page "General Description" in the introductory chapters contrives to say some new things about how the gross topography of Antarctica, as it is now known, affects the atmospheric circulation ; there is some more of this in the $5\frac{1}{2}$ pages on "Conditions influencing the formation of the meteorological régime and climate of Antarctica". In the chapters on meteorology there are tables of monthly and annual mean air temperature, and maps for January, July and the year, maximum and minimum temperatures, air temperatures by wind direction, and temperatures with depth in the snow ; there are similar treatments of other elements — atmospheric pressure, wind direction and speed, cloudiness, etc. — also some attention is given to the occurrence of ice clouds and water-drop clouds and cumulus-type clouds. There are chapters on the Antarctic winter, spring, summer and autumn and a 22-page one on the local climate — including radiation balance — of the limited areas of snow-free oasis. The heat-balance section of the book has separate short chapters on direct solar radiation, diffuse radiation, total incoming short-wave radiation, reflected radiation, absorbed radiation, radiation balance, long-wave radiation leaving the surface and received from the atmosphere, leading to one on the long-wave radiation balance ; finally there are chapters on heat and moisture exchanges in the air near the surface and heat exchange within the snow itself. The essential material of these chapters is presented both in copious tables (of monthly figures) and in diagrams which are a feature of the book.

The author and Soviet meteorology are to be congratulated on achieving such a useful presentation. And there should be widespread recognition of the Israeli enterprise in making it available in English. The price is high, but not inappropriate.

H. H. LAMB

LETTER TO THE EDITOR

Photographs of frost patterns on a glass door

The photographs (Plates III and IV) were taken at 0815 GMT on 29 December 1965 at my home just over $\frac{1}{2}$ mile north-north-west of the Meteorological Office, Bracknell. The frost patterns were on the glass door between the house and the detached garage, separating the front and back gardens. Around 1000–1100 GMT in the winter the sun can shine on parts of the glass.

On the morning of 27 December both sides of the glass were covered with frost showing no structure (see left-hand side of Plate III). The sun melted a part of this frost and a few small drops of water were left on the glass. On the morning of the 28th it was found that these droplets had frozen to give the crystalline patterns shown in the photographs. The patterns persisted all day and were photographed on the following morning, using a 4 dioptr

close-up lens (hence the loss of definition on some edges). The scales shown on the photographs indicate the actual sizes of the patterns. It is interesting to note that near the top right-hand corner of Plate III can be seen the structureless frost on the back of the glass with a crystalline pattern on the near side.

The temperatures recorded in the thermometer screen at Bracknell are given below :

	Temperature at 0900 GMT	Maximum temperature <i>degrees Celsius</i>	Minimum temperature
27th ...	- 2.3	+ 0.8	- 5.0 (at 2300 on 26th)
28th ...	- 5.6	+ 2.0	- 6.0 (at 0830)
29th ...	+ 0.9	+ 7.8	- 8.7 (at 0200)

On the 29th the temperature rose steadily from the minimum of -8.7°C at 0200 GMT to about $+3.5^{\circ}\text{C}$ at 1000 and the frost melted soon after 0900.

Meteorological Office, Bracknell

R. K. PILSBURY

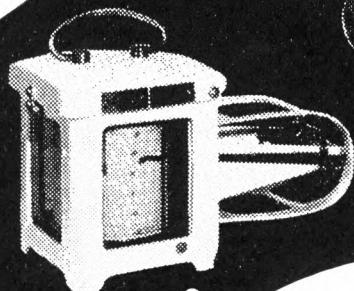
OBITUARIES

Miss A. J. Clapham.—It is with deep regret that we heard of the death of Miss A. J. Clapham on 19 December 1965. An appreciation of her many years of service in the Meteorological Office appeared on page 58 of the February 1959 issue of the Meteorological Magazine.

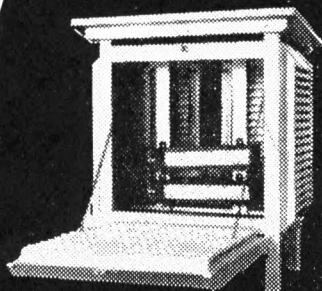
Miss E. H. Geake.—It is with deep regret that we heard of the death of Miss E. H. Geake on 8 January 1966. Miss Geake retired from the Meteorological Office as a Senior Experimental Officer in March 1952 after 32 years service.



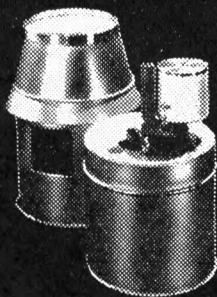
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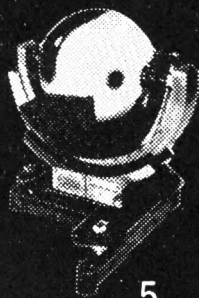
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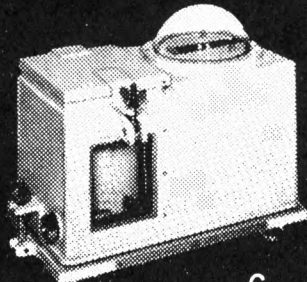
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CONTENTS

	<i>Page</i>
Cloud tops over Malaya during the south-west monsoon season. R. F. Zobel and S. G. Cornford	65
A simplified calculation of maximum vertical velocities in mountain lee waves. S. A. Casswell	68
The forecasting of shower activity in airstreams from the north-west quarter over north-west England in summer-time. C. A. S. Lowndes	80
Tornado at the Royal Horticultural Society's Garden, Wisley. T. W. Vernon Jones	91
Reviews	
Physics of the boundary layer of the atmosphere. D. L. Laikhtman. <i>F. Pasquill</i>	92
Meteorological and radiational régime of Antarctica. N. P. Rusin. <i>H. H. Lamb</i>	93
Letter to the Editor	94
Obituaries	95

NOTICES

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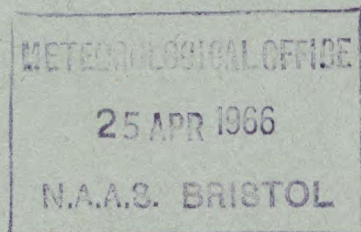
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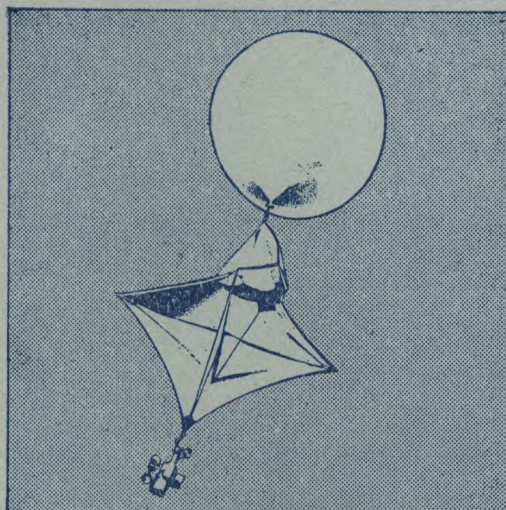
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THE METEOROLOGICAL MAGAZINE

Vol. 95, No. 1125, April 1966

RETIREMENT OF DR. A. C. BEST, C.B.E.

Dr. A. C. Best retired from the post of Director of Services in the Meteorological Office on 6 March 1966.

Alfred Charles Best was born in 1904 at Barry, Glamorgan. He was educated at Barry Grammar School and at University College, Cardiff, where he obtained his degree with first class honours in both mathematics and physics. He entered the Meteorological Office in 1926 and, after brief spells at Shoeburyness and Larkhill, was posted to Porton. This station has trained many distinguished meteorologists, and Best's contemporaries included both N. K. Johnson and O. G. Sutton who between them were to direct the Meteorological Office for thirty years. The meteorological studies at Porton were, and are, concerned principally with the dispersion of gases. Best's principal contribution was an experimental and theoretical study of the lapse rates of temperature and humidity in the lowest two metres of the atmosphere, an original and important work that has had a lasting influence on the development of diffusion theory.

In 1936 Best was posted to Malta and only returned to this country just before the outbreak of war. He spent the war years in Headquarters, apart from a brief spell towards the end when he was mobilized as a Wing Commander RAFVR and posted to India. In 1946 he joined the Research and Observatories Branch and so returned to the study of physical meteorology after a lapse of ten years. The subject had developed greatly in this interval. The importance of physical meteorology in aviation had come to be realized, and the Meteorological Research Flight had been established: while the explosive expansion of cloud physics that resulted from the first experiments in weather control was about to begin. The next eight or nine years were scientifically the most productive of Best's career, and in this period he wrote some fifty papers, covering almost the whole range of physical meteorology, though principally concerned with precipitation physics, radio-meteorology, and his original subject of diffusion. His best-known investigation was perhaps that concerned with the relationship between drop-size distribution and rate of rainfall, which is the basis of widely-used formulae for determinations by radar of rainfall intensity.

He was made Assistant Director for Special Investigations in 1953. The promotion did not interrupt his scientific work and in 1954 he was awarded

the degree of Doctor of Science by the University of Wales. From 1955 to 1960 he was Deputy Director, at first in charge of outstation services, and then, briefly, in charge of central services. In 1960 he became Director of Services, a post he held till his retirement. In the same year he was elevated to the rank of Commander of the Order of the British Empire, having been an Officer of the Order since 1953.

In this last, administrative phase, Dr. Best has guided the Services side of the Office through a series of major changes. To the layman, the most striking of these is probably the establishment of public weather centres in the great cities. More important in the life of the forecasting outstations, however, was the general introduction of facsimile, and the reorganization that facsimile rendered possible. Innovations such as the centralized forecasting systems for civil aviation are now so familiar that it is easy to forget how much hostility and suspicion they aroused when first proposed, and how cautiously they had to be introduced. Other, more recent innovations, introduced into the Services organization during Dr. Best's régime, will undoubtedly revolutionize the work of the Services side in the next few years although their effect is only beginning to be noticeable; they include the use of the computed forecast charts, computed climatological summaries, weather radar, and satellite picture receivers.

Dr. Best's favourite hobby is photography and he has been for some years the President of the Meteorological Office Photographic Society.

To me, it has been a great privilege to be associated with Dr. Best in these last few years. He has been the most considerate of colleagues, and the facility and good humour that he always shows in argument have made the normal daily exchanges a constant pleasure. His many friends will wish him a long and happy retirement.

B. C. V. ODDIE

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CRITERIA CONCERNING FINE SPELLS IN SOUTH-WEST SCOTLAND DURING THE PERIOD MAY TO OCTOBER

By R. A. S. RATCLIFFE, M.A.

Summary.—From a study of 500-mb flow patterns over the years 1957–64, criteria are deduced for the forecasting of fine spells in south-west Scotland during the period May to October. The criteria are shown to be capable of forecasting about half of all fine spells occurring in south-west Scotland. The criteria were tested on independent data over the 5 years 1953–56 and 1965 with similar success.

Introduction.—Lowndes¹ and Ratcliffe² have deduced separate models for the forecasting of fine spells in south-east England but, at the time of writing, no corresponding work appears to have been carried out for the northern part of the British Isles.

To rectify this position the current investigation was undertaken. The stations chosen for the investigation were Renfrew and Prestwick and, for the purposes of this paper, a fine spell was defined as six consecutive 12-hour periods in each of which both Renfrew and Prestwick were dry or had not more than a trace of rain. The 12-hour periods corresponded to the periods reported in the *Daily Weather Report*, i.e. 0900–2100 GMT and 2100–0900 GMT.

Data used.—All the 500-mb charts for midnight in the 8-year period 1957–64 inclusive (May to October) were scrutinized with a view to uncovering any relationship which might exist between the 500 mb flow patterns and fine spells in south-west Scotland.

The dates of the fine spells were ascertained from the rainfall data in the *Daily Weather Reports* over the same period of years.

Preliminary results.—It soon became clear that fine spells in south-west Scotland were much more commonly associated with 500 mb highs in the vicinity of the British Isles than were those in south-east England. Table I illustrates this point : about 40 per cent of the fine spells at Prestwick and Renfrew which occurred in the 8-year period began with a 500 mb high near the British Isles and at least another 40 per cent were associated with a strong upper (500 mb) ridge which, in a substantial number of cases, developed into a high on the 500 mb surface later.

Another point soon emerged from a comparison of the dates of fine spells at Renfrew and Prestwick with those occurring at Kew and London (Heathrow) Airport over the same years : almost 80 per cent of the fine spells in south-west Scotland had a counterpart in south-east England although the Scottish ones were normally for a slightly different (and usually shorter) period (Table I shows this comparison).

TABLE I—ANALYSIS OF FINE SPELLS IN SOUTH-WEST SCOTLAND

Year	Total number of fine spells in south-west Scotland	Number with a counterpart in south-east England	Number with 500 mb High at onset	Number with strong ridges 500 mb high developed later	Others
1957	13	8	2	3	4
1958	9	3	5	1	2
1959	13	13	9	3	1
1960	8	7	4	2	0
1961	10	8	0	4	1
1962	11	7	8	2	0
1963	6	4	3	1	1
1964	7	5	2	4	1
Totals	77	55	33	20	10

These preliminary results suggest that some refinement of Ratcliffe's² criteria for south-east England, together with a more precise definition of the position of the 500 mb high and the flow pattern around it, might lead to successful results in forecasting fine spells in south-west Scotland. Following on these ideas the criteria in the next paragraph were deduced.

Forecasting criteria.—The results of the investigation suggest two independent criteria for forecasting fine spells. The first of these, based on the position of the strongest 500 mb flow coupled with an upper ridge, is as follows :

1. The strongest flow in the Atlantic area roughly from 40°N to 70°N, and 10°E to 50°W should be :
 - (i) centred inside the area bounded by 55°N, 65°N, 40°W and a line joining 55°N 20°W to 65°N 10°W (see pecked lines on Figures 1–6), and
 - (ii) from between 180° and 240°.

The strong flow may continue from approximately the same direction upstream or downstream outside the area the only requirement in (i), being that the core of the strongest flow should be centred inside the area in (i) at some place along its length but the core must not extend closer to Scotland than the defined area. The following provisos must also be satisfied :

- (a) A strong 500 mb ridge with wind less than 30 knots across its axis, must be in an approximately north-south position between 20°W and 5°W. The 570-decametre contour line should reach at least 55°N.
 - (b) There must not be a 500 mb trough or vortex near the British Isles from approximately 48°N to 60°N and 5°E to 20°W.
 - (c) There must not be an equally strong 500 mb flow from between 270° and 310° immediately upstream from the strong flow.
2. The second set of criteria based on the position of the upper high at 500 mb and less restrictive 500 mb flow conditions is as follows :
- (i) a closed-contour high on the 500 mb surface of 570 decametres or higher must be in the area 50°N to 65°N, 20°W to 10°E,
 - (ii) the 500 mb wind must be less than 40 kt within 400 nautical miles of the centre and over the British Isles (not beyond 10°E), and
 - (iii) there should not be a 500 mb trough or vortex over the British Isles from approximately 48°N to 60°N and 5°E to 20°W.

Normally the fine spell is about to begin or has already begun when either of the two sets of conditions above is satisfied.

Typical 500 mb charts illustrating the criteria are shown at Figures 1 to 3, and Table II gives a summary of results obtained.

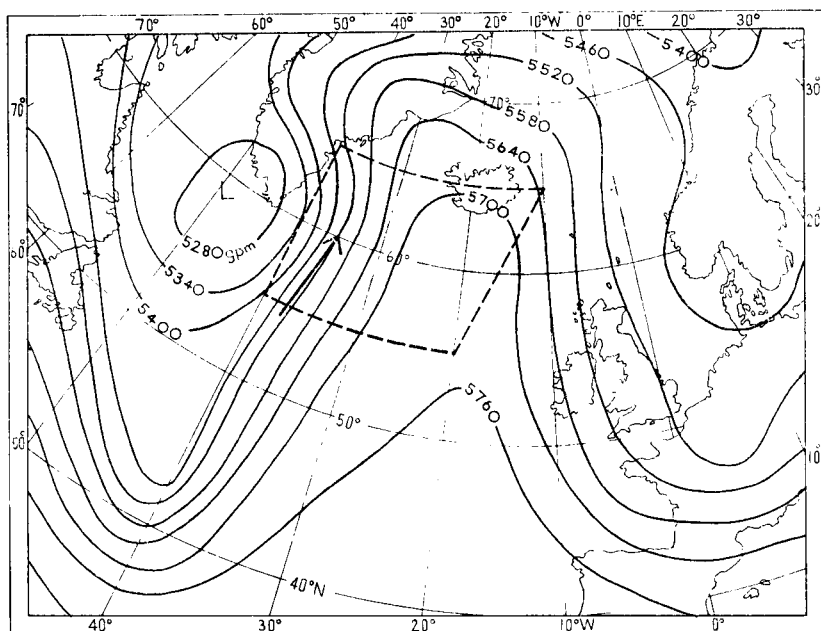


FIGURE 1—500 MB CONTOUR CHART ASSOCIATED WITH A FINE SPELL, 0000 GMT
ON 25 MAY 1962

The pecked line on Figures 1-6 shows the boundary of the defined area.
The strongest flow, indicated by the arrow, is across the west of the defined area.

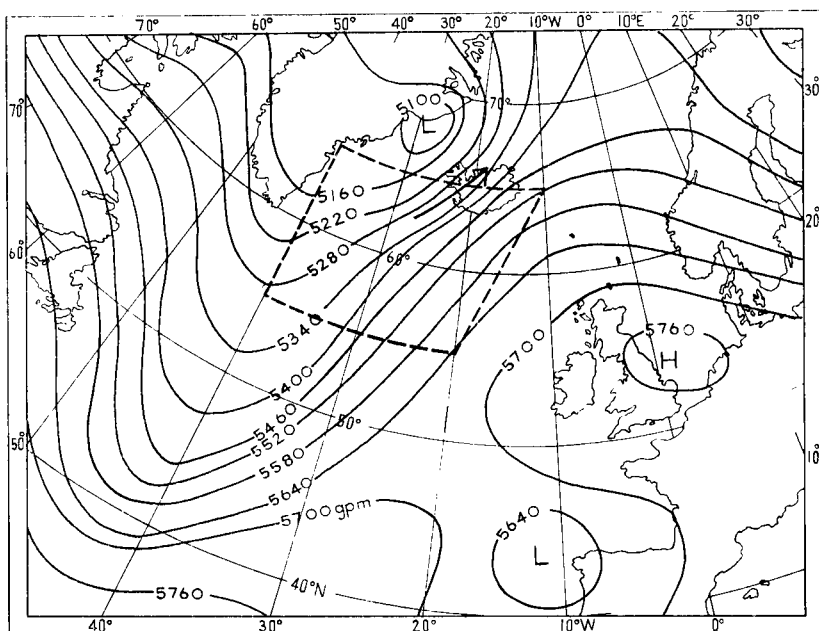


FIGURE 2—500 MB CONTOUR CHART ASSOCIATED WITH A FINE SPELL, 0000 GMT
ON 19 OCTOBER 1965

The strongest flow, indicated by the arrow, is over the north-east of the defined area.

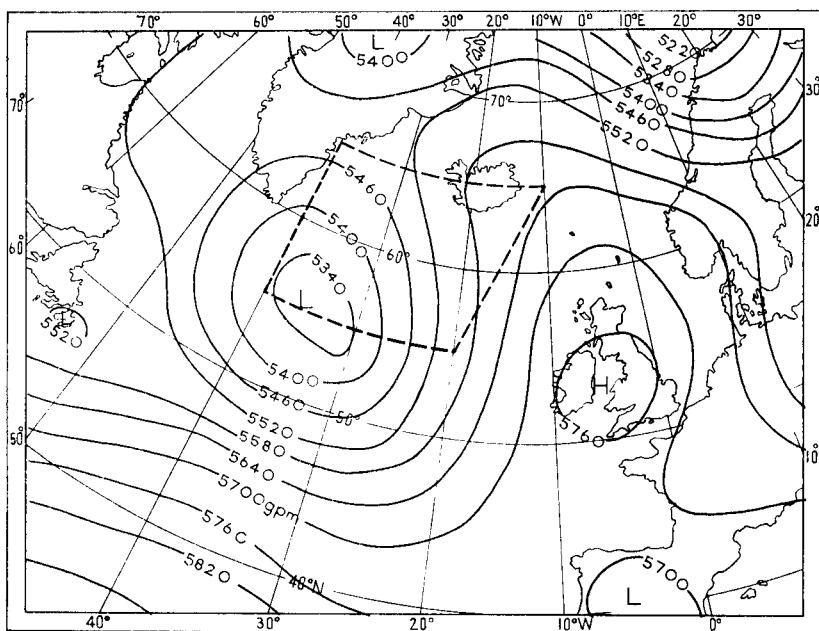


FIGURE 3—500 MB CONTOUR CHART ASSOCIATED WITH A FINE SPELL, 0000 GMT
ON 4 JUNE 1962

TABLE II—NUMBER OF FINE SPELLS IN SOUTH-WEST SCOTLAND FROM MAY TO OCTOBER 1957-64 AND THE NUMBER FORECAST BY THE CRITERIA

Year	1957	1958	1959	1960	1961	1962	1963	1964	All years
Number of fine spells ...	13	9	13	8	10	11	6	7	77
Number forecast by the criteria ...	6	5	8	6	3	8	4	4	44*

*Twenty-one by criterion 1, 23 by criterion 2.

Comments on the criteria.—A few more comments on the criteria may be helpful.

(i) The critical value of 30 kt for the wind speed through the 500 mb ridge (proviso (a) on page 100) is very important as with stronger cross-axis flow there are many cases of fronts or small depressions breaking through the ridge to prevent the occurrence of any fine spell. The 500 mb wind at Stornoway and ocean weather station India (59°N , 19°W) may be used as marking the approximate northern limit of the 30-kt restriction.

(ii) As regards proviso (b) on page 100, it is not necessary to exclude upper vortices over France and Biscay as was the case for fine spells in south-east England. A 500 mb trough embedded in north-easterly winds over south-east England may be ignored but a trough in an approximately southerly flow in the western Channel or south of Ireland is a necessary restrictive condition (for example see Figure 4).

The 500 mb ridge to the west of the British Isles should not be too skew and in particular, with ridges near or east of 10°W at 50°N , the northern portion should not be so far east as to allow south-westerly upper winds over Scotland.

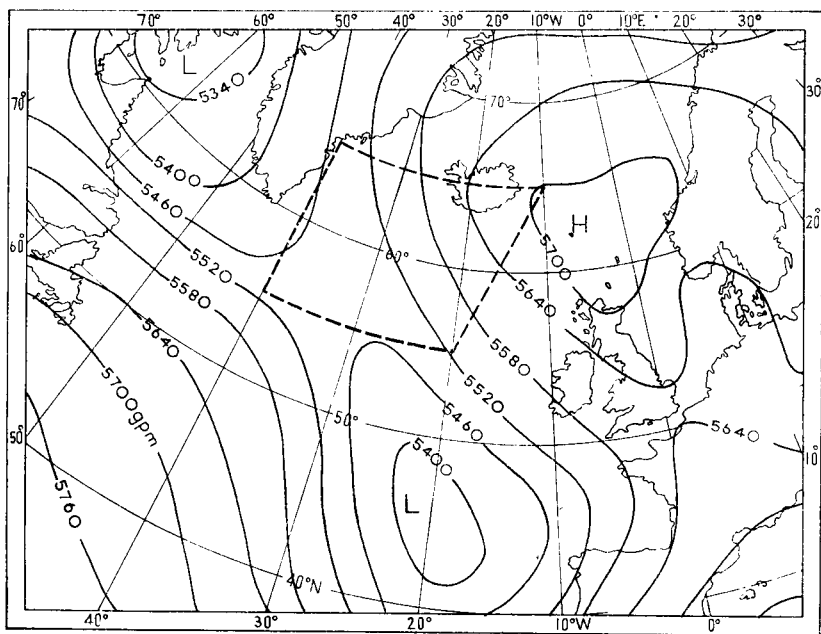


FIGURE 4—500 MB CONTOUR CHART NOT ASSOCIATED WITH A FINE SPELL,
0000 GMT ON 11 MAY 1960
Trough to the south of Ireland moved northwards.

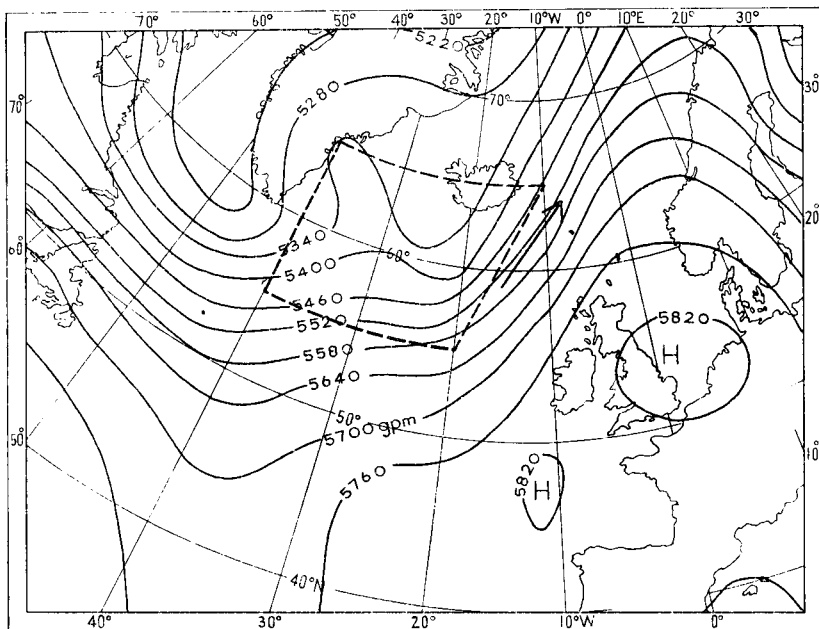


FIGURE 5—500 MB CONTOUR CHART NOT ASSOCIATED WITH A FINE SPELL,
0000 GMT ON 14 OCTOBER 1961

The south-westerly flow near north-west Scotland was too strong. The strongest flow, indicated by the arrow, is outside the defined area.

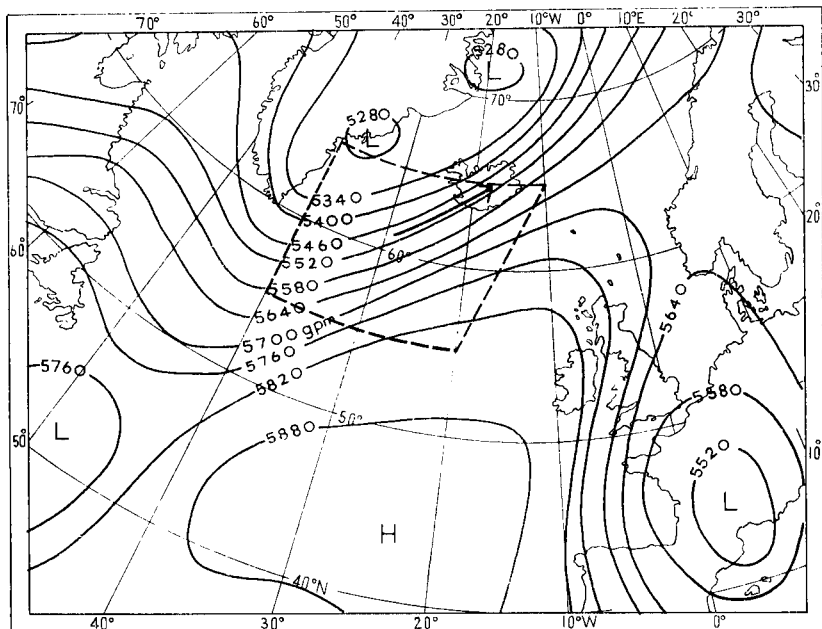


FIGURE 6—500 MB CONTOUR CHART NOT ASSOCIATED WITH A FINE SPELL,
0000 GMT ON 2 SEPTEMBER 1965

The strongest flow, indicated by the arrow, is across the centre of the defined area, but the North Sea trough moved westwards.

It is difficult to define precisely the term 'strong ridge' as thicknesses in ridges vary considerably over the months May to October but the most useful guide is to assume that the 570-decametre contour line on the 500 mb chart must extend northwards to about 55°N.

(iii) The exclusion of cases of strong north-westerly flow upstream from the south-westerly (proviso (c) on page 100) is a safeguard against a north-westerly jet causing some development of the upper trough between the two strong flows. This is really covered by the initial statement defining criterion 1 (page 100) but cases of equally strong north-westerly flow downstream are not so important.

(iv) In criterion 2 with an upper high centred south of about 56°N it is an additional safeguard if all the flow patterns of criterion 1 are satisfied, i.e. if the upper high is regarded as a strong ridge. Particular care is needed when the upper high is centred south of 56°N and east of the Greenwich meridian : in this case the 40-kt restriction on flow over the British Isles is important as far north as Stornoway (see Figure 5).

(v) Troughs in the 500 mb flow which are east of the Greenwich meridian become important only when the upper wind flow over the British Isles is predominantly from north or north-east. Figure 6 gives an example of an occasion of such flow when a fine spell did not follow.

Additional tests of the criteria.—It has been shown in Table II that the criteria can forecast more than half of the fine spells which occur in south-west Scotland. It is also necessary to show that the criteria do not occur on many occasions when there is not a fine spell. Therefore all cases when the criteria were satisfied in the years 1957-64 inclusive were examined and tested to see whether or not they were associated with fine spells. Results are shown in Table III.

TABLE III—ANALYSIS OF FORECASTS OF FINE SPELLS 1957-64

Year	Number of days on which criteria were satisfied		Comments on failures
	with success*	with failure	
1957	24	3	6 May — Small amounts on 2nd and 3rd days 2 June — Last day of spell 31 Aug. — Followed by 2½ dry days
1958	14	4	On three occasions — Small amounts on 2nd and 3rd days 18 Oct. — Definite failure
1959	40	3	On three occasions — Small amounts on 2nd and 3rd days
1960	10	5	On three occasions — Small amounts on 2nd and 3rd days 5 Sept. and 4 June — Definite failures
1961	15	2	On both occasions — Small amounts on 3rd day
1962	23	9	On all occasions — Small amounts on one day
1963	14	3	On one occasion — Last day but one of a spell 15 Oct. and 15 June — Definite failures
1964	8	3	One failure on 3rd day 25 June and 23 July — Definite failures
Totals	148	32	7 total failures

*Criteria were applied to the 0000 GMT chart for all days and were deemed to be satisfied with success if followed by 3 days of dry weather starting at 0900 GMT.

Although the number of failures is higher than for the corresponding data for south-east England, most of the failures only involve small amounts of rain on one day and the proportion of total failures is only about 5 per cent.

As a further check the criteria were tested on completely independent data for 1953-56 and 1965 (5 years in all) with the results shown in Tables IV and V.

TABLE IV—ANALYSIS OF FORECASTS OF FINE SPELLS IN TEST PERIOD 1953-56 AND 1965

Year	Number of days on which criteria were satisfied		Comments on failures
	with success*	with failure	
1953	23	1	4 Sept. — Rain at Prestwick only on one day
1954	9	1	25 Aug. — Small amounts of rain on 2nd and 3rd days
1955	29	3	11 Aug. — 0.3 mm at Prestwick on 12th only 7 Aug. and 23 Oct. — Small amounts on 2nd and 3rd days
1956	12	4	2 Sept. and 11 Oct. — Small amounts on 3rd day 21 July — Followed by 2½ dry days 27 Oct. — Spell began on 29 Oct.
1965	18	3	On all occasions — Small amounts on 3rd day
Totals	91	12	1 total failure 27 Oct. 1956

*Criteria were applied to the 0000 GMT chart for all days and were deemed to be satisfied with success if followed by 3 days of dry weather starting at 0900 GMT.

TABLE V—RESULTS OF USING THE CRITERIA OVER TEST PERIOD 1953-56 AND 1965

Year	1953	1954	1955	1956	1965	All years
Number of fine spells observed	12	5	10	11	12	50
forecast	6	3	5	6	6	26*

*Thirteen by each of the criteria.

It is encouraging to note that the results on independent data are rather better than those which followed from the original data.

Conclusions.—It is shown that about half of the fine spells which occur in south-west Scotland can be forecast by considering the 500 mb flow pattern over the British Isles and in an area of the Atlantic bounded by 55°N and 65°N, 40°W and a line joining 55°N 20°W to 65°N 10°W.

If the flow in this area is south-westerly and is the strongest in the whole Atlantic area with a strong 500 mb ridge to the west of the British Isles, then, with certain restrictive conditions, a fine spell can be forecast with a fair amount of confidence for south-west Scotland during the months May to October.

A 500 mb high cell in the area bounded by 50°N to 65°N and 20°W to 10°E, coupled with less restrictive 500 mb flow patterns over the Atlantic and British Isles, also make it possible to forecast fine spells in south-west Scotland with reasonable confidence.

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EXAMPLES OF CLOUD DETECTION WITH 8.6-MILLIMETRE RADAR

By W. G. HARPER, M.Sc.

Introduction.—A previous paper¹ based on an 18-month study at the Royal Radar Establishment, Malvern, reached conclusions on the value for meteorological purposes of 8.6-millimetre wavelength radar. Studies are now presented of selected records illustrating the resolution given by the radar when used for cloud detection. While the selection of a single record of each cloud type has its dangers, and may not be representative, nevertheless the examples which follow will illustrate the unusual capabilities of the equipment.

Millimetric radar gives echoes from small cloud particles and therefore can be used for cloud detection. Because a narrow radar beam is possible the millimetric radar gives close resolution. The radar was operated pointing vertically. Signals were displayed on a cathode-ray tube as an intensity-modulated display linear in height. By photographing the display and applying a slow lateral displacement to the trace a height-time pattern was built up of the cloud and precipitation passing overhead. Electronic markers provided a height scale on the records in thousands of feet. The horizontal band of echo at the bottom of each radar record (e.g. Plate I) is caused by the out-going transmitter pulse, which prevents observation of the lowest 1000 feet. The occasional dark vertical lines on the height-time patterns should be disregarded; they are the result of measurements of echo intensity. Sky-camera records are included when available. They are not strictly whole-sky photographs, for the angle of acceptance of the lens was only 140 degrees. The camera was usually tilted 20 degrees from the vertical to bring in the horizon in one sector, as an aid to cloud identification. In these sky-camera records the zenith has been marked with a cross. Observers' detailed reports of cloud and weather were also available, usually at 5-minute intervals. More complete details of the equipment and a photograph of its 16-foot diameter aerial can be found in the earlier paper.¹

Examples of records taken with 8.6-millimetre radar.—

(i) *High cloud detection.*—Examples are shown in Plate I of echoes from cirrus and cirrostratus. Cirrocumulus is not covered because this cloud passed through the zenith on very few occasions and no useful records were obtained.

Plate I (a) shows the detection of well-developed cirrus cloud on 24 September 1962 in the layer between 22,000 and 24,000 feet. The cirrus was probably the precursor of a cold front which had become almost stationary across Ireland to southern Scotland and the Norwegian coast. At 0910 and 0915 GMT the sky was obscured with stratocumulus at about 2000 feet (see also page 110), but by 0925 this had broken, and the observer was able to record 6/8 cirrus fibratus. The cirrus at 0910 and 0915 GMT is unlikely to have been very different. The sky-camera record for 0925, which is reproduced, shows cirrus tufts visible through a gap in the stratocumulus layer. The uniformity of the fallstreaks in the radar pattern, individually only a few hundred feet across, suggests that ice crystals with a very uniform fall velocity

were growing to a detectable size at 24,000 feet (temperature -26°C), and evaporating to become undetectable at 22,000 feet. The 0°C level was at 12,000 feet. There is a suggestion of a 'generating cell' at 24,000 feet at 0910 GMT of the type described by Marshall,² but it is not well defined. Winds were south-south-west over Malvern at cirrus levels, probably about 30 knots, giving a horizontal spacing of cirrus fallstreaks of the order of one mile. This would have been difficult to determine visually because of overlapping of fallstreaks as viewed from the ground. The slope of the streaks on the height-time pattern is evidence that the wind increased with height in the layer above 22,000 feet.

Plate I(b) shows the detection of cirrus and cirrostratus just ahead of a cold front at 1600 GMT on 31 October 1961. The front was approaching from the west and passed through Malvern some time after 1800 GMT. It was near dusk when this record was obtained, and it was not possible to use the sky camera, but the observer reported that at 1600 there was 7/8 cirrus and cirrostratus, 6/8 altocumulus and altostratus base about 12,000 feet (apparently not detected by radar), and 3/8 stratocumulus with base at about 2000 feet (see also page 110). The strong echo between 21,000 and 24,000 feet shows closely spaced fallstreak effects, with rapid growth of ice crystals probably occurring at or just below 24,000 feet. In the original negative there is a well-defined but weak echo both above and below these levels, down to 19,000 feet in faint fallstreaks, and at 25,000 feet where the echoes had a distinctly hummocked appearance, rather like those recorded from shallow cumulus (see page 109 and Plate III(a)). This echo could not have been affected appreciably by attenuation,¹ and probably defines precisely a cumuliform top to the layer. The temperature at 25,000 feet was -30°C , and the 0°C level was at 9000 feet. The winds were westerly at cirrus levels, and were probably about 50 knots at 24,000 feet in the Malvern area. Thus the calculated horizontal spacing of fallstreaks was roughly 0.5 miles.

Plate I(c) shows that by 1650 GMT the cirrostratus echo had increased both in thickness and intensity with the approach of the cold front. The echo has a fibrous top, an effect of attenuation or of growth, still mainly at 24,000 feet, but a much firmer base. At 1650 GMT 7/8 stratocumulus prevented visual observation of higher clouds, but at 1635 when the stratocumulus layer was well broken the observer reported an 8/8 layer of altostratus and altocumulus at 10,000 feet. Features in the pattern are the appearance of a 'bright band' at the melting-level at 9000 feet at 1653 GMT, and the increase of echo intensity in the fallstreaks of rain below this, a greater increase than any which can be attributed to the decreasing range of detection. This and the weakness of the bright band are almost certainly due to shear of the shafts of precipitation across the height-time section recorded by the radar. They illustrate the difficulty in interpreting variations in echo intensity made with a vertically-pointing radar. The persistence of these fallstreaks without evaporation may be evidence that they were falling through medium cloud for much of their depth, as is suggested by the observation at 1635. The stratocumulus layer is marked by a weak band of echo centred at 3000 feet, and here the fallstreaks show a reversal of slope. The point can usefully be made that a reversal of slope in a fallstreak on a height-time display does

not imply a reversal of wind direction. A reversal of slope or a vertical section of trail on this display occurs in any layer in which the wind becomes equal to the wind at the generating level of the trail. The theory of this is given by Marshall.² Trail slope on a height-time display is extremely sensitive to particle fall-velocity.

(ii) *Medium cloud detection.*—Plate II(a) is a good example of detection of altocumulus. It was associated with a weak trough of low pressure moving southward over the North Sea, while an anticyclone was centred over Ireland. The echoes have a fairly uniform base at 6000 feet and top at 8000 feet. The Aughton upper air sounding at 1130 GMT showed that the 0°C level was at 5000 feet, and that the temperature was -6°C at 8000 feet, with a pronounced 2 degree C rise of temperature and quite dry air immediately above. The height of the inversion is in good agreement with the echo top. Since temperatures in the cloud were no lower than -6°C and there was no evidence of seeding by ice crystals from higher levels it is likely that the cloud particles were unfrozen and the cloud was a water cloud. The available records suggest that this narrow-beam millimetric radar can at times validly distinguish between water cloud and ice cloud. Ice cloud has a more fibrous appearance on the display. Water cloud is more blobby in appearance, as in this example, and the weaker portions of the echo are diffuse rather than fibrous. With a wider-beam millimetric radar much of this detail would be lost.

The wind at altocumulus level was 020 degrees 18 knots (Aughton 1730 GMT), so that the time scale on the height-time pattern corresponds to a horizontal distance scale which is exactly twice as large as the vertical height scale. Thus the active cells in the pattern are rather deeper than they are broad. In parts of the record at about this time faint fallstreaks can be seen extending down to 5000 feet. The trace of echo at 5000 feet at 1639½ GMT is one of these. It can be tracked back to a tuft of echo in the main layer at 1638½.* The sky-camera photographs of Plate II(a) show typical altocumulus.

Plate II(b), recorded on 1 November 1961, shows initially a much stronger echo from cloud which, at 1425 GMT, was giving very slight rain at the ground. The observer's description was of 'spots of rain in the wind'. A warm front was very close to Malvern at the time. The front moved through rapidly however and few stations in south-west England reported more than a trace of rain. At 1430 GMT, 7/8 altostratus and altocumulus was recorded, with 2/8 stratocumulus base 3000 feet. It is difficult to discern much detail in the cloud photograph at this time. The height-time radar record shows a thin and rapidly weakening layer of echo at 7000 feet, and a second thin layer at 4000 feet which is presumably stratocumulus. By 1435 there had been a rapid clearance, the only cloud close to the zenith being hooked cirrus (cloud photograph). The echo from this can be seen at 1434 between 24,000 and 28,000 feet. The mixed altostratus and altocumulus was certainly water cloud, for the 0°C level was at 8500 feet on the Aughton sounding at 1130

* The spots of echo in the pattern (Plate II(a)) at heights up to 2000 feet are 'angels'. Plank *et alii*³ have suggested that these echoes, which can be very numerous at times on vertically-pointing millimetric radars, are caused by 'insects and discontinuities of refractive index'. The authors of the present paper prefers the first of these explanations.

GMT. A slight inversion was present at 4000 feet, which seems to correspond with the level of the lower layer of weak echo. The temperature at 26,000 feet was -34°C . The winds at 4000 and 7000 feet were west-south-west and generally between 25 and 45 knots, so that the horizontal scale of the echoes below 9000 feet in distance measure is roughly equal to the vertical scale, i.e. they appear true to shape. This would be exactly so if the clouds were moving through the beam with a 36-knot wind.¹

Plate II(c) is echo from thick altostratus. It occurred on 13 August 1962. The observer's report was of an overcast sky with cloud base at about 8000 feet and no lower cloud, and indeed the sky-camera record appears featureless. The radar record is an interesting one. The flame-like appearance above 18,000 feet is probably associated with cirrostratus, which at this time may have had its top above the recorded echo top of 24,000 feet. The tapered form and the marked intensity at these high levels suggests that large ice crystals in considerable quantity were being generated at around 24,000 feet. The temperature at 24,000 feet was -28°C , and the 0°C level was 7500 feet. A smooth fallstreak pattern can be seen in the main-layer echo between 18,000 and 12,000 feet and in fact the gap between two precipitation streaks at 12,000 feet at 1024 can be traced in the original negative continuously down to the base of the echo at 10,000 feet at 1030 GMT. An approximate value for the fall velocity of the precipitation in this layer can be determined from the slope of these streaks.⁴

Assuming a generating level at 24,000 feet, and neglecting vertical air motion, which is likely to be small compared with the particle fall-speeds, a fall velocity of about 1 m/s (3 ft/s) is obtained. This suggests that large ice crystals or snowflakes must have been present, with very rapid evaporation taking place below a cloud base at 10,000 feet (see Stewart⁴).

(iii) *Low cloud detection.*—Plate III shows a gradation of echoes received from cumulus mediocris and cumulus congestus. Because of its small droplet size cumulus humilis was not detectable even at high sensitivity and has not been included. Both Plates III(a) and (b) were recorded on 12 September 1962 in modified polar air behind a cold front which was moving away south-east and had reached the Belgian coast by 1800 GMT. The wind at 3000 feet was west-north-west 20 knots. Plate III(a) shows weak echoes from shallow cumulus mediocris whose base was estimated as 2200 feet. The cloud close to the zenith in the sky-camera record at 1325 has only light shadowing at its base. The echoes are very small, with bases at about 3000 feet, and are barely 1000 feet thick. Quite high sensitivity is needed for their detection.

The cloud photographs show that by 1345 GMT the cumulus clouds were heavier with quite dark bases (Plate III(b)). They were reported as 7+/8 cumulus mediocris with base 2200 feet, and the observer considered that some of the heaviest were reaching the congestus stage. The echo at 1343 is similar in character to that at 1327 but it is now about 2500 feet deep, with a well-defined top at 5500 feet and an ill-defined base at 3000 feet. The echo intensity near the top of this cumulus, corrected for range, was 10 decibels stronger than the much weaker echo near the echo base. This indeed was a frequent feature of mediocris echoes. It suggests that the largest droplets probably occur near the cumulus tops.

The echoes even in the few minutes of record of Plate III(b) show an interesting sequence, from a simple form at 1343 GMT to one showing a quite detailed structure at 1346, while at 1348 raindrops are clearly falling from the cloud and are lost in the transmitter pulse. It is uncertain if this very weak shower reached the ground; the observer did not report it. It is true that the highest top in this small shower may not have passed through the radar beam, and therefore may not have been recorded, but since the 0°C level at this time was 9000 feet it seems very probable that it was a 'warm' shower.

Echoes from stratocumulus are rather similar to the shallower echoes from cumulus mediocris, as for example in Plate II(b) at 1430 GMT when the layer of echo at 4000 feet has the same firm top and diffuse base, though not in as marked a form as in Plate III(a). The low cloud at 1430 was recorded as 2/8 stratocumulus at 3000 feet but this dissipated rapidly, in good agreement with the behaviour of the echo pattern. A second example is the continuous layer of echo at 3000 feet in Plate I(c), which was from stratocumulus with base reported as 2000 feet. The echo top is again stronger than the base. In the third example of stratocumulus echo, Plate I(b), there are two weak layer echoes, one with its top at 3000 feet, the other just detectable at 4000 feet. They merge and intensify, and shallow fallstreaks can be seen in the layer echo at 1605 GMT. It seems likely that droplets approaching 200 microns in diameter were forming. In all these layers the temperatures were higher than 0°C.

There is a suggestion in many of the echoes from stratocumulus and cumulus mediocris, not merely from those illustrated here, that droplet sizes are greater towards the top of the cloud. Singleton and Smith⁵ have reported some layer clouds in which this was so, but in general they found that concentrations and droplet sizes were very variable. Durbin⁶ also found from aircraft measurements that the size of the droplets in cumulus clouds tended to increase with height, with mean volume diameters of about 5 to 10 microns near cloud base, but 20 to 25 microns near the cloud tops. Variations in the vertical should be more reliably observed by millimetric radar than by an aircraft which is unlikely to penetrate precisely the same cloud when obtaining data at different levels. Radar indeed shows how rapid are the changes in cloud composition in the horizontal, even in an apparently uniform overcast layer, and these changes must affect aircraft measurements.

Plate III(c) shows the much more intense echoes from active cumulus congestus. This was on 11 July 1962, when a low-pressure area was centred over the British Isles, and outbreaks of rain occurred, locally heavy and with thunder, notably in East Anglia. A thunderstorm was reported at Ross-on-Wye only 17 miles from the radar site at Malvern. Rain was just commencing when the cloud photograph was taken at 1000 GMT. The cloud was reported as a mixture of cumulus congestus and cumulus mediocris with its main base at 2500 feet, but with some cloud fragments beneath. The dark patches on the cloud photographs at 1005 and 1010 GMT are caused by water drops on the lens, but those at 1000 are dark cloud bases. The rain was moderate at 1005, but by 1010 the edge of the darker cloud mass had almost cleared the zenith, and the sun can be seen weakly. The cloud mass seems to have passed squarely over the radar, though it is uncertain if the highest tops

passed through the beam. The echo is chaotic in appearance. Fallstreaks, where they can be detected, are nowhere consistent, probably because of varying updraughts and downdraughts and of varying local winds. Only from about 5000 to 8000 feet between 1007 and 1010 GMT is there any uniformity of slope, suggesting that this section of the shower cloud may be decaying and may contain more uniformly falling precipitation. The air temperature at 19,000 feet was -23°C , and the 0°C level was at 6000 feet, but no bright-band effect could be seen in this shower when examined at reduced gain.

The weakening of the echo above 9000 feet at 1008 GMT is an effect of attenuation, due to the strong absorption of energy by heavy rain at lower levels. Attenuation can be a very important effect at millimetric wavelengths.¹ The quite sudden increase in echo intensity at 1008½ GMT occurs when the heavier rain in the lower layers clears the beam. Attenuation effects earlier in the shower may well have been more insidious, possibly entirely preventing detection of precipitation at the higher levels in the shower.

(iv) *Detection of cumulonimbus*.—The final illustration, Plate IV, is of the echo pattern from a cumulonimbus which was recorded later on the same day as the cumulus congestus of Plate III(c). No claim can be made that this is typical of cumulonimbus because far too few have passed over the radar when it was in operation, and they were usually the edges of storms. The pattern suggests a most complex structure. It was not a particularly active cumulonimbus; there were no reports of thunder or of hail. There was a well-defined bright band at 6000 feet for most of the 20 minutes taken by the cloud to pass over the radar, coinciding almost exactly with the 6000-foot height marker. It suggests that this was a decaying stage of cumulonimbus, with precipitation falling mainly as snow from higher levels.

There is no doubt that much of the pattern of high-level echo before 1240 GMT has been lost because of rain attenuation, and it is unlikely that the true cloud top or precipitation top was being recorded in this region. The vertical shadowing of the pattern at 1232½, 1236 and 1238 GMT is a more obvious effect of attenuation. It is only after 1240, when the rainfall at the ground had become very light, that the high-level echo becomes strong, providing supporting evidence that before this time much is being lost. Further evidence that echo has been lost is shown by the brightening of the height and time marking lines, e.g. at 1235 GMT at levels up to 23,000 feet, which suggests that there was precipitation at least up to this level. In the original negative, weak echo at 1242 GMT can in fact be seen at 25,000 feet, only a little below tropopause level at 27,000 feet. The air temperature at 25,000 feet at this time was -40°C .

The most striking feature of this pattern is the chaos at the higher levels. It is hard to believe that the detail in patterns of this kind will ever be fully understood.

Acknowledgements.—The Meteorological Office is indebted to the Chief Scientist, Ministry of Aviation and to the Royal Radar Establishment, Malvern, for the opportunity to use this radar for meteorological studies.

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551.501.81:551.567.1

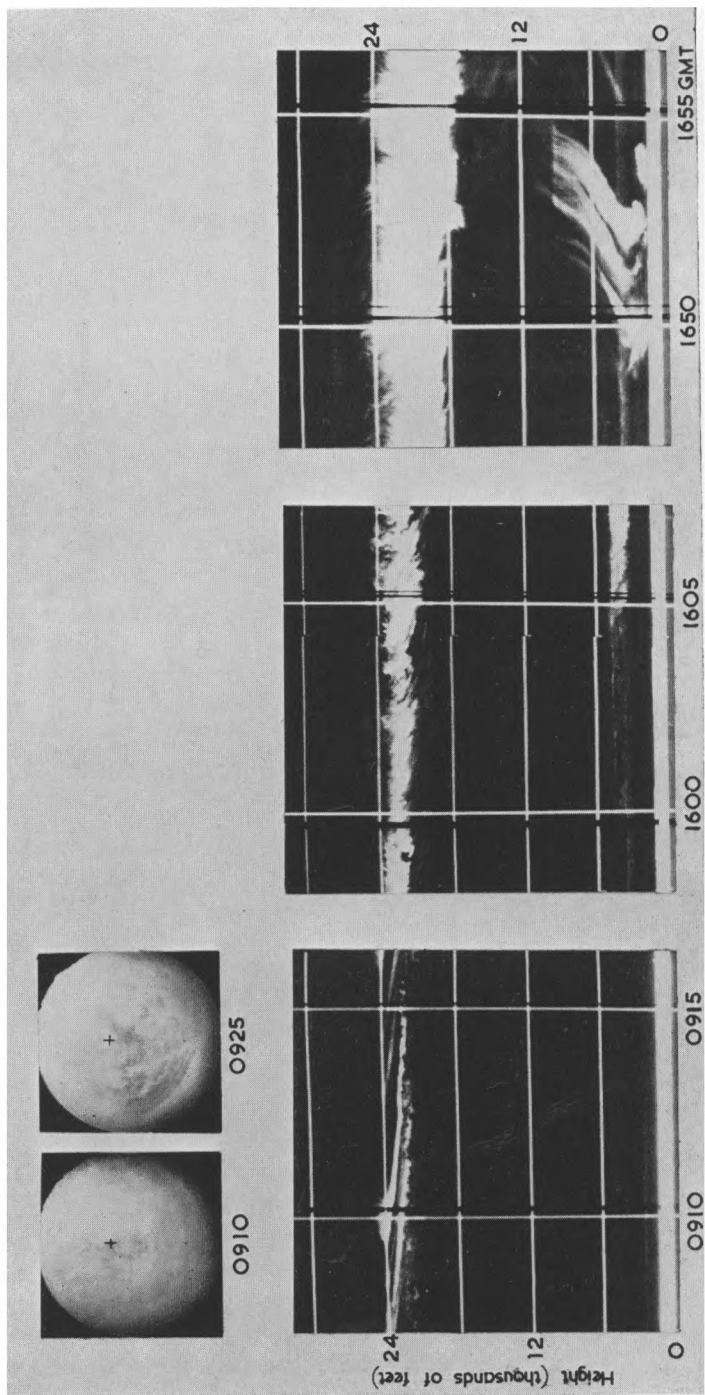
FURTHER DISCUSSION ON THE OBSERVATIONS OF CLOUD WITH 8.6-MILLIMETRE RADAR

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

The record obtained from the vertically-pointing millimetric radar on 13 August 1962, is described by Harper¹ and is particularly interesting because it shows a cloud which has a sharply-defined base even though there is precipitation falling into it from the cloud above (Plate II(c) shows part of the record). Also it is unusual in these circumstances for the cloud base to remain at virtually the same height—it only descended 1150 feet in the 65 minutes that the radar was operating. These observations can be explained either by the presence of a sufficiently strong updraught to support the precipitation particles or by the evaporation of these particles beneath the cloud. Though neither of these explanations can be completely ruled out, it seems from the following evidence that the latter is more likely.

Throughout 13 August there was a complex warm-front system nearly stationary over southern England which gave layers of cloud at about 10,000 – 13,000 ft, 16,000 – 18,000 ft and 25,000 ft above Malvern. An aerological cross-section through Malvern at approximately right angles to the front at 1200 GMT showed that the temperature at the height of the upper cloud was about – 28°C, so that it is reasonably certain that the precipitation shown by the fallstreaks was composed of ice crystals. However it is quite likely that the lower layers of cloud with temperatures of – 15°C and – 5°C contained super-cooled water drops, so that the ice crystals would become rimed as they fell through these clouds. The 0°C level at Malvern appeared from the cross-section to be at a height of 7500 ft, that is below the lowest layer of cloud, and this is confirmed by the radar traces which did not show any melting band. The Aughton radiosonde ascent showed that the air between the lower surface of the front and a height of 5000 ft was very dry — relative humidity only about 30 per cent with respect to ice.

If vertical motion alone was responsible for the base of the radar echo remaining at nearly the same height, then the updraught must have been approximately equal to the fall-speed of the precipitation particles. From the slope of the precipitation fallstreaks it is possible to calculate the fall-speeds of the particles relative to the ground, if the wind profile is known.

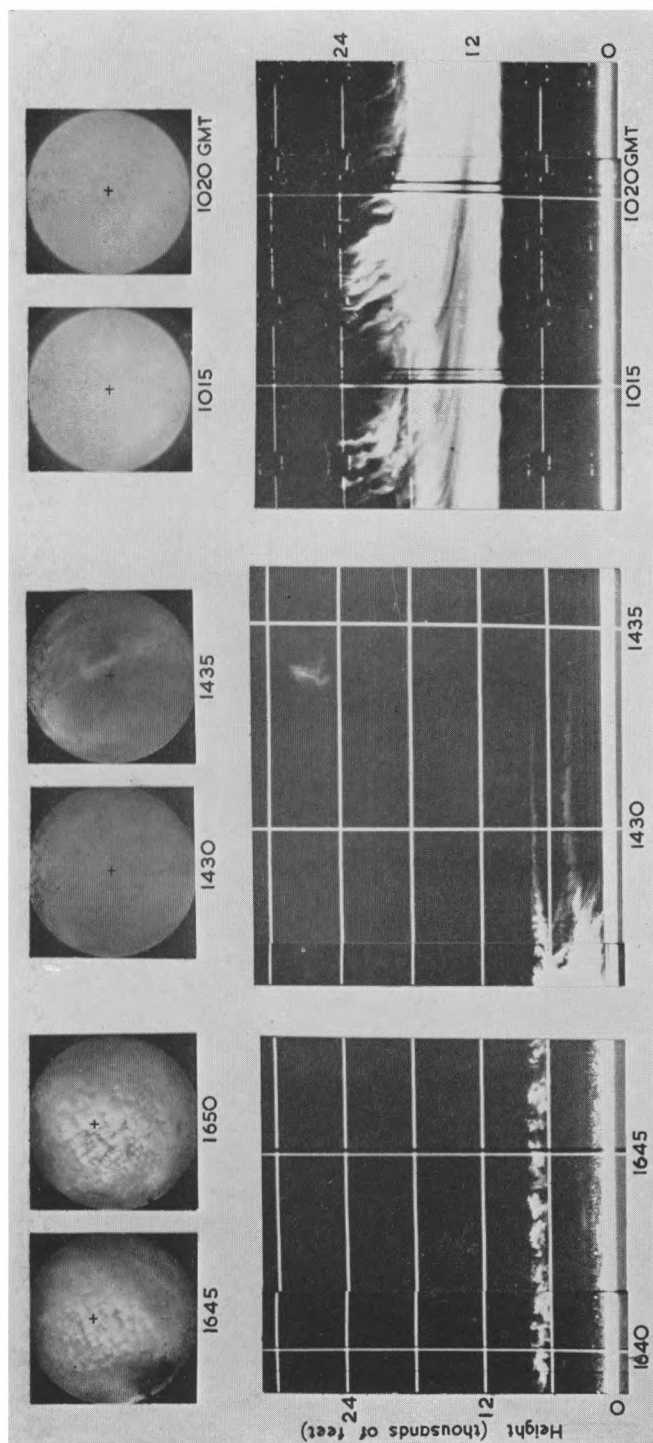


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(a) Cirrus, 24 September 1962 (b) Cirrus and cirrostratus, 31 October 1961 (c) Dense cirrostratus, 31 October 1961

PLATE I—EXAMPLES OF THE DETECTION OF HIGH CLOUD ON THE HEIGHT-TIME RECORD FROM AN 8-6-mm VERTICALLY-POINTING RADAR, WITH SIMULTANEOUS SKY-CAMERA RECORDS WHEN AVAILABLE

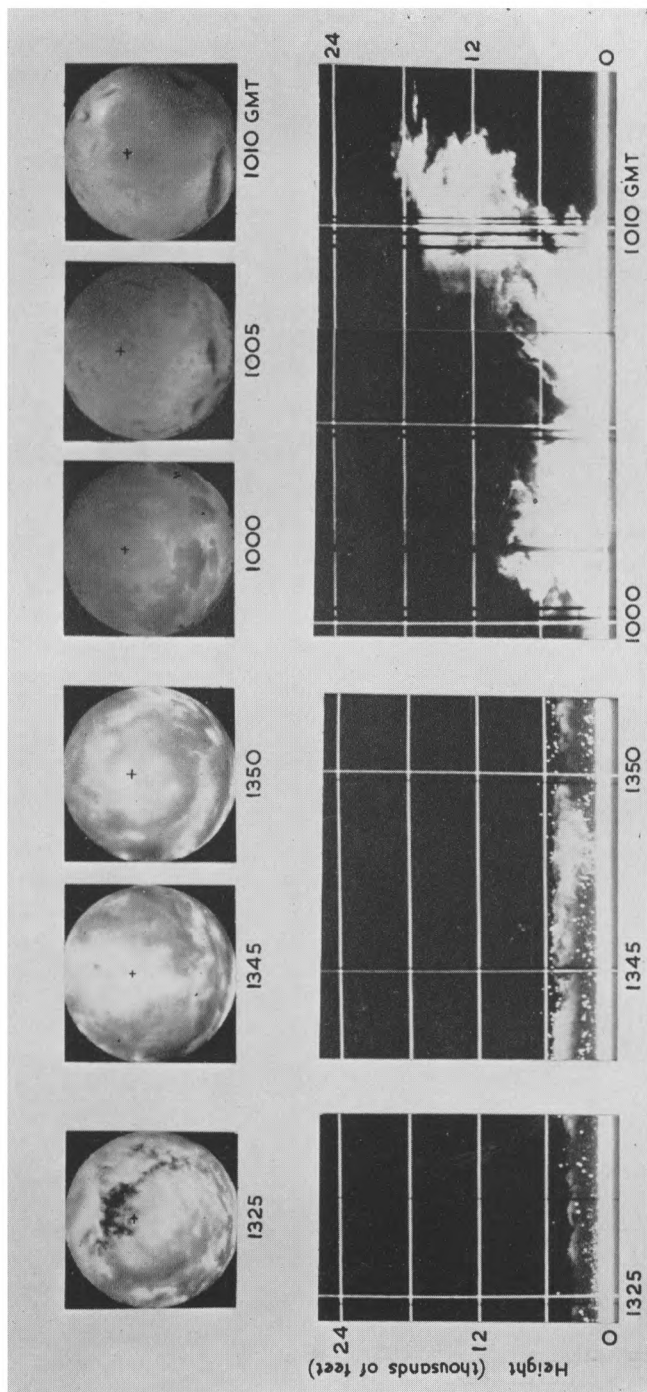
See page 106.



(a) Altocumulus, 18 September 1962 (b) Altostratus and altocumulus, 1 November 1961 (c) Thick altostratus, 13 August 1962

PLATE II—EXAMPLES OF THE DETECTION OF MEDIUM CLOUD ON THE
HEIGHT-TIME RECORD FROM AN 8.6-mm VERTICALLY-POINTING RADAR, WITH
SIMULTANEOUS SKY-CAMERA RECORDS

See page 108.

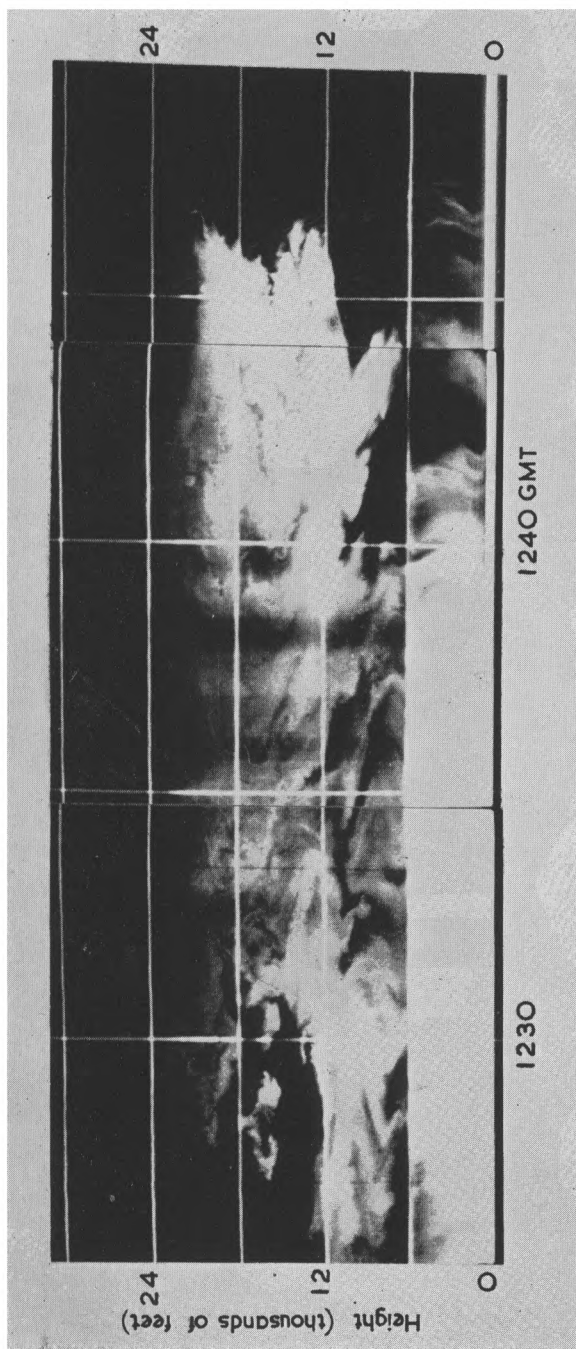


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(a) Cumulus mediocris, 12 September 1962
(b) Cumulus congestus, 11 July 1962
(c) Cumulus congestus, 11 July 1962
Cumulonimbus, 11 July 1962

PLATE III—EXAMPLES OF THE DETECTION OF CUMULUS MEDIOCRIS AND CUMULUS CONGESTUS ON THE HEIGHT-TIME RECORD FROM AN 8-6-MM VERTICALLY-POINTING RADAR, WITH SIMULTANEOUS SKY-CAMERA RECORDS

See page 109.



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PLATE IV —A PATTERN OF A CUMULONIMBUS RECORDED ON THE HEIGHT-TIME
RECORD FROM AN 8-6-mm VERTICALLY-POINTING RADAR

See page 111.

Unfortunately the available upper-wind measurements are not truly representative of the Malvern area, so that accurate calculations cannot be made. However it can be estimated that the fall-speeds were between 2 and 6 ft/second (s) with 4 ft/s as the most likely value. These estimates agree reasonably with the measurements by other workers, for example Langleben² who found that the maximum fall-speed for solid precipitation, other than hailstones, was about 5 ft/s. So to maintain the echo base at the observed height, the updraught would need to have been at least 2 ft/s at the base, and then to have decreased to nearly zero within about 1000 ft above the base, since the fallstreaks can be followed down to the echo base. The height of the base varied very little during the period that the radar was operating, which implies that the strength of the updraught would need to have been nearly constant. Also the updraught must have continued for many hours, since if this was the only effect which was preventing the precipitation reaching the ground, then any marked decrease in the updraught strength should have resulted in rain being reported in the Malvern area and none was reported at Pershore, which is only a few miles away, until 1340 GMT, even though the warm front and its associated clouds had certainly been over the area since 1000 GMT and probably for much longer.

If the alternative explanation, that the observed features of the cloud were caused by evaporation of the precipitation, is correct, then it should be possible from the radar traces to detect the layer through which evaporation was taking place and to show that evaporation was sufficiently rapid for the precipitation particles to be undetectable by the radar after falling this distance. The original radar pictures — not however the prints — show that the intensity of the echo decreased towards its base and the traces obtained with the radar sensitivity reduced show that this layer of decreasing echo strength was 600 to 1300 ft deep. This decrease in echo strength can only be attributed to the evaporation of the precipitation. To determine whether this distance would be sufficient to evaporate the ice crystals to such a size that they could not be detected by the radar, similar calculations to those of Stewart³ were carried out using appropriate values for the constants. For an estimate of the mass of the ice crystals before evaporation began, the results of Langleben² were used. He had found that rimed dendritic crystals, which had fall-speeds of 3 to 4 ft/s, had masses of $\frac{1}{2}$ to $1\frac{1}{2}$ milligrams. With these values and a relative humidity with respect to ice of 30 per cent beneath the cloud, the distance was found to be 1000 to 2000 ft, which is in reasonable agreement with the observed distance. As the evaporation of the precipitation continued, it would have progressively saturated the air beneath the cloud and so lowered the cloud base. It is therefore necessary to show that the slow rate of descent, which was observed by the radar, is consistent with a reasonable rate of precipitation from the upper cloud. Over the period of 65 minutes that the radar was operating, the echo base descended 1150 ft and from this it can be calculated that, since the relative humidity of the air beneath the cloud was only 30 per cent with respect to ice, the rate of precipitation must have been as high as 1.0 millimetres/hour.

It can be concluded from these calculations that the sharply defined base of the cloud and its slow descent can be explained by the evaporation of the precipitation in the very dry air beneath the cloud. This case again shows

that a cloud with its base above the 0°C level can produce moderate precipitation for many hours before any reaches the ground, as has been previously demonstrated by Stewart.³

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551.509.314:551.509.325(421)

FURTHER WORK ON OBJECTIVE FORECASTING OF VISIBILITY

By VALERIE D. JACK

Introduction.—Objective methods of forecasting are methods which do not involve personal judgement; they have been considered in the Meteorological Office for a number of years (Freeman¹), but ideas involving rigorous statistical methods were not practicable until the advent of the electronic computer. Diagrams based on the Freeman² objective method were produced in 1958 for predicting visibility at London (Heathrow) Airport. These were issued to Heathrow for testing during the months of November, December and January of the winters 1958/59 and 1959/60. Similar diagrams for Manchester Airport were issued in 1959 to be tested during the winter of 1959/60. The results of these tests (Freeman²) were encouraging and it was decided that further diagrams should be computed for, in the first instance, Heathrow and that they should be based on a larger amount of data to provide three-hour and six-hour forecasts from each of the eight synoptic hours. This note describes the production of diagrams to give three-hour and six-hour forecasts from most synoptic hours for most of the six winter months October to March, and includes tests of the results obtained from five of the diagrams.

Correlation coefficients (r) were calculated between the forecast visibility and the visibility which actually occurred at the time for which the forecast was made. The formula used was

$$r^2 = 1 - (SE/SD)^2$$

where SD was the standard deviation of the visibility at the time for which the forecast was made and SE (here called standard error) was obtained by finding the root mean square of the differences between the forecast visibility and that which actually occurred. Units were according to a special visibility scale described by Freeman.¹ The scale consisted of 32 steps, the latter part of the scale being approximately logarithmic, while the code figures 0-15 gave the visibility up to 2000 yd in the ranges required for operational forecasting. Thus additional emphasis was given to the lower ranges.

Figure 1 is reproduced to show the method of using the composite diagrams. The top left-hand section is entered with the appropriate value of the first predictor and the pecked line on the diagram indicates how the successive sections are entered and how the forecast is finally read from the scale on the last section.

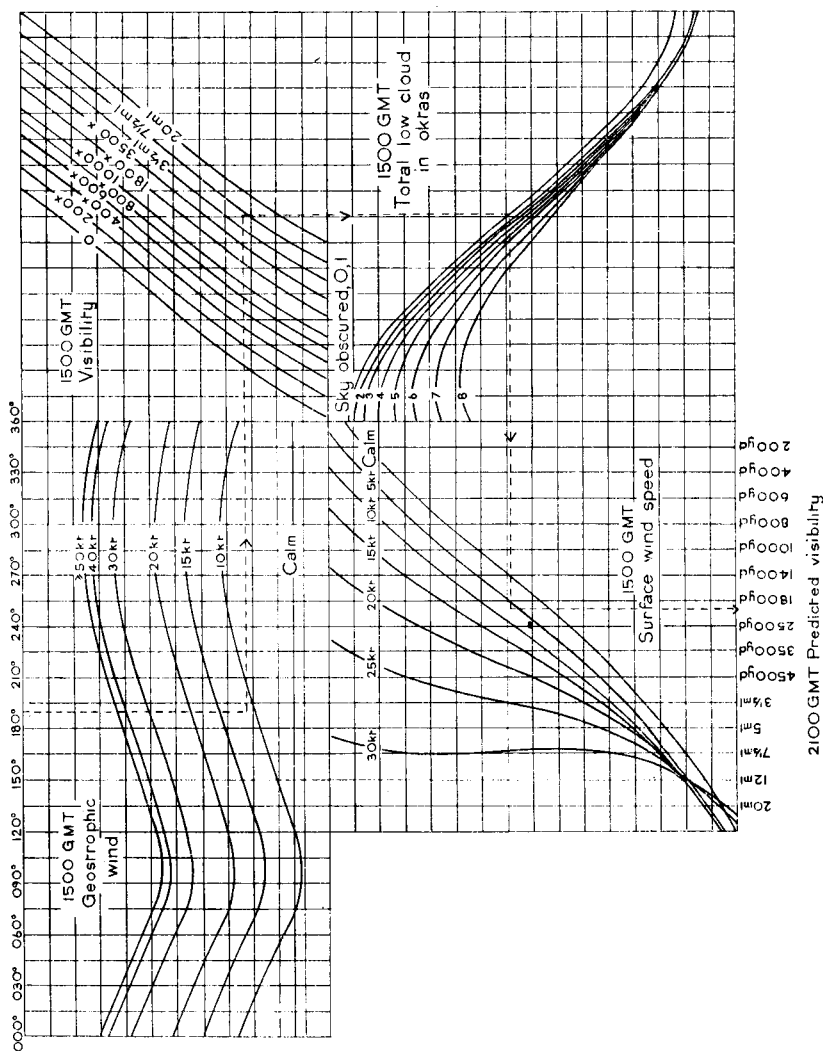


FIGURE 1—VISIBILITY PREDICTION DIAGRAM FOR LONDON (HEATHROW) AIRPORT, OCTOBER TO MARCH

The visibility at 2100 GMT is forecast from predictors at 1500 GMT. The pecked line shows how, for example, a forecast visibility of 2000 yd is obtained from the following predictors : geostrophic wind 190°, 11 kt ; visibility 6 miles (ml) ; total cloud 0 ; surface wind speed 7kt.

Selection of parameters.—In Freeman's preliminary tests up to 25 different parameters were considered. However, many of these were incorporated in other parameters ; for example, wind shear can be indicated by using geostrophic and surface winds ; and some parameters, e.g. hydro-lapse, involved much data extraction. It was therefore decided to examine the 10 parameters which previously had shown most promise amongst the original 25 parameters. The 10 parameters were :

Geostrophic wind direction	Temperature
Geostrophic wind speed	Past weather/present weather*
Surface wind direction*	Temperature lapse rate*
Surface wind speed	Total cloud amount
Visibility	Total low cloud amount
*Parameters not used in any of the five diagrams used for the tests.	

Special notes are listed under the following headings :

Wind.—In the original tests it was found that the geostrophic wind at the time of the forecast was more highly correlated with the visibility at the end of the forecast period than was the surface wind. However, geostrophic winds are neither recorded nor are they always easily available, and measuring a large number from working charts is time-consuming and may not be particularly reliable. A computer programme was therefore written which evaluated geostrophic winds from a network of mean-sea-level pressures and these calculated winds were compared with measured geostrophic winds over a test period (Freeman³). In general the winds produced by the computer appeared to be more reliable than those which were measured from the charts, and all the geostrophic winds used for the diagrams are now calculated by the computer methods.

All wind directions are in tens of degrees with north as 360°. For the geostrophic winds, light winds and calms were dealt with by making the direction zero when the speed was below a certain strength, and these observations were considered in a separate class. Wind speeds of <7, <9 and <10 knots were tested as criteria for defining the class of light winds. Correlation results with a wind speed criterion of <7 knots were not so good as with the other two criteria which gave such similar results that the diagram could be produced with a wind speed criterion of either <9 or <10 knots.

A class of light winds can also be used when examining surface wind direction as a parameter. It was found that the best wind speed criterion for such a class was lower than that for geostrophic winds. Wind direction is not easy to use as a parameter except in the first part of the composite diagram. After geostrophic wind direction has been used the surface wind direction does not give correlation results good enough to justify its use in preference to other parameters which are more easily used.

Temperature.—Data tapes were received from the Meteorological Office Punched Card Installation in degrees Fahrenheit and the data were used in this form. Curves were eventually drawn on the forecasting diagrams at nine-degree intervals on the Fahrenheit scale and renumbered as five-degree intervals on the Celsius temperature scale.

Past weather / present weather.—Correlation coefficients (between forecast and actual visibility) using past weather to forecast visibility three or six hours later were calculated during the earlier experiments and were encouraging but data tapes for past weather were available only from 1957. As tapes

for present weather were available for a much longer period it was decided to try this parameter instead. Although the correlation coefficients using present weather as a forecasting predictor were also fairly good (≈ 0.65), no improvements in the correlation coefficients resulted when the visibility was forecast by using a number of predicting parameters to which was added present weather. This may be because the relevant physical properties of the present weather are represented in the other parameters. Hence no weather parameter was used directly in any of the diagrams produced.

Temperature lapse rate.—This is one of the parameters which can be defined in several ways, very few of which are immediately available from existing recorded data. In the original tests the lapse rate in the lowest 50 mb showed promise, coming eighth best in the list of parameters tested. The data were extracted from ascents plotted on tephigrams, and consisted of the difference between the temperature at the surface and the temperature at 50 mb above the surface. As this method was very laborious it was decided in the later diagrams to try an alternative lapse rate which could be extracted by computer from data available on punched cards. This lapse rate was defined by

$$1000(T_{\text{surf}} - T_{900})/H_{900}$$

where T_{surf} is the Crawley surface temperature in degrees Fahrenheit,

T_{900} is the Crawley 900 mb temperature in degrees Fahrenheit, and

H_{900} is the 900 mb height in feet.

A correlation test was carried out with these data but the results were not encouraging. It was therefore decided not to use lapse rate as a predictor at this stage, but it is hoped that there will be time to examine this parameter more fully later.

Cloud.—Data tapes for total cloud amount and total low cloud amount were obtained from the Meteorological Office Punched Card Installation.

Method of producing diagrams.—As this has been described in detail by Freeman² it is necessary to mention only a few points. It was found that graphs produced by using polynomial quintic equations were over-complicated and this method often tried to fit anomalous observations. Quartic equations were used to produce the first figure of each diagram and thereafter cubic equations were used. These gave simpler graphs than the quartic equations, with comparable correlation coefficients.

Production of the diagrams.—The diagrams were produced from 13 years' data from winters 1949/50 up to and including 1961/62. These years include several during which fog in the ranges 1090 – 440 yards has been on the decline in the Heathrow area because of the Clean Air Act (Wiggett⁴).

All winter months October to March inclusive were used, firstly as two blocks, November, December, January (NDJ) and October, February, March (OFM), and then, if the results of these blocks were similar, all together (Table I). The correlation coefficients of the NDJ blocks were generally better than those of the OFM blocks. The two results marked with daggers in Table I, were not considered good enough for issue to Heathrow for operational use.

Diagrams based on observations made entirely during hours of darkness had not previously been produced and it is interesting to note that once the geostrophic wind speed and direction and visibility had been used as predictors

TABLE I—DETAILS OF DIAGRAMS NOW AVAILABLE FOR FORECASTING VISIBILITY
AT HEATHROW (BASED ON THE PERIOD 1949-62)

Time of predictor data	Forecast for a time 3 hours ahead					Forecast for a time 6 hours ahead				
	Number of predictors	Groups of months available	<i>SD</i>	<i>(SE)</i>	<i>r</i>	Number of predictors	Groups of months available	<i>SD</i>	<i>(SE)</i>	<i>r</i>
GMT										
0000	3	ONDJFM	7.7	3.5	0.89	4	ONDJFM	7.8	4.5	0.82
0300*	3	ONDJFM	7.8	3.5	0.90	—				
0600	4	ONDJFM	7.8	3.8	0.87	4	NDJ	7.3	4.2	0.82
						5	OFM†	5.9	4.1	0.72
0900	5	NDJ	7.3	3.5	0.88	4	NDJ	6.7	4.1	0.79
	5	OFM	5.9	3.3	0.83	4	OFM†	5.1	3.8	0.68
1200	4	ONDJFM	6.1	3.2	0.85	4	ONDJFM	6.3	3.8	0.80
1500	5	ONDJFM	6.3	3.2	0.86	5	ONDJFM	7.1	4.2	0.80
1800‡	—					—				
2100	3	ONDJFM	7.5	3.5	0.89	4	ONDJFM	7.7	4.5	0.81

SD and *(SE)* are in units of special visibility scale.^a

SD = Standard deviation of visibility at the time for which the forecast was made.

(SE) = Standard error as described in the text.

r = Correlation coefficient between the forecast visibility and that which actually occurred.

ONDJFM are initial letters of the winter months October to March.

*Diagrams have not yet been produced for forecast time 6 hours ahead.

†Not issued for operational use.

‡Diagrams have not yet been produced for forecast time 3 hours or 6 hours ahead.

any other parameter made very little improvement on either the standard error or the correlation coefficient. Table II(a) shows this effect for a three-hour forecast from 2100 GMT data. A tendency towards similar results can be seen in Freeman's results² for forecasts based on 0600 GMT data (Table II(b)).

TABLE II (a)—STATISTICS OF CORRELATION BETWEEN HEATHROW ACTUAL VISIBILITY AT 0000 GMT AND THE FORECAST VISIBILITY FOR 0000 GMT BASED ON VARIOUS PREDICTORS AT 2100 GMT*

2100 GMT predictor	<i>(SE)</i>	<i>r</i>
Direction and speed of geostrophic wind (<i>D_g</i>)	4.9	0.75
<i>D_g</i> + visibility (<i>V</i>)	3.5	0.89
<i>D_g</i> + <i>V</i> + temperature	3.5	0.89
<i>D_g</i> + <i>V</i> + surface wind speed	3.4	0.89
<i>D_g</i> + <i>V</i> + total low cloud	3.4	0.89
<i>D_g</i> + <i>V</i> + total cloud	3.4	0.89

*For the period 1949-62. *SD* for 0000 GMT visibility = 7.5.

For *SD*, *(SE)* and *r* see Table I.

TABLE II (b)—STATISTICS OF CORRELATION BETWEEN HEATHROW ACTUAL VISIBILITY AT 0600 GMT AND THE FORECAST VISIBILITY FOR 0900 GMT BASED ON VARIOUS PREDICTORS AT 0600 GMT* (AFTER FREEMAN²)

0600 GMT predictor	<i>(SE)</i>	<i>r</i>
Direction and speed of geostrophic wind (<i>D_g</i>)	5.2	0.77
<i>D_g</i> + visibility (<i>V</i>)	3.9	0.88
<i>D_g</i> + <i>V</i> + temperature (<i>T</i>)	3.7	0.89
<i>D_g</i> + <i>V</i> + <i>T</i> + surface wind speed	3.7	0.89

*For the period November 1949-January 1957.

SD for 0900 GMT visibility = 8.2.

For *SD*, *(SE)* and *r* see Table I.

Results.—Five diagrams were available at Heathrow from the beginning of October 1964, and forecasters were asked to keep a record of results obtained from these during the winter 1964/65. Tests were also carried out at Meteorological Office Headquarters, Bracknell, using independent data from winters 1962/63 and 1963/64.

TABLE III—COMPARISON OF RESULTS FROM OBJECTIVE AND SUBJECTIVE FORECASTS

Type of forecast	3-hour forecast from 0600 GMT data for ONDJFM		6-hour forecast from 0600 GMT data for NDJ		3-hour forecast from 0900 GMT data for NDJ		3-hour forecast from 2100 GMT data for ONDJFM		6-hour forecast from 2100 GMT data for ONDJFM						
	<i>SD</i>	(<i>SE</i>)	<i>r</i>	<i>SD</i>	(<i>SE</i>)	<i>r</i>	<i>SD</i>	(<i>SE</i>)	<i>r</i>	<i>SD</i>	(<i>SE</i>)	<i>r</i>			
Subjective (test on Heathrow TAF's winter 1964/65)	6.8	4.3	0.78	6.3	3.6	0.82	6.3	3.3	0.85	6.5	3.4	0.85	6.9	4.4	0.78
Objective (test on independent data winter 1964/65)	6.8	3.7	0.84	6.3	3.5	0.85	6.3	3.1	0.87	6.5	3.1	0.88	6.9	4.3	0.78
Objective (test on independent data winters 1962/63 and 1963/ 64)	7.3	3.7	0.86	6.9	4.1	0.80	6.9	3.9	0.83	7.4	3.4	0.89	7.9	4.8	0.79
Objective (dependent data period 1949-62)	7.8	3.8	0.87	7.3	4.2	0.82	7.3	3.5	0.88	7.5	3.5	0.89	7.7	4.5	0.81

Note : for definitions of *SD*, (*SE*) and *r* see Table I.

The results of these tests at Heathrow and at Bracknell are shown in Table III. Subjective forecasts for the time of the objective forecasts were obtained by interpolation from routine TAF's (coded terminal aerodrome forecasts), due allowance being made for any changes forecast during the period of validity of the TAF.

In all cases the objective forecasts from independent data for winter 1964/65 gave slightly better results than the TAF forecasts for the same period. This is encouraging, but as the amount of data was so small the results cannot be counted as conclusive. However further tests of these five diagrams and of nine additional diagrams are planned for winter 1965/66. The combined data for 1964/65 and 1965/66 should allow firmer conclusions to be drawn.

The parameters used in the five diagrams tested, together with the resulting standard errors and correlation coefficients at each stage are shown in Table IV.

TABLE IV—PREDICTORS USED IN THE FIVE TEST DIAGRAMS FOR FORECASTING VISIBILITY AT HEATHROW (BASED ON THE PERIOD 1949-62)

Time of forecast data GMT	SD	Time of predictor GMT	Predictor*	(SE)	
0900	7.8	0600	(i) geostrophic wind	5.4	0.72
			(ii) visibility	4.0	0.86
			(iii) temperature	3.8	0.87
1200	7.3	0900	(i) geostrophic wind	5.0	0.73
			(ii) visibility	3.6	0.87
			(iii) temperature	3.6	0.87
			(iv) total low cloud	3.5	0.88
0000	7.5	2100	(i) geostrophic wind	4.9	0.75
			(ii) visibility	3.5	0.89
1200	7.3	0600	(i) geostrophic wind	4.9	0.74
			(ii) visibility	4.3	0.81
			(iii) temperature	4.2	0.82
0300	7.7	2100	(i) geostrophic wind	5.3	0.72
			(ii) visibility	4.6	0.80
			(iii) total low cloud	4.5	0.81

For SD, (SE) and r see Table I

*The Roman number indicates the stage in the predictor diagram. At each stage the predictor listed is added to the ones used in the previous stage. The correlations show the improvement obtained as more stages are used.

The five diagrams for Heathrow were produced first for the following specific reasons:

(i) The three-hour and six-hour forecast diagrams from 0600 GMT data were chosen so that they could be compared with the earlier experimental diagrams produced by Freeman.² There was little difference between the new six-hour forecast diagram and the earlier six-hour forecast diagram; each was for the three months November, December, January. The standard error and the correlation coefficient obtained by using the new three-hour forecast diagram were not quite as good as those obtained from the earlier diagram, but the new diagram is for the six winter months October to March whereas the earlier diagram was for only the three months November, December and January. In addition both of the new diagrams use one less parameter than the earlier experimental diagrams and consequently are a little easier and quicker to use.

(ii) The three-hour and six-hour forecast diagrams from 2100 GMT data were chosen to give forecasts during the night as this had not previously been done. The results obtained by using these diagrams were reasonably satisfactory and similar to those obtained for forecasts during the day (see Table III).

(iii) The three-hour forecast from 0900 GMT data was chosen as this was a useful time for aviation purposes. From Table III it can be seen that for the winter 1964/65 the objective forecast was better than the subjective forecast though it must be remembered that only about 90 pairs of forecasts were compared.

Further plans.—Work has already started on preparing data for the production of diagrams for Heathrow for the summer months. It is hoped that some of these months will combine with some of the winter months (e.g. using February, March and April together) to produce more promising results than those shown in Table I.

When diagrams have been produced for Heathrow to give three-hour and six-hour forecasts from each of the eight synoptic hours for every month it is hoped that diagrams can be produced for other important aerodromes in the British Isles. Further in the future is the possibility of extending this method of objective forecasting to predict other weather elements.

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551.574.13:551.575.1

GLACIATION OF WATER FOG AND A TEMPORARY IMPROVEMENT IN VISIBILITY AT SHAWBURY

By D. J. GEORGE and R. HILL

At Shawbury at 0915 GMT on 3 February 1965, tiny rounded opaque ice crystals were observed to be falling; the sky was obscured at the time and the horizontal visibility was 50 yards. The crystals were just visible when viewed against black cloth (similar to 'diamond dust' observed in the Antarctic by the first-named author) and gradually grew in size to become ice needles of length 1 to 2 millimetres by 0928 GMT, covering the ground with a thin white coating. The visibility had meantime increased to 250 to 300 yards to the north-east and about 150 yards to the south-west, and the sky became visible so that a thin layer of upper cloud covering 5/8 of the sky could be seen. The precipitation ceased by 0935 GMT and the visibility then fell quickly to 80 to 110 yards, and the sky became obscured again. The fog cleared by 1130 GMT.

The fog top was reported as being below the tops of the local hills (400 to 680 feet above mean sea level) by several members of the public between 0600 and 0800 GMT. The minimum temperature overnight was -6.3°C , and the grass minimum temperature was -10.8°C . Negative depressions of the

ice bulb (indicating supersaturation of the air with respect to an ice surface) had occurred on several occasions after the fog formed, as shown in Table I.

TABLE I—HOURLY READINGS AT SHAWBURY

Time GMT	00	01	02	03	04	05	06	07	08	09	10
Screen temperature (°C)	-4.8	-5.0	-6.0	-5.5	-5.6	-5.2	-5.0	-5.0	-5.5	-5.2	-5.0
Ice bulb (°C)	-4.7	-4.9	-6.1	-5.4	-5.4	-5.1	-4.9	-5.1	-5.4	-5.2	-5.0
R.H. with respect to water (per cent)	98	98	92	98	100	98	98	93	98	95	96
Dew-point (°C)	-5.1	-5.3	-7.1	-5.9	-5.6	-5.5	-5.3	-6.0	-5.8	-5.9	-5.6
R.H. with respect to ice (per cent)	103	102	98	103	104	102	102	98	102	100	100
Frost-point (°C)	-4.5	-4.7	-6.3	-5.2	-5.0	-4.9	-4.7	-5.3	-5.2	-5.2	-5.0
Visibility (yards)	330	280	220	250	30	30	50	80	80	50	80
Surface wind (degrees/knots)	Calm	Calm	Calm	Calm	Calm	Calm	Calm	240/3	240/3	Calm	Calm

Synoptic situation.—At the time the area was under the influence of a slow-moving anticyclone centred over western Scotland, with a ridge of high pressure extending over southern England. Radiation fog had formed at a temperature of -5°C around midnight, and had thickened slowly, depositing rime. The upper air sounding for Aughton (near Liverpool), considered representative of the area, showed a subsidence inversion with base about 960 millibars and dry air above and a night cooling inversion at low levels (Figure 1).

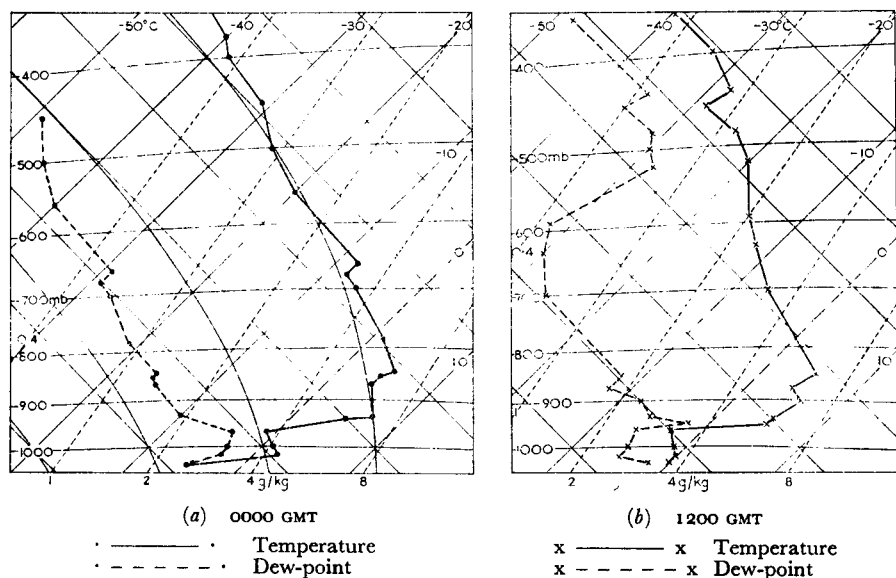


FIGURE 1—UPPER AIR SOUNDINGS AT 0000 AND 1200 GMT AT AUGHTON ON 3 FEBRUARY 1965

The surface temperature and dew-point at 0900 GMT at Shawbury has been superimposed on the 0000 GMT sounding.

Discussion.—On the evidence of the moist layer around 18,000 feet on the Aughton upper air sounding, it is probable that the layer cloud observed was about 18,000 feet and therefore it is fairly certain that the ice needles fell from the supercooled water fog. The surface temperature at the time of the precipitation was within the range of -3 to -8°C given by Mason¹ for the origin of needle-shaped crystals. The water droplets in the fog having been initially seeded with ice crystals (perhaps by slight turbulence around trees and hangars, and contact with rime accretion on trees and objects), further growth of ice crystals took place at the expense of the surrounding atmosphere which was saturated or perhaps slightly supersaturated with respect to an ice surface whilst visibility improved as the water droplets in the fog evaporated and the ice crystals fell out. The process is probably similar to that which produces fallstreak holes in a cloud sheet aloft composed of supercooled water droplets.²

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551.501.9:551.506.2(414)

THE EDINBURGH METEOROLOGICAL OBSERVER 1731-36

By H. J. MATTHEWS

Weather records of one sort or another have been kept since the times of the earliest civilizations, but they were necessarily descriptive until the invention of the barometer and thermometer about the mid-seventeenth century. Even then many years were spent in finding out how these instruments should be correctly used. An examination of *World Weather Records*¹ indicates that regular series of instrumental observations, which can be regarded as homogeneous with those of today, did not begin until the mid-eighteenth century.

The records for Edinburgh embrace the periods June 1731–May 1736 and 1764 to date for temperature, 1769 to date for pressure and 1770–76, 1780–June 1781 and 1785 to date for rainfall. These periods constitute the longest series of homogeneous observations — for all three elements — listed in *World Weather Records*. The collection, reduction and standardization of the old Edinburgh records were undertaken by R. C. Mossman² towards the end of the last century. The earliest series of observations he was able to trace were those for the period 1731–36 published in the six volumes of *Medical Essays and Observations*.³ The first volume includes a brief description of Edinburgh at that time and a detailed account of the instruments used and their general exposure. Until recently the identities of the meteorological observer and the members of the Society responsible for the publication of the essays were unknown. Mossman quoted Forbes's⁴ belief that the observer was an unknown medical man resident in the vicinity of the present City Chambers.

As a result of publicity given to this series of observations in the Meteorological Office display at the recent Battle of Britain Exhibition in Edinburgh, Mr. R. W. Munro (Hon. Editor *Clan Munro Magazine*) wrote to the Meteorological Office (Edinburgh) identifying the unknown observer as a William Monro, Bookseller. The identification was based on an article by

H. D. Erlam⁵ that was itself based on a manuscript in Professor Alexander Monro's proven handwriting.⁶ Despite the evidence of the handwriting there exist some doubts if the manuscript is truly an autobiography, but it does identify the members of the Society '... to which Monro (primus) was secretary ; who prepared the instruments for the Register of the Weather and committed the care of making the observations to his regular and accurate friend William Monro, Bookseller' — they were, in fact, related.

Short⁷ credits the observations to Dr. Andrew Plummer. This may be because the original society, of which Plummer was a member, disbanded about 1737 and was replaced by one of a more general nature — The Philosophical Society of Edinburgh. Professor Monro, owing to ill health, was unable to take up the proffered post of Secretary to the Natural Science section and the post was filled by Plummer on Monro's recommendation.

It is difficult to understand why there should be such a gap, 1736–64, in the Edinburgh records as the city abounded with able men during this period. No doubt the political troubles prior to the 1745 insurrection, and its aftermath, contributed to this hiatus. Even so, great developments took place in other branches of science, in medicine and in literature during this period so that the lack of meteorological observations is rather surprising after the promising start in 1731. Efforts have been made to trace observations that might fill the gap, but so far with no success.

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REVIEWS

Barrier waves in the atmosphere by Sh. A. Musaelyan (translated from Russian). $9\frac{1}{2}$ in \times $6\frac{3}{4}$ in, pp. viii + 112, *illus.*, Israel Program for Scientific Translations, Jerusalem. Oldbourne Press, 1–5 Portpool Lane, London, E.C.1, 1964. Price : 45s.

Qualitatively most of the phenomena associated with airflow over mountains are understood or, at least, known about. For some of them there is a precise mathematical theory ; for others there is still only a geographer's description. Many writers fall down by implying that their theory is applicable to phenomena which are quite beyond it or by generalizing 'conclusions' drawn from observations in a rather restricted field.

Authors often seem aware of only some of the very wide variety of phenomena known. This author bases his book on such work as he is familiar with rather

than on the subject matter as a whole, but writes rather as if his review were complete. Theory, observation and speculation are not well distinguished. This is particularly apparent when he describes Förchgtott's descriptive classification of flow types — a stimulating effort when written but now out of date — for he has tried to formulate a mechanical explanation of the classification as if it were a correct theory. As a result we find a kind of mumbo-jumbo which the Israeli translator (into English) seems to understand even less clearly than the Russian author, and it is not really worth trying to sort it out.

Research in the U.S.S.R. seems to have followed much the same basic lines as elsewhere, but with different emphasis : for example, the Russian scientists were for a time obsessed with the possibility of nodal (horizontal) surfaces in wave flow. They do not seem to acknowledge the fundamental work of Kelvin, Rayleigh and Lamb on lee waves, and also seem unaware that there has ever been a problem in the boundary condition at great height. The hydrostatic assumption is used unnecessarily, and the effects of the earth's rotation introduced in a very haphazard way. The significance of the large-amplitude solutions (e.g. of Long and Yih) which are nevertheless linear seems unnoticed, and there is no reference to post-war Scandinavian papers in the text although one or two are listed.

From the practical viewpoint the treatment of altimeter errors is unnecessary, because the winds which accompany them are, of course, far more important to an aircraft pilot. The first appendix is a rather unsatisfactory enlargement of the theoretical part of the introduction, the second concerns the concept of vorticity and should be much more physical and placed in the introduction, if anywhere.

The book was fun to read only because of familiarity with the subject and the different approach revealed, but nothing in it requires urgent attention in the West, and for the novice it is not nearly as good as the World Meteorological Organization publications on the subject.

Some well-known pictures are reproduced ; for example Figure 30a, a superb photograph by Betsy Woodward, and she and the other photographers deserve acknowledgement just as much as the authors of the papers mentioned in the text.

R. S. SCORER

The atmosphere in action, by I. J. W. Potheary. 8 $\frac{3}{4}$ in \times 6 in, pp. 111, *illus.*, Macmillan and Co. Ltd., Little Essex Street, London WC2, 1965. Price : 15s.

The excellent daily weather maps on television, and the commentaries which accompany them, have given many people a considerable understanding and appreciation of the work of the Meteorological Office. However the majority remain ill informed concerning the practical difficulties of weather forecasting, and the vast amount of work and research that goes into it.

Mr. Potheary, who is a Principal Scientific Officer in the Meteorological Office, supplies this information in a lucid and interesting manner. Beginning

with an account of the atmospheres of the planets, he then discusses in more detail the earth's atmosphere and general wind circulation. He proceeds to consider the influence of air masses on climate and weather throughout the world, with an important section on the westerly wind belt, which includes the British Isles. This leads on to the making of weather observations, a description of the instruments used, and the part played by artificial satellites, the latter being illustrated by excellent television pictures taken by TIROS III and IV. Finally we are told of the work of the meteorological services, with special emphasis on forecasting, and of the various investigations into weather problems at present being undertaken, including some up-to-date information on the use of computers, radar and satellites.

The book has an attractive format and is well illustrated with clearly drawn diagrams and photographs. It is written in terms which can be readily understood, and should help many people who have a little knowledge and wish to enlarge it but do not want to be confused by unnecessary scientific data. It will also prove useful as a supplementary book in the school or college library, providing valuable background knowledge for both the scientist and non-scientist.

F. R. DOBSON

The climate of London by T. J. Chandler. 10 in \times 7½ in, pp. 292, *illus.*, Hutchinson and Co. Ltd., 178-202 Great Portland Street, London W1, 1965. Price : 70s.

This book describes the climate of London indicating how its various factors are modified by the urban area and topography, special reference being paid to differences between the built-up area, the suburbs and the rural surroundings.

Dr. Chandler has not only made very good use of existing climatological data (published and unpublished) for the London area, he has also contributed some valuable new material derived from special surveys which he has organized since 1958 and from motor-car traverses which he has made across the city.

The opening chapter describes the physical and cultural setting of the metropolis and is followed by nine chapters dealing with the following climatic elements ; pressure and weather types, wind, atmospheric pollution, radiation and sunshine, temperature, evaporation and humidity, visibility, cloud amount, and precipitation. The last two short chapters cover climatic regions of London and the consequences of an urban climate.

In order to set the broad climatic scene each of the chapters on climatic elements opens with a consideration of the data for Kew Observatory ; it then goes on to discuss the variations in and around London. Particular attention is paid to weather types and singularities, and the work of Brooks, Belasco and Lamb is extensively quoted in this connexion. Unpublished climatological summaries for Kew Observatory have been made good use of and by collecting together monthly tables published in *Observatories' Year Books* and *Monthly Weather Reports*, Dr Chandler has provided us with a number of new and useful summaries covering recent periods.

The chapter on temperature is the longest and perhaps the most interesting as it includes some of the author's original work on variations across the

city in various weather situations. The term 'heat-island' is extensively used but no definition of it could be found. However, the term 'cold-island', which is used much less often, is defined as a negative temperature anomaly. Deducing that a 'heat-island' is a positive temperature anomaly it is still puzzling to find references to 'London's heat island', as if it were a single ever-present entity, and the apparently tautological statement on page 180 'The influence of London's heat-island, more particularly on night-time temperatures, is very apparent'.

A fair number of misprints were noted and also a number of errors and obscurities. It is assumed on page 29 that the lag of a wet-bulb thermometer element will be a few seconds more than that of a similar dry-bulb element, whereas the reverse is true. On page 61, it is stated that *gusts* of 50 m.p.h. are equivalent to a strong gale. On page 239, discussing differences in the percentage changes in precipitation in successive decades for stations west of, within and east of London the author says, somewhat obscurely, 'If anything the balance was towards lower percentage increases within London than outside, but there was a large, overlapping diversity of increase in all three areas'.

When considering winds over London, Dr Chandler appears to the reviewer to overemphasize the effects of topography. For example, he explains differences in wind direction frequency between Kew and Kingsway as being due to topography, whereas they are probably almost entirely due to the different data periods used for the two stations (1948 and 1949, included in the Kingsway but not in the Kew period, both had unusually high frequencies of south-west and unusually low frequencies of north-east winds).

The chapter on visibility omits any reference to Brazell's paper on London fogs*. On page 236 there is a statement about the reporting of hail which is no longer true because the various forms of wintry precipitation have been separately reported since 1960.

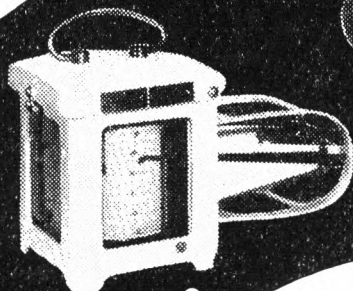
In spite of these criticisms it is considered that Dr Chandler has produced a well-written, entertaining and thought-provoking account of London's urban climate and no student of the subject can afford to be without it. The volume is well produced and illustrated and includes a good list of references and a set of appendices giving daily mean and extreme values at Kew Observatory throughout the year. The index is restricted to place names only and an index of subjects covered would have been a useful addition.

H. G. SHELLARD

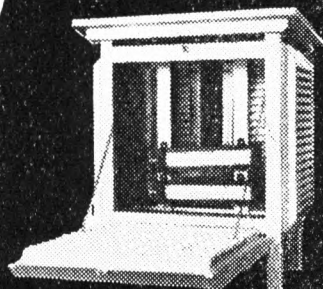
* BRAZELL, J. H. : Frequency of dense and thick fog in central London as compared with frequency in outer London. *Met. Mag., London*, **93**, 1964, p. 129.



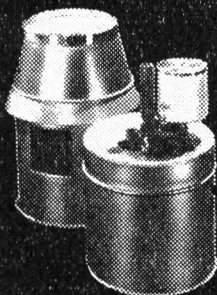
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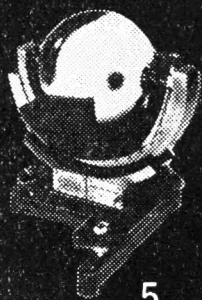
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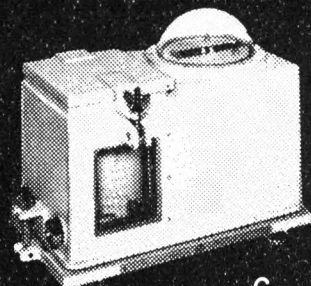
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CONTENTS

	<i>Page</i>
Retirement of Dr. A. C. Best, C.B.E. B. C. V. Oddie ...	97
Criteria concerning fine spells in south-west Scotland during the period May to October. R. A. S. Ratcliffe ...	98
Examples of cloud detection with 8.6-millimetre radar. W. G. Harper ...	106
Further discussion on the observations of cloud with 8.6-millimetre radar. J. B. Stewart ...	112
Further work on objective forecasting of visibility. Valerie D. Jack ...	114
Glaciation of water fog and a temporary improvement in visibility at Shawbury. D. J. George and R. Hill ...	121
The Edinburgh meteorological observer 1731-36. H. J. Matthews ...	123
Reviews	
Barrier waves in the atmosphere. Sh. A. Musaelyan. <i>R. S. Scorer</i> ...	124
The atmosphere in action. I. J. W. Potheary. <i>F. R. Dobson</i>	125
The climate of London. T. J. Chandler. <i>H. C. Shellard</i> ...	126

NOTICES

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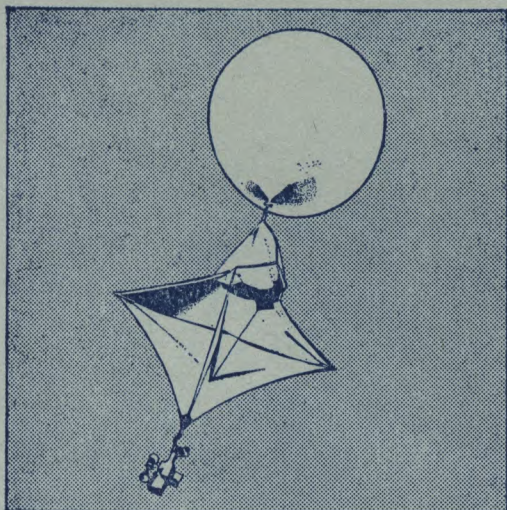
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A REGRESSION TECHNIQUE FOR OBJECTIVE FORECASTS AT 300 MILLIBARS

By A. WOODROFFE

Summary.—A regression equation technique is described for deriving forecasts at 300 mb from the results of a three-parameter numerical forecasting model. The accuracy of the forecasts is discussed and a comparison made with the 300 mb forecasts prepared by conventional methods.

Introduction.—The movement and development of large-scale atmospheric systems can be forecast by numerical methods but the necessary computations can only be performed in a reasonable time if a relatively simple model is used to represent the complex atmospheric structure. The basic variables in such a model may be the contour height fields at a few discrete pressure levels. In formulating the model a compromise is reached between the overall forecast requirements and the complexity of the model in relation to the computing facilities available, with the result that possibly not all the desired levels can be included.

The Meteorological Office operational numerical forecasting scheme is based on an improvement of the three-parameter model,¹ which predicts the contour heights at 1000, 500 and 200 mb. The 200 mb surface is identified with the tropopause and the assumption is made that the motion of air across this upper isobaric surface is negligible. Past results have shown the 500 and 200 mb numerical forecasts to be more accurate than the manually drawn charts, so that there is already a case for basing forecast procedures entirely on computed prontours. However, one of the most important forecast charts at the present time, particularly for aviation purposes, is that for the 300 mb level. Objective forecasts for 300 mb will ultimately be produced by using a multi-layer model and a programme which carries data and computes the height fields for all the required levels. At present, though, other techniques must be used.

This paper describes an objective method for obtaining 300 mb forecasts from the results of the three-parameter model, and compares their accuracy relative to the Central Forecasting Office (CFO) forecasts.

Method.—Accurate wind forecasts are especially important at 300 mb, since the cores of jet streams very often lie near this level. The numerical model already provides forecasts at 1000, 500 and 200 mb but direct interpolation between 500 and 200 mb is not possible because in temperate

latitudes the tropopause is generally found between these two levels. Winds at 300 mb are usually stronger than at either 500 or 200 mb. Good representation of jet streams is desirable in producing forecasts for aviation although it must be remembered that any technique based on numerical methods cannot include detail on a scale less than the grid length used (about 200 miles).

A simple and direct approach to the problem is to use some form of multi-level regression equation to predict the 300 mb contour height, (h_{300}), at each grid point in terms of numerically forecast parameters. An example would be

$$h_{300} = F(h_{1000}, h_{500}, h_{200}) \quad \dots (1)$$

where F is the function of the forecast heights (h_{1000} , h_{500} and h_{200}) which are obtained from the three-parameter model for the 1000, 500 and 200 mb levels at the grid point. It is mathematically convenient to work in terms of D -values (height departures from the standard values), thus

$$D_{300} = F(D_{1000}, D_{500}, D_{200}). \quad \dots (2)$$

A method² of this type has been tried in the United States with some success, using a simple linear regression equation of the form :

$$D_{300} = K + a D_{850} + b D_{500} + c D_{200}. \quad \dots (3)$$

Results have been obtained from such a multi-level regression study based on 16,307 reports covering the period March–May 1962. No geographical division was attempted, but it appears that the majority of the reports used in the analysis were from the United States and Canada. The regression equation obtained was :

$$D_{300} = -5.9 - 0.298 D_{850} + 0.991 D_{500} + 0.394 D_{200} \quad \dots (4)$$

where the D -values are in metres.

A test of this equation on 1362 independent reports in May 1962 showed a root mean square error in the predicted values of D_{300} of 22.4 metres (compared with 22.2 m for the dependent data).

The first step in developing a 300 mb forecast procedure for use in CFO was to form a set of suitable regression equations. The numerical forecasts produced using the three-parameter model extended over the area indicated in Figure 1. In this preliminary investigation it did not seem desirable to embark on a complex statistical analysis covering a large number of stations, so Ocean Weather Station (OWS) A (62°N 33°W), Crawley and Gibraltar were taken as representative of the whole area. These stations were chosen in particular because firstly they incorporated a wide range of latitude which it was hoped would indicate how the coefficients varied with position, and secondly these radiosonde observations were available on punched tape in a form suitable for analysis on a computer. Observations at 0000 GMT and 1200 GMT over the period January 1961–June 1962 were analysed for each station and sets of 1000, 500, 300 and 200 mb D -values were extracted on METEOR (a Ferranti Mercury computer). If any levels were missing on a particular occasion, the report was not used. Approximately 900 sets of data were extracted for each of the three stations.

The form of the regression equation to be fitted to the data was :

$$D_{300} = k + a D_{1000} + b D_{1000}^2 + c D_{500} + d D_{500}^2 + e D_{200} + f D_{200}^2. \quad \dots (5)$$

The coefficients k , a , b , c , d , e , and f were considered to be constant for a particular station (no seasonal variation). The programme which computed

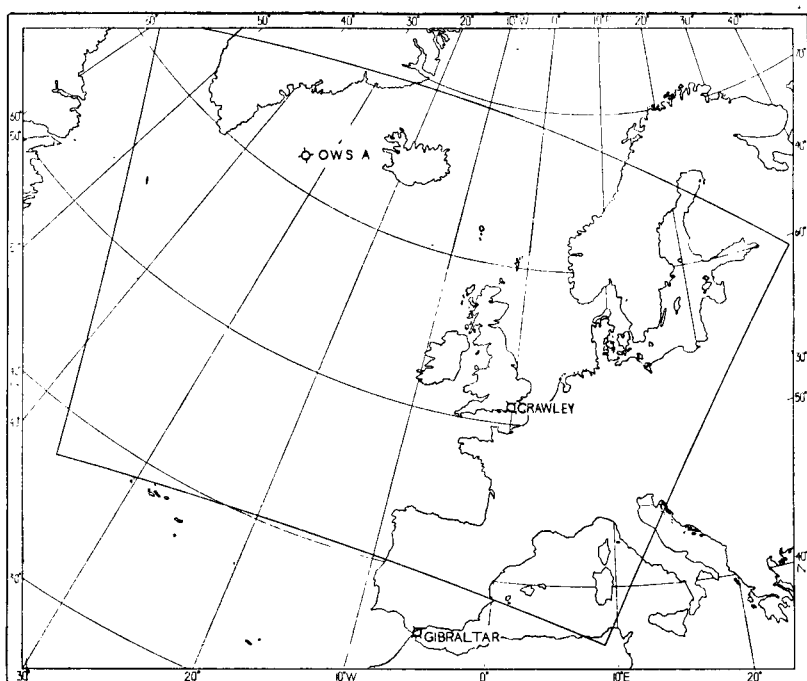


FIGURE 1—KEY STATIONS AND FORECAST AREA

the regression equations giving the best fit to the data also tested that each term was statistically significant using Student's t-test. If any of the terms were not significant at the 5 per cent level, the least significant predictor was rejected and the equation recomputed. This process was repeated until all the remaining terms were significant. The equations obtained in this way for the three stations were as follows (with D -values in metres) :

$$\begin{aligned} \text{OWS A} \quad D_{300} = & 6.6 - 0.223 D_{1000} + 1.039 D_{500} + 0.000075 D_{500}^2 \\ & + 0.340 D_{200}, \quad \dots (6) \end{aligned}$$

$$\begin{aligned} \text{Crawley} \quad D_{300} = & 3.5 - 0.207 D_{1000} + 0.000362 D_{1000}^2 + 0.908 D_{500} \\ & - 0.000470 D_{500}^2 + 0.402 D_{200} + 0.000125 D_{200}^2, \quad \dots (7) \end{aligned}$$

$$\begin{aligned} \text{Gibraltar} \quad D_{300} = & -11.0 - 0.222 D_{1000} + 0.000837 D_{1000}^2 + 0.906 D_{500} \\ & - 0.000647 D_{500}^2 + 0.494 D_{200}, \quad \dots (8) \end{aligned}$$

The root mean square errors in predicting D_{300} using equations (6), (7) and (8) on the dependent data were respectively 31.3, 24.6 and 16.6 m (overall root mean square error 24.9 m). A second set of equations were computed to fix the D -value profile more precisely by including 100 mb D -values as well. Forecast D -values are not readily available at present but changes in the 100 mb pattern are usually slow and therefore the actual D_{100} -values could be used in the forecast regression equation. In the fairly near future it is hoped that objective analyses of the 100 mb surface will be produced on a routine basis so that actual D_{100} grid-point values will be readily available.

The form of the second set of equations is :

$$D_{300} = k + a D_{1000} + b D_{1000}^2 + c D_{500} + d D_{500}^2 + e D_{200} + f D_{200}^2 + g D_{100} + h D_{100}^2 \quad \dots (9)$$

The corresponding equations for the three stations are :

$$\text{OWS A} \quad D_{300} = 20.9 - 0.178 D_{1000} + 0.752 D_{500} + 0.705 D_{200} - 0.191 D_{100} \quad \dots (10)$$

$$\text{Crawley} \quad D_{300} = 11.2 - 0.174 D_{1000} + 0.714 D_{500} - 0.000256 D_{500}^2 + 0.672 D_{200} - 0.172 D_{100} \quad \dots (11)$$

$$\text{Gibraltar} \quad D_{300} = -9.0 - 0.133 D_{1000} + 0.789 D_{500} - 0.000491 D_{500}^2 + 0.627 D_{200} - 0.130 D_{100} \quad \dots (12)$$

The root mean square errors in D_{300} for the dependent data are respectively 25.0, 20.2 and 14.6 m (overall root mean square error 20.4 m). These figures compare favourably with the value of 22.2 m from the American spring season regression equation (4), even though equations (10), (11) and (12) apply throughout the year. It seems that the inclusion of information at 100 mb largely compensates for using the same regression coefficients throughout the year. The choice of the three key stations implied that apart from seasonal variation, one of the factors determining the coefficients at any point in the forecast area is the latitude. Inspection of equations (10), (11) and (12) reveals fairly small and reasonably consistent differences between the coefficients for the three stations, even though there is a difference in latitude of 26° between OWS A and Gibraltar. The assumption has therefore been made that over the forecast area shown in Figure 1, the coefficients can be considered as constant along a given latitude circle. Moreover it is assumed that for any grid point which lies between 62°N and 36°N a prediction equation can be formed by taking a weighted mean of the coefficients for the two nearest key stations, the weighting being inversely proportional to the latitude difference between the key station and the grid point concerned. Outside this latitude range, the equation appropriate to the nearest key station can be used.

With these simple assumptions, equations (10), (11) and (12) form a set which may be used to compute the 300 mb contour field over the area of Figure 1, given the fields at 1000, 500, 200 and 100 mb. Note that the only second power term in the equations is D_{500}^2 . The other second order terms were at best only marginally significant and were consequently eliminated.

Accuracy of the equations.—It was shown in the previous section that a root mean square error of the order of 20 m is associated with the prediction equations (10), (11) and (12). If the 1000, 500, 200 and 100 mb heights used as predictors are forecast numerically (or a persistence forecast is used in the case of the 100 mb level), the overall error in computing the forecast height at 300 mb will arise from errors in the numerical forecast and from using the regression equation. The total error will depend on the correlations between the various sources of error.

Now the thickness forecasts by the three-parameter model are generally better than the prontours, a fact which suggests a positive correlation between the errors at different levels. However estimates can be made of the likely total error assuming firstly no correlation and secondly correlation coefficients of $+1$ between the numerical forecast errors at 1000, 500 and 200 mb.

It will also be assumed that the regression equation errors and 100 mb persistence errors are not correlated either with errors at the other levels or with each other. This is certainly not strictly true in practice, but should be sufficiently accurate for this calculation.

An assessment of the errors associated with the use of equations (10), (11) and (12) may be made by considering the following approximate expression for D_{300} :

$$D_{300} = -0.17 D_{1000} + 0.75 D_{500} + 0.67 D_{200} - 0.17 D_{100}. \quad \dots (13)$$

The contribution from D_{500} can be neglected as it is most often only a minor correction term. Let ϵ_p represent the error in the height at the pressure level p mb.

(a) Assuming no correlation between errors at different levels

$$\epsilon_{300}^2 = (0.17 \epsilon_{1000})^2 + (0.75 \epsilon_{500})^2 + (0.67 \epsilon_{200})^2 + (0.17 \epsilon_{100})^2 + \epsilon_R^2. \quad \dots (14)$$

where ϵ_R is the root mean square height error (estimated as 20 m) associated with the regression equation. Statistics for the 24-hour forecasts by the three-parameter model over the period January–September 1963 give :

$$\epsilon_{1000} \simeq 40 \text{ m}, \epsilon_{500} \simeq 40 \text{ m}, \epsilon_{200} \simeq 50 \text{ m}.$$

Also, from some work done in the Meteorological Office on forecasting at 100 mb :

$$\epsilon_{100} \simeq 50 \text{ m for a 24-hour persistence forecast.}$$

Thus $\epsilon_{300}^2 \simeq (0.17 \times 40)^2 + (0.75 \times 40)^2 + (0.67 \times 50)^2 + (0.17 \times 50)^2 + 400$,
therefore $\epsilon_{300} \simeq 50 \text{ m}.$

(b) Assuming perfect correlation between ϵ_{1000} , ϵ_{500} and ϵ_{200}

$$\epsilon_{300}^2 \simeq [(-0.17 \times 40) + (0.75 \times 40) + (0.67 \times 50)]^2 + (0.17 \times 50)^2 + 400, \quad \dots (15)$$

therefore $\epsilon_{300} \simeq 60 \text{ m}.$

Note that the major contributions are from ϵ_{500} , ϵ_{200} and ϵ_R . It can be concluded that the regression equation technique is likely to provide forecasts of 300 mb contour height with a root mean square error exceeding that of the other numerical pronouncements by no more than about 10 m.

Similar calculations can be made for the winds. If the regression coefficients are assumed to be constants, equation (13) reduces, by taking the gradient of both sides, to an equation relating the vector winds (\mathbf{V}_{300} , \mathbf{V}_{1000} , \mathbf{V}_{500} , \mathbf{V}_{200} and \mathbf{V}_{100}) at the various levels :

$$\mathbf{V}_{300} = -0.17 \mathbf{V}_{1000} + 0.75 \mathbf{V}_{500} + 0.67 \mathbf{V}_{200} - 0.17 \mathbf{V}_{100}. \quad \dots (16)$$

Let ϵ'_p represent the corresponding root mean square vector errors in the winds. For the 24-hour forecasts made using the three parameter model :

$$\epsilon'_{1000} \simeq 15 \text{ kt}, \epsilon'_{500} \simeq 15 \text{ kt}, \epsilon'_{200} \simeq 18 \text{ kt}.$$

Taking the most unfavourable situation of perfect correlation between ϵ'_{1000} , ϵ'_{500} and ϵ'_{200} , the wind equation corresponding to equation (15) is :

$$(\epsilon'_{300})^2 \simeq [(-0.17 \times 15) + (0.75 \times 15) + (0.67 \times 18)]^2 + (0.17 \times 15)^2 + (\epsilon'_R)^2 \quad \dots (17)$$

therefore $(\epsilon'_{300})^2 \simeq 435 + (\epsilon'_R)^2. \quad \dots (18)$

If $\epsilon'_R=0$, $\epsilon'_{300}\approx 21$ kt,
 if $\epsilon'_R=10$ kt, $\epsilon'_{300}\approx 23$ kt,
 and if $\epsilon'_R=15$ kt, $\epsilon'_{300}\approx 25.5$ kt.

The value of ϵ'_R (the root mean square vector error in the predicted 300 mb wind due to the regression equation) will depend on the variation between ϵ_R at adjacent grid points. If ϵ_R varied very gradually over the whole chart, then ϵ'_R would approximate to zero. Since the predictors are obtained from smoothed fields, random fluctuations in the errors are likely to be quite small. More important will be the error pattern associated with the different synoptic-scale systems, having a typical dimension of 3–5 grid lengths. The quality of the wind forecasts would be seriously impaired if the regression equation errors were systematically distributed, so that, for example, contour heights on the cold side of a jet were consistently overestimated, while those on the warm side were underestimated. With this in mind, 75 cases were analysed where a jet stream (with wind speeds greater than 120 kt) was indicated on the CFO 300 mb chart between OWS A and OWS C (52.7°N 35.5°W). The period chosen was April–December 1963 and easterly jets were not considered. A regression equation was formed for OWS C by the method outlined in the previous section. D_{300} was calculated for the two stations by substituting the subjectively analysed values of D_{1000} , D_{500} , D_{200} and D_{100} into the appropriate equation. The computed values of D_{300} were then compared with the height drawn at each station on the 300 mb chart; the results are summarized in Table I.

TABLE I—JET-STREAM ANALYSIS

	OWS A	OWS C <i>metres</i>	Difference*
Mean observed 300 mb D -value	-356	131	487
Mean error in calculated D_{300}	+4.9	-10.0	-14.9
Root mean square error in calculated D_{300}	22.5	19.6	—
Root mean square error in calculated D_{300} height-difference	—	—	32.0
Mean observed 200 mb height-difference	—	—	420

* Difference for OWS C minus OWS A

The regression equations tended to underestimate the mean component flow in the region of the jet streams by about 3 per cent (see difference column in Table I). However, an error of this magnitude is of no great concern, and could always be overcome by means of an empirical correction. An interesting feature of the results is that the root mean square errors in the predicted values of D_{300} at both OWS A and OWS C were lower than the errors associated with equations (10) and (11), using the dependent data. Note also that the mean flow at 200 mb was on average about 13 per cent less than at 300 mb.

The regression equations were next tested on some actual charts. Grid-point contour heights at 1000, 500, 200 and 100 mb were read from CFO analyses for several selected days in 1963, and the equations were used to compute the corresponding 300 mb fields. The objective analyses prepared in this way were compared with the actual 300 mb charts, and a note was made of any errors which recurred in association with particular synoptic features. Figures 2 and 3 show examples of a winter and summer situation respectively, together with the error fields. The main interest is in the gradient of the isopleths in Figures 2(b) and 3(b), since this indicates the magnitude of the

wind errors due to the regression equations (i.e. ϵ'_R). The error fields shown in these diagrams were actually calculated using the amended D^2_{500} term described in the next paragraph but the amendments were generally slight on these occasions.

There was a tendency to overestimate wind speeds in middle latitudes in areas of large negative D -values ; subsequently it was found that the excessive gradients arose from the D^2_{500} term in the regression equations. Normally, the contribution from this term does not exceed 30 or 40 m at 50°N and decreases to zero at 62°N (latitude of OWS A), but in certain winter situations when very low contour values penetrate well south it can locally exceed 100 m. The unrealistic wind field which then results shows that there is a definite need to limit the contributions from this term on those occasions. The coefficient d in equation (9) must therefore be multiplied by an additional factor \mathcal{Z} , where \mathcal{Z} approximates to unity for the normal range of D -values (-400 m to $+400$ m) found in middle and low latitudes, and decreases in such a manner outside this range that the maximum contribution from D^2_{500} is limited to about 40 m. A suitable form for \mathcal{Z} is :

$$\mathcal{Z} = \frac{100^2 - D^2_{500}}{100^2 + D^2_{500}}. \quad \dots (19)$$

Table II shows the effect of this additional factor on the D^2_{500} contribution at Crawley ($d = 0.000256$). The revised form of equations (11) and (12) is :

$$\text{Crawley} \quad D_{300} = 11.2 - 0.174 D_{1000} + 0.714 D_{500} - 0.000256 \mathcal{Z} D^2_{500} + 0.672 D_{200} - 0.172 D_{100} \quad \dots (20)$$

$$\text{Gibraltar} \quad D_{300} = -9.0 - 0.133 D_{1000} + 0.789 D_{500} - 0.000491 \mathcal{Z} D^2_{500} + 0.627 D_{200} - 0.130 D_{100}. \quad \dots (21)$$

TABLE II—THE MODIFYING FACTOR \mathcal{Z} AND ITS EFFECT

D_{500} metres	Normal contribution (dD^2_{500}) metres	Modifying factor (\mathcal{Z})	Adjusted contribution ($\mathcal{Z}dD^2_{500}$) metres
0	0	1.00	0
100	3	0.98	3
200	10	0.92	9
300	23	0.83	19
400	41	0.72	30
500	64	0.60	38
600	92	0.47	43
700	125	0.34	43

Cut-off cold pools at 300 mb (often associated with occluded depressions) are difficult to deal with satisfactorily, since on some occasions the bulk of the cold air is located between 500 and 300 mb. Above, there is often a low tropopause with relatively warm air in the lower stratosphere, so that by the time the 200 mb level is reached, the effects of the cold layer have been partially cancelled by the warmer air. Thus there may be little indication either from D_{500} or D_{200} as to the precise value of D_{300} . No real solution to this problem has been found, and in summer months, particularly, the regression equations slightly underestimate the depth of these cold centres. A typical example is the cold pool centred just to the north of Scotland in Figure 3(a). However, the associated error field (Figure 3(b)) shows that the wind errors are restricted to a narrow band around the centre, so that the broad-scale effects are not serious.

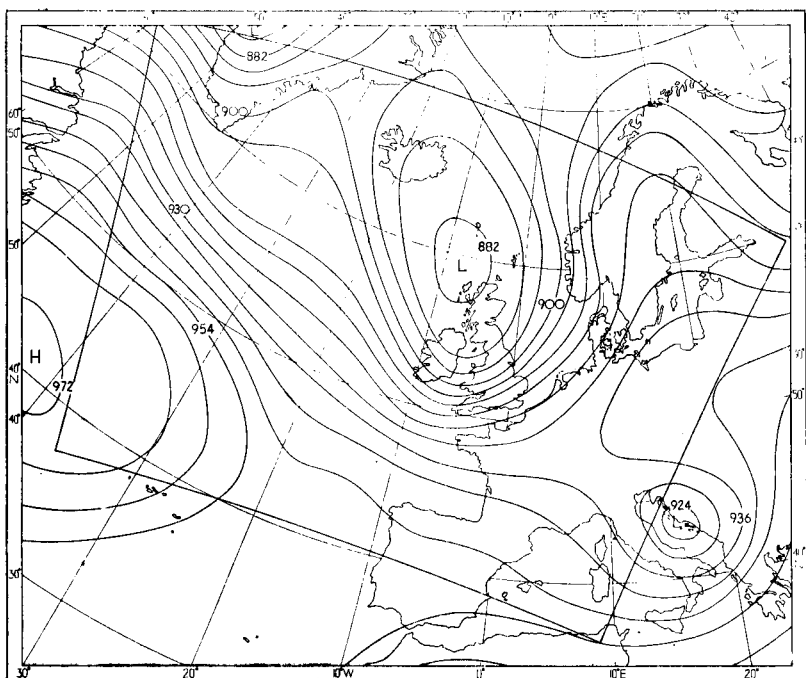


FIGURE 3 (a)—CFO 300 MB ANALYSIS FOR 0000 GMT ON 9 SEPTEMBER 1963
Contours are in decametres.

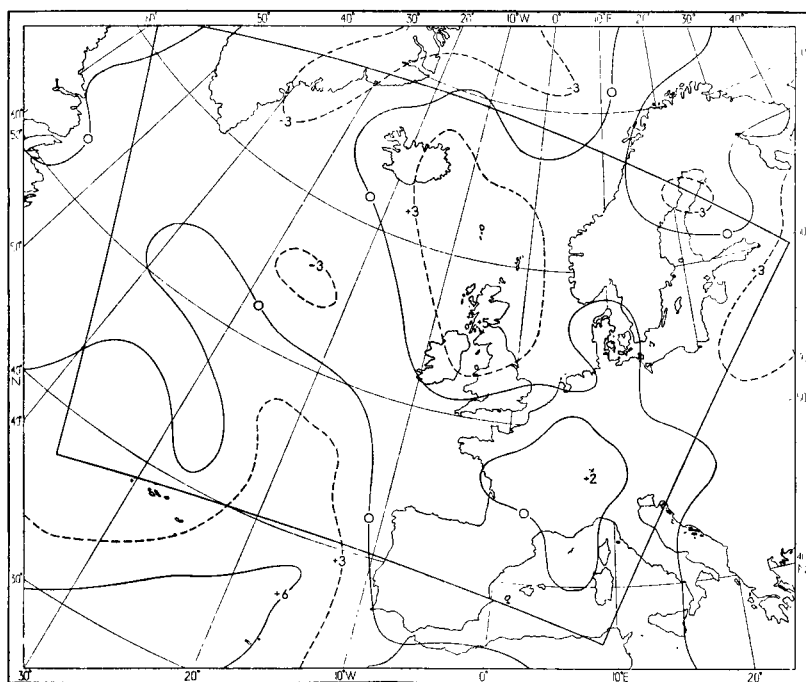


FIGURE 3 (b)—ERRORS IN OBJECTIVE 300 MB ANALYSIS FOR 0000 GMT ON 9
SEPTEMBER 1963
Objective height - CFO analysis height in decametres.

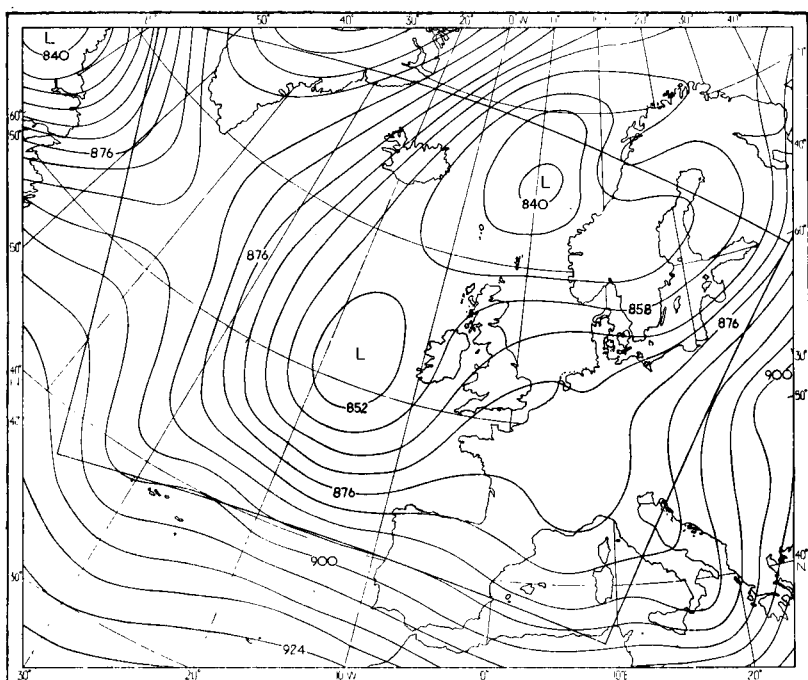


FIGURE 2(a)—CFO 300 MB ANALYSIS FOR 1200 GMT ON 5 FEBRUARY 1963
Contours are in decametres.

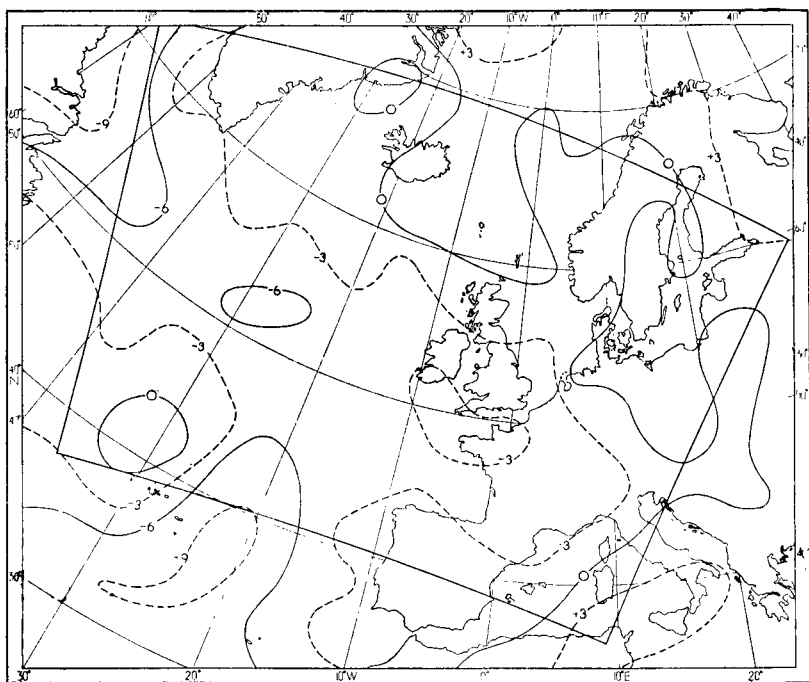


FIGURE 2 (b)—ERRORS IN OBJECTIVE 300 MB ANALYSIS FOR 1200 GMT ON 5
FEBRUARY 1963
Objective height - CFO analysis height in decametres.

Subjective examination indicated satisfactory overall agreement between the actual and objective 300 mb charts, with ϵ'_R probably not exceeding 10 kt. Substituting in equation (18), we obtain an estimate for the total root mean square vector wind error in the 300 mb objective wind forecasts of $\epsilon'_{300} \approx 23$ kt.

Over the period January–September 1963, in a collection of about a hundred CFO 24-hour prontours for 200 mb, the root mean square vector wind error was 23.3 kt. It is extremely unlikely that the CFO errors at 300 mb were less than this and they were probably larger because wind speeds at 300 mb were higher than at 200 mb. It is to be expected, therefore, that the regression technique should provide wind forecasts at 300 mb which are at least as good as the CFO products.

Statistical assessment of the objective forecasts at 300 mb.—The primary purpose of the regression technique, as was stated earlier, is to compute 300 mb prontours from the results of the operational model. Basic data for such calculations were available from the series of operational numerical forecasts made on most weekdays over the period August 1962–October 1963. The 24-hour forecast fields at 1000, 500 and 200 mb, which had been stored on punched paper tape, could be fed directly into the computer. However the use of a 24-hour persistence forecast at 100 mb meant that grid-point heights for 100 mb had to be extracted from the CFO analysis for the initial time (0000 GMT), and then punched on paper tape for input. The 300 mb prontours obtained from the regression equations were verified statistically, and compared with the corresponding forecasts made by conventional methods in CFO.

The ordinary 24-hour numerical forecasts are usually verified against the objective analysis for 0000 GMT produced on the next day. In cases where this is not possible (e.g. no operational experiment on Saturday or Sunday), the CFO subjective analysis is used as the standard against which the forecasts are checked, and it has been shown that the statistics depend to a slight extent on whether the comparison is made with an objective or subjective analysis. Since no 300 mb objective analyses were available, to ensure that any comparisons were completely unbiased, it was convenient to select only occasions when the computed 500 and 200 mb prontours had also been verified against subjective analyses. This requirement restricted the cases mainly to forecasts for 0000 GMT on Saturday computed on Friday.

Forecasts for 300 mb were computed for 25 such occasions which occurred over the period January–June 1963. The results, together with the corresponding CFO statistics for 500, 300 and 200 mb are summarized in Table III. The statistics refer to 192 grid points covering the area shown in Figure 1. Mean winds over a grid square were calculated using the geostrophic assumption.

Table III shows that there is little to choose between the root mean square height errors for the objective and CFO prontours for 300 mb. However, the main interest is in the wind errors and it is clear that here the general superiority of the numerical products at 500 and 200 mb has been retained in deriving the 300 mb fields. The error in the numerical prontours at 300 mb is 4.6 kt greater than the numerical error in 200 mb prontours, and is in accordance with the estimate made in the previous section (page

TABLE III—STATISTICS FOR 25 OCCASIONS IN JANUARY–JUNE 1963

	500 mb		300 mb		200 mb	
	Numerical	CFO	Numerical	CFO	Numerical	CFO
Root mean square height error (m)	52.7	57.5	79.3	79.9	70.5	70.1
Root mean square vector wind error (kt)	18.6	22.8	25.9	30.2	21.3	24.6
Mean maximum height error (m)	150	162	192	209	179	182
Mean maximum vector wind error (kt)	49.7	60.9	65.8	77.0	56.4	62.5
Correlation between height and height-error	-0.03	-0.05	-0.02	-0.02	-0.12	-0.08
(Forecast - actual) kinetic energy equivalent wind error (kt)	-17.4	-8.0	-21.2	-10.4	-13.0	-2.7

138), using equation (18). At 200 mb, the root mean square vector wind error for the computed charts is 13 per cent lower than the CFO figure. At 500 mb, the level of minimum error in the computed winds, the proportion is 18 per cent lower, while at 300 mb it is 14 per cent lower than the CFO figure. Thus, relative to CFO, the 300 mb objective pronouncements show about the same skill in forecasting winds as the 200 mb numerical pronouncements. The mean maximum grid-point height error and the mean maximum vector wind error (evaluated over a grid square) are also recorded in Table III.

The results indicate that there is negligible correlation between the height error and the actual contour height for both the conventional and objective forecasts at 300 mb. The absence of any such bias provides further justification for the broad assumptions made in forming the equations for individual grid points from the equations for the three key stations.

The values of (forecast - actual) kinetic energy equivalent wind error (x) in Table III are calculated from :

$$x^2 = W_f^2 - W_A^2 \quad \dots (22)$$

where W_f is the root mean square forecast wind speed over the verification area, and W_A is the root mean square actual wind speed over the same area. The statistics of (forecast - actual) kinetic energy equivalent wind in Table III show clearly the loss of energy which occurs in the process of numerical computations. If the magnitude of x is large, the strength of jet streams, where the bulk of the kinetic energy is concentrated, will not be forecast satisfactorily. The root mean square actual winds at 500, 300 and 200 mb were respectively 38.7, 50.4 and 44.8 kt. Allowing for the higher wind speeds at 300 mb, the value of x for the objective 300 mb forecasts (-21.2 kt) compares satisfactorily with -17.4 for the normal computed 500 mb forecast.

It is clear that statistically the objective 300 mb forecasts for these 25 situations were better than the CFO forecasts. Satisfactory subjective comparisons are extremely difficult to make, and none was attempted, but examination of the objective forecasts showed that jet streams were on the whole handled quite well, apart from the slight bias towards weaker flow mentioned previously.

Examples of forecasts.—The objective 300 mb forecasts for 0000 GMT on 2 February and 0000 GMT on 4 May 1963 are shown in Figures 4 and 5. These two situations were selected because in both cases the belts of strong winds were handled considerably better numerically than by CFO. The

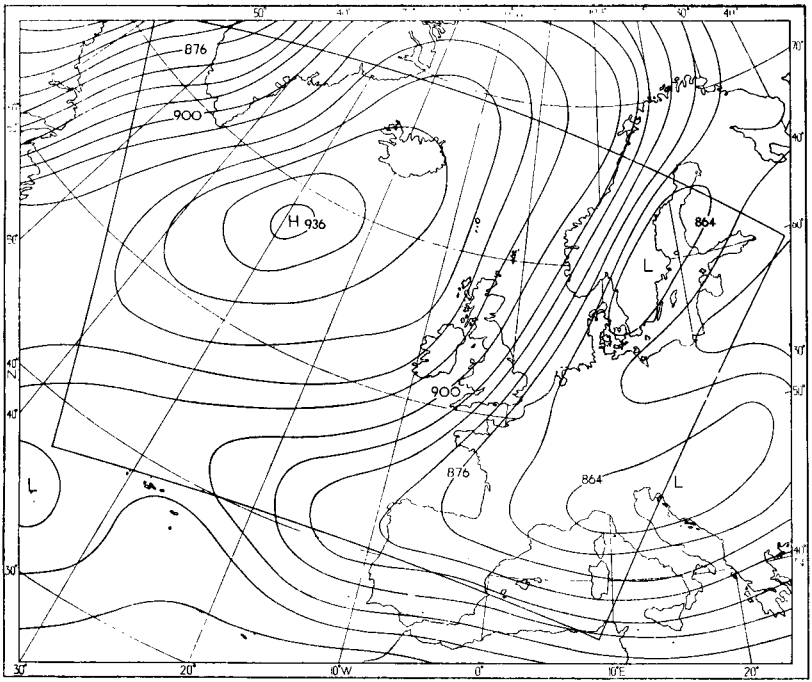


FIGURE 4 (a)—CFO 300 MB ANALYSIS FOR 0000 GMT ON 1 FEBRUARY 1963
Contours are in decametres.

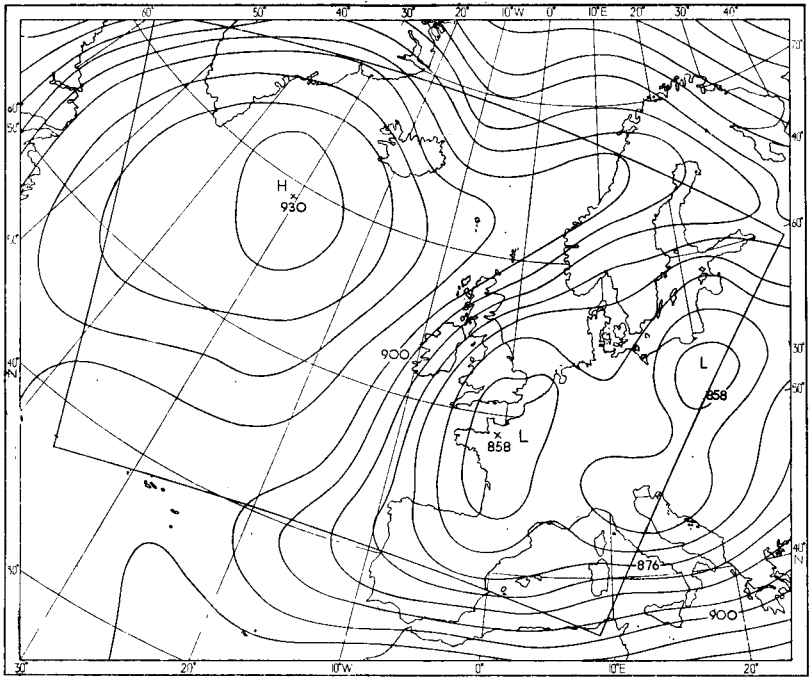


FIGURE 4 (b)—CFO 300 MB ANALYSIS FOR 0000 GMT ON 2 FEBRUARY 1963
Contours are in decametres.

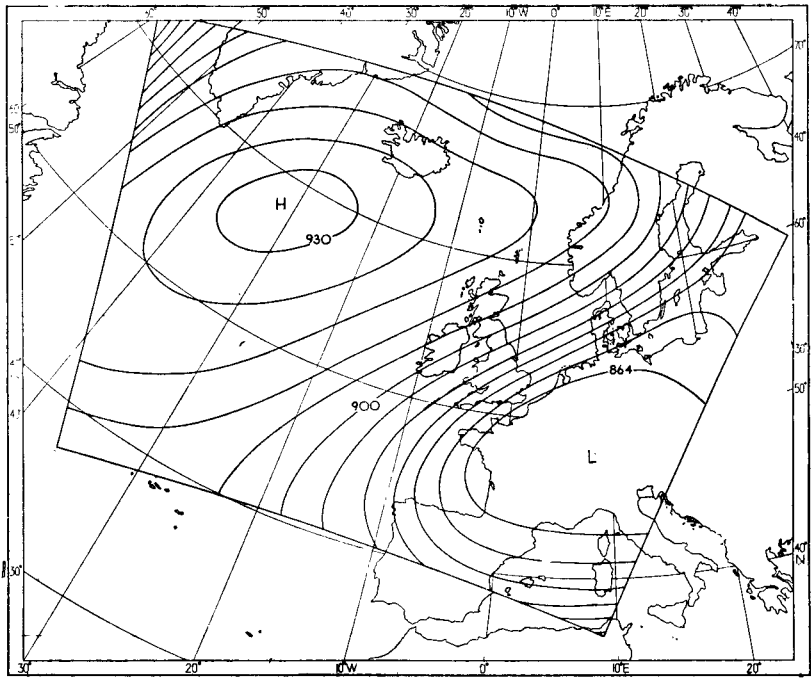


FIGURE 4 (c)—CFO 300 MB FORECAST FOR 0000 GMT ON 2 FEBRUARY 1963
Contours are in decametres.

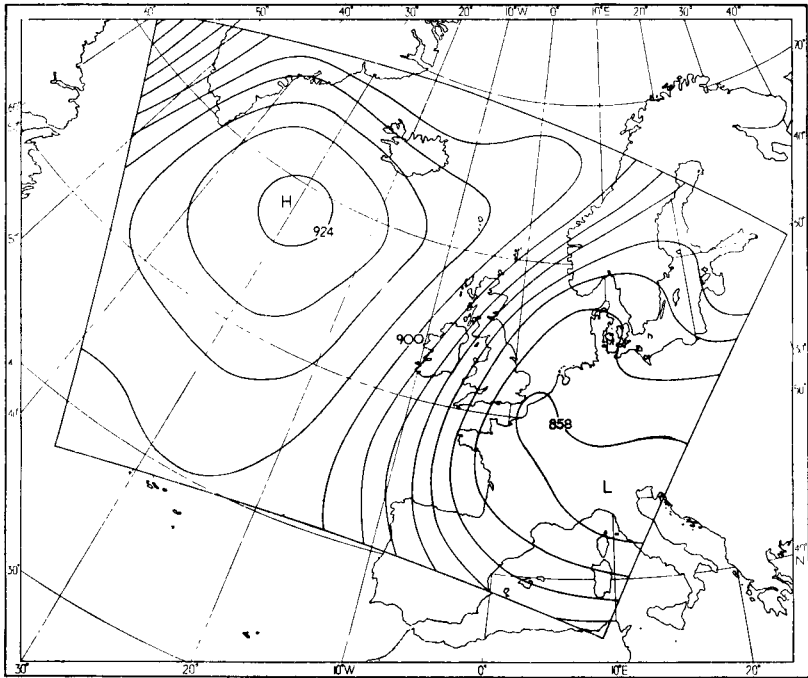


FIGURE 4 (d)—OBJECTIVE 300 MB FORECAST FOR 0000 GMT ON 2 FEBRUARY 1963
Contours are in decametres.

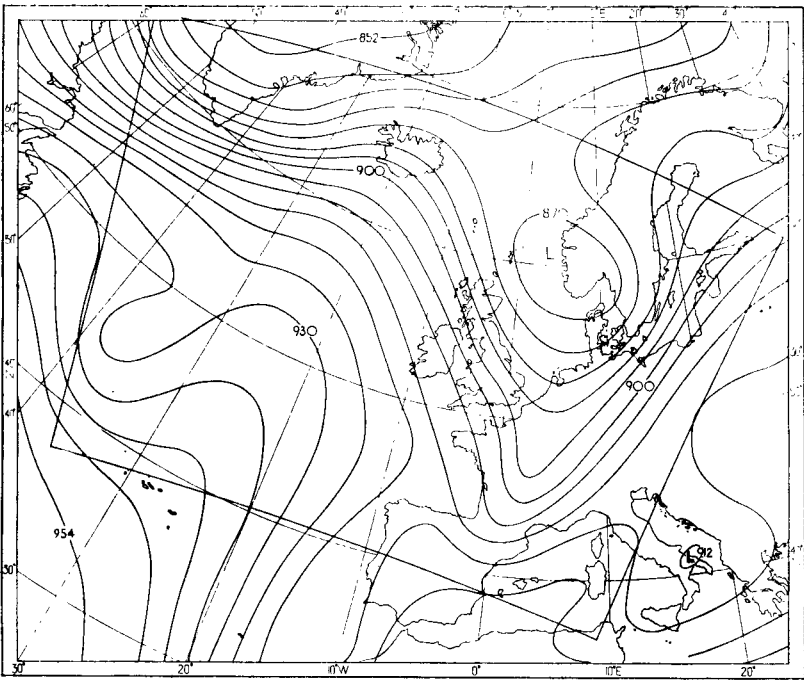


FIGURE 5 (a)—CFO 300 MB ANALYSIS FOR 0000 GMT ON 3 MAY 1963
Contours are in decametres.

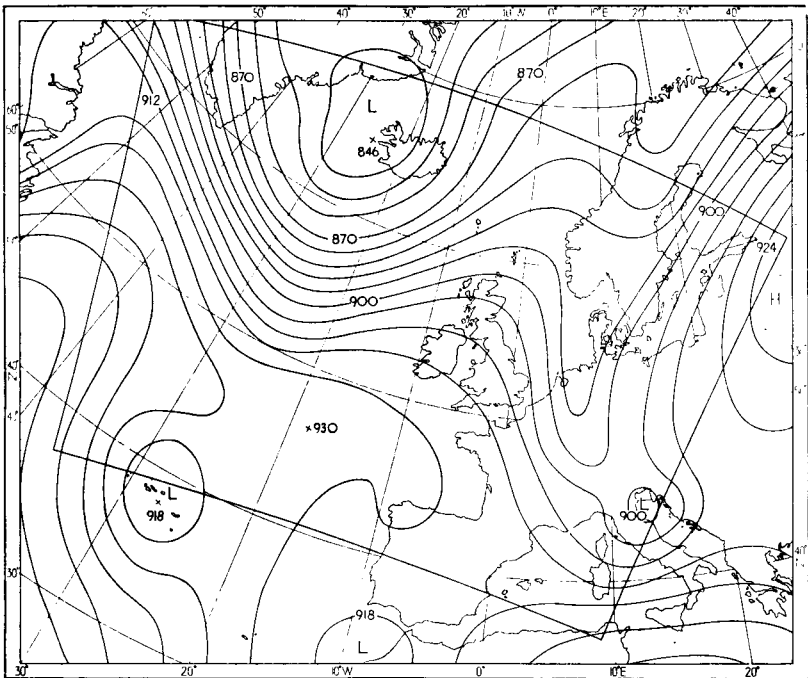


FIGURE 5 (b)—CFO 300 MB ANALYSIS FOR 0000 GMT ON 4 MAY 1963
Contours are in decametres.

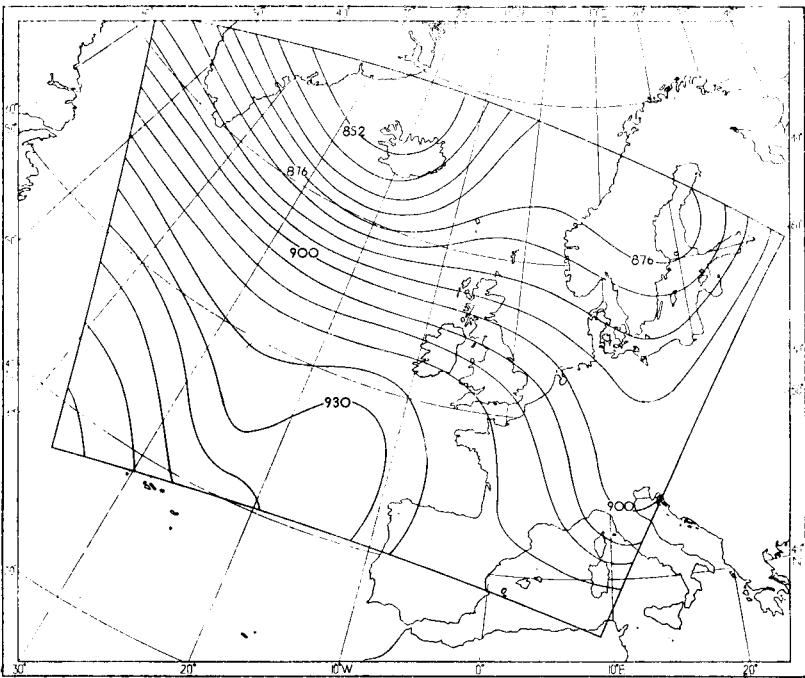


FIGURE 5 (c)—CFO 300 MB FORECAST FOR 0000 GMT ON 4 MAY 1963
Contours are in decametres.

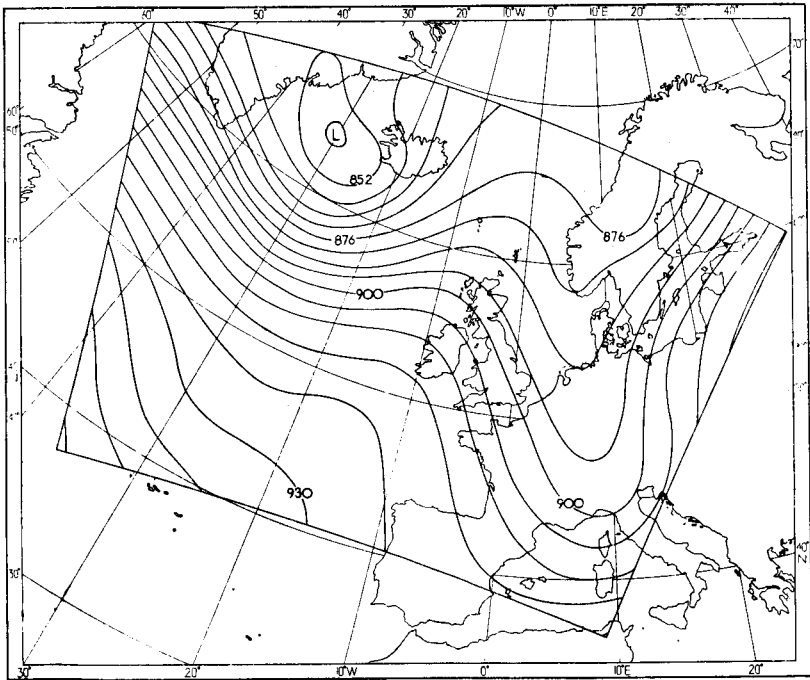


FIGURE 5 (d)—OBJECTIVE 300 MB FORECAST FOR 0000 GMT ON 4 MAY 1963
Contours are in decametres.

success at 300 mb was of course dependent upon successful forecasts at 500 and 200 mb but the examples given show that the regression technique carried the success to the 300 mb forecast.

The CFO analysis for 0000 GMT, 1 February 1963 (Figure 4(a)) shows a substantial block established to the west of the British Isles, with a north-north-east jet over south-east England. Twenty-four hours later (Figure 4(b)) the general situation was very similar, but there were some important changes in the detail of the wind pattern. The development of the low vortex over France had resulted in a slight veering of the jet and a transference north-westwards, with light winds coming in over south-east England. The CFO forecast (Figure 4(c)), although veering the jet, retained the strongest winds over the southern half of the country, but the objective method (Figure 4(d)) forecast the position, strength and orientation of the jet very well.

The 300 mb CFO analyses for 0000 GMT, 3 May and 0000 GMT, 4 May 1963 are shown in Figures 5(a) and 5(b) respectively. The main developments occurred in the Denmark Strait region, where a surface depression which had previously been moving steadily east-north-east in the strong flow over southern Greenland, occluded rapidly and became very slow moving, but deepened by a further 14 mb over the 24-hour period. This resulted in the development of a 300 mb trough just to the west of Iceland, and the veering of the jet near Greenland to north-west. Both the CFO (Figure 5(c)) and the objective forecast (Figure 5(d)) were broadly correct in this area, but the objective method predicted the trough curvature and the strength of the jet more accurately. The weak ridge to the west of the British Isles and the slow-moving downstream trough were also handled better objectively. The CFO forecast was particularly poor in dealing with the downstream trough which was taken too far east over Germany and smoothed out too much. The computed forecast, however, correctly kept the trough almost stationary in the north, while moving the southern portion steadily eastwards into Italy.

Conclusions.—The objective 300 mb forecasts based on the results of the three-parameter model are significantly better than those produced by CFO. This fact together with the convenience of computed charts, presents a strong case for their immediate application in general purpose and aviation forecasting.

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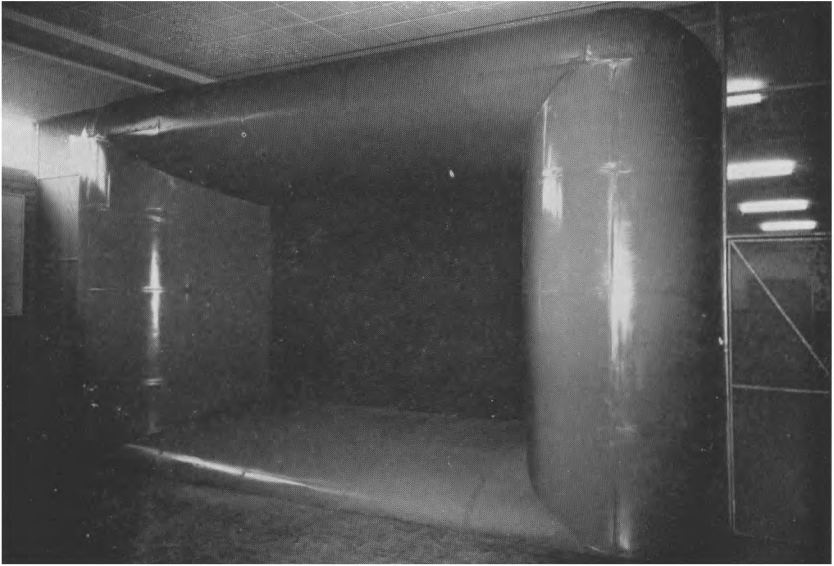
1. KNIGHTING, E., CORBY, G. A. and ROWNTREE, P. R. ; An experiment in operational numerical weather prediction. *Scient. Pap. met. Off., London*, No. 16, 1962.
2. Washington, U.S. Department of Commerce, Weather Bureau. Activities of the numerical weather prediction group national meteorological center. Third Quarter of 1962. Unpublished, copy available in the Meteorological Office Headquarters.

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WIND-TUNNELS IN THE METEOROLOGICAL OFFICE

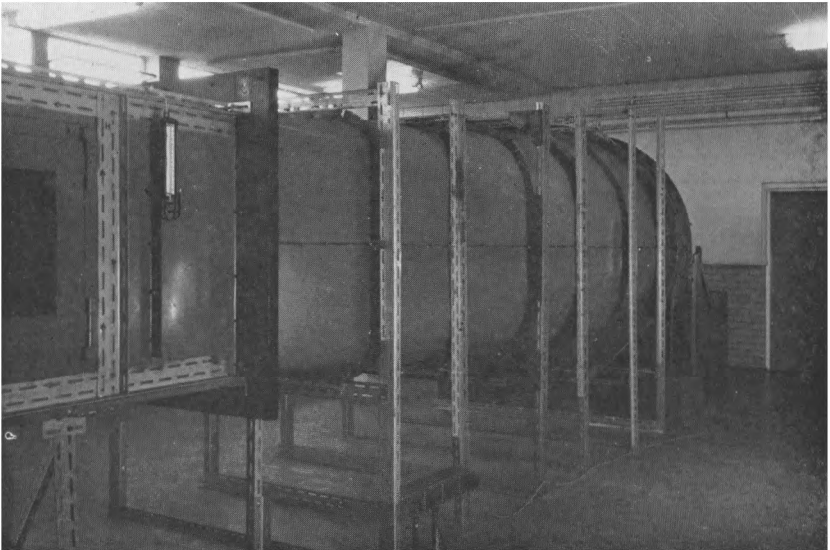
By G. E. W. HARTLEY, M.A.

Introduction.—Wind-tunnels are used in the Meteorological Office mainly for checking the performance and calibration of anemometers of various types. Some years ago, when the accepted standard recording anemometer was the pressure-tube anemograph which could be checked by a manometer test, there was no need for a wind-tunnel. Some cup contact and counter anemometers were calibrated in wind-tunnels at the National Physical Laboratory (NPL), and other anemometers of the same type were assumed to be correct



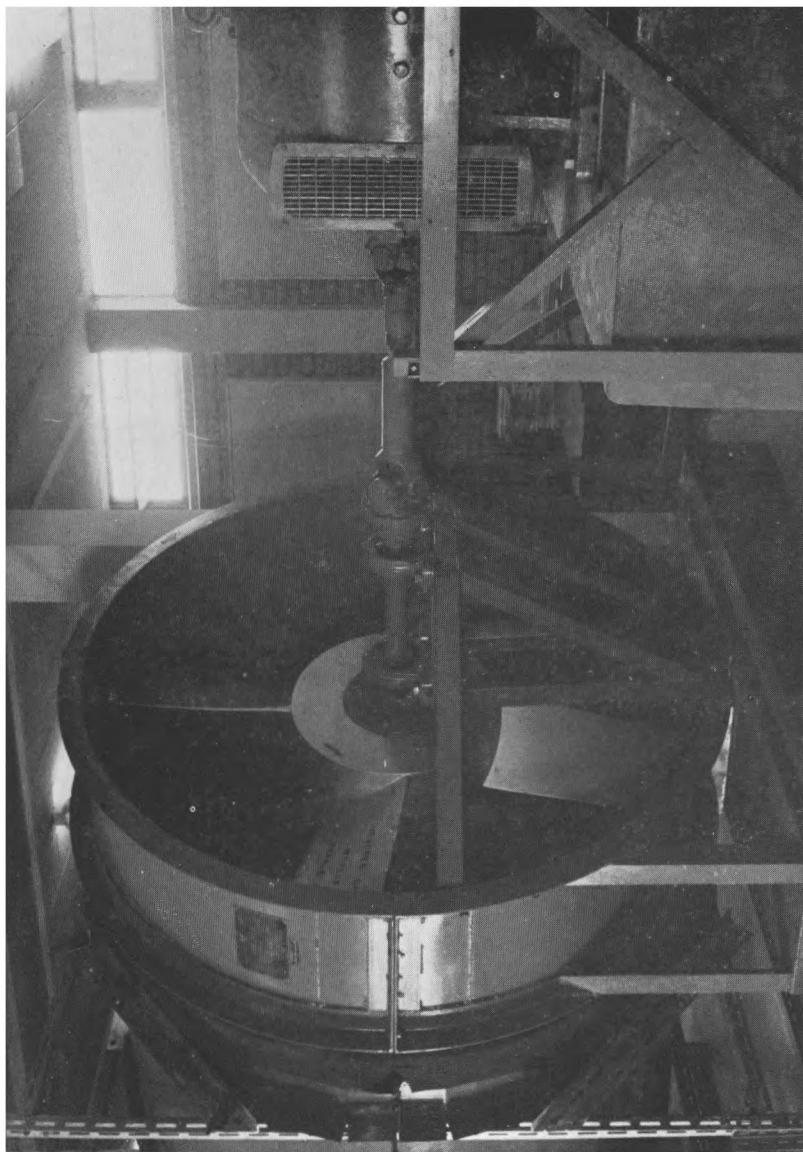
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PLATE I—TUNNEL ENTRANCE AND HONEYCOMB
See page 146.



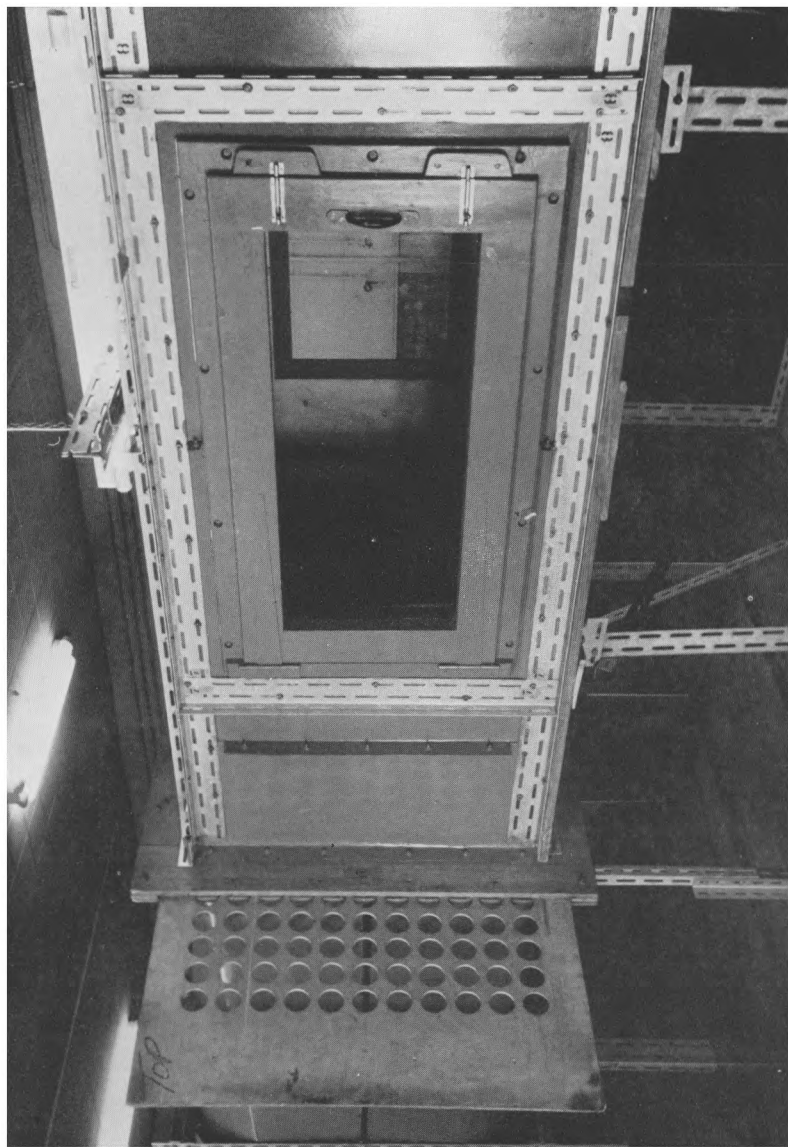
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**PLATE II—WIND-TUNNEL, SHOWING CONSTRUCTION OF EXPANDING SECTION
BETWEEN WORKING SECTION AND FAN**
See page 146.



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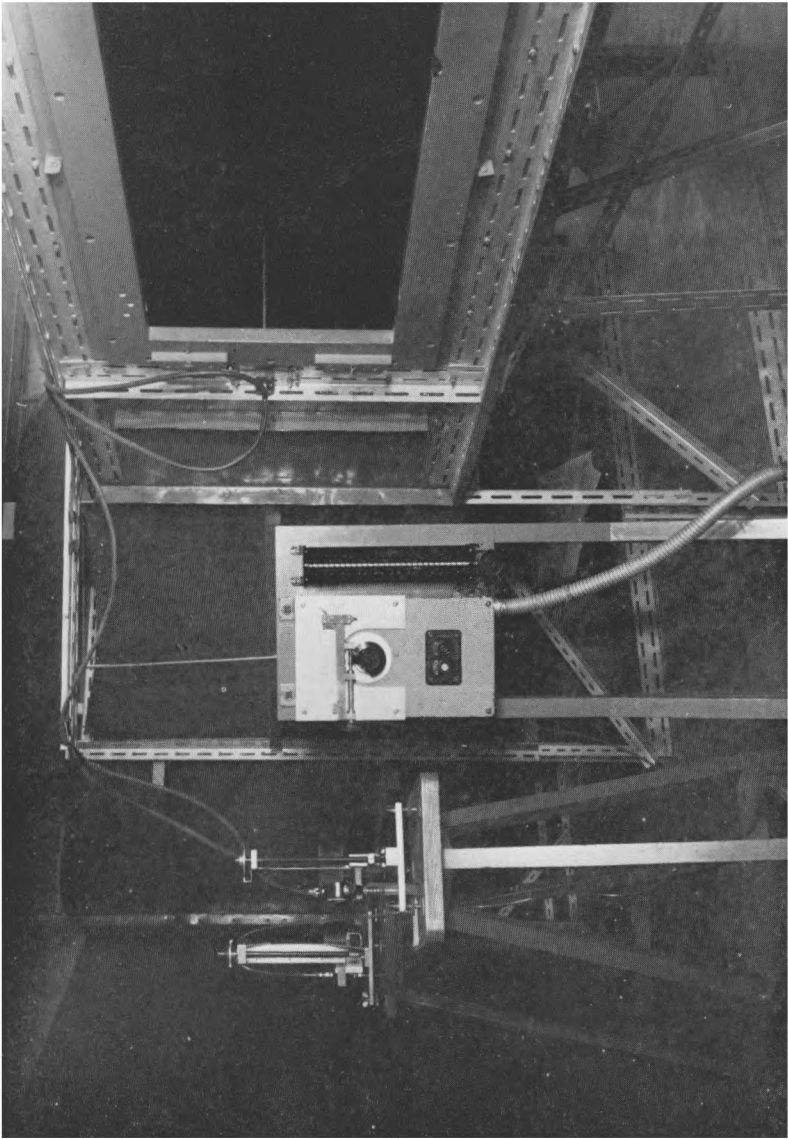
PLATE III—WIND-TUNNEL FAN, DRIVE SHAFT, AND MOTOR
See page 146.



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PLATE IV—WIND-TUNNEL WORKING SECTION SHOWING DOOR, AND GRID FOR
OBTAINING LOW SPEEDS PARTLY INSERTED
See page 146.

To face page 145



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PLATE V—WIND-TUNNEL MOTOR CONTROL PANEL, PITOT-STATIC TUBE AND
MANOMETER
See page 148.

if they passed a spinning test and if their dimensions agreed with the drawings. When the cup generator anemometer was introduced as standard Meteorological Office equipment it became necessary to carry out calibration tests on all cup anemometers ; the NPL was unable to undertake this work other than an occasional test for some special reason and so it became necessary to have a wind-tunnel as part of Meteorological Office test equipment.

Arrangements at Stonehouse.—

First wind-tunnel.—The first wind-tunnel used in the Meteorological Office was made in 1942 when part of the Office was in Stonehouse, Gloucestershire. It was a rather crude hardboard and wood structure with a working section $2\frac{1}{2}$ ft square and 4 ft long, and a contraction ratio of 4:1; it had a closed working section, and the flow was straight through the tunnel with a return flow around the tunnel room. It had a 10-h.p. constant-speed a.c. motor with a variable-diameter pulley and belt drive to a 4-bladed fan. The tunnel and fan were made in the Meteorological Office workshop ; the motor and variable-speed gear were supplied by an outside firm.

The speed range was about 13 to 40 miles per hour and lower speeds were obtained by inserting grids with evenly-spaced holes downstream of the working section. Speed measurements were made by connecting suction holes in the walls of the contraction upstream of the working section to a sloping-tube liquid manometer.

With this tunnel it was difficult to measure absolute speed in the tunnel, but anemometers of known types could have their calibration checked. It was necessary that one of the type had a known performance (for example by calibration at NPL). The anemometer of known performance was then available to calibrate the manometer, which could then be used as a standard of reference to check the calibrations of other anemometers of the same type.

Second wind-tunnel.—During 1943–44 a second wind-tunnel was designed and made with a view to obtaining higher speeds. This was an open-jet closed return-flow tunnel with a jet 18 inches in diameter, of similar design to the Royal Aircraft Establishment (RAE) 5ft open-jet tunnel,¹ but reduced in size.

This tunnel had a 9-h.p. movable-brush variable-speed a.c. motor with a speed range of 0–3000 r.p.m., driving a 6-bladed wooden fan. Speeds up to 80 miles per hour were obtainable but the distribution of wind speed in the jet was uneven. Though not large enough to calibrate standard cup anemometers it was useful for examining their performance at higher speeds ; and was used for calibration of hand anemometers, thermometer lag tests, radio-sonde windmill tests and other experimental work. It could be fitted with a means of raising the temperature inside.

This tunnel is still in use but when it was moved to Bracknell it was increased in length to give a larger contraction ratio, and fitted with a honeycomb structure upstream of the jet. This improved the flow pattern in the jet but reduced the maximum speed to about 70 miles per hour.

Arrangements at Harrow.—When the Meteorological Office moved from Stonehouse to Harrow both tunnels were brought and set up close together in the sub-basement two floors below ground, where their noise caused no inconvenience. They were so sited that the variable-speed motor

could be used to drive either tunnel by changing the belt drive from one to the other ; this gave the large tunnel a more easily controlled and infinitely variable speed range.

Third wind-tunnel.—In 1949, the design of a larger and more efficient tunnel was considered ; and after consultation with NPL, RAE, and other wind-tunnel users it was decided to make a tunnel with a working section $4\frac{1}{2}$ ft wide by 3 ft high capable of speeds up to 100 knots.

This size of working section was not as large as could be desired, but was the largest which could be accommodated in the space available. There was considerable height limitation and because of this the entrance to the honeycomb section of the tunnel was faired to the floor and ceiling so that the air flowed round the sides of the entrance into the mouth of the tunnel. This wind-tunnel operated at Harrow from 1952 to 1960. When the tunnel was moved to Bracknell it was set 1 ft higher and modified so that air entered from above as well as from both sides. This had no adverse effect on the flow pattern.

Arrangements at Bracknell.—The second and third wind-tunnels were brought to Bracknell in 1960. The general design of the large tunnel as installed at Bracknell is shown in Figure 1. It has the following principal dimensions : tunnel entrance 9 ft wide by 6 ft high with faired entry curves and honeycomb (see Plate I) ; a parallel-sided section 9 ft by 6 ft by 4 ft long ; a contraction 12 ft long changing the section to $4\frac{1}{2}$ ft wide by 3 ft high ; a working section $4\frac{1}{2}$ ft wide and 3 ft high and 8 ft long ; an expanding section 15 ft long changing to a 24-sided regular polygonal section 6 ft $\frac{1}{2}$ inch across opposite flats (see Plate II).

A 4-bladed wooden fan (see Plate III) revolving in a metal ring flexibly connected to the end of the tunnel is directly driven by a d.c. electric motor.

The methods and materials of construction of the tunnel were dictated by the availability of men and materials at the time. It was easier to obtain sheet steel and slotted angle than to obtain wood and there were a number of metal workers available and only one carpenter. Furthermore it was known that a move from Harrow would be made quite soon after completion of the tunnel, and so it was designed to be made in fairly small sections which could be prepared in the workshop, assembled in the tunnel room and subsequently taken apart again for moving.

The main skin of the tunnel is made from 21 s.w.g. mild steel sheet in sections cut from sheets 6 ft by 3 ft. Each piece has bent-over flanges with bolt-holes for bolting to adjoining pieces, the joints being sealed on the inside by adhesive tape. The skin is supported at intervals by frames made from slotted angle (see Plate II). Where there are curves in the contraction section the steel sheet is screwed to wooden frames of the correct contour.

The working section has a floor of 1-inch thick wood with $\frac{1}{2}$ -inch hardboard above ; its sides consist of hinged doors with $\frac{1}{4}$ -inch thick clear plastic window panels (see Plate IV) ; and there are clear plastic panels in the roof of the working section for illumination.

In the centre of the floor of the working section there is a hole and means of fixing in it bosses of various sizes to hold pillars on which are mounted instruments for test.

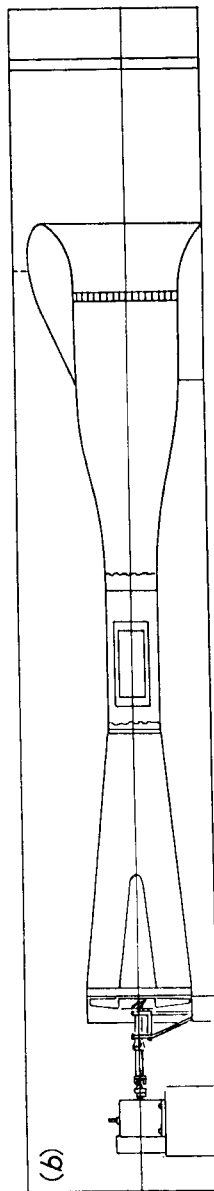
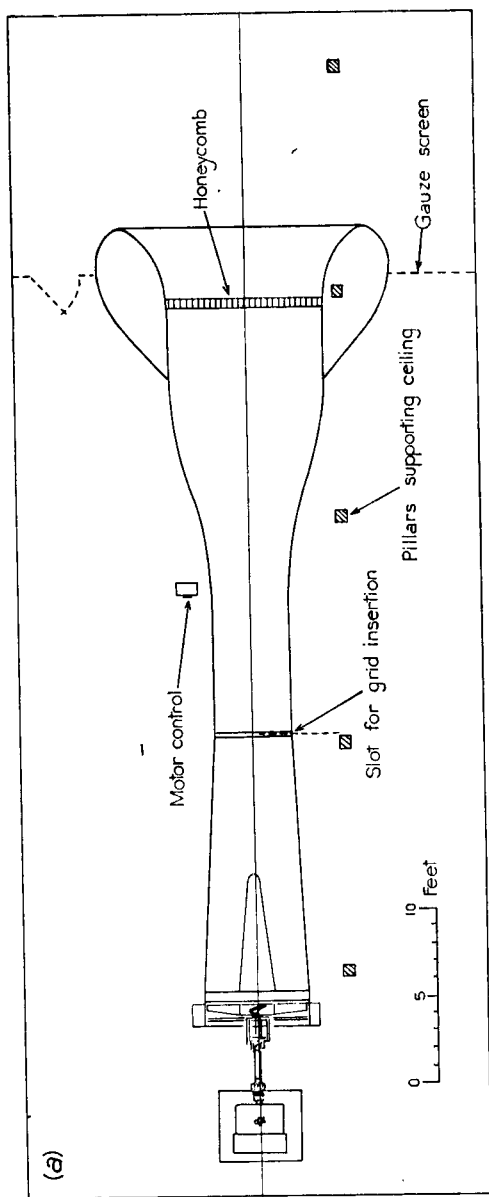


FIGURE I—WIND-TUNNEL AT BRACKNELL

- (a) Plan view
(b) Side elevation

At the fan end of the working section there is a wire guard to catch anything which breaks loose, and a wooden frame into which grids, consisting of plywood sheets with evenly-spaced round holes (Plate IV), can be fixed for obtaining low speeds in the tunnel without getting the uneven flow which results from running the fan very slowly. When the grids are not needed a plywood sheet with an opening $4\frac{1}{2}$ ft by 3 ft is fixed in the frame.

The fan boss is 25 inches in diameter and a tapered fairing is fixed in the centre of the tunnel to lead the air-flow smoothly up and past the fan boss ; the fairing is supported by rods in tension fixed to two of the frames which form part of the tunnel structure.

The entrance to the tunnel (see Plate I) is 9 ft wide by 6 ft high and has a honeycomb wall made of a resin-impregnated paper with a honeycomb structure of $\frac{3}{8}$ -inch mesh supplied in blocks 3 ft by 1 ft by 6 inches thick. This wall is glued in place and is prevented from being drawn into the tunnel by wires across the tunnel on the fan side of the wall.

Beyond the honeycomb and a short rectangular section the tunnel is contracted by suitable smooth curves (see Figure 2) until it is $4\frac{1}{2}$ ft wide by 3 ft high at the beginning of the working section, giving a contraction ratio of 4:1. Four flush suction holes with external connections for piping are made in the walls of the contraction about 3 ft upstream of the working section. The pipes are connected to a common pipe which can be connected to the suction side of a manometer. This pipe can be seen in Plate V behind and in line with the middle of the motor control panel. A pitot-static tube is mounted near the upstream end of the working section, projecting 1 ft into the tunnel at a height of $1\frac{1}{2}$ ft above the floor of the working section. The two outlets from the pitot-static tube are connected to the pressure and suction sides of a sensitive water manometer which can be read to 0.001 inches of water. (See Plate V which shows two such manometers, and the pitot-static tube inside the open door of the working section.)

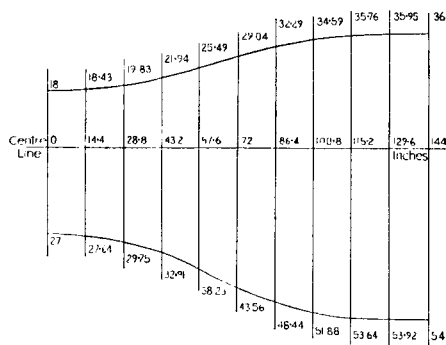


FIGURE 2—DISTANCES FROM CENTRE LINE IN CONTRACTION OF WIND-TUNNEL BEYOND THE HONEYCOMB

The fan is wooden, 6 ft in diameter, 4-bladed, and coupled directly through a short shaft with two universal joints to a 125 h.p. compound wound d.c. electric motor, which at full load takes 219 amps at 460 volts, maximum speed 1440 r.p.m. (Plate III). The power for the motor is supplied from a 400-volt 3-phase a.c. supply by a suitable transformer and mercury-arc

rectifiers. Motor speed control is by a potentiometer knob (Plate V) which can be turned directly, or by means of a worm and wheel to give fine control. This was found to be not quite sensitive enough, and an additional sliding resistance which adjusts the field current of the motor was added to give a finer speed adjustment (see Plate V on the right of the control panel).

To start the tunnel, the rectifier-transformer is first connected to 400-volt a.c. mains. Then the speed control knob is turned as far as it will go anti-clockwise, and the starter button pressed. The speed control knob is then turned clockwise to start the fan, and to increase speed. The slider of the field current control is moved up to increase speed. The manometer (Plate V) is of the type described on pages 255-6 of the 'Handbook of Meteorological Instruments',² but with the sloping-tube indicator replaced by another form of indicator in which the liquid level is adjusted until a pointer near the liquid surface and its reflection appear to meet (or just not to meet, if preferred). This form of indicator is more sensitive than a liquid meniscus in a sloping tube with a fiducial mark. The working section of the tunnel was explored by traversing a pitot-static tube, and the speed distribution is shown in Figure 3.

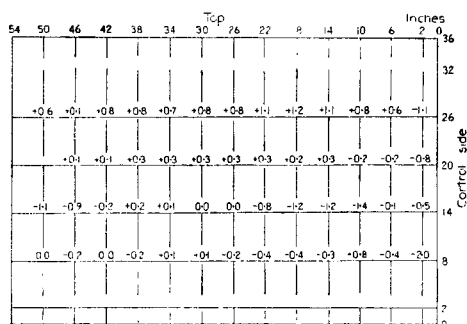


FIGURE 3—DISTRIBUTION OF WIND SPEED AT MIDDLE WORKING SECTION OF WIND-TUNNEL

Figures show percentage differences from mean speed (55.5 ft/s.).

Use of wind-tunnel for anemometer calibration. — As stated in the account of its design, the tunnel is not large enough for absolute calibration of anemometers of normal size. If the projected area of cross-section of the anemometer is an appreciable fraction of the cross-sectional area of the working section, the local speed at the anemometer position will be higher than the mean speed in the working section because the anemometer exercises a blocking effect, whose magnitude cannot easily be determined.

Several standard cup anemometers have therefore been calibrated at NPL in a wind-tunnel large enough (working section 9 ft by 7 ft) for the blockage effect to be neglected ; and one of these anemometers is then placed in the Meteorological Office wind-tunnel and used as a substandard in order to get a relation between wind speed (as obtained from the cup r.p.m.) and tunnel pitot-static pressure. From this a table of manometer readings corresponding to various wind speeds is drawn up, and subsequently these readings are used to set the tunnel speeds when testing other anemometers of the same type. Specimens of generator, counter and contact anemometers have been tested at NPL, and tables of manometer readings prepared for each type.

For smaller anemometers such as hand anemometers, fan air-meters, and small sensitive cup anemometers, direct pitot-static pressure readings are used so that these anemometers can be calibrated absolutely.

Other uses of wind-tunnels.—In conjunction with a smoke generating apparatus the tunnel has been used to explore the wind flow past scale models of various objects, such as the Rock of Gibraltar (aircraft runway wind flow investigation) and the Meteorological Office building, Bracknell (investigation of window breakages under certain wind conditions). Using streamer technique an investigation has been made of the wind flow over Ocean Weather Ships.

It is however possible that these tests are adversely affected by the fact that the wind flow is constrained by the tunnel walls, and probably an open-jet tunnel is more suitable for such work.

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SYNOPTIC DISTURBANCES CAUSING RAINY PERIODS ALONG THE EAST AFRICAN COAST

By F. E. LUMB

Introduction.—In April the Kenya coast (for map of area see Figure 1) partakes of the rainy nature of this month over Kenya as a whole (see Figure 2(a)) but in May when the rainfall inland is decreasing, by contrast on the coast it increases and May is on the average by far the wettest month of the

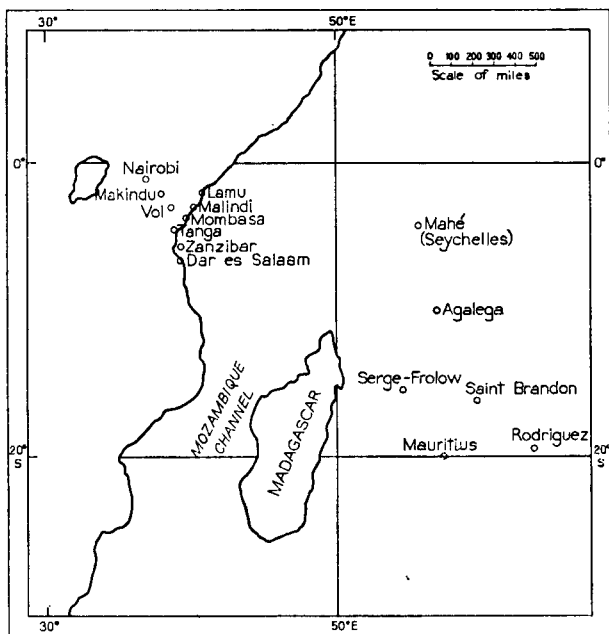
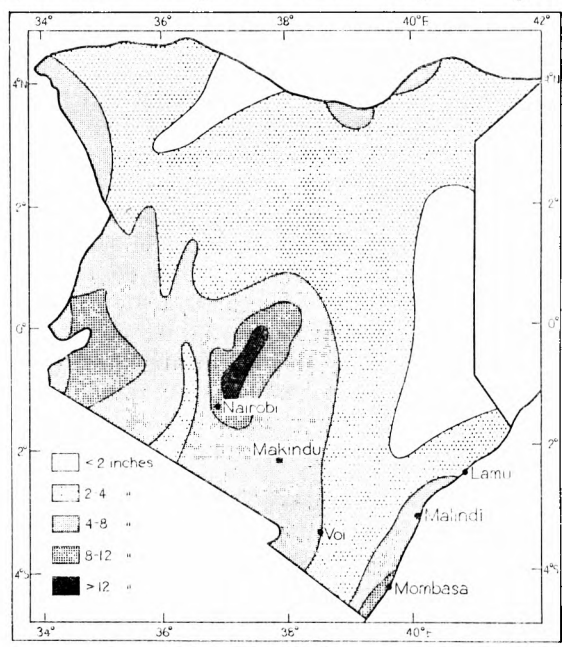
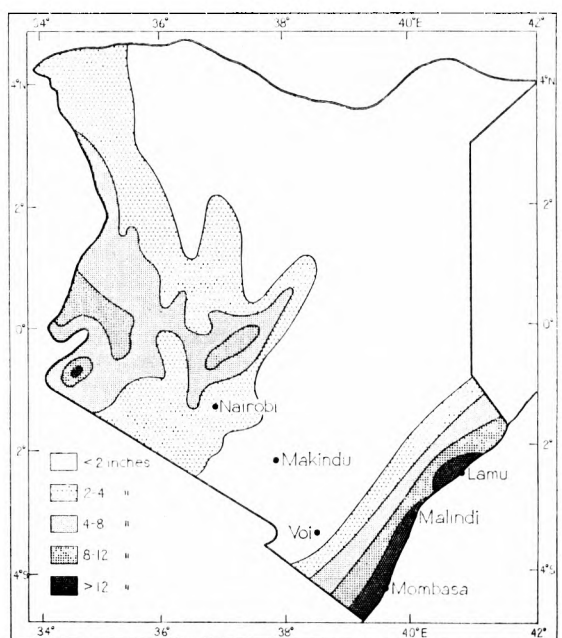


FIGURE 1—MAP OF THE AREA

year, a narrow coastal strip having an average rainfall in excess of 12 inches (see Figure 2(b)). Also during the four months June–September there is a



(a) April



(b) May

FIGURE 2—RAINFALL OVER KENYA

rapid decrease of rainfall from the coast inland, though the rainfall along the coast itself is much less than in May, and decreases from month to month. During the whole of this period the coast of East Africa is under the influence of the south-east monsoon, and the air arriving at the coast has been slowly heated from below during its passage across the Indian Ocean. Hence one might suppose that the coastal belt of high rainfall can be explained by the advection of showers from the Indian Ocean. However, this proves to be an unsatisfactory explanation. A study of the rainfall records from the coastal stations shows that during the months May–September wet spells alternate with dry spells. Showers do occur on many days, but are often only light, and make only a small contribution to the total rainfall. Thus in May 1964 at Malindi measurable rain was recorded on 22 days, with a total fall of 427 mm, but 367 mm (86 per cent of the total) fell during three rainy spells, (7 days altogether). In July 1964 at Lamu rain fell on 16 days, giving a total fall of 155 mm, but 65 per cent of this fell during three rainy spells (4 days altogether). Therefore in order to explain the rainfall at the coast it is necessary to recognize those synoptic disturbances which cause a marked intensification of precipitation over periods of the order of 1 to 2 days.

Basic explanation.—According to Voiron,¹ some of the rainy periods at the East African coast during the months May–September are caused by wave-like perturbations within the easterly current on the north side of the sub tropical high-pressure belt. In the opinion of the author the majority of the rainy periods are associated with the remnants of cold fronts which have intruded into the tropics. Their influence is usually exerted indirectly, confirming the opinion expressed by Forsdyke² that ‘the polar front has little direct significance on moving into the tropics, but it has an indirect significance, in that it may be associated with a surge of cold air which may give rise to convergence and therefore to disturbed weather’.

It is only on the rare occasions when there is an unusually strong incursion of cold air from the south that a cold front can be followed on the surface synoptic charts to the vicinity of the equator. It is more usual for cold fronts to advance west-north-westwards towards the East African coast on the north side of a high cell to the south of Mauritius. (The generalized synoptic maps given by Forsdyke show how this synoptic situation develops.) However, because of the mountainous character of Madagascar, the weak temperature contrast across the northern part of the fronts, and the complete absence of regular observations immediately north and north-west of Madagascar, in many cases it becomes very difficult to position the fronts once their southern part has reached the coast of Madagascar, and their influence on the weather along the coast of East Africa is exerted indirectly, by the generation of a weak ridge of high pressure extending north-north-east from Madagascar. As a concomitant feature a weak trough develops between the East African coast and the Seychelles. See Figure 7 for an example which will be discussed in more detail later. Convergence into the trough, within the convectively unstable air mass, results in the formation of an extensive area of cumulonimbus and altostratus clouds. Probably above the surface trough is a thermal ridge or high, as described by Lockwood,³ but owing to the small changes of height involved, and the absence of upper air data in the immediate vicinity of the trough it is impossible to confirm this.

Once formed, the trough moves slowly towards the coast of East Africa, but it weakens as it approaches the ridge of high pressure which is a permanent feature of the pressure pattern at the surface and 850 mb levels, during the months May to September. The ridge axis lies just inland from the coast at the surface and about 200 miles inland at 850 mb (see surface and 850 mb charts in the atlas 'The climate of Africa'⁴).

Why is the average rainfall along the coast in May much heavier than in the following months? Probably the main factor is that during May the surface equatorial trough is a major synoptic feature over the Indian Ocean just south of the equator, and is sharpened off the Kenya coast by the presence of a surface high over the cold area between the Gulf of Aden and the north-west Arabian Sea. Thus the overall synoptic pattern is favourable for convergence. As the south-west monsoon grows in intensity north of the equator, the trough degenerates into a minor feature, and the surface high is destroyed by the growing cyclonic circulation around the Arabian thermal low (compare sea-level pressure pattern in April and July in the above-mentioned atlas). Also the sea surface temperature is falling gradually from May onwards, so that conditions are more favourable for vigorous convection in May than in the following months.

In the remainder of this article, three synoptic examples will be presented. The first is an example of the rather rare case of a cold front having a direct influence on the weather along the East African coast. The second and third (one straightforward, the other more difficult) illustrate the more usual state of affairs when the influence of the cold front is exerted indirectly.

Example of cold front penetrating to the vicinity of the equator.—

Figure 3 shows the synoptic situation at 0600 GMT on 2 June 1965. The low

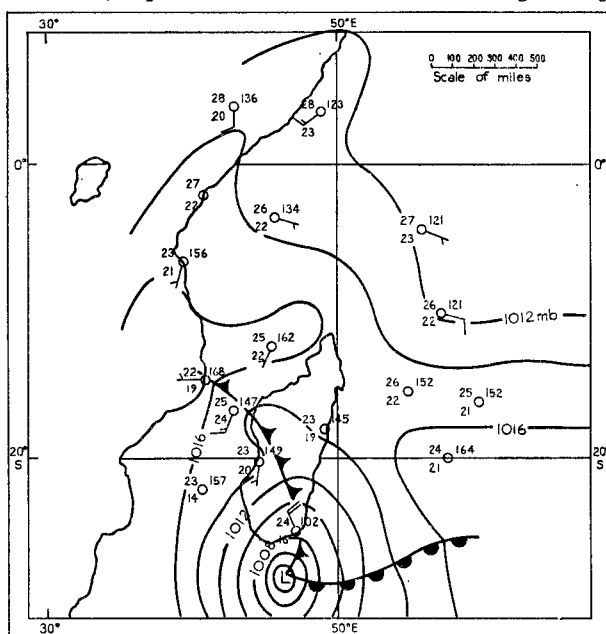


FIGURE 3—SYNOPTIC SITUATION AT 0600 GMT ON 2 JUNE 1965

In Figures 3, 4, 6, 7 and 9, temperature, dew-point, pressure and wind are plotted in the conventional manner and in Figures 7 and 9 24-hour pressure tendencies are included.

just to the south of Madagascar deepened rapidly during the next 48 hours and moved slowly east-south-east. By 0600 GMT on 4 June (see Figure 4) cold air has clearly penetrated right through the Mozambique Channel. The approximate position of the cold front is as shown in Figure 4 ; its passage was marked by a thunderstorm at Lamu. There was a large surge of pressure behind the cold front, the 1018 mb isobar having advanced with it.

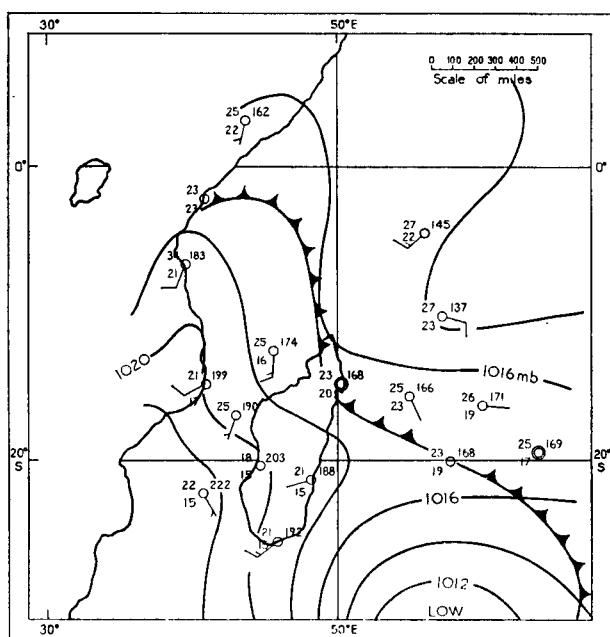


FIGURE 4—SYNOPTIC SITUATION AT 0600 GMT ON 4 JUNE 1965
Note: the temperature at Dar es Salaam should read 24°C.

The difference between the two air masses is revealed by comparing the Dar es Salaam tephigrams of 1200 GMT on 3 and 5 June (see Figure 5). The dry-bulb and dew-point temperatures fell at all heights up to 750 mb.

Rainfall amounts associated with the cold front were much larger in the north than in the south (e.g. 56 mm at Lamu, 14 at Mombasa, 1 at Dar es Salaam). This is probably explained by the fact that the predominantly southerly winds (up to 700 mb) in which the front was embedded have a rapidly increasing fetch over the sea northwards of Mombasa.

A straightforward example of trough development due to the approach of colder air.—A fairly straightforward example of trough development caused by the approach of a cold front resulted in a rainy spell on the Kenya coast on 26, 27 and 28 May 1965. At 0600 GMT on 24 May (see Figure 6) colder air has passed Saint Brandon and Mauritius and is moving west-north-west (dew-points have fallen 6°C at Saint Brandon and 3°C at Mauritius since 0600 GMT on the 23rd). By 0600 GMT on the 25th (see Figure 7) the colder air has passed Serge-Frolow and Agalega and has probably reached the Seychelles. However, the precise position of the cold front is of less importance for events on the East African coast than the effect

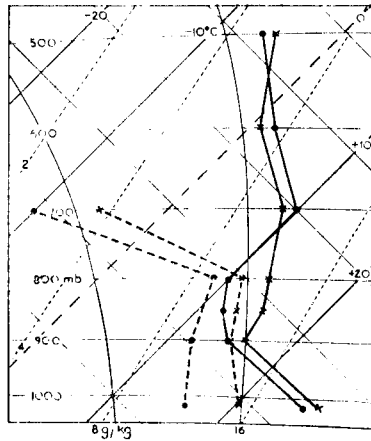


FIGURE 5—UPPER AIR ASCENT AT DAR ES SALAAM AT 1200 GMT ON 3 AND 5 JUNE 1965

1200 GMT, 3 June 1965
 x—x Dry-bulb temperature
 x—x Dew-point

1200 GMT, 5 June 1965
 ···· Dry-bulb temperature
 ···· Dew-point

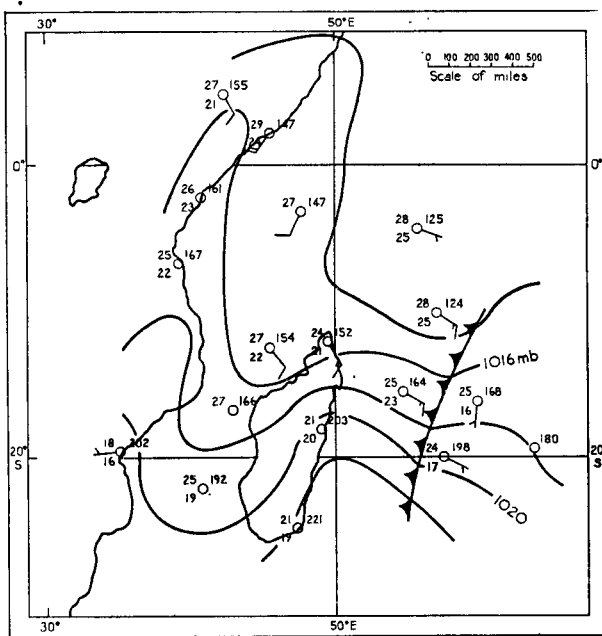


FIGURE 6—SYNOPTIC SITUATION AT 0600 GMT ON 24 MAY 1965

on the surface pressure field of the advance of the colder air from the east-south-east. Comparing Figures 6 and 7, it can be seen that the effect is to build over the east coast of Madagascar a ridge which extends northwards to about latitude 5°S (note the isallobars in Figure 7). Downstream the ship's report at 09.1°S , 44.6°E (see Figure 7) confirms that a trough has developed between the East African coast and the Seychelles.

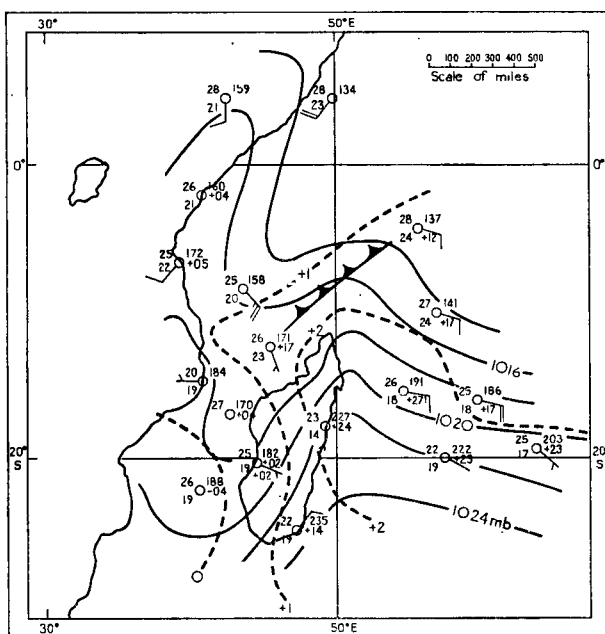


FIGURE 7—SYNOPTIC SITUATION AT 0600 GMT ON 25 MAY 1965

----- Isallobars at intervals of 1 mb (for 24 hours)

It is interesting to compare the winds up to 400 mb at Dar es Salaam at 1200 GMT on 25th and 26th (see Table I).

TABLE I—SURFACE AND UPPER WINDS AT DAR ES SALAAM, 25–26 MAY 1965

Date	Surface	900mb	850mb	800mb	700mb	600mb	500mb	400mb
					<i>degrees/knots</i>			
25 May 1965	160/13	163/13	163/12	163/18	151/09	259/11	022/14	019/09
26 May 1965	130/07	112/21	112/21	109/21	121/18	103/12	085/12	067/06

With some strengthening of the subtropical high-pressure belt (at 700 mb) extending east-west approximately along latitude 20°S, easterly winds with very little shear had become established between 900 and 500 mb by 1200 GMT on the 26th.

The sequence of events leading to rain at the coast therefore probably was as follows : between 24 and 25 May a low-level trough developed between the East African coast and the Seychelles ; convergence into the trough resulted in an extensive area of cumulonimbus and altostratus clouds ; and between the 25th and 26th the winds between 900 and 500 mb became generally easterly, and carried the rain-bearing clouds westward to the coast.

Rain reached the coast early on the 26th and spread inland as far as Nairobi during the next 24 hours, but as usual in this type of situation, the amounts of rain decreased rapidly inland from the Kenya coast, e.g. up to 0600 GMT 28 May the following amounts were reported :

Mombasa	75 mm	Voi	52 mm
Makindu	16 mm	Nairobi	2 mm

It is at first sight surprising that the rainfall should decrease so quickly inland, especially since the westward flowing air is subject to orographic uplift of some 2000 metres until reaching the Rift Valley (about 300 miles inland). However the orographic effect is counteracted by divergence and

subsidence in the lower troposphere associated with the ridge of high pressure which has already been mentioned as being a permanent feature of the pressure pattern at the surface and at 850 mb inland from the coast during the months May to September. Along and near the coast the rainfall is probably greatly augmented by convection within the rain-cooled air. Figure 8 is the upper air temperature sounding for Dar es Salaam at 1200 GMT on 28 May at the end of the rainy spell. The sounding indicates that the main cloud mass extended up to 500 mb but bearing in mind that the sea temperature off the coast was around 29°C it is clear that cumulonimbus clouds could develop with tops up to at least 400 mb.

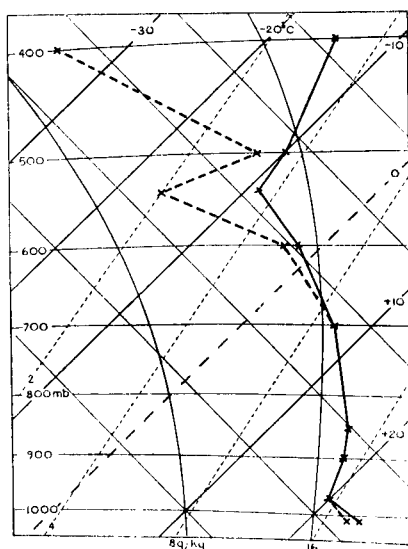


FIGURE 8—UPPER AIR ASCENT AT DAR ES SALAAM AT 1200 GMT ON 28 MAY 1965

x — x Dry-bulb temperature
x - - x Dew-point

A difficult example of trough development due to the approach of colder air.—A less clear-cut example gave the heavy rains on the coast of Kenya during 27 and 28 May 1964. (During the 48 hours ending 0600 GMT, 28 May, Mombasa recorded 95 mm and Lamu 25.) Figure 9 shows the synoptic chart for 0600 GMT, 25 May 1964. The essential features are the same as for 0600 GMT, 25 May 1965 (see Figure 7) but less well marked. Somewhat colder air has advanced west-north-west between Madagascar and the Seychelles, but has given only small falls of dew-point (1°C at Mahé, no change at Agalega, and 2°C at Serge-Frolow and Saint Brandon during the last 24 hours). As revealed by the 24-hour isallobars, there has been some ridge development from north Madagascar to the Seychelles, and also along the coast of Tanzania. (The latter was probably associated with a surge of pressure over a wide area to the south, as a vigorous cold front away to the south was followed by an intensifying anticyclone, which at 0600 GMT 26 May was centred at 35°S, 32°E.)

Trough development between the coast and the Seychelles can be expected as a consequence of the rising pressure tendencies on either side. The ship

at 04.5°S, 46.2°E (see Figure 9) gave a surface wind of 200° 18 knots and reported rain in sight and thick layers of medium cloud. This combination of wind, weather and cloud is strong evidence for the existence of a developing trough to the south-east of the ship. Rain started at the coast on the morning of the 27th, and lasted until almost midday on the 28th.

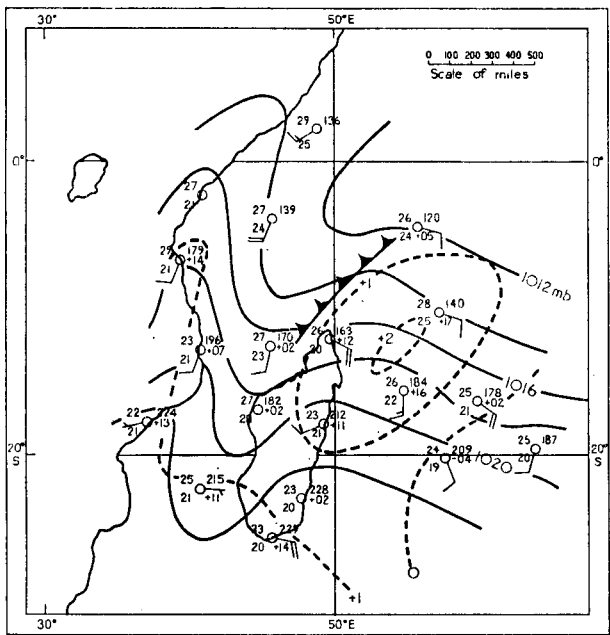


FIGURE 9—SYNOPTIC SITUATION AT 0600 GMT ON 26 MAY 1965
 - - - - Isallobars at intervals of 1 mb (for 24 hours)

It is interesting to examine the upper winds at Dar es Salaam at 1200 GMT on 27 and 28 May 1964 (see Table II) and to compare them with those for the May 1965 example already considered.

TABLE II—SURFACE AND UPPER WINDS AT DAR ES SALAAM, 27–28 MAY 1964

Date	Surface	900mb	850mb	800mb	700mb	600mb	500mb	400mb
				<i>degrees/knots</i>				
27 May 1964	181/12	175/26	166/29	160/33	109/21	109/21	088/12	015/16
28 May 1964	160/13	160/23	163/24	133/18	097/18	097/18	028/06	307/14

It is seen from Table II that the winds up to 800 mb retained a large southerly component, easterly winds being established only from 700 mb upwards. This resulted in a change in the distribution of the rainfall as compared with May 1965. Only cloud at 700 mb and above was advected westwards inland so that the rainfall inland was less than in May 1965. Voi reported only 1 mm (as compared with 52 mm in 1965) and Makindu only 2 mm (as compared with 16).

The need for cloud photographs from satellites.—These examples clearly illustrate the difficulty in forecasting rainy periods along the coast of East Africa. The surface troughs are small-scale features on a synoptic scale, and some are initiated by the approach of weak cold fronts which are

very difficult to detect from surface synoptic reports. On occasions when the development of a trough is suspected, it is a matter of chance whether a ship reports in the right place and at the right time to give direct evidence of the trough's existence.

The regular receipt of cloud photographs over the Indian Ocean from meteorological satellites by automatic picture transmission (APT) should greatly facilitate the forecasting of the onset of rainy spells along the coast of East Africa. The East African Meteorological Department has already constructed and installed APT receiving equipment, so as to make full use of the APT facilities of the operational satellite system.

Acknowledgement.—The author wishes to thank Mr. B. W. Thompson and Dr. H. W. Sansom for their very helpful comments. This paper is published by permission of the Director of the East African Meteorological Department.

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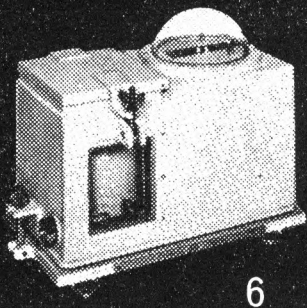
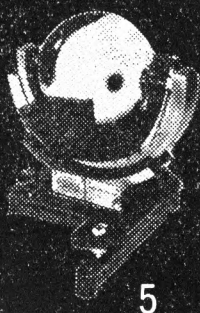
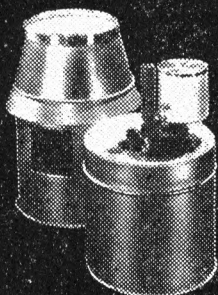
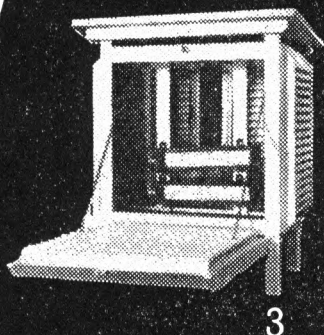
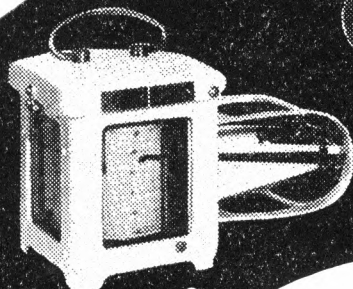
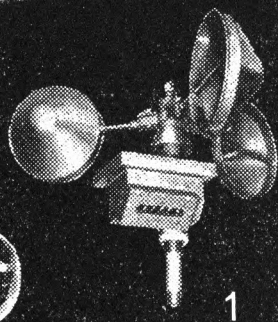
REVIEW

Cloud physics and cloud seeding by Louis J. Battan. 4 $\frac{3}{4}$ in \times 7 $\frac{1}{2}$ in, pp. xii + 144, illus., Heinemann Educational Books Ltd., 48 Charles St., London, W1. Price : 12s. 6d.

Books in the Science Study Series are intended to provide a survey of a particular field in physics and to put it within the grasp of the school physics student and the layman. This book in the series covers the physics of water droplets and ice crystals and the processes they undergo in clouds. First there is a discussion of the beginnings of condensation on nuclei and the subsequent growth of cloud particles into rain, snow and hail. In later chapters Dr. Battan discusses the scientific basis of attempts to modify clouds, stimulate rainfall and interfere with hailstorms.

In covering his subject simply Dr. Battan has mostly managed to avoid misleading over-generalizations. This is probably least true in places where the micro-physics of cloud particles is related to larger-scale meteorology and the laymen for whom the book is intended would do well to read a simple, modern, meteorological text first. They would not then, for example, be led astray by the cross-sections through a warm front and Ludlam's model of a severe storm, which make both systems appear the size of an ordinary shower. In the whole book, however, there are only a few matters of fact one would wish to question and while it lacks the authority of a textbook, this little book succeeds in being the most easily read, reasonably comprehensive, book on cloud physics now available. It can be recommended as interesting reading for those for whom it was intended and for meteorological observers. It is well produced.

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CONTENTS

	<i>Page</i>
A regression technique for objective forecasts at 300 millibars. A. Woodroffe	129
Wind-tunnels in the Meteorological Office. G. E. W. Hartley	144
Synoptic disturbances causing rainy periods along the East African coast. F. E. Lumb	150
Review	
Cloud physics and cloud seeding. L. J. Battan. S. G. Cornford	159

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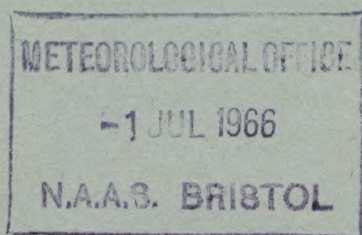
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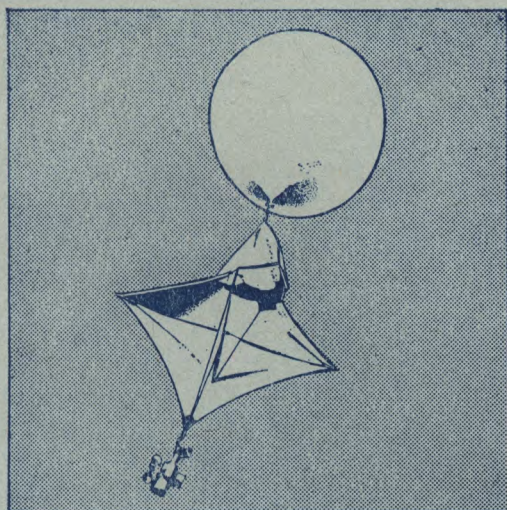
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Scientific Paper No. 21

Estimation of rainfall using radar—a critical review

by T. W. Harrold, B.Sc., D.I.C.

This publication contains a critical review of the possibilities of using a weather radar to measure rainfall over an area, such as a river catchment, as it falls. Two methods are discussed.

By relating the power reflected from the rain to the rate of rainfall it is possible to estimate the rainfall amount, the probable error in such an estimate being 25 per cent. To achieve this accuracy a narrow beam width and a wavelength greater than 5 cm are necessary. In winter in the United Kingdom the error will be larger since the beam passes above the rain into snow at larger ranges. The circuitry required to provide automatic measurements is discussed.

An alternative method is to measure the attenuation of radiation, of wavelength about 1 cm, and to relate this to the rate of rainfall. Although theoretically more accurate, practical considerations, such as the size of a reflector required at larger ranges, make this a less satisfactory method of estimating rainfall compared with measuring the reflected power.

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THE METEOROLOGICAL MAGAZINE

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A RADIOMETER SONDE

By D. G. JAMES, D. W. S. LIMBERT and J. C. McDOUGALL

Summary.—A radiometer designed by Suomi and Kuhn¹ for use on balloons has been adapted to the requirements of the Meteorological Office radiosonde ground receiving equipment by the construction of a fully transistorized electronics package. Measurements of net radiation near the ground were compared with those made simultaneously with a Kew net flux radiometer. Systematic differences between these results led to a recomputation of an equivalent thermal conductivity through the instrument, the value obtained being significantly different from that given by Suomi and Kuhn. This difference is thought to be due to a change in instrument construction. Three flights of the radiometer are described and a short discussion of the results is presented.

Introduction.—In attempting to produce a numerical forecast for periods in excess of 1 or 2 days, it is essential to know how and where heat is put into and taken from the atmosphere by non-adiabatic processes. Furthermore, since it is usual in these forecasts to divide the troposphere into several layers, it is necessary to obtain the rate of heating or cooling of each individual layer. In this paper we will be concerned only with the loss of heat by long-wave radiation from the atmosphere.

Measurement of net outgoing radiation is necessary since its calculation can only be obtained approximately even when all the radiating atmospheric constituents are known. A radiometer has been developed by Suomi and Kuhn¹ which is sufficiently light to be carried aloft by an ordinary radiosonde balloon, and sufficiently inexpensive to make regular daily soundings a practical proposition. Dr Kuhn was kind enough to present us with a dozen of his radiometers, and in this paper we describe the design and construction of an electronics package which allows us to use the Meteorological Office Cintel equipment to measure the appropriate variables of the radiometer. It should be remembered that the Suomi-Kuhn radiometer is a proven instrument, and has been flown many hundreds of times in the U.S.A. The accuracy of the measurements obtained there has been limited by the accuracy of the telemetry system of the American radiosonde (Bushnell and Suomi²), and so we have set ourselves to improve on this by obtaining an accuracy in temperature measurements of 0.1 degC. This is the bulk of the paper. We also present three test flights just to prove that the instrument behaved

satisfactorily, though we would not claim high accuracy for the results presented, since, for example, no allowance has been made for the lag of the instrument. But this is not a difficult problem.

We now feel that the radiometer and our electronics package will give accurate measurements of nocturnal rates of cooling over layers of the atmosphere of 100 mb or so, and could, for example, be used in determining the rate of cooling against height profile in large quasi-stationary anticyclones.

The Radiometer.—Only a brief description of the instrument is given here, a fuller description may be obtained from Suomi and Kuhn¹ or Suomi, Staley and Kuhn.³ The radiometer sonde is shown in Plate I.

Essentially the radiometer consists of two parallel sheets of mylar (strong plastic sheet) insulated from each other by thin layers of air and polystyrene and held in position by a circular polystyrene former (Figure 1). (Note that our diagram does not agree with that given by Suomi, Staley and Kuhn.³)

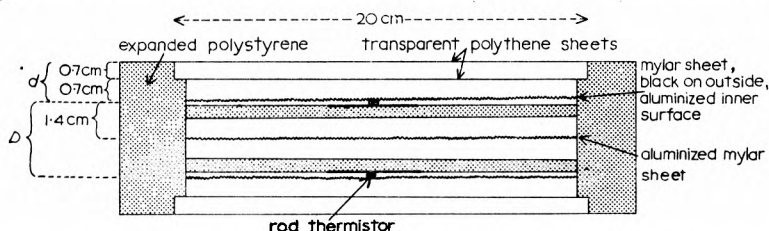


FIGURE 1—VERTICAL SECTION THROUGH RADIOMETER

The surfaces of the outward facing mylar sheets are black but the inward facing surfaces are aluminized as are both sides of another mylar sheet across the centre of the instrument. Convection at the black surfaces is reduced to a minimum by the use of two layers of thin transparent polythene sheet. The temperatures of the two black surfaces are measured by rod thermistors cemented directly beneath the mylar, and are calibrated — one spot temperature and resistance — by the manufacturer. At room temperature these resistances are of the order of 10 K ohms increasing exponentially to about 1 M ohms for temperatures in the region of -80°C , the sort of temperature expected at the top surface of the instrument in the stratosphere.

The temperatures of black surfaces are determined by :

- (i) The incoming long-wave radiation from the earth, clouds or sky modified by absorption and reflection at the polythene windows.
- (ii) The outgoing long-wave radiation from the black surfaces themselves also modified by the windows.
- (iii) Heat conducted through the polystyrene former to or from the environment, and also by the air from each black surface to its corresponding polythene shield.
- (iv) Heat conducted through the radiometer from one black surface to the other.
- (v) Heat transferred by convection inside the instrument and also from the black surfaces to the polythene sheets. These terms are small compared with the other variables influencing the heat balance according to Suomi, Staley and Kuhn.³

Following these authors the downward and upward streams of long-wave radiation (R_{\downarrow} and R_{\uparrow}) may be expressed as

$$R_{\downarrow} = \sigma T_t^4 + A(-C_i - C_t + \lambda \left(\frac{dT_t}{dt}\right) + E_t) \dots (1)$$

and $R_{\uparrow} = \sigma T_b^4 + A(C_i - C_b + \lambda \left(\frac{dT_b}{dt}\right) + E_b), \dots (2)$

where subscripts t and b refer to top and bottom black surfaces and $\frac{d}{dt}$ denotes differentiation with respect to time and

σ = Stefan-Boltzmann constant

T_t, T_b = temperatures of the top and bottom surfaces

A = constant depending on the absorptivity of the black mylar surface (0.85) and the reflectivity of the polythene sheets (0.16)

λ = constant depending on the thermal inertia of the surfaces

E_t, E_b = errors introduced by the various simplifying assumptions made

C_t = $k_t \frac{T_a - T_t}{d}$ and $C_b = k_b \frac{T_a - T_b}{d}$ = conduction terms from the black surfaces to air

and $C_i = k_i \frac{T_b - T_t}{D}$ = heat conducted between the surfaces, where

k_t, k_b and k_i are thermal conductivities, T_a = air temperature, d = distance from the black mylar surface to the outside polythene sheet and D = distance between the inner surfaces of the main mylar sheets.

The net flux of long-wave radiation R_n can now be obtained by simple subtraction.

Furthermore, rates of cooling over a layer p_1 to p_2 can be written as

$$\frac{dT}{dt} = \frac{-g \left((R_n)_2 - (R_n)_1 \right)}{c_p (p_2 - p_1)} \dots (3)$$

where p_2, p_1 are the pressures at top and bottom of the layer, $(R_n)_2, (R_n)_1$ are the corresponding net radiations, g is acceleration due to gravity and c_p is specific heat at constant pressure.

Near the ground the radiation terms and conduction terms are about equal in size in the expression for net radiation but at higher levels and certainly in the stratosphere the conduction terms become the greater by a factor of 3 or 4. The evaluation of k_t, k_b and k_i is thus of considerable importance. Suomi *et alii*³ suggest that the same value — namely the thermal conductivity of air at temperature $\frac{1}{2} (T_b + T_t)$ — be used for all three terms. However, with the variation in design of the instrument mentioned earlier there is some reason to doubt the validity of this assumption.

Some spot checks on the accuracy of the instrument at ground level were obtained by mounting it alongside a net flux radiometer at Kew Observatory and making simultaneous measurements of the temperatures of the top and bottom surfaces and of the net flux. The comparisons were performed on

two nights when the presence or absence of cloud cover was expected to give quite different results. Evaluation of the net radiation, as measured by the Suomi radiometer using the constants given in the 1958 paper,³ showed systematic differences from the readings of the Kew net flux radiometer. These differences could be explained by an error in k_i , the internal thermal conductivity. The instrument was sectioned—it was at this stage we discovered the change in design—and from accurate measurements of the thicknesses of the layers of air and polystyrene a new k_i was calculated for the appropriate temperature. Table I presents the results of the comparison using the new value of k_i .

TABLE I—COMPARISON OF KEW RADIOMETER WITH THE SUOMI-KUHN RADIO-METER USING A NEW VALUE FOR k_i

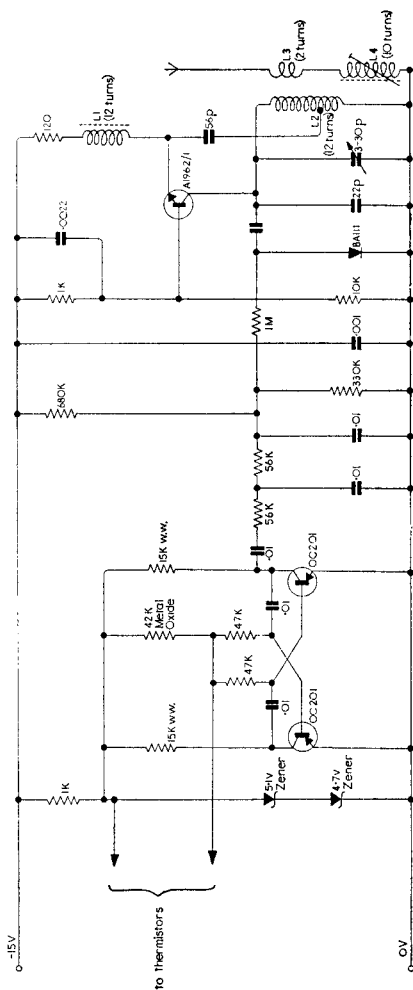
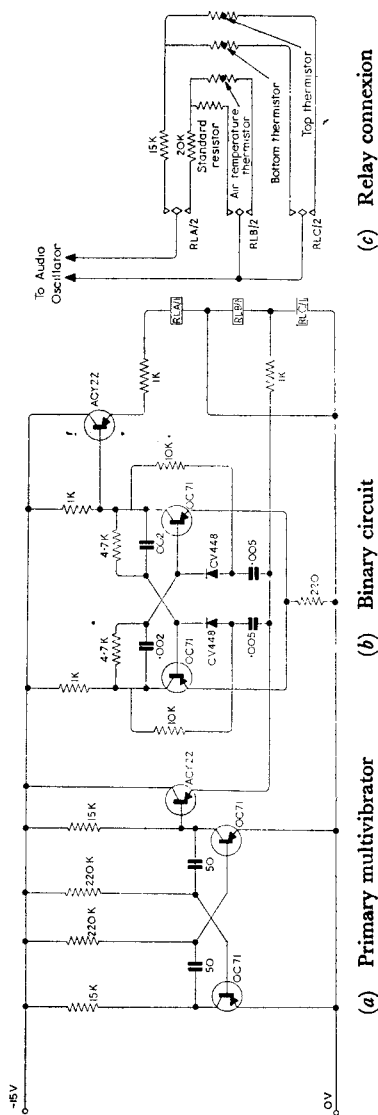
Kew net flux radiometer	Suomi-Kuhn radiometer		
	Top temperature <i>degrees Celsius</i>	Bottom temperature	Net radiation mW/cm^2
7.23	0.8	7.6	7.26
7.13	0.1	6.8	7.18
7.13	-1.2	5.6	7.13
4.64	9.0	13.2	4.69
4.97	7.6	11.9	4.64
4.68	6.4	10.8	4.66

Telemetry.—The design of the telemetry package was determined by six basic requirements. These were :

- (i) Four parameters must be measured, namely air temperature, the temperatures of the top and bottom surfaces of the radiometer and a standard resistance acting as a calibration check.
- (ii) The audio-frequency oscillator periodicity must vary with the resistance change of the thermistors in such a manner that a linear temperature change gives a near-linear change of periodicity over the range $+30^\circ\text{C}$ to -80°C the expected range of temperatures of the surfaces.
- (iii) A good radio-frequency oscillator is already available and has been test flown in the rocketsonde. The audio-frequency oscillator must therefore be designed to be compatible with this.
- (iv) Temperatures must be known to an accuracy of ± 0.1 degC.
- (v) Any temperature or voltage drift in calibration must be uniform throughout the whole periodicity range 950 to 1500 microseconds (μs) so that the one calibration standard resistance is representative for the whole range.
- (vi) Power supplies must be as convenient and as small as possible.

Windmills as used with Mk 2 radiosondes are unsuitable for switching because of the proposed slow rates of ascent, 600–800 feet per minute, and also because it was hoped to float a balloon at one level. Our present solution is a long-period multivibrator with suitable binary coupling acting on three miniature relays (Figure 2). Each position is held for about 15 seconds.

The audio-frequency oscillator is a multivibrator (Figure 3) with a variable resistance in the RC coupling. In such a circuit, resistance/periodicity changes



are linear. The exponential variation of thermistor resistance with temperature can be converted to near linearity by a combination of resistors in series and parallel with the thermistor. The actual change in the thermistor resistance of 20 K ohms at $+30^{\circ}\text{C}$ to 1 M ohms at -80°C is made to produce a net resistance change of 19 K ohms to 40 K ohms. The standard resistor is a stable 80-K ohms wire-wound resistor in parallel with 42 K ohms.

Compensation for changes of temperature in the circuit is essential for keeping a constant slope for the calibration curve of periodicity/thermistor temperature, and is achieved by using wire-wound, carbon, and metal-oxide resistors whose temperature coefficients oppose each other (Figure 3). Between $+20^{\circ}\text{C}$ and -20°C the drift of periodicity throughout the whole range is usually less than $10\text{ }\mu\text{s} \pm 1\text{ }\mu\text{s}$. The drift is given by the standard resistor. The slope of the periodicity/thermistor temperature characteristic of the audio-frequency oscillator is $10\text{ }\mu\text{s}/\text{degC}$ but only half this value at the ends of the range so that the maximum error there is $\pm 0.2\text{ degC}$. In practice the known drift has rarely exceeded $2\text{ }\mu\text{s}$ with an error correspondingly reduced to about $\pm 0.2\text{ }\mu\text{s}$, i.e. less than 0.1 degC . The rocket transmitter (Figure 3), a proven system developed for the SKUA rocket, is powered by two 9-volt PP6 batteries in series, which will sustain a current drain of 20 milliamps for 2 to 3 hours. The transmitter has the advantage that it will perform satisfactorily even when the voltage has fallen by half. Interaction between the transmitter on one hand and the audio and switching circuits on the other is avoided by giving the latter circuits a separate 15-volt supply. This is dropped to a zener-stabilized 9.8 volts across the audio circuit.

The electrical components are mounted on a circuit board of 4.8×5.8 inches and enclosed together with the batteries inside a cavity roughly $6 \times 6 \times 6$ inches hollowed from a 1-foot cube of expanded polystyrene. The radiometer itself is mounted on three wooden supports cemented into the base of the instrument and also into one of the vertical sides of the polystyrene cube. The radiation reaching the radiometer from the complete package is thus negligible, so also is that from the balloon when the radiometer is a hundred feet or more below it. In flight this long suspension ends in a bridle fitted round the package and adjusted such that the radiometer freely hangs with its surfaces horizontal. The whole package including the radiometer weighs about 2 kilogrammes.

In an early radiometer flight the switching rate increased rapidly and then ceased altogether. We suspected that this was caused by the cooling of the transistors in the switching circuit. Experiments conducted using a 12-inch cube polystyrene box with 3-inch walls similar to that enclosing the package of electrical components showed that the internal cooling rate is 20 to 25 degC per hour provided that the temperature gradient across the walls is in excess of 30 to 40 degC. The cooling rate is roughly the same by day or by night but in the daylight flights the cooling rate high in the stratosphere decreased almost to zero. In the night flights the box continued to cool at the rate quoted. To combat this, a simple heater consisting of a 10-ohm 10-watt resistor is strapped to the back of the mounting of the electrical unit and supplied with 4.5 volts from a bell battery. This also keeps the audio oscillator warm. Since using this system we have experienced no trouble from changing frequency of switching.

Calibrations.—The temperatures of the black surfaces of the radiometer are measured by two rod thermistors cemented directly below the surfaces. The resistance of the thermistor may be expressed as

$$R_{es} = R_{es_0} e^{\beta/T}$$

where R_{es_0} and β are constants depending respectively on the size of the element and its composition. The manufacturer gives one value of resistance and temperature, usually room temperature, and β . These values were checked by us for several of the radiometers by constructing the full log R_{es} against $1/T$ curve from $+30^\circ$ to -40°C and were found to be accurate within the limits of experimental error. Subsequently only one point was checked at room temperature.

The ambient air temperature is measured by a thermistor bead strapped between two of the radiometer supports. The thermistor has a resistance of about 10 K ohms at 0°C with a β of 3100°K . Each of these was checked at room temperature as well.

The resistance/periodicity calibration curve of the whole unit is constructed in detail by the use of numerous known resistors, 10 K to 1 M ohms, in place of the thermistor detectors. This calibration is performed soon after construction and is checked over the whole range (but not in such detail) immediately before a flight. We estimate that all of our temperatures are known to within 0.1°C .

Data reduction.—The telemetered data are recorded on the ground by the Meteorological Office Cintel equipment, the signals being presented as periodicities on a moving paper chart graduated from 0 to 100 μs . Although there is some noise on the trace we estimate that our readings are accurate to better than $0.5 \mu\text{s}$. This corresponds to about 0.05°C on the steepest part of the calibration curve (-20°C to -50°C) and 0.1°C elsewhere. Each sensor on the radiometer is interrogated for 15 seconds at a time which corresponds to a displacement of about $\frac{1}{4}$ inch on the Cintel chart. Generally this is ample time in which to determine the periodicity—indeed under certain conditions, for example through inversions or just above cloud top, considerable changes in temperature have been observed during one interrogation.

The first step in reducing the data from periodicity to temperature is to correct for any systematic variation in signal as disclosed by the standard resistor. In all cases this correction has been small, less than $2 \mu\text{s}$, but has been applied nevertheless. In order to obtain the net radiation, R_n , at a given point, the upward and downward radiation streams must be evaluated simultaneously at this point. Our telemetry is single channel so that the temperatures of the surface are separated by 15 seconds, perhaps 50 metres in height. Therefore the observed periodicity must be converted to temperatures and plotted against time so that

$$T_a, \quad T_b, \quad T_b, \quad \frac{dT_t}{dt} \quad \text{and} \quad \frac{dT_b}{dt}$$

can be obtained simultaneously at selected pressure intervals, usually 20 millibars.

Rates of cooling may be calculated from equation (3). However, since these involve second order differences of temperature it is desirable to keep the pressure interval as large as possible. We have used 100 mb layers in the discussion following.

Discussion of the flight results.—Although the three balloon flights described here were intended mainly as test flights for the performance of the instrument there is some merit in a closer examination of the results if only to compare them with each other, with similar ascents described in the literature and also with simple calculations based on one of the well-known radiation charts. Figures 4(d), 5(d) and 6(d) present flight data from the three ascents. Each figure shows the temperature T_t , T_b of the top and bottom surfaces plotted every 20 millibars together with the air temperature T_a . Also included are temperatures and water vapour contents from the nearest radiosonde sounding, the 2330 GMT Crawley for all cases. The left side of the figures shows the downward and upward radiation streams as obtained from equations (1) and (2) together with the net out-going radiation; units are Langleys (Ly) per minute. On two of the dates it was possible to obtain a net flux measurement at the surface from Kew Observatory; these too are plotted on the figures. Finally in the centre of the diagrams we have cooling rates in degrees Celsius per day evaluated every 50 mb over thicknesses of 100 mb. Although it was intended to fly the radiometer only when there was no cloud so that the analysis would be simplified, on two of the three occasions there was some stratocumulus, 8/8 on 13 September and, we suspect, a patch on 29 April. On all three dates there is evidence that cirrus cloud was also present but we cannot be certain about its height or its density. Thus we can only compare the three flights in the broadest of terms. We hope to carry out flights in the future in conjunction with aircraft of the Meteorological Research Flight when accurate measurements of frost-points and reliable cloud heights will be obtained.

On all three ascents the temperatures of the black surfaces decreased with height through the middle and upper troposphere, T_t falling rather faster than T_b , but became relatively constant in the stratosphere. The tops of any low cloud showed up clearly as a sharp decrease in T_t but cirrus cloud could not be detected in the same way. The rates of cooling of 100 mb thicknesses (calculated from equation (3)) are 1 to 2 degC per day in the lower troposphere falling to about zero in the upper troposphere and lower stratosphere but 3 to 4 degC per day near the top of the stratocumulus cloud. This is in good agreement with values quoted in the literature (for example Kuhn, Suomi and Darkow,⁴ Staley⁵) but for a more detailed analysis of results we will treat each case separately.

Flight of 29 April 1965.—A slack pressure gradient existed over the British Isles between a depression to the west and an anticyclone near Scandinavia. The day was one of sunny periods and at dusk the sky was clear apart from high cirrus. A final check calibration of resistance/periodicity was made before the polystyrene box was sealed and taken outside where it was allowed to cool in the clear night air. The sonde was launched at 2200 GMT from the Meteorological Office Experimental Site at Easthampstead,

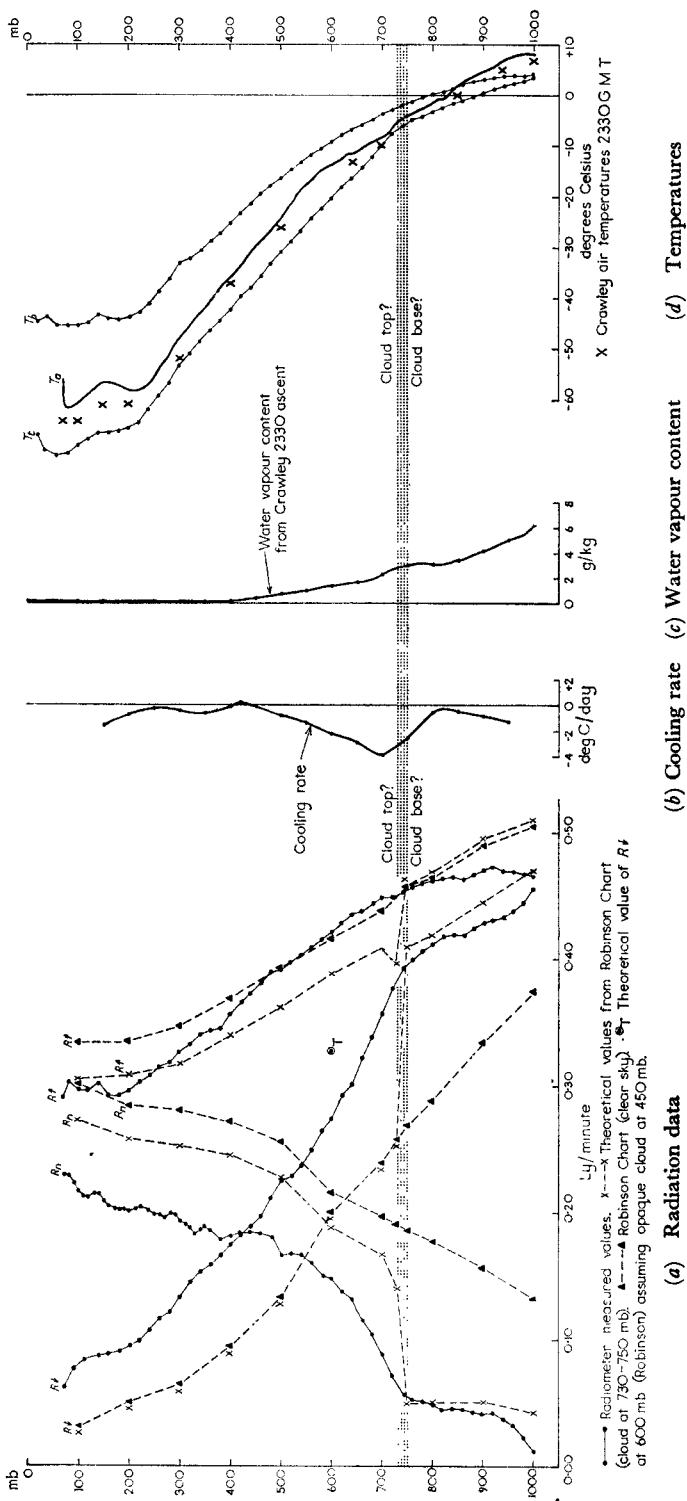


FIGURE 4—RADIOMETER FLIGHT ON 29 APRIL 1965
 T_a = temperature of air, T_s = temperatures of the top and bottom surfaces.

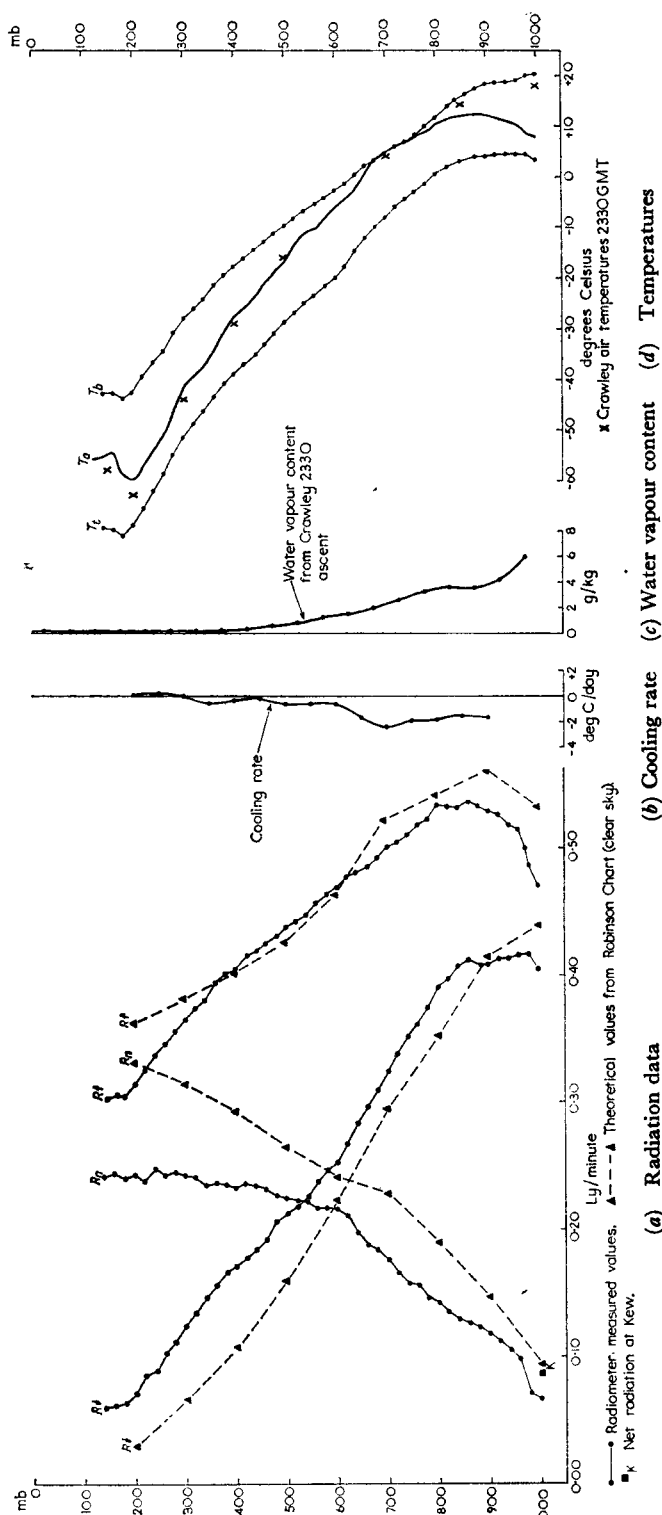


FIGURE 5—RADIOMETER FLIGHT ON 13 MAY 1965

T_a = temperature of air, T_l , T_b = temperatures of the top and bottom surfaces.

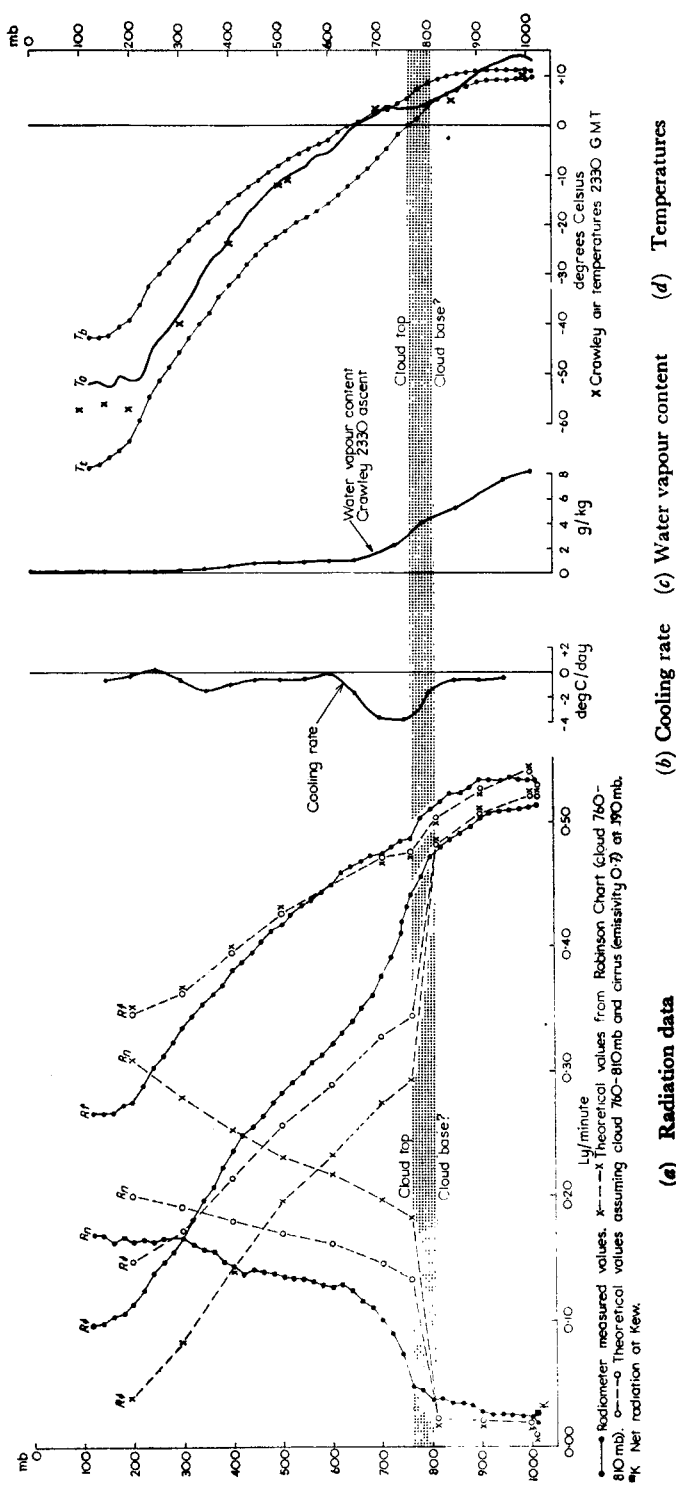


FIGURE 6—RADIOMETER FLIGHT ON 13 SEPTEMBER 1965
 T_a =temperature of air, T_t , T_b =temperatures of the top and bottom surfaces.

Berkshire. Throughout the flight all instruments functioned well. Heights were obtained by radar ranging and the rate of ascent was found to be about 4.5 m/s, rather higher than intended. The balloon burst after 105 minutes at a height of about 25 mb. A few days later the sonde was recovered from a farm in Essex; it was found to be in a workable condition and a check calibration showed very little difference from the pre-flight calibration.

The interpretation of the results of this flight (Figure 4) is complicated by the presence of cloud with a top close to 730 mb. Although there were no reports of low cloud in the immediate neighbourhood there is no doubt that it existed. The net radiation is relatively constant at 0.04 Ly per minute up to 750 mb and then increases sharply mainly because of a decrease in R_{\downarrow} . The cooling rate at 700 mb is 4 degC per day and calculations at points 25 mb above and below this level substantiate this figure. Between 375 and 475 mb the net radiation remains roughly constant at 0.18 Ly per minute, indeed there is a slight decrease in R_n leading to a slight warming near 400 mb. Although this warming is not significant when compared with the probable errors of observation the fact that R_n is constant over a depth of 100 mb certainly makes this a significant feature of the sounding.

In order to compare our results with a simple calculation of net outgoing radiation the nearest radiosonde sounding was used to obtain temperatures and optical path-lengths (although no frost-points were given above 400 mb we have assumed a linear decrease of frost-point to -78°C , i.e. mixing ratio of 2.5 parts per million at the tropopause and a constant mixing ratio above — water vapour content is shown in Figures 4(c), 5(c) and 6(c)). Figures 4(a), 5(a) and 6(a) show the results of these computations using the Robinson radiation chart. In Figure 4(a) we have calculated the outgoing radiation assuming an opaque cloud, base 750 mb and top 730 mb, and also assuming no cloud. Below cloud (except very close to the ground) our measurements of R_{\uparrow} and R_{\downarrow} are in good agreement with those calculated, but above cloud there are quite large differences in R_{\downarrow} , the observed values being the greater at all levels. That this may be due at least in part to the presence of cirrus cloud can be shown by assuming a black body at 450 mb, when R_{\downarrow} at 600 mb increases from 0.20 to 0.33 Ly per minute (the measured value is 0.27). The differences in R_{\downarrow} also show in R_n , which above cloud is about 25 per cent less than that calculated from the radiation chart.

Flight of 13 May 1965.—The British Isles lay in a ridge of high pressure between depressions in mid-Atlantic and over Scandinavia. The day was warm and sunny and at dusk the sky was clear apart from spreading contrails. The flight was conducted as before and all instruments functioned well until one of the relays stopped switching after 95 minutes and the flight was abandoned. At this time the sonde was at a height of about 120 mb having ascended at about 2.5 m/s. Later the instrument was recovered from the River Itchen at Southampton but owing to corrosion of the electronics a calibration check was impossible.

On this occasion there was no low cloud but 2/8–3/8 cirrus at 20,000 feet was reported and persistent contrails were seen near sunset. The air temperature as measured by our thermistor shows a very steep inversion, 10 degC in 20 mb,

near the ground but then follows closely the 2330 GMT Crawley sounding. The upward radiation increases slowly to 850 mb and then decreases steadily to the tropopause. The net radiation near the ground, 0.074 Ly per minute, agrees well with the Kew value of 0.082 Ly per minute. From here to about 450 mb it increases steadily to 0.24 Ly per minute after which it remains relatively constant. Calculation of the radiation streams using the Robinson chart (Figure 5(a)) shows good agreement — except near the ground — with the measured R_{\uparrow} and a systematic difference from the measured R_{\downarrow} above 900 mb, the measured values once more being the greater. This could again be due to the non-opaque cirrus at high levels.

Flight of 13 September 1965.—The British Isles lay in a ridge of high pressure at the surface with a generally north-westerly gradient at upper levels. The day was dry but mainly cloudy although at times towards dusk the cloud threatened to break. The sonde rose at about 4 m/s to about 110 mb after 66 minutes and appeared to float at this level for a further 24 minutes after which it passed out of radar range near the Channel coast. It has not been recovered.

On this occasion there was 7/8–8/8 stratocumulus, and an aircraft landing at London (Heathrow) Airport gave the base and top of the cloud as 6500 feet and 8000 feet respectively. The height of the cloud top is clearly shown by the temperature at the top surface to be at 760 mb agreeing with the aircraft observation, but since the moon was clearly visible through the cloud at Easthampstead the cloud was unlikely to have been much thicker than 500 feet. This is verified further by R_{\downarrow} which continues to decrease as the sounding approaches cloud base. Nevertheless, in the following calculations we have assumed that the cloud base is 6500 feet as given by the aircraft.

Figure 6(a) compares the measured radiation streams with those calculated from the Crawley 2330 GMT ascent on the Robinson radiation chart (pecked lines with crosses). There is good agreement at all levels in the upward radiation streams and also below cloud for R_{\downarrow} but above cloud the measured value of R_{\downarrow} is consistently greater than that calculated. This must be due in part to cirrus cloud; during the afternoon cirrus cloud could be seen faintly through gaps in the lower cloud deck. Zdunkowski *et alii*⁹ give probable particle densities and transmissivities of cirrus clouds 1 kilometre thick and for the want of better observations we assume that the cirrus cloud in this example falls into their category. For a visible cirrus cloud, particle concentrations of 0.1 to 1.0 per cm^3 are quoted leading to emissivities of 0.7 over the total long-wave spectrum. Using this value for a cirrus cloud at 200 mb we have recalculated the radiation streams. There is now very much better agreement above cloud though the measured values are still somewhat higher.

Conclusions.—We have designed, constructed and test-flown a transistorized sonde which when used with a Suomi-Kuhn radiometer gives a reading of four parameters over each period of 60 seconds. The circuit is insensitive to quite large changes in battery voltage and only slightly sensitive to temperature.

Initial calibration of the radiometer and sonde disclosed a systematic difference between values of net radiation as measured by the sonde and as given by the Kew net flux radiometer. This difference was eliminated when the internal conduction term was recalculated.

Although the test flights indicated that the instrument behaved satisfactorily there is considerable uncertainty in the interpretation of results because of lack of accurate cloud observations. Furthermore direct comparison with radiation calculations based on one of the well-known radiation charts is hampered by uncertainties in the water vapour measurements at all levels.

Acknowledgements.—We are indebted to Dr P. M. Kuhn of the U.S. Weather Bureau who donated the radiometers which started this project. Also, we must acknowledge the work of Mr J. M. Nicholls who was responsible for most of the calibrations.

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NOCTILUCENT CLOUDS OVER WESTERN EUROPE DURING 1965

By J. PATON

Table I contains a summary of displays of noctilucent clouds that were visible over western Europe during 1965.

The approximate overhead geographical position of the clouds, determined by the method described in an article in the *Meteorological Magazine*¹ is given in the third column. On occasions when the absence of low cloud allowed observations to be made when the cloud mass was illuminated to its southern border, the latitude of the overhead position of this border is given to the nearest degree. When such observation is not possible, the elevation of the highest portion of the noctilucent clouds above the northern horizon observed in a stated latitude is given under the 'notes by observers'. The extension in longitude is given to the nearest 5°.

While the frequency of occurrence of the clouds was only slightly less than that during 1964,² the displays were generally much weaker. In the latter half of the season, during July, they consisted mainly of veils, usually containing some weak bands or waves.

The most striking display occurred during the early morning of 5 July. This display remained visible in the south-western sky at a station in latitude $56^{\circ}20'N$ until 0247 Universal Time (UT), when the depression of the sun below the horizon was $5^{\circ}10'$, the lowest at which the clouds have been discernible. Unfortunately, prevailing low cloud on this night prevented observation at stations south of latitude $55^{\circ}N$.

A short-lived display observed in Denmark during the early morning of 27 June did not extend sufficiently far west to be visible in Britain. This was the only display in which 'whirls' were reported.

The clouds were first seen in 1965 10 days earlier than in 1964 and the northwards recession, usually observed to take place towards the end of July, also began rather earlier. The clouds have never been seen in central Scotland later than 3 August; in 1965 they were last seen there on 20 July.

Weak noctilucent clouds in the form of a veil were seen at Danmarkshavn, Greenland ($77^{\circ}N$ $341^{\circ}E$) at 0230 UT on 21 September, reaching an elevation of 6° at azimuth 355° . Bright bands with wave structure and veil, which may have been noctilucent clouds, were reported overhead at Tingmiariut ($62^{\circ}N$ $318^{\circ}E$) at 2320 UT on 24 October.

Suspected noctilucent clouds in the form of a veil were observed at Stanley, Falkland Islands, South Atlantic ($52^{\circ}S$ $58^{\circ}W$) at 0015–0020 UT on 28 November up to an elevation above the southern horizon of 55° .

The analysis recorded in Table I has been compiled from observations made (a) by observers at meteorological stations in Ireland and the U.K., (b) by voluntary observers in the U.K. and in Denmark, and (c) by aircrews in civil and military aircraft. We wish to thank all who have taken part in this work, either by organizing or making the observations.

These synoptic studies will continue, and we invite the co-operation of observers who may be prepared to contribute to them. Notes on observation and photography of the clouds may be obtained from the Balfour Stewart Laboratory, The University, Drummond Street, Edinburgh 8.

TABLE I—DISPLAYS OF NOCTILUCENT CLOUDS OVER WESTERN EUROPE DURING 1965

Date — night of	Times UT	Approximate geographical position		Notes by observers
		Latitude*	Longitude	
30–31 May	2230–2315		$5^{\circ}W$	Weak bands seen through gaps in low cloud in latitude 55° at elevation of 5° above northern horizon.
2–3 June	2300–0035	58°	$5^{\circ}E$ – $15^{\circ}W$	Very faint bands showing fine wave structure.
8–9 June	2240			Weak display low on northern horizon seen in latitude 56° . No details available.
12–13 June	0050–0240	55°	$15^{\circ}E$ – $20^{\circ}W$	Compact mass of cloud of moderate brightness, the lower portion consisting of cirrus-like streaks, while regular waves appeared in the upper portion.

* Of southern border, when measurable.

TABLE I—DISPLAYS OF NOCTILUCENT CLOUDS OVER WESTERN EUROPE DURING 1965

— continued

Date— night of	Times UT	Approximate geographical position		Notes by observers
		Latitude*	Longitude	
13-14 June	0130-0200		10°E-5°W	Weak bands to elevation 10° seen in latitude 53°.
26-27 June	2355-0050	55°	25°E-5°E	Seen in Denmark. None seen in U.K. though skies there were also clear. Began as single greenish band in the north, later spreading over whole eastern sky to south of the zenith. Colour described as 'milky to light green with touch of blue' and form 'like sheeps' wool and in other parts like bunches of rays'.
27-28 June	2300-2315		5°E-10°W	Bands seen through breaks in almost continuous low cloud to elevation 25° in latitude 56°, to 20° in latitude 55° and near the northern horizon in latitude 50°.
29-30 June	0150-0240	54°	5°W-15°W	Pale whitish-blue bands.
30 June- 1 July	0245-0257	54°	5°W-15°W	Pale white bands visible overhead near dawn in Isle of Man.
4-5 July	2350-0247	<55°	15°E-20°W	Brilliant display of bands and waves with fine structure and veil background.
5-6 July	2245-0310		5°E-10°W	Veil with faint streaks seen up to elevation 32° in latitude 56°.
7-8 July	2330-0105		5°E-10°W	Faint veil with occasional fine structure observed up to elevation 70° in latitude 55°.
9-10 July	2330-0050		5°E-10°W	Faint veil along northern horizon seen in latitude 55°.
10-11 July	2105-2250		15°E-10°W	Bands seen to elevation 30° from Jutland, Denmark, at 2105 UT and later from Scotland. Obscured later by low cloud.
13-14 July	2312-2330		5°E-10°W	Veil with weak isolated filaments seen to elevation 9° in latitude 55°.
15-16 July	2245-0055		5°E-10°W	Veil with ill-defined horizontal bands seen to elevation 7° in latitude 58°.
16-17 July	2245-0250		5°E-10°W	Thin veil with patches showing weak bands seen to an elevation of 57° in latitude 55° at 0250 UT.
19-20 July	2230-2330		15°E-10°W	Small patches of diffuse horizontal bands seen first in Jutland, Denmark, and later in Scotland, at elevations between 20° and 35° in latitude 58°.
26-27 July	2300-0050		5°E-10°W	Faint patches of veil with delicate cirriform structure seen to elevation of 11° in latitude 58°.
28-29 July	Not known			Clouds seen from Lerwick, Shetland Islands. No details available.
30-31 July	2255-0040		10°E-0°	A bright but not extensive display of horizontal parallel bands seen to elevation of 10° in latitude 61°.

* Of southern border, when measurable.

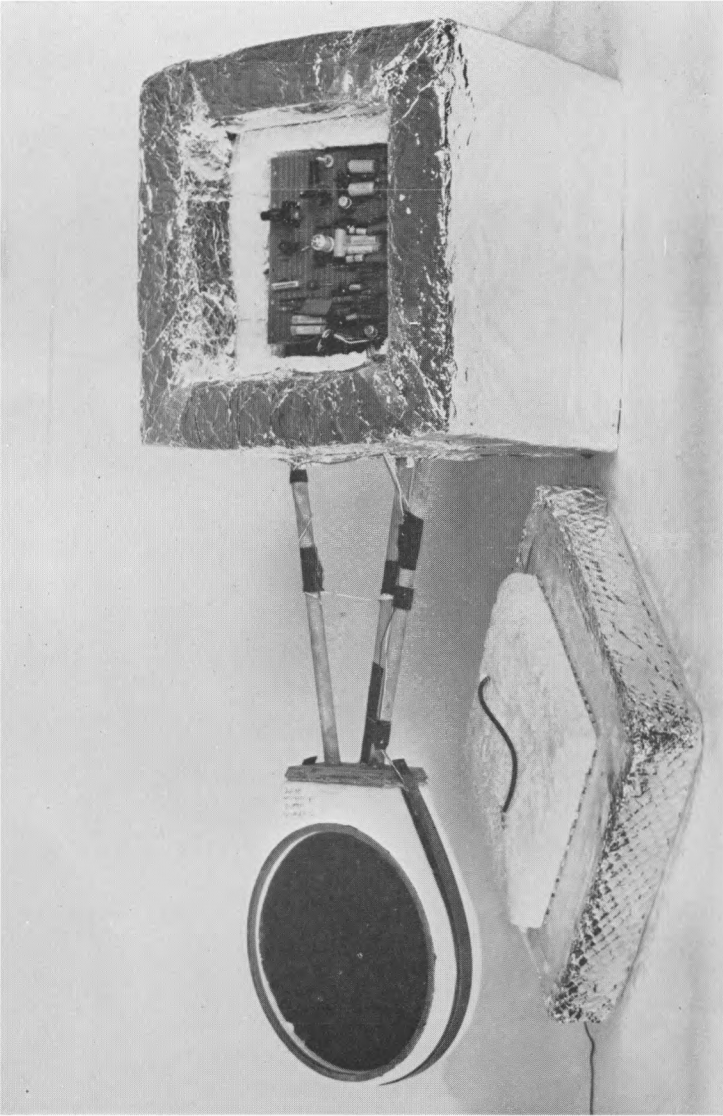
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2. PATON, J. ; Noctilucent clouds in 1964. *Met. Mag., London*, **94**, 1965, p. 180.

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PLATE I—RADIOMETER SONDE

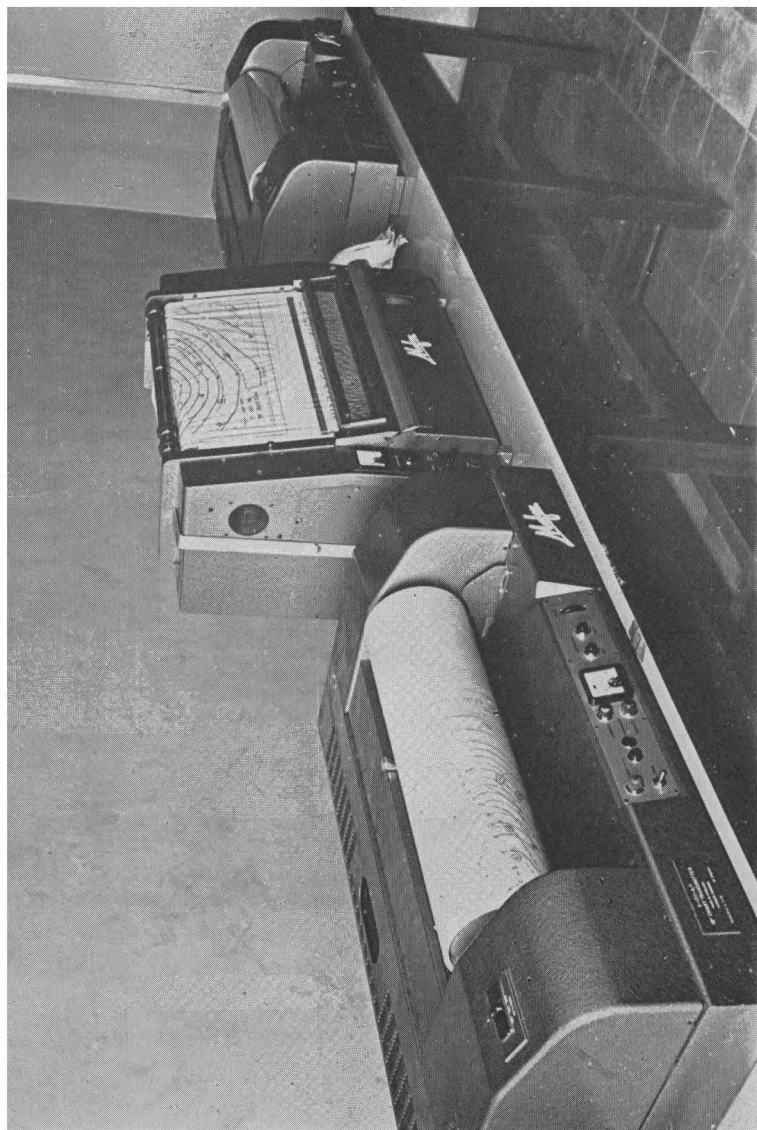
The close-fitting polystyrene cover has been removed exposing the electronics card. The thermistor for measuring air temperature is shown suspended between two of the wooden supports for the radiometer at the left of the picture (see page 162).





Photograph by G. J. Jefferson

PLATE II—METEOROLOGICAL FASCIMILE ROOM AT THE MAIN METEOROLOGICAL
OFFICE, RAF EPISKOPI, CYPRUS
Spot wind chart of London (Heathrow) Airport origin being received.



Photograph by G. J. Jefferson

PLATE III—METEOROLOGICAL FACSIMILE ROOM AT THE MAIN METEOROLOGICAL
OFFICE, RAF EPISKOPÍ, CYPRUS

Upper level forecast chart being transmitted and monitor copy on monitor recorder in
centre.

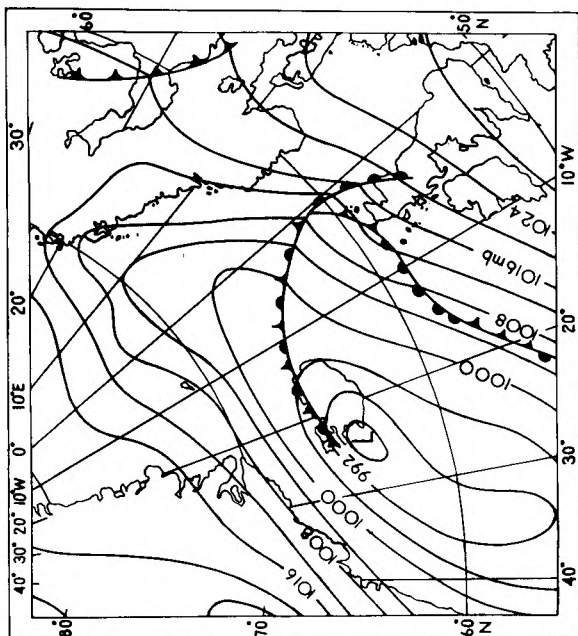
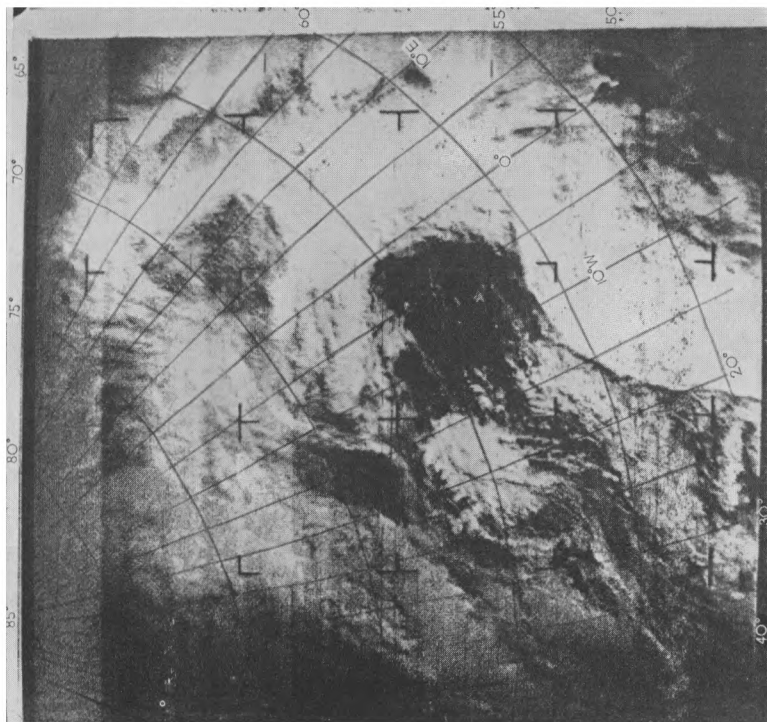


FIGURE 1—SYNOPTIC CHART FOR 1200 GMT
ON 5 MARCH 1966



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PLATE IV—SATELLITE PICTURE TAKEN AT APPROXIMATELY
1100 GMT ON 5 MARCH 1966
See page 177.

TIROS OPERATIONAL SATELLITE

By T. H. KIRK

The first of the TIROS Operational Satellites (TOS) to incorporate the Automatic Picture Transmission (APT), ESSA II, was launched from Cape Kennedy on 28 February 1966. The satellite is in a near polar orbit of inclination 101 degrees and period 113.42 minutes. The height of perigee is 1353 km and of apogee is 1413 km and the nodal period is 28.38 degrees. The facsimile transmission is on a frequency of 137.5 megacycles/second and pictures are taken at intervals of 352 seconds with a 30 per cent overlap. Further details of the satellite programme are available in a previous article.* It is now possible for anyone with suitable ground equipment, of relatively modest cost, to acquire cloud pictures on a current basis.

An example is shown in Plate IV of a picture taken on 5 March 1966 with the equipment illustrated in the *Meteorological Magazine* of December 1964. The corresponding synoptic chart covering approximately the same area is shown in Figure 1.

In the technique of APT there are three distinct aspects ; firstly, the plotting of the satellite orbit to determine the times during which it will be possible to receive pictures ; secondly, the gridding of the pictures so that each point on a picture can be given its exact geographical location ; lastly, the interpretation of the photographs. All three of these aspects are essential parts of the work but the photographic interpretation has the greatest interest for meteorologists and requires the greatest experience for its successful practice.

In preparation for the new TOS system, the Environmental Science Services Administration of the United States Department of Commerce recently organized an APT Training Course which was held in the National Environmental Satellite Center, in Suitland, Maryland, near Washington D.C., from 6 to 10 December 1965. There were 63 participants, mostly United States Army, Air Force and Weather Bureau personnel, but also some representatives of foreign services, including the Meteorological Office.

Participants were welcomed by Mr D. S. Johnson and Mr A. W. Johnson, representing the Administration, and short introductory talks were given by Mr D. W. Holmes and Mr P. E. Lehr. Most of the instruction on orbital computation and gridding techniques was given by Mr A. Schwalb while Mr Vincent J. Oliver, Chief, Applications Group, and his staff lectured on photographic interpretation and its synoptic significance for the forecaster. Students had the advantage of hearing expert comment on some hundreds of photographs chosen to illustrate different aspects of weather and technique.

The impact of the satellite on meteorology in Europe and elsewhere outside the United States has as yet been limited because pictures on a current basis have not been available and because the nephanalyses (i.e. coded or facsimile analyses of the organization of clouds), disseminated by the U.S. Weather

* JAMES, D. G. and POTHEGARY, I. J. W. ; Some aspects of satellite meteorology. *Met. Mag.*, London, **94**, 1965, p. 193.

Bureau, have been received too late to be of great significance for routine forecasting. With the introduction of the APT in the current ros programme it will be possible for forecasters to utilize cloud photographs to an ever increasing extent in their routine work and to become expert in their interpretation.

The photographs will provide not only factual information of immediate value but also increased insight into the structure of depressions and frontal systems. One can look forward to the integration of this new information into the present system of analysis and, ultimately, to the data from satellites being used as essential input data for the computer in its preparation of short- and medium-range forecasts.

551.586:631 (04)

PHYSICAL LIMITATIONS TO CROP GROWTH

The 1965 Middleton Memorial Lecture was given at the Wellcome Institute on 8 December by Dr J. L. Monteith of the Physics Department, Rothamsted, who chose for his subject the above title. He started by giving a brief historical survey of the relationships between weather and crops.

The main emphasis of his talk was on the effect of weather on the size and efficiency of the photosynthetic system. When the leaves of a plant assimilate carbon dioxide from the air around them, energy for running the photosynthetic machine is supplied by quanta of visible radiation absorbed by chloroplasts in leaves. Only a fraction of this absorbed energy is stored chemically in the final products of photosynthesis. In ideal conditions, the maximum storage of energy is equivalent to about one fifth of visible radiation in the wave band from 0.4 to 0.7 μm , constituting about half the total energy in the solar spectrum at the earth's surface. In terms of total incident radiation as measured with a conventional solarimeter, the maximum possible efficiency of photosynthesis is about 8 per cent. Because this figure represents an upper limit set by the nature of the photosynthetic process, it holds for all species that synthesize carbohydrate in daylight. The amount of energy available from solar radiation is the ultimate physical factor limiting crop growth when all other restrictions are removed.

Assuming this value of 8 per cent, Dr Monteith calculated the fastest possible rates at which dry matter could be produced from three different crops (sugar beet in England, sugar cane in Hawaii and maize in California). From these he assessed the percentage efficiency of growth. The results are shown in Table I.

TABLE I—THE CONVERSION OF RADIANT ENERGY TO CARBOHYDRATE

	Sugar beet	Sugar cane	Maize
Length of growing season (months)	6	18	4
Mean solar radiation in growing season (cal/cm ² day)	260	500	620
Carbohydrate production at 8 per cent energy conversion (g/m ² day)	60	104	140
Relative dry matter production — per cent			
(i) maximum for experimental plot	52	41	37
(ii) seasonal mean for experimental plot	30	22	22
(iii) seasonal mean for commercial farming	15	10	7

The last three lines of Table I represent the percentage efficiency of production. Limiting factors on plant growth can be listed as :

- (i) energy available for photosynthesis ;
- (ii) amount of carbon dioxide available ;
- (iii) leaf behaviour—in early stages, too few leaves to intercept all the incoming radiation, and in later stages inability of leaves to assimilate carbon dioxide quickly in very bright light and
- (iv) factors such as lack of water or fertilizer, pests and diseases, poor husbandry, waste in harvesting due to adverse weather.

Carbon dioxide variation is therefore obviously important and long-term change is of interest. There is evidence that an increase has taken place in the last hundred or so years, from 280 parts per million (ppm) to about 314 ppm, and that unless future needs for fuel are met largely by the development of nuclear power, the growing consumption of coal, gas, and oil may increase atmospheric carbon dioxide to almost 400 ppm by the year 2000. By itself, this change might be expected to increase crop yields by 10 to 20 per cent, but it is difficult to predict whether changes in the absorption of radiation by carbon dioxide will lead to changes in the earth's climate large enough to be welcomed or deplored by farmers. At the concentration of carbon dioxide prevailing in the atmosphere, the dependence of photosynthesis on light intensity follows a law of diminishing returns. In weak light, the photosynthesis of all crop plants increases linearly with light intensity, but as the light gets stronger the efficiency of photosynthesis decreases, and in full sunlight many species behave as if they were saturated with light. However, some species such as maize, sunflower, cotton and several tropical grasses seem better adapted to many climates because their leaves are not saturated with light even at the maximum intensity of tropical sunshine.

Plant growth can normally be regarded as occurring in three phases : a juvenile phase during which the ability to produce dry matter increases rapidly as the leaves expand to intercept more and more light ; a second (mature) phase when there are enough leaves to absorb all the available light and the rate of production may stay nearly constant or even decrease slightly because the rate of synthesis by a sunlit leaf gets slower as the leaf ages ; a third (senescent) phase, with production declining rapidly as the leaves die. The rate of germination depends on temperature, with the optimum range usually between 15 and 25°C. Some growth progress is however likely down to as low as 3°C in some cases and up to as high as 33°C. In Israel where germination may be inhibited by soil that is too hot, experiments in covering the soil with magnesium carbonate in the form of a white powder to reflect radiation have been successful ; at 2 cm depth a decrease of 5–10 degC was maintained for a period of several weeks.

Leaf-area growth is complex depending upon a number of factors ; up to 25°C, higher temperature gives more rapid growth — a function of temperature rather than illumination. Growth rates can be of the order of 13 per cent per day at 20°C for sunflowers and up to 45 per cent for potatoes ; the growth rate decreases by a factor of two or three when a 10 degC temperature fall takes place. Figure 1 brings out quite well the difference in development which even 2 degC make in progress ; the ordinate in this figure is the leaf-area index, which is the ratio of leaf area (counting one surface only) to the

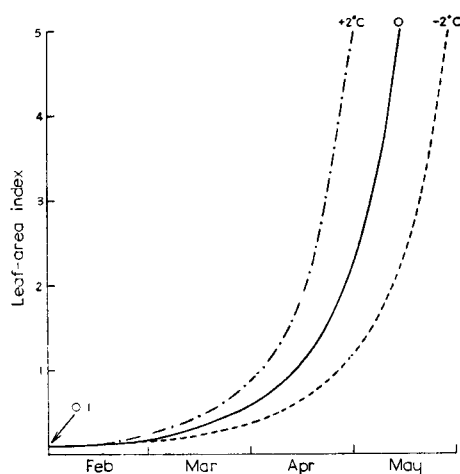


FIGURE 1—CHANGE IN RATE OF GROWTH OF LEAF-AREA INDEX IN WARM, AVERAGE AND COOL SPRINGS

— · — · — Warm spring (+2 deg C from average)
 ————— Average spring - - - - - Cool spring (-2 deg C from average)

area of underlying ground. A decrease in relative humidity slows down the rate of leaf expansion, presumably because of greater transpiration into drier air with associated greater water stress in the leaves. Wind speed too is important; for example a laboratory experiment produced a total leaf-area growth of 330 cm² in an airflow of 1 m.p.h., whereas in a wind of 33 m.p.h. a seedling grew only to 20 cm² in the same time.

Once the leaves of a field crop have expanded to form a closed canopy intercepting all the available light, the gross rate of photosynthesis becomes independent of leaf area and is therefore independent of the physical factors governing leaf area. The rate at which plants produce dry matter then depends on the balance between carbohydrate formed by photosynthesis and destroyed by respiration. Laboratory experiments show that the rate at which leaves assimilate carbon dioxide depends mainly on their illumination and on the concentration of carbon dioxide in the surrounding air. The rate of photosynthesis is much less sensitive than leaf expansion to changes of temperature and in many species the rate is relatively constant between 10 and 30°C. It has recently been shown that photosynthesis at temperatures between 0 and 10°C can be greatly increased by treating plants with a chemical which makes leaf cells more permeable to carbon dioxide—a technique which may have important implications for cold climate agriculture.

Another factor of importance is the angle of the leaves with respect to the source of light. To intercept 95 per cent of incident light, crops like clover and kale, with relatively horizontal leaves, need a leaf area three to four times the area of the field below them, whereas cereals and grasses with leaves hanging more vertically need a leaf-area index of eight or nine.

A final factor of some importance concerns the respiration. All plant organs respire carbon dioxide while they are growing, and any increase in the rate of respiration decreases the amount of dry matter remaining at harvest.

The main physical factor governing the rate of respiration is temperature and for any plant at a given stage of development an increase of temperature by 10 degC is expected to double the respiration rate. Comparatively little is known about the respiration of whole plants as distinct from individual cells, and still less is known about respiration of crops in the field.

The above account is necessarily a very abbreviated report on Dr Monteith's lecture, which will in due course be printed in full in *Agricultural Progress*.

G. W. HURST

NOTES AND NEWS

551.583.2:061.3:551.481

African lake-level changes, world rainfall pattern anomalies and related aspects of climatic change in the 1960's

Mr H. H. Lamb spoke at a colloquium given in the lecture theatre at the Headquarters of the Meteorological Office, Bracknell, on 9 February 1966. Extracts from the lecture and the discussion which followed are given below.

Since gauge measurements were begun in 1896, the level of Lake Victoria, a sheet of water between $\frac{1}{2}^{\circ}\text{N}$ and 3°S comparable in size with the southern North Sea, has varied by as much as a metre over a period of a few years. Many studies have been aimed at predicting these variations from their apparent, but unfortunately inconstant, relationships to the sunspot cycle. Since 1960, however, the level of the lake has risen abruptly by 2 metres and now appears to be varying about a new level. The other great lakes in East Africa have risen by a similar, or greater, amount. The damage to waterside activities and installations involves very big money values, and the construction of a new spillway at a cost of £2 million to make it possible to run off more of the water of Lake Victoria into the Nile is under consideration. The flow of the river Nile has also reached great heights in the 1960's.

Mr Lamb's investigation of this problem reveals principally that

- (i) the changes since 1960 appear to represent an abrupt return to the climatic régime that prevailed for some long time before 1895 and
- (ii) the related changes in the world distribution of rainfall for the years 1961-65 indicate a change in the prevailing mode of the large-scale wind circulation that has the following characteristics :
 - (a) Weaker zonal flow and increased prominence of meridional flow over extratropical latitudes in the northern and southern hemispheres, combined with changes in the locations of most frequent (surface) polar outbreaks. These effects probably indicate shorter wavelength than before in the upper westerlies.
 - (b) Intensified development of the zonal character of the equatorial trough which, however, undergoes smaller seasonal displacements north and south, and perhaps also smaller day-to-day wanderings, than formerly.

These characteristics have gone with intensified equatorial rainfall, sometimes over a quite narrow zone near the equator, whilst the sub-tropical anticyclones have been weaker and somewhat nearer the equator than formerly, at least over Africa and, from the rainfall evidence, also over other sectors.

Serious droughts have been reported in low-latitude parts of the arid zone and in well-separated parts of the temperate zones where changes in the prevailing positions of the upper cold troughs have made cyclonic rain or snow situations less frequent since 1960. Wet or snowy years have been experienced in other longitudes in the temperate zones. Corresponding changes of prevailing upper air temperatures at those stations where the series may be considered nearly homogeneous appear interesting, the greatest changes since the 1940's being (i) falls of temperature over middle and higher latitudes — though greatest near the tropic — and (ii) rises of upper air temperature in and near the equatorial rain belt.

Surface temperatures in regions affected by more frequent polar outbreaks, including Britain, also register sharp changes in the 1960's.

With so many significant changes of climatic figures in different parts of the world, meteorology is being confronted with inquiries from industry and from government agencies that amount to a demand for climate forecasting, for which no adequate scientific basis exists as yet. This demand places upon us a responsibility to extend and deepen our knowledge of the facts of climatic behaviour in the past and of the processes that appear to be involved. Among the latter must now be included indications of very slight long-term changes in the energy of the solar beam ; and in order that these may be investigated further it may be necessary to encourage quicker and more regular production of data on solar faculae from the fine series of daily heliophotographs maintained by the Royal Greenwich Observatory since 1874 and continued at the present date.

In the discussion, Mr Bushby asked to what extent the changed level of Lake Victoria could be attributed to a single disastrously heavy rainfall season in the second half of 1961 combined with the effect of the Owen Falls Dam in limiting outflow. Mr Lamb agreed that that rainy season was extreme, but there had been other very heavy rains since, especially in early 1964 and late 1965, and from 1961 to date rainfall over the catchment area averaged 25 per cent above the previous 30-year mean. Dr Forsdyke described the nature of the outlet from Lake Victoria as a steep-sided channel with a considerable fall ; water was expected to overflow the dam in high-water periods and was thought to have done so. The Nile floods at Cairo must be largely a separate matter : most of the water in the flood months around September comes from the Blue Nile which is fed by the summer monsoon rains over the mountains of Ethiopia. Also about 90 per cent of the water entering Lake Victoria is lost in evaporation and only the remainder goes down the Nile. Dr Forsdyke thought that a more reliable measure of changes of the régime in the upper air is given by the observed upper winds over the temperate zones than by the observed temperature. Mr Lamb commented that the central European mountain-top observatories provided a record of such changes since 1880–1900, but one must recognize in them changes of prevailing upper wind direction, associated with shifts of the troughs and ridges in the upper westerlies, as well as changes of prevailing wind speed. Mr Craddock made a plea for filter analysis to be applied to the African lake-level data to sort out the time-scale of fluctuations.

Miss Timpson believed that when the Owen Falls Dam was built around 1950 it was expected to raise the water-level in Lake Victoria. Mr Lamb

replied that it did not in fact rise materially until 1961, and this was undoubtedly due to the rainfall increasing : Mörth had found a correlation coefficient of +0.96 between rainfall over the preceding 12 months over the catchment area and the level of the lake, from the data for 1938 to 1964, years which straddled the building of the dam and the major change of rainfall in 1961. Miss Timpson also remarked that most of the rain in East Africa was thought to come from upper westerly winds. There was no specific information on this since 1961 (Mr Lamb replied) except in so far as local East African evidence was reported to indicate an intensified development of the equatorial trough zone, apparently with the same structure as previously supposed, though possibly over a slightly narrowed range of latitudes. Commenting on a question by Mr Bushby about the economic implications, Mr Lamb who had lately returned from Nairobi told of jetties and railway sidings submerged in Lake Victoria and a considerable loss of land around the flat shores. Professor Sutcliffe took up the question of the economic importance of climatic changes and remarked that there was enough serious investigation and research required to warrant a special institute. There was more to the understanding of this problem than the extrapolation of trends or cycles. It seemed as if the climate was also subject to step-like abrupt changes, which were fortunately rare but changed the climatic prospects and should not (or should not necessarily) be regarded as part of a trend. Was this change since 1960 such a step or had we merely experienced a few anomalous years ? The reply was that the various anomalies of the years since 1961 discussed by Mr Lamb appeared statistically significant, and no such run of years had occurred this century ; it looked like one of the four or five biggest steps in the climatic record in the last 250 years.

The paper on which this colloquium was based is to be published in full in the *Geographical Journal* (June 1966).

H. H. LAMB

Address by Professor P. M. S. Blackett, P.R.S.

On 15 March 1966, Professor P. M. S. Blackett, P.R.S. visited Bracknell at the invitation of Dr B. J. Mason, Director-General, to address the staff of the Meteorological Office on the subject of continental drift and the climates of past geological epochs. The address was given in the excellent theatre of the S. E. Berkshire College of Further Education at Bracknell, thanks to the kindness of the Principal, Mr H. B. Toft, and members of the college were able to attend.

Professor Blackett opened with a review of the history of the drifting continents hypothesis before study of rock magnetism began, a study which has added vital new evidence in the last decade or two. As early as 1620 Francis Bacon noticed the correspondence in shape between South America and South Africa and speculated that they might once have been together : this observation was made quite soon after these two continents had been reliably outlined on maps for the first time. In 1858 Snider pursued the idea further with an imaginative map showing the two continents brought together,

with some distortion, lapping Tierra del Fuego round the Cape of Good Hope. About 1910 Wegener, Du Toit and Taylor, working separately, demonstrated a number of corresponding tectonic features and palaeoclimatic evidence in the two continents. They directed particular attention to striated rocks and other evidence of a major glaciation in the Permo-Carboniferous epoch on both sides of the South Atlantic and as far away as India and Australia also. The ice flow was from south in India and Australia, from north-east in South Africa and apparently from some easterly direction in South America—all in terms of modern orientation. These directions of ice flow convey unmistakable impressions of how the land masses should fit together and where the centre of the ice-cap was. This great glaciation of 250 million years ago baffled explanation in terms of the older geology that denied continental drift. Holmes pointed out that there was not enough water in the world to make an ice-cap, of the thickness indicated by the eroding effects, covering all this vast area. This led directly to the suggested explanation in terms of a single great Urkontinent, 'Gondwanaland', in which all the land masses concerned were together around the South Pole.

The study of rock magnetism developed independently. It had been known since the beginning of this century that when Mt Etna lava cools, magnetism is induced in the iron oxide compounds (ferrites) in it in line with the earth's magnetic field. The iron compounds in sedimentary rocks are also magnetized in line with the earth's field at the time of deposition. Study of the weak remanent magnetism in the rocks today may therefore be taken as a fossil compass indicating the direction of the earth's field at the time of deposition. No difficulty is encountered in measurements on rocks less than one million years old, but 50 per cent of the measurements on older rocks are just 180° out. The earth's magnetic field appears from this to have reversed many times in the course of geological time—to have 'flicked over' at intervals of about a million years. This is difficult to explain, but because it appears as a precise reversal it is no hindrance to measurements of the former latitude at the time when the rocks formed: these depend on the fact that in a dipole field the tangent of the angle of dip is twice the tangent of the latitude. Moreover this angle of dip makes clear which hemisphere the place was in, regardless of the polarity at the time.

Triassic rocks in Britain (about 200 million years old)—e.g. the red sandstones much used in architecture—are magnetized with a shallow dip corresponding to latitude 20°N. In Cheshire, as in Germany, salt deposits 100 feet or so thick underlie this sandstone. Salt deposits are produced by evaporation in shallow seas in low latitudes—e.g. today only in a zone that extends about as far from the equator as the Caspian and the Dead Sea. Deeper in the rock structure of Europe lie the coal beds, formed apparently from tropical forest trees without annual growth rings, i.e. evidence that here, as in North America, the Carboniferous climate (of 250–300 million years ago) was producing the vegetation of the equatorial rain forest. The magnetism of the Carboniferous rocks in these areas shows no dip, in conformity with an equatorial origin. It appears that Europe has drifted from a position near 20°S around 450 million years ago more or less steadily northwards to its present position.

By contrast, the lands with evidence of Permo-Carboniferous glaciation have, to judge by the magnetic data, drifted more rapidly and not always linearly. India appears to have moved fastest, points now at 20°N having been at 50°S only 130 million years ago and possibly south of the Antarctic circle in the Permian. Rock magnetism in the Alice Springs area of central Australia, now at 20°S, shows a more complicated course from around 10°N 500 million years ago, crossing the equator at 330 million years, proceeding to 70°S about 160 million years ago and returning from there — a course consistent with the much earlier suggestion, made from a geologist's study of the rocks, of rapid refrigeration between 300 and 200 million years ago.

The most striking result of all may be the way in which all this evidence points to permanency of the zoning of climate by latitude. This has sometimes been disputed by geologists in the past ; but it now appears unnecessary to propose (as some classical geology did) the occurrence of epochs when the whole earth was hot or cold, wet or dry, and without any semblance of climatic zones. It also appears that the earth has always behaved as a magnetic dipole, and that the strength of the earth's magnetic field has not changed by more than a factor of two over hundreds of millions of years. Wandering of the poles (i.e. of the earth's rotation axis) is not sufficient to explain the rock magnetism palaeo-latitude data because of the evidence of relative motions of the different land masses and of some slewing of them. From rocks over 50–100 million years old the pole positions indicated from Europe, America, Australia and India are all different.

Coral is another good indicator of climate, since most corals will only grow in the warm seas within 20° of latitude from the equator. The corals of 250 million years ago are not related to the present equator but along a band from U.S.A. to Greenland, the British Isles and northern Europe, central Asia and Australia. Thus one can derive and plot latitudes of the geological past from (a) magnetic dip, (b) salt deposits, (c) corals and (d) coal beds. A plot of the palaeomagnetic latitude, the 'salt latitude' and the 'coral latitude' of Paris through the last 700 million years showed good general agreement.

Returning to the evidence from continental shape, Professor Blackett described the result of Sir Edward Bullard's statistical study of best fit between the edges of the continental shelves of South America and South Africa. This had produced a mean error of under 50 miles along 4000 miles of coast.

Finally, Professor Blackett considered what theories and evidence were available as to the causation of continental drift and the forces at work. Study of the distribution of epicentres of earthquakes revealed the systematic pattern of volcanically active mid-ocean ridges, notably that running through the Atlantic from Iceland to Tristan de Cunha and round into the Indian Ocean and Red Sea. These were zones of ever-opening fissures and abnormal heat flux from the earth's interior. Iceland was crossed by innumerable parallel fissures and its eastern and western parts were calculated to be drifting asunder at a rate of 1 to 5 cm a year. Other straight fault lines, such as Scotland's Great Glen and the San Andreas Fault in California, could be similarly understood though there lateral shear was also active. Earthquakes occurred when tension was suddenly released by failure of the elasticity of the rocks to hold the relative motion that was slowly going on

on either side of the fault. The theory that seemed most acceptable, illustrated by a diagram model proposed by Holmes, was that there were slow convection currents in the earth's mantle due to heat generated either by radioactivity or by chemical changes — e.g. from one silicate to another. The concept of viscous state of the mantle was supported by isostatic movements — e.g. Scandinavia's slow rebound, as yet little more than half completed, from its depression by ice-load in the Würm ice-age. According to the model the continents float like islands on the mantle and drift apart as the rising convection currents in the mantle diverge. Such convection cells appear to have a characteristic life span of the order of 250 million years and are followed by the development of new cells.

G. A. BULL

H. H. LAMB

Burma Meteorological Department

Dr Po E, Director-General of the Burma Meteorological Department, retired on 3 March 1966 and has been succeeded by Dr Tun Yin.

Meteorological Service of Portugal

Dr Antonio Silva de Sousa has succeeded Professor H. Amorim Ferreira as Director of the National Meteorological Service of Portugal.

Meteorological Service of Uruguay

Capitan de Navio Carlos F. Castro Pelaez has succeeded Capitan de Navio don Eduardo A. Laffitte as Director-General of the Meteorological Service of Uruguay.

REVIEWS

The climate of Africa, by B. W. Thompson. 20 in × 18 in, pp. 132, *illus.*, Oxford University Press, Amen House, London, EC4, 1965. Price: £9 8s.

This is the second of two substantial climatic atlases of Africa published in the last five years. The other is of course the 'Climatological Atlas of Africa'* (CAA), published by the Commission for Technical Co-operation in Africa South of the Sahara, and produced in collaboration with the World Meteorological Organization (WMO) African Regional Association. It may claim to be regarded as the model for a set of atlases, which, under WMO sponsorship, would ultimately cover all land areas of the world. One's first reaction, naturally, is to ask 'Why a second atlas?' This question is not specifically answered in the new atlas, but it is stated (in the Introduction) that the purpose of the work is to present maps which describe and assist in explaining the main elements of the climate of Africa, and (in the Preface) to assist in the training of the new generation of African meteorological personnel. In the reviewer's opinion, and in the light of these objectives the production of the new atlas is worth while, because firstly, it was wider in scope than the CAA, and secondly, it was printed entirely in black and white so that the meteorological services of the developing African countries could afford to distribute it more widely than the beautifully produced but presumably costly CAA.

* Lagos, Commission for Technical Co-operation in Africa South of the Sahara. *Climatological Atlas of Africa*. Lagos, 1961.

The atlas contains 132 charts; 75 of them on the scale 1:22M depict solar radiation, sunshine duration, rainfall, temperature and humidity for the African mainland and the Malagasy Republic. The remaining charts depict winds, contours, temperature and humidity at the standard upper levels from 850 to 200 millibars ; in order to show Africa in relation to somewhat wider aspects of the general circulation these maps are on the scale 1:30M and extend over a large part of Europe, southern Asia and the Indian Ocean.

Apart from the shading of land over 1000 metres on all except the charts of rainfall amount, no physical features are shown. Missing are the great lakes and rivers which are so helpful for spotting locations on the map of Africa. There is no latitude and longitude grid, except for a single line representing the equator ; the labelled marks at 5-degree intervals in the frame of each map are hardly adequate for precise location. But it should be said that to include these aids to location would have caused confusion, certainly on the more complicated maps.

Surprisingly, the only charts of surface elements for which the CAA and the new atlas have identical specifications are those of rainfall amounts, one chart of annual rainfall and one for each of the 12 months. Only some of the isopleths are common to both works, and it is good to note that with one or two minor and local exceptions the two atlases agree, even in detail so far as can be judged from sets of charts on different scales — greatly different scales for the annual charts.

The climatic factor of greatest economic importance to many parts of Africa is rainfall, and it is therefore appropriate that the charts of rainfall amount should be supplemented by others. These include monthly and annual charts showing the mean number of days for which the rainfall exceeds 1 mm. There is also a new set of charts showing the first month of the year and the numbers of subsequent consecutive months for which the rainfall exceeds certain specified amounts. These are particularly germane to the need for adequate rainfall at the time of planting of crops and during their subsequent period of growth. From the purely climatological aspect the charts clearly depict the seasonal distribution of rainfall. One would like to see, however, some information on rainfall variability.

Temperature is shown by isopleths of average maximum, average minimum, and mean daily temperatures for the four months January, April, July and October. Values are for station level and thus give a true comparison between the coastal and plateau areas. Charts for the same months show actual values of relative humidity near sunrise and midday. As with rainfall, these temperature and humidity charts give only broad pictures ; their small scale and complications of pattern prohibit the giving of detailed information, or the use of interpolation, in rugged country, but these are not the object of the work.

Monthly and annual charts of total radiation and bright sunshine are features which do not appear in the CAA. For these the author is to be commended. The radiation charts in particular are perforce based on scanty data, but give a useful first picture which doubtless could be reconsidered when more data become available.

The upper air charts mentioned earlier in this review are mean charts for the months of January, April, July and October. An indication of the heterogeneous nature of the data and perhaps also of some degree of subjectivity in interpretation is provided by comparison with the corresponding charts of the CAA. This is possible only for the contour charts for 850, 700 and 500 mb; the CAA has no charts for higher levels. At first sight, except outside the tropics, there are big differences between the contour patterns of the two atlases. Closer scrutiny however shows that where there are spot height differences they do not as a rule exceed 10 metres. The pattern differences, which arise mainly from showing a col in place of a closed system with a single contour, are therefore more apparent than real, especially considering that in low latitudes the contours are not closely related to the streamlines.

The 14-page Introduction is a clearly written description of the charts with a critical appraisal of the methods used in their preparation. It also contains a useful summary of the synoptic features of the tropics including the model contour patterns introduced into East African forecasting practice in the late 1950's by Johnson and Mörth.

The production of this atlas was made possible by the generosity of the Muntalp Foundation which bore the entire cost.

A. G. FORSDYKE

Computing methods by I. S. Berezin and N. P. Zhidkov. Vol. 1 and Vol. 2 (separate) 9½ in × 6½ in, pp. xxxiv + 464 in Vol. 1 and pp. xv + 679 in Vol. 2, *illus.*, (translated from the Russian by O. M. Blunn). Pergamon Press, Headington Hill Hall, Oxford, 1965. Price : £10 (for both).

Computing is not new in meteorology. Almost fifty years ago, in 1916, *The Computer's Handbook* appeared as an official Meteorological Office publication and ran into a second edition in 1921. While much of it was rather bread-and-butter stuff, such as computing barometric corrections, there was a lengthy chapter on computations associated with probability theory, backed up by practical meteorological examples. About the same time methods were being developed for correcting the trajectories of shells for the variations of the ambient meteorological conditions from standard values, involving the numerical solution of sets of ordinary differential equations, and not long afterwards computations were carried out in connexion with the partial differential equations of turbulence. Desk machines were used in all these computations. When electronic computers became available about fifteen years ago, the Meteorological Office was among the first users ; the volume and variety of computation now carried out are sufficient to warrant a computing laboratory based on the powerful KDF9 electronic computer. Meteorological problems require a great deal of computing skill, especially as many of them must necessarily be solved in a short time. Any new book on computing methods or techniques is therefore welcome.

The advent of electronic computers has inspired a lot of research into numerical analysis, multiplied the number of journals concerned with this particular aspect of mathematics and led to the publication of a great number of textbooks, all of them excellent in one way or another. As new methods became available textbooks which aimed at being comprehensive became rather large and lately the tendency has been to write monographs on

particular aspects of numerical analysis, so that there is a fairly complete coverage in the English language and a foreign text must have some particular appeal to make its translation worthwhile. In this case the translation is welcome because it gives an overall picture of computing methods in Russia.

There are two large volumes of the book by Berezin and Zhidkov, which aims at being comprehensive while realizing that it is not possible to include all worthwhile methods of attacking a problem ; it is based on a course of lectures given in Moscow State University, for specialists in computer mathematics, and is intended to cover a great deal of ground in a way that suggests methods of solving problems, rather than presenting algorithms for immediate use.

The date of original publication of the book is not given ; it is important since developments in some parts of numerical analysis have been rapid. From the contents the book was probably completed about 1960, so that some recent developments are not included as is inevitable in any publication like this.

The first volume is concerned with the problem of interpolation and the related problems of numerical differentiation and integration. It starts with an excellent chapter on how errors due to various causes can affect simple calculations. Then follows a long chapter, basic to this volume, on interpolation, which is marked by its clarity of exposition and illustrated by numerical examples. All the common interpolation polynomial formulae are dealt with — Lagrange, Newton, Gauss, Stirling, Bessel, Everett and Hermite — as well as interpolation theory for periodic functions and for more than one independent variable. This is rather a formidable chapter, as are the fifty or so problems at the end. One of the difficulties of reading texts on numerical analysis is the variation in notation adopted by different writers ; the notation used here is self-consistent but may look a little unfamiliar to some of us.

The next chapter deals with numerical differentiation and integration and is based on the interpolation formulae that have been obtained. Many integration formulae are given, the corresponding weight coefficients are given explicitly and there is also a section on how to deal with improper integrals and estimation of multiple integrals. The volume ends with two chapters on the approximation of a function by some more easily computed function and fitting by least squares.

The second volume is concerned with problems that perhaps are more familiar to meteorologists, the numerical solution of matrix problems and of differential equations. There is also a very useful chapter on solving non-linear equations. Since some of the classical methods of attacking matrix problems and of integrating differential equations are necessarily included in the text many of the familiar names, such as Runge-Kutta, Gauss-Seidel, etc., are to be found. When the developments are more recent the differences between this text and those which are written in English become more marked. Matrix methods associated with the names of Givens, Householder and Francis are not mentioned and do not appear to be given under any other name ; alternating direction implicit methods do not appear. On the other hand material developed by Russian mathematicians, which is not readily available in English texts as far as I know, is given in detail. Like

the first volume the text is carefully written and well illustrated by numerical examples both worked out and for solution.

These two large volumes will serve as a reference book and must surely be in the library of any computing unit. There are advantages in having a unified text rather than monographs, especially as regards notation and lack of repetition. Perhaps the volumes will be of more use to the professional computer user than to the occasional user, who now finds that the method employed for the solution of his problem is dictated more by the variety of library programmes available on the particular computer that he uses than by its suitability.

The books are beautifully produced and great care must have gone into the translation.

E. KNIGHTING

Chasseurs de typhons by Pierre André Molène. 8½ in×6 in, pp. 316, *illus.*, Flammarion, éditeur, 26 Rue Racine, Paris, 6^e, 1964. Price : 14F.

To M. Molène, as perhaps to any readers of this magazine, a typhoon or hurricane was just something one read of in the newspaper, a severe storm in distance places, a curious tropical phenomenon. But on his travels as an Air France navigator he found that to the inhabitants of those considerable parts of the world where typhoons pass they are terribly real, a recurrent threat of appalling disaster. So he set out to learn all he could about them and their effect on human life. His book, which is the result of his studies, tries to convey to others a vivid impression of what he found.

He saw and talked to meteorologists and others in Japan and visited the various American weather centres in the Pacific responsible for typhoon warnings. Later he was permitted to fly from Guam on weather reconnaissance flights with both the Typhoon Chasers of the USAF who penetrate typhoons in their Super-fortresses, and the U.S. Navy Typhoon Trackers with their massively-equipped radar-watch aircraft. As an experienced navigator he was well able to appreciate the task these men have and the success they achieve. Finally, he read all the books he could on the subject.

His book is, rightly, a popularization, not a scientific treatise. It is journalistic in style, and loaded, overloaded perhaps, with forceful statements and emotive adjectives. The accounts of his flights into and around typhoons are technically of interest, and to the layman they must be truly astonishing. As to typhoons in history, the origin of the emotive, to the Japanese, name 'Kamikaze' — 'Heavenly Wind' — was a typhoon that destroyed an invading Mongol fleet sent by Kubla Khan in A.D. 1281. Many other historically significant tropical cyclones are also described from the time of the Discoveries to World War II. However, M. Molène goes rather too far afield in his search for typhoon history, by including some winds that are not remotely appropriate. He mentions other effects of typhoons also, such as islands which, when short of rainwater, bless the storm that passes near, but not too near, and harmlessly refills the water tanks.

For one who has never experienced more than a severe gale the most potent illustration is perhaps the square-law relationship between the pressure exerted by the wind and its speed, and the account of the physical effects

of winds of 150 to 200 knots. The rain and the wind-driven tides do almost as much damage. In our temperate climate, however restless, we may be thankful for that qualifying adjective. By 'moderation in all things', we miss not only the best but also the worst.

D. G. HARLEY

OFFICIAL PUBLICATIONS

The following publications have recently been issued :

Ice accretion on aircraft. Meteorological Reports No. 9, 2nd edition. London, HMSO, 1965. Price 4s.

This is a revised edition of the publication of the same title which first appeared in 1951. It takes much the same form as the earlier edition but has been brought up to date, particularly with respect to some further investigational data which are included.

Modern aircraft design, equipment and operational techniques have much reduced the hazards of icing, but the subject still retains considerable importance. The publication can be easily read and understood by the informed layman and should be of interest and value to all airmen.

SCIENTIFIC PAPER

No. 22—*The solution of atmospheric diffusion equations by electrical analogue methods*, by J. B. Tyldesley, B.A.

A method of solving the two-dimensional diffusion equation by means of a resistance-capacity network is described, and an application to a continuously emitting cross-wind line source is given. This introduction to the basic analogue of diffusion is followed by a description of a more comprehensive computing method using a general-purpose analogue computer.

Methods of obtaining solutions for the continuous line source, continuous point source, and instantaneous line source are given, and some preliminary results are shown. A proposed extension of the method to deal with the instantaneous point source (cluster) is outlined. The variation with height of the parameters is not restricted to simple analytical forms.

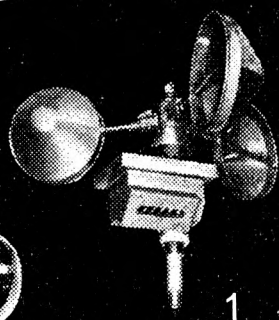
Daily Aerological Cross-sections at Latitude 30°N during the International Geophysical Year Period. London, HMSO, 1966. Price 55s.

These daily vertical cross-sections round the earth at latitude 30°N and from sea- or ground-level to 10 millibars (about 30 kilometres) show isotachs of south-to-north wind component, numerical values of west-to-east wind component and isopleths of temperature, potential temperature and humidity mixing ratio. The level of the tropopause is also indicated. The daily charts are followed by a mean chart for the month showing the same parameters. To facilitate their use the charts are printed in three colours.

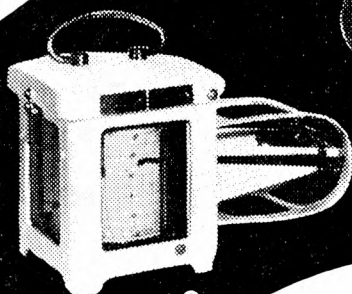
This volume, for the month of March 1958, is the first of a series of four and June, September and December will make up the other three volumes.

CORRIGENDUM

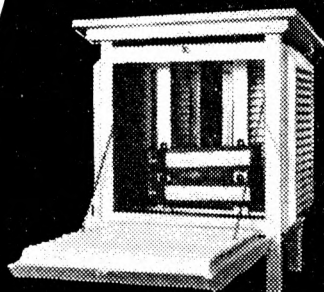
Meteorological Magazine, March 1966, Plates III and IV should be interchanged.



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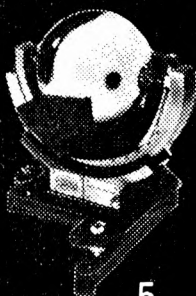
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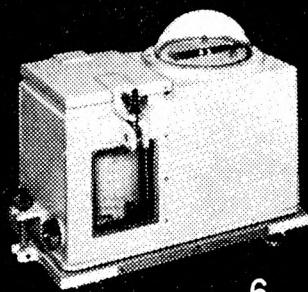
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CONTENTS

	<i>Page</i>
A radiometer sonde. D. G. James, D. W. S. Limbert and J. C. McDougall	161
Noctilucent clouds over western Europe during 1965. J. Paton	174
Tiros Operational Satellite T. H. Kirk ...	177
Physical limitations to crop growth. G. W. Hurst	178
Notes and news	
African lake-level changes, world rainfall pattern anomalies and related aspects of climatic change in the 1960's	181
Address by Professor P. M. S. Blackett, P.R.S.	183
Burma Meteorological Department	186
Meteorological Service of Portugal	186
Meteorological Service of Uruguay	186
Review	
The climate of Africa. B. W. Thompson. <i>A. G. Forsdyke</i> ...	186
Computing methods. I. S. Berezin and N. P. Zhidkov. <i>E. Knighting</i>	188
Chasseurs de typhons. P. A. Moléne. <i>D. G. Harley</i>	190
Official publications	191
Corrigendum	191

NOTICES

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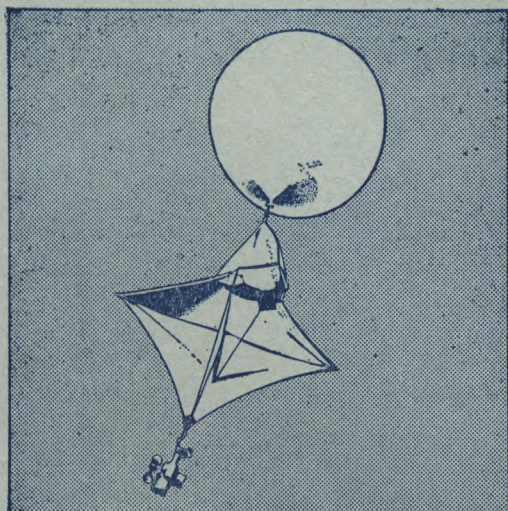
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CLIMATES OF THE U.S.S.R.

A. A. BORISOV

Edited by C. A. Halstead. Translated by R. A. Ledward.

A translation of the Russian edition, this is the most comprehensive book on the subject available today. It is essentially a book of climatic description in which climate is considered as a component of the natural geographical environment of great practical importance. It is especially noted for its use of air mass methods in classification and explanation.

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THE METEOROLOGICAL MAGAZINE

Vol. 95, No. 1128, July 1966

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SOME ASPECTS OF THE SYNOPTIC CLIMATOLOGY OF THE BRITISH ISLES AS MEASURED BY SIMPLE INDICES

By R. MURRAY and R. P. W. LEWIS

Introduction.—The Lamb catalogue of daily weather types over the British Isles covers the period from January 1873 to the present day. This catalogue is a slightly modified version of the original classification put forward by Lamb;¹ the classification consists of eight directional types each subdivided into three categories (e.g. westerly is subdivided into cyclonic westerly, westerly and anticyclonic westerly), and two non-directional types (cyclonic and anticyclonic). In addition there are some days on which the weather is unclassifiable under any of these types. Each type is designated by a letter as shown in Table I.

TABLE I—THE LAMB CATALOGUE OF DAILY WEATHER TYPES

	Anticyclonic	Unspecified	Cyclonic
Northerly	M	N	O
North-easterly	G	H	I
Easterly	D	E	F
South-easterly	J	K	L
Southerly	R	S	T
South-westerly	£	P	Q
Westerly	V	W	X
North-westerly	A	B	C
Non-directional	Y	U	Z

Each day since 1873 has been classified by one of the 27 letters given in Table I, following general rules laid down by Lamb.¹ The subjective element in the process of classifying inevitably leads to some differences of opinion on a small minority of occasions. Nevertheless the Lamb catalogue is a useful synoptic classification with practical applications. (It may be of interest to note that the percentage frequencies of occurrence of the three non-directional types Y, Z and U are 16 per cent, 14 per cent and 6 per cent respectively.)

For some purposes it is desirable to have a ready indication of the general character of a month (or other period). The full daily classification for a month contains a great deal of information about synoptic sequences and weather types, and it is often desirable to distil the synoptic essence, as it were, from such a detailed record; the indices of progression, meridionality, and cyclonicity discussed in the following sections are intended to perform this function.

A computer programme enabled the indices to be calculated for the 92 years of the catalogue in half-monthly and monthly blocks.

Derivation of the indices.—

(a) *Index of progression (P).*—The progressive synoptic types which affect the British Isles are generally those classified as westerly ; blocked types are easterly or meridional. The non-directional cyclonic and anticyclonic classes may be associated with either progressive or blocked situations. As the Lamb catalogue consists of the synoptic classification of over 33,000 days, it would be a mammoth task to re-examine synoptic maps for all these days in order to reclassify them into progressive or blocked types. The following objective specifications for the daily value of *P* are considered to be synoptically meaningful even though arbitrary. For the purpose of obtaining an index of progression representative of a period of about 15 days or more, uncertainties in the significance of scores on one or two days are usually unimportant. Certainly practical experience with the use of the *P*-index over monthly periods lends strong support to the meaningfulness of the specifications.

TABLE II—DAILY SCORES ALLOCATED TO *P* ACCORDING TO THE SYNOPTIC TYPE

Types			Score			
Westerly (ABC VWX LPQ)			2			
Easterly (GHI DEF JKL)			-2			
Meridional (MNO RST)			-1			
Unclassifiable (U)			0			
Non-directional cyclonic (Z)			depends on preceding types			
Non-directional anticyclonic (Y)			depends on preceding types			
Scores on days preceding Z or Y			Daily scores for sequences of <i>n</i> days of Z or Y			
			Z ₁	Z ₂	Z ₃	... Z _n
2	2	2	2	2	-2	... -2
-1/-2	2	2	2	0	-2	... -2
2	-1/-2	2	2	0	-2	... -2
-1/-2	-1/-2	2	2	-2	-2	... -2
		-1	-1	-1	-2	... -2
		-2	-2	-2	-2	... -2
			Y ₁	Y ₂	Y ₃	... Y _n
2	2	2	2	0	-2	... -2
-1/-2	2	2	0	-2	-2	... -2
2	-1/-2	2	0	-2	-2	... -2
-1/-2	-1/-2	2	-2	-2	-2	... -2
		-1	-1	-2	-2	... -2
		-2	-2	-2	-2	... -2

Note : U days are ignored, and -1/-2 signifies any type with scores -1 or -2.

It will be noted in Table II that the scores allocated to sequences of Z and Y types depend on the synoptic types over the preceding three days (U days being ignored) when the immediately preceding day is westerly. Thus an isolated Y following at least three westerly days is regarded as progressive, and a spell of Y's is regarded as becoming blocked after the second day as often happens when a mobile baroclinic high cell develops and slows down. However, all Y's following an isolated westerly day are regarded as blocked. Moreover, it will be noted that the scores allocated to Z or Y days are always negative if the immediately preceding day is not westerly (ignoring U days). With a mixed sequence of Y and Z types (i.e. Y following Z or Z following Y) the convention is to treat the Y (or Z) according to whether the preceding Z (or Y) is scored as progressive (2), blocked (-2) or meridional (-1).

(b) *Meridional indices (S and M).*—Scores are allocated to each synoptic type as shown in Table III.

TABLE III—DAILY SCORES ALLOCATED ACCORDING TO MERIDIONAL FLOW

Types	Score
MNO (northerly)	-2
ABC GHI (north-west or north-east)	-1
YUZ VWX DEF	0
LPQ JKL (south-west or south-east)	1
RST (southerly)	2

The *S*-index for, say, a month is taken as the algebraic sum of the daily meridional scores. In other words the *S*-index gives the bias toward southerly (positive) or northerly (negative) types during the month.

The *M*-index is the sum of the daily scores irrespective of sign. *M* is a measure of the total meridionality during the month.

(c) *Index of cyclonicity (C)*.—The scoring system is shown in Table IV.

TABLE IV—DAILY SCORES ALLOCATED TO *C* ACCORDING TO THE SYNOPTIC TYPE

Types	Score
Y (non-directional anticyclonic)	-2
MGD JR _L VA (directional anticyclonic)	-1
NHE KSP WBU	0
OIF LTQ XC (directional cyclonic)	1
Z (non-directional cyclonic)	2

Cyclonic types are given positive scores and anticyclonic types negative scores. The *C*-index for, say, a month is taken as the algebraic sum of the daily scores. The *C*-index is thus a measure of the net cyclonic or anticyclonic character of the month.

Calculation of the indices.—The indices were calculated by electronic computer for 12×92 months (1873–1964) of the Lamb catalogue. In fact the computer programme enabled a print-out to be made of the positive and negative scores achieved during the first 15 days and the second half of each month of the 92 years. These data readily gave the indices for half-monthly, monthly and mid-month to mid-month periods. The monthly and mid-month to mid-month scores for each year were also ranked and decile, quintile and tercile boundaries computed to facilitate the use of the indices in different applications.

A month is certainly a suitable unit of time over which the indices may be calculated. However, the indices may be profitably computed for various extended periods, such as a season or a year, although it is suggested that a lower limit for practical use is 10 days.

It is of interest that the four indices for a particular month can be worked out by hand in two or three minutes.

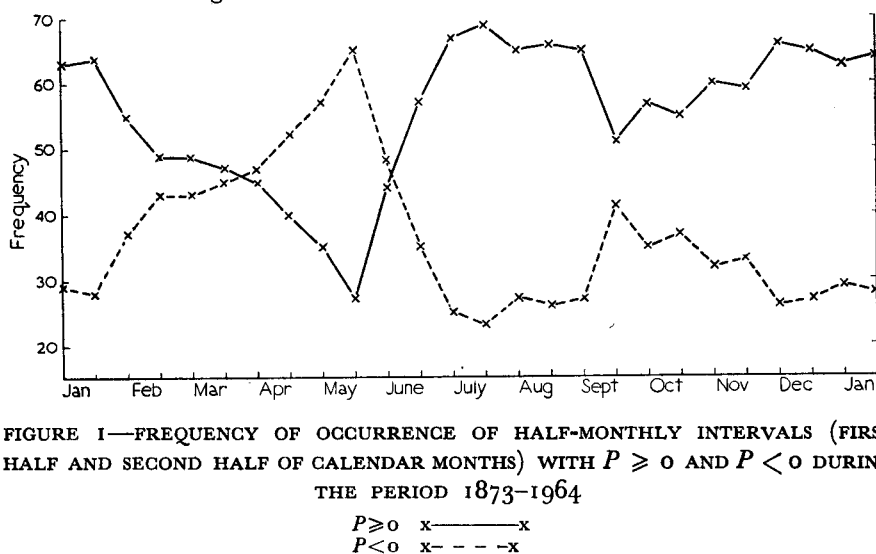
***P*-index—secular and seasonal variations.**—The secular trend and seasonal variations in progression and blocking in the neighbourhood of the British Isles may be seen from Table V.

TABLE V—MONTHLY AND YEARLY MEAN VALUES OF *P* FOR SPECIFIED PERIODS

Period	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
1873-79	13	-4	9	-1	-3	1	17	6	13	5	-1	5	60
1880-89	3	3	-5	-13	-13	-7	12	9	-1	-1	8	17	12
1890-99	5	5	13	-5	-15	-1	15	11	15	2	4	9	58
1900-09	27	12	11	6	-7	-8	17	25	1	15	9	19	127
1910-19	19	11	7	9	-9	12	9	13	9	3	16	29	128
1920-29	34	19	7	0	7	18	23	34	26	17	16	27	228
1930-39	25	6	5	-4	-12	9	30	15	4	17	14	16	125
1940-49	5	4	-8	12	-19	14	9	9	17	0	5	16	64
1950-59	5	-3	-18	-1	-17	2	8	4	16	9	5	16	26
1960-64	-5	-10	-16	-10	1	15	7	8	6	-5	0	0	-9
1873-1964	13	4	1	0	-9	7	16	14	10	5	8	15	84

Table V clearly demonstrates a secular trend in the yearly P -index from the very low value in decade 1880–89 to the notable maximum in decade 1920–29, followed by more or less steadily diminishing values. Evidently progressive synoptic types dominated the first 40 years of this century, and blocking was much more frequent before 1900 and after 1940. To a great extent the secular changes in the annual P -indices were closely reflected in the seasonal variations, particularly in winter and summer. Lamb² has demonstrated these trends from consideration of the frequency of his weather types.

The seasonal variation in blocking and progression may be seen from Figure 1, which shows the frequency of occurrence of $P \geq 0$ (i.e. overall progression) and $P < 0$ (i.e. overall blocking) for half-monthly periods (1873–1964). The predominance of progression in December and January weakens rapidly in February. On this half-monthly time scale, progression is marginally more frequent than blocking in March. Blocking becomes the more likely mode in April and increases in frequency to a notable maximum in late May, followed by a rapid fall-off in frequency in June. The important changes in frequency of the two basic types in June are undoubtedly part of a larger-scale circulation reorganization (see Brooks,³ and Bryson and Lahey⁴). In summer the major type is obviously progression. However, a well-marked decrease in frequency of progression sets in during September in the 'normal' year and leads to a secondary maximum of blocking in late September. Thereafter a slow and somewhat irregular increase in progression takes place in the autumn, culminating in a sharper increase in progression and decrease in blocking in early December. The seasonal pattern of progression and blocking is also apparent in the long-period averages of the P -index for half-months throughout the year (not reproduced). These averages show a more pronounced increase in blocking from early to late April, a secondary maximum of blocking in early October rather than in late September and a more marked increase in progression from late November to early December than are indicated in Figure 1.



Sumner⁵ has presented monthly statistics for the period 1949-56 of the frequency of blocking anticyclones in various longitude bands ; in particular Table III of his paper gives figures for the longitude zone 0 to 19°W. It is of some interest to compare the indications of blocking throughout the year as suggested by our *P* values with Sumner's statistics. Both sets of figures agree that the two minima of blocking occur in July/August and in December/January, and that the main maximum is in spring with a secondary maximum in autumn. The main difference is that Sumner's data show March (59 occurrences) and May (57 occurrences) as equally blocked months whereas our Table II or Figure 1 indicates that May is the month of maximum blocking. However, mean monthly *P* values compiled for the same 8 years which Sumner investigated give *P* = -18 in March and *P* = -16 in May ; these *P* values are clearly consistent with Sumner's data on the frequency of occurrence of blocking anticyclones. The 8 years considered by Sumner, and indeed the 25 years from 1940 to 1964, were in fact characterized by much more blocking in March than the 50 years or so before 1940.

***S* and *M*-indices—secular and seasonal variations.**—Some light may be thrown on the nature of the blocking which occurred in the different decades by examining the mean values of the meridional indices, shown in Tables VI and VII.

TABLE VI—MONTHLY AND YEARLY MEAN VALUES OF *S* FOR SPECIFIED PERIODS (SOUTHERLY BIAS BEING POSITIVE)

Period	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
1873-79	11	3	-4	3	-4	6	0	3	1	10	-3	1	27
1880-89	15	10	3	0	4	-2	3	2	2	0	4	3	44
1890-99	4	9	-1	1	1	0	-5	1	3	0	10	10	33
1900-09	8	0	-2	2	1	2	-1	1	8	6	4	6	35
1910-19	3	6	1	-4	3	-5	-6	-2	1	2	-3	3	-1
1920-29	6	6	5	-3	-2	0	-3	0	-1	7	5	2	22
1930-39	1	1	4	-3	1	1	-3	2	1	-3	3	1	6
1940-49	4	-1	3	2	2	-2	-3	-3	2	9	2	5	20
1950-59	-2	-3	9	-7	-3	-5	-6	0	2	4	2	1	-8
1960-64	1	9	9	5	-5	-6	-10	-7	4	2	-1	-4	-3
1873-1964	6	4	3	-1	0	-2	-2	0	2	4	3	3	20

TABLE VII—MONTHLY AND YEARLY MEAN VALUES OF *M* (SUM OF MERIDIONAL TYPES) FOR SPECIFIED PERIODS

Period	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
1873-79	16	13	14	14	11	13	10	9	13	19	17	13	162
1880-89	20	17	15	13	14	14	14	16	15	13	11	16	178
1890-99	16	15	11	13	12	10	12	15	11	18	18	16	167
1900-09	14	12	8	13	15	12	9	7	14	16	12	12	144
1910-19	10	9	9	8	8	8	11	5	10	12	10	8	108
1920-29	11	14	12	12	11	10	6	6	7	11	14	15	129
1930-39	7	9	14	12	12	8	6	7	10	17	10	6	118
1940-49	15	13	10	11	13	11	11	10	9	16	18	14	151
1950-59	18	19	22	17	18	14	11	14	11	15	15	15	189
1960-64	11	19	21	18	15	10	14	14	14	16	9	18	179
1873-1964	14	14	14	13	13	12	10	10	11	15	13	13	152

It appears that the most meridional decade was 1950-59 and the runner-up was 1880-89 (1960-64 was also very meridional). There were some remarkable differences between the two decades as regards the direction of the meridional flow, as shown in Table VI ; a strong southerly bias was a feature of the 1880's, especially in winter (*S* = 28), whereas in the 1950's a northerly bias was marked in summer (*S* = -11) and winter (*S* = -4). In both decades

the autumns showed a southerly bias. The least meridional decade was 1910-19, then came 1930-39, 1920-29 and 1900-09 in increasing order of meridionality. It is of interest that the least meridional decade showed a pronounced bias towards northerlies in the summer, as indeed did the most meridional decade, but the frequency of northerlies was of course less in the 1910's than in the 1950's.

The long-period average total meridionality (M) shows a minimum in the summer and a rather uniform higher value for the rest of the year with the maximum in October. The various decades generally had their lowest meridionality in the summer months as well, but the highest value was not always in October. There is a striking contrast between decade 1910-19 and decade 1950-59; on average, the month of least meridionality in the very meridional decade 1950-59 was almost as meridional as the month of greatest meridionality in decade 1910-19.

The main features of the long-period seasonal variation in S are the definite tendency to northerlies in the summer and southerlies from autumn to early spring. Even in decades when the winter southerly bias was weak or reversed (1950-59) or when the summer northerly bias was similarly abnormal (1880-89), there was a clear trend to a more northerly bias in summer relative to winter.

C-index—secular and seasonal variations.—The variations in the C -index may be seen from Table VIII.

TABLE VIII—MONTHLY AND YEARLY MEAN VALUES OF C FOR SPECIFIED PERIODS
(CYCLONIC BIAS BEING POSITIVE)

Period	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
1873-79	-6	-6	-5	-5	-11	-6	-5	4	-7	-4	-4	-7	-62
1880-89	-8	-4	-8	-6	-8	-13	2	-6	-5	-3	0	0	-59
1890-99	-7	-9	-5	-10	-10	-10	-5	-5	-8	-2	-4	-2	-77
1900-09	-2	-3	1	-3	-4	-6	-5	2	-8	4	-3	3	-24
1910-19	1	0	3	-8	-7	-1	-1	9	-9	1	5	6	-1
1920-29	4	2	-3	6	2	-3	3	7	-5	-2	-1	-1	9
1930-39	-2	-6	0	-5	-6	-7	7	-5	-6	0	-2	-3	-35
1940-49	0	-5	-12	-4	-6	-7	1	-3	-2	-7	-1	-8	-54
1950-59	-4	2	-5	-9	-4	1	1	8	-4	-6	1	3	-16
1960-64	-5	-6	-4	0	-7	-3	5	15	-3	-1	6	-5	-8
1873-1964	-3	-4	-4	-4	-6	-5	0	3	-6	-2	0	-1	-32

The most cyclonic decade was 1920-29 and the most anticyclonic was 1890-99, according to Table VIII.

The most cyclonic month in the 'normal' year is August, with July and November next; the most anticyclonic months are May and September followed closely by June, but the whole period from late winter to early summer tends to have an anticyclonic bias. However, the seasonal variation suggested by the long-term averages was not always repeated in every decade. Particularly noteworthy were the unusually anticyclonic nature of the summer months of the decade 1890-99 and the cyclonic nature of April and May in the decade 1920-29. The main features of the most recent five-year period were the unusually cyclonic high summers and the anticyclonic winters.

Comparison of the monthly averages of C with the average England and Wales rainfall (R) for the period 1873-1964 is shown in Figure 2. A correlation between C and R is evident. The six wettest months were also the months with the six highest C values. It is noteworthy that Figure 2 suggests that the same numerical value of C is generally associated with relatively less

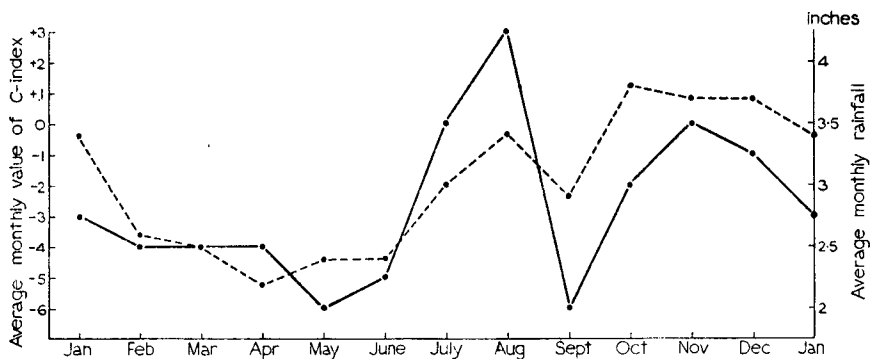


FIGURE 2—AVERAGE MONTHLY *C*-INDEX AND AVERAGE MONTHLY RAINFALL OVER ENGLAND AND WALES FOR THE PERIOD 1873-1964
C —————
 Rainfall - - - - -

rain in high summer than in autumn and winter. This feature is probably related to the character and intensity of the cyclonic systems, which are in general more vigorous from early autumn to mid-winter when evaporation and heat transfer from the surrounding seas are greatest.

Quintiles and extremes.—The actual numerical value of any of the indices is, of course, of little significance by itself; there must be some standard for comparison. For this purpose it is useful to know whether a particular value of any index is high or low relative to the other members of the set. This can most easily be done by using deciles, quintiles or terciles. The 92 years of the catalogue months of the same name were ranked according to the values of each of the indices, and the approximate percentile boundaries were obtained. The quintile boundaries, which are generally the most useful in practice, are shown in Table IX.

TABLE IX—QUINTILE BOUNDARY VALUES OF *P*, *S*, *C* AND *M* FOR EACH MONTH

(a) <i>P</i> (progression)											
Quintile	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov. Dec.
5-4	35.5	24.5	24.5	16.5	9.5	23.5	32.5	32.5	31.5	26.5	25.5 35.5
4-3	20.5	11.5	7.5	2.5	-5.5	8.5	19.5	21.5	16.5	13.5	11.5 24.5
3-2	11.5	-4.5	-8.5	-8.5	-18.5	-2.5	11.5	8.5	4.5	-0.5	2.5 12.5
2-1	-4.5	-15.5	-23.5	-18.5	-27.5	-12.5	-3.5	-1.5	-7.5	-14.5	-8.5 -2.5
(b) <i>S</i> (southerly bias)											
Quintile	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov. Dec.
5-4	12.5	15.5	9.5	5.5	8.5	3.5	3.5	5.5	7.5	12.5	10.5 11.5
4-3	7.5	8.5	4.5	1.5	3.5	-0.5	-0.5	1.5	3.5	5.5	5.5 4.5
3-2	1.5	1.5	-0.5	-3.5	-2.5	-3.5	-4.5	-1.5	0.5	0.5	0.5 0.5
2-1	-2.5	-6.5	-6.5	-7.5	-7.5	-7.5	-8.5	-5.5	-3.5*	-2.5	-5.5 -4.5
(c) <i>C</i> (cyclonicity)											
Quintile	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov. Dec.
5-4	7.5	6.5	8.5	3.5	4.5	2.5	10.5	14.5	3.5	7.5	7.5 7.5
4-3	0.5	0.5	0.5	-0.5	-3.5	-1.5	5.5	5.5	-2.5	1.5	1.5 1.5
3-2	-5.5	-6.5	-7.5	-8.5	-10.5	-7.5	-2.5	-3.5	-8.5	-5.5	-3.5 -3.5
2-1	-12.5	-15.5	-15.5	-13.5	-16.5	-16.5	-11.5	-12.5	-15.5	-12.5	-8.5 -9.5
(d) <i>M</i> (meridionalty)											
Quintile	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov. Dec.
5-4	20.5	19.5	19.5	18.5	18.5	15.5	14.5	14.5	17.5	21.5	19.5 17.5
4-3	15.5	15.5	14.5	13.5	14.5	11.5	10.5	10.5	12.5	15.5	14.5 13.5
3-2	11.5	10.5	11.5	10.5	10.5	8.5*	8.5	8.5	9.5	10.5	11.5 9.5
2-1	7.5	6.5	6.5	8.5	7.5	6.5	5.5	4.5	6.5	7.5	7.5 5.5*

Asterisks indicate the less-reliable figures.

From Table IX it is clear that, for example, the Januarys in which P was greater than 35.5 (in practice $P \geq 36$) consisted of the 20 per cent most progressive Januarys of the entire set of 92. As another example, January 1962 ($P = 31$) may be classified as in quintile 4, which puts this January in perspective as a month with predominantly progressive synoptic types, although not in the top category of progressiveness.

The extreme values of the indices and years of occurrence are summarized in Table X.

TABLE X—EXTREME MONTHLY VALUES OF P , S , C AND M WITH DATES OF OCCURRENCE IN BRACKETS

	P	S	C	M
Jan.	62 (1921, 1923) -54 (1963)	26 (1883, 1885) -21 (1945)	21 (1948) -28 (1964)	34 (1885) 0 (1919, 1920, 1921, 1933)
Feb.	50 (1908, 1910, 1943) -54 (1947)	28 (1899) -19 (1889)	24 (1923) -34 (1932)	31 (1902) 0 (1935)
Mar.	56 (1921) -41 (1909, 1964)	30 (1957) -19 (1878)	37 (1909) -46 (1953)	31 (1950) 0 (1934)
Apr.	52 (1927) -38 (1884)	17 (1894) -16 (1951)	23 (1920) -41 (1938)	33 (1950) 0 (1914, 1948)
May	40 (1934) -44 (1935)	15 (1878) -22 (1902)	30 (1958) -49 (1896)	38 (1954) 1 (1925, 1934)
June	48 (1922, 1923) -41 (1958)	22 (1879) -19 (1923)	32 (1912) -31 (1887)	26 (1879) 1 (1934)
July	56 (1915) -36 (1955)	20 (1904) -23 (1948)	24 (1936) -41 (1955)	28 (1883) 0 (1925, 1934)
Aug.	54 (1922, 1929) -36 (1947)	26 (1950) -21 (1960)	38 (1963) -30 (1880)	33 (1887) 0 (1921, 1947)
Sept.	60 (1923) -46 (1894)	20 (1901) -21 (1952)	22 (1946) -42 (1959)	30 (1903) 0 (1917, 1924)
Oct.	59 (1923) -48 (1960)	42 (1908) -23 (1887)	33 (1907) -28 (1879, 1962)	42 (1908) 0 (1935, 1937)
Nov.	58 (1917, 1922) -30 (1937)	28 (1881, 1902) -27 (1910)	31 (1963) -30 (1942)	32 (1921) 2 (1887, 1919, 1928)
Dec.	57 (1929) -46 (1927)	29 (1888) -16 (1950)	29 (1959) -26 (1879)	35 (1888) 0 (1935)
Year	62 (Jan. 1921, 1923) -54 (Jan. 1963, Feb. 1947)	42 (Oct. 1908) -27 (Nov. 1910)	38 (Aug. 1963) -49 (May 1896)	42 (Oct. 1908) 0 (17 months)

It will be seen from Table X that the biggest range of variation of the P -index was observed in January (116 units, i.e. from -54 to 62) and the smallest in May (84); for the S -index the biggest range was in October (65) and the smallest in April (33); for C the biggest range was in March (83) and the smallest in January (49); and for M the biggest range was in October (42) and the smallest in June (25). The contrast between the extreme progressiveness of the mild Januarys of 1921 and 1923 and the extreme blocking of the exceptionally cold months of February 1947 and January 1963 is particularly worthy of note amongst the many interesting climatological facts contained in Table X.

Interrelations between the indices and rainfall on a monthly time-scale.—For each month of the year multiple contingency tables relating S , C and R (average rainfall over England and Wales) and C , P and R were prepared. For this purpose the P , S and C -indices were classified in terciles and R in two categories according to whether R was above or below the median value.

The contingency tables (not reproduced) show clearly that R (rainfall) is closely correlated with the C -index ; that the correlation between S and R is virtually zero ; and that there is some correlation between P and R which arises mainly from the moderate positive correlation between P and C . A month characterized by indices C and P in tercile 3 (i.e. progressive and cyclonic) has a high probability of having rainfall above normal over England and Wales ; similarly when the monthly C and P -indices are in tercile 1 the England and Wales rainfall is very likely to be below normal.

Contingency tables were also prepared to show the relationship between C in quintiles and R in terciles. A typical association is shown in Table XI.

TABLE XI—ASSOCIATION BETWEEN C (MONTHLY CYCLONICITY INDEX) IN QUINTILES AND R (AVERAGE MONTHLY ENGLAND AND WALES RAINFALL) IN TERCILES IN JANUARY (1873–1964)

		(anticyclonic)		C (quintiles)		(cyclonic)
		1	2	3	4	5
R (terciles)	1 (dry)	13	11	3	3	0
	2	4	7	12	7	2
	3 (wet)	1	1	4	9	15

Table XI and similar tables for other months indicate a highly significant statistical relationship between C and R in all months of the year. The most anomalous cases are undoubtedly those in which C_1 (quintile 1 of C) occurs with R_3 (tercile 3 of R) and C_5 with R_1 . No anomalous case of these types was observed in February, September and November of the period 1873–1964 ; these three months exhibit a particularly high correlation between C and R . At the other extreme there were four anomalous cases in May (viz. C_1/R_3 in 1914 and 1943, C_5/R_1 in 1939 and 1940). Nevertheless the association between C and R in May is still highly significant (at 1 per cent level at least). It is of interest that there were six occasions when C_5 was associated with R_1 ; these all occurred from April to August when weak or small-scale depressions are much more likely than in autumn and winter.* On the other hand eight occasions of association between C_1 and R_3 were scattered throughout the year ; anomalous situations of this type may arise when a predominantly anticyclonic month has a few vigorous cyclonic systems which produce much rain from very moist and unstable air masses over England and Wales.

Interrelations between the indices and temperature on a monthly time-scale.—The association between the monthly P , S and C indices (in quintiles) and the mean monthly temperature anomaly (ΔT , in terciles) in central England was next examined. Tercile 1 for ΔT corresponded to the most negative (i.e. cold) anomaly.

There is a highly significant direct association between P and ΔT in the months December to March, which may be illustrated by the January relationship in Table XII ; it is clear that blocked types tend to be cold and

*In this connexion it needs to be noted that a day is classified as type Z (i.e. cyclonic) in the Lamb catalogue when a depression of any intensity is observed anywhere over the British Isles on at least one main synoptic chart ; thus a Z day with a weak or small-scale low over the periphery of the British Isles (e.g. over northern Scotland) might not be associated with much rainfall over England and Wales.

progressive types tend to be warm. April and November also show a significant though less close direct association between P and ΔT , but the relationship becomes of little or no practical use in the warmer part of the year from May to October.

TABLE XII—ASSOCIATION BETWEEN P (MONTHLY PROGRESSION INDEX) IN QUINTILES AND ΔT (MEAN MONTHLY CENTRAL ENGLAND TEMPERATURE ANOMALIES) IN TERCILES IN JANUARY (1873–1964)

		(blocked)	P (quintiles)			(progressive)
		1	2	3	4	5
ΔT (terciles)	1 (cold)	15	5	8	2	0
	2	1	10	9	5	6
	3 (warm)	1	3	2	10	14

There is generally a significant direct association between S and ΔT in all months, although it is rather weak in the winter. The association is usefully close in all non-winter months; it is particularly good in May, August and September, as exemplified by the May relationship shown in Table XIII.

TABLE XIII—ASSOCIATION BETWEEN S (MONTHLY SOUTHERLY BIAS INDEX) IN QUINTILES AND ΔT (MEAN MONTHLY CENTRAL ENGLAND TEMPERATURE ANOMALIES) IN TERCILES IN MAY (1873–1964)

		(northerly)	S (quintiles)			(southerly)
		1	2	3	4	5
ΔT (terciles)	1 (cold)	11	9	7	1	1
	2	6	8	7	5	5
	3 (warm)	0	5	5	8	13

The relationship between C and ΔT is also of interest. It is not surprising that a highly significant inverse association exists between C and ΔT in the summer months (i.e. a cyclonic month tends to be cool), which may be illustrated by the July relationship shown in Table XIV.

TABLE XIV—ASSOCIATION BETWEEN C (MONTHLY CYCLONICITY INDEX) IN QUINTILES AND ΔT (MEAN MONTHLY CENTRAL ENGLAND TEMPERATURE ANOMALIES) IN TERCILES IN JULY (1873–1964)

		(anticyclonic)	C (quintiles)			(cyclonic)
		1	2	3	4	5
ΔT (terciles)	1 (cold)	3	2	7	9	9
	2	2	8	6	6	9
	3 (warm)	15	6	4	4	1

The summer type of correlation between C and ΔT also applies in a weaker form in April, May and September. However, from November to February the association is direct (i.e. an anticyclonic month tends to be cold), but the relationship is not quite so close as the inverse association of high summer. In March and October there is little or no association between C and ΔT , and these months are evidently transitional.

Examination of all the contingency tables relating P , S or C with ΔT suggests that for practical purposes the best associations in particular months are as follows :

- (a) between P and ΔT in December, January, February and March (positive correlation) ;

- (b) between S and ΔT in April, May, September, October and November (positive correlation) ;
- (c) either between S and ΔT (positive correlation) or between C and ΔT (negative correlation) in June, July and August (these two relationships are equally good).

The associations between the various indices and temperature over central England are broadly as would be expected from synoptic and climatological experience. Similarly, for other parts of the British Isles the nature of the relationships should be broadly inferable from the indices, particularly when the P , S and C indices are sufficiently different from 'normal' values to imply predominant synoptic types.

There is no *a priori* reason to expect any worthwhile association between M and ΔT . However, the variability of temperature should be related to the index of meridionality (M), but this aspect has not been systematically investigated.

Concluding remarks.—The indices conveniently categorize in a synoptically meaningful way the main features of the weather over the British Isles over extended periods of time. The indices are particularly helpful when comparisons have to be made between weather types of different months or mid-month to mid-month periods. Such comparisons inevitably arise in searching for analogous situations in the historical record. Analogues of the large-scale circulation may be selected because of similarity in the distribution over much of the northern hemisphere of monthly mean temperature or pressure or for other reasons, but it must always be necessary to be aware of the main synoptic character of the British Isles weather associated with such broad-scale analogues: the indices usefully add this essential, local information. Moreover the indices may equally well be used to summarize the main aspects of the weather in the month (or 30-day period) following the analogue.

A search for analogues of the synoptic situation near the British Isles may be made directly through the indices, but analogues selected in this way alone are unlikely in general to be satisfactory for long-range forecasting purposes unless supported by similarity in the large-scale circulation. However, some experiments incorporating the objective (computer) selection of analogues using the P , S , C and M -indices are planned.

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TESTS OF THUNDERSTORM FORECASTING TECHNIQUES

By W. E. SAUNDERS

Introduction.—A description is given of tests of various thunderstorm forecasting techniques carried out at certain forecasting offices under the author's control during the summer of 1965.

The methods tested.—The techniques used are listed below :

The Similä method.—Similä¹ provided an instability index Δ_T for the layer between 850 and 500 mb, assuming the former to be the condensation level. Δ_T is obtained from a diagram, as a function of the temperatures at these two levels. A humidity index Δ_v is obtained as a function of temperature and dew-point on another diagram. Values of Δ_T and Δ_v are drawn on a thunderstorm tendency chart. The thunderstorm tendency is assessed with the aid of numerical values of the indices and is large for large positive values of Δ_T and Δ_v .

The Showalter method.—This well-known index² is simply obtained by assuming ascent from 850 to 500 mb at the appropriate adiabatic lapse rates and then subtracting the resulting 500 mb temperature from the observed 500 mb temperature. Negative values indicate instability.

The Galway method.—Galway³ introduced use of the forecast maximum surface temperature and the mean dew-point in the lowest 3000 feet. Using these, and assuming a dry adiabatic through the forecast surface maximum temperature, proceed to the corresponding condensation level, thence along the saturation adiabatic to 500 mb. Then proceed as with Showalter. This is known as the 'lifted index'.

The Rackliff method.—Rackliff's⁴ index (Δ_T) is given by

$$\Delta_T = \theta_{w900} - T_{500}$$

where θ_{w900} = 900 mb wet-bulb potential temperature (°C)

T_{500} = 500 mb dry-bulb temperature (°C).

High values indicate instability. In non-frontal situations a value exceeding 30 is regarded as critical.

The Jefferson method.—Jefferson⁵ suggested a modification to Rackliff's index, such that it is independent of the general temperature of the air mass. He also introduced the 700 mb dew-point depression to allow for presence of dry air in middle levels. Jefferson's index (T_{mj}) is given by

$$T_{mj} = 1.6\theta_{w900} - T_{500} - \frac{1}{2}T_{d700} - 8$$

where θ_{w900} = 900 mb wet-bulb potential temperature (°C)

T_{500} = 500 mb dry-bulb temperature (°C)

T_{d700} = 700 mb dew-point depression (°C).

A threshold value of 28 is suggested.

The Boyden method.—Boyden⁶ drew attention to the necessity for allowing for advective changes in the upper air. He proposed an index (I) given by

$$I = Z - T - 200$$

where Z = 1000–700 mb thickness (decametres)

T = 700 mb dry-bulb temperature (°C).

This therefore strictly applies only to the layer up to 700 mb. The threshold value for thunderstorms is 94. Isopleths of the index are drawn on charts and assumed to move with the 700 mb wind.

The Miller and Starrett method.—This method⁷ differs from those already listed. It consists of a graph of 850–500 mb temperature difference against 500 mb temperature, with a straight line separating thunderstorm occasions from others. The authors recommend using the diagram in conjunction with the current moisture pattern and possible trigger action.

The Hanssen method.—This is a purely objective method. Hanssen⁸ related the incidence of thunderstorms in the Netherlands to four parameters: the barometric pressure, the extreme latitude of the 500 mb trough or ridge, the saturation deficits at 850 and 700 mb, and the 1000–700 mb thickness minus the 700–500 mb thickness. Diagrams are provided to obtain from the first two of these a parameter X , and from the last two a parameter Y . Values of X and Y are then used with a contingency table to produce a thunderstorm forecast.

Testing arrangements.—Methods were allocated to stations such that, where possible, a station which was already using a method should be responsible for testing it.

Tests were carried out on Mondays to Fridays in the period 1 April to 30 September 1965.

Forecasters were asked to use 0000 GMT upper air data with the chosen technique, allow for effects of advection and surface heating as seemed appropriate, and record a simple 'yes' or 'no' forecast for thunderstorms in the area covered by the Manby group of stations in the period 1200 – 2359 GMT. The area mentioned, and the locations of stations taking part in the tests, are shown in Figure 1.

The one exception to the procedure mentioned was that Hanssen's method is purely objective, so that no adjustments were made for advection or heating.

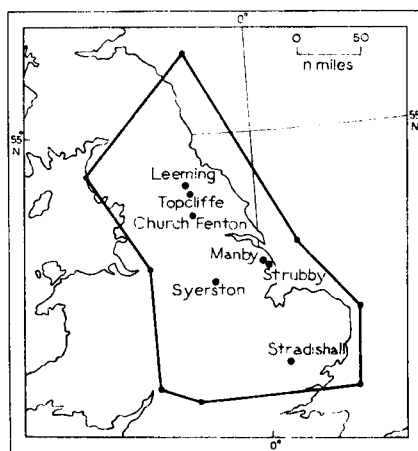


FIGURE 1—AREA COVERED BY TESTS, AND STATIONS TAKING PART

Also, at the time the tests were made, a diagram was not available for dealing with troughs or ridges lying to east of the area and on those occasions this technique was abandoned.

A record of whether thunderstorms actually occurred on each test day was kept in the main office at Manby, and subsequently used in marking results from the other stations. SFLOC reports were counted positive.

For purposes of comparison, it was considered worthwhile to include, with the results obtained for the various individual techniques, the results obtained by the Manby forecasters in the course of their ordinary forecasting practice. It was hoped that by this means, the results would show under what conditions general forecasting practice could be improved by use of the newer techniques, and which techniques are best suited for use in different circumstances. In the tables giving the results of tests, these Manby forecasts are included under the heading 'general practice'. The question whether or not thunderstorms were forecast was decided by ascertaining whether or not thunderstorms had been included in the routine forecasts or aviation warnings issued by Manby up to 1200 GMT. These forecasts and warnings relate to the same area as that covered by the tests, and the 'general practice' results are therefore fully comparable with those obtained by the other stations. Aids which were available in the forecast room at Manby included charts of the Boyden and Similä instability indices, and the objective diagrams of Hanssen. No allowance can be made for the extent to which any or all of these were used by forecasters. It may, however, be said that the separate techniques which were being tested at Manby were not dealt with by the forecasters responsible for the general forecasting, and every effort was made to test these techniques in an independent way.

Overall accuracy of thunderstorm forecasts.—Table I shows the overall correctness of forecasts that thunderstorms would or would not occur. This includes the results for all days of the tests.

TABLE I—OVERALL ACCURACY OF FORECASTS THAT THUNDERSTORMS WOULD OR WOULD NOT OCCUR

Method	Testing station	Number of forecasts	Number correct	Percentage correct
General practice	Manby	126	99	79
Rackliff	Syerston	119	91	76
Similä	Manby	125	90	72
Boyden	Topcliffe	123	87	71
Jefferson	Strubby	124	87	70
Miller/Starrett	Church Fenton	123	86	70
Hanssen	Manby	92*	64	70
Galway	Stradishall	124	81	65
Showalter	Leeming	124	80	65

*33 abandoned cases, on 8 of which thunderstorms occurred.

Overall accuracy of forecasts on frontal or trough days.—It is a matter of forecasting experience that thunderstorms are often more difficult to forecast on days when there is a front or isobaric trough over the area than on the straightforward convection days. The test results for these occasions were therefore analysed separately from the remainder.

Table II gives the overall accuracy of forecasts on days when there was a front or isobaric trough over the area.

TABLE II—OVERALL ACCURACY OF FORECASTS THAT THUNDERSTORMS WOULD OR WOULD NOT OCCUR ON FRONTAL OR TROUGH DAYS

Method	Number of forecasts	Number correct	Percentage correct
Boyden	42	35	83
Hanssen	35*	26	74
General practice	42	31	74
Jefferson	42	31	74
Similä	42	30	71
Rackliff	41	29	71
Galway	42	27	64
Miller/Starrett	41	25	61
Showalter	42	23	55

*Abandoned on 7 occasions, on 2 of which thunderstorms occurred.

Accuracy of forecasts that thunderstorms would occur on frontal and trough days.—Table III shows the accuracy of forecasts that thunderstorms would occur on these occasions.

TABLE III—ACCURACY OF FORECASTS THAT THUNDERSTORMS WOULD OCCUR ON FRONTAL AND TROUGH DAYS

Method	Number of forecasts	Number correct	Percentage correct
Boyden	16	13	81
Rackliff	10	7	70
Similä	13	9	69
General practice	16	11	69
Hanssen*	20	13	65
Jefferson	20	13	65
Galway	20	11	55
Miller/Starrett	13	7	54
Showalter	16	7	44

*See note under Table II.

Accuracy of forecasts that thunderstorms would not occur on frontal or trough days.—Table IV shows the accuracy of negative forecasts on these days.

TABLE IV—ACCURACY OF FORECASTS THAT THUNDERSTORMS WOULD NOT OCCUR ON FRONTAL OR TROUGH DAYS

Method	Number of forecasts	Number correct	Percentage correct
Hanssen*	15	13	87
Boyden	26	22	85
Jefferson	22	18	82
General practice	26	20	77
Galway	22	16	73
Similä	29	21	72
Rackliff	31	22	71
Miller/Starrett	28	18	64
Showalter	26	16	62

*See note under Table II.

The extent to which actual thunderstorms were forecast.—For some purposes, the extent to which actual thunderstorms are covered in forecasts may be more important than the accuracy of a forecast whether or not they will occur. Accordingly, the results were examined separately for days on which there were thunderstorms. These days were separated into those occasions of straightforward convection and those on which a front or trough was present.

Table V shows the extent to which actual thunderstorms were correctly included on the convection days, and Table VI the corresponding figures for the frontal or trough days.

TABLE V—INCLUSION IN FORECASTS OF THUNDERSTORMS WHICH ACTUALLY OCCURRED—CONVECTION DAYS

Method	Number of thunderstorms	Number forecast correctly	Percentage correct
General practice	29	22	76
Boyden	28	20	71
Hanssen*	23	16	70
Galway	28	19	68
Rackliff	27	17	63
Miller/Starrett	28	16	57
Jefferson	28	15	54
Showalter	28	15	54
Similä	29	15	52

*This method was abandoned on 6 days of this type.

TABLE VI—INCLUSION IN FORECASTS OF THUNDERSTORMS WHICH ACTUALLY OCCURRED—FRONTAL AND TROUGH DAYS

Method	Number of thunderstorms	Number forecast correctly	Percentage correct
Hanssen*	15	13	87
Boyden	17	13	76
Jefferson	17	13	76
Galway	17	11	65
General practice	17	11	65
Similä	17	9	53
Rackliff	16	7	44
Miller/Starrett	17	7	41
Showalter	17	7	41

*This method was abandoned on 2 days of this type.

Time occupied in applying the techniques.—The time taken in the daily routine application of a technique has a clear relation to its overall usefulness as a forecasting tool. Staff engaged on the tests were asked to give an estimate of the average time taken daily in each case. These estimates are given in Table VII.

TABLE VII—AVERAGE TIME TAKEN TO APPLY THE TECHNIQUE

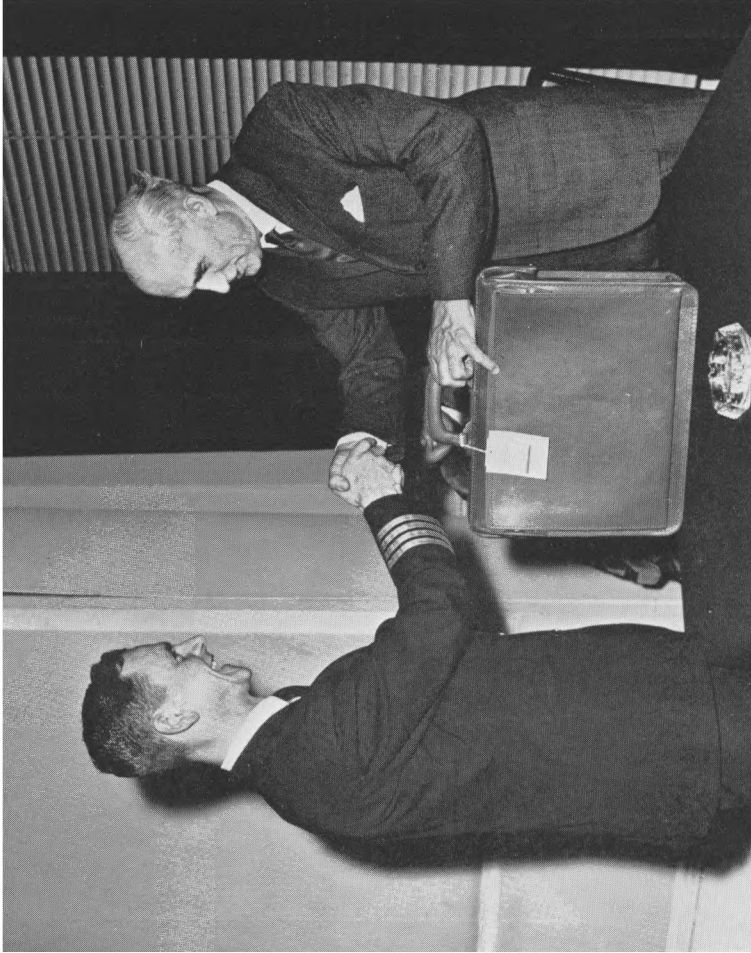
Method	Average time daily to apply method <i>minutes</i>
Galway	5
Showalter	5
Miller/Starrett	5
Hanssen	5 - 10
Rackliff	10
Boyden	10 - 15
Jefferson	10 - 20
Similä	60

Discussion of results.—It has to be emphasized at the outset that the tests were carried out only over one summer, and that not all types of thunderstorm situation were well represented.

The results in Table I show that, taking all occasions together, the normal approach of the forecaster, which includes a subjective examination of tephigrams and other data, produces results which are better, though not very much better, than if he had concentrated on one of the techniques tested.

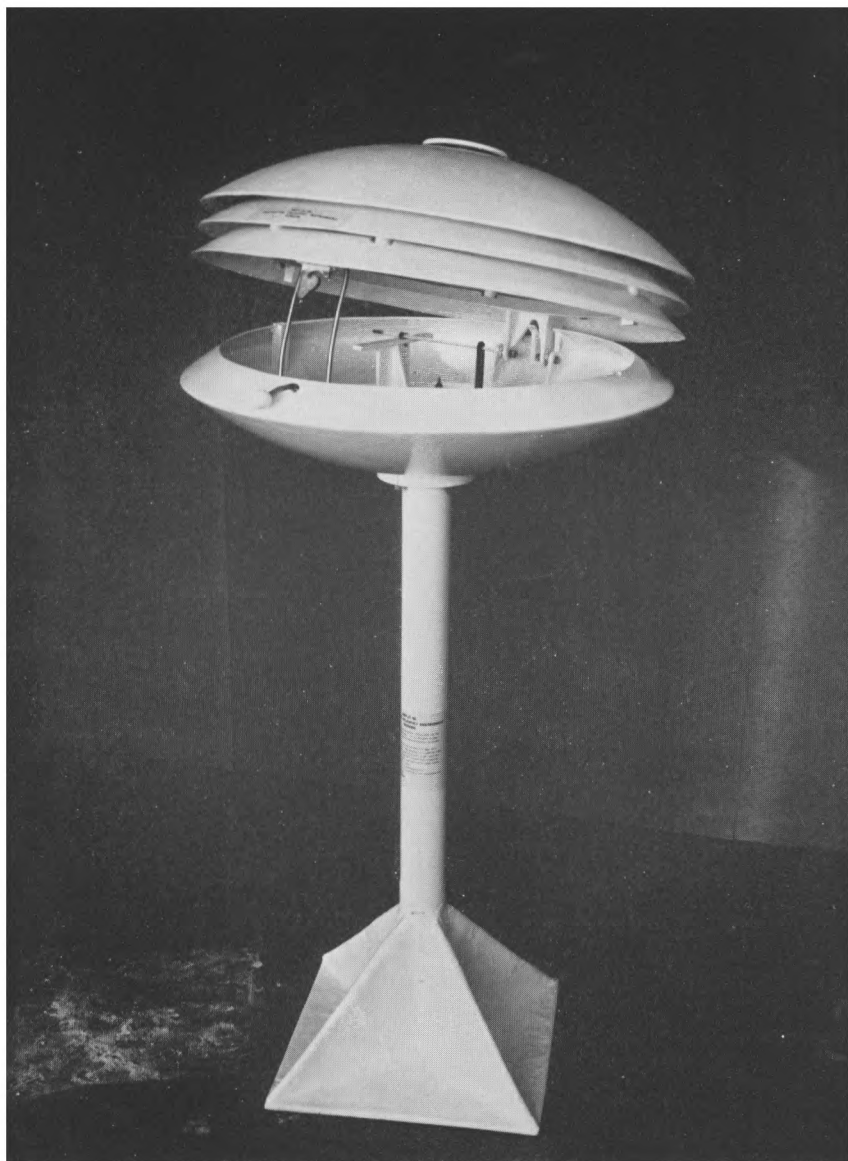
The results confirm that some more recently introduced instability-index techniques give more helpful results than earlier methods from which they were derived. The Similä method gives useful results, but takes appreciably longer to apply (see Table VII) than other methods of the same type.

Perhaps the most significant results are those in Tables II, III and IV, which show that on frontal or trough days forecasters who concentrated on



Photograph by courtesy of British Aircraft Corporation

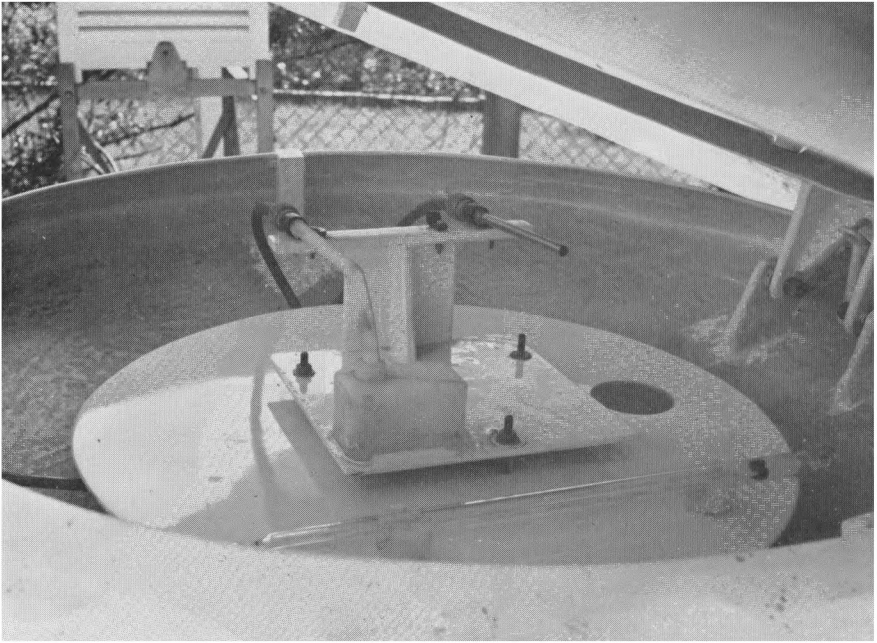
PLATE I—PRESENTATION OF METEOROLOGICAL OFFICE AWARDS AT THE HEADQUARTERS OF THE GUILD OF AIR PILOTS AND AIR NAVIGATORS ON 5 MAY 1966
Mr. B. C. V. Oddie, C.B.E., Deputy Director (Outstation Services) presenting a briefcase to Captain D. B. Wilkie of BEA (see page 220).



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PLATE II—EXPERIMENTAL INSTRUMENT SCREEN MADE OF FIBREGLASS

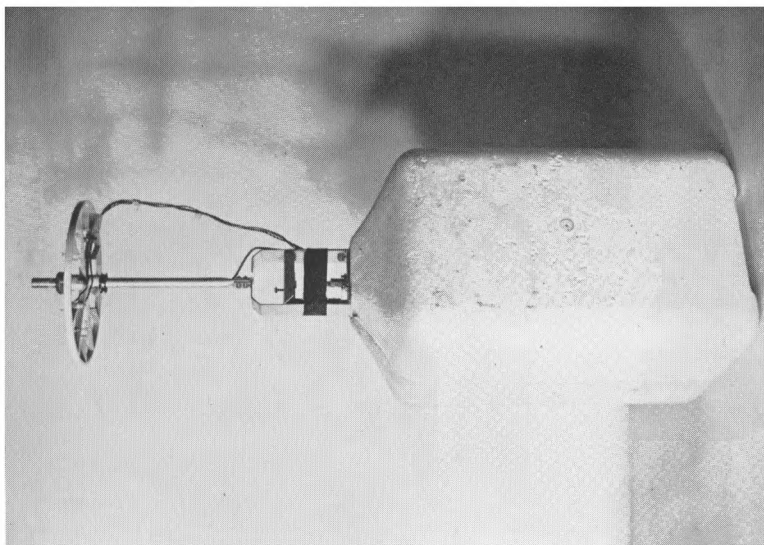
This screen is undergoing trials to determine its suitability as a replacement for the more familiar Stevenson screen. Although the screen is initially slightly more expensive, the virtual elimination of maintenance costs, the ease of repair and the complete immunity to fungoid and insect attack offer considerable advantages.



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PLATE III—INSIDE VIEW OF EXPERIMENTAL SCREEN

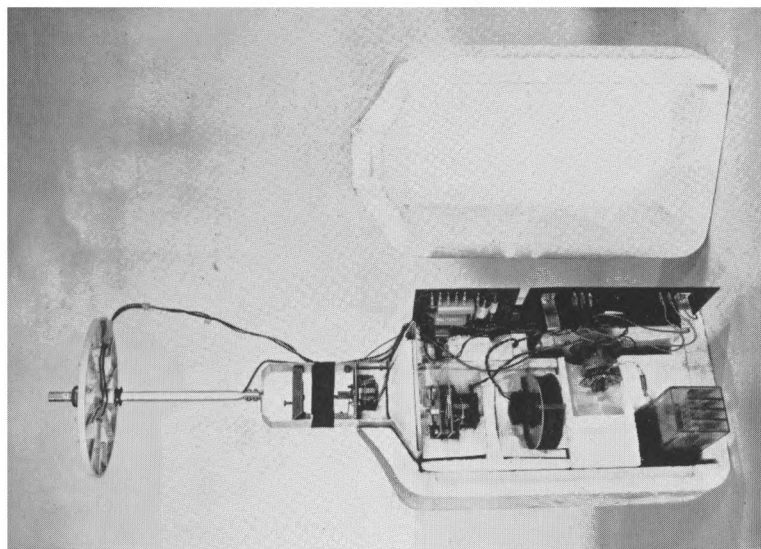
The screen which is constructed by the Instrument Development Branch is circular and has a single large louver and hinged lid. The photograph shows wet and dry resistance thermometers, and a standard glass thermometer used during comparisons with the standard wooden thermometer screen.



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PLATE IV—GENERAL VIEW OF THE NEW RADIOSONDE
MARK 3 AS PRODUCED BY AN INITIAL
MANUFACTURING CONTRACT

The thermometer element and humidity sensor are shown.



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PLATE V—RADIOSONDE MARK 3 WITH EXPANDED
POLYSTYRENE COVER REMOVED

The pressure sensor, reference inductance, batteries and
telemetry are shown.

a particular technique produced better results than forecasters using 'general practice'. The Boyden technique, which was designed to include use in the mobile type of situation, provided the most useful overall results on days of this type. The testing station (Topcliffe), where this technique had been in use since it was published in 1963, commented on its special usefulness in frontal or trough situations and also mentioned that this method often allows quite small areas of thunderstorm activity to be defined and forecast.

A further Topcliffe comment was that in straightforward convection situations the Boyden method tends to overestimate the thunderstorm probability, and on these occasions some other index is useful. Tables I and II confirm this impression and suggest that the Rackliff method is perhaps the most useful aid on these occasions. Table V, however, shows that the Boyden method is still the most useful aid on convection days if the object is to include in forecasts as many as possible of the thunderstorms which actually occur. This point is a significant one, since some users of forecasts may prefer to receive a number of wrong forecasts in order not to miss warning of storms that do occur.

Table VI is simply a rearrangement of some of the material already included in Table III, and these two tables should be regarded together. Thus, if the object is to include as many as possible actual thunderstorms, Table VI shows that on frontal or trough days the Hanssen method gives the best results when it can be used, and Table III shows the extent to which 'yes' forecasts were wrong. Table VI also shows that the Boyden and Jefferson methods were equally useful in ensuring mention of storms when they occurred, on frontal or trough days, while Table III shows that the Boyden method contributed a higher proportion of successful 'yes' forecasts.

As regards thunderstorm forecasting, the tests seem to lead to the following conclusions :

- (i) On straightforward convection days, one of the recently introduced instability index methods gives useful assistance to the forecaster. There is an indication that the Rackliff method is the most helpful.
- (ii) On days when fronts or troughs are expected in the area, more weight should be given to the instability index, and on these occasions the Boyden index seems definitely the most helpful.
- (iii) The Hanssen objective method already shows usefulness on frontal or trough days. This should be well worth further development, using British Isles data, and providing for use on all occasions.

Acknowledgement.—Some forty forecasters shared in the task of collecting data, and keeping the check sheets on which the tests were marked. Some were in the position of testing the technique which they already regarded as the most helpful, but many were well aware that the method they were testing would not necessarily be the most effective of its kind. All have contributed to the results, and it is desired to express appreciation of the efforts of all concerned.

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A REMARK ON SYNOPTIC CHARTING OF MOISTURE

By A. PAPEŽ

Institute of Physics of the Atmosphere
Czechoslovak Academy of Sciences

In his paper Kirk¹ showed that the synoptic aspects of humidity distribution have not yet been satisfactorily used in practice. He discussed also a method for charting moisture characteristics in a situation with moist air advection to western Europe.

In the present author's previous paper² another method of computing humidity characteristics for use on synoptic charts has been shown. The principle

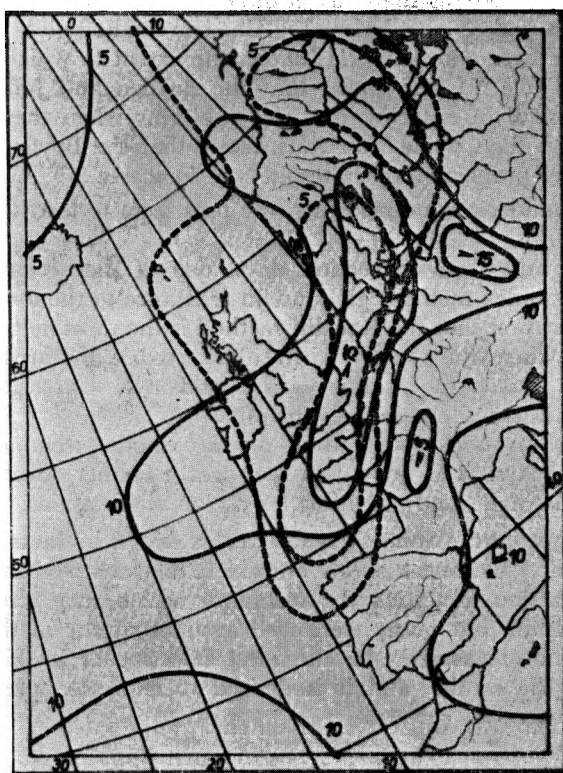


FIGURE 1—PRECIPITABLE WATER IN THE LAYER 1000–700 MILLIBARS AT 1200 GMT,
9 DECEMBER 1964

————— Precipitable water in grammes
- - - - - Isohyets in millimetres

of it is well known as 'precipitable water'. It can be derived from the equation

$$M_v = \frac{\bar{q}(p_1 - p_2)}{g} \quad \dots (1)$$

where M_v is the integral mass of water vapour in the layer between pressure surfaces p_1 and p_2 , \bar{q} is the mean specific humidity (computed as an arithmetic mean of values of specific humidity at the surfaces p_1 and p_2) and $g = 9.80665$ metres/second². We assume that the maximum possible value of precipitable water can be computed from the mean temperature of the corresponding layer in all cases.

Considering this fact we can write the equation for the relative value of precipitable water as follows :

$$M_v^R = \frac{M_v}{(M_v)_{\max}} \times 100$$

where M_v^R is the relative precipitable water, and $(M_v)_{\max}$ can be derived from equation (1) by replacing \bar{q} with \bar{q}_{\max} (i.e. specific humidity in saturated air.)

The values computed for individual aerological stations are plotted on the synoptic chart. Figures 1 and 2 show the results for M_v and M_v^R for one of the

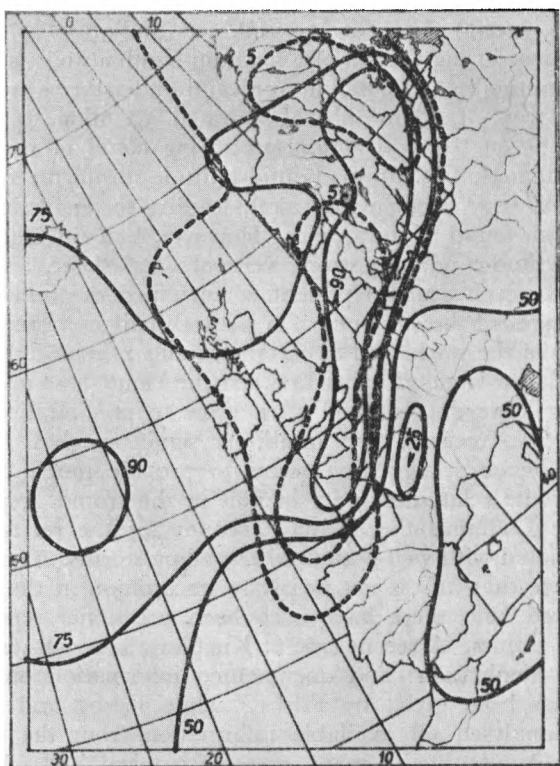


FIGURE 2—RELATIVE PRECIPITABLE WATER IN THE LAYER 1000–700 MILLIBARS
AT 1200 GMT, 9 DECEMBER 1964

———— Relative precipitable water (per cent of $(M_v)_{\max}$)
----- Isohyets in millimetres

cases computed by Kirk.¹ The pecked lines are isohyets for 0 and 5 millimetres of precipitation (for the time interval of the chart ± 6 hours).

From the pattern of relative precipitable water it follows that this method of showing humidity distribution on the synoptic charts seems to be of some use to meteorologists in the weather service.

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THE OCCURRENCE AND DISTRIBUTION OF HAIL IN AFRICA

By H. W. SANSOM

Introduction.—The incidence of thunderstorms over parts of Africa is as high as or higher than anywhere else in the world,¹ but reports of hail are relatively rare, except in certain areas. Fawbush and Miller² have stated that hail seldom occurs at the ground when the wet-bulb freezing-level is more than 3650 metres above the ground, but Ludlam³ has shown that the amount of melting during the fall of a medium-size hailstone is not very great, and so the apparent absence of hail in tropical thunderstorms must be explained in some other way. Ludlam⁴ has also drawn attention to the differences in structure between the typical hail-producing cloud of mid-latitudes and the tropical cumulonimbus. In many mid-latitude storms there is considerable wind shear, with very strong winds aloft, leading to an inclined updraught, but this is seldom found in the tropics. However, hail can undoubtedly form in temperate latitudes without strong vertical wind shear, and strong shear is not always (or even usually) present when hail does occur in the tropics. Appleman⁵ suggested the existence of a natural 'hail suppression mechanism' in certain areas of the world and at certain seasons; he postulated that when a thick, dense layer of cloud exists between the cloud base and the freezing-level, the rising large droplets will often grow to precipitation size and fall out as rain before freezing, thus inhibiting significant hail formation. On the whole, Appleman's suggestion seems to provide much the most likely explanation for the relative scarcity of hail in the tropics, especially at low altitudes, while Ludlam's theory may account for the rarity of the really large hail associated with well-organized travelling storms. There is, however, growing evidence that hail is not nearly so uncommon in the tropics as was formerly believed, and there have even been occasional reports of hail at sea level in the tropics. A recent case at Kuching, Sarawak was described by Stemmler and Stephenson⁶ and documented information on a number of known cases has been given by Frisby,⁷ while Frisby and Sansom⁸ have surveyed and analysed all available information from the entire tropical belt. There are undoubtedly many cases of tropical hail which are never reported.

Areas of hail occurrence in Africa.—Hail is virtually unknown over Africa between 20°N and 30°N, on the Atlantic coast north of 25°S, and on

the Indian Ocean coast north of 15°S ; hail has, however, been reported at Mauritius (20°S), where there is a reliable report of a hailstorm occurring over the sea, and at the Grande Comore Island (12°S) in the Mozambique Channel. There have been occasional reports of hailstorms in West Africa even at fairly low elevations, but on the east coast, where thunderstorms are much less common (see Figure 1), hail is extremely rare north of Mozambique. There have been, however, reports of occasional hail in one locality not far inland from Mombasa, Kenya. Figure 2 indicates, in very general terms, the point frequency of hailstorms over Africa ; it is based on information obtained from many sources, and covering varying periods. Figure 3 shows

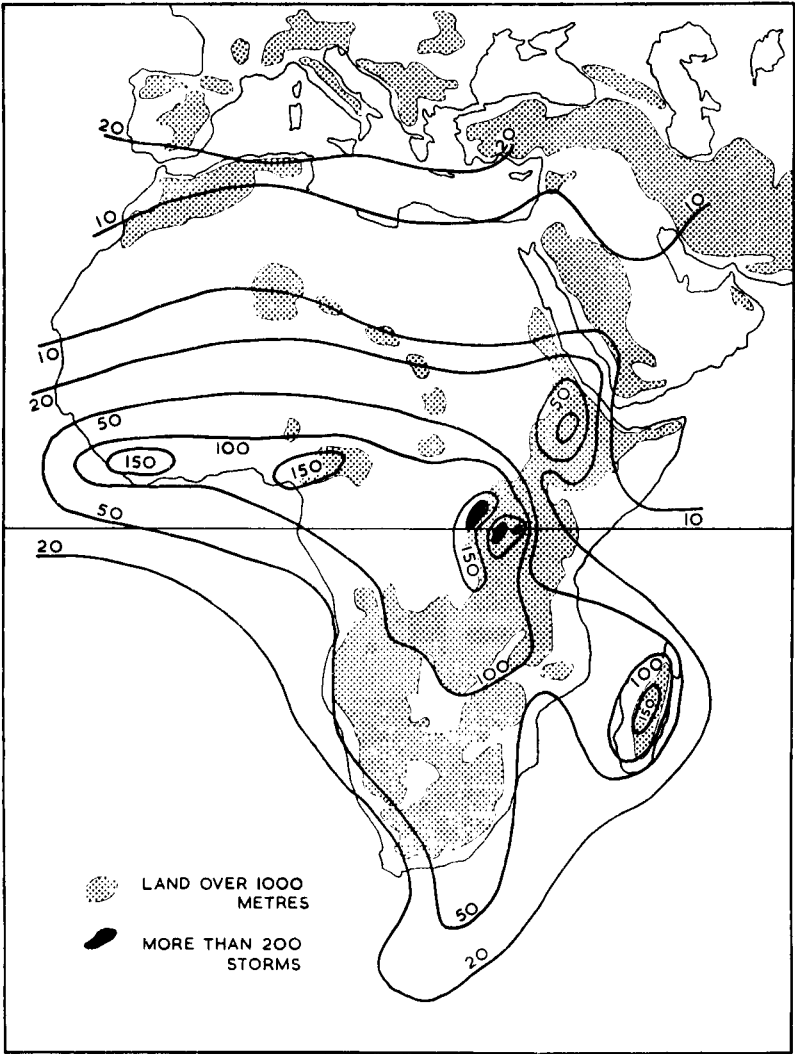


FIGURE 1—MEAN ANNUAL FREQUENCY OF THUNDERSTORM DAYS OVER AFRICA

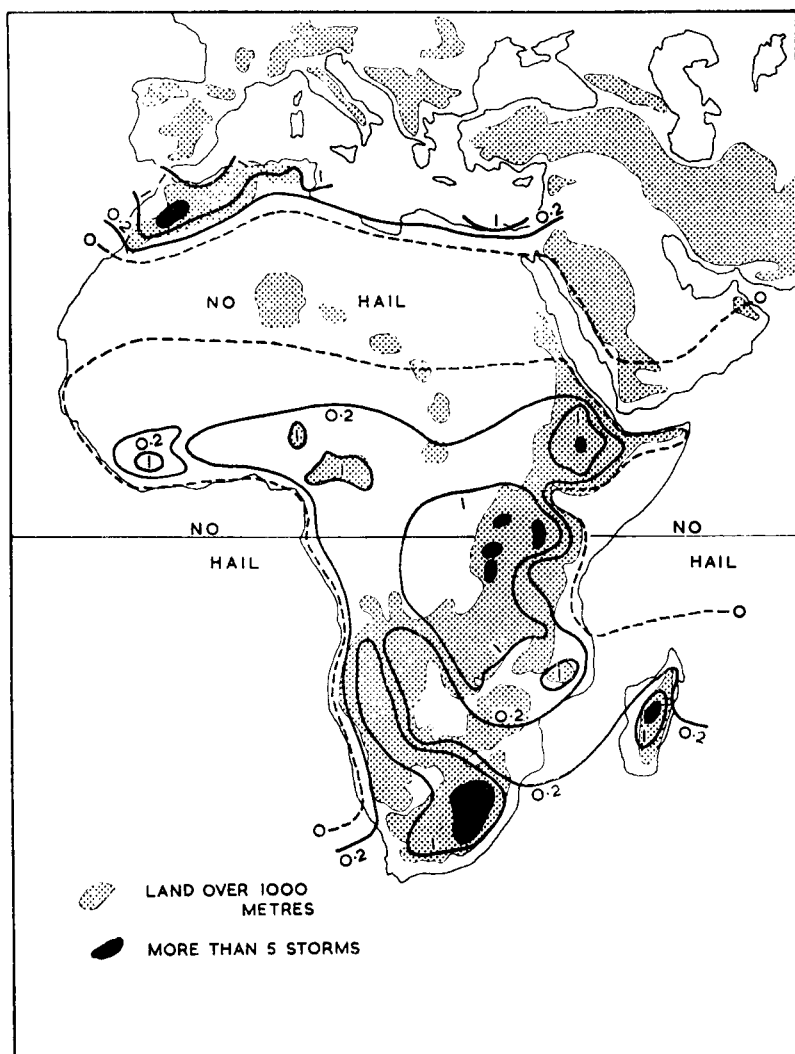


FIGURE 2—MEAN ANNUAL FREQUENCY OF HAIL AT A POINT

the main hail months in each area, but hail does, of course, often occur outside these months.

The main hail areas are :

1. Morocco (especially Atlas Mountains)
2. Rwanda, Burundi, and parts of the Congo (Democratic Republic)
3. Western Kenya
4. Western Uganda
5. Ethiopia
6. Transvaal and Orange Free State, in the Republic of South Africa ; Basutoland and Swaziland
7. The high plateau of Madagascar.

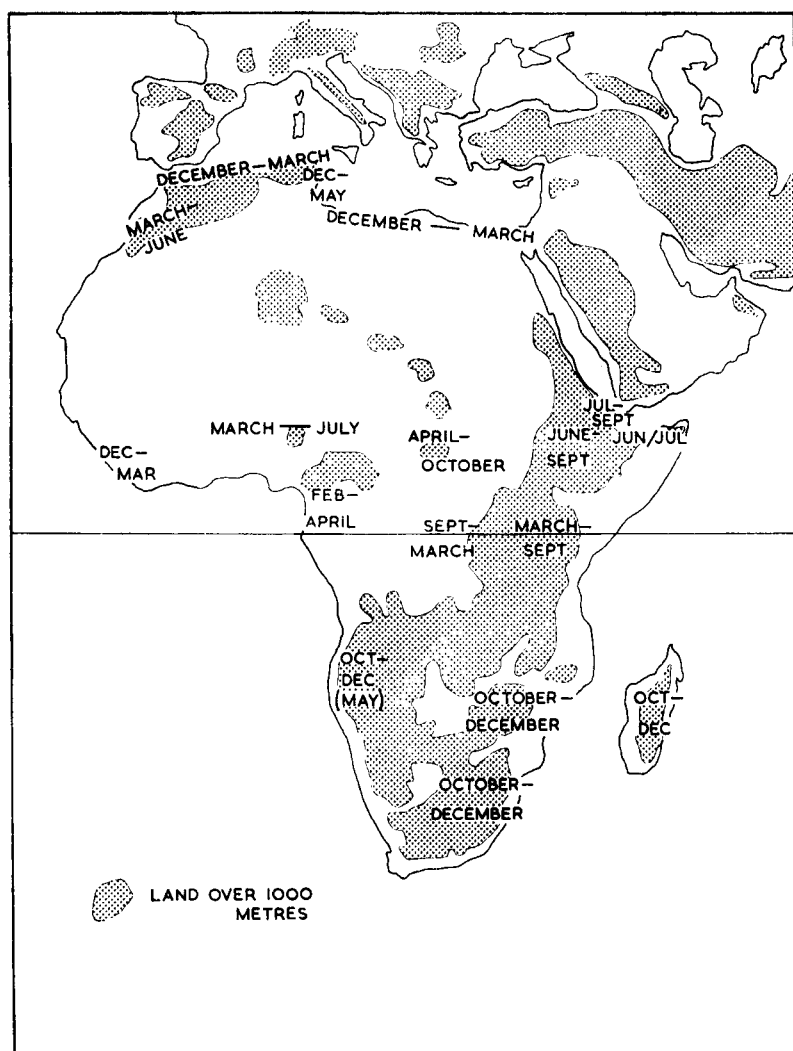


FIGURE 3—MAIN HAIL SEASONS THROUGHOUT AFRICA

These will be considered separately, and brief notes given on each area.

1. *Morocco.*—

- (a) Coastal plains : occasional storms mainly December to March.
- (b) Atlas Mountains : up to 5 storms per year, with peak frequency during months March to June.

2. *Rwanda and Burundi, and Congo.*—

- (a) Hail frequencies in excess of 5 storms per annum near the western border of Rwanda and Burundi (east of Lakes Kivu and Tanganyika), particularly during the months of September to March (peak frequency in February).

- (b) In Kivu Province of the Congo Republic, to the west and north of Lake Kivu, hail frequencies in excess of 5 storms per annum are reported (up to 9 storms per annum north of the Lake). The highest monthly frequencies occur in the months September to March with a peak in February.
- (c) Up to 2 storms per annum are reported from south-west parts of Katanga Province during the months September to March, with the highest monthly frequency in October.

Further details of the frequency of hail in this area are contained in a paper by Bultot.⁹

3. *Western Kenya.* — Sansom¹⁰ has discussed the occurrence of hail in East Africa but a recent hail reporting survey has shown that in western Kenya hail is even more frequent than was originally suspected. The hail area extends from Mount Elgon in the north, through the Nandi Hills to the Kericho area. The hail frequency at a point exceeds 5 storms per annum over much of the area, and reaches 10 in parts of the Kericho district. No month is free from hail.

The number of days per annum on which hail is reported somewhere in the western Kenya hail area (1°N to 1°S, 34°E to 36°E) is well over 100, with over 50 days per annum in the Kericho area alone (i.e. on the 25,000 acres of tea estates, nearly all of which are within 10 miles of Kericho township at 0°22'S, 35°17'E).

TABLE 1—THE MONTHLY AND MEAN ANNUAL OCCURRENCE OF HAIL IN WESTERN KENYA (1960–64)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Days of thunder	10	11	16	21	23	18	15	18	20	18	17	13	200
Days of hail													
(W. Kenya)	5	6	13	9	9	13	10	15	15	10	5	4	114
Days of hail													
(Kericho area)	2	3	6	3	4	6	6	5	7	7	2	3	54

A more detailed temporary hail-reporting scheme introduced during August and September 1965 indicated that hail was reported on 51 out of 61 days during these two months. It therefore seems clear that a high proportion of thunderstorms in this area contain some hail.

Although the sizes of hailstones normally reported are quite small (generally below 1 cm in diameter) hailstones of diameter greater than 2.5 cm are not uncommon, and golf-ball size stones are occasionally reported.

4. *Western Uganda.*—Hail is occasionally reported in thunderstorms around the north-western shores of Lake Victoria, and no part of Uganda is entirely free from hail, but the highest frequency occurs in Toro, near the Ruwenzori Mountains, where the point frequency is between 5 and 10 per annum, occurring mainly during the months September/October and January to March.

5. *Ethiopia.*—Over the Ethiopian plateau around Addis Ababa, thunderstorms are very frequent from March to October, and hail is quite often reported between June and September, but severe hailstorms also occasionally occur during April. The average frequency is 6 storms per annum.

6. *Transvaal, Orange Free State, Basutoland and Swaziland.*—Point frequencies in excess of 5 per annum occur over quite a wide area, and the high ratio of hail days to thunderstorm days indicates that the great majority of thunderstorms in this area contain hail. The peak hail months are October to March, with a very marked maximum in November (when most of the large hail occurs) and a secondary maximum in March. A few winter hailstorms also occur in May, June and July. Quite large hailstones (over 4 cm in diameter) are sometimes reported. Further information on hail in the area around Pretoria has been given by Carte.¹¹

7. *Madagascar.*—Over the high ground of Madagascar, around Tananarive, hail frequencies up to 6 per annum occur, and the peak months are October to December. Hail has occasionally been reported on the coast, mainly in the Mozambique Channel, but also at Grande Comore (Comore Islands, 12°S).

8. *Hailstorms in other parts of Africa.*—Although hail is far from common in the southern Sudan and Chad, where the frequency of occurrence is about once in 5 years (during April to October), quite large hailstones are reported to have fallen in both countries. At Fort Archambault in Chad, in October 1958, a man was killed by a hailstone weighing over 50 grammes (diameter perhaps 6 cm), and in a storm at Daga Post (9°N, 34°E) in the southern Sudan in April 1954, hailstones 'the size of a man's fist' were reported, with an alleged weight of over 2 kg. Such a vast weight would require a diameter of about 16 cm, and some exaggeration in the weight must be suspected, although the report was emphatically confirmed by the local District Commissioner after specific enquiries had been made by the Government Meteorologist.

A considerable amount of information on hail in West Africa (the former French territories) is contained in a paper by Bougnol¹² who mentions a hailstorm at St Louis on the coast of Senegal. All available information from this and many other areas has been reviewed and analysed by Frisby and Sansom,⁸ who quote monthly hail frequencies wherever possible for individual stations.

Conclusion.—It should be noted that in most areas the peak hail frequency does not necessarily occur in the wettest month, but more often towards the beginning and end of rainy seasons, or at the end of a dry spell in the rainy season. Sansom¹⁰ showed that hail is unlikely when there is widespread low-level convergence; tropical hailstorms are usually associated with diurnal instability thunderstorms when intense local convection gives rise to the very strong upcurrents required for hail formation. Geographical and topographical features undoubtedly lead to the existence of certain favourable hail 'breeding-areas'.

No attempt has yet been made to relate the incidence of hail over Africa to particular synoptic situations, but it is now evident that many tropical thunderstorms contain hail, and that the frequency of hail in some parts of Africa is surprisingly high.

The problem of forecasting hail in tropical Africa is not likely to have a simple solution, but it seems probable that the best results will be obtained by using some form of stability index.

Acknowledgements.—This paper, which was originally prepared for a Seminar on Tropical Meteorology held in Nairobi in November 1965, is

published with permission of the Director, East African Meteorological Department. The assistance of the Directors of other meteorological services throughout Africa in supplying detailed information is most gratefully acknowledged. Miss J. E. Tomsett assisted in the preparation of the final copies of the diagrams.

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551.586:061.3

BIOMETEOROLOGICAL CONFERENCE IN LEBANON, 1 - 6 APRIL 1966

This, the first Biometeorological Conference of the Middle and Far East, was organized by Dr S. W. Tromp, Head of the Biometeorological Research Centre, Leiden, Holland. No formal papers were presented ; instead a team of invited consultant specialists in human, animal and plant biometeorology was assembled to discuss problems of health and economic development with their opposite numbers in the Middle East. The cost was in great part borne by the Lebanese Government and various organizations in the Lebanon, such as the Development Bank. The conference was held in the 5000-foot winter resort of Laklouk.

Among the invited consultants were about ten scientists from the United Kingdom including R. W. Gloyne and G. W. Hurst of the Meteorological Office ; in the fields of entomological, pathological and veterinary studies British scientists were also well represented. Six working groups were formed to conduct discussions in between the opening and closing plenary sessions. Two were closely related to meteorological problems : one on agricultural biometeorology, chaired by Dr Gloyne, and another on crop protection, chaired by Dr J. M. Hirst, Rothamsted Experimental Station, Harpenden.

The original intention had been to discuss Middle and Far East problems generally, but representation from outside the Lebanon was very low, because of financial and other difficulties, and in fact deliberations were mostly confined to the Lebanon. Below are indicated briefly subjects discussed of direct meteorological interest.

Agricultural biometeorology.—The real need was for co-ordination of meteorological services to meet agricultural requirements. At least three different authorities were interested in climatology in the Lebanon, and perhaps to some extent they went their separate ways ; the network of 40 climatological and 80 rainfall stations did not therefore represent quite as satisfactory an organization as might be expected. Instruments required improvement and standardization—many differently designed rain-gauges were in use, for example. Improvement was needed in measurement of solar radiation, the recording of temperatures below the ground, and also in assessment of the deposition of dew. Deliberations were greatly helped by the presence of Dr G. A. de Veille, the World Meteorological Organization agricultural meteorology specialist temporarily in the Lebanon, and Dr L. A. R. Ramdas (a retired Indian meteorologist) with a wide background of semi-arid climates. Valuable contributions were also made by other consultants in the group, including Professor H. Gaussen and Dr P. Legris, French ecological climatologists, and Mr A. J. W. Borghorst, a Dutch instrument specialist. Visits were paid by the author to the Beirut civil airport meteorological office which controlled the synoptic network and a few of the climatological stations, to the observatory at Ksara and to Abde, a Ministry of Agriculture research station near Tripoli. The office at Beirut was the only forecast office in the Lebanon, and obviously provided the high standard of professionalism expected from an international civil airport. Ksara was an observatory of long standing where seismological observations were also maintained. Some of the equipment in use was old, and some very up-to-date ; strange to British eyes were the 22-cm diameter pluviometers equipped with taps and standing $1\frac{1}{2}$ metres high, and a screen 2 metres high large enough to house half a dozen normal Stevenson screens. At Abde, instruments included thermometers at several depths, and also lysimeters.

Aside from questions of administration and networks, problems were somewhat different from expected. Irrigation was, of course, of major importance, but water itself was fairly readily available from wells and springs, and rainfall was adequate for about half the year in many areas ; melting snow was also a water source. Shelter too was a real problem, and much in the way of somewhat *ad hoc* shelter belts already existed, especially near the coast, where salt problems also occurred.

Crop protection.—The author divided his time between the agricultural biometeorology and the crop protection working groups ; the latter embraced both entomological and pathological questions.

In entomology, as in meteorology, there were some highly qualified Lebanese specialists and much was known about some of the most modern ideas of pest population control, etc. The main difficulty appeared to be communication between the scientists and the farmers—many of whom were very small land owners or users who farmed as a part-time job. It was fascinating to see oxen and a hand plough still in use in some mountain areas ; this was much more surprising here than it would have been elsewhere in the Middle East as Lebanon is a wealthy country with a degree of development in many ways comparable with western standards. Much of the more steeply sloping land was terraced and tilled in very small units, of which the more remote were being given up

(with some consequent erosion problems) because of emigration from the countryside. A morning was spent discussing insect migration and its possible relevance to Lebanese problems. Some mention was also made of relating meteorology to insect populations. An indication was given of the role of meteorology in the British Ministry of Agriculture extension services. Dr T. Lewis of the Experimental Station, Rothamsted, Harpenden (Chairman of the sub-section on entomology) gave an account to members of the agricultural group of his work on relationships between insect distributions and shelter belts.

A little time was also spent by the pathology sub-group in discussing meteorological matters, mainly on spore movements and disposal, and the relationships between current weather and diseases such as potato blight. There seemed a more serious shortage of specialist pathologists than of most other scientists, and in some particular fields (for example, nematodology) no specialist existed in the country.

The meeting finished on the evening of 6 April with the presentation by the respective Chairmen of recommendations of the six working groups.

G. W. HURST

NOTES AND NEWS

Meteorological Office awards to captains and navigators of civil aircraft

A pleasant ceremony was arranged on Thursday, 5 May 1966, by the Guild of Air Pilots and Air Navigators at their headquarters in South Street, Mayfair, with the Master of the Guild, Marshal of the Royal Air Force, Sir Dermot Boyle, G.C.B., K.C.V.O., K.B.E., A.F.C., presiding.

The annual Meteorological Office awards for long and meritorious service in the provision of weather reports from aircraft were made for 1965 to Captain D. B. Wilkie of British European Airways and Captain P. Siegel of British United Airways. They received presentation briefcases from Mr B. C. V. Oddie, C.B.E., Deputy Director (Outstation Services), Meteorological Office (Plate I).

Presenting the briefcases on behalf of the Director-General of the Meteorological Office, Mr Oddie stressed the importance of reports of the weather conditions existing over the air lanes, and expressed gratitude to the airlines and aircrew for their voluntary service in furthering the development of accurate weather forecasting. The reports were a very valuable contribution towards the safe and economic operation of the airlines.

Fifteen awards of books, suitably inscribed, are also being given by the Meteorological Office to the following captains and navigators who have provided the best series of reports (in-flight, post-flight or on debriefing) during the 12 months ended 31 December 1965 : Captains J. D. Barnes, G. R. Buxton, W. M. Reid, E. E. Langmead, S. M. Gooch, and G. Hall of BOAC; Captains J. Welford, B. J. Thwaites, A. L. French, E. Caesar-Gordon, D. H. Turnbull and K. R. Blevins of BEA ; and Messrs J. F. Archer, R. R. Webb, and G. W. Simpson, navigating officers of BUA.

REVIEWS

The biological significance of climatic changes in Britain, edited by C. G. Johnson and L. P. Smith. 9½ in × 6 in, pp. x + 222, *illus.*, Academic Press Inc., (London) Ltd., Berkeley Square House, Berkeley Square, London, SW1, 1965. Price: 42s.

During the summer half-year agricultural meteorologists are kept fully occupied with seasonal tactics. During the winter, however, they have more time to worry over questions of longer-term strategy. One such problem which has recently been coming increasingly to the forefront is that of the biological implications of climatic fluctuations. Current farming practice and agricultural policy are largely geared to weather conditions as experienced by the present generation; what repercussions, particularly on food production, might be expected to flow from the degree of climatic change for which past records suggest that we ought, in prudence, to plan?

In 1964, Iowa State University organized a symposium on 'Weather and our food supply' which was mainly concerned with grain production as affected by climatic change. The present publication, which consists of the proceedings of a symposium held in London in October 1964 under the auspices of the Institute of Biology, covers a far wider biological field. It opens with a masterly summary by Mr H. H. Lamb of what is known of the dimensions of past climatic change in Britain, and a consideration by Mr James A. Taylor of the biological consequences in marginal upland and peat areas, where the effects can be most clearly seen. It closes with a synopsis by Mr L. P. Smith of the agricultural significance of possible future seasonal trends, and an analysis by Professor A. N. Duckham of the broad repercussions of short-term climatic change on different types of farming operations. In between, the consequences of meteorological fluctuations are related not only to vegetable crops and farm livestock, but also to grasses, wild plants, fish and other marine organisms.

No one with the slightest knowledge of the complex biometeorological problems involved will expect to find a neat series of answers at the end of this book. What it does supply is an authoritative survey of the present position in this fascinating and important field, a pinpointing of the aspects of the problem which require further research, and (by no means least valuable) a bibliographic guide to the maze of interdisciplinary literature in which details of the most recent work is hidden.

For agricultural meteorologists—and for many others concerned with the interaction of climate and living things—this book is a must! It would also, I suggest, be an excellent investment for ambitious young scientists in search of an uncrowded research niche with a promising future.

P. M. AUSTIN BOURKE

Atmosphärische Elektrizität, Teil II, by H. Israël. 6½ in × 9½ in, pp. x + 503 + 5 folded maps, *illus.*, Akademische Verlagsgesellschaft, Geest and Portig K.-G., Leipzig C1, Sternwartenstrasse 8, East Germany, 1961. Price: DM 66.

This second volume completes Professor Israël's large 'Handbuch' on atmospheric electricity. The first volume (reviewed in *Met. Mag.*, **88**, 1959, p. 119) consisted mainly of a survey of basic facts and relevant basic physics, followed by a long and detailed technical discussion of atmospheric ionization.

The present volume is divided into three main heads : electric fields, electric charges and electric currents ; an appendix includes a detailed account of methods of measurements.

It is a somewhat depressing commentary on the state of the literature that the author in his introductory chapter, after discussing the confusion over sign conventions, recommends that we cease to speak of positive and negative fields and currents, and refer rather to the fine-weather direction and its reverse ; he further decides to write out every equation twice, firstly in c.g.s. units, secondly in 'rationalized' units.

The work is encyclopaedic in its scope ; the bibliographies in the two volumes list, in all, nearly 2000 papers. An attempt at completeness on this scale has its disadvantages ; the reader who desires to get an up-to-date picture may waste time in tracking down references which are unimportant or outmoded.

Again, the arrangement of the book leads to difficulties. If a reader is seeking information, for example, about phenomena of disturbed weather, he will find certain aspects in all three main sections and there is inevitably some repetition and need for referring back or forward from section to section and even from volume to volume.

One suspects that Professor Israël's real interest lies in the electrical phenomena of fair weather. Here the discussion is detailed, comprehensive and stimulating. By comparison, the treatment of field-charges due to lightning and of atmospherics — both of these are considered under electric fields — is brief and superficial. Rather surprisingly the full derivation, from Maxwell's equations, of the field due to a radiating elementary dipole is given in an appendix.

This is of course a book which any serious worker in the field must have accessible. Professor Israël is to be congratulated on its completion.

T. W. WORMELL

Auroral phenomena (experiments and theory), edited by Martin Walt. 9½ in × 6½ in, pp. vi + 170, *illus.*, Oxford University Press, Amen House, Warwick Square, London, EC4, 1965. Price : 40s.

This book contains nine chapters based on papers read at a symposium on aurora organized by, and held at, the Lockheed Missiles and Space Company in January 1964. The purpose of the symposium was to provide not only a forum for the discussion of recent research, but also an opportunity for specialists, using widely different techniques for investigating one and the same phenomenon, to meet and discuss their problems and results.

The first two chapters on morphology and spectroscopy review the results of surface observations, and the third, on the interaction of energetic particles with the atmosphere, is concerned with the interpretation of auroral luminosity in terms of excitation mechanisms. On the basis of the appearance of auroral forms, their height and their spectral characteristics, auroral displays may be classified into five apparently distinct groups, namely, the polar glow appearing sometimes over the polar cap ; the polar cap aurora consisting of weak discrete forms inversely correlated with sunspot number and magnetic activity ; high red arcs in the F-region ; medium grey arcs at heights around 200 km ; and the familiar 'polar aurora' of arcs, bands and rays. In the

last chapter, summarizing the symposium, Omholt however classifies the aurora according to excitation mechanisms into four groups. These are the polar glow aurora associated with polar cap absorption events caused by protons in the MeV range ; the high red arc which may result from local electric discharge mechanisms but whose origin is not yet clear ; the electron-excited aurorae consisting of the well-known forms which are caused by electrons accelerated in the vicinity of the earth through the interaction of the solar wind with the outer magnetosphere ; and the proton-excited aurora consisting of a weak glow, with relatively strong hydrogen lines, in the form of a broad band elongated geomagnetically east-west which before midnight lies south of, and in the early morning hours north of, the bright electron aurora.

There are chapters on balloon measurements of X-rays in the auroral zone ; on satellite studies of the precipitation of energetic particles into the atmosphere ; on electromagnetic measurements of aurorae, i.e. on radio noise associated with aurora, on scintillations and on radar auroral reflection ; and on co-ordinated measurements by satellite of the distribution of particle fluxes, optical luminosities and ionospheric electron densities. Finally, preceding Omholt's summary, there is a critical appraisal of recent work on the theory of auroral particles and bombardment.

The book provides a valuable account of the present state of investigations of aurora by the various physical techniques.

J. PATON

The story of gliding, by Ann and Lorne Welch. 5½ in × 8¾ in, pp. xv+211, illus., John Murray, 50 Albemarle St, London, W1, 1965. Price : 28s.

Meteorologists who become involved in gliding usually learn from the sport, not so much by acquiring factual data as by the accumulation of impressions gleaned from experience in the air and from talking and reading about the subject.

The latest book by Ann and Lorne Welch is another of the type that conveys to the reader realistic impressions of the art and science of soaring flight.

After describing the almost legendary earliest attempts at gliding, the authors give an account of the daring experiments of the 18th and 19th centuries, then they trace the 20th century progress that stemmed from the application of scientific method to the principles and practice of flight.

The book provides light entertaining reading, and for the meteorologist can stimulate speculation on what concepts of airflow and convection the pioneers had in mind as they planned and eventually carried out this particular conquest of the air.

C. E. WALLINGTON

CORRIGENDA

Meteorological Magazine, March 1966, page 78, Table II : in heading for 'Figure 5' read 'Figure 6' ; under 20.11.3., against $T_{700} - T_{300}$, for '45' read '44'.

Meteorological Magazine, May 1966, page 135, equation (19) ; for '100²' read '1000²'.

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CONTENTS

	<i>Page</i>
Some aspects of the synoptic climatology of the British Isles as measured by simple indices. R. Murray and R. P. W. Lewis	193
Tests of thunderstorm forecasting techniques. W. E. Saunders	204
A remark on synoptic charting of moisture. A. Papež	210
The occurrence and distribution of hail in Africa. H. W. Sansom	212
Biometeorological Conference in Lebanon, 1-6 April 1966. G. W. Hurst	218
Notes and news	
Meteorological Office awards to captains and navigators of civil aircraft	220
Reviews	
The biological significance of climatic changes in Britain. Edited by C. G. Johnson and L. P. Smith. <i>P. M. Austin Bourke</i>	221
Atmosphärische Elektrizität, Teil II. H. Israël. <i>T. W. Wormell</i>	221
Auroral phenomena (experiments and theory). Edited by Martin Walt. <i>J. Paton</i>	222
The story of gliding. Ann and Lorne Welch. <i>C. E. Wallington</i>	223
Corrigenda	223

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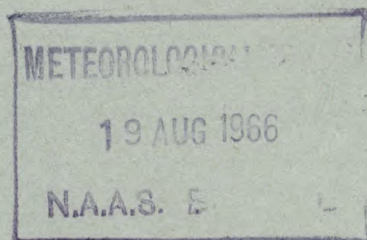
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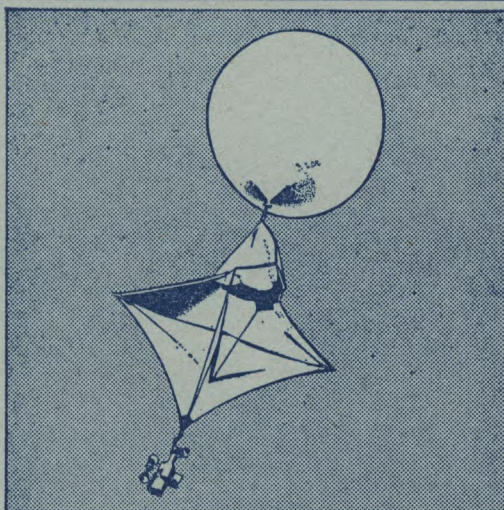
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THE METEOROLOGICAL MAGAZINE

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SOME FEATURES OF THE LARGE-SCALE CIRCULATION ANOMALIES AND THE WEATHER OVER THE BRITISH ISLES IN AUTUMN 1965

By R. MURRAY

Summary.—The autumn of 1965 was remarkable both for the large inter-monthly changes and for the pronounced character of the weather within each month over the British Isles. This note shows how the anomalous circulation over the British Isles was related to the large-scale circulation over the northern hemisphere.

Broad-scale weather in Britain.—The weather of September 1965 was disturbed, wet and cool and continued the trend of the preceding summer. In the average year, September is significantly more anticyclonic than July and August, but on this occasion September was exceptionally cyclonic over the British Isles. The average monthly rainfall over England and Wales was 5.6 in (i.e. 187 per cent of the normal*) ; this has been exceeded on three occasions, namely 1927, 1918 and 1896, in the past 90 years, but the frequency of depressions over or very close to the British Isles was less in these Septembers than in September 1965. It was cool for most of the month, and the mean monthly temperatures were generally in the lowest decile or quintile of the distribution.

In spite of an unsettled start and a very stormy end, October was dominated by an anticyclonic block, i.e. the anticyclone of a blocking situation. Rainfall over the month was below normal nearly everywhere ; in particular over England and Wales the average rainfall was 1.2 in (i.e. 33 per cent of normal), and the only October in the past 150 years with less rain was in 1947. Mean monthly temperatures were generally above the long-term average, mostly in the warm quintiles 4 and 5. The contrast between the synoptic character and weather of September and October could hardly have been more marked ; both months were abnormal in quite different ways.

After a cyclonic westerly type at the beginning of November there was a reversion to an anticyclonic block for a week or so. However, after the 12th the weather became generally disturbed. Several vigorous depressions moved eastwards on tracks between northern France and southern Scotland ; the cyclonic systems produced blizzards, chiefly over south and central Scotland and the northern half of England and Wales. In extent and depth of snow lying and in frequency of snow falling, many places in northern England and southern Scotland experienced the most severe November weather for at least 100 years. The month had an exceptional deficiency of westerly synoptic

* In this paper normal for surface features refers to the period 1916–50.

types ; the blocking pattern was rather anticyclonic over Britain in the first half and very cyclonic in the second half of the month. The average rainfall for the month over England and Wales was about 115 per cent of normal, but it was very wet in north-east England (e.g. Durham had 250 per cent of the normal rainfall and much of the precipitation fell as snow). However, rainfall decreased to well below normal in northern Scotland. Monthly mean temperatures were mostly in the lowest quintile or decile, largely because of the severe wintry weather in the second half of the month.

Thus on a monthly time-scale the weather over the British Isles during each of the autumn months was highly abnormal in diverse ways. Antipersistence was a feature of the month-to-month relationships ; but a good deal of persistence of weather type occurred within each month on a smaller time-scale. It is instructive to relate the abnormal developments over the British Isles to the large-scale circulation anomalies and changes in circulation patterns over much of the northern hemisphere. A multitude of maps would be needed to represent all relevant aspects of the morphology of the general circulation at different levels and in different sectors of the northern hemisphere, throughout the entire autumn. However, it is possible to depict many significant features of the large-scale circulation by means of a few skeleton diagrams, selected to highlight special points. The following two sections describe some important anomalous features and relationships on, first, a monthly time-scale and second, a time-scale of a few days.

The monthly circulation over the northern hemisphere.—The nature of the low-level circulation over the northern hemisphere each month can be inferred qualitatively from the locations and intensities of the mean monthly surface pressure anomaly centres shown in Figure 1. The pronounced negative anomaly centres (NAC) in September and November and the positive anomaly centre (PAC) in October near England epitomize the enormous month-to-month changes which took place over the British Isles. Thus the extreme cyclonicity of September is consistent with the NAC over central England. The anticyclonic blocking of October is evident from the PAC over the North Sea, surrounded by three NACs, namely west of Portugal, south of Greenland and over the northern Urals. Finally the cyclonic blocking with highly anomalous north-easterly winds over the British Isles in November is quite consistent with the NAC over north France and the large PAC (equal to at least $2\frac{1}{2}$ times the standard deviation of monthly mean pressure) on the Greenland coast near the Denmark Strait.

Some significant features may be noted over the Pacific side of the hemisphere. The September PAC of 10 mb (equal to about $2\frac{1}{2}$ times the standard deviation) at the head of the Gulf of Alaska in combination with smaller NACs in north-east Canada, south-west U.S.A. and in mid-Pacific is typical of a large-scale blocking pattern, with highly anomalous northerly flow over western America. However a drastic reorganization took place from September to October, as implied by the replacement of the large PAC by the NAC in the Gulf of Alaska. In spite of the collapse of the anticyclonic block near Alaska, the flow was anomalously meridional over the north-east Pacific as suggested by the two NACs at about the same longitude and the small PAC farther west in mid-Pacific. Thus the large-scale pressure changes over the Gulf of Alaska from September to October were the reverse of those

near the British Isles. In November the large PAC south of the Aleutians (13 mb or 3 times the standard deviation) together with the large NAC off the Californian coast (-10 mb or 3 times the standard deviation) confirm that blocking, with which was associated highly anomalous northerly flow over much of the eastern Pacific, predominated during the month.

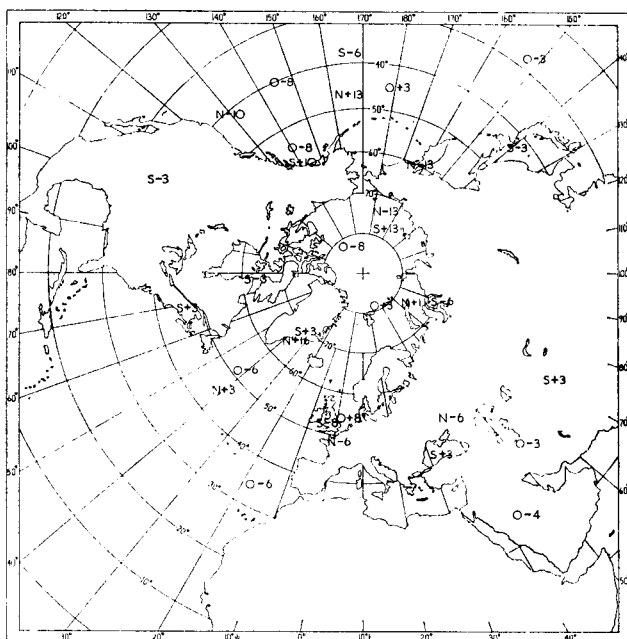


FIGURE 1—MONTHLY MEAN SURFACE PRESSURE ANOMALY CENTRES
IN SEPTEMBER (S), OCTOBER (O) AND NOVEMBER (N), 1965
Centres at positions of + and - signs, pressure in millibars.

It is interesting to note the shift eastwards of the NAC in the Pacific at about 40°N from 170°W in September to 150°W in October to 130°W in November. Another interesting feature is that the high-latitude blocking over north-east Asia in September (suggested by the PAC in the Arctic and the NAC over Japan) weakened in October, but markedly anomalous meridional flow clearly developed in high latitudes in November (note the PAC near the Kara Sea and the NAC near the Arctic coast some 50 degrees of longitude to the east of the Kara Sea).

Various anomalous features of the upper circulation may be visualized with the assistance of Figure 2 which shows the positions of the main troughs on the monthly mean 300 mb maps and the locations of the polar vortices. That part of a trough between contours 940 and 900 geopotential decametres is shown as a continuous line; the broken lines extend the trough to the 880 contour when the pattern allows this to be done. The troughs at 300 mb are in fact representative of the middle and upper troposphere. The 'normal' trough positions in October-53 are taken from *Geophysical Memoirs* No. 103¹ and refer to the period 1949-53.

Usually there is a mean trough in the autumn in eastern Europe but none near western Europe. Figure 2 confirms that the upper circulation in the autumn of 1965 was extremely unusual in the European sector. In addition to significant troughs in eastern Europe in September and October, another trough occurred over the British Isles in September and westward of Ireland in October. No eastern European trough existed in November, but a marked trough was situated off south-east England, along the western European seaboard.

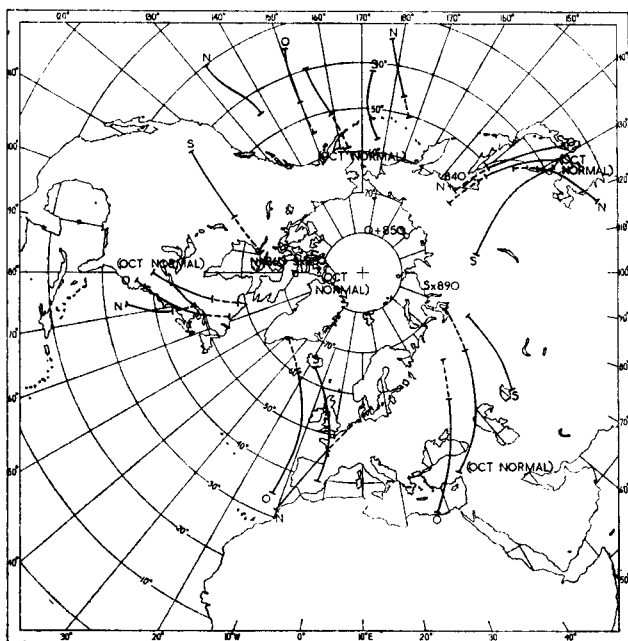


FIGURE 2—MONTHLY MEAN 300 MB TROUGHS IN SEPTEMBER (S), OCTOBER (O) AND NOVEMBER (N), 1965

Continuous line is trough from 940 to 900 geopotential decametres and broken line extends trough to 880 geopotential decametres whenever possible.

The next upstream trough is normally over eastern America ; on this occasion a pronounced trough was located exceptionally far west near the Rocky Mountains in September, but in October and November it was situated in the extreme east of America, a little east of the 'normal' position. Further upstream over the Pacific it is noteworthy that a mean trough was in positions successively farther east and in lower latitudes each month, whilst a second trough developed in the mid-Pacific in November. Over eastern Asia the trough positions each month do not appear to have been very abnormal.

It is particularly noteworthy and significant that the mean troughs in October were farther south than usual (about 5° latitude on average, judging by the positions of the 940 contours). The latitudinal extension in September appears to have been less abnormal except near western Europe, but in

November the troughs not only extended farther south than in October, as shown in Figure 2, but they penetrated to unusually low latitudes for the month of November. Such extensions to anomalously low latitudes were naturally associated with the fact that the main baroclinic zones and jet streams were stronger and further south than usual, especially near the base of the main troughs where the polar jet stream merges into the subtropical jet stream.

Further interesting characteristics of the upper circulation are worth noting, namely (i) the wave number each month was five in middle latitudes, (ii) the circulation in the Arctic was bipolar in September and November, (iii) a 3-trough system in high latitudes emanated from a single vortex in October and (iv) the main blocking ridge extended north into Alaska in September, to the Norwegian Sea in October and to Greenland in November.

The anomalous low-level flow implied by the distribution of pressure anomaly centres (Figure 1) and the locations of upper troughs (Figure 2) which are generally associated with cold tropospheric air near or somewhat west of their axes largely account for the mean monthly surface temperature anomaly distribution shown in Figure 3. For example, the exceptionally cold air over western America in September was largely the result of the very anomalous northerly surface flow (Figure 1) which brought much cold air far to the south; the warm area in October from south-west France to the Norwegian Sea shown in Figure 3 was also clearly a consequence of the

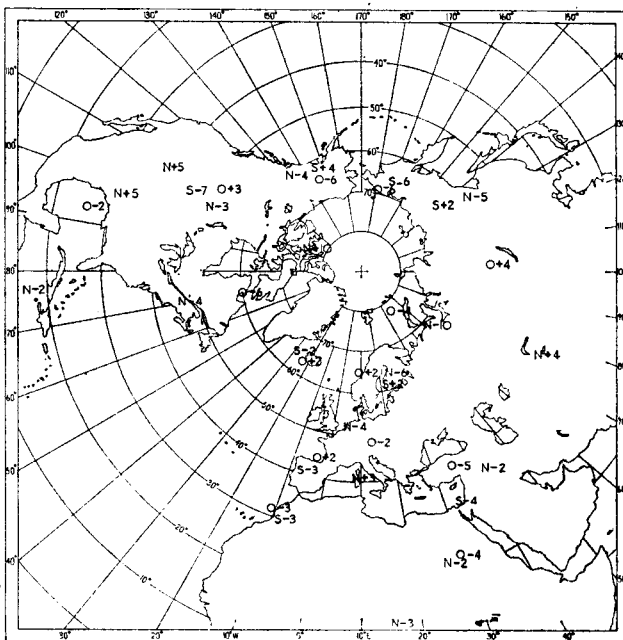


FIGURE 3—MONTHLY MEAN SURFACE TEMPERATURE ANOMALY CENTRES IN SEPTEMBER (S), OCTOBER (O) AND NOVEMBER (N), 1965

Significant centres with inner isotherm $\geq 2^{\circ}\text{C}$ or $\leq -2^{\circ}\text{C}$; centres at positions of + and - signs.

anomalous southerly advection implied by the large positive pressure anomaly centre in the North Sea (Figure 1) and the trough west of Ireland (Figure 2) ; and other instances may readily be seen.

Rainfall will not be discussed except to say that its distribution was broadly consistent with the location of the tropospheric troughs and the pressure anomaly centres (e.g. the above-normal rain over the British Isles in September was closely related to the upper trough and the large negative pressure anomaly).

The circulation on a time-scale of about five days.—On a time-scale much smaller than a month an increase in complexity is inevitable, and considerable simplification of diagrammatic representation is essential if bewildering details are to be avoided.

Important synoptic phases in the Atlantic sector can be linked to simple graphs (Figure 4) which show the time variation of 5-day mean surface

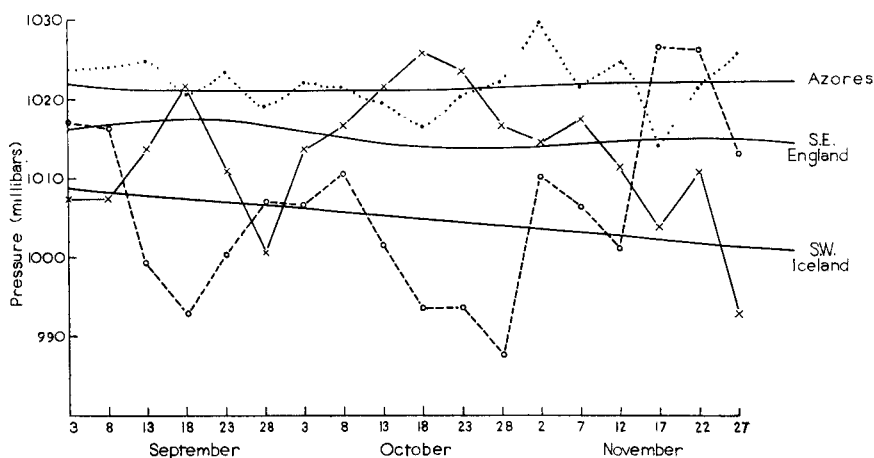


FIGURE 4—5-DAY MEAN PRESSURE AT THREE PLACES IN AUTUMN 1965

..... Azores, 35°N 30°W
 x—x South-east England, 50°N 00°
 o--o South-west Iceland, 60°N 35°W
 — Long-period average based on data from 1900-39

pressure at three points, namely near south-east England and at the two 'centres of action' near Iceland and the Azores. The large out-of-phase oscillations of the pressure curves for south-east England and Iceland are closely in agreement with the main cyclonic and anticyclonic phases near the British Isles and farther afield over the Atlantic. Pressure near south-east England was mostly below the long-period average (1900-39) until early October, apart from a short spell after mid-September associated with abnormally low pressure near Iceland. A major block developed near the British Isles and pressure rose to a maximum well above average in the third week of October before declining slowly ; after about 10 November pressure was increasingly below normal (this period was markedly cyclonic), whilst above-normal pressure near Iceland resulted from the great intensification of the polar anticyclone over Greenland (central pressure equalled or exceeded

1050 mb on 19 and 20 Nov.). The pressure oscillations near the Azores were clearly smaller in amplitude and more frequent than those at the other two places.

Longitudinal changes with time of positions at 50°N of minima in the 1000–500 mb thickness (Figure 5) help to clarify the picture of circulation change. The colder than usual major cold trough A remained nearly 50 degrees of longitude west of its average position (averaged over 1949–63) over America until past mid-September when it progressed quickly to a position somewhat east of its average longitude. Meanwhile significant variations took place downstream as shown by the movements of the thermal troughs and ridges in Figure 5. Troughs A, B, C and D all experienced a net drift eastwards in September, although trough A remained quasi-stationary for some 10 days longer than the other troughs and ridges. The exceptional nature of the circulation in September is emphasized again by the mere existence of troughs C and D in sectors where mean thermal troughs

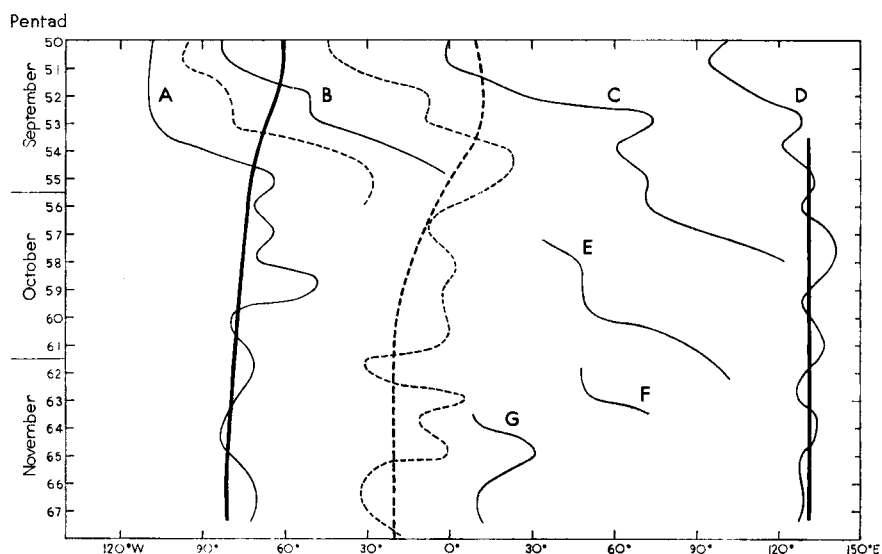


FIGURE 5—VARIATION OF 5-DAY MEAN 1000–500 MB COLD TROUGHs AND WARM RIDGES AT 50°N FOR PENTADS 50–67 (SEPTEMBER–NOVEMBER) 1965

— Cold trough
 - - - Warm ridge
 — Average cold trough
 - - - Average warm ridge
 (All data averaged over period 1949–63)

do not usually form. It was not until the latter part of September that trough D moved to the normal longitude over east Asia, where subsequently it settled down and intensified. The cyclonicity over the British Isles in September was linked to trough C in the first half and to trough B later in the month, whilst the temporary anticyclonic period already referred to (e.g. see pressure maximum in Figure 4) was related to the warm ridge. The anticyclonic block near the British Isles in October and early November occurred with a warm ridge near or just east of the average position and with no cold trough

over the British Isles or western Europe. During this phase there was generally a trough over eastern Europe or western Asia ; but in the second week of November another important cold trough appeared over western Europe, and this was part of the large-scale changes which brought cold, cyclonic weather back to the British Isles (as suggested also by the trend of the curves in Figure 4).

On a broad time-scale there was clearly general similarity in behaviour of the two most intense troughs (A and D) and the eastern Atlantic ridge, but on the pentad time-scale the picture was not so simple. For instance the progressive and retrogressive shifts of troughs A and D were in phase from pentads 54 to 57, but thereafter they were clearly out of phase. It is hard to avoid the conclusion that the behaviour of the American trough was largely independent of the behaviour of the east Asian trough. However, the behaviour on the 5-day scale of the eastern Atlantic ridge was apparently linked to the shifts of the American trough with a lag of a pentad or two (Figure 5). Moreover, the re-formation of thermal troughs over Europe whenever the pre-existing European trough progressed into Asia was evidently in response to the lengthening wavelength between the progressing trough and the American trough.

Anomalous features of the tropospheric thermal structure throughout the autumn may be looked at rather differently with the aid of Figures 6, 7 and 8, which show the distribution of 5-day mean 1000–500 mb thickness anomaly centres, together with superimposed skeleton monthly mean 500 mb maps on which a few contours have been selected to show the main pattern of mid-tropospheric flow. Figure 6 suggests that the synoptic patterns were fairly

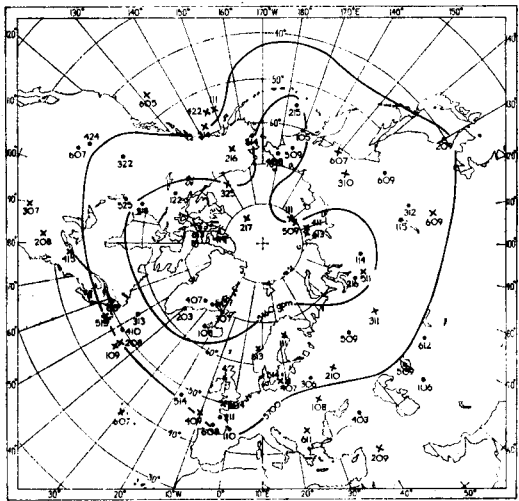


FIGURE 6—5-DAY MEAN 1000–500 MB THICKNESS ANOMALY CENTRES IN SEPTEMBER 1965

.	Negative centres (NAC)	5-day periods in September	
x	Positive centres (PAC)	No.	Begins
—	Selected monthly mean 500 mb contours in geopotential metres	1	3rd
	In the 3-figure groups the first figure is the pentad number and the remaining figures give the anomaly in geopotential decametres.	2	8th
		3	13th
		4	18th
		5	23rd
		6	28th

homogeneous in September in many sectors (e.g. note the cluster of PACs in the Gulf of Alaska and the complete absence of positive anomalies from Greenland to south-western U.S.A.) ; evidently the cumulative effect of synoptic processes of similar type over several pentads was consistent with the circulation on the monthly scale, as shown in Figures 1, 2 and 3. A gradual increase in zonal flow from the Aleutians to northern Canada set in late in September more or less simultaneously with the eastwards motion of a depression across Alaska ; this significant change was associated with the transference of the NAC (525) from near Hudson Bay to NAC (613) near Newfoundland (a decaying cell (607) was left behind east of the Rockies), and with the weakening and movement south-eastwards of the PAC in the Gulf of Alaska (514 to 605). Meanwhile increased meridionality in the Atlantic led to blocking, characteristically shown by various interrelated features, such as the plunging south-eastwards of depressions towards the Bay of Biscay, the stagnation in the same area of the previously progressive NAC (608) and the thrust northwards of warm air over western Europe shown by the PAC (613) off the Norwegian Coast. Superficially the cyclonic block over the British Isles in the last week of September was similar to the cyclonic pattern of the first half of September. However, there were already symptoms of significant differences in the large-scale circulation, notably the tendency for higher pressure in the Norwegian Sea, the development of a thickness PAC off the Norwegian coast and the rapid retrogression of a NAC (613) to north Baffin Land from east Greenland, in addition to the sudden progression of the American cold trough (Figure 5).

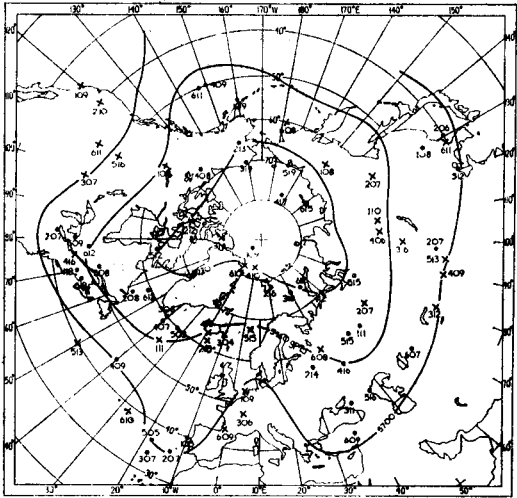


FIGURE 7—5-DAY MEAN 1000-500 MB THICKNESS ANOMALY CENTRES IN OCTOBER 1965

- Negative centres (NAC)
 - x Positive centres (PAC)
 - Selected monthly mean 500 mb contours in geopotential metres
- In the 3-figure groups the first figure is the pentad number and the remaining figures give the anomaly in geopotential decametres.

5-day periods in October	
No.	Begins
1	3rd
2	8th
3	13th
4	18th
5	23rd
6	28th

Figure 7 for October shows clearly that no NAC was observed over western America after these changes were set in train in the last week of September ; and also that negative centres clustered over eastern America for most of October in association with a persistent or recurrent large-scale thermal trough, apart from a spell after mid-October (note NAC 416) when zonality across America to mid-Atlantic between latitudes 40° and 60° N was at a maximum relative to the flow earlier and later in October. Other noteworthy clusters of anomaly centres, confirming the existence of rather homogeneous large-scale circulation and thermal patterns, were the NACs near the Barents Sea, near southern Russia, off Portugal and near Alaska, and the PACs in or near the Norwegian Sea and near north Greenland.

The NAC over the Bay of Biscay and the associated cyclonic system over the British Isles late in September quickly sank south-westwards to form a very persistent cut-off depression near Portugal in October (note the cluster of NACs). This cutting-off development was part of the large-scale blocking process over the Atlantic and western Europe, but in turn the subsequent persistence of the cold depression near Portugal favoured persistence of broad-scale blocking by ensuring that the southern branch of the upper westerlies was held in unusually low latitudes in the eastern Atlantic. The northern branch of the upper baroclinic zone was usually in very high latitudes and depressions were steered eastwards in latitudes north of 65° N, although a temporary southwards shift of the blocking pattern around mid-month brought the depression track across the central Norwegian Sea. The virtual disappearance of the blocking pattern late in October was associated with a marked increase in zonality across the Atlantic and western Europe and with a depression track from the Davis Strait to the Baltic : this important phase can be related to increased zonal flow upstream over America about mid-month and progressively farther east later, consistent with the eastwards movement of the PAC (416) from east of the Great Lakes to the Azores some 10 days later.

The cyclonic westerlies over the British Isles late in October changed rapidly at the beginning of November ; very marked amplification of the upper pattern took place (warm ridge over Atlantic and cold trough over western Europe), and the blocking pattern of the October type quickly emerged near western Europe. The location of the PAC (108) in the northern Atlantic and the NAC (109) off Portugal, shown in Figure 8, confirms that the thermal pattern was markedly amplified at this time. However, before mid-November the blocking pattern retrogressed to Greenland ; the American circulation favoured much warm advection to the west of Greenland, and this led to strong anticyclonic development over Greenland. Almost simultaneously, very cold air moved west then south over western Europe, and the subsequent proximity of the quasi-stationary upper cold trough meant that vigorous cyclonic systems moved over or near the south of the British Isles throughout the second half of the month.

It is interesting that the November pentad thickness anomalies of the same sign were also grouped in limited geographical areas (Figure 8), particularly noteworthy being the clusters of NACs in the Gulf of Alaska, over eastern America, over north-west of Europe to off the south-west of the British Isles and over Siberia, suggestive of long spells with broad-scale homogeneity in circulation characteristics. Moreover, comparison of Figures 7 and 8 shows

that there was considerable broad-scale resemblance from the western Pacific to off eastern America. However, the marked dissimilarities over western Europe essentially resulted from the retrogression of both the eastern European cold trough and the western European block.

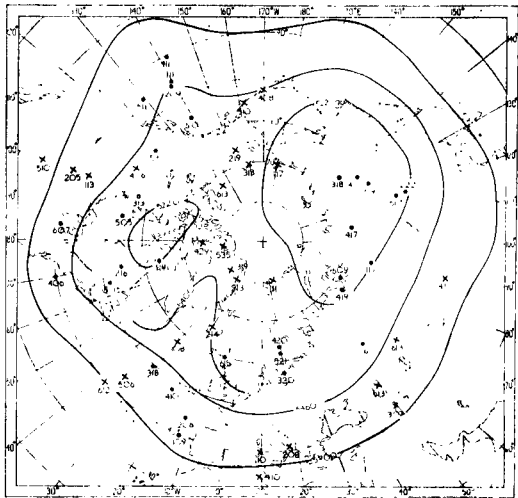


FIGURE 8—5-DAY MEAN 1000-500 MB THICKNESS ANOMALY CENTRES IN NOVEMBER 1965

.	Negative centres (NAC)	5-day periods in November	
x	Positive centres (PAC)	No.	Begins
—	Selected monthly mean 500 mb contours in geopotential metres	1	2nd
	In the 3-figure groups the first figure is the pentad number and the remaining figures give the anomaly in geopotential decametres.	2	7th
		3	12th
		4	17th
		5	22nd
		6	27th

General remarks.—This descriptive account must be restricted in the interests of simplicity and clarity. Nevertheless, it should be clear that large anomalies and big month-to-month changes in circulation occurred in other sectors of the northern hemisphere as well as near the British Isles. The radical changes from September to October over the western Pacific and America and also over the eastern Atlantic and Europe were related to a marked shortening of the wavelength of the upper flow ; this was achieved by a quite sudden and large shift eastwards of the American cold trough, which had been exceptionally far west of the normal position, and to the retrogression of anomalous cold troughs near eastern and western Europe, as well as to warm ridge amplification between the European troughs. Anti-persistence in broad-scale synoptic type over the British Isles from October to November was related to complex changes which effectively resulted in retrogression of the European block to high latitudes of the Atlantic and Greenland and of the eastern European trough to western Europe, whilst the cold trough near eastern America progressed little compared with the major progression from September to October. The troughs on each side of the Atlantic in November were unusually cold and concentrated in lower-middle latitudes with the result that the subtropical jet stream was stronger

than usual, and the upper westerlies between 40° and 70°N were abnormally weak from the Rockies to the Urals. Additionally it is well worth stressing that the abnormal cold troughs near western Europe in September and November, associated in each case with cold cyclonic weather over the British Isles, managed to exist with the American trough in strikingly different positions; and that the quite different circulation pattern over western Europe in October was linked with an American trough which was not far away from the same position in November.

What can be said about the circulation anomalies within each month? The 5-day anomalies clustered within, say, a square of side about 15 degrees of latitude suggest that certain broad-scale circulation patterns commonly persisted for a few pentads, then changed to a new mode or returned to the original one after a transitional period of about a pentad. Around the transitional period the day-to-day synoptic changes in one sector were not only predictable by the normal subjective or objective procedures but were often obviously related to preceding modifications of the circulation in adjacent sectors. However, the interdependence of circulations in sectors very far apart (e.g. western Europe and western Pacific) was rarely obvious; in these cases linkages were complex and indirect.

The ultimate causes of the large-scale circulation anomalies, such as those of the autumn of 1965, are not known. The importance of air-sea interaction is certainly well recognized (e.g. Namias² and Sawyer³), but our understanding of the interrelationship and feed-back mechanisms on different time-scales is still extremely limited.

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COMPARISON OF BRITISH STRATOSPHERIC AND MESOSPHERIC TEMPERATURE MEASUREMENTS WITH VALUES FROM AVAILABLE ATMOSPHERIC MODELS

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Bedford, Mass.

Temperature observed between 30 and 70 km at West Geirinish, Scotland (57°21'N, 7°23'W), during the period January and February 1964 and January to April 1965, are compared to the temperature-height profiles of various atmospheric models developed to represent mean monthly conditions near 60°N. Profiles from the Committee on Space Research (COSPAR) International Reference Atmospheres,¹ the Committee on Extension to the Standard Atmosphere (COESA) U.S. Standard Atmosphere Supplements,² and Air Force Cambridge Research Laboratories (AFCRL) models developed by Kantor and Cole,³ are included in the comparison. The COESA models

have been published as Air Force Interim Atmospheres, Cole and Kantor.⁴

The temperature measurements for West Geirinish were made with the SKUA meteorological rocket recently developed by the British Meteorological Office. The instrument package consists of a temperature measuring sonde attached to a parachute. The method of temperature measurement, immersion thermometry using a very fine tungsten wire, provides data at altitudes up to 60 to 65 km.

Vertical temperature structures of the atmospheric models were developed primarily from meteorological and experimental rocket soundings over North America. These soundings employed various types of sensors including bead thermistors, grenades, falling spheres and pressure gauges. The majority of the observations were taken at Churchill, Canada ($58^{\circ}44'N$, $93^{\circ}49'W$).

Temperature-height profiles for an interpolated COSPAR January $57\frac{1}{2}^{\circ}N$ atmosphere and the mean $60^{\circ}N$ January COESA Atmospheres are compared

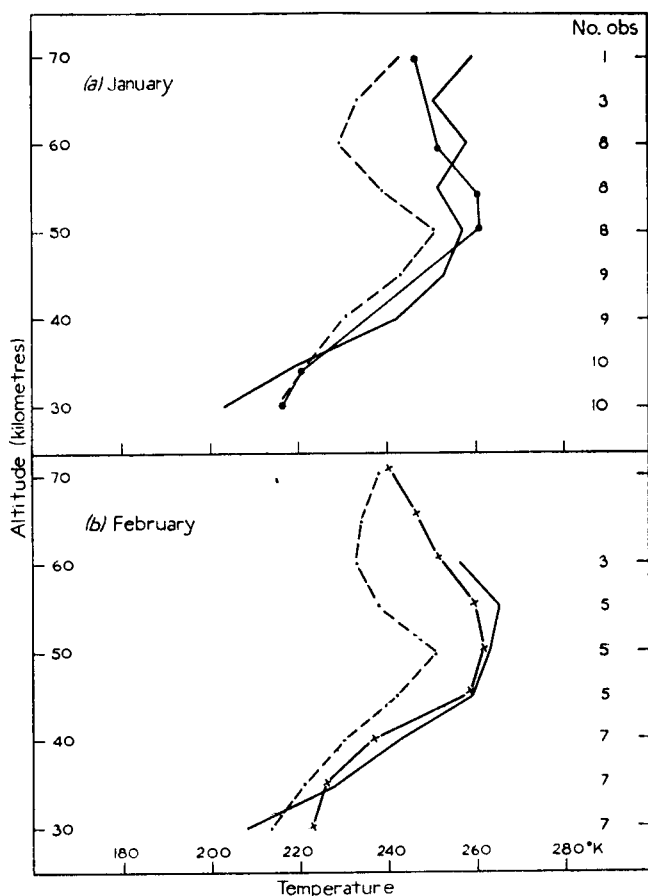


FIGURE 1—COMPARISON OF RECENTLY OBSERVED JANUARY AND FEBRUARY TEMPERATURE-HEIGHT PROFILES WITH THOSE FROM PREVIOUSLY ESTABLISHED ATMOSPHERIC MODELS

— West Geirinish, $57^{\circ}N$ $7^{\circ}W$, observations - - - COSPAR, $57\frac{1}{2}^{\circ}N$
 ····· COESA, $60^{\circ}N$ x—x AFCRL, $60^{\circ}N$

in Figure 1(a) with the observed January means given by Farmer,⁵ for West Geirinish. The number of observations on which the observed means are based is indicated on the right-hand margin. Similar comparisons are made between the observed data and temperature-height profiles for the AFCRL and COSPAR monthly atmospheres for February, March and April in Figures 1(b), 2(a), 2(b), respectively.

The observed monthly mean temperatures for West Geirinish are in relatively good agreement with the COESA and AFCRL temperature-height profiles but differ considerably from the COSPAR values. Observed values are 1 to 5 degC warmer than the AFCRL and COESA models between 35 and 50 km and slightly cooler in three of the four months between 50 and 55 km. The largest differences occur at 30 km where the January and February West Geirinish temperatures are 10 to 20 degC colder than those in the AFCRL models. Part of this difference is accounted for by the fact

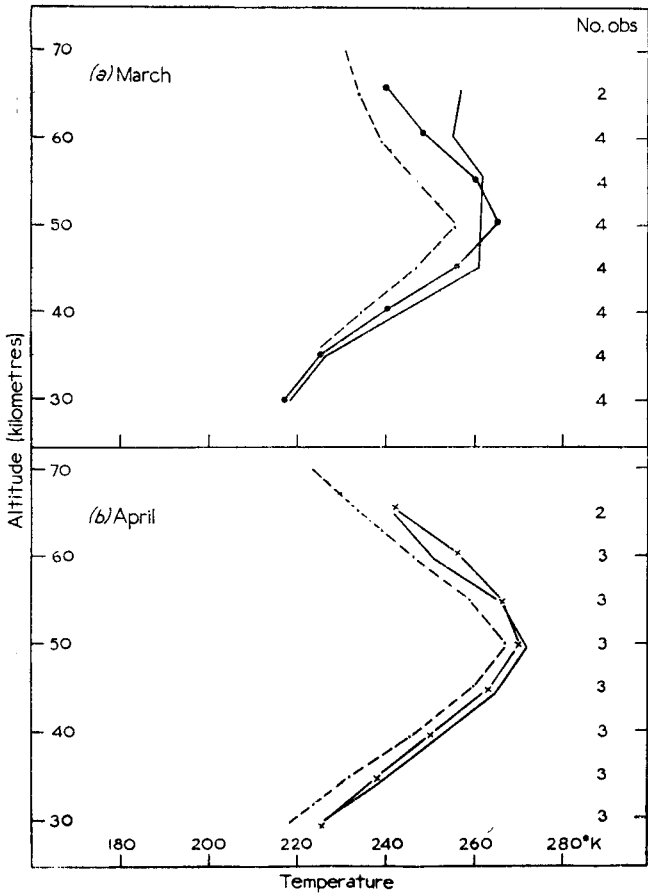


FIGURE 2—COMPARISON OF RECENTLY OBSERVED MARCH AND APRIL TEMPERATURE-HEIGHT PROFILES WITH THOSE FROM PREVIOUSLY ESTABLISHED ATMOSPHERIC MODELS

— West Geirinish, 57°N 7°W, observations - - - COSPAR, 57½°N
 COESA, 60°N x—x AFCRL, 60°N

that the COESA and AFCRL temperatures at this level are based on hemispheric means computed from radiosonde data. An inspection of available radiosonde summaries indicates that the mean monthly January and February temperatures between 25 and 30 km for the region near West Geirinish are roughly 8 to 10 degC colder than the hemispheric mean at latitude 60°N. A possible explanation for the large differences between the COSPAR and AFCRL models which were prepared and published at approximately the same time and from the same data is that different weighting factors may have been used for the various types of observations.

The good agreement of the observed temperature-height profiles with the COESA and AFCRL atmospheres above 35 km suggests that conditions near Churchill, Canada, are similar to those at West Geirinish. It is also interesting to note that the large day-to-day temperature changes which are frequently observed in the upper stratosphere and lower mesosphere during January at Churchill, Canada, also occur at West Geirinish, Farmer⁵ indicating that these phenomena may be a characteristic of all subarctic locations.

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METEOROLOGICAL CONTRIBUTIONS TO THE 1966 PHYSICS EXHIBITION

By J. I. P. JONES

Introduction.—From 28 to 31 March this year, the Institute of Physics and the Physical Society held their exhibition of scientific apparatus at the Alexandra Palace, London, the entire exhibition being gathered under one roof for the first time since 1955. The exhibition was the 50th in the series started by the Physical Society in 1905 with a modest three hours opening and 17 exhibitors. This year's contributors included 100 commercial firms, 21 government establishments, 24 universities and similar institutions of learning and 26 publishers.

Contributions comprising new wind measuring instruments and a cathode-ray tube (CRT) display technique were made by the Meteorology Research Division, Porton. Considerable interest was shown in the exhibits both by visiting scientists and by fellow contributors, and the Porton demonstrators were kept busy answering numerous questions. A brief description of the exhibits follows.

Portable sensitive anemometer* and wind velocity-component resolver.—These instruments¹ are shown in Plate I. The anemometer is fitted with a 12-cup rotor constructed of expanded polystyrene in order to obtain extra rapid response, but this may readily be replaced by a conventional 3-cup aluminium rotor if desired. The anemometer contains a photoelectric switch and a ratemeter which are supplied with power (12 V, 40 mA) from an external source. Both a.c. and d.c. outputs with frequency and voltage respectively proportional to wind speed, are provided by the instrument.

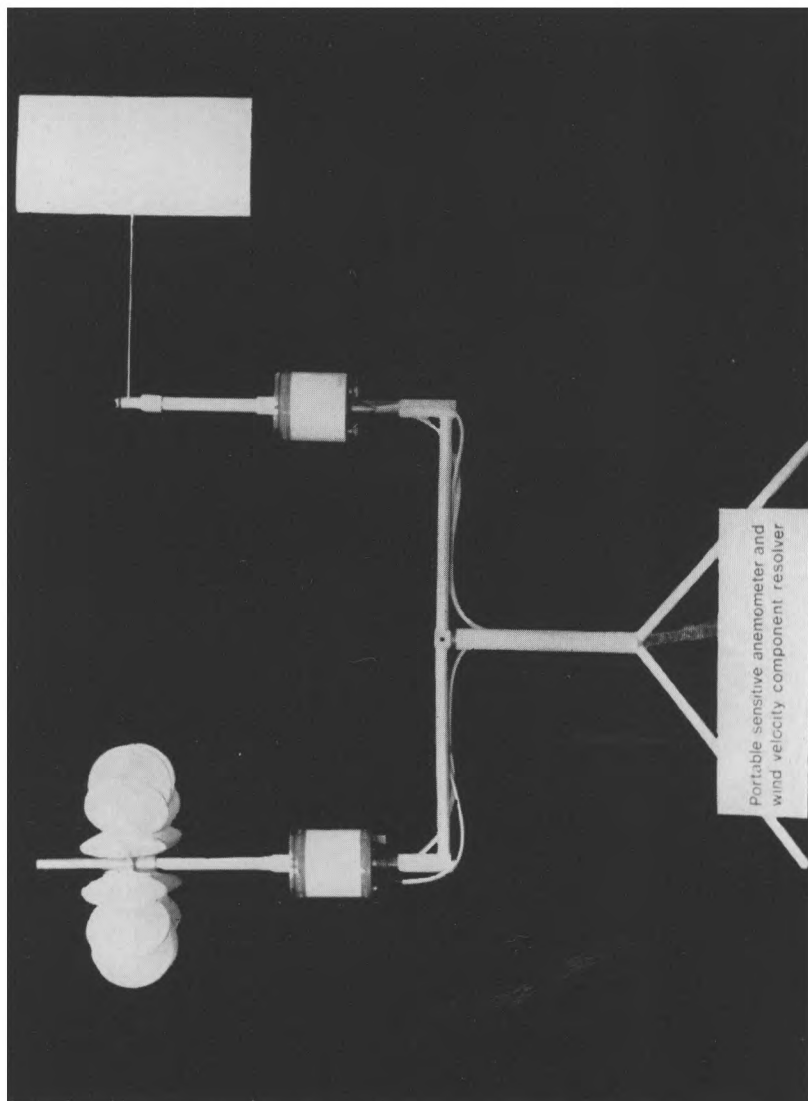
The resolver contains a low-friction sine-cosine potentiometer, and this is supplied directly with the d.c. voltage from the anemometer. Lightly sprung contacts, operating at 90° relative to one another on the potentiometer, are directly coupled to the wind vane, and provide output voltages proportional to orthogonal wind velocity-components. By appropriate orientation of the resolver case, voltages which represent algebraically two velocity-components in any specified mutually perpendicular directions, such as along and at right angles to the runway of an airfield, may be obtained.

The anemometer and resolver on display were designed originally as portable instruments for research into the statistics of atmospheric turbulence and the structure of wind eddies. All-weather instruments developed subsequently, having the same principle of operation though with a remote ratemeter of controllable output sensitivity, were mounted on the roof of the Palace for the exhibition. Outputs from these instruments were displayed on the stand using meters to indicate N-S and E-W 'sliding 2-min average' component velocities and wind speed. The voltages from the resolver were also processed electronically using the new CRT display technique outlined below, and the wind velocity was presented in vector form on a display oscilloscope. Duplexing at 200 c/s was employed to present, in effect simultaneously, both smoothed and fluctuation wind vectors. Plate II shows oscillograms of this type of display taken over periods of approximately 30 seconds.

Apparatus for displaying two-dimensional flow patterns using the cathode-ray tube.—This apparatus^{2†} was designed for observing the surface wind field in real time by means of vectors on a cathode-ray tube, and for recording wind eddy patterns. Two voltages, representing orthogonal velocity-components of the wind, are passed to the apparatus (Plate IIIa) from each of a number of anemometer-resolver sets at selected positions in the field, and the winds are displayed, correspondingly arranged, as vectors on the cathode-ray tube. Oscillograms of eddy patterns (Plate IIIb) are obtained with the aid of electrical band-pass filters which emphasize fluctuations of the components within a particular frequency range as eddies traverse a cross-wind array of sensors. Alternatively, residual-vector displays, obtained by analogue subtraction of the spatial mean vector, can be used to examine eddy structure.

The system employs a combination of digital and analogue techniques in which all pairs of orthogonal input voltages are filtered, multiplexed, chopped and time-integrated, and then added sequentially to adjustable beam-switching voltages. The two final output signals are applied to the inputs

*United Kingdom Patent No. 1028494. †United Kingdom Patent application No. 21661/64.



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PLATE I—PORTABLE SENSITIVE ANEMOMETER AND WIND VELOCITY-COMPONENT
RESOLVER

See page 239.

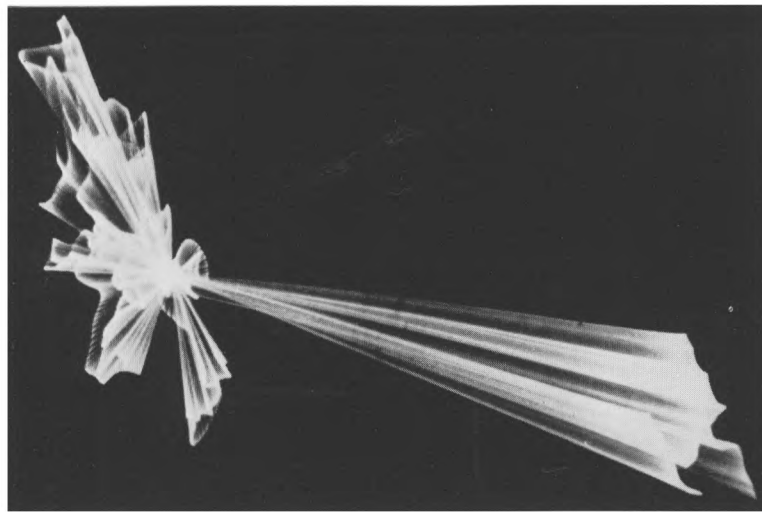
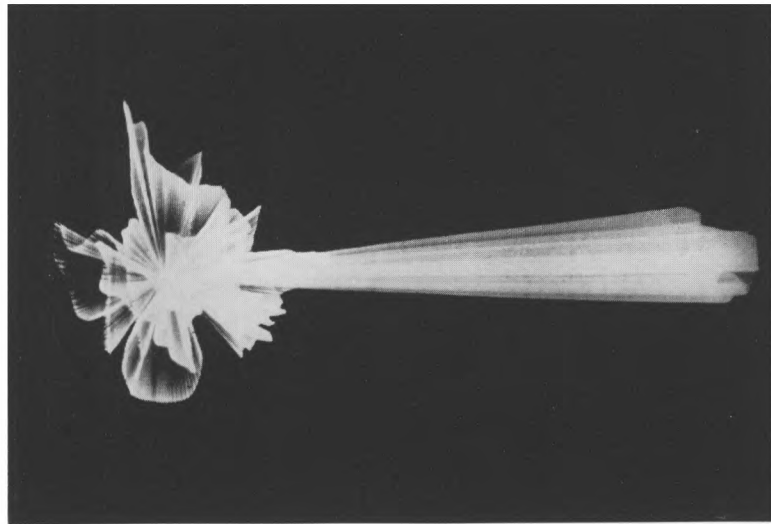


PLATE II—OSCILLOGRAMS OF WIND VELOCITY VECTORS

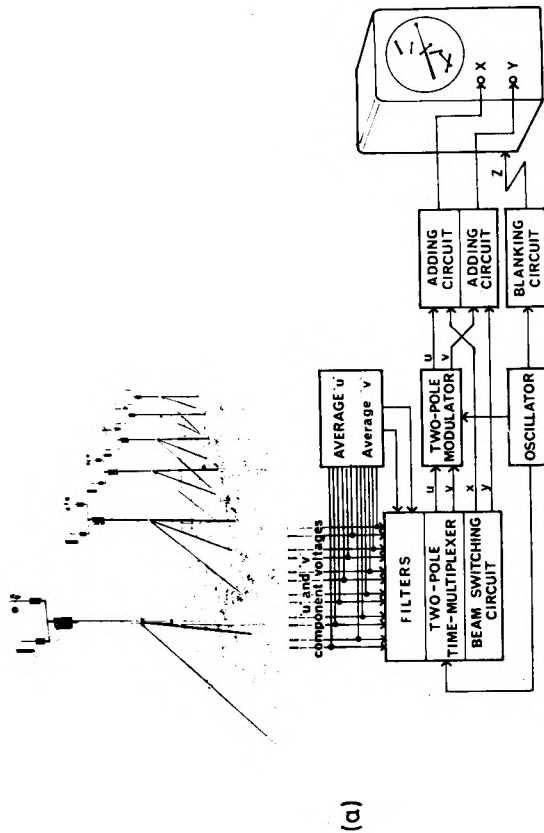
Photographed at the rate of 400 per second and showing both 'running mean' and fluctuation wind velocities over periods of approximately 30 seconds (see page 239).

CRT vector presentation of surface wind data

This apparatus was designed for observing the surface wind at various positions in the field by means of vectors, correspondingly arranged, on a cathode-ray tube.

Two voltages, which represent orthogonal wind velocity-components, are passed to the apparatus from an anemometer-resolver set at each field position. All pairs of input voltages are multiplexed, chopped and time-integrated, and then added sequentially to beam-switching voltages. The final output signals are supplied to an X-Y oscilloscope, together with a blanking voltage to suppress the beam during switching and to eliminate direction ambiguity.

Oscillograms of eddy patterns are obtained with the aid of filters which emphasize wind fluctuations as the eddies traverse a linear array of sensors.

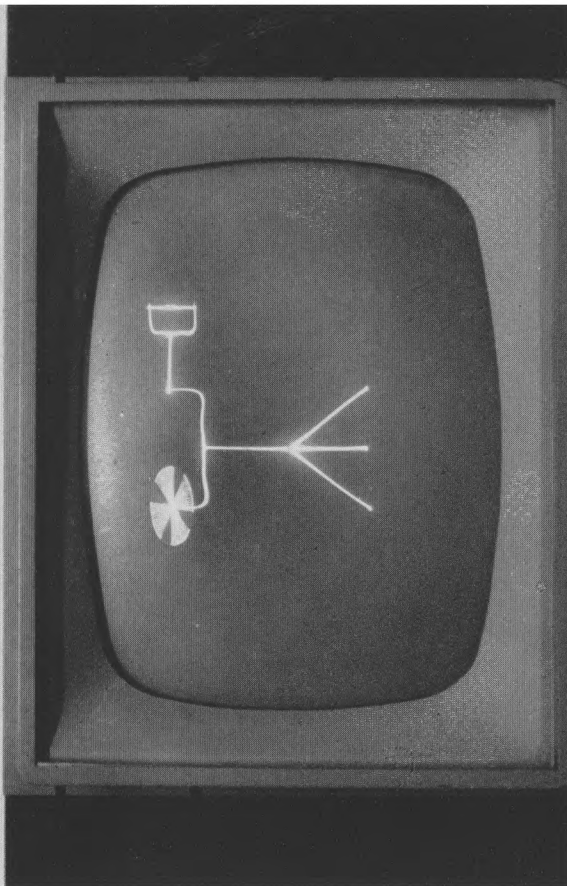


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PLATE III—CATHODE-RAY TUBE VECTOR PRESENTATION OF SURFACE WIND DATA

- (a) The block circuit diagram of the system for recording oscillograms of eddy structure.
- (b) An example of recorded eddy patterns at an open exposure at height 2 metres. Vectors of wind velocity fluctuations recorded as eddies pass through a cross-wind array of six sensors.
- Scales — Vertical, 5 metres between vectors ; Horizontal, 1 second between vectors.
- Filters used — Band-pass, centre frequency 2 c/min.

This equipment was designed to display seven separate vector quantities in any desired arrangement on a C.R.T. By the use of appropriate input signals, however, and by suitably positioning the patterns thus formed, line illustrations such as that of the anemometer and resolver may be produced



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PLATE IV—LINE PICTURE PRODUCED WITH THE MULTI-VECTOR OSCILLOSCOPE DISPLAY EQUIPMENT AND USED TO DEMONSTRATE THE APPLICATION OF THE APPARATUS TO DISPLAY SYSTEMS IN GENERAL

A scanning frequency of 200 c/s was used (see page 239).

of an X - Y oscilloscope, together with a synchronized blanking signal to suppress the beam during switching from one vector position to the next and to eliminate direction ambiguity. Vectors are produced in sequence on the tube, although at a sufficiently high frequency to give the effect of simultaneity, the minimum scanning frequency being approximately 50 c/s. Each vector may be adjusted separately to any desired position on the tube by potentiometer control of the appropriate X and Y beam-switching voltages.

The flexibility of the apparatus and its consequent applications to display systems in general was demonstrated at the exhibition by displaying, on an oscilloscope, a line illustration of an anemometer and resolver mounted on a tripod (Plate IV), a rotating four-bladed rotor being produced by the application of quadrature 50 c/s voltages to one pair of input terminals.

Acknowledgements.—Acknowledgement is made to the Director, CDEE, Porton Down for the facilities provided, and to Messrs I. H. Simpson, G. D. Nichols and J. B. Tyldesley, Meteorological Office, who ably demonstrated the exhibits.

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551.510.42:551.524.4:551.553.6

AN INDICATOR OF SURFACE WIND DIRECTIONS POTENTIALLY FAVOURABLE FOR ATMOSPHERIC POLLUTION

By E. N. LAWRENCE

Summary.—At Crawley, Sussex, winter midday low-level inversions (taken to indicate at least 12 hours persistent inversion) are analysed according to light-wind direction (surface and 900 mb) and are shown to be associated more with light easterly winds than with westerlies. Inversions at Crawley with easterly winds tend to persist longer than those with westerlies. The distribution of temperature inversions with wind direction may thus indicate a light-wind direction favourable for persistent temperature inversion and hence potentially favourable for high concentrations of air pollution. The surface light-wind rose for all occasions may give some indication of directions favourable for persistent temperature inversion if some allowance is made for the fact that westerlies are generally more frequent than easterlies.

Introduction.—It is well known that atmospheric pollution is associated with stable atmospheric lapse rates or inversions of temperature near the ground.^{1,2} Such inversions are usually associated with light winds, and so it might be thought that the surface light-wind rose would be a good indicator of the distribution, according to wind direction, of frequencies of low-level inversions and so indicate the wind directions potentially favourable for atmospheric pollution.

In some locations such as a sheltered valley, and during nights with high net outgoing radiation, there may be a simultaneous development of both a temperature inversion near the ground and a characteristic light local wind from a particular direction. A typical example has been described³ for Point Arguello, California, where nocturnal surface inversions based below 1000 feet occur mostly with downslope surface winds. However, there need

not necessarily be an all-round similarity between the direction rose for all occasions of light winds and the direction rose for winds which occur with low-level inversions.

Again, local winds are not necessarily light or very light and inversion frequencies do not always increase with decreasing surface wind speed. For example, an investigation into characteristics of low-level inversions at Budapest⁴ shows that the highest percentage frequencies of inversions occur with medium wind speeds of 3-4 metres/second and not with lighter winds. Furthermore, over flatter terrain, light or very light winds could be more frequent from the prevailing wind directions, and these directions are not necessarily associated with persistent atmospheric stability.

Hence it does not follow that a strong relationship exists in general between the distribution of light winds and of low-level inversions according to the direction of wind, and the following study of persistent inversions at Crawley shows that in winter they are associated with light easterly winds more than with westerly light-wind directions. It is also shown that inversions at Crawley with easterly winds tend to persist longer than those with westerly wind directions. Thus the light-wind direction rose for winter inversions may be taken as an indicator of the wind direction potentially favourable for atmospheric pollution, though the direction rose for all occasions of light winds may not be a suitable indicator.

Data used.—The study was made for the meteorological station site at Crawley ($51^{\circ}05'N$, $0^{\circ}13'W$, 471 feet above mean sea level) which is situated on the western end of a ridge running roughly east-west with broad valleys to the north and south beyond which lie the North and South Downs respectively (see Figure 1). The data refer to the five-year period from April 1960 to March 1965. Temperature profiles are obtained in considerable detail since the introduction of automatic (Cintel) radiosonde techniques in 1960.

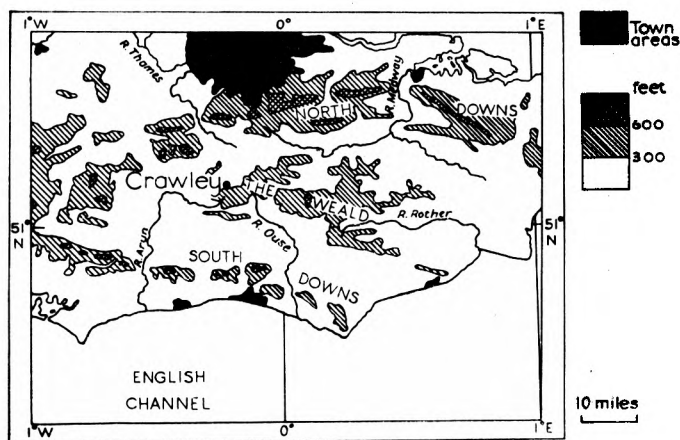


FIGURE 1—DIAGRAM SHOWING CRAWLEY IN RELATION TO LONDON AND THE NORTH AND SOUTH DOWNS

Analysis and discussion.—Figure 2 shows (i) the frequencies of light-wind directions at Crawley, (ii) the frequencies, according to light-wind direction, of inversions of base below 2000 feet above ground and (iii) the percentage ratios of (ii) to (i). The percentages indicate to what degree the number of inversions with winds from a particular direction is large as a result of a large number of winds from that direction.

The data are presented separately for midnight, midday, winter half-year (October–March) and summer half-year (April–September), and for surface wind speeds in the ranges of calm, 1–4 knots and 5–9 knots. Frequencies are given also for 900 mb wind speeds in the range 1–19 knots. Winds at 900 mb have the advantage over surface winds of being more representative of the region, and also the 900 mb wind speed is only rarely reported as calm. In contrast, the surface wind is often reported as calm; for example, in winter, about 25–30 per cent of all occasions of inversion of base below 1000 feet above the ground occurred with reported calm.

It can be seen from Figure 2 that winds at midday with an easterly component have a greater proportion of inversions of base below 2000 feet than

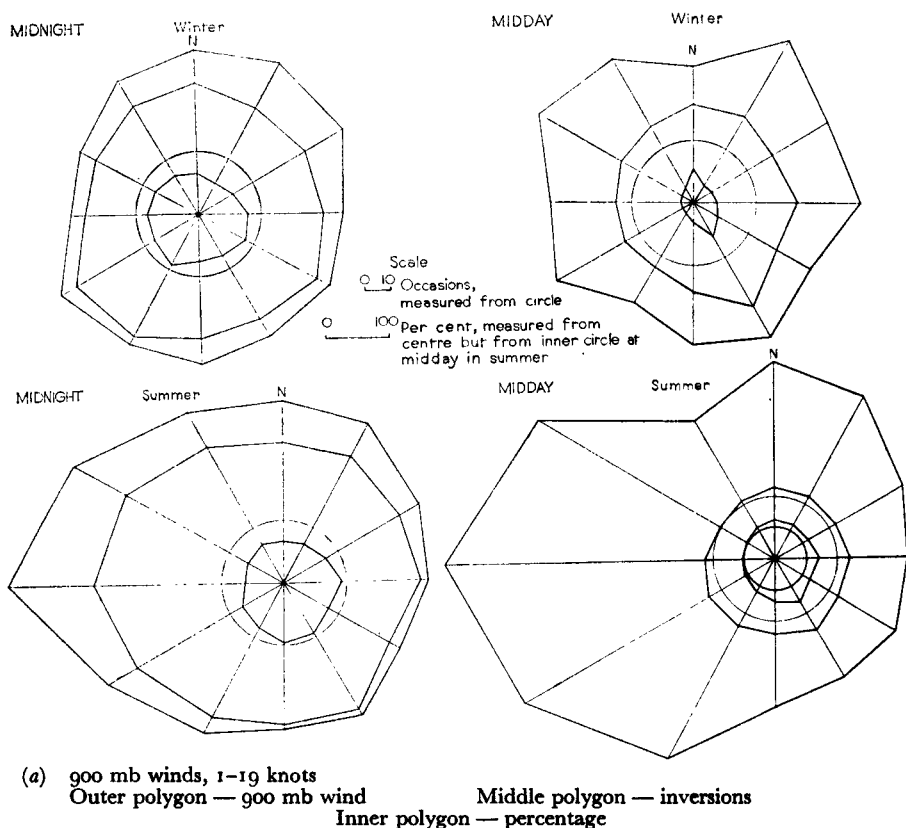
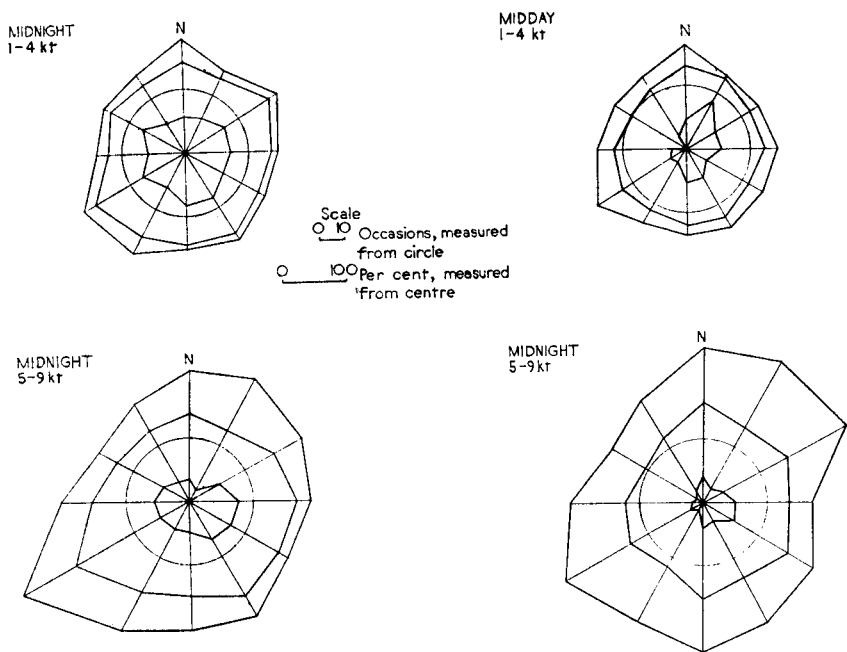


FIGURE 2—LIGHT-WIND DIRECTION ROSES FOR 900 MB AND SURFACE FOR VARIOUS TIMES AND SEASONS COMPARED WITH THE ROSES FOR OCCASIONS OF INVERSION BASE BELOW 2000 FEET ABOVE GROUND AT CRAWLEY DURING THE PERIOD APRIL 1960 TO MARCH 1965

winds with a westerly component. On the other hand, the midnight data, at least for winter, do not show the same contrast between east and west percentages. At midnight for the 900 mb level in winter, Figure 2(a) shows a tendency for the reverse pattern, possibly reflecting the frequency of warm south-west airstreams over cold ground.



(b) Surface winds, winter

Outer polygon — surface wind	Middle polygon — inversions	
	Inner polygon — percentage	
	Midnight	Midday
Total number of calms	171	99
Number of calms with inversions	138	34
Inversion calms as percentage of total calms	81	34

(The diagram at bottom right is for Midday, not Midnight)

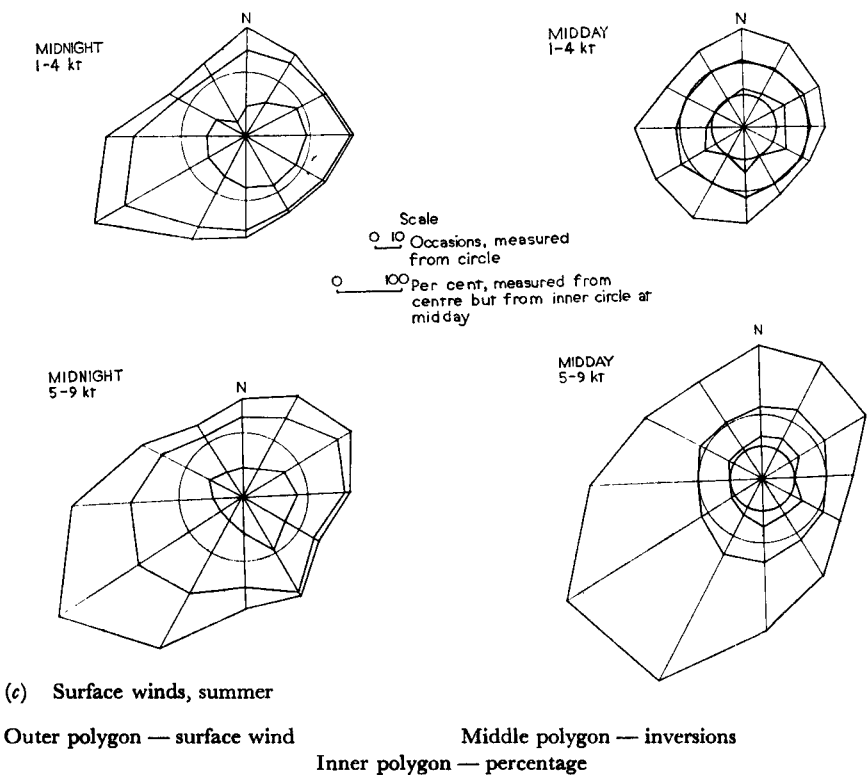
FIGURE 2—continued

The probability of the dependence of (ii) on (i) was also examined by means of chi-square (χ^2) tests, Table I gives χ^2 obtained by comparing the two sets of frequencies. The degrees of freedom are listed as well as the probability that χ^2 would be exceeded by chance.⁵ The degrees of freedom vary because in some categories the direction classes are combined in order to give classes with sufficient numbers for the application of the chi-square test.

Table I shows that for the midnight results for the various heights of inversion base, it is highly probable that inversion frequencies are dependent on the wind frequencies but that for the midday results the dependence is less.

The tendency for inversions to occur with preferred wind direction is rather more marked for surface wind speeds of 5–9 knots than for speeds of 1–4 knots, possibly because of the random nature of very light wind directions. At 900 mb the tendency for a preferred direction at midday in winter is more

noticeable for inversions with base below 2000 feet than for inversions with base below 250, 500, or 1000 feet, presumably because the lower inversions are more likely to occur with light and variable winds.



	Midnight	Midday
Total number of calms	282	75
Number of calms with inversions	222	6
Inversion calms as percentage of total calms	79	8

FIGURE 2—continued

Persistent inversions can be shown to be occasions of real importance from the pollution aspect. An inversion at midday probably follows an inversion at midnight and can be taken to indicate an occasion of over 12 hours persistent inversion. From the pollution aspect therefore the occasions of *midday* inversion are likely to be more significant than occasions of *midnight* inversion. The *midnight* low-level inversions of base below 250 feet were more frequent in the summer half-year than in the winter half-year ; namely 474 and 375 occasions respectively. However the corresponding *midday* frequencies are 2 and 31. Thus during the summer half-year, low-level inversions are not persistent through the day and so any air pollution occurring at night would have a chance to disperse during the day. The greater number of *midday* inversions in the winter half-year indicates that there are more persistent inversions and that a greater retention of air pollution is possible.

TABLE I—VALUES OF THE PROBABILITY OF THE DEPENDENCE OF LIGHT-WIND DIRECTION FREQUENCIES DURING INVERSIONS ON THE TOTAL LIGHT-WIND DIRECTION FREQUENCIES, PERIOD OCTOBER 1960–MARCH 1965

(a) 900 mb winds, 1–19 knots

Half-year	Time of observation	Base of inversion below : <i>feet above ground</i>	Chi-square	Degrees of freedom	Probability range
October to March	midnight	250	7.14	11	0.80–0.70
		500	6.26	11	0.90–0.80
		1000	8.13	11	0.80–0.70
		2000	7.10	11	0.80–0.70
	midday	250	3.72	3	0.30–0.20
		500	1.86	4	0.80–0.70
		1000	12.40	10	0.30–0.20
		2000	24.25	11	0.02–0.01
April to September	midnight	250	7.31	11	0.80–0.70
		500	7.95	11	0.80–0.70
		1000	8.37	11	0.70–0.50
		2000	9.24	11	0.70–0.50
	midday	2000	27.58	6	<0.001

(b) Surface winds

Half-year	Time of observation	Surface wind speed <i>knots</i>	Base of inversion below : <i>feet above ground</i>	Chi-square	Degrees of freedom	Probability range
October to March	midnight	1–4	250	4.09	11	0.98–0.95
			500	3.82	11	0.98–0.95
			1000	4.08	11	0.98–0.95
			2000	2.31	11	1.00–0.99
		5–9	250	13.18	11	0.30–0.20
			500	14.61	11	0.30–0.20
			1000	14.20	11	0.30–0.20
			2000	12.67	11	0.50–0.30
	midday	1–4	1000	12.64	11	0.50–0.30
			2000	11.58	11	0.50–0.30
		5–9	1000	10.45	11	0.50–0.30
			2000	21.23	11	0.05–0.02
April to September	midnight	1–4	250	9.50	11	0.70–0.50
			500	9.11	11	0.70–0.50
			1000	8.34	11	0.70–0.50
			2000	7.26	11	0.80–0.70
		5–9	250	11.63	11	0.50–0.30
			500	16.43	11	0.20–0.10
			1000	20.21	11	0.05–0.02
			2000	15.83	11	0.20–0.10
	midday	5–9	2000	14.91	6	0.05–0.02

Inversion spells longer than a day.—In the problem of air pollution from an external source it is important to consider persistent inversions in which wind directions are reasonably steady. The persistence of inversion spells according to the various persisting wind directions was analysed as follows. A stable spell was defined as a period of two or more consecutive

midday observations with an inversion below 1000 feet above the ground (at Crawley) and with intermediate midnight observations also having such an inversion, and with the 900 mb wind directions remaining not more than 30° from the direction at midday on the first day of the spell, or not more than 50° for speeds smaller than or equal to 4 knots. The dates and wind directions for all such spells were listed. The second observation of a spell was given two points, the third observation was given three points and so on. The total number of points for each wind direction 30° , 60° , etc. was referred to as the relative persistence factor for that direction. The procedure was repeated for midday observations only and the whole procedure repeated for spells with inversion base below 2000 feet above the ground. The results in Figure 3 show peak values of the factor for 900 mb wind directions of 150° to 090° . These directions are approximately the range of 900 mb (1-19 knots) wind directions for the highest frequency of inversions of base below 2000 feet at midday (see Figure 2).

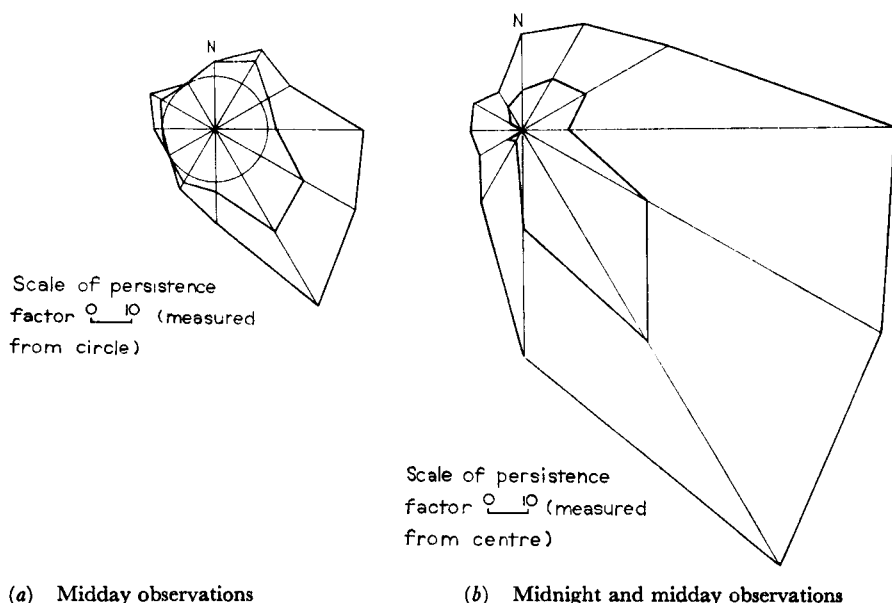


FIGURE 3—VARIATION WITH 900 MB WIND DIRECTION OF SPELLS OF TEMPERATURE INVERSION, AS INDICATED BY RELATIVE PERSISTENCE FACTORS, AT CRAWLEY DURING THE WINTER HALF-YEARS IN THE PERIOD OCTOBER 1960 TO MARCH 1965

Inner polygon refers to inversions of base below 1000 feet.
Outer polygon refers to inversions of base below 2000 feet.

Application.—The results which relate wind directions to frequencies of low-level inversions apply in general to the 900 mb level at Crawley as well as to surface data. Therefore the conclusions apply not merely to the site at Crawley but more generally to inland areas of south-east England which could reasonably be assumed to have 900 mb winds similar to those at Crawley.

In air pollution problems, wind speed and direction at a site must be considered in relation to the distances and directions of any pollution sources.

In any assessment of possible air pollution it should be borne in mind that there may be significant differences between wind rose data obtained over different periods. For example the frequency of easterlies at Crawley during the winter half-years of the period October 1960 to March 1965 was greater than in the previous five-year period 1955-59 and was probably distinctly above the long-term average.

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THE FORECASTING OF SHOWER ACTIVITY IN AIRSTREAMS FROM THE NORTH-WEST QUARTER OVER SOUTH-EAST ENGLAND IN OCTOBER TO APRIL

By C. A. S. LOWNDES

Introduction.—In an earlier paper¹ a study was made of the shower activity in airstreams from the north-west quarter over south-east England in summer-time and the relative usefulness of a number of predictors for forecasting shower activity, thunder and hail was evaluated. This paper deals in the same way with the problem of forecasting shower activity over south-east England in the months October to April. The investigation was restricted to airstreams which approached the British Isles from the north-west quarter. The factors associated with shower activity which were considered were the same as in the previous investigation¹ and as before, the intensity of shower activity was classified as follows :

- A Widespread showers with a good proportion of moderate or heavy showers (8 or more mentions of showers ; more than 25 per cent moderate or heavy showers).
- B Widespread showers with few moderate or heavy showers (8 or more mentions of showers ; 25 per cent or less of moderate or heavy showers).
- C Few showers (less than 8 mentions of showers).
- D No showers.

Association with surface synoptic features.—

The position of the associated depression at midday.—No significant relationship could be found between the position of the depression with which the polar air was associated and the intensity of shower activity.

The curvature of the surface isobars over England.—On many days of widespread showers, a surface trough moved eastwards or southwards across England. Of the troughs which moved eastwards, 25 per cent were major features with the trough axis some 600 to 1000 miles in length and 75 per cent were minor perturbations with the trough axis some 200 to 600 miles in length. Of the 10 troughs which moved southwards, all but one were minor perturbations. Table I shows the number of these occasions for each class of shower activity.

TABLE I—SHOWER ACTIVITY RELATED TO THE CURVATURE OF THE SURFACE ISOBARS OVER ENGLAND (OCTOBER TO APRIL 1950-65)

	Class of shower activity			
	A	B	C	D
	number of occasions			
Surface trough moved eastwards across England	11	5	4	1
Surface trough moved southwards across England	5	5	0	0
Uniform cyclonic isobars over England	2	2	6	0
Neither surface trough nor uniform cyclonic isobars	13	14	34	37
Total	31	26	44	38

On 46 per cent of occasions of widespread showers (classes *A* and *B*) a surface trough moved eastwards or southwards across England. Of the 6 days on which a major surface trough moved across England, 5 were associated with widespread showers and thunder. Of the 25 days on which a minor perturbation moved across England, 21 (84 per cent) were associated with widespread showers and 14 (56 per cent) with thunder. Of the 10 days with uniform cyclonic isobars over England, only 4 were associated with widespread showers. There was only one occasion of widespread showers when the isobars over England were anticyclonic. On 94 per cent of occasions of few or no showers (classes *C* and *D*) no surface trough moved across England. On 23 per cent of occasions of few or no showers the isobars over England were anticyclonic.

Table II shows the number of occasions of each class of shower activity for days when no surface trough moved across England, for each month.

TABLE II—SHOWER ACTIVITY ON DAYS WHEN NO SURFACE TROUGH MOVED ACROSS ENGLAND, FOR EACH MONTH FROM OCTOBER-APRIL 1950-65

	Class of shower activity				Total
	A	B	C	D	
	number of occasions				
October	5	2	6	8	21
November	1	0	10	5	16
December	0	0	7	5	12
January	0	1	7	6	14
February	0	2	6	6	14
March	3	1	2	1	7
April	6	10	2	6	24

Most of the days with widespread showers (classes *A* and *B*) occurred in the Autumn and Spring and few in the winter months November to February. Table III shows the number of days with few or no showers (classes *C* and *D*) with no surface trough, expressed as a proportion of the days when no surface trough moved across England, for each month.

TABLE III—PROPORTION OF DAYS, IN EACH MONTH, WITH FEW OR NO SHOWERS WHEN NO SURFACE TROUGH MOVED ACROSS ENGLAND (OCTOBER-APRIL 1950-65)

Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
14/21	15/16	12/12	13/14	12/14	3/7	8/24

For the winter months November to February 1950-65, 93 per cent of the days with no surface trough were associated with few or no showers. On the other hand, for the months October, March and April, the proportion ranged from 33 per cent for April to 67 per cent for October. It is clear that for the winter months November to February, widespread showers are unlikely in the absence of a surface trough. Of the 18 days during the winter months when a surface trough moved across England, 15 (83 per cent) were associated with widespread showers and 9 (50 per cent) with thunder.

Association with 700 mb temperature and surface pressure.—The following data were extracted for the period 1950-65 :

- (i) The 700 mb temperature anomaly at Crawley for 1200 GMT (1500 GMT before 1957) ; for 1950-52 Larkhill was used. The anomaly was based on the 5-day mean temperatures given in Table IV.
- (ii) The mean-sea-level pressure at Heathrow for 1200 GMT.

TABLE IV—FIVE-DAY MEAN 700 MB TEMPERATURE AT CRAWLEY* IN °C

Period	Mean	Period	Mean	Period	Mean
28 Sept. - 2 Oct.	-2	25 Feb. - 1 Mar.	-10	1 - 5 Apr.	-8
3 - 7 Oct.	-2	2 - 6 Mar.	-9	6 - 10	-8
8 - 12	-2	7 - 11	-9	11 - 15	-8
13 - 17	-3	12 - 16	-9	16 - 20	-7
18 - 22	-3	17 - 21	-8	21 - 25	-7
23 - 27	-3	22 - 26	-8	26 - 30	-7
28 Oct. - 1 Nov.	-4	27 - 31	-8		

* Obtained from 5-year monthly means² for the period 1951-55.
(Larkhill 1951-52, Crawley 1953-55)

It became clear that the 700 mb temperature anomaly and mean-sea-level pressure were of no use as predictors for the winter months November to February. However, for the months October, March and April, Figures 1, 2 and 4 of the earlier paper¹ can be used to give some indication of shower activity, rainfall amount and thunder. The skill scores obtained are given in Table VI. The skill score S^3 is defined by

$$S = \frac{\text{number of correct forecasts} - \text{number correct by chance}}{\text{total number of forecasts} - \text{number correct by chance}}$$

It ranges from 0 for no success to 1 for complete accuracy.

Association with 1000-500 mb thickness and surface pressure.—

The 1000-500 mb thickness anomaly at Crawley for 1200 GMT (1500 GMT before 1957) was extracted for the period 1950-65 ; for 1950-52 Larkhill was used. Anomalies were measured from the 5-day mean 1000-500 mb thickness values for Crawley given in Table V.

TABLE V—FIVE-DAY MEAN 1000-500 MB THICKNESS AT CRAWLEY* IN DECA-METRES

Period	Mean	Period	Mean	Period	Mean
28 Sept. - 2 Oct.	550	25 Feb. - 1 Mar.	534	1 - 5 Apr.	538
3 - 7 Oct.	550	2 - 6 Mar.	535	6 - 10	539
8 - 12	549	7 - 11	536	11 - 15	539
13 - 17	549	12 - 16	537	16 - 20	540
18 - 22	548	17 - 21	537	21 - 25	541
23 - 27 Oct.	547	22 - 26	538	26 - 30	542
28 Oct. - 1 Nov.	546	27 - 31	538		

* Obtained from 5-year monthly means² for the period 1951-55.
(Larkhill 1951-52, Crawley 1953-55)

Analyses were carried out with the 1000–500 mb thickness anomaly in place of the 700 mb temperature anomaly and again no useful results could be obtained for the winter months November to February. For the months October, March and April, Figures 6, 7 and 8 of the earlier paper¹ can be used to give some indication of shower activity, rainfall amount and thunder. The skill scores obtained are given in Table VI.

An analysis was also carried out with the 1000–700 mb thickness anomaly in place of the 700 mb temperature anomaly and similar results were obtained. The corresponding skill scores for the months October, March and April are also shown in Table VI.

Association with the instability indices.—The Boyden instability index,⁴ the Rackliff instability index,⁵ the Jefferson instability index⁶ and the modified Jefferson instability index⁷ were calculated for the Crawley 1200 GMT ascents (1500 GMT before 1957). The critical values of the indices which gave the highest skill scores in forecasting either widespread showers or few showers/no showers were obtained. A similar procedure was carried out for rainfall amount, thunder and hail. Some skill scores of 0·5 or above were obtained for the months October, March and April, but not for the winter months November to February. The skill scores and critical values of the indices for the months October, March and April are given in Table VI.

The relative usefulness of the predictors.—Assuming that the predictors can be forecast, their relative usefulness in forecasting shower activity, rainfall amount, thunder and hail can be assessed by a comparison of skill scores. Table VI shows the skill scores obtained and the critical values of the indices for the months October, March and April.

TABLE VI—A COMPARISON OF SKILL SCORES FOR OCTOBER, MARCH AND APRIL

Predictors	Shower activity	Rainfall (limit 0·1 mm)	Rainfall (limit 0·5 mm)	Thunder	Hail
700 mb temperature anomaly and surface pressure	0·58	0·58	0·35	0·50	0·35
1000–500 mb thickness anomaly and surface pressure	0·54	0·54	0·34	0·47	0·34
1000–700 mb thickness anomaly and surface pressure	0·58	0·51	0·30	0·44	0·30
Boyden instability index	0·64	0·58	0·51	0·57	0·32
(critical values)	(93/94)	(93/94)	(94/95)	(94/95)	(94/95)
Rackliff instability index	0·58	0·58	0·43	0·42	0·37
(critical values)	(28/29)	(28/29)	(30/31)	(30/31)	(30/31)
Jefferson instability index	0·45	0·52	0·39	0·46	0·26
(critical values)	(20/21)	(20/21)	(23/24)	(23/24)	(23/24)
Modified Jefferson instability index	0·58	0·58	0·40	0·49	0·21
(critical values)	(18/19)	(18/19)	(19/20)	(24/25)	(24/25)

The Boyden instability index gives the highest scores in general. However, which predictor is to be preferred depends largely on which is easiest to forecast. None of the predictors provide a useful indication of the likelihood of hail. The skill scores are mostly lower than those obtained for the summer months May to September.¹

Forecasting thunder in the winter months November to February.—

A useful indication of thunder during the months November to February can be obtained from the instability indices if thunder is forecast only when the mean-sea-level pressure at Heathrow at 1200 GMT is expected to be less than 1005 mb. Table VII shows the skill scores obtained and the critical values of the indices.

TABLE VII—A COMPARISON OF SKILL SCORES FOR NOVEMBER TO FEBRUARY

Predictors	Thunder	Thunder*
Boyden instability index (critical values)	0·21 (93/94)	0·40 (93/94)
Rackliff instability index (critical values)	0·32 (33/34)	0·53 (33/34)
Jefferson instability index (critical values)	0·46 (25/26)	0·64 (25/26)
Modified Jefferson instability index (critical values)	0·40 (23/24)	0·56 (23/24)

* Including mean-sea-level pressure as a predictor

The Jefferson instability index gives the highest score. It is interesting to note that the Boyden index which provides the highest scores in the remaining months of the year is of little use in the winter months.

Conclusions.—This investigation was concerned with airstreams from the north-west quarter affecting south-east England in the months October to April and was restricted to days when no fronts were situated over south-east England. Widespread showers are likely if a major trough or minor perturbation moves across England and thunder is likely to occur on about half of these occasions. During the winter months November to February widespread showers or thunder are unlikely to occur in the absence of a surface trough. For the months October, March and April the best indication of shower activity, rainfall amount and thunder is given by the Boyden instability index. For the winter months November to February no predictor provides a useful indication of shower activity. However, a good indication of the likelihood of thunder can be obtained from the Jefferson instability index and the surface pressure. The relative usefulness of the predictors has been evaluated ; which is to be preferred in forecasting depends largely on how successfully each can be forecast.

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REVIEWS

Humidity and moisture : Volume two, *Applications*, edited by Elias J. Amdur. 10½ in × 7 in, pp. xv + 634, *illus.*, Chapman and Hall Ltd., 11 New Fetter Lane, London EC4, 1965. Price : £11.

This is the second of four substantial volumes containing a group of 74 papers presented at the 1963 International Symposium on Humidity and Moisture held in Washington, D.C. The volume concerns 'measurements unique or special to various fields or disciplines ; studies and investigations in which humidity or moisture is the critical parameter'. The volume is divided into : I. Biology and Medicine (10 papers) ; II. Agriculture (19 papers) ; III. Environmental Chambers (7 papers) ; IV. Air Conditioning (11 papers) ; V. Process Control (6 papers) ; VI. Meteorology (12 papers) ; VII. Radio Propagation and Atmospheric Refraction (9 papers). Deliberately there was no strong, overt, editorial policy, and papers range from 'descriptive reviews which may be evaluated by any technically trained person having a general familiarity with humidity instrumentation, to reports of investigations which can properly be reviewed only by specialists.' Clearly therefore it is presumptuous of one person to attempt a review in other than general terms.

When faced with a compendium of this sort one asks : (1) Are all the obvious user interests catered for ? (2) Under any particular head, is a wide spectrum of interest covered ? (3) Is the documentation sufficient, or such as to 'open-up' the literature ? (4) Is the layout, presentation, and indexing such as to permit ready access to papers on any topic ?

With respect to (1), readers will be disappointed not to find papers dealing explicitly with the processing of timber and construction materials generally (there is nothing on metal corrosion), on the handling of long-distance cargo and freight and the packaging and storage of retail goods, and possibly also on the interactions between aerosols and atmospheric moisture. However a topic expected by the reviewer of Volume I,* but noted as missing, namely micro-wave refractometry is here dealt with in some detail—suggesting that inquirers on some particular topic might be advised to consult all volumes rather than that which appears most appropriate (no cross-volume indexing is provided). Regarding (2), all sections start with, in effect, a general survey and move on to papers of specialist interest. On (3), the references are almost exclusively from U.S.A. and only in Section VI are a substantial number of U.K. workers mentioned—notably those presenting or analysing Meteorological Office Research Flight data. Concerning (4), the subject index contains little more than the key words in the titles of papers, but together with the informative titles given in the 'Contents', easy access to any topic is provided. It is worth mentioning that the Fahrenheit scale is used in most applications except those in Sections VI and VII.

In Section VI apart from three papers—one on 'the state of the art' in measuring atmospheric humidity, a second on 'dew' and a somewhat unexpected paper on the forecasting of five-day precipitation patterns by correlation methods—the topic considered is the estimation of moisture in the upper atmosphere or the whole atmosphere either by ground-based or balloon-carried equipment

*SPARKS, W. R.; *review of Humidity and moisture* ; Volume one, Principles and methods of measuring humidity in gases. *Met. Mag., London*, **94**, 1965, p. 377.

(namely spectroscopy, adsorption and other direct sampling devices, and frost-point indicators), and includes comparisons between different methods. Papers 60, 61, 62, 63, contain critical discussions of the distribution of moisture and suggestions for 'model' atmospheres. The same topic is examined by radio-refractometry in Section VII (which is perhaps the most severely technical of all the sections).

Boundary layer phenomena are dealt with in Papers 5, 42, 44 (in Number 5 by radio-refractometry). The determination of soil moisture by neutron scattering, and of moisture in hygroscopic substances by nuclear resonance, are described respectively in Papers 14 and 19.

Amongst papers on evaporation (Numbers 6, 7, 9, 12, 14), Number 7 deals with the method of measuring transpiration by following the movement, up the stem of the plant, of sap heated electrically to a moderate temperature by a coil wrapped around the stem.

Applied climatologists will find much of value in Sections I and II although whenever external conditions are relevant, these are almost invariably of hot-dry or hot-wet climates.

The volume is well produced, with clear diagrams and remarkably few 'printer's errors' (Figure 9 on p. 500 is printed upside down). There is some repetition, e.g. the psychrometric chart is described in a number of papers—but to the 'specialist' inquirer this is a convenience. All four volumes are obviously desirable for both reference and browsing.

R. W. GLOYNE.

Elements of cloud physics by H. R. Byers. $9\frac{1}{4}$ in \times $6\frac{1}{4}$ in, pp. ix + 191, illus., The University of Chicago Press, 6a Bedford Square, London WC1, 1965. Price : 56s.

One's first impression is that this is a well-produced book, pleasant to handle, well laid out, well illustrated and clearly printed on good quality paper. In his preface Professor Byers says that he designed the book for meteorologists taking up cloud physics—rather than for the physicists and chemists who also take up the subject. His first chapter covers the thermodynamics of moist air and is clearly of more use to the non-meteorologist who must be introduced to such concepts as virtual temperature, wet-bulb temperature and adiabatic processes with vapour condensation. Nevertheless it is convenient for meteorologist and non-meteorologist alike to have meteorological book-work within the covers of a cloud physics text and it is disappointing therefore that this chapter contains several misprints which make it difficult to recommend as a handy reference. Two examples will suffice. On page 5, mC_v should be m^1C_v . On page 15 there is confusion over the sign of lapse rates in equation 1.54 and g has been omitted.

Professor Byers's stated aim is to stress basic principles. He does this in a logical fashion for the microphysics in Chapters 2 to 6. Chapters 2 and 3 cover the physical chemistry of phase changes, the equilibrium between phases and over solutions, the processes of nucleation of the vapour to initiate the liquid phase and nucleation to initiate the ice phase. Chapter 4 is a comprehensive account of both condensation and ice nuclei found in the atmosphere and is perhaps the best chapter in the book. Chapter 5 deals

with the growth of cloud particles from the vapour and Chapter 6 the subsequent growth by collision. The treatment in these chapters is straightforward and specialists will find it convenient that some of the tables and results presented in them have been brought together.

While stressing basic principles Professor Byers has also given a comprehensive review of the nucleation and growth of cloud particles. In contrast, his treatment of the growth of precipitation is brief, surprisingly brief when for so many people the water which clouds release—or may perhaps be induced to release—is the subject's main interest.

Chapter 7 on cloud dynamics is also brief and much that might be regarded as part of the core of the subject has been left for consideration in special treatises on this topic.

The main virtue of this book is that its eminent author has given most weight to the best-founded parts of the subject. As indicated in the preface, however, several aspects have been excluded or given scant treatment so that meteorologists and students of cloud physics must be recommended not to rely on this book alone.

S. G. CORNFORD

OBITUARIES

Mr E. E. Jessop.—It is with deep regret that we have to report the death of Mr E. E. Jessop, Chief Experimental Officer, at his home in Edinburgh on 8 April, 1966. Although he had been ill for some time, he fought with characteristic courage and determination, and, although recovery appeared to be slow, the news of his death when it came was a profound shock to his many friends.

Mr Jessop joined the Meteorological Office in 1937, but some years before becoming a professional meteorologist his interest in the subject had found expression in post-graduate research at the University. He went first to Calshot in the days when forecasting for flying boats was an important task. Subsequently, like many others in those days of pre-war expansion and actual war, he served in a number of places, including Marham, Norwich, Aldergrove and Iceland. He was commissioned in the RAFVR in 1943. During the latter part of the war and for some years subsequently he was on the forecast roster at Prestwick. This was work which he thoroughly enjoyed and here he developed the full powers as an analyst and forecaster in which he was quite outstanding. This was followed by a tour in Germany as Senior Meteorological Officer, No. 83 Group from which post he returned to the United Kingdom to become Senior Meteorological Officer, No. 18 Group, Pitreavie.

It is impossible in cold print to do full justice to Edgar Jessop. He was unusually clear-thinking and able, co-operative and loyal to his colleagues and of absolute integrity and honesty. A hard worker always setting himself the highest standards, there was nothing he asked of others which he was not prepared and able to do himself.

He will be greatly missed as a friend and as a colleague who can ill be spared. We offer our sincerest sympathy to his widow and family.

H. M.

Mr G. A. W. Clark.—We deeply regret to report the unexpected death of Mr George Clark in Athens on 18 April 1966 at the comparatively early age of 47. Mr Clark was one of the band of forecasters who came to the

Meteorological Office as Assistant Grade III just before World War II. His early promise well merited his promotion to forecasting duties in 1942 followed by commissioning in the RAFVR in 1943. After his demobilization in 1947, George Clark's service was concerned largely with forecasting for the Royal Air Force at many stations at Home and abroad including Libya and Pakistan. He was promoted to Senior Experimental Officer in 1957 and later spent some years working with the Army at the Artillery Ranges, Shoeburyness, before leaving for the tour in Muharraq from which he was returning at the time of his death. Apart from his other interests which included the Church, much of Mr Clark's leisure in latter years was spent with his young family. The deep sympathy of his friends and colleagues is extended to his widow and two children in their tragic loss.

D.W.R.

Mr W. J. Fowler.—It is with deep regret that we have to record the death of Mr W. J. Fowler on 28 April 1966. Mr. Fowler, a disestablished XO at Hurn, joined the Office as a Boy Clerk over 50 years ago. An appreciation of Mr Fowler's work was published on page 30 of the January 1961 issue of the *Meteorological Magazine*.

HONOURS

The following awards have recently been announced:

I.S.O.

Mr A. F. Crossley, Principal Scientific Officer, Meteorological Office, Bracknell.

B.E.M.

Miss D. J. Wordsworth, Scientific Assistant, Meteorological Office, Bracknell.

I.S.M.

Mr. N. W. Howlett, M.B.E., Radio Supervisor (retired)

Mr. E. W. E. Reid, Radio Operator (retired)

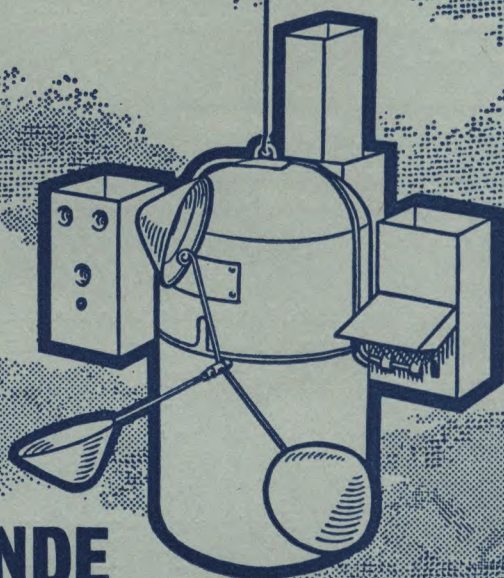
AWARD

We note with pleasure that the International Meteorological Organization Prize for outstanding work in meteorology and international collaboration has been awarded for 1966 to Professor Tor Bergeron of Sweden by the Executive Committee of the World Meteorological Organization during its 18th session.

CORRIGENDA

Meteorological Magazine, May 1966, page 157, line 15 : for '0600 GMT, 25 May 1964' read '0600 GMT, 26 May 1964' ; page 158, Figure 9 : for '26 May 1965' read '26 May 1964'.

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CONTENTS

Page

Some features of the large-scale circulation anomalies and the weather over the British Isles in autumn 1965.	
R. Murray	225
Comparison of British stratospheric and mesospheric temperature measurements with values from available atmospheric models. A. E. Cole	236
Meteorological contributions to the 1966 Physics Exhibition.	
J. I. P. Jones	239
An indication of surface wind directions potentially favourable for atmospheric pollution. E. N. Lawrence... ..	241
The forecasting of shower activity in airstreams from the north-west quarter over south-east England in October to April. C. A. S. Lowndes	248
Reviews	
Humidity and moisture : Volume two, Applications. Edited by Elias J. Amdur. <i>R. W. Gloyne</i>	253
Elements of cloud physics. H. R. Byers. <i>S. G. Cornford</i>	254
Obituaries	256
Honours	256
Award	256
Corrigenda	223

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, and marked "for Meteorological Magazine."

The responsibility for facts and opinions expressed in the signed articles and letters published in this magazine rests with their respective authors.

All inquiries relating to the insertion of advertisements in the Meteorological Magazine should be addressed to the Director of Publications, Her Majesty's Stationery Office, Atlantic House, Holborn Viaduct, London E.C.1. (Telephone: CItY 9876, extn. 6098).

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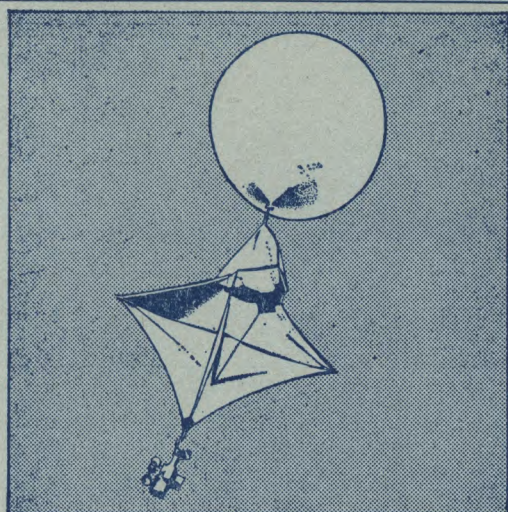
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THE METEOROLOGICAL MAGAZINE

Vol. 95, No. 1130, September 1966

551.507.362.2:551.509.31 (41/42):778.35/.36

A CASE ILLUSTRATING THE VALUE OF SATELLITE PICTURES IN FORECASTING FOR THE BRITISH ISLES

By R. A. S. RATCLIFFE, M.A.

Introduction.—TIROS satellites have been taking pictures of the cloud structure for a number of years and nephanalyses* based on these pictures are being regularly disseminated on the transatlantic facsimile network from America. These nephanalyses are received in Bracknell and redistributed over the British facsimile network whenever the senior forecaster considers they are likely to be of value to outstations.

More recently ESSA satellites have been launched and photographs from this series of satellites can be received directly by any suitable receiving station. The ESSA satellite pictures are now being received regularly at Bracknell, up to a maximum of about 10 pictures per day.

The importance of ESSA lies in the fact that the forecaster can now see pictures within about an hour of the photographs being taken instead of being compelled to wait for a much longer time (up to 10 hours) in the case of TIROS.

TIROS photographs are not available at the time they are taken. They can be received only when the satellite comes within range of one of the three American tracking stations and the total delay before the photographs are available is due to the need to wait for this to happen, coupled with the time necessary to convert the photograph to a nephanalysis and for subsequent transmission on the intercontinental facsimile network. The value of these pictures is often doubted; many people are under the impression that even when available the pictures add little to the forecaster's knowledge of the synoptic situation, at least in our latitudes. To counter this belief a case in which a satellite photograph helped in the preparation of a successful forecast for the British Isles 12–24 hours ahead is illustrated.

The synoptic situation on 8 April 1966.—The synoptic situation as originally analysed by the Central Forecasting Office (CFO) on the afternoon

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

of 8 April is shown in Figure 1. This shows the 1500 GMT chart for that date with a frontal system approaching south-west England and a cold front (CB) lying across the Bay of Biscay and close to the Portuguese coast. There were

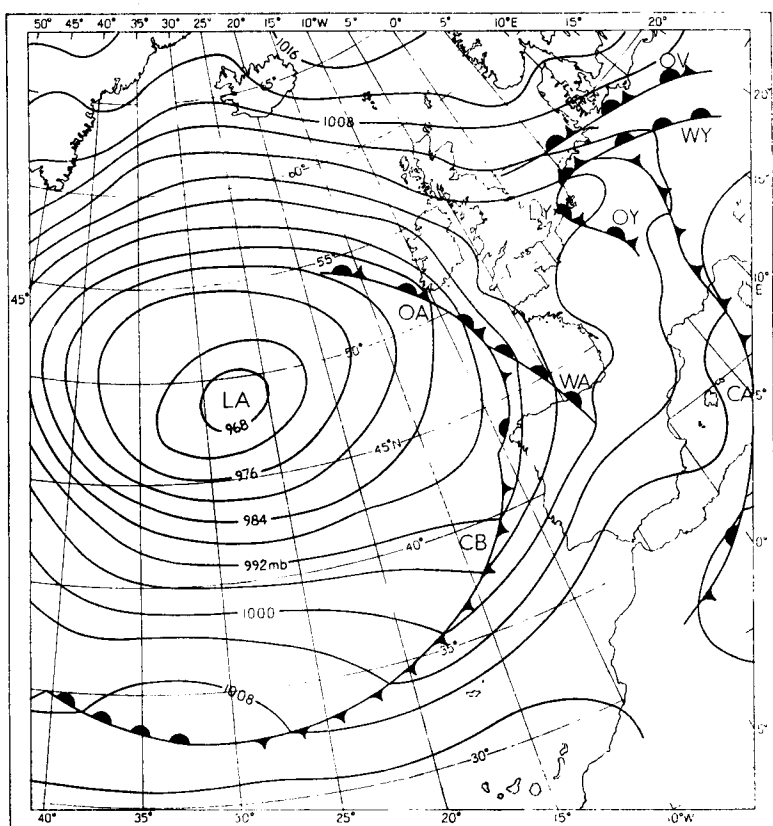


FIGURE 1—SURFACE CHART FOR 1500 GMT, 8 APRIL 1966

not many ship reports to aid in placing the cold front but it was a logical extrapolation of the position on the 1200 GMT chart which was better (though still not very well) served with ship reports. The 1800 GMT chart was initially drawn on the basis of the 1200 and 1500 GMT analyses but, at about the time the chart was being completed at CFO, a TIROS nephanalysis for 1429 GMT was received over the international facsimile network.

An outline of this cloud analysis is shown as Figure 2 together with the revised position of the cold front based on the satellite information. The cloud analysis clearly suggests that the cold front was somewhat further east in its southern portion than had been suspected and, more important, that there was a fairly well-developed wave on the cold front in the Bay of Biscay nearer to the British Isles than indicated on the original drawing of the 1500 GMT chart.

The revised 1500 GMT analysis, with subsequent time adjustments, was found to conform well with available 1800 GMT observations and the amended

analysis was used in the preparation of the surface prognosis for 1800 GMT 9 April. The line of reasoning of the forecaster is clearly indicated in the following extracts from the synoptic review issued at 2235 GMT on 8 April.

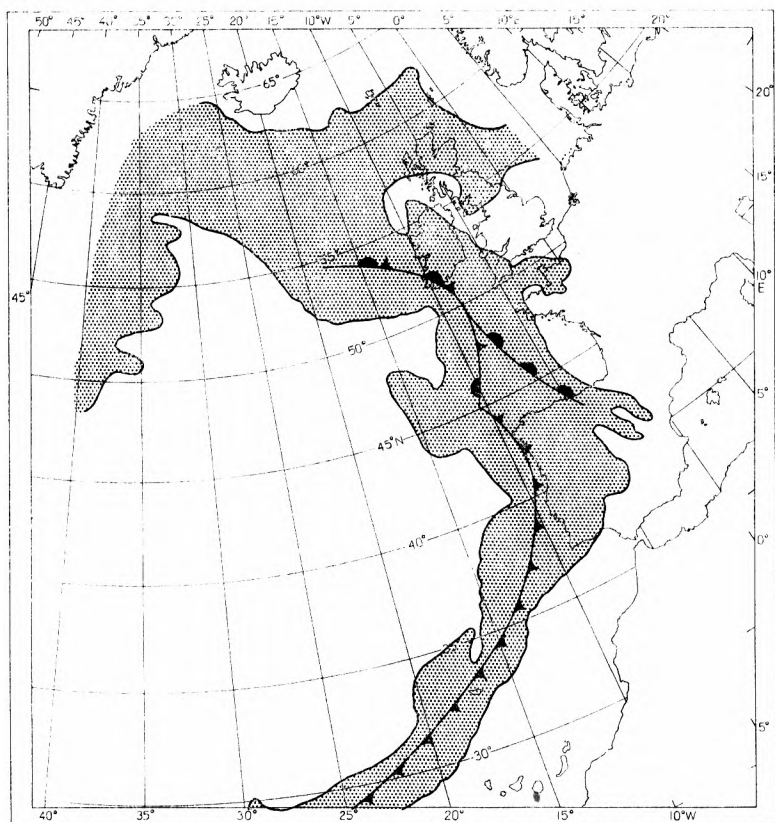


FIGURE 2—TIROS NEPHANALYSIS AND REVISED SURFACE ANALYSIS, 1500 GMT, 8 APRIL 1966

'Earlier TIROS pictures coupled with the 1800 GMT observations indicate a wave on cold front CB to the south-west of Cornwall. This (wave) is embedded in a southerly upper flow and will move north, later north-west or west, to amalgamate with (the main depression) LA moving north-east. This will hold up CB temporarily but the front will later advance quite steadily across Southern districts but will be slower moving over Northern Ireland.

The rain over South-west England and Wales is temporarily held up by a wave near Scilly but will soon begin to progress across Southern districts of England . . . By morning the rain is expected to be covering Northern Ireland, Wales, the Midlands and much of South-east and central Southern England and will move to Northern England and East Anglia during the day. Brighter weather with sunny spells and showers will follow the rain, reaching parts of South-west England by morning and most of Wales, the Midlands, central Southern and South-east England by evening.'

Figures 3 and 4 show the surface prognosis for 1800 GMT 9 April and the actual chart at that time.

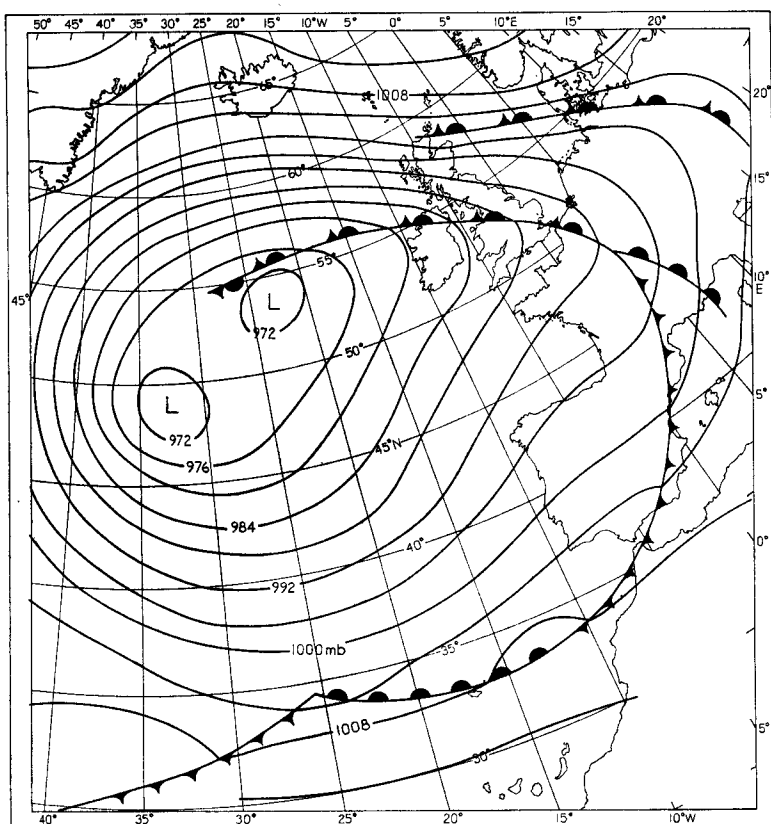


FIGURE 3—SURFACE PROGNOSIS FOR 1800 GMT, 9 APRIL 1966, COMPLETED AT 2145 GMT ON THE PREVIOUS DAY

The continuous rain which had started in extreme south-west England in the early afternoon of the 8th reached Plymouth at 1800 GMT and then took 4 hours to reach Exeter. This was the period when the wave to the south-west of England was holding up the cold front. In the next 6 hours the area of continuous rain swept across Southern England to reach London by 0400 GMT on 9 April and by 0900 GMT the same day it had reached East Anglia. Subsequently it moved more slowly north (as had been expected) with the wave moving north over Ireland and later west, reducing the northward gradient on the front.

In this case it is doubtful whether such accuracy in the forecast could have been achieved without the help of the TIROS nephanalysis.

Conclusion.—It is seen that TIROS pictures can provide help in more detailed and accurate analyses even in the region of relatively abundant observations near the British Isles. On some occasions the improved analyses are likely to lead to more accurate forecasts and this may well happen more often than is generally supposed. The above example is based on a TIROS

photograph received at CFO 7 hours after it was taken and it becomes clear that ESSA will be potentially much more useful, pictures being available for study by the forecasters 1 or 2 hours after the photographs are taken.

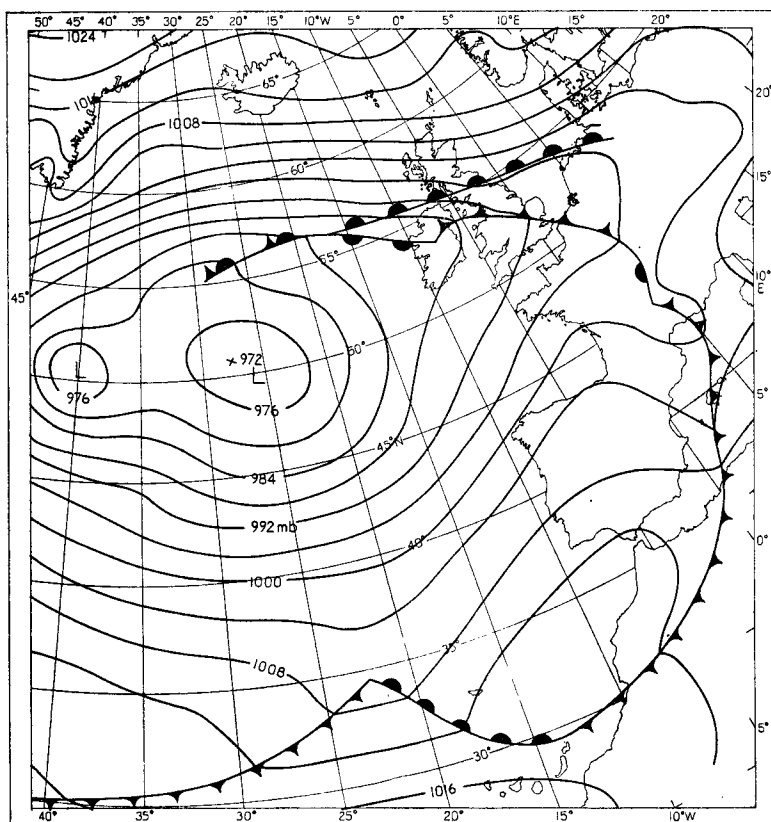


FIGURE 4—ACTUAL CHART FOR 1800 GMT, 9 APRIL 1966

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THE METEOROLOGICAL CONDITIONS LEADING TO STORM SURGES IN THE NORTH SEA

By J. F. KEERS

Summary.—The meteorological forces which generate a storm surge are discussed from an elementary viewpoint and a simple explanation is given of how a storm surge is propagated in the North Sea. The meteorological conditions leading to storm surges in the North Sea are classified into four main types and examples are given of the effects of each of these upon the sea-level.

Introduction.—As a result of the disastrous flooding of the Thames on 6–7 January 1928 the Meteorological Office, together with the Hydrographic Department of the Admiralty and the Liverpool Tidal Institute, were requested

by the Government to undertake an investigation into the cause of such floods. The Meteorological Office had the specific task of investigating the practicability of giving useful warnings of abnormally high tides in the Thames. Dines¹ showed that the onset of a pressure gradient over a considerable part of the North Sea with a geostrophic wind of 60 mph or over from between north-west and north was likely to be followed within a period of 7–16 hours by a rise of the water by 4 ft or more above the astronomically predicted level at Southend.

From 1930 until 1953 the Meteorological Office issued warnings of meteorological conditions satisfying this empirical rule. It is perhaps worth noting here that on 31 January 1953 a danger warning was issued more than 12 hours before the 1953 flood disaster which in south-east England alone, caused the death of 350 people and £50 million worth of damage. The sea-level at Southend on that occasion was nearly 8 ft above the astronomically predicted level and, superimposed upon the astronomical tide, resulted in the danger level at Southend being exceeded by 3 ft. Fortunately such dangerous storm surges are rare but if one defines a storm surge as a raising of the astronomically predicted sea-level by at least 2 ft at more than one port on the east coast of England then one finds an average frequency of occurrence of 14 surges each year.

After the 1953 flood disaster the Storm Tide Warning Service² (STWS), or Flood Warning Organisation as it was initially called, was set up on the recommendation of an inter-departmental Committee presided over by the late Lord Waverley. The staff of the STWS are officers of the Hydrographic Department, Ministry of Defence, and since these officers must work in close liaison with the weather forecasters they have an office at the Meteorological Office Headquarters. The function of the STWS is to give warnings some hours in advance when unusually high sea-levels are expected to occur on the east coast of England. Before proceeding to describe particular meteorological conditions favourable for generating large disturbances of the sea-level it is necessary to answer three important questions.

What is a storm surge ?—A storm surge is defined as the difference, due to meteorological causes, between the observed tide and the astronomical tide predicted by considering the gravitational forces of the moon and sun on the earth. From the analysis of past tidal records these forces, and hence the astronomical tide, can be predicted for as far ahead in time as required. Figure 1 shows the astronomically predicted tide for Southend on 10 December 1965 and the observed tide which is higher than predicted because a storm surge occurred near to the time of predicted high water. The observed tide was recorded by a tide gauge installed at the end of Southend Pier. The tide gauge measures the height of a float free to rise and fall inside a well which allows water to pass through a restricted hole in its base ; the size of the restriction is chosen so as to remove the ordinary wind waves from the recording. Plotted below in Figure 1 is the storm surge profile with time, i.e. the difference between the astronomically predicted tide and the observed tide. A very important point is that not every storm surge results in flooding. This is because not every storm surge coincides with astronomically predicted high water and even if it did flooding would not occur unless the surge was

unusually large or unless the astronomical tide was unusually large, as for instance at the time of the high spring tides associated with a new or full moon.

In order to track the surge as it travels along the east coast there are seven distant-recording tide gauges situated at the following places : Wick,

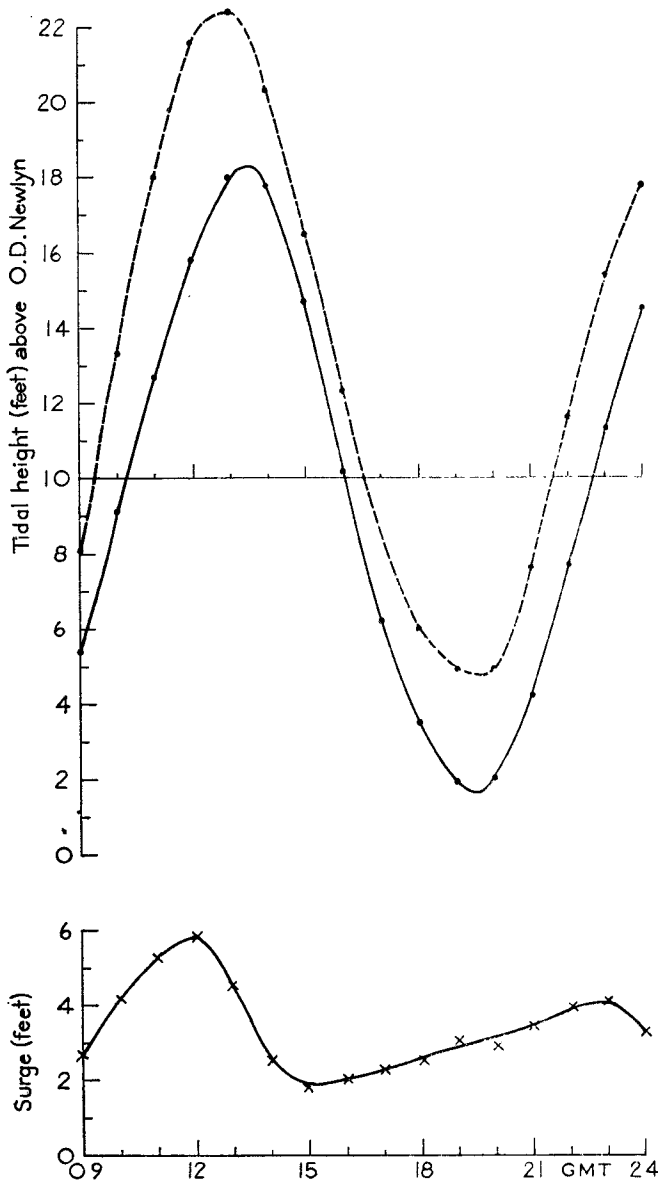


FIGURE 1—TIDAL AND STORM SURGE PROFILES FOR SOUTHEEND ON 10 DECEMBER 1965

· — · — · Observed tide
 · — · — · Astronomically predicted tide
 × — × — × Observed minus predicted

Aberdeen, Tyne, Immingham, Lowestoft, Harwich and Southend. The tide gauges are connected to recorders at the Storm Tide Warning Service at Bracknell by GPO telegraph lines and give a continuous, up-to-the-minute, record of the sea-level.

How are storm surges generated ?—Storm surges are a direct result of interaction between the atmosphere and the sea by way of :

- (i) The statical effect of the atmospheric pressure depressing or raising the sea surface.
- (ii) The tractive force of the wind on the surface of the sea.
- (iii) The propagation of the disturbance introduced by (i) and (ii) under the dynamical laws controlling the motion of a shallow layer of water on a rotating globe.

Static pressure effect.—For steady conditions the effect of a change from normal atmospheric pressure is to disturb the sea-level by an amount given by the ordinary hydrostatic law,

$$dh = - \frac{1}{\rho g} dp$$

where h is the depth of the sea, p is the atmospheric pressure, ρ is the density of sea water and g is the acceleration of gravity.

Wind effect.—The growth of the ordinary wind waves and the generation of wind driven currents are inseparable features associated with a strong wind blowing over the surface of the sea. The accepted relationship between the shearing stress, τ , of the wind on the surface of the sea and the wind speed, V , is $\tau = k\rho_a V^2$, where ρ_a is the density of air and k is a parameter usually taken to be a constant.

Mass transportation of water occurs because of sea currents but in certain circumstances it also occurs with ordinary wind waves. The effect of the wind on the sea-level of a confined sea or channel is to pile up the sea at one end, as for example during an easterly wind blowing up the Thames Estuary. In the equilibrium state a return flow is set up in the bottom layers and the slope of the sea surface is such that the hydrostatic pressure gradient balances the tractive force of the wind. If the sea is not confined then on-shore winds blowing against a long straight coastline may set up horizontal as well as vertical circulations.

Winds blowing parallel to the coastline may also have an important effect on the sea-level. Indeed the most effective wind direction for raising the sea-levels on the east coast of England is from north-west to north. This is because the wind-induced current tends to turn right because of the Coriolis force and thus mass transportation of the water occurs to the right of the wind direction.

So far we have discussed only positive disturbances of the sea-level. Winds from between south-east and south-west cause a lowering of the sea-level along the east coast and although the lowering effect alone does not threaten flooding it is often a prelude to a large positive surge travelling down the east coast. There is some speculation as to whether this oscillatory effect is due to the natural period of the North Sea or to the fact that gale force southerly

winds are usually associated with a depression moving eastwards across the British Isles and bringing north-westerly winds into the North Sea behind it.

Dynamic effects.—Once a surge, however small, has been generated it will be propagated according to certain laws of wave motion. Provided that the wavelength is much greater than the depth of the sea, which in turn is much greater than the amplitude of the wave, then the speed of propagation of the wave is $(gh)^{\frac{1}{2}}$. To explain the dynamic effect let us suppose that the meteorological forces move at a speed v , which is less than the phase speed, $(gh)^{\frac{1}{2}}$, of the surge. The newly developed surge will move ahead of the meteorological forces and tend to decay unless other effects, such as the convergence of an estuary or the gradual decrease in the depth of the sea, cause it to do otherwise. On the other hand if the meteorological forces move at a speed equal to the phase speed of the surge then the surge will be building up throughout its progression and be in resonance with the forces. Another type of resonance occurs when the period of the surge is equal to the natural period of the sea.

In the North Sea the surge travels at a speed $(gh)^{\frac{1}{2}}$ only near the coasts, and in shallow water with a mean depth of 120 ft this speed is approximately 37 kt so that a depression travelling at about this speed in a south-easterly direction would induce a relatively large amplitude because of the dynamic effect involved.

How is a storm surge propagated ?—In order to explain what happens to a surge once it has been generated let us consider a rectangular basin of water oscillating in the fundamental mode related to the length and depth of the basin. If the basin is not rotating, i.e. if there is no Coriolis force, then the water will oscillate from one end to the other and the level will remain unchanged along a line called the nodal line. The oscillation will therefore be a standing wave.

If we now introduce the Coriolis force by imagining a basin rotating with the earth a standing oscillation will be replaced by a progressive wave travelling anticlockwise around a central nodal point, that is a point at which the sea-level remains unchanged. One form of progressive wave which can be propagated in a rotating basin is a Kelvin wave, in which the amplitude increases towards the right of the direction of propagation. The pressure gradient thus balances the Coriolis force due to the earth's rotation. Darbyshire and Darbyshire³ showed that in the case of a rotating rectangular basin with one open end the waves can proceed from the open end down one side, then round the closed end and up the other side. The North Sea can be considered as such a basin, or better still as two basins ; a large one in the north and another taking in the Flemish Bight. Storm surges, and the astronomical tide which is also a long-wave disturbance of the sea-level, are therefore propagated southwards down the east coast before turning left and affecting the Dutch and German coasts.

A number of empirical formulae, which are useful forecasts of surge height for at least four hours ahead, depend on the southward propagation of long waves down the east coast of the North Sea ; the forecast surge heights are based on the heights observed at stations further north with allowances for local winds, both observed and forecast, and other local effects.

The meteorological conditions.—The meteorological conditions leading to storm surges in the North Sea can be classified into four basic types :

- Type I : A depression moving northwards or north-eastwards over the relatively shallow waters of the continental shelf to the west of the British Isles.
- Type II : A depression travelling eastwards, south-eastwards or southwards over the North Sea.
- Type III : A steady north-westerly wind over the North Sea.
- Type IV : Easterly or north-easterly winds associated with a depression over the southern North Sea or further south.

The surge associated with the conditions of Type I is called an external surge whereas the surges associated with the other basic types are called internal surges, i.e. generated wholly within the North Sea. Most storm surges in the North Sea are a combination of internal and external surges, that is they are caused by a combination of the four basic types of meteorological conditions.

Example of Type I conditions and associated surge.—The storm surge of 15–16 October 1963 was caused by a meteorological disturbance of Type I. The meteorological situation at 1200 GMT on the 15th and 0600 GMT on the 16th is shown in Figure 2, and the resultant surge profiles recorded by the tide gauges on the east coast are shown in Figure 3. The surface winds in the North Sea were never veered north of west and consequently it can be assumed that they played no part in raising the sea-levels on the east coast ; this is not always the case. The surge was propagated according to elementary

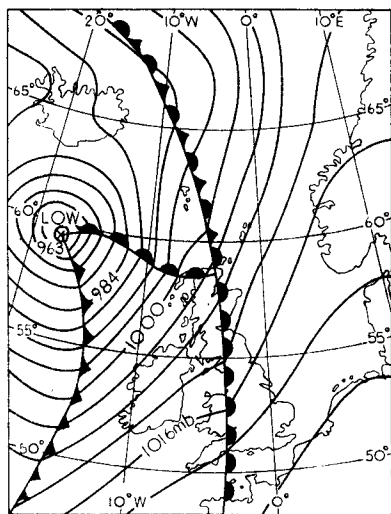


FIGURE 2(a)—SYNOPTIC SITUATION AT
1200 GMT ON 15.10.63

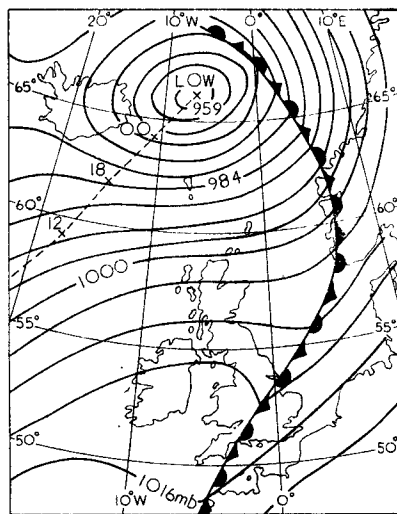


FIGURE 2(b)—SYNOPTIC SITUATION AT
0600 GMT ON 16.10.63

theory and the surge profile remained almost unchanged. The decay of the surge due to frictional forces was balanced by the effects of the gradual decrease in the depth of the sea as the surge was propagated southwards. The surge on this occasion is a good example of an external surge.

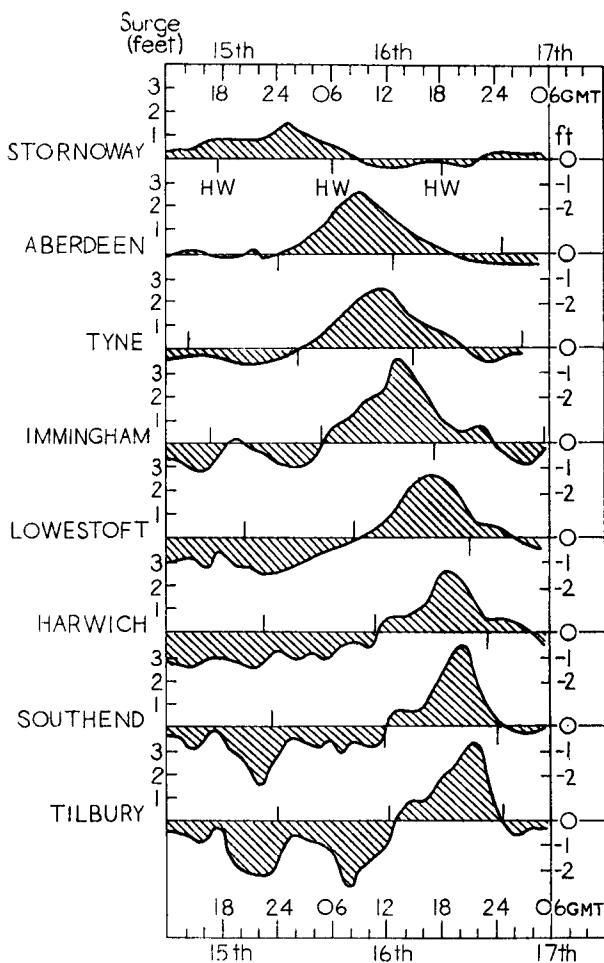


FIGURE 3—SURGE PROFILE DIAGRAM OCTOBER 1963
Vertical dash indicates the time of High Water (HW)

An example of a combination of Type I and Type II conditions and the associated surge.—The most dangerous type of meteorological conditions for the raising of the sea-levels on the east coast is a combination of Type I and Type II conditions. (It was such a combination which led to the disastrous flooding on 1 February 1953. Detailed accounts of this storm surge and the associated meteorological conditions are plentiful^{4 5}.) The meteorological developments on 9 and 10 December 1965 were of Type I and II. The resultant surge on this occasion was caused by a deep low and its associated trough which moved south-eastwards across the North Sea,

see Figure 4. A definite sea-level pulsation due to a cold front and trough moving across the North Sea was recorded by the tide gauges at Immingham,

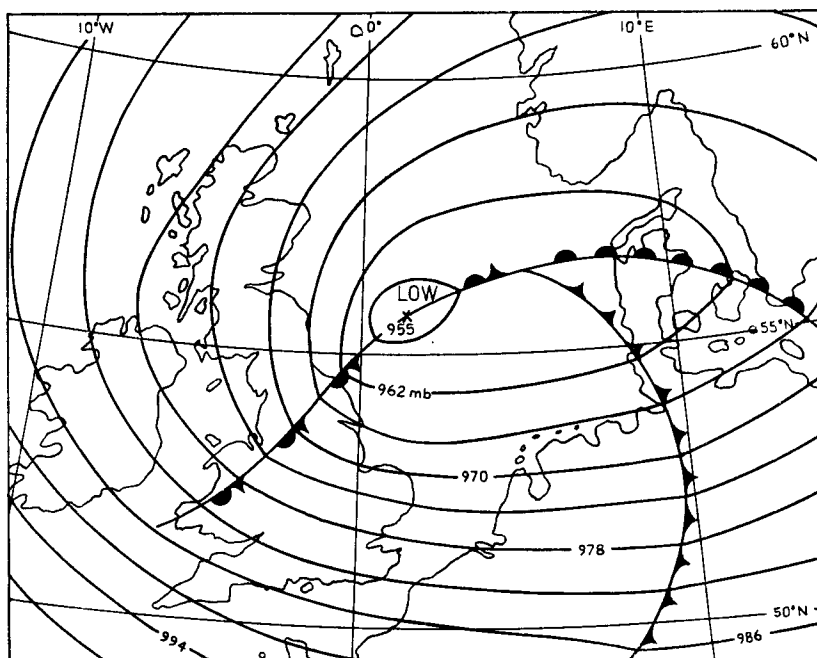


FIGURE 4(a)—CFO ANALYSIS FOR 0000 GMT ON 10 DECEMBER 1965

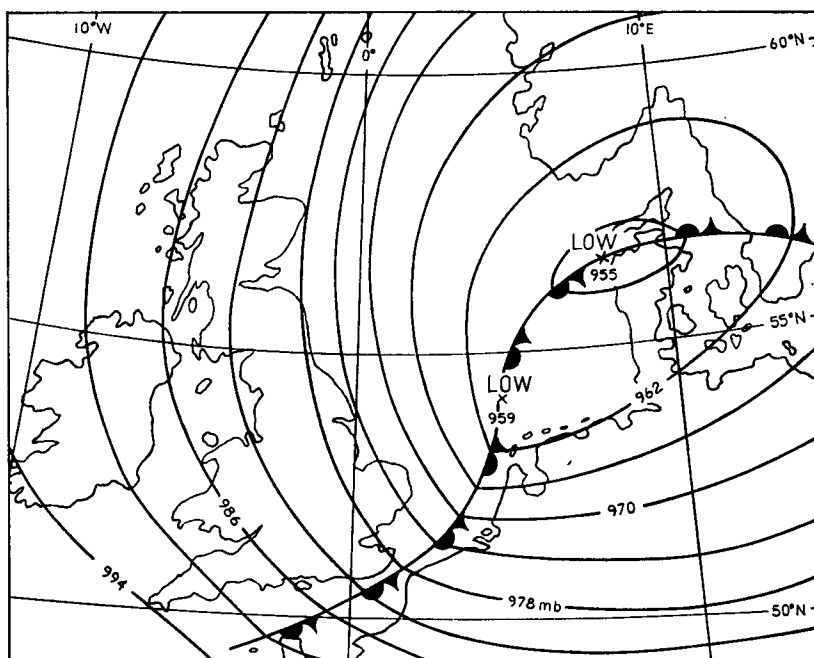


FIGURE 4(b)—CFO ANALYSIS FOR 0600 GMT ON 10 DECEMBER 1965

Lowestoft, Harwich and Southend. Figure 5 shows the variation of the geostrophic wind component along 360 degrees for an area covering most of the Flemish Bight and the resultant pulsation of the sea-level at Southend.

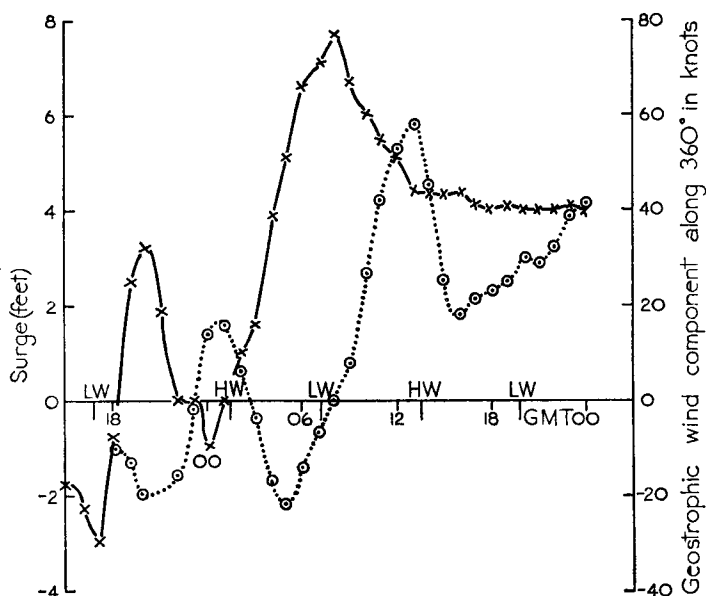


FIGURE 5—ASSOCIATION BETWEEN SURGE AT SOUTHEND AND MEAN GEOSTROPHIC WIND MEASURED OVER AN AREA OF THE FLEMISH BIGHT ON 9-10 DECEMBER 1965

× — × — × Geostrophic wind component along 360° ; ○ . . . ○ . . . ○ Southend surge
 HW = High Water LW = Low Water

The average speed of movement of the trough as it moved south-eastwards was approximately the same as that of the astronomical tide travelling down the east coast. Therefore large dynamic effects were present and the meteorological disturbance and astronomical tide were in phase so as to cause a large disturbance at the time of astronomically predicted high water. The lag of 5 hours between the maximum effective wind over the Flemish Bight and its effects upon the sea-level at Southend is mainly due to the delayed effect of the Coriolis force and the time the disturbance takes to travel to Southend. It is interesting to note that the storm surge which caused the Thames to be flooded on 6 January 1928 was due to a meteorological development analogous to that of 10 December 1965.

Example of Type III conditions and the associated surge.—Steady winds from the north-west raise the sea-level as a whole, perhaps for two or three days at a time but there is a strong tidal disturbance in these cases, a marked and persistent semi-diurnal oscillation being prominent in the storm surge profile. The tidal disturbance is caused by interaction between the surge and the astronomical tide and is most pronounced at the shallow water ports with a large range of tide.

On 11 and 12 October 1960 the winds were gale force north-westerlies over most of the North Sea and the resultant surges affecting the east coast are shown in Figure 6. The effect of interaction at Lowestoft, where the range of the astronomical tide is small, is much less than that at, say, Southend.

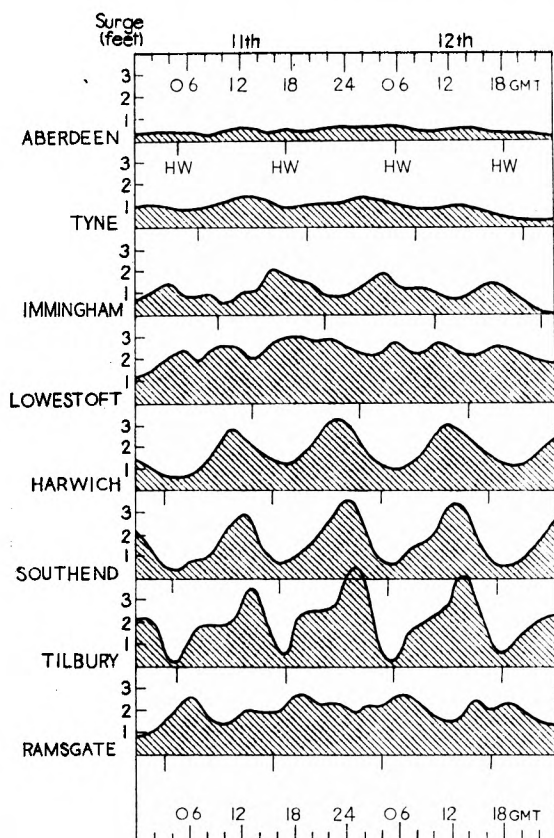


FIGURE 6—SURGE PROFILE DIAGRAM OCTOBER 1960

Interaction between surge and the astronomical tide is present to a greater or lesser extent in all the surges which travel down the east coast but observational evidence suggests that interaction is least when the surge and the meteorological forces are moving at the same speed, i.e. resonating.

Examples of Type IV conditions and associated surge.—An example of an internal surge is the storm surge of 25 February 1958 which was caused by meteorological conditions of type IV, see Figure 7. A depression moved eastwards across southern England and the Flemish Bight and the winds in the North Sea were gale force north-easterlies backing northerly later. The surge associated with these meteorological conditions is shown for Sheerness in Figure 8 (pecked line) together with the wind component along 350 degrees (full line). There was a correlation coefficient of 0.92 between the wind speed and the height of the surge on this occasion. There was an equally

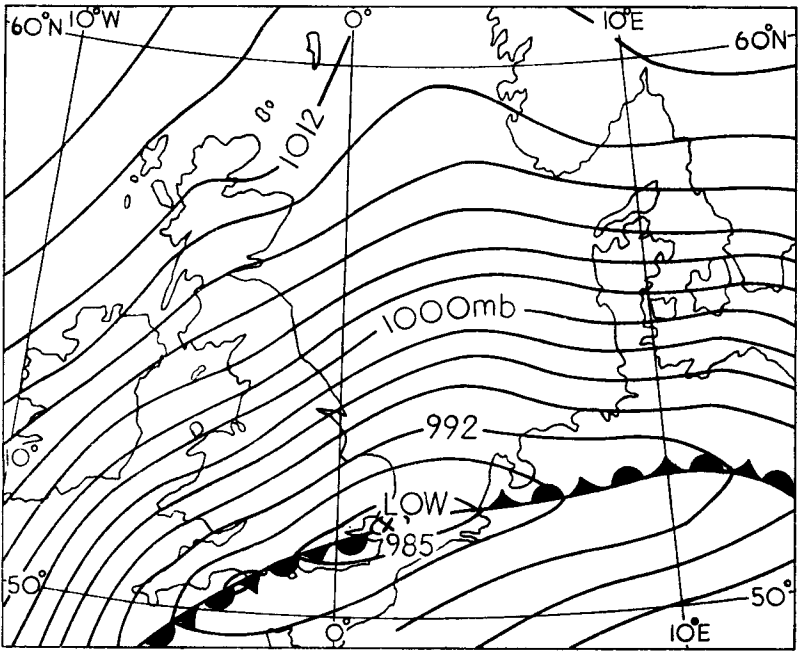


FIGURE 7(a)—CFO ANALYSIS FOR 0600 GMT ON 25 FEBRUARY 1958

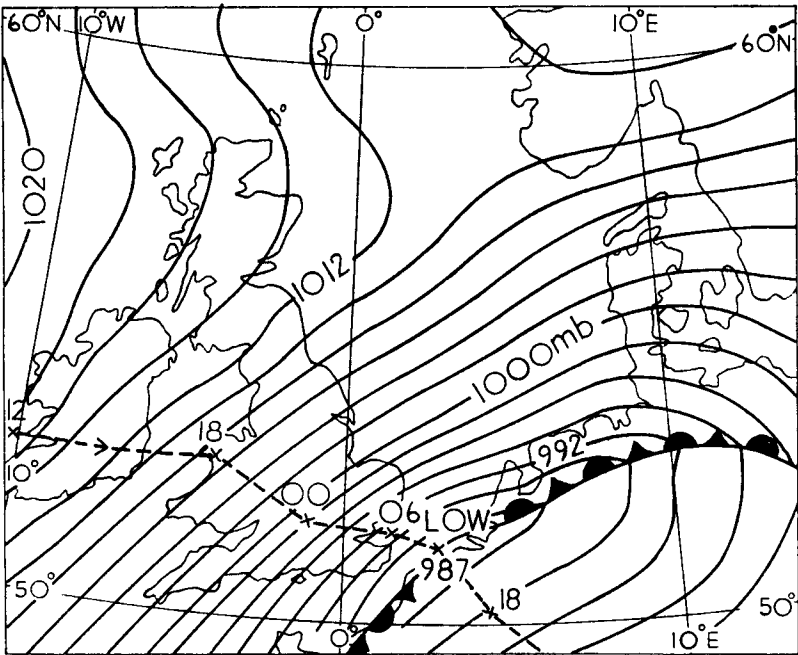


FIGURE 7(b)—CFO ANALYSIS FOR 1200 GMT ON 25 FEBRUARY 1958

good correlation between the surge at Immingham and the wind at Spurn Head and also between the surge at Lowestoft and the wind at Gorleston. The winds referred to here are the mean hourly winds from anemograph tabulations and since the winds were mainly on-shore winds they were representative of the winds over the sea.

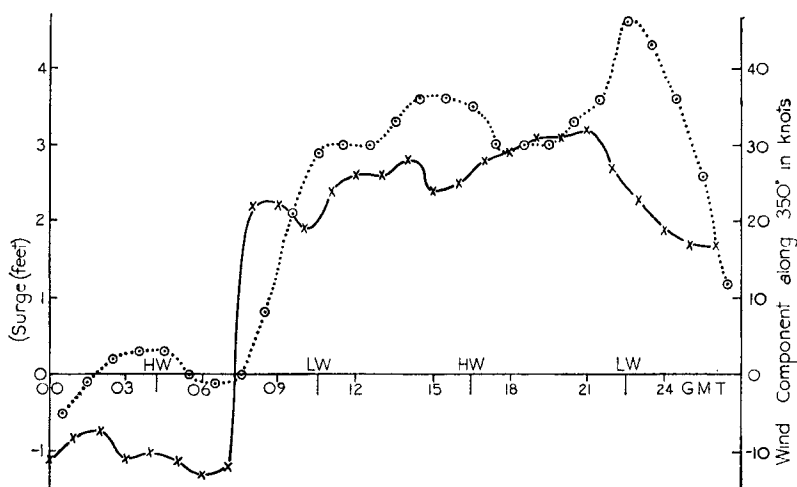


FIGURE 8—ASSOCIATION BETWEEN WIND AND SURGE AT SHEERNESS ON 25 FEBRUARY 1958

× — × — × Shoeburyness wind component along 350° ; ○ . . . ○ . . . ○ Sheerness surge
HW = High Water LW = Low Water

The calamitous surge in the Thames on 18 January 1881 was caused by severe easterly gales in the Flemish Bight and Thames Estuary associated with a deep depression almost stationary in the English Channel. The wind speed reached a mile a minute at Kew and was gale force for 15 hours in all. The tide on this occasion was the highest Thames tide on record at that time. The surge of 6-7 January 1928 caused a still higher tide, and that of 1953 is the highest now on record, 15.1 ft. (above ordnance datum Newlyn) at Southend.

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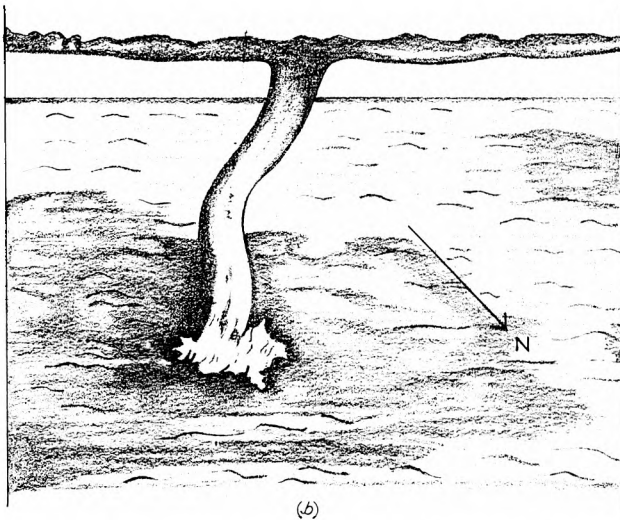
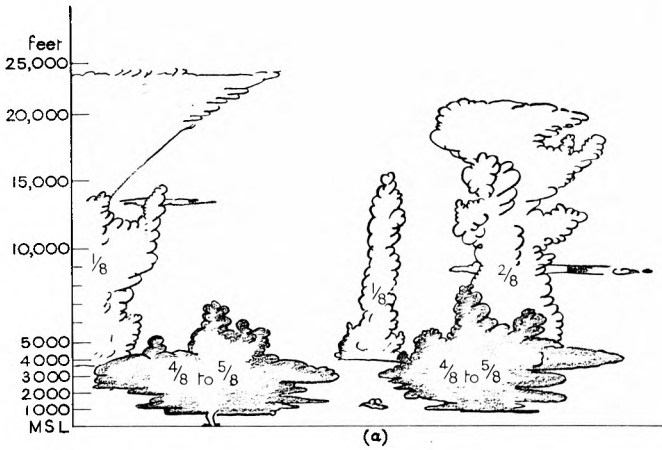
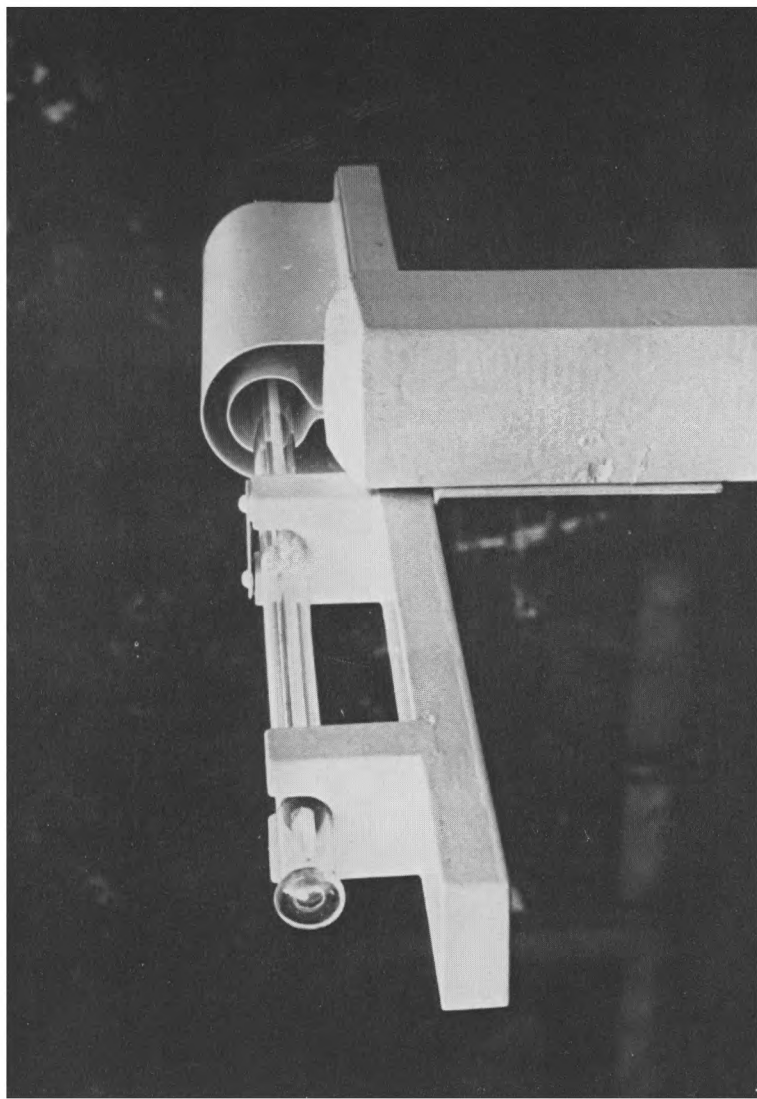


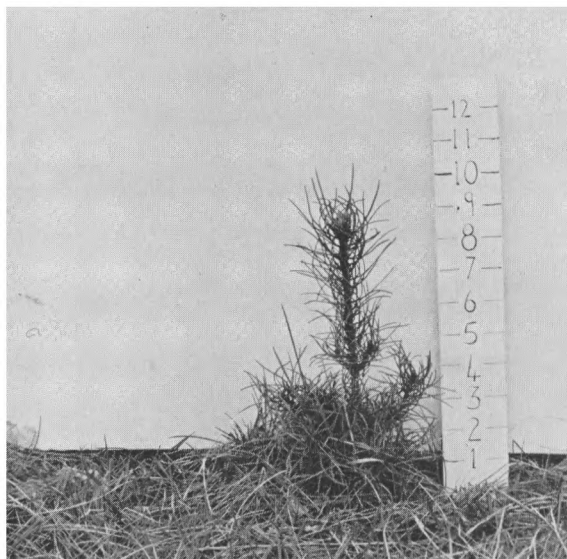
PLATE I—(a) WATERSPOUT AND CLOUD DISTRIBUTION 10 MILES SOUTH-WEST OF SUMBURGH HEAD SHORTLY AFTER 1535 GMT, 22 NOVEMBER 1965 (b) DETAILS OF THE WATERSPOUT FROM A SKETCH PROVIDED BY THE AIRCREW.

It was reported by the Captain that the waterspout was 'very similar to photographs I have seen of tornados, though somewhat less trailing'.

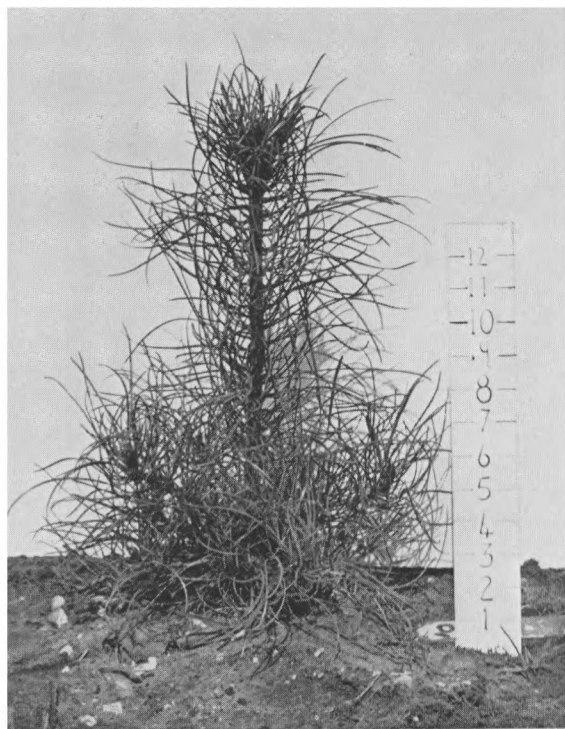


Photograph by courtesy of Forestry Commission

PLATE II—COCOA-TIN THERMOMETER MOUNT (see page 274)



(a) Sapling grown in grass-covered soil



Photographs by courtesy of Forestry Commission
 (b) Sapling grown in bare soil

PLATE III—TWO CORSICAN PINE SAPLINGS IN THETFORD CHASE, SHOWING THE GREATER EFFECT OF FROST DAMAGE ON THE SAPLING GROWN IN GRASS-COVERED SOIL THAN ON THE SAPLING GROWN IN BARE SOIL
 Both trees were planted two years ago (see page 277)



Photograph by S/Ldr B. Jenkins, RAF

PLATE IV—CUMULONIMBUS WITH STREAMING ANVIL

The photograph was taken at Butterworth, Malaysia in January 1966 looking south-west towards the Malacca Straits and Sumatra. This photograph may be compared with the streamer shown facing p. 80 in the *Meteorological Magazine* for March 1966.

TEMPERATURES IN THE FOREST OF THETFORD CHASE

By G. W. HURST

Summary.—Young Corsican pine has been lost recently in Thetford Chase because of frosting, and this paper describes a minimum temperature investigation to find the factors involved. Conclusions emerged that planting over bare soil would reduce frost risk, but that the size of the clearing did not appear very significant. No significant difference appeared to exist in the incidence of late spring frosts in the last few years compared with that of the 1920's when Corsican pine was first (successfully) introduced.

Introduction.—An examination has been made, in conjunction with Forestry Commission research pathologists, of temperatures in different places and exposures in Thetford Chase, Suffolk. The investigation was started because newly planted Corsican pine was being lost where it had previously been established and grown for about 40 years. This loss is potentially serious, because if the replacement of Corsican pine by Scots pine were enforced upon the Forestry Commission, the quantity of timber per acre would fall by about 25 per cent.

Symptoms of frost damage to the young Corsican pine shoots were observed, and in both 1964 and 1965 experiments were carried out with thermometers exposed at heights of 4 feet and 6 inches in a number of different sites and exposures. A vertical sounding from 2 in to 6 ft above ground was made in one place. This paper is concerned with a comparison of temperatures at 4 ft and 6 in in 1965, with cross-reference to 1964 results as necessary.

Sites.—It is not worthwhile to discuss in full detail all the sites which were used, and site plans are not given with this paper. The notes below are sufficient to give a general indication of the characteristics of the various sites. Dimensions quoted relate to areas contained within surrounding forest, which is mostly composed of trees in the height range 25–40 ft. Thermometers were installed at heights of 4 ft and 6 in unless otherwise stated.

Harling Nursery. This was a fairly large open area mostly covered with bare earth, approximately 8 acres in extent. Proneness to air stagnancy would not be expected. The thermometers were exposed in the middle of the nursery, from which position there was a very slight down slope to the west.

Harling. This was a very large clearing about 500 by 700 yd (70 acres) and flat, but it contained many small trees or even miniature coppices, and the air tended therefore to be very stagnant. Three thermometer positions were established, one over forest litter, one over rough grass and one over a square chain of bare soil. There appeared to be no obvious difference in the general exposure of the three positions chosen.

Lynford. This was a fairly large clearing about 300 by 450 yd (some 25 acres), with a slope of about 1° downwards to the north. The ground surface in 1965 was rough grass, but had been mainly litter covered in 1964. Two 4-ft thermometer positions were chosen here, one in the centre and one in the low north corner. A 6-in thermometer was exposed at the central site only.

Mundford. This was another fairly large clearing, 200 by 400 yd (about 17 acres), in which thermometers were exposed in three places, the centre,

near an edge and halfway between in 1964, but only in the central position in 1965. Mundford was the area chosen for the vertical sounding from 2 in to 6 ft.

West Tofts. This was a long narrow clearing 80 by 250 yd (4 acres) with a slight upslope of $\frac{1}{2}$ -1° from west to east, the length of the clearance. The ground was rough grassed and thermometers were exposed at 6 in at the centre and also at 4 ft near the western and eastern ends.

Santon Nursery. This clearance was very small, 70 by 35 yd ($\frac{1}{2}$ acre) and thermometers at 4 ft and 6 in were placed near the centre.

Kings. This lies to the south of the main part of Thetford Forest, and thermometers were put here to obtain temperatures representative of the most open part within the Forestry Commission area, as there were several hundred acres of open, fairly level, unwooded land.

Exposure of thermometers.—The 4-ft thermometers were exposed in cocoa-tin mounts (see Plate II), but the 6-in thermometers were without protection. The cocoa-tin mount is one used specially for obtaining minimum temperatures cheaply at a number of different points in the same area. The thermometer is held horizontally and firmly by being clipped in at two support points. For protection against direct radiation the bulb is placed inside a roughly cylindrical shield open at each end. The shield has double walls which are made of metal and are separated by an air space. The shield and mount are painted white. Although previous comparisons have been made, a special comparison was made of the minimum temperatures obtained from the screen at Grime's Graves, the agromet station within the Thetford Chase area, and those obtained from a shielded 4-ft thermometer placed near the screen. The comparison showed that

$$T_s = T_m + 1.0 + 0.2T$$

where T_s = 24-hour minimum temperature in °F with conventional screen exposure, T_m = 24-hour minimum temperature with cocoa-tin exposure, T = difference between screen and grass night minimum temperatures. It was assumed that this correction ($1.0 + 0.2T$) could be applied to T_m everywhere in the forest area to give an estimate of the screen temperature T_s .

Frost frequencies defined by years in 10.—A comparison is made between 4-ft corrected temperatures and those at a long-term standard station to arrive at a frequency of years in 10 when a frost can be expected. The long-term station nearest to Thetford is the airfield at Mildenhall, where acceptably homogeneous records (based on a good open exposure) have been maintained for many years. It has therefore been used for the comparison. The lowest, second lowest and third lowest temperatures (i.e. effectively minima on radiation nights) each week for each station separately are compared with similar figures for Mildenhall. Departures of the experimental stations from the standard station enable the long-term averages for the latter to be used to yield figures of the number of years in 10 when temperatures 32°F and 28°F will occur at the experimental stations from the various weeks from 1 April to 26 May (Smith¹) ; a similar technique was extended by the author to cover June.

It is not worth quoting here figures for both criteria, and Table I gives the numbers of years in 10 when temperatures below 28°F might be expected in April, May and June ; the lower criterion was selected because of the greater spread in readings, and because the Forestry Commission pathologists considered 28°F to be a more critical temperature for potential frost damage than 32°F.

TABLE I—FROST RISK, EXPRESSED AS YEARS IN 10 WITH SCREEN TEMPERATURES FALLING BELOW 28°F ON OR AFTER DATES SHOWN

Week commencing	Harling				Lynford		West Tofts			Others			
	A	B	C	D	E	F	G	H	I	J	K	L	M
1 April	10	10	10	10	10	10	10	10	10	10	10	10	8
8	10	10	10	10	10	10	10	10	10	10	10	10	7
15	9	10	10	10	10	10	10	10	10	10	10	9	6
22	9	10	10	10	10	10	10	10	10	10	10	9	5
29	9	10	10	10	10	10	10	10	10	10	10	8	3
6 May	8	10	10	10	8	10	10	9	9	9	10	5	1
13	7	10	10	10	7	9	9	9	9	9	10	4	0
20	4	9	8	6	3	9	6	5	8	7	8	2	0
27	2	5	6	3	*	*	3	3	4	4	4	1	0
3 June	1	3	3	2			2	2	3	2	2	+	0
10	0	1	2	1			1	1	1	1	1	0	0
17	0	+	1	+			+	+	+	+	0	0	0
24	0	0	+	0			0	0	0	0	0	0	0

+ indicates 0.1 to 0.4

* thermometer not available from early June

The sites are :

A Harling Nursery	H West Tofts (centre)
B Harling (over grass)	I West Tofts (east end)
C Harling (over litter)	J Santon Nursery
D Harling (over bare soil)	K Grime's Graves
E Lynford (centre)	L Kings
F Lynford (corner)	M Mildenhall
G West Tofts (west end)	

Notes : Mundford 4-ft. thermometer became increasingly and demonstrably in error during the period, and its results are therefore not quoted above. Figures for this table were worked out to the nearest decimal point, but to indicate the order of accuracy involved they have been rounded to the nearest whole number.

Several striking points are seen in this table. In the stagnant Harling area at the end of May a 50 per cent chance still exists of moderate frost over grass or litter, and the lower risk over bare soil can be seen from May onwards. The Lynford figures are incomplete (the thermometers were stolen early in June) but the greater coldness of the low corner is obvious. Differences in the West Tofts sites are not large, and may perhaps lie in the thermometers themselves and not in site characteristics. Possibly the wider approach rides in the east compared with those in the west may have facilitated the penetration of cold air. Santon Nursery (and Grime's Graves) are obviously frost-prone sites, only a little better than the vegetative covered Harling, but the freedom from late moderate frosts at Kings and especially at Mildenhall contrasts with the other sites.

A similar analysis was made using the 1964 data, and a comparison was possible for several of the stations. That year, like 1965, was comparatively frost free, but the technique of obtaining years in 10 of frost risk gave very comparable results. If anything, however, Table I probably fails safe, with some overstatement of frost risk in Thetford Chase especially if there is an increase in windiness in late spring.

Comparison of 4-ft thermometers with Mildenhall temperatures.—

The difference between the minimum temperatures at the various sites and at Mildenhall was averaged for each week of the 13 weeks from 1 April to 30 June, and as an illustration Figure 1 shows the weekly average differences for Harling Nursery and for Harling over bare soil and over grass. It is clear that Mildenhall is warmer than Harling Nursery and much warmer than the other two Harling sites, but an interesting feature is that the difference between the stations and Mildenhall is conspicuously smaller in weeks 3 and 9 than in the other weeks. Examination of the data over the three-month period showed that these were two weeks with limited radiation.

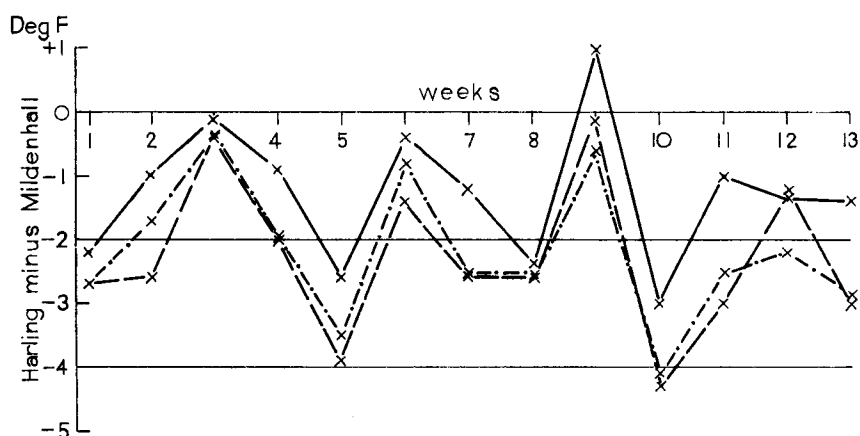


FIGURE 1—WEEKLY AVERAGE DIFFERENCES IN MINIMUM TEMPERATURE AT A STANDARD HEIGHT OF 4 FT BETWEEN HARLING SITES AND MILDENHALL, 1 APRIL —30 JUNE 1965

———— Harling (Nursery) ; — — — Harling (over bare soil) ;
- · - · - Harling (over grass)

There is a correlation coefficient of -0.73 between (*a*) the overall average for Thetford Chase stations minus Mildenhall and (*b*) the weekly difference between maximum and minimum temperatures for Mildenhall. This correlation supports the theory that when there is little difference between maximum and minimum temperatures (i.e. the weather is mostly dull) the spread of minimum temperatures at the sites themselves is less than on clear nights. It is also probably fair to conclude that the big open sites, Harling Nursery, Kings and Lynford are relatively warm at night compared with the ill-drained and more stagnant areas such as Harling, Santon Nursery and West Tofts. It is worth adding that Oliver² has found Grime's Graves in many respects the coldest meteorological station below 1000 ft in Britain. He quotes data showing it conspicuously cold in the summer months, and remarks that there is no month completely free of frost ; the lowest known recorded June temperature in Britain of 22°F occurred at Grime's Graves on 1 June 1962. Grime's Graves is an irregular 40-acre clearing in the forest, and the thermometer enclosure is almost at the bottom of a frost hollow.

Thermometers exposed at a height of 6 in.—Thermometers were exposed at 6 in above ground (with vegetation kept fairly well down) on wooden supports with no attempt at bulb shielding. The thermometers were also left out for 24 hours, read at 0900 GMT only, and were equipped with black sheaths over the stem to prevent condensation of spirit on the walls of the tube. Much the same set of sites was used for these readings as for those at 4 ft. Only during April and May were observations at 6 in taken at Mildenhall, which could therefore not be used as a standard. Instead, the open Kings site was used, and Figure 2 shows the difference between temperature at 6 in there and at Harling Nursery, Harling over

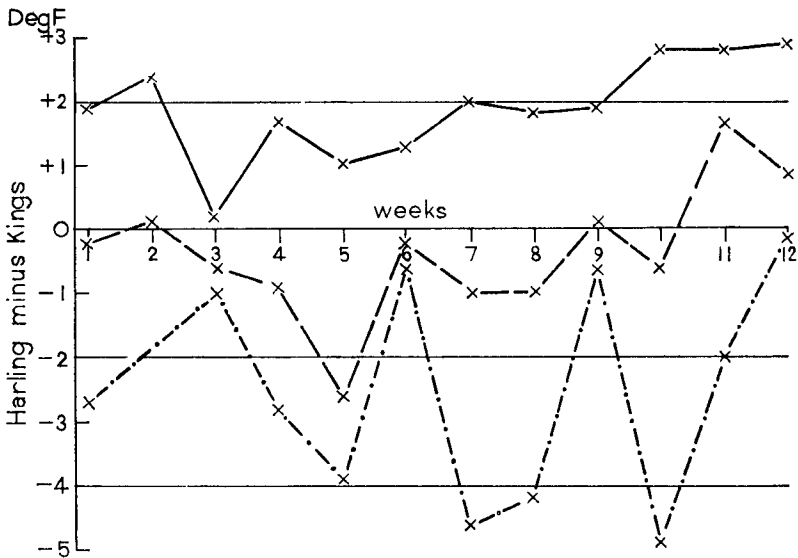


FIGURE 2—WEEKLY AVERAGE DIFFERENCES IN MINIMUM TEMPERATURE AT A HEIGHT OF 6 IN BETWEEN HARLING SITES AND MILDENHALL, 1 APRIL—23 JUNE 1965

———— Harling (Nursery) ; — — — Harling (over bare soil) ;
 - · - · - Harling (over grass)

grass and Harling over bare soil. This is the same selection of sites as in Figure 1, but the differences are dramatically greater. At 6 in, the bare-soil thermometer of Harling Nursery gives a higher temperature than Kings throughout the entire period (restricted to 12 weeks because of much thermometer trouble in the last week) and the difference in character between the grass cover and the small bare soil patch at Harling itself is striking. Equally arresting was the spectacle of two similar saplings, planted about two years earlier and seen in Plate III. The one planted in bare soil was thriving and doing well and the other with a grass carpet was stunted with obvious frost damage. Root competition may have been a factor, but the forest pathologists thought lack of frosting was the main reason for the excellent progress over bare soil.

A further factor controlling growth may possibly have been the lower average soil temperature under grass compared with bare soil. As an indication of the dimensions involved, Rider³ found that in May and June 1954 the average difference between daily maximum temperatures 2 in below soil and 2 in below short grass cover was + 4.2 deg.F, and the corresponding difference in minimum temperatures - 1.8 deg.F, giving an average temperature below bare soil 1.2 deg.F higher than under short grass. The average difference in temperature under the clay near Cambridge becomes small at depths of a foot or more.

Temperatures now and at first planting.—The recent trouble in establishing Corsican pine in Thetford Chase has arisen in areas being replanted, and a possible explanation of difficulties now compared with the first plantings in the 1920's could lie in some climatic change between the earlier years and now, particularly in relation to low temperatures in late spring and early summer. The nearest place with a temperature record running through from 1920 to the present day is the Botanical Gardens at Cambridge, and grass minimum temperatures during the critical months April, May and June were examined. A comparison was made of the frequency of varying degrees of frost severity in 1921-30 and 1958-65. A detailed analysis is not justified in this paper, but the conclusion seems inescapable that the 1920's were every whit as frost prone as the later period. The critical temperature was taken as 28°F, and frequencies of days with grass minimum temperatures lower than this averaged 7.4, 1.8 and 0.1 respectively in April, May and June of the early period, and 4.6, 1.6 and 0.3 for the same months of the late period. Averages of extreme grass minimum temperatures were very similar, and although the year 1962 was exceptionally cold with lowest May and June grass minimum temperatures of 20 and 24°F respectively, the corresponding temperatures were 24 and 26°F in 1923, 21 and 29°F in 1927 and 22 and 29°F in 1921. Only on two occasions (both in 1962) in the years 1958-65 did the May/June grass minimum temperature fall below 24°F, compared with four occasions in 1921-30 (all separate years).

Further experimental work.—More experiments are being conducted during 1966 partly to confirm results already obtained and partly to try out one or two different ideas. Two thermometers are being placed in the Battle Area, a large open space controlled by the Ministry of Defence (Army), but within the general forest boundaries; and a second vertical array of thermometers will be erected, providing data over bare soil as well as over grass. It is hoped that during the season very narrow strips will be cleared, and an assessment can then be made of the potential advantages, if any, of such very narrow strips.

Conclusions.—To some extent this must remain an interim report, as modified experiments are being made again this year, and probably will be made next year also. Some points can, however, be made with little fear of major error.

- (i) The nature of the ground cover appears to be a very important factor in determining the frequency, intensity and duration of frost. The Harling sites bring this out very clearly as the small 16-perch bare patch showed markedly less frost at 6 in than over the nearby grassed area.

It is probable that this island of 16 perches is insufficient in size to reflect itself in the temperature at 4 ft, but the difference in character between Harling Nursery and Harling may well be mostly a function of the absence or presence of a grassed surface.

(ii) There seems little advantage in making particularly small clearings in forests. Two such were introduced during the experiment, near Santon Nursery and at West Tofts, and they were among the poorer sites as far as frost risk was concerned. Very narrow strips may, however, be more suitable.

(iii) Slope can make a difference if the area is fairly large and regular. Thus, pooling results in distinctly lower temperatures at the corner of Lynford although the slope of 1° was fairly gradual. Probably anything less than 1° does not signify and at West Tofts ($\frac{1}{2}$ –1°) for example little difference could be discerned in the results between the low west end and the other sites.

(iv) Techniques of assessing years in 10 of frost have produced very similar figures for 1964 and 1965 (although both were untypical years for frost occurrence).

(v) It is doubtful whether climatic change contributes the difficulties of establishing Corsican pine now compared with the 1920's. Winters may have been colder in the last few years than in the 1920's, but frosting in the late spring and early summer is probably a vital factor, and no apparent difference is evident in this respect.

Acknowledgements.—This work has been done in close collaboration with Dr D. H. Phillips and Messrs J. D. Low and B. J. W. Greig (pathologists), and Mr J. M. B. Brown (ecologist) at the Forestry Commission Research Station at Alice Holt, and their co-operation is much appreciated. Very real gratitude is also due to the staff at Thetford Chase for maintaining observations over the three months, mostly to a very high standard of accuracy.

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551.551.5 (262+564.3):629.13

AN INCIDENT OF SEVERE LOW-LEVEL TURBULENCE

By G. J. JEFFERSON

On 14 April 1966, a Canberra aircraft took off from Akrotiri (which lies on the southernmost point of Cyprus) for an exercise flight and climbed away at 3000 feet per minute on a course of 220 degrees over the sea. Turbulence was experienced from take-off but when, at 1730 GMT the aircraft reached a point 25 nautical miles from Akrotiri and an altitude of 8500 feet it experienced some very severe turbulence which turned the aircraft completely over. The pilot managed to regain control, and after completing a half loop, levelled out at 4000 feet and returned to Akrotiri. The aircraft

was fitted with an accelerometer and the crew stated that they observed readings between $+7$ and $-3 g$.

Investigation of the incident soon revealed that it was by no means an isolated case. Another Canberra returning from El Adem at 1000 feet landed at Akrotiri at 1610 GMT on 14 April after experiencing severe turbulence over the last 80 miles of the flight to Cyprus. Yet another Canberra which took off from Akrotiri on an exercise at 1550 GMT climbed from 10 miles south of Akrotiri on a course of 270 degrees. It experienced very severe turbulence while climbing from 4000 to 16,000 feet, accelerometer readings from $+3$ to $-1\frac{1}{2} g$ being observed. Yukon aircraft of the Royal Canadian Air Force reported clear air turbulence over the Nicosia Flight Information Region at 1615 GMT (exact position and height unknown). At 1940 GMT a Comet reported moderate to severe clear air turbulence at 7500 feet, 17 nautical miles north-east of Akrotiri. A Viscount aircraft of Cyprus Airways en route from Tel Aviv to Nicosia flying at 14,000 feet reported light clear air turbulence to 20 miles south of Cyprus. From this point into Nicosia where it landed at 1310 GMT it reported severe clear air turbulence over the mountains.

Some turbulence was still in existence some hours after this as evidenced by a British United Airways Britannia aircraft on a trooping flight from Gatwick to Akrotiri which landed at 0332 GMT on 15 April. A member of the meteorological office staff who was travelling on this aircraft reported that there was light, occasionally moderate, turbulence in medium layer cloud on descent from 24,000 feet and some slight turbulence just before landing. A Comet aircraft of Olympic Airways flying from Beirut which landed at Nicosia at 0740 GMT on 15 April reported severe clear air turbulence above 8000 feet but the exact height, position and duration are unknown.

The turbulence on the 14th and 15th occurred in a fairly densely flown area and a number of other reports are available in addition to the primary one of great severity.

Interesting features which come to light are

- (a) that although primarily at low levels, turbulence was experienced nearly as high as 24,000 feet, and,
- (b) the period over which it is known to have extended was from about 1300 GMT 14 April to 0740 GMT 15 April, about $18\frac{1}{2}$ hours.

It seems likely however from the reports that turbulence at the higher levels was associated with unstable medium cloud and that there was also orographic turbulence over Cyprus.

Reports from Cyprus stations show that there was a complete cover of medium cloud throughout the period. The only low cloud was well-broken stratocumulus but much of the time there was nil.

It is clear therefore that the major low-level turbulence was not associated with convection cloud. The winds at the time were not in an off-shore direction in southern Cyprus and in view of the distance of the major incident from the nearest high ground it seems likely that it was not caused by orographic effects.

As with the Derna case described by Grimmer¹ the worst turbulence occurred in clear air about 25 miles from the nearest land but in this case

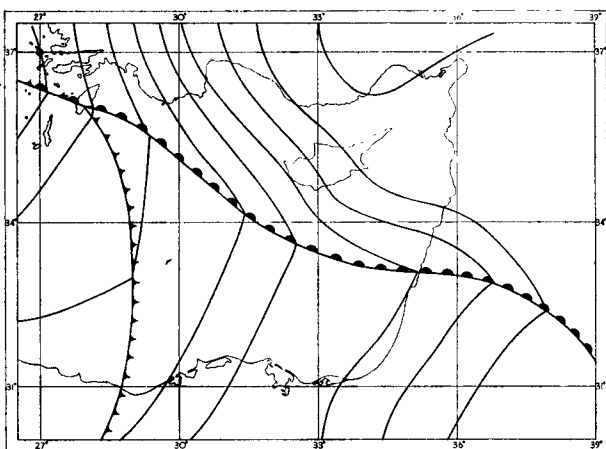


FIGURE 1(a)—SYNOPTIC SITUATION 1200 GMT 14 APRIL 1966

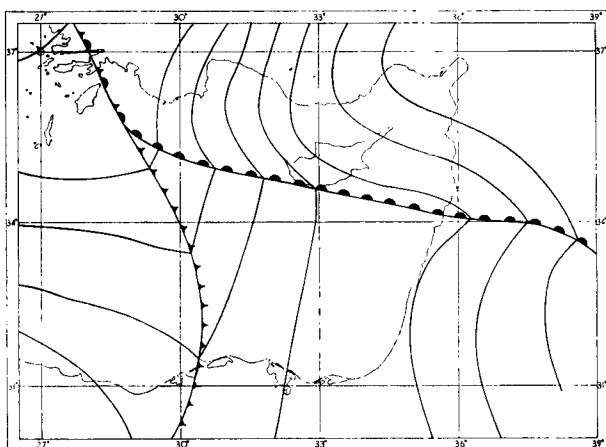


FIGURE 1(b)—SYNOPTIC SITUATION 1800 GMT 14 APRIL 1966

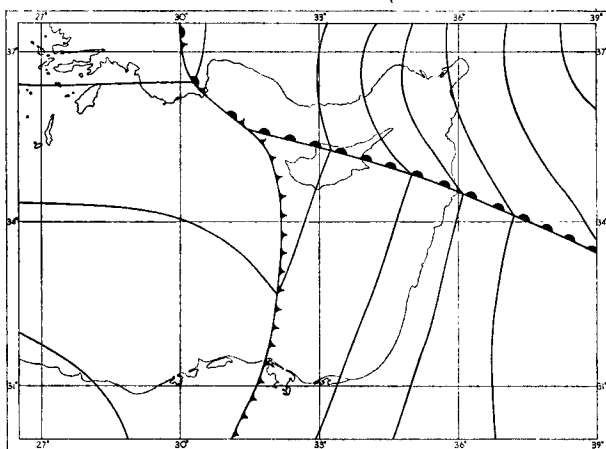


FIGURE 1(c)—SYNOPTIC SITUATION 0600 GMT 15 APRIL 1966
Isobar interval 2 mb; pressure at 31°N 30°E rose from 1004 to 1005 mb.

well on the windward side of it. It could not therefore have been caused by the rotor streaming effects of orographic turbulence.

An inspection of the synoptic situation shows similarities to the features associated with the Derna case as described by Kirk². Figures 1(a) – (c) show the surface analysis at 1200 and 1800 GMT on 14 April and 0000 GMT on 15 April—copied from the working charts at Episkopi. At 1800 GMT, approximately the time that the worst turbulence was encountered, a depression centre lay well to the west over Greece and a warm front is shown lying east to west almost touching the south coast of Cyprus. A cold front lies north to south near 30°E.

The surface frontal analysis is also shown on the 850 mb charts for 1200 GMT on 14 April (Figure 2a) and 0000 GMT on 15 April (Figure 2b), which clearly show a tongue of warm air corresponding to the warm sector.

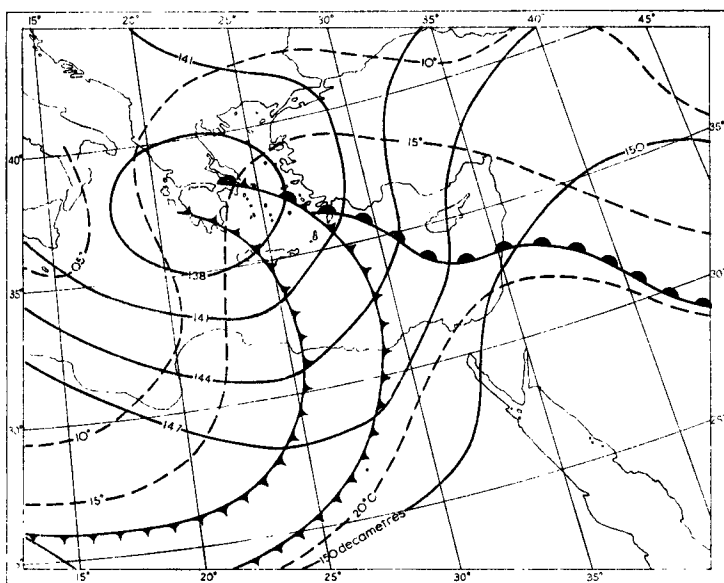


FIGURE 2(a)—850 MB CONTOURS AND ISOTHERMS AT 1200 GMT 14 APRIL 1966
 ————— Contours - - - - - Isotherms

The penetration of warm air over Cyprus is well shown by the Nicosia ascents for 1200 GMT on 14 April and 0000 GMT on 15 April (Figure 3) which indicate that the warming was confined to layers below 700 mb. The ascent at 1200 GMT is generally similar to that for Tobruk (Kirk²) with an inversion layer between layers whose lapse rates were near the dry adiabatic.

The rise of surface temperature took place in the Episkopi-Akrotiri area about 1700 GMT and was quite noticeable at the time. The rise is shown on the thermograms for Episkopi (Figure 4a) and Akrotiri (Figure 4b). After a fall in the afternoon at Episkopi there was a sudden rise from 20°C to 23°C in a few minutes followed by a more gradual rise to 25°C.

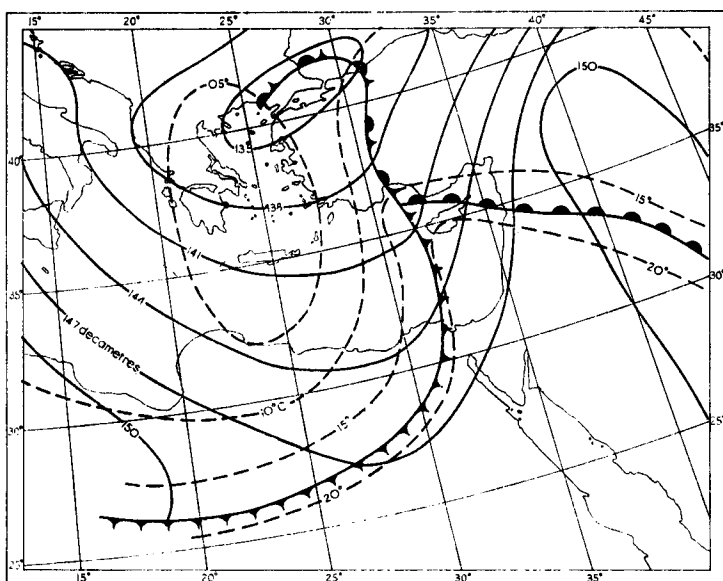


FIGURE 2(b)—850 MB CONTOURS AND ISOTHERMS AT 0000 GMT 15 APRIL 1966

————— Contours - - - - - Isotherms

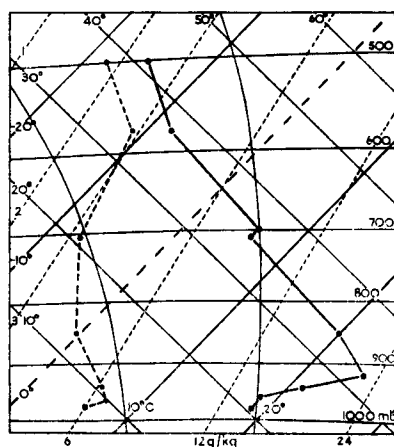
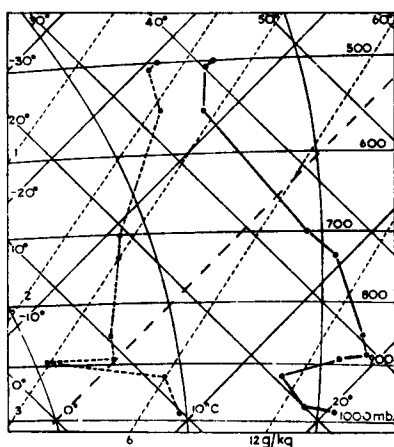


FIGURE 3—NICOSIA RADIOSONDE OBSERVATIONS

(a) 1200 GMT 14 APRIL 1966

(b) 0000 GMT 15 APRIL 1966

————— Dry-bulb

- - - - - Dew-point

At the same time the barograms for Akrotiri and Episkopi (Figures 5a and 5b) both show rapid pressure oscillations between 1630 GMT on 14 April and 0600 GMT on 15 April with a small pressure jump at about 1730 GMT. The possibility therefore exists, especially in view of the limited vertical extent of the warm air, that the warm front drawn on the chart was more

n the nature of a line disturbance of the flow as described by Kirk and that the turbulence may well have been associated in this case also with gravity waves at the interface.

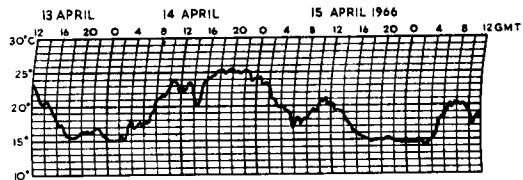


FIGURE 4(a)—EPISKOPI THERMOGRAM 13-16 APRIL 1966

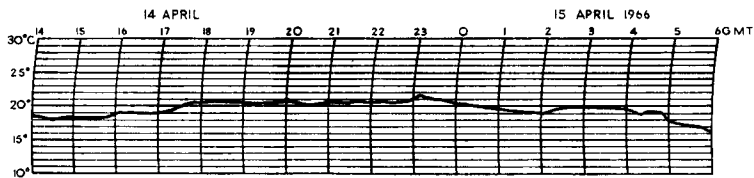


FIGURE 4(b)—AKROTIRI THERMOGRAM 14-15 APRIL 1966
The temperature record reads low ; screen temperature at 1800, 0000 and 0600 GMT were 21.3, 20.8 and 17.5°C.

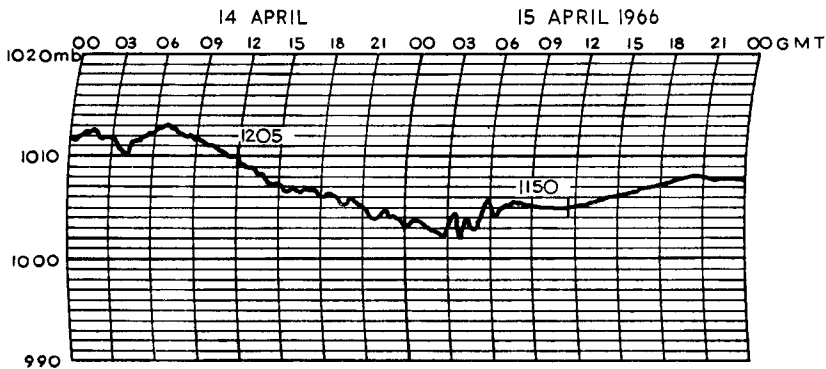


FIGURE 5(a)—AKROTIRI BAROGRAM 14-15 APRIL 1966

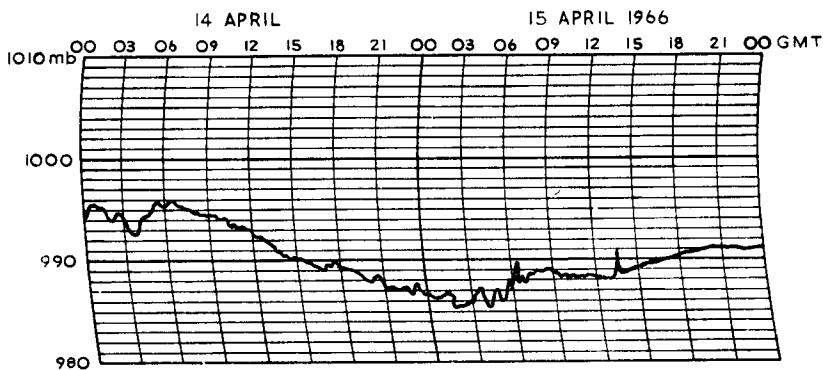


FIGURE 5(b)—EPISKOPI BAROGRAM 14-15 APRIL 1966

The 850 mb charts (Figures 2*a* and 2*b*) bear a strong resemblance to those of the Derna case (Kirk² Figures 9 and 10) with a sharp warm ridge, but with the difference that on 14 April the turbulence occurred in a position where warm air advection was occurring.

Another feature similar to the Derna case is that the winds for 1800 GMT on 14 April at Cyprus stations given in Table I show a very marked veer with height in the lower levels.

Although no attempt is made at a more detailed explanation of the mechanism which could produce turbulence of the severity observed well away from land in what would previously have been regarded as unlikely conditions of clear air at low levels, certain common factors are noted which may enable some attempt to be made to forecast such occurrences on future occasions. They are

- (a) a surface warm or cold 'front' with oscillating pressure including pressure jumps,
- (b) a sharp thermal ridge at 850 mb,
- (c) rapid veer of wind with height in the lower layer and
- (d) tephigram showing an inversion or stable layer between layers whose lapse rates are near the dry adiabatic.

TABLE I—UPPER WINDS IN CYPRUS 1800 GMT 14 APRIL 1966

Height in feet	Ayios Nicolaos	Nicosia <i>degrees/knots</i>	Paphos
1000	060/29	—	120/26
3000	160/23	140/26	190/34
5000	225/20	210/29	230/36
7000	240/30	220/35	
10000		220/37	

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REVIEWS

Investigation of the bottom 300-meter layer of the atmosphere edited by N. L. Byzova. 9 $\frac{3}{4}$ in \times 7 in, pp. v + 112, *illus.*, (translated from the Russian by the Israel Program for Scientific Translations, Jerusalem), Oldbourne Press, 1-5 Poolpool Lane, London, EC1, 1965. Price : 27s.

This set of papers published by the Academy of Sciences of the U.S.S.R. and now appearing in translated form provides an interesting reflection of the Russian position in the study of atmospheric diffusion and transport processes. All the papers involve measurements made on a 300-m mast, the geographical location and other details of which are, however, completely omitted. Seven deal with instruments and measuring techniques, three discuss the wind and temperature profiles and turbulence data so obtained, two are concerned with experiments on the spread of material from a point source and one with the statistical representation of turbulence measurements.

Not surprisingly the main fundamental background is provided by the well-known Russian developments in similarity theory of profiles and inertial sub-range theory of turbulence, but the collection is not without reference to Western contributions. In the context of diffusion from a continuous point source research workers here may be surprised at the emphasis given to inertial sub-range considerations and also at the adherence to a K-theory for cross-wind spread. On the whole, however, the collection makes stimulating and informative reading for anyone with a special interest in this particular field.

F. PASQUILL

Objective analysis of meteorological fields, by L. S. Gandin. 9 $\frac{3}{4}$ in \times 7 in, pp. vi + 242, *illus.*, (translated from the Russian by the Israel Program for Scientific Translations, Jerusalem), Oldbourne Press, 1-5 Portpool Lane, London, EC1, 1965. Price : 81s.

The requirement for real-time production of numerical forecasts as a routine has stimulated investigation of two allied problems—automatic processing of coded data, and methods of objective analysis of surface and upper air charts. They are now however assuming major importance in their own right ; their successful solution could eliminate many of the meteorologist's more laborious tasks. With the former considerable success has been achieved ; data extraction by computer is already fully as efficient as the human variety. In the field of analysis, subjective methods still have a long lead, but much progress has been made.

Though this book discusses the whole field of objective analysis, it is primarily concerned with upper air contour charts. The various objective methods have a common approach in that they attempt to estimate contour heights at a network of points independently—a fundamentally different approach from the human analyst's. In his initial chapter, the author reviews methods developed outside the U.S.S.R. Basically these are two in number. One starts with an initial guess field normally derived from an earlier forecast, and successively modifies it in the light of observations. This method is in operational use in the U.S.A. and elsewhere. The other consists in fitting the best surface in the vicinity of each grid point to accommodate both observations and forecast field, suitable relative weighting factors being allotted. This is in current use in the Meteorological Office, additional corrections having been introduced to correct particular defects. The author comments reasonably enough that the arbitrariness of these approaches hardly justifies the term 'objective'.

The main part of the book describes a third approach developed in the Soviet Union at the Main Geophysical Observatory. This makes use of the statistical correlation of meteorological elements with distance. In the case of a contour chart, the differences of observed heights from their seasonal means are used to form estimated values using computed correlation functions. Winds, converted to geostrophic gradients, are handled similarly. The treatment is mathematically logical, and avoids the empiricism of such parameters as distance weighting functions employed by other systems. The method may be extended to other elements, and examples are shown of correlation functions for 500 mb height, surface pressure, and 850 mb dew-point.

Comparisons given by Gandin of the different analysis techniques appear to favour the Russian system.

However one must confess to some doubts. The conditions of the comparison hardly do justice to the alternative methods, and the statistical verification itself is too clearly allied to the proposed analysis technique. In the examples of charts derived objectively by the correlation method, the analyses are excellent over land areas, but the quality over the Atlantic appears poor. One can also visualize the risk of an occasional 'howler', such as a small high in the centre of a depression. However, the technique is clearly capable of further development. So far no meteorological service has been able to rely on routine objective analyses without human monitoring.

The final chapters deal with other practical aspects of the production of computed analyses, from data processing to methods of chart output, but in this fast-developing subject, the ideas have been overtaken by events. The book itself is well produced and includes a comprehensive bibliography. Published in Israel as one of a series of scientific translations, it leaves nothing to be desired in clarity of expression and completeness of editing.

P. GRAYSTONE

Weather Studies, by L. P. Smith. 7 $\frac{3}{4}$ in \times 5 $\frac{1}{4}$ in, pp. vii + 131, *illus.*, Pergamon Press, Headington Hill Hall, Oxford, 1966. Price : 15s.

This book, which is part of a series on Rural Studies, is written in a clear, straightforward style and should be easily understood by the average person. It is divided into a large number of topics, for each of which there is an explanation followed by an 'assignment'. The latter consists of experimental work to enable the reader to discover facts for himself, and thus gain a better understanding of the subject.

The book contains five parts, covering weather observations and measurements, the plotting of the measurements on graphs, the relationship between the various aspects of weather, local weather, and finally some hints on weather forecasting based on the reader's own observations. The work is well illustrated by graphs, diagrams, maps and a number of photographs of common cloud types.

'Weather Studies' should prove useful to teachers, especially those in charge of school weather stations. It is suitable for pupils of all ages in Secondary schools and in the final year in Junior schools. It could form part of a general science course particularly in schools in rural and coastal areas. It could also be used as a supplementary book by students of physics and geography and should have a place in the school library for the use of individual pupils.

This is a stimulating book which should appeal to anyone who is interested in the weather, and should encourage many who are considering setting up their own weather stations. Perhaps a small section on the siting and equipping of such a station at a minimum of cost would have been a useful addition to the book. The author's preference for the Fahrenheit scale of temperature seems a little out of place in a book which will be used in schools where teachers are trying to persuade their pupils to think in terms of the centigrade scale.

F. R. DOBSON

LETTER TO THE EDITOR

551.515.3

Waterspout seen off Shetland on 22 November 1965

Weather conditions off Shetland on 22 November 1965 and details of a waterspout observed (Plate I) are given in the following account by Captain J. A. MacDonald of BEA.

'The aircraft landed at Sumburgh Airport at 1410 GMT in a heavy snow shower which had lasted for over an hour. The wind was north-north-westerly, about 10 knots, temperature was just above freezing, and the snow was coming from a large cumulus or cumulonimbus cloud which gave complete cloud cover in the vicinity. Shortly after the landing, the shower passed and the sky cleared, with a drop in temperature to below freezing. Such were the conditions when the aircraft took off again at 1535 GMT.

Immediately after take-off, a left turn was initiated on to a south-west heading. Although the sky was clear immediately overhead, the aircraft was heading towards a bank of smallish cumulus or fracto-cumulus cloud with an estimated base of 800-900 feet above sea level. Visibility was good and the temperature was steady at around -1°C from take-off to 600 feet (not noted above this height). The cloud looked perfectly normal and innocuous, except for the cone of cloud which, following a crooked path, stretched from the base of the cloud to the surface of the sea (see Plate I). In appearance, it was curved and dense with an average diameter estimated at 30 feet, though at the top the diameter was slightly larger. Where it touched the surface of the sea, the sea was turbulent and appeared to be luminescent. There was no precipitation in the immediate area, which was approximately 10 miles south-west of Sumburgh Head.

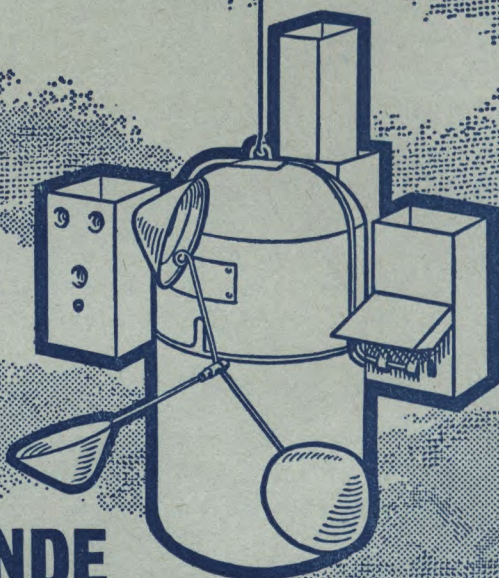
During the climb into a neighbouring bank of similar-looking cloud some 2 miles from the waterspout, slight turbulence was experienced.'

On 22 November a northerly airstream brought an unstable polar air mass over the Shetland Isles. The 1000-500 mb thickness of 5120 geopotential metres (gpm) at 1130 GMT at Lerwick was unusually low—the minimum over the five-year period 1950-54 was 5160 gpm. The unstable air gave rather frequent showers of snow and hail some of which were heavy and prolonged. Surface temperatures reported by Lerwick Observatory were at or below freezing-point though sea surface temperatures were around 9°C . The frequency of waterspouts* in the northern hemisphere reaches its maximum in October-November but occurrences are relatively rare in the latitude of Lerwick.

R. WILSON

* GORDON, A. H. ; Waterspouts, *Mar. Obsr, London*, 21, Part I p. 47 and Part II p. 87.

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CONTENTS

	<i>Page</i>
A case illustrating the value of satellite pictures in forecasting for the British Isles. R. A. S. Ratcliffe	257
The meteorological conditions leading to storm surges in the North Sea. J. F. Keers	261
Temperatures in the forest of Thetford Chase. G. W. Hurst	273
An incident of severe low-level turbulence. G. J. Jefferson	279
Reviews	
Investigation of the bottom 300-meter layer of the atmosphere. Edited by N. L. Byzova. <i>F. Pasquill</i>	285
Objective analysis of meteorological fields. L. S. Gandin. <i>P. Graystone</i>	286
Weather Studies. L. P. Smith. <i>F. R. Dobson</i>	287
Letter to the Editor	288

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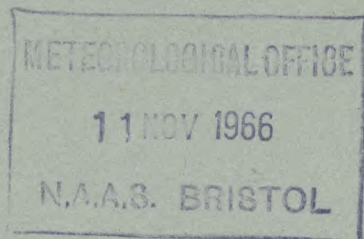
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THE METEOROLOGICAL MAGAZINE

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551.5:06

WORLD METEOROLOGICAL ORGANIZATION FOURTH SESSION OF THE COMMISSION FOR SYNOPTIC METEOROLOGY

By C. J. M. AANENSEN

The Fourth Session of the Commission for Synoptic Meteorology (CSM) was held at Wiesbaden by invitation from the Government of the Federal Republic of Germany. The Session commenced on 7 March 1966 and lasted four weeks. There were over 130 representatives from 54 countries. The United Kingdom delegation consisted of Messrs V. R. Coles, L. H. Starr and C. J. M. Aanensen from the Meteorological Office and Instructor Captain J. R. Thorp, RN, from the Naval Weather Service.

All the meetings took place in the Kurhaus at Wiesbaden and, for the first time, simultaneous translations in five languages were available for the plenary meetings.

After welcoming speeches by the Director of the Deutscher Wetterdienst, by the Mayor of Wiesbaden, by a member of the Government of the Land of Hesse and by the Secretary General of the World Meteorological Organization, the work of the Conference got under way with Dr S. N. Sen of India as President and Dr K. T. Logvinov of U.S.S.R. as Vice-President. As is customary three committees were established, one to deal with codes, one for telecommunications and the third to deal with other matters. Some items of the agenda were dealt with to some extent by all three committees and in particular the impact of numerical data handling and World Weather Watch (WWW) was evident at many stages of the discussions.

There was a considerable exchange of views on the aspects of WWW, which are of direct concern to the Commission. The latter expressed its support in principle of the general lines of the planning effort described in a Secretariat document. Many delegates expressed the view that one of the major objectives of WWW should be to aim at a more uniform world-wide network of observations, that consequently special attention should be given to the ocean areas particularly of the southern hemisphere and that there was a need to improve the availability of southern-hemisphere data in the three World Meteorological Centres established for WWW. The Commission also expressed the view that increased attention should be given to the establishment of data archives at appropriate centres for the benefit of research workers. It was also noted that the output from Regional Meteorological Centres will vary, being dependent on the requirements of the associated National Centres. It was pointed out by some delegates that the

success or failure of WWW would be judged primarily on the service it renders to the small countries and to the emergent ones. It was realized that the planned output of the various centres will provide considerable assistance to those Services which are providing support for international aviation and maritime interests. Consideration was given to the present success in, and to the future possibilities of, obtaining observations (including upper air) from merchant ships and from commercial aircraft, but it was also realized that there were many areas of the world for which such observations could not be available.

There was considerable discussion on the engineering and organizational aspects of the global telecommunications system, and the Commission paid particular attention to the problems associated with the main trunk circuit which figures importantly in WWW planning. Various specialized studies relating to high-speed transmissions have been recently completed or will be in the near future. As part of its review of telecommunications the Commission examined the contents of the northern-hemisphere exchanges in respect of the type of data, selection of stations and frequency of transmission and also compiled a detailed list of stations whose reports should be included. Considerable emphasis was placed by the Commission on speeding up the collection of national reports, and on the use of approved telecommunication procedures and internationally agreed technical standards for transmission. Delegates also heard that plans were afoot to upgrade the New York-Offenbach cable to accommodate information in digital, non-digital and graphic form and at high speed (2400 baud), and that considerable improvements were planned for the circuit Moscow-Cairo. The Commission reviewed the exchange of southern-hemisphere data and the exchange of data between the northern and southern hemispheres and welcomed the planned improvements which were reported. Though the orders of priority of transmissions after restoration of a disrupted circuit were discussed for a long time it was not found possible to come to any agreement except that recent TEMP and TEMP SHIP part A reports should have first priority with recent hemisphere SYNOP and SHIP data. The Commission re-established its Working Group on Telecommunications.

The Commission discussed the dissemination and synoptic use of meteorological satellite data and expressed appreciation to the U.S.A. for their continuing efforts to advance the science of meteorology by means of satellites and for making current satellite products available to other Services. The Commission re-established the Working Group on the synoptic use of satellite data for the purpose of studying and preparing advice on the various related requirements. The increasing use of hydrological forecasting was recognized by the Commission who appointed a rapporteur to collect and prepare guidance material and liaise with the Commission for Hydrometeorology. The report of the Working Group on long-range weather forecasting was studied but no action was taken apart from appointing a rapporteur. Following consideration of the report of the Working Group on Methods of Analysis and Prognosis in the Tropics, the Commission agreed it could not make recommendations regarding methods for trial ; it appointed a rapporteur, instead of re-establishing the working group, and arranged for liaison on tropical matters with the Commission for Aerology (CAe). The re-establishment of the joint CAe/CSM Working Group on numerical weather prediction

was recommended with terms of reference to formulate requirements on codes, telecommunications, and presentation of output data.

Terms and definitions relating to visibility came under fire and it was recommended that certain terms should be dropped since they gave rise to misconceptions. On the question of the definition of mist and fog there was much discussion and despite some disagreement on the physical processes it was decided that the present conventional dividing line at 1000 metres is convenient and should be retained. A proposal by the Commission for Maritime Meteorology (CMM) to adopt a new table of equivalent wind speeds for the Beaufort Numbers was in effect referred back since new studies had become available since CMM-IV. Important advances in the physics of hydrometeors in recent years caused the Commission to recommend the establishment of a Working Group to deal with definitions and description relating to these items.

Following on the recommendations of the Working Group on Codes which had studied the minimum observational requirements according to the uses of the data for analysing and predicting small-scale phenomena of short duration, medium-scale and hemispherical-scale movements, the Commission reviewed the data requirements for all observations. For surface observations the Commission compiled a provisional list of requirements for further study. In particular there was a need for very considerable study of the requirements for observations of past and present weather and on this point the Commission considered that the findings of the Working Group were not a true minimum requirement but were admirable as a basis for further study. Agreement was reached as to minimum requirements for upper air observations. The main points of change which were recommended were that the dew-point depression should be reported in place of the dew-point and that provision should be made for reporting as standard levels data for 900 and 800 mb instead of 850 mb and for the addition of 600 mb data : data for 850 and 250 mb would not be required on a hemisphere basis. It was also agreed that the resolution of the reported wind should be changed from 10° to 5° . More specific criteria were developed for the determination of significant levels with respect to wind and maximum-wind levels. There was considerable discussion of the requirements in respect of non-meteorological data in messages and here computer requirements were often not acceptable to manual working. However, there was agreement on a proposed change in the identification of ship reports, the reporting of ship positions and in the identification format of TEMP and PILOT reports. Proceeding from these decisions the Commission then discussed code forms and made various recommendations, of which the following are of considerable interest. No changes were recommended for surface reporting codes except in the initial groups of the SHIP code and certain amendments in the subsidiary groups to allow better and simpler reporting of swell and sea temperature. New code forms were recommended for upper air reports. These codes are logical developments from the above-mentioned decisions as regards requirements and, in addition, make provision for an indication of the units used for the wind reports and incorporate a new way of indicating the sign of the temperature and the temperature to a resolution of 0.2 degC . It was recommended that these changes in code forms should all take place on 1 January 1968, but that changes of levels of upper air reports might have to be delayed

because they would produce an increased load on communications which is not acceptable until higher speeds are available on at least certain exchange routes.

As foreshadowed by the recommendations of the Working Group, the specialized aviation weather report code (AERO) was severely criticized and an entirely new code form was recommended. This code form includes only those elements which are required for aeronautical purposes and they are arranged in a self-evident form in the order of the corresponding plain language form. Certain indicator letters are introduced and provision is made for the reporting of weather by letter abbreviations as well as figures. Corresponding changes were also made to the forecast aviation codes. The present AERO code will however be retained for non-aviation uses. It was recommended that the Working Group on Codes be re-established under the more correct title 'Data Needs and Codes'.

On one afternoon, as a break from the continuous discussion, a symposium was held at which the following four lectures were given : 'Objective interpretation of forecast charts' by Dr O. Lönnqvist, Sweden, 'Numerical experiments leading to the design of an optimum global network' by D. M. Hanson, U.S.A., 'NMC numerical programme for the tropics' by F. W. Burnett, U.S.A., and 'Meteorological activities on board fishing protection vessels' by Dr H. Walden, Federal Republic of Germany.

Towards the end of the Session Dr S. N. Sen of India was re-elected as President of the Commission and Dr N. G. Leonov of U.S.S.R. was elected Vice-President.

The hospitality of our German hosts was much appreciated. In particular, the sight-seeing tour of the Taunus mountains and the valley of the Rhine, arranged by the Director of the Deutscher Wetterdienst will long be remembered by all delegates. The hospitality of the City Council of Wiesbaden and the Government of the Land of Hesse will also be pleasant memories.

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STRATOCUMULUS — A REVIEW OF SOME PHYSICAL ASPECTS

By S. G. CORNFORD

Summary.—Present knowledge of the physical aspects of stratocumulus on which investigators have mainly concentrated is summarized and commented upon. Principally these aspects are the temperature and humidity structure, turbulence, liquid water-content, droplet size and concentration, radiation, shape of cloud top, turbulent exchange at the cloud top, cellular convection and effects of wind shear. Some problems which require further investigation are listed.

Introduction.—This article reviews the present state of knowledge of some of the physical aspects of non-precipitating stratocumulus cloud and the processes which govern its behaviour. The physical requirements for some types of altocumulus and stratus cloud are similar so that although attention is directed towards stratocumulus (Sc) much of the text will apply also to altocumulus (Ac) and stratus (St).

In temperate latitudes Sc is probably the most frequently reported type of low cloud. This is partly because in routine observations Sc is often the classification given to ill-defined forms which must nevertheless be classified.

Fortunately difficulties over the demarcation between cloud types will have had little effect on the findings reviewed here because most are based on clearly defined occurrences, usually associated with anticyclones.

Apart from the scientific desirability of understanding the formation, existence and dissipation of Sc there is a day-to-day need to use this understanding in forecasting practice. The formation and dissipation of Sc have large effects on the heat balance of the air near the ground and hence on surface visibility, fog, frost and even surface wind. There would be considerable economic benefit if the behaviour of a Sc sheet could be understood in a way that could be easily used in forecasting practice. No new forecasting techniques are suggested in this article which is rather an attempt to review the physical aspects of Sc which have already been examined and to indicate those which warrant further research.

Temperature.—Vertical profiles of temperature through Sc have been published by Schwerdtfeger,¹ Čurinova,² James³ and Moore.⁴ A notable and common feature is a marked inversion above the cloud top with temperature increases of up to 8 degC. Both James and Moore show occasions when an 8 degC change occurred through a layer only 100 m deep. In an analysis of 823 aircraft ascents over the Atlantic Ocean near 60°N 13°W Schwerdtfeger found 106 occasions of typical anticyclonic Sc. On nine of these the relationship of the cloud observations to the temperature profile was somewhat ambiguous and the observations were discarded, but on the other 97 there was invariably an inversion associated with the cloud top.

The temperature increase in the inversion layer appears to be related to the presence or absence of higher cloud above the Sc. On each of Schwerdtfeger's selected occasions there was no cloud above, or at the most 4/8 cirrus. James does not mention the presence or absence of upper cloud but his flights took place in anticyclonic conditions and so were probably free of thick upper cloud. (He certainly assumes that there was none when calculating the clouds' heat budget.) For nine of his eleven occasions Moore does not mention upper cloud: there was an inversion in each instance. On the other two Ac was reported above the Sc. With 3/8–4/8 Ac 2800 m above the Sc top he found a temperature change of 6 degC but with 7/8 Ac only 1500 m above the Sc there was no inversion. Čurinova too shows that when there is cloud above a Sc sheet, in the mean there is also a lapse and not an inversion of temperature above it. Her results are summarized in Table I. One surprising feature of this table is the zero lapse rate in the mean above a single sheet of Sc. This is quite opposite to the experience of the other workers,^{1, 3, 4, 11} who found clearly defined inversions (although sometimes inversions had isothermal layers above them).

TABLE I—RELATION BETWEEN THE OCCURRENCE OF AN INVERSION ABOVE LAYER CLOUD AND THE ABSENCE OF CLOUD ABOVE IT

Cloud type	St	Sc	Sc	Sc	Sc
Height of top (km)	1.0	1.1	0.9	1.1	0.9
Number of layers above	0	0	1	2	3
Number of layers below	0	0	0	0	0
Mean lapse rate above cloud top (degC/km)	-3	0	3	4	1
Number of cases	33	21	24	11	6

Schwerdtfeger's soundings fell easily into two groups. Both showed a marked inversion but the first group showed a steep lapse rate above the

inversion whereas in the second the layer above the inversion was almost isothermal. Specific humidity continued to decrease in the isothermal layer. Schwerdtfeger concluded that in the second case the Sc had really formed beneath a boundary between air masses. No comment seems to have been made on Schwerdtfeger's work by other authors, nor is there any other evidence for two easily distinguishable types of temperature profile. It is possible that air-mass differences across the inversion arise because of the existence of the inversion. The limited movement of air through the inversion ensures that non-adiabatic effects which directly affect only air beneath the inversion, are little diluted by vertical mixing.

Hrgian⁵ too found an inversion associated with the cloud top, but whereas in general the base of the inversion is found to coincide with the top of the cloud sheet, Hrgian found in 30 per cent of the occurrences of Sc-St near Moscow between 1951 and 1954 that the inversion extended down into the upper part of the cloud itself. He suggests that this is typical of old winter clouds and supports the suggestion with the argument that destabilization of the cloud by radiation from the cloud top and hence growth of the cloud up into the inversion is probably more active in winter than in summer. Presumably this is because there is more water vapour above the cloud in summer and perhaps because the nights in winter are longer. The observation that the cloudy inversion is found mainly in old clouds is interesting and may possibly explain why the feature has not been reported extensively and why it is not found near Moscow in the summer. Elsewhere the cloud may be less persistent than it is over the U.S.S.R. in winter.

Humidity.—Associated with the temperature inversion there is commonly a marked lapse of humidity above the cloud top.^{1, 3, 4} The most extensive results are Schwerdtfeger's, obtained with meteorographs during the ascent on routine reconnaissance flights. They are shown in Table II. However,

TABLE II—FREQUENCY OF A GIVEN DECREASE IN RELATIVE HUMIDITY IN ASCENDING THROUGH THE INVERSION AT THE CLOUD TOP

R.H. decrease (per cent)	10	20	30	40	50	60	70	80
No. of cases (out of 95)	1	11	13	25	23	14	6	2

more accurate measurements were reported by James and Moore who used Dobson-Brewer frost-point hygrometers during level runs. They found that the average humidity above the cloud was about 20 per cent and that most of the sharp decrease in humidity occurred through a layer about 100 m thick.

Of the humidity inside cloud sheets there are no reliable measurements. Most show relative humidities less than 100 per cent. Such values are acceptable near the base and top of the cloud as averages of observations made both in and out of cloudy air, but it would be quite unexpected if they were the true values well inside a continuous sheet of Sc where the opacity is often very uniform.

There is also some doubt about the humidity below cloud. Sometimes the turbulent mechanisms maintaining a Sc sheet reach down to the ground and are influenced by the roughness of the surface, at other times the

turbulence is not associated with the ground and ceases some way above it. Schwerdtfeger's 97 ascents were on occasions when a dry-adiabatic lapse rate existed from the sea surface up to cloud base. He found that the humidity mixing ratio in two typical cases decreased from 4.5 and 4.9 g/kg at 10 to 40m above the sea surface to 4.2 and 4.6 g/kg respectively at the cloud base (corresponding to a dew-point decrease of about 1 degC) and concluded that convection from below did not play a decisive role in cloud production. However, as the relative humidity over the sea surface was about 70 per cent and as it is likely that water vapour was being exported through the top of the cloud, it seems more probable that this small humidity gradient persisted despite the 'convection' and played its part in the upward transfer of water vapour.

One might have expected James's and Moore's observations below cloud to be the more reliable since they are averages of several determinations made during level runs with what is regarded as a precise and well proven instrument. However, three out of James's four instances show humidity mixing ratios in the sub-cloud layer which were too low to give condensation at the level of the cloud base. Four of Moore's eleven observations show the same effect, despite lapse rates close to the dry adiabatic and humidity mixing ratios constant with height. Relative humidity was also measured as less than 100 per cent at cloud base and in cloud. The anomalies may be the result of an instrumental fault but certainly warrant examination.

Turbulence.—Turbulence of the air in Sc has been examined by a number of British and Russian workers. Čurinova,² Matveev and Kožarin⁶ and Abramović and Hrgian⁷ use the Richardson number which they define as $Ri = \tau/\sigma$, as an indicator of the intensity of turbulence. The thermal stability term $\tau = g (\Gamma - \gamma)/\bar{T}$ is obtained from aircraft soundings and $\sigma = (\partial u/\partial z)^2 + (\partial v/\partial z)^2$ is obtained from wind measurements by balloon. The term $(\Gamma - \gamma)$ denotes the difference between the adiabatic lapse rate and the observed lapse rate ($\Gamma = \text{DALR}$ in clear air and SALR in cloud), g is the acceleration due to gravity, \bar{T} is the mean absolute temperature of the layer, and $\partial u/\partial z$ and $\partial v/\partial z$ denote the vertical wind shears in two perpendicular directions. There is general agreement that Ri increases markedly above the cloud top with a corresponding decrease in the intensity of the turbulence. Results of these measurements are summarized in Table III.

TABLE III—TURBULENCE CHARACTERISTICS IN AND NEAR STRATOCUMULUS

Mean height base/top metres	Mean τ			Mean σ			Mean Ri		
	Below cloud s^{-2}	In cloud s^{-2}	Above cloud s^{-2}	Below cloud s^{-2}	In cloud s^{-2}	Above cloud s^{-2}	Below cloud	In cloud	Above cloud
* 800/1100	1.6×10^{-4}	0.6×10^{-4}	3.4×10^{-4}	1.3×10^{-4}	1.0×10^{-4}	0.2×10^{-4}	1.2	0.6	14
† 1400/1800	—	—	—	—	—	—	14	1.4	62.7

* 21 occasions with no cloud above or below, after Čurinova

† 16 occasions after Matveev and Kožarin

As their indicators of the intensity of turbulence James,³ Moore⁴ and German⁸ used the vertical accelerations which the turbulence induced in aircraft. Although, as pointed out by Scorer,⁹ the fact that an aircraft being flown straight and level suffers vertical accelerations does not necessarily imply that it is in air that is turbulent in the sense that properties could be transferred by turbulent diffusion, nevertheless the erratic accelerograms

obtained do appear in most cases to have arisen from disordered air motions and hence turbulence. James interpreted his records qualitatively and found that up to about 60 m above the cloud top the turbulence was similar to that found in the cloud, but in the 100 m above that the turbulence decreased to almost zero. German evaluated a 'turbulent exchange coefficient' using a formula due to Dubov¹⁰ and, as might be expected, found a similar decrease in turbulence above the cloud top. The vertical profile for one of his occasions is shown in Figure 1. From measurements in different cloud types German found the predictable result that Sc was moderately turbulent; environments in order of increasing turbulence were: Ci, clear air at 2 km, Cs, St, Ns, Sc, As, jet-stream Cs, Ac, jet-stream Ci, Cu-Cb. There is no evidence in German's paper for or against James's hypothesis of an increase in the turbulence in Sc at night. Moore's results were similar to James's.

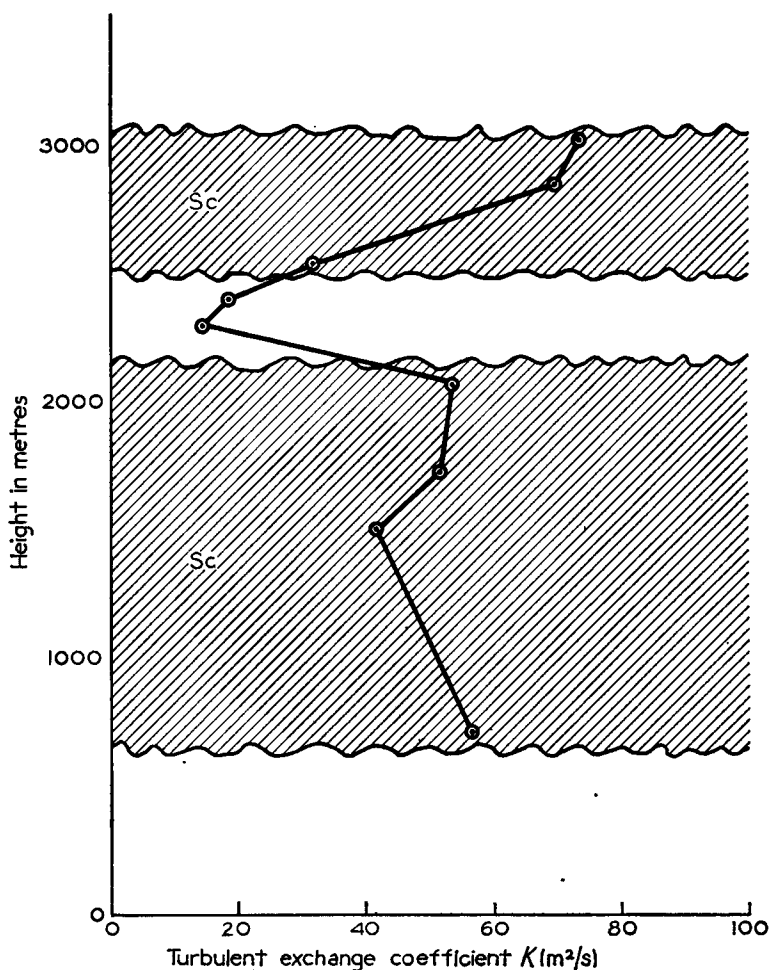


FIGURE 1—VERTICAL PROFILE OF THE TURBULENT EXCHANGE COEFFICIENT CALCULATED BY GERMAN⁸ FROM AIRCRAFT ACCELEROGRAMS

(This coefficient, K , is not identical with the conventional meteorological coefficient of turbulent diffusion)

Liquid water-content.—The liquid water-content in Sc is of interest from the point of view of aircraft icing and the possible growth of precipitation. It could easily be calculated if the ascending air in fact behaved as one assumes it to do when deriving the saturated adiabats on a tephigram. At a level with air density ρ kg/m³ and saturation humidity mixing ratio (SHMR) x g/kg the adiabatic liquid water-content, as it is called, would then be

$$W_a = \rho(x_0 - x) \text{ g/m}^3$$

where x_0 is the SHMR at cloud base. At Sc levels this means that the adiabatic water-content increases by about 1 g/m³ for each km above the cloud base.

Measured values of the water-content in non-precipitating Sc, as summarized by Hrgian^{5, 11} and Jones¹² for example are usually related to the adiabatic values. Water-contents are superadiabatic close to the cloud base, then gradually increase with height up to a maximum in the upper third of the cloud and decrease sharply to the zero value at the cloud top. The increase with height in the main part of the cloud gives a vertical gradient which is $\frac{1}{3}$ to $\frac{2}{3}$ of the adiabatic gradient, tending to the higher figure at low temperatures. The water-content profile for one particular occasion is shown in Figure 2. This profile is a typical one in the sense that, although the superadiabatic values near the base are missing and just below the level of maximum water-content the gradient approaches the adiabatic value, the overall appearance is typical and such departures from the mean profile are themselves typical.

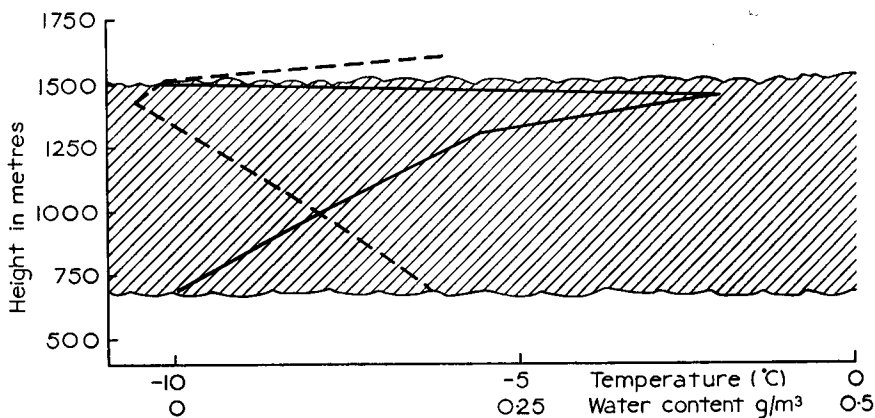


FIGURE 2—WATER-CONTENT AND TEMPERATURE PROFILES FOR ONE PARTICULAR STRATOCUMULUS SHEET, RIGA, 20 DECEMBER 1957 (after Hrgian⁵)

———— liquid water-content ; — — — — air temperature

Because of the general relation between water-content and height above cloud base, many of the published tables giving frequencies of occurrences of different values of water-content must be used with caution: the values found depend partly on the distribution of Sc thicknesses in the area where

the measurements were made and may not apply in other areas. Another effect is that, because of the speed of the aircraft from which the measurements are made, locally high values are resolved only by fast responding instruments. This means that the frequency with which various values are found depends on the period over which the measurements were averaged and that comparisons ought only to be made within a coherent set of data. Such a set, taken from Hrgian⁵ shows the expected result that the higher water-contents occurred at higher temperatures. At all temperatures 50 per cent or more of the values were 0.2 g/m^3 or less. Even in the temperature range in which high values were most often found ($+5$ to $+10^\circ\text{C}$) 1.0 g/m^3 was exceeded on only 3 per cent of occasions. In some American observations by Lewis¹³ the median value was again 0.2 g/m^3 . Lewis's observations were made in connection with aircraft icing studies and refer only to temperatures below 0°C . He used sampling times which were longer than those used in the Russian work and this may account for the comparative lack of large values. It would seem that the commonest values at temperatures below 0°C really are higher over the United States of America than over Russia. No comparable data are available for the United Kingdom.

Cloud droplet size and concentration.—Again the most comprehensive review is given by Hrgian⁵ who discusses not only work in Russia but also in America and elsewhere. Droplets in cloud are found in a range of sizes. In Sc the largest sometimes reach the size of drizzle and even small rain drops (e.g. Singleton¹⁴). Mason¹⁵ has suggested that they are drops which have had their effective fall path through the cloud much extended because of turbulence. While the bulk of the droplets grow for only short periods as they move in random eddying motion between the interior and the boundaries of the cloud, just because the motions are random a few drops may remain inside the cloud for several hours, long enough to grow to drizzle size, first by condensation and then, as they grow appreciably larger than their neighbours, by coalescence. The effect of turbulence on the growth of cloud particles has also been considered by Sedunov¹⁶ who concluded that condensation in the fluctuating supersaturations associated with turbulent eddies is important in broadening an initially narrow droplet size spectrum to the stage where the broadening may be continued by coalescence.

Because there is this range of sizes with each size present in a different concentration, the effective diameter of the drops depends on the method of measurement or the use which is being made of the measurements. The simple average diameter $\Sigma nD/\Sigma n$, where n is the concentration of droplets of diameter D , gives weight to the large numbers of small drops. There is however doubt about the true concentrations of the smallest drops and considerable disagreement as to whether there are perhaps 10,000 droplets per cubic centimetre with diameters less than $2 \mu\text{m}$ or very few at all. Consequently determinations of the average diameter cannot be relied on. A common method of measuring the droplets in Sc is to measure the angular diameter of the corona around the sun, or more commonly, the moon (see for example Humphreys¹⁷). The diameter obtained in this way is a measure of the mean cross-sectional area of the droplets, and is about $10 \mu\text{m}$. It is the effective diameter when we detect a cloud by eye just as the mean volume diameter $(\Sigma nD^3/\Sigma n)^{1/3}$ is when we detect a cloud by means of devices sensitive to the

mass of water they encounter. The mean volume diameter is used in work on aircraft icing, although more often it is the median value which is used. Typical values for Sc are between 10 and 20 μm . (Analogously, $(\Sigma nD^4/\Sigma n)^{\frac{1}{4}}$ is the significant diameter when considering rainfall rate — because the fall speed of a raindrop is approximately proportional to its diameter — and $(\Sigma nD^6/\Sigma n)^{\frac{1}{6}}$ is the significant diameter when ‘seeing’ by radar. Since in general droplet concentrations decrease as diameters increase the higher the index of D the more important the few large droplets become.) Considering diameters greater than 2–4 μm , typical concentrations of droplets in Sc range from one hundred to several hundred drops per cubic centimetre. On average, therefore drops are one to two millimetres apart.

Radiation effects.—Because of the longevity of Sc , radiation effects are important in its heat economy. Schwerdtfeger,¹ James,³ Moore,⁴ Hewson,¹⁸ Gold,¹⁹ Houghton and Brewer²⁰ and Feigel’son²¹ have all discussed the heating and cooling rates of Sc because of radiation. Houghton and Brewer measured the long-wave radiation flux divergence through a Sc sheet as equivalent to a cooling rate of 0.4 degC/h. From calculations of the absorption of solar radiation and the loss of long-wave radiation in a typical cloud (and assuming a coefficient of turbulent diffusion in the cloud of 10 m^2/s), Feigel’son found a daytime net cooling rate of 0.8 degC/h. James³ considered that at night the absence of solar radiation and hence increased cooling at the cloud top increased the turbulence within the cloud and the layer of clear air next to the cloud top so that the mixing in of clear, warmer, drier air might cause the cloud to dissipate. In an earlier paper,²² he found that daytime sheets of Sc with a dry layer above them tended to break at night whereas those with a less dry layer persisted. This may be because mixing with moister air is less of a dissipating influence but it is also consistent with a reduction of turbulence through the partial radiative blanketing effect of water vapour in the upper layer.^{19, 21}

There is then general agreement that radiation plays a large part in the heat economy of an existing Sc sheet. There is less agreement over its role in cloud formation. Mal²³ suggested in 1931 that cloud could form at an inversion purely as a result of radiative flux divergence and this has been corroborated by Feigel’son’s calculations and Staley’s²⁴ recent measurements of the radiative cooling of initially clear humid air lying below a layer of dry air. No case study of an actual occurrence is known, however, and cloud formation by this process is not considered by most authors.

Shape of the cloud top.—The shape of the top surface of the cloud is a significant factor in the study of a Sc sheet because it indicates the depth of the layer in which exchange between the clear and cloudy air occurs.^{3, 4, 22} The shape appears to be related to the radiative cooling of the cloud and the stability of the air in and above the cloud layer. Nepovitova²⁵ has found that for a given lapse rate in the cloud the top of Sc is much smoother beneath an inversion than it is when there is a cloud layer above the Sc . The statement must be worded in this way. The data as presented do not allow the simpler statement that the top is much smoother beneath an inversion than it is when there is no inversion above, nor can it yet be said that the top is smoother when there is no cloud above and vice versa, although the implication is that both these statements are likely to be true.

Turbulent exchange at the cloud top.—James,³ Moore⁴ and Turner and Yang²⁶ have proposed that an important mechanism for maintaining the cloud is the turbulent exchange between the cloud sheet and the clear air above it. James assumed that the heat needed to replace that lost by radiation came from diffusion, into the cloud, of warmer air from the turbulent lowest 100 m or so of the inversion and that water vapour lost by the cloud accumulated there. Moore came to the same conclusion. Like James he also concluded that the coefficient of turbulent diffusion must be of the order of $0.3 \text{ m}^2/\text{s}$ by day and $1 \text{ m}^2/\text{s}$ by night. This mechanism implies a general ascent of the cloud top through the air. James found the height of the cloud top above the ground to be almost constant and supposed that this was achieved by a general subsidence of the whole air mass. Moore, however, found no need to invoke a general subsidence as he found the cloud tops did gradually extend upwards.

Turner and Yang emphasize the fact that the evaporation of a cloud into the dry air just above its top causes cooling and that this cooling may affect the rate at which the cloud top grows upwards. The evaporation which occurs when cloudy air is mixed with dry air to produce an unsaturated mixture results in the mixture being denser than either of its components. Turner and Yang carried out laboratory experiments with liquids (such as combinations of alcohol and water) which also produce mixtures denser than either of their components. Such mixing they call 'non-linear'. They arranged a lighter fluid resting over a denser one. They found that for a given level of turbulence in the lower fluid the rate of mixing of the two fluids was slower in the non-linear case than it was with ordinary 'linear' liquids and that a stable transition region formed above the interface between the non-linear liquids. They regard this stable transition region as being analogous to the inversion layer overlying a Sc sheet and they regard the top of the layer as the 'dynamical top' of the cloud. They find that the rate of advance of the dynamical top of the cloud into the undisturbed air above it can be expected to be slightly less than it would be if some of the air were not cloudy and no evaporation were taking place; they do not assess the effect on Sc quantitatively but state that it may be negligible in practice.

There is a difficulty with Turner and Yang's model in that they require a cloudfree, moist and turbulent inversion layer, whereas in the layers examined by James and Moore the humidity fell off very rapidly in the bottom of the layer and the turbulence died well below the top of the layer.

Cellular convection.—Thin layers of Sc often show a cellular structure which invites comparison with convection as observed in the Bénard cell, where viscous forces oppose the buoyancy forces. The name F-cell describes a cell in which ascent occurs in the centre and descent at the edges and G-cell one in which fluid in the centre descends. F-cells form in fluids whose viscosity decreases with temperature and G-cells in those whose viscosity increases with temperature, such as gases. It seems contrary to experience that the cells in Sc should be G-cells, as this suggests, except possibly in the rare variety *lacunosus* which appears to have descending motion between tenuous filaments of extremely small water-content. Hrgian¹¹ refers to experiments in which F-cell convection occurred in air which had tobacco smoke mixed with it to increase its viscosity. By analogy, he suggests that

F-cells are usual in Sc because the water-content, and consequently the viscosity, increases with height, i.e. as the temperature decreases. No experimental work on the viscosity of cloudy air is known and theoretical considerations do not support this argument. For dilute suspensions of (rigid) spheres (of uniform size and small compared with the separation between them) in an incompressible medium Taylor and Glasstone²⁷ give the viscosity of the suspension as

$$\eta = \eta_0(1 + 5/2\varphi) \quad (1)$$

where η_0 is the viscosity of the medium and φ is the fractional volume of the medium occupied by spheres. Equation 1 is often used practically for situations analogous to natural clouds. If it does apply to them then φ is of the order one millionth and we may conclude that the suspended water drops have a negligible effect on the viscosity and that the vertical gradient of water-content could play a decisive role in determining the sign of the viscosity gradient only in a closely isothermal layer when the viscosity gradient is itself very small. It must be concluded that the subject of the sense of the convection in cellular Sc still has many uncertainties and requires further study.

Other effects.—On a scale of several hundred miles Findlater²⁸ found that anticyclonic Sc tended to coincide with colder areas of air and clear skies with relatively warm areas. He was able to show that these cold and warm areas originated from successive pulses of cold and warm air which retained their identity after the fronts separating them had been omitted from the routine analysis. It is also likely, however, that initial air-mass temperature differences were accentuated as radiative cooling at the cloud top promoted convection and led to a cooling of the cloud and of the clear air beneath it which had no counterpart in the areas free of Sc.

A process which might lead to the formation of Sc or St has been discussed by Novožilov.²⁹ On some nights the wind profile develops a maximum in the lowest 1000 m — a so-called meso-jet — so that turbulence is likely to be greater above and below the wind maximum than at it where there is no shear. Novožilov found from balloon ascents that this sometimes led to the formation of a temperature inversion at the level of the maximum wind with lapse rates approaching the adiabatic above and below it. A case study of a meso-jet by Yutaka Izumi and M. L. Barad³⁰ showed the transfer upwards of a ground level inversion during the formation of the meso-jet and the establishment of less stable (but still isothermal) conditions from the ground up to 150 m. During the rise of the inversion its level corresponded with the progressively rising level of the wind maximum. Novožilov's data indicated that inversions rarely formed by this process alone. In 86 per cent of his cases an existing inversion was sharpened in association with the formation of a meso-jet.

A close following of the shape of the cloud top by corrugations in the inversion surface has been found by Zajcev and Ledohovič³¹ (quoted by Hrgian¹¹) in the Arctic. It was also noticed on a flight from Farnborough on 18 February 1965. In the clear air close to the cloud top the temperature fell by three to five degrees Celsius as the aircraft passed over cloud elements and rose again as it passed over the crevices between them. No such variations could be detected above the very smooth top found on 23 February.

Work on the degree of raggedness of the base of Sc by Zak and Marfenko³² and by Perlat³³ has been summarized by Hrgian.⁵ Fluctuations with an amplitude of 100 m or more have been measured with periods ranging from one to six hours down to fractions of a minute. Thus it seems that the reporting and forecasting of the heights of cloud bases with an accuracy smaller than 100 m is meaningless.

Detailed features within the main cloud sheet that have excited interest are rolls of cloud or thicker cloud along the wind³⁴ and across the wind. These have been discussed by Scorer³⁵ and result from convection within a shallow layer in the presence of strong and weak vertical wind shear, respectively. In otherwise continuous sheets of Sc, holes are commonly found downwind of hills. In many cases they are an extreme result of waves formed in the cloud sheet in the same manner as the more familiar lenticular cloud; the typical temperature profile through a sheet of Sc with its inversion above a convective layer is just that which is so often associated with lee waves. An instance of rolls in Sc forming standing waves downwind of the Welsh mountains is given in reference 36.

Final remarks.—Stratocumulus is frequently a cloud form of great extent; horizontally it may be as broad as a small depression. The prime cause of cloud formation on this scale is usually thought of as the cooling by adiabatic expansion of ascending air, but such cooling can be of little importance in forming and maintaining Sc which is usually overlain by subsiding air and suffers only small pressure decreases as it moves along its trajectory. The cloud forms primarily as a result of non-adiabatic processes: heating from below alters the temperature profile to produce a cooling at what then becomes the cloud level, evaporation from the surface moistens the air aloft or water is injected into the layer beneath an inversion by the evaporation of spreading cumulus. On a smaller scale Sc may form both near to and well above the surface when wind shear provides the initiating turbulence while (because of the patchiness of the humidity and air temperature in the horizontal) the consequent differential advection leads to changes in the vertical profiles of humidity and temperature. It may also be that Sc on a smaller scale sometimes forms by radiative cooling of moist air.

Once formed the cloud is maintained as a result of the dynamic equilibrium between absorption of sunshine, loss of long-wave radiation, heating or cooling from below and mixing with warmer air from above the inversion. (The inversion itself is a subsidence inversion sharpened by erosion by the turbulent cloud and probably by radiative cooling of the cloud top.) The rate at which heat is redistributed by turbulence depends probably not only on wind shear but also on the intensity of convection brought about by radiative cooling of the cloud top. The pattern of turbulence is doubly important since, for the cloud to persist unchanged there must also be a dynamic balance between the transport of moisture into the cloud from below and its export through the inversion.

The practical application of our knowledge of Sc is mainly in forecasting its occurrence, persistence and dispersal. The only recent attempt at producing a forecasting rule has been James's work on nocturnal dissipation. It can be expected that some of the conflicting views and evidence presented in

this review will eventually be resolved. The resulting improved insight into the mechanisms of Sc will lead to better forecasts of its behaviour.

Some of the problems which seem to justify further work immediately are, not necessarily in order of importance :-

- (i) What are the quantitative effects of radiative heating and cooling on the cloud and the clear air beneath it ?
- (ii) What is the flux of heat and moisture through the inversion at the cloud top ?
- (iii) Does turbulence increase in the cloud over the sea at night ?
- (iv) How and why does the cloud thickness vary over the sea by day and night ?
- (v) How far are changes observed over the sea applicable over the land where they are complicated by topography ?
- (vi) Does cloud sometimes reach up into the inversion and if so is the cloud's behaviour affected ? Is it mainly older cloud which extends up into the inversion ? Do radio-soundings sometimes indicate saturated or moist air in the inversion when horizontal runs by aircraft show that the inversion does not extend down into the cloud ?
- (vii) Does Sc sometimes form primarily from radiative cooling of moist air below a dry layer ?
- (viii) Are Moore's and James's values of humidity below cloud too low ?
- (ix) Does the presence of higher cloud affect the validity of James's rule²² ?
- (x) To what extent does wind shear lead to small scale Sc formation and dissipation ?
- (xi) What factors govern firstly the formation of extensive Sc by the spreading out of Cu and secondly its persistence or dispersal ?

Ultimately what are required are measurements of the various quantities in the heat and moisture budgets of the cloud system, an assessment of how and why individual quantities change with time and the effect of the changes on the behaviour of the cloud as a whole.

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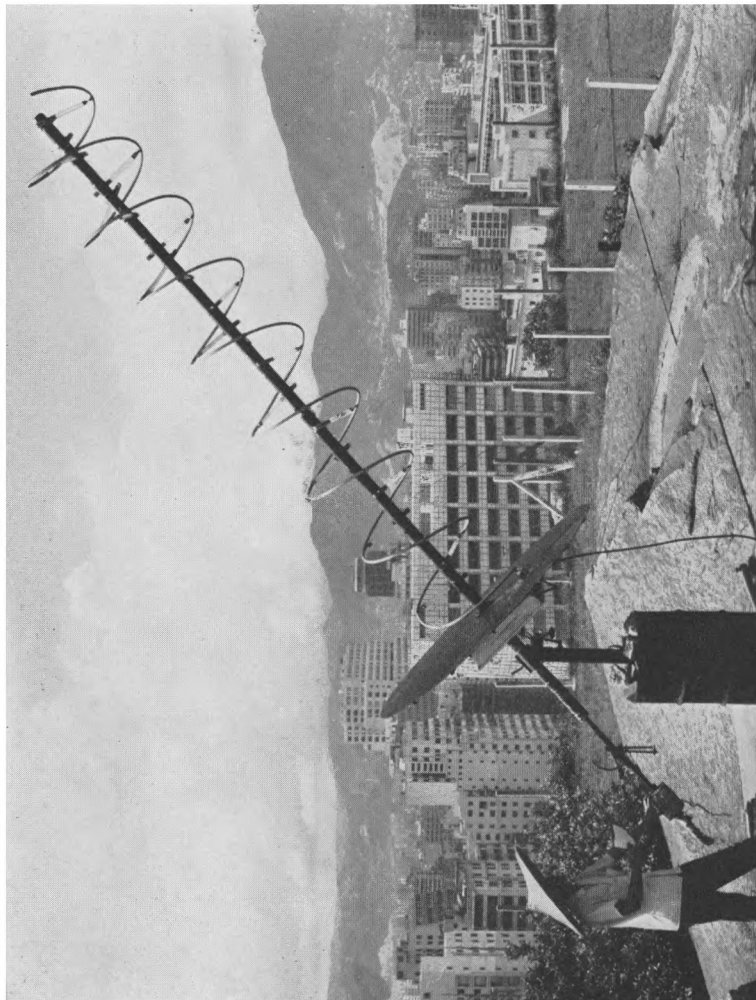
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MESO-SCALE INVESTIGATION OF A SQUALL-LINE

By R. R. McNAIR and J. A. BARTHRAM

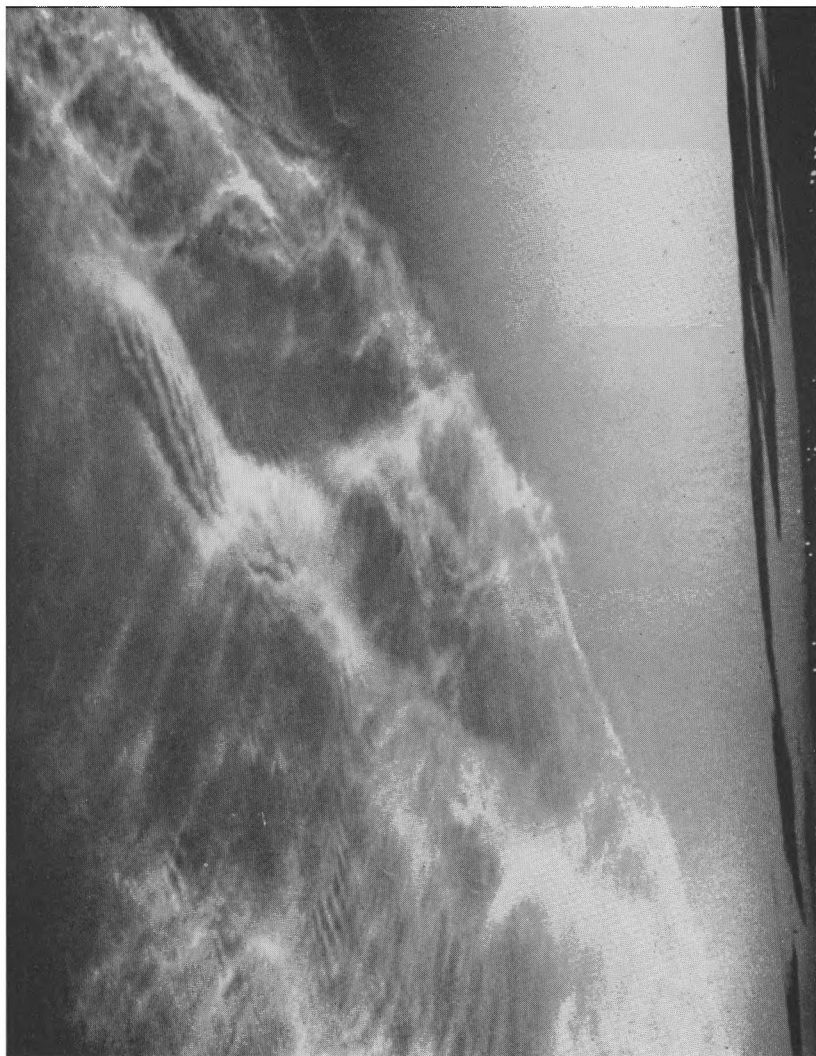
Summary.—An analysis was made of a squall-line which moved over southern England on 3 July 1965. Isobars at $\frac{1}{2}$ mb intervals were drawn to demonstrate the development and movement of an isobaric escarpment, but barogram traces showed no severe or rapid fluctuations. Various isochrones were drawn to show the movement of the squall-line and its effects. The highest gusts were related to the maximum fall of temperature in accordance with rules for thunderstorm gusts. The surface temperature changes were compatible with the temperature changes to be expected because of a downdraught due to precipitation cooling. Squall-lines of the type described may occur when showers are slow moving and produce cooling in one area so that thermal gradients are accentuated.



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PLATE I—SATELLITE TRACKING AERIAL AT THE ROYAL OBSERVATORY, HONG KONG

Signals from American weather satellites are intercepted by this aerial, stored on magnetic tape and fed into a converted television set. The displayed pictures are then photographed. The results obtained with this improvised apparatus are so encouraging that a more conventional system is being installed. (Official photograph supplied by Government Information Services, Hong Kong).



Photograph by R. K. Pilsbury

PLATE II—NOCTILUCENT CLOUD

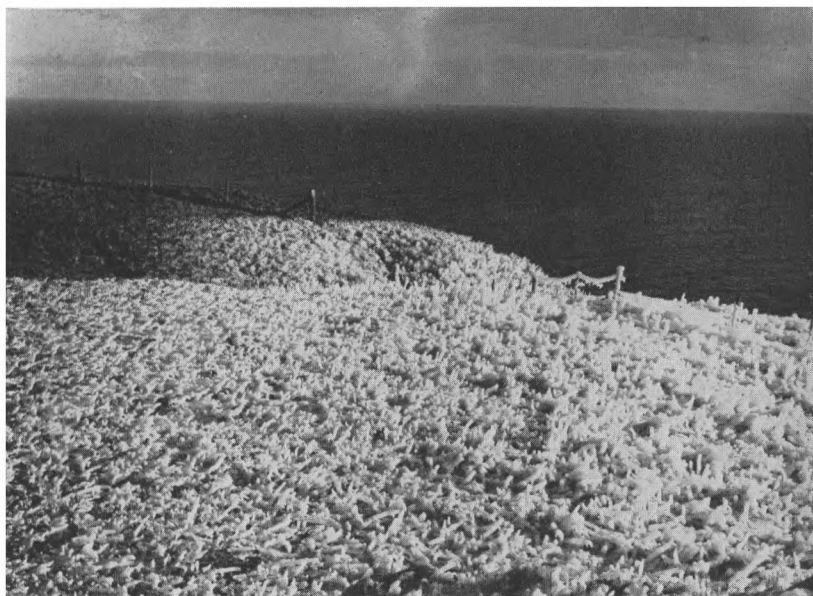
(taken about 2215 GMT 27 June 1966 looking NW from Mumbles, Swansea)



Photograph by Miss Kay Pittbury

PLATE III—NOCTILUCENT CLOUD

(taken about 2215 GMT 27 June 1966 looking WNW-NW from Bracknell, Berkshire)
This cloud is the same cloud as in Plate II and estimations show that it was over the Dublin area and at a height of about 86 km.



Photographs by J. C. Nicolson

PLATE IV—UNUSUAL 'ICICLE' FORMATIONS

These photographs were taken on 16 February 1966 looking east over the sea near Wick, Caithness. The cliffs are about 200 ft high and the ice formations were caused by water from a stream which normally flows over the edge of the cliff being blown back and freezing on the grass and twigs. The 'icicles' were up to 2 inches in diameter and a foot in length. The phenomenon lasted for about 10 days from the 7th and had never been seen before by local residents.

Introduction.—During the late afternoon of 3 July 1965 a squall-line developed over the south Midlands and moved southwards across southern England at about 20 kt, to merge eventually with the east-north-easterly flow over the English Channel.

General situation.—At 1200 GMT on 3 July 1965 pressure was high over and to the west of Ireland and relatively low over France and Germany. This gave a gradient for light northerly winds over England and Wales, with geostrophic wind values generally less than 10 kt. The air over England was rather cool for July ; the midday Aughton sounding gave a freezing level of 5500 ft, and was sufficiently unstable for scattered showers to be reported at this time north of about 53°N. Figure 1 shows the positions of the reporting stations mentioned in this article.

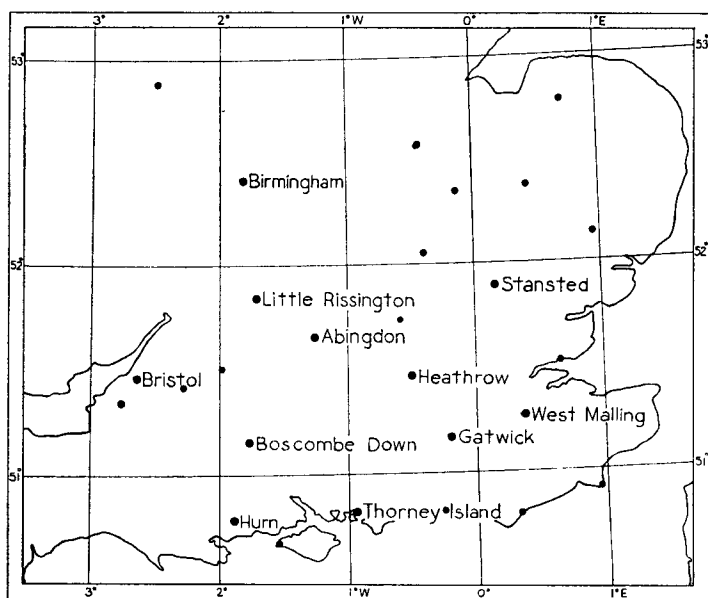


FIGURE 1—KEY MAP SHOWING NETWORK OF STATIONS USED IN INVESTIGATION
Stations referred to in the text are named

Development.—By 1500 GMT shallow heat lows had formed over southern England and the south coast sea breeze had penetrated inland to about 51°N. The surface isotherms showed a fairly even rise in temperature south-westwards from the Wash to the southern counties. These features are shown in Figure 2. Scattered light showers were occurring over the Midlands, notably in the Birmingham area, though being slow moving in the slack gradient they were reported as intermittent rain in some places.

The pattern was similar at 1600 GMT, with a continued tightening of the pressure gradient in a narrow band along 52°N. At the same time temperatures were beginning to fall in the Birmingham area as cooling by precipitation took effect.

and gusts up to 31 kt were recorded, with temperature changes of 4–5 degC. This temperature change occurred within 15–20 minutes of the arrival of the squall.

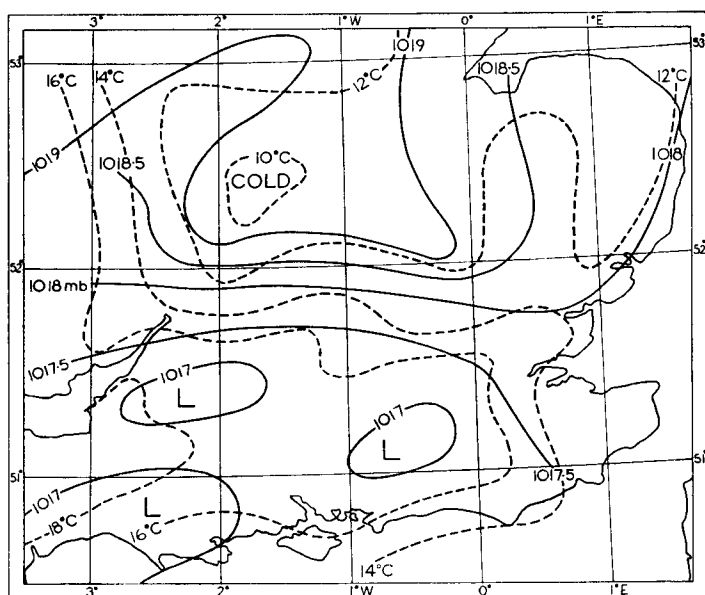


FIGURE 3—ISOTHERMS OF SCREEN TEMPERATURE AND ISOBARS AT 1700 GMT
ON 3 JULY 1965

-- Isotherms ($^{\circ}\text{C}$); — Isobars at $\frac{1}{2}\text{mb}$ intervals

Over the eastern side of southern England the gusts were not so strong and mainly less than 20 kt, (examples are Stansted 17 kt at 1725 GMT and Gatwick 18 kt between 1950–2020 GMT), but strong synchronous gusts occurred along a line which moved southwards and was readily identifiable as far east as West Malling. However London/Heathrow Airport experienced a squally spell with gusts to 27 kt between 1840–1850 GMT. All observations for the area showed a fall in temperature of 3–4 degC within the hour following the stronger wind.

Figure 4 gives the position of the system at 2000 GMT, and is typical of the hourly chart analysis, showing how sharply marked the discontinuities appeared.

By 2100 GMT the shallow pressure lows over southern England had been displaced into the easterly flow over the English Channel, although the isobaric escarpment on the northern flank was still identifiable until 2200 GMT. Hurn, Calshot and Thorney Island were affected by gusts of 21 kt between 2050–2120 GMT, and had temperature falls of 2.5–3.5 degC.

The geostrophic-scale value of the pressure step was 45–50 kt during the period 1800–2200 GMT, and surface wind gusts up to 34 kt were recorded, with temperature falls of 4–5 degC in 30 minutes or less.

Rainfall and the associated temperature and wind changes.—

Hourly charts were drawn delineating the areas where rain was occurring, irrespective of amount. Rain reported in the past hour was advected, and continuity was preserved across areas without observations to link with

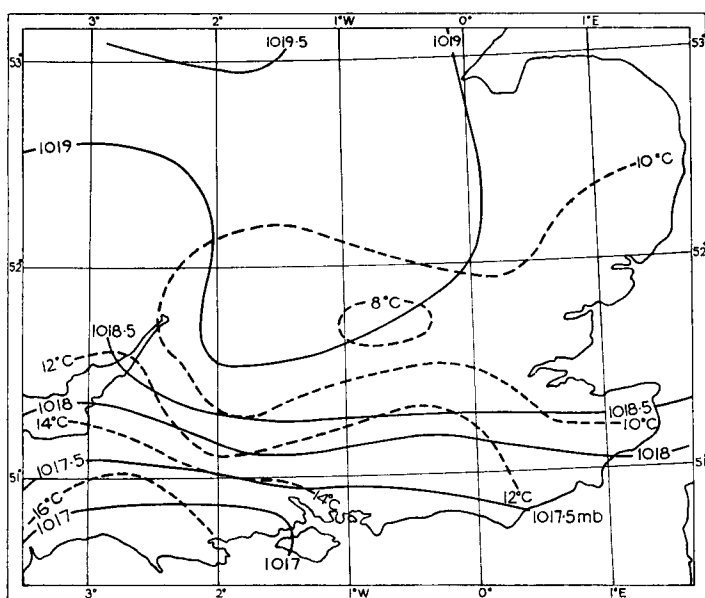


FIGURE 4—ISOTHERMS OF SCREEN TEMPERATURE AND ISOBARS AT 1500 GMT

ON 3 JULY 1965

--- Isotherms ($^{\circ}\text{C}$);

————— Isobars at $\frac{1}{2}$ mb intervals

subsequent reports further south. Figure 5 shows the southward displacement at two-hourly intervals of the expanding area of precipitation which was associated with, or rather generating, the squall-line, and also the southward progression of the maximum reported hourly temperature falls. Figure 6 gives the isohyets of the rainfall during that period, and the isochrones of gustiness. An interesting feature shown by these two charts is that although the squall was most readily identified as moving south or south-south-westwards, the area of rain moved south-eastwards and expanded in an easterly direction. It appears that the gustiness was carried southwards by the north to north-easterly surface winds whilst the north-westerly 850 – 700 mb flow displaced the main rain area from the Midlands to give a maximum over Kent.

The pool of cold air produced by the rain moved south-eastwards too, and Figures 3 and 4 show that a closed isotherm of 10°C near Birmingham at 1700 GMT became a centre of 8°C near London at 2000 GMT. These temperature values seem to be in good agreement with an article by Wallington,¹ which states that the Celsius temperature of air reaching the ground in a downdraught due to precipitation cooling may be as low as, but not lower than, $1\frac{1}{2}$ times the height of the 0°C isotherm in thousands of feet. On this day with a 0°C isotherm level of 5500 ft the expected temperature would be about 8°C .

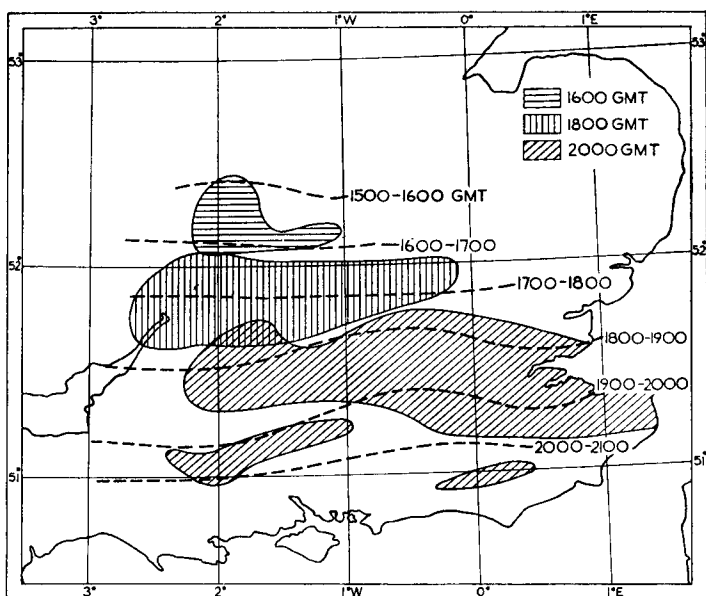


FIGURE 5—MAIN RAIN AREAS AT 1600, 1800 AND 2000 GMT ON 3 JULY 1965 AND LINES SHOWING THE PROGRESSION OF THE MAXIMUM REPORTED HOURLY FALLS OF TEMPERATURE DURING THE EVENING
(Fall > 3 degC except for 1500-1600 GMT when it is > 2 degC)

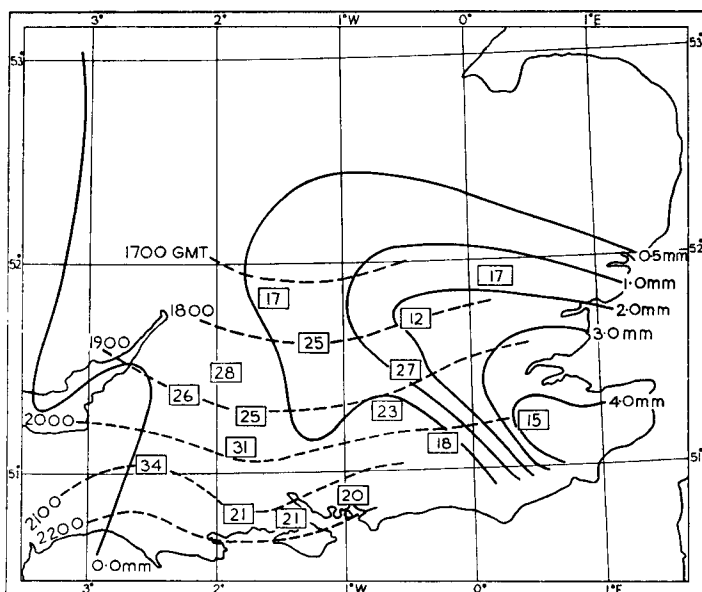


FIGURE 6—ISOCHRONES OF GUSTINESS AND ISOHYETS BETWEEN 1500 AND 2100 GMT ON 3 JULY 1965
- - - Isochrones of gustiness; Isohyets;
Boxes contain spot values of maximum gust in knots

Figure 5 demonstrates how the isochrones of maximum temperature fall advanced with the leading edge of the rain. A feature in the area west of 1°W , where the main gustiness occurred, is that only two places reported heavy rain and these only briefly — Little Rissington at 1832 GMT and Hurn at 2120 GMT. In general, in this area, a line of only very light rain or showers accompanied the squall. A further outbreak which followed the squall was also mainly slight and some places remained dry throughout.

A further point of interest is to apply the rules suggested by Fawbush and Miller² regarding gustiness in thunderstorms. They found a high correlation between the surface temperature change and the highest gust of a thunderstorm. If a fall of $4-5^{\circ}\text{C}$ is applied to their diagram then an expected maximum gustiness of $30-34$ kt is found. This speed is very close indeed to the values recorded during the passage of the squall, although the depth of instability was in this case well below the requirement for thunderstorms. The upper air soundings indicated cloud tops between 6000–8000 ft at midday, and the midnight ascents showed that these tops would have risen to 8000–10,000 ft during the afternoon and evening.

Pressure changes.—A comparison of the 1200 GMT chart for 3 July 1965 with the 0000 GMT chart for 4 July shows remarkably little change in the pattern and value of the pressure field; the disturbance had developed and disappeared with little or no trace. Even during the critical period 1500–2100 GMT there was only about $1.5-2.5$ mb variation at individual stations, and in the north and south of the affected area changes were 1 mb or less. Barograms showed no severe or extremely rapid fluctuations such as occur on occasions near instability squalls. Over the Salisbury Plain area they showed a slow fall from midday, a step of 0.5 mb at about the time of the squall (1900–1930 GMT), then a steady rise of 2 mb by 2100 GMT. A similar pattern is repeated on the barograms further east, but the sharpness of the step is lost.

Conclusions.—The essential features to produce this type of squall-line seem to be: (1) an air mass sufficiently moist and unstable to produce showers over the Midlands; (2) winds initially sufficiently light to make the showers slow moving, thereby concentrating cooling due to precipitation to one area and accentuating the thermal gradient. These features may be present for example when heat lows develop over southern England in a light northerly airstream.

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KENT FARMERS' FIELD DAY, EYNSFORD JUNE 1966

By J. COCHRANE

On 29 June a Field Day was arranged at Eynsford, Kent by the National Agricultural Advisory Service (NAAS) and the Agricultural Land Service of the Ministry of Agriculture, Fisheries and Food, in association with Wm Alexander (Eynsford) Ltd. The main purpose of the Field Day was to demonstrate the owners' approach to the problems involved in making the best possible use of the land and resources available to them.

The present complex of farms which covers about 1650 acres and extends for about 4 miles along the Darenth valley and varies in height from 100 to 560 feet above sea level, has grown steadily from the original 100-acre Home Farm which was bought in 1892.

The farming system was originally established around a dairy herd, and such a herd is still one of the six main enterprises. Activities now include breeding for beef and growing crops of barley, wheat, ryegrass, lucerne (own variety), beans and peas, apples, hops and the recent innovation of 'year-round' chrysanthemums under glass.

In this diversified type of farming the owners make extensive use of Meteorological Office facilities, subscribing to the 'fine-spell' service as well as maintaining frequent contact with the London Weather Centre. The County Agricultural Adviser felt that this close association between the owners and the Meteorological Office offered a good opportunity to bring home to a large section of the farming community the range of meteorological services and advice which can be offered to farmers.

At the Field Day a display under the title 'Meteorology and Agriculture' was arranged by the Meteorological Office. It consisted of wall cards detailing the services available to farmers by subscription, where to obtain forecasts by telephone, and examples of the type of problem which could be handled experimentally or by advice through local NAAS offices. Cards showing how the available meteorological services were used on this complex of farms during the year were prepared by NAAS and arranged around a $\frac{1}{2}$ -inch map of Kent which depicted the distribution of average annual rainfall and the location of rain-gauges in the county.

Instruments used in agricultural investigations were also displayed, among them a working thermograph and hygrograph and a surface-wetness recorder working under simulated intermittent rainfall, as well as a rain-gauge and sunshine recorder.

Of the thousand or so people who visited the farms rather more than half visited the meteorological exhibit. Many of them came just to look at the display but about a hundred asked definite questions and quite a number made comments on the work of the Office, the majority of them being favourable.

About a quarter of the inquiries concerned the 'fine-spell' service and quite a number of farmers came up to say that they used the service and found it very helpful and reliable. A telegram addressed to Wm Alexander giving the start of a 'Fine-Spell Bravo' from the morning of the 29th was on display and caused considerable comment.

The map of rainfall distribution caused a good deal of discussion as well as some inquiries as to the availability of copies of it as teaching aids. These inquiries, as well as an offer of new rainfall records on the Isle of Sheppey, were referred to the Climatological Branch of the Meteorological Office.

Several farmers made inquiries about the cost of instruments and were referred to the instrument makers. Answering inquiries kept two people fairly busy throughout the eight hours of the Field Day, and the amount of interest shown made one feel that the time spent in preparing the exhibit had not been wasted and that this type of exercise might well be repeated with reasonable expectations of benefit both to the Office and to the farming community.

NOTES AND NEWS

Address by Dr Joseph Smagorinsky

At Bracknell on 23 June 1966, members of the Meteorological Office staff were privileged to hear a lecture by Dr Joseph Smagorinsky, Director of the Geophysical Fluid Dynamics Research Laboratory of the United States Environmental Science Services Administration.

The research on the general circulation of the atmosphere carried out by Dr Smagorinsky and his colleagues has won wide acclaim. It constitutes the greatest advance in the science of meteorology of the last decade, and has opened up possibilities for many exciting developments. In the experiments, the atmosphere has been modelled numerically, and its behaviour with time studied by predicting the changes implied by basic physical laws. The calculations have required the largest electronic computers yet manufactured. In general, the objective is to supply as little information to the model as possible at the initial time so that it has to build up its detailed picture of what the atmosphere is like from the physical processes known to be acting. It is usual for instance to start with an atmosphere that is isothermal and at rest. Then as the sun's radiation is absorbed and cooling by loss of infra-red radiation occurs, thermal gradients and hence winds are created. The characteristic vertical structure of the atmosphere gradually evolves. Later, the conditions for baroclinic instability are realized and middle latitude depressions and anticyclones appear. Eventually a state of statistical equilibrium is achieved and at this stage the statistics of the motions can be compared with the statistics for the real atmosphere. Some of these general circulation experiments have been taken to upward of 300 simulated days.

On this occasion, Dr Smagorinsky chose to talk mainly about the use of his general circulation model for medium-range forecasting, that is starting from real initial data and forecasting for up to 4 days ahead. Any model which treats the general circulation of the atmosphere successfully should also do well as a forecasting tool, and since it is quite possible in long-term integrations to obtain the right statistical properties of the atmosphere for the wrong reasons, it is evidently desirable that forecasts produced by this model should be tested on occasions when very detailed comparisons of forecast and actual changes can be made.

The model carries information — that is winds, contour heights, water vapour content and so on — at nine levels. The highest is at about 9 mb (included mainly so that radiative transfers involving ozone can be calculated), and the lowest is at about 991 mb, a level which is within the friction layer. Information at each level is mapped on to a polar stereographic projection of the northern hemisphere and finite-difference analogues of the primitive equations are solved over the hemisphere on a mesh of points that usually numbered 5000 per level. This gives a horizontal grid spacing of about 270 km at 45°N. New fields of the variables were calculated at each 5 minutes of simulated time. Water vapour is carried as a variable so that condensation, evaporation and the resultant changes in heat content are properly allowed for. Rainfall amount can be deduced, both that due to large-scale motions and that due to convection. In the model used for medium-range forecasting, radiative transfer of heat, and the transfer of heat between the atmosphere and the underlying surface were at first suppressed (they are of course included

in the full general-circulation model). Thus the model had no sources of energy, but acted only on the energy initially present. On the other hand certain effects which have not yet been put into the general-circulation experiment were included. The differential effect of land and sea was allowed for by assuming a constant climatological temperature for the sea, while the temperature of the land was determined by the condition of radiative equilibrium. Also, the topography of the earth's surface was allowed to produce vertical motions at the lower boundary.

Forecasts for 4 days ahead were made with 3 sets of initial data, 0000 GMT on 22 January 1959, and 1200 GMT on 9 and 14 January 1964 though most of the results discussed referred to the latter two. Because of difficulties in obtaining data for the equatorial zone, the fields were extrapolated smoothly southwards from areas of adequate data coverage. For this and other reasons the initial conditions for the model were unrealistic in certain respects and it took almost a day for instance for realistic mean rainfall amounts to be achieved. The forecasts differ from those in routine operational use in that for a period after they start off their accuracy improves with time. A characteristic feature is that, although they do not improve much on the results obtained by more conventional numerical models (such as are now used for shorter-period forecasts, up to perhaps 24 hours ahead), their accuracy beyond 24 hours falls off much less quickly. There are good reasons for hoping therefore that they will go a long way towards solving the medium-range forecasting problem, though this objective cannot be achieved quickly since the computing time required is too long with present computers for the model to be used operationally.

By any standard the results of the forecasts shown by Dr Smagorinsky were extremely good, but the audience was particularly impressed by the rainfall forecasts, which more familiar numerical models are unable to make with any accuracy. Forecast 12-hour cumulative totals over the United States for each 12-hour period were compared with the rainfall totals measured at 3000 observation points averaged to give 166 areal mean values. The correlation coefficients between forecast and observed totals were 0.7 on the first day falling to about 0.3 on the fourth day ; while a simple rain or no-rain verification showed that the model was correct for about 90 per cent of the area of the United States on the first day and for about 70 per cent on the fourth day. Charts showing computed and observed values demonstrated convincingly that, even on the fourth day, the computations gave a lot of useful information.

Finally Dr Smagorinsky showed the results of an integration which had been completed only a week or two before the lecture. This integration treated the same initial data as before, but the effects of radiation and sensible heat transfer were now included. A comparison of the fourth-day surface pressure fields for the integrations showed that significant improvements had resulted from the inclusion of the additional terms. The depth of a depression in the Atlantic was much improved as was the handling of a depression over Asia that had developed since the beginning of the forecast period.

To obtain forecasts of such a quality over such a period of time represents a monumental achievement and confirmed for his audience the pre-eminence of Dr Smagorinsky's group in the application of numerical methods to the study of the atmosphere.

A. GILCHRIST

First round-the-world flight of southern-hemisphere weather balloon

At a joint meeting of the World Meteorological Organization (WMO) Advisory Committee and the Committee on Atmospheric Sciences of the International Council of Scientific Unions at the WMO Headquarters in Geneva, on 22 April 1966, Mr V. E. Lally (head of balloon research of the National Center for Atmospheric Research in the U.S.A.) reported the first results of the launching of experimental free-floating weather-observing balloons designed for flight at constant height levels in the atmosphere of the southern hemisphere. He described the first round-the-world flight of a southern-hemisphere balloon which completed its first circuit on 9 April 1966, 9 days and 23 hours after its launch on 30 March from Christchurch, New Zealand. The balloon flew at an altitude of about 15 kilometres and returned to the longitude of its launch at a distance of approximately 2000 kilometres towards the equator, thus demonstrating the equatorward drift of the parcel of air in which it was embedded.

This first round-the-world flight was the successful culmination of a five-year research and development effort to design a balloon and radio transmitter system capable of tracing airflow over all the world, for ultimate use in an improved global weather-observing system.

The balloon flight was performed through the joint efforts of the U.S. and New Zealand, with endorsement of WMO and co-operation from many countries of the southern hemisphere. The balloon development programme was supported by the Environmental Science Services Administration of the U.S. and the flights were launched in New Zealand under Mr Lally's direction. Flights of the new lightweight balloons commenced on 4 March 1966, and during March the joint U.S. - New Zealand group released 16 balloons. During coming months approximately 90 more such balloons will be flown. Each balloon carries a radio transmitter, powered by sunlight, that is capable of being received up to distances of over 5000 kilometres. From the radio signals the positions of the balloons can be ascertained and the values of their weather measurements derived. The radio signals are received by a network of amateur radio observers at 11 locations scattered throughout the southern hemisphere. Reports are then mailed to the NCAR headquarters in Boulder, Colorado, where the balloon trajectories are compiled.

The balloons and radios are of an extremely lightweight design and the balloons are of 'super-pressure' type, which allows them to float at a constant height in the atmosphere for indefinite periods — until finally they fail or develop leaks. Later balloons in the series are expected to make as many as six or seven full flights around the southern hemisphere. Not only will the flights test the feasibility of the new balloon techniques but they will also give valuable new data on the windflow of the southern hemisphere where weather networks are sparse. The experiment, if successful, will result in new weather observing methods later to be used in the World Weather Watch — a co-operative weather observing and research effort now being planned by WMO in co-operation with the International Council of Scientific Unions and the International Union of Geodesy and Geophysics.

Noctilucent cloud

The noctilucent cloud shown in Plates II and III, which are reproduced from photographs taken near Swansea and at Bracknell, was also seen from many other parts of the country. An article on noctilucent clouds by J. Paton was published in the June 1964 issue of the *Meteorological Magazine*.

HONORARY DEGREE

We have pleasure in announcing that the University of Nottingham conferred the degree of D.Sc. (*honoris causa*) on the Director-General, Dr B. J. Mason, at a ceremony held in Nottingham on 3 September 1966.

METEOROLOGICAL OFFICE NEWS

Retirement of Mr G. A. Bull

The Director-General records his appreciation of the services of Mr G. A. Bull, B.Sc., who retired from the Meteorological Office on 21 July 1966. Mr Bull was a Sherbrooke Scholar of East London College, University of London, where he graduated with First Class Honours in Mathematics in 1925. He joined the Office in March 1926 as a Junior Professional Assistant at Cranwell. Subsequent postings included Felixstowe, Weston Zoyland, Renfrew, Malta and several Headquarters Branches, and during the war he was attached for a time to Headquarters, Balloon Command.

After the war Mr Bull's long association with library work began. At Harrow, and later at Bracknell, he was for many years responsible for the National Meteorological Library, the Editing Section and the Cartographic Drawing Office. His wide knowledge of the literature of meteorology made him a valued source of information on the various branches of the subject. For a long time he was Editor of the *Meteorological Magazine* and earned the gratitude of many contributors for the help he gave them. In the international field he served from 1953 to 1959 as the United Kingdom member of the World Meteorological Organization Technical Commission on Bibliography and Publications, and he was for some time the Vice-President of the Commission.

Mr Bull took a major part in the planning of the Library at Bracknell, and another of his tasks was the setting up of the Meteorological Office Archives. This was consequent upon the Public Records Act of 1958 and involved a completely new system for the preservation and disposal of departmental records.

A man of varied interests, Mr Bull includes among his achievements a proficiency in several languages, including German and Russian, and this was put to good use in the translation of papers coming to the Library. He encouraged the formation of a translating section in the Library, and his personal supervision contributed a great deal to its success.

The last phase in Mr Bull's career as an established civil servant began when he took up an Assistant Directorship in 1960, first in charge of Support Services and later in the rapidly developing field of Data Processing. In these posts he was increasingly involved in automation in the Office. It was at his suggestion that the name COMET was given to the present computer.

On retirement from established service at the end of March 1965, Mr Bull became a Senior Scientific Officer in the Forecasting Techniques Branch, where he produced two memoranda on procedures used in the preparation of numerical forecasts by the Meteorological Office.

He gave valued service to the Royal Meteorological Society and undertook the Honorary Librarianship from 1960 to 1964. His library interests also led him to become a Member of the Institute of Information Scientists.

In June of this year Mr Bull was offered the post of Administrative Secretary in the Library of the University of Reading and he took up this appointment on 1 September 1966. George Bull will be remembered as a good companion and a splendid colleague of equable temperament. We wish him well in his new venture, one for which he is so admirably fitted by qualifications and experience.

C.W.G.D.

REVIEWS

A history of the theories of rain and other forms of precipitation by W. E. Knowles Middleton. 9 in \times 5 $\frac{3}{4}$ in, pp. viii + 223, Oldbourne Book Co. Ltd, 1-5 Portpool Lane, London, EC1, 1965. Price 45s.

Dr Middleton comments in the preface to this book that he believes the history of meteorology has had less attention than that of any other scientific discipline of comparable scope. He has now done much towards the filling of this large gap in the history of science by writing his 'History of the Barometer', as well as the book now under review, and one which is now in course of production on the history of the thermometer; in scientific journals he has written articles on the history of atmospheric optics and of the visibility problem.

This book covers the history of theories of all forms of precipitation, including dew, from the earliest writings in the Bible and by the classical Greek authors to about 1914. The first chapter brings us in 18 pages up to the beginning of the 17th century. From then to 1914 requires 198 pages. Besides the history of theories of precipitation there is much on theories of wind and on the relation of barometric variations to weather.

Volume I of Shaw's 'Manual of Meteorology' contains a roughly similar account of classical Greek views on wind, clouds, and precipitation but on more recent history is much less full than Dr Middleton's book.

Dr Middleton has read and absorbed a vast amount of literature which most of us would find strange and difficult. He expounds his knowledge in a clear, well-co-ordinated and witty fashion with many an apt quotation.

Many of the ideas which have been propounded through the centuries seem to us now quite fantastic. As examples can be quoted: wind as not air in motion but a 'dry exhalation' from the earth; squeezing of clouds by wind to produce rain; cloud droplets as hollow bubbles (called vesicles); air in motion as exerting less pressure than calm air; clouds as holding up the air above them to account for reduced pressure in cloudy weather in which otherwise the weight of water in the air would be expected to lead to higher pressure. As recently as 1849 such eminent physicists as Clausius and Bravais accepted the vesicle theory of cloud droplets.

In all the welter of strange ideas Dr Middleton is a clear guide careful to bring out the first glimmerings of the truth.

It is noteworthy that by no means all first discoverers of an important truth receive credit for it in modern literature. Until reading this book the reviewer had never heard of P. J. Coulier as the first to discover condensation nuclei or of P. H. Maille as the first to realize the importance of the latent heat of condensation in the cooling of rising saturated air.

A major lesson of the story is, as Dr Middleton emphasizes, that no real progress in explaining phenomena so complex as those involved in precipitation could be made until the relatively simple basic laws of thermodynamics and radiation had been established. A surprising number of physicists, now eminent for real progress in simpler fields, went seriously astray in meteorology.

G. A. BULL

Long-range hydrodynamic weather forecasting, edited by E. N. Blinova. 9 $\frac{3}{4}$ in \times 7 in, pp. iv + 124, *illus.*, (translated from the Russian by the Israel Program for Scientific Translations, Jerusalem), Oldbourne Press, 1-5 Portpool Lane, London, EC1, 1965. Price : 27s.

This is a valuable collection of major Russian papers about dynamical long-range forecasting, admirably translated as part of the Israel Program for Scientific Translations. The increasing volume of Russian literature currently becoming available from this source represents excellent progress in the dissemination of research. In the absence of such a service many workers without access to adequate translation facilities must inevitably remain poorly informed of Russian work and suffer accordingly.

The present volume under the overall editorship of Blinova, herself an acknowledged authority in this field, contains seven papers by workers in the Department of Planetary Atmospheric Dynamics and of Hydrodynamic Weather Forecasting.

Blinova's own contribution describes a 10-level, divergent, vorticity equation model formulated with long-range forecasting in mind and incorporating a simplified treatment of radiative exchanges and other physical effects. She sets out in considerable detail a partially implicit numerical procedure for solution of the equations but no results are given in the paper. For extended forecasts clearly very powerful computing facilities would be required and these may not yet be available for the purpose.

Kurbatkin's model, originally proposed by Blinova, is of the vertically differenced vorticity equation type with two levels at 300 and 700 mb. He integrates the system over the northern hemisphere for up to 5 days by means of a Green's function technique using a 4-hour time step and a grid of 5 degrees latitude by 10 degrees longitude. Initial results show a spurious accumulation of zonal kinetic energy in middle latitudes believed to be a consequence of errors in the prediction of zonal velocity. These lead to excessive displacement of the pattern in middle latitudes and accordingly a convergence of westerly momentum there. A special form of smoothing of the non-linear terms was introduced as a means of stabilizing the zonal winds and this enabled forecasts to be taken to 5 days with a useful predictive value. Experimental forecasts have apparently been prepared using this method on an operational basis for the past few years.

Galin discusses the interesting question of predicting the zonally averaged properties of the circulation directly from the dynamical equations using covariance terms to represent the turbulent motions, predictive equations for the covariances also being developed from the dynamical equations. For some studies this is an attractive alternative to extended integrations giving the evolution in detail and it is known that there is interest in this approach elsewhere. Galin specializes the approach to a two-level model but unfortunately does not present results. Smirnov's related paper fills in the background by

giving some hemispheric distributions of covariances of 500 mb parameters. Current fields of these would of course be required as part of the initial data for any predictions on the lines of Galin's work.

Musaelyan discusses the way in which humidity prediction could be incorporated into dynamical forecasting schemes. His basic humidity forecasting equation is linearized making possible solutions in terms of associated Legendre polynomials.

Chekirda considers the well known analytic solutions of the linearized non-divergent vorticity equation which depend on the meridional profile of zonal wind having a particular form. He examines the effect of departures from this special form and shows, for example, how forecasts made by Blinova's 1943 method can be improved by correcting for the real zonal profile.

The final paper by Smirnov is concerned with long range forecasting of the zonal circulation. The paper contains examples of predictions of 70-day average circulations and these appear to have good predictive value.

The book provides a useful and up to date picture of the extent to which dynamical methods are being focused on long-range forecasting problems and clearly the effort in this direction in the U.S.S.R. is on a considerable scale.

G. A. GORBY

LETTERS TO THE EDITOR

Synoptic representation of moisture

An article by T. H. Kirk describing moisture representation using 'dew-point thicknesses' appeared in the July 1965 issue of the *Meteorological Magazine*. The same basic idea was employed in designing an overlay for computing precipitable water directly from plotted Canadian tephigrams.¹ It would be a simple matter to adapt the overlay to the British tephigram. Using a three-layer computation a rapid and accurate measurement of the 1000-500 mb precipitable water can be obtained from the plotted dew-point curve. In each layer an 'equal area' method analogous to the Väisälä technique is employed. Similarly the 'saturation precipitable water' can be obtained from the temperature curve. The mean relative humidity is the ratio of the precipitable water to the saturation precipitable water. The determination of all three quantities from a plotted radiosonde report can be carried out in less than a minute. The use of precipitable water as a moisture parameter has many advantages not the least of which is that it is a directly measured physical quantity while the 'dew-point thickness' is a more abstract moisture-related parameter. In addition all of the comments regarding the usefulness of 'dew-point thickness' apply equally well to the use of precipitable water.

The use of a 3-layer model in computing precipitable water values is advisable because on the average the precipitable moisture is concentrated in the lowest levels. Typically there is considerably more moisture in the 1000-850 mb layer than in the 700-500 mb layer, for example. The surface to 500 mb precipitable water might be considered a more meaningful quantity over mountainous terrain than the precipitable water in a particular isobaric layer.

The difficulty of forecasting moisture patterns is well known. It seems reasonable to expect, however, that the precipitable water field should be more conservative than the dew-point or dew-point depression patterns at a single

level. Success in forecasting moisture must depend on the accuracy, representativeness, and conservatism of the moisture parameter and the accuracy of the initial (observed) field. It is felt that the precipitable water patterns might be found particularly useful in short-range weather forecasting over restricted regions. It should be possible, for example, to determine accurate 'spot' values of precipitation rate from a combination of mean upward vertical motion, precipitable water and mean relative humidity based on a multiple-layer model. Such a procedure could be programmed for the computer to produce short-range quantitative precipitation forecasts.

315 Bloor Street, West, Toronto, 5, Ontario.

H. L. FERGUSON

Comments on 'Precipitable Water' and 'Dew-point Thickness'

In any scheme for the quantitative forecasting of rain a knowledge of the vertical and horizontal distributions of moisture is required as well as a knowledge of the distribution of vertical motion. During the course of a semi-operational experiment conducted in the Forecasting Research Branch in 1963 into the rainfall forecasting problem, precipitable water charts, rather similar to those illustrating the article by Papež,² were constructed on a routine basis. The precipitable water in various layers and combinations of layers was examined in an attempt to determine the most useful for forecasting purposes and more particularly for use with the computed mean 1000–600 mb vertical motion fields which were available from the numerical forecasting experiment. The use of an overlay, as suggested by Ferguson,^{1, 3} was contemplated but was not considered worth pursuing at that time: there were other difficulties which had to be overcome before it was considered possible to draw sufficiently detailed charts of any moisture parameter. One difficulty was the suspected inconsistency of performance between the humidity sensors used in different types of radiosonde. A greater difficulty of analysis arose because over the area to west and south-west of the British Isles the radiosonde network was inadequate for sampling the atmosphere in time and space as often as required. It was in an attempt to overcome this difficulty and to provide a more objective chart of moisture that certain proposals were made by Benwell.⁴

The 'dew-point thickness' charts proposed by Kirk⁵ are to all intents and purposes the same as precipitable water charts, as Ferguson³ remarks. Either 'precipitable water' or 'dew-point thickness' charts would be acceptable in a rainfall forecasting scheme if it were possible to construct these in sufficient detail, but since both parameters are computed from the same basic data, the difficulties mentioned above are not removed if 'dew-point thickness' is used instead of the normal 'precipitable water' parameter.

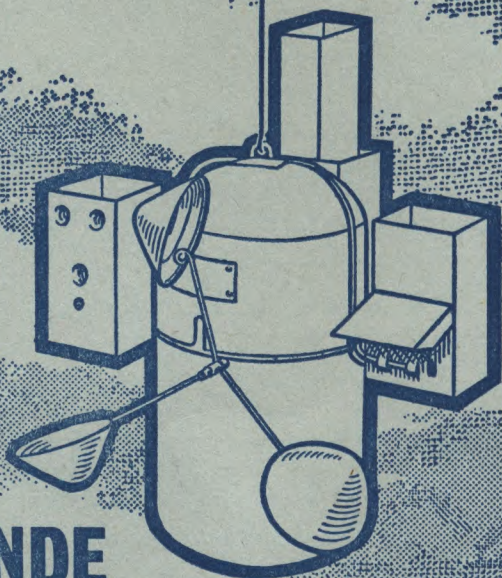
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G. R. R. BENWELL

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CONTENTS

	<i>Page</i>
World Meteorological Organization Fourth Session of the Commission for Synoptic Meteorology. C. J. M. Aanensen	289
Stratocumulus—a review of some physical aspects. S. G. Cornford	292
Meso-scale investigation of a squall line. R. R. McNair and J. A. Barthram	304
Kent Farmers' Field Day. J. Cochrane	310
Notes and news	
Address by Dr Joseph Smagorinsky	312
First round-the-world flight of southern-hemisphere weather balloon	314
Noctilucent cloud	315
Honorary Degree	315
Meteorological Office News	
Retirement of Mr G. A. Bull	315
Reviews	
A history of the theories of rain and other forms of precipitation. W. E. Knowles Middleton. <i>G. A. Bull</i>	316
Long-range hydrodynamic weather forecasting. Edited by E. N. Blinova. <i>G. A. Corby</i>	317
Letters to the Editor	318

NOTICES

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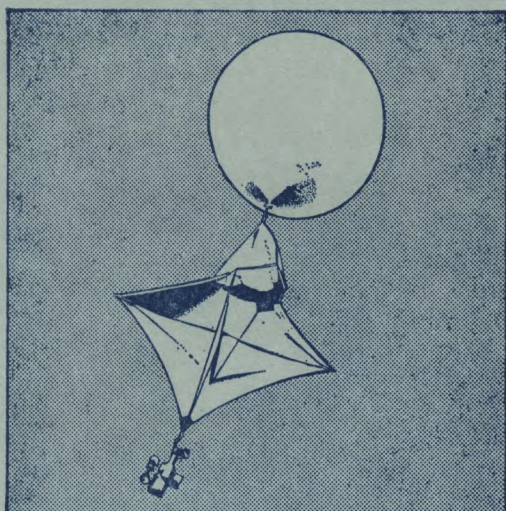
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THE METEOROLOGICAL MAGAZINE

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THE ACCURACY OF LONG-RANGE FORECASTS ISSUED BY THE METEOROLOGICAL OFFICE

By M. H. FREEMAN, O.B.E.

The twice-monthly publication of forecasts for a month ahead in '*Monthly Weather Survey and Prospects*' commenced in December 1963. The accuracy of each forecast is assessed by a panel of meteorologists and the results from the first 33 months are summarized below. Each forecast contains statements about the expected mean temperature and the total rainfall for the whole month together with additional information on type of weather and incidence of such things as snow, frost or thunderstorms.

The expected mean monthly temperature is given as one of the five categories: much above average, above average, near average, below average or much below average. The limits for these categories have been chosen such that in the period 1931-60 each category occurred equally frequently. The category boundaries therefore vary a little from month to month and from one part of the country to another. Some typical values for London and Edinburgh are given in Table I.

TABLE I—DIFFERENCES OF MONTHLY MEAN TEMPERATURE FROM THE 1931-60
AVERAGE FOR EACH FORECAST TEMPERATURE CATEGORY

Temperature category	London (Kew)				Edinburgh (Blackford Hill)			
	Jan.	Apr.	July	Oct.	Jan.	Apr.	July	Oct.
Much above Average	>1.7	>1.1	>1.2	>0.9	>1.4	>1.1	>0.7	>0.9
Above Average	1.7 to 0.8	1.1 to 0.6	1.2 to 0.4	0.9 to 0.2	1.4 to 0.3	1.1 to 0.4	0.7 to 0.2	0.9 to 0.4
Near Average	0.7 to -0.3	0.5 to -0.4	0.3 to -0.3	0.1 to -0.3	0.2 to -0.2	0.3 to -0.3	0.1 to -0.3	0.3 to -0.3
Below Average	-0.4 to -1.4	-0.5 to -1.1	-0.4 to -1.0	-0.4 to -1.1	-0.3 to -1.3	-0.4 to -1.3	-0.4 to -0.7	-0.4 to -0.9
Much below Average	<-1.4	<-1.1	<-1.0	<-1.1	<-1.3	<-1.3	<-0.7	<-0.9

A forecast of rainfall is given in a similar way as one of three equally likely categories, above average, near average or below average. The limits are

expressed as percentages of the average monthly rainfall and Table II shows some values for London and Edinburgh.

TABLE II—PERCENTAGES OF THE 1931-60 MONTHLY AVERAGE RAINFALL FOR EACH RAINFALL CATEGORY

Rainfall category	London (Kew)				Edinburgh (Blackford Hill)			
	Jan.	Apr.	July	Oct.	Jan.	Apr.	July	Oct.
Above					<i>percentages</i>			
Average	> 110	> 116	> 119	> 117	> 115	> 117	> 107	> 120
Near	110	116	119	117	115	117	107	120
Average	to 65	to 72	to 71	to 79	to 83	to 70	to 76	to 67
Below								
Average	< 65	< 72	< 71	< 79	< 83	< 70	< 76	< 67

The temperature and rainfall forecasts are checked separately for each of the 10 regions of the British Isles shown in Figure 1. Initially one station



FIGURE 1—FORECAST REGIONS OF THE BRITISH ISLES

in each area was taken as representative, but for most of the period average values for each area have been calculated from stations which appear in the *Daily Weather Report*.* The mean temperature for the month is calculated from the average of the daily maxima and minima, and the area mean anomaly is found as the average of the anomalies of the stations in the area. The rainfall at each station is expressed as a percentage of its normal (1931-60), and these percentages are averaged to give the area mean for the month. These calculations, and numerous others needed for routine long-range forecasting and research, are carried out on the COMET computer using a very versatile general-purpose programme.¹

The preparation of monthly normals of temperature and rainfall for the period 1931-60 presented difficulties in respect of some of the 44 checking stations used which had not been reporting for the whole of this period, but representative figures were obtained by adjusting values from nearby stations. Figures for mid-month to mid-month periods were not available, so normals for these periods were obtained by interpolation from the monthly figures. The monthly data were subjected to harmonic analysis; smoothed values for both the whole month and mid-month to mid-month periods were then calculated using the first two terms of the harmonic series. The quintile boundaries of the temperature categories and the rainfall terciles were calculated in this way as well as the area normals.

A score for each area is calculated according to the tables shown in Table III.

TABLE III(a)—SCORES FOR TEMPERATURE FORECASTS

ACTUAL	FORECAST				
	Much below	Below	Average	Above	Much above
Much below	4	1	-3	-4	-4
Below	2	4	1	-2	-2
Average	0	1	4	1	0
Above	-2	-2	1	4	2
Much above	-4	-4	-3	1	4

TABLE III(b)—SCORES FOR RAINFALL FORECASTS

ACTUAL	FORECAST		
	Below	Average	Above
Below	4	-2	-4
Average	0	4	0
Above	-4	-2	4

In a sample of situations which has about equal frequency of occasions in each category the average score for a random forecast will be zero, as will be the average score for a climatological forecast, i.e. always forecasting the normal. Each correct forecast scores four points. Temperature forecasts which are one category (out of five) wrong have a small positive score, but all other errors have negative or zero scores.

From the scores for each area an average score for the whole country is calculated and is used to provide an assessment of the accuracy of the forecast as one of the following categories :

- A No serious discrepancy
- B Good agreement
- C Moderate agreement
- D Little agreement
- E No real resemblance.

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

The scores corresponding to each category are not rigidly laid down, as some account is taken of the pattern of temperature anomaly and rainfall as shown by the individual stations. If for instance the gradient of temperature anomaly is correctly forecast as relatively warm in the north-west and cool in the south-east but the dividing line is wrongly positioned this is considered superior to a forecast which gained a slightly higher score by having some areas correct in a wrongly orientated pattern. Scores allotted to each category have been : *A* 4.0 to 2.2, *B* 2.4 to 1.0, *C* 1.4 to -0.2, *D* 0 to -1.5, *E* -1.2 to -4.0.

The assessment of the accuracy of the additional information about weather types and snow, etc., is necessarily a more subjective matter. Such phenomena as thunderstorms, fog and frost are normally included in the forecast only if they are expected to be notably more or less frequent than usual. No credit is given for statements that are little more than climatology. Each statement in the forecast is considered separately by the panel and a mark *A-E* awarded to it and then a single mark for the additional information as a whole is given. Finally the marks for temperature, rainfall and additional information are compounded to give an overall mark of the accuracy of the forecast as a whole. Table IV shows the frequency with which the various assessments were made in the 33-month period since December 1963.

TABLE IV—NUMBER OF FORECASTS FALLING IN VARIOUS CATEGORIES OF SUCCESS.
PERIOD—DECEMBER 1963 TO AUGUST 1966

Category	Mean Temperature	Rainfall <i>Number of forecasts</i>	Additional Information	Overall Marking
<i>A</i> = No serious discrepancy	10	10	12	1
<i>B</i> = Good agreement	24	10	17	24
<i>C</i> = Moderate agreement	12	20	19	23
<i>D</i> = Little agreement	8	17	14	15
<i>E</i> = No real resemblance	12	9	4	3

An overall marking of at least moderate agreement was obtained on 73 per cent of occasions. It was rare for forecasts of temperature, rainfall and additional information simultaneously to be very good or very bad, so that overall marks of *A* or *E* were few.

Good forecasts of temperature were made more often than good forecasts of rainfall. This is in agreement with the experience of short-range forecasters that rainfall is the more difficult element to predict precisely. In the 66 forecasts made for each of 10 areas the temperature category was exactly right 170 times (26 per cent) and only one wrong (out of five) 280 times (42 per cent), compared with chance expectation of 20 per cent and 32 per cent respectively ; thus 68 per cent of temperature forecasts were correct or about correct. The correct rainfall category (out of three) was forecast 237 times (36 per cent) ; 51 per cent of the forecasts were one category wrong and the remainder, 13 per cent, two categories wrong. This is an improvement on the chance expectation of 33, 45 and 22 per cent respectively ; there is a useful reduction in the large errors but the overall improvement is not great.

The middle categories of both temperature and rainfall were forecast too often, and the extreme categories too rarely. In fact temperatures much below average and much above average were forecast on only 4 per cent and 3 per cent of occasions, whereas they occurred on 29 per cent and 9 per cent of occasions respectively. Average rainfall was forecast 49 per cent of the time but occurred on only 35 per cent of occasions.

All forecasts included information on the general weather type or the incidence of wet and dry spells or warm and cold intervals, and about 60 per cent of this information was considered of definite value. Other items which received specific mention were :

	Number of mentions	Number substantially correct
Frost	26	17
Snow	20	15
Fog	11	9
Thunderstorms	11	8

Previous experience had shown that autumn was the most difficult season in which to make monthly forecasts and this was borne out in the past 33 months. Of the autumn forecasts 58 per cent received overall marks of *D* or *E* ; nevertheless the only forecast to receive an overall mark of *A* was an autumn one. Summer had fewest poor forecasts, three *D*'s out of 18 forecasts.

The foregoing results cannot engender complacency in our long-range forecasters, but they do represent a solid achievement. As techniques are refined we can hope for a gradual increase in the detail included and perhaps a small improvement in accuracy, but advances will necessarily be slow.

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A NOTE ON THE USE OF HOURLY RAINFALL OBSERVATIONS

By D. E. JONES

Introduction.—Since May 1965 quantitative observations of rain have been made hourly by 63 meteorological offices in the United Kingdom and distributed over the teleprinter network for use in forecasting. This note has been written to assist in the interpretation of these observations and to indicate how they can be used.

'Present weather' observations.—A statistical investigation has shown that although the 'present weather' observations reported in the SYNOP code give some indication of the amount of rain that has fallen in the previous hour, the range of rainfall amounts corresponding to any given code figure is extremely wide, making it difficult to assess how much rain is in fact falling from a system. The main reason for this wide spread of values is that the reported rain intensity is assessed for a ten-minute interval at the time of observation and no account is taken of the precipitation intensity in the 50 minutes since the previous (hourly) report. Thus it is quite possible for a considerable amount of rain to have fallen at a station reporting 'slight rain' or 'rain in the past hour'. Also a station reporting 'continuous heavy rain' may have had for example as little as 0.5 mm or as much as 10 mm in the previous hour. A further factor increasing the spread of values is that the rates of rain are often subjectively assessed and reported on a rather crude three-class scale.

The 'present weather' reports are useful for determining the general level of activity of a large rain system provided enough observations are available, but they are not adequate for describing precipitation patterns in the detail required for short-period forecasting of rain, quantitative or otherwise.

Quantitative observations of rainfall naturally give a better indication of the intensity of rain systems particularly when only a few observations are available, and it is also found that details in the rain patterns are easier to follow than when using 'present weather' reports alone. They also have the advantage that they are easier to summarize when forecasts are being verified. However, 'present weather' reports of precipitation are unlikely to be completely replaced by quantitative values, since they indicate the character of the precipitation and because they are easier observations to make, requiring no apparatus.

Interpretation of hourly values for short-period forecasting.—Quantitative rainfall observations suffer from a number of peculiarities not found with other meteorological variables. Because they are cumulative in character they are subject to spurious variations if the time interval between observations departs greatly from one hour. In particular an unexpectedly large value at one hour following a zero or nil observation should be viewed with suspicion (especially if the zero value itself was unexpected) since it may represent an accumulation of more than one hour. It is also important to differentiate between reports of 'no rain' and missing reports.

When a narrow belt or area of rain crosses a region, the sequence of hourly values observed at a station will depend on how the period of rain is distributed with respect to the observing times, e.g. a period of rain lasting one hour may be reported as one large amount at one hour or as two smaller amounts at two consecutive hours. Thus the apparent intensity of such a system will fluctuate from hour to hour by a factor as large as 2.

Since the observations refer to rain in the whole of the previous hour, rain apparently falling behind a moving front may actually have all fallen ahead of it and the faster the front moves, the more marked this effect becomes. The 'present weather' observations help to clarify this point.

Use of quantitative values.—The large variations in rainfall that occur on a short space- or time-scale are a constant source of difficulty when studying or forecasting rain. These variations may be orographic (or topographic) in origin or may be due to the presence of meso-scale rain-producing dynamical systems which apparently often occur in the rain area of larger systems.

Isolated thundery outbreaks often travel across the country as meso-scale systems and can be tracked by using 'present weather' observations on the usual large-scale synoptic charts. If quantitative values are also used it is found that the main centres of activity are defined more satisfactorily (although the details usually move in an irregular way) and a much better idea is obtained of the intensity of the storms.

Studies of hourly rainfall observations show that in widespread frontal or cyclonic rain it is often possible to discern lines or cells of more intense rain 50 to 150 miles in extent which move fairly continuously from one chart to the next and have a lifetime of several hours. An example is given in a later section ; others are illustrated by Wallington.¹

Unfortunately little is known about the types of feature that can occur or about their life-history ; their progress may be obscured by the presence of convection or by the effects of topography, but since they have a life of several hours it is important for the forecaster to be able to detect them and to forecast their movement and development for a few hours ahead.

For this purpose the observations are best plotted on a large-scale chart ($1 : 3 \times 10^6$) onto which the positions of fronts, pressure troughs and centres have been marked. It will be found that rough isopleths of rainfall can be drawn provided the interval between the isopleths is not too small. The series of isopleths for amounts ≤ 0.1 , 1, 2, 4, 8, 12, ≥ 16 mm has been found satisfactory in most cases, although when the amounts are small a line for 0.5 mm is useful. At the advancing edge of widespread rain, especially ahead of a warm front, the distribution of traces and 0.1 mm is usually very irregular and it is often preferable not to enclose these observations by an isopleth unless they are closely associated with larger values.

The drawing of isopleths over the British Isles (Figure 1) is usually rather subjective, especially for example over Wales, the west Midlands and Sussex, where there are but few observations. Great attention needs to be paid to maintaining continuity with previous patterns which may require re-drawing in the light of later observations.

The 'present weather' observations can be called upon for filling some of the gaps and they may be interpreted in a rough quantitative way by using Table I, which was derived from a statistical analysis of observations of 'present weather' and hourly rainfall.

When 'present weather' reports corresponding to small amounts of rain are associated with those corresponding to larger amounts, the former are likely to represent higher amounts than are given in Table I. When the estimates based on this table are not in agreement with the plotted quantitative values the latter should be adopted. It must be emphasized that the range of hourly values corresponding to a given code number is very wide.

TABLE I—QUANTITATIVE INTERPRETATION OF 'PRESENT WEATHER' OBSERVATIONS
OVER THE BRITISH ISLES

Examples of code figure for present weather	Meaning of code figure	Suggested values of hourly rainfall
60	intermittent slight rain	not significant, i.e. < 0.1 mm
61	continuous slight rain	not significant if isolated, otherwise 0.1–0.5 mm
62	intermittent moderate rain	0.5–1.0 mm
63	continuous moderate rain	1.0–2.0 mm
64	intermittent heavy rain	about 2.0 mm but covers a very wide range of values
65	continuous heavy rain	> 2.0 mm
80	slight rain shower(s)	not significant if isolated, otherwise 0.1–0.5 mm
81	moderate or heavy rain shower	> 1.0 mm

Maximum rain intensity.—If meso-scale systems are to be used in forecasting over the British Isles they must be detected before they have progressed very far into what is a relatively sparse network of observations over a small area and some assistance is obtained by plotting the progress of lines or centres of maximum rain intensity.

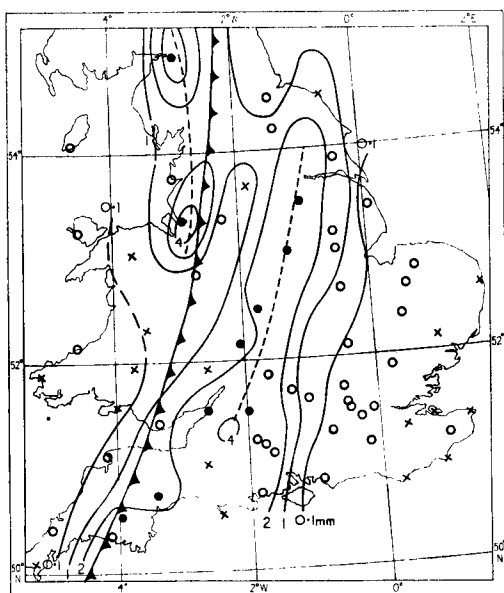


FIGURE 1(a)—ISOPLETHS OF HOURLY RAINFALL 1100–1200 GMT, 24 SEPTEMBER 1963

An isopleth is represented by a dashed line when the drawing is very uncertain. The frontal position is given for 1200 GMT.

— — — 1200 GMT position of line of maximum value

o rainfall report; ● rainfall report maximum; × present weather observation only

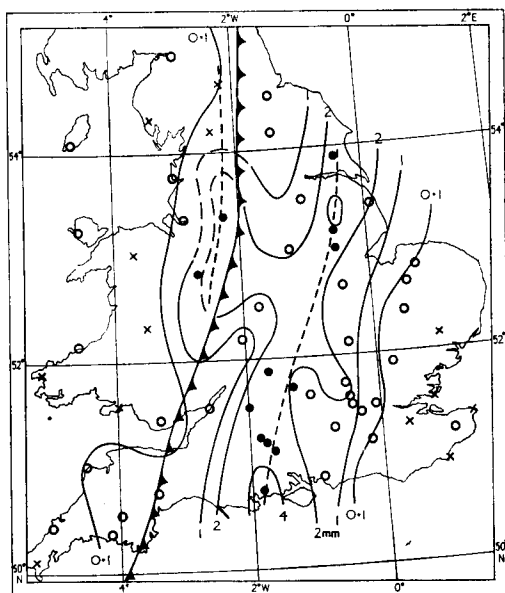


FIGURE 1(b)—ISOPLETHS OF HOURLY RAINFALL 1200–1300 GMT, 24 SEPTEMBER 1963

An isopleth is represented by a dashed line when the drawing is very uncertain. The frontal position is given for 1300 GMT.

— — — 1300 GMT position of line of maximum value

o rainfall report; ● rainfall report maximum; × present weather observation only

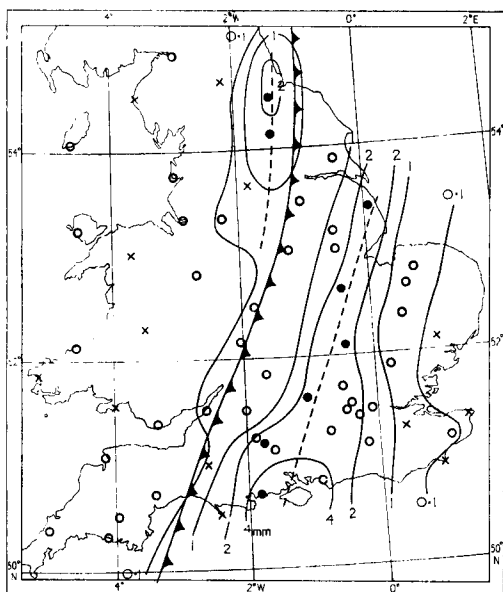


FIGURE 1(c)—ISOPLETHS OF HOURLY RAINFALL 1300-1400 GMT, 24 SEPTEMBER 1963

An isopleth is represented by a dashed line when the drawing is very uncertain. The frontal position is given for 1400 GMT.

----- 1400 GMT position of line of maximum value

o rainfall report; ● rainfall report maximum; × present weather observation only

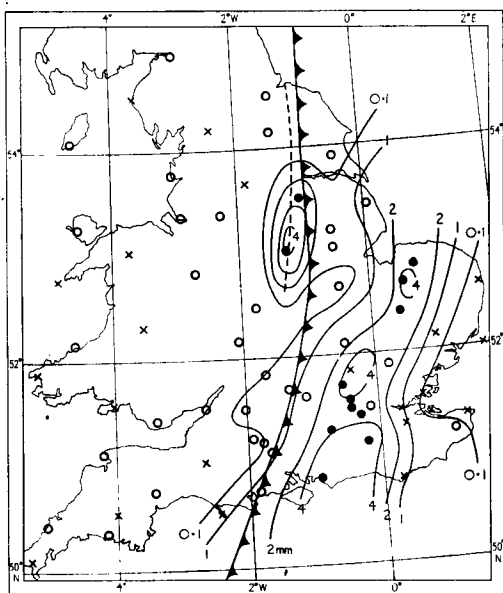


FIGURE 1(d)—ISOPLETHS OF HOURLY RAINFALL 1400-1500 GMT, 24 SEPTEMBER 1963

An isopleth is represented by a dashed line when the drawing is very uncertain. The frontal position is given for 1500 GMT.

----- 1500 GMT position of line of maximum value

o rainfall report; ● rainfall report maximum; × present weather observation only

If a narrow band or small area of rain moves steadily across the country, the rain intensities which occur may vary considerably from station to station and so may the total rain and the duration of the rain, especially if some stations are exposed at a high altitude and others are in a rain shadow. The isopleths of hourly amounts will move irregularly: the higher-valued isopleths will tend to jump ahead to the higher-level stations, lingering there when the main belt has passed, but completely by-passing stations in the rain-shadow. Likewise isochrones of the time of onset of rain will move in an irregular way.

However, unless the dynamical system causing the rain is very greatly affected by the topography it is feasible to expect that the time at which the maximum rain intensity is experienced at each station should progress at the same steady speed as the dynamical system itself.

Indeed an analysis of time cross-sections of rainfall shows that it is not unusual for stations which are within a few hundred miles of each other to experience similar sequences of intensity peaks even though the exposures and the total rain catches are quite different at the stations. The isochrones of maximum intensity often move regularly even when the intensities themselves are rather variable. When more than one peak occurs the time lapse between peaks is often the same at different stations.

Isochrones of maximum intensity are useful not only for identifying and tracking meso-scale features but also for identifying two parts of what is effectively the same meso-scale feature, the portion between them having been suppressed by topography.

It is unfortunate that it is not possible to decide whether or not a particular hourly value is a maximum until the next report is available but it has been found practicable to apply this principle of maximum intensity to hourly rainfall charts by underlining the maximum value at a station in some distinctive colour and then examining two or three successive charts to see whether the marked values form a consistent sequence.

Complications occur in the marking of the charts and in Table II a scheme is suggested.

A certain amount of latitude of timing must be allowed when following the maximum from chart to chart since random irregularities may displace the maximum from one hour to another. If the reported hourly maximum value is not much larger than the previous value it is likely that the real maximum rain intensity occurred in the first half of the hour of accumulation, whereas the real maximum would probably be in the second half of the hour if the reported maximum is not much larger than the following value. The markings in the table will assist in marking a line of maximum values on the chart.

Thus XX or XX indicates a maximum near the mid-point of the hour

XX_E or XX_E indicates a maximum in the first half of the hour

XX_L or XX_L indicates a maximum in the second half of the hour.

If the rain bands are present near a front they are most likely to be orientated along the front and moving at the same speed. On the other hand

TABLE II—SCHEME FOR MARKING MAXIMUM RAIN VALUES

<u>XX</u>	Hourly maximum : at least 10 per cent greater than the previous or the following value Underline plotted value (XX) with full line to indicate maximum near the mid-point of the hour
<u>XX_E</u>	Hourly maximum : but less than 10 per cent greater than the previous value Underline with full line and add subscript E to indicate maximum in first half of the hour
<u>XX_L</u>	Hourly maximum : but less than 10 per cent greater than the following value Underline with full line and add subscript L to indicate maximum in second half of the hour
<u>XX</u> ---	Hourly maximum : but less than 10 per cent greater than both the previous and the following value Underline with dashed line to indicate less definite maximum near mid-point of the hour
<u>XX_E</u> ---	Value greater than the following value but equal to the previous value Underline with dashed line and add subscript E to indicate maximum in first half of the hour
<u>XX_L</u> ---	Value greater than the previous value but equal to the following value Underline with dashed line and add subscript L to indicate maximum in second half of the hour

it is difficult to forecast whether areas which are more circular in form will progress with the front or move in a direction closer to that of the thermal wind, and for the present the procedure must be one of detecting the areas as soon as possible and extrapolating the movement observed during the past few hours.

In warm sectors the quantitative observations define quite well the stripes of rain that form downwind of gaps between high ground, e.g. eastwards from the Bristol Channel.

Using the analysis of maximum intensity it has been found that occasionally tongues of rain extending eastwards or south-eastwards around the north and south flanks of the Welsh mountains ahead of a warm front are apparently two parts of the same dynamical system, namely a line of maximum intensity orientated north-south, the centre part of which has been suppressed in the lee of the mountains. The link is indicated by small amounts of rain falling at stations such as Ross-on-Wye and Birmingham Airport at about the time that a line joining the time maxima to the north and to the south crossed these stations. The two rain areas sometimes join up again further to the east well away from the orographic features. The occasion of 2 September 1948 quoted by Wallington is apparently of this type, although on this occasion the rain was completely suppressed in an area just to the lee of the Welsh mountains.

Example of 24 September 1963.—The hourly charts for 1200 GMT to 1500 GMT, 24 September 1963 are shown in Figure 1 (a) to (d). The cold front was well defined by a strong wind shift across it. The main belt of rain ahead of the front was well defined by the isopleths and by the line of maximum values except near the south coast. The rain associated with the cold front itself was not at all well defined by the 'present weather' observations, and the closed isopleths moved erratically on the rainfall charts but every station north of Shawbury had a maximum about the time of passing of the front

(including Blackpool Airport at 1100 GMT) and its separation from the previous rain is easy to see on these charts. In the southern part of the area it is clear that the cold front is not bringing any intensification of the rain.

Conclusion.—Hourly rainfall observations may eventually be used to define meso-scale rain features and to forecast their future movement and development. The requisite forecasting technique has not yet been developed, but meanwhile the plotted observations can be used for estimating the intensity of rain systems and an extrapolation method could be used for forecasting a few hours ahead. Forecasters would find a study of hourly rainfall charts of considerable interest and a great help towards an understanding of the apparently anomalous distributions of longer-period rain totals.

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551.507.362.2:551.509.311:77

SATELLITE PICTURES OF AN OLD OCCLUDED DEPRESSION AND THEIR USEFULNESS IN ANALYSIS AND FORECASTING

By I. J. W. POTHECARY and R. A. S. RATCLIFFE

Summary.—Satellite photographs of an old occluded depression are described to show their use in the analysis of the structure and movement of the depression and its associated fronts. The position of the core of the associated jet stream can also be deduced, as well as the presence of sea-ice.

The satellite photographs, received from the automatic picture transmission (APT) facility on ESSA II, are shown to have played an important part in the integration of the observed data and their immediate availability was a major factor in the formulation of a correct forecast.

Introduction.—Satellite television pictures have been received daily in the Central Forecasting Office, Bracknell, since the beginning of March 1966 from the automatic picture transmission (APT) facility on ESSA II, the second satellite of the United States operational satellite system.

Experience in the interpretation and use of directly received APT satellite pictures is accumulating and many occasions have occurred when satellite cloud pictures have made significant contributions to analysis and have been an important aid in the preparation of forecasts. Interpretation has also been successfully extended to the location of jet streams and the identification of the nature and limits of sea-ice in northern waters. Information on snow cover has also been obtained.

A case-study of an old occluded depression is presented as an illustration of the use of observational data available in APT satellite photographs.

APT satellite parameters.—Automatic transmission of satellite television pictures is currently being made from ESSA II, the second of the TIROS operational satellites (TOS),¹ launched by the United States on 28 February 1966. The satellite is in a slightly elliptical near-polar orbit with an apogee

of 1413 km and a perigee of 1353 km. The period of the orbit is 113.4 minutes and successive crossings of the equator are 28.4 degrees further west, effectively keeping pace with the sun and passing over the same area on the earth's surface twice daily at fixed local times, once near midday when the satellite is moving from slightly east of north to slightly west of south and once near midnight when the satellite is completing its orbit over the dark side of the earth.²

The interval between successive APT pictures is 352 seconds and the reception of each picture is completed within 184 seconds of the time the picture is taken. Each picture covers a square with sides of about 1500 n. miles. The overlap between successive pictures on the same orbit is about 500 n. miles and the overlap between pictures from successive orbits is about 350 n. miles in the latitude of the British Isles. The resolution at the centre of each APT picture is about 2 n. miles, reducing to about 4 n. miles at the edges.

The satellite must be above the horizon for APT pictures to be received, but even with this limitation it is possible to receive pictures at Bracknell covering an area including the North Pole, central Siberia, the Black Sea, the eastern Mediterranean, North Africa, the Atlantic from the Canary Islands to Nova Scotia, Labrador, Baffin Island and the Davis Strait. The coverage varies with satellite altitude and with the quality of reception for low aerial elevations.

APT analysis for 0950 and 1143 GMT on 5 May 1966.—

Cloud organization.—The dominant feature in the organization of the cloud shown in the APT pictures for 0950 and 1143 GMT on 5 May 1966 (Plates I and II) is the vortex centred at about 56°N 16°W. This vortex showed no detectable movement, within the accuracy of location, over the 113 minutes between the pictures. The cloud in the lines forming the vortex was assumed to be largely convective, particularly in the southern part of the vortex where granulated structure is more apparent. It was also assumed that the lines of cloud were stretched out along the shear vector, indicating the thermal pattern in the layer containing the cloud rather than the actual flow.³ As the depression was an old occluded system the position of the vortex centre was taken as a reasonable approximation to the surface position of the depression centre.^{4,7}

The APT picture, reproduced in Plate I and given in nephanalysis form in Figure 1, shows a broad and continuous band of cloud covering southern Scandinavia and spiralling in towards the centre of the vortex. The high reflectivity and intense whiteness of the cloud over most of the band confirmed that this was active and well-organized frontal cloud reaching to high levels in the troposphere. The sharp change to clear dry air along the western boundary of the cloud system, with evidence that dry air had already penetrated to the centre of the vortex, showed that this was, as indicated in the surface analysis for 1200 GMT on 5 May 1966 (Figure 2), the main occluded front of the depression.

The granulated structure of the cloud over a large area around the depression away from the vicinity of the occlusion showed the presence of convective cloud — evidence that the cold air in the lower troposphere was

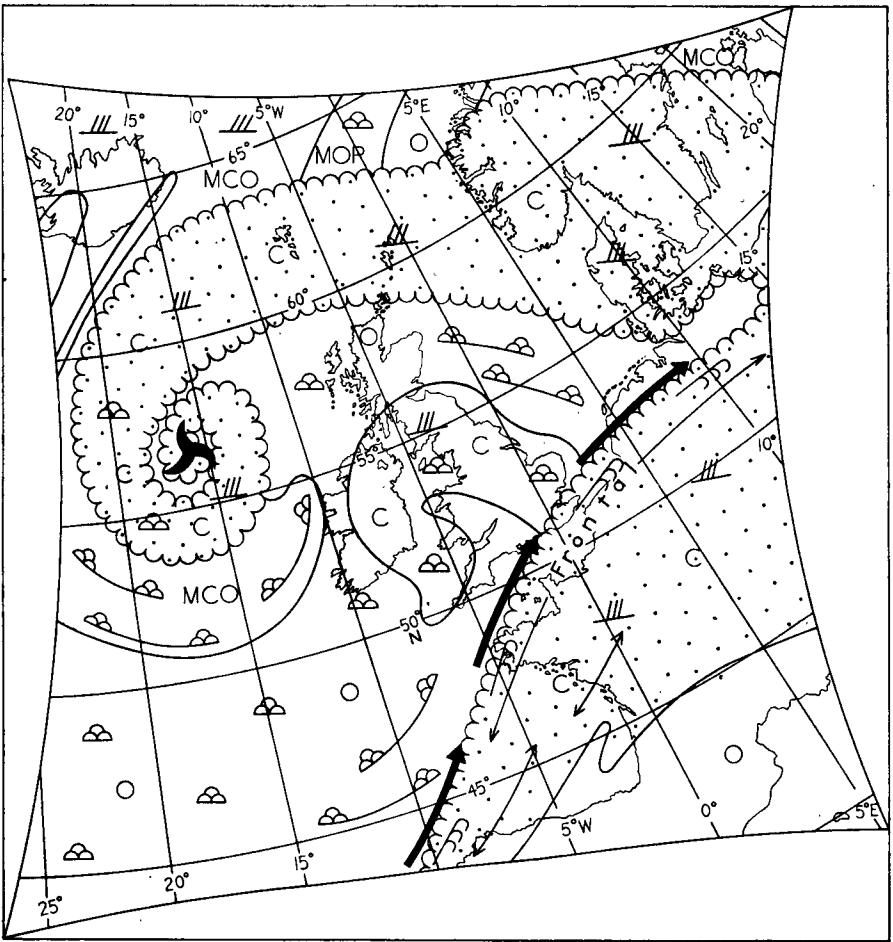
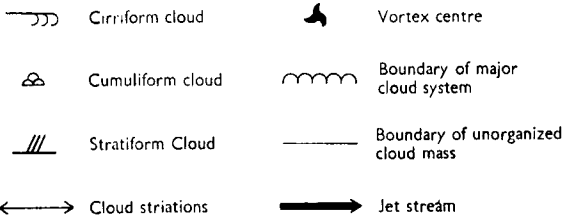
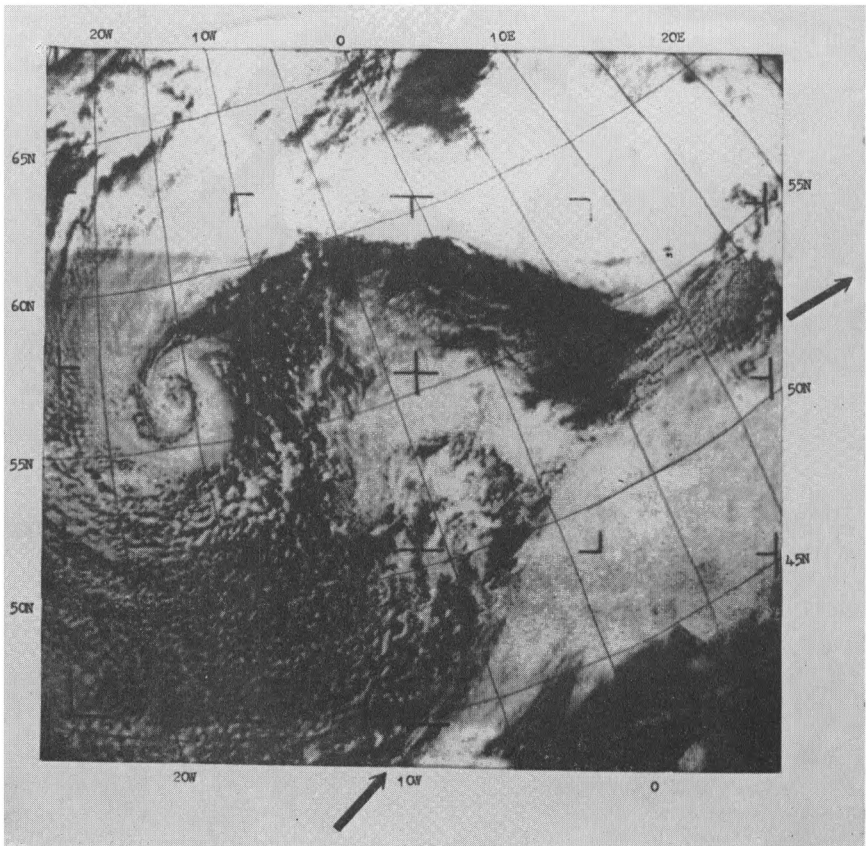


FIGURE 1 — NEPHANALYSIS BASED ON ESSA II APT SATELLITE TELEVISION PICTURE
AT 0950 GMT ON 5 MAY 1966



O	20 per cent coverage
MOP	20-50 per cent coverage
MCO	50-80 per cent coverage
C	80 per cent coverage

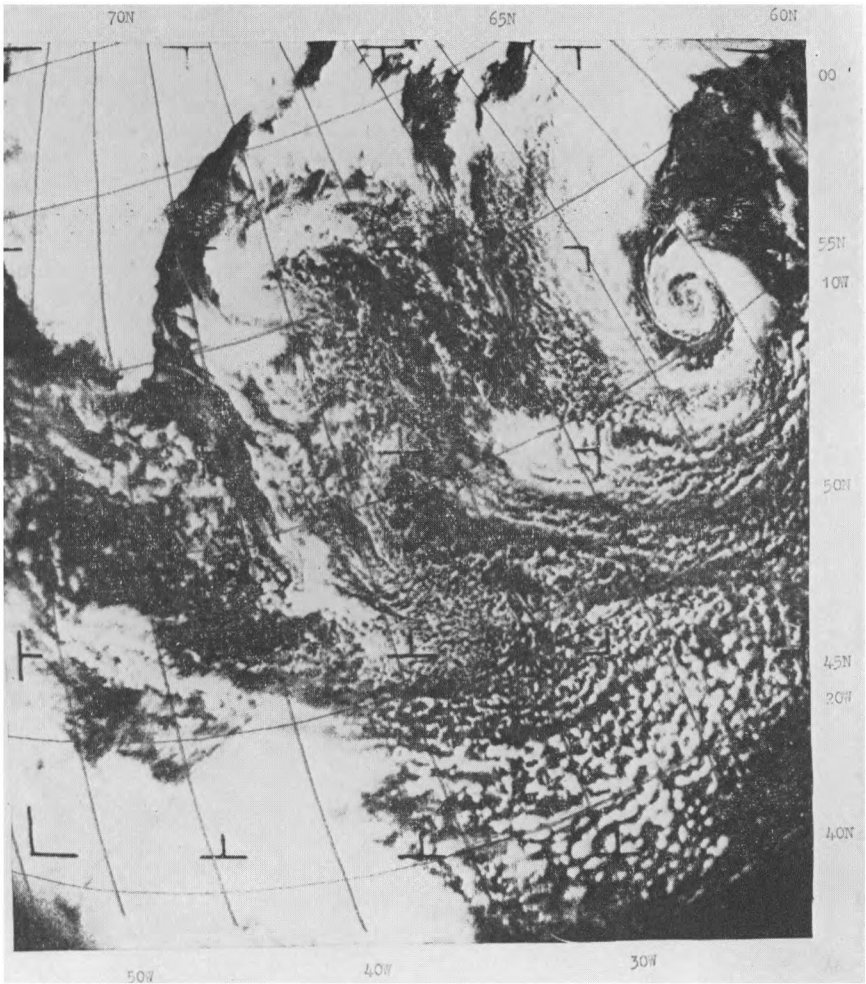
Stippling represents cloud organization considered to be synoptically significant



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PLATE I—ESSA II APT SATELLITE TELEVISION PICTURE—CENTRED OVER SOUTHERN SCOTLAND AT 0950 GMT ON 5 MAY 1966 ON ORBIT 835 AT A HEIGHT OF 1353 KM (The arrows locate the assumed position of the core of a jet stream).

To face page 335



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PLATE II—ESSA II APT SATELLITE TELEVISION PICTURE—CENTRED OVER MID-ATLANTIC ($56^{\circ}\text{N } 32\frac{1}{2}^{\circ}\text{W}$) AT 1143 GMT ON 5 MAY 1966 ON ORBIT 836 AT A HEIGHT OF 1353 KM.

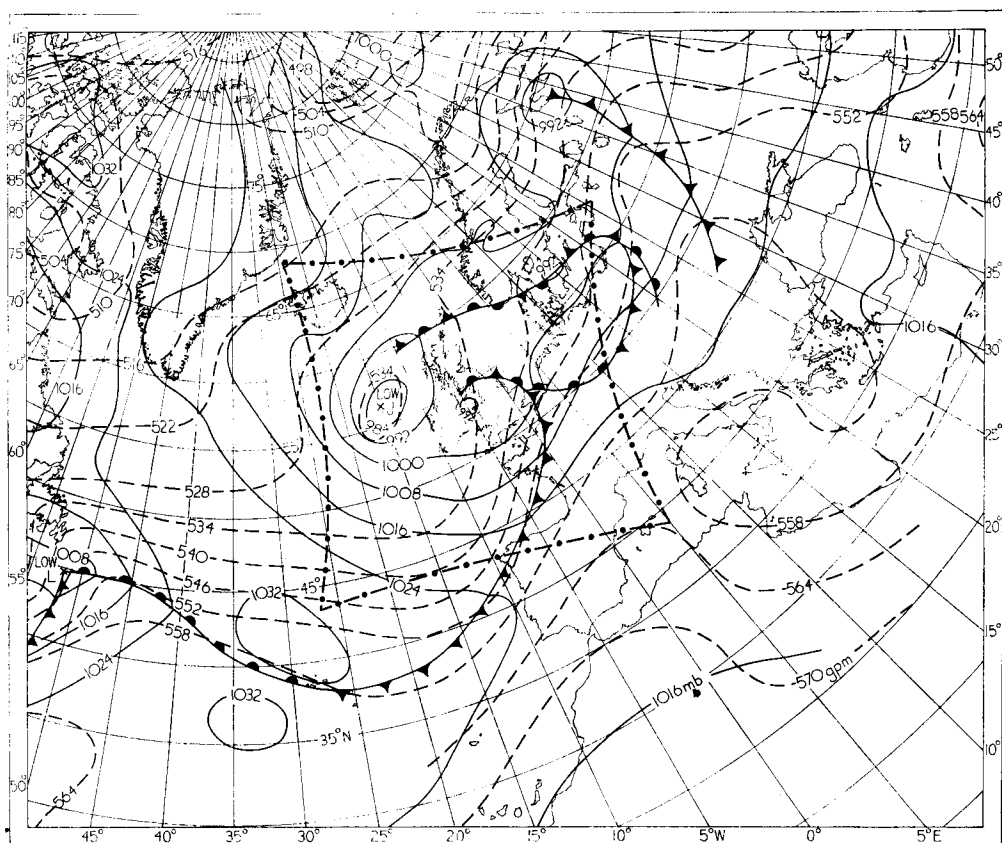


FIGURE 2 — SURFACE ANALYSIS AND 1000-500 MB THICKNESS FOR 1200 GMT ON 5 MAY 1966

--- Boundary of area covered by satellite photograph (Plate I)

unstable for sea surface temperatures. As the maximum resolution does not go below about 2 n. miles the granulations represent clumps of convective cloud rather than individual cumulus or cumulonimbus.

The smooth boundary to the dense white reflection from Greenland (top left of Plate II) shows the presence of sea-ice in coastal waters. Later in the year, following the melting of the ice, the indented nature of the Greenland coast was clearly shown. The same dense whiteness is also typical of reflection from the snow-covered Alps which are frequently seen on APT pictures received at Bracknell and are usually clearly recognizable by their 'fern-like' appearance due to the snow-free valleys.

The surface analysis (Figure 2) shows a short occlusion drawn over the British Isles from a shallow depression over the Irish Sea to a wave tip near East Anglia. The wave occurred on the cold front running through northern Germany, the Low Countries and northern France. The occlusion had been followed through ship observations over the eastern Atlantic but the satellite picture (Plate I) showed that the organization which should have been

present if the occlusion had retained its structure was lacking. On the original facsimile copy it can be seen that the cloud over most of the British Isles had a granulated structure, randomly arranged. This detailed structure is partly obscured by the increased contrast in the photographic reproduction. The random arrangement of the convection suggests that the occlusion had degenerated into cloud more typical of the increased convection in a broad trough in the circulation of the depression rather than an organized frontal system.

Jet-stream identification.—The satellite photograph (Plate I) shows a mass of cloud covering the Bay of Biscay, northern France and the Low Countries. The cloud was associated with the cold front shown in the surface analysis (Figure 2), and the high reflectivity shown in the picture suggests that the cloud was dense and extended to high levels. The northern edge of the cloud sheet is marked by long thin streaks of cloud stretching over a considerable distance, through about 44°N 10°W and extending northeastwards over the English Channel before curving eastwards across Germany. The striations, which have a lower reflectivity than other cloud systems in the picture, appear to run over the lower convective cloud suggesting that they were features of the cloud cover at high levels and were probably thick cirrus.⁵

The northern limit of the striations, with clear air at high levels to the north, was assumed to give the position of the core of the jet stream associated with the occluded depression.⁶ The assumed position of the jet is marked by arrows on the southern and eastern edges of the satellite photograph (Plate I) and is shown in the nephanalysis prepared from the picture (Figure 1).

The satellite picture should be compared with the 300 mb chart for 1200 GMT on 5 May 1966 (Figure 3). The isotach maximum, interpolated over the Atlantic through a very sparse network of upper air observations, is carried round the upper trough to the north-westerly jet stream over mid-Atlantic in line with the operational analyses. The core of the jet located from the satellite evidence coincides with the isotach maximum eastwards from about 10°W but west of that longitude the striations continue south-westwards and can be followed on the next satellite picture in the same orbit to about 40°N 20°W . If the interpretation of the striations as a locator for the jet core is correct then the assumed continuity of the jet around the upper trough was not present and two separate jet streams existed. The sparseness of the upper air network over the Atlantic prevents the confirmation of this configuration of the jet but the coincidence of the isotach maximum and the cloud streaks through the close upper air network in western Europe suggests that the location of a jet may be derived from satellite evidence alone in regions where insufficient upper air data is available for detailed analysis.

Synoptic situation on 5 May 1966.—On 4 May a fairly deep depression had moved quickly north-eastwards towards Scotland over the Atlantic. It was expected that this depression would cross Scotland to be near the Shetland Islands by midday on 5 May. Instead it slowed down over the eastern Atlantic and by the morning of 5 May it was slow-moving west of the Hebrides. Another shallow depression of complex origin, the fronts of which were at all times embedded in the strong south-westerly upper flow

on the south side of the main low, made steady progress north-eastwards until by midday on 5 May this depression was over the Irish Sea as a weak centre (Figure 2). The associated 300 mb analysis for 1200 GMT on 5 May is shown in Figure 3.

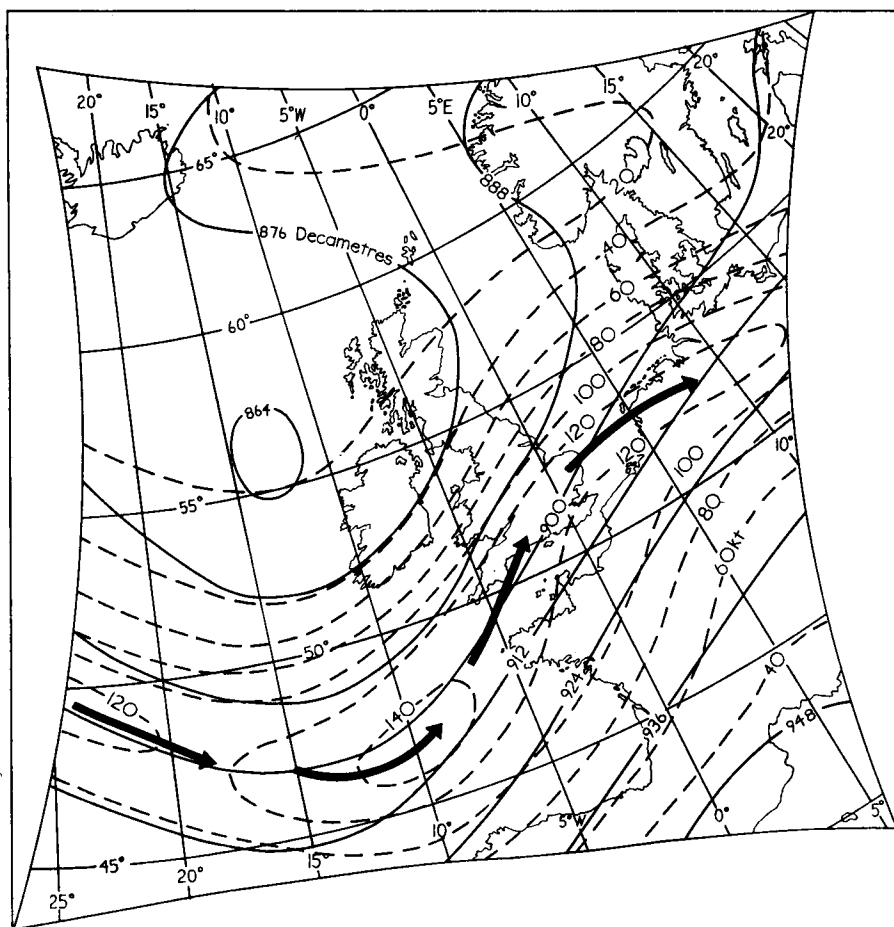


FIGURE 3—300 MB CONTOUR AND ISOTACH CHART FOR 1200 GMT ON MAY 5 1966,
COVERING THE AREA SHOWN IN PLATE I

————— Contours at 12-decametre intervals

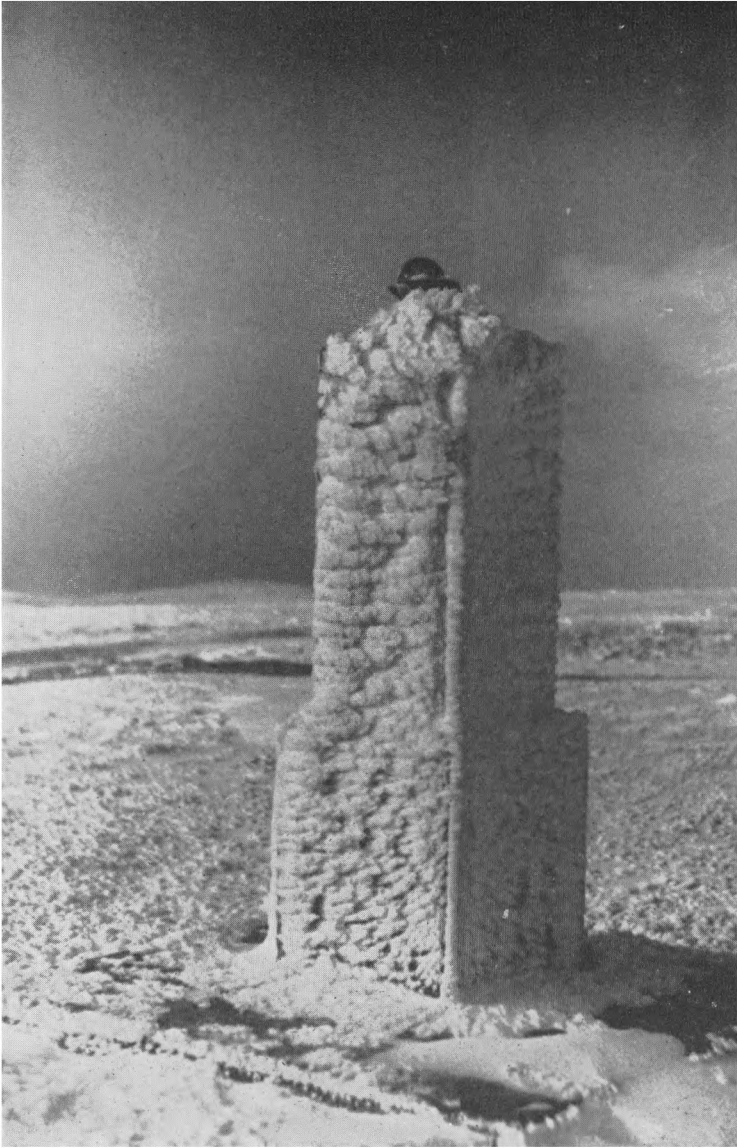
- - - - - Isotachs at 20-kt intervals

The jet stream is indicated by a series of bold arrows

Synoptic systems on the other side of the Atlantic had an important bearing on the compilation of 24-hour surface prognostic charts on 5 May and it is necessary to refer to them if the situation is to be fully understood. The main feature was the very intense cold trough over Hudson Bay with a smaller trough near Nova Scotia. This latter trough, although much smaller than the Hudson Bay trough, contained some quite cold air and was associated

with a shallow depression which was showing signs of deepening by midday on 5 May. The Hudson Bay trough was too large and well established to move or disappear quickly and, with the two upper troughs separated only by about 30 degrees of longitude, the expected development was that the forward trough and its associated depression (Low L in Figure 2) would move quickly eastwards over the Atlantic, increasing the trough separation and allowing a limited deepening of the centre. This evolution of the pattern was supported by computed forecasts. The eastward movement of the depression was likely to be fast enough for the ridge ahead of it to be approaching western districts of Britain during 5 May.

The use of APT in forecasting on 5 May 1966.—It was evident that the position of the cloud vortex shown on the APT pictures was to the south of the surface centre of the depression as analysed on the synoptic charts. This would have been expected if the depression had been a baroclinic system, but with an old occluded depression it was more likely that the cloud vortex and the position of the surface centre of the depression would show a much closer relation than appeared to be the case.^{4,7} The APT pictures prompted a fresh look at previous charts, particularly that for 0600 GMT on 5 May on which late ship observations were available. As a result of re-analysis it appeared that the main depression had been moving only slowly for some time. At this stage an early ship report on the 1200 GMT chart gave a pressure of 980 mb and a westerly wind at a position just south of the centre of the vortex shown on the APT pictures. The available synoptic data, integrated into the analysis with the assistance of the APT pictures, suggested that the surface centre of the depression was almost certainly at about $56\frac{1}{2}^{\circ}\text{N}$ 15°W at 1200 GMT on 5 May. Drawing the depression in this position resulted in a very tight gradient on the south-west side. With the whole system then regarded as a barotropic vortex the future movement was likely to be controlled more by the strongest flow than by any other factor. No movement could be detected within the limits of accuracy of location over the interval between the two APT pictures suggesting that at this stage at least the depression was moving only very slowly. The surface prognostic chart for 1200 GMT on 6 May was therefore constructed on the assumption that the depression would move slowly south-east for the first 12 hours as the depression near Nova Scotia developed. It was expected that the south-eastward movement of the depression J would then tighten the gradients on the southern side as the gradients to the west relaxed, causing the centre to turn left and probably accelerate across northern England to a position over the North Sea by the end of the 24 hours. As a barotropic vortex it would almost certainly fill but at 1200 GMT on 5 May its depth was about 976 mb and such a strong vortex was considered likely to stay fairly deep, at least for the first 24 hours. The surface pressure of the centre was therefore forecast to be 989 mb in 24 hours time. In fact by then it had filled to 995 mb and the depression did not turn east as much as was expected during the second half of the forecast period, probably because the oncoming Atlantic ridge maintained the gradient on its western flank. The errors in the forecasts issued on the prognostic chart were minor compared to the errors which would have been made had earlier forecasts of a continued north-eastwards movement of the centre been maintained.



Photograph by D. Ford

PLATE III—RIME ICE ACCRETION ON THE SUNSHINE RECORDER PILLAR AT THE
MINISTRY OF AVIATION RADIO STATION, LOWTHER HILL, LANARKSHIRE ON 14
FEBRUARY, 1966



Crown copyright

PLATE IV—RIME ICE ON A WOODEN AERIAL MAST AT THE MINISTRY OF AVIATION RADIO STATION, LOWTHER HILL, LANARKSHIRE, ON A DAY IN NOVEMBER 1962
The timbers are 4 inches square, so the rime is about 12 inches thick. The wind was from the north ; the discoloration of the ice is due to the industrial haze from Clydeside.

Conclusions.—The accumulation of experience in the interpretation and use of APT satellite pictures in operational forecasting is providing some convincing evidence of the importance of this new source of observational data and giving new insights into the organization of the cloud, and hence the weather-producing systems of a wide variety of synoptic features. Experience has already shown that it is the exception if no new information can be deduced about the synoptic analysis from a careful study of APT pictures, including information which can be used, if the appropriate associated upper cloud structure is present, to locate jet streams.

As an example of the operational use of satellite data the structure of an Atlantic depression and its movement were deduced several hours before the surface and upper air data were available from the area, making possible a substantially correct assessment of its future movement and intensity. APT pictures have shown their value on many other occasions as a substantial aid in operational forecasting, both in their use in integrating other observed data and in their immediate availability.

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551.509.318:551.513

A NOTE ON THE LARGE-SCALE FEATURES OF THE 1962/63 WINTER

By R. MURRAY

Summary.—The circulations at 500 mb and 1000 mb over the northern hemisphere during the exceptional winter of 1962/63 are briefly described and compared with the long-period average winter circulations. Charts are also given for January 1963 illustrating the main departures from normal, and special reference is made to the features near the British Isles. Temperature and rainfall anomalies for the winter are shown as well as the main anomalous features in January 1963 of the sea surface temperature, snow cover and sea-ice. No convincing explanation is put forward for the large-scale circulation developments though anomalous patterns of sea surface temperature appear to have characteristics which harmonize with large-scale blocking patterns near western Europe.

Introduction.—Other winters have had prolonged spells of very cold weather (e.g. 1878/79, 1890/91, 1894/95, 1916/17, 1939/40, 1946/47), but in the past 100 years only the winters of 1878/79 and 1946/47 approached the severity of 1962/63 over Britain as a whole. Moreover, the 1962/63 winter was the coldest in central England since 1739/40. Notable cold spells over Britain during the third week of November 1962 and early in December 1962 were almost premonitory, but the persistently severe weather finally set in on 22/23 December 1962 and lasted in most places until 4/5 March 1963 when Atlantic air spread north-eastwards and brought a general thaw.

The severe winter over the British Isles was one localized aspect of a winter which was in fact exceptional on a far larger scale, and it is worth discussing some of the unusual features of the hemispherical circulation.

Broad-scale circulation.—The general circulation in the middle troposphere (e.g. at 500 mb¹) in winter is predominantly westerly, but the mean flow has troughs over eastern North America (about 80°W at 50°N) and near the east coast of Asia (about 140–145°E at 50°N) with a much weaker third trough over eastern Europe (about 45°E at 50°N). The troughs at 500 mb are generally cold and the ridges are warm with the result that the average pattern of 1000–500 mb thickness is broadly similar to the average 500 mb flow. The sea-level counterpart of the upper pattern is well known; the main features or ‘centres of action’ are the low-pressure areas to the south-west of Iceland (the ‘Icelandic low’) and near the Aleutians (the ‘Aleutian low’), the subtropical anticyclones in the Atlantic (the ‘Azores high’) and in the Pacific (the ‘Pacific high’) and an extensive continental area of high pressure centred over Mongolia.

It is worth recalling the main differences between the winter circulation of 1962/63 and the normal, long-period average, picture. The European upper trough was much more intense than usual and generally west of its normal position; the American trough was also more pronounced than usual; the third major trough was relatively weak in high latitudes over eastern Asia, but broad-based from southern Japan to mid-Pacific. The corresponding surface pressure patterns were equally abnormal; in particular the ‘Icelandic low’ was virtually non-existent for much of the winter and pressure was unusually high in the Iceland region.

The characteristic feature of this winter was the abnormal degree and frequency of blocking, particularly over the North Atlantic and western Europe but also in the Pacific sector. Blocking was greatest in January as may be inferred from the highly anomalous mean monthly charts for January 1963 shown in Figure 1 for surface pressure and in Figure 2 for 500 mb contours. Particularly noteworthy in Figure 2 are the great amplitudes of the troughs and ridges, the three-trough system and the twin vortices (one north of Hudson Bay and the other near the North Pole). The upper tropospheric and lower stratospheric circulations in January 1963 were broadly similar to the 500 mb flow.

The abnormality of the winter circulation in different longitudes of the northern hemisphere is indicated in greater detail in Figure 3(a) (500 mb) and Figure 3(b) (1000 mb). These figures depict the anomalies of mean geostrophic west-wind between latitudes 40° and 60°N on a 5-day time-scale from early December 1962 to the end of March 1963. The outstanding feature is the stability of the patterns of anomalously weak westerly flow on very large space- and time-scales. It is also striking that the markedly sub-normal westerly flow over the Atlantic and western Europe set in rather suddenly after 20 December 1962, persisted into February 1963 and then gradually changed to a slightly enhanced westerly circulation.

The negative anomaly of westerly flow shown in Figures 3(a) and 3(b) was naturally associated with many other unusual features of the circulation on a regional basis, such as highly abnormal southerly and northerly flow according to the locations of the major long waves, as well as anomalously strong jet streams in certain sectors in very high and very low latitudes.

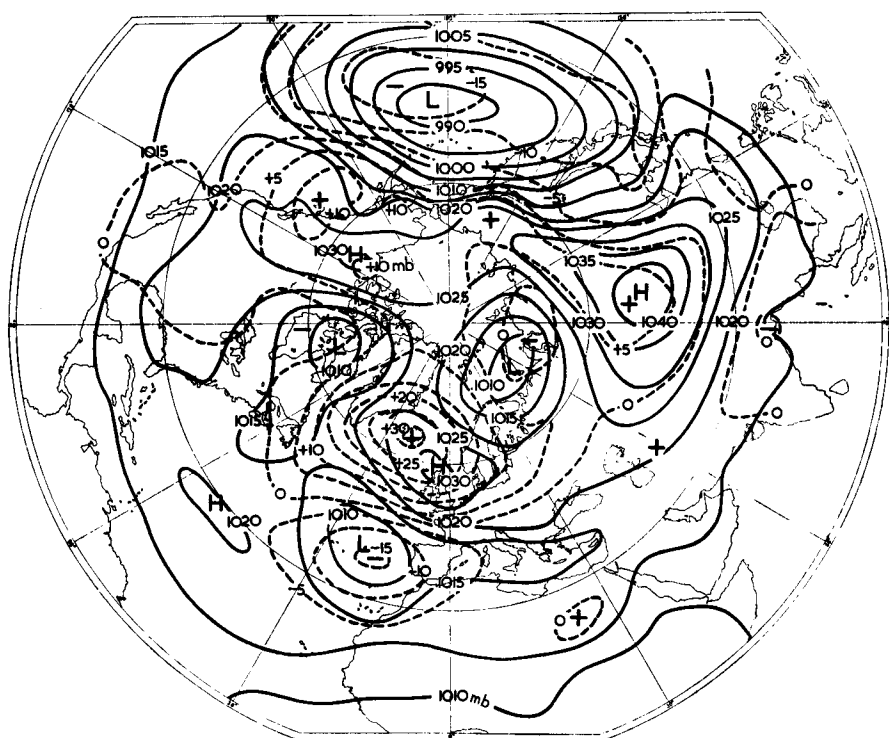


FIGURE 1—MONTHLY MEAN SEA-LEVEL PRESSURE AND ANOMALIES FOR JANUARY 1963

- isobars at intervals of 5 mb
 - - - anomaly isopleths at intervals of 5 mb

Temperature and rainfall anomalies.—The anomalies of air temperature and rainfall in the winter are shown in Figures 4 and 5, where the conventional three winter months are used.

Figure 4 shows the main anomalously cold centres over the Russian Arctic, over central Europe and over America just south of the Great Lakes, as well as equally notable centres of unusually warm air over the Davis Strait and over north-east Siberia. Each of the three winter months had broadly similar large-scale temperature patterns, but the monthly anomalies were greatest in January 1963 (e.g. -10 degC in Poland and $+11$ degC near the Bering Strait).

The broad-scale rainfall distribution is shown in Figure 5. The winter was wetter than average along a characteristic depression track from the Azores to south-eastern Europe (over 200 per cent of normal rainfall at many places), over eastern Europe on the forward side of the upper cold trough, near eastern coastal areas of North America on the forward side of the American cold trough and also over Alaska and western Canada where southerly advection of moist Pacific air was unusually pronounced. Drier than usual weather occurred over a large area from Iceland to north-western Europe where anticyclonic blocking was the dominant circulation feature.

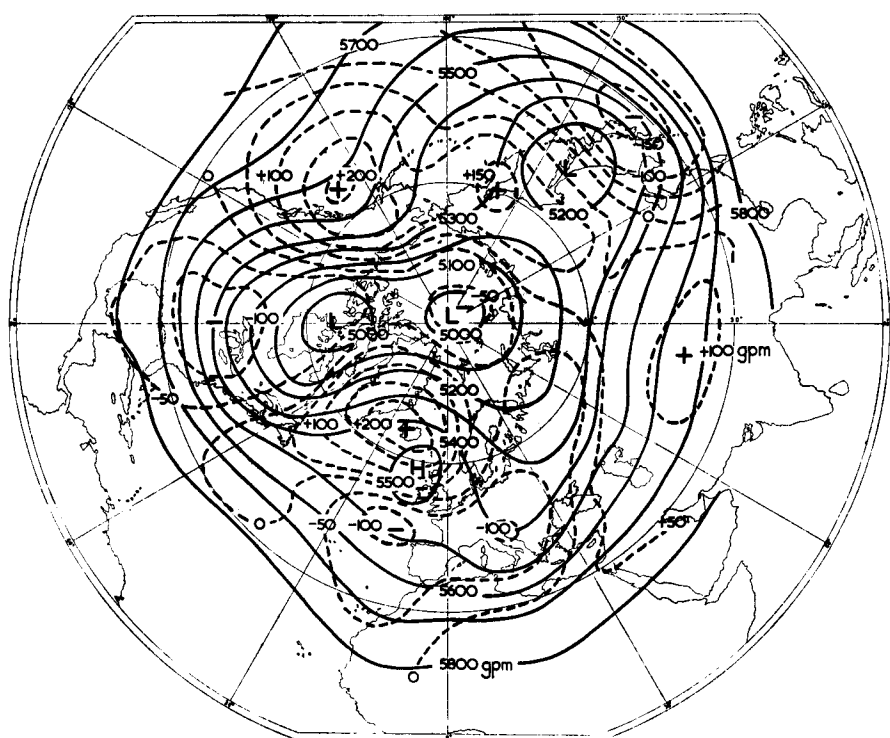


FIGURE 2—MONTHLY MEAN 500 MB CONTOURS AND ANOMALIES FOR JANUARY 1963

- contours at intervals of 100 geopotential metres
- - - - anomaly isopleths at intervals of 50 geopotential metres

The underlying surface.—Figure 6 summarizes the main anomalous features of sea surface temperature, snow cover and polar ice in January 1963 at the height of the severe winter.

Namias² has pointed out that the surface waters of the North Pacific were unusually warm throughout the winter and in the preceding autumn and summer. For example in September 1962 positive anomalies exceeding 1 degC covered much of the North Pacific with a peak of +4 degC at about 42°N 173°W. In January 1963 the peak anomalies were not quite as large as in the preceding months or as in February 1963, but positive anomalies extensively exceeded 1 degC, and the broad-scale sea temperature pattern did not change much.

The North Atlantic sea surface was persistently warmer than usual in high latitudes from near southern Greenland to the southern Norwegian Sea. Early in the winter this anomalously warm area was weakly linked over the eastern Atlantic to an extensive warm band which stretched across the Atlantic in lower middle latitudes. With the onset of the severe weather, the sea temperatures soon became abnormally cold around the British Isles (Figure 6) and ice developed in the North Sea along the coast. Meanwhile an anomalously cold area in mid-Atlantic near ocean weather station 'C'

($52^{\circ}45'N$, $35^{\circ}30'W$) in December 1962 expanded southwards in January 1963 and linked up with an area of slightly cooler than average water already in existence in December in the subtropics. By the end of February 1963 negative anomalies were observed in a band across middle latitudes in the Atlantic and around the British Isles. The limits of snow cover late in January 1963 are indicated in Figure 6. Moreover, snow cover was more general than it usually is over western Europe and the British Isles from late December 1962

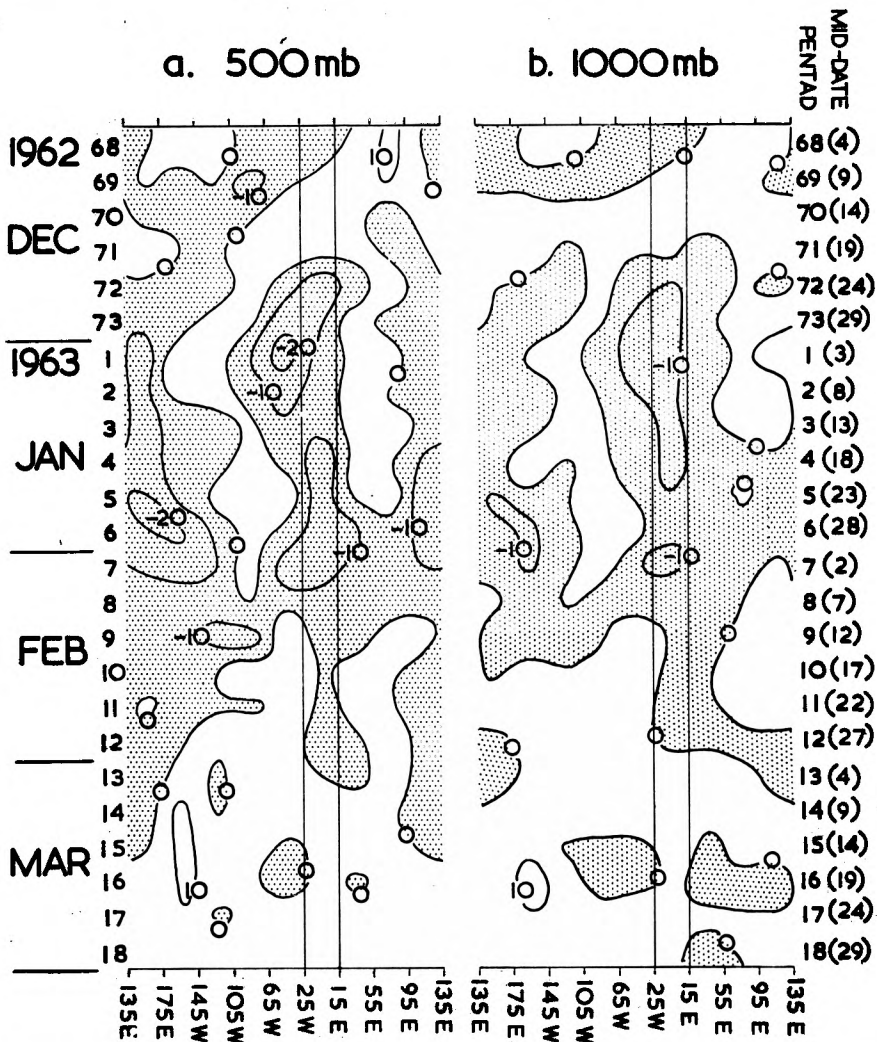


FIGURE 3—ANOMALIES OF 5-DAY MEAN WESTERLY GEOSTROPHIC WIND BETWEEN $40^{\circ}N$ AND $60^{\circ}N$ FOR NINE SECTORS OF THE NORTHERN HEMISPHERE FROM PENTAD 68 (2-6 DECEMBER) 1962 TO PENTAD 18 (27-31 MARCH) 1963 AT (a) 500 MB AND (b) 1000 MB

Vertical lines are drawn at $25^{\circ}W$ and $15^{\circ}E$ to indicate the sector centred over the British Isles

to early March 1963. Throughout the severe winter the area of extensive snow and frozen ground over Europe persisted except during one or two temporary periods of slow thawing near the Atlantic seaboard, chiefly over France, when Atlantic air encroached upon the mainland over limited sectors.

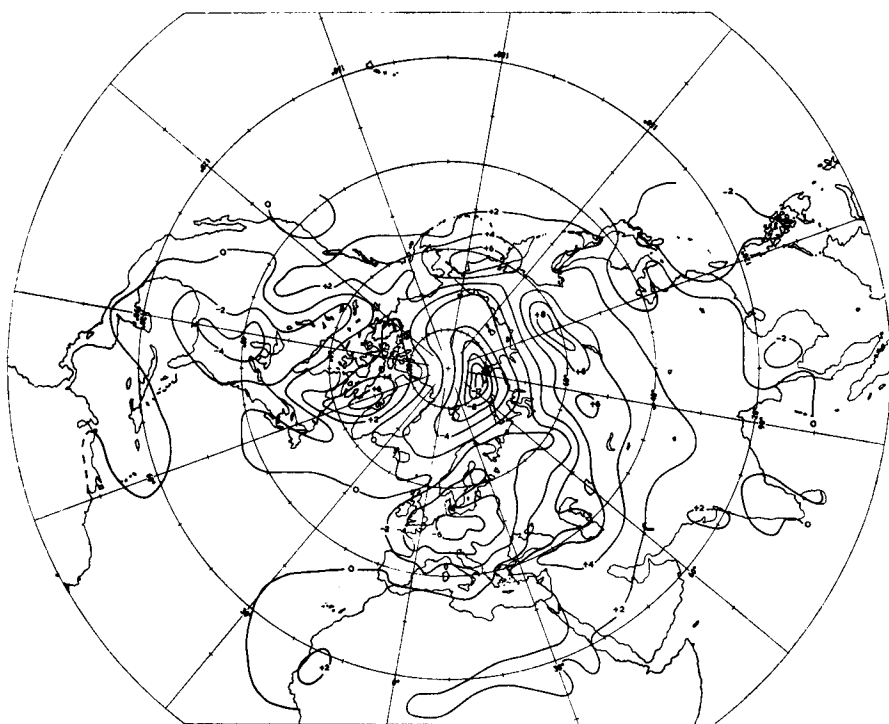


FIGURE 4—SURFACE TEMPERATURE ANOMALIES FOR DECEMBER 1962 TO FEBRUARY 1963

——— anomaly isopleths at intervals of 2 degC

Over America, the boundary of significant snow cover was south of the average position intermittently in December 1962 and more generally so later in the winter. Examination of synoptic charts suggests that there was less snow than usual over south-west Asia but more than usual over eastern Asia ; certainly exceptionally heavy snowfalls occurred over Japan, especially in January 1963.³

As regards the polar ice it need only be mentioned that it was much more extensive than usual off east Greenland and in the Barents Sea in the winter, but the area of the anomaly pattern for excess amounts of ice was on a small scale compared with other surface anomaly patterns.

Discussion.—Namias² has suggested that the persistently warm waters of the central and eastern parts of the North Pacific were the primary cause of the anomalous circulation developments, but this is not yet proven. However, certain repetitive synoptic developments in the North Pacific were

not inconsistent with the existence of an unusually persistent energy source in the abnormally warm surface of the ocean.

In November 1962 the upper flow, unlike later patterns, was mainly zonal and synoptic disturbances generally progressed eastwards on a track in high latitudes to the north of the anomalously warm waters. Early in December the upper westerlies shifted to lower latitudes ; the depressions then travelled

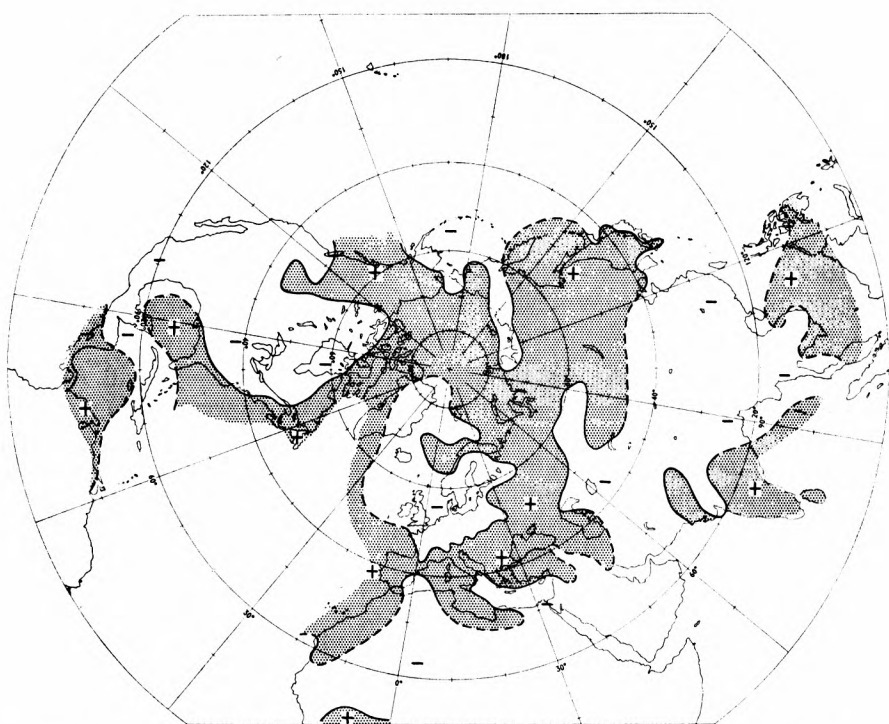


FIGURE 5—AREAS WITH RAINFALL IN THE 1962/63 WINTER BELOW (NEGATIVE) AND ABOVE (POSITIVE) THE SEASONAL AVERAGE

- + above normal rainfall
 - below normal rainfall
 - isopleth of 100 per cent normal rainfall (dashed in regions of scanty evidence)
- Shading is used to indicate areas with above normal rainfall

eastward, deepened considerably near the warm pool of surface water, and turned sharply in a northerly direction between longitude 170°W and 140°W. A strong upper ridge then developed farther east over the eastern Pacific and western America ; immediately downstream the American cold trough extended southwards, whilst farther downstream other oscillations in the upper air pattern were set up. For the rest of December, and indeed throughout most of the winter, cyclonic activity was vigorous near the unusually warm pool of water in the North Pacific and depressions generally turned on a northerly track. The cyclonic development was associated with significant upper-trough extension in mid-Pacific, upper-ridge amplification near the

west coast of America and upper-trough extension over America. Synoptic experience suggests that such highly amplified patterns often lead in turn to marked meridionalities downstream. In December 1962 there was an increasing tendency for amplified patterns in the Atlantic-European sector; a major block eventually evolved when smaller-scale synoptic features phased into the large-scale upper pattern in such a way as to facilitate a marked Arctic outbreak over Europe. Some retrogression of the blocking pattern immediately took place, as was to be expected from wavelength considerations in view of the marked diminution of zonal flow over a wide sector from the Pacific to Europe; the severe winter weather therefore settled in over the British Isles as well as most of Europe.

The large-scale blocking pattern over the Atlantic and western Europe dominated the rest of the winter, despite phases of weakening and intensification, slight progression and retrogression. The synoptic-scale developments of December were repeated in various sectors during the winter and operated in such a way as to maintain a blocking mode; in particular there was repeated cyclogenesis in the east-central Pacific with warm upper-ridge amplification near the west of North America and Arctic outbreaks in broadly the same longitude bands over America and Europe.

The importance of the sea surface temperature over the North Atlantic in helping to stabilize the blocking mode is not clear. However, it is probably significant that some features of the sea surface temperature anomaly pattern, namely the positive anomalies in high latitudes and negative anomalies farther south in an area including ocean weather stations 'C' and 'D', were broadly analogous to those shown on a map of mean sea surface temperature anomalies, prepared by Namias,⁴ for the 27-month period from September 1958 to November 1960 when frequent blocking occurred over and near western Europe. This type of sea surface temperature distribution thus appears to have some characteristics which harmonize with large-scale blocking. Certainly some computations (not reproduced here) of fluxes of latent and sensible heat at the Atlantic ocean weather stations for each of the winter months, show anomalies that appear to be broadly consistent with the anomalous lower-level circulation and the associated surface air

FIGURE 6—*Explanatory notes.*

(a) Sea surface temperature anomalies

Isopleths of anomaly are drawn for 0, -2 and -4 degC.

Note: sea surface temperature anomalies over the North Pacific for January 1963 are after Renner⁵ and over the North Atlantic for the 10-day period 21-30 January 1963 are based on harmonically smoothed long-period normals from M.O. 527.⁶

(b) Snow anomalies

— Overland — position of the one-inch snow limit over Europe on 27 January 1963 and over North America on 28 January 1963.⁷

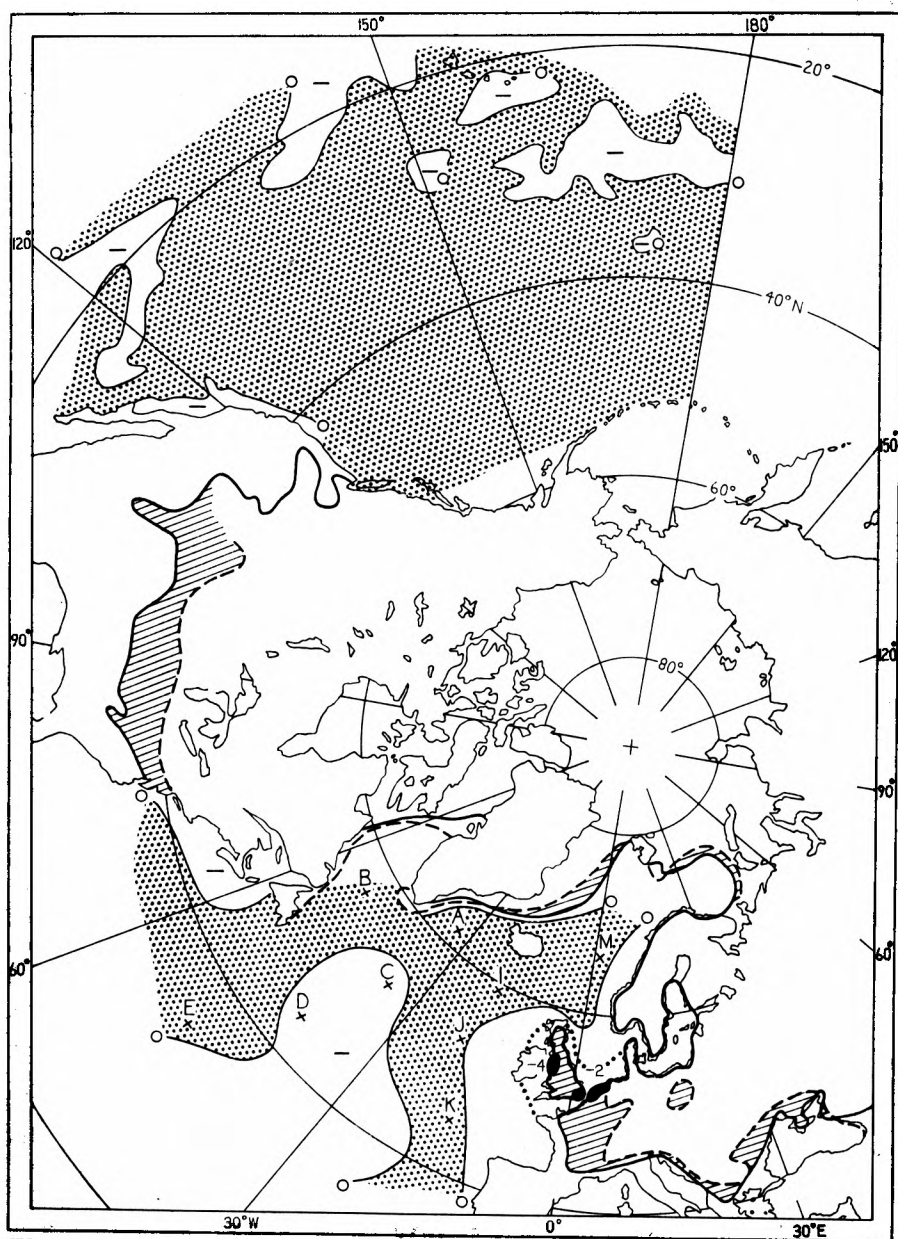
— — — Overland — normal position of one-inch snow limit on 31 January.⁸

(c) Ice anomalies

— Oversea — position of Arctic ice limit (i.e. 5/10 or more cover) at end of January 1963.

Note: open water over Baltic but general ice in Gulfs of Bothnia and Finland with patches near the coasts of the southern North Sea and Baltic.

— — — Oversea — normal position of Arctic ice limit at end of January.



Above normal sea surface temperatures.
 Sea surface temperature anomaly $>-4^{\circ}\text{C}$ (Irish Sea and southern North Sea).
 Oversea-excess ice; overland-excess snow.

FIGURE 6—COMPOSITE MAP SHOWING THE PHYSICAL STATE OF THE LAND AND SEA SURFACE FOR VARIOUS PERIODS IN JANUARY 1963

See facing page for explanatory notes.

temperature and humidity. For instance, both sensible and latent heat fluxes at ocean weather station 'A' to the south-west of Iceland were below the averages for the period 1950-59, as might be expected qualitatively in view of the weaker winds and moister and more stable air associated with the anticyclonic block in the north-eastern Atlantic.

Another factor of significance was the development of very cold surfaces early in the winter in relatively low latitudes over Europe, America and eastern Asia under the large-amplitude cold upper troughs. The European trough in particular was associated with unusually extensive snow and frozen ground as far south as about 45°N over western Europe, and this favoured intense radiational cooling in the frequently cloudless weather over central and western Europe associated with an airflow from the abnormally cold source in the European Arctic.

An unusually cold surface may help to maintain a cold upper-trough position over a few days. However, unless the circulation itself favours the persistence of a cold surface there will normally be a gradual warming; therefore the abnormal cold surface is not likely to be the major factor controlling the upper-trough position over many weeks.

So far it has not been possible to give a convincing explanation of large-scale circulation developments of the 1962/63 winter. It appears that the physical state of the underlying surface contributed to the stability of the blocking mode, but the complexity of the physical and dynamical feed-back effects on all time-scales is a formidable obstacle to our understanding of general circulation problems. It is hoped that a radical advance in both understanding and prediction will ultimately come from intensive attacks on these problems by modern numerical methods.

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REVIEW

Climates of the U.S.S.R. by A. A. Borisov. 10 in \times 6 $\frac{1}{4}$ in, pp. xxi + 255, *illus.* Oliver and Boyd Ltd, Tweeddale Court, 14 High Street, Edinburgh 1, 1965. Price : 75s.

The Russian contribution to observational meteorology and to the literature of climate has been great, and this good straightforward text on climatology continues a fine tradition. Translated by R. A. Ledward from the Russian

edition of 1959, and edited by C. A. Halstead, Lecturer in Geography at the University of Glasgow, it is a commendable work of its kind and it includes a great deal of interesting information, with a useful bibliography. There is a very thorough opening chapter under the title of climate-forming factors, beginning with the radiation régime, and followed by the atmospheric circulation and the characteristics of the air masses with good comments on frequency and on rate of modification. The third section discusses the moisture cycle. It appears that as a result of the work of man in southern Russia the components of the moisture cycle have substantially changed. One can indeed appreciate that determined Russian faith in the prospect of modification of the iron grip of his climate. Recalling the effects of the great Pleistocene water bodies that accompanied the ice age further north, their efforts might fairly derive some encouragement.

It is interesting to read that the average annual radiation balance is deemed to be positive throughout the U.S.S.R. except in the Arctic and other glacial areas ; and there are some informative radiation maps. One can pick out many plums, such as those on p. 27 where a nice table of the number of fronts per annum in different areas is accompanied by a most intriguing map associating the differing extension of ridges of high pressure in the warm and cold halves of the year with the limits of occurrence of certain forest trees.

The style is not without interest to western readers. Frequently the opinions of earlier authorities are compared and criticized against those of their successors and it is evident that the masterly logic of the newer generation prevails. None the less, the work of the great Russian climatologist Voeikov, in the Köppen-Buchan era, is cordially acknowledged. Appropriate regard too is paid to the earlier Lomonosov, who was indeed a surpassingly accomplished scientific pioneer ; although he is here credited with the invention of the anemometer, which many will incline to question. That the first regular notes on the weather were made in the 17th century by watchmen appointed to the Kremlin guard for retention in a secret office seems very proper.

Meteorologists who enjoy the décor of the Moscow hotels will find the solid qualities of this work a little old-fashioned but comforting. Much of it is reminiscent of the earlier Kendrew, although one cannot conceive that classically minded scholar allowing the use of that dreadful word *isoline*. Geographers will rejoice in the folded maps and others accompanying the critical discussion of classification of regional climates, in which we are led steadily forward to the genetic classification of Alisov. Regional discussion occupies the later part of the book. There is a good chapter on the climates of the seas ; then come the plains and lowlands, and the mountainous areas. Industrialization influences the annual duration of bright sunshine at Leningrad ; with about 1390 hours this approaches 10 per cent less than that of the surrounding country, an effect comparable with, and perhaps exceeding that of London. There is much comment on the remarkably sunny and calm climate of the Yakutsk region along the middle Lena, in addition to the more familiar features around Lake Baikal. The dry warm south-east to east winds — the *sukhovei* — that cause so much loss of moisture in the marginal agricultural areas bordering the semi-desert steppe are noteworthy, and it is interesting to hear of a 'dry fog' around the Sea of Aral (p. 133) that has not been fully studied. Air-mass frequencies for Central Russia appear to differ on p. 160 from those on p. 95.

We have long appreciated the Russian regard for their vast and spacious land ; it is attractively brought to our minds in the elegant quotation from Turgenev on p. 164. Russian climatology as presented in this book makes a welcome product of a country whose climate is indeed real. Even the most ruthlessly dynamical meteorologist will not fail to find food for thought if he browses among the abundance of well-presented factual material that has been integrated in this commendable work.

G. MANLEY

NOTES AND NEWS

State Meteorological Service of the Federal Republic of Germany

Official notification has been received that Dr E. Süssenberger has succeeded Dr G. Bell as Director of the Deutscher Wetterdienst. Dr Bell retired on 31 July 1966.

METEOROLOGICAL OFFICE NEWS

Dr F. Pasquill—Special Merit Promotion to Deputy Chief Scientific Officer

In 1954 Dr F. Pasquill was promoted to Senior Principal Scientific Officer under the scheme which permits the promotion of scientists of exceptional ability in research without any consequential change in their administrative responsibilities. Since that time Dr Pasquill has continued to be a leading international figure in the study of turbulence and diffusion in the lower atmosphere, and has made several important contributions to the subject. His many colleagues will be delighted that his work has been recognized by his further promotion to Deputy Chief Scientific Officer.

Dr Pasquill's work since 1954 has been carried out first at the Chemical Defence Experimental Establishment at Porton and latterly at the Meteorological Office Headquarters at Bracknell. On the theoretical side he has made contributions to the applications of modern similarity theory to atmospheric turbulence and diffusion. He has also initiated important experimental work in measuring the turbulent energy in the lower atmosphere and in determining the diffusion of airborne material over distances of tens of miles. Dr Pasquill has also been responsible for significant advances in the application of knowledge of atmospheric turbulence to the practical problems of estimating the dispersal of chimney effluents and other aerosols and his book 'Atmospheric Diffusion', published in 1962, fills a serious gap which previously existed in the meteorological literature.

The Meteorological Office is fortunate that as a D.C.S.O. Dr Pasquill will be able to continue to devote his efforts to the important problems of atmospheric turbulence and diffusion.

J.S.S.

Retirement of Mr J. C. Cumming

Mr J. C. Cumming, O.B.E., M.A., retired from the Meteorological Office on 10 August 1966 after more than 36 years service.

Born in Inverness in 1907, Mr Cumming was educated at Robert Gordon's College, Aberdeen, and at Aberdeen University where he read mathematics and natural philosophy.

After graduating, he joined the Office in 1930 as a Junior Professional Assistant in Met.O.4 then in Met.O.2. Appointments at Renfrew, Lerwick and Upper Heyford were followed by a posting in 1938 to Croydon. Overseas service from 1939 to 1943 included posts in Egypt and Palestine and was followed by posts at HQ No. 2 Group, RAF, and with the Four Powers Allied Control Commission in Berlin. Demobilization brought him back to take charge of the Empire School of Navigation Meteorological Office at Shawbury from 1947 to 1949.

For the next 17 years 'Jock' Cumming served civil aviation, firstly at London Airport, then as Head of the Civil Aviation Branch and finally as Chief Meteorological Officer at LAP.

During these 17 years both the LAP Meteorological Office and the demands made on it grew apace from the personalized service given to a relatively few piston-engined aircraft of the late 1940's to the vast forecast factory of today, serving the latest generation of jet airliners not only at LAP but also at many other airports in Britain through the recent development of CAMFAX, the facsimile forecast service for civil aviation centred on LAP as the source. For the major part of this period 'Jock' Cumming was at the helm steering a difficult course between what is technically desirable and what is operationally possible. The existing high regard that aircrew have for LAP Meteorological Office is sufficient tribute to his skill in this role.

Shrewd and knowledgeable in argument with an impish delight in playing 'the Devil's advocate' he gained the unstinted respect of both the Airport Authorities and the Operators. The welfare of his staff and the good name of LAP Meteorological Office were always near to his heart and he was ever quick to rise to their defence.

He is widely known in many parts of the Western civil-aviation world both to foreign meteorologists and to airline operators to many of whom 'Jock' Cumming and LAP Meteorological Office are synonymous.

During the 1950's he was a member of the United Kingdom delegation at many meetings of both the International Civil Aviation Organization and the World Meteorological Organization and his knowledge of procedures and recommendations became prodigious.

In the New Years Honours List of 1953 Mr Cumming was made an Officer of the Order of the British Empire.

Mr Cumming is retiring to the West Country and his many friends, both inside and outside the Office, will join me in wishing him and Mrs Cumming many years of happiness in their well-earned retirement.

L. SUGDEN

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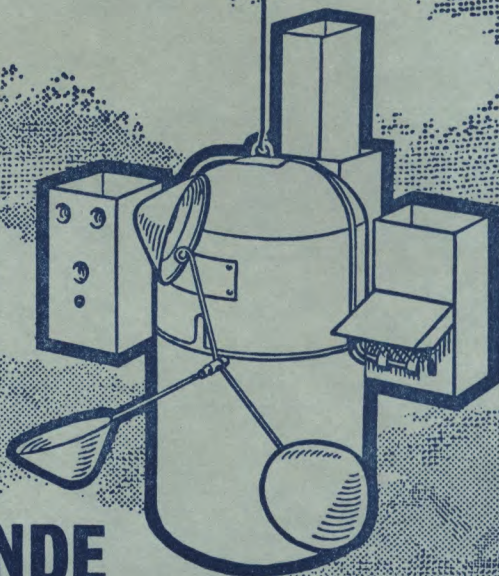
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CONTENTS

	<i>Page</i>
The accuracy of long-range forecasts issued by the Meteorological Office. M. H. Freeman	321
A note on the use of hourly rainfall observations. D. E. Jones	325
Satellite pictures of an old occluded depression and their usefulness in analysis and forecasting. I. J. W. Potheary and R. A. S. Ratcliffe	332
A note on the large-scale features of the 1962/63 winter. R. Murray	339
Review	
Climates of the U.S.S.R. A. A. Borisov. <i>G. Manley</i>	348
Notes and news	
State Meteorological Service of the Federal Republic of Germany	350
Meteorological Office news	
Dr F. Pasquill — Special Merit Promotion to Deputy Chief Scientific Officer	350
Retirement of Mr J. C. Cumming	351

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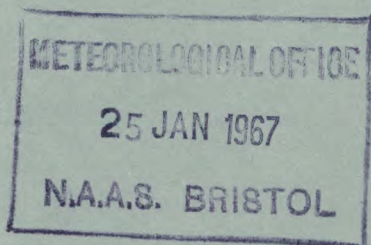
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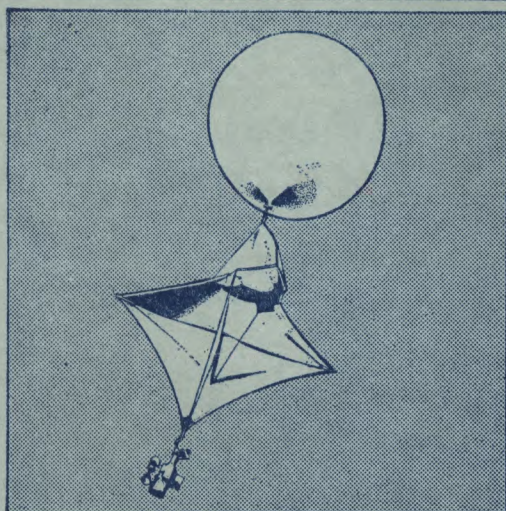
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CROSS-EQUATORIAL JET STREAMS AT LOW LEVEL OVER KENYA

By J. FINDLATER

Summary.—Mean monthly winds up to 10,000 ft for an equatorial station in East Africa have been calculated. Considerable differences are noted from comparable values for Nairobi. High-energy flow, in the form of low-level jet streams, has been observed during the period of the south monsoon, and the associated vertical shears have attained remarkable values.

Introduction.—Since 1963, reports have been received from aircraft operating at low levels over the North Eastern Province of Kenya that, on occasions, winds in the height band 4000–7000 ft above MSL have been very strong and on at least two occasions aircraft flying at 80–100 kt have been unable to make much headway against them. The area is sparsely populated and most of the international air traffic flying over north-east Kenya does so at heights in excess of 10,000 ft; that these winds have received scant attention has been because of the lack of low-level air traffic, the relative infrequency of really extreme winds, and the fact that the only regular series of pilot-balloon soundings in the area, at Garissa, commenced as late as 1962. In a private communication, however, Mr J. E. B. Raybould has stated that the existence of these strong winds was suspected in the years 1944–46. Since that period occasional reports of strong wind have been received by the East African Meteorological Department.

Sufficient pilot-balloon data have now been accumulated to enable an analysis to be carried out and this paper furnishes mean monthly winds up to 10,000 ft above MSL for one observing station in the area, and discusses some of the extreme winds which have been measured. These extreme winds, with one exception, were all from a southerly point and occasionally reached peak speeds of 90–100 kt well below the 10,000-ft level.

The monsoon pattern.—The area to which this paper refers lies astride the equator and on the western edge of the great monsoon system which may be considered as starting with the south-east trade winds of the southern Indian Ocean. These winds (see Figure 1) curve through Madagascar and the Comores Islands as south-easterlies to become southerlies over the coastal strip of East Africa and the adjacent sea areas in the vicinity of the equator. North of the equator the winds curve to south-south-westerlies at Mandera

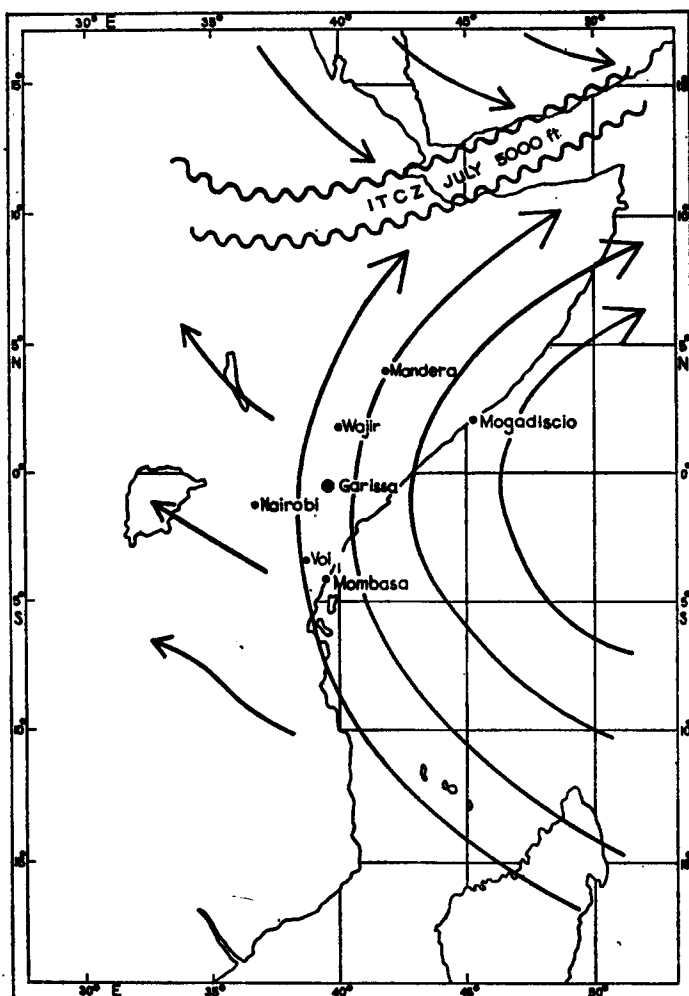


FIGURE 1 — LOCATION OF STATIONS AND GENERAL PATTERN OF STREAMLINES AT 5000 FT IN JULY

and to south-westerlies over the northern parts of Somalia. Thence the winds travel across the northern Indian Ocean as the south-west monsoon. This monsoon, which blows from about May to September, is barely traceable on the higher ground of East Africa, as shown by Ramsey's analysis of winds at Nairobi.¹ Nevertheless the southerlies blow over the flat low-lying areas of Tanzania, Kenya and Somalia east of longitude 38°E with considerable force. South of the equator this wind is known as the south-east monsoon and north of the equator as the south-west monsoon. Since the mean direction at the equator is from almost due south all further references in this paper to results for Garissa will be to the south monsoon. References to the south-east and south-west monsoons will be to the monsoon at some distance from the equator, southwards and northwards respectively.

From December to February or March the north-east monsoon from Arabia blows over Kenya and the adjacent areas of the Indian Ocean, but wind speeds are generally light.

Patterns of average streamlines for July, at the 5000-ft level, are shown in Figure 1 and stations to which reference is made in the text are shown also.

Data used.—Pilot-balloon ascents have been made since January 1962 at Garissa whose position, latitude $00^{\circ}29'S$ longitude $39^{\circ}38'E$, lies in the flat semi-desert area of the North Eastern Province of Kenya. The altitude of the station is 420 ft above MSL.

A total of 614 soundings were available and only winds up to 10,000 ft were considered since the aim of the investigation was directed towards winds which might prove hazardous to aircraft operating at low level. Data were carefully scrutinized to omit winds whose accuracy was in doubt, and after these restrictions had been made 4758 individual winds remained for analysis. Many of the soundings did not reach the 10,000-ft level because of cloud or strong winds.

The extreme speeds recorded on some of the ascents are such that their validity might be questionable. Possible errors might be due to :

- (i) Leaking balloons
- (ii) Lee-wave effects or convection
- (iii) Incorrect computation.

Causes (i) and (ii) could result in incorrect high wind speeds when the assumed constant rate-of-ascent technique is used. However, it is noteworthy that many of the cases of high wind speed at Garissa have been confirmed by aircraft flying in the area, by high winds being recorded on the same day at Voi, Mombasa, Mogadiscio or Mandera, and by the Garissa balloon being lost in the distance at low heights. Also, the terrain is flat and is unsuitable for the generation of lee waves. Convection currents could result in either high or low wind speeds being recorded, but very wide and sustained down-draughts of the magnitude necessary to produce really high speeds from the computation are unlikely. No aircraft reports are known of lee waves in the area, and convection patterns at low level tend to be so narrow that interference from them, over a period of a few minutes, would most likely be self-cancelling. A few cases of incorrect computation have been noticed and where possible these have been corrected. When it has not been possible to correct computational errors the winds have been neglected.

In view of the foregoing it is considered that the winds which have been used in the analysis are reasonably accurate within the limitations of the constant rate-of-ascent technique.

Upper winds at Garissa have been measured at many daylight hours of the day but in the analysis they were grouped into morning and afternoon ascents only. Morning ascents were those between dawn and 0900 GMT, and afternoon ascents thereafter. Local time in the area is three hours in advance of GMT.

Analysis and discussion.—

Monthly mean winds.—For each 1000-ft level up to 10,000 ft, with the exception of the 9000-ft level for which no winds were calculated, monthly mean winds have been computed separately for morning and afternoon.

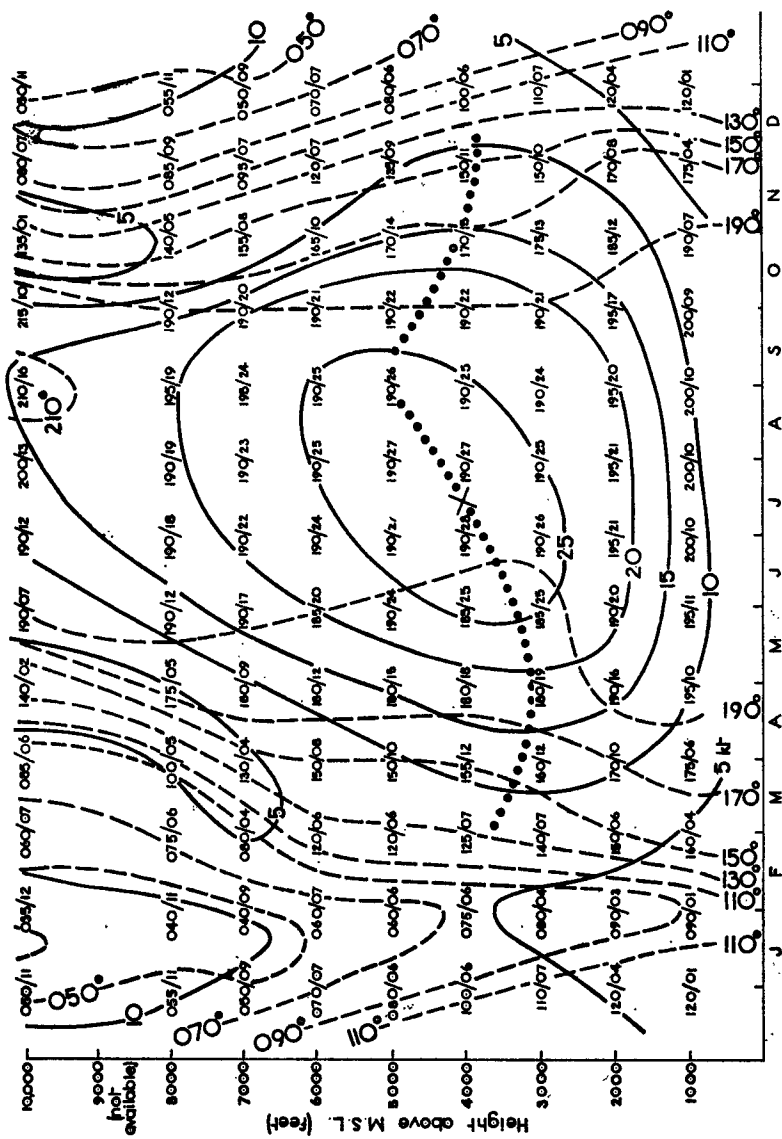


FIGURE 2—MEAN MONTHLY UPPER WINDS AT GARISSA, KENYA FOR 1962 TO 1964 INCLUSIVE
Means have been computed using one month overlapping (see text) and results are ascribed to the first day of each month.
— Isogons ; ——— Isotachs ; Level of maximum wind ; X=Core of south monsoon.

Several of the mean values showed irregularities in speed which might have been due to the inclusion of extreme values in some classes where the total number of soundings was few. To obtain an overall view of the monsoon pattern at Garissa, morning and afternoon soundings were combined and means computed using an overlap of one month, the results being ascribed to the first day of each month, e.g., January and February averages were combined and the resulting mean value was ascribed to 1 February. These results are shown in Figure 2.

Several features of interest are apparent in Figure 2. The south monsoon and the north-east monsoon are clearly defined, and are separated by winds of less than 10 kt associated with closely packed isogons. The south monsoon is dominant at low levels from March to November, reaching peak mean speeds in June, July and August and attaining its greatest depth, somewhat more than 10,000 ft, in August and September. Peak speeds generally occurred between 3000 ft and 4000 ft during the first half of the monsoon, and between 4000 ft and 5000 ft during the second half. In the whole of the south monsoon period the mean wind direction is nearly constant from 190° .

The north-east monsoon is mainly an upper feature and it barely reaches down to the 1000-ft level in January and February, and mean speeds are only about 10 kt even at 10,000 ft. Ramsey, in his analysis of upper winds at Nairobi (Dagoretti) ($01^{\circ}18'S$ $36^{\circ}45'E$, height 5900 ft), noted that the north-east monsoon extended over a longer period at 10,000 ft than at lower levels. Only from July to September was the north-east monsoon absent at 10,000 ft at Nairobi. Results for Garissa broadly confirm this finding, but the persistence of the north-east monsoon is less marked than at Nairobi. At Garissa it is evident at 10,000 ft into April, about a month after it has disappeared from lower levels, and it reappears at 10,000 ft in November.

In the case of the south monsoon the patterns for Nairobi and Garissa are quite different. Ramsey noted that, for the 10,000-ft level at 0000 GMT, little trace of the south monsoon could be found, but at 1200 GMT it could just be discerned in the months from June to September inclusive. At Garissa however, the dominance of the south monsoon is in striking contrast to the pattern for Nairobi. Monthly mean winds at 5000 ft and 10,000 ft at Garissa are plotted on a polar diagram in Figure 3(a) to illustrate these effects, and from Ramsey's published data a similar diagram, Figure 3(b), has been prepared for winds at 10,000 ft at Nairobi, showing also the diurnal changes at that level. Comparison of the two diagrams reveals the marked changes between the two stations. It is evident that the south monsoon blows over the flat low-lying eastern part of Kenya with considerable force, yet it hardly affects the highland areas a little further to the west. On the other hand, the north-east monsoon which is just discernible at low levels at Garissa is well in evidence at Nairobi.

Extreme speeds — south monsoon.—The mean speed of the core of the south monsoon for the period investigated was about 28 kt (Figure 2), but frequently speeds rose to over 40 kt and on a number of occasions reached speeds of 60–100 kt at surprisingly low levels. An analysis of all core speeds in excess of 40 kt has been made and related to the height of the core. The results, as shown in Table I, reveal that of the 101 cases where core speeds were ≥ 40 kt, most occurred at or below 7000 ft. It would seem that there are two favoured levels for very high core speeds, 4000 ft and 7000 ft, and at

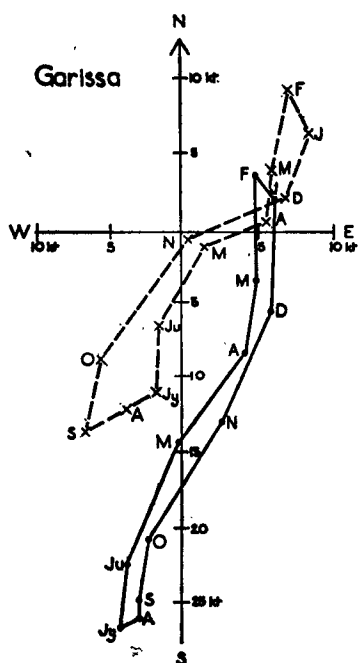


FIGURE 3(a) — MONTHLY MEAN WINDS AT 5000 FT AND 10,000 FT ABOVE MSL AT GARISSA, KENYA FOR 1962 TO 1964 INCLUSIVE

— = 5000 ft; x — x = 10,000 ft.

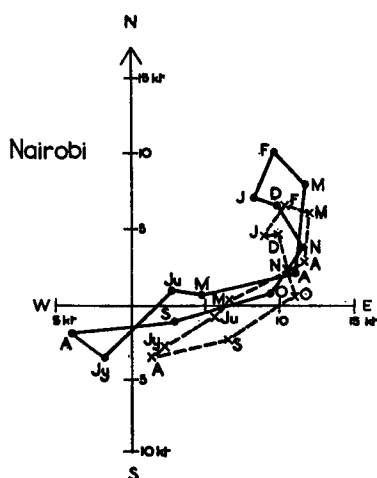


FIGURE 3(b) — MONTHLY MEAN WINDS AT 10,000 FT ABOVE MSL AT NAIROBI, KENYA (FROM DATA GIVEN BY RAMSEY¹ FOR 1959-63)

— = 10,000 ft; x — x = 1200 GMT.

both of these levels wind speeds of over 90 kt have occurred. From Figure 2 it has already been noted that the mean level of maximum speed lies between 3000 ft and 5000 ft, but the really high-speed cases occur most often at 4000 ft or 7000 ft.

TABLE I—OCCURRENCES OF CORE SPEEDS RELATED TO HEIGHT OF CORE (Based on 101 cases during the south monsoon at Garissa in the years 1962-64 inclusive, where core speed ≥ 40 kt.)

Height of core of maximum wind above MSL (ft)	Speed of core of maximum wind (kt)						All speeds
	40-49	50-59	60-69	70-79	80-89	90-99	
10,000	4	2	1				7
9000			winds not computed for this level				
8000	5	1		1			7
7000	5	3	4			2	14
6000	6	3	2	1			12
5000	13	5					18
4000	12	5	3		1	1	22
3000	14	3	2				19
2000	1	1					2
1000							0
All heights	60	23	12	2	1	3	101

The highest wind speed which has been measured in the south monsoon at Garissa during the period of the analysis is 150°/98 kt which was recorded on the afternoon of 5 April 1963 at 7000 ft. The highest speed recorded at 4000 ft was 190°/91 kt on the morning of 26 May 1963.

The high wind speeds, when they do occur, do so in very shallow layers in similar fashion to that of jet streams at high level. To illustrate the variation of wind with height, 18 cases where the wind speed at Garissa was ≥ 60 kt are plotted in Figure 4 to compare the profile of speed above and below the level of maximum wind. All of these cases occurred during the south monsoon, and the average direction of the 18 cases was 183°. The profiles show some remarkable shear values; the maximum value of shear recorded above the core was 71 kt/1000 ft and the maximum below the core was 46 kt/1000 ft. On a number of occasions a secondary core occurred 2000 ft to 3000 ft below the main core.

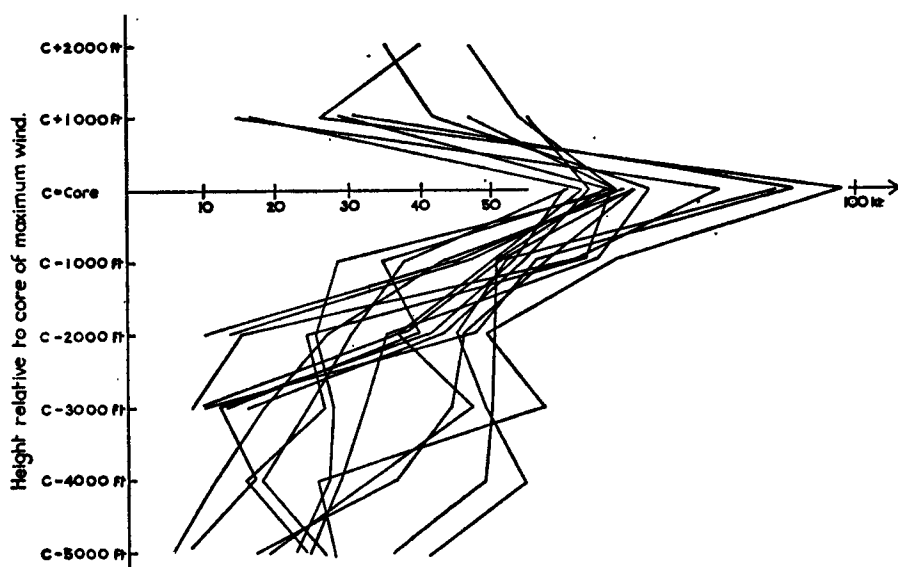


FIGURE 4—PROFILES OF SPEED FOR 18 CASES WHERE CORE SPEED ≥ 60 KT
 Ascents on which speeds of 60 kt or more were recorded are considered as having reached the core of the stream even though the true maximum speed may not have been recorded.

Riehl,² in a comprehensive study of jet streams at high level, refers to a case of high-level shear of 20 kt/1000 ft as 'extraordinary' but he adds that it is as yet uncertain how large vertical shears can become. The shears reported from Garissa are remarkable, and the only other shears of this magnitude to which reference can be found are those reported by Crossley.³ Pilots of aircraft who have met the extreme winds over Kenya have reported that by changing altitude by 2000 ft or 3000 ft, either upwards or downwards, they found that their observed wind speed was reduced by half or more.

Turbulence near the layers of fast-moving air has been reported as being of the 'cobblestone' or high-frequency judder type although the aircraft have been flying at speeds of about 100 kt.

Cloud in the area during the occurrence of high wind speeds is usually in the form of morning stratocumulus which lifts and breaks during the day to become cumulus fractus in the region of strong shear below the level of maximum wind. A few cases of cloudless skies have been noted also.

A profile of mean speeds, based on the eighteen cases where core speeds were ≥ 60 kt in the south monsoon, is shown in Figure 5. Average values of vertical shear are 38 kt/1000 ft above the core and 21 kt/1000 ft below, and the general form of the average (and individual) profile is similar to that noted by Riehl.² He states that :

- (i) Vertical shear and maximum wind are often correlated ; the stronger the jet stream, the stronger the vertical shear above and below the core.
- (ii) Vertical shear just above the core of a jet stream is usually greater than that just below the core.
- (iii) Most jet streams show little change of direction with height.

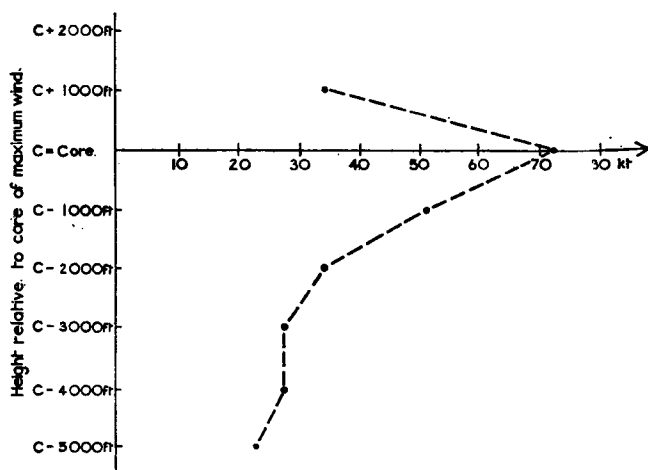


FIGURE 5—MEAN PROFILE OF SPEED ABOVE AND BELOW CORE

(Based on 18 cases where core speed ≥ 60 kt.) Average shear above core = 38 kt/1000 ft. Average shear below core = 21 kt/1000 ft. Note : few soundings reached more than 1000 ft above the core.

The Garissa profiles in Figures 4 and 5 show that they conform to the characteristics (i) and (ii) above and an inspection of the individual soundings confirms that characteristic (iii) is satisfied also.

Extreme speeds — north-east monsoon.—During the north-east monsoon upper wind speeds are generally much lighter than in the south monsoon. Only one case was recorded at Garissa where the speed of a north-easterly wind exceeded 40 kt below 10,000 ft. This occurred on 30 January 1964 when the wind at 5000 ft was 040°/65 kt. Since no other occurrence of high speed in the north-east monsoon has been observed, the solitary case has been omitted from the analyses of Table I, Figures 4 and 5, and the foregoing discussion. In the private communication referred to earlier, however,

Raybould has commented that on a few occasions high speeds in the north-east monsoon were noted over Kenya and Uganda in the period 1944-46, but these were recorded in highland areas where the topography could generate pronounced lee waves or cause the airflow to be channelled.

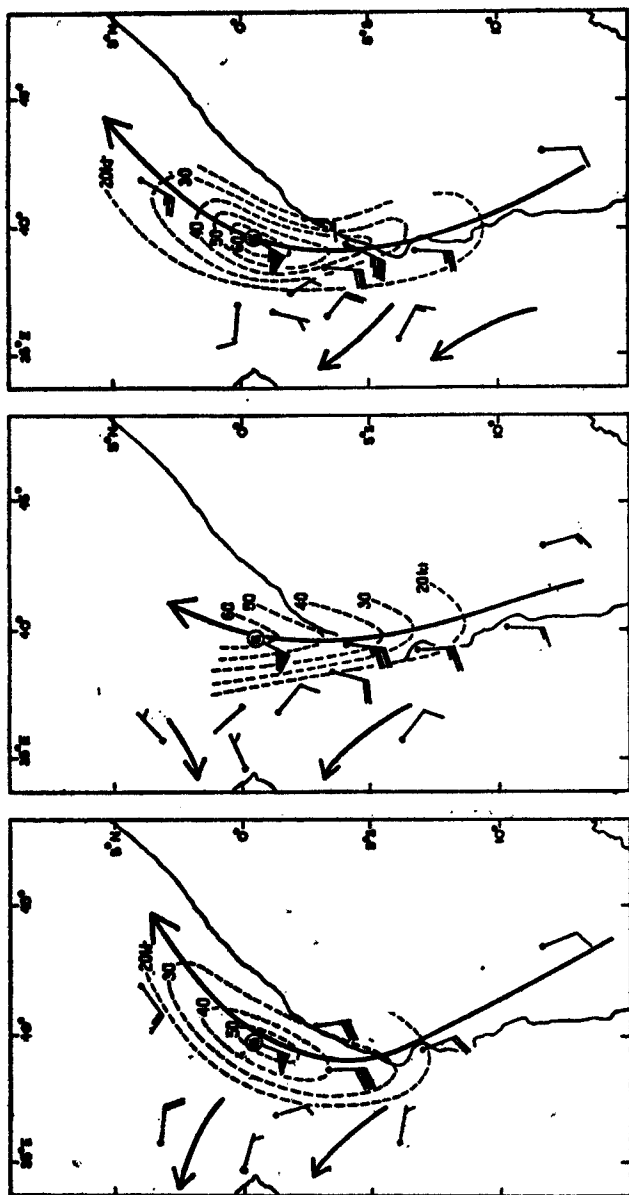
Extreme speeds — Persistence.—In the south monsoon speeds of 60 kt or more do not appear to exist at Garissa for very lengthy periods. On most occasions the time period over which high speeds occur at any one level at Garissa is about 12 to 48 hours.

Extreme speeds — Horizontal extent.—From the foregoing paragraph it is apparent that the core of highest speed varies in height and is associated with very strong vertical shears. Reports indicate also that the core moves horizontally to a limited extent along the general pattern of streamlines but since this analysis was restricted to Kenya it is not at present known if the core of high speed is restricted to an area near the equator or if it moves into Kenya from the south and passes through the country. There is also a suggestion from pilots' reports that the core may be found to the east of Garissa on some occasions. Although the network of upper wind reporting stations is not dense, it is known that the strong southerlies do not affect Nairobi. It is evident also that when extreme winds (≥ 50 kt) occur at Garissa, high speeds (≈ 40 kt) are sometimes, but not always, reported from Mombasa, Mandera or Mogadiscio on the same day. Thus it is clear that strong lateral shears exist and in the case of the section from Nairobi to Garissa it is known that the shears are often concentrated along the edge of the high ground at about 38°E . In the mean, lateral shears at 7000 ft between Nairobi and Garissa in July are about 20 kt/150 n. miles but this value must be more than trebled when very high speeds are recorded at Garissa. Eastwards from Garissa values of lateral shear appear to be considerably less than those to the west.

Charts have been plotted for the 5000-ft level and several cases have been selected to show the horizontal extent of the high-speed flow. These cases, illustrated in Figures 6(a)–(f), were chosen because a sufficient number of pilot-balloon reports were available to permit isotachs to be drawn with reasonable confidence, but it does not follow that 5000 ft was the level of maximum wind in each case. For example, a wind speed at 5000 ft (≈ 850 mb) of 65 kt at Garissa is shown in Figure 6(c) but this value is not included in Table I because the core lay at a higher level in this case.

It will be noted that the six examples illustrated all show high-speed flow from a south-south-westerly direction although it has been pointed out previously that the average direction of the high winds at Garissa is from almost due south. The reason for the bias is that when winds are from south or south-south-east the onshore winds at the coast produce low cloud which restricts the number of balloons reaching the 5000-ft level, thus precluding accurate isotach analysis.

With regard to the maximum speeds recorded at Garissa, the velocity and shear profiles which have been discussed, the horizontal dimensions of the high-speed flow evident in Figures 6(a)–(f), and the associated lateral shears, there is a marked similarity between the flow described here and the well-documented high-level jet streams. The World Meteorological Organization definition of a jet stream⁴ relates specifically to streams in the upper



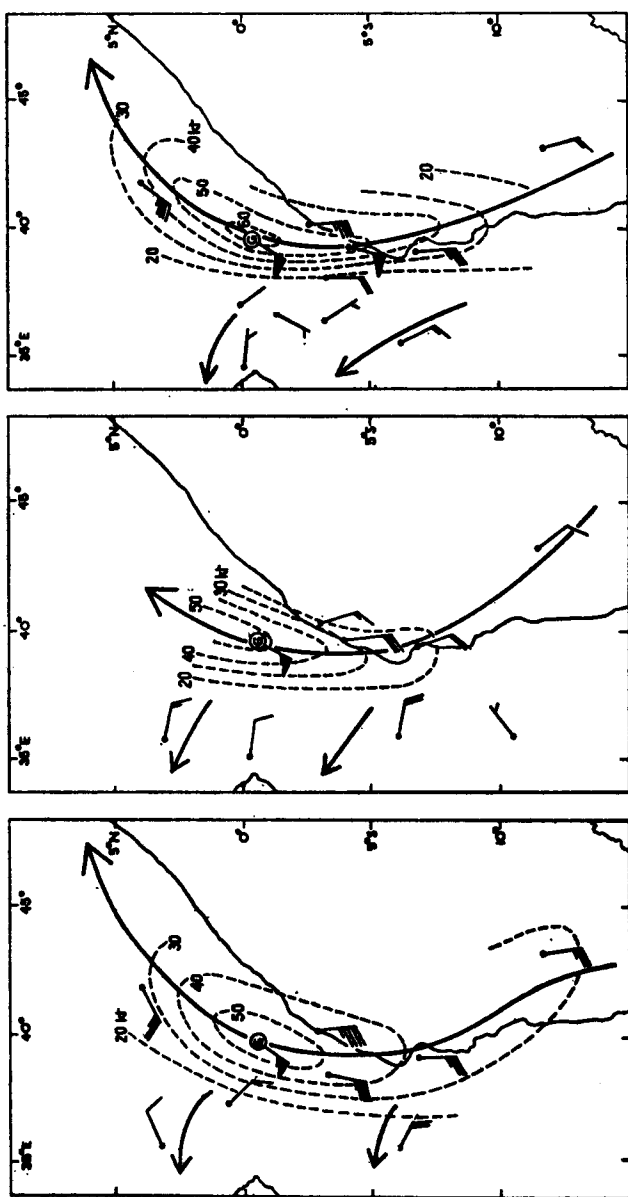
(c) 5000 ft, 0600 GMT
27 June 1964

(b) 5000 ft, 0600 GMT
29 June 1964

(a) 5000 ft, 0600 GMT
16 May 1964

G = Garissa ; - - - Isotachs at 10-kt intervals ; Major streamlines and the axis of the maximum wind speed are denoted by long arrows ; Minor streamlines are denoted by shorter arrows.

FIGURE 6—EXAMPLES OF LOW-LEVEL JET STREAMS OVER KENYA



(d) 5000 ft, 0600 GMT
7 July 1964

(e) 5000 ft, 0600 GMT
13 July 1964

(f) 5000 ft, 0600 GMT
19 July 1964

G= Garissa ; - - - Isobars at 10-kt intervals ; Major streamlines and the axis of the maximum wind speed are denoted by long arrows ; Minor streamlines are denoted by shorter arrows. (The wind speed at Mandera in (f) was 35 kt not 45 kt.)

FIGURE 6—continued

troposphere, or stratosphere, but the high-speed flow over eastern Kenya exhibits so much similarity with high-level jet streams that it would seem appropriate to refer to the phenomena described in this paper as low-level jet streams. The periodic strengthening of the south monsoon may produce considerable effects downstream also.

Diurnal variations.—Pilot-balloon ascents from Garissa have been grouped according to whether they were made during the morning or afternoon, but all ascents were made during daylight and it is unlikely that any satisfactory deductions regarding the diurnal variation can be made therefrom. Ideally, winds measured just before dawn should be compared with measurements made about the time of maximum heating, but in the case of the Garissa data many morning ascents may have been made as late as 0800 GMT (=1100 local time) when surface heating near the equator is powerful and turbulent mixing is likely to extend above 3000 ft.

An inspection of the data, and some trial analyses, have indicated that at present there are insufficient data to attempt a study of diurnal changes at low level. Nevertheless it is of interest to note that very high wind speeds (>90 kt) have been recorded during both morning and afternoon.

Cause.—It is not clear how the accelerations of the south monsoon are initiated but it is likely that some part is played by the confluence of the streamlines towards the equator as the airflow curves from south-easterly to south-westerly, especially when the flow is partly restricted by high ground west of 38°E. The basic cause of the accelerations, however, may lie much further afield than in East Africa.

Conclusions.—The monthly mean values of wind up to 10,000 ft which have been calculated reveal some interesting features of the monsoon patterns, especially when compared with the analysis for Nairobi. A notable feature is the dominance of the south monsoon over the flat eastern areas of Kenya and the comparative lack of an effective north-east monsoon in the area at surface levels.

The south monsoon is at times concentrated into a high-energy flow at low levels which shows many of the features normally associated with high-level jet streams, except that the vertical shears reach much higher values. These jet streams with speeds over 60 kt at low levels are of great importance to aircraft operations in the area.

Acknowledgements.—The writer is grateful to the Director of the East African Meteorological Department for making the Garissa pilot-balloon data readily available, and to Professor A. F. Jenkinson and Dr H. T. Mörtz for helpful discussions during the course of the analysis. Thanks are also due to several members of the Meteorological Office staff at Eastleigh for assistance in the transcription and checking of the data.

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METEOROLOGY AND GLIDING — 1966

By P. G. WICKHAM

In spite of or perhaps, because of, the unsettled weather of the summer, the gliding movement called on the Meteorological Office for considerable numbers of weather forecasts during 1966. Apart from some routine forecasts prepared for certain of the bigger gliding clubs, and a large number of non-routine inquiries from individual pilots, special forecast facilities have again been provided for the more important gliding competitions. At the National Championships, held at Lasham (Hampshire) in May, a temporary forecast office was set up. This was manned by a staff of two forecasters and an assistant, with a Channel 1 teleprinter on the site providing the normal working data. At most of the Regional Competitions, held at five different sites during the summer, no official forecasting service was laid on. However, at four of these meetings, individual forecasters, working in their own time and drawing their working data from nearby meteorological offices, provided a forecast service which was very greatly appreciated by the organizers of the competitions.

Cross-country competition flying by gliders depends very largely on the plentiful occurrence of thermals and, quite simply, thermals occur where there is sunshine. A day with no sunshine is generally a day with no flying at a gliding competition, and such days were rather common this year, as the following table shows.

TABLE 1—GLIDING COMPETITIONS IN ENGLAND IN 1966

Location	Period	Length of competition	Number of contest flying days
Bicester (Oxon.)	8 - 17 April	10 days	1 day
Long Mynd (Salop)	8 - 11 April	4 days	1 day
Lasham (Hants.)	21 - 30 May	10 days	5 days
Nympsfield (Glos.)	18 - 26 June	9 days	5 days
Camphill (Derbyshire)	2 - 10 July	9 days	5 days
Dunstable (Beds.)	30 July - 7 August	9 days	3 days
Bicester (Oxon.)	20 - 29 August	10 days	8 days

In all gliding competitions the pilots are set a specific task to fly each day. The task may be a race, in which points are awarded for the glider's speed over a set course, or it may be a distance task, in which speed is not rewarded but points are gained simply for the distance flown. The overall success of a competition depends very much on the right task being set each day, and the meteorological advice given to the task-setters each morning is crucial in this.

High on the list of his special considerations comes the forecaster's assessment of the likely convection activity throughout the day. As well as predicting the height to which convection will penetrate, and the time that usable thermals will start and finish, the forecaster must try to assess the possibility of any meso-scale patterns in the organization of the convection. Systems of cloud-streets; patterns produced by lee-wave effects; convergence lines and sea-breeze cloud formations—any of these may form important irregularities in the basic field of convection and should be forecast. To overestimate the general vigour of the convection may lead to an impossible task being set, while an underestimate can be wasteful if the most is not made of a really good day. This year has been a rather stormy one, with strong

winds and rapidly changing conditions much in evidence. All too frequently it has been a delicate matter to decide in advance whether or not a short period of soarable sunny weather will last long enough to allow a fleet of some 30-40 gliders to be launched on a task that is equally fair to all competitors. Since there may be a difference of something like one and a half hours in the times at which the first and last gliders are launched, it is necessary to have some four hours of fairly uniform conditions if every pilot is to have an equally fair chance. A further difficulty in strong wind conditions is that gliders tend to be blown rather quickly either towards a coast-line, or towards some controlled air-space. With such conditions it has often been necessary this year to set tasks involving some very stiff cross-wind flying in order both to clear the forbidden Control Zones and also to avoid having all the aircraft landing early in the day on the same stretch of coast-line. The latter situation would contribute nothing at all to the result of the competition and would probably involve all the pilots and their aircraft in a long and tedious journey home which would be doubly frustrating and pointless.

On the other side of the ledger, a forecaster gets in return for his forecast each day the aggregate experience of many deeply interested and observant pilots who, with varying skill and success, have spent the day sampling the behaviour of the atmosphere in the area to which they have been sent. There is invariably much that can be learnt from this. Sometimes a particular meso-scale feature may have been encountered and described, but more often there is a valuable general impression of the weather and its variations in relation to the topography. The scale of interest is usually smaller than that which can be studied on a normal synoptic chart, but it is nevertheless one that is extremely important for detailed local weather forecasting.

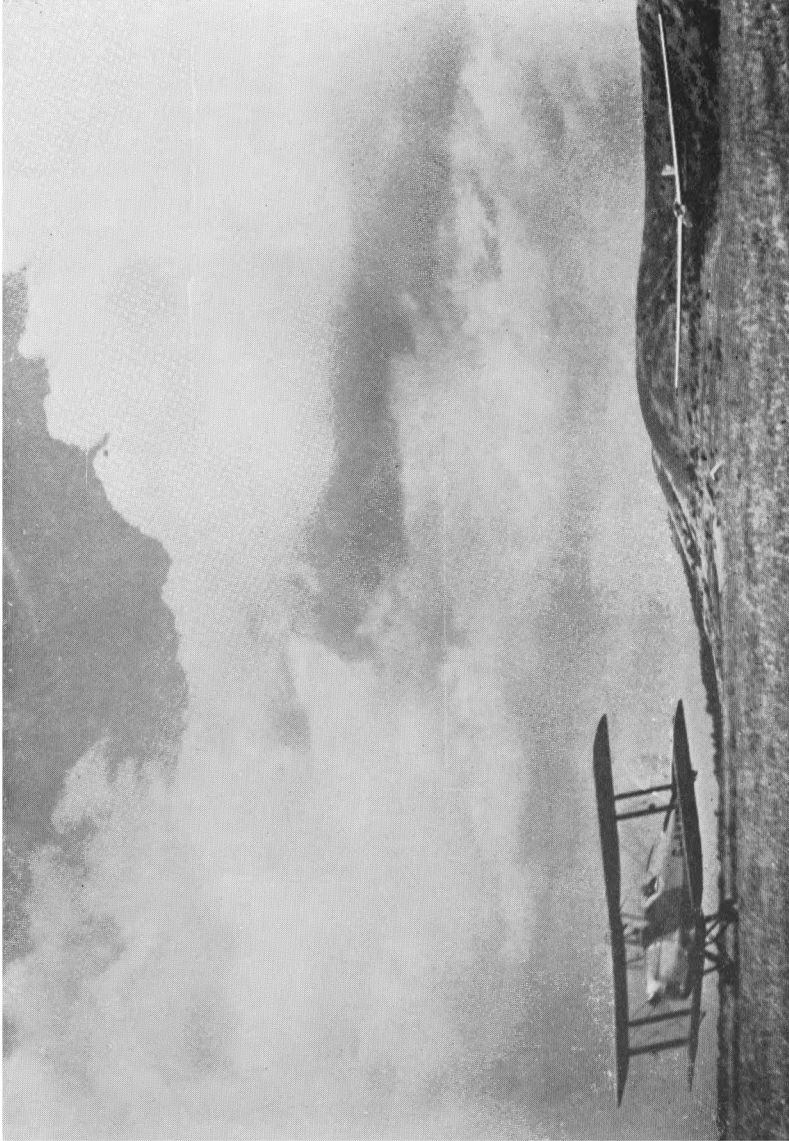
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AN EXAMPLE OF FORECASTING RAINFALL IN CYPRUS BY USING THE 300 MB JET STREAM IN CONJUNCTION WITH A 700 MB ANALYSIS

By R. M. MORRIS

Introduction.—The dynamical significance of the 300 mb jet stream has received a fair amount of attention in meteorological literature, and one of the most comprehensive and up-to-date treatments has been given by Riehl.¹ In particular, the fast moving and fairly short (1000 nautical miles) jet streams can have considerable significance. If moisture is available there will be an area of cloud and perhaps precipitation in the well-known area of ascent in the 'left-exit' region of a jet stream. On the other hand, areas lying to the warm side of the jet core are often characterized by very dry and stable air indicating marked descent in the middle troposphere. The prominence of this dry zone associated with both warm and cold fronts has been described by Sawyer,² Freeman,³ Miles⁴ and Boyden.⁵

In the eastern Mediterranean the synoptic analyst often has considerable difficulty in explaining weather in terms of the conventional frontal-analysis technique. This is because the three-dimensional structure of the troposphere shows considerable asymmetry and often changes markedly over short periods of time (24 hours) compared with north-west Europe and the North



Photograph by P. G. Wickham

PLATE I—LAUNCHING A GLIDER AT THE LONDON GLIDING CLUB, DUNSTABLE

A picture taken during the Regional Gliding Competition held at Dunstable in early August. In most competitions the gliders are towed up to a height of 2000 feet before being released. In the background is the edge of the Dunstable Downs.



Photograph by A. H. P. Jarrett

PLATE II—UPPER CLOUD STRIATIONS

The photograph was taken at London (Heathrow) Airport looking south-south-east at 1115 GMT 7 September 1966. It shows dense cirrocumulus at about 39,000 feet, cross-striated in complex mode, and at about 15,000 feet altocumulus with billows in two directions. Strato-cumulus is seen at the top of the picture. Many variations in the upper cloud structure were seen on the same day.

Atlantic. Whilst the mean-sea-level chart represents an essential basis upon which the forecaster can analyse the weather, it seems desirable to produce on one chart the salient three-dimensional features of the troposphere which cannot be deduced from the mean-sea-level chart. This type of analysis is similar to one of the type outlined by Sawyer,⁶ and makes use basically of the 700 mb chart to describe the state of the lower middle troposphere (see Figure 1). The contours of the 700 mb height are smooth and indicate the direction of advection of cloud in the middle troposphere. Isotherms depict the areas of warm and cold air, and isopleths of dew-point depression depict dry and moist zones. A note of caution is required since on a single occasion the dew-point depression at exactly 700 mb may not be representative of a complete layer; furthermore a small dew-point depression may be a consequence rather than a cause of a rain-producing process. The 300 mb jet core is added to this chart with approximate speeds indicated at various points along its length. Undoubtedly the paucity and unreliability of data in the Mediterranean impose limitations upon the accuracy of jet-stream analysis. Nevertheless the principal object of this type of analysis is to locate the approximate position of the jet core together with its entrance and exit regions rather than to locate precise isotachs. The various regions of jet streams can generally be located with some confidence. A final addition to the 700 mb chart is the area of precipitation taken from the mean-sea-level chart.

FIGURE 1—SYNOPTIC ANALYSIS 0000 GMT 18 DECEMBER 1965

Bold arrows and associated figures denote jet streams at 900 mb and their speed in knots. Precipitation areas are shaded.

This note deals with an occasion on which this type of analysis was used to illustrate rapid development in the middle troposphere occurring in association with a 300 mb jet stream which veered steadily and extended southwards.

Analysis at 0000 GMT 18 December 1965.—Figure 1 shows the analysis represented on the 700 mb chart for 0000 GMT on 18 December 1965 at Episkopi Main Meteorological Office. The 700 mb contours showed a light to moderate west to north-west flow across south-east Europe and Turkey. There was also an extensive area of moist air across the Balkans with a sharp boundary. A strong narrow 300 mb jet core was advancing south-east across Poland. Note the area of precipitation at the left exit of this jet. The warm air advection at the northern end of the jet core was stronger than advection in the south, mainly as a result of the stronger gradient in the lower layers. The indication was, therefore, that the jet would veer steadily with time.

Analysis at 1200 GMT 18 December 1965.—At 1200 GMT (Figure 2) the veering winds over Italy and backing winds across Turkey at 700 mb suggested a weak trough somewhere near the Aegean Sea but otherwise there was little change. The advancing jet had reached 25°E, indicating a speed of about 25 kt in the north and about 14 kt in the south, and had veered about 45 degrees. A careful estimation indicated that the jet had extended south along its axis at about 25 kt. The moist area had moved south of east to the Crimea with outbreaks of rain and snow. Note also the appearance of some

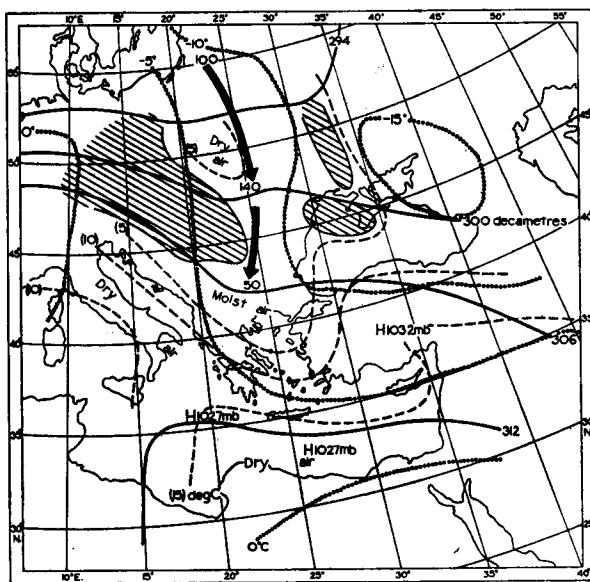


FIGURE 2—SYNOPTIC ANALYSIS 1200 GMT 18 DECEMBER 1965

———— 700 mb contours ; - - - - 700 mb dew-point depression ;
 700 mb temperature.

Bold arrows and associated figures denote jet streams at 300 mb and their speed in knots. Precipitation areas are shaded.

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Volume 95

INDEX

	Pages		Pages
January	1-32	July	193-224
February	33-64	August	225-256
March	65-96	September	257-288
April	97-128	October	289-320
May	129-160	November	321-352
June	161-192	December	353-384
Aanensen, C. J. M. ; World Meteorological Organization Fourth Session of the Commission for Synoptic Meteorology, 289			
Accuracy of long-range forecasts issued by the Meteorological Office ; M. H. Freeman, 321			
Address by Professor P. M. S. Blackett, P.R.S. ; G. A. Bull and H. H. Lamb, 183			
Address by Dr Joseph Smagorinsky ; A. Gilchrist, 312			
African lake-level changes, world rainfall pattern anomalies and related aspects of climatic change in the 1960's ; H. H. Lamb, 181			
Atmospheric diffusion slide-rule ; C. E. Wallington, M.Sc., <i>official publication</i> , 383			
Austin Bourke, P. M. ; The biological significance of climatic changes in Britain (ed. by C. G. Johnson and L. P. Smith), <i>review</i> , 221			
Barthram, J. A. and McNair, R. R. ; Mesoscale investigation of a squall-line, 304			
Behaviour of the first six zonal wave numbers at 50 and 500 millibars during some winter months in 1958 and 1959 ; G. R. R. Benwell, 33			
Benwell, G. R. R. ; The behaviour of the first six zonal wave numbers at 50 and 500 millibars during some winter months in 1958 and 1959, 33			
Benwell, G. R. R. ; Comments on 'Precipitable Water' and 'Dew-point Thickness', <i>reply to letter</i> , 319			
Bergeron, Professor Tor ; awarded International Meteorological Organization Prize, 256			
Biometeorological Conference in Lebanon, 1-6 April 1966 ; G. W. Hurst, 218			
Bull, G. A. ; A history of the theories of rain and other forms of precipitation (W. E. Knowles Middleton), <i>review</i> , 316			
Bull, G. A. ; <i>retirement</i> , 315			
Bull, G. A. and Lamb, H. H. ; Address by Professor P. M. S. Blackett, P.R.S., 183			
Burma Meteorological Department, 186			
Bushby, F. H. ; Weather prediction by numerical process (L. F. Richardson), <i>review</i> , 383			
Case illustrating the value of satellite pictures in forecasting for the British Isles ; R. A. S. Ratcliffe, 257			
Cashmore, R. A. ; Severe turbulence at low levels over the United Kingdom, 17			
Casswell, S. A. ; A simplified calculation of maximum vertical velocities in mountain lee waves, 68, <i>corrigenda</i> , 223			
Clapham, A. J. ; <i>obituary</i> , 95			
Clark, G. A. W. ; <i>obituary</i> , 255			
Cloud tops over Malaya during the south-west monsoon season ; R. F. Zobel and S. G. Cornford, 65, <i>photograph facing</i> 80			
Cochrane, J. ; Kent Farmers' Field Day, Eynsford, June 1966, 310			
Cole, A. E. ; Comparison of British stratospheric and mesospheric temperature measurements with values from available atmospheric models, 236			
Comparison of British stratospheric and mesospheric temperature measurements with values from available atmospheric models ; A. E. Cole, 236			
Corby, G. A. ; Long-range hydrodynamic weather forecasting (ed. by E. N. Blinova), <i>review</i> , 317			
Cornford, S. G. ; Cloud physics and cloud seeding (L. J. Battan), <i>review</i> , 159			
Cornford, S. G. ; Elements of cloud physics (H. R. Byers), <i>review</i> , 254			
Cornford, S. G. ; Stratocumulus — a review of some physical aspects, 292			
Cornford, S. G. and Zobel, R. F. ; Cloud tops over Malaya during the south-west monsoon season, 65, <i>photograph facing</i> 80			
Criteria concerning fine spells in south-west Scotland during the period May to October ; R. A. S. Ratcliffe, 98			
Cross-equatorial jet streams at low levels over Kenya ; J. Findlater, 353			
Crossley, A. F. ; awarded I.S.O., 256			
Cunningham, J. C. ; <i>retirement</i> , 351			
Cumulonimbus with streaming anvil ; <i>photograph facing</i> 273			
Daily Aerological Cross-sections at Latitude 30°N during the International Geophysical Year Period (March 1958) ; <i>official publication</i> , 191			
Dines, L. H. G. ; <i>obituary</i> , 63			
Dobson, F. R. ; The atmosphere in action (I. J. W. Potheary), <i>review</i> , 125			
Dobson, F. R. ; Weather Studies (L. P. Smith), <i>review</i> , 287			
Edinburgh meteorological observer 1731-36 ; H. J. Matthews, 123			
Example of forecasting rainfall in Cyprus by using the 900 mb jet stream in conjunction with a 700 mb analysis ; R. M. Morris, 366			
Examples of cloud detection with 8.6-millimetre radar ; W. G. Harper, 106, <i>photographs between</i> 112, 113			
Experimental instrument screen made of fibreglass ; <i>photographs between</i> 208, 209			
Ferguson, H. L. ; Synoptic representation of moisture, <i>letter</i> , 318			

- Ferreira, Professor H. A. ; *retirement*, 31
- Findlater, J. ; Cross-equatorial jet streams at low levels over Kenya, 353
- First International Symposium on Methods in Agroclimatology, Reading, 23-30 July 1966 ; C. V. Smith, 376
- First round-the-world flight of southern-hemisphere weather balloon, 314
- Forecasting of shower activity in airstreams from the north-west quarter over north-west England in summertime ; C. A. S. Lowndes, 80
- Forecasting of shower activity in airstreams from the north-west quarter over south-east England in October to April ; C. A. S. Lowndes, 248
- Forecasting of shower activity in airstreams from the north-west quarter over south-west England and South Wales in summertime ; C. A. S. Lowndes, 1
- Forsdyke, A. G. ; The climate of Africa (B. W. Thompson), *review*, 186
- Fowler, W. J. ; *obituary*, 256
- Freeman, M. H. ; The accuracy of long-range forecasts issued by the Meteorological Office, 321
- Frost, R. ; Major storms in West Pakistan in September in relation to the Mangla Dam Project, 57
- Further discussion on the observations of cloud with 8.6-millimetre radar ; J. B. Stewart, 112
- Further work on objective forecasting of visibility ; Valerie D. Jack, 114
- Geake, E. H. ; *obituary*, 95
- George, D. J. and Hill, R. ; Glaciation of water fog and a temporary improvement in visibility at Shawbury, 121
- Gilchrist, A. ; Lecture by Dr Joseph Smagorinsky, 312
- Glaciation of water fog and a temporary improvement in visibility at Shawbury ; D. J. George and R. Hill, 121
- Gloyne, R. W. ; Humidity and moisture : Volume two, Applications (ed. by E. J. Amdur), *review*, 253
- Graystone, P. ; Objective analysis of meteorological fields (L. S. Gandin) ; *review*, 286
- Groves, (L. G.) Memorial Prizes and Awards ; 26, *photographs between* 16, 17
- Harley, D. G. ; Chasseurs de typhons (P. A. Molène), *review*, 190
- Harper, W. G. ; Examples of cloud detection with 8.6-millimetre radar, 106, *photographs between* 112, 113
- Harrold, T. W. ; Meteorological Office participation in severe storm investigation in the U.S.A. in 1965, 19
- Hartley, G. E. W. ; Wind-tunnels in the Meteorological Office, 144, *photographs between* 144, 145
- Hill, R. and George, D. J. ; Glaciation of water fog and a temporary improvement in visibility at Shawbury, 121
- Holland, D. J. ; Evaporation from a reservoir near London, (C. F. Lapworth), *essay review*, 22
- Howlett, N. W. ; awarded I.S.M., 256
- Hurst, G. W. ; Biometeorological Conference in Lebanon, 1-6 April 1966, 218
- Hurst, G. W. ; Physical limitations to crop growth, 178
- Hurst, G. W. ; Temperatures in the forest of Thetford Chase, 273, *photographs between* 272, 273
- Ice accretion on aircraft ; *official publication*, 191
- Incident of severe low-level turbulence ; G. J. Jefferson, 279
- Indicator of surface wind directions potentially favourable for atmospheric pollution ; E. N. Lawrence, 241
- Inertial navigation and gust measurement from Meteorological Research Flight aircraft ; I. Ross, 370, *photograph facing* 371
- Instability index ; *letter from* G. J. Jefferson, 381
- International Antarctic Meteorological Research Centre ; 31
- International Symposium on Dynamics of Large-scale Processes in the Atmosphere, Moscow, 23-30 June 1965 ; E. Knighting, 20
- Jack, Valerie D. ; Further work on objective forecasting of visibility, 114
- James, D. G., Limbert, D. W. S. and McDougall, J. C. ; A radiometer sonde, 161, *photograph facing* 176
- Jarrett, A. H. P. ; Upper cloud striations, *letter*, 382, *photograph facing* 367
- Jefferson, G. J. ; An incident of severe low-level turbulence, 279
- Jefferson, G. J. ; Instability index, *letter*, 381
- Jessop, E. E. ; *obituary*, 255
- Jones, D. E. ; A note on the use of hourly rainfall observations, 325
- Jones, J. I. P. ; Meteorological contributions to the 1966 Physics Exhibition, 239, *photographs between* 240, 241
- Jones, T. W. Vernon ; Tornado at the Royal Horticultural Society's Gardens, Wisley, 91, *photographs between* 80, 81
- Keers, J. F. ; The meteorological conditions leading to storm surges in the North Sea, 261
- Kent Farmers' Field Day, Eynsford, June 1966 ; J. Cochrane, 310
- Kirk, T. H. ; Tiros operational satellite, 177, *photographs facing* 177
- Knighting, E. ; Computing methods, Volumes 1 and 2 (I. S. Berezin and N. P. Zhidkov), *review*, 188
- Knighting, E. ; International Symposium on Dynamics of Large-scale Processes in the Atmosphere, Moscow, 23-30 June 1965, 20
- Lamb, H. H. ; African lake-level changes, world rainfall pattern anomalies and related aspects of climatic change in the 1960's, 181
- Lamb, H. H. ; Die Tagebücher Franz de Paula Haslingers. Witterung und Klima von Linz (ed. by G. Wacha), *review*, 25
- Lamb, H. H. ; Meteorological and radiation régime of Antarctica (N. P. Rusin), *review*, 93

- Lamb, H. H. and Bull, G. A. ; Address by Professor P. M. S. Blackett, P.R.S., 183
- Lawrence, E. N. ; An indicator of surface wind directions potentially favourable for atmospheric pollution, 241
- Lecture by Professor David Atlas ; W. T. Roach, 379
- Lewis, R. P. W. and Murray, R. ; Some aspects of the synoptic climatology of the British Isles as measured by simple indices, 193
- Limbert, D. W. S., James, D. G. and McDougall, J. C. ; A radiometer sonde, 161, *photograph facing 176*
- Low minimum temperatures at Santon Downham, Norfolk ; J. Oliver, 13
- Low-level wind flow at Nairobi ; B. Ramsey, 47
- Lowndes, C. A. S. ; The forecasting of shower activity in airstreams from the north-west quarter over north-west England in summertime, 80
- Lowndes, C. A. S. ; The forecasting of shower activity in airstreams from the north-west quarter over south-east England in October to April, 248
- Lowndes, C. A. S. ; The forecasting of shower activity in airstreams from the north-west quarter over south-west England and South Wales in summertime, 1
- Lumb, F. E. ; Synoptic disturbances causing rainy periods along the East Africa coast, 150, *corrigenda*, 256
- Major storms in West Pakistan in September in relation to the Mangla Dam Project ; R. Frost, 57
- Manley, G. ; Climates of the U.S.S.R. (A. A. Borisov), *review*, 348
- Mason, Dr B. J. ; Award of Honorary Degree, 315
- Matthews, H. J. ; The Edinburgh meteorological observer 1731-36, 123
- McDougall, J. C., James, D. G. and Limbert, D. W. S. ; A radiometer sonde, 161, *photograph facing 176*
- McNair, R. R. and Barthram, J. A. ; Mesoscale investigation of a squall-line, 304
- Meso-scale investigation of a squall-line ; R. R. McNair and J. A. Barthram, 304
- Meteorological conditions leading to storm surges in the North Sea ; J. F. Keers, 261
- Meteorological contributions to the 1966 Physics Exhibition ; J. I. P. Jones, 239, *photographs between 240, 241*
- Meteorological facsimile room at the Main Meteorological Office, RAF Episkopi, Cyprus ; *photographs between 176, 177*
- Meteorological Office awards to captains and navigators of civil aircraft ; 220, *photograph facing 208*
- Meteorological Office participation in severe storm investigation in the U.S.A. in 1965 ; T. W. Harrold, 19
- Meteorological Service of Portugal, 186
- Meteorological Service of Uruguay, 186
- Meteorology and gliding — 1966 ; P. G. Wickham, 365, *photograph facing 366*
- Morris, R. M. ; An example of forecasting rainfall in Cyprus by using the 300 mb jet stream in conjunction with a 700 mb analysis, 366
- Murray, R. ; A note on the large-scale features of the 1962/63 winter, 339
- Murray, R. ; Some features of the large-scale circulation anomalies and the weather over the British Isles in autumn 1965, 225
- Murray, R. and Lewis, R. P. W. ; Some aspects of the synoptic climatology of the British Isles as measured by simple indices, 193
- National Farmers' Union letter to the Prime Minister ; 27
- New radiosonde Mark 3 as produced by an initial manufacturing contract, *photographs facing 209*
- New Zealand Meteorological Service ; 31
- Noctilucent cloud ; 315, *photographs between 304, 305*
- Noctilucent clouds over western Europe during 1965 ; J. Paton, 174
- Note on the large-scale features of the 1962/63 winter ; R. Murray, 339
- Note on the use of hourly rainfall observations ; D. E. Jones, 325
- Occurrence and distribution of hail in Africa ; H. W. Sansom, 212
- Oddie, B. C. V. ; Retirement of Dr A. C. Best, C.B.E., 97
- Oliver, J. ; Low minimum temperatures at Santon Downham, Norfolk, 13
- Papež, A. ; A remark on synoptic charting of moisture, 210
- Pasquill, F. ; Investigation of the bottom 300-meter layer of the atmosphere (ed. by N. L. Byzova), *review*, 285
- Pasquill, F. ; Physics of the boundary layer of the atmosphere (D. L. Laikhtman), *review*, 92
- Pasquill, F. ; Special Merit Promotion to Deputy Chief Scientific Officer, 350
- Paton, J. ; Auroral phenomena (experiments and theory) (ed. by M. Walt), *review*, 222
- Paton, J. ; Noctilucent clouds over western Europe during 1965, 174
- Photographs of frost patterns on a glass door ; *letter from R. K. Pilsbury, 94, photographs facing 81, corrigendum*, 191
- Physical limitations to crop growth ; G. W. Hurst, 178
- Pilsbury, R. K. ; Photographs of frost patterns on a glass door, *letter, 94, photographs facing 81, corrigendum*, 191
- Pothecary, I. J. W. and Ratcliffe, R. A. S. ; Satellite pictures of an old occluded depression and their use in analysis and forecasting, 332, *photographs facing 334, 335*
- Press conference ; 28, *photograph facing 17*
- Radiometer sonde ; D. G. James, D. W. S. Limbert and J. C. McDougall, 161, *photograph facing 176*
- Ramsey, B. ; Low-level wind flow at Nairobi, 47

- Ratcliffe, R. A. S. ; A case illustrating the value of satellite pictures in forecasting for the British Isles, 257
- Ratcliffe, R. A. S. ; Criteria concerning fine spells in south-west Scotland during the period May to October, 98
- Ratcliffe, R. A. S. and Potthecary, I. J. W. ; Satellite pictures of an old occluded depression and their use in analysis and forecasting, 332, *photographs facing* 334, 335
- Regression technique for objective forecasts at 300 millibars ; A. Woodroffe, 129, *corrigendum*, 223
- Reid, E. W. E. ; awarded I.S.M., 256
- Relation between Beaufort force wind speed and wave height ; R. Frost, B.A., *official publication*, 383
- Remark on synoptic charting of moisture ; A. Papež, 210
- Retirement of Dr A. C. Best, C.B.E. ; B. C. V. Oddie, 97

REVIEWS

- Atmosphärische Elektrizität, Teil II (H. Israël) ; *review* by T. W. Wormell, 221
- Atmosphere in action (I. J. W. Potthecary) ; *review* by F. R. Dobson, 125
- Auroral phenomena (experiments and theory) (ed. by M. Walt) ; *review* by J. Paton, 222
- Barrier waves in the atmosphere (Sh. A. Musaelyan) ; *review* by R. S. Scorer, 124
- Biological significance of climatic changes in Britain (ed. by C. G. Johnson and L. P. Smith) ; *review* by P. M. Austin Bourke, 221
- Chasseurs de typhons (P. A. Molène) ; *review* by D. G. Harley, 190
- Climate of Africa (B. W. Thompson) ; *review* by A. G. Forsdyke, 186
- Climate of London (T. J. Chandler) ; *review* by H. C. Shellard, 126
- Climates of the U.S.S.R. (A. A. Borisov) ; *review* by G. Manley, 348
- Cloud physics and cloud seeding (L. J. Battan) ; *review* by S. G. Cornford, 159
- Computing methods, Volumes 1 and 2 (I. S. Berezin and N. P. Zhidkov) ; *review* by E. Knighting, 188
- Die Tagebücher Franz de Paula Haslingers, Witterung und Klima von Linz (ed. by G. Wacha) ; *review* by H. H. Lamb, 25
- Elements of cloud physics (H. R. Byers) ; *review* by S. G. Cornford, 254
- Evaporation from a reservoir near London ; (C. F. Lapworth), *essay review* by D. J. Holland, 22
- History of the theories of rain and other forms of precipitation (W. E. Knowles Middleton) ; *review* by G. A. Bull, 316
- Humidity and moisture : Volume two, Applications (ed. by E. J. Amdur) ; *review* by R. W. Gloyne, 253
- Investigation of the bottom 300-meter layer of the atmosphere (ed. by N. L. Byzova) ; *review* by F. Pasquill, 285
- Long-range hydrodynamic weather forecasting (ed. by E. N. Blinova) ; *review* by G. A. Corby, 317
- Meteorological and radiational régime of Antarctica (N. P. Rusin) ; *review* by H. H. Lamb, 93
- Objective analysis of meteorological fields (L. S. Gandin) ; *review* by P. Graystone, 286
- Physics of the boundary layer of the atmosphere (D. L. Laikhtman) ; *review* by F. Pasquill, 92
- Story of gliding (Ann and Lorne Welch) ; *review* by C. E. Wallington, 223
- Weather prediction by numerical process (L. F. Richardson) ; *review* by F. H. Bushby, 381
- Weather studies (L. P. Smith) ; *review* by F. R. Dobson, 287
- Rime at Lowther Hill ; *photographs facing* 338, 339
- Roach, W. T. ; Lecture by Professor David Atlas, 379
- Ross, I. ; Inertial navigation and gust measurement from Meteorological Research Flight aircraft, 370, *photograph facing* 371
- Sansom, H. W. ; The occurrence and distribution of hail in Africa, 212
- Satellite pictures of an old occluded depression and their use in analysis and forecasting ; I. J. W. Potthecary and R. A. S. Ratcliffe, 332, *photographs facing* 334, 335
- Satellite tracking aerial at the Royal Observatory, Hong Kong ; *photograph facing* 304
- Saunders, W. E. ; Tests of thunderstorm forecasting techniques, 204
- Scorer, R. S. ; Barrier waves in the atmosphere (Sh. A. Musaelyan), *review*, 124
- Severe turbulence at low levels over the United Kingdom ; R. A. Cashmore, 17
- Shellard, H. C. ; The climate of London (T. J. Chandler), *review*, 126
- Simplified calculation of maximum vertical velocities in mountain lee waves ; S. A. Casswell, 68, *corrigenda*, 223
- Smith, C. V. ; First International Symposium on Methods in Agroclimatology, Reading, 23-30 July 1966, 376
- Solution of atmospheric diffusion equations by electrical analogue methods ; J. B. Tyldesley, *official publication*, 191
- Some aspects of satellite meteorology ; D. G. James and I. J. W. Potthecary, 193 (1965), *corrigendum*, 63
- Some aspects of the synoptic climatology of the British Isles as measured by simple indices ; R. Murray and R. P. W. Lewis, 193
- Some features of the large-scale circulation anomalies and the weather over the British Isles in autumn 1965 ; R. Murray, 225
- State Meteorological Service of the Federal Republic of Germany, 350

- Stewart, J. B. ; Further discussion on the observations of cloud with 8-6-millimetre radar, 112
- Stewart, K. H. ; Special merit promotion to Senior Principal Scientific Officer, 30
- Stratocumulus—a review of some physical aspects ; S. G. Cornford, 292
- Surface and 900 mb wind relationships ; J. Findlater, T. N. S. Harrower, M.A., B.Sc., G. A. Howkins, M.B.E., B.Sc. and H. L. Wright, M.A., *official publication*, 383
- Synoptic disturbances causing rainy periods along the East Africa coast ; F. E. Lumb, 150, *corrigenda*, 256
- Synoptic representation of moisture ; *letter from* H. L. Ferguson, 318, *reply from* G. R. R. Benwell, 319
- Temperatures in the forest of Thetford Chase ; G. W. Hurst, 273, *photographs between* 272, 273
- Tests of thunderstorm forecasting techniques ; W. E. Saunders, 204
- Tiros operational satellite ; T. H. Kirk, 177, *photographs facing* 177
- Tornado at the Royal Horticultural Society's Garden, Wisley ; T. W. Vernon Jones, 91, *photographs between* 80, 81
- Unusual icicle formations ; *photograph facing* 305
- Unusual icicles at Farnborough ; *photograph facing* 16
- Upper cloud striations ; *letter from* A. H. P. Jarrett, 382, *photograph facing* 367
- Wallington, C. E. ; The story of gliding (Ann and Lorne Welch), *review*, 223
- Waterspout and cloud distribution 10 miles south-west of Sumburgh Head ; *illustrations facing* 272
- Waterspout seen off Shetland on 22 November 1965 ; *letter from* R. Wilson, 288
- Wickham, P. G. ; Meteorology and gliding, 365, *photograph facing* 366
- Wilson, R. ; Waterspout seen off Shetland on 22 November 1965, *letter*, 288
- Wind-tunnels in the Meteorological Office ; G. E. W. Hartley, 144, *photographs between* 144, 145
- Woodroffe, A. ; A regression technique for objective forecasts at 300 millibars, 129, *corrigendum*, 223
- Wordsworth, Miss D. J. ; awarded B.E.M., 256
- World Meteorological Organization Fourth Session of the Commission for Synoptic Meteorology ; C. J. M. Aanensen, 289
- Wormell, T. W. ; Atmosphärische Elektrizität, Teil II (H. Israël), *review*, 221
- Zobel, R. F. and Cornford, S. G. ; Cloud tops over Malaya during the south-west monsoon season, 65, *photograph facing* 80

dry air just to the warm side of the jet stream. As at 0000 GMT, the warm advection in the lower layers was stronger in the north than in the south suggesting that the jet should continue to veer as it extended south.

Analysis at 0000 GMT 19 December 1965.—At 0000 GMT (Figure 3) a rise of contour height across the Adriatic and a fall over central Turkey at 700 mb, indicated a general veer in the flow although the 0000 GMT 700 mb wind at Izmir ($38^{\circ} 20'N$, $27^{\circ} 13'E$) was westerly thus emphasizing that the precipitation in west Turkey, with moderate and heavy outbreaks of rain and snow, was largely developmental and not the result of advection.

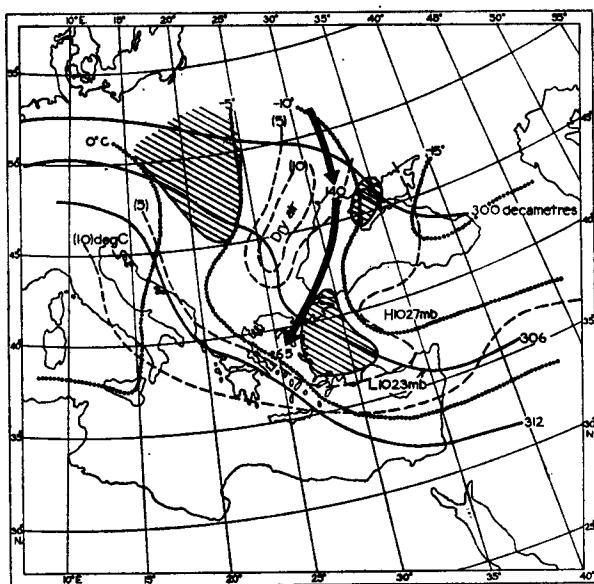


FIGURE 3—SYNOPTIC ANALYSIS 0000 GMT 19 DECEMBER 1965

———— 700 mb contours ; - - - - 700 mb dew-point depression ;
 700 mb temperature.

Bold arrows and associated figures denote jet streams at 300 mb and their speed in knots. Precipitation areas are shaded.

The 300 mb jet core had continued to veer and could be located down the western Black Sea into the north Aegean Sea. Note the location of the precipitation relative to this jet core and furthermore note the long narrow tongue of dry subsided air on the warm side of the jet core. The precipitation area subsequently moved across Cyprus where the average rainfall, for the period 0600 GMT 19th to 1800 GMT 19th at five meteorological stations in Cyprus (Paphos, Episkopi, Akrotiri, Nicosia and Ayios Nicolaos), was 12.5 mm.

Surface analysis.—It is worthy of mention that during this period the Black Sea, central and eastern Mediterranean were under the influence of a broad ridge of high pressure, everywhere in excess of 1024 mb, and the only indication of development in the middle and upper troposphere was the formation of a small depression of 1022 mb over eastern Bulgaria which subsequently moved south towards Egypt.

Conclusions.—The technique of using a combined 700 mb – 300 mb analysis showed quite clearly a sequence of rapid development illustrating how a 300 mb jet stream, veering and extending along its axis across fairly moist air in the lower and middle troposphere, can produce copious rainfall associated with the left exit of the jet, irrespective of the value of mean-sea-level pressure.

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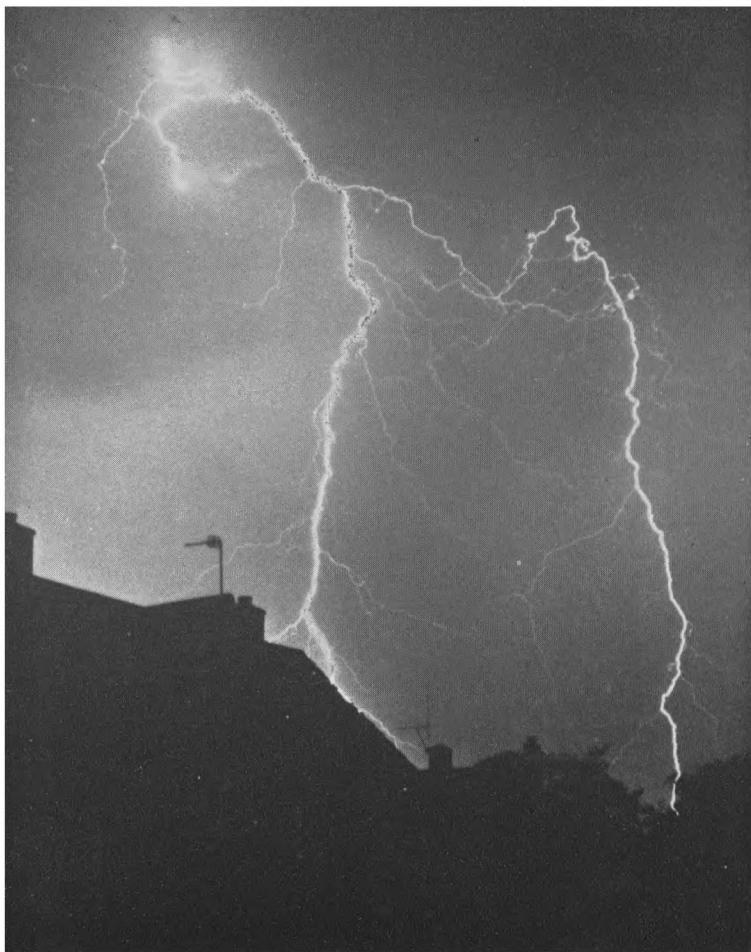
INERTIAL NAVIGATION AND GUST MEASUREMENT FROM METEOROLOGICAL RESEARCH FLIGHT AIRCRAFT

By I. ROSS

Summary.—Equipment originally designed for inertial navigation purposes has been adapted to meteorological research, in particular to the measurement of gusts in regions of the atmosphere and in situations where the aircraft is the best experimental vehicle.

Introduction.—Vertical air movements are of great importance in the atmosphere, from the large-scale slow uplift at a front to the relatively small-scale but more vigorous updraughts in cumulus cloud. Methods based on the equations of motion and thermodynamics can be applied to estimate vertical motions over lateral dimensions of the order of 200 miles but for the measurements of updraughts in clouds and clear air these methods are not practicable and measurements from aircraft seem to offer the best approach. Such measurements have been made with varying degrees of success by the Meteorological Research Flight (see for example Zobel¹) but recent developments in equipment for inertial navigation have greatly increased the possible accuracy for a given length of run.

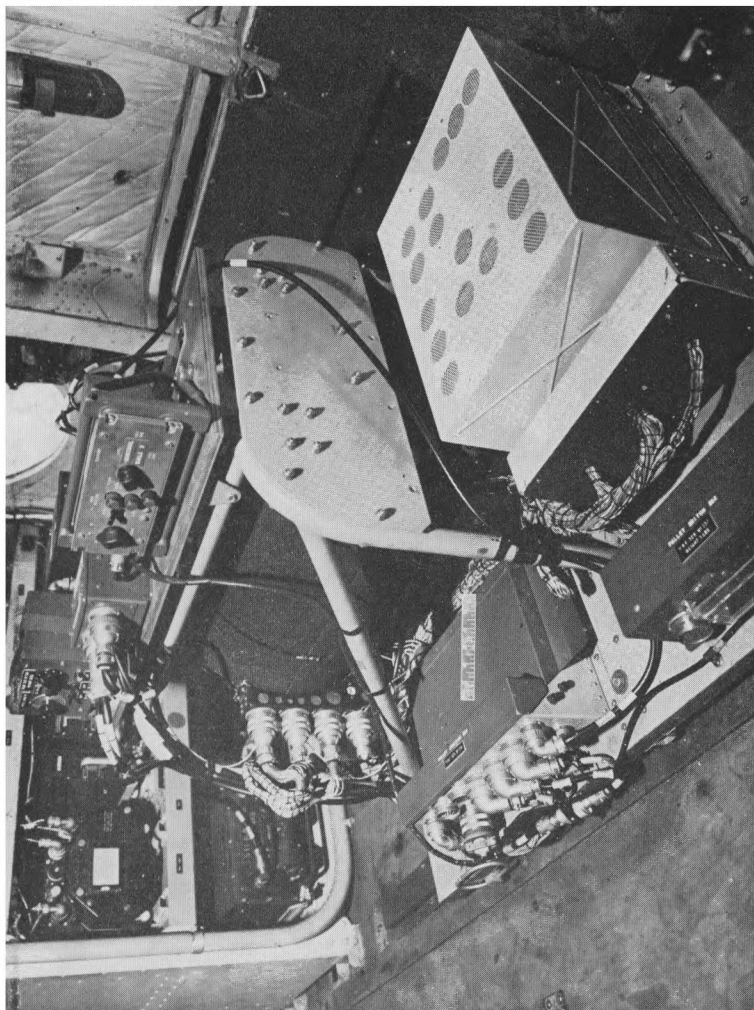
Among the first attempts to measure vertical gust velocities from aircraft was the installation of an accelerometer fixed rigidly to the airframe. From the dimensions, weight and other characteristics of the aircraft some estimate could be made of the magnitude of the gust from the acceleration experienced. The pitching, rolling and yawing motions which all aircraft perform even in non-gusty conditions (and also any pilot-induced motions) were neglected at first in this approach and an improvement came with the stabilization of the accelerometer against these motions by means of aircraft gyroscopes. A further refinement involved the addition of small wind vanes on a nose probe, and this equipment obviated the calculation of a particular aircraft's response to a gust but necessitated the accurate measurement of pitch and roll angles and aircraft vertical velocity in order to relate the gusts — measured relative to the aircraft by the wind vanes — to the earth. Aircraft gyroscopes



Photograph by P. C. Mitchell

PLATE III—CONTORTED PATH OF A LIGHTNING FLASH

During a storm near Borough Green, Kent, on the evening of 10 June 1966 an electricity sub-station was struck by lightning. The district was plunged into darkness and the BBC VHF transmitter at Wrotham Hill was temporarily off the air.



Photograph by courtesy of Royal Aircraft Establishment

PLATE IV—THE STABLE PLATFORM IN THE METEOROLOGICAL RESEARCH FLIGHT
HASTINGS AIRCRAFT

The gyroscopes and accelerometers together with some ancillary electronics are contained in the large cylinder in the centre of the photograph. The cylinder is fixed in the tubular steel frame which in turn is fixed rigidly to the floor of the aircraft. The other boxes in the picture contain power, control, output, switching and testing units (see page 373).

such as the Artificial Horizon were used in this measurement of pitch and roll. A so-called Stable Platform, developed for the TSR2 aircraft for inertial navigation purposes, uses much higher quality gyroscopes than normal aircraft equipment and by virtue of this, allows reliable observations to be made over longer periods than previously. Equipment associated with the Stable Platform provides a complete picture of the attitude (i.e. of the pitch, roll and yaw) of the aircraft and also, by integration of three mutually perpendicular components of acceleration, the velocity components and, by further integration, the distance flown.

By geometry the equation relating the vertical gust to the attitude, vertical velocity and airspeed of the aircraft and the deflexion of the wind vanes is :

$$w = U (\tan\alpha \cos r - \tan\beta \sin r - \tan\theta) \cos\theta + V_z + L(d\theta/dt) \quad \dots (1)$$

where : w = vertical gust

U = airspeed

θ = pitch angle

r = roll angle

α = angular deflexion of a horizontal wind vane

β = deflexion of vertical wind vane

(α and β are relative to axes fixed in the aircraft.)

V_z = aircraft vertical velocity

L = distance between Stable Platform and wind vanes.

Similar equations can be written for the lateral and longitudinal gusts :

$$v = U [(\tan\alpha \sin r + \tan\beta \cos r) \cos\phi - (\cos\theta + \tan\alpha \cos r \sin\theta - \tan\beta \sin r \sin\theta) \sin\phi] + V_{LAT} + L(d\phi/dt) \quad \dots (2)$$

$$u = U [(\cos\theta + \tan\alpha \cos r \sin\theta - \tan\beta \sin r \sin\theta) \cos\phi + (\tan\alpha \sin r + \tan\beta \cos r) \sin\phi] + V_{LONG} \quad \dots (3)$$

where : ϕ = yaw angle, i.e. deviation from the mean heading over the run

V_{LAT} = lateral velocity of aircraft (i.e. across the direction of the mean heading)

V_{LONG} = longitudinal velocity of the aircraft (i.e. along the direction of the mean heading).

A computer is necessary to handle the equations because of the large number of observations available in any flight record.

Inertial navigation.—The heart of an inertial navigation system is a platform which carries accelerometers maintained in fixed directions by gyroscopes. It is well known that a spinning gyroscope maintains the direction of its angular momentum vector in space. Three gyroscopes aligned along mutually perpendicular directions are therefore sufficient to provide a Cartesian reference system fixed in space. The rate of rotation of the earth, which is constant, can be allowed for automatically so that the reference system rotates with the earth. An accelerometer measures acceleration along a particular direction — its sensitive axis. The most accurate type of accelerometer is the force-balance type where the acceleration is measured by the electromagnetic force required to rebalance a pivoted coil against an input acceleration. The output of the force-balance accelerometer is a voltage proportional to the input acceleration. The acceleration integrated with respect to time gives velocity along the direction of the sensitive axis of the

accelerometer and a double integration gives distance travelled in that direction.

For our purposes the constant directional properties of gyroscopes are used to maintain three accelerometers in directions fixed with respect to the earth, i.e. in the north-south, the east-west and the local vertical direction. Because of slight imbalances and because of friction in the bearings a practical gyroscope tends to drift from its initial direction. This drift, although it may be small as 0.01° per hour in modern gyroscopes, must be corrected if information obtained from the accelerometer is not to be in error after some hours of operation. The accelerometers themselves can be used to supply this correction in the following manner :

Consider the Stable Platform as a horizontal table on which three accelerometers are mounted with their sensitive axes along three mutually perpendicular directions, two horizontal and one vertical. When the table is quite level and not accelerating horizontally the vertical accelerometer gives an output corresponding to the acceleration due to gravity (one g at the earth's surface) and the two horizontal accelerometers experience no acceleration along their sensitive axes. If the table becomes tilted slightly for some reason, say gyroscope drift, then the horizontal accelerometers experience a small acceleration due to the component of the earth's gravity along their sensitive axes. The integrated outputs from the accelerometers (which are error velocities) can be amplified and fed to erection motors which rotate the table about a horizontal axis in the direction necessary to level it, that is until both accelerometers give no output (see Figure 1(a)). Such a table will in fact tend to oscillate about the horizontal with a period dependent on the characteristics of the feedback loop ; the platform can be regarded as a pendulum.

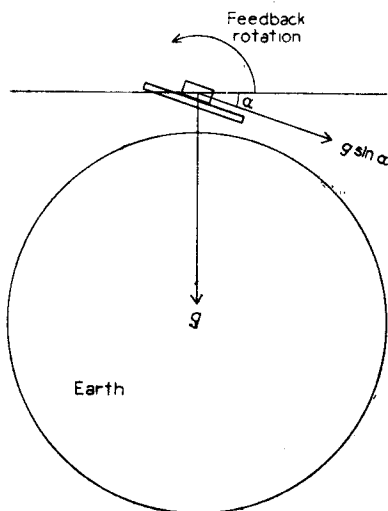


FIGURE 1(a)—PLATFORM TILTED WITH RESPECT TO THE LOCAL VERTICAL
The apparent velocity is fed back to rotate the table. Rotation takes place when the vehicle is actually accelerating and travelling around the earth.

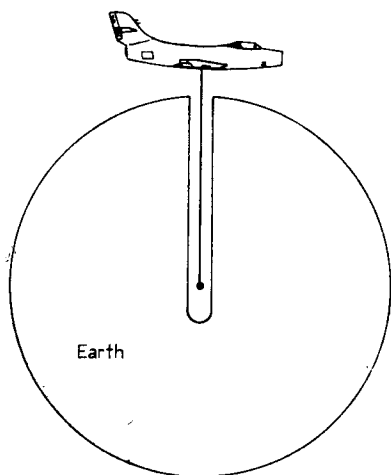


FIGURE 1(b) — THE PENDULUM STRING ALWAYS REMAINS VERTICAL AS THE AIRCRAFT FLIES AROUND THE EARTH

It can be seen that with this arrangement a horizontal acceleration of the vehicle supporting the platform will be sensed by the accelerometers, with a resulting rotation of the table. Analogously, the string of a pendulum mounted on an accelerating vehicle will become inclined to the vertical at an angle proportional to the acceleration. However, if the pendulum bob were at the centre of the earth, the string would always remain along the local vertical no matter what horizontal acceleration were applied at the top of the string (see Figure 1(b)). The natural period of such a simple pendulum is easily shown to be 84.4 minutes. Now if the period of oscillation of the Stable Platform is made to be 84.4 minutes by adjustment of the feedback loop, any accelerations of the platform in the horizontal do not affect the horizontal alignment of the table — accelerations give rise to a rotation of the platform which exactly matches the rotation of the accelerating vehicle about the earth. The 84.4-minute 'tuning' is called Schuler tuning after Schuler who first formulated the theory in 1923; the oscillation is termed the Schuler oscillation.

It has been shown that the platform is automatically compensated to keep pace with the rotating earth and with any movement of the supporting vehicle about the earth and that, although it is a pendulous system, accelerations do not affect its alignment with the horizontal. Compensations must also be made for the Coriolis force, for height above the earth's surface, for variations of g from place to place and for the centripetal force resulting from the travel at constant altitude around the curved surface of the earth. These corrections are often very small but are nevertheless necessary to maintain accurate alignment of the platform with the local horizontal. The corrections can be automatically computed and fed back from the various output stages of the platform which in effect 'knows' its position and velocity at any time given the co-ordinates of the starting point.

The platform performs a Schuler oscillation both while in flight and stationary. A typical amplitude of this oscillation is of the order 10 minutes of arc in present stable platforms and the oscillation, as can be expected, gives rise to errors, more especially in the values of horizontal acceleration (and therefore velocity and distance travelled). Although the vertical accelerometer is not affected to the same extent by the Schuler oscillation it normally senses one g and this acceleration has to be backed off electrically. The backing off cannot be done perfectly and therefore the vertical acceleration, velocity and distance outputs show a drift from the true values.

In an operational inertial navigation system the errors arising from the Schuler oscillation and from the vertical drift can be allowed for by 'mixing' with independent sources of information. For example the horizontal velocity can be compared with the velocity as measured by Doppler radar. Over periods greater than about 10 minutes the Doppler is more accurate than the inertial system; for short periods the platform outputs can be used to measure the variations in speed which the Doppler cannot measure accurately.

The Meteorological Research Flight Stable Platform.—The Meteorological Research Flight Hastings has recently been fitted with a Stable Platform FSP100, developed by Ferranti Ltd and the Inertial Navigation Division of the Instruments and Electrical Engineering Department, Royal Aircraft Establishment, Farnborough (see Plate IV). It is hoped to complete

shortly a similar installation on the Canberra. The Meteorological Research Flight installation does not make use of automatic mixing but it is possible to correct the Schuler oscillation error in the horizontal velocity outputs by taking readings of the Doppler velocity while recording the platform outputs. Combination of the two can be made on the ground after the flight. The drift in the vertical velocity is fairly linear and is therefore allowed for by finding the best-fit straight line to the velocity output. The drift must not be allowed to proceed too far as the platform could then 'think' it was many miles from the surface of the earth with corresponding effects on the various corrective feedbacks. This requirement places a limitation on the period for which the vertical velocity can be allowed to drift, which is about 10 minutes with the FSP100; after 10 minutes the drift must be zeroed, a process which takes a few minutes. When Doppler mixing is used there is no such limitation on the computation of the horizontal velocities but the effect on the vertical velocity of the absence of mixing (e.g. by comparison with an altimeter) means that the Meteorological Research Flight Stable Platform can be used only to measure *changes* in vertical velocity from a given point and not the absolute values. In computation of gust velocities the velocity at the starting point is at first assumed to be zero and the gusts through the sampling run are related to this arbitrary zero. A good estimate of the absolute values can be made later, for if the aircraft does not change height appreciably over the run it is safe to say that the aircraft's mean vertical velocity is about zero.

The platform outputs together with the wind-vane deflexions are recorded by a photographic galvanometer recorder. The deviations of the various parameters from their values at the starting point are read off from the record at fixed time intervals. The data are punched on tape suitable for processing by computer to solve the equations at each time step. The airspeed U used in the equations is a mean value over the run because the gusts themselves affect the static vent of the pitot-static system and make the instantaneous accurate measurement of airspeed impossible. Examination of equations (1), (2) and (3) shows that although U is large compared with the vertical and lateral gusts, errors in U give rise to only small errors in them. Errors in U do however cause considerable errors in the longitudinal gusts.

Some idea of the accuracy of vertical velocity measurement may be obtained by asking the pilot to manoeuvre the aircraft in pitching and rolling motions in non-turbulent air, say above an inversion. The computation of the equations in this case should give the vertical velocity as zero. From this type of experiment it can be deduced that the error in vertical gust velocity arising from instrumental and trace reading errors is about ± 1 ft/s. Considering that the Hastings cruises at about 300 ft/s this order of accuracy is remarkably high.

Some results.—Some measurements of vertical gusts in shallow cumulus over southern England on 29 March 1966 are shown in Figure 2. The aircraft flown was the Hastings which then had a single wind vane mounted horizontally on a boom at the side of the fuselage. This arrangement is unsatisfactory because airflow around the fuselage affects the wind vane and because no provision is made for the measurement of β (see equations) for which a second, vertical wind vane is required. However, the term $\tan\beta \sin\alpha$

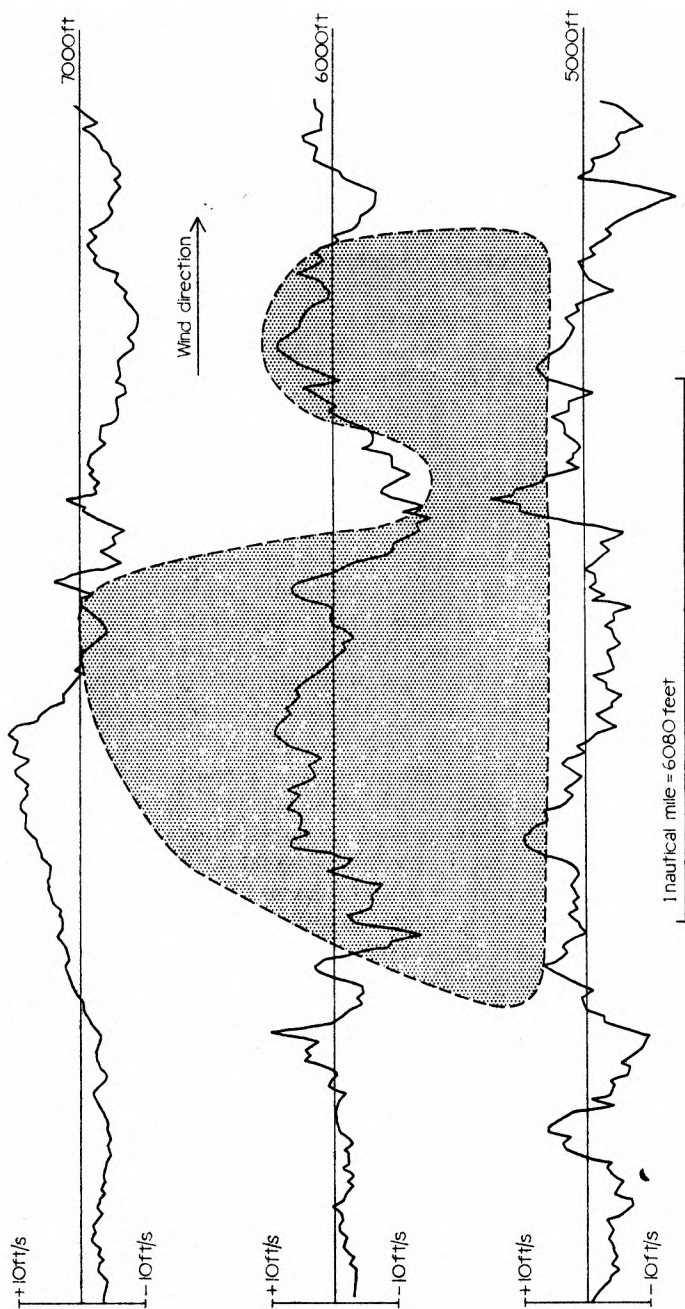


FIGURE 2—VERTICAL GUSTS IN SHALLOW CUMULUS OVER SOUTHERN ENGLAND

ON 29 MARCH 1966

The shading shows the approximate extent of the cloud.

in equation (1) is in general much smaller than the term $\tan\alpha\cos r$, and the neglect of this term does not cause a large error in the vertical gust measurement. The Hastings aircraft is to be fitted with a nose probe similar to that of the Canberra which allows measurement of both α and β .

The cloud was penetrated near the top and about the middle and just below the base. Each run, made straight and level either upwind or downwind, was carefully timed, as were the turns and descents between runs, in order to relate, if possible, the gusts at each level. The cloud was about 2000 ft deep, top 7000 ft, base 5100 ft. The regions of cloudy air are marked on the graph of vertical velocity measurements. The updraughts in the cloud itself with downdraughts at the edges are well marked as is the decrease of turbulence towards the top of the cloud where there was a well-marked inversion.

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THE FIRST INTERNATIONAL SYMPOSIUM ON METHODS IN AGROCLIMATOLOGY, READING, 20-30 JULY 1966

The Symposium was organized by the United Nations Educational, Scientific and Cultural Organization (UNESCO) with the understandable interest and co-operation of the Food and Agriculture Organization (FAO) and the World Meteorological Organization (WMO). Its formal purpose was 'to review critically the current progress of methods of measurement, analysis and presentation in agroclimatic studies and the practical uses to which they can be put.'

One can hope to convey the substance but not the savour of the opening speaker's remarks. Dr Austin Bourke, having established the relation between agrometeorology and agroclimatology took as a definition that 'the task of the agrometeorologist is to apply every relevant meteorological skill to helping the farmer to make the most efficient use of his physical environment, with the prime aim of improving agricultural production — both in quality and quantity.' The key question was the practical utility of agroclimatic classification and its application to overall agricultural strategy. After underlining some of the difficulties of handling meteorological and biological data, and of establishing relationships between the two, Dr Bourke indicated some of the hazards that may occur when models of behaviour are formulated. The only valid test of any agrometeorological rule was 'Does it give practical results?' A procedure that worked with an efficiency of 80 per cent would be a reasonably good one in the agricultural world.

After these general remarks, the papers became more specific. Professor Budyko, speaking on solar radiation and its use by plants, showed how purely meteorological data could be developed into an agroclimatic index. The intensity and amount of solar radiation reaching the earth's surface may either be measured directly, or the components of the radiation régime derived by computation from observations of basic meteorological elements. One of the results of the International Geophysical Year, for example, was

to show that mean monthly and annual values of total radiation may be derived with an error not exceeding a few per cent.

Dr Rijtema showed that agreement is possible between observed and derived values of transpiration and emphasized the possibility of transferring empirically derived crop parameters from one climatic region to another. He briefly mentioned some of the early empirical methods of calculating evapotranspiration, for example those based on monthly mean temperature, but soon moved on to methods taking fuller account of the meteorological processes involved, as well as to factors relating to the plant and the physical condition of the soil.

After the review by Dr Rijtema, Dr Slatyer was able to focus attention on the problems of using soil water balance data for agroclimatic purposes in regions where meteorological observing stations are few and record only one or two elements.

Agroclimatic models using soil water balance data are usually set up on the basis of a water budget in which precipitation (or irrigation) minus run-off (or plus run-on) is added to the soil water store, which is then depleted by deep drainage and evapotranspiration. Because of inaccuracies in measuring or assessing the individual items of the soil water budget, the method is restricted to regions of relatively high potential evapotranspiration rates and characteristically intermittent rainfall. It was demonstrated by reference to models developed for the Alice Springs area of central Australia.

A typical result might be, in regions where both summer and winter rainfall are alone inadequate to carry a crop through, the recommendation of a summer fallow, followed by a winter crop which could realize a harvest by drawing on the soil water reserves established in the summer. Soil water balance estimates, in addition to providing an index of regional climate, have found a use in the calculation of irrigation need, the estimation of drought hazard, and in studies of the leaching of soils and of water-table levels.

Dr Waggoner's paper was in its way a very compendium of examples of ways of manipulating meteorological data and the limiting agrometeorological factors — of passing from primary observation to derived data and back again — of examples of the utility of a limited run of observations already available, and of the diminishing marginal utility of additional observations as the run increases.

Whilst on the subject of data manipulation, this is perhaps a convenient point to draw attention to the paper by Dr Sharon. In agroclimatology and particularly in microclimatology, observations may be taken over limited periods and conclusions drawn from a small number of observations only. Dr Sharon was interested in the size of sample necessary to achieve a pre-determined degree of reliability. The procedure was illustrated by examination of the number of observations necessary to determine the frost liability of a site.

Dr Waggoner kept before us the need to concentrate on the weather phenomena most relevant to a given problem, or the kind of parameter to be written into the 'decision matrix'. A decision matrix is a contingency table in which the resultant profit is tabulated under the various combinations of two variables, one being the relative probability of alternative weather or climatic features and the other being alternative farming systems or actions.

Dr MacQuigg gave examples relevant to the agrometeorological field, both for decisions made over periods of time which rule out the use of weather trends and for decisions which can incorporate the use of a medium-range forecast. An example of the latter type was in the choice of a planting date for cotton ; but he was able to show that weather information does not have to be perfect to be of use and an interesting by-product was that it is possible to place an economic value on forecasts whose accuracy ranges from 50 per cent to 100 per cent in the example.

After this general review and examples of the application of observed and derived meteorological data to the establishment of crop/climate relationships, the specialists were permitted to have their field day — for there are obviously considerations other than the purely meteorological environment to be taken into account when attempting to assess the agricultural potential of an area. The total environment includes factors such as soil fertility (its maintenance or restoration), insects and other pests, plant disease, etc.

Whilst others present may have been hoping for ways of identifying climatic trends and for means of 'getting in on them at the bottom and out at the top,' the meteorologists present were perhaps resigned to the conclusions of Professor Sutcliffe. There are difficulties in establishing scientifically based relations for fluctuations and trends in climate and we have to fall back on a statistical approach to future events on the broader time scale. This view was not entirely accepted and Dr Penman pointed out that, when faced with a system of many variables, a standard approach was to look first for the more conservative elements and to take them outside the problem. In this country, the climatic factors deciding between arable and grassland farming were rainfall and evaporation. When considering possible shifts in the pattern of farming here over the next 20 years, rainfall would be the determining factor since potential evaporation might be expected to remain reasonably constant. We should probably find though that the farmers would have adapted to a changed rainfall régime before the climatologists had agreed that there was a trend.

These papers were followed by others which offered the basis for some action. The population dynamics of pests and the foci of plant disease are influenced by much the same meteorological elements as the plants themselves, reacting to temperature, moisture, light and wind. An understanding of the part these factors play at the various stages of the life cycle of the pest opens the way to the possibility of prediction from meteorological data and of control.

The recent report of a WMO Working Group on shelter left Dr van Eimern free to concentrate on outstanding problems, for example the estimation of wind danger in hilly areas, and the need for reports to be compiled in such a way that the results of different investigations can be compared. The point was made by several speakers that despite a suitable macroclimate, local climatic conditions need to be studied in deciding the suitability of small areas for agriculture, particularly with regard to frost liability.

Professor Mahadevan spoke on the relation between climatic factors and animal production, though his main interest was in the adaptation (through selective breeding for heat tolerance) of high-yielding temperate-zone animals to the tropics.

The methods employed in the recent FAO/UNESCO/WMO surveys were presented by Mr Cochemé and Dr Wallén. The surveys had been of the arid and semi-arid areas of the Levant and of that part of West Africa south of the Sahara. With the emphasis on water availability as a crop-limiting factor, much attention naturally centred on rainfall and evapotranspiration.

The meeting closed without formal resolutions or formal recommendations for future work, but there was an attempt to obtain some consensus of opinion on the problems to be tackled over the next few years and the data that would help. On the latter point, there was a definite requirement for radiation networks, for a convenient assemblage of instruments for topoclimatological studies and there was little doubt that lysimeters of the sunken-pan type were to be preferred. Future progress is dependent upon money and, in summarizing or looking ahead, speakers were at pains to demonstrate their interest in profit or economic gain.

G. V. SMITH

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NOTES AND NEWS

Lecture by Professor David Atlas

Meteorologists are familiar with the use of radar as a powerful tool in the study of cloud physics, and Professor Atlas of Chicago University has been a leading figure in this field since it began 20 years ago. In recent years, however, Professor Atlas's interest has shifted to the use of radar to probe the properties of the *cloudless* atmosphere, and his recent work in this field formed the subject of his lecture at the Meteorological Office, Bracknell, on 15 September 1966.

Since the earliest days of radar, workers have reported signals from an apparently cloudless atmosphere which have been called 'clear-air returns' or 'angels'. These angels were generally ascribed either to birds and insects, or to local inhomogeneities in the refractive index of the atmosphere caused mainly by fluctuations in water-vapour concentration. However, little systematic effort to identify the origin of angels was made until fairly recently when the advent of more powerful and sophisticated equipment began to attract radar meteorologists to this field.

The most comprehensive attack on the study of angels to date has recently been made by Professor Atlas using three powerful radars operating at wavelengths of 3.2, 10.7 and 71.5 cm and installed at Wallops Island, Virginia. This combination of different wavelengths and great power has led to an analysis which Professor Atlas described with great enthusiasm.

He distinguished between two basic angel types: discrete echoes which appear to emanate from a point in space and are called 'point' or 'dot' angels; and diffuse echoes of some horizontal extent appearing as bands or cells on PPI (Plan Position Indicator) or RHI (Range-Height Indicator) displays.

Dot angels may be produced either by birds and insects, or by partial specular reflection from the concave (downwards) regions of smooth, undulating laminar layers.

Atlas claimed the two causes could be distinguished by the wavelength dependence of the signal intensity. Birds and insects scatter radiation roughly isotropically with an intensity roughly proportional to λ^{-4} (Rayleigh's Law) and thus appear strongest on the 3.2-cm radar, whereas partial reflections have a wavelength dependence which is weak and may be slightly positive, and so appear strongest at 71.5 cm.

The use of insects as wind tracers has already been exploited by several workers — notably Lhermitte who studied the structure of the nocturnal low-level jet over Oklahoma — while the motions of the insects relative to their local wind (i.e. their airspeed) can also be studied, and this may be of interest to entomologists. Professor Atlas predicted that radar could well replace the radiosonde as a wind-finder over the next 10 years !

Diffuse angels may appear in various forms. The best known are thin horizontal layers which have been shown by Saxton and Lane of the Radio and Space Research Station, Slough, to correlate perfectly with stable layers in the lower troposphere containing sharp refractivity gradients.

Professor Atlas also reports these low-level layers as a common feature but, at Wallops Island this summer, a faint layer was observed at the tropopause on six occasions, which led Professor Atlas to suggest (from theoretical considerations) that clear-air turbulence should be detectable from *forward-scattered* beams with equipment of moderate power since forward-scattered intensities would be 100 to 10,000 times the back-scattered intensities detected with the powerful Wallops Island equipment.

These ideas gave rise to a good deal of discussion. It was pointed out that the scales of turbulence detected by radar were one or two orders of magnitude less than those detected by aircraft, and implied an assumption regarding flux of energy down the spectral scale of turbulence. It was also by no means clear that turbulence experienced by an aircraft would always be detectable by radar particularly if it was in the form of wave motion of hundreds of metres wavelength. Objections to the identification of 'refractivity turbulence' with mechanical turbulence were also made : the former could occur without the latter (e.g. moist patches left by evaporating cloud in non-turbulent air) and vice versa (e.g. the tendency for turbulence to mix out any gradients of water-vapour concentration).

Professor Atlas agreed, but suggested that refractivity turbulence and mechanical turbulence will generally occur close enough in space and time for practical purposes.

The other features of interest were the detection of diffuse echoes from sea-breeze fronts and thermal convection cells. Mr Lane of the Radio and Space Research Station was present, and described his observations at Wallops Island in collaboration with Professor Atlas where he flew a radio refractometer suspended 80 feet below a helicopter through thermals over the sea, and was able to identify the turbulent shells of thermal cells with the regions of diffuse echoes shown by the radar complex. Thus it is clear that this represents a powerful technique for studying low-level convection, although one of the members of the audience claimed it showed nothing he would not have expected 'by looking out of his bedroom window'. This is perhaps rather unfair, since unexpected features might well appear on closer

inspection and this work should be especially relevant to recent work on low-level convection.

The discussion was brought to a close at 5 p.m. and Professor Atlas was thanked by the Director-General for his stimulating and exciting talk.

W. T. ROACH

REVIEW

Weather prediction by numerical process, by L. F. Richardson. $9\frac{1}{4}$ in \times $6\frac{1}{2}$ in, pp. xvi+236, *illus.*, Constable & Co. Ltd, 10 Orange Street, London, WC2, 1966. Price : \$2.00.

This book by L. F. Richardson is one of the outstanding scientific books of his era. The scientific content of the book, however, is now mainly of a historical nature, despite the publisher's claim that this is one of the best textbooks on dynamical meteorology ever written, and I do not recommend that this book should be used as a classroom text. Nevertheless, this book is of considerable interest to all active workers in the field, and Dover Publications are to be congratulated on their decision to reprint it.

Richardson sets out a systematic method of computing the future state of the atmosphere given its initial condition, and computes six-hour changes in fundamental parameters such as pressure, wind and temperature. Unfortunately, his one example produced pressure changes more than an order of magnitude too large, and he attributed this to errors in evaluating the horizontal divergence from the wind field. The subject then lay dormant until the advent of modern electronic computing machinery when methods of numerical weather prediction which did not depend upon evaluating the horizontal divergence were developed by Charney, Phillips and others. Recently, it has been shown by Hinkleman and others that the basic equations used by Richardson can be used to predict weather changes, provided certain precautions are taken. It is essential that there should be no spuriously large divergences implied by the initial wind field, and it is necessary that the time-step should be of the order of a few minutes in order to stop the amplification of sound and fast-moving gravity waves, rather than the six hours used by Richardson.

Thus it is true to say that whilst all workers in numerical weather prediction should read this book, it is unlikely that anyone can make very much useful progress in this field without studying much more up-to-date textbooks and research papers.

F. BUSHBY

LETTERS TO THE EDITOR

551.509.317:551.509.56

Instability index

A recent article by Saunders¹ describing tests of thunderstorm forecasting techniques states that the time taken to apply the modified Jefferson index² (T_m) was 10–20 minutes using 0000 GMT upper air data and allowing for the effects of advection and surface heating as seem appropriate.

The figure of 10–20 minutes could certainly be substantially reduced by using the procedures now adopted at Episkopi.

(i) The formula for the index has been slightly modified by adopting a wet-bulb potential temperature at 850 mb, θ_{w850} , instead of at 900 mb. Thus when T_{500} is the air temperature ($^{\circ}\text{C}$) at 500 mb and T_{d700} is the dew-point depression in degC at 700 mb the formula reads

$$T_{m_j} = 1.6 \theta_{w850} - T_{500} - \frac{1}{2} T_{d700} - 8$$

and can be calculated from readings at the standard pressure levels reported in the upper air message.

The modification makes little difference to the index itself and may in fact be an advantage in the Mediterranean area. I think it would have little if any adverse effect if it were used in the United Kingdom area.

(ii) A table has been constructed to give θ_{w850} to the nearest half-degree Celsius from dry-bulb and dew-point readings. The table on page 94 of *Meteorological Magazine*, Volume 92, 1963, can be used to give T_j from θ_{w850} and T_{500} . The table on page 314 of *Meteorological Magazine*, Volume 92, 1963, gives the further correction to T_j to obtain T_{m_j} from T_{d700} . All tables can be laid under perspex on the plotting bench.

(iii) Using these tables T_{m_j} can be evaluated in not more than 30 seconds per station direct from the upper air message. At Episkopi such evaluations are carried out and a chart of the index plotted station by station.

By using all ascents received for the area of the map and not merely those for which tephigrams are plotted, an additional upper air chart is produced to stand alongside the normal contour charts for standard levels but showing the spatial distribution of instability. While not replacing the usual study and analysis of the plotted ascents available it does form a very useful additional aid to analysis.

Episkopi, Cyprus.

G. J. JEFFERSON

[It is learned that a test is being made in the United Kingdom of the Jefferson index using θ_{w850} . Ed. M. M.]

REFERENCES

1. SAUNDERS, W. E. ; Tests of thunderstorm forecasting techniques. *Met. Mag., London*, **95**, 1966, p. 204.
2. JEFFERSON, G. J. ; A further development of the instability index. *Met. Mag., London*, **92**, 1963, p. 313.

551.557.5:551.576.11:77

Upper cloud striations

On 7 September 1966 an inactive warm front was moving slowly north-east over south-west England and the Channel area. The photograph (Plate II) shows cloud to the south-south-east of London (Heathrow) Airport at 1115 GMT. At 1200 GMT the maximum wind at Crawley, Sussex was $250^{\circ}/90$ knots at about 40,000 ft but the core of the jet stream lay over northern England. Although the clouds shown were in association with a frontal system and some distance from the core of the jet stream the complexity of their structure is typical of the structure of clouds near a jet stream.*

19 Ensign Way, Stanwell, Staines, Middlesex.

A. H. P. JARRETT

* JEFFERSON, G. J. Photographs of jet-stream clouds. *Met. Mag., London*, **93**, 1964, p. 91.

OFFICIAL PUBLICATIONS

SCIENTIFIC PAPERS

No. 23—*Surface and 900 mb wind relationships*, by J. Findlater, T. N. S. Harrower, M.A., B.Sc., G. A. Howkins, M.B.E., B.Sc. and H. L. Wright, M.A.

The paper presents an analysis of surface and 900 mb wind relationships made during a search for an objective method of forecasting the surface wind from the geostrophic wind. A basis was obtained for a forecasting technique for surface wind over sea areas but little progress was made for land areas.

Nearly 17,000 observation pairs for two locations over the sea and two over the land were used to make a comprehensive analysis and results are presented in some detail because of their interest in relation to general questions of turbulence. Particular attention is paid to the influence of lapse rate in the lower layers.

No. 24—*An atmospheric diffusion slide-rule*, by C. E. Wallington, M.Sc.

The paper describes a slide-rule that can be used to calculate concentrations and dosages in clouds of aerosols being transported and diffused by atmospheric wind and turbulence.

The slide-rule includes scales for incorporating into the calculations several methods of assessing depths and widths of diffusing clouds, but the relative merits of the methods are not discussed in detail ; the main purpose of the paper is to present the slide-rule as a calculating aid.

The slide-rule is not intended for laymen to the subject of atmospheric diffusion ; it is more for those who have at least a little understanding of the theoretical background. For such users the slide-rule provides a means of predicting or assessing experimental diffusion observations ; it facilitates comparison of various methods of diffusion calculations and it enables a user to compile tables or graphs suitable for use by laymen.

No. 25—*The relation between Beaufort force wind speed and wave height*, by R. Frost, B.A.

In this paper it is shown that the present internationally agreed wind-speed and wave-height equivalents of the Beaufort numbers are incompatible with the wind/wave relationships obtained by oceanographers, and a new set of wind equivalents is proposed. With winds measured in metres per second at the internationally agreed height of 10 metres above the surface, the wind-speed equivalents (W) of the Beaufort numbers (B) are shown to be for all practical purposes independent of the atmospheric stability and to be given by

$$(i) \quad W = 1.38 B^{7/6} \text{ over the open oceans,}$$

$$\text{and (ii) } W = AB^{14/9} \text{ over coastal waters,}$$

where A varies with the fetch. (In particular, with a fetch of approximately 35 kilometres this formula yields the present international equivalents.)

It is hoped that the paper will prove of value not only to meteorologists and oceanographers but also to the increasing number of other scientists and engineers who need to have a knowledge of sea state conditions.

MARK 111 RAINGAUGES

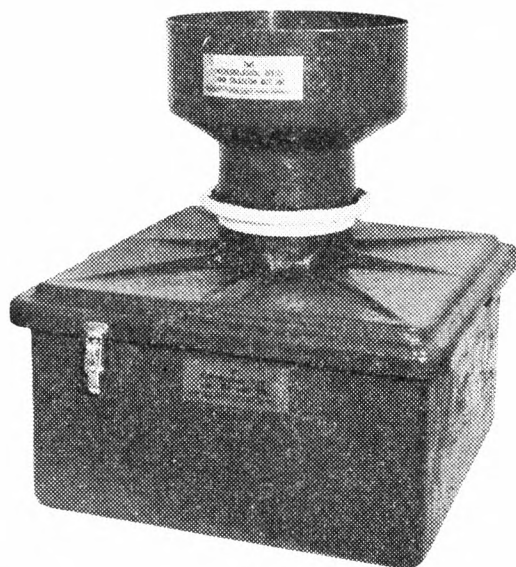
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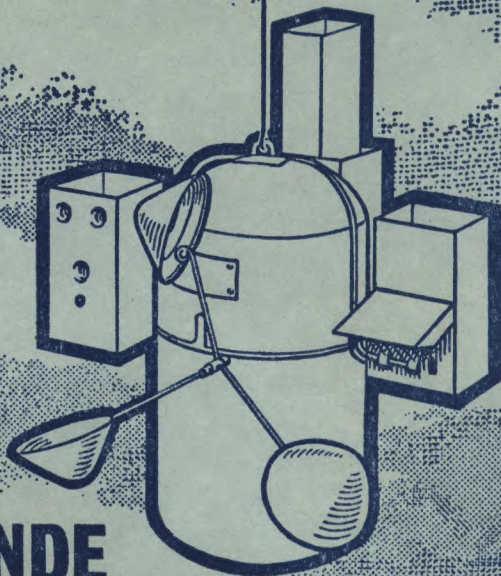


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CONTENTS

	<i>Page</i>
Cross-equatorial jet streams at low levels over Kenya. J. Findlater	353
Meteorology and gliding — 1966. P. G. Wickham	365
An example of forecasting rainfall in Cyprus by using the 300 mb jet stream in conjunction with a 700 mb analysis. R. M. Morris	366
Inertial navigation and gust measurement from Meteorological Research Flight aircraft. I. Ross	370
The first International Symposium on Methods in Agroclimatology. C. V. Smith	376
Notes and news	
Lecture by Professor David Atlas	379
Review	
Weather prediction by numerical process. L. F. Richardson. <i>F. Bushby</i>	381
Letters to the Editor	381
Official publications	383

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