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A NOTE ON THE AVERAGE ANNUAL MEAN OF DAILY EARTH TEMPERATURE IN THE UNITED KINGDOM

By R. W. GLOYNE

Summary. An average annual mean daily earth temperature of 46°F (8°C) is considered to be relevant to aspects of soil formation, and an attempt has been made to display the run of the 46°F isopleth over the United Kingdom. A diagram is given which shows the 46°F isotherm at a height of about 2400 ft above mean sea level along the south coast of England, falling to about 1000 ft at 54°N and to 200–400 ft in north Scotland and the northern Islands.

In the course of the work several useful relations also emerged, viz. :

(i) That an addition of between 0·5 and 1·0 degF to the annual mean earth temperature (based on observations at 09 GMT) at 8 in (20 cm) depth and one of 1·0 to 1·5 degF to the corresponding observation at 4 in (10 cm), would suffice to produce average annual values appropriate to mean values computed on a 24-hour basis.

(ii) That the lapse rate of the annual mean earth temperature is about 1 degF/290 ft (0·63 degC/100 m) in south-east England and in a wide coastal band up the east coast to south Scotland, and 1 degF/330 ft (0·55 degC/100 m) elsewhere.

Introduction. A request for a map showing the run of the isopleths of average annual earth temperature of 8°C (46°F) — a level believed by pedologists to be an important discriminant in relation to soil formation — involved a reassessment of available data on soil temperatures at levels down to 4 ft below the surface.

Three groups of difficulties arose; the first concerned the adjustment needed to obtain from readings made once daily at a fixed hour an acceptable estimate of the daily mean value of an element subject to diurnal variation; the second arose from the irregularity of the network of reporting stations, and in particular the dearth of stations in hilly areas; and the third group of difficulties had to do with the presentation of the results in map form.

Annual mean earth/soil temperature at different depths. In a homogeneous soil, the annual mean temperature from the surface to a depth of several metres is equal at all levels. However the amplitude of the seasonal wave, and of any superimposed diurnal variation, increases towards the surface. Broadly speaking the seasonal fluctuation will be reduced to a fraction of a degree Celsius at a depth of 10 metres and any diurnal fluctuation will be similarly reduced at a depth of about 1 metre — indeed during most of the year in the generally cloudy climate of Great Britain the daily fluctuation at 1 ft (30 cm) under short turf is rarely more than a degree Celsius or so; for pertinent data see Meteorological Office,[1] Gloyne[2] and Rambaut.[3]

Data available for the current study are :

(i) Mean values of readings at 09 GMT of earth temperature under short turf at depths of 1 ft (30 cm) and 4 ft (122 cm), together with some additional short-period results (Gloyne[4]).

(ii) Mean values of soil temperature at depths of 4 in (10 cm) and 8 in (20 cm) under bare soil and at 2 ft (60 cm) under turf for certain agrometeorological stations (thrice-daily readings at 09, 15 and 21 GMT for 1924–31 and once-daily readings at 09 GMT from 1932 onwards*).

Sarson and Applegate[5] used the thrice-daily readings at 4 in and 8 in to establish a 'true' daily mean and computed its deviation from the mean value for 09 GMT. The first seven columns of Table I are extracted from their data and the means for depths of 1 ft and 4 ft have also been included.

The data indicate that an addition of between 0·5 degF and 1·0 degF to the mean 09 GMT value read at a depth of 8 in is needed to obtain a mean daily value; the corresponding figure for a depth of 4 in ranges from 1·0 to 1·5 degF. There is a tendency for the lower figures to be appropriate to stations in the north of England. Furthermore (Reference 1, pp. 18–24), it is apparent that the 1931–60 averages are a few tenths of a degree Celsius above those for 1921–50. Upward adjustments of the type described, when applied to the 1926–55 means for 09 GMT at depths of 4 in and 8 in, will render these latter values close to the 1931–60 means for depths of 1 ft, 2 ft and 4 ft, and so provide a further set of estimates of the values of average annual earth temperature.

Variation of average annual earth temperature with height above mean sea level. The second type of difficulty mentioned in the introduction can be partially surmounted by deriving some estimate of the rate of change of earth temperature with height. Many references were scrutinized, amongst them Geiger,[7] Hann,[8,9] Maurer,[10] Scultetus[11] and some recent work by Alcock.[12] Details of such an examination are set out in Gloyne.[4] The outcome of this study may be summarized as follows :

(i) In most parts of continental Europe average annual earth temperature decreases at rates between about 0·5 and 0·6 degC for an increase in height of 100 m up to a level of about 500 m and thence more slowly, at about 0·4 to 0·5 degC per 100 m. Average air temperature falls off rather more rapidly by approximately an additional 0·1 degC per 100 m, accordingly the difference (average earth temperature minus average surface air temperature) increases with height, and all the continental authors quoted comment on this result. It must however be realized that whilst in the United Kingdom cloudiness tends to increase from sea level to the tops of our highest peaks, in many continental regions the upper parts of the mountains are frequently above much of the cloud. It is therefore to be expected that the difference between the temperature on and under a snow-free, sun-irradiated mountain surface, and that of the ambient air will increase with height.

(ii) Stations in the United Kingdom, judged subjectively as being within the same climatic régime but at different elevations, were grouped and the decrease of average earth temperature with height was computed.

* Unpublished summaries of meteorological observations at agro met stations prepared by the Meteorological Office for the Agricultural Meteorological Scheme of the Ministry of Agriculture and the Ministry of Agriculture, Fisheries and Food.

TABLE I—AVERAGE ANNUAL VALUES OF SOIL AND EARTH TEMPERATURES AT SEVERAL DEPTHS, AND DEVIATION OF MEAN OF 09 GMT READINGS FROM TRUE MEAN

	Four inches*			Eight inches*			Two feet**	One foot†	Four feet†	Period‡
	True mean	09 GMT mean	Difference	True mean	09 GMT mean	Difference	True mean	09 GMT mean	09 GMT mean	
	degrees Fahrenheit							degrees Fahrenheit		
Aber(a)	50·1	49·1	1·0	50·0	49·4	0·6	50·4	N/A	N/A	
Aberystwyth	49·9	49·0	0·9	49·8	49·4	0·4	49·9	N/A	N/A	
Cannington	51·6	50·6	1·0	52·1	51·0	1·1	52·1	N/A	N/A	
East Malling	50·6	49·5	1·1	50·7	49·5	1·2	51·0	51·1	N/A	1931–60
Ellbridge	52·8	51·0	1·8	52·9	51·8	1·1	N/A	N/A	N/A	
Gulval	53·4	52·1	1·3	54·3	52·9	1·4	N/A	N/A	N/A	
Houghall(a)	48·0	46·8	1·2	48·1	47·6	0·5	48·5	N/A	N/A	
Long Ashton(a)	50·3	49·3	1·0	50·9	49·7	1·2	51·8	51·4	N/A	1931–60
Long Sutton(a)	50·4	49·6	0·8	51·0	50·3	0·7	51·1	51·0	49·5	1921–50
Cockle Park(a)	46·8	46·1	0·7	47·3	46·3	1·0	N/A	46·9	47·7	1931–60
Newport	49·2	48·1	1·1	49·3	48·3	1·0	N/A	N/A	N/A	
Newton Abbot	51·6	50·3	1·3	52·0	50·9	1·1	N/A	N/A	N/A	
Newton Rigg(a)	47·4	46·7	0·7	47·9	47·3	0·6	N/A	N/A	N/A	
Rothamsted	49·4	48·1	1·3	49·7	48·5	1·2	49·7	49·7	49·4	1921–50
								49·8	49·3	1931–60
Sprowston	49·2	48·4	0·8	49·6	48·6	1·0	N/A	N/A	N/A	
Sutton Bonington	49·2	48·2	1·0	49·4	48·4	1·0	N/A	49·6	49·6	1921–50
								49·3	50·2	1931–60
Wisley	50·4	50·0	0·4	51·2	50·3	0·9	51·6	51·2	51·2	1921–50
								51·8	52·5	1931–60
Woburn	50·0	48·7	1·3	50·6	49·4	1·0	50·9	50·3	50·5	1921–50
								50·4	50·4	1931–60
Wye	50·7	49·8	0·9	50·9	49·9	0·8	51·1	N/A	N/A	

* Adjusted to a 1926–55 basis.
** Data available on a 1926–55 basis from Sarson and Applegate.[5]
† Data available from published normals for 1921–50[6] and 1931–60.[1]
‡ The periods apply to the one-foot and four-foot data.
(a) Stations regarded as relevant to the situation in northern Britain.
N/A = not available.

(iii) A further constraint was imposed by the spatial pattern of observed differences between average annual earth temperature and average annual air temperature. Zero or negative differences up to 1 degC occurred in a narrow zone of the west Midlands which broadens north-eastwards into Lincolnshire and Yorkshire and reappears along parts of the immediately coastal strip of east Scotland. Excesses of up to 1 degC or a little higher were found south of a line from London to Bristol, and the highest values occurred along the Channel coast; similar, or rather greater differences were registered at several high-level stations in Wales, northern England and Scotland. Elsewhere in Wales, north-west England and most of Scotland the excess was 0·75 degC or less.

The evidence having been reviewed, it was decided to adopt two estimates for the lapse rate of average annual soil temperature with height, namely :

(a) 1 degF/290 ft (0·63 degC/100 m) and

(b) 1 degF/330 ft (0·55 degC/100 m).

In general rate *(a)* was found appropriate to stations in south and south-east England and the eastern Midlands and along a broad coastal strip from the Thames to Aberdeen, and rate *(b)* elsewhere. The final run of the isopleths was also constrained as described in (iii) above and a somewhat irregular transition from east to west was therefore unavoidable.

The graphical presentation of the data. Obviously the straightforward solution of mapping the run of the 8°C (46°F) isotherm would result in a pattern with all the complexities of a contour map. Accordingly an alternative solution was adopted in which, at each station, the estimated height above mean sea level of the isothermal *surface* for 46°F was noted, and this led to the pattern represented in Figure 1.

To facilitate direct use with existing contour maps the heights above mean sea level of the 46°F surface were given in feet. The user would therefore only need to compare the absolute height *above* mean sea level with that of the computed 46°F surface to ascertain firstly whether or not the value appropriate to his site was above or below 46°F, and secondly the approximate vertical distance (positive or negative) from the site to the 46°F surface.

Some comments on the results (Figure 1). Over the United Kingdom the height of the surface at which the average annual earth temperature is 46°F ranges from 2400 ft along the coast of southern England to 1000 ft at about 54°N to 600–800 ft in the Fourth–Clyde valley and to a minimum of about 200 ft inland in northern Scotland. There it rises towards the coast to about 400 ft — a figure valid also for the Orkneys — and resumes its general decrease northwards, reaching a little over 300 ft above mean sea level in the Shetlands.

If, as has been suggested by pedologists, the 46°F isotherm of average annual earth temperature is an important discriminant in relation to soil formation, then certain soil characteristics common to large areas of Scotland will probably not be encountered in southern England (i.e. south of the Wash), except on the highest parts of Dartmoor. Much of the high ground of Wales and northern England, however, rises above the 46°F surface, and, except in parts of south and south-west Scotland, an average annual earth temperature of less than 46°F can be expected over all but the low coastal plains of northern Britain.

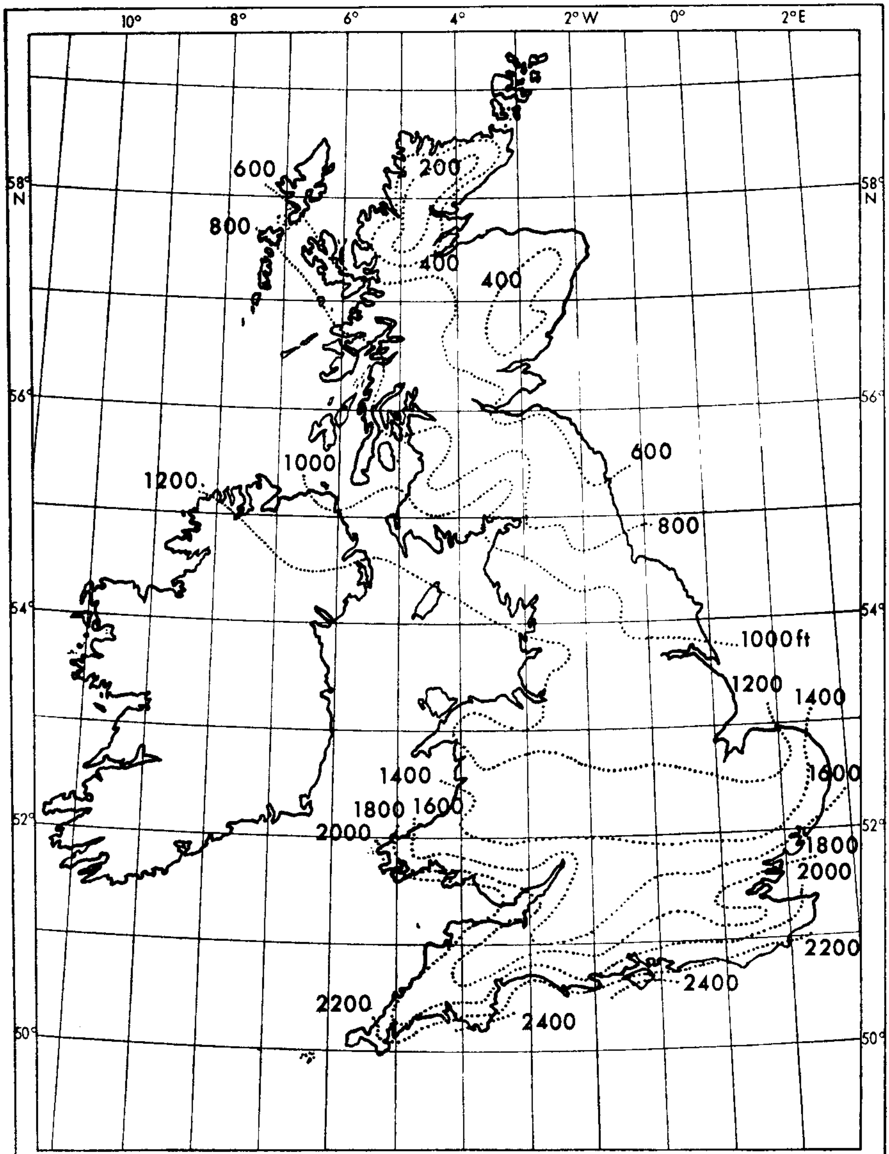

FIGURE 1—COMPUTED CONTOUR HEIGHT AT WHICH A MEAN ANNUAL EARTH TEMPERATURE OF 46°F (8°C) WOULD BE EXPECTED TO OCCUR

Heights are shown in feet.

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551.524.3:629.12

DAY-TIME TEMPERATURE MEASUREMENTS ON WEATHER SHIP 'WEATHER REPORTER'

By C. K. FOLLAND

Summary. This report discusses the influence of screen position on the observation of dry- and wet-bulb temperatures taken aboard a British Ocean Weather Ship. Particular attention is paid to the 'standard' screen exposures on the bulwarks of the bridge deck. The temperatures in the leeward screen were often lower than in the windward screen. Several other screen positions were tried, and one on the roof of the balloon shed gave decidedly lower temperatures than either of the standard positions and would be suitable at least for remote readings on a routine basis.

Introduction. The most suitable position for a thermometer screen on board ship is one where the air will come directly to the screen from over the sea before passing over any part of the ship. The ship is a local source of heat; radiation takes place from the hull and from sunny decks, deck-houses, etc., especially in the tropics. Warm draughts of air may be felt from galleys, engine and boiler rooms, stokehold and funnel. The thermometer screen in use normally stands as far as possible forward and outboard from all such sources of local heating since these tend to give false indications of the true air temperatures, particularly on days when the relative wind is light. The choice of a screen mounting position on the bridge avoids some of these sources of heating. Nevertheless, the bridge-deck screens on large bulk carriers are often many feet inboard of the boat-deck bulwarks. On weather ships the bridge-deck bulwarks are directly above the main-deck rail (Plate I).

The standard practice on British Ocean Weather Ships is to fit two screens to the bridge, and to use that on the windward side (see p. 8) together with an aspirated psychrometer placed near the main-deck rail, also on the windward side of the ship.

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PLATE I—GENERAL VIEW OF *Weather Reporter*

See page 6

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PLATE II—STANDARD PORT-BRIDGE SCREEN WITH 'OUTER' PORT SCREEN TO THE LEFT

See page 7

Recently Edwards* has demonstrated that the differences in temperature observations obtained from aspirated psychrometers and from screens exposed in the standard fashion on British Ocean Weather Ships and on R.R.S. *Discovery* probably depend on the precise details of exposure of both the aspirated psychrometers and the screens. A limited number of readings taken in light winds during the present investigation suggest that the psychrometer dry- and wet-bulb temperatures are at least as low on almost all occasions as the lower of the temperatures recorded by either of the bridge-deck screens. The problem which arises when different instruments are used as well as different exposures becomes very complex, so further consideration of aspirated-psychrometer observations will not be attempted here.

The investigation. The readings were made in the summer and autumn of 1969. Dry- and wet-bulb temperatures were taken on *Weather Reporter* on voyages 86 (July–August) and 87 (August–September) at a number of non-standard screen positions on the ship at the same time as the standard measurements. Mercury-in-glass thermometers were used throughout and readings were confined to the period 08–21 GMT. At these times of the day the ship may be regarded as a source of heat and the effect of the ship, if any, is to increase the local air temperature.

In daylight the screens themselves may be at higher than ambient temperature owing to the interception of solar radiation. The measurements were taken at ocean weather station 'I' (59°N 19°W). The ship was drifting freely or travelling at a slow speed. The standard screen position on the port bridge-deck bulwarks can be seen in Plate II and Figure 1 (there is a corresponding screen on the starboard bridge-deck bulwark).

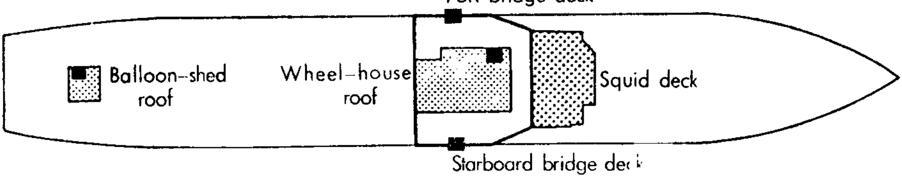

FIGURE 1—PLAN OF *Weather Reporter* SHOWING POSITIONS OF THE THERMOMETER-SCREEN EXPOSURES REFERRED TO IN THE TEXT

The screens are attached to vertical stanchions inboard of the bulwarks, with the bases of the screens level with the tops of the bulwarks. The screens are 10 feet (approximately 3 m) from the wheel-house walls, which extend about 20 feet forward and 8 feet aft from these points. The wheel-house wall is 10 feet high while the wheel-house itself is 20 feet wide. The standard positions are a little nearer the bow of the ship than the stern and about 35–40 feet above the sea.

Seven non-standard exposures were tried, three of them deliberately chosen as 'bad exposures'. The three bad exposures were : above the 'squid deck', near the bow on the starboard side and near the bow on the port side. The

* EDWARDS, P.; Temperature measurements in ships. *Q J R Met Soc, London*, **96**, 1970, pp. 130–131.

temperatures measured in these positions were mostly higher, as expected, than those measured in the standard screens and will not be discussed further. The other non-standard positions were the balloon-shed roof, the 'outer port' position (Plate II), a similar 'outer starboard' position and a position on the wheel-house roof.

The following measurements were also made :

(i) Relative wind speed and direction, to the nearest 5°.

(ii) Intensity of short-wave radiation on a horizontal surface, averaged over the hour previous to the time of observation of the temperature.

A total of 683 pairs of readings of dry- and wet-bulb temperatures have been analysed. The results have been divided according to whether the wind was incident on the port side of the ship or on the starboard side. The majority of observations were taken while the ship drifted slowly. This resulted in a preponderance of observations with wind from the port beam as this particular weather ship tends to drift sideways with the wind blowing directly on to the port side. The few occasions when the wind blew from within 10° of bow or stern have been neglected as they represent a different wind–ship interaction régime from that occurring with other directions and too few observations exist for analysis.

The following comparisons are presented :

(i) *Wind incident on the port side of the ship.*

(a) Comparison of the port and starboard standard screens (228 occasions), Figures 2 and 3.

(b) Port-bridge screen compared with a screen on the wheel-house roof (176 occasions), Figures 4 and 5.

(c) Starboard-bridge screen compared with a screen on the wheel-house roof (176 occasions), Figures 4 and 5.

(d) Port-bridge screen compared with balloon-shed screen (33 occasions), Figure 6.

(ii) *Wind incident on the starboard side.* A comparison of the standard positions (32 occasions), Figures 2 and 3.

Results. To facilitate the comparison, the relative wind speeds and radiation intensities have been grouped to give an approximately equal number of observations in each group.

Relative wind speed categories	Radiation intensity categories (on a horizontal surface)
(1) 0–11 kt	(1) 0–7 mW/cm^2
(2) 12–16 kt	(2) 8–26 mW/cm^2
(3) 17–20 kt	(3) ≥27 mW/cm^2
(4) ≥21 kt	

Note. The lower limit of bright sunshine as measured by the solarimeter is near the lower limit set for category (2), and ≥27 mW/cm^2 is referred to in the text as 'strong insolation'.

Case (i) *(a) — Wind from port side (comparison of standard screens).* Figure 2 illustrates the mean dry-bulb temperature differences. The vertical lines represent the standard error of the mean differences. On average the port dry- and wet-bulb temperatures are higher than the starboard ones. In fact when the wind was light (≤11 knots) the port-bridge screen excess averaged

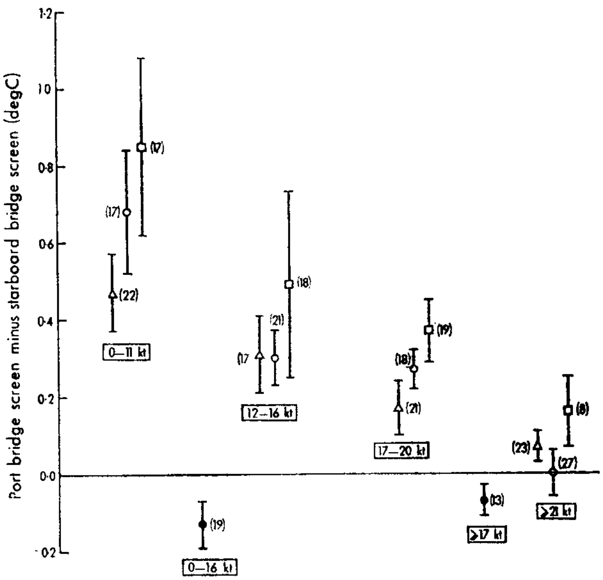

FIGURE 2—COMPARISON OF DRY-BULB TEMPERATURES IN PORT AND STARBOARD STANDARD SCREENS FOR VARIOUS WIND AND SUNSHINE CONDITIONS

□ ≥27 mW/cm² } Port to windward (case (i)*(a)*)
○ 8–26 mW/cm²
△ ≤7 mW/cm²
● All sunshine conditions : Starboard to windward (case (ii))
Vertical lines represent standard errors of the mean differences.
Numbers in brackets are the numbers of observations.

0·47 degC in dull conditions and 0·85 degC in strong insolation. On several occasions the port screen was 2·0 degC higher than the starboard one when the sun shone brightly, with a difference as big as 2·8 degC on one occasion. The port bridge-deck screen and the port wheel-house wall were probably more exposed to direct sunlight in the middle of the day than the starboard screen as the prevailing wind was from the south-west and the port side was facing into wind. The main cause, however, is probably the formation of a windward-side eddy on the bridge deck. The starboard screen was warmer than the port on occasion but the largest starboard excess was less than half that of the largest port-screen excess. Thus pockets of warmer air can also collect, as one might expect, on the leeward side, but not very frequently. A close look at relative wind directions suggests that many occasions of higher temperatures on the lee side occur when the winds are blowing within 30° of the bow direction or stern direction. This suggests a sharp change in the nature of the airflow over the bridge screens near this angle of incidence. A few occasions are accounted for by the sun shining more directly on to the starboard side of the ship than the port.

When the air is not well mixed the port screen is usually warmer. In really windy conditions (≥21 knots) the two screens are likely to agree exactly about half the time and are unlikely to disagree by more than 0·5 degC whether the sun is shining or not.

Figure 3 illustrates that the differences in wet-bulb temperature are similar though slightly smaller than those found in Figure 2 for dry bulbs. The relative humidities deduced from the screen measurements may differ by over 5 per cent on occasion but over a period of time there would be almost no difference in the average values. For relative humidities between 60 per cent and 100 per cent the average wet-bulb temperature excess of the port screen over the starboard would have to be about 90 per cent of the corresponding dry-bulb temperature excess for no net difference in relative humidity to be observed.

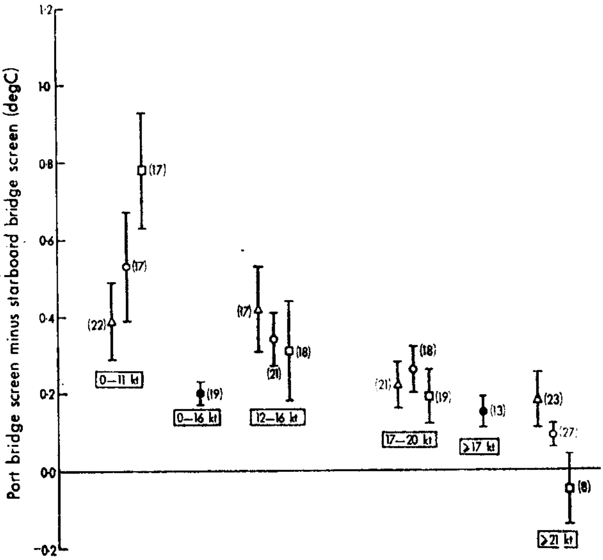

FIGURE 3—COMPARISON OF WET-BULB TEMPERATURES IN PORT AND STARBOARD STANDARD SCREENS FOR VARIOUS WIND AND SUNSHINE CONDITIONS

□ ≥27 mW/cm² ⎫
○ 8–26 mW/cm² ⎬ Port to windward (case (i)*(a)*)
△ ≤7 mW/cm² ⎭
● All sunshine conditions : Starboard to windward (case (ii))
Vertical lines represent standard errors of the mean differences.
Numbers in brackets are the numbers of observations.

Case (ii) — *Wind from starboard (comparison of standard screens).* The low frequency of winds from the starboard quarter is illustrated by the fact that only 32 observations were noted. In Figures 2 and 3 the observations have been divided into occasions when the wind was ≤16 knots or ≥17 knots respectively. On average the dry bulb in the port screen read 0·15 degC lower than in the starboard in the winds ≤16 knots and 0·10 degC lower in the winds ≥17 knots. The wet bulb in the port screen read higher than the standard readings, though the differences were small. The majority of case (ii) occasions resulted from the ship being on passage at a slow speed across the area of station 'I' and so are not strictly comparable with case (i) *(a)*. On one of these occasions the starboard screen dry-bulb reading was 1·1 degC higher than the port reading but both wet bulbs agreed so that relative-humidity differences of over 10 per cent are possible between the two screens.

Cases (i) *(b) and (c) — Wind from port side (standard screens compared with screen on wheel-house roof).* See Figures 4 (dry-bulb temperatures) and 5 (wet-bulb temperatures). The wheel-house-roof dry-bulb temperatures were decidedly lower than those in either of the standard screens. The mean difference between the dry bulb in the starboard-bridge screen and the dry bulb in the screen on the wheel-house roof was 0·50 degC in light winds (⩽11 knots) and strong insolation, and there was a difference of as much as

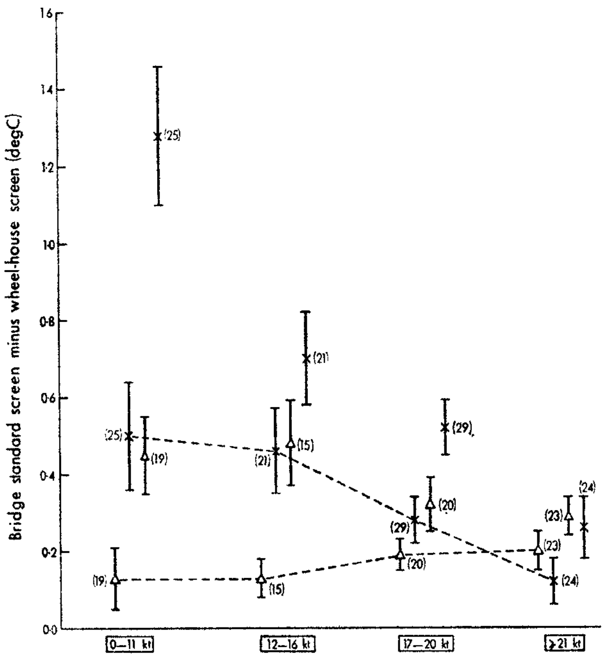

FIGURE 4—COMPARISON OF DRY-BULB TEMPERATURES IN STANDARD SCREENS WITH THOSE IN WHEEL-HOUSE SCREEN FOR VARIOUS WIND AND SUNSHINE CONDITIONS (PORT TO WINDWARD)

X ⩾8 mW/cm² } The observations of case (i)*(c)*, i.e. starboard minus wheel-house, are
△ ⩽7 mW/cm² } distinguished from those of case (i)*(b)*, i.e. port minus wheel-house, by being joined by a dashed line.

Vertical lines represent standard errors of the mean differences.

Numbers in brackets are the numbers of observations.

1·28 degC when the port screen was similarly compared. The wet-bulb temperatures show similar results. The stronger the wind the less the differences between the screens so that in dull windy conditions the mode of the differences between all three screens is zero. Nevertheless, in these conditions the mean wheel-house dry-bulb temperatures are 0·2 degC less than those of the bridge screens, which is more than can be accounted for by the difference in height.

On one occasion in strong insolation and light winds the port-bridge screen dry bulb read 3·3 degC higher than the wheel-house screen while the wet bulb was 2·6 degC higher.

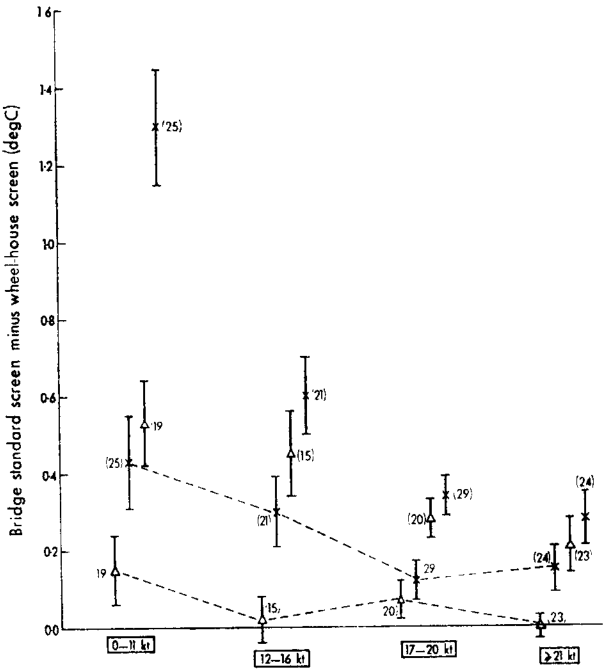

FIGURE 5—COMPARISON OF WET-BULB TEMPERATURES IN STANDARD SCREENS WITH THOSE IN WHEEL-HOUSE SCREEN FOR VARIOUS WIND AND SUNSHINE CONDITIONS (PORT TO WINDWARD)

X $\geqslant$8 mW/cm² } The observations of case (i)*(c)*, i.e. starboard minus wheel-house are distinguished from those of case (i)*(b)*, i.e. port minus wheel-house, by being joined by a dashed line.
Δ $\leqslant$7 mW/cm²

Vertical lines represent standard errors of the mean differences.
Numbers in brackets are the numbers of observations.

Case (i) *(d) — Wind from port side (port screen compared with balloon-shed screen).* Only 33 occasions were noted and the results are illustrated in Figure 6. On the whole the balloon-shed screen shows itself to be cooler than the wheel-house-roof screen, though no direct comparisons were made. This is shown by the very large excess of the mean port-bridge screen dry-bulb temperature in winds $\leqslant$16 knots of 1·70 degC and in winds $\geqslant$17 knots of 1·18 degC. The mean wet-bulb excesses were 0·97 degC and 0·74 degC respectively. The effect of stronger winds is thus to reduce the day-time port-bridge screen temperature much more than either the balloon-shed or wheel-house-roof readings. In fact in every instance the balloon-shed temperatures were as low as or lower than the lowest values from the standard screens. The fact that the mean difference of wet-bulb temperatures between port-bridge screen and balloon-shed screen was considerably less than the dry-bulb temperature difference is important. If the balloon-shed values are accepted as being near the truth and if it is remembered that both standard screens give similar average relative humidities the real effect of using bridge-screen measurements is to give estimates of relative humidity which are below the true value by about 8 per cent for wind speeds $\leqslant$16 knots and 5 per cent for speeds $\geqslant$17 knots.

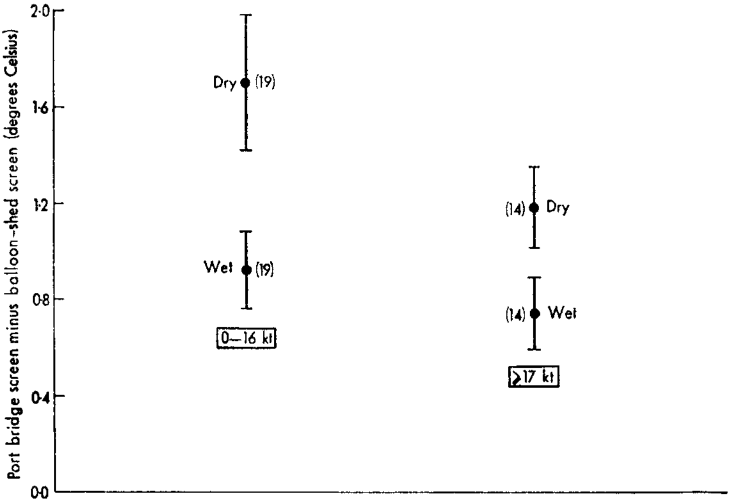

FIGURE 6—COMPARISON OF TEMPERATURES (DRY- AND WET-BULB) IN PORT SCREEN WITH THOSE IN BALLOON-SHED SCREEN FOR VARIOUS WIND CONDITIONS (PORT TO WINDWARD)

● All sunshine conditions : case (i)*(d)*, i.e. port balloon-shed roof.
Dry-bulb and wet-bulb temperatures are annotated accordingly.
Vertical lines represent standard errors of the mean differences.
Numbers in brackets are the numbers of observations.

Discussion. The roof of the balloon shed seems to give a much better exposure for marine screens than does the bridge. The balloon-shed screen was attached to a rail which presented little resistance to the airflow. Furthermore there were no large obstacles to leeward to give rise to eddies. The wheel-house-roof exposure was next best and better than either standard bridge screen on the whole, though this screen does read higher than the leeward standard screen from time to time. If it were placed higher above the wheel-house deck the results might improve but it would be inconvenient and might be more affected by funnel smoke.

Analysis of nine pairs of readings from the 'outer port bridge-deck' and 'outer starboard bridge-deck' screens was inconclusive. The results suggested that the windward 'outer' screen was cooler than the standard windward exposure in 8 cases out of 9. The windward 'outer' screen was often cooler than the standard leeward screen but not always. This re-emphasizes the complex flow patterns, influenced in part by the screens themselves, which must be occurring.

The balloon shed would be a practical position for a screen if remote-indicating temperature equipment were used. It would then be necessary to visit the screen only at intervals of a few days for checking purposes and to change the wet-bulb wicks. However, further work is needed to determine the best compromise between ideal and practical positions, not only on the weather ships but also on merchant ships of different types.

It is clear from the foregoing that present observational practices are wrong and that significant improvements in the readings would result from the adoption of the following procedure for entries in the official returns.

(i) Select the lower of the two dry-bulb temperatures read in the standard bridge screens (usually the leeward screen) as the dry-bulb observation.

(ii) The wet-bulb temperature should be taken from the same screen.

(iii) When the dry-bulb temperatures are the same in both screens, select the windward wet-bulb temperature.

The effect of this procedure (at least in summer in the North Atlantic) would be to reduce the mean dry- and wet-bulb temperatures by 0·3 degC, but by 0·6 degC in sunny conditions and moderate winds. The above procedure assumes (for the present) that aspirated-psychrometer readings will continue to be taken when the wind speed is light and the sun is shining.

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A CASE STUDY OF THE SPECTACULAR DEVELOPMENTS AND MOVEMENT OF A FEBRUARY STORM

By R. M. MORRIS

Summary. An example of synoptic evolution is described, using the routine twice-daily computed analyses at the Central Forecasting Office (CFO), Bracknell. The study reveals, with the aid of the omega and vorticity equations, how the various terms in the equations are functional in determining the translation and development of the isobaric contour and thickness fields. In particular the importance of latent heat release and sensible heat flux from the sea surface is demonstrated in the generation of cyclonic vorticity in the lower layers of the troposphere.

Introduction. Between 10 and 12 February 1970 a frontal wave depression moved east-north-eastwards across the Atlantic Ocean towards south-west England. The depression deepened considerably and subsequently moved up the English Channel with an intense circulation in the lower layers of the troposphere. The evolution of this system illustrated in a clear manner the role played by the different terms in the equations relating to dynamical evolution in tropospheric motion. The theoretical aspects of the case study will be based upon the vorticity equation (see, for example, Petterssen[1]) and the omega equation.[2]

The equations are briefly described as follows :

$$\left[\nabla^2 - \frac{f^2}{\sigma}\frac{\partial^2}{\partial p^2}\right]\omega = -\frac{f}{\sigma}\frac{\partial}{\partial p}\left[\mathbf{V}.\nabla Q\right] - \frac{g}{p\sigma}\nabla^2(\mathbf{V}.\nabla h_{TT}) \quad \ldots (1)$$

$$\frac{\partial}{\partial t}Q_5 = -\mathbf{V}_5.\nabla Q_5 - \omega\frac{\partial Q}{\partial p} + \frac{\partial \mathbf{V}}{\partial p}\times\nabla\omega.\mathbf{k} \quad \ldots (2)$$

$$\frac{\mathrm{d}}{\mathrm{d}t}Q_{10} = -(\mathbf{V}_5.\nabla Q_5 - \mathbf{V}_{10}.\nabla Q_{10}) - \omega\frac{\partial Q}{\partial p} + \frac{\partial \mathbf{V}}{\partial p}\times\nabla\omega.\mathbf{k} - \frac{R}{f}\nabla^2\left[\frac{-g}{R}(\mathbf{V}.\nabla h_{TT}) + S + H\right]. \quad \ldots (3)$$

The various symbols have the following meaning :

ω (omega) $= \dfrac{dp}{dt}$ the total time derivative of pressure representing the vertical velocity in pressure co-ordinates.

$\mathbf{V}$ = the quasi-horizontal velocity vector on an isobaric surface.

$Q = (\zeta + f)$ = the absolute vorticity about a vertical axis, i.e. the sum of the relative vorticity ζ and the earth's vorticity f.

∇, ∇^2 = the operators denoting respectively the gradient and Laplacian of a function on the isobaric surfaces.

$\mathbf{k}$ = a unit vector in a direction normal to the isobaric surfaces and approximately vertical; the dot and cross products have their usual vector meaning.

S = the static stability term, $\omega(\Gamma_a - \Gamma) \log \dfrac{1000}{500}$ meaned over the layer from 1000 mb to 500 mb.

Γ_a, Γ = adiabatic lapse rate, actual lapse rate in terms of pressure.

H = the adiabatic heating term, $\dfrac{1}{c_p} \dfrac{dW}{dt} \log \dfrac{1000}{500}$ meaned over the layer.

$\dfrac{dW}{dt}$ = the heat, other than latent heat, supplied to, or removed from, unit mass in unit time.

σ = a static stability parameter which in practice is usually negative, $\dfrac{1}{\rho\theta} \dfrac{\partial\theta}{\partial p}$.

θ = potential temperature.

ρ = air density.

g = gravitational acceleration.

R = the gas constant.

h_{TT} = the thickness of the 1000–500-mb layer.

Subscripts 5 and 10 refer to the 500-mb level and 1000-mb level respectively.

The omega equation (1) has been derived by Thompson[2] but was adapted in the present form by Sanders[3] who has extensively investigated the interpretation and uses of the equation in relation to synoptic charts. The equation relates the three-dimensional Laplacian of vertical velocity in a layer to the vertical derivative (through the layer) of vorticity advection on the isobaric surfaces and the Laplacian of thickness advection within the layer. By restricting the analysis to areas of maximum vertical motion it follows that :

$$\nabla^2\omega \approx -\omega,$$

and also, confining interest to qualitative estimates of magnitude only, equation (1) becomes

$$\omega \approx -\frac{\partial}{\partial p}(\mathbf{V}.\nabla Q) - \nabla^2(\mathbf{V}.\nabla h_{TT}). \qquad \ldots (1a)$$

Thus descending air (ω positive) occurs in association with relatively strong negative (anticyclonic) vorticity advection aloft and/or a maximum of cold advection in the layer. If equation (1*a*) is applied to the 1000–500-mb layer the mean vertical velocity in the layer depends upon the difference between the vorticity advection at 500 mb and at 1000 mb and the advection of the thickness by a mean wind in the layer. In this study equation (1*a*) is used to assess the sign of vertical motion in the middle and lower troposphere.

Equation (2) expresses the balance of vorticity transfer at 500 mb assuming negligible divergence.[1,4] The first term on the right-hand side represents the quasi-horizontal advection of vorticity at 500 mb, the second term represents the vertical transfer of vorticity to and from different levels and the third term is the twisting term. In other words the horizontal advection of vorticity represents the transfer of existing resources at 500 mb whereas the other terms represent the relatively small additions to and subtractions from other levels of the fluid.

Equation (3) relates the changes of vorticity in the moving system at 1000 mb to the various functions in the 1000–500-mb layer.[1] The first term on the right-hand side (in brackets) is synonymous with the first term on the right-hand side in equation (1) and the second and third terms are equivalent to the corresponding terms in equation (2). The fourth term (in brackets) contains a thickness advection term similar to that in equation (1) and also static stability and non-adiabatic heating terms. The stability term expresses the thickness changes due to adiabatic warming or cooling associated with vertical motion whilst the non-adiabatic term expresses changes of thickness due to latent heat, sensible heat and radiative transfer, etc.

Vorticity changes at 500 mb are closely related to the contour-height changes at this level. If the horizontal advection of vorticity at 1000 mb is temporarily neglected in equation (3) it follows that the changes of vorticity at 1000 mb (left-hand side) can be expressed as a balance between the 500-mb contour-height changes and the 1000–500-mb thickness changes.

The basic data. The operational numerical forecast procedure at CFO, Bracknell, includes an objective analysis of the synoptic data at 00 GMT and 12 GMT. The computed output includes surface, 500-mb, and 1000–500-mb thickness analyses and a distribution of vertical velocity in the 1000–600-mb layer.[5,6] These charts are scrutinized by forecasters at CFO and, if necessary, additional information is fed into the computer to improve the objective analyses. Thus there is available a reasonably accurate objective analysis of the synoptic situation twice daily and these data have been used to illustrate the case study.

Although the computer does not solve equation (1) to derive the field of vertical motion, the omega equation is one of the few that offers a satisfactory basis for estimating the large-scale vertical motion. An analysis of the 1000–500-mb layer will be presented and comparisons made between the objectively derived vertical-motion field and subjective estimates using equation (1*a*). Equations (2) and (3) will be used to describe the evolutions that have occurred and will also be the basis of any tentative and consistent predictions that can be made at each stage.

The analysis.

(i) *Synoptic analysis at 00 GMT, 11 February 1970.* Figure 1*(a)* depicts the 1000–500-mb thickness and superimposed 1000-mb contour-height flow at the time; arrows indicate the recent 12-hour movement of ridges and troughs in the thickness field. An intensifying large anticyclone was moving east close to Newfoundland with well-marked thickness advection fields on its eastern and western flanks. A small frontal wave in the 1000-mb flow was detectable about 49°N 25°W and was associated with a thermal ridge moving eastwards. Figure 1*(b)* depicts the 500-mb contour flow with superimposed isopleths of thickness advection ($\mathbf{V}.\nabla h_{TT}$) calculated from Figure 1*(a)* and using $\mathbf{V}_{10}$ as the advective component of wind in the 1000–500-mb layer and a grid length of 100 nautical miles.* (1000-mb contours were drawn at intervals of 30 gpm to improve the accuracy of $\mathbf{V}_{10}.\nabla h_{TT}$.) Arrows indicate the movement of 500-mb contour troughs and ridges during the previous 12 hours.

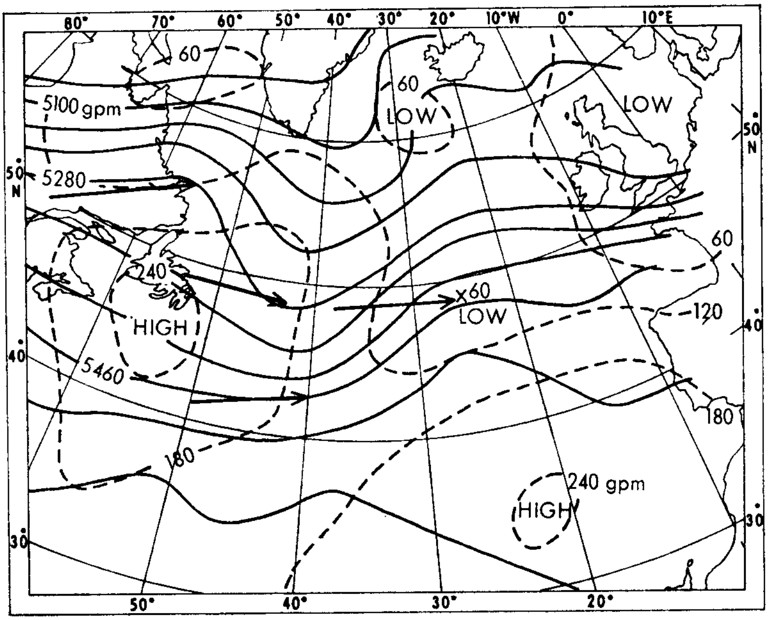

FIGURE 1*(a)*—1000–500-mb THICKNESS AND 1000-mb CONTOURS AT 00 GMT, 11 FEBRUARY 1970

——— Thickness - - - Contours

The 500-mb flow consists of two distinct flow patterns. In the north a trough was advancing across Labrador with a downstream trough axis near ocean weather station 'C'. In the south an upper ridge was amplifying over and to the south of Newfoundland and a downstream trough had become more sharply defined (i.e. cyclonic curvature had increased at the trough axis) near ocean weather station 'D', which was reporting a wind of 290° 90 kt at the time. The two patterns merged into a confluent ridge over the eastern

* The units for grid length have been quoted in nautical miles because knots were used as speed units. Thus the final units for thickness advection are geopotential metres per hour. For speeds measured in metres per second the appropriate grid-length units would be metres and the thickness advection units would then be geopotential metres per second (1 knot ≈0·5 m/s; 1 nautical mile ≈1850 m).

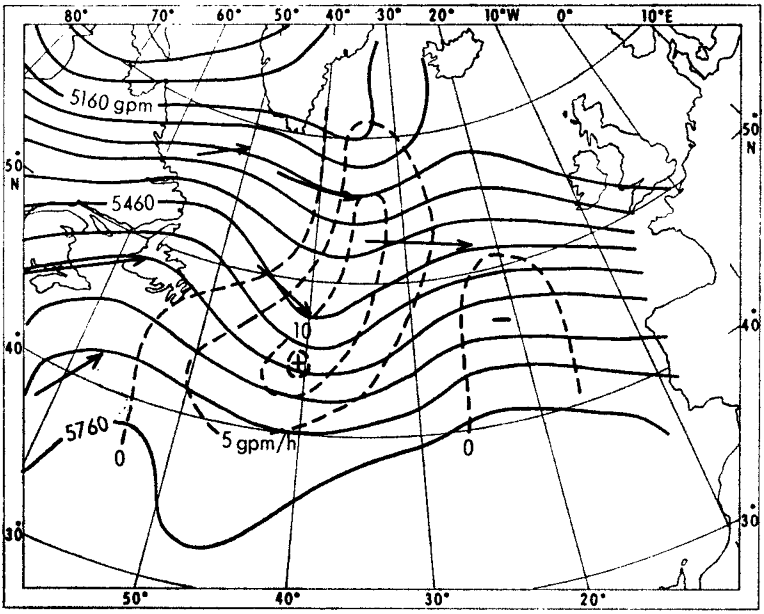

FIGURE 1(*b*)—500-mb CONTOURS AND ISOPLETHS OF THICKNESS ADVECTION AT 00 GMT, 11 FEBRUARY 1970

——— Contours - - - Isopleths of thickness advection

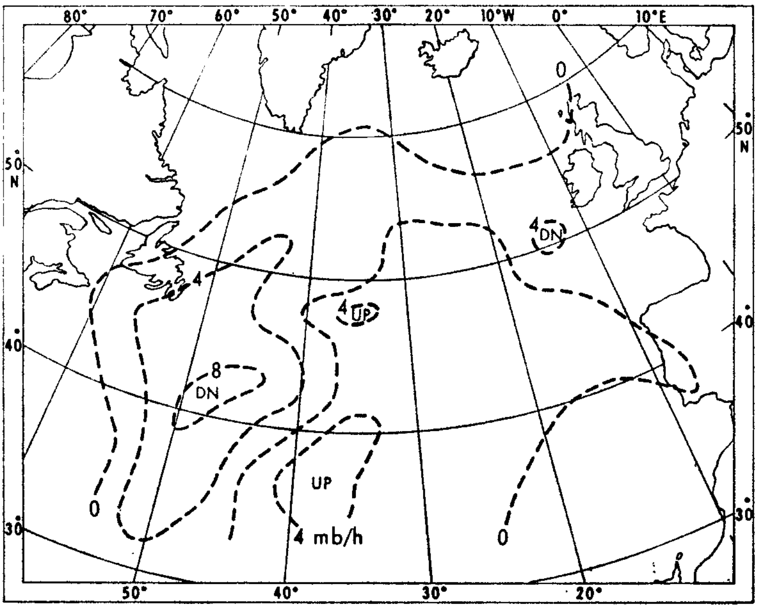

FIGURE 1(*c*)—MEAN VERTICAL VELOCITY IN THE 1000–600-mb LAYER AT 00 GMT, 11 FEBRUARY 1970

DN = down

Atlantic. It will be seen that a tongue of maximum cold advection extends from just east of the northern upper trough axis across the base of the southern trough. Referring to equation (1*a*), if the vorticity advection at 1000 mb is neglected in comparison with the vorticity advection at 500 mb, it can be seen that the vorticity advection term is negative just ahead of the northern trough axis (advection of cyclonic vorticity) and therefore opposes the thickness advection term (positive), which implies that the vertical velocity will be small. The cold advection maximum is centred just behind the axis of the southern contour trough and extends south-westwards; the vorticity advection term vanishes in the axis of the contour trough but is strongly positive west of the trough. Thus it may be inferred that descending motion is occurring beneath the upper trough axis and is occurring strongly to the west of the trough axis. The vorticity advection term is only weakly opposed by the thickness advection term ahead of the upper contour trough, which implies ascent of air in this region.

Figure 1*(c)* depicts the distribution of mean vertical velocity in the 1000–600-mb layer as produced by the computer.[5,6] Most of the subjective assessments are clearly substantiated, with a broad area of descending air embracing the central and rear region of the southernmost trough and a small significant area of ascending air just ahead of this trough. A broad area of weaker ascent embraces the thermal ridge (frontal wave) presumably associated with the advection of cyclonic vorticity near the confluent upper ridge.

A comprehensive assessment of the analysis above is the basis for tentative predictions about the contour and thickness fields in accordance with equations (2) and (3). The movement of troughs and ridges at 500 mb is largely in response to the quasi-horizontal advection of vorticity at that level but for the present it can simply be noted that the two 500-mb troughs in mid-Atlantic are moving eastwards. The tongue of cold advection extends across areas of ascending and descending motion from which it can be deduced that a marked lowering of thickness should occur north-east of ocean weather station 'D' whereas relatively small changes are likely to the west. An area of weak ascent embraces the thermal ridge associated with the frontal wave so that adiabatic cooling should lower the thickness unless latent heat is released to offset the cooling. The ascending motion may increase in the vicinity of the frontal wave in association with the advancing 500-mb trough since there appears to be an area of stronger upward motion near 48°N 35°W (Figure 1*(c)*).

(ii) *Synoptic analysis at 12* GMT, *11 February 1970.* Figures 2*(a)*, *(b)* and *(c)* depict the analysis at 12 GMT on the 11th. The upper contour pattern has transferred eastwards at a consistent rate and the southernmost trough has become confluent under the influence of the thickness advection field. The thickness pattern has also been transferred eastwards largely in accordance with expectation except that thickness values have not fallen in the thermal ridge, from which it may be inferred that non-adiabatic heat has been added at some stage during the previous 12 hours. This heat has clearly produced the necessary imbalance in equation (3) to increase the circulation at 1000 mb. The increase in circulation has intensified the cold advection field and also created a warm advection field. In fact the warm advection field must have been the only mechanism able to transfer the thermal ridge eastwards since 00 GMT on the 11th.

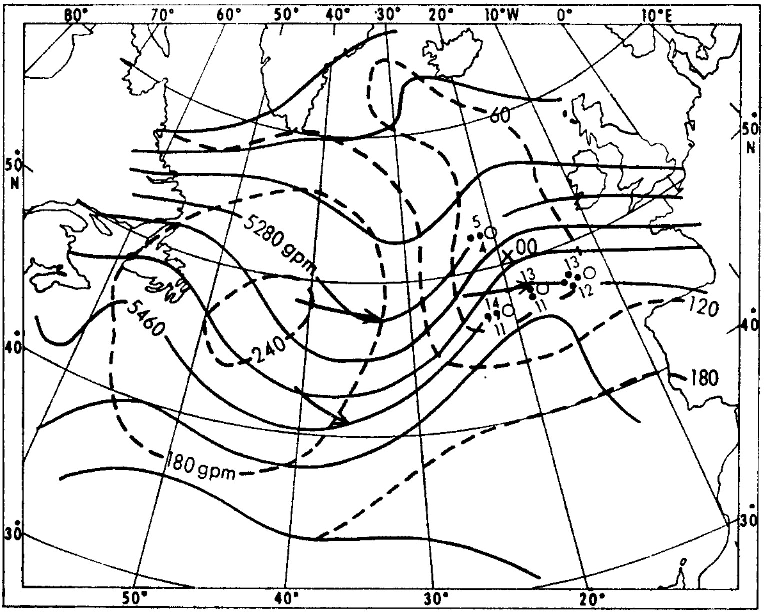

FIGURE 2(*a*)—1000–500-mb THICKNESS AND 1000-mb CONTOURS AT 12 GMT, 11 FEBRUARY 1970
——— Thickness - - - Contours

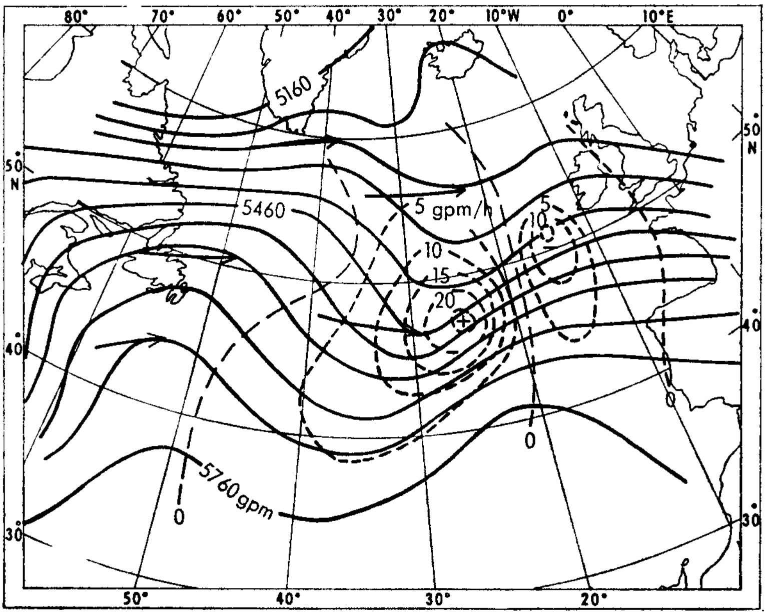

FIGURE 2(*b*)—500-mb CONTOURS AND ISOPLETHS OF THICKNESS ADVECTION AT 12 GMT, 11 FEBRUARY 1970
——— Contours - - - Isopleths of thickness advection

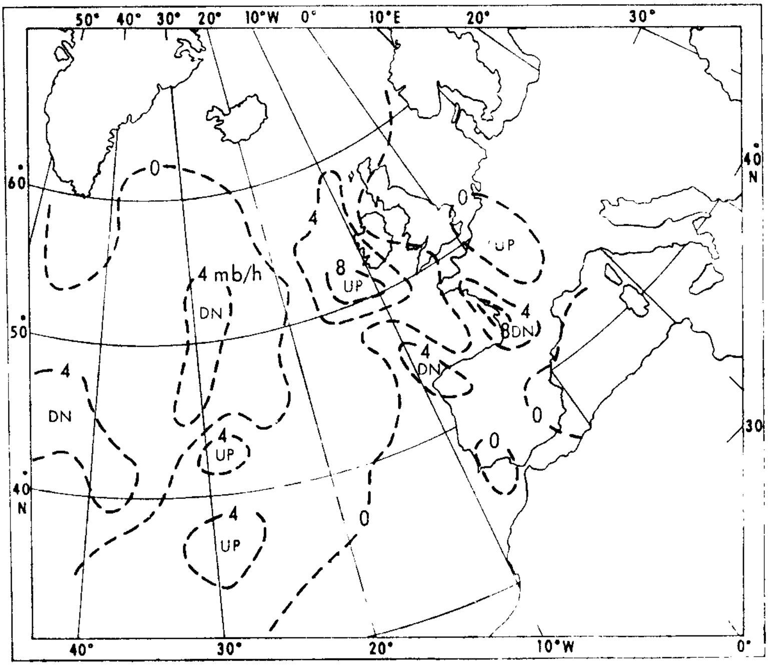

FIGURE 2(*c*)—MEAN VERTICAL VELOCITY IN THE 1000–600-mb LAYER AT 12 GMT, 11 FEBRUARY 1970
DN = down

Figure 2(*b*) shows that the core of strong cold advection is located just ahead of the upper contour trough and therefore opposes the vorticity advection term, which suggests that the vertical velocity will be small (see Figure 2(*c*)). It is of considerable interest to compare the position of maximum warm advection with the area of ascending air. Comparison of Figure 2 with Figure 1 reveals that the most significant development has been the greatly enhanced upward motion associated with the intensifying warm advection field.

The analysis shows that cold advection and descending motion are located west of the thermal ridge whilst warm advection and ascending motion are located east of the thermal ridge. This symmetry about the axis of the thermal ridge means that the thermal ridge should tend to be translated eastwards without significant distortion. At the same time relatively weak ascending motion is occurring in the thermal ridge south of 49°N, which implies a lowering of thickness values by adiabatic cooling. On the other hand it appears that heat is already being supplied to the thermal ridge as a result of condensation, which suggests that adiabatic cooling may be insignificant in the region around the 1000-mb centre. The upper contour trough is confluent, and cyclonic (positive) vorticity advection tends to be concentrated in the southern portion of the trough forward of the trough axis (the so-called right-hand entrance region) and implies ascending motion. Anticyclonic (negative) vorticity advection tends to be concentrated in the northern portion of the trough (the so-called left-hand entrance region) and implies descending motion; Figure 2*(c)* tends to support these assertions. The strong cold advection field is situated in a region of weak descending motion so that substantial cooling by advection is likely towards the south-east.

(iii) *Synoptic analysis at 00* GMT, *12 February 1970.* Figures 3*(a)*, *(b)* and *(c)* depict the analysis at 00 GMT on the 12th. The thickness pattern has been transferred eastwards at about twice its speed during the previous 12 hours, furthermore thickness values have actually increased in the ridge in the region of the 1000-mb centre. It can be deduced that the warm thickness advection field and non-adiabatic heat supply must have over-compensated the adiabatic cooling due to ascending motion. The role of the terms for thickness advection and non-adiabatic heat in equation (3) is particularly striking since a rapid increase in circulation at 1000 mb has occurred beneath the thermal ridge. At the same time the upper contour heights have fallen about 120 gpm above the low-level centre, which represents a substantial change in the evolution of the 500-mb flow. Further inspection of Figure 2*(b)* suggests that it was hardly possible for the quasi-horizontal vorticity advection field to account for the changes at that level.

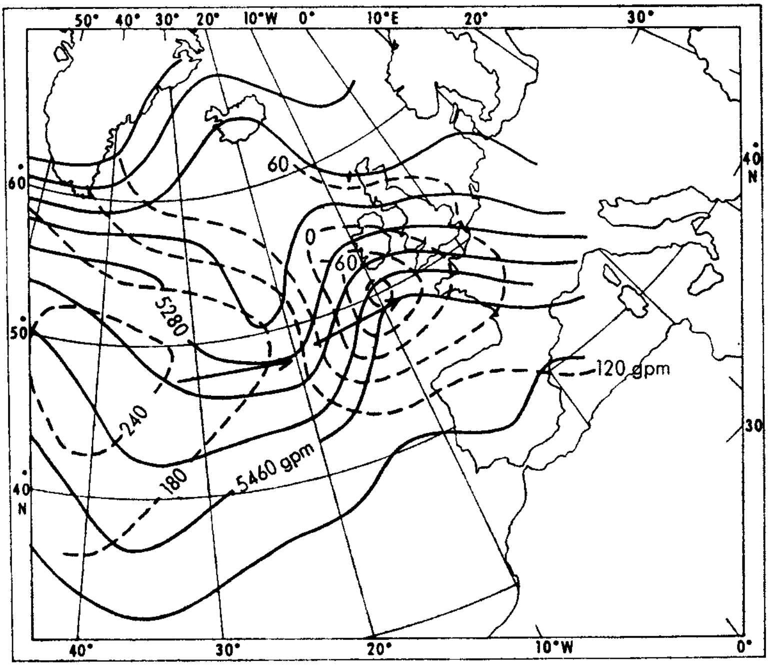

FIGURE 3*(a)*—1000–500-mb THICKNESS AND 1000-mb CONTOURS AT 00 GMT, 12 FEBRUARY 1970

——— Thickness - - - Contours

If the whole of the first term on the right-hand side of equation (3) is assumed to be small at 12 GMT on the 11th near the centre of the depression, then the subsequent large positive value of the left-hand side must have been due to the combined effects of thickness advection and non-adiabatic heat in excess of the opposing stability term plus any contribution from the vertical-advection term and the twisting term. It follows also that the increase in

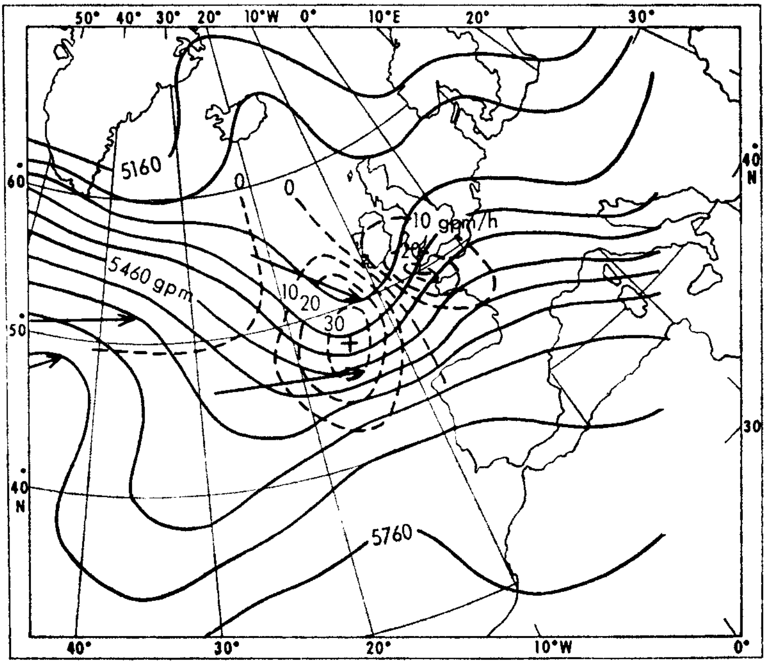

FIGURE 3(*b*)—500-mb CONTOURS AND ISOPLETHS OF THICKNESS ADVECTION AT 00 GMT, 12 FEBRUARY 1970

——— Contours – – – Isopleths of thickness advection

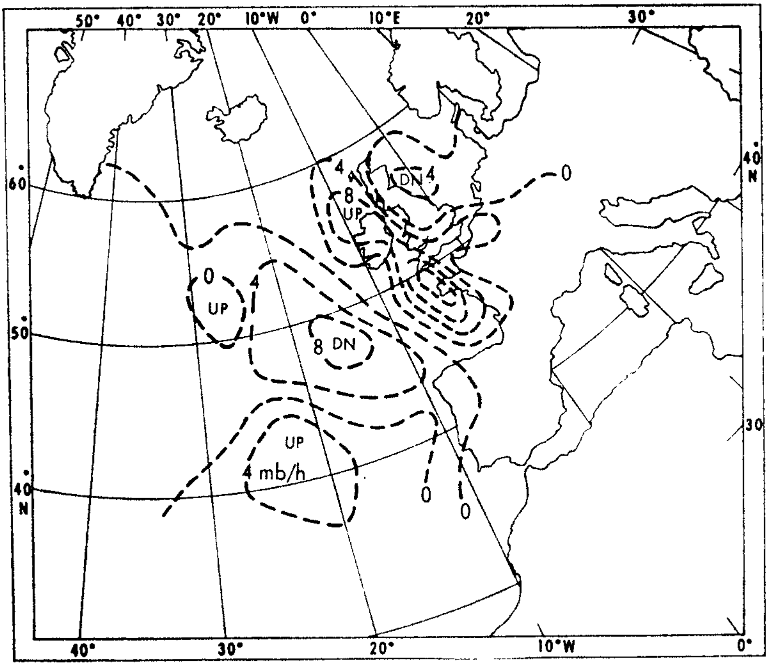

FIGURE 3(*c*)—MEAN VERTICAL VELOCITY IN THE 1000–600-mb LAYER AT 00 GMT, 12 FEBRUARY 1970

DN = down

500-mb vorticity above the low-level centre must have been largely due to the vertical-advection term and the twisting term, as required by equation (2). Comparison of Figures 2*(a)* and 2*(c)* with 3*(a)* and 3*(c)* suggests that the upward transfer of cyclonic vorticity has increased from small values near 15°W at 12 GMT on the 11th to fairly large values over Ireland and the South-west Approaches at 00 GMT on the 12th. This is simply because the upward motion and low-level cyclonic vorticity have increased together. Comparison of Figures 2*(b)* and 3*(b)* reveals that it is in this region that the greatest fall has taken place in the 500-mb contour heights in the trough during its eastward progress. The fall in contour height is most probably synonymous with an increase of cyclonic vorticity at this pressure level. The twisting term will be zero where the vertical velocities are at a maximum ($\nabla\omega = 0$) and also zero where the thermal wind vector is parallel to the horizontal gradient of vertical velocity ($\partial \mathbf{V}/\partial p \times \nabla\omega = 0$). Comparing Figures 2*(a)* and 2*(c)* suggests that $\partial \mathbf{V}/\partial p$ is almost parallel to $\nabla\omega$ in the thermal ridge between 50°N and 55°N but there is probably a significant angle between the vectors just south of 50°N between 10°W and 20°W. The rotation is such that cyclonic contour vorticity is being increased in the latter region with a corresponding decrease of thermal wind. It will be seen in Figure 3*(a)* that a decrease of thermal wind only occurred south of 49°N. Thus it seems fair to conclude that the warm thickness advection and non-adiabatic heat terms were the prime functions responsible for the development of the intense low-level circulation with subsidiary contributions from the vertical-advection term and the twisting term.

The intensity of the low-level circulation at 00 GMT on the 12th makes it more difficult to assess the vertical derivative of the vorticity advection term; nevertheless subjective estimates can be made. The 1000-mb field (Figure 3*(a)*) consists of three troughs radiating south-east, north-north-west and south-westwards from the cyclonic centre. Thus it appears that positive vorticity advection over the western English Channel (ahead of a trough) lies beneath a region of positive vorticity advection at 500 mb (Figure 3*(b)*) so that the vertical derivative is probably small. The maximum of warm thickness advection in this region therefore probably determines the sign of vertical motion, as suggested in Figure 3*(c)*.

The 1000-mb trough which extends north-north-westwards just west of Ireland lies beneath negligible flow at 500 mb so that the vorticity advection term suggests ascending motion east of the low-level trough and descending motion to the west. The thickness advection field tends to support the vorticity advection term since a tongue of warm advection extends north across Ireland and a tongue of cold advection extends north to the west of Ireland. These deductions are consistent with Figure 3*(c)*.

The vorticity advection term is clearly most difficult to assess in the region between the low-level centre and ocean weather station 'K'. The upper and low-level troughs appear to lie close together but there is a marked difference in orientation, which accounts for the strong cold thickness advection field. Although it may be presumptuous to assert that the vorticity advection term is probably weak, there can be little doubt about the striking connection between the pattern of cold advection (Figure 3*(b)*) and descending motion (Figure 3*(c)*).

Since the vertical velocity maxima and the thickness advection fields are still almost symmetrical about the thermal ridge, a continuation of the eastward translation of the system is to be expected. The close conjunction of the upper and lower centres means that further deepening of the low-level centre can only occur through excessive latent and sensible heat release in the ascending air east of the thermal ridge. The warm thickness advection field cannot advect any air warmer than that already present above the surface centre. It is worth noting however that the thermal ridge is more pronounced than it was 12 hours previously and comparison of Figures 3*(a)* and 3*(c)* suggests that the twisting term may be significant in the narrow zone between the axis of the thermal ridge and the axis of maximum upward motion extending from north of Ireland to north-west France. The direction of vectors $\partial \mathbf{V}/\partial p$ and $\nabla \omega$ suggests a 'twisting' of the thermal wind into cyclonic vorticity in the contour flow.

(iv) Figure 4 depicts the 1000-mb and thickness fields at 12 GMT on the 12th. The low-level circulation has remained fairly constant in association with an undistorted thermal ridge. It is interesting to see that the thermal wind has decreased significantly above the low-level circulation; this may be attributed to the effect of the twisting term.

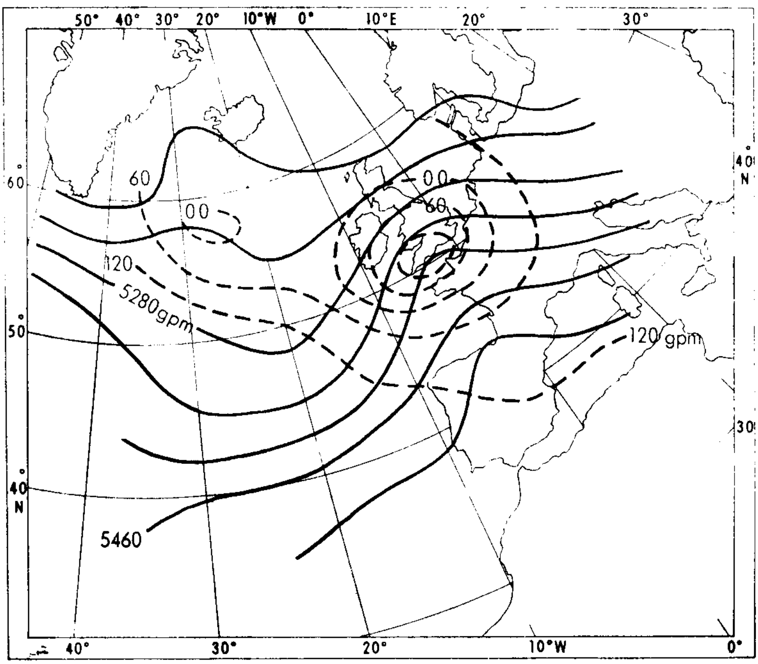

FIGURE 4—1000–500-mb THICKNESS AND 1000-mb CONTOURS AT 12 GMT, 12 FEBRUARY 1970
——— Thickness - - - Contours

Evidence for the release of latent and sensible heat. The track taken by the frontal wave makes it difficult to reach firm conclusions based upon an analysis of the upper air soundings from the various weather ships; however at 12 GMT on 11 February the frontal wave seemed to have passed just south of ocean weather station 'J' and was located about 200 nautical miles south-east of the station. The 12 GMT sounding from OWS 'J' is shown in Figure 5 and it can be seen that the air is moist and marginally unstable to surface temperatures. It is rather surprising to find no evidence of warmer air at medium levels so close to the frontal wave. This suggests that the thermal ridge (Figure 2*(a)*) consisted largely of warm air in the lowest 200 mb of the troposphere. SHIP reports are plotted in Figure 2*(a)* and give the temperature, dew-point and present weather. Saturated air at 12–13°C was present in the warm sector close to the wave tip and the reports of moderate to heavy rain verified the upward motion deduced earlier. If the lowest 200 mb of the sounding in Figure 5 is modified to the form of a saturated lapse from

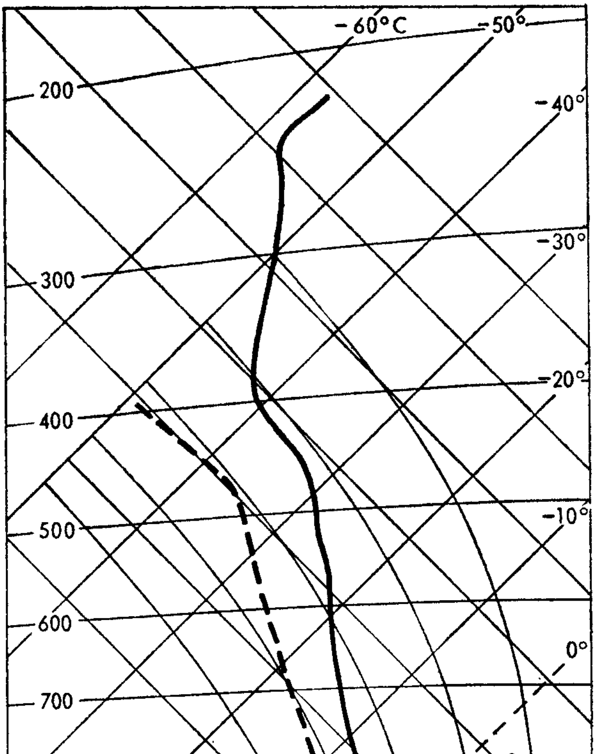

FIGURE 5—UPPER AIR SOUNDING FOR OCEAN WEATHER STATION 'J' AT 12 GMT, 11 FEBRUARY 1970

The corresponding profile of temperature above the frontal wave tip is indicated at the right-hand side of the tephigram.

——— Dry-bulb temperature - - - Dew-point temperature

Photograph by Mrs Mary Holmes

PLATE III—FOG FORMATION AT BRACKNELL ON THE AFTERNOON OF 10 DECEMBER 1969

(Photographs taken from the roof of the Meteorological Office)

PLATE IV—AWARDS TO CIVIL AIRLINE PILOTS

From left to right : Captain and Mrs R. D. Hall, Director-General of the Meteorological Office, Mrs Caesar-Gordon, Captain E. Caesar-Gordon (see p. 32).

a temperature of 13°C at 1000 mb, it will be clear that considerable instability was present just north of the wave tip. Even allowing for the uncertainties in the upper air structure above the surface centre, the evidence strongly suggests that copious supplies of latent and sensible heat were being released at 12 GMT and contributed largely to the rapid development of the surface centre during the next 12 hours.

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MINIMUM TEMPERATURES AT THE SURFACES OF CONCRETE ROADS AND CONCRETE SLABS

By G. E. PARREY, W. G. RITCHIE and S. E. VIRGO, O.B.E.

Summary. This paper discusses the results of forecasting night minimum temperatures by applying the methods which were devised for concrete roads at Watnall and Wyton to four other sites at which the only available minimum temperatures have been measured on Meteorological Office standard concrete slabs.

The authors have reported[1] the results of three methods of forecasting night minimum temperatures at the surfaces of roads built of concrete some 8 inches deep at Watnall and Wyton. One method involves direct regression from the temperature and dew-point the previous day. The other two methods, devised by Parrey[2] and Ritchie,[3] depend upon a forecast of air minimum temperature, M_A, by one of the recognized methods, and then a forecast value of $M_A - M_R$ has to be subtracted to obtain M_R, the forecast minimum temperature at the road surface. For the observations on which the tests were based ordinary minimum thermometers were used with their bulbs resting on the road surface.

Most forecasters, however, are dependent on observations made with minimum thermometers exposed as in the road experiments but on the concrete slabs 3 feet × 2 feet × 2 inches thick (1 foot ≈30 cm) which have now become standard equipment in some Meteorological Office instrument enclosures. This paper reports the results of applying the methods which were developed for the two roads to data obtained from the concrete slab at Watnall and also to data from four other places in the Midlands and East Anglia where the only data available were obtained at the surfaces of standard concrete slabs.

As Parrey's method and Ritchie's method both depend on forecast values of the air minimum temperature, it was necessary to choose places for which the errors in forecasting this quantity had already been assessed. Steele, Stroud and Virgo[4] have done this for a number of places and from their list Waddington, Marham, Wittering and Finningley were chosen for the present investigation.

Comparison of minimum temperatures over concrete roads with those over concrete slabs. The first step is to compare minimum temperatures over the roads at Wyton and Watnall with those over neighbouring concrete slabs. Table I shows that the difference is less than ¾ degC throughout the winter months of October to March inclusive, and between 1 and 2 degC during the months of April to September inclusive. This suggests that the year falls naturally into two seasons and that the six months from October to March could be considered as the winter season; but the main practical application is to frost prediction, predicting when temperatures of 0°C or less will occur, and as forecasters have to assess the probability of frost in April, this month has been included in the period of the year for which the various forecasting methods have been tested. The distribution for the whole year is shown in Figure 1. Like the other two distributions illustrated in Ritchie's paper[3] it has a sharper peak than the normal distribution.

TABLE I—MONTHLY MEANS AND STANDARD DEVIATIONS OF ROAD MINIMUM TEMPERATURE MINUS CONCRETE-SLAB MINIMUM TEMPERATURE

Site and period		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year	Oct.–Apr.
								degrees Celsius							
Wyton	Mean	0·0	0·5	0·6	1·3	1·1	1·9	1·6	1·1	1·2	0·7	0·2	0·3	0·9	0·5
Jan. 1969–Dec. 1969	S.D.	0·6	0·7	0·8	1·2	0·7	1·0	0·8	0·6	0·8	0·9	1·0	0·7	1·0	0·9
Watnall	Mean	0·3	−0·1	0·2	1·3								0·1	—	0·4
Dec. 1968–Apr. 1969	S.D.	0·7	0·9	0·8	1·1								0·5	—	0·8

The tests described below relate to data obtained over concrete slabs. Some forecasters however may still have to do forecasts for places from which observations are available of grass minimum temperature only, or perhaps these may be the only data available for assessing the accuracy of their forecasts; Table II has been compiled for their benefit.

TABLE II—MONTHLY MEANS AND STANDARD DEVIATIONS OF ROAD MINIMUM TEMPERATURE MINUS GRASS MINIMUM TEMPERATURE

Site and period		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year	Oct.–Apr.
								degrees Celsius							
Wyton	Mean	1·3	1·2	1·2	2·6	2·5	3·3	3·3	2·0	2·6	1·7	0·2	0·4	1·8	1·2
Jan. 1969–Dec. 1969	S.D.	0·6	1·0	1·2	1·4	1·1	2·0	1·8	1·0	1·8	1·5	1·4	0·9	1·6	1·2
Watnall	Mean	0·8	1·1	1·9	3·4						1·7	1·2	0·8	—	1·5
Oct. 1967–Apr. 1968	S.D.	1·4	1·2	1·4	2·2						1·3	1·4	1·5	—	1·8

The data for road minimum temperatures minus grass minimum temperatures in Table II for the two sites for the months October–April taken as a single period are not samples of the same population, but a *t*-test performed on the figures for the same months taken together in Table I gives strong grounds for asserting that these are indeed samples of the same population; if we reject this assertion, we shall be wrong on 85 per cent of occasions. The best estimates of the mean and standard deviation of this population are

$$\text{mean} \quad (\delta) = +0{\cdot}45 \text{ degC},$$
$$\text{standard deviation} \quad (\sigma_0) = 0{\cdot}85 \text{ degC}.$$

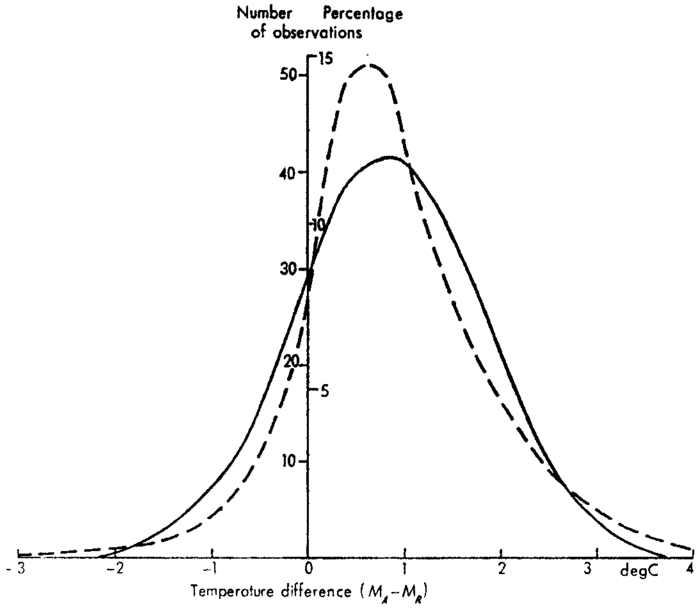

FIGURE I—ROAD MINIMUM TEMPERATURE MINUS CONCRETE-SLAB MINIMUM TEMPERATURE

– – – Actual distribution of temperature differences
——— Normal distribution with the same mean and standard deviation for 345 observations made at Wyton during the year 1969

Forecasting errors involved in the direct regression method. As in previous papers an error is reckoned as the forecast minimum temperature minus the observed minimum temperature. By applying the direct regression method, forecast errors were obtained on the assumption that the road minimum temperature was always the same as the slab minimum temperature. This is not so, and the real mean must therefore be obtained by subtracting $\delta = 0{\cdot}45$ degC from the estimated mean. To obtain the corresponding standard deviation, let σ_1 be the standard deviation calculated on the assumption that the road minimum temperature and the slab minimum temperature are the same. Then the total standard deviation σ is derived from the relation

$$\sigma^2 = \sigma_0{}^2 + \sigma_1{}^2 = (0{\cdot}85)^2 + \sigma_1{}^2.$$

Table III gives the means and standard deviations obtained by the direct regression method after these adjustments have been made and shows the

TABLE III—MEANS AND STANDARD DEVIATIONS OF ERRORS ARISING FROM THE DIRECT REGRESSION METHOD AFTER ADJUSTMENTS HAVE BEEN MADE FOR THE DIFFERENCES IN MINIMUM TEMPERATURES OVER ROADS AND OVER SLABS

Place	Number of occasions	Without cloud correction		With cloud correction	
		Mean	σ	Mean	σ
		degrees Celsius		*degrees Celsius*	
Waddington	253	−1·03	2·97	−0·53	2·77
Marham	129	−0·33	2·86	+0·06	2·63
Wittering	246	−0·27	3·19	−0·40	2·88
Finningley	248	−0·71	2·92	−0·04	2·70
Watnall and Wyton	554	−0·14	2·56	+0·38	2·42

approximate accuracy which could be expected if the direct regression equation derived from observations on a road at Watnall were used to forecast minimum temperatures on roads at the other four sites. Figures for Watnall and Wyton have been included for comparison. For Waddington, Wittering and Finningley the data comprised observations for the 12 months, December 1968–April 1969 and October 1969–April 1970, but observations on the slab at Marham did not start till October 1969. Occasions when a front passed the site between 12 GMT and 06 GMT next morning have been excluded from the analysis. Likewise all occasions when the dew-point at 12 GMT the previous day exceeded 10°C have been excluded. Since the cloud amount was estimated in retrospect from the *Daily register*, there are no forecasting inaccuracies and the improvement obtained by applying the cloud correction is therefore the maximum possible.

Forecasting errors involved in Parrey's and Ritchie's methods. Because these two methods forecast the quantity $M_A - M_R$ and depend on a forecast of M_A by some other means, the calculations of mean and standard deviation each involve three components instead of two.

Let m_1 be the mean error in the forecasts of $M_A - M_R$ on the assumption that the road minimum temperature and the slab minimum temperature are the same,

and m_2 be the mean error in the forecasts of M_A.

Then the mean for the whole operation is given by

$$m = m_1 + m_2 - \delta = m_1 + m_2 - 0{\cdot}45.$$

Similarly, if σ_0 has the same connotation as before (p. 29),

σ_1 is the standard deviation of the errors in forecasts of $M_A - M_R$ on the assumption that temperatures on road and slab are the same,

and σ_2 is the standard deviation of the errors in the forecasts of M_A,

then $\sigma^2 = \sigma_0{}^2 + \sigma_1{}^2 + \sigma_2{}^2$

$= (0{\cdot}85)^2 + \sigma_1{}^2 + \sigma_2{}^2.$

In these formulae the terms have not been weighted in proportion to the numbers of occasions from which they were derived; it has been assumed that the values in each case are the best possible values for the quantities concerned.

Estimates of m_2 and σ_2 were obtained by compounding the figures given by Steele, Stroud and Virgo[4] for clear and cloudy nights for the period October 1967–March 1968 and making the assumption that what is valid for one year is equally valid for another. The results are given in Table IV, together with the figures for Ritchie's method for Wyton taken from the previous paper.[1] The test at Watnall was done for the period October 1969–April 1970 with forecast values of M_A and the values of m and σ (although therefore not strictly comparable) have been included in the table.

Discussion of Table III and Table IV. Table IV shows that there is little to choose between Parrey's method[2] and Ritchie's method[3] but a comparison with Table III shows that both are superior to the direct regression

TABLE IV—MEANS AND STANDARD DEVIATIONS OF ERRORS ARISING FROM PARREY'S AND RITCHIE'S METHODS

Place	m_2	σ_2	Parrey's method m_1	σ_1	m	σ	Ritchie's method m_1	σ_1	m	σ
	degC		*degC*				*degC*			
Waddington	−0·23	1·74	+0·01	1·01	−0·67	2·18	−0·19	1·02	−0·81	2·19
Marham	+0·01	2·47	−0·24	1·11	−0·66	2·84	−0·43	1·05	−0·87	2·82
Wittering	+0·61	1·73	+0·33	1·29	+0·49	2·29	+0·07	1·23	+0·23	2·26
Finningley	−0·04	1·51	+0·24	1·27	−0·25	2·15	−0·03	1·19	−0·52	2·10
Wyton	−1·10	2·79					0·00	1·09	−1·14	2·97
Watnall					−0·45	2·20				

The number of occasions are the same as in Table III (96 for Watnall and 468 for Wyton). The symbol at the head of each column has the connotation given in the text.

method. The main error in Parrey's and Ritchie's methods is in the forecast of air minimum temperature and, as Steele, Stroud and Virgo[4] have shown, this varies widely from place to place. Doing the forecast in two stages allows the forecaster to take this variation into account.

Analysis of variance shows that the distributions of errors either in Parrey's method or in Ritchie's method at the various places are not samples of a single population; it would have been most surprising if they had been. Nevertheless they are all of the same magnitude, and therefore Parrey's method and Ritchie's method are offered as aids to forecasting frost on roads in the Midlands and East Anglia — at least until a better method becomes available.

Two of the component populations which have gone into computing the final means and standard deviations in Table IV are normally distributed, but, as Figure 1 shows, the third and smallest component is not normally distributed. If however it is accepted as a reasonable approximation to a normal distribution, the final means and standard deviations obtained by both Parrey's method and Ritchie's method may be regarded as referring to populations which themselves approximate to normal distributions. On that basis tables similar to Table V of the paper by Steele, Stroud and Virgo[4] can be constructed from the data of Table IV of the present paper. They lead to the working rule that with a forecast road minimum temperature of + 2°C the probability of a temperature of 0°C or less on roads is about 20 per cent and with a forecast of − 2°C the probability is about 80 per cent. In other words, with a forecast of + 2°C the odds are 4 to 1 against a temperature of 0°C or less on roads and with a forecast of − 2°C the odds are 4 to 1 on.

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NOTES AND NEWS

Meteorological Office awards to captains, first officers and navigators of civil aircraft

A system of awards was introduced in 1954 to encourage the making of air reports by civil airline pilots and navigators.

The awards are in two categories. Books, suitably inscribed, are awarded to the captains and navigators who have provided the best series of reports during the year under review, while aircraft captains who have given long and meritorious service in the provision of air reports receive brief-cases.

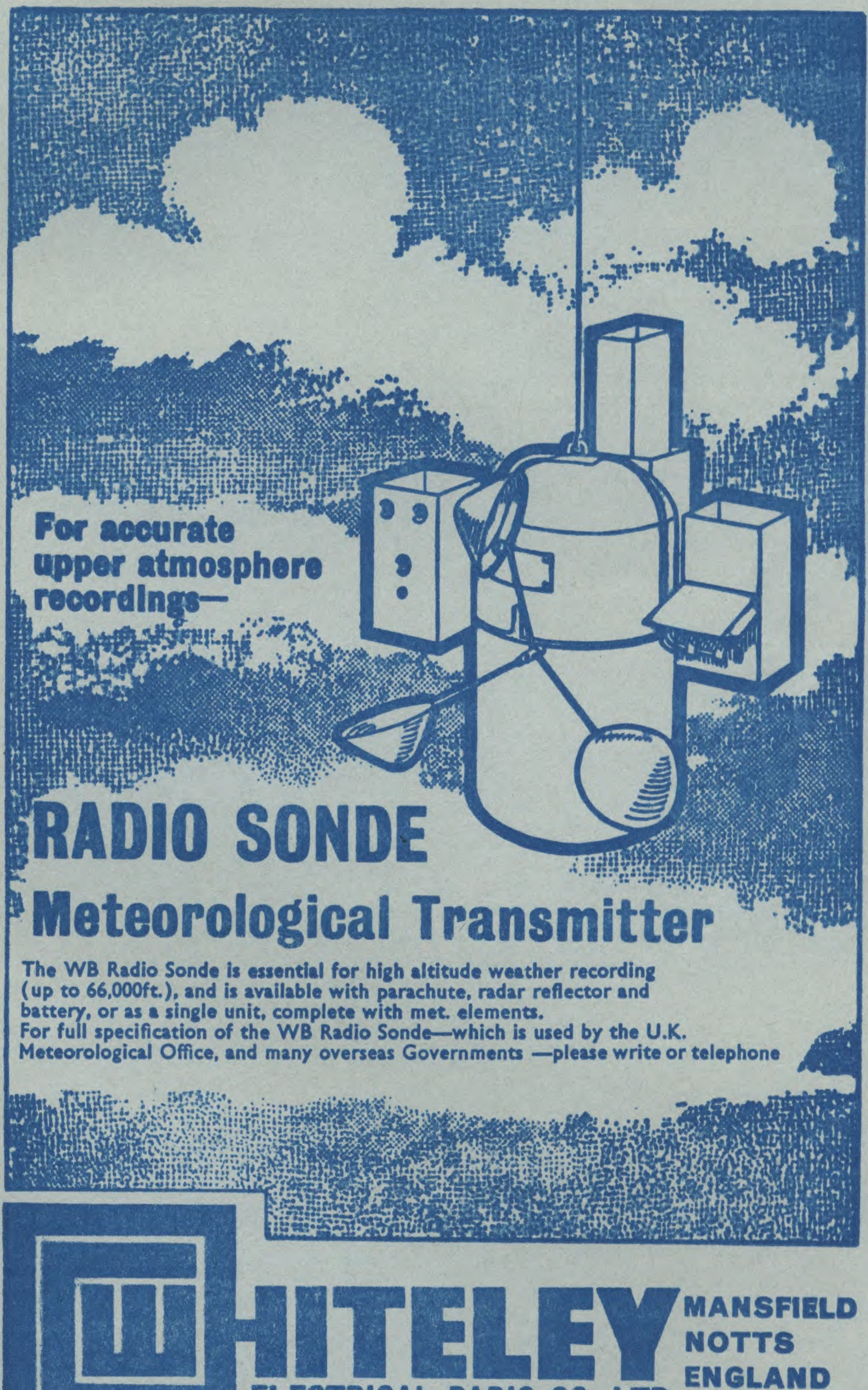
This year brief-cases were awarded to Captain R. D. Hall of BOAC and Captain E. Caesar-Gordon of BEA by the Director-General at a ceremony held in the Headquarters of the Meteorological Office at Bracknell on Thursday, 24 September 1970. Plate IV shows the Director-General with the recipients and their wives.

Book awards for the year 1969 have been sent to :

Captains D. H. Banton, J. H. Wickson, C. H. Earthrowl, G. R. Sharp, J. S. Cooksey and W. F. Strange, and 1st Officers P. C. E. Cox, Peter D. Adams, P. H. Jefferies, R. A. Lake, D. G. Wyard and A. N. Moffat of BOAC, Captains W. J. Ferries, J. Cunningham, K. Mountney, H. Tarran-Jones, H. J. King, K. D. G. Mitchell, G. G. Bell, G. A. Stone, J. McCarthy and C. Cooper of BEA, and Navigating Officers H. L. Chandor, R. H. Williamson, R. Webb, H. F. Musker, K. R. Charles, J. I. Jones, A. L. Brzezina and J. F. Archer of BUA.

OBITUARY

It is with regret that we have to announce the death of Mr C. W. Cozens (Scientific Assistant) on 15 September 1970.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A NOTE ON THE CALCULATION OF 'CUT-OFF' MACH NUMBER

By J. M. NICHOLLS

Summary. The paper gives a theoretical derivation of the Mach number which an aircraft must reach in order that any sonic bang produced will just reach the ground ('cut-off' Mach number). The derived formula is compared with a derivation, used in other literature, which was based on an incorrect assumption. A method of calculation of cut-off Mach number is presented together with an assessment of the probable errors in the calculated value.

Introduction. The Mach number, M, of an aircraft is defined as the ratio of its airspeed, V, to the local sound speed, a_A (suffix A denotes values at the aircraft); if the aircraft is travelling supersonically (i.e. $V \geqslant a_A$) then $M \geqslant 1$ and a shock wave (whose formation will be described in the next section) will be propagated from the aircraft but will not necessarily reach the ground because the path depends on atmospheric refraction. The 'cut-off' Mach number, M_c, is defined as the value of M which the aircraft must reach at any altitude in order that any shock wave produced at that altitude will just reach the ground. A 'sonic bang' is the noise which is heard as the shock wave passes the ear of an observer. If M_c varies markedly with height it may be possible during the transonic acceleration phase for aircraft to fly at greater speeds at some heights than at others without the shock wave reaching the ground. Airline operators *may* therefore require forecasts of the relationship between M_c and height. The purpose of this paper is threefold, namely (i) to familiarize forecasters with the concept of cut-off Mach number, (ii) to develop a formula from which M_c can be calculated in any atmosphere, elaborating on and correcting some previous work[1] on the subject and (iii) to deduce a reasonably accurate method of calculating M_c by hand.

Formulae for calculating M_c.

(i) *Level flight.* A generalized description of sonic bang formation and propagation can be found in other literature (e.g. Nicholls[2]), and only the propagation geometry which is needed to describe the subject of this paper is reproduced here.

Consider an aircraft travelling with constant supersonic velocity V in a still, isothermal atmosphere. For each point on the flight track a single acoustic compression wave originating at the instantaneous aircraft position can be imagined, as shown in Figure 1. After a time T the waves originating at times t_0, t_1, . . . , T will be spheres of radius $a(T-t_0)$, $a(T-t_1)$, . . . , 0, where a is the speed of sound. The individual waves have an envelope where reinforcement takes place to give a shock wave, and in the atmosphere under consideration it can be seen that the reinforcement takes place along lines of propagation which are normal to the wavefront; the set of these lines (or wavenormals) from any point on the flight track forms a 3-dimensional cone known as a 'bang cone', which has an apex half-angle of $\cos^{-1}(1/M)$. The wavefront of the shock is also a cone known as the 'Mach cone', whose apex travels with the aircraft, with the apex half-angle $\sin^{-1}(1/M)$.

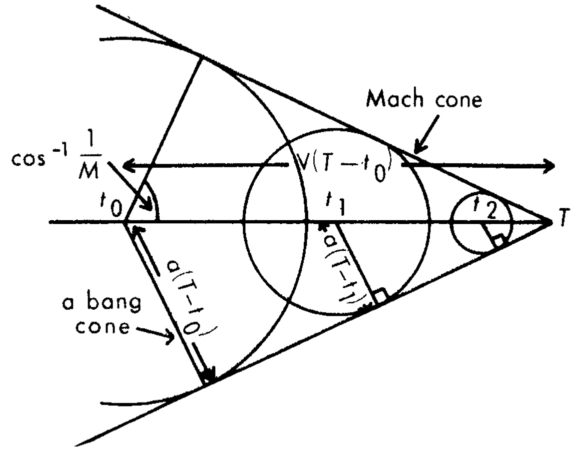


FIGURE 1—LOCATION OF MACH CONE AND COMPRESSION WAVES AT TIME T

a Speed of sound V Aircraft airspeed

t_0, t_1, t_2, . . . , T Times at which the aircraft is at points shown

In an atmosphere with vertical variations of temperature and horizontal wind present, it can be shown (utilizing an axial system which moves with the wind at aircraft altitude) that the initial wavenormals still form a cone whose apex half-angle remains equal to $\cos^{-1}(1/M)$. Consider a co-ordinate system (x, y, z), as shown in Figure 2, with origin at the instantaneous aircraft position and whose x-axis lies along the projection of a wavenormal on the horizontal plane and whose z-axis is vertical; the x-direction cosine, l_A, of the wavenormal at the point of origin is given by

$$l_A = \frac{1}{M \cos \theta}, \qquad \ldots (1)$$

where θ is the angle between the x-axis and the airspeed vector. The sign convention for θ is shown in Figure 3. Figure 4 shows how the wavefront is propagated at any level in the atmosphere beneath the aircraft, for which a is the sound speed and u is the wind component in the x-direction; l is the x-direction cosine of the wavenormal. In the non-stationary atmosphere under consideration the path of the wavefront is not described by the normals to the wavefront, but by 'rays', a 'ray' being defined as the path followed by an element of wavefront from the point of origin. As shown by Milne[3] the

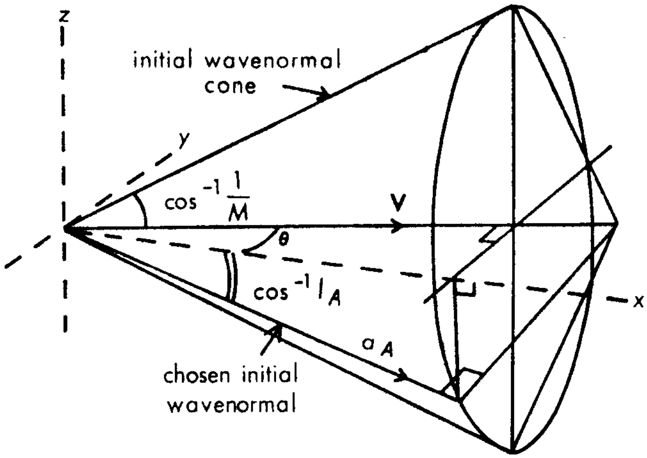


FIGURE 2—INITIAL WAVENORMAL GEOMETRY, LEVEL FLIGHT

a_A Speed of sound at aircraft **V** Airspeed vector

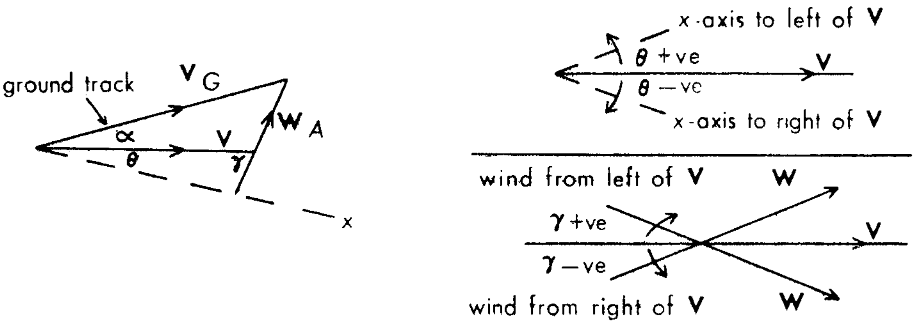


FIGURE 3—RELATIONSHIP BETWEEN AIRSPEED AND GROUNDSPEED, AND SIGN CONVENTIONS

V Airspeed vector **W** Wind vector $\mathbf{V}_G$ Groundspeed vector

A = Aircraft level

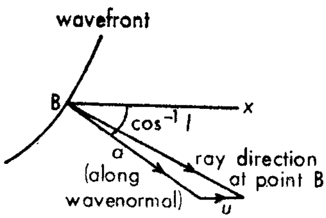


FIGURE 4—WAVEFRONT PROPAGATION AT ANY LEVEL BENEATH AIRCRAFT

a Speed of sound u Wind component along x direction

l x-direction cosine of the wavenormal normals to the wavefront along a ray remain parallel to the vertical plane in which the initial wavenormal lay.

According to Snell's Law, the variation of l along a ray is given by

$$\frac{a}{l} + u = C = \frac{a_A}{l_A} + u_A, \qquad \ldots (2)$$

where C is a constant. Thus, given any value of the initial angle θ, and the variation with height of a and u, this law makes it possible to calculate values of l at descending levels in the atmosphere. If, on doing this, it was found that $l > 1$ for a certain level, the physical meaning is that the ray would have been reflected upwards before it reached that level. The condition, therefore, that the wavefront just reaches the ground along a ray whose wavenormal was initially specified by θ is that a maximum value of l occurs between the aircraft and the ground (for wavenormals lying parallel to the x, z plane) and that this value is unity; in mathematical terms, the conditions are that $\partial l/\partial z = 0$ for $l = 1$, and l is never greater than unity. If equation (2) is differentiated with respect to z, then

$$\frac{1}{l}\frac{\partial a}{\partial z} - \frac{a}{l^2}\frac{\partial l}{\partial z} + \frac{\partial u}{\partial z} = 0, \qquad \ldots (3)$$

and applying the conditions $l = 1$ and $\partial l/\partial z = 0$, this becomes

$$\frac{\partial (a + u)}{\partial z} = 0. \qquad \ldots (4)$$

Thus $l = 1$, $\partial l/\partial z = 0$ at the level where the vertical gradient of $a + u$ is zero and, by studying equation (2), it can be seen that at this level $a + u$ takes its maximum value which may be written $a_H + u_H$, suffix H denoting the height at which $a + u$ is a maximum. Then the condition that the wavefront just reaches the ground along a ray whose initial wavenormal is specified by the angle θ, hereafter called the θ ray, is that

$$\frac{a_A}{l_A} + u_A = a_H + u_H \qquad \ldots (5)$$

since $l_H = 1$. Substituting for l_A from equation (1) and expanding the wind components u in terms of wind speed and direction, we find that the airspeed V_θ which the aircraft must reach before the wavefront reaches the ground along the θ ray is given by

$$V_\theta \cos\theta + W_A \cos(\gamma_A + \theta) = a_H + W_H \cos(\gamma_H + \theta), \qquad \ldots (6)$$

where W is the wind speed, and γ the angle between the airspeed and wind-velocity vectors (see Figure 3). Rearrangement of the last equation gives :

$$V_\theta = \frac{a_H}{\cos\theta} + (\mathrm{u}_H - \mathrm{u}_A) - (\mathrm{v}_H - \mathrm{v}_A)\tan\theta, \qquad \ldots (7)$$

where u and v are the components of wind speed along and normal to the airspeed vector. Further development of the theory varies according to the way in which H is dependent on θ.

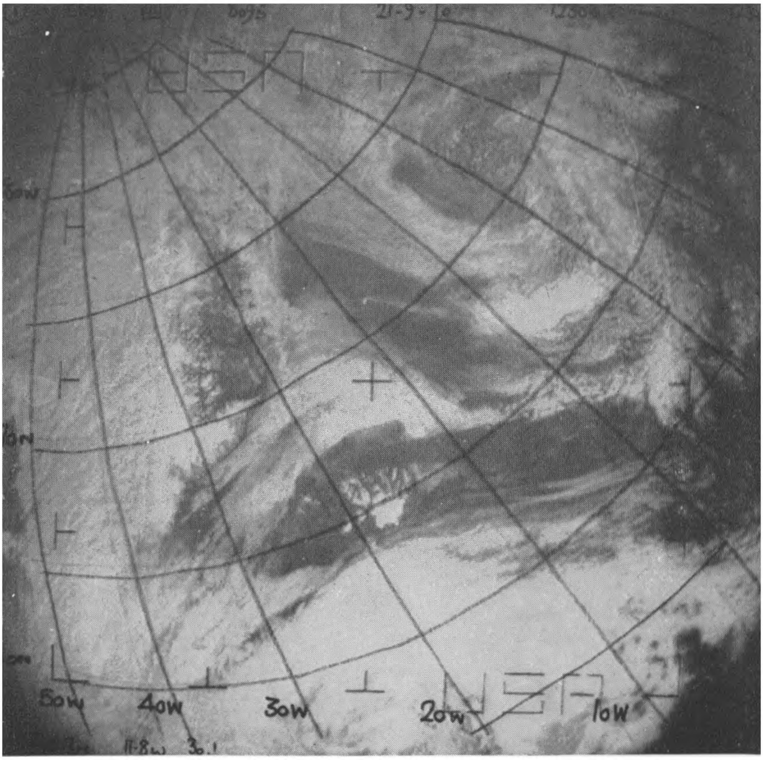


PLATE I—SATELLITE PHOTOGRAPH AT 1230 GMT, 21 SEPTEMBER 1970 SHOWING EMISSION FROM AN ACTIVE VOLCANO ON JAN MAYEN ISLAND

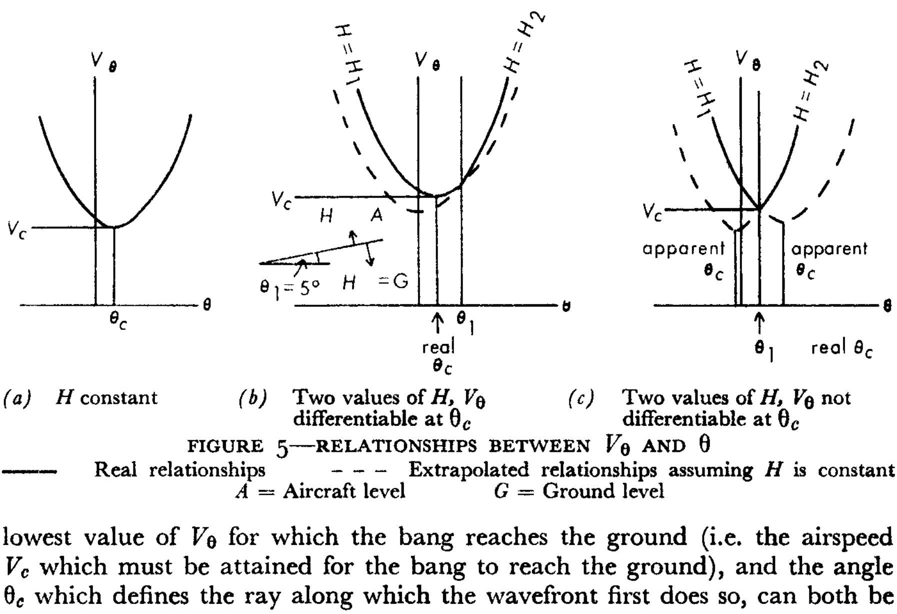
To face page 37

Photograph by C. S. Broomfield

PLATE II—CUMULONIMBUS MAMMATUS LIT BY THE RAYS OF THE EVENING SUN AT GRAINAU, BAVARIA, 1840 GMT, 24 JULY 1970

The mountain peak is 1644 metres above sea level.

(a) Cases for which H is independent of θ. In the normal case H is found to be independent of θ over the whole range of values of θ for a given ground track. Note of course that this range does not extend from $-180°$ to $+180°$ but is dependent on M; e.g. for $M = 1{\cdot}5$ we find that $-48° < \theta < +48°$, and for $M = 2{\cdot}0$ then $-60° < \theta < +60°$ (approximately). It can be seen from equation (7) that in these cases V_θ is a continuous function of θ, as shown in Figure 5*(a)*, which is differentiable at all points over the θ range. The



(a) H constant *(b)* Two values of H, V_θ differentiable at θ_c *(c)* Two values of H, V_θ not differentiable at θ_c

FIGURE 5—RELATIONSHIPS BETWEEN V_θ AND θ

—— Real relationships – – – Extrapolated relationships assuming H is constant
A = Aircraft level G = Ground level

lowest value of V_θ for which the bang reaches the ground (i.e. the airspeed V_c which must be attained for the bang to reach the ground), and the angle θ_c which defines the ray along which the wavefront first does so, can both be found by solving the relationship $\partial V_\theta / \partial \theta = 0$. The solutions are :

$$\sin \theta_c = \frac{v_H - v_A}{a_H} \qquad \ldots (8)$$

and

$$V_c = a_H + (u_H - u_A) - \frac{(v_H - v_A)^2}{2a_H} - R, \qquad \ldots (9)$$

where R is a negligible remainder, the maximum value of the ratio R/V_c being 0·0017. Also

$$M_c = \frac{a_H}{a_A} + \frac{(u_H - u_A)}{a_A} - \frac{(v_H - v_A)^2}{2a_A a_H}. \qquad \ldots (10)$$

With the sign conventions described in Figure 3, u is positive for a tailwind component and negative for a headwind component, and v is negative for winds *from* the right of the airspeed vector (looking along it) and positive for those from the left. Since M_c is dependent on wind components measured along and normal to the airspeed vector it is obviously dependent on the direction of this vector. If the direction does not change then M_c can be simply and accurately evaluated from equation (10). Usually, however, the aircraft would be flying on a straight-line ground track and if it is in an atmosphere with a substantial sidewind component, the direction of the airspeed vector will change as it accelerates; to obtain an exact solution of M_c in this case equation (10) would have to be solved simultaneously with an equation describing the aircraft heading.

Since the third term of equation (10) is always negative the highest value of M_c will be found on condition that $v_H - v_A = 0$; if H is at the ground (corresponding variables denoted by suffix G) v_H will be approximately zero and the above condition will normally be satisfied if the aircraft is flying directly into or with the wind. In fact for a_H and $u_H - u_A$ to take their maximum values, H must be at or near the ground (because temperature and the speed of sound have maximum values near the ground) and the aircraft must be flying into the wind (in which case u_A is negative). If the largest coexisting values of a_G/a_A and $(u_G - u_A)/a_A$ are substituted in equation (10) (the appropriate values of u_G, u_A, a_G, and a_A being 6 kt, 197 kt, 644 kt and 564 kt respectively, over the period 1961–67) it appears that the highest value of M_c likely to occur over the United Kingdom, for an aircraft flying horizontally in the upper troposphere or lower stratosphere, is about 1·48. The lowest value for an aircraft flying at a similar height obviously occurs for $H = A$, i.e. when H is at the height of the aircraft ($u_H = u_A$, etc.), which gives $M_c = 1$.

(b) Cases for which H is dependent on θ. Now consider the minority of cases for which H is a function of θ, and thus for which the above equations (8–10) do not strictly give valid solutions for θ_c, V_c and M_c. In these cases the form of the relationship between V_θ and θ is as shown in either Figure 5*(b)* or 5*(c)* (deduced by changing the value of H in equation (7)), and normally H will take two values as shown, i.e. H_1 for $\theta \leqslant \theta_1$, and H_2 for $\theta \geqslant \theta_1$. Since $(a+u)_{H1} = (a+u)_{H2}$ for $\theta = \theta_1$, V_θ is a continuous function of θ but it is not a differentiable function at θ_1. The dotted lines in the two figures are the extrapolated V_θ, θ curves keeping H constant at either value. The 'apparent' values of θ_c (shown against the dotted lines) are still given by equation (8), and by substituting extreme values (i.e. $\pm$ 200 kt) for $v_H - v_A$ in the equation it can be shown that both 'real' and 'apparent' values of θ_c lie in the range $-19° \leqslant \theta_c \leqslant +19°$. Thus for equations (8), (9) and (10) to give correct solutions it is only necessary for H to be constant for θ in the range $-19° \leqslant \theta \leqslant +19°$. In terms of meteorological conditions it is possible for H to vary over this range of values of θ if a tailwind component of 60–100 kt exists at the aircraft (assuming $A > 28\,000$ ft), depending on the temperature structure between the aircraft and the ground.

The case shown in Figure 5*(b)* is illustrated by the example shown in the inset. For $\theta_1 = 5°$, and $\theta_1 \leqslant \theta \leqslant 19°$ height H is at the aircraft and for $-19° \leqslant \theta \leqslant \theta_1$ it is at the ground. For rays defined by $\theta > \theta_1$, then $v_H = v_A$ and $\theta_c = 0°$. However, this solution for θ_c does not lie in the range of values of θ ($5° \leqslant \theta \leqslant 19°$) for which H is at the aircraft and is thus a non-valid solution. The valid solution for θ_c is obtained by using the value of H for the rays defined by $\theta \leqslant \theta_1$. As in this example it can be shown that generally the value of H which should be used in these cases is that which pertains to the family of rays which includes that specified by $\theta = 0°$, and the correct value of M_c will be found by substituting the appropriate values of a_H, u_H, and v_H in equation (10).

If neither part of the curve contained a real minimum value as in Figure 5*(c)*, then use of the three equations with either value of H would yield non-valid solutions of θ_c, V_c and M_c; the valid solution for θ_c is of course $\theta_e = \theta_1$, and θ_1 could be calculated from the atmospheric data. In this case M_c would be given by

$$M_c = \frac{a_H}{a_A \cos\theta_1} + \frac{(u_H - u_A)}{a_A} - \frac{(v_H - v_A)\tan\theta_1}{a_A}, \qquad \ldots (11)$$

where H can take either of the values H_1 or H_2, one of which will be pertinent to the $\theta = 0°$ ray.

(c) Comparison with other work; cases for which $\theta_c = 0°$. In other literature it has been assumed that θ_c is always zero, and it has been shown here that this is incorrect. The assumption that $\theta_c = 0$ leads to the following equation for M_c:

$$M_c = \frac{a_H}{a_A} + \frac{(u_H - u_A)}{a_A}, \qquad \ldots (12)$$

which is strictly only valid if $v_H - v_A = 0$. Use of this equation will always overestimate M_c in an atmosphere with sidewinds to the aircraft heading, the maximum possible error being about 0·06; however, for values of $v_H - v_A$ of less than 100 kt the error is < 0·016.

(ii) *Climbing aircraft.* The previous section considered the Mach number which an aircraft in horizontal flight would have to reach before the bang it was producing locally reached the ground. For a climbing aircraft there exists a cut-off Mach number at each flight altitude, and if the aircraft is flying below that Mach number at any altitude then the bang will not reach the ground from that altitude. Since M_c is wind and temperature dependent it is obviously a function of height; it cannot, however, be simply derived from equations (10) or (12) since the effect of climb angle β must be taken into account. The initial wavenormal geometry for a climbing aircraft is shown in Figure 6, θ now being considered the angle between the x-axis and the projection of the airspeed vector on the x, y plane.

For a climbing aircraft the relationship between l_A and θ is given by

$$l_A = \frac{\cos\theta\cos\beta + \sin\beta\,(M^2\cos^2\theta\cos^2\beta + M^2\sin^2\beta - 1)^{\frac{1}{2}}}{M(\cos^2\theta\cos^2\beta + \sin^2\beta)}, \qquad \ldots (13)$$

where M is the Mach number of the climbing aircraft. Substitution of this relationship in equation (5) and expansion of the u terms gives

$$\frac{V_\theta\,(\cos^2\theta\cos^2\beta + \sin^2\beta)}{\cos\theta\cos\beta + \sin\beta\,(M^2_\theta\cos^2\theta\cos^2\beta + M^2_\theta\sin^2\beta - 1)^{\frac{1}{2}}} = a_H + (u_H - u_A)\cos\theta - (v_H - v_A)\sin\theta\,. \qquad \ldots (14)$$

where M_θ is the Mach number the aircraft must reach before the wavefront reaches the ground along the θ ray.

For small values of β it can be shown, as in the non-climbing case, that θ_c is usually given by equation (8); the proof of this is very arduous and will not be given here, but the result is intuitively obvious from the geometry of

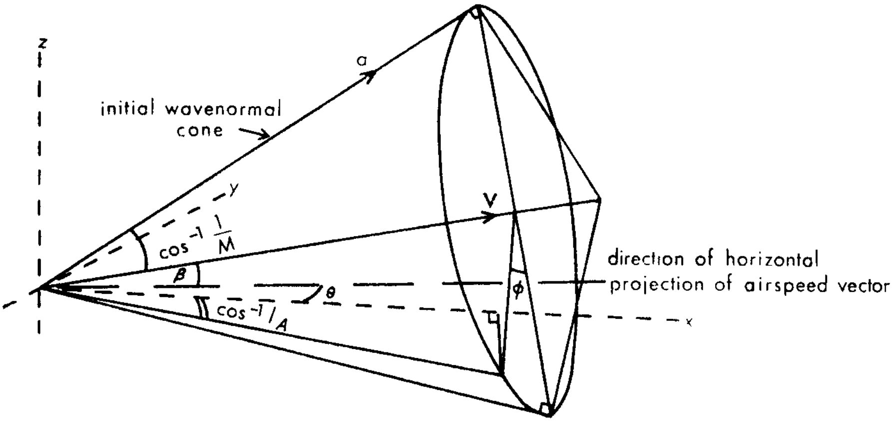


FIGURE 6—INITIAL WAVENORMAL GEOMETRY FOR CLIMBING AIRCRAFT

β Climb angle θ Angle between horizontal projection of airspeed vector and x-axis
a Speed of sound **V** Airspeed vector

The x-axis lies along the horizontal projection of a chosen wavenormal, for which l_A is the x-direction cosine at the aircraft. (Note : φ may be used to specify the wavenormal.)

the situation. If $\theta = \theta_c$, the right-hand side of equation (14) is equal to $(V_c)_0 \cos\theta_c$, where $(V_c)_0$ is the cut-off velocity for an aircraft in horizontal flight for any altitude under consideration. Thus letting $\theta = \theta_c$ and dividing each side by a_A yields the following expression

$$(M_c)_\beta = \left\{(M_c)_0 \cos\theta_c\right\} \times$$
$$\times \left\{ \frac{\cos\theta_c \cos\beta + \sin\beta\ \left((M_c)^2_\beta \cos^2\theta_c \cos^2\beta + (M_c)^2_\beta \sin^2\beta - 1\right)^{\frac{1}{2}}}{\cos^2\theta_c \cos^2\beta + \sin^2\beta} \right\}, \qquad \ldots (15)$$

where $(M_c)_\beta$ is the cut-off Mach number for an aircraft climbing with climb angle β through any altitude and $(M_c)_0$ is the cut-off Mach number for an aircraft flying horizontally at the same altitude. Rearrangement gives

$$(M_c)_\beta = \frac{(M_c)_0}{\cos\beta - \sin\beta \left\{ (M_c)^2_0 - \dfrac{1}{\cos^2\theta_c} \right\}^{\frac{1}{2}}}. \qquad \ldots (16)$$

If $\theta_c = 0$, then

$$(M_c)_\beta = \frac{1}{\cos\left\{ \cos^{-1} \dfrac{1}{(M_c)_0} + \beta \right\}}. \qquad \ldots (17)$$

If $\theta_c \neq 0$, use of the last equation will always result in an overestimate of $(M_c)_\beta$; the errors would be extremely small however (e.g. for $\beta = 5°$ the largest possible error would be 0·009), and the equation can be used to determine $(M_c)_\beta$ for small values of β. The relationship between $(M_c)_\beta$ and $(M_c)_0$, as calculated from equation (17) is shown in Figure 7 for various values of the climb angle β. Thus $(M_c)_\beta$ can be calculated by first finding $(M_c)_0$; changes in aircraft heading should be taken into account since they may be quite large, owing to vertical wind shear. The extreme values of

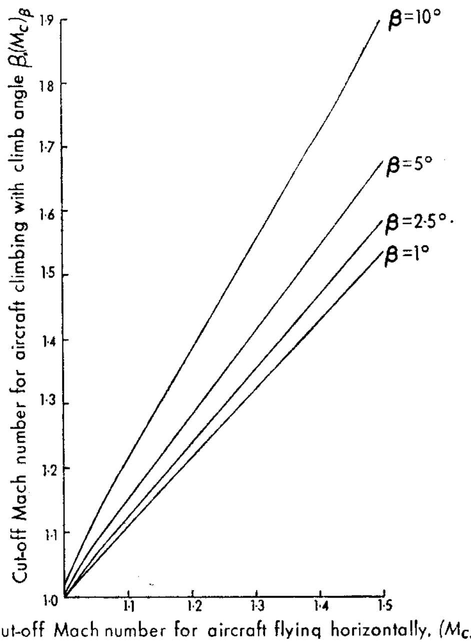


FIGURE 7—VARIATION OF $(M_c)_\beta$ WITH $(M_c)_0$ AND β

$(M_c)_\beta$ for an aircraft climbing at 5° over the United Kingdom are 1·004 and 1·64 for the lower stratosphere or upper troposphere.

A method of calculating $(M_c)_\beta$ by hand. Normally an aircraft accelerating transonically will also be climbing and most of this section is devoted to a climbing aircraft. It should first be emphasized that there would be several advantages in calculating the $(M_c)_\beta$–height profile by a computer; indeed this would be a necessity if profiles were required for several flights a day especially if acceleration corridors on various headings were used. As well as the advantage of time saving, calculations by computer (which could be based solely on the theory described in this paper) would involve making none of the assumptions and approximations which have to be made in order to derive a useful method of calculation by hand. The method given below is, however, fairly accurate and could be used for non-routine flights.

It is first of all assumed that the aircraft is flying along a straight-line ground track and that it accelerates from $M = 1{\cdot}0$ to $M = 1{\cdot}66$ over any height range between 25 000 ft and 45 000 ft. Now $(M_c)_\beta$ is dependent, for a given ground track, on the drift angle α (since α defines the heading, see Figure 3) which in turn is dependent to a slight extent on the airspeed at a given height; however, prescribing the airspeed–height profile would reduce the benefits of calculating the variation of $(M_c)_\beta$ with height since one reason for doing this calculation is to *deduce* a beneficial airspeed–height or Mach number–height relationship, for the portion of the flight in which the transonic acceleration takes place. In deriving the $(M_c)_\beta$–height profile it is therefore assumed that the aircraft flies with an airspeed V which corresponds to an average value of $(M_c)_\beta$ at all heights, and V is therefore assumed to be 700 kt. The final assumption is that height H at which $a + u$ is a maximum is constant over the θ range $-19° \leqslant \theta \leqslant +19°$ for all actual directions of the airspeed vector. The errors caused by all these assumptions are discussed in the next section.

The forecast profile of $(M_c)_\beta$ against height can either be based on forecast wind velocity and temperature–height relationships (for the area of the acceleration), or on persistence of the latest measured data. If persistence type forecasts are made the data used need not be simultaneous; greater accuracy would be achieved by taking the latest hourly reports of surface wind and temperature together with the latest 6-hourly upper wind data and 12-hourly upper air temperature data for the area under consideration. The latter temperature data could be (mentally) slightly adjusted to make it fit the other (later) data, if need be.

The method is given, together with an example (see Table I), showing its application to a standard atmosphere with a 160-kt south-westerly wind at 32 000 ft, which decreases linearly (with constant direction) to zero knots at both the ground and 48 000 ft. The ground-track heading is taken in the example as 270° and the climb angle as 2·5°; both of these quantities must be supplied as well as the wind and temperature profiles. The method, based on equations (6) and (7), is as follows :

(i) Tabulate the temperature and winds at all significant levels up to 45 000 ft, and at 25 000 ft and 45 000 ft.

(ii) Estimate v' the wind component normal to the ground track at 25 000 ft, 45 000 ft, and intermediate significant levels (see Table I for application to example). Using Figure 8 calculate the associated aircraft headings and choose an average heading.

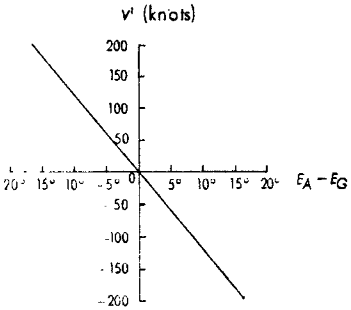


FIGURE 8—CALCULATION OF AIRCRAFT HEADING

E_A Aircraft heading (to be calculated) E_G Ground track heading (given)
v' Wind component normal to ground track
Calculated value of E_A is accurate to within ¼° for $\beta \leqslant 10°$.

(iii) For this average heading calculate and tabulate the wind components u (along the heading) and v (normal to it) at all tabulated heights. Note the sign convention on Table I.

(iv) Using tables relating sound speed to temperature, tabulate sound speeds at all the heights and add to the u values to give a + u.

(v) Tabulate the values of H at which the maximum value of $a + u$ occurs between the aircraft and the ground, and tabulate a_H. Note that as the aircraft climbs, with an increasing depth of atmosphere beneath it, H may vary with altitude (but it normally does not). If two equal maxima occur, make calculations for either value of H.

(vi) For the calculated aircraft heading at 25 000 ft find the wind components along and normal to this heading at the appropriate height H (u_H and v_H) and at 25 000 ft (u_A and v_A). Repeat and tabulate for all heights up to 45 000 ft using the individual headings and appropriate H values each time. Note that if the total change in aircraft heading is $\leqslant 5°$ the values of u_H, v_H, u_A and v_A can be taken as those (appropriate) values already calculated for the *mean* heading. This considerably shortens the procedure.

(vii) Calculate $(M_c)_0$ from equation (10), or if $|v_H - v_A| \leqslant 100$ knots for all heights use the simplified equation (12).

(viii) Using Figure 7 calculate the $(M_c)_\beta$–height profile.

The full procedure just described takes about 25 minutes; however, in the large majority of cases step (vi) is unnecessary and use of the simplified equation (12) is adequate, reducing the working-out time to about 15 minutes (after experience).

For flights at a constant aircraft heading, u and v obviously need calculating only for the one heading. For flights at constant altitude the heading may be assumed constant. Figure 9 shows the $(M_c)_\beta$–height profile calculated for a quarter headwind (as for example in Table I), together with profiles for a direct headwind of 160 kt and a direct tailwind of 160 kt (decreasing to zero knots at the ground and at 48 000 ft); as before, standard atmospheric temperatures were used. The corresponding cut-off airspeeds and groundspeeds are also shown.

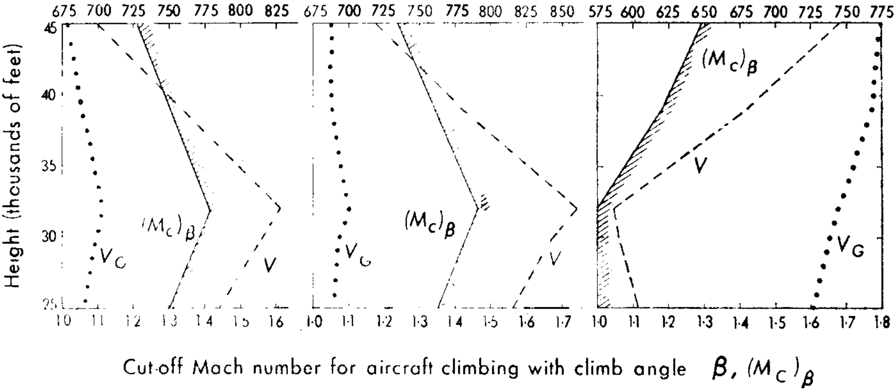


FIGURE 9—CUT-OFF MACH NUMBER, AIRSPEED AND GROUNDSPEED
V Airspeed V_G Groundspeed

Error analysis. The main sources of error are (i) the provision of incorrect atmospheric data and (ii) the provision of an incorrect climb angle β, or its

TABLE I—CALCULATION OF $(M_c)_\beta$

Height	Temp.	Wind Direction	Wind Speed	v'	E_A	Components for mean heading v	Components for mean heading u	a (and a_A)	a+u	H	u_H	u_A	v_H	v_A	a_H	$(M_c)_0$	$(M_c)_\beta$
ft	°*C*	*deg*	*kt*	*kt*	*deg*	*knots*		*knots*				*knots*			*kt*		
0	+15	225	0			0	0	661	661								
5 000	+5·8	225	26			16	−19	651	632								
10 000	−2·1	225	50			33	−38	641	603								
18 000	−17·1	225	90			59	−68	623	555								
25 000	−32·9	225	125	+89	262½	82	−94	604	510	Ground	0	−99	0	+76	661	1·26	1·30
30 000	−44·3	225	150	+106	261	98	−113	590	477	Ground	0	−121	0	+88	661	1·33	1·38
32 000	−46·7	225	160	+114	260½	105	−120	587	467	Ground	0	−130	0	+93	661	1·35	1·41
39 000	−54·4	225	90	+64	264½	59	−68	577	509	Ground	0	−69	0	+57	661	1·27	1·31
45 000	−52·5	225	30	+21	268	20	−23	579	556	Ground	0	−22	0	+20	661	1·18	1·21

Notes: Climb angle β (given) = 2·5°. Ground track heading E_G (given) = 270°.
Mean aircraft heading taken as 264°.
u Positive for tailwind components, negative for headwind components.
v Positive for winds from left of heading (looking along it), negative for those from right.

$$(M_c)_0 = \frac{a_H + (u_H - u_A)}{a_H} \text{ (eq. 12), and } (M_c)_0 = \frac{a_H + (u_H - u_A)}{a_A} - \frac{(v_H - v_A)^2}{2a_A a_H} \text{ (eq. 10)}$$

for all calculations when $v_H - v_A > 100$ kt at any flight level.

variation with height. These sources will of course cause error no matter what method of calculation is used. Even if correct data are provided the particular method described above may introduce errors due to *(a)* differences in aircraft heading from those used (assuming an airspeed of 700 kt), *(b)* the existence of two values of H over the θ range and *(c)* the use of the shortened formula. These three sources are the least common and will be dealt with first.

Errors due to the use of incorrect headings or drift angles (which are dependent on the airspeed for a given ground track) are unavoidable as already explained; for this reason $(M_c)_\beta$ can be underestimated by a maximum of 0·03 at the height for which the actual Mach number is unity and, at the most, overestimated by the same amount for the height at which it is 1·5; these errors are slightly dependent on β also but it is assumed in this section that $\beta \leqslant 2{\cdot}5°$.

The existence of two values of H, and the use of one of them to deduce $(M_c)_\beta$ (in the case depicted by Figure 5*(c)*) can result in an underestimate by a maximum of 0·07, or a maximum overestimate of 0·03; these errors are inclusive of any due to simultaneous use of an incorrect heading. In fact this source of error will seldom occur, especially for westbound flights when a 60–90-knot easterly wind component at the aircraft would normally be required to produce two similar H values (i.e. the aircraft height and the ground). Even then the wind speed at the aircraft would need to be about 200 kt to produce the errors referred to. It is only necessary, therefore, to remember this source as a possible but infrequent reason for large error.

The maximum error due to the use of the shortened formula is about 0·02. The average value of the errors resulting from the three sources discussed above is $<0{\cdot}002$ in each case.

The most frequent source of error in a calculated value of $(M_c)_\beta$ would be the use of incorrect atmospheric data resulting from a forecasting error; errors so caused would be independent of the method of calculation. For the normal case where height H is at or near the ground, vector wind errors of, for example, 60 kt or 20 kt at the aircraft would cause errors in $(M_c)_\beta$ of up to $\pm 0{\cdot}10$ and $\pm 0{\cdot}03$ respectively, depending on the direction of the vector. It is of interest to deduce the errors in a calculated value of $(M_c)_\beta$ based on persistence of measured data for a time 6 hours after an upper air ascent (measuring temperature and wind), and one hour after measured surface observations. Using wind and temperature data[4,5,6] it can be shown that for the cases where H is at the ground (by far the majority of cases for flights which are on a heading between south-west and north-west) the standard deviations of $(M_c)_\beta$ at 30 000 ft and 40 000 ft would be approximately 0·03 and 0·02 respectively, and the associated probable errors are thus 0·02 and 0·013. If the errors at 30 000 ft are considered, $(M_c)_\beta$ will be in error, because of the use of persistence type forecasts, by greater than 0·08 on one occasion in 100 and by greater than 0·04 on one occasion in 20. The probable errors calculated above will also be the approximate values for *all* cases, since a large majority of cases fall into the family for which the calculations were made.

Errors resulting from the use of an incorrect value of β are a function of both β and (M_c), but they can be deduced directly from Figure 7 and may be additive to the errors resulting from the use of incorrect atmospheric data. For example for $\beta = 2{\cdot}5°$, $(M_c) = 1{\cdot}5$, an error of 1° in β will cause an error of $\pm 0{\cdot}03$ in $(M_c)_\beta$.

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THE STRANGE WINDS OF RAS ASIR (FORMERLY CAPE GUARDAFUI)

By J. FINDLATER

Summary. The complex wind structure near Ras Asir (formerly Cape Guardafui) during the northern summer has been examined using surface and upper-wind reports from adjacent stations and sea areas. It is deduced that the pronounced horizontal and vertical variation of wind is consistent with a persistent and mesoscale eddy linked to the environs of Ras Asir, and embedded in the edge of the strong flow of the south-west monsoon.

Introduction. A recent study of the airflow at low levels over eastern Africa and the western Indian Ocean (Findlater [1,2]) analysed a low-level air current which lies near the western boundary of the (northern) summer monsoon circulation. The core of the current can first be identified to the east of Madagascar and from there the current enters the northern hemisphere over the low-lying eastern areas of Kenya. It passes through eastern Ethiopia and Somalia before leaving the continent of Africa near Ras Hafun to cross the Arabian Sea and reach India. The mean speed of the core is about 15 m/s at 1500 m but speeds of between 25 and 50 m/s have been recorded occasionally.

More recently all available pilot-balloon data in the area have been examined to derive monthly mean winds for levels between 1000 m and 3000 m and define the climatological framework within which the high-speed current develops. The results are to be published in the near future (Findlater[3]), but Figure 1 reproduces a small and simplified section of this analysis in the vicinity of Ras Asir (formerly known as Cape Guardafui) for the 1000-m level in July — neglecting mesoscale distortions. The names of some stations are also included in Figure 1*(a)*.

Ras Asir — the strange winds. A pilot-balloon station operated from January 1930 to June 1933 near the lighthouse at Ras Asir. The balloon ascents were made from the settlement at Tohèn, position 11° 44′N, 51° 15′E

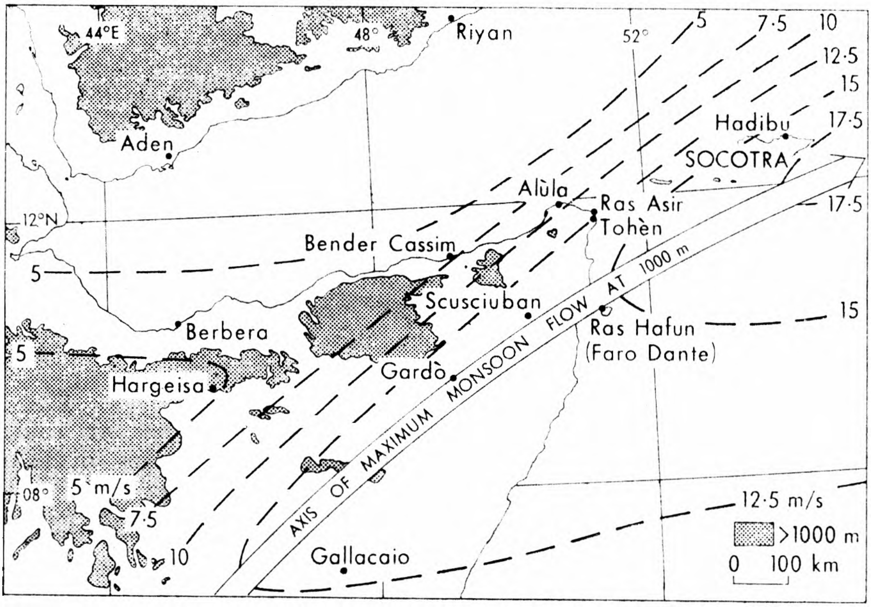


FIGURE 1(*a*)—MEAN FLOW AT 1000 m IN JULY, AND LOCATION OF STATIONS

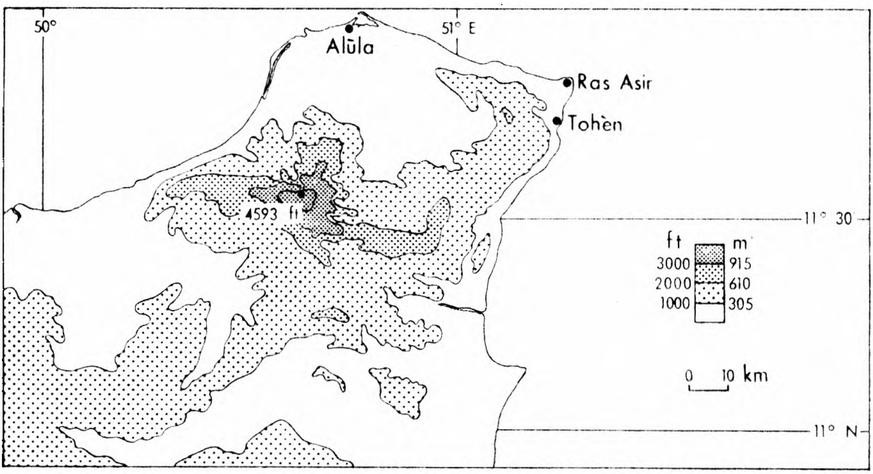


FIGURE 1(*b*)—TOPOGRAPHY OF AREA

and height 80 m above MSL. The lighthouse is 11 km to the north of Tohèn with its base 244 m above MSL at 11° 49′ 30″N, 51° 16′ 10″E. The positions of the two stations are included in Figure 1(*b*) which shows the detailed topography of the area. Of particular interest is the arc of high ground which lies aslant the summer monsoon flow.

The published data[4] from twice- or thrice-daily soundings have been examined but few of the soundings reached the 1000-m level during the summer months. Nevertheless, the winds reported near the surface were so strange in speed and direction that the records at all levels up to 1000 m were studied in an attempt to reconcile the values with the broad-scale features of the flow at 1000 m as represented in Figure 1.

In the summer months Ras Asir lies under the north-western edge of the strong monsoon flow, yet despite the strength and high constancy of the south-westerly flow in the area the pilot-balloon records show a moderate or strong south-south-easterly wind in a shallow layer close to the surface, overlain by lighter winds from a northerly point. A series of consecutive soundings is shown in Table I to illustrate the type of flow prevalent in the period June to September.

TABLE I—A SERIES OF CONSECUTIVE PILOT-BALLOON SOUNDINGS AT TOHÈN, SHOWING MODERATE OR STRONG SOUTH-SOUTH-EASTERLY WINDS OVERLAIN BY LIGHTER WINDS FROM A NORTHERLY POINT, 12–15 JULY 1932

Height above surface	12th 15 GMT		13th 10 GMT		13th 15 GMT		14th 10 GMT		14th 15 GMT		15th 10 GMT		15th 15 GMT	
metres		*m/s*		*m/s*		*m/s*		*m/s*		*m/s*		*m/s*		*m/s*
0	SSE	8·0	SSE	8·5	SSE	8·5	SSE	28·0	SE	10·0	SSE	5·5	SSE	8·5
75	SSE	14·8	SSE	13·8	SSE	10·8	SSE	28·2	SSE	11·5	SSE	12·8	SSE	17·5
150	SE	9·6	SSE	9·2	SSE	11·3	NW	13·6	SSE	6·5	SSE	10·0	SSE	12·6
300	N	3·9	SE	6·5	NE	1·2	NNW	4·8	N	0·7	NE	2·6	N	1·0
450	ENE	6·0	NNW	11·8	NNW	2·2	NNW	4·6	N	2·0	NE	3·3	NW	3·6

On many occasions, however, the shallow low-level south-south-easterly winds strengthen to remarkable speeds, sometimes to more than 50 m/s, and the overlying stream becomes north-westerly. Some of the most extreme examples of this type of flow are shown in Table II. It is noteworthy that these extreme speeds have been recorded at all three sounding times, 04–05, 09–10 and 14–15 GMT and are not only an early morning phenomenon. Local zone time in the area is three hours in advance of GMT.

TABLE II—SEVEN OF THE MOST EXTREME SOUNDINGS RECORDED BY PILOT BALLOON AT TOHÈN

	1930						1932							
Height above surface	29 June 04 GMT		30 June 14 GMT		1 July 04 GMT		16 July 10 GMT		9 August 15 GMT		10 August 15 GMT		14 August 10 GMT	
metres		*m/s*		*m/s*		*m/s*		*m/s*		*m/s*		*m/s*	SSE	*m/s*
0	SSE	21·0	SSE	21·0	SSE	25·3	SE	20·0	SSE	16·0	SSE	18·0	SSE	18·0
75	SSE	51·0	SSE	37·5	SSE	37·5	SSE	54·0	SSE	42·0	SSE	51·0	N	47·6
150			WNW	5·0	NNW	11·4	NNW	38·4	NNW	21·0	NNW	16·7	W	16·9
300					NW	5·6					E	1·3	WNW	2·4
450					SSW	3·1								

An analysis of the pilot-balloon data of 1930–33 by Eredia[5] indicates that in July the most frequent wind directions at specified heights above the station were :

Height (m)	0	75	150	300	450	600	750	900
Direction	SSE	SSE	SSE	Var.	Var.	WNW	WNW	WNW

Eredia comments that south-westerlies were almost non-existent at the surface in the summer months of 1930–33 at Tohèn, but Fantoli[6] has published summaries of surface wind directions at the lighthouse for the combined periods 1936–39 and 1954–58 which show that south-westerlies occurred with almost the same frequency as south-easterlies, whilst southerly winds

TABLE III—SURFACE WIND DIRECTION FREQUENCIES DURING JUNE, JULY AND AUGUST

Station and period	Month	N	NE	E	SE	S	SW	W	NW	Calm	Total
Scusciuban	June	1	42		2	30	198	261	108	10	652
1953–58	July	7				10	391	261	71		740
	Aug.	1			5	54	410	205	34	7	716
Gardò	June					248	490	12			750
1938	July					247	285	243			775
1953–58	Aug.					261	464	19			744
Bender Cassim	June	62	322	11	89	231	230	5	128	62	1140
1934–39	July	96	163	4	67	291	206	18	147	104	1096
1953–58	Aug.	109	125	2	43	251	175	25	195	90	1015
Alùla	June	159	156	6	1	1		3	23	223	572
1953–58	July	112	184	95	7	25	5	21	12	147	608
	Aug.	126	265	33	15	11	13	20	16	121	620
Ras Asir	June	6		5	243	136	249	5	9	157	810
1936–39	July				321	91	337			14	763
1954–58	Aug.		1	3	373	141	302	3	1	28	852
Faro Dante	June				20	70	90	90			270
1936–39	July						279				279
	Aug.						279				279

were of much lower frequency (see Table III, Ras Asir). Because of the differing positions and altitudes of the two stations, the lack of site details and the difference in periods, it is difficult to explain the discrepancy between the two sets of data. One plausible explanation would be the existence of persistent small-scale eddies tied to the local topography, and another would associate the south-westerlies at Ras Asir, which is 164 m higher than Tohèn, with the layer of changing direction evident at about 150 m above Tohèn when winds are strong, as indicated in Table II. However, despite the lack of an adequate explanation of the south-westerly periods at Ras Asir and their non-occurrence at Tohèn, the fact remains that at both stations south-south-easterly or south-easterly flow, often very strong, is of frequent occurrence in July.

Analysis of surface winds. It might be suspected, because the upper winds were based on an assumed rate of rise of the pilot balloons, 2·5 m/s, that the strong winds were unreal. However, the very strong south-south-easterlies close to the surface are confirmed by anemometer readings from Tohèn and Ras Asir, and by reports from ships of very strong southerly winds near and to the east of the cape, where south-westerly flow might be expected. The long-period mean surface winds over the Gulf of Aden and the Arabian Sea from the atlases of the Royal Netherlands Meteorological Institute[7,8] and the most frequently reported wind directions from land stations in Somalia (Fantoli[6]) may be used to represent the character of the surface flow in July, as in Figure 2.

The short arrows over the land show the most frequently reported wind directions over land, based on three observations daily, and those over the sea the mean direction and mean speed in metres per second (converted from data published in Beaufort forces) within the circle denoting the middle of the sea area to which each report refers. These areas are 2-degree quadrangles eastward from 50°E and 1-degree quadrangles westward into the Gulf of Aden.

The striking feature of Figure 2 is the predominant north-easterly wind at Alùla, confirming that flow near Ras Asir is complex. The observations from

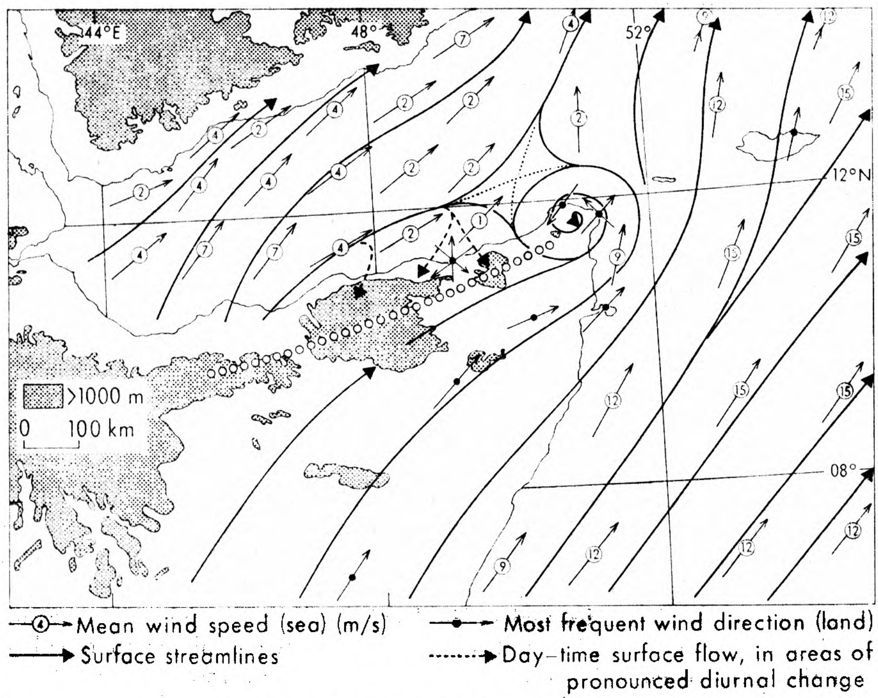


FIGURE 2—MEAN SURFACE FLOW IN JULY

oooooo Sea-breeze convergence zone

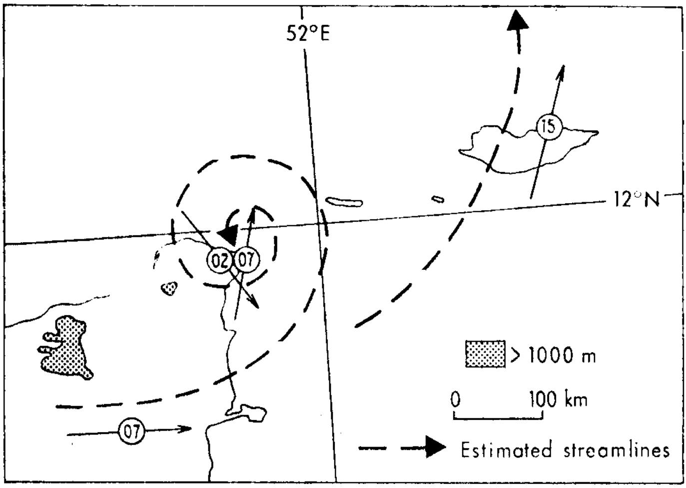
which the most frequent wind direction at Alùla was calculated by Fantoli[6] were made at 04, 10 and 15 GMT, yet the most frequent direction was from the north-east and the least frequent from the south-west.

Surface wind data for Alùla and nearby stations, also extracted from Fantoli's work, are shown in Table III for the months of June, July and August. It can be deduced that the small number of reports of south-westerlies at Alùla in all three months preclude the existence of a significant number of south-westerlies at 04 GMT. The prevailing north-easterlies are therefore not due to a simple sea-breeze system. For example, Table III includes 186 observations at 04 GMT (dawn) in July and most of these winds come from a northerly point.

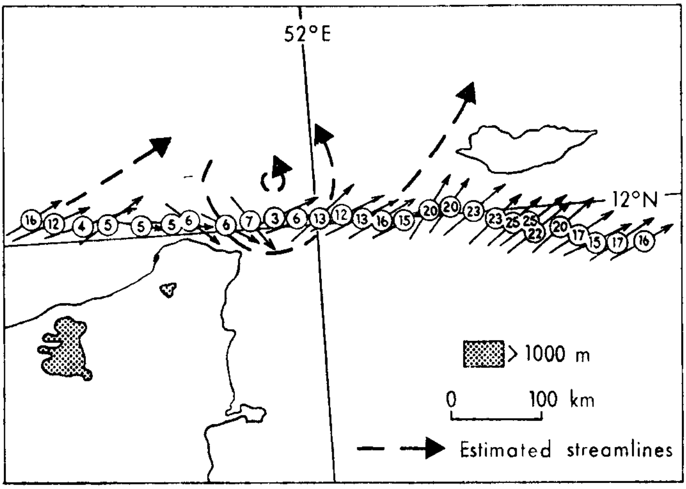
Figure 2, analysed by streamlines, reveals a small-scale eddy centred between Ras Asir and Alùla, on the north-western edge of the main monsoon stream. Though the diameter of the closed circulation is only about 200 km its influence is seen in the deformation of the flow over a much wider area of about 500 km diameter. Winds at Scusciuban are veered and those near Socotra are backed from the broad-scale flow. Also, an area of light mean winds lies to the north-west side of the eddy.

Analysis of upper winds. No attempt is made here to challenge the validity of the winds measured by pilot balloons from Tohèn. Any attempt to do so would probably be inconclusive and enable the strange effects to be dismissed without adequate explanation. Rather, the approach in this paper is to demonstrate that the observed values, especially those of direction, are quite consistent with the mesoscale eddy noticed in the monthly mean surface wind field.

At the 450-m level the mean wind in July 1930 was 190°, 6·6 m/s and in July 1932 was 325°, 2 m/s and both of these values are plotted in Figure 3. In July 1931 no soundings were followed beyond the second minute of the ascent, 300 m. These values compared with a July mean for Socotra at 500 m



(a) Mean winds at 450 or 560 m in July (June at Scusciuban); wind speed (m/s) in centre of circle, wind direction shown by short arrow.



(b) Doppler radar winds at 560 m on 1 September 1964 (after Bunker[9]).

The aircraft position is marked by a circle with wind speed (m/s) in the centre and a short arrow to show wind direction.

FIGURE 3—SOME FRAGMENTARY WIND DATA AT 450–560 m NEAR RAS ASIR DURING THE SUMMER MONTHS

of 200°, 15 m/s for the years 1942–45, and the well-known strong south-westerly winds south and east of Ras Asir, indicate the existence of a lighter and variable wind area or eddy at 450–500 m in the area. Furthermore, the July mean wind at 1000 m at Tohèn is 280°, 5 m/s and between June and September varies only in the range 270–285°, 4·5–5 m/s, though there are barely sufficient data at this level to determine a true mean value. Nevertheless, westerly to north-westerly winds must exist on a considerable number of occasions.

These data suggest that the eddy centred just west of Ras Asir at the surface lies further eastward or north-eastward with increasing altitude and extends high enough to influence the 1000-m level.

The general flow over the north-eastern tip of Somalia changes little between June and September, and use may be made of a little more evidence for the existence of an eddy. The only known set of aircraft upper winds at Ras Asir are those measured by airborne Doppler radar at 560 m on 1 September 1964 and published by Bunker.[9] These winds are illustrated in Figure 3 together with other data near the 500-m level, and are compatible with the existence of a pronounced and persistent mesoscale eddy.

Factors of importance in the formation of the eddy. These may be summarized as :

(i) The small ridge of hills just south of Alùla lies across the flow of the south-west monsoon. Higher mean speeds at the eastern end than at the western end of the range favour cyclonic eddy formation on the leeward side.

(ii) The strong flow of the monsoon circulation over eastern Africa, especially Kenya and eastern Ethiopia, brushes against the high mountains and plateaux and generates large horizontal shears by lateral friction (see July mean flow in Figure 1*(a)*). Cyclonic vorticity resulting from the shear is contained between the edge of the high ground and the core of the current. The maximum value lies along line A in Figure 4.

(iii) The surface winds on the north coast of Somalia undergo a pronounced daily sea-breeze cycle and the front formed by the southward-moving sea air lies a little way inland. This front is a major feature frequently identifiable as a semi-continuous cloud band on photographs from earth satellites. The front, or convergence zone, is also a line of maximum (cyclonic) vorticity and is indicated by line B in Figure 4.

(iv) A minor sea-breeze frontal régime on the east coast of Somalia is not thought to be a significant feature but any contribution it might make would be additive to those of (ii) and (iii) above. The approximate location of this system is indicated by line C in Figure 4.

(v) The eddy lies near the area where at least two zones of maximum vorticity meet, and the position is also that at which these vorticity-generating mechanisms cease to operate; friction on the western boundary of the stream and differential heating near the coast cease as the air reaches the coast. It is probable that the eddy forms there to exhaust the cyclonic vorticity continuously advected into the area from the south-west quadrant.

The structure of the eddy. Some features of the eddy which can be deduced or inferred from surface and upper wind data are :

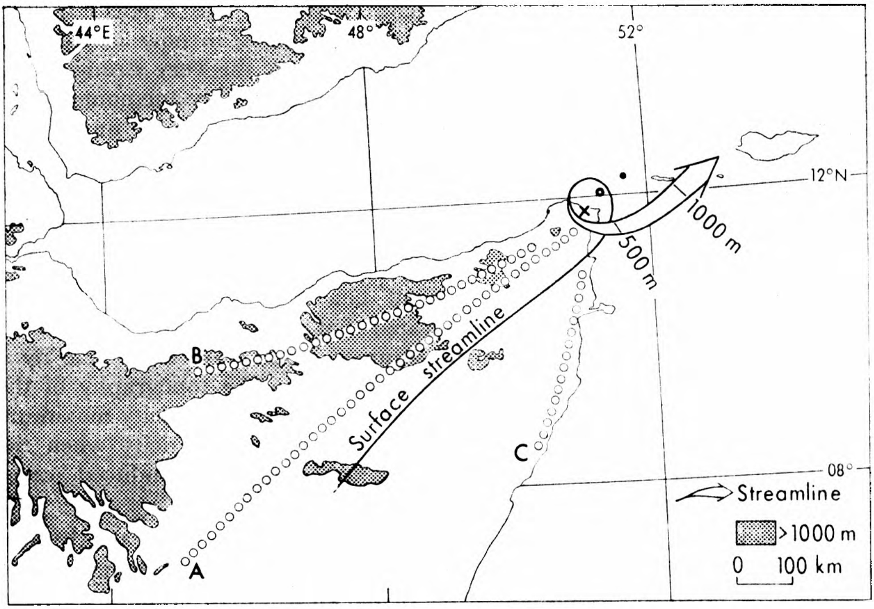


FIGURE 4—SCHEMATIC REPRESENTATION OF ZONES OF MAXIMUM VORTICITY IN RELATION TO THE MESOSCALE EDDY

ooooo Zones of maximum (cyclonic) vorticity

Approximate position of eddy centre : x at surface
o at 500 m
. at 1000 m.

(i) It is linked to the topography of Ras Asir and environs.

(ii) It is evident only in the summer months and is sufficiently persistent between June and September to show up in monthly mean values.

(iii) The eddy is of mesoscale dimensions, having a diameter at the surface of about 200 km though it is associated with distortion of the wind field over an area of about 500 km diameter.

(iv) It extends upward to between 500 and 1000 m and the axis slopes to the north-east with increasing altitude. The slope of the axis, deduced from fragmentary data, is about 1:100 although there is no direct evidence that the flow is a closed circulation at the upper levels.

An eddy with a quasi-horizontal axis sloping across Ras Asir would provide an explanation for the peculiar structure of the wind in the vertical as illustrated in Tables I and II, and for the previously unexplained simultaneous occurrence of surface south-south-easterlies at Tohèn (80 m) and south-westerlies at Ras Asir (244 m). However, the eddy is likely to generate upward motion near its centre to connect the flow at various levels and the present evidence suggests that the three-dimensional flow, illustrated schematically in Figure 4, may be similar to that experienced, i.e. a very strong south-south-easterly or southerly overlain by a lighter wind from the north-west quadrant. It follows from these arguments, however, that vertical motion exists and the validity of the original measurements is now called into question. Nevertheless, there is no reason to suspect the very strong winds near the surface since these have been confirmed by the anemometers at Tohèn and Ras Asir, but the north-westerlies aloft may be imperfectly measured. That the direction of the upper régime might not be too inaccurate may be inferred from the fact that on the only day when airborne Doppler winds were measured in the area a localized north-westerly régime was located in the Ras Asir disturbance.

Conclusions. Using mean surface wind data and fragmentary data from pilot balloons and aircraft it is demonstrated that the strange winds reported in the vicinity of Ras Asir during the summer months are explicable by a mesoscale eddy, of remarkable persistence, linked to the topography of the area. The eddy lies in an area where at least two zones of vorticity maximum meet, and the eddy may serve to exhaust some of the vorticity when the vorticity-generating mechanisms, which are topographically induced, cease to operate as the air reaches the coastline.

The axis of the eddy slopes gently upwards to the north-east and the disturbance cannot at present be traced above the 1000-m level. Small changes in the position, size, intensity, and angle of tilt of the eddy would account for most of the strange effects which have been reported, and their day-to-day changes.

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FORECASTING MAXIMUM AND MINIMUM TEMPERATURES OVER THREE DAYS

By S. G. ABBOTT

Summary. The practical approach to a requirement for forecasts of maximum and minimum temperatures for each of three consecutive days ahead over a large area in south-west England is discussed and the forecast errors analysed. A regression equation technique based on climatological mean temperatures is shown to give some improvement in forecasts for the third day, with a worthwhile reduction in the number of large errors.

The requirement. Temperature forecasts for sets of three consecutive days were supplied to the South West Electricity Board (SWEB), Taunton Group, by the Meteorological Office at Plymouth/Mount Batten during the winter of 1968/69. The opportunity was taken to prepare the forecasts over a full year to test the forecasting techniques used. The stated requirement was the supply by 09 clock-time daily of area average forecasts in degrees Celsius of maximum and minimum temperatures for the next 24 hours (Day 1) and the following 24 hours (Day 2), with trends for a third 24-hour period (Day 3). The total area covered by the forecasts was about half of Somerset, and parts of north Devon and of west Dorset, as shown on the map (Figure 1).

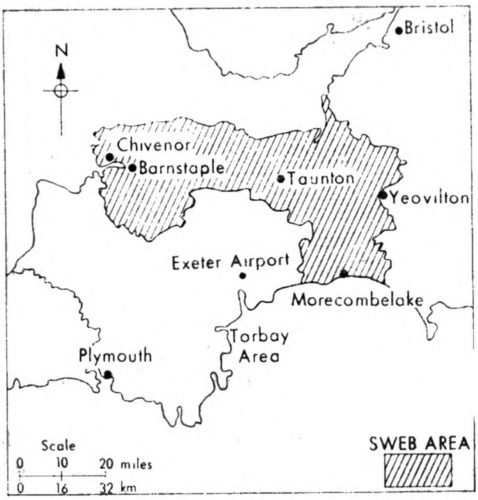

FIGURE 1—MAP SHOWING SOUTH WEST ELECTRICITY BOARD AREA

The forecasting problem. Over such an area large variations of maximum and minimum temperatures can occur from place to place. The only available regularly reporting stations were Exeter Airport, Morecombelake, Yeovilton and Chivenor. Exeter and Yeovilton are probably reasonably representative of the main inland centres of population, with Chivenor representing the northern coastal zone and Morecombelake the Lyme Bay coastal zone. It was therefore thought reasonable to reduce the problem to providing a mean maximum and minimum temperature forecast for these four stations for each 24-hour period. Forecasts for the first period were prepared using current synoptic data and forecast charts (prepared by Central Forecasting Office (CFO), Bracknell) for midnight. Day maximum temperatures were forecast using the Gold-square techniques,[1] as modified by Jefferson[2,3] and Johnston,[4] on suitable days. Night minimum temperature forecast techniques used were those developed by Tinney and Menmuir,[5] based on the work of Saunders[6,7] and Barthram,[8] which have been found to give good results in this area. The forecasting problem for Days 2 and 3 is similar to that facing CFO when providing weekend guidance forecasts for the Central Electricity Generating Board (CEGB). The 48- and 72-hour forecast charts for midnight, issued by CFO on the previous afternoon, were used to assess air-mass changes and parameters for use with the techniques employed for Day 1, taking into account any major changes in the forecasts suggested by the latest current synoptic data and forecast charts.

Analysis of forecast errors. An analysis of similar forecasts issued for part of the previous winter had indicated that subjective forecasts were consistently better than persistence forecasts. The present analysis was therefore performed in two parts :

(i) The forecast maximum and minimum temperatures were compared with the area mean values, calculated from the daily maximum and minimum temperatures recorded at the four stations.

(ii) To check a technique currently in use in the Meteorological Office for forecasting temperatures for CEGB for the third day of week-end periods, revised forecasts for Day 3 were prepared on the basis of the following regression equation :

$$\text{Day 3C forecast} = \frac{\text{Day 2 forecast} + \text{climatological mean}}{2} .$$

The climatological mean was obtained from the mean maximum and minimum temperatures at Exmouth, Cullompton and Ilfracombe for 10-day periods.[9]

Discussion of results. The results of the analysis are shown in Tables I and II along with the errors obtained when the regression equations are used to produce the forecast values listed as Day 3C. The mean errors indicated that there was no significant tendency to bias forecasts except in January, when the forecast temperatures were biased on the low side for Days 2 and 3. The mean deviations, indicating the mean magnitude of errors irrespective of sign, and the root-mean-square errors, indicating the spread of errors, increased from Day 1 to Day 3 except in September. The extreme error ranges showed little systematic variation apart from the expected increase beyond Day 1. Occasional large errors occurred on all three days, reflecting the synoptic difficulties. Errors in forecasting the tracks and development of depressions from the Atlantic were the main source of large errors. The very large ones in December arose from a 2-day period during which a very mild warm sector occluded over the South-west Approaches and south-west England eventually had cold easterly winds. The revised forecasts for Day 3 (Day 3C) showed decreases in mean deviations and root-mean-square errors but large errors were not eliminated entirely.

Applying the *t*-test to the two sets of forecast errors for Day 3 indicated that there were significant differences at the 5 per cent level in only two of the months. When considering errors of 5 degC or more, however, the regression-equation technique reduced the total of such errors in Day 3 forecasts by about two-thirds and to this extent was a worthwhile improvement. It is interesting to compare the mean errors and root-mean-square errors for the minimum temperature forecasts with those obtained during a test of forecasting techniques in eastern England for the period October 1963 to March 1964, described by Gordon and Virgo.[10] The forecasts for Days 1, 2 and 3 bear comparison with these, considering that the eastern England forecasts

TABLE I—ERRORS IN FORECASTS OF MAXIMUM TEMPERATURES (AREA MEAN MINUS FORECAST TEMPERATURE)

Month	Mean errors Day 1	Mean errors Day 2	Mean errors Day 3	Mean errors Day 3C	Mean Deviation Day 1	Mean Deviation Day 2	Mean Deviation Day 3	Mean Deviation Day 3C	Root-mean-square errors Day 1	Root-mean-square errors Day 2	Root-mean-square errors Day 3	Root-mean-square errors Day 3C	Extreme error range Day 1	Extreme error range Day 2	Extreme error range Day 3	Extreme error range Day 3C
	degrees Celsius															
1968																
Sept.	−0·3	−0·2	−0·1	−0·2	1·0	1·1	1·0	0·9	1·4	1·6	1·3	1·3	2 to −5	2 to −4	2 to −3	2 to −3
Oct.	−0·4	−0·4	−0·2	+0·3	0·8	0·8	1·0	0·8	1·0	1·1	1·3	1·1	1 to −3	1 to −3	3 to −3	2 to −2
Nov.	−0·6	−0·4	−0·3	−0·8	0·8	1·6	2·2	1·9	1·0	2·0	2·6	2·1	1 to −3	3 to −5	5 to −6	3 to −6
Dec.	0·0	−0·7	−0·7	−1·4	1·2	2·3	3·3	2·0	1·6	2·7	3·6	2·1	3 to −4	4 to −6	7 to −9	3 to −6
1969																
Jan.	+0·4	+0·8	+1·2	+1·0	0·8	1·3	1·9	1·7	0·9	1·5	1·9	1·7	2 to −1	5 to −2	6 to −1	4 to −3
Feb.	+0·5	−0·1	+0·1	−1·5	1·2	2·0	2·8	2·3	1·3	2·7	3·6	2·3	3 to −2	6 to −6	9 to −5	4 to −5
Mar.	+0·3	+0·1	+0·4	−0·6	1·2	1·9	2·2	2·1	1·5	2·7	2·8	2·4	3 to −4	7 to −6	6 to −5	5 to −7
Apr.	+0·4	+0·7	+0·2	+0·5	0·9	1·5	1·9	1·7	1·1	1·7	2·7	2·1	2 to −2	4 to −4	5 to −4	5 to −4
May	+0·1	−0·2	+0·3	−0·7	1·1	1·3	1·6	1·4	1·4	1·7	2·0	1·5	3 to −3	3 to −5	4 to −4	3 to −4
June	0·0	+0·1	+0·4	+0·3	0·7	1·5	2·2	1·7	0·9	1·9	2·8	2·3	2 to −2	5 to −4	5 to −5	5 to −3
July	+0·3	−0·2	−0·3	+0·5	0·9	1·5	1·9	1·7	1·2	1·9	2·7	2·1	3 to −3	5 to −4	3 to −8	5 to −5
Aug.	−0·5	−0·7	−0·8	−0·4	0·8	1·5	1·8	1·7	1·0	1·9	2·1	1·9	2 to −2	2 to −6	4 to −5	4 to −4

	Day 3	Day 3C
Total errors of 5 degC or more	34	14

TABLE II—ERRORS IN FORECAST MINIMUM TEMPERATURES (AREA MEAN MINUS FORECAST TEMPERATURE)

Month	Mean errors				Mean deviation				Root-mean-square errors				Extreme error range			
	Day 1	Day 2	Day 3	Day 3C	Day 1	Day 2	Day 3	Day 3C	Day 1	Day 2	Day 3	Day 3C	Day 1	Day 2	Day 3	Day 3C
	degrees Celsius															
1968																
Sept.	+0·3	0·0	+0·5	−0·2	1·4	1·5	1·8	1·5	1·7	1·9	2·2	1·8	3 to −3	3 to −3	5 to −4	3 to −4
Oct.	+0·1	+0·1	+0·6	+0·9	1·2	1·3	1·6	1·6	1·6	1·7	2·1	1·6	4 to −3	3 to −3	5 to −4	4 to −3
Nov.	−0·3	−0·1	+0·2	−0·6	1·7	1·9	3·1	2·0	1·9	2·7	3·9	2·8	2 to −4	7 to −6	7 to −8	5 to −8
Dec.	+0·2	+0·7	−0·5	−1·3	2·2	2·9	3·6	2·5	2·8	3·9	4·7	3·1	5 to −6	5 to −13	8 to −11	5 to −11
1969																
Jan.	+0·6	+1·1	+2·1	+1·5	2·0	2·0	2·9	2·0	2·5	2·3	3·0	2·1	6 to −4	6 to −4	7 to −3	5 to −3
Feb.	+0·7	+0·6	+0·7	−1·2	1·1	1·9	2·8	2·1	1·2	2·2	3·2	2·3	3 to −1	5 to −4	6 to −5	3 to −7
Mar.	+0·1	−0·1	−0·2	−0·9	1·7	2·1	2·3	1·7	2·0	2·3	2·8	2·0	4 to −3	5 to −4	5 to −6	3 to −4
Apr.	+0·8	+0·5	−0·2	0·0	1·6	2·6	2·9	2·1	1·9	2·8	3·6	2·5	5 to −3	5 to −5	5 to −7	4 to −4
May	−0·4	−0·4	−0·3	−0·3	1·2	1·5	2·0	1·3	1·8	2·0	2·7	1·8	3 to −7	4 to −6	4 to −6	3 to −5
June	−0·2	−0·1	+0·2	−0·6	1·6	1·8	2·3	1·5	2·0	2·6	3·0	2·1	6 to −3	6 to −6	5 to −8	4 to −6
July	+0·3	+0·2	+0·1	0·0	1·6	1·7	1·7	1·7	1·4	2·0	2·2	2·0	3 to −2	4 to −4	4 to −4	3 to −4
Aug.	+0·1	+0·1	−0·7	−0·5	1·5	2·2	2·3	2·0	1·9	2·5	2·6	2·3	5 to −5	6 to −4	6 to −6	4 to −5

	Day 3	Day 3C
Total errors of 5 degC or more	58	18

were made for single nights at times more synoptically convenient, when some of the parameters had been recorded. The occasional large errors in the forecasts for Days 2 and 3 could have been serious for Electricity Authority load estimations but the expected advances in synoptic forecasting should eventually reduce such errors.

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AWARDS

L. G. Groves Memorial Prizes and Awards

The 24th award of the prizes was made on Friday, 27 November 1970, at the Ministry of Defence, Whitehall, by Major and Mrs K. G. Groves; the award is in memory of their son, Sergeant Louis Grimble Groves, RAFVR, who was killed on a meteorological sortie in 1945. The Vice-Chief of the Air Staff, Air Marshal Sir Denis Smallwood, presided at the ceremony. (See Plates III, IV and V.)

The Aircraft Safety Prize has been awarded jointly to Squadron Leader A. P. Fletcher and Squadron Leader D. J. Phillips, formerly of Royal Air Force Laarbruch, with the following citation :

> 'There have been many instances of birdstrikes on the nose of Canberra aircraft and in some cases the shattering of the nose transparency has caused injury to the navigator in the nose prone position. Squadron Leader Fletcher and Squadron Leader Phillips devoted much thought and energy to a means of alleviating this situation and conceived the idea of a transparent screen between the nose transparency and the navigator's face. The 'Macrolon Screen' which they created is now fitted in all Canberra B(I)8s of RAF Germany and not only achieves the primary object of shielding the navigator but also affords a measure of protection to the aircraft. It represents the first worthwhile advance for some time in the sphere of birdstrikes.
>
> By diligent application to a serious problem Squadron Leader Fletcher and Squadron Leader Phillips have made a very valuable and practical contribution to flight safety.'

The Meteorology Prize has been awarded jointly to Mr R. A. S. Ratcliffe, Senior Principal Scientific officer, and Mr R. Murray, Principal Scientific Officer, Meteorological Office; the citation reads :

'In recognition of their work in determining the relationships between anomalies of sea temperature in the Atlantic and subsequent long-term anomalies in the large-scale atmospheric circulation. Relationships between the temperature of the Atlantic and subsequent weather have been suspected for many years but Messrs Ratcliffe and Murray have for the first time demonstrated conclusively the existence and nature of such relations. They have also shown how use can be made of them for the improvement of prediction of weather anomalies over the British Isles for periods of a month or more ahead.'

The Meteorological Observers' Award has been awarded to Mr D. P. Smith, Senior Experimental Officer, Meteorological Office, the citation reading :

'The Board of Trade has for the past two winters maintained a weather advisory ship, the *Orsino,* north of Iceland, to keep contact with British trawlers in that area and to provide them with weather forecasts and warnings. Mr D. P. Smith served as meteorologist aboard the *Orsino* for over 4 months during the 1968–69 winter and did the first tour of duty in 1969–70.

His zeal and devotion to duty contributed largely to the success of the operations, and his pioneering activity played a notable part in the development of satisfactory procedures under working conditions that were often very difficult. The activities of the *Orsino* undoubtedly increased the safety of British trawlers off Iceland and the weather advice provided by Mr Smith played a significant part in making the operations successful.'

The second Memorial Award has been awarded to Mr D. N. Axford, Principal Scientific Officer, Meteorological Office, with the following citation :

'Mr D. N. Axford has made important contributions to the understanding of small-scale air motions in the free atmosphere. Under his direction the complex measuring capabilities of the Canberra aircraft of the Meteorological Research Flight have been developed into a system of remarkable precision for determining the motion of the air in three dimensions. The observations which have thus been obtained with an accuracy not previously achieved have given new insight into the air motions which contribute to the elusive but important phenomena of clear-air turbulence.'

551·5:92

OBITUARY

Professor Richard Scherhag

Professor Richard Scherhag died on the last day of August 1970 after only a short illness. He was then almost 63 years of age and had been as active as ever in his remarkably energetic and productive work as a Professor in the Free University of Berlin and Director of the Institute for Meteorology and Geophysics, an appointment which he had taken up in 1951. His work in

PLATE III—AWARD WINNERS WITH MAJOR AND MRS K. G. GROVES AND AIR MARSHAL SIR DENIS SMALLWOOD

Left to right: Squadron Leader A. P. Fletcher, Squadron Leader D. J. Phillips, Mr D. N. Axford, Major and Mrs K. G. Groves and Air Marshal Sir Denis Smallwood (see page 59).

PLATE IV—MAJOR K. G. GROVES WITH MR R. A. S. RATCLIFFE (CENTRE) AND MR R. MURRAY (LEFT) JOINT WINNERS OF THE MEMORIAL PRIZE FOR METEOROLOGY

(See page 59.)

PLATE V—MAJOR K. G. GROVES WITH MR D. N. AXFORD, WINNER OF THE SECOND MEMORIAL AWARD

(See page 59.)

Berlin was quite outstanding and indeed unique, for his institute was responsible not only for a heavy programme of teaching and research as a university department but also for a weather service for Berlin, complete with synoptic weather communications, chart construction analysis and a public forecasting service. He had of course his own observation station, very well equipped, including a radiosonde station which was perhaps the first in the world to become completely computerized. His satellite cloud mosaics produced most efficiently from the output of U.S. satellites were also a unique and impressive technical accomplishment. They were circulated to subscribers to his 'daily meteorological bulletin' and 'upper air charts', a set of publications, known and valued throughout the world, which covered the whole northern hemisphere and which was extended in recent years to 30 mb and 10 mb. That so much could be accomplished by an institution working with the handicaps peculiar to the Berlin of our day continued to astonish all who were aware of his position. That in his last years he should not have escaped some of the extra pressures brought about by widespread student unrest was indeed an injustice for one who had given so much. His regard for his students was one of his endearing qualities and over some years he would use weeks of his vacation in visiting other countries (Britain amongst them) with a group of students.

Professor Scherhag was of course ideally qualified for the combination of academic work and public service which occupied the last half of his professional life for previously he had, in peace and war, much varied experience starting in 1933 at the famous Deutsche Seewarte in Hamburg. Already before the 1939 war he had attracted international notice by many papers in the German literature but it was when exchange of scientific work became established again after the war that Scherhag's name became known everywhere. First perhaps he will be thought of as a synoptic-dynamical meteorologist, and anyone who had the privilege of seeing Scherhag in action with the analysis of current synoptic charts has witnessed that scientific art at its best. But his published work must be his permanent monument and it is a notable edifice, with some 150 entries in the library of the Meteorological Office. His textbook 'New methods of weather analysis and forecasting' published first in German in 1948 but later also in English translation was, apart from his daily weather charts, perhaps his greatest single achievement. His approach was fully three-dimensional from the beginning and his 'divergence theory' of synoptic development, already foreshadowed in the thirties drew much attention. His early upper air interests as a synoptic meteorologist and dynamical climatologist extended naturally into the higher levels of the stratosphere reached by sounding balloons (work in which his own station became extremely successful) and in 1952 he was the first to draw attention to what he called the explosive warming of the stratosphere in 1951–52. This discovery set in train a whole branch of stratospheric research familiarized everywhere by the name 'stratospheric sudden warming'.

The decision recently announced by the Executive Committee of the World Meteorological Organization to make the award of the Fifteenth International Meteorological Organization Prize to Professor Scherhag posthumously will be universally applauded as according to a leading scientist the kind of recognition which, as a world meteorologist in every sense, he would so much have valued.

R. C. SUTCLIFFE

REVIEWS

Boundary-layer meteorology. Volume 1, No. 1, March 1970, edited by R. E. Munn. 240 mm × 160 mm, pp. 111, *illus.,* D. Reidel Publishing Company, P.O. Box 17, Dordrecht - Holland, 1970. Price: Dfl. 140 per volume of 4 issues (reduced rate for private subscription.)

One result of the increasing, and seemingly inevitable, specialization within science is the introduction of journals which no longer attempt to cater for one of the major branches but for only one part of that branch. 'Boundary-layer meteorology' is one of the first in the meteorological sphere to devote itself in this way. Furthermore it aims to provide an opportunity for dialogue between two disciplines by inviting papers not only on the physical aspects of the boundary layer — the strictly meteorological problems — but also on the biological processes which interrelate with them. Examples of these are concerned with the transfers of heat, water and carbon dioxide from plants and animals on a time-scale which enables the interaction with the physical atmosphere to be explored and documented.

Whether this desirable bringing together of the two disciplines will work remains to be seen. The first number carries papers entirely devoted to the physical side, and it must be the target of the impressive editorial board to encourage writers on the biological side to come forward to achieve the right balance. If it succeeds in this, and at the same time can maintain a high standard in the quality of the papers it accepts, then it will perform a very useful function.

The journal is very pleasingly printed and produced.

F. B. SMITH

The chemical physics of ice, by N. H. Fletcher. 220 mm × 140 mm, pp. x + 271, *illus.,* Cambridge University Press, Bentley House, 200 Euston Rd, London NW1, 1970. Price: £4.

Readers of Professor Fletcher's book on *The physics of rainclouds* will be pleased to find in this new book the characteristically lucid style and clear exposition with which they are already familiar.

Although it is clear that this book is sufficiently comprehensive to become a standard reference for all who are concerned with the physics of ice, it is not — and, indeed, is not intended to be — an encyclopedic collection of the data on ice. Rather, it is, as the author says in his preface, a book about chemical physics as well as ice. It was written with two classes of readers in mind. Firstly, there are advanced students who may benefit from applying their knowledge of general physical and chemical principles to a detailed study of one material — ice. Secondly, there are readers — like some meteorologists and cloud physicists — who already have a special interest in certain aspects of the subject, but who would like to have an up-to-date survey of the whole field.

Accordingly, Professor Fletcher begins with a detailed description of the individual water molecule. Using this picture as a basis, he then goes on to consider the structures of various forms of ice and the transition between the liquid and the solid state. In the final chapters, he uses this knowledge, together with the information which we now have about structural defects in ice, to discuss the thermal, mechanical and electrical properties of ice. The text is supported throughout by numerous references to published scientific papers so that the reader can pursue his studies further if he so wishes.

If there is a weakness in this book, it is perhaps in the question of the readership for whom it is designed. Firstly, it seems unlikely that many students who do not have a definite research interest in some aspect of ice will want to spend as much time on a single substance as this book implies. On the other hand, I suspect that many research workers will be disappointed to find the treatment of their own particular interest rather uncritical and will wonder whether other parts of the book suffer in the same way. However, this is probably an inevitable characteristic of a book of this size and scope.

In conclusion, the reviewer has no hesitation in recommending this book wholeheartedly to all who are seriously interested in the chemical physics of ice.

J. T. BARTLETT

551.578.466

NOTES AND NEWS

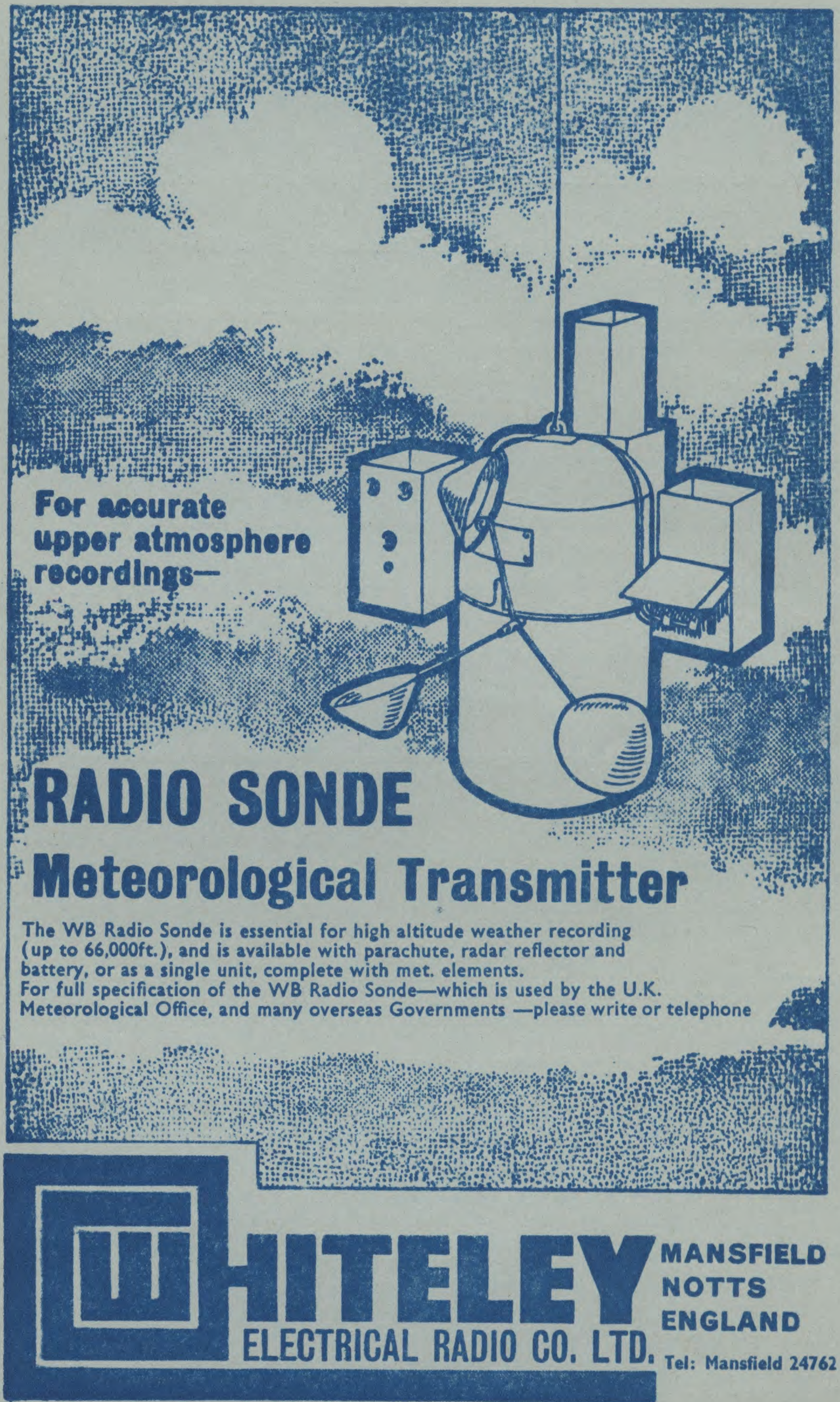
The following note appeared in *Symon's Rainfall Circular* for March 1865. This monthly circular was superseded in January 1866 by *Symons's Meteorological Magazine*, the forerunner of the present *Meteorological Magazine*. Reports of snow rollers have been given in the issues for June 1968 (p. 192), November 1968 (p. 350) and December 1969 (p. 387).

SNOW ROLLERS

In last month's circular a description of these singular formations was promised and in fulfilment thereof, the following statement has been drawn up from several communications forwarded by the observer (Rev. C. Clouston), who first drew attention to them in 1847, by a note in the *Philosophical Magazine*. They have hitherto only been observed in the vicinity of Sandwick Manse, and even there only on four occasions, viz. — Feb. 11, 1847, March 5, 1862, Feb. 18, and (a few) March 26, 1865, — a combination of the following conditions being necessary: (1) a recent fall of loose snow-flakes in calm weather; (2) temperature near 32° to give adhesion to the snow without thawing it; (3) a good brisk wind rising after the fall. Under these conditions, the snow ripples up, as it were, and the ripples breaking into sections, the wind rolls each in its own path, until, just like a schoolboy's snow-ball, they rapidly increase in size, and have been found 3½ feet long, and 7 feet in circumference; while others are not as many inches. "On examination, they are all found to be cylindrical, like hollow-fluted rollers, or ladies' swandown muffs, of which the smaller ones much remind me, from their lightness and purity. The centre is not quite hollow, but in all there is a deep conical cavity at each end, and in many there is a small opening through which one can see." Their density seems to be about one-ninth that of water, as one 3 feet long, and 6½ feet in circumference weighed 64lbs. Their number is variable; in 1847, 133 were counted in one acre, and nearly 400 acres were covered with them. It may be well to add that the manse stands near the top of a very gentle slope, rising from the sea, whence it is distant about two miles; the coast which is generally fringed with cliffs of considerable height, drops to, and even below the level of the sea, west of the manse, and allows the sea to form an arm, running nearly up to the manse grounds. There is no high ground in the neighbourhood, but gentle undulations in all directions. I cannot help thinking that the briny breeze which thwarts all attempts at growth on the part of trees in the open country, produces these beautiful snow rollers, though the relative influence of the wind and the salt remains to be investigated.

CORRECTION

Meteorological Magazine, December 1970, p. 363, 8th line, U.D.C. to read : 551.509.324.2:551.577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THE METEOROLOGICAL MAGAZINE

Vol. 100, No. 1184, March 1971

RETIREMENT OF DR R. FRITH, O.B.E.

Dr R. Frith retired from the Meteorological Office on 31 December 1970 after more than 34 years' service. Joining the Office in 1936, Dr Frith was for ten years engaged either in forecasting duties or in the organization of forecasting services to the Royal Air Force.

In 1946 Dr Frith was appointed as Senior Meteorological Officer of the Meteorological Research Flight and under his direction the flight carried out a number of important investigations. The dryness of the stratosphere was established and the small-scale variability of the temperature and humidity throughout the troposphere extensively studied. Under Dr Frith's guidance the Meteorological Research Flight also demonstrated that clearly observed effects could be produced by seeding stratocumulus cloud.

Dr Frith was appointed an Officer of the Order of the British Empire in the 1951 Birthday Honours List. In the same year he took charge of the instrument development branch and later occupied various other directing posts on the research side of the Office. In 1960 he was appointed Assistant Director in charge of the newly formed branch for High Atmosphere Research. Under his direction a small but very active team established themselves rapidly as one of the effective groups undertaking experiments from outer space. Successful experiments to measure ozone and molecular oxygen were flown on the British satellites ARIEL 2 and ARIEL 3. Several complementary experiments were also conducted on large rockets fired from Woomera, Kiruna and other ranges. A Meteorological Office programme for exploring the mesosphere and upper stratosphere was also developed using the specially developed SKUA rocket and Dr Frith and his team demonstrated the remarkable variability of the high atmosphere over the British Isles in winter.

In 1968 Dr Frith was promoted to the post of Deputy Director (Physical Research) and assumed responsibility for the experimental and observational research of the Office, applying to this task his remarkable ability to pick out the essential aims of an experiment and to ensure that the true objectives are achieved.

Dr Frith has been an active member of a number of national and international committees concerned with physical meteorology. In particular he has been a much valued member of Working Group VI of COSPAR (Committee for Space Research) which has been largely responsible for demonstrating how the requirement for world-wide observations for a Global Atmospheric Research Programme (GARP) can be formulated in a manner which is practicable by satellite techniques.

Dr Frith's colleagues in the Meteorological Office wish him health and happiness in his retirement.

J. S. SAWYER

551·515·53:551·577·31

DIURNAL INCIDENCE OF RAIN AND THUNDER AT ASMARA AND ADDIS ABABA, ETHIOPIA

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

Summary. Diurnal variations of rainfall and thunder have been tabulated for Asmara and Addis Ababa on a monthly basis for the five-year period 1958–62. In the absence of autographic data, conventional data on the occurrences of rain and thunder were used for the eight three-hourly periods of each day. Contemporaneous afternoon peaks in incidence of rain and thunder at both places indicate the dominance of day-time convection on the development of precipitation. Persistence of essentially non-thundery rains after midnight at Addis Ababa suggests the presence of a diurnally varying mechanism of mass ascent over the Ethiopian plateau. A broad-scale anabatic circulation with a period comparable to one day is a possible mechanism, evidence for which has already been suggested by the diurnal rainfall régime over the Nile valley in neighbouring Sudan.

Introduction. In a previous paper,[1] concerned with the diurnal incidence of monsoon rainfall over the Sudan, evidence was given to indicate that a large-scale circulation, set up each day over the Ethiopian plateau, was able to inhibit afternoon convection over the Nile plains of the Sudan. If such a circulation exists there should be a corresponding promotion of rainfall over the plateau. Some evidence is presented in this note, based on an examination of the diurnal incidence of rain and thunder over the plateau, which supports the existence of a broad-scale circulation of an anabatic type.

Whereas the Sudan study was based on records from autographic gauges, such records are not available from Ethiopia over a period sufficiently long for analysis. As an alternative, station registers of observations were consulted, and occasions of rain were noted in each of eight three-hourly periods daily during the five years 1958–62. For convenience, the eight periods have been named as in the previous paper. For example, using local times, 12–15 h has been called 'early afternoon', and 15–18 h 'late afternoon'. Rain is considered to have fallen during the early afternoon, for example, if it was recorded either at 15 h or at some time during the previous three hours, but not at 12 h. During the years 1958–62 only two stations in Ethiopia kept a continuous 24-hour watch — the international airports at Asmara (15° 17′N 38° 55′E, altitude 2325 m) and Addis Ababa (09° 00′N 38° 44′E, altitude 2324 m). See Figure 1 for their locations. Whereas during the day-time observations were hourly, at night-time they were three-hourly, so it is possible that some light night-time falls were missed. Occasions of thunder were noted similarly.

Table I lists, for each three-hour period, the number of periods during which rain fell; similarly, periods with thunder are listed in Table II.

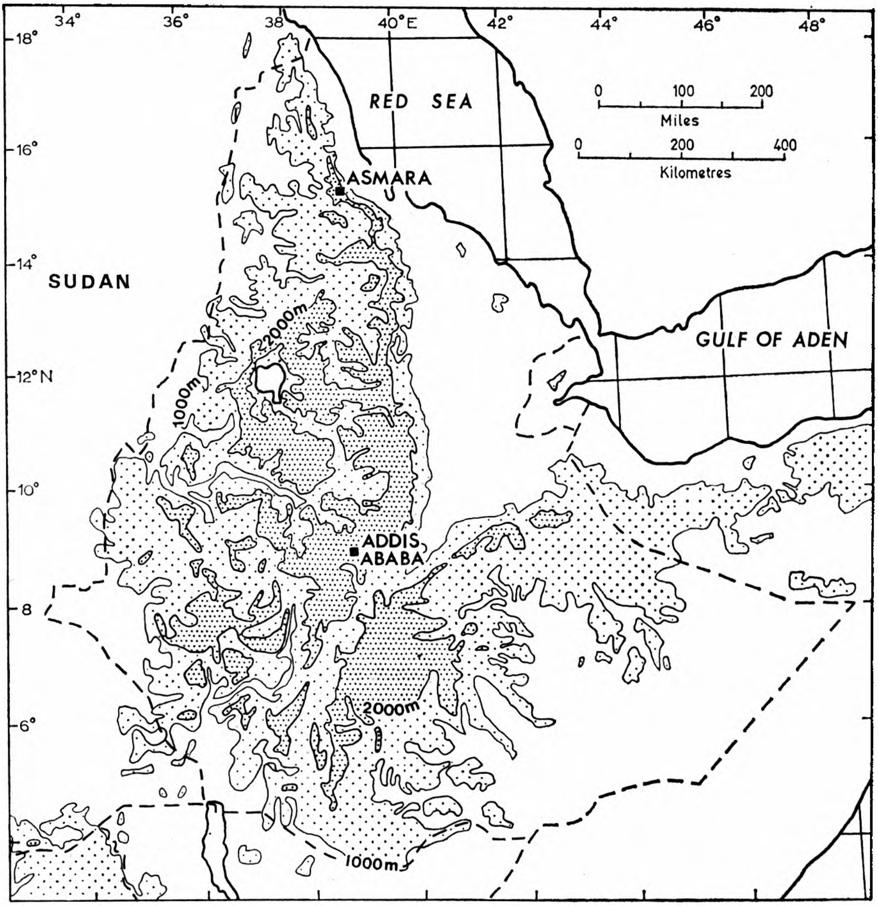

FIGURE 1—MAP SHOWING LOCATION OF ASMARA AND ADDIS ABABA ON THE PLATEAU OF ETHIOPIA

Rain at Asmara. In most years there are two rainy seasons at Asmara[2] — the 'little rains', approximately March to mid-May, and the 'long rains', approximately mid-June to mid-September. The period mid-September to February is essentially rainless, but in some years significant rains fall in late October and November. Between the two rainy seasons there is usually a short dry spell, but its timing varies from year to year. For convenience, the year has been divided into : March–May, 'little rains'; June–September, 'long rains'; October–November, 'late rains'; and December–February, 'dry season'.

Table I shows that the little rains have a sharp frequency maximum in the early and late afternoon; falls can be expected on average about 2–4 days per month during each of these two three-hourly periods. Falls decrease rapidly in frequency during the evening, and very seldom occur during the night or morning. In March, falls are almost entirely confined to the afternoon.

TABLE I—NUMBER OF OCCASIONS WHEN RAIN FELL IN EACH OF THE EIGHT THREE-HOURLY PERIODS DURING THE YEARS 1958–62 AT ASMARA AND ADDIS ABABA

Local time	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
						(a) ASMARA						
00–03	0	1	1	4	4	0	12	9	2	0	5	0
03–06	0	1	0	0	2	0	9	8	3	0	0	0
06–09	1	2	0	1	2	0	12	22	3	0	0	0
09–12	2	1	0	1	6	3	13	23	4	1	0	0
12–15	2	5	12	21	15	18	65	54	16	6	18	2
15–18	4	7	12	22	19	15	84	58	15	9	22	7
18–21	3	3	1	12	9	6	32	23	2	1	5	1
21–00	2	3	1	9	4	2	15	10	1	0	4	1
						(b) ADDIS ABABA						
00–03	8	5	14	7	5	11	33	36	21	2	5	2
03–06	4	5	12	12	5	10	38	46	32	6	6	0
06–09	3	3	13	3	2	5	49	56	33	4	7	4
09–12	4	3	5	6	4	5	42	39	25	7	6	3
12–15	2	7	19	25	25	60	49	62	75	21	3	1
15–18	5	6	27	24	31	57	67	76	49	11	9	2
18–21	7	5	18	19	15	23	33	36	25	5	6	3
21–00	9	5	17	15	9	13	23	32	12	3	7	4

During the long rains, falls are more frequent and not so strongly peaked about the afternoon, but there is still a maximum at that time of day, with 8–10 days per month during the early afternoon and also the late afternoon periods. Falls are least frequent in the early hours (about one per month).

Diurnal incidence of the late rains is very similar to that of the little rains, with falls largely confined to the afternoon — 2–4 days per month.

From December to February, falls are few and occur mostly in the late afternoon, but even at that time of day they are observed only about once per month.

Thunder at Asmara. Table II shows that during the little rains thunder is almost entirely confined to the afternoon (4–5 occasions per month in both

TABLE II—NUMBER OF OCCASIONS WHEN THUNDER WAS HEARD IN EACH OF THE EIGHT THREE-HOURLY PERIODS DURING THE YEARS 1958–62 AT ASMARA AND ADDIS ABABA

Local time	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
						(a) ASMARA						
00–03	0	0	0	2	2	0	1	4	2	0	2	0
03–06	0	0	0	0	2	0	0	1	1	0	0	0
06–09	0	0	0	0	2	0	0	2	0	0	0	0
09–12	0	0	0	1	3	4	16	11	4	0	1	0
12–15	1	6	7	25	23	19	81	73	22	9	18	2
15–18	2	8	9	25	27	20	75	68	25	10	24	3
18–21	1	6	1	13	9	4	21	24	3	4	6	1
21–00	0	1	0	7	1	1	3	7	1	2	4	0
						(b) ADDIS ABABA						
00–03	5	0	4	1	1	1	4	14	5	0	0	0
03–06	0	0	2	0	0	1	0	2	6	0	0	0
06–09	0	0	0	0	0	0	1	2	0	0	0	0
09–12	0	0	0	0	0	1	2	4	3	2	0	0
12–15	0	0	4	8	14	46	23	39	43	7	0	0
15–18	0	3	15	15	9	40	39	45	40	9	1	0
18–21	4	1	15	11	7	10	11	15	16	3	1	1
21–00	2	2	10	6	3	2	6	12	6	0	0	0

April and May), but there are also one or two occasions per month with thunder in the early evening. As the season progresses, the chance of thunder in the late morning increases, but is still less than once per month in May. During the long rains, thunder is heard more widely during the day, but there is still a sharp maximum in the afternoon (about 15 days per month during the early afternoon and also during the late afternoon). In this season, thunderstorms develop earlier than during the little rains (there are 2–3 days per month with thunder during the late morning), and they are also heard in the early evening (3–4 days per month). During the late rains, diurnal incidence of thunder is much the same as during the little rains.

Rain at Addis Ababa. There is really only one rainy season, March to October. From November to February, falls are few and they are distributed fairly evenly through the day — about once per month in each of the eight three-hour periods. In March, the incidence of rainfall shows a maximum in the late afternoon (about 5 days) but there are also 2–3 days per month with falls in most of the other periods. In April and May, the diurnal variation becomes more pronounced although there is little increase in frequency. A maximum occurs in the afternoon (about 5 days per month in the early afternoon and also in the late afternoon), and a minimum in the early morning (less than once per month).

At the height of the rainy season, in July and August, the diurnal incidence is less-strongly peaked. There is a maximum in late afternoon (15 days per month) and a minimum in the late evening, whilst a noticeable secondary maximum in frequency of falls occurs in the early morning (10 days per month). By September, the diurnal variations become stronger again, with a maximum in the early afternoon (15 days per month) and a minimum in the late evening (2 days), whilst a secondary maximum still occurs around dawn (6 days per month, in the early hours and also in the early morning). October resembles May, with a maximum in the early afternoon (4 days per month), and a minimum around midnight.

Thunder at Addis Ababa. From March to May, thunder is heard progressively earlier in the day. During March there is a distinct frequency maximum near dusk (3 days per month during late afternoon and also during early evening), but by May it has moved to early afternoon. June shows a big increase in frequency of thunder, which is heard most often in mid-afternoon (8–10 days per month during the early afternoon and also during late afternoon). There is little thunder at night in June and it is almost unknown in the morning.

From July to September, thunder occurs at almost any time of day, but in each month there is a strong frequency maximum around mid-afternoon (8–10 days per month in the early afternoon and also in the late afternoon), whilst it is almost unknown around dawn. October resembles the early part of the rainy season, with a maximum in the late afternoon (2 days per month). From November to February, thunder is almost unknown.

Discussion. The afternoon maximum of rainfall frequency in all rainy months, at both Asmara and Addis Ababa, can clearly be identified with convection released by day-time insolation; contemporaneous peaks in both rainfall and thunder incidence support this conclusion. At the beginning and end of the rainy season at Addis Ababa, thunder frequency rapidly decreases during the night, as might be expected with progressive decay of convective storms starting in the afternoon, but rains are more persistent. Such rains are either the remnants of previous days' storms, or they are the result of another mechanism that produces widespread stratiform clouds at night. Although some of the rains occurring up to midnight are likely to be the residues of earlier convective storms (the ratio of frequencies of rain and thunder does not change much until after midnight), some of the rains during the early hours and the morning (not thundery, and falling from stratiform clouds) are more likely to be the result of widespread uplift. Synoptic disturbances seem unlikely to account for these rains for such disturbances are not expected to have any significant diurnal variation in incidence. The tendency for rains to decrease in frequency from midnight to midday suggests a lifting mechanism with a diurnal variation in intensity, weakening from midnight to midday. Such a mechanism is a broad-scale anabatic flow towards the Ethiopian plateau that is to be expected as a result of day-time insolation. Because of the breadth of the plateau, this circulation would have a life-cycle comparable to one day, and it might well reach a maximum intensity after dusk. Accompanying subsidence over neighbouring plains would be expected to inhibit afternoon and evening convection there. Some evidence for this inhibition over the Sudan has been already presented.[1]

Night-time thunderstorms at Addis Ababa during the height of the rainy season could be attributed to the release, by widespread anabatic ascent, of potential instability known to be present. However, this mechanism cannot account for the early-morning secondary maximum in rainfall incidence. This occurs at a time of minimum thunder frequency and is associated with stratiform clouds. Similar secondary maxima are observed widely during the monsoon rains over West Africa,[3] the Sudan[1] and East Africa,[4] and do not appear to be linked to topography. They are probably associated with the thermal tide which produces a maximum in lower tropospheric convergence around 07 h.[5]

A broad-scale anabatic circulation which, it is suggested here, affects the incidence of rain and thunder at Addis Ababa, would be expected to be less effective at Asmara, where the plateau is much narrower and the circulation consequently shorter lived. The persistence of rain and thunder into the night should be much less pronounced and, in fact, as the tables show, Asmara has a characteristically sharp afternoon maximum of both rain and thunder in all rainy months. Only during the long rains is thunder relatively frequent in the early evening; it is during this season that individual convective storms are largest and most persistent.

There is little evidence for the tidal effect at Asmara. In this respect, the diurnal incidence of rain is similar to that at the beginning and end of the rains at Addis Ababa. The relatively few occurrences of rain and thunder from midnight to early morning at Asmara are probably associated with unusual synoptic disturbances, but during the long rains, drizzle from low, stratiform clouds forming in the moist monsoon (deflected to a north-westerly over the plateau) accounts for most of the falls in the early morning.

During the dry season, the infrequent rains at Addis Ababa, falling at any time of day, probably mostly come from stratiform clouds accompanying synoptic disturbances, but even at this time of year some of the falls from late afternoon to late evening are convective, as indicated by a few occurrences of thunder. The rarity of night and morning falls at Asmara in this season suggests that synoptic disturbances do not strongly influence the occurrence of rainfall.

Conclusions. Apart from the obvious effects of insolation on the diurnal incidence of rain and thunder, there is some evidence to support the hypothesis that a broad-scale anabatic circulation develops between the Nile plains and the Ethiopian highlands. Such a circulation would account for the observed enhancement over the highlands of afternoon convective rains and of night-time rains from stratiform clouds. Evidence for a corresponding inhibition of rains over the neighbouring plains of the Sudan has already been presented. Once again, an interaction of local and broad-scale convective systems has been suggested; the role of synoptic disturbances remains to be explored.

Acknowledgements. Sincere thanks are due to the Director and Staff of the Meteorological Service of the Imperial Ethiopian Government for kindly making available original records used in this study. Mr R. G. Wilson assisted in the extraction and tabulation of the records, and the results are published with the permission of the Director, Anti-Locust Research Centre.

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TWO DECOMPOSITION THEOREMS FOR THE MEAN VECTOR VELOCITY OF AN AREA IN A TWO-DIMENSIONAL FLOW FIELD

By R. DIXON

Summary. Two integral equations are derived which may be viewed as decomposition theorems for the mean vector velocity within a plane fluid area. One of the theorems sheds some light on the difference between wind fields as used in primitive equation models and those used in vorticity models.

It is a familiar fact that the vorticity (ζ) and the divergence (Div $\mathbf{V}$) may be expressed in terms of the spatial derivatives of the velocity vector $\mathbf{V}$ having components (u, v) as

$$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}, \quad \text{Div}\,\mathbf{V} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}. \qquad \ldots (1)$$

Less familiar to meteorologists are relationships which relate vorticity and divergence to the undifferentiated velocity field. Two such relationships

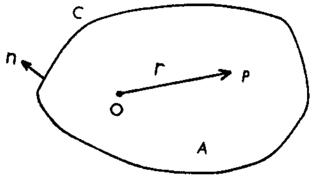

FIGURE 1—DIAGRAM OF CURVE C AND AREA A

may be derived by considering a plane area of fluid, A, bounded by a closed curve C, Figure 1. Let any point P in the area A be defined by a position vector $\mathbf{r}$ with respect to some origin O. If use is made of some well-known vector formulae, Weatherburn,[1] the following may be obtained

$$\nabla(\mathbf{V}\cdot\mathbf{r}) = \mathbf{V} + \mathbf{r}\cdot\nabla\mathbf{V} + \mathbf{r}\times\zeta\mathbf{k}, \qquad \ldots(2)$$

$$\nabla\cdot(\mathbf{r}\,\mathbf{V}) = 2\mathbf{V} + \mathbf{r}\cdot\nabla\mathbf{V}, \qquad \ldots(3)$$

$$\nabla\times(\mathbf{r}\times\mathbf{V}) = -\mathbf{V} - \mathbf{r}\cdot\nabla\mathbf{V} + \mathbf{r}\,\mathrm{Div}\,\mathbf{V}. \qquad \ldots(4)$$

From (2) and (3) it follows that

$$\mathbf{V} = \nabla\cdot(\mathbf{r}\,\mathbf{V}) - \nabla(\mathbf{V}\cdot\mathbf{r}) + \mathbf{r}\times\zeta\mathbf{k}, \qquad \ldots(5)$$

where $\mathbf{k}$ is the unit vertical vector and now, by integrating (5) over the area A and using Gauss's Theorem relating to the integral round curve C, there follows

$$\int_A \mathbf{V}\,dA = \oint_c (\mathbf{n}\cdot\mathbf{r})\,\mathbf{V}\,dc - \oint_c \mathbf{n}\,(\mathbf{V}\cdot\mathbf{r})\,dc + \int_A \mathbf{r}\times\zeta\mathbf{k}\,dA, \qquad \ldots(6)$$

where $\mathbf{n}$ is the outward unit normal vector to the curve C.

By dividing through by A and by combining the first two terms on the right-hand side the following may be obtained

$$\mathbf{V}_m = \frac{1}{A}\left\{\int_A \mathbf{r}\times\zeta\mathbf{k}\,dA + \oint_c (\mathbf{n}\times\mathbf{V})\times\mathbf{r}\,dc\right\}, \qquad \ldots(7)$$

where $\mathbf{V}_m$ is the mean velocity over the area.

If, instead, the same sequence of manipulations is carried out on equations (3) and (4) there results

$$\mathbf{V}_m = \frac{1}{A}\left\{\oint_c (\mathbf{n}\cdot\mathbf{V})\,\mathbf{r}\,dc - \int_A \mathbf{r}\,\mathrm{Div}\,\mathbf{V}\,dA\right\}. \qquad \ldots(8)$$

The point of selecting (2) and (3), and (3) and (4) for these manipulations is to eliminate the term $\mathbf{r}\cdot\nabla\mathbf{V}$, which contains the spatial derivatives of $\mathbf{V}$, thereby obtaining expressions for Div $\mathbf{V}$ and ζ which do not involve these derivatives. However, in the event, the resulting expressions are more readily interpreted as decomposition theorems for the mean vector velocity over an area.

Equation (7) may be written as

$$\mathbf{V}_m = (\mathbf{r} \times \zeta\,\mathbf{k})_m + \frac{1}{A}\oint_C (\mathbf{n} \times \mathbf{V}) \times \mathbf{r}\, dc, \qquad \ldots (9)$$

showing that the mean velocity vector is made up of a component due to the mean moment over the area of the vertical vorticity vector $\zeta\,\mathbf{k}$ about the origin, plus a component due to the moment of the tangential component of the velocity on the bounding curve (note that the effect of the operation $\mathbf{n} \times$ in the second term of (9) is to eliminate the normal component of $\mathbf{V}$ and to rotate the tangential component into the vertical).

Equation (8) may be written as

$$\mathbf{V}_m = \frac{1}{A}\oint_C (\mathbf{n} \cdot \mathbf{V})\, \mathbf{r}\, dc - (\mathbf{r}\ \mathrm{Div}\ \mathbf{V})_m, \qquad \ldots (10)$$

and this shows $\mathbf{V}_m$ composed of an areal mean involving Div $\mathbf{V}$, together with a boundary contribution depending on the component of $\mathbf{V}$ normal to the boundary.

By combining (9) and (10), or else by starting the manipulations with (2) and (4), an expression for $\mathbf{V}_m$ involving both Div $\mathbf{V}$ and ζ may be obtained. It is also possible to find an expression corresponding to (7) and (8) which expresses $\mathbf{V}_m$ in terms of the deformation field.

Equations (9) and (10) shed considerable light on the relationship which must exist between conditions on a boundary and the flow in the interior of an area. For example in the numerical forecasting suite of programmes, as currently used in the Meteorological Office, the wind field for the vorticity model is obtained by ellipticizing and solving the balance equation in the form

$$f\zeta + 2J(u, v) - \mathbf{k} \cdot \mathbf{V} \times \nabla f - g\nabla^2 h = 0, \qquad \ldots (11)$$

subject to the condition

$$\mathbf{V} = \mathbf{k} \times \nabla\psi, \qquad \ldots (12)$$

which implies that

$$\mathrm{Div}\ \mathbf{V} = 0. \qquad \ldots (13)$$

It follows directly from (12) that in this case the mean velocity vector is determined by the boundary conditions, and this is confirmed by (10) in view of (13). However, in determining the wind field for the unfiltered primitive equation model the more general form of the balance equation may be used

$$f\zeta - (\mathrm{Div}\ \mathbf{V})^2 + 2J(u, v) - \mathbf{k} \cdot \mathbf{V} \times \nabla f - g\nabla^2 h = 0. \qquad \ldots (14)$$

and the theorem (10) applies in full. Thus (10) pin-points an essential physical difference between the wind fields used in a vorticity model and those used in a primitive equation model.

Truesdell[2] states that the formula (9) was first established by J. J. Thompson for the case of the three-dimensional flow of an incompressible fluid. Truesdell also shows that (9) may be obtained as a special case of a very general form of Gauss's Theorem. A slight slip in his algebra leads Truesdell to say that (9) is only true if Div $\mathbf{V} = 0$, but this is not so, as the above derivation shows. Westberg[3] obtained (9) for the special case of irrotational motion. The author has not been able to trace (10) in the literature.

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THE CYPRUS WATERSPOUTS AND TORNADOES OF 22 DECEMBER 1969

By R. N. HARDY

Summary. The transformation of a waterspout on crossing the coastline into a highly destructive tornado appears to be an extremely rare phenomenon. A case which occurred in Cyprus is discussed.

Introduction. On the afternoon of 22 December 1969 the southern coastal region of Cyprus was the scene of very active convection and waterspouts. On the eastward passage of a trough line a series of six intense waterspouts hit the shore line and several continued inland as tornadoes. Of these, one continued as a tornado across the centre of the Akrotiri peninsula, creating considerable damage (e.g. to married quarters) before it faded out. Another crossed the tip of the peninsula, traversed the bay, and then, as a tornado some 200 yards* in width, it cut through the west and north of Limassol and continued inland up into the hills. The loss of life (one at Akrotiri, three in Limassol) was remarkably low considering the havoc. Past records are very scanty in Cyprus but this family of tornadoes is the most destructive known to the author. The fact that they originated as waterspouts makes this occurrence of great interest.

Description of the waterspouts and tornadoes. The map at Figure 1 shows the town of Limassol on the south coast of Cyprus together with Akrotiri lying on a low peninsula to the south-south-west and Episkopi to the west. Limassol is the second largest town in Cyprus.

In the early afternoon the weather took on a very threatening appearance and by 15 hours (13 GMT) waterspouts were seen out to sea appearing to be roughly in line and orientated east–west, although this cannot be verified. The number visible at any time varied between two and seven and whilst some appeared to persist others decayed and new ones formed. Towards

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* Distances and heights are given in traditional British units.
Conversion factors to metric units are : 1 foot = 0·3048 m; 1 mile = 1·6 km; 1 knot ≈ 0·5 m/s.

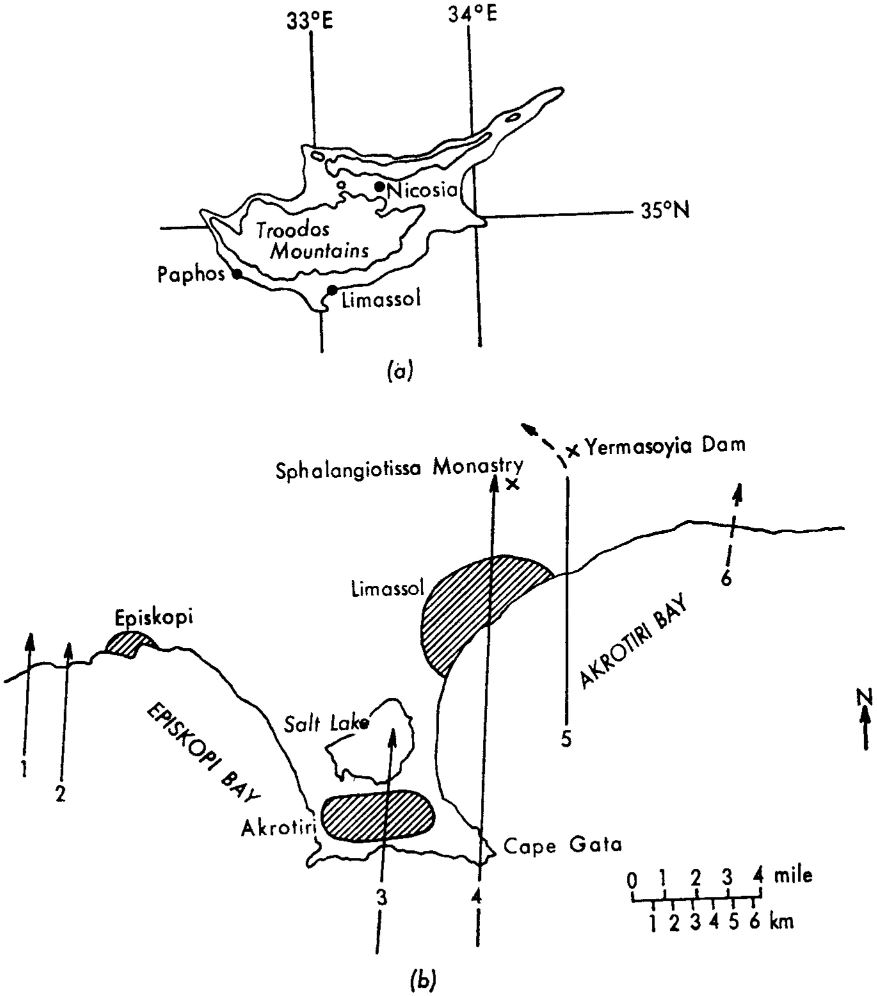


FIGURE 1—WATERSPOUTS AND TORNADOES IN SOUTHERN CYPRUS ON 22 DECEMBER 1969

(a) Map of Cyprus *(b)* Approximate tracks of waterspouts and tornadoes

1530 hours (1330 GMT) most waterspouts were hidden from view by an intense hailstorm accompanied by thunder, which, it transpired, was just one part of an extremely large storm which affected much of southern Cyprus. The hail was most intense in the eastern sector; a report from a motorist (a trained meteorologist) 10 miles south of Nicosia speaks of visibility being reduced to two or three yards in hail, halting all traffic. Paphos in the west had thunder but no hail.

Out of this storm a family of waterspouts emerged each travelling in a direction of approximately 010° and striking the coastline. No. 1 crossed the coastline about one mile west of Episkopi and travelled up a narrow steep-sided valley before dying away at the valley head some 600 yards inland. No. 2 struck the headland some 400 yards nearer to Episkopi but did not penetrate inland. Then a gap occurred of several miles to the extremely active group of Nos. 3, 4 and 5, spaced over about two miles, of which the middle one (No. 4) struck the coastline just west of Cape Gata. This was followed by a further wide gap to No. 6 about eight miles east of Limassol, which was similar to No. 1.

Episkopi. The hail shower was short at the Main Meteorological Office at Episkopi and it was noted that two distinct types of hailstone fell simultaneously. About 80 per cent were spherical with the appearance of frosted glass and of almost uniform size about 8 mm diameter (⅜ inch). The remainder were jagged where it appeared that two and sometimes three of the former type had partially melted and joined together. A few had fractured and showed several onion-like layers. The jagged stones were mostly larger than the rime-ice covered hailstones, the maximum axis measuring up to 15 mm (⅝ inch).

When the hailstorm finished, two waterspouts came into view, clearly visible against the brightening sky to the south though the cloud was still black overhead (Plate I). Both waterspouts were moving at about 25 kt but when the nearer one (No. 2) reached the cliffs the progress of the base appeared to be completely arrested whilst the part near the cloud base continued forward. The result was a stretching and a lateral contraction until it resembled a long black rope, see Plate II. The lower portion weakened quickly, first becoming a transparent sheath in the lowest hundred feet or so, and then wobbled as it quickly contracted and disappeared. Soon afterwards the cloud edge crossed from the south.

Akrotiri. No. 3 and No. 4 struck the Akrotiri peninsula after a short but intense hailstorm. From a cine-film sequence taken at the time it seems that the hailstones were mostly larger than those at Episkopi; observers report that there were mis-shapen ones where two or more had joined together at some stage in their development. No. 3 crossed the coastline about 4 miles west of Cape Gata, surmounting a cliff 100 feet high before continuing forward through a housing estate, some offices, scrubland and a helicopter pad before reaching the salt lake where it decayed. Damage was severe in places, especially to roofs and prefabricated buildings; a helicopter was damaged, whilst the private car shown in Plate III *(a)* had been lifted over the bungalow and deposited in the back garden. No. 4 turned out to be the most powerful. It struck the Akrotiri peninsula about 2 miles to the east of No. 3 in an area of low scrub and rock and proceeded for about a mile across this sort of terrain before, as it emerged into Akrotiri Bay, it destroyed the Sub-Aqua Club building (Plate III *(b)*). It crossed the bay, struck Limassol town and went on inland for some 4 miles with only a very slight deviation from a straight path throughout.

Limassol. Plate IV *(a)* shows waterspout No. 5 before it became a tornado. After a hailstorm, waterspouts No. 4 and No. 5 struck the Limassol coastline. No. 5 crossed the eastern outskirts of Limassol, where the population is relatively sparse, but it added considerably to the confusion by bringing down large trees across the main Nicosia road, effectively cutting off Limassol. This somewhat weaker tornado was channelled about 30 degrees to the left of its original track along a small valley when it encountered the Yermasoyia dam about 3½ miles inland.

The records of weather in Cyprus are extremely scanty before the British occupancy commenced in 1878. The tornado which started as waterspout No. 4 is the most intense in living memory in southern Cyprus and it struck near the centre of Limassol with its crowded streets near the waterfront and more modern spaced-out development inland. It crossed the waterfront just west of the harbour into the Turkish quarter and immediately demolished several houses built of mud bricks and removed the top half of a brick-built minaret, see Plate IV *(b)*. It continued thereafter in an almost straight line slightly east of north leaving a path of damage up to 300 yards wide for a distance of about 4 miles, and finally dissipated when it came up against a steep escarpment where it caused some damage to the Sphalongiotissa Monastery at an altitude of 600 feet.

It is clear that the density of buildings reduced the damage at ground level, for where it crossed open ground the adjacent buildings were more severely affected and cars overturned, see Plate IV *(c)*. Some idea of the destructive power of the rotating air can be gauged from the fact that water-filled tanks of roof-top solar heaters weighing two or three hundred pounds were lifted and carried away; some of the larger debris in Plate V* may consist of these heaters. The noise of the vortex was described as equivalent to several jet aircraft flying low overhead.

Synoptic situation. Any analysis of weather in the eastern Mediterranean is hampered by lack of data, especially when so-called mesoscale phenomena are involved. This difficulty is accentuated by the effects of local topography which often mask air-mass characteristics.

A frontal low deepened markedly over Italy on 19 December and with a stationary high persisting over north-east Europe, a long easterly low-level flow was established from central Russia into the circulation of the depression. This cold low-level flow helped to maintain the area of low pressure, and a mobile warm-sector depression approaching the British Isles from the west was deflected north-eastwards by the weak block over Europe. The resultant veering of the strong high-level flow from the North Sea to Italy soon resulted in a cut-off upper low just west of Greece coincident with the surface-low complex. Figure 2 shows the surface analysis for 12 GMT on 21 December. There was widespread thundery activity from western Turkey to the coast of north-west Libya. The two troughs extending southwards from the centres were based on little evidence but were shown to be real features on subsequent charts. The occlusion was intense and active east of 20°E but west of that the colder air to the north was dry. Central pressure in the low area was rising slowly with warming at all levels. Another feature of the chart that may be significant is that the weak low-level south-easterly from the Persian Gulf had brought moist air to much of Iraq.

A change in the upper flow became evident in the next 12 hours. The 300-mb low centre had moved slowly north-eastwards since it first formed at 12 GMT on 20 December, see Figure 3; but at midnight on 22 December it became apparent that a second centre had formed some 150 miles west

* This is number 21 of a remarkable sequence of photographs taken by Sgt D. L. Pownall of RAF Episkopi. The sequence starts with waterspouts well out to sea, continues with shots of a tornado approaching and ends with pictures of damage to the house opposite.

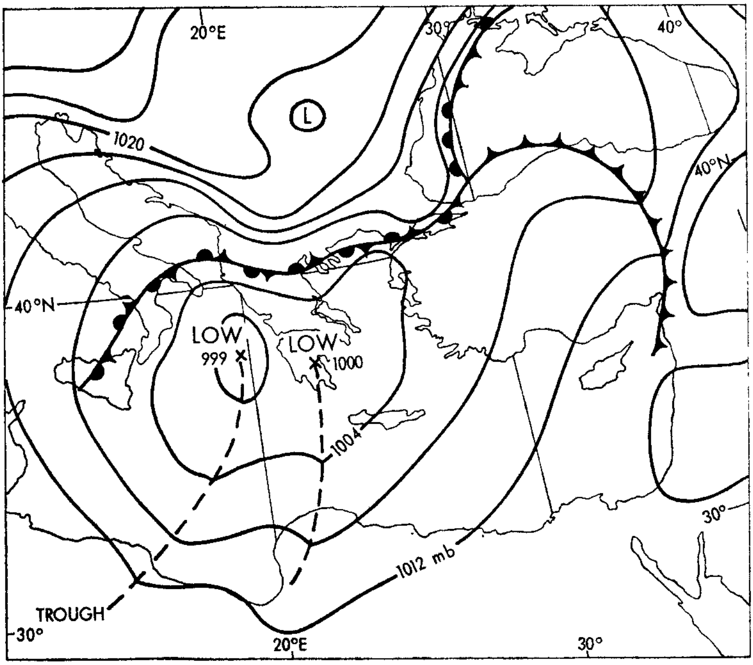


FIGURE 2—SURFACE ANALYSIS, 12 GMT ON 21 DECEMBER 1969

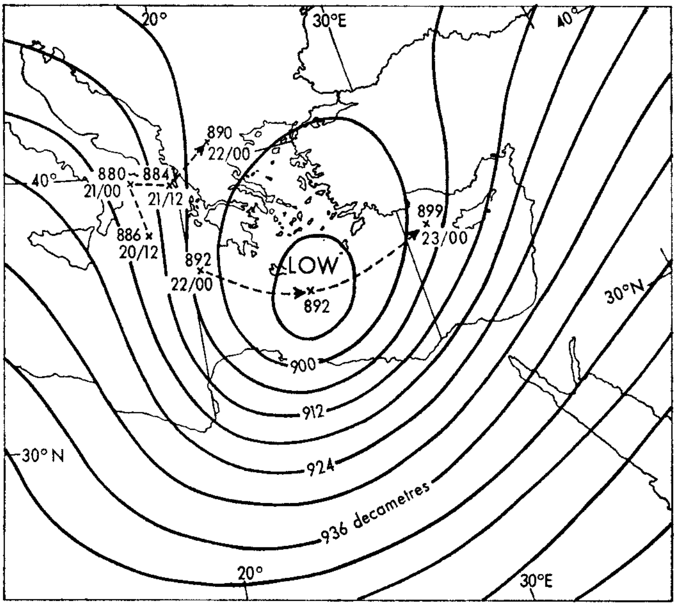


FIGURE 3—CONTOURS AT 300 mb, 12 GMT ON 22 DECEMBER 1969

x – – x Track and pressure of centre, with date/time (GMT) of Crete. This seemed to mark a resumption of mobility at these latitudes and perhaps also the genesis of the severe storm. Subsequently the 300-mb centre moved eastwards at about 20 kt and the surface low also accelerated east towards Cyprus.

From the time-section of upper winds at Episkopi and the hodograph of winds at 12 GMT on 22 December shown in Figure 4, can be seen the gradual

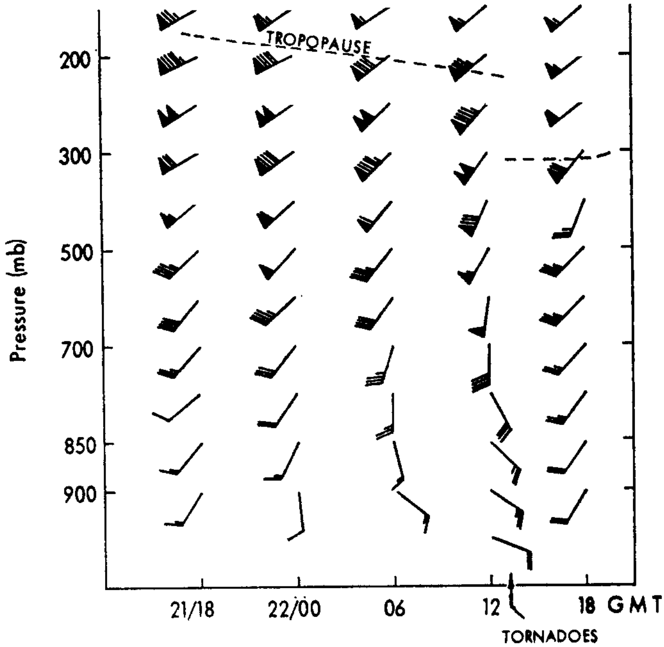


FIGURE 4 *(a)*—SEQUENCE OF UPPER WINDS AT EPISKOPI, 18 GMT ON 21 DECEMBER TO 18 GMT ON 22 DECEMBER 1969

Wind directions and speeds are in the normal international symbols.

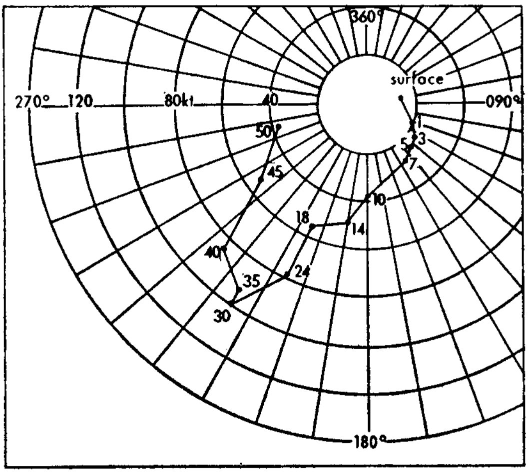


FIGURE 4 *(b)*—EPISKOPI WINDS, 12 GMT ON 22 DECEMBER 1969

Heights in thousands of feet (10 000 ft = 3048 m).

setting up and intensifying of the wind shear and how strong this was near the time of the tornadoes. The radiosonde ascent from Episkopi at 12 GMT on the 22nd is shown in Figure 5 together with the temperatures 12 hours before and 12 hours after. The severe storm that gave birth to the tornadoes is believed to be shown at A in Plate VI *(a)* though its orientation at the time that the satellite ESSA 8 picture was taken, 0727 GMT, does not correspond with the observed clearance from the south. At 0815 GMT, less than one hour later, the NIMBUS photograph (Plate VI *(b)*) showed the same feature but now with a more dense section having developed. The analysis for 12 GMT on the 22nd is shown in Figure 6.

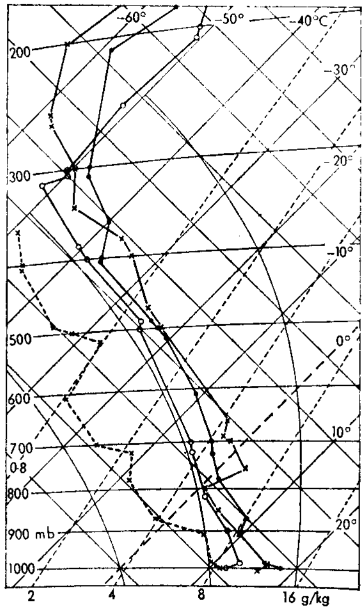


FIGURE 5—EPISKOPI UPPER AIR ASCENTS, 22–23 DECEMBER 1969

x ——— x Temperature at 00 GMT on 22nd
· ——— · Temperature at 12 GMT on 22nd
x – – – x Dew-point at 12 GMT on 22nd
o ——— o Temperature at 00 GMT on 23rd

Discussion. Perhaps the most interesting aspect of these tornadoes is their rarity. Tornadoes are not unknown in Cyprus but are usually comparatively weak summer features associated with the sea-breeze front, an example of which was recently recorded by McGinnigle.[1] The only other severe storm tornado reported since the last war was recorded in 1946 when several aircraft were damaged by hail and wind at Nicosia. Waterspouts are more common and may be seen several times in most years by a keen observer, but never before have waterspouts been known to have developed to such an intensity and crossed the coast to cause widespread damage well inland. It should be noted however, that these waterspouts/tornadoes struck heavily built-up areas, whereas over 90 per cent of the southern Cyprus coast is unpopulated; thus it is quite possible that previous occasions have passed unremarked.

Photograph by R. J. Drury

PLATE I—WATERSPOUTS NOS. 1 AND 2 APPROACHING EPISKOPI CLIFFS, 22 DECEMBER 1969

Photograph by Mr. Harper

PLATE II—DECAYING STAGE OF WATERSPOUT NO. 1

PLATE III(*a*)—DAMAGE CAUSED BY WATERSPOUT/TORNADO NO. 3

PLATE III(*b*)—THE SUB-AQUA CLUB BUILDING DESTROYED BY NO. 4

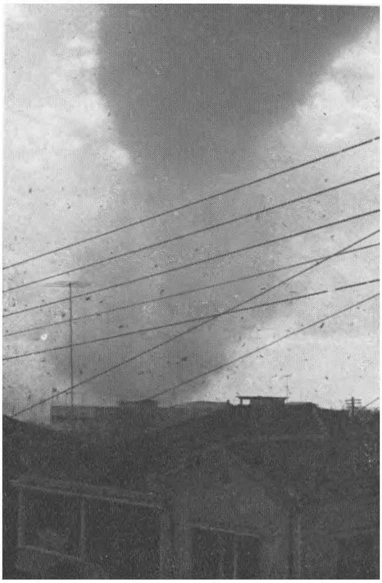
Photograph by A. Cox

PLATE IV(*a*)—WATERSPOUT NO. 5 APPROACHING EASTERN LIMASSOL

PLATE IV(*c*)—LIMASSOL DAMAGE FURTHER INLAND

PLATE IV(*b*)—TRAIL OF DAMAGE IN LIMASSOL FOLLOWING NO. 4

Note minaret.



Photograph by Sgt D. L. Pownall, RAF

PLATE V—TORNADO NO. 4 IN LIMASSOL MOVING TOWARDS CAMERA

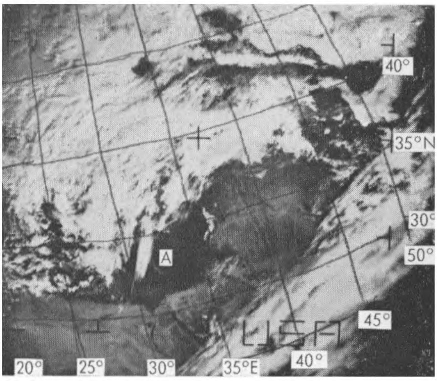


PLATE VI(*a*)—ESSA 8 PHOTOGRAPH AT 0727 GMT ON 22 DECEMBER 1969 SHOWING SEVERE STORM CIRRUS CANOPY AT 'A'

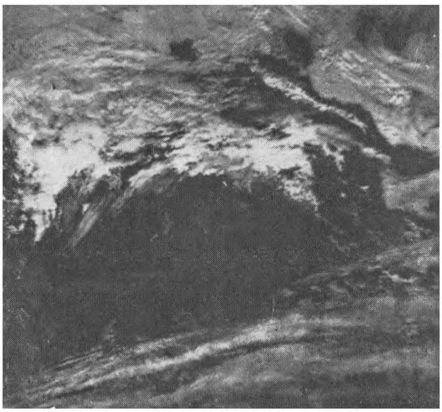


PLATE VI(*b*) — NIMBUS PHOTOGRAPH AT 0815 GMT ON 22 DECEMBER 1969; NOTE DEVELOPMENT OF MORE DENSE CELL WEST OF CIRRUS

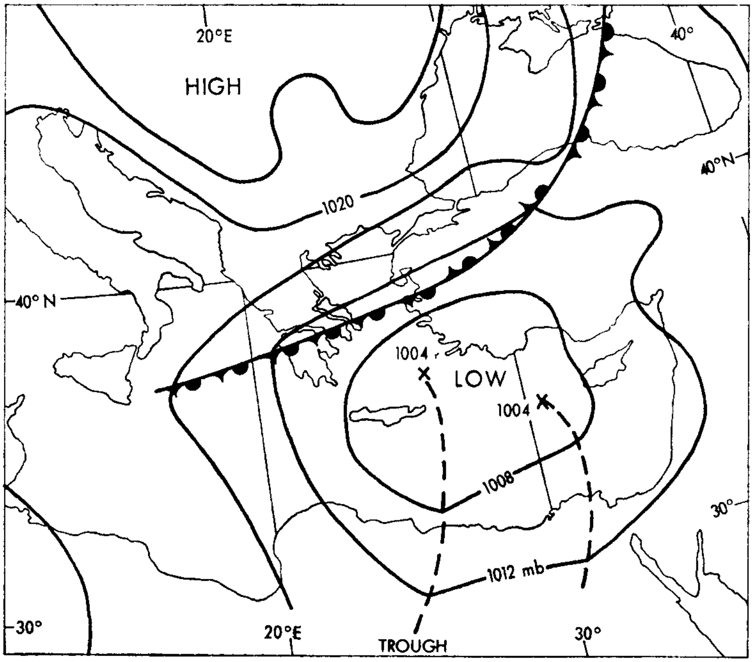


FIGURE 6—SURFACE ANALYSIS, 12 GMT ON 22 DECEMBER 1969

Many features of this occasion were similar to those recorded at Malta on 14 October 1960[2] which, in turn, agreed with tornado reports outside the Mediterranean area. These are :

(i) A dry stable layer above a moist, potentially unstable surface layer: can be seen near 900 mb in Figure 5.

(ii) Pronounced vertical wind shear in the lower layers.

(iii) Cold dry air above the stable inversion layer.

(iv) The occurrence of hail.

It seems certain that the Cyprus tornadoes were associated with a severe storm on the lines of the model described by Browning.[3] A great deal of work has been done, particularly in the U.S.A., regarding the physical processes involved in the production of tornadoes; nevertheless, the reasons for tornado genesis are still not fully understood.

It may be that one reason tornadoes are mostly associated with severe self-perpetuating storms is the large area covered by the low-level convergence field. This will be much greater than that associated with the more common thunderstorm, because of both the low-level inversion and the long life-cycle of the severe storm. If the low-level flow has any shear in the horizontal this could lead to vorticity and angular momentum becoming concentrated at the storm centre.

There are many similarities between the synoptic events which led up to the tornadoes of 22 December and events leading to occasions of severe low-level clear-air turbulence near Cyprus, one of which was discussed by

Jefferson.[4] It is clear that the forecaster in Cyprus concerned with aviation must recognize that an area of strong vertical wind shear ahead of a cold front or trough can be associated with extreme conditions.

Acknowledgements. The author is grateful to the Chief Meteorological Officer, HQNEAF, for his helpful suggestions, to Mr D. Imrie of the Main Meteorological Office, RAF Episkopi, for his help in collecting data, and to the many other people in Cyprus who supplied photographs, cine films and eye-witness reports.

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A PRESSURE-ACTUATED RELEASE FOR METEOROLOGICAL BALLOONS

By H. CHARNOCK, A. I. REES and P. K. TAYLOR
Department of Oceanography, University of Southampton

Introduction. This note describes a pressure-actuated release used to separate two parts of a balloon-borne instrument train. It was developed originally for use over the sea. A ship disturbs the lower atmosphere and it is difficult to launch a slowly ascending balloon from it. When low-level measurements of the atmosphere are needed the method adopted is to use two balloons to send the instrument train rapidly to a predetermined pressure where one balloon is released so that the instruments sink slowly back to the sea. This allows undisturbed measurements to be made down to very near the sea surface.

A number of methods have been used to effect the release. Systems involving pressure-actuated electrical circuits are known but they are relatively expensive, heavy and unreliable. Other methods which act after a preset time interval are better on all these grounds. The cheapest seems to be a length of slow-burning fuse, but this is dangerous to use with hydrogen balloons. Small clockwork timers have been found to work reasonably well for periods of about 30 minutes but are difficult to make sufficiently reliable.

The device described here uses the atmospheric pressure directly to perform the release. It is cheap to make and if carefully tested before use is very reliable.

Description. The device (Figure 1) is a chamber of plastic which can be partially evacuated so that the lid is held on by the excess atmospheric pressure. It is used to join the two parts of the balloon train. When the train has risen to the height where the external pressure equals that inside the chamber, the lid comes off and the train separates.

The device weighs 150 g and will withstand complete evacuation. When evacuated so as to release at 850 mb it will stand a tension of about 10 kg at sea level.

Results. The device has been used on 34 occasions, 11 at the Meteorological Office Station at Shanwell, Fife, 15 during the June 1970 cruise of R.R.S. *Discovery* in the trials for the Royal Society's U.K. Air–Sea Interaction Project and 8 from the weather ship *Cumulus* during the same period. Of these, 33 operated satisfactorily, the other is thought to have leaked.

Figure 2 shows the atmospheric pressure at release, derived from radar or radiosonde observations, plotted against the preset internal pressure. With the one exception all agree within the limits of measurement.

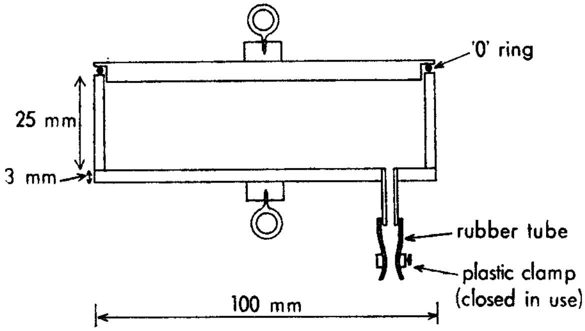

FIGURE 1—CROSS-SECTION OF PRESSURE-ACTUATED RELEASE

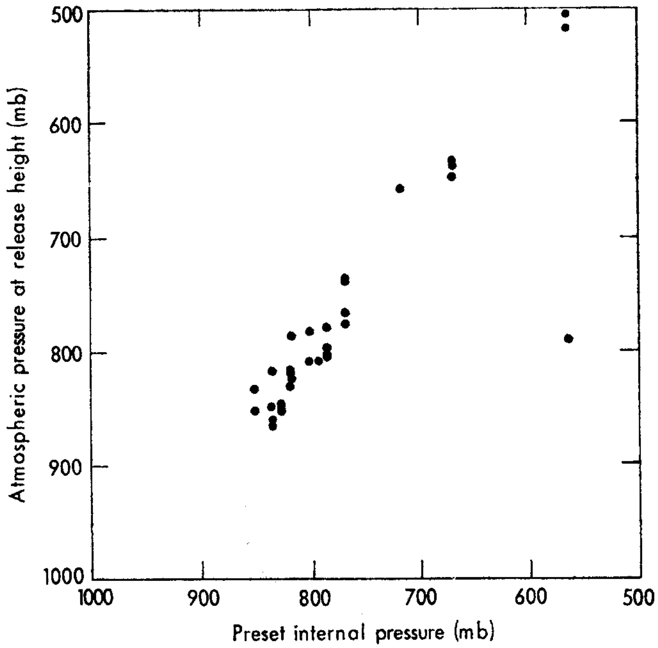

FIGURE 2—ATMOSPHERIC PRESSURE AT RELEASE, DERIVED FROM RADAR OR RADIOSONDE OBSERVATIONS, PLOTTED AGAINST THE PRESET INTERNAL PRESSURE

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PERIODIC FLUCTUATIONS IN EQUATORIAL STRATOSPHERIC TEMPERATURES AND WINDS

By R. A. EBDON

Summary. The 50-mb and 30-mb temperature and wind data for Canton Island (02° 46′S 171° 43′W) are analysed by means of a band pass filter technique to determine the relative importance of the quasi-biennial, the annual and the semi-annual oscillations. It is shown that the quasi-biennial oscillation dominates the behaviour of the zonal wind components and is important as far as temperatures are concerned. The annual variation becomes important when considering temperatures but the semi-annual variation is of little significance with both temperatures and winds.

During the last decade much interest has been shown in, and many papers have been written about, the behaviour of stratospheric winds and temperatures in the equatorial stratosphere. In the early 1960s[1,2] attention was first drawn to the approximately 26-month or quasi-biennial oscillation in winds and temperatures and there is now a very extensive literature on that subject, although there is still no completely satisfactory explanation for the existence of the oscillation.

In more recent years[3,4] interest has been focused on another interesting feature in the stratosphere — namely the 6-monthly or semi-annual oscillation which is now known to exist in the higher stratospheric winds and temperatures. When the climatology of the stratosphere is studied the problem to be faced is the determination of the relative importance of the quasi-biennial (approximately 26 months), the annual (12 months) and the semi-annual (6 months) oscillations. Angell and Korshover[4] point out that for zonal wind components the quasi-biennial oscillation is at a maximum near 30 km over the equator, the annual is at a maximum near 60 km over middle latitudes and the semi-annual is at a maximum near 50 km over the equator.

For temperatures they show that the maximum of all three oscillations is to be found in polar regions; the quasi-biennial near 35 km, the annual near 40 km and the semi-annual at the stratopause. They also indicate the existence of a weaker maximum in the semi-annual temperature oscillation between 30 and 40 km in equatorial regions.

In this paper attention is restricted to the equatorial region. The wind and temperature data at the 50-mb and 30-mb levels (approximately 20·5 km and 24 km respectively) for Canton Island (02° 46′S 171° 43′W) for the 12-year period January 1955 – December 1966 are analysed by means of a band pass filter technique as described in detail by Craddock[5] and as used by Geraldine Edmond in an earlier article on this subject.[6]

Figures 1*(a)* and 1*(b)* show the monthly mean temperatures and zonal wind components for Canton Island for the period 1954 to 1967 (when radiosonde ascents there ceased). From these curves it can be seen that the so-called 'approximately 26-months' or 'quasi-biennial' oscillation is a very important feature and many of the now well-known facts concerning the oscillation are apparent on studying the curves.

The zonal wind component curves at both levels show that the quasi-biennial oscillation is the dominant feature and it is also clear that there is considerable variation in the length of the period. The temperature curves show that there is a well-marked annual variation at 50 mb and the presence

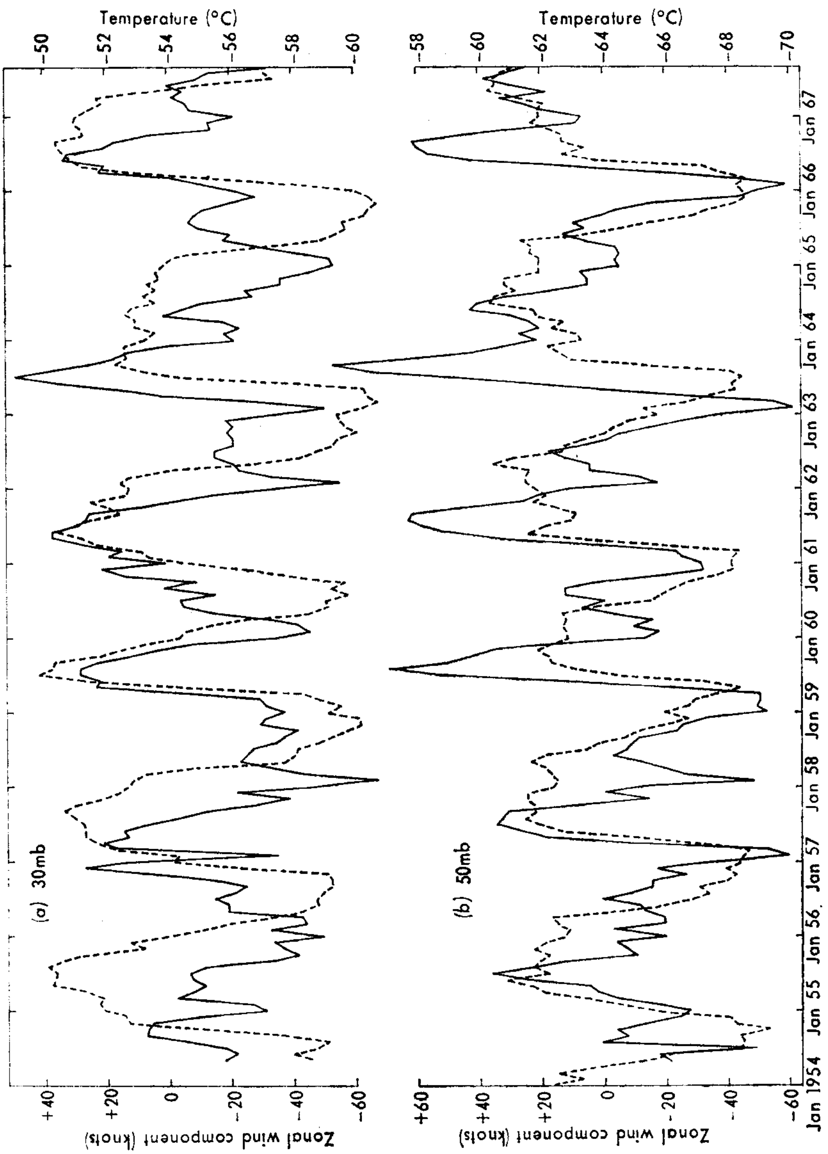

FIGURE 1—MONTHLY MEAN ZONAL WIND COMPONENTS AND TEMPERATURES AT CANTON ISLAND

——— monthly mean temperature - - - - monthly mean zonal wind component (components towards the east are positive) of the quasi-biennial oscillation is shown by the regular variations in the level of the annual maxima and minima. This regularity is upset during the period 1964–66 and it has been suggested that the cause of this disturbance in the behaviour of the oscillation could have been the volcanic eruption at Mount Agung, Bali (8°S 115°E), on 17 March 1963.[7] At the 30-mb level the monthly mean temperatures show the existence of both the quasi-biennial and the annual variations but there is also a suggestion of a shorter-period oscillation.

Figures 2*(a)* and 2*(b)* show the correlograms of the 50-mb and 30-mb data and from these it is clear that as far as the zonal wind components are concerned the main feature is certainly the quasi-biennial oscillation. The temperature correlograms, although highlighting the approximately 26-month oscillation, also suggest an important annual oscillation, particularly at 50 mb. None of the correlograms give a clear indication of a 6-monthly oscillation.

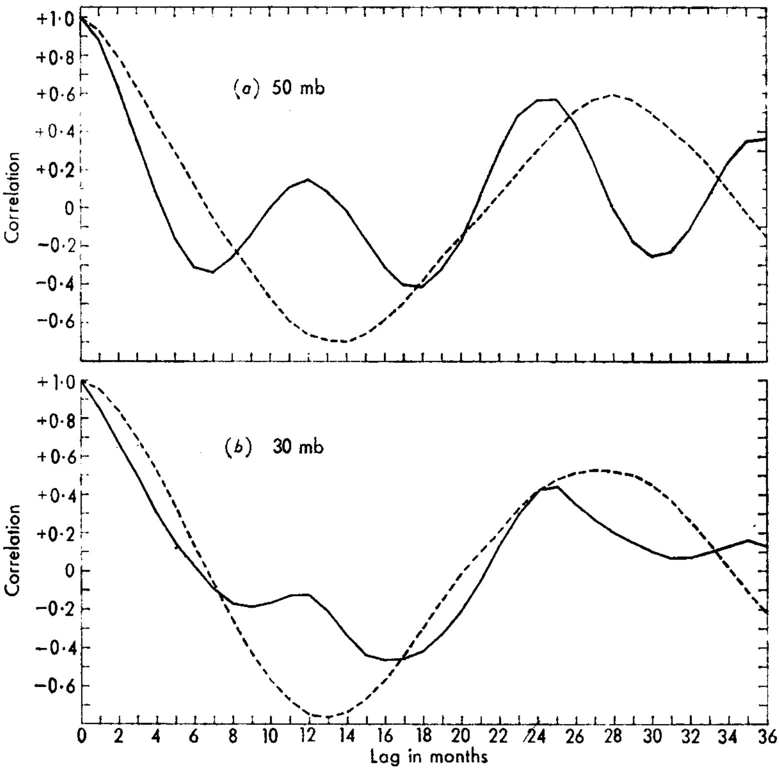

FIGURE 2—CORRELOGRAMS OF MONTHLY MEAN TEMPERATURES AND ZONAL WIND COMPONENTS AT CANTON ISLAND FOR JANUARY 1955–DECEMBER 1966
——— monthly mean temperature – – – – monthly mean zonal wind component

In order to determine the relative importance of the three oscillations at the 50-mb and 30-mb levels, thirteen 25-point filters designed by Craddock[8] were applied to each set of data. The curves of the filtered values are shown in Figures 3 and 4, and Table I gives the percentage of the total variance

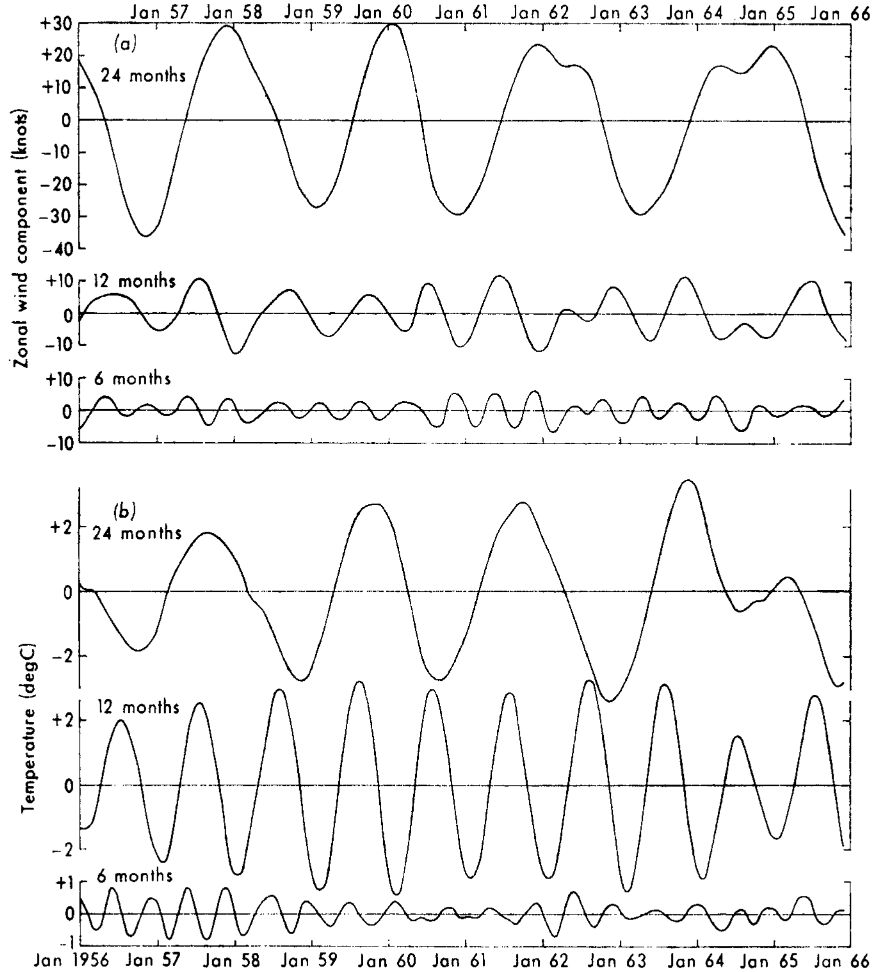

FIGURE 3—MONTHLY MEAN ZONAL WIND COMPONENTS AND TEMPERATURES AT 50 mb AT CANTON ISLAND FILTERED TO SHOW OSCILLATIONS, WITH VARIOUS PERIODS

(a) Monthly mean zonal wind components (components towards the east are positive)
(b) Monthly mean temperatures

TABLE I—VARIANCES OF FILTERED SERIES OF TEMPERATURES AND ZONAL WIND COMPONENTS AT 50 mb AND 30 mb AT CANTON ISLAND

Peak period of oscillation	Effective range of period	Percentage of total variance occurring in each band			
		Temperatures at		Zonal wind components at	
months	*months*	50 mb	30 mb	50 mb	30 mb
24	48–16	33	46	65	70
12	16–9·6	42	23	6	4
6	6·9–5·3	1	5	1	1

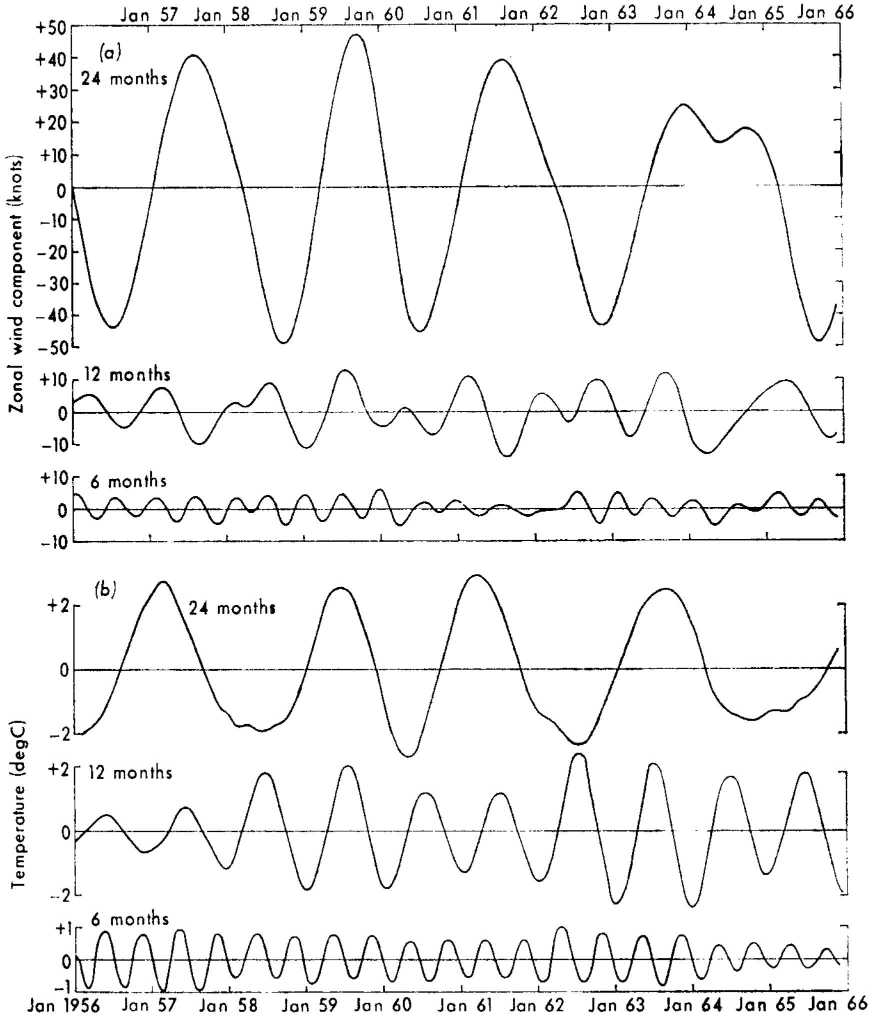

FIGURE 4—MONTHLY MEAN ZONAL WIND COMPONENTS AND TEMPERATURES AT 30 mb AT CANTON ISLAND FILTERED TO SHOW OSCILLATIONS, WITH VARIOUS PERIODS

(a) Monthly mean zonal wind components (components towards the east are positive)
(b) Monthly mean temperatures

covered by each oscillation. The zonal wind component curves show that most of the variance can be attributed to the quasi-biennial oscillation — at 30 mb this oscillation accounts for 70 per cent and at 50 mb for 65 per cent of the total. The annual oscillation is very much less important and accounts for only 4 per cent and 6 per cent respectively while the semi-annual oscillation accounts for only about 1 per cent of the total variance.

The temperature curves in Figure 4 show that at 30 mb the quasi-biennial oscillation accounts for nearly half (46 per cent) of the total variance, the annual oscillation for about a quarter (23 per cent) and the semi-annual is much less important, contributing only 5 per cent. At 50 mb the quasi-biennial and the annual oscillations are of almost equal importance with values of 33 per cent and 42 per cent respectively but the semi-annual contribution accounts for only 1 per cent of the total variance. In order to test the significance of these results two sets of random numbers within the range −50 to −60 were generated and processed in the same way as the wind and temperature data. The corresponding filtered values are shown on the curves in Figure 5. For these numbers the percentage of total variance occurring in each of the three bands was within the range 7–12 per cent for

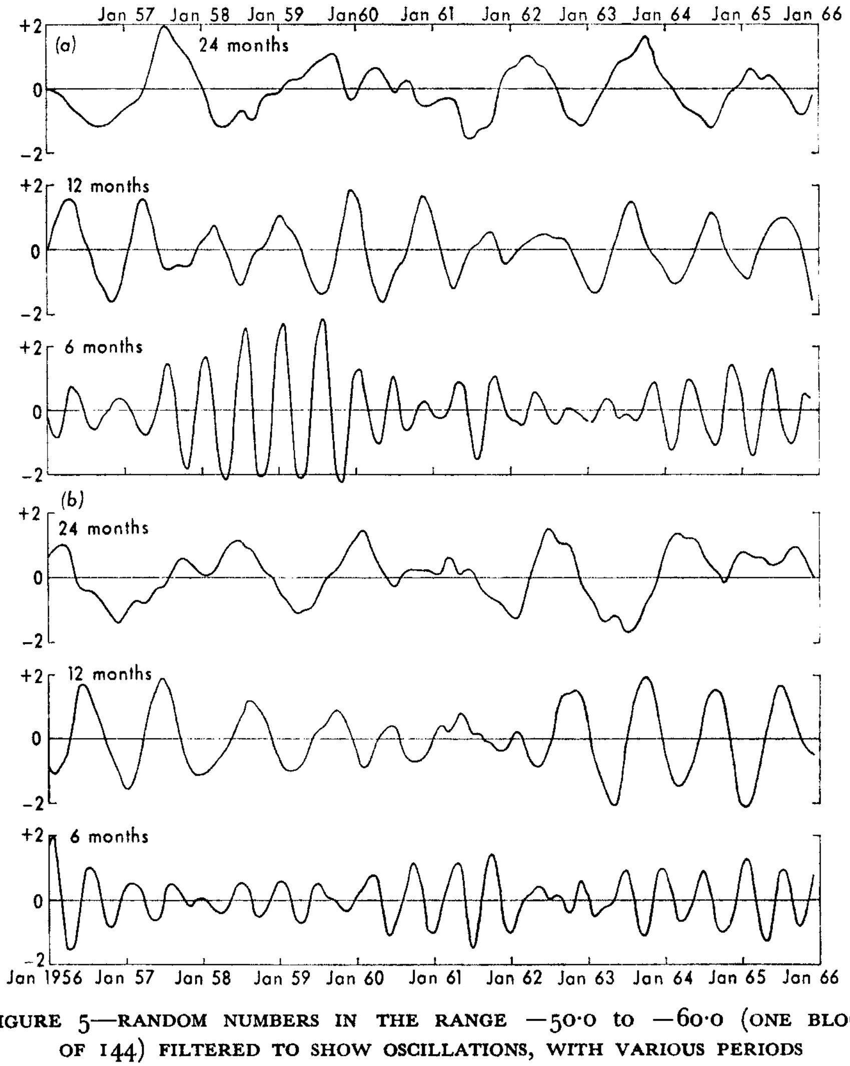

FIGURE 5—RANDOM NUMBERS IN THE RANGE −50·0 TO −60·0 (ONE BLOCK OF 144) FILTERED TO SHOW OSCILLATIONS, WITH VARIOUS PERIODS

(a) Set 1 *(b)* Set 2

one set and 6–12 per cent for the other set, indicating that the six larger percentages in Table I are appreciably greater than could be expected by chance.

This analysis confirms that, as far as zonal wind components at the 50- and 30-mb levels in the equatorial region are concerned, the quasi-biennial oscillation is the dominant feature and the annual and semi-annual oscillations are relatively unimportant. However, with temperatures the annual variation assumes increasing importance and in the lower stratosphere (50 mb) accounts for rather more of the total variance than is attributable to the quasi-biennial oscillation. The data show that, at these levels, the 6-monthly oscillation is of little significance although it must be remembered that these results are for only one station and can be regarded only as representative of the equatorial region. It would be of interest to obtain results for other levels and from stations in other latitudes where long and homogeneous records of stratospheric wind and temperature are available.

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551·509·323:551·524·36

A COMPARISON OF THE McKENZIE AND SAUNDERS METHODS OF FORECASTING NIGHT MINIMUM SCREEN TEMPERATURES

By W. G. RITCHIE

A test of three methods of forecasting night minimum screen temperatures was carried out at Mildenhall and was reported in the *Meteorological Magazine* of June 1968.* The methods were those due to Craddock and Pritchard, McKenzie, and Saunders using Menmuir and Tinney's cooling curves. The test showed that the McKenzie and Saunders methods gave the best results, and that there was little to choose between them. In view of the speed

* GORDON, J. and VIRGO, S. E.; Comparison of methods of forecasting night-minimum temperatures. *Met Mag, London*, **97**, 1968, pp. 161–164.

and simplicity of the McKenzie method this result seemed surprising, and it was decided to see if the same thing applied to Wyton which is 40 km west of Mildenhall.

Continuous observations for Wyton are available from January 1954. McKenzie constants were computed from observations for the years 1954 to 1967, the number of suitable nights being 386. The constants are shown in Table I.

TABLE I—VALUES OF McKENZIE'S CONSTANT FOR WYTON

Average surface wind speed	Average low-cloud cover in oktas				
	0	1–2	3–4	5–6	7–8
knots			*degrees Celsius*		
Calm	7	6	5	4	3
1–3	6	5	4	3	2
4–6	6	5	4	3	2
7–10	5	4	3	2	2
11–16	4	3	2	2	1
17–21	3	2	2	1	1
22–27	2	2	1	1	1

A comparison of the McKenzie method using the constants computed for Wyton, and the Saunders method using Menmuir and Tinney's cooling curves was carried out at Wyton during the two years ending on 30 November 1969. As at Mildenhall this was a true forecasting test done with real forecasts before the event. The test was not done at week-ends or on nights during which there was precipitation. The total number of suitable nights was 392.

The root-mean-square error was 2·6 degC for both methods, and the distribution of errors was similar. To see if the distribution of errors was normal, a normal frequency-distribution curve was drawn for 392 observations with a standard deviation of 2·6. The distribution of errors about the mean was plotted for both methods (Figure 1), and both distributions appeared to be a reasonable approximation to the normal — as was the case at Mildenhall.

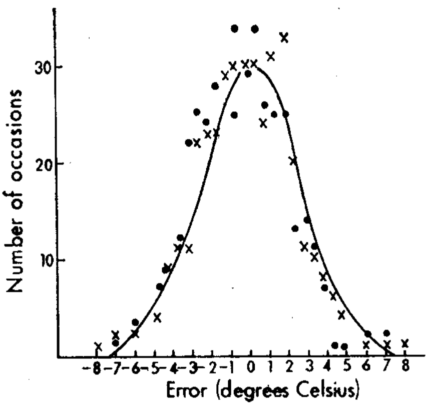


FIGURE 1—DISTRIBUTION OF ERRORS BY THE McKENZIE AND SAUNDERS METHODS

——— Normal frequency-distribution curve
x Errors by McKenzie method
. Errors by Saunders method

The nights were then divided into two seasons, April to September (summer), and October to March (winter). The root-mean-square errors were as follows :

	Winter	Summer
	degrees Celsius	
McKenzie	2·8	2·4
Saunders	2·9	2·2

This test confirms the Mildenhall conclusions that there is little to choose between the methods as far as accuracy is concerned. Examination of the daily results showed that, as for Mildenhall, when large errors occurred they were common to both methods.

REVIEWS

Hydrometeorology, by C. J. Wiesner. 255 mm × 190 mm, pp. viii + 232, *illus.*, Chapman and Hall Ltd, 11 New Fetter Lane, London EC4 (New York, Barnes and Noble Inc.), 1970. Price: £3·00.

This book is written primarily for hydrologists and in particular for those interested in the estimation of probable maximum precipitation (PMP), and is purposely restricted to the study of the atmospheric phase of the hydrological cycle.

The first eight chapters outline the meteorological aspects. Chapters 1 and 2 describe the hydrological cycle and the atmospheric heat-balance; Chapters 3 to 8 give a brief account of the general circulation and the meteorological elements — temperature, water vapour, wind, pressure, air masses and fronts. What is needed in this section is a chapter on world climatology, with special reference to the climatology of heavy falls of rain. This could have been done with a simplified map of Köppen's classification, illustrated by climatological statistics from a selection of representative stations, giving, as well as monthly mean rainfall, temperature and dew-point, observed extremes of temperature and dew-point, and of monthly and daily rainfall, and giving also for daily rainfall the mean annual maximum fall and the fall with, say, a 50-year return period. This is the fundamental background knowledge wanted by the typical reader.

Chapter 9 gives an account of evaporation and its measurement, with a worked example of Penman evaporation. But data of potential evaporation in different parts of the world should have been given as background information.

Chapter 10 deals with the interrelationships between rainfall depth, duration and return period at a given point, and gives regional formulae for these, with some examples of relations with other parameters such as annual rainfall and thunderstorm days; but only one set of data is given, of annual maximum 5-minute falls for Sydney. How much better if similar sets for different durations had been given for Sydney, and these displayed on extreme probability paper, instead of the blank diagram Figure 10·8, and on a depth-duration diagram instead of the unspecified data of Figure 10·10; and the data used to illustrate the formulae.

Chapter 11 gives a satisfactory account of estimation of areal rainfall, and of depth-duration analysis of storms using the data from an actual Australian storm.

Chapter 12 gives a brief summary of the few useful methods of estimation of snow melt.

Chapters 13 to 15 give a good account of estimations of available water for precipitation and their application to the most useful elementary storm models. Chapter 16 illustrates the estimation of PMP using these models; a case-study for a given area would have made the chapter more lively.

Chapter 18 gives a current list of the world's greatest observed rainfalls for durations from one minute to two years; and maximum depth-duration-area data for the United States, and justifies the generalization of these to make preliminary PMP estimates for other parts of the world. An outline is also given of the Hershfield statistical method for estimating PMP.

The book unfortunately seems to be orientated more towards the university student than to the working hydrologist; but it is the first to cover this field and is welcome.

A. F. JENKINSON

The value of the weather, by W. J. Maunder. 220 mm × 145 mm, pp. xxiv + 388, *illus.*, Methuen and Co. Ltd, 11 New Fetter Lane, London, EC4 (New York, Barnes and Noble Inc.), 1970. Price: £3·75 (University Paperback edition £2·00).

At a time when world-wide emphasis is being placed on the importance of the environment and the conservation of those environmental features that are essential to our well-being, it is appropriate that a book of this kind should be available. It is concerned with the involvement of the weather and climate in the affairs of mankind.

In the opinion of James D. McQuigg, writing in the Foreword, the book is important because it clearly emphasizes two important ideas :

'Man is affected both by the atmosphere *and* by information about the atmosphere.

Man is not just a passive object, subject to weather events without recourse, but he can and does react to the atmosphere through his ability to make decisions.'

The author's purpose is 'to bring together, for the first time, the most significant and pertinent associations between man's economic and social activities, and the variations in his atmospheric environment' and he expresses the hope that the book will 'bridge the gap between the physical, dynamical and descriptive aspects of the atmosphere, and the economic, social, political and legal aspects of man and his environment'.

The Introduction, which is but two pages long, stresses the concept of the atmosphere as a 'resource' — 'we have to learn how to live within our climatic income'. Subsequent chapters and their approximate contents are as follows :

Weather variations
The natural atmosphere (violent storms, precipitation extremes).
The modified atmosphere (air pollution, atmospheric modification).

Economic activities
Primary activities (agriculture, forestry, fishing).
Secondary activities (manufacturing, construction).
Tertiary activities (transportation, utilities, commerce).

Sociological and physiological aspects
Human aspects (weather and human behaviour, human classification of climate).
Health aspects (human biometeorology, effects of weather on certain ailments, weather and mortality).
Recreation and sport.

Economic analysis of weather
Evaluation of weather and climate (problems of identification and measurement, econoclimatic models).
Applications (regional, national, international).

Weather knowledge: benefits and costs
Weather information (types, use, value).
Weather forecasting (atmospheric predictability, presentation of weather forecasts, economic and social value of weather prediction, decision making, benefits and costs of weather forecasting services, foreseeing the future: problems and prospects).
World Weather Watch (history and formulation, the World Weather Watch plan, potential benefits of World Weather Watch).
The modified atmosphere (weather knowledge and modification, economic and social aspects, engineering aspects, medical aspects, controlling the urban environment).

Political, planning and legal aspects
Politics and policies (politics and the atmosphere, policies towards weather modification).
Planning aspects (the importance of atmospheric resources, man the modifier).
Legal aspects (the law and the atmosphere, the law and weather modification).

This list of contents has been given as the best means of emphasizing the value of this book which consists principally in its comprehensive sweep over a whole range of disciplines and activities. Examination of particular aspects shows that the treatment is often superficial but the wide bibliography — some 750 references of which more than 400 have appeared since 1965 — offers sufficient inducement for anyone desiring further information.

In the reviewer's opinion, the title of the book, useful though it may be as a means of attracting readers, has its difficulties. There are ambiguities involved in 'value' which, coupled with the additional concept of the atmosphere as a 'resource', lead to minor irritations for the reader.

This book will be of greatest value to forecasters and others with basic knowledge who wish to see weather in its broadest context. Present tendencies are for forecasters to become less involved with the making of forecasts (because of the impact of numerical techniques) and more involved with their application to the needs of the customer. This book will be useful to them in making the necessary adjustments of outlook.

It is hinted in the book that science (as opposed to geography, economics and sociology) is not sufficiently concerned with many of the aspects dealt with, in particular with the changing environment. Readers may therefore wish to note that the International Council of Scientific Unions (ICSU) is setting up a 'Scientific Committee on Problems of the Environment (SCOPE)' which will be concerned with the promotion of environmental monitoring, evaluation of the effects of environmental disturbances, simulation modelling and predictions, and the study of the social effects of man-made changes in the environment.

T. H. KIRK

Atmospheric circulation systems, International Geophysical Series, Volume 13, by E. Palmén and C. W. Newton. 230 mm × 160 mm, pp. xvii + 603, *illus.*, Academic Press Inc. Publishers, 111 Fifth Avenue, New York, New York 10003, U.S.A. 1969. Price $26·00.

The aim of this book has been to provide a comprehensive account of atmospheric circulations on all scales from thunderstorms to the mean global circulation of the troposphere and lower stratosphere. In each case the principal observed features and basic structure are described in some detail and a large number of synoptic examples are presented and discussed. Many diagnostic studies, based largely on a thorough review of modern literature, but also supplemented by new work by the authors, are also included and used to illustrate and interpret the roles of the different systems in forming the general climatology and producing the observed weather. Interrelations between the different scales are discussed and emphasis is also given to their budgets and transfers of energy, momentum and water vapour.

The first three chapters are concerned with global mean wind and temperature structures, their seasonal and spatial variability and the mechanism of the general circulation in terms of energy and momentum exchanges. The principal air masses, fronts, jet streams and tropopauses are described in Chapter 4 and the development of the polar front theory in Chapter 5. The next six chapters include detailed treatments of the large-scale extratropical systems, i.e. the planetary waves in the middle and upper troposphere, anticyclones, depressions, jet streams and fronts. These are interrelated and their principal features analysed and linked using theoretical ideas based on baroclinity and vorticity considerations, divergences and computed vertical windfields and three-dimensional trajectories. In addition the conditions for their formation, evolution and dissipation are discussed at some length. The complex relations between the disturbances and weather phenomena are considered in Chapter 12 — and organized convective systems and severe-storm phenomena in middle latitudes are the subject of Chapter 13. The authors then turn in the next two chapters to circulations in the tropics and critically assess modern research and present knowledge of tropical systems including cyclones, hurricanes and typhoons. Chapter 16 is devoted to the general problem of energy conversions in circulation systems and finally

Chapter 17 provides an extended summary of the global picture given in the preceding sections. Some readers may prefer to read this first to obtain an overall view before studying the earlier chapters in detail. Altogether this coverage adds up to a very large amount of subject matter. Many American and some European case studies, which are all well documented and illustrated with several figures, are also included.

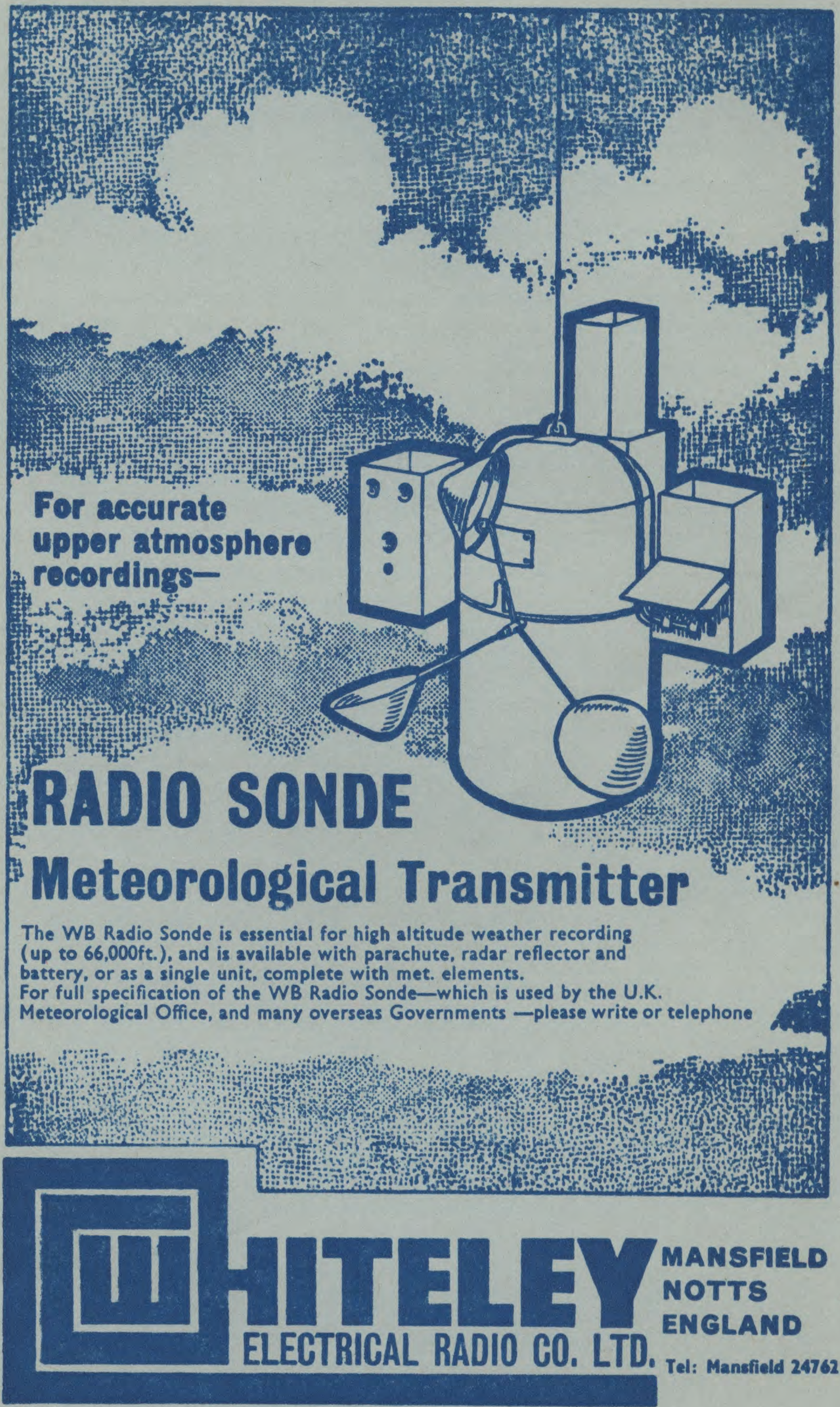
The authors, who are world authorities in this subject, have clearly produced an outstanding addition to the meteorological literature now available to research workers, students and professional meteorologists concerned with understanding and forecasting the movement and development of atmospheric circulation systems. The recent research effort in synoptic and dynamical meteorology has tended to centre on numerical forecasting models and the modern, theoretically well-grounded, diagnostic studies discussed in this book have probably not attracted in recent years the attention they deserve. However, it is these studies, largely expanded and developed in the decade or so following the Second World War and systematically continued over recent years, that have elucidated the main features of atmospheric structure that the models must simulate. The synthesis of results of the diagnostic studies so admirably introduced and presented in this book will be of considerable help to anyone seeking insight into the mechanisms at work. Numerous references are also given for further reading.

Although much of the text is descriptive and non-mathematical a basic knowledge of dynamical meteorology is essential before many of the explanations and interpretations can be fully appreciated. Since the descriptions of the case studies are very detailed (perhaps sometimes excessively so) the reader will often need considerable time and patience before he can fully assimilate many of the conclusions and their implications. Although the production is very good (only a very few minor errors were noted) some of the diagrams are necessarily very complicated and they will also need much detailed study. This, however, will not deter the serious student and in many sections even the casual reader will quickly learn a good deal about the atmosphere from this book. It is certain to come into constant use for a long time by meteorological libraries, universities, and similar organizations concerned with the detailed understanding and study of the atmosphere.

R. J. MURGATROYD

OBITUARY

It is with regret that we record the death on 29 November 1970, of Mr J. H. S. Manson, Scientific Assistant, Lerwick.


For accurate upper atmosphere recordings—
RADIO SONDE
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A DISCUSSION OF THE TEMPERATURES OF INLAND KENT WITH PARTICULAR REFERENCE TO NIGHT MINIMA IN THE LOWLANDS

By A. A. HARRISON

Summary. An examination was made of air minimum temperatures at 4 ft at 21 inland rural sites in Kent and east Sussex for the period March 1968–May 1969. Over the 137 nights selected for analysis, averages for stations on a valley floor but at various heights above MSL were almost identical. When the station averages were plotted against height above the valley floor (a.v.f.) adjacent to the station a linear relationship was obtained giving an increase of temperature with height (a.v.f.) of 1·5 degF/100 ft. For 28 chosen radiation nights the rate was about 2·8 degF/100 ft and for 4 extreme radiation nights it was about 3·6 degF/100 ft. Over short distances near steep slopes rates exceeding 9 degF/100 ft are known. Departures from expected temperatures occur because of the warming effects of increased turbulence over steep slopes, and there may be heat island effects, e.g. at Wye College.

For stations within 50 ft of the valley floor the frequency of frosts was twice that for stations exceeding 250 ft a.v.f. High diurnal ranges were found to be quite common.

Introduction. The purpose of this note is twofold. The original intention was to show that the low night minimum air temperatures frequently recorded at London/Gatwick Airport are not peculiar to the basin in which Gatwick lies, but that they are indicative of an extensive lake of cold air at night throughout the Low Weald of Kent bordered by the North Downs and the Ragstone Ridges in the north and the Forest Ridges in the south. (Frost and low night temperatures are particularly important in this fruit-growing area. Much of it is wholly devoted to horticulture as opposed to agriculture.)

However, during the course of the investigation a relationship between night minima and topography emerged and it is thought that this is the main outcome of the project.

The preliminary results were encouraging and it was decided to extend the survey outside the Low Weald and include all parts of rural Kent and some of east Sussex excluding only the coastal regions. The survey was confined to rural areas, as far as possible, since Chandler[1] in one of his reports on London's climate observed '. . . there is no simple, certainly no linear relationship between the extent of an urban area and the intensity of its heat island . . . one can imagine a small settlement, probably no more than a hamlet, warmer by several degrees than its rural setting . . .'.

Observers. The number and also the distribution of official stations regularly recording temperatures in this area is clearly inadequate for a close survey and it was necessary to augment the official network; suitable people in the area were therefore asked to co-operate. Advice was taken from the Regional Horticultural Advisers (of the National Agricultural Advisory Service), who know the farming community intimately, and people known to be reliable and keenly interested in such activities were approached. Another, most important, requirement was that they had to be available and willing to make observations day in and day out. Nine supplementary stations were set up.

The voluntary observers were visited fairly frequently in the early stages, not only to show continuing interest but also to make sure the instruments were in good condition and that the sites had not become overgrown. There were also a few emergency calls when 'bubbles' developed in thermometers.

Personal errors were very few in number and fairly easy to detect, taking the form of misreading by 5 or 10 degF — a mistake that even the trained observer occasionally makes.

Sites. All the stations, official and otherwise, are listed in Appendix I together with the names of the voluntary observers, and a code letter has been allocated to each station which gives its location in Figure 1. References to stations will be given by name followed by the code letter, e.g. Gatwick (C).

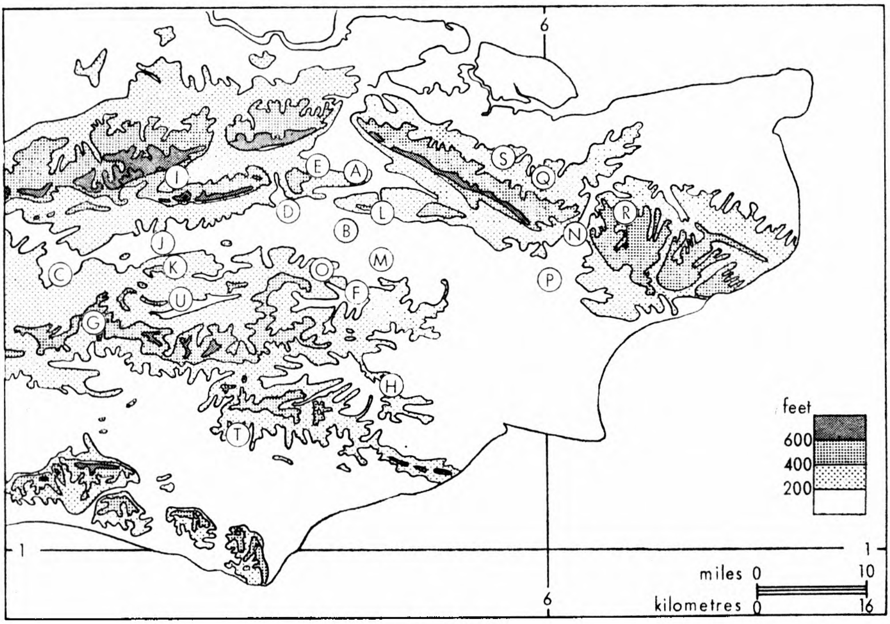

FIGURE 1—DISTRIBUTION OF 21 STATIONS
See Appendix I for identification of code letters.

Instruments and equipment. Most of the voluntary observers maintained their own weather records and had some sort of thermometer of their own but it was thought preferable that instruments be supplied by the Meteorological Office since this would help to standardize the readings and would also provide an opportunity to resite some of the thermometers.

Fahrenheit temperatures were used for the investigation because of the requirements of the horticultural community, and for convenience in relating results to previous work. Temperatures in Celsius at various official sites were converted to Fahrenheit to the nearest decimal place. The main results are given in degrees Celsius per 100 metres in the conclusions.

To avoid transporting bulky equipment it was decided to expose the thermometers in the shielded mounts which are commonly referred to as 'cocoa-tin screens' (described by Gloyne and Smith[2]), supported by simple stakes. This complicated matters somewhat since some thermometers were housed in 'cocoa-tins' and some (at the official stations) in thermometer screens, and a relationship had to be found between the two. Numerous papers were read on the subject but, with respect to their authors, none seemed wholly convincing. So at Collier Street (B), in the heart of the area, a small thermometer screen was installed by the side of the 'cocoa-tin' to establish this relationship. It was found that a similar pairing of 'cocoa-tin' and conventional screens existed at East Malling (A) so the semi-sum of the correction at these two stations each night was applied to the readings made at all the other unofficial stations on that night. This correction was never very great, usually being an addition to the 'cocoa-tin' temperature of between 1 and 2 degF. The average correction for all the nights considered was 1·1 degF.

All the thermometers were exposed at a height of 4 ft (1 ft = 0·3048 m) over grass, and the small screen at Collier Street (B) was also used to house a maximum thermometer.

Paper work was kept to a minimum. Each voluntary observer was provided with a set of stamped addressed post cards, the blank side of which was ruled-up and headed with the station name and the month so that all the observer had to do was to enter the temperature each morning and post the card at the end of the month. In addition, however, each station was provided with a small note-book suitably prepared so that the observers could keep records for their own use. This would have been invaluable had one of the cards been lost in the post.

A total of about 12 740 temperatures were obtained from 21 sites during a period of 15 months between the beginning of March 1968 and the end of May 1969.

Technique. The problem now arose as to which nights to select for analysis. It is felt that most papers dealing with night temperatures fall into one of two categories. Either they confine their discussion to calm clear nights with virtually uninhibited long-wave radiation or they accept all nights, disregarding whether they be cloudy, wet and windy, or still and starlit, and deal with average values, monthly or even annual. As katabatic drainage and the establishment of nocturnal temperature inversions, indeed the whole concept of valley temperature at night, depend on radiation from the ground there must be, in an experiment of this nature, a bias towards the calm, clear radiation night; but (i) a period of only 15 months did not provide enough instances of 'radiation' nights, and (ii) there are many nights during which radiation plays an important part but its effect is reduced by other factors such as variable cloud and its counter-radiation, and also turbulence caused by wind.

To have included all nights would have masked to a very great extent the contrasts it was intended to highlight. Accordingly it was decided to steer a middle course and the nights were passed through the following sieves :

(i) *Daily Weather Reports** were examined and nights that were wet or predominantly cloudy were discarded. Furthermore the proximity of a frontal trough with its attendant complications of advection made the night unacceptable.

(ii) Wind tabulations from Gatwick (C) and anemograms from East Malling (A) were considered and only those nights with mean wind speeds of less than 10 kt (1 kt$\approx$0·5 m/s) and no marked gustiness were used.

(iii) If long-wave radiation from the ground is the main cause of the fall of temperature throughout the night rather than advection of a different air mass, it seems likely that the lowest values of temperature will occur at the end of the night, or, better still, soon after dawn as the balance of incoming and outgoing radiation swings the other way; if the lowest temperature is reached early in the night some air-mass change at or above the surface has probably taken place. So thermograms from East Malling (A) were scrutinized and if the traces were irregular or showed that the minimum temperature had not been reached during the dawn period the night's observations were excluded from the experiment. It is suggested that this is a very good and speedy, though subjective, method of selecting nights on which radiation has been effective. This method of selection left 137 nights (more than 33 per cent of the total) for analysis from the 15-month period.

Analysis. Average values of minimum temperature on the selected nights were obtained for each station for :

(i) The whole 15-month period.

(ii) The combined springs (March, April and May) of 1968 and 1969.

(iii) The spring of 1968.

While most months were covered only once, the important months from the fruit-growing point of view were covered twice. The results are given in Table I with the number of occasions taken shown in brackets.

It was hoped, at first, that it would suffice to draw isotherms based on these averages and that the isotherms would be sympathetic with the main height contours. They are to a certain extent, see Figure 2, but despite the scarpland topography and comparatively simple drainage of the area it was found that there were some stations which were not easy to fit, e.g. Brasted (I), Brenchley (O) and Linton (L), and there seemed a need for a less crude method of analysis.

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

TABLE I—AVERAGE MINIMUM TEMPERATURES

	East Malling (A)	Collier Street (B)	Gatwick (C)	Hadlow (D)	West Malling (E)	Goudhurst (F)	Wakehurst (G)	Bodiam (H)	Brasted (I)	Marsh Green (J)
					degrees Fahrenheit					
Whole period	38·5 (137)	36·5 (137)	36·8 (137)	37·4 (137)	39·5 (131)	37·8 (137)	40·6 (137)	37·9 (137)	—	36·9 (137)
Combined springs 1968/69	34·8 (68)	33·3 (68)	32·7 (68)	33·8 (68)	35·8 (62)	33·9 (68)	37·1 (68)	33·9 (68)	34·6 (68)	33·0 (68)
Spring 1968	35·5 (40)	33·9 (40)	33·5 (40)	34·4 (40)	36·6 (40)	34·4 (40)	37·5 (40)	34·8 (40)	35·9 (40)	33·5 (40)

	Cowden (K)	Linton (L)	Marden (M)	Wye (N)	Brenchley (O)	Kingsnorth (P)	Throwley (Q)	Anvil Green (R)	Doddington (S)	East Hoathly (T)	Hartfield (U)
						degrees Fahrenheit					
Whole period	37·3 (136)	40·7 (118)	36·9 (135)	39·5 (136)	39·0 (137)	38·1 (137)	40·3 (137)	41·1 (137)	39·3 (128)	37·1 (137)	— —
Combined springs 1968/69	33·3 (68)	36·7 (59)	33·2 (68)	35·9 (67)	35·7 (68)	34·5 (68)	36·8 (68)	37·7 (68)	35·9 (66)	32·9 (68)	— —
Spring 1968	34·5 (40)	37·6 (40)	33·9 (40)	36·8 (40)	36·4 (40)	35·3 (40)	37·4 (40)	38·5 (40)	37·0 (40)	34·0 (40)	35·5 (38)

Note: (i) Observations from Brasted (I) were missed during August and September 1968 due to a defective thermometer.
(ii) Observations from Hartfield (U) were discontinued after spring of 1968.
(iii) Number of occasions taken shown in brackets.

A method which took into account the slope of ground was first considered but this approach was not pursued since most land profiles are curved and irregular and it was impossible to decide over what horizontal distance the change of height was to be taken; and also because Lawrence[8] was unable '. . . to draw any firm conclusions concerning the relation between slope of ground and the rate of increase of temperature with height . . .'.

As altitude is fundamental to the investigation the temperatures were plotted against height above mean sea level; see Figure 3.

Despite a correlation coefficient of 0·8 between height and temperature this graph reveals a scatter that is too great for the correlation to be meaningful, especially between 75 and 225 ft above MSL.

However, it was noticed that there was no great disparity between temperatures at Gatwick (C), Marsh Green (J), Marden (M) and Collier Street (B) which lie on the floor of the valley running east–west through the area. It was found that average temperatures at these stations were almost exactly the same despite the fact that their heights varied between nearly 200 ft and less than 50 ft above MSL; see Table II.

It seemed that this fact would provide a foundation from which to work. Temperatures were therefore plotted against height above the valley floor (a.v.f.), rather than above sea level to see if a more coherent pattern would result.

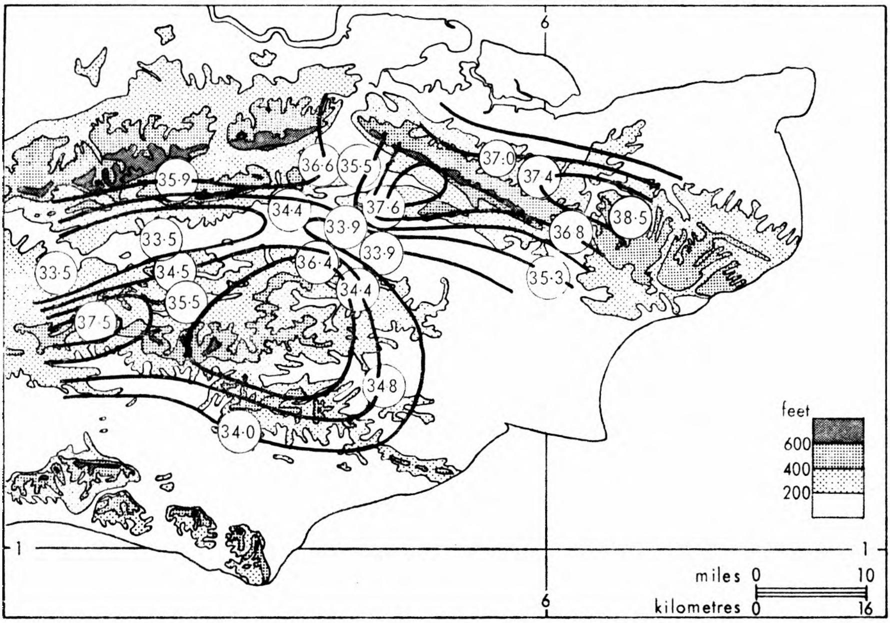

FIGURE 2—ISOPLETHS OF NIGHT MINIMUM TEMPERATURE IN SPRING OF 1968

——— Isotherms at intervals of 1 degF (values at individual stations in °F).

This period was chosen because the greatest number of stations (21) was reporting and the greatest number (40) of nights of any season was used.

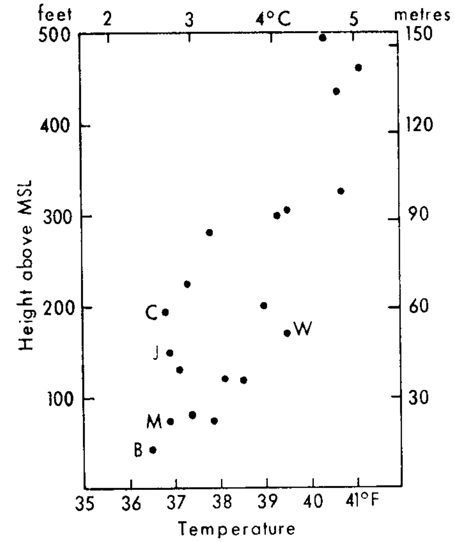

FIGURE 3—NIGHT MINIMUM TEMPERATURES PLOTTED AGAINST HEIGHT ABOVE MSL
19 stations (omitting Hartfield and Brasted), 137 nights, 15-month period
C Gatwick, J Marsh Green, M Marden,
B Collier Street, W Wye (N in Figure 1)

TABLE II—AVERAGE MINIMUM TEMPERATURES AT VALLEY FLOOR STATIONS

	Gatwick (C) *194 ft	Marsh Green (J) 150 ft	Marden (M) 75 ft	Collier St (B) 45 ft
		degrees Fahrenheit		
Whole period March 1968–May 1969 incl.	36·8	36·9	36·9	36·5
Spring 1968	33·5	33·5	33·9	33·9
Spring 1969	31·6	32·1	32·2	32·5
Combined springs	32·7	33·0	33·2	33·3

* Heights above MSL; 100 ft = 30·48 m.

The height of each station a.v.f. was determined, e.g. the height of Linton (L) is 325 ft above MSL but the height of the valley adjacent to it is 50 ft above MSL; so its height a.v.f. is 275 ft. There are, however, some stations which do not drain (katabatically) directly into the broad valley running through the area and Goudhurst (F) in Bedgebury Forest is a noteworthy example of this. Inspection of a 2½-inch Ordnance Survey Map (1:25 000) showed that the katabatic drainage from this station was into a sizeable lake called the Great Lake. This reduced the effective height of Goudhurst from 280 ft to 110 ft. Each station was considered individually (using 2½-inch maps) and heights a.v.f. were determined. There is admittedly a subjective element in this procedure but three people were given this height determination as an exercise and it was found that they were all in reasonably close agreement. A list of the stations used showing their heights above sea level and their heights above the adjacent valley floor is given in Table III.

King[4] has investigated two sites, S_1 and S_2 situated on the floor of the Chess Valley in the Chilterns, the notorious Rickmansworth frost hollow discussed

TABLE III—HEIGHTS OF STATIONS ABOVE MSL AND ABOVE VALLEY FLOOR

		Height above MSL (feet)	Height above valley floor (feet)
East Malling	(A)	120	100
Collier Street	(B)	45	0
Gatwick	(C)	194	0
Hadlow	(D)	80	40
West Malling	(E)	304	234
Goudhurst	(F)	280	110
Wakehurst	(G)	437	260
Bodiam	(H)	73	53
Brasted	(I)	400	125
Marsh Green	(J)	150	0
Cowden	(K)	225	70
Linton	(L)	325	275
Marden	(M)	75	0
Wye	(N)	170	75
Brenchley	(O)	200	125
Kingsnorth	(P)	120	95
Throwley	(Q)	493	270
Anvil Green	(R)	460	290
Doddington	(S)	300	200
East Hoathly	(T)	130	30
Hartfield	(U)	253	85

100 ft = 30·48 m

by Hawke.[5] King found that these two sites, only 1·2 miles apart and one 50 ft above the other, had significantly different night minima. This might appear to vitiate the line of approach used above; but between the two sites, S_1 and S_2, there is (or was) a woodland, and cold air from the leaf canopy is likely to drain towards one site rather than the other. Oliver,[6] looking at an abnormally cold spot (Grime's Graves in the Breckland of west Norfolk), has attributed the very low night temperatures there to cold air draining off a leaf canopy (which with its low thermal capacity would be a very effective heat exchange surface), and accumulating in the clearing in which Grime's Graves lies. Thus the woodland may well explain the differing night minima found by King at his two sites in the Chilterns.

Results. Figure 4*(a)* shows the average temperature of all the 137 selected nights during the whole 15-month period plotted against height a.v.f., and Figure 4*(b)* shows the average temperatures (using the same nights) of the valley floor stations plotted against height above MSL.

It is seen by inspection that temperature increases with height a.v.f. at the rate of about 1½ degF per 100 ft and that there is a high degree of correlation. Using the method of least squares the regression equation is

$$T = 0{\cdot}014\,H + 36{\cdot}6,$$

with a correlation coefficient of 0·9, where T = temperature (°F) and H = height (ft). Temperatures on the valley floor are almost identical despite differing heights above MSL; see Figure 4*(b)*.

Similar scatter diagrams were constructed for spring 1968 and for the combined springs of 1968 and 1969; see Figures 5 and 6. The regression equation for Figure 6 (combined springs) is

$$T = 0{\cdot}015\,H + 32{\cdot}9,$$

with a correlation coefficient of 0·96.

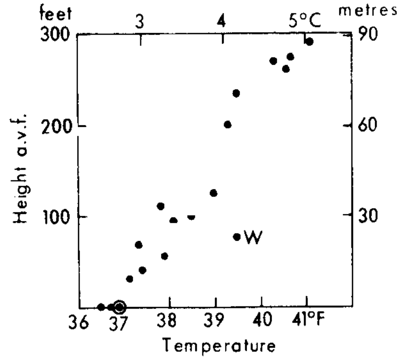

FIGURE 4(*a*)—NIGHT MINIMUM TEMPERATURES PLOTTED AGAINST HEIGHT A.V.F., MARCH 1968–MAY 1969

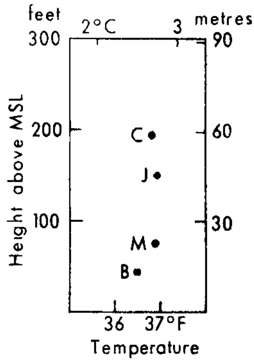

FIGURE 4(*b*)—VALLEY FLOOR NIGHT MINIMUM TEMPERATURES PLOTTED AGAINST HEIGHT ABOVE MSL, MARCH 1968–MAY 1969

19 stations (omitting Hartfield and Brasted), 137 nights

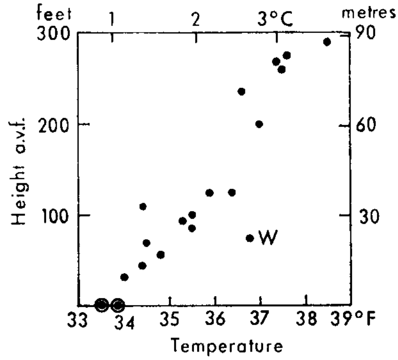

FIGURE 5(*a*)—NIGHT MINIMUM TEMPERATURES PLOTTED AGAINST HEIGHT A.V.F., MARCH–MAY (SPRING) 1968

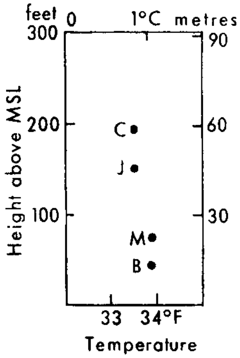

FIGURE 5(*b*)—VALLEY FLOOR NIGHT MINIMUM TEMPERATURES PLOTTED AGAINST HEIGHT ABOVE MSL, MARCH–MAY (SPRING) 1968

21 stations

It has been well established by Geiger[7] and others that, in general, the sides of valleys are warmer at night than both the valley floor and the plateaux on either side. These graphs (Figures 4(*a*), 5(*a*) and 6(*a*)) show an almost linear increase of temperature with height a.v.f., but there are no plateaux observations. During a previous investigation of the area[8] between Linton (L) and a point near Goudhurst (F) an almost linear relationship was also found to extend from the bottom of the valley to 220 ft above MSL. But neither that investigation nor the present one have really covered the highest ground and the use of a network of stations which included stations on flat high-level ground might have indicated lower temperatures at higher levels in agreement with Geiger's findings, although 'plateaux' is scarcely an apt term to describe the hills of Kent.

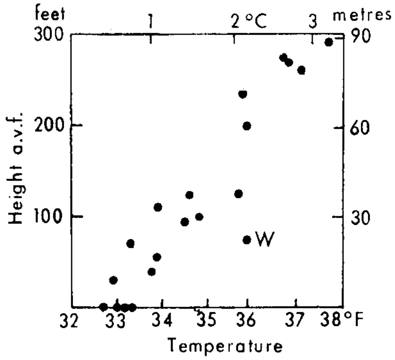

FIGURE 6(*a*)—NIGHT MINIMUM TEMPERATURES PLOTTED AGAINST HEIGHT A.V.F., COMBINED SPRINGS 1968 AND 1969

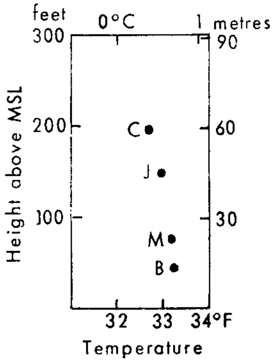

FIGURE 6(*b*)—VALLEY FLOOR NIGHT MINIMUM TEMPERATURES PLOTTED AGAINST HEIGHT ABOVE MSL, COMBINED SPRINGS 1968 AND 1969

20 stations (omitting Hartfield)

Results for selected radiation nights. Figures 4, 5 and 6 deal with many nights on which outgoing radiation was considerably reduced and the overall range of temperature was only 4 to 5 degF between the valley floor and 290 ft above it. It was noticed when logging the data that there were a number of occasions when this range was much greater.

The 137 nights first selected for investigation were therefore reconsidered. The *Daily Weather Reports* for each occasion were examined to find nights during which the effect of radiation was predominant. (It was not found possible to work to any of the objective criteria normally used in papers on night cooling because of the paucity of cloud and wind observations and because a fairly large area was under consideration rather than one station.) Twenty-eight nights were adopted; they were mainly anticyclonic with generally light winds and little or no cloud; see Table IV.

For each station the average of the minimum temperatures on these 28 nights is plotted against height in Figure 7. Here, again, there is a good fit. The overall range of temperature is about 8 degF from the valley floor to 290 ft above it, i.e. the increase of temperature with height is about 2·8 degF per 100 ft. The regression equation is

$$T = 0{\cdot}025H + 34{\cdot}3$$

with a correlation coefficient of 0·9

The increase of minimum temperature with height a.v.f. is in close agreement with the average rate of 2·7 degF per 100 ft found in the mobile survey[8] between Linton (L) and Goudhurst (F).

Extreme variation of temperature with height. Even the 28 nights already discussed covered quite a wide range and in an attempt to isolate an extreme variation of temperature with height the four nights with the greatest temperature/height response were considered; see Figure 8.

TABLE IV—TEMPERATURES ON 28 SELECTED RADIATION NIGHTS

	East Malling	Collier Street	Gatwick	Hadlow	West Malling	Goud-hurst	Wake-hurst	Bodiam	Marsh Green	Cowden	Linton	Marden	Wye	Brench-ley	Kings-north	Throw-ley	Anvil Green	Dodd-ington	East Hoathly
									degrees Fahrenheit										
1968																			
28.3	31·0	28·1	29·0	30·0	30·7	32·0	39·0	28·0	28·1	30·0	36·5	27·5	33·0	31·0	31·2	34·0	41·0	34·2	32·0
8.4	24·2	24·9	22·1	25·0	28·8	24·0	27·0	28·0	20·2	23·0	31·0	23·8	28·0	25·7	25·2	33·0	30·0	27·9	24·1
9.4	24·4	21·3	23·5	22·0	24·6	23·0	29·0	23·0	21·3	22·0	32·5	22·8	25·0	23·5	21·5	28·0	28·0	29·5	20·7
10.4	28·6	26·4	24·8	29·0	33·6	27·0	33·0	25·0	24·0	27·0	33·7	24·8	33·0	30·4	27·9	31·0	36·0	28·4	24·6
25.4	36·8	35·8	35·7	38·0	41·0	37·0	43·0	37·0	36·4	36·0	39·9	35·8	38·0	38·6	35·0	40·0	39·0	37·0	34·9
26.4	33·7	31·3	32·5	31·0	40·1	31·0	41·0	31·0	32·6	32·0	38·4	33·1	33·0	33·8	32·8	39·0	39·0	35·6	30·9
23.5	38·1	36·8	34·5	37·0	42·3	37·0	41·0	36·0	35·0	36·0	42·7	38·1	45·0	38·0	35·9	42·0	45·0	42·1	32·7
31.5	42·2	37·0	38·8	40·0	47·7	40·0	49·0	38·0	37·2	40·0	48·1	38·9	47·0	43·6	45·9	43·0	45·0	39·9	37·9
1.6	42·4	37·0	38·8	39·0	48·2	40·0	45·0	39·0	36·9	39·0	47·1	40·4	48·0	42·9	40·5	44·0	46·0	40·8	37·4
4.7	43·6	39·2	41·0	40·0	42·8	41·0	45·0	42·0	41·3	40·3	45·3	40·9	42·0	42·5	41·3	45·0	45·0	—	38·8
28.7	44·8	40·8	45·0	44·0	50·5	43·0	50·0	43·0	42·3	45·2	47·6	43·5	45·0	46·2	43·8	49·0	50·0	46·6	42·6
19.8	42·3	38·4	39·0	41·0	42·8	43·0	45·0	41·0	39·6	41·2	43·5	39·1	44·0	43·2	40·8	48·0	45·0	46·6	37·6
24.8	51·3	50·3	47·8	52·0	55·0	50·0	54·0	50·0	49·6	49·3	54·9	49·8	55·0	53·3	51·9	55·0	54·0	51·1	49·6
7.9	45·1	40·1	45·7	43·0	52·5	43·0	51·0	42·0	46·4	46·1	51·6	42·5	53·0	45·1	43·1	52·0	50·0	44·8	41·0
10.9	55·4	47·9	54·3	50·0	55·9	56·0	58·0	54·0	52·8	51·9	57·3	49·9	56·0	53·4	54·9	56·0	57·0	53·4	59·4
19.9	43·6	41·3	39·7	43·0	50·4	45·0	45·0	49·0	41·1	41·1	49·0	43·3	53·0	44·1	43·7	49·0	52·0	46·0	44·6
6.10	49·0	45·9	47·7	50·0	49·3	49·0	51·0	50·0	47·8	46·3	51·3	46·1	52·0	49·1	49·5	52·0	52·0	52·2	45·7
15.10	37·9	35·8	37·8	41·0	39·9	43·0	43·0	37·0	38·5	39·3	41·5	36·7	41·0	41·8	38·5	44·0	43·0	44·1	36·7
5.11	31·0	29·7	26·2	30·0	35·6	29·0	36·0	30·0	27·3	31·1	—	28·7	32·0	30·8	31·3	40·0	37·0	34·5	29·7
12.11	31·2	28·0	30·0	30·0	34·5	32·0	38·0	28·0	30·2	32·9	—	29·1	33·0	29·9	33·9	34·0	34·0	31·1	32·4
3.12	30·0	27·0	31·6	29·0	33·6	32·0	37·0	28·0	30·8	28·0	—	29·3	30·0	31·5	30·0	36·0	36·0	31·1	36·1
1969																			
23.2	35·1	35·8	34·3	36·0	37·9	38·0	40·0	37·0	37·9	36·9	40·8	35·8	38·0	35·4	36·3	39·0	39·0	37·9	40·3
7.3	24·3	23·3	19·0	27·0	29·1	23·0	25·0	26·0	22·9	20·9	23·3	22·9	31·0	27·4	24·1	31·0	30·0	28·4	20·8
3.4	26·9	28·0	24·8	31·0	32·0	27·0	36·0	31·0	27·8	26·3	—	27·1	33·0	31·2	32·7	32·0	34·0	31·1	28·2
8.4	38·2	35·3	32·4	35·0	42·1	35·0	42·0	34·0	33·3	32·5	—	36·5	—	39·5	33·6	39·0	39·0	35·4	34·7
9.4	35·2	33·2	33·8	35·0	42·1	37·0	41·0	34·0	34·0	33·5	—	35·5	36·0	39·5	32·8	39·0	43·0	37·6	33·1
20.4	22·1	21·1	21·7	22·0	—	22·0	30·0	21·0	20·4	21·4	31·5	24·3	26·0	25·1	23·6	28·0	28·0	23·7	22·1
7.5	38·7	33·4	39·0	37·0	38·8	41·0	41·0	36·0	36·2	39·2	41·2	35·2	41·0	38·3	34·8	41·0	41·0	—	33·4
Total	10271	9531	9705	10070	11018	10200	11550	9980	9719	9884	9287	9814	10710	10548	10165	11430	11580	9910	9820
Average	36·7	34·0	34·7	36·0	40·8	36·4	41·3	35·6	34·7	35·3	42·2	35·1	39·7	37·7	36·3	40·8	41·3	38·1	35·1

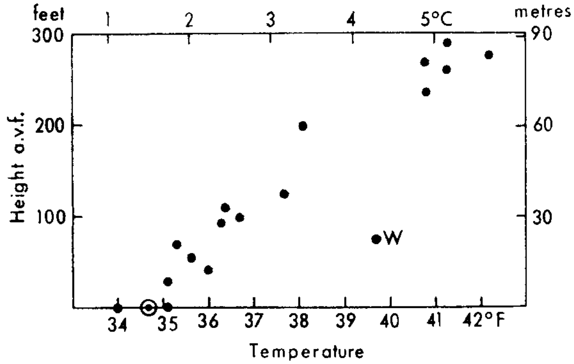

FIGURE 7(*a*)—NIGHT MINIMUM TEMPERATURES PLOTTED AGAINST HEIGHT A.V.F. FOR NIGHTS WHEN RADIATION EFFECTS OUTWEIGHED OTHERS

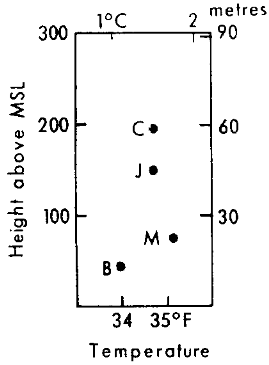

FIGURE 7(*b*)—VALLEY FLOOR NIGHT MINIMUM TEMPERATURES PLOTTED AGAINST HEIGHT ABOVE MSL FOR NIGHTS WHEN RADIATION EFFECTS OUTWEIGHED OTHERS

28 selected radiation nights, 19 stations (omitting Hartfield and Brasted)

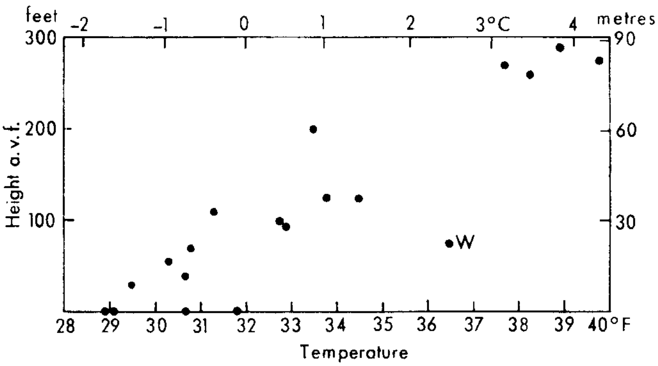

FIGURE 8—AVERAGES OF THE FOUR NIGHTS ON WHICH NIGHT MINIMUM TEMPERATURE INCREASE WITH HEIGHT WAS GREATEST

19 stations (omitting West Malling and Hartfield)

The variation over the 300-ft band was nearly 11 degF, i.e. 3·6 degF per 100 ft. It must be emphasized at this point, however, that this is an average rate over an area the size of a county. Each region must still be treated on its own merits and over short distances, especially near scarp slopes, rates exceeding 9 degF per 100 ft are not uncommon.[8]

It is interesting to note, perhaps paradoxically in this context, that in this set of figures there is a considerable variation of minima along the valley floor. In fact if Figures 4, 7 and 8 are compared it is seen that the variation of valley floor temperatures increases with the variation of temperature with height, albeit to a lesser extent. It is suggested, however, that a possible explanation of this is the spatial variation of the incidence of fog or of high water vapour content. This is far from being a dry valley, containing numerous water courses. Frequent observations across it have shown that there are but few radiation nights on which at least patchy ground fog does not form. Even on occasions of no fog, if there are light winds and a stable stratification of the surface layers there must be a variation of water vapour content sufficient to cause unequal outgoing long-wave radiation. The stronger the outgoing radiation the more cellular the distribution of water vapour in the surface layers.

Frequency of frosts. While the depth of air frost, i.e. night minimum temperature, is important, perhaps, to a horticulturalist at least, the frequency of frosts is even more important. Figure 9 shows the percentage frequency of frosts among the 137 nights first selected for investigation. It is seen that the ratio of the number of frosts on or near the valley floor to the number of frosts at heights exceeding 250 ft above it is very nearly 2:1. It is interesting that this frequency is much the same within 50 ft of the bottom of the valley. Perhaps a constant cold pool concept is applicable here.

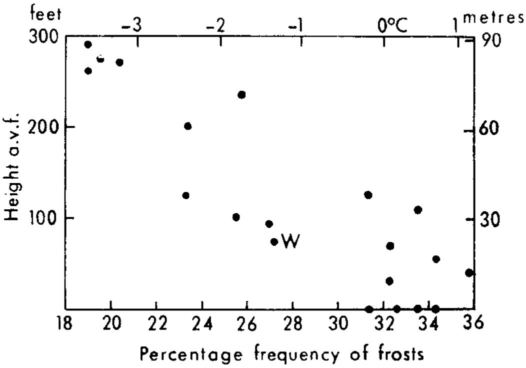

FIGURE 9—COMPARATIVE PERCENTAGE FREQUENCY OF FROSTS
20 stations (omitting Hartfield), 137 nights, 15-month period

Diurnal range of temperature. Until recent times the incidence of a diurnal range of temperature of 40 degF or more seems to have been regarded by climatologists as a rarity anywhere in the British Isles (Hawke[5]). At Greenwich there were no more than 10 examples of a diurnal range reaching or exceeding 40 degF during a period as long as 102 years. Indeed, during the early years of this century variations of a mere 35 degF or so between maximum and minimum temperatures were not infrequently considered worthy of comment in learned publications.

At Collier Street (B) during this short period of 15 months the diurnal range exceeded :

30 degF on 19 occasions, 35 degF on 5 occasions,
38 degF on 4 occasions and 40 degF once.

A range of 50·9 degF has been recorded[5] at Rickmansworth and statistical considerations indicate a limiting value of 55 or 56 degF. Rickmansworth is, however, in a dry valley whereas the Low Weald of Kent has many rivers and streams which must have a mitigating effect, not only because of the absorption of outgoing long-wave radition by water vapour but also because of the slight surface turbulence resulting from the temperature difference between the water and the adjacent land. Although diurnal variations of temperature in Kent are therefore liable to be larger than might have been expected, it seems unlikely that values as high as those found at Rickmansworth would occur.

Notes on particular sites. While it is hoped that the method of analysis outlined above goes some way towards rationalizing the diversity of minimum temperatures in this area, it is obviously not the complete answer and many sites have still to be treated on their own merits.

It was mentioned earlier that the connection between slope of ground and variation of night temperature proved too difficult to handle on the broad scale but it clearly has a marked effect when certain sites are under consideration, since the katabatic winds induced by steep slopes must increase turbulence in the surface layers, effectively entrain warmer air from a level a little above the surface and consequently reduce the rate of cooling at screen level.

Linton (L) is situated on the scarp slope of the Ragstone Ridges and its night minima are high, even considering its height a.v.f., in consequence of the excellent run-off of cold air and the surface turbulence caused by the katabatic wind. Brenchley (O) is also relatively warm for the same reason.

There was one station which defied any form of analysis. This was Wye Agricultural College which makes, of course, most reliable observations. However, when the site was visited (to check, as a last resort, the night minima against the autographic records) it was discovered that not only was the college site contiguous with the township of Wye, but that the instrument enclosure was in close proximity to heated glass-houses some two acres in extent.

It is not surprising, therefore, that for its height a.v.f. it is 'too warm' by 1½ degF on Figure 4 (137 nights) by 3½ degF on Figure 7 (28 nights) and by 5½ degF on Figure 8 (4 nights), i.e. relative warmth increased as the occasion tended to the perfect radiation night.

Conclusions.

(i) The low night minima frequently recorded at Gatwick are applicable to valley floor sites in Kent.

(ii) On average, during selected nights when the minimum temperature was reached during the dawn period, the increase of temperature with height a.v.f. is about 1·5 degF per 100 ft (2·7 degC per 100 metres).

(iii) On nights when the effect of radiation has been predominant this rate is about 3·5 degF per 100 ft (6·4 degC per 100 m) though on exceptional nights and over short distances the rate may be far greater, especially near scarp slopes.

(iv) For stations within 50 ft of the valley floor the frequency of frosts is twice that for stations exceeding 250 ft a.v.f.

(v) High diurnal ranges are found to be quite common.

Acknowledgements. Appreciation must be expressed to the voluntary observers for their support and perseverance; without them the project

would not have been possible. It was suggested that their enthusiasm would wane before sufficient observations had been collected but this was far from the case; only one observer dropped out and a replacement was found immediately. It is most gratifying to record that although the observers were asked to make these observations for 15 months in the first instance, most of them have elected to continue so that ultimately a far more comprehensive study can be made.

In addition, the author wishes to thank Mr G. F. Trowell for making records readily available at East Malling, Mr G. H. Parker for checking the original manuscript, Mr R. J. Ogden for helping prepare the final draft and especially Miss A. M. Davis, who gave invaluable assistance at all stages of the work.

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8. HARRISON, A. A.; Variations in night minimum temperatures peculiar to a valley in mid-Kent. *Met Mag, London*, **96**, 1967, pp. 257–265.

Appendix I

Supplementary stations

B	Collier Street	Mr A. Todd, Jarmon's Farm, Collier Street, Kent.
I	Brasted	Mr R. S. Steven, Court Lodge Farm, Westerham, Kent.
J	Marsh Green	Mr F. W. Gilbert, Magpie Cottage and Mr Bufford, Cornwallis Gardens, Marsh Green, Edenbridge, Kent.
K	Cowden	Mr L. M. Adam, Uphill Fruit Farm, Cowden, Edenbridge, Kent.
L	Linton	Mr G. C. Smith, Loddington Farm, Linton, Maidstone, Kent.
M	Marden	Mr S. Tomsett, Springfield, Marden, Kent.
O	Brenchley	Mr P. J. Gibbons, Bell Cottage, Hatmill Lane, Brenchley, Kent.
P	Kingsnorth	Mr W. J. Chantler, Court Lodge Farm, Kingsnorth, Nr Ashford, Kent.
U	Hartfield	Mr K. W. Paul, Chiswell House, Hartwell Farm, Hartfield, Kent.

Official stations

		Type
A	East Malling	Agrometeorological
C	London/Gatwick Airport	Synoptic
D	Hadlow	Agrometeorological
E	West Malling	Synoptic
F	Goudhurst	Agrometeorological
G	Wakehurst	Climatological
H	Bodiam	Climatological
N	Wye College	Agrometeorological
Q	Throwley	Agrometeorological
R	Anvil Green	Auxiliary
S	Doddington	Auxiliary
T	East Hoathly	Auxiliary

551.515.3

WATERSPOUTS OFF CYPRUS, 14 JANUARY 1970

By W. D. HYDE

Summary. A storm which generated a family of waterspouts is examined for distinctive features. A comparison is made with an earlier case when damaging tornadoes resulted from waterspout activity.

Introduction. Waterspouts occasionally occur in the Mediterranean in almost any season except summer. Until recently they were regarded by meteorologists as interesting but hardly dangerous phenomena. Hardy[1] described the destruction in the south of Cyprus on 22 December 1969 when waterspouts failed to decay on crossing the coastline. That occasion emphasized the need to study situations in which waterspouts are generated and maintained by self-perpetuating storms. An opportunity to do this occurred on 14 January 1970; the outcome of the storm on that day was not nearly as spectacular as on 22 December but a comparison of the two occasions contributes towards a solution of the forecasting problem.

Synoptic situation. The surface and 300-mb charts for 00 and 12 GMT on 14 January 1970 are shown in Figures 1–4. Surface lows centred in the

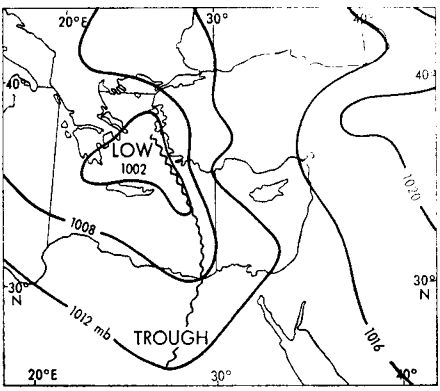


FIGURE 1—SURFACE ANALYSIS, 00 GMT ON 14 JANUARY 1970

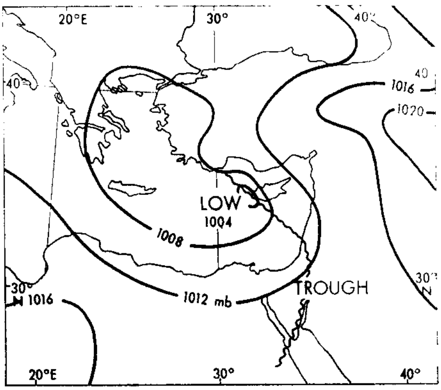


FIGURE 2—SURFACE ANALYSIS, 12 GMT ON 14 JANUARY 1970

Ionian Sea area at 12 GMT on 13 January transferred to the Aegean Sea and subsequently to the west coast of Cyprus, as the rather short upper jet stream propagated east-south-east near the north coast of Africa. By 00 GMT on the 14th (Figure 3) a defined upper vortex at 300 mb near western Crete had separated from the sharp upper trough to the north-west. Atmospherics sources (SFLOCs) were reported near the surface trough over the sea during the 13th and the possibility of a 'severe storm'[2] situation developing in the Cyprus area was considered. The 00 GMT sounding from Episkopi on the 14th (Figure 5) revealed an inversion at 900 mb surmounted by fairly dry mid-level air and a moderate wind shear through the troposphere. The ESSA 8 satellite picture is given at Plate V. This shows a clearly defined rear edge to cloud associated with the surface trough at about 34°N 30°E (i.e. south-west of Cyprus).

To face page 112

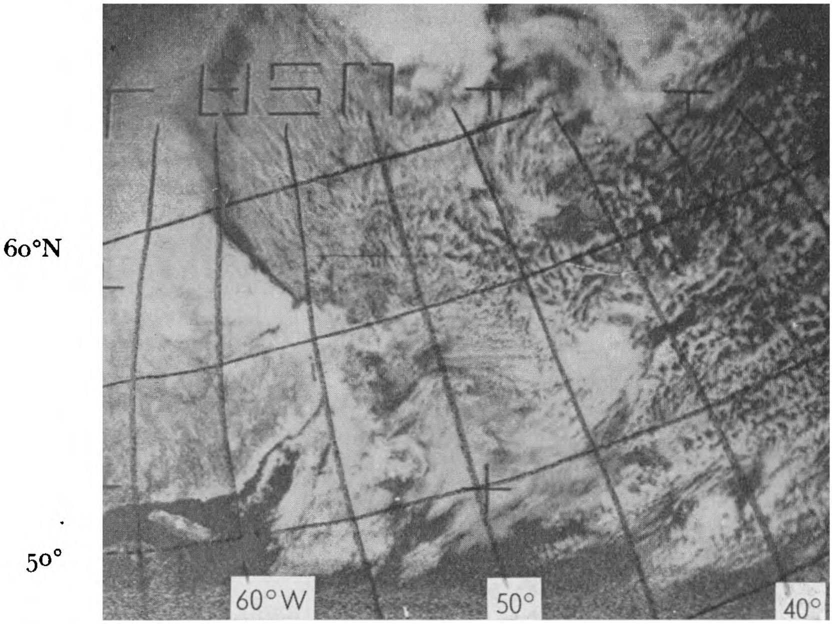


PLATE I—SATELLITE PHOTOGRAPH FROM ESSA 8 AT 1336 GMT ON 20 MARCH 1970
See page 118.

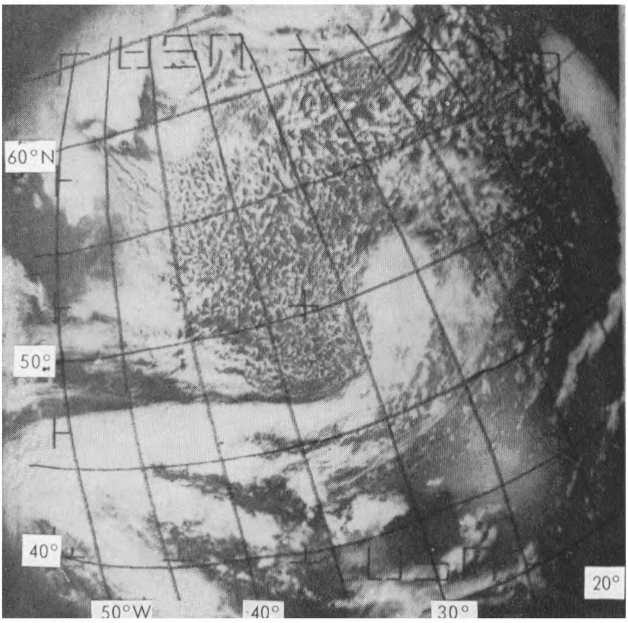


PLATE II—SATELLITE PHOTOGRAPH FROM ESSA 8 AT 1232 GMT ON 21 MARCH 1970
See page 118.

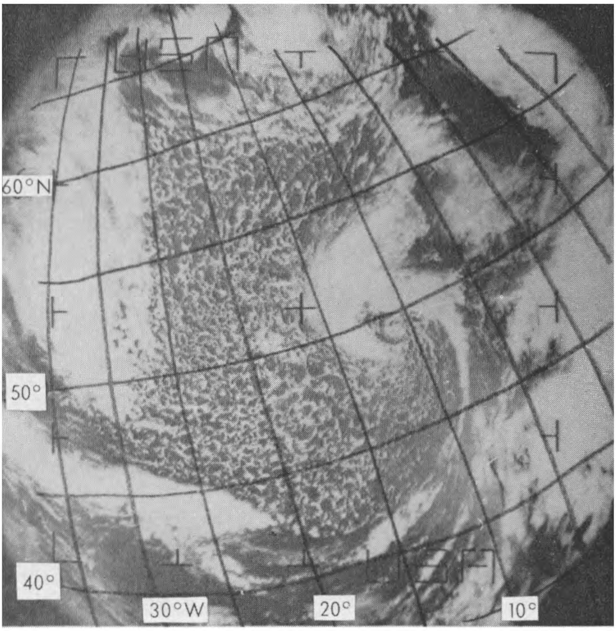


PLATE III—SATELLITE PHOTOGRAPH FROM ESSA 8 AT 1128 GMT ON 22 MARCH 1970

See page 118.

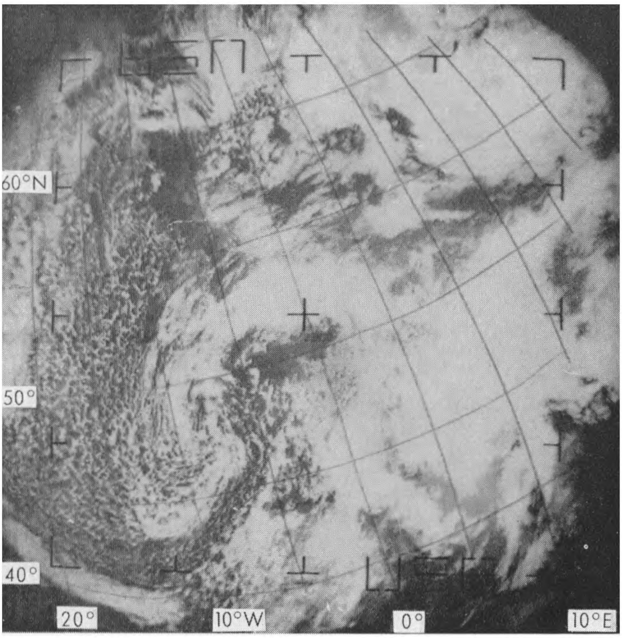


PLATE IV— SATELLITE PHOTOGRAPH FROM ESSA 8 AT 1025 GMT ON 23 MARCH 1970

See page 118.

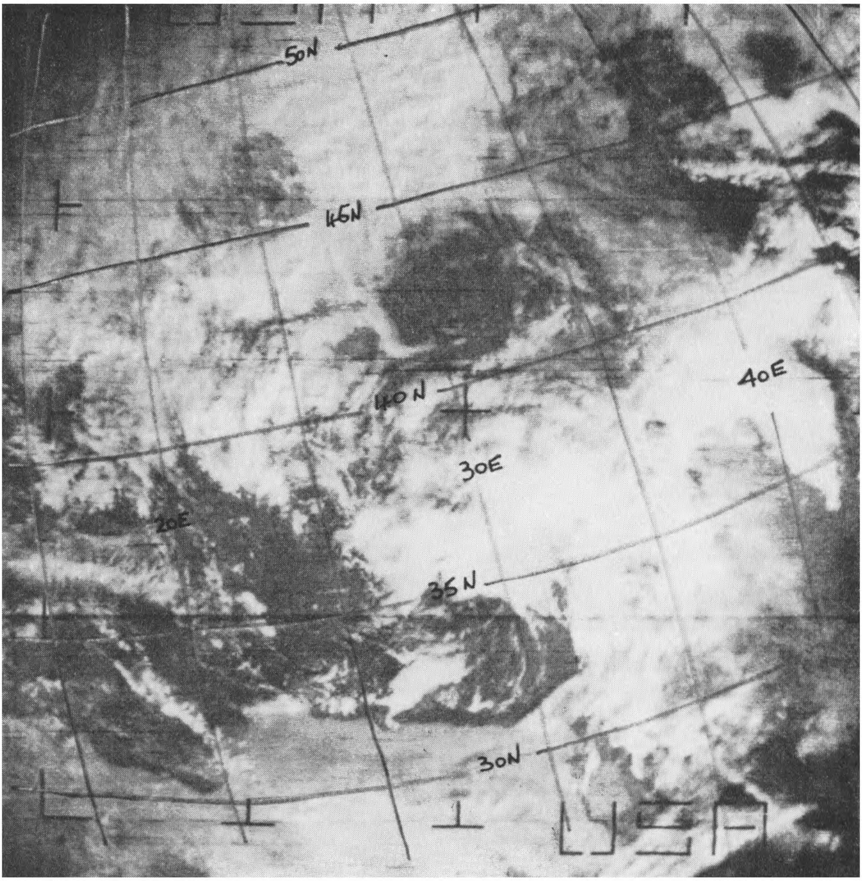
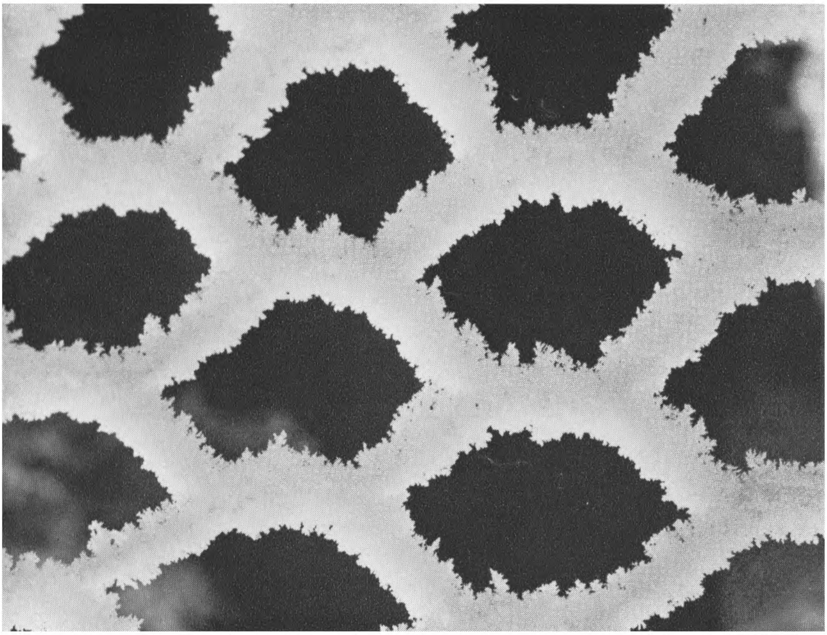


PLATE V—SATELLITE PHOTOGRAPH FROM ESSA 8 AT 0757 GMT ON 14 JANUARY 1970

A clearly defined rear edge to cloud associated with the surface trough can be seen at about 34°N 30°E (see page 112).



Photograph by R. K. Pilsbury

PLATE VI—RIME ON WIRE-NETTING AT BRACKNELL ON 5 JANUARY 1971

The wire-netting has a 2-inch mesh.

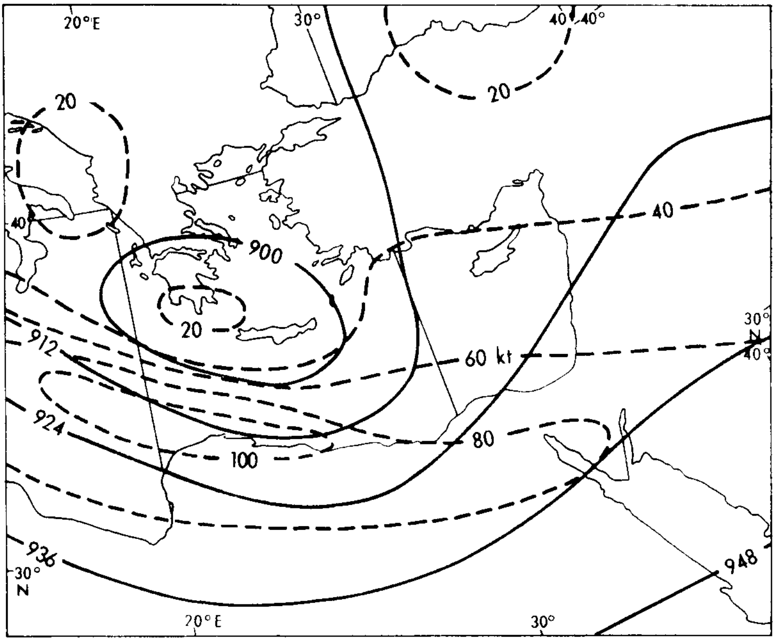


FIGURE 3—CONTOURS AND ISOTACHS AT 300 mb, 00 GMT ON 14 JANUARY 1970
——— Contours at intervals of 12 geopotential decametres
– – – Isotachs at intervals of 20 kt

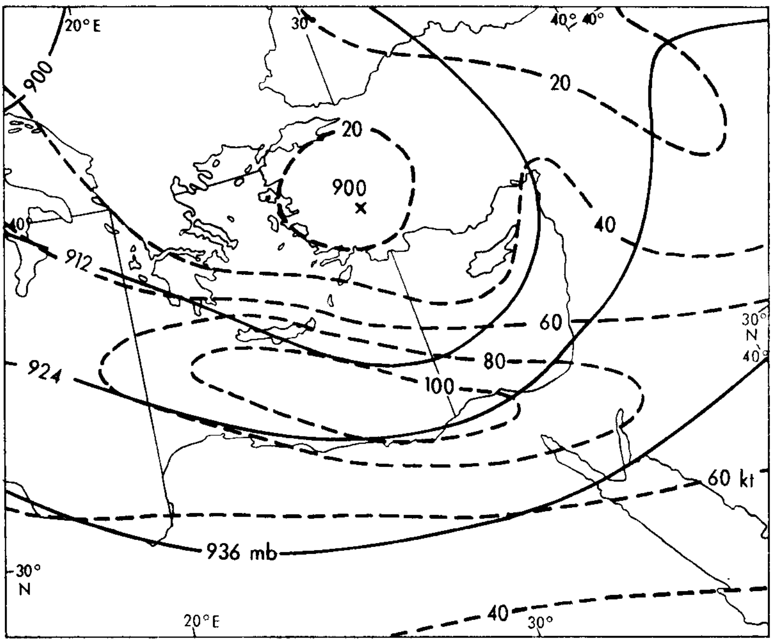


FIGURE 4—CONTOURS AND ISOTACHS AT 300 mb, 12 GMT ON 14 JANUARY 1970
——— Contours at intervals of 12 geopotential decametres
– – – Isotachs at intervals of 20 kt

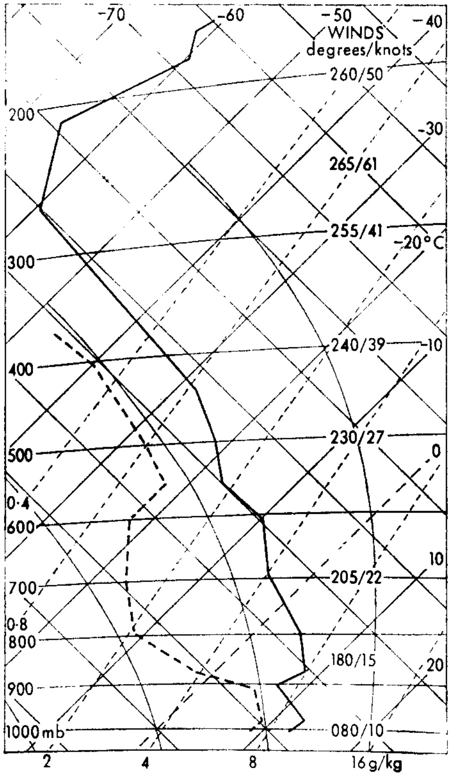


FIGURE 5—EPISKOPI UPPER AIR ASCENT, 00 GMT ON 14 JANUARY 1970
——— Temperature - - - Dew-point

Waterspout detection. Early on the morning of 14 January the crew of the routine flight to El Adem was briefed and attention drawn to the need for information over the sea. The subsequent reports for 0820 and 0830 GMT indicated a very active 'front' with severe turbulence and a wind of 210° 45 knots at 14 000 feet.* The position of the aircraft is shown in Figure 6. The aircraft traversed the trough between cumulonimbus cells; no hail was encountered and no waterspouts were seen. As soon as the report was received at Akrotiri, arrangements were made to monitor developments by radar. The intensity and growth of the radar echoes were judged to be sufficient to merit air reconnaissance. The track of the aircraft is shown in Figure 6. The pilot was directed to descend to low level at the rear edge of the radar echo. Almost immediately he started to report waterspouts at intervals of about 1½ nautical miles. There were about 12 spouts in various stages of development and decay; at least 4 were large and well developed (about 15 yards in diameter at the base). The aircraft then climbed through the cloud, emerging at 34 000 ft. It was turbulent from 10 000 to 25 000 ft, but hail was not encountered. A waterspout was also seen from

* Wind speed, heights and distances are given in traditional British units. Conversion factors are : 1 kt ≈ 0·5 m/s; 1000 ft ≈ 305 m; 1 n. mile ≈ 1·85 km; 10 yd ≈ 9·1 m.

Episkopi at 1225 GMT. Nothing was seen from Akrotiri apart from appendages from the main belt of cloud, which may have been the remains of decaying vortices.

Cyprus weather. There were thunderstorms with abundant small hail; the evening road report from Troodos (about 5000 ft above MSL) indicated hail two inches deep. The main storm damage occurred on the west side of Famagusta, where a citrus-packing house collapsed, a laundry was severely damaged and cars were overturned. Eye witnesses described a swath of minor damage in the same area. This may well have been caused by a small tornado, though a line-squall cannot be entirely discounted. There were no reports of waterspouts off Famagusta.

Radar data. The outlines of echoes received by an airborne radar at 40 000 ft are shown in Figure 6 and these data provide the most westerly

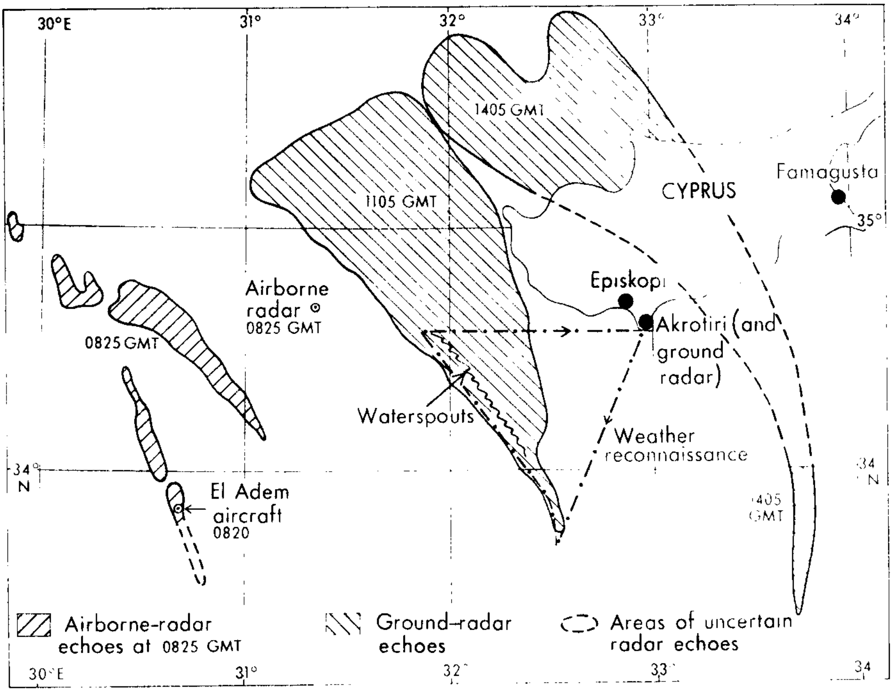


FIGURE 6—RADAR ECHOES ON 14 JANUARY 1970

delineation of the storm. A notable feature is the double line of echoes about 20 nautical miles apart (the radar operators recall a similar structure in the December storm). The El Adem aircraft crossed the rear line, which subsequently degenerated into star-shaped echoes and decayed altogether some two hours later. Meanwhile, the storm to the north was developing and moving towards Cyprus. The other two 'fixes' in Figure 6 are derived from ground-radar photography. They are not strictly comparable with the airborne-radar data but this factor is not important in the overall study. There is some uncertainty about the echo position over Cyprus but the northern and southern extremities are quite distinct. During the air reconnaissance a careful watch was maintained on the ground-radar display for features which might help to identify waterspouts, but there were none. The intensity of the intervening precipitation and the large vertical beam width of the radar negated any chance of success.

Discussion. The movement of the radar echoes in relation to the upper winds is shown on the hodograph (Figure 7). It is clear that the storm travelled towards a direction to the right of and more slowly than the mid-level winds, thus falling into the 'Severe Right' (SR) storm category proposed by Browning.[2] The life of the waterspouts spawned near the rear of the storm is uncertain but the interval between the air reconnaissance and the Episkopi sighting was 1 hour 20 minutes. Comparison of data for 22 December[1] and 14 January reveals many similarities. Those occurring on the synoptic scale assist in the identification of a potential severe-storm situation, which forms a part of normal forecasting practice. On the mesoscale the forecaster is faced with assessing the severity of particular storm systems; or he may be asked to provide guidance on whether or not tornadoes are likely in Cyprus. Table I compares selected features of the December and January storms.

TABLE I—COMPARISON OF METEOROLOGICAL FEATURES ON TWO OCCASIONS OF WATERSPOUTS AT CYPRUS

Meteorological features	22 December 1969	14 January 1970
Cloud tops (by aircraft)	37 000–38 000 ft (very turbulent at 41 000 ft)	35 000–40 000 ft
Maximum number of waterspouts observed in a family at one time	7	12
Waterspout diameter at surface	50 m	15 m
Shear vectors at 12 GMT (deg/kt)		
Surface–850 mb	185/11	190/28
850–700 mb	220/28	230/27
700–500 mb	245/25	315/27
500–300 mb	230/46	325/18
Hail size	Large (1–2 cm)	Small
Inversion at 00 GMT	3 degC at 800 mb	1 degC at 900 mb
700-mb dew-point depression at 00 GMT	10 degC	13 degC

Despite the importance of initial low-level stability and the appropriate vertical distribution of moisture content, the 12-hourly sampling by radiosonde is hardly sufficient to ensure enough detail in the Cyprus area. As far as forecasting waterspouts is concerned, it may be sufficient to assume that stability and moisture content are features inherent in the synoptic situation common to both cases. Hail size may well be a relevant factor in assessing the severity of a storm system since it depends to some extent upon the intensity of convection; the difference between the two storms was very marked in this respect, though the comparison is difficult because the occurrence of large hail may be limited to a small area and go unnoticed. Probably the most important difference to emerge from the comparison concerns the shear in the 500–300-mb layer; note, on Figure 7, the increase above 500 mb on 22 December and the decrease on 14 January. A large shear value in the upper part of the storm favours high-level divergence, which in turn bears on the activity and life of the system. This feature is relatively easy to forecast and is of added significance for this reason.

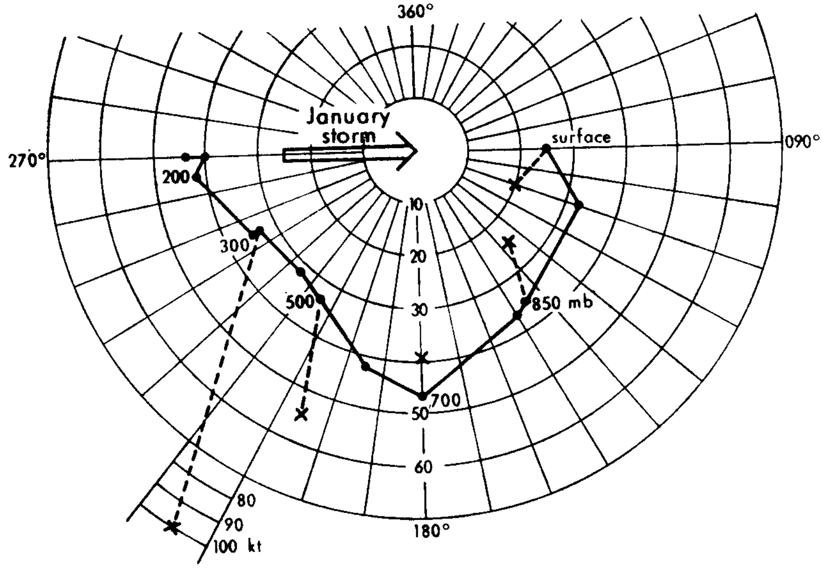


FIGURE 7—EPISKOPI WINDS AT 1119 GMT ON 14 JANUARY 1970 COMPARED WITH THOSE ON 22 DECEMBER 1969

.——. Winds on 14 January 1970 x Winds at 12 GMT on 22 December 1969
– – – Vector difference bewteen 22 December and 14 January

Conclusions. The SR storm on 14 January 1970 spawned a family of waterspouts which were hardly comparable in size with those associated with the December 1969 storm. The features which were especially important in assessing the severity of the storm system were the shear in the 500–300-mb layer and the hail size. In the Cyprus area the best chance of achieving warning of exceptionally large waterspouts, with the possibility of tornadoes, is to use radar for severe-storm diagnosis and tracking, combined with air reconnaissance and a special coastal watch; the forecaster plays an important part in co-ordinating these activities.

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2. BROWNING, K. A.; The organisation of severe local storms. *Weather, London*, **23**, 1968, pp. 429–434.

551.507.362.2:551.511.32:551.576.2

DEVELOPMENT OF COLD AIR VORTICITY MAXIMUM AS SEEN BY SATELLITE

By B. K. LLOYD

Areas of cyclonic vorticity are often visible on the satellite pictures, frequently behind cold fronts. They are easily recognizable in the early stage of development as lines of cumulus curving towards a common centre. With advection of the vorticity centre considerable upward motion takes place in the atmosphere, and middle- and high-level clouds are produced ahead of the centre and form the characteristic 'comma' shape. Some centres develop entirely within the cold air and form a separate cloud system behind a major frontal band while others form along the frontal band itself.

On Friday, 20 March 1970 a complex area of low pressure existed in the northern Atlantic with a broad upper trough at about 45°W. The afternoon picture (Plate I) of the western Atlantic revealed cold-air instability with an area of enhanced cloudiness at 52°N 44°W. This was favourably situated for cyclonic development forward of the diffluent trough (Figure 1). In the

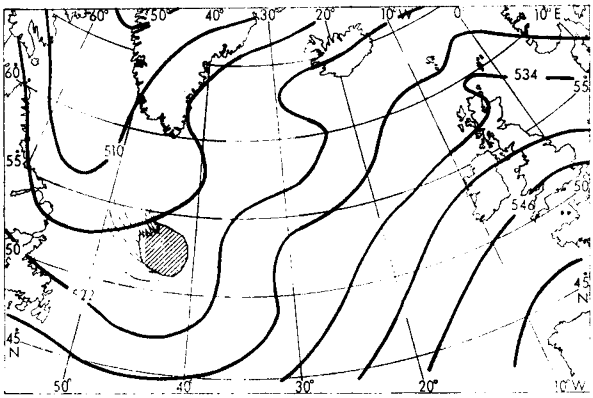


FIGURE 1—THICKNESS CHART FOR 1000–500 mb AT 12 GMT ON 20 MARCH 1970 WITH DIAGRAMMATIC REPRESENTATION OF CLOUD DEVELOPMENT SHOWN ON PLATE I

——— Thickness contours at intervals of 6 geopotential decametres

satellite picture (Plate I) the southern tip of Greenland, the ice off the coast of Labrador, and Newfoundland can be seen.

By Saturday considerable development had taken place and the midday picture (Plate II) showed the cloud mass more organized and 'comma shaped'. The cold air made visible by the convective cells was beginning to be drawn into the circulation. The upper trough had moved eastwards to 27°W and further deepening was likely (Figure 2).

The midday picture (Plate III) on Sunday showed the cold air well entrained into the 'comma' with a clear slot located to the north of the centre indicating no further development (Figure 3). The upper trough was sharpening and there were indications that it would become disrupted.

By midday on Monday the trough was cut off leaving a cold pool to the south-west of the British Isles. The morning picture (Plate IV) still showed the 'comma shape' but the cloud bands had become fragmented with cloud-free areas appearing between the bands. This cloud pattern was associated with a cold pool and a well-developed, but dissipating, surface low. The frontal band had separated from the vortex centre and can be seen lying across Wales and central and eastern England. Northern England, Scotland, Northern Ireland and south-west England were partly cloudy and the English Channel was free of cloud.

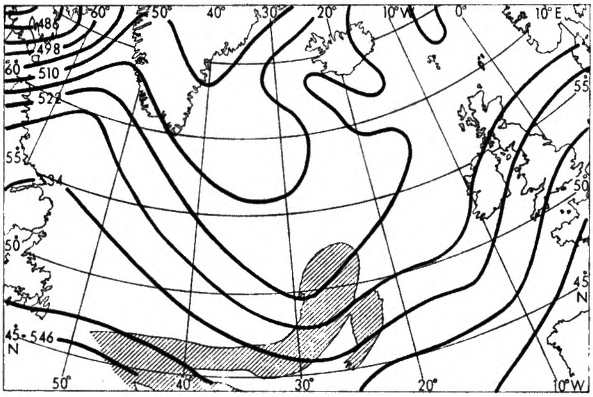


FIGURE 2—THICKNESS CHART FOR 1000–500 mb AT 12 GMT ON 21 MARCH 1970 WITH DIAGRAMMATIC REPRESENTATION OF CLOUD DEVELOPMENT SHOWN ON PLATE II

——— Thickness contours at intervals of 6 geopotential decametres

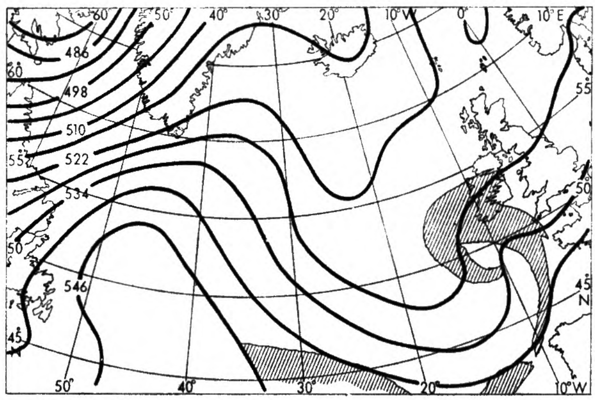


FIGURE 3—THICKNESS CHART FOR 1000–500 mb AT 12 GMT ON 22 MARCH 1970 WITH DIAGRAMMATIC REPRESENTATION OF CLOUD DEVELOPMENT SHOWN ON PLATE III

——— Thickness contours at intervals of 6 geopotential decametres

In conclusion this was an example of the vorticity developing entirely in the cold air and careful examination of the satellite pictures revealed this area of cyclonic vorticity at least 18 hours before it was evident from the surface observations.

REVIEWS

Voeikov Main Geophysical Observatory 1917–1967, M. I. Budyko, Editor. 245 mm × 170 mm, pp. iv + 362, *illus.* (translated from the Russian by Israel Program for Scientific Translations, Jerusalem). Ann Arbor-Humphreys Science Publishers Ltd, 5 Great Russell Street, London, WC1. 1970. Price: £6·30.

The purpose of this volume is to give an account of the scientific work carried out at the Voeikov Main Geophysical Observatory at Leningrad during the fifty years from 1917 to 1967 and the method chosen was the writing, by present staff members, of nearly thirty short papers reviewing the historical development of different aspects of the meteorological research, with very extensive bibliographies. There is also reference to work carried out in the period before that under review, dating back to the foundation of the Observatory in 1849, and since for much of this time the meteorological services were also centred on Leningrad the book effectively gives a survey of the development of meteorology in Russia — a somewhat one-sided survey since the emphasis is naturally on the achievements of the Leningrad group. These have ranged over much of meteorology, being perhaps specially notable in studies of climatology, the energy balance and dynamical meteorology, and many of the foremost figures of pre-war meteorology, such as Mulchanov, Multanovski, Friedmann, Sasinov, appear as contributors to the forward advance as do their equally illustrious successors. The work of the Voeikov Main Geophysical Observatory has commanded great respect in the past, does so even more today and clearly has a bright future to be described in 2017 AD.

E. KNIGHTING

Instant weather forecasting, by Alan Watts. 220 mm × 143 mm, pp. 64, *illus.*, Rupert Hart-Davis Educational Publications, 3 Upper James Street, Golden Square, London W1, 1970. Price: 90p.

This book is not intended for the professional forecaster, but is a sort of do-it-yourself handbook for those engaged in weather-sensitive activities, to help them decide, for example, whether the next few hours will be wet or dry, or windy.

It begins with some very basic ideas: the frontal depression, air masses, and a glossary. There are some brief cloud descriptions and the Beaufort scale. The remainder of the book, about three-quarters, consists of a series of double-page presentations, showing a cloud photograph on one side with an inference and forecast on the other. The user selects the picture most closely resembling the sky he can see, checks from a number of clues (for example wind direction and the relative motions of lower and upper clouds) that he has made the right selection, and then reads the likely developments, given under the headings : wind, visibility, precipitation, cloud, temperature and pressure. It is an attractive little book, substantial enough to be taken and used where it is wanted — in the open air or even at sea.

To the critical reader Mr Watts is disarming. In an introduction he says 'when the sky has a certain look about it then very often a certain sequence of weather follows. There is nothing *certain* about it however.' Nevertheless he suggests that despite the limitations of having to select from only 24 pictures there will be perhaps 75 per cent of occasions when the forecasts will be largely correct. And, of course, one's score might be expected to improve with experience. Mr Watts, who is a former professional forecaster but now a lecturer in physics, does not pretend that there is any quick and easy way to becoming a forecaster, but implies that by building on the experience in the book the layman can do as well as the shepherd of folklore. (Those of us who are professional forecasters might benefit too from lifting our eyes occasionally to study the real sky outside the window!)

There are difficulties in interpretation of some of the cloud photographs, stemming from the omission to state the time of day and direction of the camera. For example, opposite page 40 is a picture of distant cumulonimbus with associated ragged clouds. One might fairly infer that the sky above and behind the observer is as clear as the top part of the picture. Thus the scene becomes an evening sky, with activity confined to the sea in the distance. But the forecast is heavy showers within half an hour or so. On the other hand most of the photographs illustrate very well what the author has in mind, and one should remember that the book is undoubtedly for the reader prepared to persevere. There is an interesting optical illusion opposite page 24; at close quarters it seems to show clearing stratus under a blue sky, yet the description gives a totally overcast, lowering sky, with ragged cloud beneath, and when one stands back to look this is what appears. Indeed all the pictures take on a more realistic perspective when studied from a few feet away.

There are some oddities: cool but fair with good visibility is not an adequate description of returning polar maritime air, and it is puzzling to be told (page 16) that vigorous depressions form some hundreds of miles on the equatorial side of jet streams. There are other examples, important to the meteorologist, but minor in this context. There is a misprint on page 10, Sb for St.

The more this book is studied the more it grows on one. It seems to be an admirable attempt to provide the sportsman and the outside worker with a basis on which to develop a 'weather eye.'

D. J. CLARK

Look and forecast chart, by Alan Watts. 1 m×0·7 m, wall chart in colour, Rupert Hart-Davis Educational Publications, 3 Upper James Street, Golden Square, London W1, 1970. Price: 70p.

This wall chart is derived from *Instant weather forecasting* by Alan Watts. It shows 12 coloured photographs of clouds, a weather map of a frontal depression indicating the relative position of each photograph, and a set of rules for forecasting.

The first four photographs illustrate the changing sky at the approach of a frontal depression. Next come the passage of the warm front, the warm sector and the cold front, shower clouds in polar air, evening anticyclonic conditions and, finally, three photographs of cumulus or thunder clouds.

The initial series of photographs is well chosen, but some implications of the text may easily mislead the inexperienced, for whom, presumably, the chart was designed. It states that low-pressure systems move at about 30 mph; by noting the relative position of the representative cloud picture, and using the printed scale on the weather map, the timing of the passage of the warm front may be forecast. One doesn't need to be a forecaster to see the dangers of over-simplification of the speed aspect. Again, the would-be forecaster is advised to look in the direction from which the wind is blowing for the break at the warm front. Experience suggests that the break, if it appears, is just as likely to come from his right, or even over his right shoulder because of the backing of wind ahead of the front. Incidentally, the photograph showing the approach of the break is indicated as being behind the warm front.

The photograph indicated as being appropriate to conditions just ahead of the cold front is of distant cumulonimbus clouds and includes in the caption the words 'Often hot and airless before storms'. In Watts's book the same photograph is described as being in polar air, and he is quite explicit that conditions are relatively cool and not sultry. Another cumulus picture is indicated as appropriate to the axis of the pre-frontal ridge, whereas a position on the forward side would fit in better both with the cloud and the description 'cool for the time of year'.

Forecasting can be improved, the text goes on to say, if the observer stands with his back to the wind and notes the relative motion of the upper clouds; and nobody would quarrel with that. But the direction of the wind is to be determined from 'low cloud movement, smoke, flags, or a wind vane'. It would be better to concentrate on low cloud, and in its absence to use Watts's rule of thumb of an average backing of 10° or 30° (for sea or land as appropriate) between the wind at low-cloud level (which is the wind required) and the wind at the surface.

The poster is attractive and the layout is very suitable for display in the club house or school, but it is marred by the sort of error indicated.

A more careful distillation of Watts's little book would be most useful.

D. J. CLARK

Aviation climatology, by G. Ya. Narovlyanskii. 245 mm × 170 mm, pp. vi + 218, *illus.* (translated from the Russian by the Israel Program for Scientific Translations, Jerusalem), Ann Arbor-Humphreys Science Publishers Ltd, 5 Great Russell Street, London WC1, 1970. Price: £5.

This is a well-written book which presents an excellent review of methods which have been developed for producing statistical summaries of those meteorological factors which are important for the design or operation of aircraft. A good deal of the material presented relates to methods which have been standard practice for many years but the results of much recent work in the U.S.S.R. are also given. It must also be noted that proper provision of standard World Meteorological Organization climatological summaries obviates the need for some of the indices outlined.

The book has two main parts which consider two basic problems. Chapters 1 to 3 deal comprehensively with the development of climatological indices for use in connection with the provision and use of airports as well as with the operation of air routes. This part of the book is well presented and most aspects of the problem are studied. Chapters 4 and 5 make up the second part which is concerned with the problems associated with preparation of aviation climatological summaries for various regions of the world. This second part is considerably less satisfying than the first.

Chapter 1 is an introductory chapter which looks at general matters related to the processing of climatological data. Chapter 2 deals with the calculation of indices for those parameters which must be allowed for during the design or operation of airports. There is a very full study of wind, temperature, pressure and of cloud/visibility combinations as they affect take-off or landing of aircraft. Problems of airport alternates, airport usability and airport which can be concisely supplied. Chapter 3 passes on to the conditions likely to be experienced along air routes. It gives good reviews of methods for supplying statistics of winds or equivalent winds, wind gradients, jet-stream climatology, temperature in the free air and on cloudiness though the final sections, on icing and bumpiness, are sketchy.

Chapter 4 is concerned with the techniques involved in the preparation of climatological summaries for specific regions. It gives a number of useful suggestions as to the form the summaries should take though no reference is given to the standard layouts which have been recommended in WMO publications. Chapter 5 ably applies the ideas of Chapter 4 to several air routes but the summaries are far too brief to meet many of the requirements of operators. For example, the local conditions at individual airports on the North Atlantic routes are too sketchy to be of real value. The reference to conditions at London/Heathrow Airport is somewhat outdated and misleading as regards incidence of poor visibility.

The book is well produced and amply illustrated though a number of minor editing mistakes remain. It is a translation of the original Russian version and the standard of translation is generally excellent, though occasionally the phraseology used necessitates care in reading. There is no doubt that the book represents good value and should be of use to all those concerned with the supply of meteorological data for the needs of aviation.

J. BRIGGS

The climate of Africa, Part 1, Air temperature and precipitation, edited by A. N. Lebedev. 245 mm × 170 mm, pp. iv+482, *illus.* (translated from the Russian by the Israel Program for Scientific Translations, Jerusalem), Ann Arbor-Humphrey Science Publishers Ltd, 5 Great Russell Street, London WC1, 1970. Price: £8·40.

This volume largely consists of tables of monthly and annual climatological statistics for a large number of meteorological stations in some 48 African states and territories. The tables, occupying well over 90 per cent of the pages, present information on air temperature (749 stations) and precipitation (1564 stations) only. Since the preceding text entitled *Technique of calculating and analyzing climatic parameters* covers not only temperature and precipitation, but also humidity, cloudiness, wind and aeroclimatic characteristics, and refers to tables not included in Part 1, it is assumed that Part 2 will consist almost entirely of tabular material concerning these latter elements.

A considerable part of the data presented has been collected from various existing publications. Those particularly referred to are the Meteorological Office *Tables of temperature, relative humidity and precipitation for the world* and *World weather records* published originally by the Smithsonian Institute, U.S.A., and later by the U.S. Environmental Data Service. Other data sources mentioned are periodical publications of the meteorological services of France, Belgium, Portugal and of the African countries of Morocco, Algeria, United Arab Republic and South Africa. The periods of years covered by the data vary widely but the great majority are in the range 5 to 30 years. They are given separately for each element in a table which also gives the position and altitude of each station.

Some rather surprising statements appear in the introduction. For example, 'There are no sufficiently good current surveys of the climate either of Africa as a whole, or of its individual states'; 'The only known literature on the subject is an old survey of *The climate of the African Continent* published by A. Knoch in 1911'; 'there is at present very little literature on the climate of Africa' and 'The present volume . . . contains in general form all the most up-to-date data on the distribution of meteorological elements . . .'. The authors seem to have been unaware of the existence, for example, of the *Climatic atlas of Africa,* prepared under the direction of Professor S. P. Jackson, with support from the African Regional Association of World Meteorological Organization (Regional Association I) (WMO (RA I)) and published in 1961 by the Commission for Technical Co-operation in Africa South of the Sahara, or of the fact that RA I has been considering the possible revision and improvement of this atlas. Another major work apparently overlooked is *Climate of South Africa* published in nine parts between 1954 and 1966 by the South African Weather Bureau. Even more surprising is that a book which claims to be 'the most complete of all such publications' should not contain a single map.

A good feature of the book, on the other hand, is that it does not simply present a large mass of data, but also gives a procedure for assessing its accuracy. After explaining that the widely spaced network of stations makes it impossible to use existing reduction techniques, nomograms are presented which enable the user to judge the accuracy of any given mean value, making use of standard deviations that have been computed and tabulated for selected stations and the length of the record. This seems to be a useful approach although it might be objected that monthly precipitation amounts are not normally distributed. However, Table 16 gives for a considerable number of stations the 5, 10, 20, 30, 40, 50, 60, 70, 80 and 90 percentiles of monthly precipitation, as well as the highest and lowest values for each month, thus providing a very good indication of the actual distributions.

A number of errors were noticed, the most important being some obviously too large standard deviations of monthly mean temperature for two South African stations in Table 3.

This could be a valuable reference book for those frequently requiring, for places in Africa, monthly temperature or rainfall data not available elsewhere, but those concerned should first compare its value with the soon to be published *Climates of Africa* in the *World survey of climatology* series, edited by H. E. Landsberg (published by Elsevier).

H. C. SHELLARD

A century of weather service: a history of the birth and growth of the National Weather Service 1870–1970, by Patrick Hughes. 225 mm × 150 mm, pp. xii+212, *illus.*, Gordon and Breach, Science Publishers Ltd, 12 Bloomsbury Way, London WC1, 1970. Price: Hardcover £5, paperback £2·50.

This volume has been produced to celebrate the centenary of the founding of the first official weather service in the U.S.A. The writer, who serves in the Environmental Data Service of the Environmental Science Services Administration, has drawn his material from many services, and includes a great number of photographs.

The story he has to tell is one of great complexity and continuous rapid change covering as it does the period of enormous growth and development of the United States itself as well as of the science and practice of meteorology. The size and variety of the national territory and the later global interests of the U.S.A. meant that many kinds of service and many different organizations were developed, which have made a clear account difficult to write. The style is rather that of a publicity brochure than of a serious history, but quantities of dates and names are quoted. In consequence the book is neither a sober balanced account nor a popular booklet: for the latter, concentration on a few main themes would have been necessary. A tendency to journalistic 'purple' language does not encourage reliance on its accuracy of detail. Samples which the reviewer noticed include 'the frozen stratosphere' (which reminds one of the pilot's report of 'solid cloud') and the following sketch of L. F. Richardson 'working for 10 years he solved numerous complex equations to approximate atmospheric behaviour and finally arrived at a forecast'.

Nevertheless there is much of interest, particularly for the early years such as the weather maps of 1870 and 1871, almost completely blank over the then empty western half of the country, the early demand for knowledge of the climate of the newly opened West, and the scale of demand for warnings of forest fire and flood, hurricane and tornado, storms on the Great Lakes and frost and snow.

D. G. HARLEY

Introduction to meteorology, by Franklyn W. Cole. 228 mm × 158 mm, pp. xiv+388, *illus.*, John Wiley and Sons, Inc., Baffins Lane, Chichester, Sussex, 1970. Price: £8·40.

This is another meteorological textbook which follows a well-trodden path in the selection of topics covered. Starting with a general description of the atmosphere and its properties, the reader is led through a discussion of physical processes, atmospheric motion and circulation, weather disturbances and finally applied meteorology. Only in 20 pages of the final section is any serious consideration given to the major problem of weather forecasting.

Where this book differs from most others is that the reader is assumed to be devoid of any prior knowledge of mathematics or physics. It is, in fact, intended for 'college and university liberal arts students who elect a course in meteorology to meet part of their science requirements'. Consequently, in the early chapters much space is devoted to a detailed and thorough verbal description of common physical ideas. To a reader with any acquaintance with the physical sciences gained at school, this part must make rather tedious reading. However, the author, who is Professor of Meteorology and Engineering at Foothill College, Los Altos Hills, California, has had extensive teaching experience in the United States. He had obviously found such painstaking detail justified for the type of student he envisages.

Later chapters in the book make much more interesting reading and Professor Cole does not hesitate to deal with more advanced ideas, even though he is unable to develop them mathematically. For example, the reviewer found the section on frontogenesis and frontolysis well in tune with modern ideas. What a pity then, that in the synoptic treatment of fronts he reverts to the stylized pictures common in textbooks 20 years ago. This particular case illustrates a general weakness. Professor Cole is very sound indeed when dealing with the academic side of meteorology, but appears to be out of touch with the day-to-day work of the synoptic meteorologist. In general though, this is a very well-produced book which will give the non-science student a sound and sympathetic appreciation of meteorology.

The main criticism however, must be of the parochial nature of the book, for rarely does it look beyond the boundaries of the continental United States. Only one reference to a non-American source was found and the whole book is directed to the student in the United States. There is little uniformity in the system of units, degrees Fahrenheit being cheek-by-jowl with degrees Celsius and certainly no mention of SI units is made. There are a number of instances too, where descriptions of observational practices and the behaviour of weather systems could be quite misleading in another context.

P. D. BORRETT

Elements of meteorology, by Albert Miller and Jack C. Thompson. 225 mm × 150 mm, pp. xiv+402, *illus.*, Charles E. Merrill Publishing Company, Columbus, Ohio, 1970. Price: £5.

In the preface the authors state that 'the text is meant for those who are curious about their physical environment but have little formal training in physics and mathematics'. Operating within such constraints they reveal great ingenuity, which obviously stems from the authors' experience as staff members of the Meteorology Department of San José State College, California.

The refusal to use anything but the simplest of mathematics does imply, however, that the standard of treatment of various topics is going to be rather uneven. The subjects of the last three chapters on 'Structure of the Atmosphere', 'Atmospheric Measurements', and the 'Energy of the Atmosphere' are well suited to this type of treatment. As a result the authors have achieved a complete and up-to-date account. On the other hand, Chapter 4 on 'Atmospheric Motions, Causes' suffers badly from the lack of mathematics, and the standard appears rather elementary compared to the foregoing chapters. The next two chapters on 'Atmospheric Motions; Circulation Patterns' and 'Atmospheric Motions; Vortices' again lend themselves well to the descriptive approach. The idea of scales of motion is particularly well developed but it is a pity that the discussion of frontal depressions is restricted to such a simple idealized model.

Whereas the first part of the book is primarily theoretical the last few chapters deal essentially with applied meteorology. The topics are Climate, Weather Forecasting, Application to Agriculture, Aviation, Industry, etc., and finally the Modification of Weather and Climate. Generally the treatment is comprehensive and well balanced although the discussion on Weather Forecasting appears to describe the situation a few years ago, before the more recent strides in numerical forecasting. It is in this latter part of the book that the reader is made particularly aware that it has been written with the student in the United States very much in mind. Consequently, the European reader may gain the impression that forecasting is a much simpler process than it actually is on the western margin of a continent. The applications of meteorology to industry and agriculture are however readily applicable to a European environment.

Although they have used little mathematics, the authors are to be congratulated on the way in which the reader is made aware of orders of magnitude at every stage, frequently by reference to every-day events. The collections of problems at the end of each chapter are very valuable both to students and teachers. The book is handsomely bound, the diagrams clear and apposite and the printing excellent. All in all the authors have succeeded in producing an interesting, accurate and very readable text.

It is difficult to imagine the person who would not wish to supplement this volume with a more specialized textbook. However, it is to be recommended as background reading to teachers incorporating meteorology in a general science course, to Scientific Assistants in the Meteorological Office, to mariners and to pilots of both powered aircraft and gliders. The book is probably rather expensive for most people who wish to acquire an individual copy, but it would be a very worthwhile addition to the shelves of many libraries.

P. D. BORRETT

OBITUARY

It is with regret that we record the death on 5 January 1971, of Mr G. W. Hurst, B.Sc., D.I.C., Principal Scientific Officer.

HONOUR

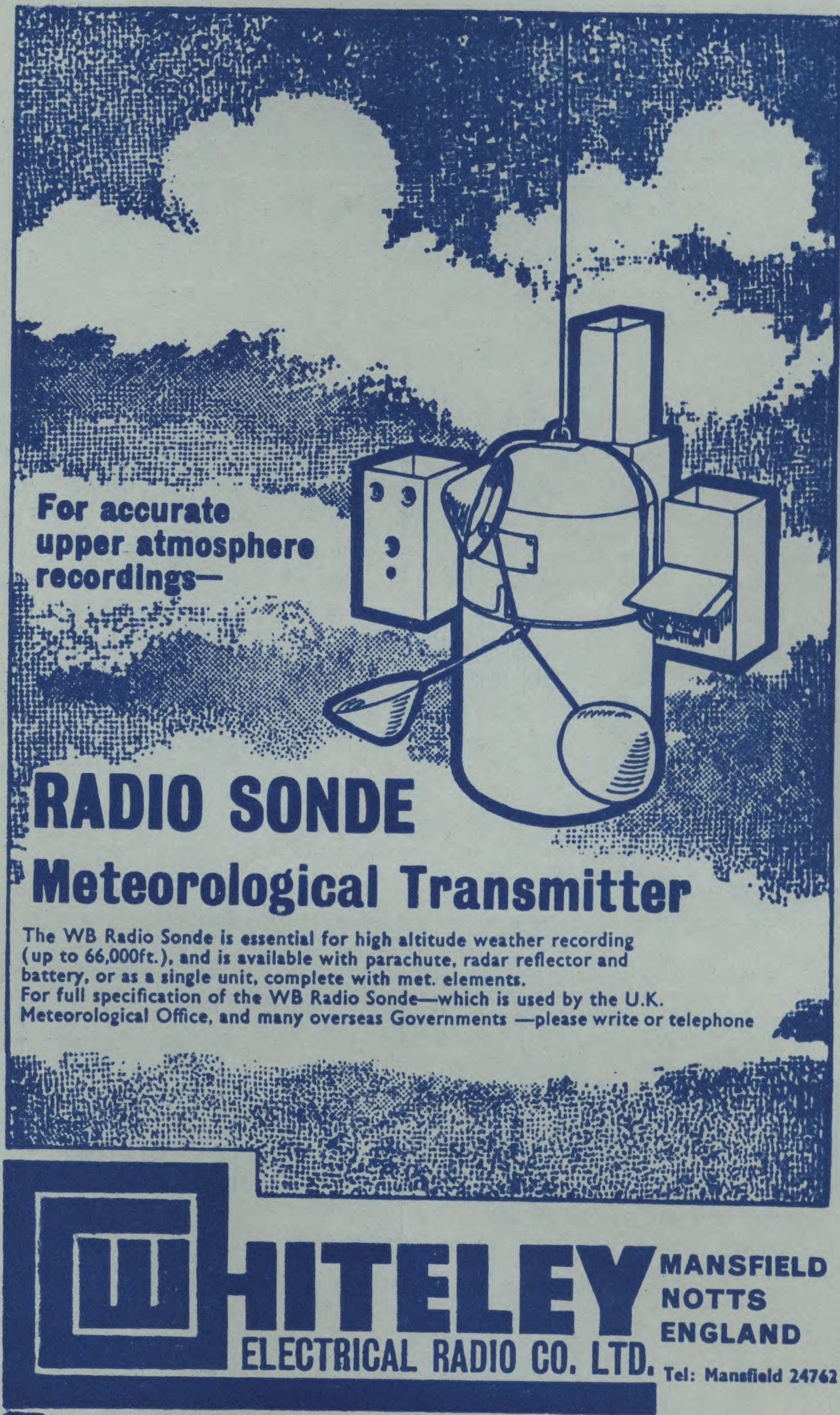
The following award to a member of the Meteorological Office was announced in the New Year's Honours List, 1971 :

O.B.E.

A. A. Worthington, Assistant Director (Telecommunications).

CORRECTION

Meteorological Magazine, February 1971, Plate V: delete 'Mr D. N. Axford, winner of the second Memorial Award' and insert 'Mr D. P. Smith, winner of the Meteorological Observers' Award'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THE METEOROLOGICAL MAGAZINE

VOL. 100 NO. 1185 APRIL 1971

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the meteorological magazine

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A Course in Elementary Meteorology

This book has been written for the weather observer, to explain how the physical processes occurring in the atmosphere determine our weather. As an introductory textbook of theoretical meteorology it requires of the reader only a modest knowledge of physics, equivalent to that of the 'O' Level of the G.C.E. More advanced ideas are introduced as required. Each chapter combines the results of modern research with older ideas, and the selected bibliographies will enable the reader to extend his studies. The physical approach enables far more explanation to be given than is normally found in elementary books, which are often largely descriptive, but at the same time the extensive mathematics of advanced textbooks is avoided.

The book has been written primarily for observers ashore in the U.K., but the general meteorology is treated in an interesting and modern way, and it might prove useful to some mariners.

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METEOROLOGICAL OFFICE Met.O.841

THE METEOROLOGICAL MAGAZINE

Vol. 100, No. 1186, May 1971

551.551.21:551.553.6:629.7.08

A NOTE ON THE OPTIMUM AVERAGING TIME OF WIND INFORMATION FOR CONVENTIONAL AIRCRAFT LANDINGS

By W. R. SPARKS and BARBARA KEDDIE

Summary. From detailed analysis of wind measured by a single anemometer 10 metres above open level ground, and consideration of Shiotani's observations with a horizontal array of anemometers, it is concluded that the optimum averaging time for wind measured by a single anemometer should not be less than four minutes.

Introduction. At some stage during an aircraft approach it is necessary to pass to the pilot the wind expected in the touch-down area at the time his aircraft will reach that area. Since it is not possible to site a conventional anemometer in the touch-down area this necessitates the extrapolation of measured wind information in both time and space, and prompts the question : what can be measured with the normal airfield anemometer to give the best estimate of the wind that an aircraft will encounter in a different position and at a later time?

Before it is possible to begin to answer that question, what information the pilot requires must be known. There is no general agreement on this, but discussions with aviation experts suggest that the average wind over a period of 4 or 5 seconds just before touch-down when the aircraft is descending from about 30 m to 15 m is of critical importance. During that period the aircraft would travel about 300 m. If the validity of Taylor's hypothesis of frozen turbulence is assumed (Panofsky *et alii*[1]), the analogous measurement from a stationary anemometer is the average speed of a 300-m run of wind (U_{300}).

Let the wind measured at the anemometer be averaged over a time T to obtain a value U_T and that average be used as an estimate of U_{300} at some later time. How wrong can it be? A good measure of the errors is the root-mean-square difference between U_{300} and U_T divided by σ_{300}, the standard deviation of U_{300} over N observations, i.e.

$$(1/\sigma_{300})\sqrt{\Sigma\,[(U_{300}-U_T)^2/N]}.$$

Results and discussion. From observations made with an anemometer 10 m above flat open country at Cardington (near Bedford), the above ratio has been calculated for averaging times T from $\frac{1}{2}$ minute to 15 minutes. (The observations are described in Appendix I.) The ratio does of course depend on the interval between the observation of U_T and the time that U_{300} is required, see Appendix II. Two intervals have been considered, 10 minutes and zero minutes. The results of these calculations are shown n Figure 1.

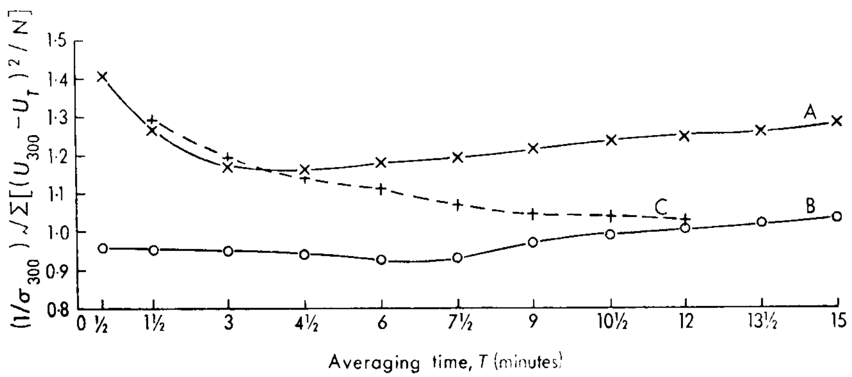

FIGURE 1—ERRORS IN ESTIMATING U_{300} FROM U_T (AVERAGED OVER SIX DATA RUNS)

A For a 10-minute interval between U_T and U_{300}
B For a zero time interval between U_T and U_{300}
C Theoretical curve for zero correlation between short-period means at two points

Curve A, which gives the results when there is a 10-minute interval between the observation and its use, i.e. between the end of the averaging time T and the beginning of the run of wind, shows that the minimum error is made when an averaging time of 4 to 5 minutes is used. Curve B shows that even when the information is used immediately after the observation, no increased accuracy is obtained by reducing the averaging period to any less than the 4 minutes suggested by curve A.

Curves A and B show the results that would be obtained if the anemometer could be sited in the touch-down area. Consider now the effect of measuring some distance from that area. The reduction in accuracy is a function of the correlation between the wind at the measuring point and the wind in the area of interest. This correlation depends on the separation between the instrument site and the area of interest and the averaging periods used.

On a normal airfield the anemometer would be several hundred metres from the touch-down area. The results from Shiotani's[2] observations with a horizontal row of anemometers suggest that the correlation between the airfield anemometer's indication of short-period means and simultaneous observations in the touch-down area could well be zero.

Curve C, determined as in Appendix II, shows the errors in estimating U_{300} in the touch-down area if the long-period means (say hourly running means) at the anemometer and in the touch-down area are equal and constant but the variations of the short-period means about the long-period mean are uncorrelated at the two points. The variances of U_{300} and U_T used to construct curve C were the values measured at Cardington during Run No.3 (see Appendix I).

If the anemometer is sited a considerable distance from the touch-down area, curve C is applicable and it can be seen that any attempt to use an averaging period of less than the 4 minutes suggested by curve A would increase the errors even if the information were used immediately after the observation.

It has been demonstrated that, even if the wind information required by the pilot is a mean over a shorter period, the best estimate of the required information that can be obtained from a conventional anemometer is a mean value over a period of at least 4 minutes. It would also be possible, and may be desirable, to give the pilot some measure of the uncertainty of the estimate.

Although these conclusions are based on limited data (Appendix I) they are in excellent agreement with those of Rijkoort and Wieringa[3] and it is reasonable to assume that they are applicable to the well-stirred conditions in neutral equilibrium which accompany strong winds near the ground. The sudden arrival of squalls associated with the near approach of thunderstorms or the passage of a cold front would probably prove to be a source of large errors, but such errors would be expected in any method relying on observations from a single anemometer. There is however, a need for information on the effects of spatial separation between the anemometer site and the touch-down area.

Appendix I

Description of data analysed. The data were obtained from a three-cup anemometer with a distance constant of 5 m and a wind vane with a sine/cosine potentiometer. The data analysed were the westerly components of winds from directions between 240 degrees and 280 degrees. The anemometer was sited 10 m above open level country at Cardington. The site was fully described by Giblett[4] in 1932 and has not changed significantly since that time. The data were logged on 31 March 1969. During most of the period Cardington was in a warm sector and the winds were sufficiently strong to ensure near neutral stability. The mean wind was not, however, steady; during one data run it changed by about 10 kt in three minutes.

The data were logged at one-second intervals with each data run lasting about 50 minutes. The main features of the wind during each run are shown in Figure 2 by plots of consecutive one-minute means for Runs 2, 3 and 5. The features of Runs 1, 4 and 6 are similar to those of Run 3.

Figure 1 (page 130) shows average values over all six runs of the ratio

$$(1/\sigma_{300})\sqrt{\Sigma[(U_{300}-U_T)^2/N]}.$$

Figures 3 and 4 show the same information for individual runs.

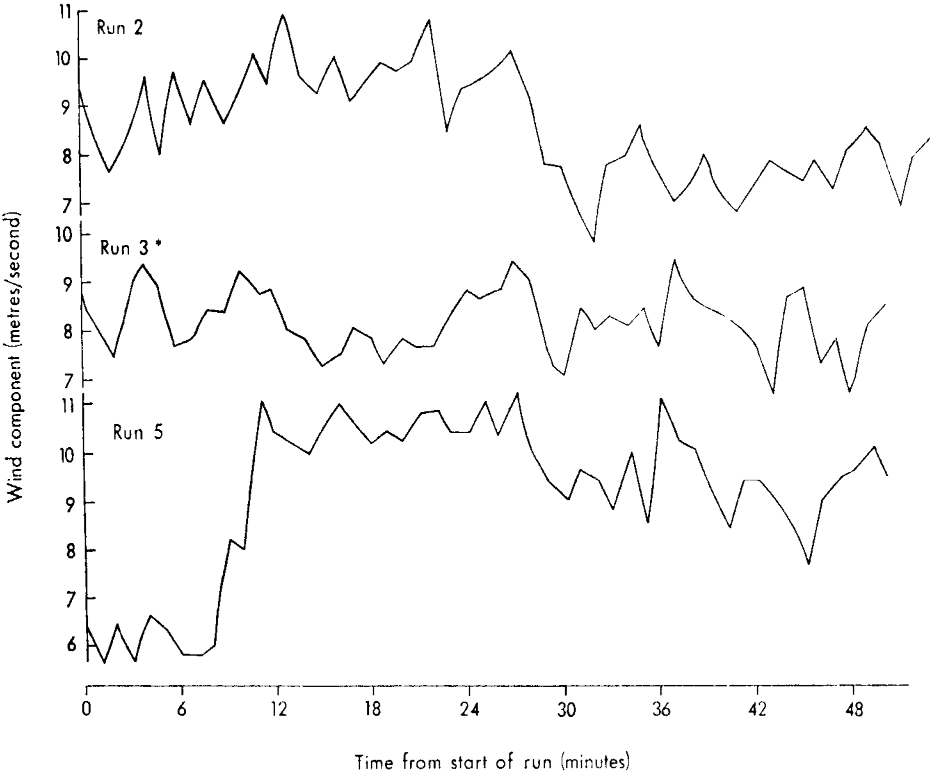

FIGURE 2—ONE-MINUTE MEANS OF THE WESTERLY COMPONENT FOR RUNS 2, 3 AND 5

* Runs 1, 4 and 6 show similar features.

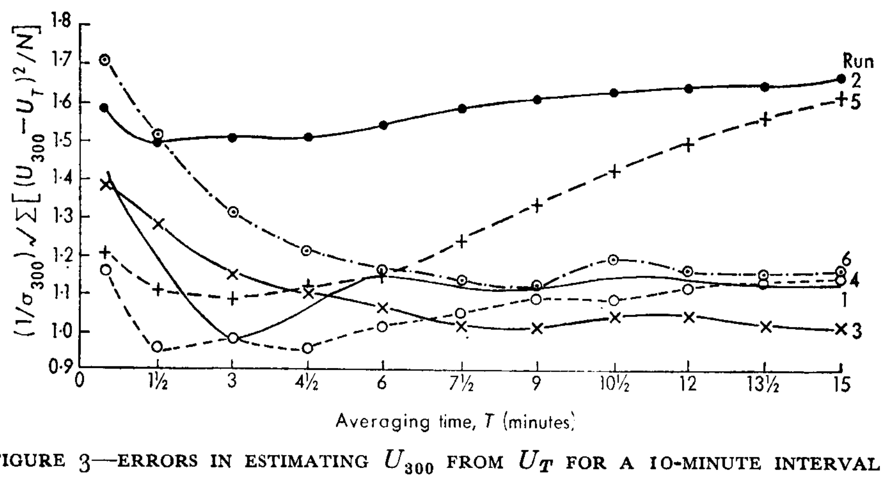

FIGURE 3—ERRORS IN ESTIMATING U_{300} FROM U_T FOR A 10-MINUTE INTERVAL BETWEEN THE TWO OBSERVATIONS

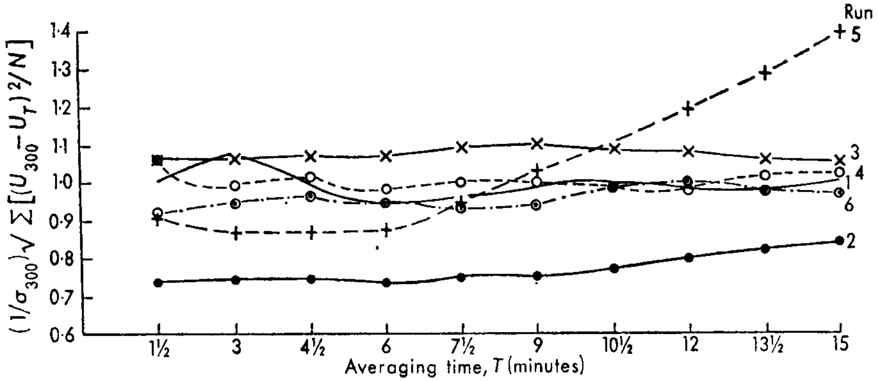

FIGURE 4—ERRORS IN ESTIMATING U_{300} FROM U_T FOR A ZERO TIME INTERVAL BETWEEN THE TWO OBSERVATIONS

Appendix II

The construction of the theoretical curve for zero correlation between short-period means at two points. U_T can be expressed as the sum of a long-term mean U_M appropriate to the mid-point of the interval T and the departure U'_T from that mean, i.e. $U_T = U_M + U'_T$.

Also U_{300} can be expressed as the sum of a long-term mean U_m appropriate to the mid-point of the interval of time for U_{300} and the departure U'_{300} from that mean, i.e. $U_{300} = U_m + U'_{300}$.

Consider the term

$$F = \frac{1}{N} \Sigma (U_{300} - U_T)^2,$$

where N is the number of observations of U_{300};

$$\mathrm{F} = \frac{1}{N} \Sigma (U_m - U_M + U'_{300} - U'_T)^2$$

$$= \frac{1}{N} \Sigma (U_m - U_M)^2 + \frac{2}{N} \Sigma (U_m - U_M)(U'_{300} - U'_T) + \frac{1}{N} \Sigma (U'_{300} - U'_T)^2.$$

The second term will be zero if the difference between the two departure terms is not correlated with the trend in the long-term mean.

$$\text{Then } F = \frac{1}{N} \Sigma (U_m - U_M)^2 + \frac{1}{N} \Sigma (U'_{300})^2 + \frac{1}{N} \Sigma (U'_T)^2 - \frac{1}{N} \Sigma 2 U'_{300} U'_T$$

$$= \frac{1}{N} \Sigma (U_m - U_M)^2 + \sigma^2_{300} + \sigma^2_T - 2r\sigma_{300}\sigma_T,$$

where r is the correlation between the variations of the short-period means from the long-period means.

This final equation for F may be used to explain the construction of curve C in Figure 1. If the long-period means at the anemometer and in the touch-down area are equal and constant, i.e. $U_m = U_M$ = constant, but the variations of the short-period means about the long-period means are uncorrelated at the two points, i.e. $r=0$, the expression for F becomes

$$F = \sigma^2_{300} + \sigma^2_T = \frac{1}{N}\Sigma(U_{300} - U_T)^2.$$

Hence in the construction of curve C, the ratio

$$(1/\sigma_{300})\sqrt{\Sigma[(U_{300} - U_T)^2/N]}$$

becomes

$$\sqrt{(1 + \sigma_T^2/\sigma_{300}^2)}.$$

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SOME ASPECTS OF WIND INFORMATION REQUIRED IN THE LANDING OF AIRCRAFT

By BARBARA KEDDIE

Summary. Wind measurements were made each second with a single anemometer over a period of about an hour for six independent wind régimes. Detailed analysis was made of the maximum difference between a mean speed U_T measured over $4\frac{1}{2}$ minutes and the speed U_{300} 10 minutes later over a 300-m run of wind. The maximum value of $U_{300} - U_T$ in various samples of sizes from 4 to 20 minutes was predicted by assuming a normal distribution. Theoretical curves were derived which were in reasonable agreement with curves drawn from the analysed data. Actual values were also compared with predicted values of (i) maximum deviation of $U_{300} - U_T$ from the mean in various samples, and of (ii) the maximum difference in various samples.

Finally comparison was made of data from different sampling periods or runs of wind so that if the maximum departure of one sample from the mean wind was known the maximum departure for other samples could be estimated.

Introduction. Pilots and others concerned with the operation of aircraft need a description of the airfield low-level wind which is used as a forecast of the wind expected a few minutes later as an aircraft touches down. At present the pilot is given the 'surface wind' by the controller about 10 minutes before touch-down. The problem is to find what information could be given to the pilot which would best describe conditions 10 minutes later.

The behaviour of the wind in the last 30 m of descent, in particular between 30 m and 15 m, is most important to a descending aircraft whether a manual or an automatic landing is being carried out. An aircraft normally travels about 300 m while descending from 30 m to 15 m, thus the 300-m run of wind defines one scale of eddy of importance to aviation. Therefore it would be useful to find a measurement which is representative of the 300-m run of wind 10 minutes later.

It has been assumed here that Taylor's hypothesis of frozen turbulence holds. According to this hypothesis a space correlation in the direction of mean wind, x, can be determined from the time correlation function by replacing time t by x/u, where u is the mean wind speed (Panofsky[1]).

By comparing the mean speed over a 300-m run of wind with that measured over a period T ending 10 minutes earlier, for values of T between 1½ and 15 minutes, the optimum averaging time T has been found to be at least 4 to 5 minutes (Sparks and Keddie[2]). For the limited data considered here, the best estimate of the mean wind speed over 300 m to be expected in 10 minutes' time was taken to be the mean speed over the last 4½ minutes, as longer averaging times did not appear to give an improvement in the accuracy of the estimate.

A pilot also requires information on the gustiness of the wind, but the anemometers in general use on airfields cannot measure gusts on a very small linear time-scale. At Cardington there is an anemometer placed 10 m above flat open country from which a read-out every second can be obtained (see Sparks and Keddie, Appendix I). By adding together the run of wind for successive seconds until a 300-m run has been obtained and dividing by the number of seconds, the mean wind speed over a 300-m run of wind can be found. Similarly mean speeds can be found for other lengths of run of wind. By comparing the wind extremes for different runs of wind a relationship might be determined whereby, if the maximum speed of one run of wind was measured, that of a different run of wind could be estimated.

Data available. The data used were obtained during six Runs at Cardington on 31 March 1969; details are given in Table I. A warm front passed through the station just after 08 GMT and the associated cold front passed between 17 and 18 GMT followed by a trough soon after 19 GMT, i.e. near the start of Run 5. The data consist of a read-out every second of the westerly component for winds from between 240 and 280 degrees, measured in metres per second at a height of 10 m (see Sparks and Keddie, Appendix I).

TABLE I—DATA OBTAINED DURING SIX RUNS AT CARDINGTON ON 31 MARCH 1969

Run number	Start time	Duration		Mean speed	Mean direction
	GMT	*min*	*s*	*m/s*	*degrees true*
1	1313	48	19	13·7	240
2	1555	55	56	12·0	240
3	1702	52	28	11·2	245
4	1805	52	58	10·5	245
5	1906	53	0	11·7	260*
6	2004	52	55	11·2	265

* Discontinuous, 250° at first becoming 270° after 3 minutes gradually backing to 255° by 1945 GMT.

For successive 300-metre runs of wind the mean speed U_{300} was found and compared with U_T, the mean wind speed over a $4\frac{1}{2}$-minute period ending 10 minutes earlier. The mean of the differences $(U_{300}-U_T)_m$, and standard deviation of the differences σ_{300-T}, were calculated for each Run. If the differences are normally distributed a prediction within given confidence limits can be made of the maximum $(U_{300}-U_T)$ likely in a given period with a steady régime.

Comparison of values predicted for the maximum $(U_{300}-U_T)$, assuming a normal distribution, with those actually obtained. Assuming a normal distribution, the probable maximum value of $(U_{300}-U_T)$ in a sample of N values may be defined either as (i) the value likely to be equalled or exceeded once in a sample of N (Durst[8]), or as (ii) the value likely to be exceeded once in a sample of $2N$ (Brooks and Carruthers[4]).

Samples of 8, 16, 24 and 32 values of $(U_{300}-U_T)$ were considered, 30 random samples of each size being taken for each Run. The mean maximum of $(U_{300}-U_T)$ was found for each set of 30 samples and standardized by subtracting $(U_{300}-U_T)_m$ and dividing by σ_{300-T} to facilitate comparisons with predictions based on normal distributions. Figure 1 shows the results together with curves, normal (1) and normal (2), determined from the normal distribution for definitions (i) and (ii) of the probable maximum value.

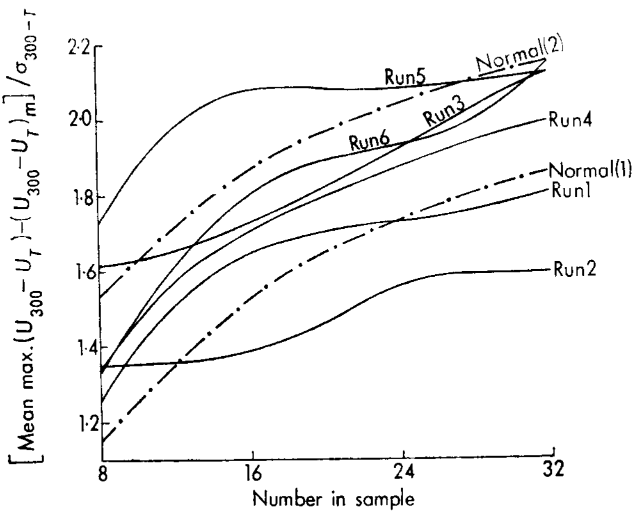

FIGURE 1—COMPARISON OF MEAN MAXIMUM $(U_{300}-U_T)$ OBTAINED IN RANDOM SAMPLES OF VALUES OF $(U_{300}-U_T)$ WITH THE MAXIMUM PREDICTED ASSUMING A NORMAL DISTRIBUTION

Definition (i) is perhaps more appropriate to the way in which the maximum is found from the samples. The curves are seen to be in reasonable agreement, except for Runs 2 and 5. Near the beginning of Run 5, there was a large increase in wind speed, about 10 kt in 3 minutes, and therefore there were some values of $(U_{300}-U_T)$ at the beginning of the Run which were much larger than the mean. The probability of one of these large values being included in a random sample is quite high, especially in the larger samples, and so the 'mean maximum' is likely to be high. On the other hand, in Run 2 there was a decrease in wind speed in the middle of the Run, leading to several large negative values of $(U_{300}-U_T)$. This lowered the value of the mean maximum and also led to a large standard deviation, and hence the values plotted for Run 2 seem abnormally low.

Thus it seems reasonable to assume a normal distribution, at least in cases where there are no rapid and permanent changes of the wind, and to use definition (i). However, in practice it is not random values of $(U_{300}-U_T)$ that one is concerned with, but the maximum gust which is likely in a certain length of time, or in a certain number of consecutive values of $(U_{300}-U_T)$. Since a 300-m run of wind took from 30 to 40 seconds, sample sizes of 8 to 32 consecutive runs of wind represent time intervals of from about 4 to 20 minutes, which is adequate for the consideration of prediction for 10 minutes ahead. Figure 2 shows the results obtained using samples of 8, 16, 24 and 32

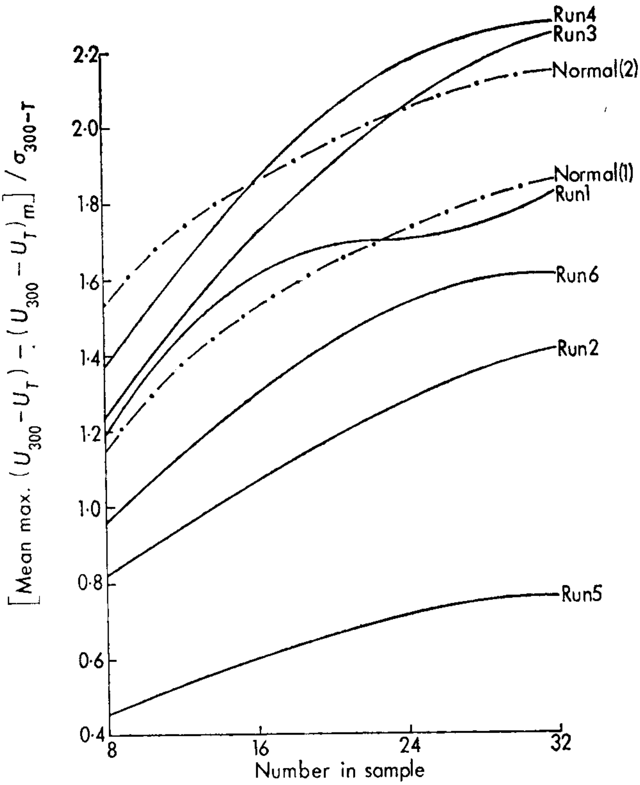

FIGURE 2—COMPARISON OF MEAN MAXIMUM $(U_{300}-U_T)$ OBTAINED IN SAMPLES OF CONSECUTIVE VALUES OF $(U_{300}-U_T)$ WITH THE MAXIMUM PREDICTED ASSUMING A NORMAL DISTRIBUTION

consecutive values of $(U_{300}-U_T)$. The number of samples of each size varied as the Runs were not all of the same length; for the shortest Run there were 23 samples of 8, 19 of 16, 15 of 24, and 11 of 32; and for the longest Run there were 34 samples of 8, 30 of 16, 26 of 24, and 22 of 32. The curves are not in very close agreement with either of the normal curves, although they show a similar shape. The lack of agreement could be because of changes in the mean wind speed over the Run. To overcome this effect the range was considered instead of just the maximum value, i.e. for each sample the difference between the maximum and minimum values of $(U_{300}-U_T)$ was found and the mean taken over a number of samples. By dividing this mean range by twice the standard deviation, σ_{300-T}, standardized curves can be obtained (Figure 3) which can be compared with the normal curves used in Figures 1 and 2.

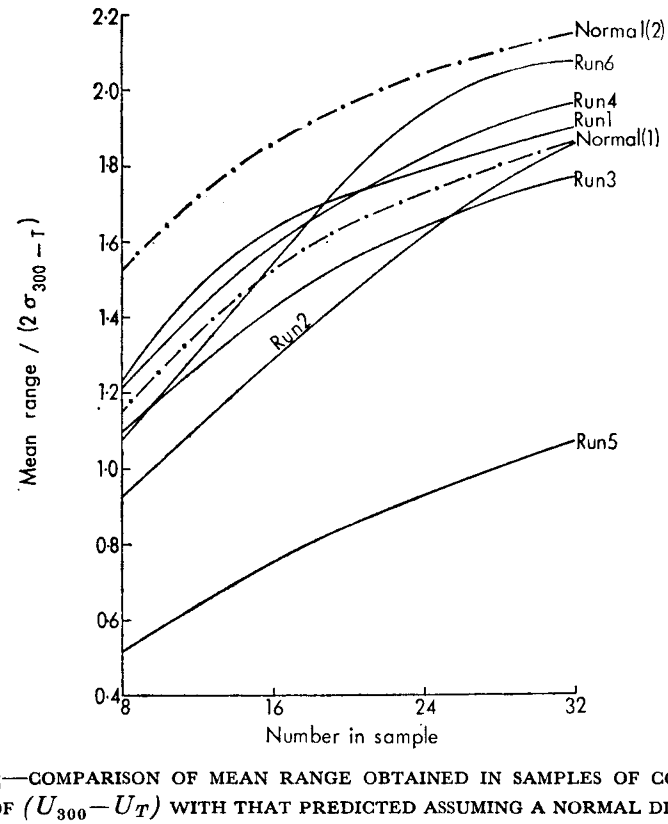

FIGURE 3—COMPARISON OF MEAN RANGE OBTAINED IN SAMPLES OF CONSECUTIVE VALUES OF $(U_{300}-U_T)$ WITH THAT PREDICTED ASSUMING A NORMAL DISTRIBUTION

The standardized curves obtained in Runs 1, 3 and 4 are quite close to the normal (1), and these were Runs where conditions were fairly steady. Run 5 is again abnormal, the very low values being due to the large standard deviation.

Although the values in Figures 2 and 3 are in some cases rather far from the normal, the slopes of the curves appear to be similar, implying that the ratios of points on the curves are similar for each Run. Figures 4 and 5 show the ratios of values for samples of 16, 24, and 32 to those for samples of 8, corresponding to Figures 2 and 3 respectively, for each Run and for the normal curve (1). The agreement between all the Runs and the normal in

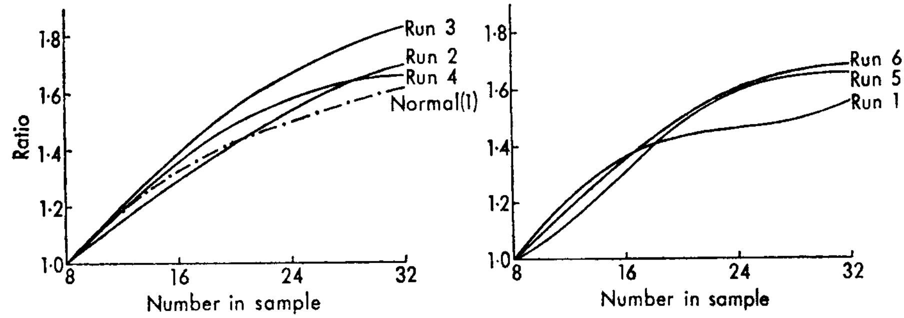

FIGURE 4—RATIO OF MAXIMUM DEPARTURE OF $(U_{300}-U_T)$ FROM THE MEAN FOR DIFFERENT SIZED SAMPLES TO THAT FOR A SAMPLE OF 8

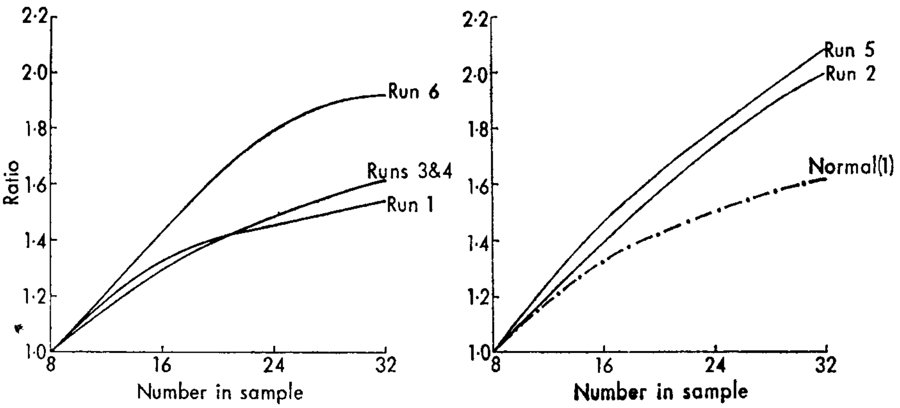

FIGURE 5—RATIO OF MEAN RANGE FOR SAMPLES OF $(U_{300}-U_T)$ TO THAT FOR A SAMPLE OF 8

Figure 4 is very good. The agreement between the normal and Runs 1, 3 and 4, when conditions were fairly steady, in Figure 5 (which considers range instead of maximum) is extremely good, but for the remaining Runs the result is not as good as in Figure 4, indicating that for general use the range is not such a good parameter as the maximum value as far as ratios are concerned. This shows that if the maximum gust in a sample of a certain size is measured then the maximum likely in larger samples can be estimated by assuming a normal distribution and using the appropriate ratio. Almost equivalent to this is the statement that if the maximum gust in a certain period of time is measured then the maximum likely in a longer period can be estimated.

Table II*(a)* gives an indication of the errors obtained in using the normal assumption in practice. For each Run, the maximum positive deviation of $(U_{300}-U_T)$ from the mean was found for consecutive samples of 8 and for the larger samples, each of these starting with the sample of 8. The values obtained were compared with those predicted — using the ratios shown in the normal curve in Figure 4 — from the data of the sample of 8. The table shows that, apart from some large errors in Run 5, the errors in all other forecasts are within the range ± 2 m/s.

TABLE II(*a*)—ERRORS IN THE MAXIMUM DEVIATION OF $U_{300}-U_T$ FROM THE MEAN IN VARIOUS SAMPLES AS PREDICTED* FROM THE DATA OF A SAMPLE OF 8

Run number	Maximum deviation of $U_{300}-U_T$ from the mean (metres per second)				Predicted maximum deviation minus actual (metres per second)		
	Sample of 8	Sample of 16	Sample of 24	Sample of 32	Sample of 16	Sample of 24	Sample of 32
1	1·17	1·17	1·17	1·17	0·39	0·59	0·73
	−0·60	1·07	1·07	1·50	−0·27	−0·17	−0·53
	1·07	1·07	1·50	1·50	0·35	0·11	0·23
	0·62	1·50	1·50	1·50	−0·68	−0·57	−0·50
2	2·10	2·10	2·10	2·10	0·69	1·05	1·30
	2·03	2·03	2·03	2·03	0·67	1·02	1·26
	0·84	0·84	0·84	0·84	0·28	0·42	0·52
	0·56	0·56	0·74	1·36	0·18	0·10	−0·45
	−0·25	0·74	1·36	1·69	−0·41	−0·98	−1·28
3	0·20	0·46	2·03	2·03	−0·19	−1·73	−1·71
	0·46	2·03	2·03	2·03	−1.42	−1·34	−1·28
	2·03	2·03	2·03	2·03	0·67	1·02	−1·26
	0·98	0·98	0·98	1·11	0·32	0·49	0·48
4	0·15	1·11	1·13	1·49	−0·91	−0·90	−1·25
	1·11	1·13	1·49	1·49	0·35	0·18	0·31
	1·13	1·49	1·49	1·49	0·01	0·21	0·34
5	4·83	4·83	4·83	4·83	1·59	2·42	2·99
	4·47	4·47	4·47	4·47	1·48	2·24	2·77
	1·31	1·31	1·31	1·31	0·43	0·66	0·81
	0·41	0·41	0·41	0·41	0·14	0·21	0·25
	−0·53	0·34	0·34	0·34	0·36	0·46	0·52
	0·34	0·34	0·34	0·44	0·11	0·17	0·11
6	2·79	2·79	2·79	2·79	0·92	1·40	1·73
	0·97	0·97	1·58	1·58	0·32	−0·12	−0·01
	0·28	1·58	1·58	1·58	−1·21	−1·16	−1·13
	1·58	1·58	1·58	1·58	0·52	0·79	0·98
	0·83	1·33	1·33	1·33	−0·23	−0·08	0·01

* By multiplying by a factor based on the probable maximum values in a sample size if distribution is normal.

$(U_{300}-U_T)_m$ is the mean value of $(U_{300}-U_T)$ over the whole Run which it is to be hoped will be approximately zero. Table II(*b*) shows the errors that would occur if the mean were assumed to be zero, i.e. just considering the maximum value in a sample and not subtracting $(U_{300}-U_T)_m$. The table shows that this compares favourably on the whole with the first method on these occasions.

Comparison of different sampling periods (distances). The Cardington data consist of a read-out every second, each being in fact a mean over about 0·9 seconds. The first 45 minutes of each Run were divided into a number of consecutive periods of T seconds duration, and the mean wind V_T in each T-second period was found. The maximum departures from V_T of the 1-second values and means of runs of wind over 40, 100, 200, 300, and 400 m were found for each period T. By dividing each run of wind by the mean wind over the whole 45 minutes, the approximate equivalent number of seconds, t, was obtained for each run-of-wind distance.

The mean wind speed over t seconds may be written

$$V_t = V_T + v_t,$$

where V_T is, as defined above, the mean wind speed over a longer period T, and v_t is the mean deviation from V_T over the period t seconds. Let v_t (max)

TABLE II(*b*)—ERRORS IN THE MAXIMUM DIFFERENCE $U_{300}-U_T$ IN VARIOUS SAMPLES AS PREDICTED* FROM THE DATA FOR A SAMPLE OF 8

Run number	Maximum difference Sample of 8	Predicted maximum difference minus actual Sample of 16	Sample of 24	Sample of 32
		metres per second		
1	1·43	0·47	0·72	0·89
	−0·34	−0·88	−0·82	1·21
	1·33	0·44	0·24	0·39
	0·88	−0·59	−0·44	−0·33
2	1·74	0·57	0·87	1·08
	1·67	0·55	0·84	1·03
	0·48	0·16	0·24	0·30
	0·20	0·07	−0·08	−0·68
	−0·61	0·43	−0·08	−0·34
3	0·05	−0·24	−1·80	−1·80
	0·31	−1·47	−1·41	−1·38
	1·88	0·62	0·94	1·17
	0·83	0·27	0·42	0·37
4	−0·25	−0·38	−0·35	−0·69
	0·71	0·21	−0·02	0·06
	0·73	−0·12	0·10	0·09
5	5·40	1·78	2·70	3·35
	5·04	1·66	2·52	3·12
	1·88	0·62	0·94	1·17
	0·98	0·32	0·49	0·61
	0·04	−0·86	−0·85	−0·85
	0·91	0·30	0·46	0·46
6	2·59	0·85	1·30	1·61
	0·77	0·25	−0·22	−0·13
	0·08	−1·27	−1·26	−1·25
	1·38	0·46	0·69	0·86
	0·63	−0·29	−0·18	−0·11

* By multiplying by a factor based on the probable maximum values in a sample size if distribution is normal.

be the maximum value of v_t during a sample duration of T seconds. To compare different sizes of gusts, the ratio $R(T, t\colon \theta, s)$ may be used. This is defined as

$$R(T, t\colon \theta, s) = \frac{v_{T,t}\ (\max)}{v_{\theta,s}\ (\max)},$$

where θ, s are respectively sample durations and averaging times, which may not be the same as T and t (Brook and Spillane[5]).

In the Runs considered 100 metres is approximately equivalent to $12\frac{1}{2}$ seconds for the wind speeds, so the ratio $R(T, t\colon T, 12\frac{1}{2})$ was calculated for each period T, where t is the number of seconds equivalent to a run of wind. As the 1-second value is actually a mean over about 0·9 seconds, the value of t in this case was taken to be 0·9. Two values of T were considered, $4\frac{1}{2}$ minutes and 9 minutes, and for each Run there were ten $4\frac{1}{2}$-minute periods and five 9-minute periods. The mean values of the ratios for $T = 270$ seconds and $T = 540$ seconds were found for each value of t and for each Run, and the results compared with those obtained by Brook and Spillane which were worked out on the basis of 't-second gusts' and not runs of wind (Figures 6 and 7). The Brook and Spillane points in Figures 6 and 7 were obtained from Figure 4c in their paper, which gives values of the ratio $R(T, t\colon T, 5)$. Two graphs were drawn, one for $R(270, t\colon 270, 5)$ and one for $R(540, t\colon 540, 5)$,

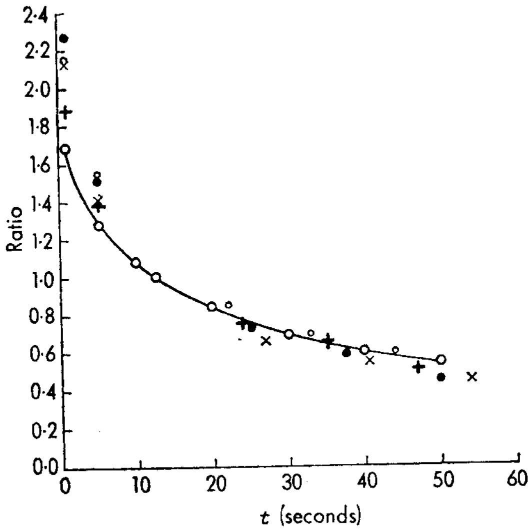

FIGURE 6—RATIOS OF MAXIMUM DEPARTURES FROM THE $4\frac{1}{2}$-MINUTE MEAN WIND OF MEANS OVER t SECONDS TO THE MEAN OVER A 100-METRE RUN OF WIND

–o– Predicted values from Brook and Spillane[5]
\+ Measured values from Cardington Run No. 2
● Measured values from Cardington Run No. 3
× Measured values from Cardington Run No. 4
o Measured values from Cardington Run No. 5

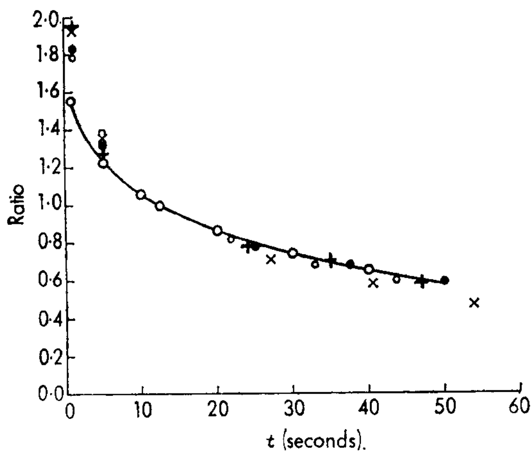

FIGURE 7—RATIOS OF MAXIMUM DEPARTURES FROM THE 9-MINUTE MEAN WIND OF MEANS OVER t SECONDS TO THE MEAN OVER A 100-METRE RUN OF WIND

–o– Predicted values from Brook and Spillane[5]
\+ Measured values from Cardington Run No. 2
● Measured values from Cardington Run No. 3
× Measured values from Cardington Run No. 4
o Measured values from Cardington Run No. 5

and the two values of $R(T, 12\frac{1}{2}: T, 5)$ obtained from the graphs. By dividing the Brook and Spillane values of $R(T, t: T, 5)$ by the obtained value of $R(T, 12: T, 5)$ the required ratios $R(T, t: T, 12\frac{1}{2})$ were obtained, and these are plotted in Figures 6 and 7. The agreement in both cases is very good, the 9-minute results being perhaps slightly better than the others. However, in both cases, the ratios obtained from the Cardington data are greater than those of Brook and Spillane for values of t of 1 second and 5 seconds. This is almost certainly due to the presence of high-frequency 'noise' in the Cardington data. Thus, if the maximum departure of one sample from the mean wind over, say, 9 minutes can be measured, the maximum departure of other sample lengths can be estimated.

Conclusion. A pilot can be given information which will give him an estimate of the mean speed and variability of the wind 10 minutes later. A mean wind speed measured over $4\frac{1}{2}$ minutes gives a reasonable estimate of the mean speed over a 300-m run of wind 10 minutes later. If the maximum departure of $(U_{300}-U_T)$ from the mean were measured over a short period, the maximum likely in a longer period could be estimated, assuming a normal distribution and using the appropriate ratio; for example, if the maximum in a sample of 8, i.e. about 4 minutes, were measured, then multiplication by a factor 1·62 would give an estimate of the maximum likely to occur in a sample of 32, i.e. about 16 minutes which would include the time for the sample of 8 and the 10-minute period before the aircraft reaches the critical position, as well as the actual period of descent from 30 m to 15 m and then on to touch-down. The maximum gust appropriate to different aircraft sampling could also be estimated, using the methods of Brook and Spillane.

The results outlined above are based on one day's observations only.

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551.553.6(729)

EXTREME WIND SPEEDS IN THE COMMONWEALTH CARIBBEAN

By H. C. SHELLARD

Summary. A short description is given of Thom's method of estimating the frequency of extreme winds. The method does not require data over a long period and is based on the expression $G(v)$ for the mixed Fréchet type distribution of the extreme value v, where $G(v) = p_E \exp[-(v/\beta)^{-9}] + p_T \exp[-(v/\beta)^{-4\cdot5}]$ in which the first term allows for extratropical storms and the second for tropical storms. p_E and p_T are the probabilities of an annual extreme being produced by an extratropical and a tropical storm respectively, and $p_E = 1 - p_T$. The parameter β is related to the highest average monthly mean wind speed.

An example is given of the detailed computation of the extreme-value wind distribution for Seawell, Barbados. For a selection of stations in the Caribbean, tables are given indicating 'fastest mile' speeds and some corresponding maximum 3-second gust speeds, for various return periods. The British Standard Code of Practice on Wind Loading has adopted the maximum 3-second gust speed at 10 metres with a return period of 50 years as the basic wind speed for design purposes and corresponding basic design speeds are given for various Caribbean countries.

Introduction. For the design of buildings and other structures the engineer requires information on the statistical probability of short-duration wind speeds. Ideally, rational design wind speeds should be based on the statistical analysis of suitable wind speed recordings covering periods of 20 years or more from a well-distributed network of meteorological stations. Unfortunately such data are available for only very few parts of the world.

In the Commonwealth Caribbean, suitable wind records for the purpose are currently being obtained and, in some cases, have been available for quite a number of years. Until recently, however, few of these records have been subjected to routine measurement and tabulation and even if some of the longer records could be located and analysed it is fairly certain that no homogeneous set of records covering a sufficiently long period would result.

Thus, if estimates of extreme wind speeds having stated probabilities are to be obtained for the Commonwealth Caribbean area now, some alternative procedure must be used. Fortunately such a procedure has been developed by Thom[1] and this paper is concerned with the application of his method to places in the Caribbean and the presentation of the results.

The quasi-universal extreme wind distribution (Thom). Extreme-value wind distributions that have been established for areas with suitable long-period records, such as the U.S.A. (Thom[2]) and the U.K. (Shellard[3,4]), are determined by two parameters: a shape parameter γ and a scale parameter β. The shape parameter defines the shape of the frequency distribution and the scale parameter determines the wind speeds themselves. Thom has shown that for extratropical storms and thunderstorms in the U.S.A. the Fréchet distribution of the extreme value v,

$$F(v) = \exp[-(v/\beta)^{-\gamma}], \qquad \ldots (1)$$

has a shape parameter γ which approaches a value of 9 as record length increases. He also found that the scale parameter β is well correlated with the highest average monthly mean wind speed. Hence a method of approximating the extreme wind distribution in extratropical storm areas was obtained. When the limited data available for tropical storm areas were examined Thom found that the scale parameter could be estimated in the same way as for extratropical storms but that the shape parameter was only about half that found for extratropical storms. This result was based on data from nine stations, only three of which, Miami (Florida), San Juan (Puerto Rico) and Hong Kong, had records covering more than 20 years. Nevertheless, Thom concluded, very reasonably, that since in the southern North Atlantic and the Caribbean some of the annual extreme wind speeds are due to extratropical storms (or thunderstorms) the annual extreme population will be a mixture of extremes from tropical and extratropical storms, giving a mixed extreme-value distribution function :

$$G(v) = p_E F_E(v) + p_T F_T(v), \qquad \ldots (2)$$

where $$F_E(v) = \exp[-(v/\beta)^{-9}], \quad \ldots (3)$$

$$F_T(v) = \exp[-(v/\beta)^{-4.5}] \quad \ldots (4)$$

and $$p_E = 1 - p_T, \quad \ldots (5)$$

where p_E and p_T are the probability of an annual extreme wind being produced by an extratropical and a tropical storm, respectively. He went on to show that p_T could be estimated from the mean number of tropical storm passages per year through the area concerned and presented a map of this parameter (Figure 3 of Thom's paper[1]), covering the southern North Atlantic and the Caribbean and based on storm tracks for the years 1901–63.

The relationships between β and v_m, the highest average monthly mean wind speed, and between p_T and f, the mean number of tropical storms per year, established by Thom are :

$$\beta = (320.5\, v_m + 248.7)^{\frac{1}{2}} - 15.7, \quad \ldots (6)$$

$$p_T = 1/[1 + 99 \exp(-3.0 f)]. \quad \ldots (7)$$

Application to stations in the Commonwealth Caribbean. Using Thom's results, summarized above, it is clear that an extreme wind distribution can be estimated for any station for which v_m can be computed from available observations of wind speed, or reasonably estimated. Values are given in Table I for a number of stations in the Caribbean, together with the period of records used and the corresponding values of β. Also given are the appropriate values of f taken from Thom's map and the corresponding values of p_T. San Juan was included in Table I so that extremes estimated by this method might be compared with those computed in the more usual way (analysis of the annual extremes over a long period) and given by Thom in Table 2 of his 1968 paper.[2]

TABLE I—DATA REQUIRED FOR ESTIMATION OF EXTREME WIND DISTRIBUTION FOR CARIBBEAN STATIONS

Station	v_m *mile/h*	Period	β	f	p_T
San Juan, Puerto Rico	12·9	1940–55	50·5	1·2	0·27
Palisadoes, Jamaica	13·4	1950–62	51·7	1·1	0·22
Coolidge, Antigua	15·0*	1941–48	55·4	1·2	0·27
Seawell, Barbados	16·5	1954–60	58·7	0·9	0·13
Pearls, Grenada	13·0	1954–60	50·7	0·8	0·10
Piarco, Trinidad	8·1	1954–60	37·5	0·7	0·08
East coast, Trinidad	12·0*		48·3	0·7	0·08
Crown Point, Tobago	13·0*		50·7	0·7	0·08

* Estimated.

In three cases the values of v_m were estimated. The only average wind speed datum readily available for Coolidge, Antigua, was an annual average of 13·4 mile/h over the years 1941–48, and 15·0 mile/h is therefore a conservative estimate of the highest average monthly mean wind speed. The mean speed given for Piarco was considered to be unrepresentative of Trinidad for the purpose of estimating a design wind speed since Piarco is rather sheltered and well inland in relation to the prevailing winds. A mean speed some 50 per cent higher was therefore estimated as representative of the east coast and hence of more exposed areas generally in the island, bearing in mind that winds associated with a tropical storm may blow from any direction.

The mean speed given for Crown Point was based on the analysis of 6 months of concurrent hourly wind speeds from Crown Point and Piarco, giving a mean ratio of 1·65 between the two stations.

An example of the detailed computation of a mixed extreme-value wind distribution is given by Thom, but another is given in Table II using the data for Seawell, given in Table I. As Thom indicated, the distribution $G(v)$ must be computed for a series of values of v and the speed that will be exceeded with any desired probability must then be obtained by interpolation. To compute F it is convenient to rearrange equation (1) in the form

$$\ln \ln (1/F) = -\gamma \ln (v/\beta), \qquad \ldots (8)$$

giving

$$1/F = \exp \exp [-\gamma \ln (v/\beta)]. \qquad \ldots (9)$$

Also, since, for Seawell, $\beta = 58·7$ and $p_T = 0·13$, we have to evaluate the mixed distribution

$$G(v) = 0·87 \exp [-(v/58·7)^{-9}] + 0·13 \exp [-(v/58·7)^{-4·5}], \qquad \ldots (10)$$

and this is done in Table II for a series of values of v.

TABLE II—COMPUTATION OF MIXED EXTREME WIND DISTRIBUTION FOR SEAWELL, BARBADOS

v mile/h	$\ln(v/58·7)$	$-9 \ln(v/58·7)$	$-4·5 \ln(v/58·7)$	$1/F_E$	$1/F_T$	$0·87F_E$	$0·13F_T$	G
50	−0·1602	1·4418	0·7209	68·7	7·815	0·013	0·017	0·030
60	0·0219	−0·1971	−0·0985	2·273	2·475	0·383	0·053	0·436
80	0·3097	−2·7873	−1·3937	1·063	1·282	0·818	0·101	0·919
100	0·5327	−4·7943	−2·3971	1·008	1·095	0·863	0·118	0·981
120	0·7149	−6·4341	−3·2171	1·002	1·041	0·869	0·125	0·994

The values of v and G may be plotted on extreme-value probability paper as in Figure 1, from which the speed corresponding to any desired cumulative probability (or return period) may be read off. For example, the speed

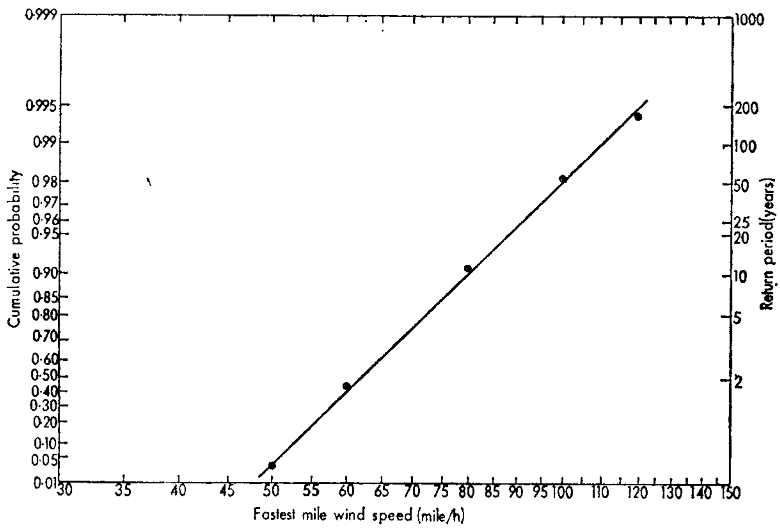

FIGURE 1—ESTIMATED FRÉCHET EXTREME WIND DISTRIBUTION, SEAWELL, BARBADOS

having a cumulative probability of $G = 0{\cdot}98$ is 100 mile/h. In other words a wind speed of 100 mile/h at Seawell is likely to be exceeded on the average only once in 50 years.

Similar computations have been carried out for all the places listed in Table I with the results set out in Table III. It is important to emphasize here that these speeds are 'fastest mile' speeds, i.e. they are estimates of the fastest mile of wind. This is because Thom's distribution is based on observations made in the U.S.A., where the extreme wind speed variable that is most widely available is the fastest mile. The values given in brackets on the first line of Table III are the Puerto Rico fastest mile values published by Thom[2] and mentioned earlier. It will be noted that the agreement between the two sets of values is quite good.

TABLE III—FASTEST MILE SPEEDS* FOR RETURN PERIODS OF 10, 20, 25, 50, 100 AND 200 YEARS

	Return period (years)					
	10	20	25	50	100	200
			mile/h			
San Juan, Puerto Rico	72(65)	80	83(80)	94(95)	105(110)	118
Palisadoes, Jamaica	71	79	83	93	105	117
Coolidge, Antigua	78	88	91	102	113	126
Seawell, Barbados	79	88	91	100	110	121
Pearls, Grenada	67	74	77	85	94	104
Piarco, Trinidad	48	54	56	63	69	77
East coast, Trinidad	63	69	72	78	86	93
Crown Point, Tobago	67	74	77	85	93	103

* The speeds given in mile/h can be converted to knots by multiplying by 0·868, and to metres/seconds by multiplying by 0·447.

Figures in brackets are the Puerto Rico fastest mile values published by Thom.[2]

In the West Indies the fastest mile of wind is not normally measured and the British practice of extracting the highest hourly mean speed and the highest gust speed for each day is generally followed. The anemographs in most general use have response characteristics such that the maximum gust speed is equivalent to a speed averaged over a period of approximately 3 seconds. The fastest mile speeds given in Table III may be converted into their equivalent 3-second gust speeds, by making use of experimental measurements that are available on the relationship between wind speeds averaged over different periods of time. Such measurements, over open level country, have been made, for example, at Cardington, England (Durst[5]), and at Sale, Australia (Deacon[6]), the two sets of results being in excellent agreement. By making use of these and remembering that v mile/h is equivalent to a speed averaged over $60/v$ minutes (or $3600/v$ seconds), a simple relationship can be deduced between the fastest mile speed (v) and the corresponding 3-second gust speed (g). This relationship is :

$$g = 1{\cdot}09\,v + 8 \text{ mile/h}. \qquad \ldots (11)$$

Hence the maximum (3-second) gust speeds corresponding to the fastest mile speeds of Table III may be calculated and these are set out in Table IV, which thus gives estimated maximum gust speeds for places in the Commonwealth Caribbean for return periods of 10, 20, 50 and 100 years.

TABLE IV—MAXIMUM GUST SPEEDS FOR RETURN PERIODS OF 10, 25, 50 AND 100 YEARS

	Return period (years)			
	10	20	50	100
	mile/h			
Palisadoes, Jamaica	85	94	110	123
Coolidge, Antigua	93	104	120	132
Seawell, Barbados	94	104	117	128
Pearls, Grenada	81	89	101	111
Piarco, Trinidad	60	67	76	83
East coast, Trinidad	76	83	93	102
Crown Point, Tobago	81	89	101	110

It may be noted that the British Standard Code of Practice on Wind Loading *(British Standard Code of Practice* 3, Chapter V, Part II, 1970) has adopted the maximum 3-second gust speed at 10 metres (33 ft) above the ground, with return period of 50 years, as the basic wind speed for design purposes. Thus, corresponding basic design wind speeds for some Commonwealth Caribbean countries, based on the figures in column 4 of Table IV, might be suggested for adoption in any new code of practice for use in the area, as indicated in Table V.

TABLE V—SUGGESTED BASIC DESIGN WIND SPEEDS FOR SOME COMMONWEALTH CARIBBEAN COUNTRIES

	mile/h
Jamaica Leeward and British Virgin Islands Barbados, St Vincent, St Lucia	120
Grenada, Tobago	100
Trinidad	90
Guyana	50

In the last line of this table a figure of 50 mile/h has been inserted for Guyana, which is not affected by tropical storms. This is based on the fact that in a record commencing in 1927, the highest gust speed recorded at Georgetown (Botanic Gardens) was one of 43 mile/h.

Finally, in view of the fact that wind speeds of 150 to 160 mile/h have been measured in well-developed hurricanes, and these are means over periods of a minute or longer, it might be thought that the speeds in Table V are on the low side. However, it must be pointed out that the return period of a well-developed hurricane in any particular place is probably much greater than 50 years. Moreover, an engineer who wishes to design a structure to withstand the full force of a major hurricane may be expected to take this into account, and to use a design wind speed of about 160 mile/h or more, with a return period of perhaps 1000 years, depending on an assessment of the risk of failure in relation to the purpose, probable lifetime and cost of the structure concerned.

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551.509.325:551.591

VISIBILITY DETERIORATIONS DURING WINTER MORNINGS

By W. E. SAUNDERS

Summary. A study of visibility deteriorations on clear winter mornings at a number of aerodromes in eastern England shows that the probability of deterioration varies markedly with the position of a site in relation to smoke sources and low-lying areas. Wind direction is therefore of great importance. The likelihood of deterioration is shown to decrease with increasing wind speed. It is also shown that on the majority of occasions when the lowest visibility reached during the morning did not exceed 2 km the wind was calm or the direction was from smoky or damp, low-lying areas. The time of reaching the lowest visibility is shown to vary from station to station.

It is well known to forecasters that following a clear night, which has been free from fog, visibility frequently decreases during the morning, especially during the winter. This may be due to industrial or domestic smoke, or in some locations to the drift of mist or fog from low-lying or fen areas. In either case, the diurnal increase in wind speed and turbulence after sunrise contributes to the effect.

The records for 10 aerodromes between Northumberland and the Cambridge area (see Figure 1) for the months November to February for five winters (November 1965 to February 1970), were examined in order to assess the incidence of these morning deteriorations. Cases included were those in which at 04 GMT there was no fog and the cloud amount did not exceed 3/8, excluding broken cirrus. The initial time of 04 GMT was selected because this is the last observation available before forecasts require to be issued for many day-time activities. The sunrise times vary between about 0645 and 0830 GMT.

For the purpose of this study, a deterioration was regarded as having occurred if the visibility decreased from within one of the following ranges at 04 GMT into any lower range within the period 06–13 GMT:

1·0 – 1·9 km
2·0 – 3·9 km
4·0 – 8·0 km
over 8 km

Cases where a visibility deterioration was due to precipitation were omitted.

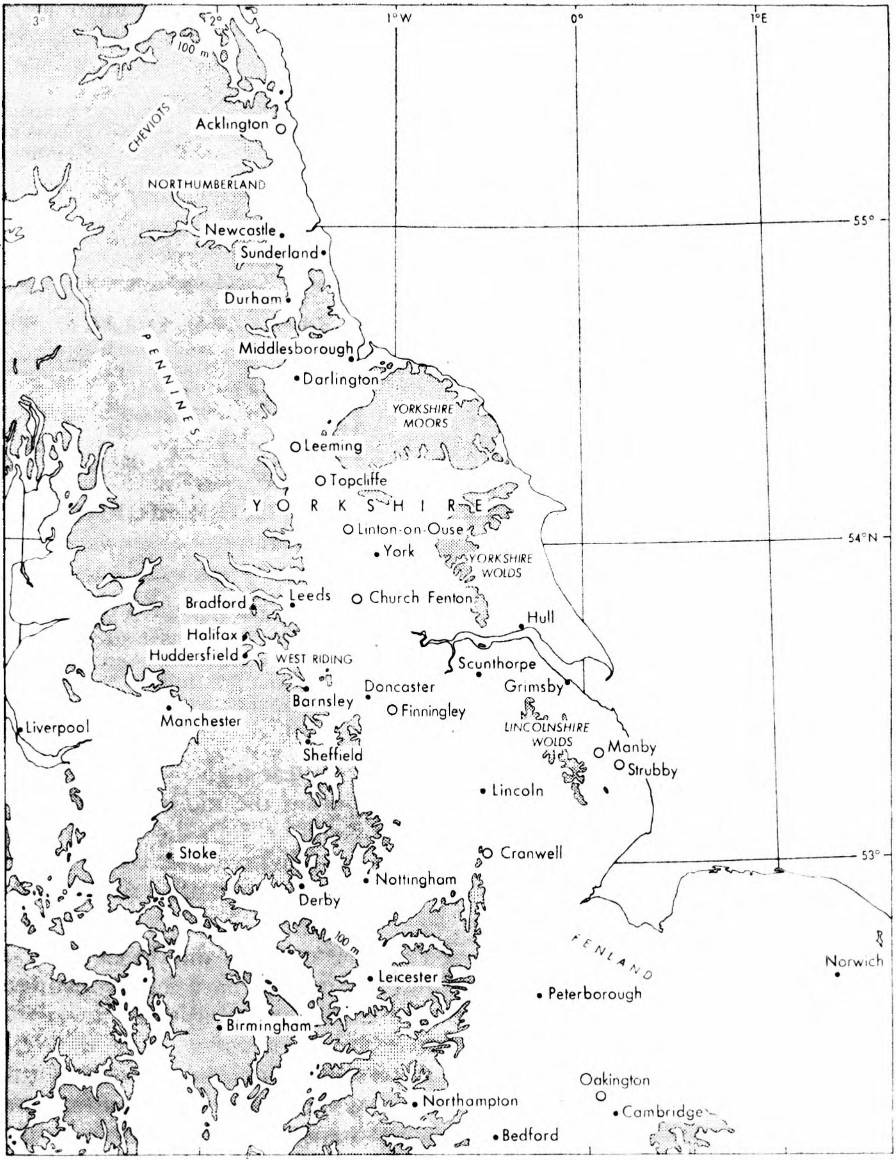

FIGURE 1—MAP OF AREA
o Aerodromes mentioned in text

The overall position regarding deteriorations is given in Table I. This shows considerable consistency north of about York, with deteriorations on around 30 per cent of the clear mornings. The probability of deterioration increases in south Yorkshire, because of the proximity of Church Fenton and Finningley to the smoke sources of the West Riding and urban areas further south, and of the low-lying ground near these aerodromes. However, the difference between the frequency of deteriorations at stations Acklington

TABLE I—INCIDENCE OF DETERIORATIONS IN VISIBILITY BETWEEN 06 AND 13 GMT ON MORNINGS WHICH WERE CLEAR* AT 04 GMT, NOVEMBER 1965 TO FEBRUARY 1970

Station	Number of days clear at 04 GMT	Incidence of deteriorations Number of days	Percentage
Acklington	164	44	27
Leeming	173	51	29
Topcliffe†	133	38	29
Linton-on-Ouse†	105	33	31
Church Fenton†‡	96	56	58
Finningley	189	121	64
Manby	169	89	53
Strubby†	109	41	38
Cranwell†	109	40	37
Oakington†	131	52	40

* No fog and cloud not exceeding 3/8, excluding broken cirrus.
† These stations normally report on Mondays to Fridays only.
‡ At Church Fenton 06 GMT was taken as the initial time instead of 04 GMT.

to Linton-on-Ouse and the frequency at Church Fenton and Finningley is also partly due to the original selection of clear nights. Cloudless weather during the night and early morning is most likely at Acklington and in north Yorkshire with gradient winds from between west and north, and the figures reflect lack of smoke sources within this quadrant for stations down to Linton. Also, of course, these airstreams have crossed the Cheviot and Pennine hills, and are relatively dry. The stations south of Finningley are affected by a variety of smoke sources, and by drift from low-lying ground, but the likelihood of deterioration is rather less than in south Yorkshire.

Table II shows the effect of wind speed on the incidence of deteriorations. In general the probability of deterioration decreases with increasing wind speed.

The effect of wind direction is shown in Table III. For each station, omitting the days of calm, the occasions were separated according to mean wind direction in the period from 06 GMT to the time of lowest visibility; those with wind directions from smoky or low-lying areas were separated from those with 'clean' wind directions. An attempt to separate the smoky occasions from those with drift from low-lying areas by use of a relative-humidity criterion was not satisfactory. Table III shows that wind direction is of great importance at Vale of York stations, especially at Leeming. The results imply that the smoke trails which affect that aerodrome are very sharply defined. South of York the differences due to wind direction become less pronounced.

In Table IV the lowest visibility in the period 06–13 GMT has been tabulated against wind speed, with the mean directions grouped as in Table III. This emphasizes the importance of smoke pollution, or in some cases drift from low-lying ground, in the formation of fog on winter mornings. Out of 129 occasions of morning fog formation, the mean wind direction was from smoky or low-lying directions, or calm, on 115 occasions, and from 'clean' directions on 14 occasions. Similarly, out of 116 occasions when the lowest visibility was 1·0–1·9 km, the mean wind direction was from smoky or low-lying areas, or calm, on 100 occasions, and from 'clean' directions on 16. Even allowing for the fact that there were more total occasions with winds from smoky or low-lying areas, or calm (857), than from 'clean' areas (521), there is the strong implication that pollution is a major factor in deteriorations.

TABLE II—VARIATION OF INCIDENCE OF DETERIORIATIONS IN VISIBILITY BETWEEN 06 AND 13 GMT WITH THE MEAN WIND SPEED BETWEEN 06 GMT AND THE TIME OF LOWEST VISIBILITY ON MORNINGS WHICH WERE CLEAR AT 04 GMT, NOVEMBER 1965 TO FEBRUARY 1970

Station	Calm: Number of days clear at 04 GMT	Calm: Incidence of deteriorations: Number of days	Calm: Incidence of deteriorations: Percentage	1–5 kt: Number of days clear at 04 GMT	1–5 kt: Incidence of deteriorations: Number of days	1–5 kt: Incidence of deteriorations: Percentage	6–9 kt: Number of days clear at 04 GMT	6–9 kt: Incidence of deteriorations: Number of days	6–9 kt: Incidence of deteriorations: Percentage	Over 9 kt: Number of days clear at 04 GMT	Over 9 kt: Incidence of deteriorations: Number of days	Over 9 kt: Incidence of deteriorations: Percentage
Acklington	3	3	100	15	12	80	57	21	37	89	8	9
Leeming	20	11	55	37	22	59	39	11	28	77	7	9
Topcliffe	21	8	38	50	18	36	33	10	30	29	2	7
Linton-on-Ouse	25	15	60	24	13	54	23	3	13	33	2	6
Church Fenton	9	8	89	15	9	60	35	23	66	37	16	43
Finningley	20	19	95	19	15	79	62	45	73	88	42	48
Manby	0	0	—	19	12	63	44	28	64	106	49	46
Strubby	2	0	0	6	3	50	36	18	50	65	20	31
Cranwell	6	4	67	15	10	67	38	18	47	50	8	16
Oakington	1	1	—	12	7	58	38	23	61	80	21	26

TABLE III—VARIATION OF INCIDENCE OF DETERIORATIONS IN VISIBILITY BETWEEN 06 AND 13 GMT WITH THE MEAN WIND DIRECTION BETWEEN 06 GMT AND THE TIME OF LOWEST VISIBILITY ON MORNINGS WHICH WERE CLEAR AT 04 GMT, NOVEMBER 1965 TO FEBRUARY 1970

Station	Wind from smoky or damp, low-lying areas				Wind from 'clean' areas			
	Wind direction *degrees true*	Number of days clear at 04 GMT	Incidence of deteriorations: Number of days	Incidence of deteriorations: Percentage	Wind direction *degrees true*	Number of days clear at 04 GMT	Incidence of deteriorations: Number of days	Incidence of deteriorations: Percentage
Acklington	130–210	18	13	72	220–120	143	28	20
Leeming	140–190 360–060	34	31	91	070–130 200–350	119	9	8
Topcliffe	140–220 340–020	42	20	48	030–130 230–330	70	10	14
Linton-on-Ouse	120–230 330–020	25	11	44	030–110 240–320	55	7	13
Church Fenton	170–270 020–030	34	25	74	040–160 280–010	53	23	43
Finningley	180–330	144	91	63	340–170	25	11	44
Manby	120–360	160	86	54	010–110	9	3	33
Strubby	120–360	105	41	39	010–110	2	0	0
Cranwell	070–160 250–340	83	30	36	170–240 350–060	20	6	30
Oakington	260–210	105	46	44	220–250	25	5	20

TABLE IV—VARIATION OF INCIDENCE OF LOWEST VISIBILITY BETWEEN 06 AND 13 GMT WITH MEAN WIND SPEED AND DIRECTION* ON MORNINGS WHICH WERE CLEAR AT 04 GMT, NOVEMBER 1965 TO FEBRUARY 1970

Station	Calm					Wind from smoky or damp, low-lying areas						Wind from 'clean' areas					
	<1 km	1·0–1·9 km	2·0–3·9 km	4·0–8·0 km	>8 km	Wind speed kt	<1 km	1·0–1·9 km	2·0–3·9 km	4·0–8·0 km	>8 km	Wind speed kt	<1 km	1·0–1·9 km	2·0–3·9 km	4·0–8·0 km	>8 km
	number of occasions						*number of occasions*						*number of occasions*				
Acklington	3	—	—	—	—	1–5	2	2	—	—	—	1–5	1	1	3	5	1
						6–9	—	1	—	—	—	6–9	1	1	5	13	36
						>9	1	—	4	4	4	>9	—	—	2	3	71
Leeming	5	4	3	3	5	1–5	9	3	—	6	—	1–5	—	1	1	6	11
						6–9	3	1	2	4	1	6–9	—	—	—	3	25
						>9	—	—	3	1	1	>9	—	—	1	4	67
Topcliffe	5	1	3	4	8	1–5	6	—	4	5	10	1–5	3	2	—	2	18
						6–9	3	—	1	3	3	6–9	1	—	4	1	17
						>9	—	—	3	—	4	>9	—	—	1	1	20
Linton-on-Ouse	8	5	1	6	5	1–5	4	2	3	—	3	1–5	1	1	1	3	6
						6–9	—	2	—	2	1	6–9	—	—	—	2	16
						>9	—	—	1	2	5	>9	—	—	—	1	24
Church Fenton	3	5	1	—	—	1–5	2	1	2	1	—	1–5	2	3	2	1	1
						6–9	1	2	4	3	—	6–9	1	—	7	9	8
						>9	1	3	2	8	4	>9	—	—	—	6	13
Finningley	12	5	2	1	—	1–5	2	5	3	1	—	1–5	2	2	2	2	—
						6–9	6	8	21	14	1	6–9	—	3	2	5	2
						>9	—	1	14	35	33	>9	—	—	1	1	3
Manby	—	—	—	—	—	1–5	8	2	4	2	1	1–5	1	—	—	—	1
						6–9	5	8	6	19	1	6–9	—	—	1	1	3
						>9	—	4	11	53	36	>9	—	—	—	2	—
Strubby	—	—	—	1	1	1–5	—	2	3	1	—	1–5	—	—	—	—	—
						6–9	2	5	16	9	4	6–9	—	—	—	—	—
						>9	2	—	5	31	25	>9	—	—	1	1	—
Cranwell	2	2	—	2	—	1–5	2	4	3	1	—	1–5	1	—	2	2	—
						6–9	4	7	7	7	7	6–9	—	—	3	2	1
						>9	1	1	7	10	22	>9	—	—	2	3	4
Oakington	—	1	—	—	—	1–5	4	5	—	3	—	1–5	—	—	—	—	—
						6–9	7	5	12	8	4	6–9	—	2	—	—	—
						>9	2	3	8	19	25	>9	—	—	6	5	12

* Wind directions are grouped as in Table III.

There is no doubt that the wind directions which have been taken as basically 'clean' in this investigation often carry some pollution from minor sources, and it is important in forecasting to identify and allow for these sources. It is also true that topographical effects sometimes lead to smoke arriving at an aerodrome from a direction which is normally 'clean'. For example, at Topcliffe the wind direction for arrival of West Riding smoke is normally 180–220°, but with light winds under a winter inversion the smoke may reach the station from the south-east, having been confined to the east side of the Vale of York by high ground further east.

In Table V, the time of reaching the lowest visibility within the period 06–13 GMT has been related to certain wind directions for a selection of stations. For Leeming, with wind directions which bring West Riding smoke, there are maxima at 07–08 and 11–12 GMT. For Finningley, with winds from smoky or low-lying directions, there is a pronounced maximum of lowest visibility between 08 and 10 GMT. For Manby, the times have been given separately for the direction bands 010–170° (wind off the sea, or from damp, low-lying ground), and from 280–360° (predominantly smoky). This shows that with direction 010–170° the lowest visibility is reached in the early morning, but that with 280–360° there are maxima at later times, including one as late as 12–13 GMT. This emphasizes that deteriorations due to smoke from remote sources tend to occur in the late morning.

TABLE V—VARIATION OF TIME OF INCIDENCE OF LOWEST VISIBILITY IN PERIOD 06 TO 13 GMT WITH CERTAIN WIND DIRECTIONS ON MORNINGS WHICH WERE CLEAR AT 04 GMT, NOVEMBER 1965 TO JANUARY 1970

Station	Mean wind direction *degrees true*	Time of lowest visibility, GMT 06–07	07–08	08–09	09–10	10–11	11–12	12–13
		Incidence of lowest visibility (number of days)						
Leeming	140–190	2	6	3	2	1	8	5
Finningley	180–330	22	19	41	47	5	1	5
Manby	010–170	14	2	4	1	—	5	—
Manby	280–360	16	7	11	12	2	9	14

Acknowledgement. The author is indebted to outstation staff for their considered opinions on the smoke sources, and for extracting the data.

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SAND STREETS

By J. D. HASTINGS

Summary. During a flight over a 'ghibli' between El Adem (Libya) and the coast on the morning of 14 February 1969, it was noticed that lines were visible below in the rising sand in a number of places. The lines were analogous to cloud streets aligned in the direction of the winds.

It is suggested that what had been observed was the process of longitudinal dune formation in action. Study of the upper air data for that day shows that the diameter of helical eddies would have been about 300 m and the spacing between them 600 m to 900 m, that is to say about half a nautical mile.

A Hercules aircraft of Air Support Command took off from RAF El Adem at about 0930 GMT on 14 February 1969 in conditions known locally as 'ghibli', i.e. the south-south-easterly winds were gusting at times to 40 kt* and visibility was reduced to a few hundred metres by rising sand. Not long after take-off when permission was given to release seat belts and when as far as could be estimated the aircraft was approaching the Jebel Akhdar to the south of Derna at a height of 10 000 ft, it was noticed on looking out of the port-side window that lines showed up quite clearly in the rising sand below; they occurred in a number of places and appeared to be aligned along the direction of the winds. Unfortunately, external vision is very limited in a Hercules aircraft except from the flight deck so it was not possible to form any idea of how widespread the phenomenon was, nor was there a camera readily available to photograph it.

Initial reaction was to speculate whether the phenomenon showed up on pictures by automatic picture transmission (APT) but although an examination was made at El Adem of such pictures of the area on occasions of ghibli going back almost a year, it proved quite fruitless. At the time it was not appreciated that the distance between the streets (approximately 0·5 to 1 km) would be so much less than the present resolution (4 km) of the satellite cameras. Later in the year while attempting to explain the phenomenon, not entirely satisfactorily, on the basis of 'thermal streeting' (Konrad[1]) the author's attention was drawn to a paper by Hanna.[2] In it he states that satellites orbiting 200 to 300 km above the earth have confirmed the presence of longitudinal dune systems in nearly every large desert area of the world.

Satellite pictures show the dunes aligned north-north-west to south-south-east over Libya and Egypt, turning north-east to south-west over Chad and the Sudan. This direction over Libya is in accord with statistics which show that for El Adem 50 per cent of winds at 06 and 12 GMT of force four or more are from 330/360° and 11 per cent from 150/180°. The spacing over the Fezzan is estimated to be 2 to 3 km but in general over the world the average is 1 to 2 km.

Longitudinal vortices have been observed in the motion of neutral-lift balloons. Angell *et alii*[3] observed helical circulations of 600-m diameter over the Los Angeles basin and in 1968[4] noted counter-rotating helical circulations over the Idaho desert having a diameter of 1·5 to 2·5 km.

Cloud-street spacings appear to range from 0·5 km to as much as 30 km. Kuettner[5] made a thorough investigation into cloud streeting and found the average spacing to be between 5 and 10 km, a value usually twice to three times the depth of the convective layer. He gives the following conditions as conducive to streeting :

(i) flat underlying terrain,
(ii) little variation of wind direction with height,
(iii) wind speed higher than normal,
(iv) strong curvature of wind-speed profile, and
(v) unstable lapse rate close to the surface (and an inversion at the top of the convective layer).

* Conversion factors to metric units are : 1 knot$\approx$0·5 m/s; 1 foot = 0·3048 m.

When these conditions are met the dominant form of motion in the convective layer is a longitudinal roll vortex approximately parallel to the mean flow and having a wavelength about twice the thickness of the layer.

After considering alternative approaches to the problem of helical eddy formation Hanna believes Kuettner's theory to be the most applicable to the boundary layer of desert areas. The process envisaged is shown in Figure 1.

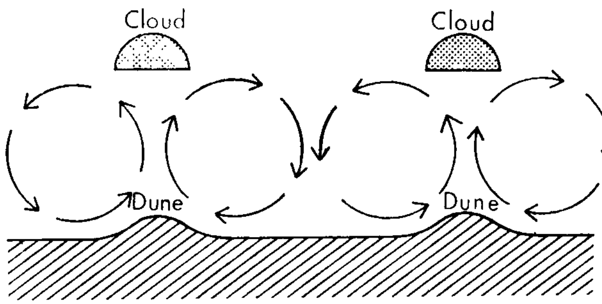


FIGURE 1—MECHANISM OF DUNE AND CLOUD FORMATION

It was therefore decided to see how well Kuettner's five conditions were satisfied on the occasion when the sand streets were noted. The wind profiles for El Adem for 05 GMT and Tobruk for 00, 06 and 12 GMT are shown in Figure 2. For comparison the mean wind profile found by Kuettner for cloud streeting is included. The ascents from Tobruk for 00 and 12 GMT are given in Figure 3.

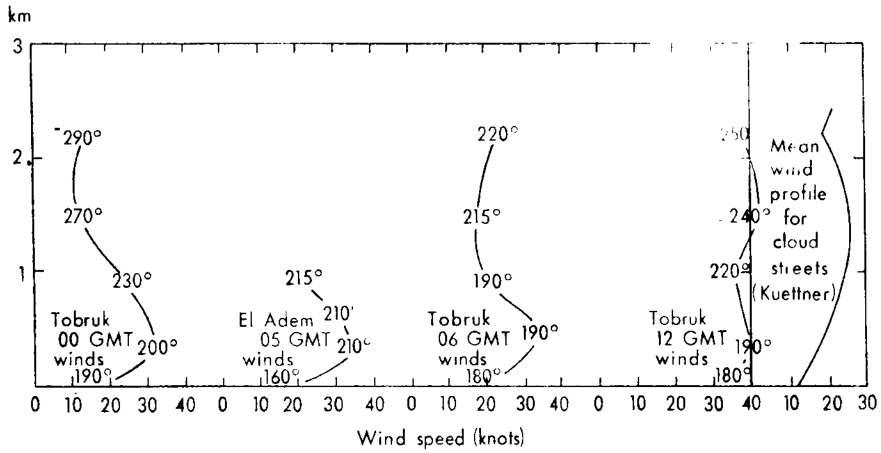
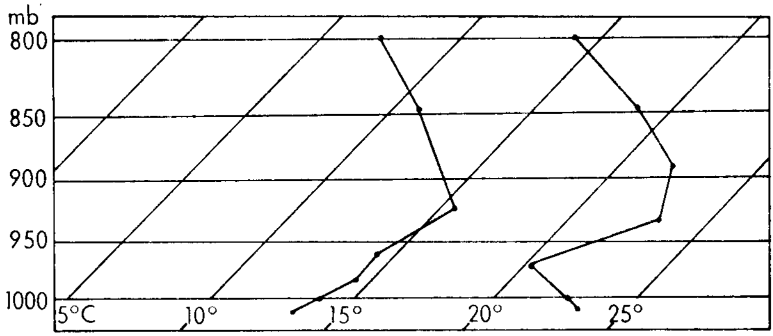


FIGURE 2—WIND PROFILES FOR TOBRUK AND EL ADEM, 14 FEBRUARY 1969

Hanna has noted that the wind must pass over a minimum distance of flat surface before longitudinal vortices will develop and, using the time period T of the circulations within observed vortices of about 2000 s and a



00 GMT 12 GMT

FIGURE 3—ASCENT TEMPERATURES FROM TOBRUK FOR 00 AND 12 GMT, 14 FEBRUARY 1969

typical wind speed U of about 10 m/s, arrives at a value for this minimum of $T \times U = 20$ km approximately. Although there is some uncertainty as to the exact location where the sand streets were seen it is thought that condition (i) as well as the requirement of a 'fetch' of more than 20 km were both satisfied.

From the wind-speed profiles it will be seen that at both El Adem and Tobruk at 06 GMT in particular, there is only a small variation of direction with height in the lowest kilometre. By 12 GMT although direction is still unchanged in the lowest half kilometre a veer of 30° has taken place at 1 km and above. Condition (ii) is however met within the convective layer.

Surface winds at El Adem and Tobruk were 20 kt at 05/06 GMT and had increased to 25/30 kt with gusts to 40 kt from 160° by 09 GMT. Condition (iii) is evidently satisfied.

It will also be seen from the wind-speed profiles that a maximum speed was reached at a height of about 300/450 m followed by a decrease of speed to about 1500 m. This effect is still noticeable on the 12 GMT profile, although much less pronounced, and the decrease above 1 km no longer obtains. Condition (iv) was certainly met at 05/06 GMT and most probably at the time of sighting the streets, but only to a lesser extent by 12 GMT.

Finally, the lapse rate near the surface, condition (v) : by interpolation between the two ascents it is evident that, taking the 09 GMT surface temperature of 20°C, a marked inversion from about 300 m to 1 km must have existed and that therefore convection must have been restricted to the layers below it.

Applying the empirical relationship of the spacing being two to three times the depth of the convective layer gives spacing values of 600 to 900 m or about half a nautical mile. These figures correspond to the lowest of the range of spacings for cloud streets or longitudinal dunes.

These distances are well below the resolution possible at present on APT pictures but not on high-level aerial photographs such as made from Gemini spacecraft. The National Aeronautical Space Administration (NASA) Manned Spacecraft Centre at Houston, Texas, provided three colour transparencies of the south-west of Libya which were the only photographic coverage available of the country. An approach was then made to the Joint Air

Reconnaissance Interpretation Centre (JARIC) but again, unfortunately, without success. Finally however, a series of photographs covering the area was obtained from the Survey Liaison Staff (UK) Royal Engineers (SLS (UK)RE) from which it was evident both to skilled and unskilled eyes that no permanent dune formations could be seen at least at the time that the photographs were taken.

From the most recent maps and from personal knowledge of the area it is apparent that while there is sufficient sand to produce serious deteriorations of visibility with strong winds it is not enough for permanent dunes to form. Any which did during the period of a ghibli could be expected to be of little vertical extent and of a temporary nature, being easily destroyed subsequently by winds blowing from another direction. Nevertheless, it has been shown that the conditions for longitudinal dune formation as postulated by Hanna were satisfied on the morning of 14 February 1969 and it is suggested that what appeared to be sand streets was, in all probability, this process as it would appear from above.

The author would like to acknowledge with thanks the transparencies provided by NASA and the help given by both JARIC and SLS(UK)RE.

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REVIEW

Atmospheric optics (translated from the Russian), edited by Nikolai B. Divari. 270 mm × 210 mm, pp. 191, *illus.*, Consultants Bureau, London, Donnington House, 30 Norfolk Street, London WC2, 1970. Price: $27·50.

This book contains the proceedings of conferences on atmospheric optics sponsored by the committee on the optical instabliity of the atmosphere of the Astronomical Council of the Academy of Sciences of the U.S.S.R. The meetings were held in Pulkovo in November and December 1965 and in November 1966.

There are 31 short papers, about 10 of which are of mainly astronomical interest. The remainder deal with atmospheric transmission coefficients, atmospheric scattering, spectral brightness of the sky, polarization and twilight phenomena, including the evaluation of dust in the upper atmosphere by the twilight method.

J. PATON

OBITUARIES

It is with regret that we record the death on 10 February 1971, of Mr H. J. Groom, Experimental Officer, Met O 8, and the death on 5 February 1971, of Mr J. W. Armstrong, Senior Scientific Assistant, Acklington.

OFFICIAL PUBLICATIONS

Geophysical Memoirs

No. 113. An observational study of the meridional flux of energy and angular momentum in the troposphere and lower stratosphere at latitude 30°N using 1958 IGY data. By A. E. Parker.

This memoir discusses the results of the calculations made from information amassed during the International Geophysical Year, 1958, concerning the transport of momentum, heat and energy northwards across latitude 30°N. Four months — March, June, September and December — were chosen as being the most representative for the year.

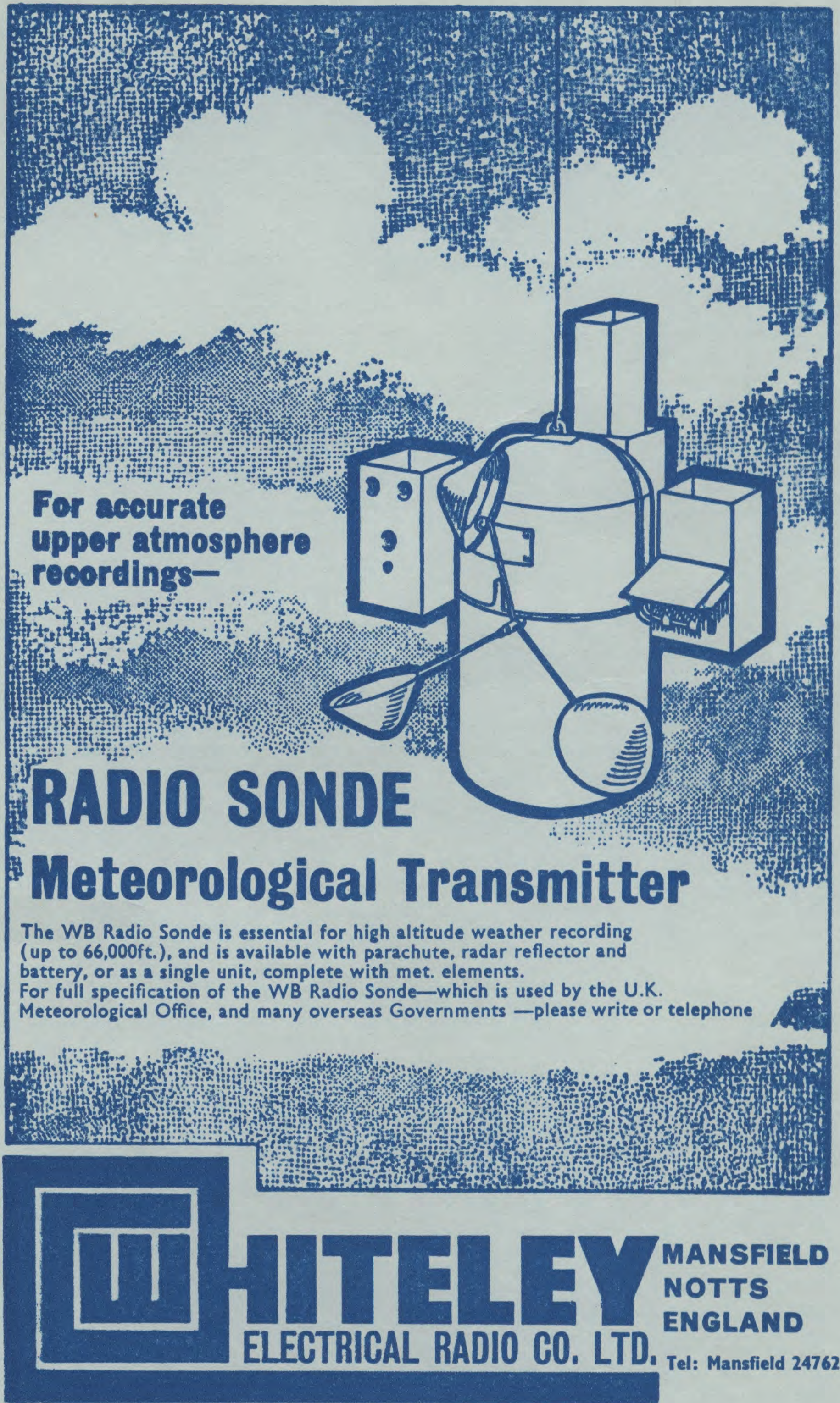
Scientific Paper

No. 31. The three-dimensional analysis of meteorological data. By R. Dixon, B.Sc. and E. A. Spackman, M.Sc.

Before meteorological observations can be used by a computer for the purpose of forecasting the weather, the raw observations have to be processed within the computer so that they can serve as initial data for the mathematical model of the atmosphere which actually does the forecasting. The advent of modern observational devices such as satellites and long-life free drifting balloons has greatly complicated the process of data analysis by computer. This paper presents a possible method for effecting this data analysis by fitting a high-power polynomial to all the observations from within a large volume of the atmosphere.

The following publication has recently been issued : *Monthly charts of dew-point temperatures over the Indian Ocean.*

This publication consists of charts of the mean and the 95 and 5 percentile surface dew-point temperatures over the Indian Ocean for each month of the year. It is an addition to *Monthly meteorological charts of the Indian Ocean* (HMSO, 1949). These dew-point temperature charts were prepared from punched cards of ships' observations, mainly British, for the period April 1953 to December 1961. This representation of humidity will be useful to shippers and packers who are concerned with problems of cargo ventilation in the Indian Ocean area.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THE METEOROLOGICAL MAGAZINE

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FORECASTING MARCH TEMPERATURE AND RAINFALL FOR ENGLAND AND WALES

By R. MURRAY

Summary. The large-scale monthly mean circulation patterns over the north-east Atlantic and western Europe typical of particular classes of temperature and rainfall over England and Wales are discussed with the help of monthly mean surface pressure anomaly maps. Several forecasting rules, mostly based on *PSCM* indices, are presented. The main rules are as follows :

(i) Northerly cyclonic Februarys are generally followed by cold Marches, whereas southerly cyclonic Februarys are followed by warm Marches.

(ii) Blocked anticyclonic winters are mostly followed by wet Marches (i.e. antipersistence in rainfall) and progressive anticyclonic by dry Marches (i.e. persistence in rainfall).

(iii) Blocked northerly types in the January to February periods are usually followed by wet Marches and progressive northerly by dry Marches.

Refinements of the forecasting rules and their relation to sea surface temperature anomalies are discussed.

Introduction. In British climatology it is conventional to regard March as the first month of spring but it could equally well be taken as the last month of winter. Certainly many winters end before March whilst others are prolonged well into March or even into April, as in 1970. September has also a somewhat equivocal position in relation to summer and autumn: September can often be regarded as a summer month (e.g. 1959) even though it is conventionally the first month of autumn.

The purpose of this paper is to present some synoptic-statistical relationships concerning March and to indicate how the mean monthly temperature and rainfall in March can be predicted by simple objective methods.

It is appropriate to mention here that the *PSCM* indices, which are employed for objective specification of large-scale circulation anomalies and in long-range forecasting in the British Meteorological Office, were originally put forward by Murray and Lewis.[1] These indices were recently discussed by Murray[2] and by Murray and Benwell[3] after having been recomputed to take account of the revision by Lamb[4] of his catalogue of daily synoptic types over the British Isles.

In the following pages mean temperature will generally refer to mean monthly temperature over central England — see Manley.[5] Central England mean temperature is representative of mean temperature over England and Wales. In point of fact, in March the spatial correlation of mean monthly temperature falls off quite slowly with increasing distance from central

England, being about 0·9 near the Scottish border, Cornwall and the Low Countries and greater than 0·8 in Scotland, Ireland, northern France and western Germany.

As is normal practice in long-range forecasting, mean temperatures are employed in their quintile form. In other words the ranked temperature distribution is divided into five equal classes and the coldest 20 per cent are called quintile 1 or T_1, the next coldest 20 per cent are quintile 2 or T_2 and so on. Two or more quintiles may be referred to as T_{12}, etc. Quintile boundary values for temperature 1873–1963 are given by Murray,[6] and for *PSCM* indices 1869–1968 by Murray and Benwell.[3] Rainfall is usually classified into three groups and the driest is tercile 1 or R^1. Tercile boundary values for rainfall 1866–1965 are given by Murray.[7] In general the positive or high values of a measured quantity are placed in the quintile or tercile with the highest number. Pressure anomalies are measured as departures from the 1873–1968 mean. The various associations given in this paper are based on sets of data for temperature, rainfall, pressure and *PSCM* indices, whose periods overlap to some extent and give a resultant period of about 100 years.

Unless otherwise stated, the term 'significant' is to be regarded as meaning statistically significant at the 5 per cent level or better, and 'highly significant' as statistically significant at the 1 per cent level or better in chi-square or *t*-tests.

Circulation, temperature and rainfall in March. It is useful to have a picture of the broad-scale circulation which is typically associated with specific types of temperature and rainfall as indicated by percentiles. Figure 1*(a)* depicts the mean pressure anomaly pattern associated with very cold (quintile 1 or T_1) Marches. In this composite map mean pressure is significantly above average over a large region centred roughly on Greenland and significantly below average over an extensive belt in middle latitudes of Europe and in slightly lower latitudes of the North Atlantic. A strong north-east anomaly of flow is shown over the north-east Atlantic and the British Isles. The composite map for T_2 Marches (not shown) is much weaker than Figure 1*(a)*. The T_2 map has a significant positive area (i.e. above average pressure) over the Kara Sea and a significant negative area from Algeria to the Black Sea with a rather weak north-east anomaly of flow over the British Isles, but no significant area over Greenland, North America and the North Pacific.

Figure 1*(b)* shows the mean anomalous circulation associated with very warm *(*T_5*)* Marches. There is a strong south-west anomaly of flow over the British Isles. The mean pressure anomaly pattern is practically the reverse of that shown in Figure 1*(a)*. The T_4 map (not shown) is much weaker than Figure 1*(b)*; it has a significant positive area over central and east Europe and a significant negative area near south Greenland but no significant anomalies over Asia, the North Pacific and North America.

It is interesting that the composite map for T_3 Marches (not shown) has a very weak pattern over western Europe and indeed no significant anomalies from 60°W eastwards to 140°E. However, pressure is significantly above average over the Aleutians and significantly below average near the south of Hudson Bay.

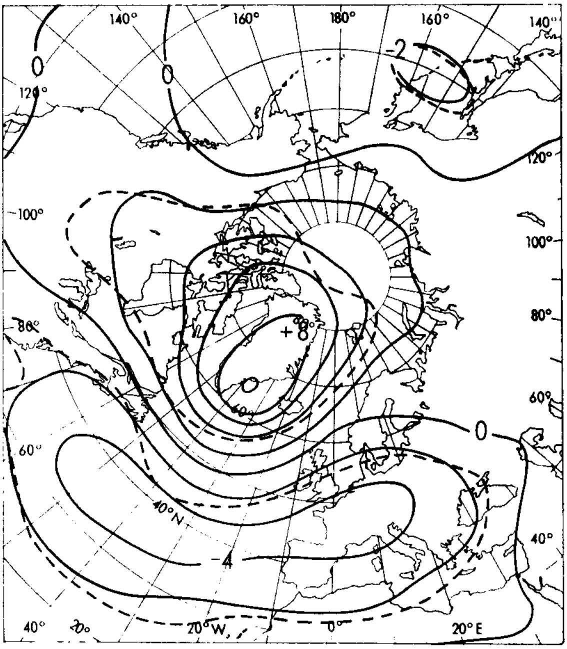

FIGURE 1(*a*)—MEAN PRESSURE ANOMALY PATTERN ASSOCIATED WITH VERY COLD (QUINTILE 1) MARCHES OVER CENTRAL ENGLAND

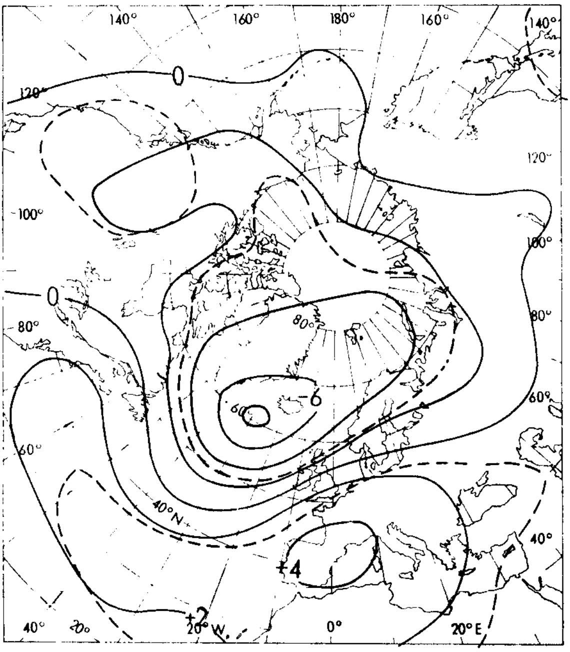

FIGURE 1(*b*)—MEAN PRESSURE ANOMALY PATTERN ASSOCIATED WITH VERY WARM (QUINTILE 5) MARCHES OVER CENTRAL ENGLAND

Broken lines indicate area within which the pressure anomaly is significant at the 5 per cent level according to the *t*-test. Pressure anomalies (mb) are from the 1873–1968 mean pressure.

Figures 2*(a)* and 2*(b)* show the composite mean pressure anomaly patterns associated with dry (tercile 1) and wet (tercile 3) Marches as given by the general rainfall over England and Wales. Over most of the northern hemisphere an area of positive (or negative) anomaly in Figure 2*(a)* becomes an area of negative (or positive) anomaly in Figure 2*(b)*; on both maps the anomaly patterns are significantly different from zero over a large area centred on Ireland. It is not surprising that the composite map (not shown) associated with average rainfall over England and Wales is very weak and featureless over Europe and the North Atlantic and indeed over most of the northern hemisphere.

Persistence in temperature and rainfall. It is well known that temperature tends to be persistent from winter months to March. Indeed Craddock and Ward[8] have shown that there is a highly significant association between mean monthly temperature in February and March over most of Europe, including central England. Actually, temperature persistence in central England is still in evidence from March to April but not from April to May. Craddock and Ward employed terciles of monthly mean temperature based on the ranking of temperature anomalies from 8-year moving averages. It is of interest to present in Table I the temperature associations between winter and March and between February and March when terciles are based on the ranking of mean temperature for the period 1873 to 1963 without attempting to allow for secular variation in the way adopted by Craddock and Ward.

TABLE I—ASSOCIATIONS BETWEEN MEAN TEMPERATURE IN CENTRAL ENGLAND IN *(a)* WINTER AND MARCH AND *(b)* FEBRUARY AND MARCH IN THE PERIOD 1873–1968

	(a) Winter and March				*(b)* February and March		
	March temperature (terciles)				March temperature (terciles)		
Winter temperature (terciles)	1	2	3	February temperature terciles)	1	2	3
1	18	12	6	1	16	14	5
2	9	10	11	2	12	8	12
3	6	9	17	3	5	9	17

The two associations given in Table I are significant according to the chi-square test, the contingency table *(b)* showing a marginally stronger relationship.

There is no corresponding rainfall persistence from February to March. Murray[9] has already pointed out that there is not a synchronous association between mean monthly temperature and monthly rainfall in March; the differences between the composite maps shown in Figures 1 and 2 also tend to confirm the lack of rain/temperature association.

Prediction of temperature. Although temperature persistence must always be considered in forecasting mean temperature in March, it is clearly desirable to look for objective parameters based on circulation or on other physical factors. As Ratcliffe and Murray[10] have pointed out, the sea surface temperature anomaly pattern in the North Atlantic and the mean circulation are closely linked and useful general indications of temperature over western Europe in March can be obtained in many cases. In this paper, however,

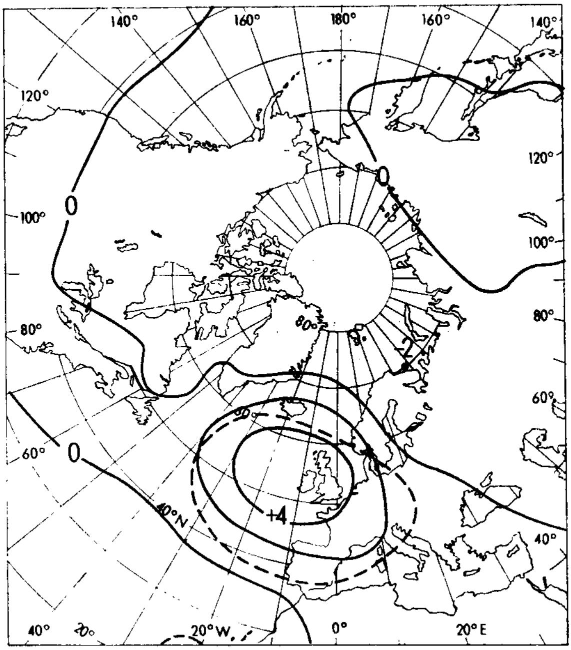

FIGURE 2(*a*)—MEAN PRESSURE ANOMALY PATTERN ASSOCIATED WITH DRY (TERCILE 1) MARCHES OVER ENGLAND AND WALES

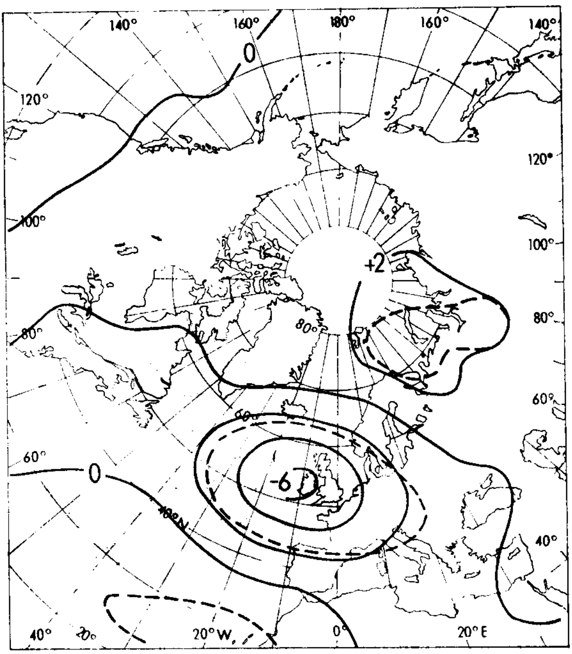

FIGURE 2(*b*)—MEAN PRESSURE ANOMALY PATTERN ASSOCIATED WITH WET (TERCILE 3) MARCHES OVER ENGLAND AND WALES

See note at foot of Figure 1(*b*).

the emphasis will be on the broad-scale circulation, measured objectively by the *PSCM* indices, as a predictor of March temperature.

The strongest associations concern certain combinations of the indices in February and mean temperature in March. The bias to southerly or northerly circulation over the British Isles in February is closely related to subsequent mean temperature in March; this is partly a reflection of temperature and circulation persistence to March. The S index objectively measures any bias in south–north flow and Table II summarizes the simplest type of relationship.

TABLE II—ASSOCIATION BETWEEN S INDEX IN FEBRUARY AND MEAN TEMPERATURE IN MARCH OVER CENTRAL ENGLAND

	March temperature (quintiles)				
S index in February	1	2	3	4	5
S_{12}	15	16	7	6	4
S_3	3	4	4	5	3
S_{45}	3	5	7	12	14

The highly significant association in Table II shows that S_{12} (i.e. northerly bias) in February tends to go with T_{12} (i.e. below normal temperature) in March, and S_{45} with T_{45}. Further examination of the cases indicates that the sub-class involving the cyclonic or C_{45} Februarys has a more significant association with March temperature, as shown in Table III.

TABLE III—ASSOCIATION BETWEEN NORTHERLY CYCLONIC AND SOUTHERLY CYCLONIC FEBRUARYS NEAR THE BRITISH ISLES AND MEAN TEMPERATURE IN MARCH OVER CENTRAL ENGLAND

	March temperature (quintiles)				
February indices	1	2	3	4	5
$S_{12}C_{45}$ (northerly cyclonic)	9	10	1	2	0
S_3C_{45}	1	1	3	0	2
$S_{45}C_{45}$ (southerly cyclonic)	0	2	3	4	5

Table III shows that $S_{12}C_{45}$ Februarys have a strong tendency to be followed by T_{12} (i.e. cold) Marches and $S_{45}C_{45}$ Februarys by T_{45} Marches. The relationship is highly significant, as can readily be shown by applying a chi-square test to the 2×2 table obtained by sharing S_3C_{45} equally with $S_{12}C_{45}$ and $S_{45}C_{45}$ and sharing T_3 equally with T_{12} and T_{45}.

The broad-scale anomaly of flow in February depicted by the $S_{12}C_{45}$ class is shown in Figure 3*(a)* and the circulation of the $S_{45}C_{45}$ class in Figure 4*(a)*. Figures 3*(b)* and 4*(b)* show the corresponding anomaly of flow in March. Figures 3*(a)* and 4*(a)* give further evidence that the broad-scale anomaly of circulation over a large area can be represented in a simple, quantitative way by suitable combinations of the *PSCM* indices.

Figure 3*(b)* has a large and significant area with above average pressure in high latitudes and a corresponding area with below average pressure over middle to low latitudes in Europe and the North Atlantic; the blocking pattern is on a huge scale. The circulation change from February to March shown in Figures 3*(a)* and *(b)* shows a build-up of pressure in the Arctic

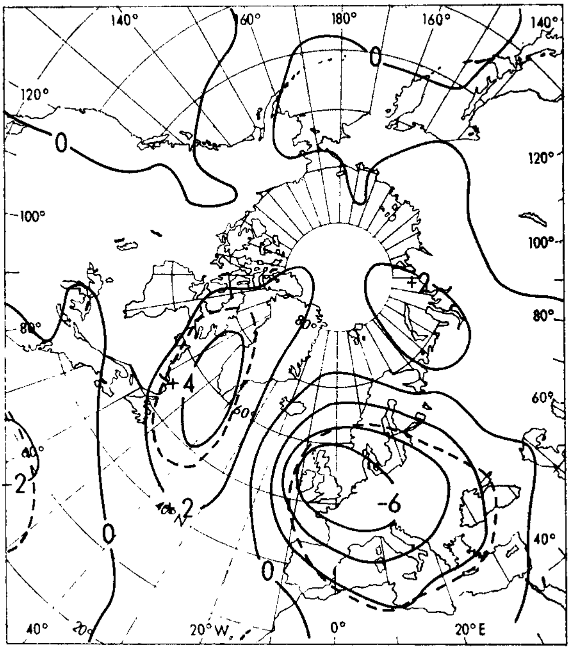

FIGURE $3(a)$—MEAN PRESSURE ANOMALY PATTERN IN FEBRUARY ASSOCIATED WITH THE $S_{12}C_{45}$ (NORTHERLY CYCLONIC) CLASS OF FEBRUARY

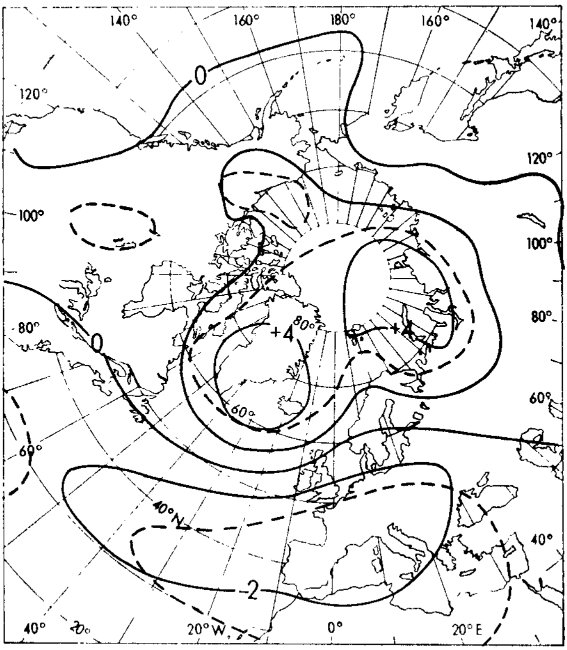

FIGURE $3(b)$—MEAN PRESSURE ANOMALY PATTERN IN MARCH FOLLOWING THE $S_{12}C_{45}$ (NORTHERLY CYCLONIC) CLASS OF FEBRUARY

See note at foot of Figure $1(b)$.

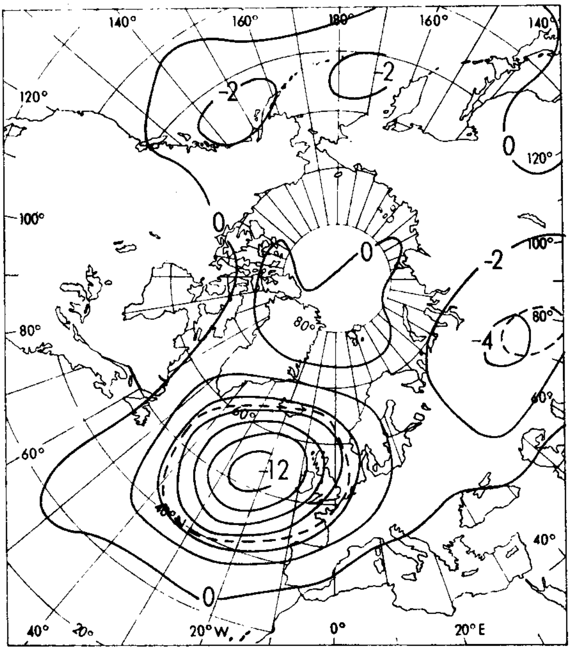

FIGURE 4(*a*)—MEAN PRESSURE ANOMALY PATTERN IN FEBRUARY ASSOCIATED WITH THE $S_{45}C_{45}$ (SOUTHERLY CYCLONIC) CLASS OF FEBRUARY

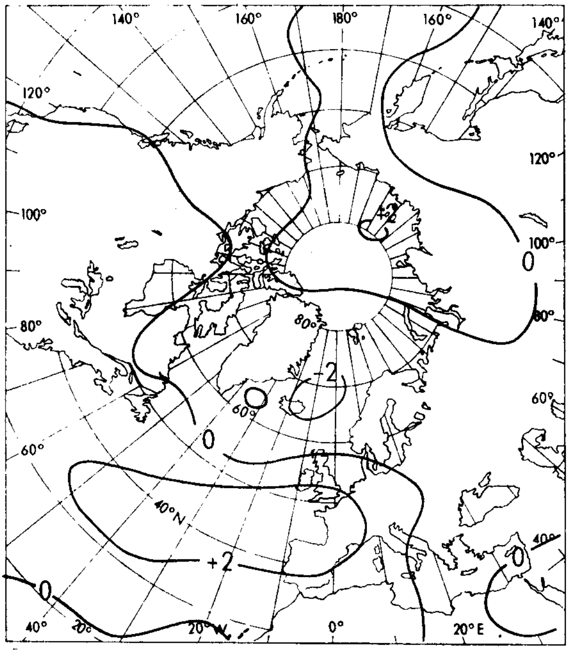

FIGURE 4(*b*)—MEAN PRESSURE ANOMALY PATTERN IN MARCH FOLLOWING THE $S_{45}C_{45}$ (SOUTHERLY CYCLONIC) CLASS OF FEBRUARY

See note at foot of Figure 1(*b*).

and some weakening and drift southwards of the pre-existing area of below average pressure over western Europe. In the normal year there is a build-up of pressure between February and March in high latitudes centred on Greenland (+4 mb approximately over south Greenland) and a fall of pressure over North America, Asia and southern Europe; the pressure changes following $S_{12}C_{45}$ Februarys are in the same sense as the seasonal changes in the Atlantic/European sector.

The circulation pattern in March following $S_{45}C_{45}$ Februarys is shown in Figure 4*(b)* and it is nearly the reverse of Figure 3*(b)*. However, the positive area over and to the west of south-west Europe is just about significant at the 5 per cent level near north Spain.

The predictive relationships in Tables II and III may be supplemented by further associations involving circulation types in Table IV.

TABLE IV—VARIOUS ASSOCIATIONS BETWEEN CIRCULATION TYPES NEAR THE BRITISH ISLES IN FEBRUARY AND MEAN TEMPERATURE IN MARCH OVER CENTRAL ENGLAND

	March temperature (quintiles)				
February indices	1	2	3	4	5
$P_{12}S_{12}$ (blocked northerly)	7	6	5	2	0
$P_{12}S_{12}$ or $S_{12}C_{45}$ (5 common years counted once)	13	14	6	4	0
$P_{45}S_{45}$ (progressive southerly)	1	2	3	2	8
$P_{45}S_{45}$ or $S_{45}C_{45}$ (6 common years counted once)	1	3	4	6	10

It is of interest that none of the rules contained in Tables III and IV involve C_{12} (anticyclonic) Februarys. Actually $S_{12}C_{12}$ and $S_{45}C_{12}$ Februarys have a weak tendency to be followed by cold and warm Marches respectively, but the relationships are apparently determined by the S index. Indeed C_{12} by itself (i.e. whatever the value of S) shows no predictive value, since the March temperature distribution following C_{12} Februarys is $8T_1$, $9T_2$, $10T_3$, $11T_4$, $6T_5$.

Prediction of rainfall. The poor correlation between monthly rainfall and temperature in March means that 'rules' used for prediction of temperature are unlikely to be equally helpful in rainfall forecasting. For instance, the $S_{12}C_{45}$ and $S_{45}C_{45}$ types of February, shown in Table III to be very useful in forecasting temperature in March, are not satisfactory predictors of rainfall over England and Wales in March.

The broad-scale circulation during winter (December+January+February) and over the two-month period January+February appear to be much better indicators of March rainfall than does the circulation in February. P_{12} (blocked) winters tend to be followed by wet Marches ($10R_1$, $14R_2$, $23R_3$) but P_{45} (progressive) winters show only a weak association ($19R_1$, $13R_2$, $12R_3$). Similarly C_{12} (anticyclonic) winters show some association with wet Marches ($12R_1$, $14R_2$, $18R_3$), but C_{45} (cyclonic) winters show none. S_{12} (northerly) and S_{45} (southerly) winters have no relationship with rainfall in March. For the C_{12} winters subdivided according to their progressiveness the association shown in Table V is highly significant.

TABLE V—ASSOCIATION BETWEEN BLOCKED ANTICYCLONIC AND PROGRESSIVE ANTICYCLONIC WINTERS NEAR THE BRITISH ISLES AND RAINFALL IN MARCH OVER ENGLAND AND WALES

Winter indices	March rainfall (terciles) 1	2	3
$P_{12}C_{12}$ (blocked anticyclonic)	2	5	14
P_3C_{12}	2	5	2
$P_{45}C_{12}$ (progressive anticyclonic)	8	4	2

Clearly, blocked anticyclonic winters are mostly followed by wet Marches, whereas progressive anticyclonic winters are biased towards dry Marches. The composite mean pressure anomaly maps associated with the $P_{12}C_{12}$ winters and the following Marches are shown in Figures 5*(a)* and *(b)* respectively. Figure 5*(a)* shows a large-scale blocking pattern near western Europe, typical of the $P_{12}C_{12}$ type winter. In March, following $P_{12}C_{12}$ winters, there is evidently a general fall of pressure over the eastern Atlantic and the British Isles and it is not surprising that above average rainfall typically occurs in March as indicated in Table V. Incidentally, the composite map (not shown) representing the $P_{45}C_{12}$ winters of Table V has positive pressure anomalies over south and central Europe, with a significant area (>3 mb) over France, and negative pressure anomalies in higher latitudes with a significant area (<-4 mb) near and over the Barents Sea. The composite map (not shown) for the Marches following $P_{45}C_{12}$ winters has a significant positive anomaly centre (>4 mb) between the Azores and Ireland, which implies a retrogression of the pre-existing centre of positive anomaly over France in the winter. Moreover, the composite map for March shows a north-west anomaly of flow and pressure slightly above average over the British Isles.

From Table V it is seen that two dry Marches followed the $P_{12}C_{12}$ winters. It is of interest that these dry Marches are eliminated from the statistics if a further proviso is made that there should be a northerly component in the anomaly of flow over the British Isles (i.e. the anticyclonic block shifted a little west of the mean position shown in Figure 5*(a)*). The $P_{12}S_{12}C_{12}$ winters were in fact associated with seven wet, four average and no dry Marches.

Examination of the circulation indices for the two-month period January to February suggested that $P_{12}S_{12}$ (blocked northerly) and $P_{45}S_{12}$ (progressive northerly) types were useful indicators. Actually $P_{12}C_{12}$ and $P_{45}C_{12}$ types give similar, but weaker, indications to those given in Table V. However, the best associations are presented in Table VI.

TABLE VI—ASSOCIATION BETWEEN BLOCKED NORTHERLY AND PROGRESSIVE NORTHERLY TYPES IN JANUARY TO FEBRUARY NEAR THE BRITISH ISLES AND RAINFALL IN MARCH OVER ENGLAND AND WALES

January to February indices	March rainfall (terciles) 1	2	3
$P_{12}S_{12}$ (blocked northerly)	2	7	9
P_3S_{12}	4	3	3
$P_{45}S_{12}$ (progressive northerly)	12	2	1

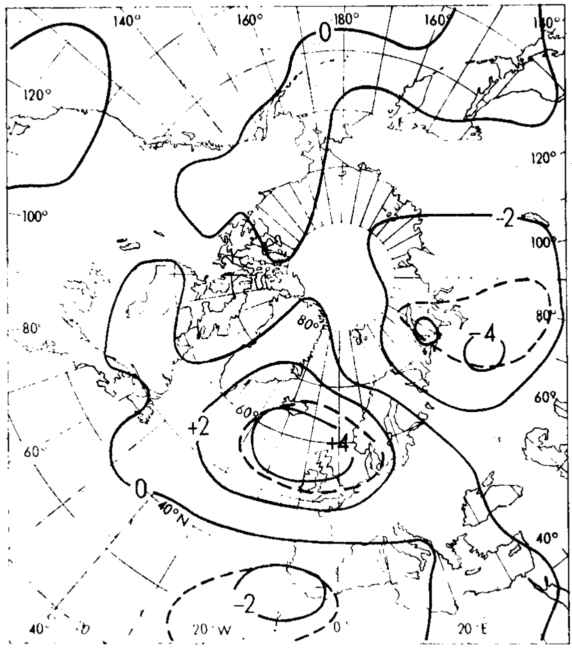

FIGURE 5(*a*)—MEAN PRESSURE ANOMALY PATTERN IN WINTER ASSOCIATED WITH THE $P_{12}C_{12}$ (BLOCKED ANTICYCLONIC) CLASS OF WINTER

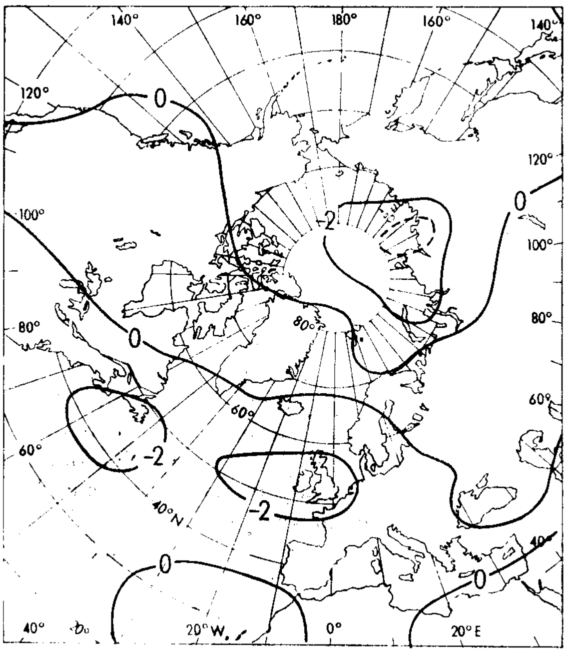

FIGURE 5(*b*)—MEAN PRESSURE ANOMALY PATTERN IN MARCH FOLLOWING THE $P_{12}C_{12}$ (BLOCKED ANTICYCLONIC) CLASS OF WINTER

See note at foot of Figure 1(*b*).

Table VI is highly significant. The relationship between $P_{45}S_{12}$ in January plus February and dry Marches is notably strong.

Tables V and VI were next examined for common years. The results are summarized in Table VII.

TABLE VII—ASSOCIATION BETWEEN SPECIFIED CIRCULATION CLASSES NEAR THE BRITISH ISLES AND RAINFALL IN MARCH OVER ENGLAND AND WALES

Circulation indices: Winter		January to February	March rainfall (terciles) 1	2	3
$P_{12}C_{12}$	and	$P_{12}S_{12}$	0	2	5
$P_{3}C_{12}$	and	$P_{3}S_{12}$	1	0	1
$P_{45}C_{12}$	and	$P_{45}S_{12}$	5	0	0

There are not enough cases in Table VII to permit a statistical significance test.

By counting the common years only once and combining the Tables V and VI, a highly significant contingency table is obtained as shown in Table VIII.

TABLE VIII—ASSOCIATION BETWEEN SPECIFIED CIRCULATION CLASSES NEAR THE BRITISH ISLES AND RAINFALL IN MARCH OVER ENGLAND AND WALES

Circulation indices: Winter		January to February	March rainfall (terciles) 1	2	3
$P_{12}C_{12}$	and/or	$P_{12}S_{12}$	4	10	18
$P_{3}C_{12}$	and/or	$P_{3}S_{12}$	5	8	4
$P_{45}C_{12}$	and/or	$P_{45}S_{12}$	15	6	3

Concluding remarks. Anomalous circulation types given by particular combinations of indices, such as $P_{12}C_{45}$ in February, are generally on a large scale, affecting much of the North Atlantic and Europe. These large-scale patterns of anomalous circulation are similar to those recently discussed by Sawyer,[11] but he was unable to disentangle the physical processes relating to their formation and persistence or change with time. The exchange of heat from ocean to atmosphere is likely to be one factor of importance, but it is not yet possible to use this in a practical forecasting rule. However, it is of interest that the $S_{12}C_{45}$ and $S_{45}C_{45}$ Februarys (Table III) were examined in terms of the sea surface anomaly patterns (WP and CP) of Ratcliffe and Murray.[10] The pattern WP is characterized by an extensive area of positive sea surface temperature anomaly to the south of Newfoundland and CP by an extensive area of negative anomaly in the same general area. Of the 22 cases of $S_{12}C_{45}$ Februarys only eight years could be classified (the other years had inadequate or no data or ill-defined patterns) but five of these were the WP type and all were followed by average or cold (T_{123}) Marches. Similarly the 14 $S_{45}C_{45}$ Februarys were classifiable in terms of sea surface temperature patterns in only seven cases; these were all CP type and were followed by average or warm (T_{345}) Marches. There is evidently a link here. However, it is also clear that for practical forecasting, at least in this instance, the *PSCM* indices can be applied on many more occasions. A similar conclusion was arrived at after looking at the sea surface temperature patterns in January and February associated with some of the *PSCM* rules for predicting the rainfall over England and Wales in March. In this paper the simple objective procedures which are given enable useful prediction of March temperature and rainfall to be made on many occasions.

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FIFTY YEARS AT LERWICK OBSERVATORY

By J. B. TYLDESLEY

Introduction. Lerwick Observatory celebrates its fiftieth anniversary on 7 June 1971. In 1950 Harper[1] produced an excellent account of the work of the Observatory up to that time. In this article some historical information on the setting up of the Observatory is given, with brief reference to the work of the first 30 years and a somewhat fuller description of developments since 1950. Plate I shows the Observatory as it was in 1965.

The foundation of the Observatory. After the First World War, the Meteorological Office had a development plan which included setting up meteorological stations in Orkney and Shetland. In 1919 the Norwegian Government asked other countries, including Britain, to set up stations in northerly latitudes to make geophysical observations in connection with Amundsen's polar voyage. Also there was a need for a magnetic observatory in the far north of the British Isles. Not only was Kew increasingly troubled with artificial disturbance but records from Eskdalemuir Observatory (set up in 1908) had shown that the day-to-day magnetic variations there were about twice as great as at Kew. In terms of latitude, approximately half of the

British Isles is north of Eskdalemuir, and moreover this half is on the southern edge of the auroral zone, so that on all counts, further increase of magnetic variation was expected in the far north.

These three factors — meteorological observations, help for Amundsen, and magnetic observations — appear (with different emphasis) in all the correspondence on setting up the Observatory. In February 1920 the Director, Sir George Simpson, wrote to Dr Charles Chree, his Superintendent at Kew, about the project; and Chree immediately got in touch with Dr Crichton Mitchell at Eskdalemuir and arranged to include provision for a station in Shetland in the estimates for the following year.

Thereafter things moved rapidly. In April the Director set up a powerful committee consisting of Dr Chree, Mr Lempfert, Lieutenant-Colonel Gold, Dr Crichton Mitchell, Mr Richardson and Mr Corless. Mr Watson Watt was to advise on radio communication. The committee considered the work to be done and various sites including places in the north isles of Yell and Unst, and on the north mainland, as well as near Lerwick. Crichton Mitchell was sent to Shetland to investigate, and came down in favour of the old Admiralty wireless station on the outskirts of Lerwick, largely because there were existing houses which could be used both as offices and for accommodating staff. He submitted a most comprehensive report on all that needed to be done, both scientifically and domestically. On the accommodation, he said : 'The houses are very small. The largest room in No. 1' (which was to be the Superintendent's house) 'is only about 10 feet square. They have been constructed on the lines of artisans cheap houses and are not of such a character as the men to be posted to the Observatory can have been accustomed.' There was an element of special pleading in this, for Crichton Mitchell went on to argue the case for charging low rents for the houses, in order to make a spell at such an 'outlandish place' reasonably attractive to the staff.

In November 1920 the Director visited Shetland himself, and in December he sought and received Treasury permission to go ahead. Times were hard, and he was expected to run the Observatory without receiving any extra staff or funds. The proposed station in Orkney was forgone, largely because the Navy no longer required it, and that helped with staffing. Equipment was mostly to be borrowed from the other observatories and refurbished. However a non-magnetic hut for the absolute instruments was required, also a magnetograph house of non-magnetic construction. Dr Chree was much exercised by the magnetograph house. The continuously recording magnetic instruments of the day were seriously affected by changing temperatures, which had to be reduced to a minimum. At Eskdalemuir the problem had been solved by making a cavern in the hillside, but funds were not available to do this at Lerwick. Two designs were considered. One was for a hut within a hut, the outer of three thicknesses of concrete blocks, with a six-inch air space and a second six-inch space filled with slag wool, and triple glazing. The inner hut, supported on piers, would have been a double skin of timber and plaster, again with slag-wool filling. The other, which was eventually adopted, was for a monolithic concrete structure with a half-cylindrical top. The object was to reduce outside diurnal variations of 5 degC to 0·05 degC inside. Dr Chree wrote to the Director at length about the design, deploying his knowledge of non-steady-state heat-conduction theory, and walls up to three feet thick were contemplated. It is interesting that Chree's lengthy notes were in his own hand, and went to Dr Simpson personally at South Kensington.

The Observatory was opened on 7 June 1921 by Dr Crichton Mitchell, who stayed until 13 June. He left Mr J. Crichton as officer-in-charge, with a staff of two probationers, a caretaker, and a wireless operator. There is no record of any celebrations, and all the evidence is that it was very much a working visit to get the Observatory going. While at Lerwick, Crichton Mitchell added his share to the weight of calculations on the magnetograph house, bemoaning the absence of tables of Bessel functions in Shetland. He favoured the use of coke breeze to give an insulating concrete, but tests at Eskdalemuir showed that the local material was strongly magnetic. In the end shingle was used as aggregate. Work began in 1921 and finished in the spring of 1922. Plate II shows the house as it is today, and Plate III, taken while the work was in progress, suggests that it taxed local resources severely. In the background of the latter photograph, the Admiralty wireless masts and the original houses can be seen.

The magnetic work. The photographically recording magnetographs are described by Harper.[1] Although fires were kept burning continuously in the house for the first six months, damp was always a problem, and continued to be so for many years, until it was possible to install electric heaters in 1946. In 1926 a bizarre method of drying, suggested by the Director on a visit, was tried. A canvas bag filled with calcium chloride was hung from the ceiling and a bucket placed beneath to catch the drippings. Temperature effects were also troublesome. The variations in the house were never as small as the calculations concerning the 2½-foot walls had indicated, probably because it was necessary to ventilate the house continuously with outside air to reduce condensation. Despite all these difficulties, reliability improved gradually over the years, and the house is still in use. Plate IV shows the scene when the lights were switched on briefly in July 1965. The quick-run La Cour magnetograph is nearest the camera, with the variometers on the left and recorders on the right. The supplementary (storm) magnetograph is beyond. The wiring has an improvised look, and various black screens intended to eliminate stray light may be seen. The picture emphasizes the difficulty of doing this taxing technical work in almost complete darkness.

The magnetographs are standardized by absolute instruments housed in a separate hut. The Kew magnetometer has been used for declination since 1922, but all the other instruments have been superseded. The biggest change was the introduction of the proton vector magnetometer in 1964. In this instrument the frequency of precession of protons in the earth's field is measured electronically. The proton sample consists of a plastic bottle of water around which exciting and sensing coils are wound. Large Helmholtz coils surround the sample, and remove in turn the unwanted components of the earth's field. Plate V shows the sensor and coils, and beside it may be seen the Kew magnetometer. An advantage of the proton instruments, over their predecessors incorporating 'permanent' magnets, is that the magnetic moment of the proton is the same at all places and times. Thus inter-observatory comparisons are no longer required; a fact which is in some ways regretted by the staffs of these isolated stations.

In recent years modern instruments have also been tried as variometers. In 1961 a digitally recording version of the proton magnetometer was installed, and also a rubidium vapour magnetometer, which makes use of the Zeeman splitting of the electronic energy levels of that element. Experiments with the latter have continued to the present. In 1965 fluxgate magnetometers were installed. Up to now, however, none of these instruments has proved sufficiently reliable and sufficiently stable to be incorporated in the basic observatory routine, and the 40-year-old La Cour design still holds sway.

The original purposes of the magnetic observations were to assist navigation, and for the reduction of magnetic surveys made for geological purposes. These functions still continue, and recently the latter has become important again as the search for oil and natural gas spreads into the northern North Sea. The day-to-day variations of the magnetic field are due to electric currents in the earth's upper atmosphere, and the Lerwick readings, along with those of many other observatories, have helped to elucidate these currents and their variations. This work also has received added stimulus in recent years. Whereas formerly the electric currents could only be deduced indirectly from ground observations, rockets and satellites can now penetrate the parts of the atmosphere concerned. Because these pass rapidly through the regions of interest, the ground-based magnetic observations have renewed importance in forming a framework for the satellite data.

In 1965, national responsibility for geomagnetism was vested in the Institute of Geological Sciences of the Natural Environment Research Council. The Meteorological Office continued to carry out the geomagnetic work at Lerwick as an agent of NERC until 1969, when NERC sent two of their own staff to the Observatory.

Aurora. This subject is mentioned next, because of its close connection with the magnetic work. The aurora is caused by electrical excitation of the upper atmosphere by energetic protons and electrons flowing from the sun. Naturally the electric currents in the magnetosphere are also affected, so aurora is often accompanied by notable magnetic disturbance. Lerwick is on the southern edge of the auroral zone and therefore well placed to observe these connections.

It had from the first been intended to observe aurora in Shetland. Crichton Mitchell's first report on the proposed stations puts auroral parallax-photography at the head of the list of possible observations. He envisaged a second station at Hillswick, about 42 km north-north-west of the Observatory, with a staff of two throughout the winter. No doubt he had Störmer's pioneer work on the determination of the height of the aurora in mind, because the man in charge was to be sent to Norway for training, and two special cameras were to be bought there. Although a nightly auroral watch in winter was soon instituted, it was several years before photography could be begun. In 1928 a single Krogness camera was put into use, and in 1932 another was added under the charge of a voluntary observer near Hillswick. After the Polar Year 1932–33 not much photography was done until 1963 when an all-sky camera of modified Alaskan type was set up on behalf of Edinburgh University. This is now operated on every clear night, and at an increased rate as soon as aurora is observed visually.

Although Lerwick is in a good geomagnetic latitude for auroral work, two factors are against it. One is the high winter cloudiness; and the other is

PLATE I—LERWICK OBSERVATORY FROM THE SOUTH IN 1965

PLATE II—THE MAGNETOGRAPH HOUSE AS IT IS TODAY
Absolute magnetic huts in the centre, and main Observatory buildings on the right.

PLATE III—THE CONSTRUCTION OF THE MAGNETOGRAPH HOUSE IN 1921/2

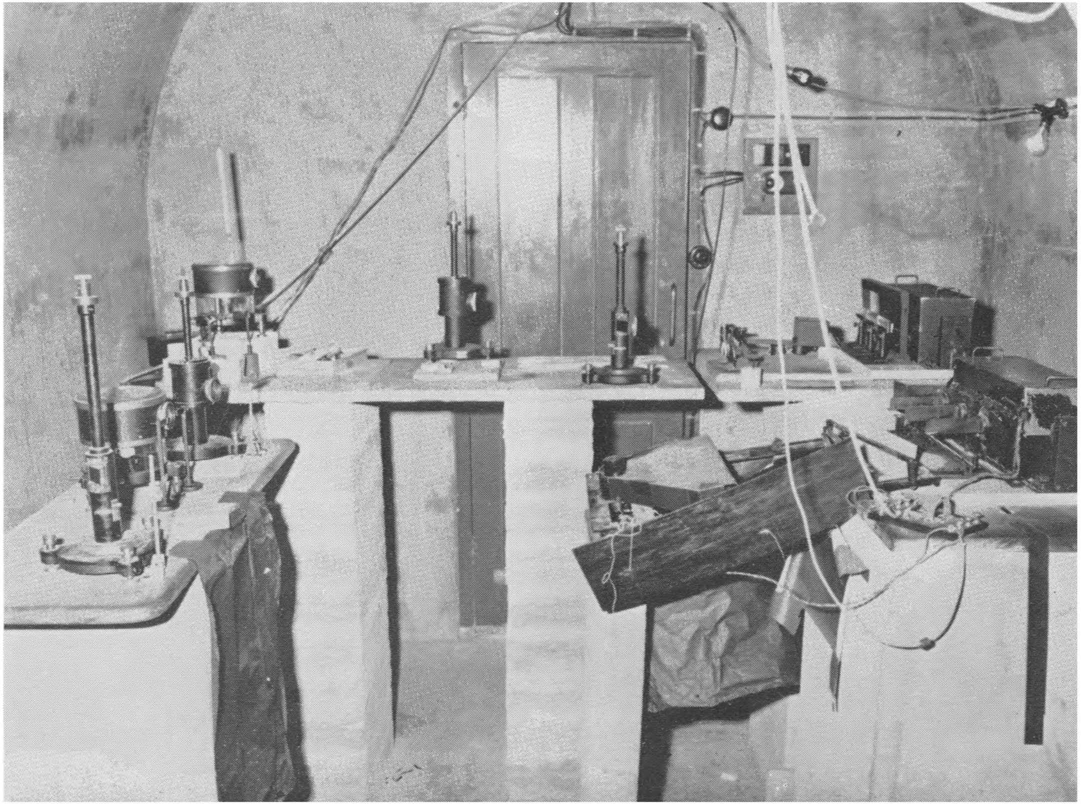

PLATE IV—INTERIOR OF THE MAGNETOGRAPH HOUSE IN 1965

Quick-run La Cour magnetograph nearest camera on left and supplementary (storm) magnetograph beyond.

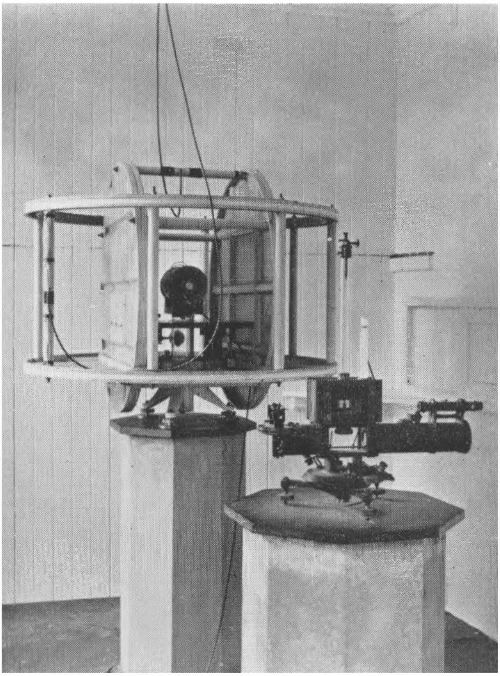

PLATE V—ABSOLUTE MAGNETIC INSTRUMENTS OLD AND NEW

Kew declinometer on near pillar; sensor and bias coils of proton vector magnetometer beyond.

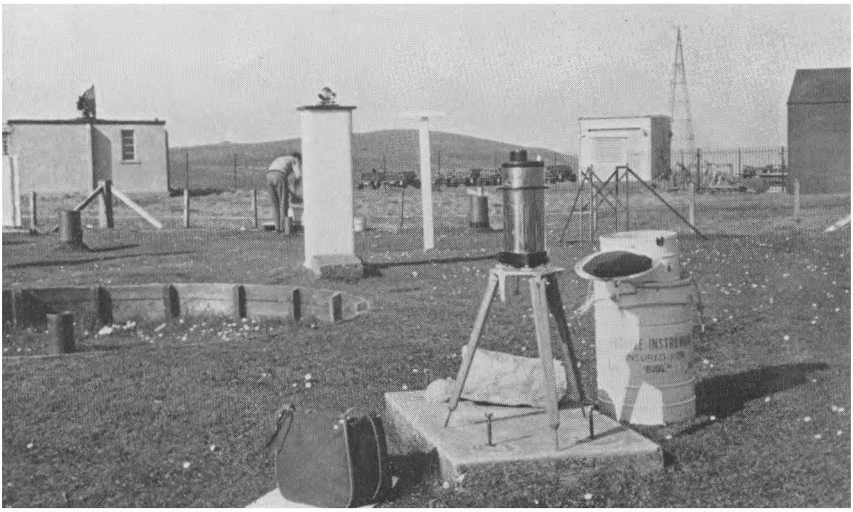

PLATE VI—GRAVIMETER SET UP TEMPORARILY IN THE INSTRUMENT ENCLOSURE IN 1961

In the background on the left the Meteorological Office wind-finding radar (G.L.3), and the balloon-filling shed at centre right.

the increasing brightness in the northern sky due to street lighting in the town of Lerwick. Of recent years, to assist in doubtful cases, observers have had the use of a pair of goggles fitted with interference filters which isolate the yellow-green auroral line.

Meteorology. Initially the Observatory was equipped with quite a comprehensive set of meteorological instruments, and observations were made five times a day. Soon staff shortage caused a reduction and by 1927 there was only one observation a day. The reduction was acceptable because the coastguard station in Lerwick was making and transmitting synoptic observations.

In 1940 Lerwick became a radiosonde station, with flights four times daily, and in 1942 upper wind measurements were added, by direction-finding on the sonde transmission, using two outstations on the north and west of the Shetland mainland. This meant a big increase in staff, many of whom were in RAF uniform. In 1946 wind finding by radar was introduced, enabling the outstations to be closed and staff reduced; and in the last decade automatic-radar-following and automatic reception have made further reductions possible. Launching conditions at Lerwick are often very difficult, and the Lerwick staff are renowned for their skill and zeal in getting the flights away.

Not even during the war did the Observatory become a synoptic reporting station, but in 1945 this came about, because of the closure of the RAF flying stations in Shetland. It then became, and is still, a full 24-hour reporting station.

The weather in Shetland varies a good deal from place to place. The Office has been for many years, and still is, fortunate in its voluntary observers here. At present full climatological stations are maintained at Hamnavoe, Burra, in the west, and at Baltasound, Unst, in the north. In addition there are a number of rainfall stations.

Other activities. It is impossible in the space of this article to describe all the scientific activities which the Observatory has undertaken, but a brief list will be given. Some have been initiated by the Office and others by individual scientists or outside organizations.

Measurement of atmospheric potential gradient began in 1922 with a radium collector and a Dolezalek electrometer, which was replaced in 1925 by a Benndorf electrometer. Other measurements in atmospheric electricity were planned, but insulation in the Lerwick climate was such a problem that they were never begun. In 1930 the safer polonium collectors were introduced, and there was no other important instrumental change until the Benndorf was replaced in 1959 by a valve voltmeter designed at Kew. This has proved very satisfactory and insulation troubles are much reduced. The justification for this long period of recording appeared when decrease of potential gradient at Lerwick in the 1950s gave warning of an unsuspected increase of beta-activity due to nuclear-bomb tests. The importance of Lerwick was that pollution was unlikely to be a complicating factor.[2]

Ozone was first measured using a photographic spectrograph in 1926/27 In 1939 a Dobson spectrophotometer was installed, and measurements were made intermittently up to 1946. They began again in 1951 and are now made regularly. On selected days the clear air at Lerwick has proved favourable for determining the constants of the instrument.[3,4]

A number of radio investigations have been made at Lerwick, the first being direction-finding and atmospherics experiments in the 1920s. In the 1960s the Radio and Space Research Station had their own staff at the Observatory, and operated an ionosonde and a neutron monitor.

Recording of solar radiation began in 1951, and now global and diffuse short-wave radiation, illumination, and radiation balance are recorded continuously. Many investigations of the relations between the elements have been made, but have not been published. Two articles, on some anomalies in the measurements, have appeared.[5,6]

Varied air-sampling work has been done, beginning with smoke concentration in 1948. Chemical sampling of air and rain began in 1958, and 'enormous quantities' of salts were collected. In January 1958 the total was 36 grammes per square metre of ground. Lista, an exposed station on the Norwegian coast, hardly collects as much in a year.[7] Sampling of air and rain-water for the Atomic Energy Research Establishment, Harwell, started in 1962. Sampling of carbon dioxide for isotopic composition began in 1967, and the last addition was sulphur-dioxide sampling in 1969. All these activities have continued to the present.

The Observatory has always made its facilities available to visiting scientists, from whatever discipline, who wished to make measurements in Shetland. Such visits help to keep the staff in contact with the wider scientific world and are much appreciated. Plate VI shows a gravimeter set up temporarily in the enclosure in 1961. In recent years French scientists have visited Lerwick and made measurements of high-frequency magnetic pulsations. In this case Lerwick was part of a network stretching from Tromsö to Addis Ababa.

Publication of results. For many years the main vehicle was the *Observatories' Year Book*, in which all the Lerwick results were published together.* These year books also contain interesting accounts of the techniques used, and photographs of the site and buildings at different times. The International Geophysical Year (1958/59) began a tendency for collection of each type of measurement in international data centres, which has continued. The *Observatories' Year Book* is no longer published. The final volume of the series was that for 1967 and it contains details of where the data are to be published in future.

Life at the Observatory. In early years conditions were rigorous, especially for those from the south, though generally enjoyable. Today the Observatory has most of the modern amenities. Town water arrived in 1943. The first mains electricity also came during the war years, but it was a small supply for essential scientific purposes only, and not too reliable. In 1945 oil lamps were finally banished, but the electricity supply was only adequate for lighting. Abundant mains power from the public supply did not arrive until 1952. After many years of 'making do', a new office building was put up in 1961, and five houses in 1962. The new houses are more spacious than the

* London, Meteorological Office. *Observatories' Year Book.*

old, but do not resist the Shetland weather as effectively as the 'artisans cheap dwellings' of 60 years ago, which still give good service. By winter 1962, the whole station had oil-fired heating from a central plant.

Despite its inconveniences, life in Shetland is often well liked by those who work here. Many local staff are employed, while others marry local girls and settle down. In time we come to regard the Observatory with affection. In the past three years, three previous Superintendents have visited us while on holiday in Shetland, and all expressed nostalgia for their time here.

The writer thanks the many past and present members of the Observatory staff who have helped him with information, both written and verbal, for use in this article.

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551.593. 53

NOCTILUCENT CLOUDS OVER WESTERN EUROPE DURING 1970

By J. PATON
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Table I contains a summary of observations of noctilucent clouds (NLC) made at stations in western Europe in 1970 during the period from late May to early August when these clouds normally appear. On nights when tropospheric clouds hinder observation so that no reliable conclusion can be reached as to the presence or absence of NLC, 'Cloudy' is entered in the third column. On nights when the sky is clear at a number of stations and no trace of NLC is detectable, 'No NLC' is entered in the third column.

When NLC are observed, the periods of time, in Universal Time (UT), during which they remain visible are given in the second column and notes on the characteristics of the display in the third. Observations of the extent of the display (maximum elevation above the northern horizon and limiting azimuths) seen from selected stations at stated times are given in the remaining four columns. The latitude and longitude of the observing stations are given to the nearest half degree.

In the case of faint displays, it is often difficult to be certain that what is observed is actually NLC. If, in these circumstances, a report of suspected NLC is received from one station only, when other stations with favourable observing conditions are reporting no NLC, it is assumed that the occurrence is doubtful and the report is disregarded.

TABLE I—DISPLAYS OF NOCTILUCENT CLOUDS OVER WESTERN EUROPE DURING 1970

Date — night of	Times UT	Notes	Station position	Time UT	Max. elev. (degrees)	Limiting azimuths (degrees)
26–27 May	2245–0115	Faint bands seen from northern England before dawn.	55·5°N 1·5°W	0115	15	045–090
27–28		No NLC				
28–29		No NLC				
29–30		No NLC				
30–31		No NLC				
31 May–1 June		No NLC				
1–2 June		Cloudy				
2–3		No NLC				
3–4		No NLC				
4–5		No NLC				
5–6		No NLC				
6–7		No NLC				
7–8		No NLC				
8–9		No NLC				
9–10		No NLC				
10–11		Cloudy				
11–12	2115–0115	Cloudy over the British Isles. Fine display of bluish-white and greenish-white bands seen during whole night from Copenhagen, mainly in the north-east segment of the sky. Billows and whirls seen around midnight.	55·5°N 12·5°E	2350	70	000–090
				0015	90	
12–13		No NLC				
13–14		No NLC				
14–15	2335–0050	Cloudy over the British Isles. Faint display seen from Copenhagen extending sometimes in narrow thread-like bands to the zenith, with amorphous surfaces nearer the northern horizon.	55·5°N 12·5°E	0005	90	
				0035	90	
15–16	2325–0050	Cloudy over British Isles. Faint veil and greenish bands, with increase in brightness around midnight and 0025 UT seen from Copenhagen.				
16–17	0035	No NLC seen from British Isles. Bright short-lived display reported from Copenhagen.				
17–18	2130–2305	No NLC seen from British Isles. Faint bands seen from Bornholm, Denmark.	55°N 15°E	2305	7	
18–19		No NLC				
19–20		No NLC				
20–21		No NLC				
21–22		No NLC				
22–23		No NLC				
23–24		Cloudy				
24–25		No NLC				
25–26	2310–0020	Faint bands observed in central and southern England.	53·5°N 0°	2310	5	350
			51°N 4°W	0020	20	350–010
26–27		Cloudy				
27–28	2340–0134	Single bright band seen close to horizon from three stations in the only region where skies clear. Bright at first; later broke into three patches and became faint.	53·5°N 3°W	2340	1	350–030
			53°N 1·5°W	2355	2·5	300
			53°N 2·5°W	0110	5	010–020
				0125	3·5	007–013
				0134	3·5	007
28–29		Cloudy				
29–30	0135–0240	Faint bands appeared in later part of night.	55°N 4·5°W	0135	8	000–025
			51·5°N 2°W	0220	12	060–110
				0240	15	070–120
30 June–1 July		No NLC				
1–2 July	0205–0240	Faint bands seen from southern England. Cloudy elsewhere.	51·5°N 2°W	0205	12	000–050
2–3		No NLC				
3–4		Cloudy				
4–5		No NLC				
5–6		Cloudy				
6–7		Cloudy				
7–8		No NLC				
8–9		No NLC				
9–10	2215–2340	Faint bands and billows with occasional whirls seen only during the earlier part of night. Southern border at about latitude 59°N.	57°N 2°W	2240	19	035–060
				2300	17	035–055
				2311	18	035–055
			56·5°N 3°W	2305	12	050–065
			56°N 3°W	2330	6	000–025
			53·5°N 3°W	2241	5	

TABLE I—*continued*

Date — night of	Times UT	Notes	Station position	Time UT	Max. elev. (degrees)	Limiting azimuths (degrees)
10–11	2135–2330	Cloudy over the British Isles. Moderately bright bands seen from Denmark until 2330 UT when they were obscured by low cloud.	56°N 10°E	2140	23	340–020
			56°N 12·5°E	2325	10	
11–12	2135–2145	NLC seen from Denmark through temporary break in low cloud.	56°N 10°E	2135	18	340
12–13		Cloudy				
13–14		No NLC				
14–15	2345–0230	Bands, tinted blue or green in places.	55·5°N 4·5°W	2345	8	320–350
				0025	8	310–040
				0120	7	310–010
			54°N 1·5°W	0052	3	030
			53°N 1·5°W	0230	33	350–020
15–16		Cloudy				
16–17		No NLC				
17–18		Cloudy				
18–19		Cloudy				
19–20		Cloudy				
20–21		Cloudy				
21–22		No NLC				
22–23		Cloudy				
23–24	2230	Single band seen close to northern horizon from Unst, Shetland.	61°N 1°W			
24–25		Cloudy				
25–26		No NLC				
26–27		No NLC				
27–28		Cloudy				
28–29		No NLC				
29–30		Cloudy				
30–31		Cloudy				
31 July–1 Aug.		No NLC				
1–2 Aug.		No NLC				
2–3		No NLC				
3–4		No NLC				
4–5		No NLC				
5–6		No NLC				

The clouds were observed on only 15 nights during 1970; they were reported on over 20 nights during the previous six summers, the maximum frequency being 33 nights during 1967. The date of first appearance, 26–27 May, equals the earliest that NLC have been seen from Scotland; they were seen on this date also in 1889 and 1890 (from Ben Nevis Observatory) and in 1960. As in previous years, the clouds receded northwards at the end of the observing season, the last observation, a band close to the northern horizon, being made on 23–24 July from Unst, the most northerly island in the Shetlands. This northwards recession of the clouds probably indicates that the temperature at the mesopause in middle latitudes has now begun to increase from its normal summer minimum. This occurred early during the summers of 1969[1] and 1970. Normally, the last observation from the British Isles is recorded in early to mid-August.

A large number of reports were received of suspected NLC, observed between 2300 and 2330 UT on the night of 4–5 June. Some observers sent photographs and sketches showing a roughly circular patch, and the bearings given from the different stations indicated that it was situated to the west of Scotland. Inquiry at the Meteorological Office, Bracknell, confirmed that what was seen was an ejection of barium at a height of 156 km from a rocket launched from South Uist.

The assistance of the large number of observers who, by providing visual observations, photographs and sketches, have made this analysis possible, is gratefully acknowledged. These synoptic studies are continuing and we

invite the co-operation of observers who may be prepared to contribute to them. Notes on observation of NLC appeared in the *Meteorological Magazine*, June 1967.[2] Observations made in western Europe should be sent to the Balfour Stewart Laboratory, University of Edinburgh, Drummond Street, Edinburgh EH8 9UA, Scotland.

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551·577·36

THE AVERAGE ANNUAL FREQUENCY OF DAILY RAINFALL AMOUNTS

By A. B. THOMSON

Summary. A method is described for obtaining an estimate of the average annual frequency for a station in the United Kingdom of a specified daily fall of rain, and an example is given of the use of the method.

The method uses the relationship $\log y = ar + c$, where y is the average per year of the integrated frequency of daily rainfall amount r, and specimen graphs are shown.

The constant a is inversely proportional to the average daily rainfall and the pattern of the constant of proportionality is shown for the United Kingdom.

The constant c is found by inserting in the equation the value of a for the selected station, and a value of y for daily rainfall amount of 0·40 inch. For stations in the United Kingdom this value of y is given by $R - 10{\cdot}69$, where R is the average annual rainfall in inches for the period 1916–50.

Historical. The annual number of 'rain days', 0·01 inch (0·2 mm) or more, has been published since the earliest volumes of *British Rainfall*[1] and the number of 'wet days', 0·04 inch (1·0 mm) or more, has appeared since 1920. Monthly averages of rain days and of wet days for the period 1916–50 are given in the 1959/60 volume of *British Rainfall* while maps, based on monthly averages, for the period 1901–30, of rain days are published in the *Climatological atlas of the British Isles.*[2] In the same publication there is a map showing the annual frequency of very wet days, 0·40 inch (10 mm) or more.

Glasspoole[3] in 1926 made a critical study of the annual frequency of rain days and of wet days for the period 1881–1915. He produced a map showing the distribution of rain days based on the records from 300 stations in the British Isles. In 1928 Glasspoole[4] published maps of the average number of rain days during each month of the year for the period 1881–1915.

Sowerby Wallis[5] in 1902, using records made at Camden Square, London, over the period 1858–1902 and Dunbar[6] in 1932, utilizing data from Kilmarnock, Ayrshire, for the period 1902–30 examined the fluctuations of daily rainfall, i.e. the amounts within specified limits. In 1932 Bilham and Lloyd[7] widened the scope of the problem by studying the fluctuations at 24 stations scattered throughout the British Isles, and they produced statistics and graphs which gave an indication of the probability of occurrence of a specific daily rainfall amount in the various regions of the British Isles during the four seasons of the year.

The Kilmarnock data published by Dunbar were re-examined by Brooks and Carruthers[8] who showed that the logarithms of the 'integrated' frequencies of the daily rainfalls (i.e. the number of days with 0·01 inch or more, 0·02 inch or more, etc.) when plotted against the daily rainfall lie on a straight line except for the very small and the very large amounts.

Aim of the investigation. In areas having a good network of rain-gauges there are usually several gauges sufficiently accessible to be read daily, thus providing data for processing to supply the needs of planners, engineers, contractors and others whose work depends on a knowledge of the frequency of specific daily falls of rain. Some regions, however, have only a few rain-gauges, none of them read daily, while other parts, particularly in the uplands, have no gauges at all.

This investigation, the results of which are set out below, was undertaken in the hope that an analysis of the existing daily rainfall data would provide an empirical method of estimating the frequencies of daily rainfalls in areas with inadequate information. It must be stressed that the method should not be used for rainfall events rarer than once a year.

Method. From the findings of Brooks and Carruthers in their analysis of the Kilmarnock data, it seemed possible that the straight line

$$\log y = ar + c, \qquad \ldots (1)$$

where y is the average per year of the integrated frequency of the daily rainfalls r, would give an acceptable fit to the data, the intercept c on the y axis and a, the slope of the line, having values relevant to a particular locality. The value of a will be negative.

The daily rainfall data for the period 1916–50 for each of about 100 stations* were plotted on graphs with r as abscissa and $\log y$ as ordinate.† A straight line was then drawn, by eye, among the points. It was found that, in all cases, the integrated frequencies lay on straight lines except that in some the frequencies of the small amounts less than 0·08 inch (2 mm) were underestimated. The extreme (high) values of r, as would be expected from the smallness of their frequency, showed divergence from the general pattern of the intermediate values of r. The straight lines gave a good representation over a large and important range of the daily rainfall values. To most users, the frequency of days with small amounts are of little practical consequence, while the very high values are best treated by an extreme-value technique such as the Gumbel[9] method.

The graphs of eight places scattered throughout Great Britain and Northern Ireland are reproduced as illustration in Figure 1. They are typical of the graphs for the other stations.

It should be noted that the first point plotted (at 0·01 inch) on each graph is the logarithm of the frequency of days with 0·005 inch or more (i.e. measurable rain) and that the straight lines do not cut the $\log y$ axis at a point which indicates the logarithm of the total number of days in the year.

* London, Meteorological Office. *Hydrological Memoranda.* (Unpublished, copies available in the Meteorological Office Library, Bracknell.)

† For convenience of reference to the older data the graphs have been constructed for rainfall measurements in inches.

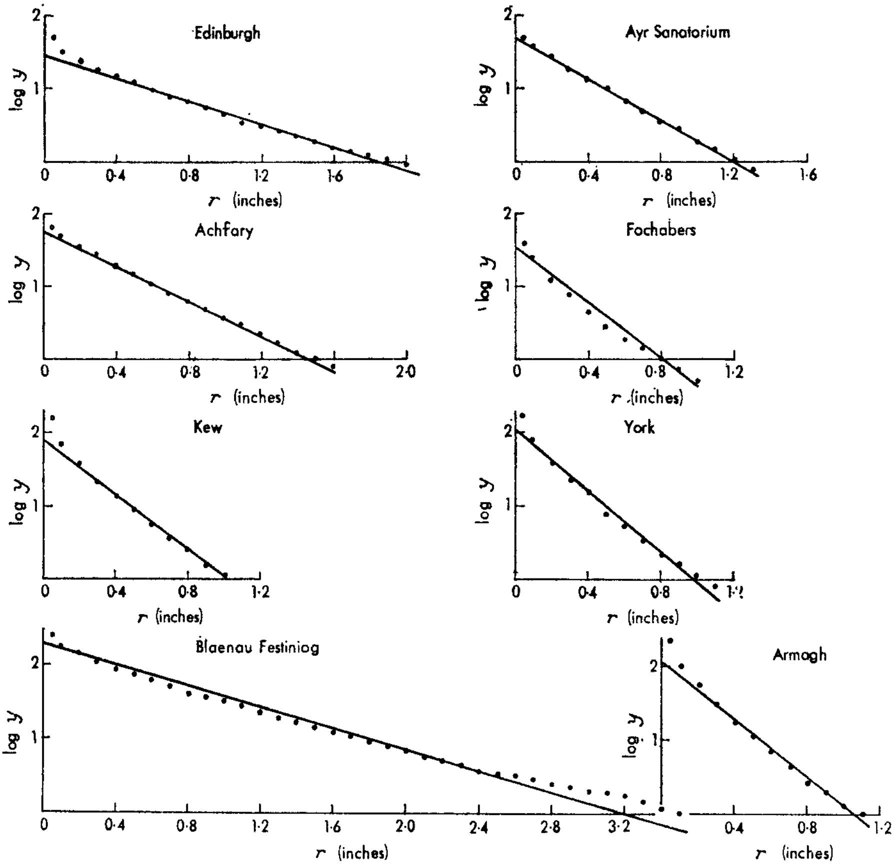

FIGURE 1—SPECIMEN GRAPHS OF $\log y = ar + c$, 1916–50
y = Integrated frequency of days with rain of specified amount r.

The problem now lay in finding an empirical method of evaluating a (the slopes of the lines) and c (the intercepts on the $\log y$ axis).

The climatological factor about which there exists considerable and reasonably accurate knowledge is the annual average rainfall, and reliable estimates can be read off the map[10] for Great Britain on the scale 1:625 000 (approximately 10 miles to 1 inch) published by the Director-General of the Ordnance Survey for the period 1916–50. An annual average rainfall map is also available for Northern Ireland.[11]

It was decided, therefore, to try to relate the parameters determining the daily frequencies at a place to its annual average rainfall.

Evaluation of slope, a. An inspection of the graphs suggested that the slope, a, would be related inversely to the rainfall for the station. The value

$$b = ar_m, \qquad \ldots (2)$$

where r_m is the mean daily rainfall (i.e. $R/365$, R being the annual average rainfall), was worked out for each station, and then the values then mapped (Figure 2). It will be seen that the values of b show a well-defined pattern, b being in general small in the south and east and larger towards the west and north. The pattern is such that the value of b can be read from the map with a reasonable degree of accuracy for any particular locality, thus providing a means of obtaining a, the slope of the line.

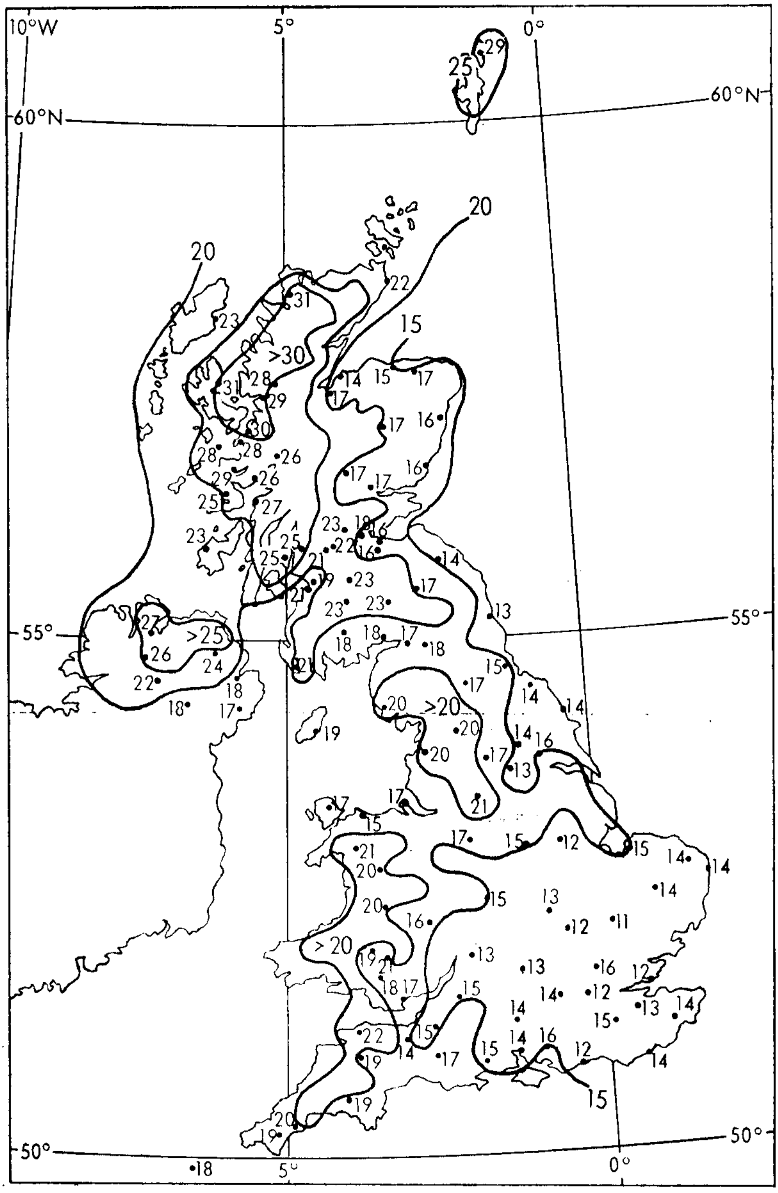

FIGURE 2—VALUES OF 100 × b (NEGATIVE)

Evaluation of intercept, c. In the *Climatological atlas of the British Isles*[2] a map is published showing the frequencies over the country of days with 0·40 inch (10 mm) or more of rain, and it is stated therein that the frequency for any particular place is very nearly represented by ($R-8$), where R is its annual average rainfall in inches for the period 1901–30. This relationship was re-examined by using all the stations in Great Britain and Northern Ireland, numbering about 100, for which frequency data for the period 1916–50 are available.[9] The average annual frequencies, $y_{0\cdot40}$, of days with 0·40 inch (10 mm) or more were plotted (see Figure 3) against the average annual rainfalls, R inches, and the average relationship for the 100 stations was found to be the straight line, fitted by least squares,

$$y_{0\cdot40} = 1\cdot00R - 10\cdot69. \qquad \ldots (3)$$

The scatter was surprisingly small, the correlation coefficient being 0·99.

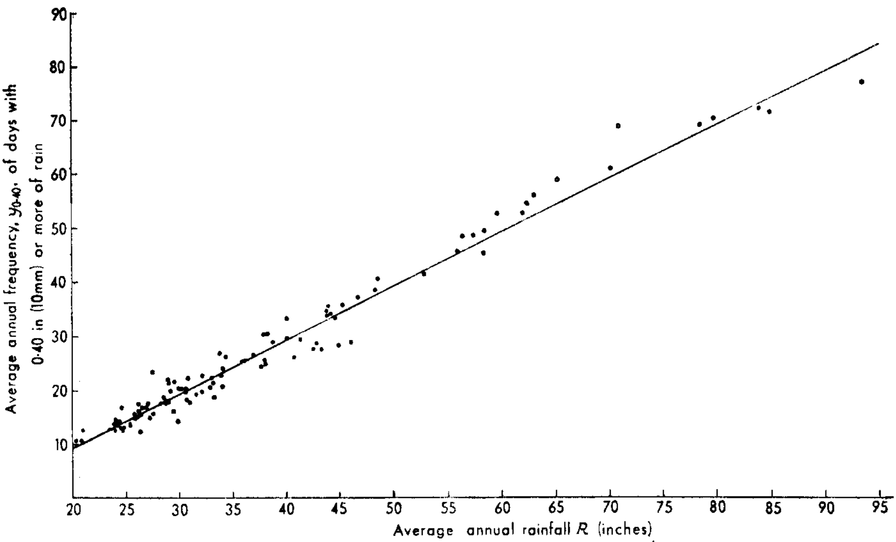

FIGURE 3—AVERAGE ANNUAL FREQUENCY OF DAYS WITH 0·4 INCH PLOTTED AGAINST AVERAGE ANNUAL RAINFALL, 1916–50

$$y_{0\cdot40} = R - 10\cdot7.$$

This relationship could now be used to find $y_{0\cdot40}$, i.e. the average annual frequency of days with 0·40 inch (10 mm) or more, for any particular locality whose average annual rainfall is known.

This frequency value, in turn, could be substituted for y in equation (1) to find the value of c appropriate to that frequency at the locality selected. Thus, as $b = ar_m$, equation (1) can be written

$$\log y = \frac{br}{r_m} + c. \qquad \ldots (4)$$

As b, r_m and c could now be ascertained for any locality, the integrated frequency, y, of any required daily rainfall, r, could be found.

It should be noted that, putting $\log y = 0$, i.e. $y = 1$, the intercept $(-cr_m/b)$ on the r axis is the value of r reached or exceeded once per annum.

Example.

Locality : Near Dundee, Nat. Grid Ref. NO (37) 420300

Rainfall : Average annual $(R) = 31$ inches

r_m (mean daily) $= 0{\cdot}085$ inch

b (from Figure 2) $= -0{\cdot}16$ and therefore $a = -1{\cdot}882$.

Frequency of days with 0·40 inch or more from equation (3) is :

$$y_{0\cdot40} = R - 10{\cdot}7 = 20{\cdot}3 \quad (\log 20{\cdot}3 = 1{\cdot}307).$$

Substituting in equation (4)

$$\log y = \frac{br}{r_m} + c,$$

$$1{\cdot}307 = \frac{-0{\cdot}16 \times 0{\cdot}40}{0{\cdot}085} + c, \quad \therefore c = 2{\cdot}060.$$

Thus $\log y = -1{\cdot}882r + 2{\cdot}060$ and this expression gives the integrated frequencies (y) for any daily amount (r inches or more).

The 'once per annum value' of r is

$$\frac{-cr_m}{b} = \frac{-2{\cdot}060 \times 0{\cdot}085}{-0{\cdot}16} = 1{\cdot}09 \text{ inches.}$$

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551.553.21:551.465.5

EARLY REVERSAL OF THE INDIAN OCEAN CIRCULATION IN 1956

By P. B. WRIGHT

The sudden changes in the tropospheric circulation patterns over the Indian Ocean and adjacent areas accompanying the onset of the Indian south-west monsoon in May and June have been described by Wright.[1] In an extension of the study (Wright and Stubbs[2]) it was shown that the effect of the changes was widespread, extending well into the Pacific and involving a net mass flux out of the northern hemisphere. Evidence for these conclusions was provided by the fact that in 1956 all the changes occurred about a month earlier than usual.

It is known that the sea surface currents in the Indian Ocean undergo a reversal of direction about the same time of the year. Rochford[3] showed that the current off the coast of Western Australia participates in this reversal. Evidence for this included an analysis of the variations in sea surface salinity off Rottnest Island (32°S 115½°E) during 1951–57. His Figure 1, reproduced here, shows that the salinity normally changes rapidly from a high value during January to April, associated with a current from the south, to a low value during June to September, associated with a current from the north.

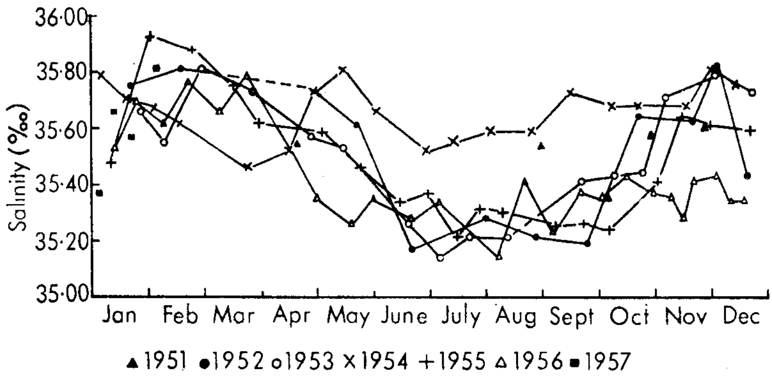

FIGURE 1—VARIATIONS IN SALINITY AT 50 m AT THE ROTTNEST I. 50 m STATION (32°S 115°25′E) DURING 1951–57

Data from CSIRO Oceanographical Station List Volume Nos. 14, 17, 18, 24, 27, 30 and 33.

It can be seen from Figure 1 that the year 1956 was exceptional in that the change of salinity occurred a month earlier than in the other years (1954 was also exceptional but in a quite different way). This implies that the reversal of the current also occurred a month early in 1956. This evidence points strongly to the conclusion that the reversal of the surface circulation of the Indian Ocean is closely linked with the changes in the atmospheric circulation.

The author is indebted to Dr D. J. Rochford for permission to reproduce his diagram.

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REVIEW

Process and method in Canadian geography, Weather and climate, selected readings, edited by J. G. Nelson, M. J. Chambers and R. E. Chambers. 225 mm × 150 mm, pp. x+420, *illus.*, Methuen and Co. Ltd, 11 New Fetter Lane, London, EC4, 1970. Price: £3·50.

This is not a textbook on *weather and climate* but a collection of papers on *weather and climate and the human economy,* and deals mainly with agrometeorological and hydrological problems. Because of the wealth of excellent material available, the selection is 'somewhat arbitrary'. The papers illustrate research techniques and methods of analysis and the study of processes, with special reference to the Canadian scene; and they provide important primary source material for research and study in Canadian geography. Some papers are reviews or partly so. The original bibliographies have been retained because these are regarded as important to readers wishing to follow up research problems.

There are articles on the Arctic circulation, the location of the Arctic front and upper air features over the Canadian dry belt. Other topics discussed are : drought indicators, soil moisture under crop and fallow surfaces, moisture deficit, latent evaporation and evapotranspiration, precipitation and the moisture budget, drought patterns in the prairies and precipitation variations in a forested watershed. Problems peculiar to cold regions are especially stressed in papers on the forecasting of ice conditions, evaporation from snow cover, and the thermal régimes of permafrost under various types of vegetation.

Further interesting articles deal with the distribution and causes of hail, Chinook winds and their influence on snow cover, climatic changes in Canada over the last 14 000 years and climatic trends on the prairies during the last 100 years. Other papers discuss the concept of heat units and crop growth, and the variation of temperature with latitude, longitude and altitude. Agroclimatological relationships, in general, and the subject of human response to weather and climate are reviewed. Special instrumentation problems concern the measurement of lake surface temperatures by aerial survey, the study of ice formation on the Niagara River, and soil-moisture sampling grids.

The book does not include any articles on urban climate, as was originally intended, though the urban heat-island effect is suggested as a possible cause of a downwind area of maximum hail duration. A section on the impact of urbanization and industrialization on surrounding agriculture and forestry would have been a useful and appropriate addition to this volume. As this volume includes several papers relevant to topics which form the subject of future books in the series, care will be needed in the later books to avoid excessive overlap.

The presentation of *Weather and climate* could be improved by making the diagrams more complete and self-contained. The inclusion of a physical map of the Canada region, for general reference, would be especially helpful to non-Canadian readers. It is questionable whether 9 pages of information on 'degree-days' and 12 pages of maps of temperature deviation can be justified.

The book should prove extremely useful to members of related disciplines and research workers in interdisciplinary fields. It is aimed to help at various academic levels: namely the new student, more advanced undergraduates in meteorology and related courses, and graduates concerned with recent developments in research. The first two groups of readers, at least, would expect to borrow a copy of the book from a library.

E. N. LAWRENCE

NOTES AND NEWS

Retirement of Mr A. A. Worthington, O.B.E.

Mr Arthur Agnew Worthington joined the Office as a Technical Officer in 1939 and spent most of the war years providing forecasts covering long routes for aircraft of Coastal and Transport Commands. He was mobilized as a Flight Lieutenant in 1943 and following his release from the RAFVR in 1946 spent the next three years in Malta.

Early in 1950 he was promoted to Principal Scientific Officer and was posted to Prestwick where he spent nearly eight years as a Senior Forecaster.

In late 1957 Mr Worthington was posted from Prestwick to Headquarters where, over the course of the next nine years, he dealt with meteorological matters connected with civil aviation and played a major part in many international meteorological arrangements including the setting up of the ICAO Area Forecast System. In 1966 he was promoted to Senior Principal Scientific Officer and took charge of the Telecommunications Branch of the Office.

Arthur Worthington has always been a great believer in the 'eyeball to eyeball' confrontation method of decision making and in the post of Assistant Director in charge of meteorological telecommunications has been able to use this working technique to full advantage in planning and organizing the Office's new telecommunications system. He retired on 3 May 1971 and so remained in his post long enough to see his plans begin to come to fruition. He was appointed an Officer of the Order of the British Empire in the New Year's Honours List this year.

Arthur's indefatigable energy will now, I understand, be turned to his life-long love of music for which he has had little time in the last few years. He plans to put to serious purpose his competence as a church organist.

All his colleagues wish Arthur and his wife many happy years of retirement.

V. R. COLES

LETTER TO THE EDITOR

517.512.2

Introduction to the Fast Fourier Transform (FFT) in the production of spectra

I have read with interest the article 'Introduction to the Fast Fourier Transform (FFT) in the production of spectra' by R. Rayment.* In connection with this it may be of interest to readers to know that the Meteorological

* RAYMENT, R.; Introduction to the Fast Fourier Transform (FFT) in the production of spectra. *Met Mag, London*, **99**, 1970, pp. 261–270.

Research Flight, Farnborough, has a programme incorporating the FFT technique written in ICL 1900 FORTRAN. The programme has been developed primarily for, but is not restricted to, the analysis of data collected by MRF aircraft. On the ICL 1907 computer the programme occupies just under 20K words of core store with $3N+10$ real variables being required for data handling (N = number of data points). Up to six channels of data may be handled simultaneously giving full or part cross spectral analysis according to the user's requirements. The core store requirement is not affected by the number of data channels supplied. The programme includes automatic plotting routines which present the main outputs on convenient log $\times$ log and log $\times$ linear scales.

The output from the programme consists of two main sets of results :

(i) $N/2$ smoothed spectral estimates for each data channel supplied.

(ii) $N/2$ corresponding values of $S_{xy}(n)$, $Q_{xy}(n)$ as described by Mr Rayment; and three further cross spectral quantities derived from these after averaging, namely : cross spectral amplitude $SA_{xy}(n)$, phase angle $PHI_{xy}(n)$ and coherence $COH_{xy}(n)$.

Further details may be supplied on application to Meteorological Research Flight, Farnborough.

Meteorological Research Flight, Farnborough P. R. COCKRELL

OFFICIAL PUBLICATIONS

Scientific Paper

No. 32. The Bushby-Timpson 10-level model on a fine mesh. By G. R. R. Benwell, M.A., A. J. Gadd, Ph.D., J. F. Keers, B.Sc., Margaret S. Timpson, B.Sc. and P. W. White, Ph.D.

A full description is given in this paper of the 10-level numerical weather prediction model which has been developed during the past few years by the Forecasting Research Branch of the Meteorological Office for use in investigating the dynamics of fronts and in predicting frontal rainfall. The basic model as originally proposed treated a considerably idealized atmosphere, but the formulation now includes representations of the effects of surface friction, topography, surface exchanges of sensible and latent heat, sub-grid-scale convection, and lateral diffusion. Considerable improvements have also been made in the method by which initial wind fields are obtained for the model.

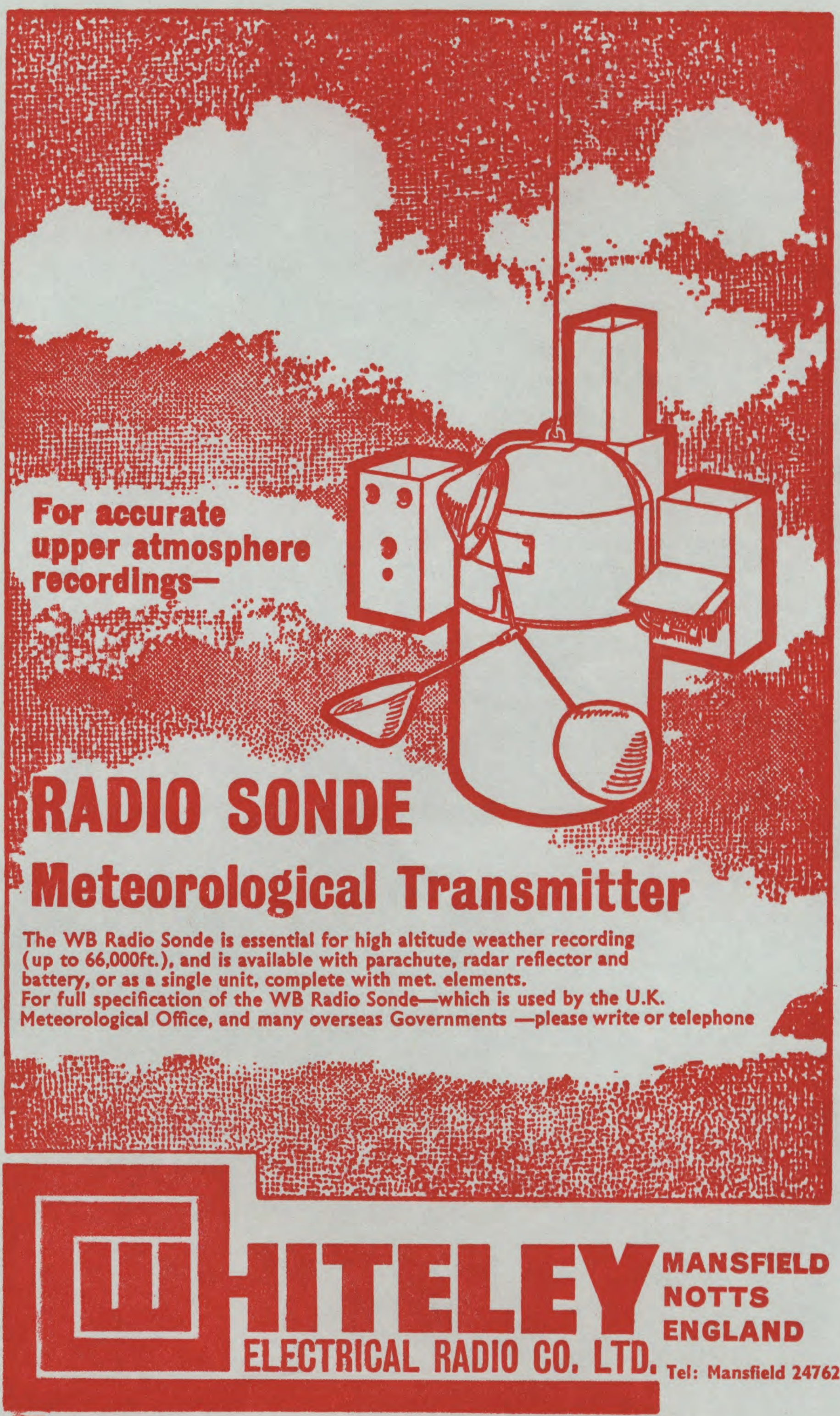
The model is still undergoing development; this paper describes the stages of the development up to the end of 1969, and an example of a recently computed forecast is included.

The following publication has recently been issued : *The practice of weather forecasting*. By P. G. Wickham.

Modern weather forecasting is a mixture of electronic computations and human judgement. This book is concerned with the latter, and it was written mainly for young professional forecasters. However, no reader who has a modest grounding in elementary meteorology and who wishes to find out how weather maps are used in day-to-day forecasting need be deterred by it. The discussion is, throughout, entirely simple and non-mathematical and the text is copiously illustrated by weather maps.

The early chapters are each devoted to particular weather elements, such as wind, temperature, clouds, and the analysis of these elements is discussed in some detail. In later chapters the principles of forecasting are described and some cameo sketches of forecasters thinking aloud as they work are included.

To round off the book and bring the discussion into perspective, a brief description is included of the place of computers in the large weather forecasting organizations of today. There is also a glimpse at how this partnership of man and computer may develop in the future, but it is the human half of the partnership that is the principal subject matter of the book.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THE METEOROLOGICAL MAGAZINE

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METEOROLOGICAL OFFICE

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JULY 1971 No 1188 Vol 100
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RECENT PUBLICATIONS

Scientific Paper No. 31 The three-dimensional analysis of meteorological data.

By R. Dixon, B.Sc. and E. A. Spackman, M.Sc.

The advent of modern observational devices such as satellites and long-life free drifting balloons has greatly complicated the process of data analysis by computer. This paper presents a possible method for effecting this data analysis by fitting a high-power polynomial to all the observations from within a large volume of the atmosphere.

37½p (40p by post)

Scientific Paper No. 32 The Bushby-Timpson 10-level model on a fine mesh.

By G. R. R. Benwell, M.A., A. J. Gadd, Ph.D., J. F. Keers, B.Sc., Margaret S. Timpson, B.Sc., and P. W. White, Ph.D.

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55p (57½ by post)

METEOROLOGICAL OFFICE Met.O.841

THE METEOROLOGICAL MAGAZINE

Vol. 100, No. 1188, July 1971

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SUBSTANTIAL SNOWFALLS OVER THE UNITED KINGDOM, 1954–69

By C. A. S. LOWNDES

Summary. Data are given on the frequency of substantial snowfalls (7 mm or more of precipitation in 24 hours) during the period 1954–69 at 41 stations in the United Kingdom. Frequencies are given for each month and year, for each day of the month, and also for occasions when subsequently there was a complete snow cover for periods of at least 24 hours, 3 days, 5 days, 10 days and 20 days. Maps are given to show the corresponding geographical distributions.

The frequency of substantial snowfall is given for various synoptic situations and a description is given of the situation during persistent snow cover in the period December 1962 to February 1963.

Introduction. For this investigation, a substantial snowfall was defined as at least 7 mm of precipitation falling as snow or sleet,* sometimes with hail, during 24-hour periods beginning at 09 GMT and 21 GMT. This represents in general a snow depth of about 8 cm.[1] A study was made of all such occasions which occurred at the 41 reporting stations in the *Daily Weather Report*,† shown in Figure 1, for the 15 'winter seasons' 1954–55 to 1968–69, the 'winter season' being defined as the 8 months October to May. Of the 41 stations, 8 did not report for the whole period and nearby stations were also used. The 8 stations and their substitutes with the heights of the stations above mean sea level in metres were as follows :

Thorney Island (4 m)/Tangmere (16 m) up to 1957/58
Wattisham (89 m)/Felixstowe (3 m) up to 1960/61
St Mawgan (103 m)/St Eval (103 m) up to 1957/58
Finningley (10 m)/Lindholme (5 m) up to 1957/58
Kilnsea (12 m)/Spurn Head (9 m) up to 1964/65
Leeming (32 m)/Dishforth (32 m) up to 1964/65
Carlisle (26 m)/Silloth (8 m) up to 1960/61
Abbotsinch (5 m)/Renfrew (8 m) up to 1955/56

The difference in height between the station and its substitute is 5 m or less for five of the stations and the substitute snowfall values are probably reasonably representative of the station. At the other three stations,

* Sleet is here defined as snow and rain (or drizzle) together or snow melting as it falls.
† London, Meteorological Office. *Daily Weather Report.*

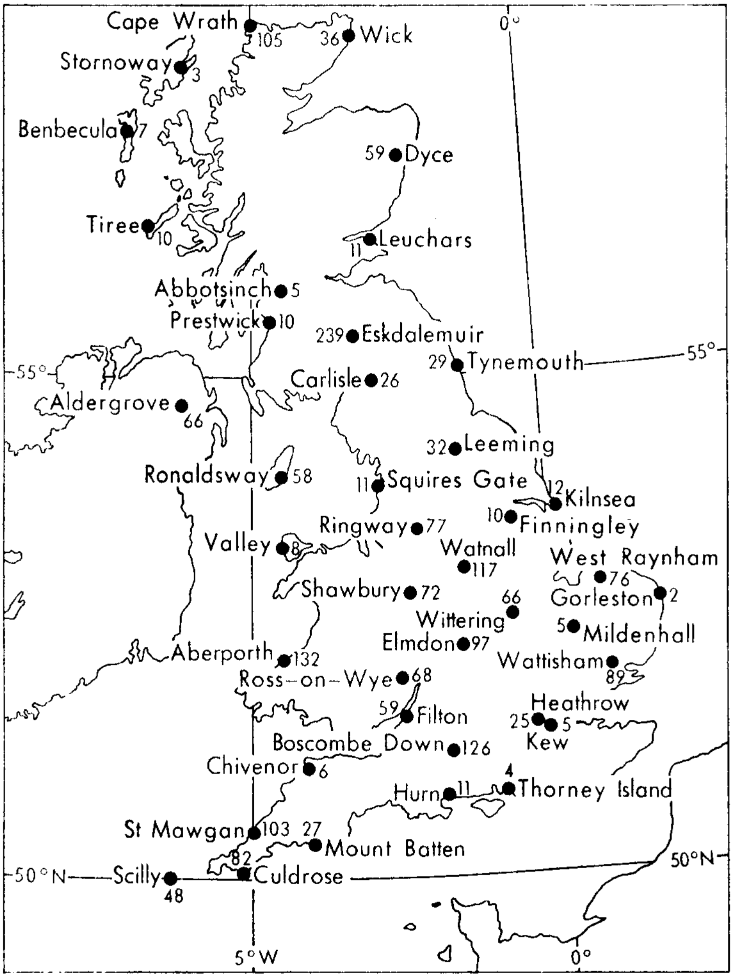


FIGURE 1—POSITIONS OF STATIONS USED

Figures show height above MSL in metres

Wattisham, Carlisle and Thorney Island, the difference in height is 86 m, 18 m, and 12 m respectively, and the substitute snowfall values should be treated with due caution.

The frequency of substantial snowfalls. Table I shows the total number of occasions for each month when there was substantial snowfall. All occasions for each of the 41 stations are included.

TABLE I—NUMBER OF OCCASIONS* WITH SUBSTANTIAL SNOWFALL FOR THE MONTHS OCTOBER TO MAY 1954–69

Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Total
1	34	110	142	164	88	22	1	562

* All occasions for each of the 41 stations are included. For example, if 5 stations had a substantial snowfall during a particular 24 hours, then this was counted as 5 occurrences. (Contrast Table III p. 196.)

Of the total number of occasions, about 30 per cent occurred in February and 25 per cent in January. A further 20 per cent occurred in December and about 15 per cent in March. Roughly 5 per cent occurred in each of the months November and April. There was only one occasion in October and one in May, i.e. on 17 October 1967 and 14 May 1955. On both occasions the station concerned was Dyce and the snow and sleet were associated with a polar low in a northerly airstream. However, the snow cover dispersed in less than 24 hours on each occasion. Of the total number of occasions, 36 (6 per cent) were associated with 20 mm or more in 24 hours; of the 36, slightly less than half occurred at stations in Scotland. On 7 occasions, the precipitation totalled 30 to 39 mm in 24 hours.

Figure 2 shows the frequency of occurrence of substantial snowfalls over the United Kingdom for each day of the months November to April. If one or more stations had a substantial snowfall on a particular day, then this was counted as one qualifying day. The number of days with substantial snowfall averaged about 1 for the second half of November and increased to an average of about 2 for the first 10 days of December. After the 10th there was a decline until Christmas after which the number of days averaged about 3 until the end of the month. The number of days averaged about 2 for January and 2–3 for February. For 18 January and 19 and 20 February there was substantial snowfall in five of the 15 years. There was a decline towards the end of February to an average of 1–2 days which continued to 24 March. From 25 March to the end of April only the first three days of April had more than one occurrence of substantial snowfall.

Table II shows the number of occasions of substantial snowfall when subsequently there was a complete snow cover which lasted for at least (i) 24 hours, (ii) 3 days, (iii) 5 days, (iv) 10 days and (v) 20 days. All such occasions for each of the 41 stations are included. Of the total number of occasions with substantial snowfall (562) only 57 per cent resulted in a complete snow cover which persisted for at least 24 hours. There were no such occasions in October and May, and only one in April. On 30 per cent of occasions the snow cover persisted for 3 days or more and on 17 per cent of occasions for 5 days or more. There were no such occasions in October, April and May. The 6 per cent of occasions when the snow cover persisted for 10 days or more occurred in the four months November to February and the 15 occasions when the snow cover persisted for 20 days or more occurred in the three months December, January and February.

TABLE II—NUMBER OF OCCASIONS* WITH SUBSTANTIAL SNOWFALL FOR THE MONTHS OCTOBER TO MAY 1954–69 WHEN SUBSEQUENTLY THERE WAS A COMPLETE SNOW COVER FOR VARIOUS PERIODS

Snow cover persisted for at least	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Total
(i) 24 hours	0	12	74	106	100	30	1	0	323
(ii) 3 days	0	9	44	60	49	9	0	0	171
(iii) 5 days	0	7	22	35	30	2	0	0	96
(iv) 10 days	0	2	7	13	10	0	0	0	32
(v) 20 days	0	0	5	5	5	0	0	0	15

* All such occasions for each of the 41 stations are included. For example, if 5 stations had a substantial snowfall during a particular 24 hours when subsequently there was a complete snow cover for at least 3 days, then this was counted as 5 occurrences of type (ii).

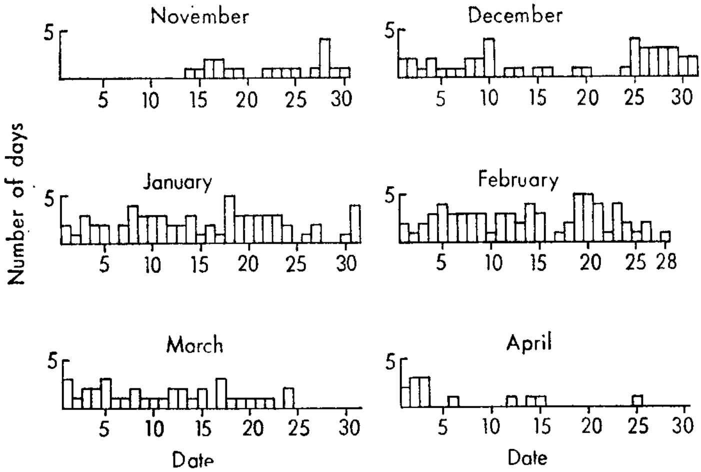


FIGURE 2—FREQUENCY OF OCCURRENCE* OF SUBSTANTIAL SNOWFALL FOR EACH DAY OF THE MONTHS NOVEMBER TO APRIL OVER 15 YEARS 1954–69

* If one or more stations had a substantial snowfall on a particular day, then this was counted as one qualifying day. See also Table III.

Table III shows the number of days with substantial snowfall over the United Kingdom for each month of the 15 winter seasons, i.e. if one or more stations had a substantial snowfall on a particular day, then this was counted as one qualifying day. Considering only the months November to April, the number of days has increased since 1961 for all months except January. The increases in the months November, December and April are large enough to suggest that they might be significant. Similar increases were noted by Clarke[2] for November, December, March and April in a study of snowfalls of any intensity over south-east England for the same 15-year period. There was no substantial snowfall in January and February in only one or two of the 15

TABLE III—NUMBER OF DAYS* WITH SUBSTANTIAL SNOWFALL OVER THE UNITED KINGDOM FOR EACH MONTH OF THE 15 WINTER SEASONS 1954–69

	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Total
1954–55	0	0	0	10	11	5	0	1	27
1955–56	0	0	3	9	7	0	0	0	19
1956–57	0	1	3	2	3	0	0	0	9
1957–58	0	0	1	7	9	9	2	0	28
1958–59	0	0	1	9	0	0	0	0	10
1959–60	0	0	0	6	1	0	0	0	7
1960–61	0	0	0	1	1	0	1	0	3
1961–62	0	1	8	1	1	4	1	0	16
1962–63	0	5	8	7	6	0	1	0	27
1963–64	0	1	0	0	2	3	0	0	6
1964–65	0	1	6	4	2	5	0	0	18
1965–66	0	8	3	2	5	1	4	0	23
1966–67	0	2	3	0	2	2	0	0	9
1967–68	1	0	4	4	4	1	4	0	18
1968–69	0	0	5	4	14	5	0	0	28
Total	1	19	45	66	68	35	13	1	248

* If one or more stations had a substantial snowfall on a particular day, then this was counted as one qualifying day.

winters but in November and April there was no substantial snowfall in 8 or 9 of the 15 winters. There was only one substantial snowfall in October and one in May.

Table IV shows the synoptic situations associated with substantial snowfalls for each month. All occasions for each of the 41 stations are included. Some 51 per cent of occasions were associated with warm fronts or warm occlusions, the majority of which moved from (or were situated to) the south, south-west or west of the station. Many of these fronts, in particular those to the south of the station, approached the station but did not reach it, becoming quasi-stationary before dispersing or retrogressing. This effect was often the result of small waves or wave depressions moving in an easterly direction along the front. Clarke[2] found that 75 per cent of warm fronts from the south which gave snow over south-east England did not reach the area. A further 32 per cent of occasions with substantial snowfall were associated with polar lows or troughs in northerly airstreams. Relatively few of these occasions were in November and April and only one in both October and May. Polar lows or troughs which moved westwards in easterly airstreams accounted for 6 per cent of occasions. There were no such occasions in October, November, April and May, and only one in December during the 15 years. A further 6 per cent were associated with showers, mainly in northerly and easterly airstreams; 3 per cent with cold fronts or cold occlusions mainly from the north or east; one per cent with wave depressions moving from the west or north-west over or in the vicinity of the station and one per cent with troughs

TABLE IV—SYNOPTIC SITUATIONS ASSOCIATED WITH OCCASIONS* OF SUBSTANTIAL SNOWFALL

Synoptic situation		Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Total	
Polar lows or troughs in northerlies		1	12	39	43	52	24	8	1	180	
Polar lows or troughs in easterlies		0	0	1	11	14	7	0	0	33	
Warm fronts or warm occlusions (direction of approach)	S	0	3	32	43	51	9	4	0	142	288
	SW	0	8	1	3	14	12	5	0	43	
	W	0	4	20	21	14	13	3	0	75	
	NW	0	1	4	0	3	10	0	0	18	
	N	0	0	2	0	6	1	0	0	9	
	E	0	1	0	0	0	0	0	0	1	
Cold fronts or cold occlusions (direction of approach)	N	0	0	1	5	1	2	0	0	9	15
	E	0	0	2	2	1	0	0	0	5	
	S	0	0	0	1	0	0	0	0	1	
Wave-depressions (direction of approach)	W	0	0	2	0	0	0	0	0	2	8
	NW	0	0	0	2	0	4	0	0	6	
Showers (surface geostrophic wind direction)	N	0	3	4	5	1	0	0	0	13	32
	NE	0	0	0	0	0	4	0	0	4	
	E	0	1	0	2	4	0	0	0	7	
	SE	0	0	1	1	2	0	0	0	4	
	W	0	0	0	0	0	0	1	0	1	
	NW	0	1	0	0	1	1	0	0	3	
Troughs in westerlies		0	0	1	2	0	1	1	0	5	
Complex depression		0	0	0	1	0	0	0	0	1	
Total		1	34	110	142	164	88	22	1	562	

* All occasions for each of the 41 stations are included. For example, if 5 stations had a substantial snowfall during a particular 24 hours then this was counted as 5 occurrences.

in westerlies, often to the rear of a cold front. One occasion was associated with a small depression moving within a large, slow-moving complex depression.

Geographical distribution of substantial snowfalls. Figure 3 shows the number of occasions of substantial snowfall during the 15 winters at each of the 41 stations. As might be expected, the highest number (52) occurred at Eskdalemuir which at a height of 239 m is to some extent representative of the high ground in Scotland. The snowfalls at Eskdalemuir were mainly associated with warm fronts or warm occlusions which moved from (or were situated to) the south or west and relatively few with polar lows or troughs.

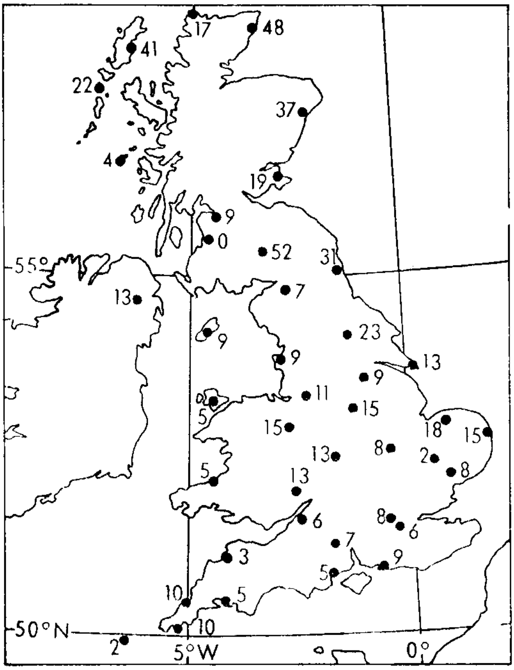


FIGURE 3—NUMBER OF OCCASIONS OF SUBSTANTIAL SNOWFALL DURING THE 15 WINTERS AT EACH OF THE 41 STATIONS

The second highest number of occasions (48) occurred at Wick (36 m) and the third highest (41) at Stornoway (3 m), the snowfall at both stations being mainly caused by polar lows or troughs in northerly airstreams. It is interesting to note that at Cape Wrath (105 m), situated on the north coast of Scotland in much the same latitude as Wick and Stornoway, there were only 17 occasions, also mainly associated with polar lows or troughs in northerlies. It is probable that the low number of occasions at Cape Wrath is associated with a relatively over-exposed rain-gauge situated at a height of 105 metres, within the lighthouse enclosure, near the edge of a sheer cliff facing northwards.

The fourth highest number of occasions (37) occurred at Aberdeen/Dyce (59 m) on the east coast of Scotland and the fifth highest (31) at Tynemouth (29 m) on the east coast of northern England. The snowfalls at Dyce were mainly associated with polar lows or troughs in northerlies and with warm fronts or warm occlusions which moved from (or were situated to) the south or west. At Tynemouth they were mainly associated with warm fronts or warm occlusions which moved from (or were situated in) the south-west quarter and with polar lows or troughs in northerlies and easterlies. At Leuchars (11 m) on the east coast of Scotland about halfway between Dyce and Tynemouth there were relatively few occasions (19), probably because of the shelter afforded by high ground to the north and south and to the relatively low altitude of the station. The occasions at Leuchars were mainly associated with the same synoptic types which brought the snowfalls to Tynemouth.

The lowest number of occasions (0) occurred, not as might be expected at Scilly/St Mary's, but at Prestwick Airport (10 m) on the west coast of southern Scotland. Prestwick is sheltered by high ground to the north, east and south, is adjacent to the relatively warm sea and is at a low altitude. It is interesting to note that the 9 occasions at nearby Abbotsinch (now Glasgow Airport) (5 m) were mostly associated with warm fronts or warm occlusions from the west or south-west which brought snow to Abbotsinch but which tended to bring rain rather than snow to Prestwick. None of the 9 occasions were associated with polar lows or troughs.

The second lowest number of occasions (2) occurred at Mildenhall (5 m) and Scilly (48 m). At Mildenhall, both occasions were associated with a warm occlusion situated to the south of the station. Other stations in East Anglia such as West Raynham (76 m), Gorleston (2 m) and Wattisham (89 m) had 18, 15 and 8 occasions respectively. Most of these occasions were associated with polar lows or troughs in northerly or easterly airstreams which presumably brought substantial snowfalls only to coastal areas of East Anglia. This supposition is supported by the fact that the 8 occasions of substantial snowfall at Wittering (66 m), which is situated to the west of East Anglia, were mainly associated with warm fronts or warm occlusions which moved from (or were situated to) the south and on only one occasion with a polar low or trough; also the 6 to 8 occasions at Kew (5 m) and London/Heathrow Airport (25 m), which are situated to the south of East Anglia, were nearly all associated with warm fronts or warm occlusions which moved from (or were situated to) the south and none with a polar low or trough. At Scilly, both occasions were associated with a polar low or trough in a northerly airstream but as might be expected on an island surrounded by a relatively warm sea, the snow cover lasted for less than 24 hours.

The fourth lowest number of occasions (3) occurred at Chivenor (6 m) in south-west England. Two occasions were associated with warm fronts and one with a polar low or trough in a northerly airstream but the snow cover lasted for less than 24 hours on two of the three occasions.

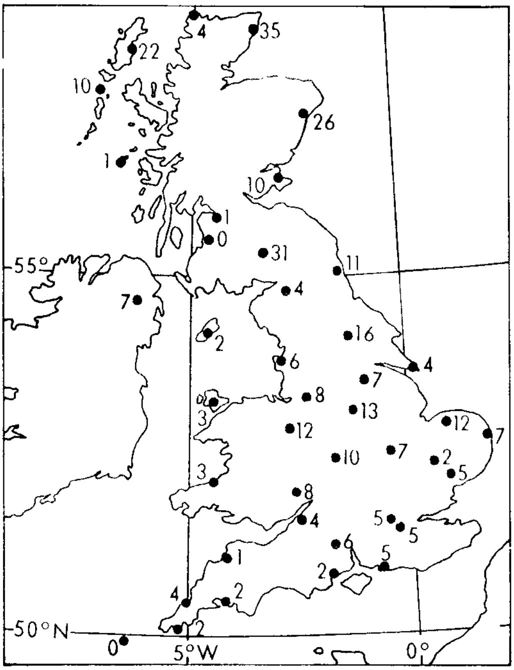
The fifth lowest number of occasions (4) occurred at Tiree (10 m) which is situated to the west of Scotland. It is interesting to note that whereas the 41 occasions at Stornoway and the 22 occasions at Benbecula were mainly associated with polar lows or troughs in northerlies, all of the 4 occasions at Tiree were associated with warm fronts or occlusions and none with polar lows or troughs. It has been noted above that neither Abbotsinch nor Prestwick had substantial falls associated with polar lows or troughs. However, 5 of the 13 occasions at Belfast/Aldergrove Airport (66 m) to the south of Tiree were caused by polar lows or troughs in northerlies.

For the 30 occasions when substantial snowfalls occurred at Stornoway in association with a northerly airstream, usually with a polar low or trough embedded in it, the average surface temperatures at Stornoway, Tiree and Aldergrove were 0°C, 1·5°C and 0·5°C respectively. There is a suggestion that coastal regions of western Scotland as far north as Tiree were free from substantial snowfalls associated with polar lows or troughs.

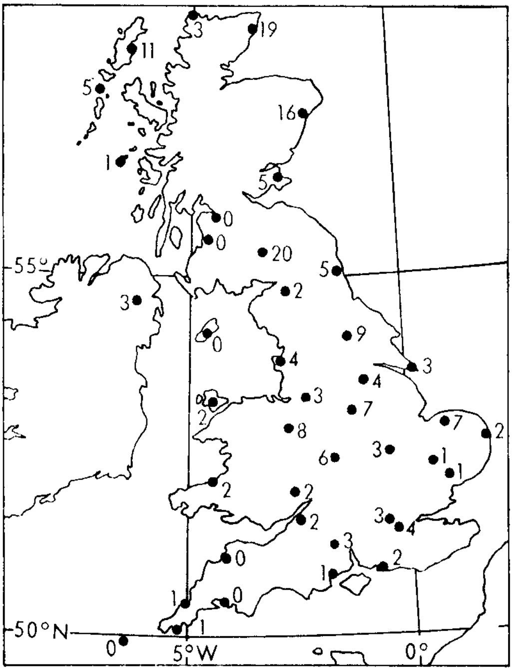
Figure 4*(a)* shows the number of occasions of substantial snowfall during the 15 winters at each of the 41 stations when subsequently there was a complete snow cover for at least 24 hours. The number of occasions at each station, with the exception of Prestwick and Mildenhall, is lower than the corresponding number shown in Figure 3 and on average lower by 43 per cent. The snow cover lasted for less than 24 hours on about 70 per cent of all occasions associated with warm fronts or warm occlusions which moved from the south-west or west, often when the front moved through the station rather than becoming slow moving before reaching it. For other synoptic types the corresponding figures were: polar low or trough in northerly, 40 per cent; warm front from south, 30 per cent; polar low or trough in easterly, 20 per cent. In general, the number of occasions was 4 or less in the western coastal regions of Great Britain as far north as Tiree, including Anglesey and the Isle of Man, and in the south coastal regions of England. The numbers, in general, ranged from 5 to 13 for inland districts of England and Northern Ireland and for the eastern coastal districts of Great Britain as far north as Leuchars. For coastal districts of northern Scotland the numbers, in general, ranged from 10 to 35. The number of occasions at Eskdalemuir, to some extent representative of the high ground in Scotland, was 31. On the other hand there were only two occasions at Mildenhall in central East Anglia.

Figure 4*(b)* shows the number of occasions of substantial snowfall during the 15 winters at each of the 41 stations when subsequently there was a complete snow cover for at least 3 days, a situation likely to cause considerable inconvenience. In general, the number of occasions was two or less in the western coastal districts of Great Britain as far north as Tiree, including Anglesey and the Isle of Man, and in the south coastal regions of England. The numbers, in general, ranged from 3 to 9 for inland districts of England and Northern Ireland and from 1 to 7 for the eastern coastal districts of Great Britain as far north as Leuchars. For coastal districts of Northern Scotland the numbers, in general, ranged from 5 to 19. The number of occasions at Eskdalemuir was 20. There were no occasions at Scilly, Plymouth/Mount Batten and Chivenor in south-west England; at Ronaldsway Airport in the Isle of Man; at Prestwick and Abbotsinch in Scotland.

Figure 4*(c)* shows the number of occasions of substantial snowfall during the 15 winters at each of the 41 stations when subsequently there was a complete snow cover for at least 5 days. There were no occasions at Scilly, Culdrose, Mount Batten and Chivenor in south-west England; at Mildenhall and Wattisham in East Anglia; at Kilnsea (Spurn Head); at Valley (Anglesey) and Ronaldsway (Isle of Man); at Prestwick and Abbotsinch in Scotland. There were 15 occasions at Eskdalemuir and for the coastal districts of northern Scotland the numbers, in general, ranged from 4 to 10. In England the highest numbers were 7 at Leeming, 4 at Shawbury and 3 at Tynemouth, Elmdon (now Birmingham Airport) and West Raynham.

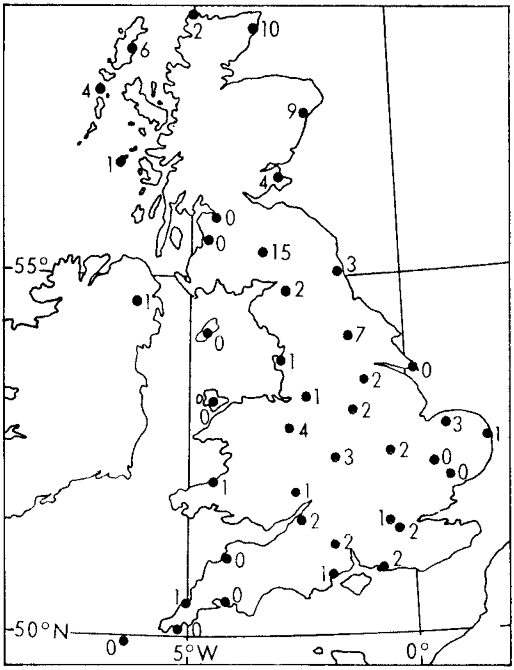


(a) When subsequently there was a complete snow cover for at least 24 hours

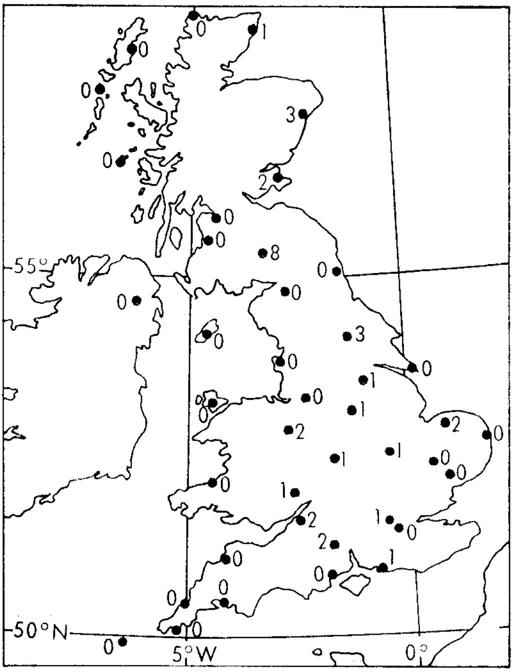


(b) When subsequently there was a complete snow cover for at least 3 days

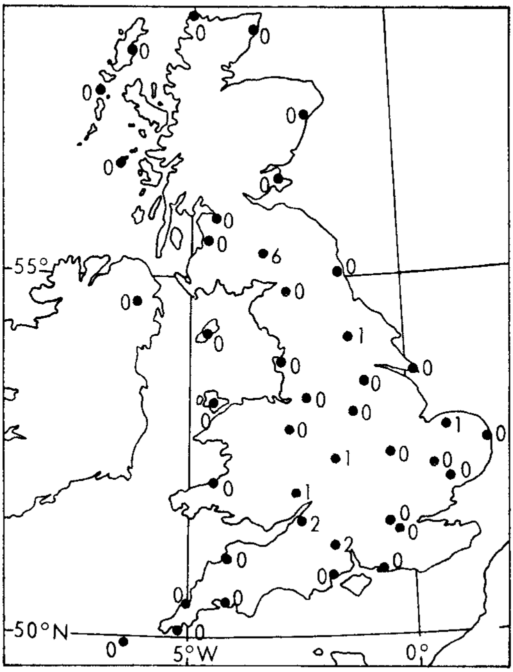
FIGURE 4—NUMBER OF OCCASIONS OF SUBSTANTIAL SNOWFALL DURING THE 15 WINTERS AT EACH OF THE 41 STATIONS



(c) When subsequently there was a complete snow cover for at least 5 days



(d) When subsequently there was a complete snow cover for at least 10 days



(e) When subsequently there was a complete snow cover for at least 20 days

FIGURE 4—*continued*

Figure 4*(d)* shows the number of occasions of substantial snowfall during the 15 winters at each of the 41 stations when subsequently there was a complete snow cover for at least 10 days. There were 8 occasions at Eskdalemuir and for the eastern coastal districts of Scotland the numbers ranged from 1 to 3. In England the highest numbers were 3 at Leeming and 2 at Shawbury, West Raynham, Bristol/Filton and Boscombe Down. There was one occasion at Finningley, Watnall, Elmdon, Wittering, Ross-on-Wye, Heathrow and Thorney Island.

Figure 4*(e)* shows the number of occasions of substantial snowfall during the 15 winters at each of the 41 stations when subsequently there was a complete snow cover for at least 20 days. There were 6 occasions at Eskdalemuir, 2 occasions at Filton and Boscombe Down and one at Ross-on-Wye, Elmdon, West Raynham and Leeming. All of the occasions at the English stations and 4 of the occasions at Eskdalemuir occurred during the months December 1962 to February 1963.

Occasions when the snow cover persisted for 20 days or more during the period December 1962 to February 1963. Figure 5 shows the surface chart for 18 GMT on 26 December 1962. At this time, a warm occlusion which was moving slowly southwards over central England marked the boundary between a cold northerly airstream and an even colder air mass over the Continent. It brought a substantial fall to Elmdon where a complete snow cover persisted for the following 32 days. The front continued to move southwards and reached the Channel region by 00 GMT on 27 December,

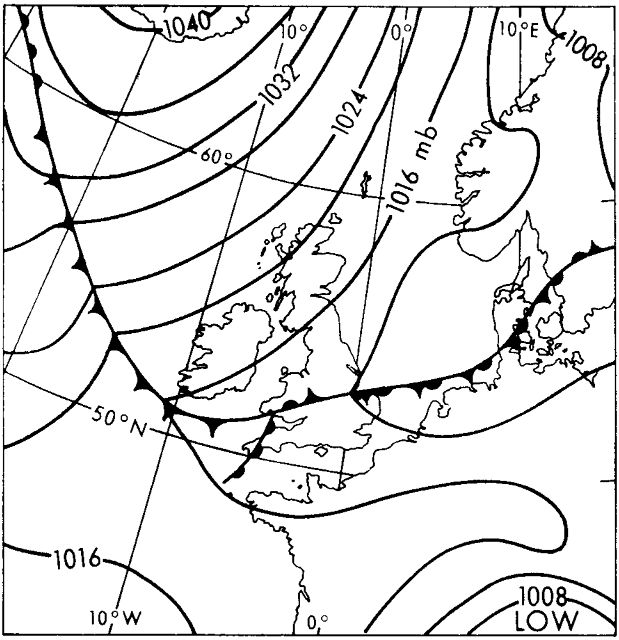


FIGURE 5—SURFACE CHART FOR 18 GMT ON 26 DECEMBER 1962

becoming quasi-stationary until losing its identity by 12 GMT on 29 December. By 18 GMT on 30 December (Figure 6) a wave depression had moved northwards from Biscay to a position south of Ireland having become partially

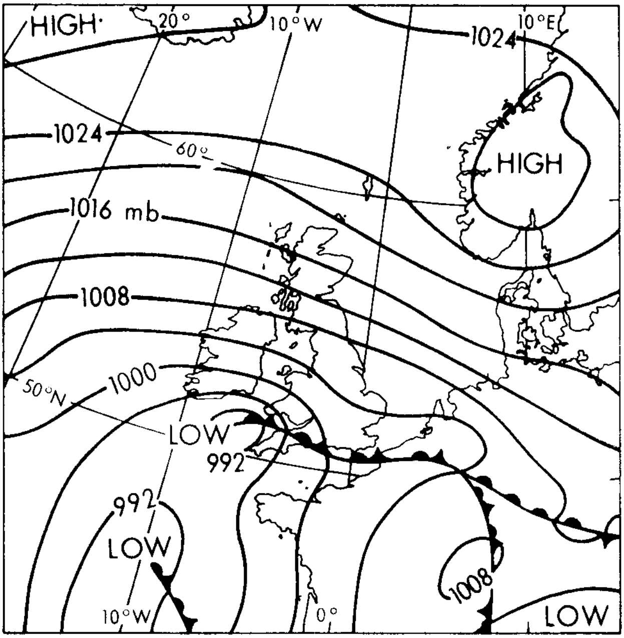


FIGURE 6—SURFACE CHART FOR 18 GMT ON 30 DECEMBER 1962

occluded with the warm occlusion moving very slowly northwards in the Channel region. A cold easterly airstream covered most of the British Isles. The front brought substantial snowfalls to Boscombe Down, Ross-on-Wye and Filton where a complete snow cover persisted for the following 30 days, 41 days and 32 days respectively. On 31 December, showers in a strong easterly airstream brought a substantal fall to Eskdalemuir where a complete snow cover persisted for the following 26 days. The front remained quasi-stationary in the Channel region until 12 GMT on 3 January 1963 causing further substantial falls at Boscombe Down and Filton where the snow cover persisted for the following 28 days at both stations. It moved northwards to northern England by 00 GMT on 4 January bringing a further substantial fall to Eskdalemuir where the snow cover persisted for the following 22 days. By 18 GMT on 4 January (Figure 7) it had moved southwards to East Anglia bringing substantial snowfalls to West Raynham where the snow cover also persisted for the following 22 days. The remarkable persistence of the snow

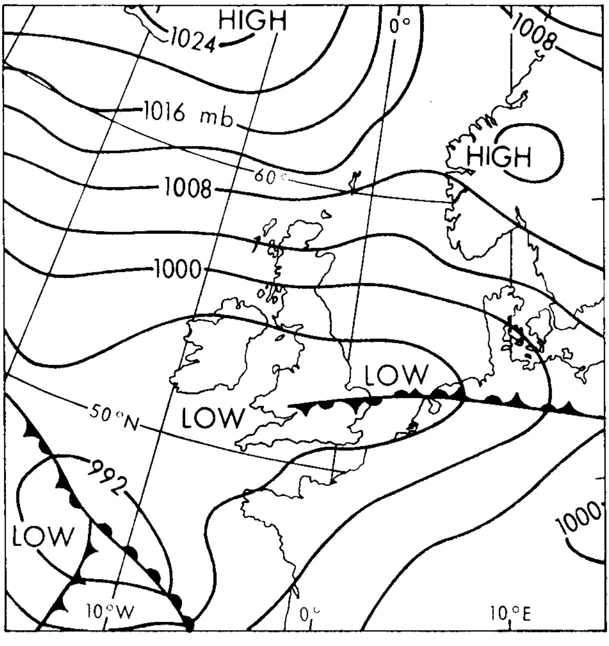


FIGURE 7—SURFACE CHART FOR 18 GMT ON 4 JANUARY 1963

cover throughout January 1963 was due to the cold easterly or anticyclonic types which predominated over the British Isles. On 31 January a cold front from the east brought a further substantial snowfall to Eskdalemuir where the snow cover persisted for the following 32 days. By 6 February, a deep depression was slow moving to the west of the British Isles and two warm occlusions moved northwards across the British Isles during the 6th to the 8th bringing substantial snowfalls to Leeming and Eskdalemuir where the snow cover persisted for the following 22 days and 25 days respectively. Figure 8 shows the surface chart for 00 GMT on 8 February when the second warm occlusion was moving northwards over England. The persistence of the snow cover throughout February was associated with the cold south-easterly or anticyclonic types which predominated in particular over eastern districts of the British Isles.

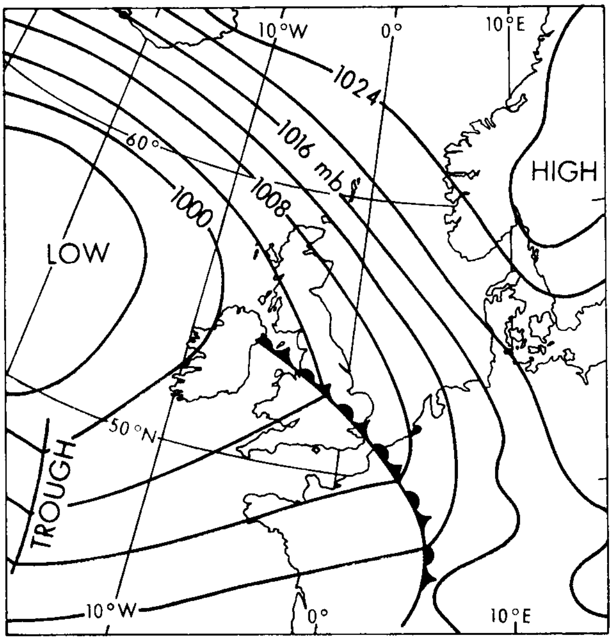


FIGURE 8—SURFACE CHART FOR 00 GMT ON 8 FEBRUARY 1963

Conclusions.

(i) During the 15 years 1954–69, substantial snowfalls (7 mm or more of precipitation in 24 hours) over the United Kingdom occurred almost entirely in the 6 months November to April and 90 per cent in the 4 months December to March.

(ii) On 43 per cent of the occasions of substantial snowfall, the resulting snow cover lasted for less than 24 hours.

(iii) Occasions when the snow cover persisted for 24 hours or more were limited almost entirely to the 5 months November to March and 86 per cent occurred in the 3 months December, January and February.

(iv) Occasions when the snow cover persisted for 3 days or more occurred in the 5 months November to March and 89 per cent in the 3 months December, January and February.

(v) There is a suggestion of a significant increase in substantial snowfalls in the months November, December and April from 1961 onwards.

(vi) There were substantial snowfalls in nearly all Januarys and Februarys but in only about half the Novembers and Aprils.

(vii) Half the substantial snowfalls were associated with warm fronts or warm occlusions which moved from (or were situated to) the south, south-west or west and a third with polar lows or troughs in northerly airstreams.

(viii) Polar lows or troughs in northerly or easterly airstreams brought a number of substantial falls to coastal stations of East Anglia but none to Mildenhall in central East Anglia.

(ix) There is a suggestion that coastal regions of western Scotland as far north as Tiree were free from substantial snowfalls associated with polar lows or troughs.

(x) On occasions of substantial snowfall when subsequently the snow cover persisted for at least 24 hours (Figure 4*(a)*) the highest frequency of occasions occurred at Eskdalemuir and in the eastern coastal districts of northern Scotland. The lowest frequencies occurred at Scilly, in the coastal districts of south-west England, in the west coast districts of Wales, northern England and Scotland as far north as Tiree, and at Mildenhall in East Anglia. There were no occasions at Scilly and Prestwick.

(xi) On occasions of substantial snowfall when subsequently the snow cover persisted for 3 days or more (Figure 4*(b)*) the distribution of frequencies was similar to that described in (x). There were no occasions at Scilly, Mount Batten, Chivenor, Ronaldsway, Prestwick and Abbotsinch.

(xii) The remarkable persistence of the snow cover at a number of stations in England in the winter of 1962–63 was associated with easterly or anticyclonic types which predominated during both January and February, in particular over eastern districts of the British Isles.

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1. THOMSON, A. B.; Water yield from snow. *Met Mag, London*, **92**, 1963, pp. 332–335.
2. CLARKE, P. C.; Snowfalls over south-east England, 1954–1969. *Weather, London*, **24**, 1969, pp. 438–447.

551.508.54

A RECORDER FOR RECORDING RUN-OF-WIND

By G. E. W. HARTLEY

Summary. Constructional details and photographs are given for a run-of-wind recorder. Easily variable gearing changes which facilitate range adjustments and the incorporation of the maximum number of standard or readily available parts are features that may be of special interest.

In March 1969 the Operational Instrumentation Branch of the Meteorological Office was asked to construct six recorders to be used with contact anemometers to record the run-of-wind in statute miles. Such an instrument made at Rothamsted Experimental Station, Hertfordshire, was available as a specimen.

The action of the recorder is as follows : the electrical impulses received from the anemometer energize the coil of a solenoid which, by means of a ratchet lever, turns a toothed wheel; the toothed-wheel spindle carries a worm gear which engages with a worm wheel on another spindle carrying a cam; the cam follower is attached to a pivoted pen-arm, and the pen is lifted up the chart, falling to its low position by gravity after passing the highest point of the cam. The downward movement is slowed by an air dash-pot. There is no new principle involved, and recorders of this general type have been listed by meteorological-instrument makers for many years. Such a recorder can be used to record any quantity which can be transmitted in the form of electrical impulses.

The requirements for this particular recorder were :

(i) It should work with a standard (Mk 4) cup-contact anemometer.

(ii) If possible, it should be able to work with a Type 4 sensitive anemometer; but this was not proceeded with.

(iii) It should have some range adjustment, giving 50, 100 or 200 statute miles as full-scale deflexion.

(iv) It should use a standard Meteorological Office weekly clock and drum, and make use of an existing chart (Barograph Form 4237) on which 10 mb would represent 5, 10 or 20 miles, the pen arm being of the same length as the barograph pen appropriate to the chart.

(v) It should work on 6 volts d.c.

Calculation of gear ratios and impulse wheel teeth. In the Mk 4 cup-contact anemometer, each contact represents 49 cup revolutions; and a speed of 50 knots gives 490 rev/min or 10 contacts/minute. So 50×6080 feet are represented by 10×60 contacts from which it can be shown that 50 statute miles $= 50 \times 5280$ feet $= 522$ contacts.

The cam must therefore raise the pen in 522 contacts for 50 miles, 1044 for 100 miles, and 2088 for 200 miles. Since $522 = 29 \times 18$, the impulse wheel has 29 teeth, and drives the cam spindle through an 18 : 1 worm reduction gear.

For 100 and 200 miles, the worm ratios are 36 : 1 and 72 : 1 respectively. These three choices of ratio are obtained by having three different worm wheels each with 72 teeth, and three worm gears of 1, 2 and 4 starts, the worm-wheel teeth being cut at angles appropriate to the worms of 1, 2 and 4 starts. This arrangement gives the same centre distance between worm and worm wheel for the three ratios.

Worms and worm wheels are fixed to their spindles by grub screws; when the desired range has been selected and its gears fixed to their spindles, the other two pairs are 'parked' out of the way on the spindles on either side of the gears in use. The gears are colour-coded for easy selection.

The recorder is illustrated in Plates I to III.

Plate I Shows the recorder complete with cover.

Plate II Shows the recorder with the cover removed; the 29-tooth impulse wheel can be seen to the right of the clock drum, with the solenoid below it; the glass pen and reservoir are shown at the end of the pen arm, and the slots in the pen arm hold the cross-bar which lifts the plunger of the air dash-pot.

Plate III Shows the worms and worm wheels; 18 : 1 gears are engaged.

Acknowledgement. The instruments were made in the workshop of the Operational Instrumentation Branch of the Meteorological Office at Bracknell, and the author acknowledges with thanks various design suggestions and excellent workmanship from the head of workshop and the craftsmen concerned.

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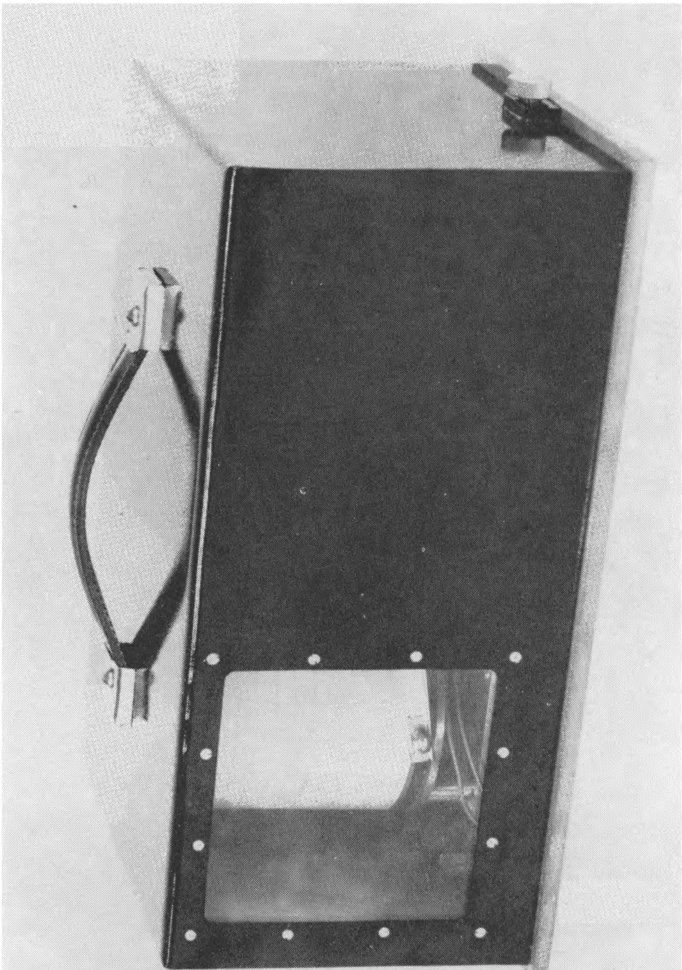

PLATE I—RUN-OF-WIND RECORDER, COMPLETE WITH COVER

See page 208.

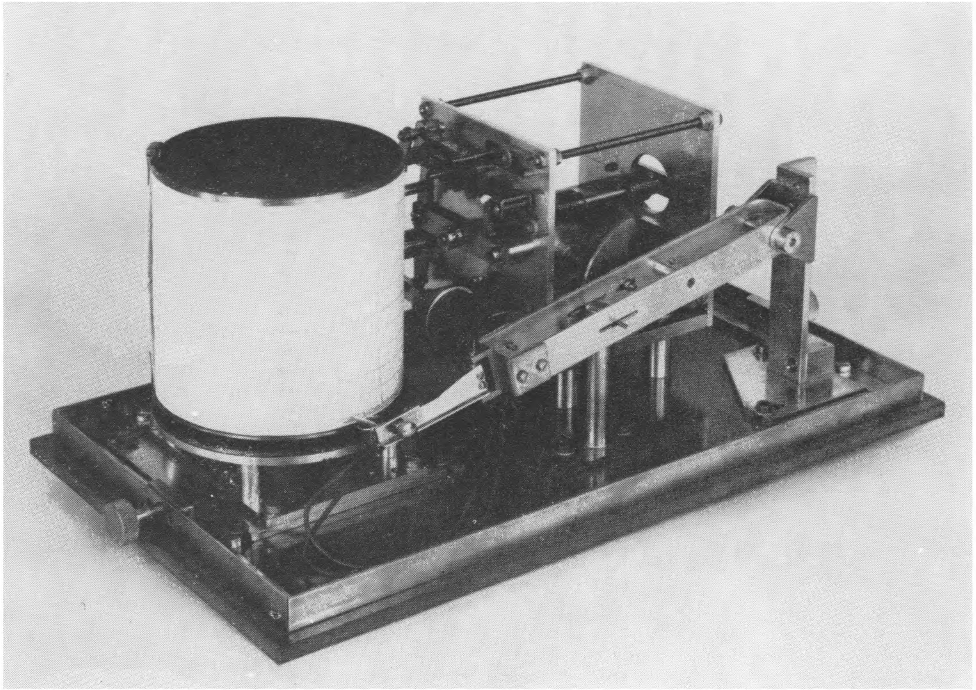

PLATE II—RUN-OF-WIND RECORDER WITH COVER REMOVED

See page 208.

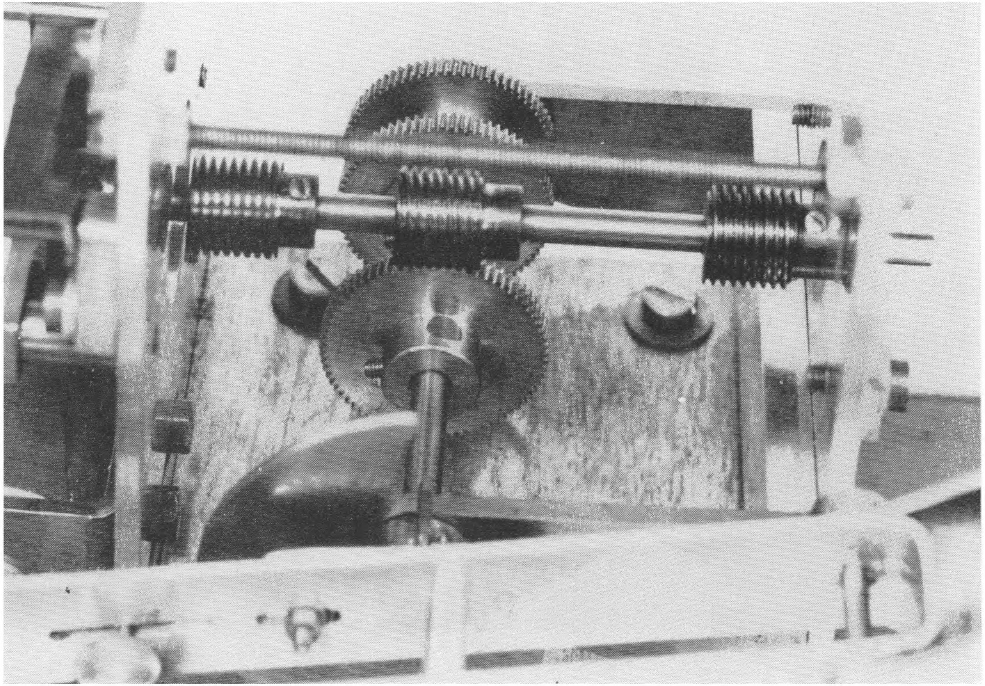

PLATE III—RUN-OF-WIND RECORDER SHOWING WORMS AND WORM WHEEL

See page 208.

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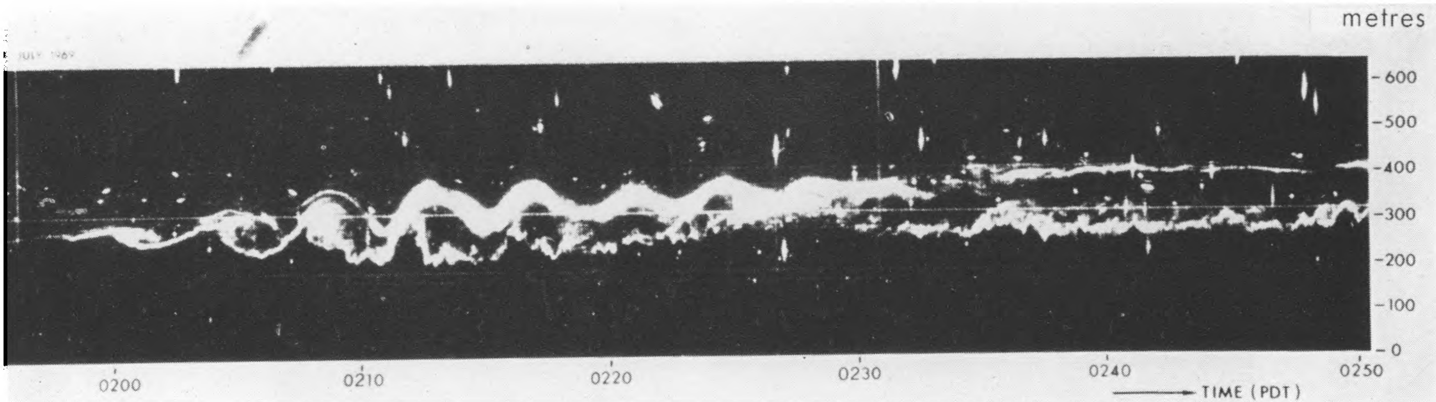


PLATE IV—TIME–HEIGHT RECORD OF WAVES AND TURBULENCE FORM RADAR DISPLAY ON 19 JULY 1969, WITH 2-m VERTICAL RESOLUTION (after Atlas *et alii*[11])

Unstable waves and subsequent turbulence in lower layer contrast with smooth structure of the upper layer. The double layer structure observed after 0230 is characteristic of many clear-air echoes. (See page 216)

551.509:329:551.511.3:551.551.5

GRAVITY WAVE SEVERE TURBULENCE NEAR CYPRUS

By R. N. HARDY

Summary. On several occasions in recent years aircraft have encountered severe low-level turbulence near Cyprus which could not have been induced by topography or convection. Some case histories are summarized, a possible cause discussed and forecasting rules suggested.

Some case histories. Table I summarizes the six occasions of turbulence considered here. If g is the acceleration due to gravity then $\pm\frac{1}{2} g$ is generally accepted as marking the threshold of severe turbulence and it is clear from the table that in some cases pilot reports and accelerometer readings indicate extremely severe turbulence. It is also worthy of note that all the cases occurred in the period February to April.

1. *21 March 1962 near Derna (see Figure 1).* The first tabulated occasion was reported by Grimmer[1] and analysed by Kirk;[2] only the main synoptic features are summarized here.

(i) The nearest radiosonde ascent, Tobruk (see Figure 1) for 12 GMT 21 March, was very dry and showed a narrow inversion near 900 mb with near dry adiabatic layers above and below.

(ii) There was a strong low-level southerly flow and a trough associated with a deepening low over north-west Tunisia was moving towards the area.

(iii) Winds decreased and veered with height above 900 mb.

(iv) All nearby barograms showed jumps and oscillations.

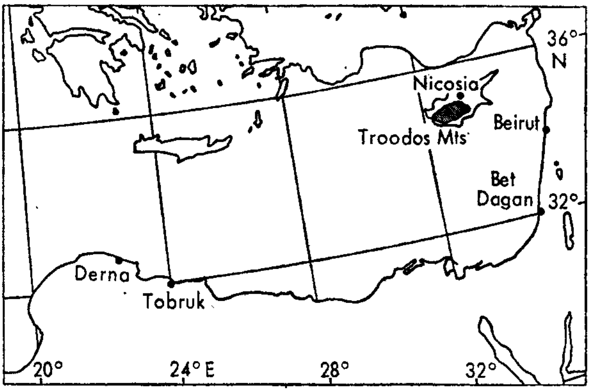


FIGURE 1—EASTERN MEDITERRANEAN

2. *14 April 1966 south of Cyprus.* This case was recorded in detail by Jefferson[3] and the similarities with the Derna case did not go unremarked. Here, however, not only was the turbulence very severe, but it persisted for about 18 hours and extended to nearly 24 000 feet.* Features noted were as follows :

(i) Both the Nicosia ascents during the period of turbulence showed a deep layer with near dry-adiabatic lapse rate (DALR) and an intense low-level inversion.

* Distances and heights are given in traditional British units. Conversion factors to metric units are : 1 foot = 0·3048 m; 1 mile = 1·6 km; 1 knot ≈ 0·5 m/s.

TABLE I—OCCASIONS OF SEVERE LOW-LEVEL TURBULENCE IN THE EASTERN MEDITERRANEAN

	Date	Time(s) GMT	Approximate location	Height(s) feet	Intensity of turbulence	Cloud
1.	21 Mar. 1962	0600	25 miles north-east of Derna	4500	'More severe than cumulonimbus'	Clear
2.	14 Apr. 1966	1300	Over Cyprus mountains	14 000 and below	Severe	Not reported
		1600	10 miles south of Cyprus	4000 to 16 000	$+3$ to $-1\frac{1}{2}\ g$*	Not reported
		circa 1610	From 80 miles south to Cyprus	1000	Severe	Not reported
		1730	25 miles south-west of Cyprus	8500	$+7$ to $-3\ g$	8/8 medium, good breaks overnight
		1940	Over south Cyprus	7500	Moderate to severe	Not reported
	15 Apr. 1966	*circa* 0300	West of Cyprus	Descending from 24 000	Occasional, moderate	In layered cloud
3.	18 Feb. 1968	1110	2 miles south of Cyprus	1500	$\pm 1\frac{1}{2}\ g$, 'very sudden concentrated bumps'	8/8 medium
		1200	Over and near south Cyprus	1500 to 10 000	Severe	Not reported
4.	28 Feb. 1968	1530	50 miles south-west of Cyprus	7000 to 12 000	Moderate to severe	Mostly 7/8 medium and high
			From 150 miles west-south-west to Cyprus	33 000 to 28 000 and 12 000 to 3000	Moderate, locally severe	Not reported
	29 Feb. 1968	0820	Over south Cyprus	1000 to 4000	Up to 2 g	Not reported
5.	12 Mar. 1968	0830	South Cyprus to 25 miles east-south-east	Surface to unspecified height	$\pm 1\ g$	6–8/8 medium with thick dust haze beneath
		0915–1030	Over Cyprus	1000 to 9000	Moderate to severe, 'some rapid altitude variations of about 500 ft/min'	Not reported
6.	17 Feb. 1969	0330–1200 (approx.)	Over and to south and south-east of Cyprus	2000 to 20 000	Moderate, occasionally severe	Generally large amounts of medium cloud
				7000	Moderate to severe	
				{6000 to 12 000	Severe	
				{12 000 to 18 000	Moderate to severe	
				3000 to 7000	Severe	

* g = acceleration due to gravity

(ii) Barograms from stations on the southern coast of Cyprus showed short-period oscillations of up to 3 mb.

(iii) Winds were strong at low levels and veered rapidly with height.

(iv) A strong 850-mb warm ridge preceded an eastward-moving trough.

(v) A depression was centred over Greece with an associated cold front accelerating towards Cyprus.

(vi) There was a complete cover of medium cloud throughout the period.

Jefferson suggested that in view of the similarity with Case 1 near Derna, factors (i) to (iv) may be useful parameters for forecasting future occurrences and, with minor refinements, this has been done successfully.

3. *18 February 1968 over and south of Cyprus.* Reports of turbulence on this occasion covered a period of only one hour but one aircraft experienced almost continuous severe clear-air turbulence (CAT) whilst descending from 10 000 to 1500 ft, clearly a potentially dangerous event.

The period 16–18 February 1968 was one of cyclogenesis over Greece with a deepening low moving north-east and an intensifying cold front accelerating eastwards. Figure 2 shows the 12 GMT surface analysis with 1000–500-mb thickness pattern superimposed for 16, 17 and 18 February; note particularly the increasing thermal gradient across the front. Simultaneously, anticyclogenesis took place over north Iraq producing an easterly component in the flow across the extreme north-east Mediterranean.

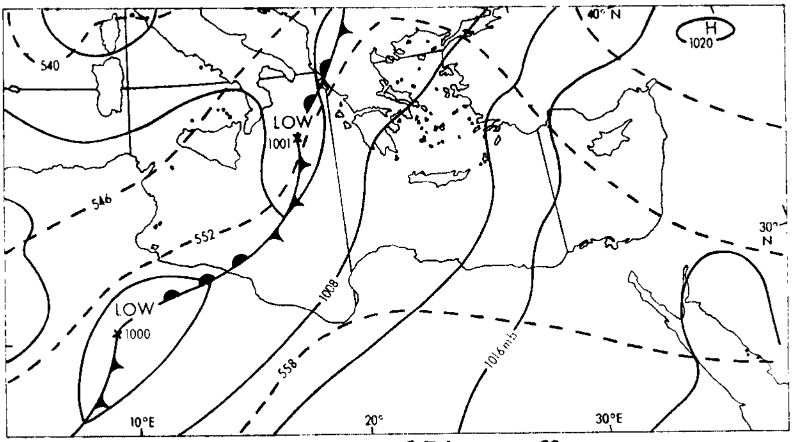
The development of the surface low can be related to a sharpening upper trough which moved to 19°E by 00 GMT on 18 February, and an associated jet near 300 mb with core speeds up to 140 kt which moved through the upper pattern and reached Cyprus between 06 and 12 GMT on 18 February.

Figure 3 shows the Nicosia radiosonde ascent curves for 12 GMT on 17 and 18 February. These profiles will have been modified by any waves in the atmosphere because Nicosia is to the north of the Troodos Mountains (see Figure 1); nevertheless the profiles clearly show that a layer with near DALR developed over Cyprus in the 24 hours up to 12 GMT on 18 February, with strong warming at 850 mb and cooling above 800 mb. Thick cloud above about 12 000 ft is also apparent ahead of the cold air.

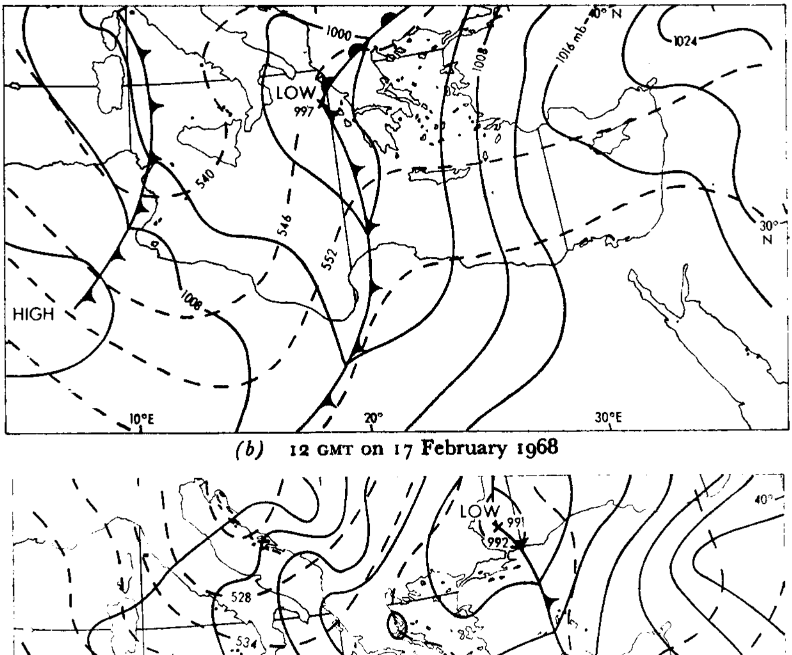
Cyprus stations reported only intermittent slight rain from 11 GMT but thundery activity was widespread behind the trough.

The cold front passed through Tobruk during the evening of 17 February preceded by 8/8 altocumulus and altostratus accompanied by blowing sand in strong southerly winds. The Tobruk radiosonde ascent for 12 GMT on 17 February in Figure 4 is very similar to the Nicosia profile at 00 GMT on 14 April 1966[3] (Case 2) and the 06 GMT winds (Table II) compare closely with those on 20 March 1962[2] (Case 1), particularly as regards the strong shear at low levels.

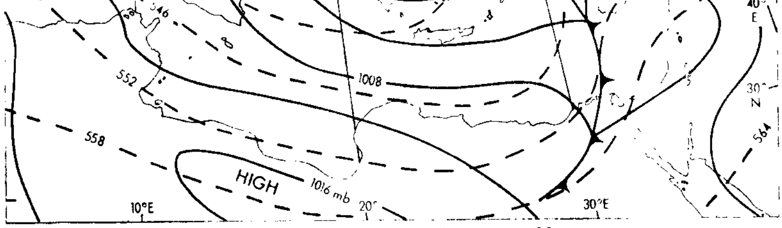
Barograms for all Cyprus stations show a three-hour period with marked pressure oscillations and jumps of up to 2 mb from 11 GMT on 18 February; the disturbances were less marked at Nicosia to the lee of the main mountain range. The Tobruk pressure record shows disturbances from 17 GMT on 17 February for about six hours though the amplitude of the oscillations appears



(*a*) 12 GMT on 16 February 1968



(*b*) 12 GMT on 17 February 1968



(*c*) 12 GMT on 18 February 1968

FIGURE 2—SURFACE ANALYSIS AND 1000–500-mb THICKNESS

——— Isobars — — — Thickness in geopotential decametres

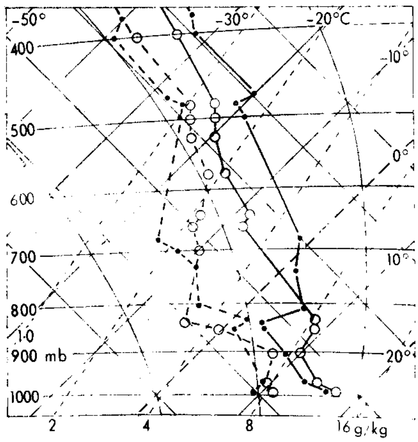


FIGURE 3—NICOSIA ASCENTS, 17 AND 18 FEBRUARY 1968

17 February	18 February
• —— • Temperature	o —— o Temperature
• – – – • Dew-point	o – – – o Dew-point

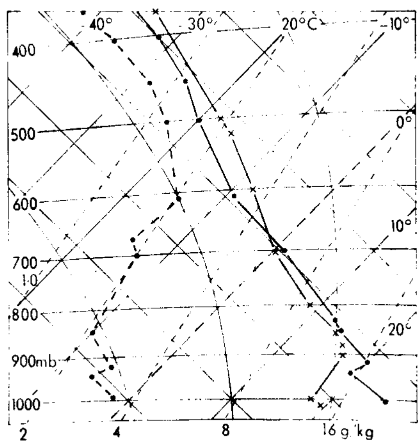


FIGURE 4—TOBRUK ASCENTS, 00 AND 12 GMT ON 17 FEBRUARY 1968

00 GMT	12 GMT
• —— • Temperature	x —— x Temperature
• – – – • Dew-point	

to be less than at Cyprus stations; this may reflect differences between the instruments concerned. Barograms for Beirut and Beit Degan (see Figure 1) showed some trace of pre-frontal oscillations but not to the same degree as those recorded by Cyprus stations.

4. *28 and 29 February 1968 near Cyprus.* The duration and area of turbulence reported on this occasion more nearly corresponds to that of Case 2. Severe turbulence was encountered from 1000 ft to the base of a nearly complete cover of medium cloud at 12 000 ft and in addition moderate, locally severe, turbulence was reported from 28 000 to 33 000 ft associated with a high-level jet stream.

TABLE II—TOBRUK WINDS 17 FEBRUARY 1968

Pressure level	00 GMT		06 GMT		12 GMT	
mb	*deg*	*kt*	*deg*	*kt*	*deg*	*kt*
300	240	64	235	61	230	47
400	240	55	235	47	235	41
485	230	51				
500	235	54	235	42	225	36
524					225	30
592	205	22				
600	210	22	255	22	220	28
700	235	15	220	07	220	29
764					225	32
800	230	19	210	25	223	34
829	220	18				
850	210	17	205	28	220	34
900			185	40	211	36
963					205	32
970	170	37				
1000	180	18	190	25	190	22

The period 27 to 29 February 1968 was again one of marked cyclogenesis west of Cyprus. A depression developed in an area of almost uniform pressure some 300 miles west of Tobruk; from a central pressure of 1004 mb at 06 GMT on 28 February the low deepened to 981 mb at 12 GMT on 29 February having moved north-eastwards to a position 300 miles west of Cyprus. An associated cold front that originally extended southwards from the centre accelerated markedly to cross the island from the south between 12 and 18 GMT on 29 February.

The time section of Nicosia winds in Figure 5 shows the increasing shear at low levels up to 12 GMT on 29 February and also the strong high-level jet.

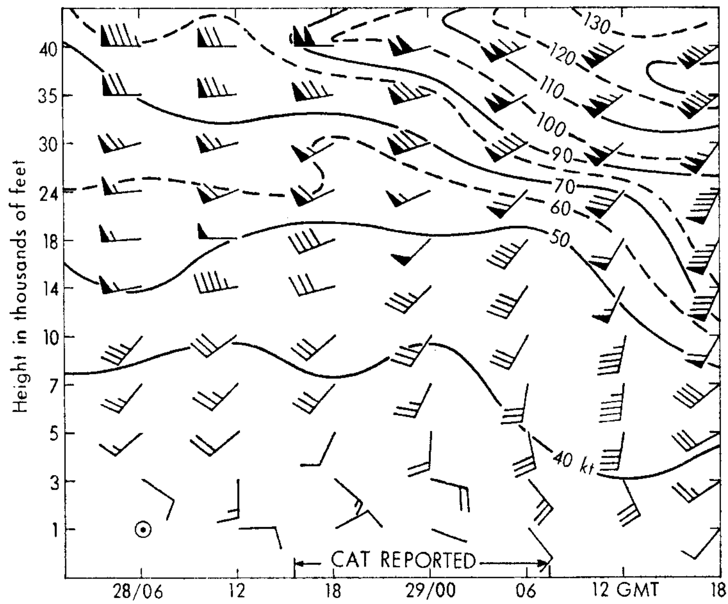


FIGURE 5—TIME SECTION OF UPPER WINDS AT NICOSIA FROM 06 GMT ON 28 FEBRUARY TO 18 GMT ON 29 FEBRUARY 1968

Wind speeds and directions plotted in usual international symbolic codes.

Figure 6 shows the Nicosia radiosonde ascents for 28 and 29 February; again the marked low-level warm advection gradually became established and extended a layer of near DALR at the same time modifying more stable layers above and below.

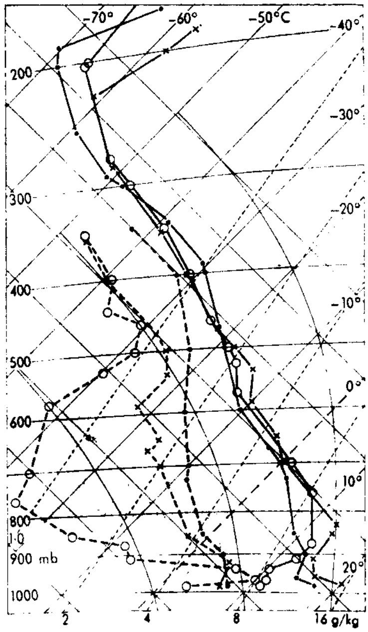


FIGURE 6—NICOSIA ASCENTS, 28 AND 29 FEBRUARY 1968

28 February	29 February	
12 GMT	00 GMT	12 GMT
· —— · Temperature	o —— o Temperature	x —— x Temperature
· - - - - · Dew-point	o - - - o Dew-point	x - - - x Dew-point

Isolated outbreaks of slight rain from 8/8 medium cloud were reported on the south coast of Cyprus, but there were breaks in the cloud cover overnight between 28 and 29 February. Blowing sand was reported over North Africa on both sides of the front and dust haze was widespread over Cyprus on the 29th. Barograms show the typical unsettled traces of the previous occasions.

5. *12 March 1968 and 17 February 1969.* These occasions of severe turbulence near Cyprus were broadly similar to those already described but each contributed one significant item of additional information.

On 12 March 1968 a pilot described the turbulence as taking the form of 'some rapid altitude variations of about 500 ft/min', implying wave motion.

On 17 February 1969 there was no marked surface trough associated with the area of turbulence. In this case an intensifying 850-mb trough with associated strong baroclinic zone accelerated towards Cyprus and became associated with a developing surface low south-south-west of the island.

Discussion.

Common factors. The synoptic patterns and sequences of events leading to the six occasions of severe low-level turbulence were very much alike.

Common factors were :

(i) All occasions were in the period February to April.

(ii) Warm dry air was being advected at low levels by a strong south to south-east flow.

(iii) An intensifying front or trough usually associated with a surface low and strong upper jet had accelerated towards the area.

(iv) Winds veered from south to south-east at the surface to between west and south-west above about 10 000 ft.

(v) Unsteady surface pressure records with oscillations and jumps were a feature of each occasion.

(vi) Except in the first case — near Derna — there was always a large amount of medium and high cloud.

(vii) The stratification shown by the nearest ascent invariably showed a near DALR through a considerable depth of the low troposphere. Over the sea there would be an intense low-level inversion or isothermal layer.

(viii) All known reports concern the eastern Mediterranean.

Gravity waves. Mountain waves, familiar to most forecasters, are just one member of a wider family of gravity waves in the atmosphere. It is probable that gravity waves are a feature of all intense inversions though mostly they are low-amplitude long-wavelength features of no operational importance. Occasions are on record of larger-amplitude waves propagating over long distances whose origins have been traced to (i) cyclogenesis,[4] (ii) intense convection[5] and (iii) evaporation downdraughts.[6] Factors (i) and perhaps (iii) may have been operative in these cases.

It is possible that waves travelling along an inversion which is becoming shallower but more intense can amplify and disrupt, giving areas of severe turbulence. Amplifying gravity waves could be the cause of the pressure and wind oscillations that have been noted in the Mediterranean[7] and Persian Gulf.[8] If the 'broken' wave differs in character from the oscillatory wave in the same way as a sea wave, turbulent zones may travel along the hitherto undisturbed inversion downstream to produce discrete pressure jumps.

Kelvin-Helmholtz instability (KHI). KHI does not belong to the gravity-wave family but is a form of dynamic instability produced by strong vertical shear in stably stratified fluids. It takes the form of wave-like disturbances in which the crests grow and roll up into horizontal vortices (billows) which then 'burst' into general turbulence after a short time (less than one minute). Photographs of KHI development in the ocean thermocline have been taken by Woods[9] and more recently, radar pictures of what appears to be atmospheric KHI have been obtained.[10,11] (See Plate IV.)

It has been shown (see for example the discussion of billow clouds by Ludlam[12]) that this 'liberation' of kinetic energy from shear layers can only occur if the Richardson number, (Ri), is less than some critical value about 0·25 where, over a layer of thickness Δz,

$$(Ri) = \frac{g}{\theta} \frac{\Delta\theta}{\Delta V} \frac{\Delta z}{\Delta V},$$

where θ = potential temperature, g = acceleration due to gravity and $\Delta\theta$ and ΔV are the differences of potential temperature and wind velocity over the layer.

Normally it appears that (Ri) is reduced to its critical value in very narrow zones across which direct measurements of the shear and potential temperature gradient are not practicable. Computations of (Ri) from radiosonde ascents do however give a useful guide since the layer (Ri) is always greater than the true (Ri) at some point in that layer. In other words if (Ri) computed over a layer of say 1 km approaches 0·25 then it is almost certain to be less than the critical value over part of the layer.

By calculating values of (Ri) for the occasions of severe low-level turbulence described in the case histories and comparing the profiles with those occasions when KHI was detected by radar, it should be possible to assess the likelihood of KHI and the probable depth of atmosphere affected. Unfortunately the lack of representative data prevents a detailed analysis; in particular Nicosia radiosonde ascents cannot be used since Nicosia lies to the lee of a mountain range. Tobruk radiosonde ascent and winds for 17 February 1968 shown in Figure 4 and Table II respectively are considered broadly representative of the type of profile on all occasions of turbulence except that the lowest layers would be much more stable over the sea. Suitably modified (Ri) profiles are shown in Figure 7 with the shear and gradient of potential temperature also given separately. There is some evidence that KHI could have occurred in the layer 850–800 mb near 00 GMT, because not only is (Ri) well below 0·25 but the 06 GMT profile shows a reduction of (Ri) above and below this layer with a marked increase in the layer itself, a feature which has been noted during radar investigations of KHI. A forecaster would be justified in predicting locally severe turbulence from the 06 GMT (Ri) profile where the critical value is almost certainly reached at some point between 900 and 850 mb. Furthermore, a relatively small increase in shear or decrease in stability would reduce (Ri) below the critical value at 12 GMT.

Caution should be used in interpreting (Ri) profiles. With a near DALR there is uncertainty as to the exact value of (Ri), furthermore, it is known that dry adiabatic lapse rates (or even superadiabatic lapse rates) occur in the lower layers without leading to severe turbulence. Possibly the destabilization caused by overrunning colder air in a region of shear is of major significance. If it occurs above an inversion which isolates it from the small-scale turbulence near the ground then energy is dissipated in large-scale rather than small-scale eddies. Clearly it is the values of (Ri) in the shear layer that are most important.

The effect of gravity waves on the low-level inversion on (Ri) values may be critical; (Ri) will be reduced at the crests and troughs where shear is concentrated, triggering KHI where it would not otherwise have occurred.

The persistence of the turbulence on some of the occasions described is probably due to the generation of shear ahead of the frontal trough counterbalancing the dissipation due to KHI; this process is discussed in detail by Roach[13] elsewhere. It is likely that the vertical extent of turbulence is a function of stability above the KHI layer; in these cases the disturbances are allowed to propagate upwards virtually undamped through the layer of near DALR.

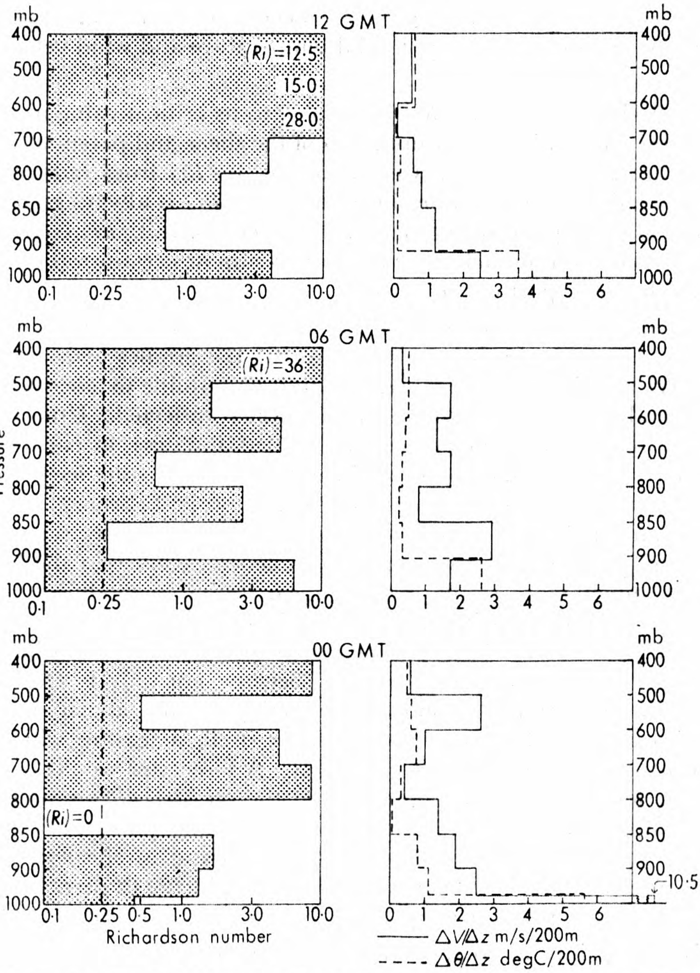


FIGURE 7—PROFILES OF RICHARDSON NUMBER, VERTICAL SHEAR AND GRADIENT OF POTENTIAL TEMPERATURE FOR TOBRUK ON 17 FEBRUARY 1968

V = Wind velocity θ = Potential temperature
Δz = Thickness of layer

General considerations. The severe CAT reported in the eastern Mediterranean occurred in regions where a particular intense form of KHI might be expected. It occurs when cyclogenesis to the west establishes a strong wind shear in the vertical which in turn, because of the geography of the area, means the establishment of a layer of near DALR in the lower troposphere. During the period January to April an intense low-level inversion is inevitable over the eastern Mediterranean in this situation, which tends to concentrate shear and forms a basis for wave motion.

KHI may be triggered by local minima of *(Ri)* produced by local distortion of shear layers by travelling gravity waves (e.g. Woods[9]) which themselves may be generated by downdraughts or the cyclogenesis itself. However, until more information becomes available the forecaster can only assume a random distribution of turbulence in the horizontal within the zone of potential KHI. There is some evidence that the tendency of KHI to concentrate stability at the top and bottom of the layer of turbulence causes the turbulence to persist longest in these regions, see Plate IV, but the upper boundary of KHI (near Cyprus at least) is likely to be marked by the base of extensive medium cloud; the lower boundary may well be at the surface.

It may be possible to advise aircrew on occasions to fly in the medium cloud or if that is impossible then to fly midway between the likely bounds of KHI. Ideally, descent through or take-off into the layer would be delayed until after the passage of the surface front.

Forecasting rules. There are few difficulties in forecasting qualitatively the probable occurrence of this type of turbulence in the eastern Mediterranean or its likely vertical extent. The horizontal area is difficult to specify except in so far as the surface front marks the rear boundary.

The synoptic events leading to occasions of severe turbulence are almost identical to those preceding the devastating tornadoes of December 1969.[14] The most significant difference lies in the month of occurrence; it is probable that the higher sea temperatures of December and hence moister air ahead of the front led to the genesis of waterspouts rather than to KHI.

The conditions for turbulence of this type, all of which are interrelated, are as follows :

(i) A deepening depression to the west of the area.
(ii) An associated trough or cold front moving towards the area.
(iii) Strong low-level winds veering with height, giving warm advection at low levels and often accompanied by cold advection aloft.
(iv) A near DALR through a considerable depth of the lower troposphere with an inversion beneath.
(v) Unsteady barograph traces, often with discrete jumps.
(vi) Usually hazy conditions at low levels with a complete cover of medium cloud.
(vii) The preceding night minimum temperature is always well above normal.

Now that radiosonde ascents are made from Episkopi on the south coast of Cyprus it may be possible to investigate the profiles of *(Ri)* in more detail on future occasions. A great deal more could be learnt by using high-power radar; it appears that the eastern Mediterranean would be a most suitable area for such research.

Acknowledgement. The author is indebted to Dr W. T. Roach for useful discussions on the nature of KHI.

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551.524.36

THE ESTIMATION OF MEAN DRY-BULB TEMPERATURE DURING DAYLIGHT HOURS

By D. G. ARMOUR, J. BALLOCH and R. W. GLOYNE

Summary. Botanists state that the mean temperature during the hours of daylight is a useful parameter for studying phenological data. Relatively few stations make observations of temperature at each hour; many, however, record the daily maximum and minimum. Empirical expressions have been derived for obtaining an estimate of mean temperature during the day by subtracting from the average of daily maxima a proportion of the average daily range. Values for the constant of proportionality are presented. These vary from about 0·25 for California (with little or no seasonal variation) to rather higher absolute values (exhibiting a seasonal variation) of between 0·32 and 0·46 for selected stations in England and Scotland.

Introduction. The mean temperature during the hours of daylight (and equally during the hours of darkness) has been found to be a useful concept for organizing and analysing certain phenological data. A request for mean day-time temperature by months for several places provided the opportunity to examine formulae for deriving this parameter from readily available data on average mean daily maximum and average mean daily minimum temperatures for individual months.

Average monthly values of hour-by-hour dry-bulb temperatures for the period 1957–66 were readily available for Edinburgh (Edinburgh/Turnhouse Airport) and London (London/Heathrow Airport) and these, together with estimates (based on observations for each three hours) for Paris (St Maur)[1] for the period 1951–60, form the basic material for the computations.

Method and analysis.

(i) *Data.*

London : Mean hourly dry-bulb temperatures (month-by-month) for 1957 to 1966 (Metform 3257).
Average daily maximum and minimum temperatures for 1957 to 1966 (Metform 3259).

Edinburgh : Mean hourly dry-bulb temperatures (month-by-month) for 1957 to 1966 (Metform 3257).
Average daily maximum and minimum temperatures for 1957 to 1966 (Metform 3259).

Paris : Estimates of mean hourly dry-bulb temperatures based on 3-hourly observations for 1951 to 1960.[1]
Average daily maximum and minimum temperatures.[2]
Day lengths for the 15th day of each month were taken from the Nautical Almanac.[3]

(ii) *Procedures.* The method consists of subtracting a proportion of the mean daily range from the mean daily maximum — average values of these quantities having been derived for months of given name, i.e. the expression is of the form

$$T = X - a\,(X - N),$$

where

T = average value of the mean temperature during daylight hours,
X = average value of daily maximum temperature,
N = average value of daily minimum temperature,
a = a coefficient to be determined from the data.

A mean temperature quoted for a particular hour (hh) was regarded as the mean value for the period (hh−30 min) to (hh+30 min). Temperatures for incomplete 60 minutes at sunrise and sunset were weighted according to the convention :

$\leqslant$15 min :	0 × hourly value
16 to 45 min :	$\frac{1}{2}$ × hourly value
> 45 min :	1 × hourly value

Values for the coefficient a were computed from

$$a = (X - T)/(X - N).$$

The magnitude of a was noted to be rather sensitive to decisions as to the weightings to be attributed to incomplete hours. Accordingly the simple graduation formula was employed, viz,

$$a = \tfrac{1}{4}(a_{n-1} + 2a_n + a_{n+1}),$$

where a_{n-1}, a_n, a_{n+1} are the computed values for successive months, and a is the 'smoothed' mean value for month n (Conrad[4]).

(iii) *Results.* The values for London, Edinburgh and Paris are set out in Table I, together with those derived by Brooks[5] for California and Smith[6] for Aberdeen and Kew.

TABLE I—PROPORTION OF MEAN DAILY RANGE TO BE SUBTRACTED FROM MEAN DAILY MAXIMUM TO OBTAIN A MEAN DAY-TIME TEMPERATURE

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Edinburgh (Turnhouse)	0·34	0·35	0·38	0·39	0·41	0·45	0·42	0·40	0·37	0·35	0·36	0·34
London (Heathrow)	0·36	0·39	0·39	0·40	0·42	0·46	0·43	0·41	0·42	0·36	0·39	0·32
Kew (from Smith[6])	0·33	0·34	0·35	0·35	0·37	0·41	0·39	0·39	0·35	0·33	0·32	0·30
Aberdeen (from Smith[6])	0·35	0·35	0·34	0·36	0·39	0·43	0·40	0·39	0·35	0·29	0·30	0·36
Paris (St Maur)	0·31	0·39	0·38	0·37	0·37	0·39	0·41	0·40	0·37	0·35	0·30	0·24
California (from Brooks[5])	0·25	0·25	0·25	0·25	0·25	0·25	0·25	0·25	0·25	0·25	0·25	0·25

Clearly there are two groups representing respectively the results for the British Isles and those for France (Paris) on the one hand and the U.S.A. (California) on the other. In this second group the factors show little or no seasonal variation about an average of 0·25; in the first absolute values are higher and there is a seasonal maximum in summer.

It was noted that the unsmoothed monthly values for the British Isles followed a more irregular sequence after, as compared with before, the summer peak.

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REVIEW

Measurement of humidity, Notes on Applied Science No. 4, fourth edition, by M. J. Hickman. 243 mm × 150 mm, pp. v+33, *illus.*, HMSO, 49 High Holborn, London WC1, 1970. Price: 20p.

This is one of the excellent series of booklets on applied physical topics issued by the National Physical Laboratory. It is an introduction to practical methods of humidity measurement as required in industry and laboratories and brings the previous editions up to date. As Mr Hickman explains, the notes make no pretension to detail or completeness and are meant for the non-specialist. Those interested in the measurement of humidity in the open air for meteorological purposes are referred to books issued by the Meteorological Office.

The booklet starts with a brief description of physical principles and continues with an outline of the main types of hygrometer likely to be useful in solving practical problems — the wet- and dry-bulb hygrometer, dew-point hygrometer, mechanical hygrometer and electrical hygrometer — with a brief mention of some miscellaneous types.

The wet- and dry-bulb hygrometer is undoubtedly one of the most convenient instruments for obtaining quite accurate measurements so, quite rightly, more detail is given of this type of hygrometer than any other together with a fairly comprehensive list of sources of error.

The section on dew-point hygrometers makes little mention of completely automatic types and the statement is made that such instruments are complicated and expensive. However, the manually operated types of dew-point hygrometer require a skilled operator while the automatic types do not. A wide variety of automatic instruments is now becoming available, some of which are not unduly expensive. They further have the advantage of potentially remote operation and relatively high accuracy as well as automatic indication.

After a description of mechanical hygrometers and of hygrometers which can be used for low humidities, there is a section on the need for operators to check their instruments frequently, something which is not always done as much as it should be, as the accuracy of most hygrometers is subject to deteriorating influences. A further section gives guidance on the choice of methods to be considered especially in relation to the accuracy required. Finally there are a few concluding remarks about methods of generating air-streams of known humidity.

A comprehensive reference section at the end of the booklet makes it a useful introduction for the intending specialist too; nevertheless the references are laid out so that the non-specialist can easily pick out those few papers which he is likely to wish to study.

This is a booklet which all who have any connection with humidity problems ought to have on their bookshelves.

C. K. FOLLAND

LETTER TO THE EDITOR

551.578.45:625.1

A railway problem during the heavy snowfall of 4 March 1970

It is regretted that the series of observations for Cardington and Northolt given in Table I of the above article* should be from 06 to 15 GMT and not 07 to 16 GMT. Also, Cardington is not closed overnight; gaps appear in the Table because the data were not relevant to the argument. The text on page 300 should now read '. . . at Cardington and Northolt between 10 and 12 GMT' and on page 303 '. . . at Northolt between 09 and 12 before snow returned by 13 GMT', but the general argument of the article is not altered.

It should be pointed out however, that the latent heat released by the freezing of rain on a sub-zero pantograph would quickly raise the temperature, and accretion by this process is limited.

Dr Bartlett has made some estimates of the time required for a pantograph temperature of −2°C to become 0°C. He has assumed that the pantograph is constructed of bars which are the equivalent of solid steel bars about 1 inch (2·54 cm) diameter, though the construction is somewhat lighter than this, with an approximate specific heat 0·1 and density 7·9 g/cm^3. The pantographs normally exert an upward thrust equivalent to a weight of 20 lb (about 10 kg).

(i) *For a dry pantograph.* At a relative airspeed of 30 mile/h (15 m/s) with an environment temperature of 0°C the pantograph temperature would rise to 0°C in 6 to 10 minutes, i.e. over a distance of 3 to 5 miles.

(ii) *Under wet conditions.* At a relative airspeed of 60 mile/h (30 m/s) with the equivalent of slight rain (0·5 mm/h on the ground) the pantograph temperature would rise to 0°C in about 6 minutes.

In moderate to heavy snow the weight accumulated on a pantograph with a surface area of about 1 square metre would be about 10 kg/m^2 in 6 minutes at a relative airspeed of 60 mile/h (30 m/s), i.e. over a distance of about 6 miles.

* PARREY, G. E.; A railway problem during the heavy snowfall of 4 March 1970. *Met Mag, London*, **99**, 1970, pp. 299–304.

Slight rain (equivalent to 0·5 mm/h on the ground) mixed with the snow is assumed to freeze on the pantograph and result in all the precipitation sticking to the pantograph.

It will be seen from these figures that a cold pantograph very quickly reaches 0°C and that rather special conditions are required before water drops could freeze on a cold pantograph and lead to a weight of snow and ice sufficient to lower the pantograph. The air-temperature change from −2°C to 0°C would need to occur within about 5 miles and the amount of water actually freezing would need to be minimal; most of the weight accumulating would be of snow.

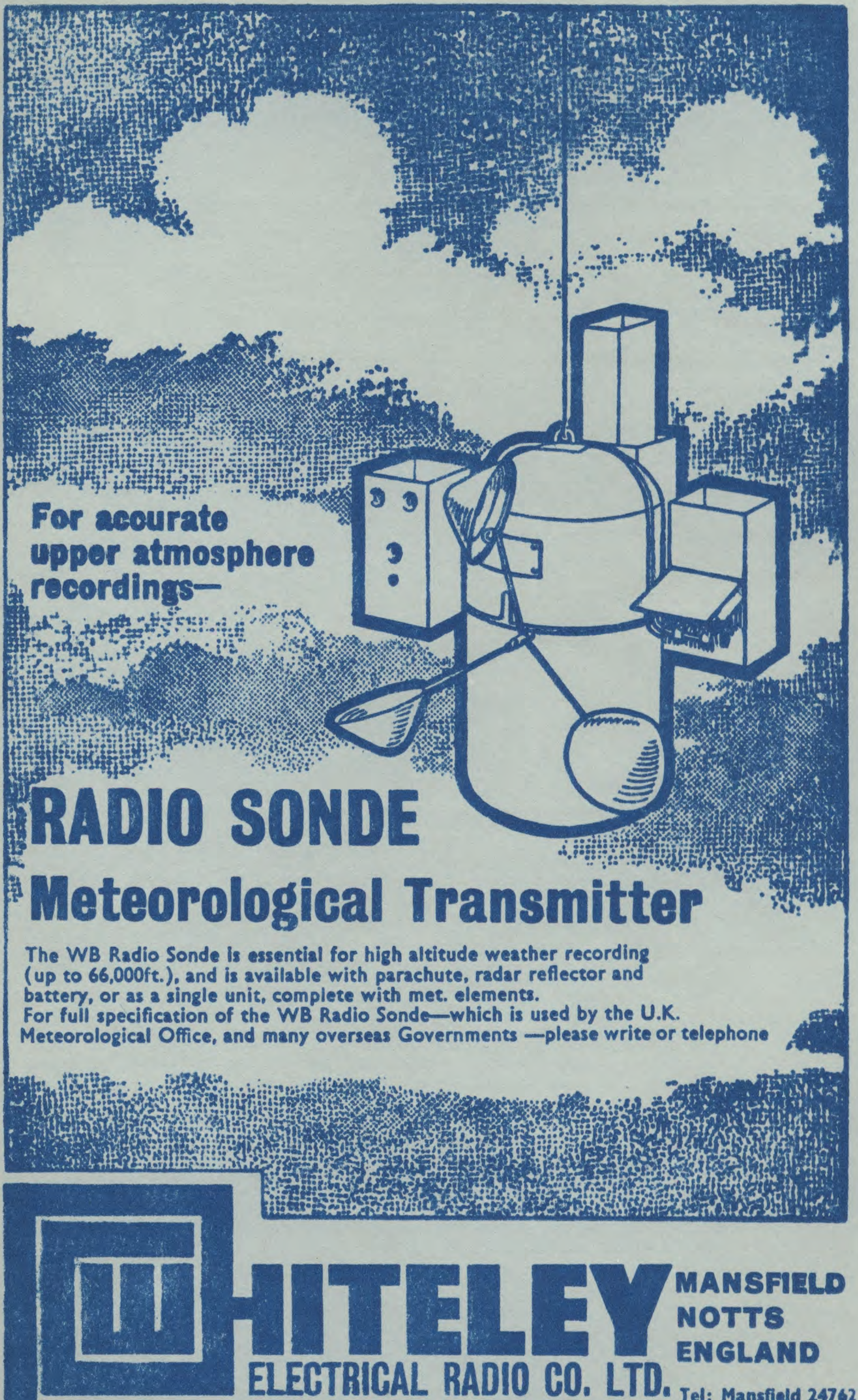
Meteorological Office, Watnall G. E. PARREY

OBITUARY

It is with regret we record the death of Mr R. A. Smith, Senior Scientific Assistant, Birmingham Airport, on 3 March 1971.

PUBLICATION RECEIVED

Vayu Mandal (literally the Atmosphere) is the official Bulletin of the Indian Meteorological Society and will be published quarterly. Its annual subscription is Rs. 8 in India and $2·00 abroad. Vol. 1 No. 1 for January 1971 has now appeared, with a wide variety of articles on meteorology.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NORTH ATLANTIC SEA TEMPERATURE CLASSIFICATION 1877–1970

By R. A. S. RATCLIFFE

Summary. A classification system has been devised for anomalies of monthly mean sea surface temperature on the North Atlantic. The different types of sea surface temperature anomaly pattern are described and a catalogue, using all available data in the period 1877–1970, is given for most months of that period. Some uses of the catalogue for long-range forecasting purposes are referred to.

Introduction. It has long been clear that the overlying atmosphere affects ocean temperatures, and it has long been suspected by meteorologists that the temperature of the ocean surface may have an appreciable effect on the development of atmospheric systems. It was in studying this latter aspect of air/sea interaction that the need arose to recognize and classify the various patterns of anomaly of sea temperature. The task of getting together the necessary data for classifying almost 100 years of ocean temperature anomalies was a very formidable one and there is still a certain amount of doubt about the pattern in some months.

Data sources. The classification given here is based on four main data sources, viz. :

(i) Sea surface temperature anomalies for 5 degree squares of latitude and longitude produced by Professor Riehl[1] for the region south of 50°N for each month of the period 1888–1936.

(ii) Anomalies produced by the Danish Meteorological Institute[2] for irregular areas north of 50°N for the same or a longer period.

(iii) British and German marine card data for the period 1877–1961 available in the British Meteorological Office.

(iv) Various types of operational data available in the British Meteorological Office for the period 1961–70.

Data sources (iii) and (iv) have been compared with the averages of sea surface temperatures given in an American publication[3] in order to produce the anomalies. Sources (i) and (ii) have their own averages of sea surface temperature but the resulting anomalies in general agree with those produced independently from the data source (iii) so that the entire series is regarded as being as homogeneous as is currently possible. In cases of disagreement in the type of anomaly between the various sources, the month in question has been left unclassified.

The classification. The main classification concerns the sign of the anomaly of sea surface temperature in the area between 35/50°N and 40/60°W, particular importance being given to the sign of the anomaly between 40 and 45°N (see cross-hatching on Figure 1). If there is a well-defined warm

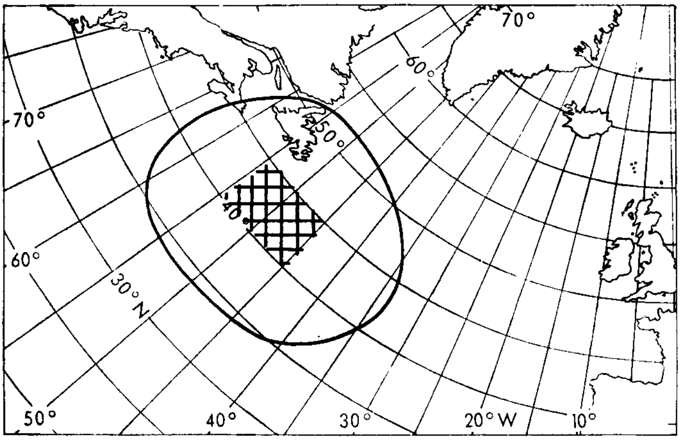


FIGURE 1—AREA OF OCEAN WARMER OR COLDER THAN USUAL FOR MAIN CLASSIFICATION TYPES WP5 (WARM CASE) AND CP5 (COLD CASE)

Displacements east and west of the main anomaly centres by up to 10° are defined as WPE or WPW for the warm cases and CPE or CPW for the cold cases.

or cold pool, anomaly exceeding 1 degC, covering much of this area the classification is WP5 for a warm pool centred near 50°W (Figure 1), WPE for warm pool displaced up to 10° eastwards (i.e. centred between 40 and 50°W), WPW for warm pool displaced up to 10° westwards (i.e. centred between 50 and 60°W) and three similar categories for cold pools, i.e. CP5, CPE and CPW. In the E and W cases particularly the warm and cold pools may extend beyond the eastern or western boundaries respectively of the area as defined. Some overlapping of the classification frequently occurs but this is not important in subsequent research work since similar types lead to similar results. In addition to the 6 main types defined so far, in some months other classifications are possible for a sufficiently large number of years to give a statistically useful sample. These are :

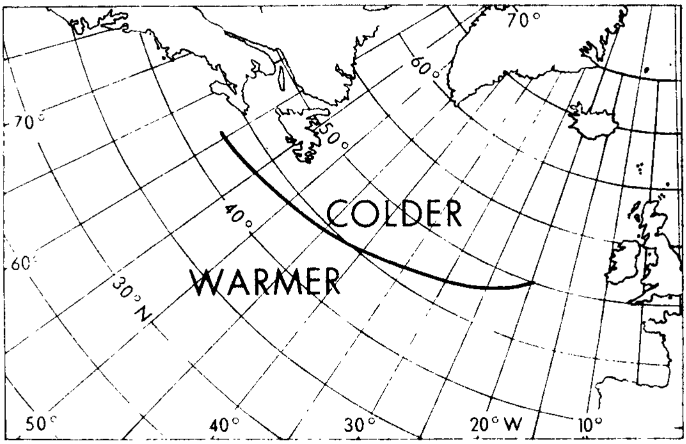
(i) *EZ or enhanced zonality.* In this class the ocean is colder than usual in the north-west Atlantic and warmer than usual in the southern and eastern part of the North Atlantic (Figure 2*(a)*). The line of enhanced sea surface temperature gradient is taken as approximately 40/45°N 60°W to 45°N 40°W to 50°N 20°W.

(ii) *DZ or decreased zonality.* In this case the ocean is warmer than usual in the north-west Atlantic and colder than usual in the southern and eastern part of the Atlantic with the decreased gradient of sea surface temperature approximately along the same line as for EZ (Figure 2*(b)*).

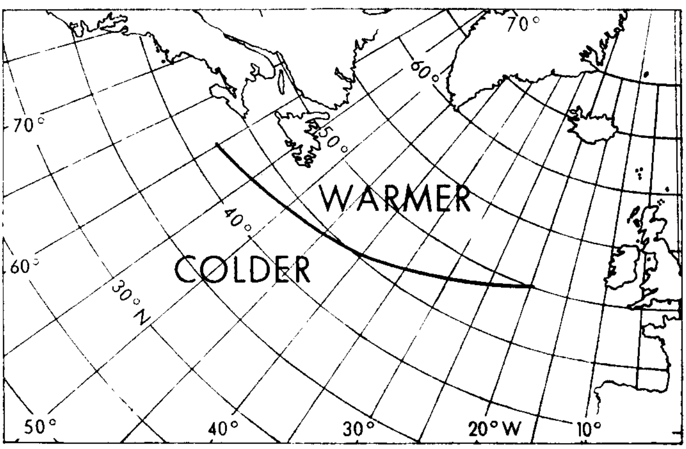
(iii) *MWW or meridional warm west.* When the ocean is warmer than usual in the west (west of about 30°W) and colder than usual east of 30°W including the North Sea and Biscay.

(iv) *MCW or meridional cold west.* When the ocean is colder than usual in the west (west of about 30°W) and warmer than usual east of 30°W including the North Sea and Biscay.

The last two types occur less frequently than any of the others. For some months several classifications are possible, for example DZ often occurs with CP and EZ with WP classification (but rarely vice versa). A blank in the catalogue normally means that the pattern was not sufficiently definite to be classified but occasionally, e.g. during the two world wars and prior to 1888, a blank is due to lack of data.



(*a*) Enhanced zonality EZ.



(*b*) Decreased zonality DZ.

FIGURE 2—AREA OF OCEAN WARMER OR COLDER THAN USUAL FOR EZ AND DZ CLASSIFICATION

Uses of the catalogue. The catalogue has been put to a number of uses, for example Ratcliffe and Murray[4] explained how it was possible to use sea surface temperature anomalies as an aid in predicting mean monthly pressure, temperature and rainfall anomalies a month ahead. Their work, which was based on an earlier edition of this catalogue, has since been considerably extended and revised. As a result mean pressure, temperature and rainfall anomalies in months following occurrences of each of the eight main sea temperature anomaly patterns (WP5, WPE, WPW, CP5, CPE, CPW, EZ, DZ) are now available for the British Isles and western Europe together with charts giving some idea of the statistical significance of the results. A further useful by-product of the catalogue has been the deduction of the mean duration of cold and warm patterns in the west Atlantic. If a run of warm or cold months is *not* considered broken by one unclassified month, then the mean duration of cold patterns (CP5, CPE, CPW taken together) is 4·4 months, while the mean duration for warm patterns (WP5, WPE, WPW taken together) is 4·3 months.

The catalogue has also enabled one to deduce the most likely months for the sea temperature anomaly pattern to change. Namias[5] has shown that in the North Pacific, patterns are most persistent during the period December–March and the catalogue results for the North Atlantic are similar.

The most likely period for starting or finishing a run of one particular type of pattern is autumn and spring. A change is most likely at those times on theoretical grounds if one considers that a shallow warm (or cold) layer at the top of the ocean in summer may persist for some months under suitable weather conditions but, once autumn storms begin, the water becomes mixed in greater depth so that an almost isothermal layer becomes established in the top 60 metres or so and when this happens the sign of the anomalies becomes more conservative. Similar arguments can be applied in reverse when the ocean thermocline is established in spring. The chance of a warm or cold pattern which exists in November lasting more or less unchanged over January is approximately 70 per cent while only about 15 per cent change to an opposite pattern; the remaining 15 per cent become indefinite. At the other end of the year approximately 75 per cent of warm or cold patterns existing in May last over July while only about 10 per cent change to the opposite pattern. These facts are important in deducing likely weather for the winter and summer seasons respectively.

February and August patterns (which are important for spring and autumn forecasting) rather surprisingly show at least equal persistence over two months (i.e. to April and October respectively). In each case warm and cold patterns persist on at least 75 per cent of occasions while rather less than 10 per cent change to the opposite type.

In the catalogue in Table I the meaning of the groups is as follows :

CP	CP5	cold anomaly exceeding 1 degC centred near 50°W
	CPE	cold anomaly exceeding 1 degC between 40° and 50°W
	CPW	cold anomaly exceeding 1 degC between 50° and 60°W
WP	WP5	warm anomaly exceeding 1 degC centred near 50°W
	WPE	warm anomaly exceeding 1 degC between 40° and 50°W
	WPW	warm anomaly exceeding 1 degC between 50° and 60°W
DZ		decreased zonality
EZ		enhanced zonality
MWW		meridional warm west, ocean warmer than usual west of about 30°W
MCW		meridional cold west, ocean colder than usual west of about 30°W.

TABLE I—CATALOGUE OF ANOMALY PATTERNS OF MONTHLY MEAN SEA SURFACE TEMPERATURE IN THE NORTH ATLANTIC 1877–1970

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
1877					CPW								1877
1878					CPW	CPW		CPW		DZ	CPW, DZ	CPW, CP5	1878
1879					WPE, WP5	CPW	CP5, CPE DZ	CPW, CP5	WPE		CP5		1879
1880				CP5	CP5	CPW	CPW		CPW, DZ		CPW, WPE		1880
1881													1881
1882						CPE							1882
1883				WP5			CP5, DZ		CPW, EZ				1883
1884			CP5				CPE						1884
1885													1885
1886			CP5	CPW, CP5	WPE, WP5, EZ	WP5	WP5, WPE	CP5	CPW	CPW			1886
1887		CP5	DZ–WP5	CPW, DZ	WPE		CP5	CP5, MCW	CP5		CP5, WPE		1887
1888	DZ	DZ	DZ, DZ–WP5, CPW–WP5	DZ	DZ, DZ–WPE	CP5, DZ, DZ–WP		CP5, DZ	CP5, DZ	DZ	CPE, CP5, CPW, DZ	CP5, DZ	1888
1889	DZ, CP5	CPW, CP5 DZ	DZ, DZ–WP5	CPE, DZ	WP5	WPW	WP5, WPE	DZ, MWW	WP5, DZ	WPE	WPE, WP5	WPW, WP5	1889
1890	CPW, CP5				EZ		WPE	WP5	WPE		CP5	CP5	1890
1891	CPW, CP5	DZ	CPW–WP5	WPE, DZ, DZ–WP	DZ, DZ–WPE	CP5, DZ, DZ–WP	CP5	CPW		CPE, CP5, EZ	CPE	DZ	1891
1892	WP5, MWW, WPE	WP5	WP5	WPE, DZ, DZ–WP	WPE, CPW, DZ, DZ–WPE	CPW, DZ, CP5	CPW, DZ	WPW, DZ		CPW, DZ	CP5, CPW, DZ	CPW, CP5, DZ	1892
1893	DZ	CPW, CP5, DZ	CP5, DZ, CPW	CPW, CP5, DZ	CP5, CPW, DZ, DZ–WPE	CPW, DZ, CP5	CP5, CPW, DZ	CPW, MCW	CPW, CP5, DZ	CP5, DZ	DZ	CPE	1893
1894	CPE	CPE	CPE			CPE		CPW	CPE, CP5, DZ	CPE	CPE, CP5	CPW, CP5	1894
1895	CPW, DZ, CP5			CPW, CPE, DZ	CPE	CPE	CP5, DZ	CPE, CP5	CPE, CP5, DZ	CPE, CP5	CPE	DZ	1895
1896	CPW, DZ, CP5		CPW, CPW–WP5	CP5	CP5, CPW	CPW	CPW	CPW, EZ		WPW	DZ	CP5, DZ	1896
1897				WP5			CPE	CPE	CPW, CPE, DZ	CP5, CPW, DZ	CPE, CP5, DZ	CP5, CPE	1897
1898	CPW, CP5				WPE		WPE	WPE, WP5		CPE		WP5	1898
1899	DZ	CPW, CP5	DZ, CPW–WP5, DZ–WP5	CPW, WPE	WPE, CPW, DZ, DZ–WPE	DZ	CP5	CPW, MCW	CPW, CP5	CP5, CPW, DZ		DZ	1899
1900		DZ	DZ	DZ	DZ	CPE, DZ, DZ–WP	CPE, DZ	CPE	CPE	EZ	EZ	CPW, EZ	1900
1901						WPW		WPW				WPE	1901
1902	WP5, MWW	WP5, WPE	DZ	DZ	DZ, DZ–WPE	CPW, CP5, DZ, DZ–WP	CPW, DZ	CPE, DZ	CPE, DZ	CPE, DZ	CPE	CPE	1902
1903	CPE	CPE	CPE	CPE	CPE	CP5, CPE	CPE	CPE, DZ	CPE, DZ	CPE, CPW, DZ	CPE, DZ		1903
1904	CPE		CPE	CPE	CPE	CPE	CPE	CPE	CPE		CPW	CPW, CPE	1904

N.B. Groups separated by a 'dash' are hybrids with characteristics of both types.

TABLE I—*continued*

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
1905	CPE		CPE, CPW		CPE	CPE	CPE	CPE	CPW	CPW, EZ	CPW	EZ	1905
1906	MWW		WP5					CPE				CPW	1906
1907		EZ	WP5, EZ	EZ				CP5	EZ	CPW, EZ	EZ	EZ	1907
1908			CP5	CPE		EZ, WPW	WPE			CPE	CPE	EZ	1908
1909				CP5	CP5	CP5			WPE	WP5	WPE	WP5, WPE	1909
1910	WP5, MWW	WP5		WP5	WP5						WP5	DZ	1910
1911							DZ	WP5			EZ		1911
1912	CPE	CPE	CPE	CPE	CPE, DZ	CPE	CPE	CPE, DZ				CPE	1912
1913	CPE	CPE	CPE	CPE	CPE, EZ		EZ			WP5, WPW			1913
1914		CPE	CPE		EZ	EZ	EZ	EZ	CPE, CP5, EZ	CPE, CP5, EZ	CPE, CP5		1914
1915	WP5, WPE	WPW	WP5, WPW		EZ		CP5	CP5, MCW	CP5	CPE			1915
1916			EZ, CPW	WP5, EZ	WP5, EZ		WPE					CP5	1916
1917				CPW	CPW, DZ	CPW		CPW					1917
1918													1918
1919		WP5	WP5, CPW–WP5	WP5			WPE	WPE				CPE	1919
1920			EZ	EZ	CPW	EZ	EZ	WP5, EZ		CPE	CPE	CPE	1920
1921			WPW	CPE, EZ	EZ	EZ		CPW, CP5	CP5, EZ	CP5, EZ	CP5	CP5	1921
1922		EZ	EZ	EZ	EZ	WP5, EZ	WP5, EZ	WP5, EZ	WP5	CP5	CP5, CPW, DZ		1922
1923		CP5, EZ	EZ	WP5, EZ	WPE, CPW	EZ		EZ	WPE, EZ	WPE	WPE, WP5	WPW	1923
1924	WP5, MWW, WPE	WP5	WP5, CPW–WP5	WP5	CPW, DZ			WP5, MWW	WPE, WP5	CPW, WPE		CPE	1924
1925	WPW	WP5	WP5, EZ, WPW	WP5, EZ	EZ	WP5, EZ	EZ	WPE, WP5, MWW	WPE	CPW	CP5		1925
1926	DZ, CP5, CPW	CPW, CP5	CP5, CPW	WPW, CPE, CP5	CP5, DZ	CPW	CPE	CPE, MCW	CPW	WP5	WPE, WP5	WP5, WPE	1926
1927	WP5, MWW, WPW	WP5					WP5	WP5, MWW	WPE			WPW	1927
1928		EZ, WPE	EZ	CPW	CPW, DZ		WP5	CPE	WP5				1928
1929	CP5	CP5	CP5, WPW		CPE	CPE, WPW		WPE	WPE, WP5, EZ	WP5, WPW	EZ	EZ	1929
1930		EZ	EZ			WP5, WPW, EZ	WP5	WPE	WP5	WP5	WPW	WPE	1930
1931	WP5, MWW, WPE	WP5, EZ, WPE	WP5	WPE, WP5	WP5	WP5		WPE	WPE, DZ	WPE, WPW		CPE	1931
1932				WPE				WPE, WP5	WPE, WP5	WPE	WPW	WPW, WPE	1932
1933	WPW	WPE	WPW	DZ	WPE, WP5					WP5			1933
1934			EZ	EZ		WPW		WPW	WP5	WP5, WPW	WP5		1934
1935		CP5, EZ	EZ	CPW, CP5, DZ	DZ–WPE	WP5	WP5	WP5	WPE	WPE, WP5, EZ	WP5	WPW, WP5	1935
1936	WPE	DZ, CPW, WPE		CPW, DZ–WP		WP5	WPE	WPE	CPW, WPE			WPW, EZ	1936
1937		WPW			WP5, EZ	WP5	WPE	WPW, WP5	WP5	WPE, EZ		WPW	1937
1938					WP5	WP5, WPW	WP5	WP5	WPE, WP5	WPE			1938
1939			WP5	CP5	CP5, CPW	EZ	CP5	CP5		WP5	CPW, WPE	DZ	1939
1940			CP5	CPW, CP5			WPE						1940
1941			CP5, DZ										1941

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
1942													1942
1943					CPE	CP5		CP5					1943
1944										WPE			1944
1945											CPE		1945
1946		CP5	WPW	CP5		EZ	EZ	WP5	WP5	WPW, DZ	CPE, WPW, DZ	CPE, WPW	1946
1947	DZ, CPE, CP5	CPE, WPW	WPW	CPE	CPE	CPW, CPE	CPE	CPE, WPW	CPE			CPE	1947
1948	DZ	CPW, CP5		CPW, CP5, EZ	WP5, CPE	CPW	CP5		CPW, EZ	CPE	CPE	CPE	1948
1949		WPW	WPW			CPE	CPE	CP5, WPW			WPW, EZ	WPW	1949
1950	WPE	EZ			CP5	EZ	CPE	WP5, EZ	WPE	WPE, WPW, EZ	WPW	WPW, WP5	1950
1951	WP5, WPW	WP5, WPW, WPE	WP5, WPW	WPE, WP5	WPE, WP5	DZ, WPW, DZ–WP	WP5	WPW		WPW, EZ	WP5, WPW	WPW, WP5	1951
1952	WP5, WPW	WP5, WPW	WP5, WPW	WPE, WP5	WPE	WP5	WP5, WPE	WP5, MWW	CP5	WPE, DZ		DZ	1952
1953	DZ, WPW	DZ		DZ, DZ–WP	WP5, DZ, DZ–WPE	EZ	WP5, EZ	EZ	CPE		WPW, EZ	WPW, DZ	1953
1954	DZ, WPW	WP5, WPW	WPW		WP5		WP5, WPE	WPE, MWW	CPW, WPE EZ	EZ	EZ	WPW, WP5, WPE	1954
1955	WP5, WPW	DZ	WP5, DZ–WP5		CP5, CPE, DZ		CP5	EZ, MCW	EZ	EZ		CPW, DZ	1955
1956	DZ	DZ	DZ–WP5			CPW, EZ	CPW	CP5				EZ	1956
1957		CP5	WPW	CPW, CP5	CP5	CP5	CP5		WPE	CP5, CPW		WPW, WP5	1957
1958	WP5	DZ	WP5	WP5, DZ–WP	WP5, DZ, DZ–WPE	DZ, DZ–WP	CPE, DZ	CPE, DZ	CPE, DZ	CP5, CPW, DZ		CPW, DZ	1958
1959	CPW, CP5, DZ	CPW, CP5	CPE	CPW, CP5	CP5, CPW	CP5, CPE	CPE		CPE	CPE, WPW	EZ	WPW	1959
1960				CPE		WP5		WPW, WP5, MWW	WP5	WP5, WPW	WP5	WP5	1960
1961		CPW, CP5, EZ	EZ	CPW	CPW			WPW, EZ	WP5	WPW	WPW	WPE	1961
1962	WPE		CPW–WP5, CPW	CPW, WPE	WPE, CPW	CPE	CP5		CPE			WP5	1962
1963		CPE, WPW	CP5, CPE, DZ, CPW		CP5, CPW	CP5		EZ		WPW, EZ	WPW	WPW	1963
1964	DZ	CPW, CP5, DZ	CPE, DZ, CPW, DZ, WP5		CPE				CPE	WPW	WPW	WPW	1964
1965	CPW, DZ		CPW	DZ, DZ–WP		CPE, DZ				WP5	WP5	WP5	1965
1966	CPE, DZ	CPE, DZ	CPE	DZ, DZ–WP	CPE	DZ, DZ–WP	CPW	DZ		CPE, WP5	WP5, DZ	WP5	1966
1967	WPE	WP5, WPE		WPE, EZ	CPW			WP5, EZ, MWW	WP5, EZ	WPE, WP5	EZ	CPW, WPE	1967
1968	CPW					CP5, CPE	CPE, DZ	CPE, MCW	CPE	CPE, WPW, DZ	CPE, DZ	WPW, WP5, EZ	1968
1969		DZ, WPW	CPW–WP5		CP5	DZ, DZ–WP	CP5, CPW, CPE	CPE			WP5	WP5	1969
1970	WP5	WP5	WP5	DZ, CPW, DZ–WP	CPE		CPE	WPW	WPE		WP5, WPW	WP5	1970

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THE EFFECT OF CLOUD ON SOLAR RADIATION RECEIPT AT THE TROPICAL OCEAN SURFACE

By D. E. PARKER

Summary. Statistical relationships between hourly amounts of total solar radiation and solar elevation at Gan are derived for various states of sky over the island. The investigation begins by making use of cloud observations made from the surface. This treatment is followed by a similiar examination involving cloud data obtained by means of satellites.

Notation.

a	Estimate of the y-axis intercept of a regression line.
b	Estimate of the gradient of a regression line.
C_L, C_M, C_H	The fractional covers of low, medium, and high cloud, according to standard synoptic observations made from the surface.
c_l, c_m, c_h	The actual fractional covers of low, medium, and high cloud.
f	The fraction of solar radiation transmitted by the atmosphere in unspecified conditions.
f'	The fraction of solar radiation transmitted by the atmosphere in cloudless conditions.
N	The fractional cloud cover, according to standard synoptic observations made from the surface.
N_D	Number of data pairs.
Q	The total solar radiation incident on unit area of a horizontal surface at sea level, in the local apparent time (LAT) hour during which the relevant local standard time (LST) cloud observation was made from the surface.
Q_A	The total solar radiation incident on unit area of a surface at the top of the atmosphere and normal to the direction of propagation, during the period of receipt of Q.
r	Correlation coefficient.
s	The mean of the sines of the solar elevation at the beginning and end of the period of receipt of Q.
σ_a, σ_b	Estimates of the standard errors of a, b.

Introduction. This investigation was an extension of work done by Lumb[1] on the influence of cloud on hourly amounts of total solar radiation at the ocean surface in temperate latitudes. Lumb classified the synoptic cloud observations made from the ocean surface and then studied the linear regression of $Q/(Q_A s)$ on s for each category. Because Lumb's classification of cloud types was inappropriate for the tropics, another set of cloud categories for observations from the surface was devised for the present work (Appendix I). This set was so designed that any cloud observation could be fitted into one, but only one, category. The first part of this study consisted of performing linear regression of $Q/(Q_A s)$ on s for each of these categories, comparing the results for the different categories, and making a comparison both with Lumb's results and with figures suggested by Gadd and Keers.[2]

It would be very useful to be able to infer surface radiation from satellite nephanalyses. For this reason the second part of this investigation made use of cloud categories based on satellite observations. These categories (Appendix II) were much broader than those for observations from the surface because of the relatively low resolution of satellite photography. The results of the linear regressions of $Q/(Q_A s)$ on s for these categories were used to make an estimate of the average vertical fractional transmission of solar radiation by the tropical atmosphere.

Data.

(i) *The observing station.* Gan (00° 41′S, 73° 09′E) is an island of area about one square mile on the Addu Atoll in the Indian Ocean. No part of Gan is more than 10 feet (3 m) above sea level, and observations from the island have been assumed to be representative of oceanic conditions.

(ii) *Cloud data.* Cloud observations made from the surface at Gan shortly before the hour (LST), and recorded in the standard synoptic code, were extracted and categorized.

Daily satellite nephanalyses for 1967, covering the tropics between 30°N and 30°S from 15°W via 0°E to 165°E, had previously been prepared by Dent, Parker, and Preedy for research purposes. They were similar to operational nephanalyses but contained rather more detail. Estimates of conditions over Gan were extracted and categorized. The passage of the satellite over Gan was generally about an hour after local noon.

(iii) *Solar radiation.* Solar radiation at Gan was measured by means of a Kipp solarimeter. When the data-logging equipment was working perfectly there were 60 readings of radiation intensity in each hour. Initially, the data used were restricted to hourly totals in 1967 evaluated from at least 50 readings. To obtain reliable regression lines for the less-common surface-observed cloud categories it was necessary to include some 1968 and 1969 data and to relax the requirement from 50 to 30 readings per hour. All the hourly solar radiation totals were for integral LAT hours.

(iv) *Solar elevation.* Solar elevation data for 1967 were supplied with the solar radiation data, in the form of values of s as defined above. Corresponding data for 1968 and 1969 were extracted from astronomical tables.

(v) *The solar constant.* The solar constant was taken to be 135 mW/cm^2.

Results — Part I. The results of the linear regressions of $Q/(Q_A s)$ on s for the 12 cloud categories for observations from the surface are given in Table I. The regressions take the form $Q/(Q_A s) = a + bs$.

The value of $Q/(Q_A s)$ is given by $(a + b)$ when $s = 1$, i.e. when the sun is at the zenith. Hence it is a direct measure of the short-wave radiation transmission of the atmosphere. The values of $(a + b)$ relate in a well-ordered fashion to the cloud categories. The discrepancy in $(a + b)$ for category C was caused by the use of more than two decimal places in the calculations.

TABLE I—RESULTS OF LINEAR REGRESSIONS OF $Q/(Q_A s)$ ON s FOR THE 12 CLOUD CATEGORIES FOR OBSERVATIONS FROM THE SURFACE AT GAN

Cloud category	N_D	a	b	σ_a	σ_b	$(a+b)$	r
A	37	0·57	0·24	0·03	0·05	0·81	0·67
B	21	0·45	0·35	0·05	0·08	0·80	0·73
C	31	0·52	0·22	0·05	0·08	0·73	0·47
D	45	0·49	0·28	0·05	0·06	0·77	0·57
E	33	0·60	0·08	0·04	0·07	0·68	0·22
F	21	0·35	0·35	0·08	0·11	0·70	0·59
G	88	0·46	0·21	0·04	0·06	0·67	0·37
H	80	0·40	0·21	0·04	0·06	0·61	0·37
I	89	0·26	0·19	0·04	0·07	0·45	0·29
J	24	0·38	0·07	0·12	0·17	0·45	0·09
K	37	0·18	−0·03	0·03	0·05	0·15	−0·11
L	12	0·03	0·00	0·02	0·04	0·03	−0·01

When s becomes small, a becomes the dominant term in $(a + bs)$. If a is to be large there must be good transmission when the solar elevation is low. This requires that the absorption should be low and also that only a small proportion of incident solar radiation be reflected. If b is to be large the absorption should be low.

All the results in Table I suffer from statistical scatter. The values of r, the coefficient of correlation between $Q/(Q_A s)$ and s, are included in Table I. These values are significantly different from zero at the 0·1 per cent level for categories *A*, *B*, *D* and *G*, and at the 1 per cent level for categories *C*, *F*, *H* and *I*; but they are not significantly different from zero even at the 5 per cent level for the remaining categories.

Graphs of the linear regression of $Q/(Q_A s)$ on s for cloud categories *A* and *K* are shown in Figures 1 and 2. The grouping of data with respect to s arose because the observations were at fixed hours and the seasonal change of solar elevation at Gan was slight, especially at times of day when the elevation was low. The scatter in all the results was probably caused by the multiplicity of conditions that could be included in the same cloud category. An additional cause may well have been changes of category during the hour.

The correlation between a and b, as calculated from the 12 pairs of values of a and b in Table I, was 0·52. This value is not quite significantly different from zero at the 5 per cent level. A significant positive correlation would indicate that clouds which only weakly absorb insolation also only weakly reflect it.

The frequencies of occurrence of each cloud category at various times of day in 1967 were calculated (Appendix III). The total frequencies were used to calculate a weighted mean of $(a + b)$ for Gan for 1967. This weighted mean was 0·64, the weighted means of a and b being 0·44 and 0·20 respectively. Note, however, that the frequencies of the cloud categories varied with the time of day, and hence with s. In particular categories *D* and *G*, which refer to strongly convective situations, were more common at 14 LST than at 08 LST.

Some non-linear regressions of $Q/(Q_A s)$ on s were performed for each category but yielded nothing of great value.

Discussion of Part I results. Comparison of the above results with those of Lumb is difficult because the cloud categories used are different from those used by Lumb. Generally, however, the values of $(a + b)$ obtained

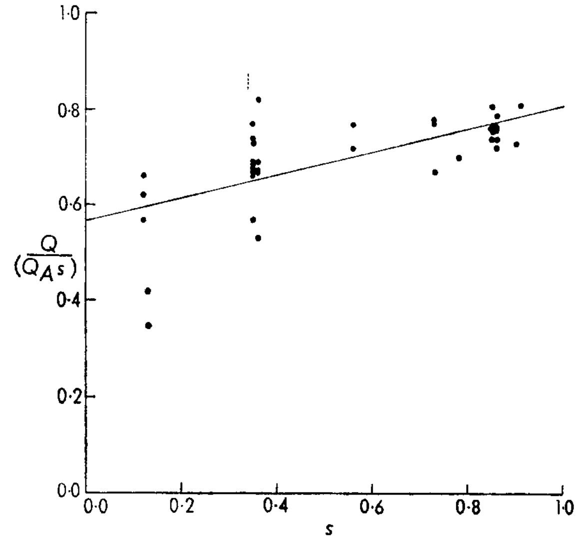

FIGURE 1—LINEAR REGRESSION OF $Q/(Q_As)$ ON s FOR CLOUD CATEGORY A

The straight line is given by $Q/(Q_As) = 0{\cdot}57 + 0{\cdot}24s$.

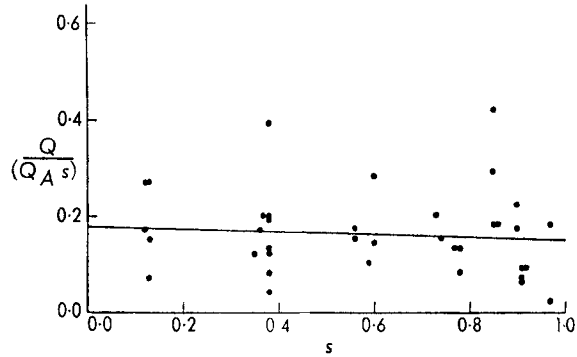

FIGURE 2—LINEAR REGRESSION OF $Q/(Q_As)$ ON s FOR CLOUD CATEGORY K

The straight line is given by $Q/(Q_As) = 0{\cdot}18 - 0{\cdot}03s$.

here are similar to those found by Lumb for similar conditions. However there is a tendency for the values of a to be higher and the values of b lower than Lumb's for similar states of sky.

The significance levels of the values of r in Table I are not all that could be desired; nevertheless they are on the whole higher than those obtained by Norris,[3] who repeated Lumb's method using Melbourne data and found the method totally unreliable as a means of predicting hourly insolation totals.

Gadd and Keers proposed an expression

$$f = f' \ (1 - 0{\cdot}4c_h) \ (1 - 0{\cdot}7c_m) \ (1 - 0{\cdot}7c_l),$$

where $f' = 0{\cdot}6 + 0{\cdot}2s$; f is equivalent to Q/Q_As, and the expression predicts $(a + b) = 0{\cdot}8 \ (1 - 0{\cdot}4c_h) \ (1 - 0{\cdot}7c_m) \ (1 - 0{\cdot}7c_l)$. Note that the fractional covers of high, medium, and low cloud are actual ones and not those which would be synoptically reported : they are inferred from humidities in the model discussed by Gadd and Keers. Assuming appropriate values of c_h, c_m, and c_l, values of $(a + b)$ for each cloud category have been predicted from the above expression and compared with the estimated values (Table II). In most cases the predicted values of $(a + b)$ are much lower than the estimated ones. This discrepancy is partly due to the fact that Gadd and Keers chose f' to be equal to the expression for f obtained by Lumb for his category 1, thus assuming that c_h, c_m, and c_l were all zero for this category. If, as assumed for the very similar category A in Table II, $c_h = c_l = 0{\cdot}1$ and $c_m = 0$ for Lumb's category 1, then $f = 0{\cdot}89f'$ for this category, assuming the above expression for f, and Gadd and Keers's value of f' is about 10 per cent too low.

TABLE II—COMPARISON OF ESTIMATED VALUES OF $(a + b)$ WITH PREDICTED VALUES

Values predicted by the expressions :

$$f = (0{\cdot}6 + 0{\cdot}2s)\ (1 - 0{\cdot}4c_h)\ (1 - 0{\cdot}7c_m))\ (1 - 0{\cdot}7c_l)$$

and $$(a + b) = 0{\cdot}9\ (1 - 0{\cdot}2c_h)\ (1 - 0{\cdot}4c_m)\ (1 - 0{\cdot}4c_l)$$

Cloud category	Assumed c_h	c_m	c_l	$(a + b)$ as predicted by 1st expression	$(a + b)$ as predicted by 2nd expression	Estimated $(a + b)$
A	0·1	0·0	0·1	0·71	0·85	0·81
B	0·3	0·1	0·1	0·61	0·77	0·80
C	0·3	0·1	0·4	0·47	0·67	0·73
D	0·3	0·1	0·4	0·47	0·67	0·77
E	0·7	0·1	0·1	0·50	0·71	0·68
F	0·7	0·1	0·4	0·38	0·62	0·70
G	0·7	0·1	0·4	0·38	0·62	0·67
H	0·5	0·4	0·3	0·36	0·60	0·61
I	0·5	0·7	0·3	0·26	0·51	0·45
J	0·5	0·5	0·7	0·22	0·47	0·45
K	0·9	1·0	0·7	0·08	0·31	0·15
L	0·9	0·9	1·0	0·07	0·28	0·03

The values of $(a + b)$ obtained in this investigation are well approximated by the expression $0{\cdot}9\ (1 - 0{\cdot}2c_h)\ (1 - 0{\cdot}4c_m)\ (1 - 0{\cdot}4c_l)$, with the exception of the values of $(a + b)$ for categories K and L for which this expression gives values which are too high. This may be because a complete cloud cover over Gan is usually associated with intense systems giving very thick cloud and consequently severe depletion of solar radiation; categories K and L indicate over 80 per cent and over 95 per cent respectively for insolation depletion by the cloud cover, although with statistical scatter. Although category K permits broken low cloud below the medium-cloud overcast, these values contrast with figures of 50 to 60 per cent for medium-cloud overcasts and 65 to over 80 per cent for low-cloud overcasts given by Haurwitz[4] who used data for Blue Hill near Boston, Massachusetts, U.S.A.

Allowing for the possible presence of higher cloud above the overcasts, Haurwitz's figures would together indicate coefficients of about 0·5 for c_m and about 0·6 for c_l in the latter expression. The coefficient of 0·2 for c_h, however, agrees with Haurwitz's estimate of 20 per cent depletion of insolation by high-cloud overcasts. Haurwitz's investigation referred to here was restricted to cases where there was a complete overcast of a given cloud type.

The results of Mooley and Raghavan[5] who studied insolation at Madras under various overcasts, mainly of high cloud, would indicate a coefficient nearer 0·3 for c_h. However, Raman[6] in his study of data for Poona, found depletion of insolation by thick cirrostratus overcasts to be about 20 per cent and by thin ones about 10 per cent. Raman also gave figures of 30 to 60 per cent for medium-cloud overcasts and 75 to 85 per cent for thick overcasts of very low cloud.

The values of $(a + b)$ predicted by the expression $(a + b) = 0{\cdot}9\ (1 - 0{\cdot}2c_h)\ (1 - 0{\cdot}4c_m)\ (1 - 0{\cdot}4c_l)$ are included in Table II.

Results — Part II. The results of the linear regressions of $Q/(Q_A s)$ on s for the four cloud categories based on satellite observations are shown in Table III, which is analogous to Table I. The cloud category for a given day was regarded as valid for all hourly measurements of Q during that day.

TABLE III—RESULTS OF LINEAR REGRESSIONS OF $Q/(Q_A s)$ ON s FOR THE FOUR CLOUD CATEGORIES FOR OBSERVATIONS FROM SATELLITES

Cloud category	N_D	a	b	σ_a	σ_b	$(a + b)$	r
1	81	0·33	0·37	0·05	0·07	0·71	0·53
2	79	0·52	0·17	0·04	0·06	0·69	0·31
3	56	0·35	0·18	0·06	0·10	0·53	0·24
4	86	0·23	0·06	0·06	0·08	0·29	0·09

The results in Table III all show considerable scatter. The values of r for categories 1 and 2 are significantly different from zero at the 0·1 per cent level and the 1 per cent level respectively; but those for categories 3 and 4 are not significantly different from zero even at the 5 per cent level. A graph of the linear regression of $Q/(Q_A s)$ on s for category 1 is shown in Figure 3. The scatter in all these results was probably caused both by the multiplicity of conditions that could be included in one cloud category and by changes of category during the course of a day. The four sets of results were based on 11, 10, 7 and 12 days' satellite data respectively.

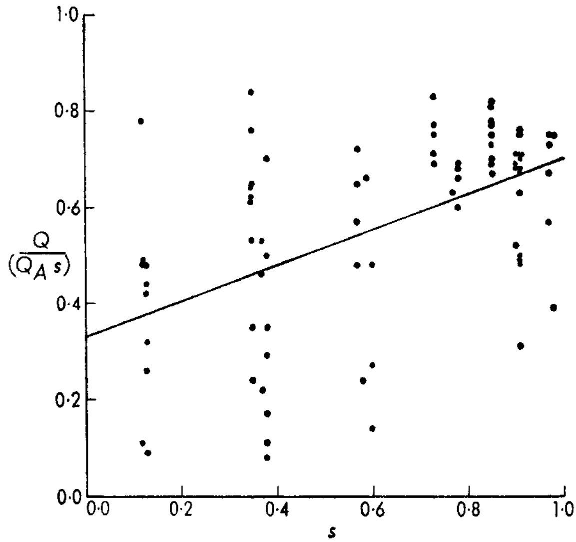

FIGURE 3—LINEAR REGRESSION OF $Q/(Q_A s)$ ON s FOR CLOUD CATEGORY 1

The straight line is given by $Q/(Q_A s) = 0{\cdot}33 + 0{\cdot}37s$.

In the cases of categories 1, 3, and 4, Gan was usually near a category boundary. This probably made the estimate of $(a + b)$ too low for category 1 and too high for categories 3 and 4.

The four categories were allotted to Gan for 118, 131, 43, and 73 days of 1967 respectively, resulting in weighted means for Gan of 0·60 for $(a + b)$, 0·38 for a and 0·22 for b.

Each one-degree square in the area 30°N to 30°S, 15°W via 0°E to 165°E was assigned one of the four categories for each day of 1967. The mean proportions of the total number of squares allotted to the respective categories were 42·5, 22·8, 18·5, and 16·2 per cent. Applying the values of $(a + b)$ in Table III and neglecting variations of square size with latitude resulted in estimates of weighted means for the whole area of 0·60 for $(a + b)$, 0·36 for a and 0·24 for b.

The weighted mean values of a and b for Gan obtained by means of satellite cloud data (0·38 and 0·22) are very similar to those obtained by means of standard synoptic cloud data (0·44 and 0·20). This established the general reliability and usefulness of the satellite method.

The weighted means from satellite data of a and b for Gan and for the large area of the tropics are also very similar. This is in spite of a distribution of categories at Gan considerably different from the mean distribution: the differences cancel out.

The weighted mean from satellite data of $(a + b)$ for the large area of the tropics indicates that the tropical atmosphere transmits about 60 per cent of vertically incident solar radiation. When it is considered that the transmission will be less than this for solar radiation not vertically incident, this figure can be seen to indicate a lower level of insolation in the tropics than the 64 per cent implied by Vonder Haar and Hanson.[7] However, the figures given by these authors were for the zone 0°N to 20°N around the globe, whereas the figure given here refers to the zone 30°N to 30°S around only half the globe.

Conclusions. It is evidently impossible to predict individual hourly radiation totals at a given point at the tropical ocean surface either from synoptic cloud observations made from the surface, or from satellite cloud photographs, at least without narrowing the cloud categories considerably from their width in this investigation. The scatter was considerable in all the results obtained.

However, given sufficient data it would be possible to estimate a and b for each cloud category more precisely than has been done here; as a result, the mean radiative conditions for a given cloud category and a given value of s would be more accurately known. In particular, it would be possible to determine with considerable precision the total solar radiation receipt at the tropical ocean surface over a large area in a given hour by means of the satellite photographs. The uncertainty in the present work of the estimates of a and b is highlighted by the values of σ_a and σ_b in Tables I and III.

Increased precision in the estimation of the spatial weighted means of a and b by means of satellite photographs would be of value to albedo determinations. Latitudinal variations of a and b for a given category would have to be taken into account in such a project. This would require the relation of radiation measurements at the ocean surface to satellite observations at perhaps 10-degree latitude intervals, and similar work for continental and high-altitude surface radiation measurements.

If the relationships in all latitudes of a and b to cloud amounts at specific levels were investigated further, improved results might be obtained from empirical radiation schemes in general circulation models. Such an investigation might also improve the representation in these models of the role of the tropics in the general circulation of the atmosphere.

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Appendix I

Cloud categories for observations from the surface.

Category	Synoptic code description	Visual description
A	$C_L \leqslant 1$ okta. $N \leqslant 2$ oktas	Clear or virtually clear sky
B	$C_L \leqslant 1$ okta. $N \geqslant 3$ oktas Either $C_M \leqslant 2$ oktas or no C_M in 8-group Either $C_H \leqslant 3$ oktas or no C_H in 8-group	Little or no low cloud but small to medium amounts either of medium cloud or of high cloud or of both.
C	$C_L = 2$ to 4 oktas C_L not of type 2, 3, or 9 No C_M in 8-group Either $C_H = 3$ oktas or no C_H in 8-group	Small to medium amounts of low cloud with little vertical development. Either no medium or high cloud, or small to medium amounts either of medium cloud or of high cloud or of both.
D	$C_L = 2$ to 4 oktas C_L of type 2, 3, or 9 No C_M in 8-group Either $C_H = 3$ oktas or no C_H in 8-group	Small to medium amounts of low cloud with moderate or strong vertical development. Medium and high clouds as in *C*.
E	$C_L \leqslant 1$ okta Either $C_M \leqslant 2$ oktas or no C_M in 8-group $C_H \geqslant 4$ oktas	Little or no low cloud. Either no medium cloud or small to medium amounts of medium cloud. Sky at least half covered with high cloud.

F	$C_L = 2$ to 4 oktas C_L not of type 2, 3 or 9 No C_M in 8-group $C_H \geqslant 4$ oktas	Small to medium amounts of low cloud with little vertical development. Medium and high clouds as in *E*.
G	$C_L = 2$ to 4 oktas C_L of type 2, 3 or 9 No C_M in 8-group $C_H \geqslant 4$ oktas	Small to medium amounts of low cloud with moderate or strong vertical development. Medium and high clouds a sin *E*.
H	$C_L = 0$ to 4 oktas $C_M = 3$ or 4 oktas	Sky up to half covered with low cloud and half or nearly half covered with medium cloud.
I	$C_L = 0$ to 4 oktas $C_M = 5$ to 7 oktas	Sky up to half covered with low cloud and largely covered with medium cloud.
J	$C_L = 5$ to 7 oktas $C_M \neq 8$ oktas	Sky mostly covered with low cloud, without a complete overcast of medium cloud.
K	$C_M = 8$ oktas	Complete overcast of medium cloud not completely obscured by low cloud.
L	$C_L = 8$ oktas	Sky completely covered with low cloud.

Appendix II

Cloud categories for observations from satellites.

Category	Estimated fractional cloud cover *per cent*
1	< 20
2	20 to 50
3	50 to 80
4	> 80

Appendix III

Frequencies of the cloud categories for observations from the surface for Gan during 1967.

Cloud category	08 LST	11 LST	14 LST	17 LST	Total
A	40	42	32	35	149
B	15	15	15	22	67
C	10	10	8	9	37
D	48	65	82	52	247
E	59	52	36	43	190
F	6	3	3	3	15
G	57	66	76	78	277
H	39	36	44	46	165
I	55	43	34	47	179
J	15	16	12	11	54
K	16	13	21	18	68
L	5	4	2	1	12

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ON THE PERFORMANCE OF VARIOUS TYPES OF RAIN-GAUGE IN THE FIELD

By L. S. CLARKSON

Summary. An array of rain-gauges of various types was set up at Easthampstead to include standard Mark 2 copper gauges and a range of the newer glass-fibre laminate or plastic gauges. Rainfall was recorded from June 1969 to September 1970. The total collection from each gauge was expressed as a percentage of a standard, and an estimate was made of the variability of catch for monthly and daily rainfall.

The overall characteristics of the copper rain-gauges and the newer types were very similar but the newer types collected more condensation (dew or hoar-frost). The 750-cm^2 gauge with rim at 30 cm collected more than one with rim at 45 cm which gave a catch comparable to that of a Mk 2 gauge at 30 cm. The Mk 2 gauge at 30 cm collected less than a Mk 2 with rim flush with an anti-splash surround. Two apparently identical versions of a commercially available gauge collected different amounts, probably because of a change in the slope of the exterior bevel below the edge of the rim. The field-calibrated 750-cm^2 tipping-bucket rain-gauges at Easthampstead, Filton, Glasgow Airport and Turnhouse collected overall about the same as or rather more than the Mk 2 standard rain-gauge.

Introduction. An ideal rain-gauge intercepts and collects all the liquid precipitation which would otherwise have fallen on the ground. In a practical, well-designed and well-exposed instrument, errors due to splash-in, splash-out and evaporation are made negligible. The remaining error is mainly an indirect result of turbulent wind flow over and within the collecting funnel of the gauge. This causes loss of catch because some of the raindrops which fall into the zone of turbulence immediately above the gauge are diverted over and out of the funnel. Such errors are a complex function of the wind speed at rain-gauge height, the raindrop size distribution and the shape of the above-ground part of the rain-gauge. On a perfectly uniform site, with surrounding trees, buildings, etc., located at a distance of more than about four times their height, it would not be expected that, for cumulative rainfall totals over reasonably long periods, there would be any difference between the true cumulative point rainfalls at different positions on such a site. However, when identical standard rain-gauges are exposed at different positions on a 'normal' site, their cumulative readings are found to be slightly but systematically different. These differences are considered to be due to small differences in the mean wind speed (during the precipitation) over the rims of the rain-gauges, brought about by small irregularities of exposure from one position to another on the normal site. Few normal sites are perfectly uniform all over — there are usually irregularities in the height of the ground; furthermore, some parts of a practical site may be slightly, but persistently, less sheltered from the mean wind prevailing during rainfall than other parts of the same site. Such site effects must be determined and taken into account when the performances of different types of rain-gauges positioned on the site are compared.

The site. On a site covering an area of approximately 100 ft by 30 ft (30 m × 9 m) at Easthampstead, Berkshire, an array of rain-gauges of various types has been set up. The site slopes downwards slightly from the north-east to the south-west, the height difference being about 1 ft; there are also minor undulations of a few inches between the gauges. The nearest building is 60 ft to the north-west, having a distance to height ratio of 5. The site is neither well sheltered nor unduly over-exposed, and is typical of the sort of location that in practice might be chosen for installing a standard rain-gauge for obtaining climatological rainfall data.

The rain-gauges. Standard 5-inch copper Mk 2 rain-gauges were installed with their rims at 30 cm above the ground at positions P9, P1, P4, P13, S1 and S2 as shown in Figure 1. The flush gauge marked in Figure 1 consisted of nine 5-inch Mk 2 gauges in a pit with a 'venetian-blind' type anti-splash surround. Two glass-fibre laminate 750-cm^2 collectors with their rims at 30 cm and at 45 cm were mounted at positions P2 and P6 respectively, whilst similar collectors with their rims at 45 cm, and fitted with tipping buckets and counters were installed at positions P5 and P12. Three 150-cm^2 glass-fibre conical collectors were mounted with their rims at 30 cm; that at P7 was straight-sided (SS), whilst those at P10 and P11 were slightly modified versions of this (SM). At P8 was a commercially available 150-cm^2 plastic collecting funnel (C). Photographs of some of these various rain-gauge collectors are available.

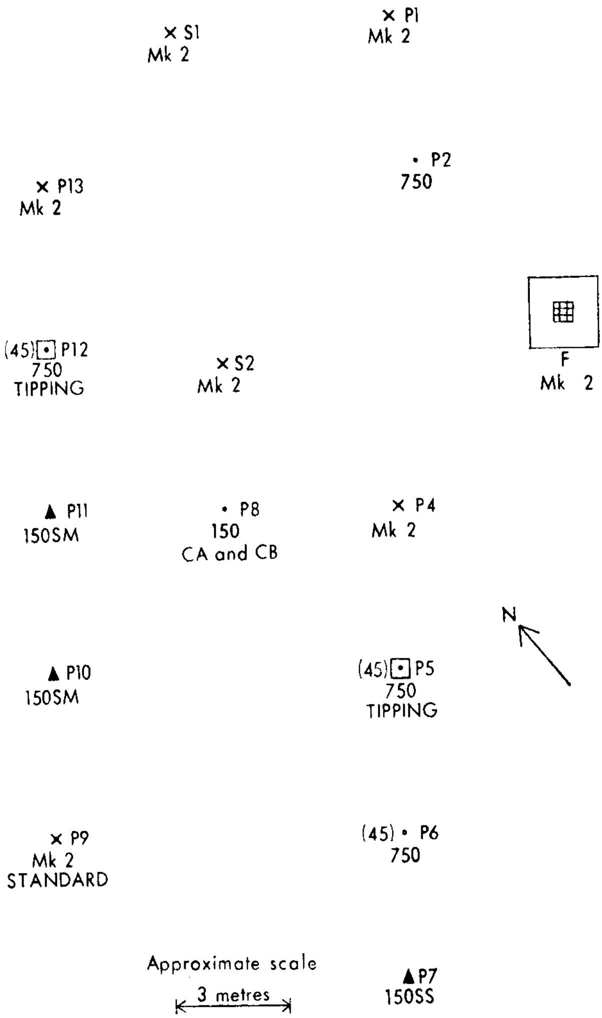

FIGURE 1—POSITIONS AND TYPES OF RAIN-GAUGES AT EASTHAMPSTEAD

(45) Height of rim (cm) of P5, P6 and P12, all others are 30 cm.

The measurements. Except for the gauges fitted with tipping buckets, the water in the collecting bottle of each rain-gauge was measured daily — but not during precipitation — in a 150-cm² collector measuring cylinder, and these measurements were tabulated. An amount registering below the 0·05 graduation in the cylinder was logged as a trace, and for some purposes counted as a reading of 0·025 graduations. The daily recorded measurements were then multiplied by the factors 1·000, 1·184 and 0·200 and rounded to the nearest 0·1 mm to obtain the daily rainfall in millimetres collected by the 150-cm², 5-inch and 750-cm² gauges respectively. Daily readings were taken from the centre rain-gauge of the nine Mk 2 rain-gauges forming the flush gauge. For the 750-cm² rain-gauges fitted with tipping buckets and counters, the number of tips shown by the counter was recorded daily. The buckets were calibrated *in situ* using a technique described fully in the installation instructions. In brief, rain-water is slowly run into the 750-cm² funnel from a burette and the volume required to cause the buckets to tip 12 times is measured. This volume, divided by 900 gives the calibration factor K, defined as the rainfall in millimetres equivalent to one tip. The buckets are designed and adjusted before installation for K to have a nominal value of 0·2 mm. For each of the 750-cm² tipping-bucket gauges at P5 and P12, K was determined from the mean of 12 tips on each of 5 separate occasions towards the beginning, in the middle and at the end of the trial period. The overall mean value of K for both gauges was found to be 0·207 mm, with a standard error of approximately 0·006 mm, or about 0·3 per cent.

Treatment of the data. Data representing occasions on which some or all of the precipitation fell as snow were ignored. Owing to the well-known uncertainty in the measurement by conventional rain-gauges of small quantities of precipitation and dew, data representing occasions on which less than 1 mm of precipitation was measured on the daily reading of the 5-inch Mk 2 rain-gauge at P9 were also ignored in the main analysis. This left rainfall measurements for each of the rain-gauges deployed, for each of a series of daily occasions on which 1 mm or more of rain fell. Each such occasion was called a rainfall event, and the number of these occurring in a stated period was designated by the letter n. The data were first examined by comparing the total rainfall collected by each of the gauges for all rainfall events which were common to the gauges being compared.

For all non-recording gauges except the straight-sided 150-cm² gauge at P7 and the 150-cm² gauge at P8, daily measurements started on 25 June 1969 and there were 116 common rainfall events for analysis up to 30 September 1970. The results of this analysis are in Table I*(a)*, wherein each gauge's total collection is expressed as a percentage of that collected in the flush gauge (F), in the standard 5-inch gauge at P9, and of the mean amount (MS) collected in the six standard 5-inch gauges. Similarly, in Table I*(b)* are analysed the 107 rainfall events common to all the non-recording gauges in the period from 22 August 1969 to 30 September 1970. However, the 150-cm² collector (CA) which was at P8 from 22 August 1969 until 12 June 1970 was replaced on 13 June 1970 by an externally apparently identical model (CB), in which the interior collecting surface was bowl-shaped rather than funnel-shaped. On careful examination, however, the external details were found in fact to be very slightly different; the discontinuity between the metal knife-edged rim and the adjacent plastic flange was slightly greater,

TABLE I—COMPARISON OF RAIN-GAUGES AT EASTHAMPSTEAD FOR RAIN DAYS EACH WITH AT LEAST 1 mm MEASURED IN THE 5-INCH STANDARD RAIN-GAUGE AT P9

		(a) 25 June 1969 to 30 September 1970 $n = 116$				(b) 22 August 1969 to 30 September 1970 $n = 107$			
	Site position	Rainfall *mm*	Per cent of F	Per cent of P9	Per cent of MS	Rainfall *mm*	Per cent of F	Per cent of P9	Per cent of MS
150 cm²									
CA	P8	—				} 574·6	101·26	105·59	106·27
CB	P8	—							
SS	P7	—				547·4	96·17	100·27	100·92
SM	P10	670·5	95·95	99·45	100·10	543·2	95·43	99·51	100·15
SM	P11	676·9	96·87	100·40	101·06	548·4	96·35	100·46	101·11
750 cm²									
Rim at 30 cm	P2	685·6	98·11	101·69	102·36	557·3	97·91	102·09	102·75
Rim at 45 cm	P6	677·9	97·01	100·55	101·21	550·1	96·64	100·77	101·42
5 inch									
Flush	F	698·8	100·00	103·65	104·33	569·2	100·00	104·27	104·94
Standard	P9	674·2	96·48	100·00	100·66	545·9	95·91	100·00	100·65
Standard	P1	666·9	95·44	98·92	99·57	540·6	94·98	99·03	99·67
Standard	P4	669·8	95·85	99·35	100·00	542·8	95·36	99·43	100·07
Standard	P13	672·5	96·24	99·75	100·40	544·9	95·73	99·82	100·46
Standard	S1	666·7	95·41	98·89	99·54	539·1	94·71	98·75	99·39
Standard	S2	668·8	95·71	99·20	99·85	541·1	95·06	99·12	99·76
Mean standard	MS	669·8	95·85	99·35	100·00	542·4			
Standard deviation		3·0				2·6			
Coefficient of variation		0·5%				0·5%			

n = number of rainfall events

and this flange was about 2° more nearly vertical. The performances of these two versions of the 150-cm² gauge at P8 were found to be different; consequently the combined data for the two versions in Table I*(b)* are shown bracketed in the first line, and the table is subdivided into Table II *(a)*, which covers the 76 rainfall events common to the CA and the other gauges in the period 22 August 1969 until 12 June 1970, and Table II *(b)* which analyses the 31 rainfall events from 13 June until 30 September 1970 during which the 150-cm² collector CB was at P8.

The distant-reading tipping-bucket rain-gauges at P12 and P5 were not installed until 2 December 1969; thereafter there were 71 rainfall events when both tipping-bucket gauges were functioning together with the other 750-cm² and standard 5-inch collectors, and these are analysed in Table III.

Discussion. For the six identical 5-inch rain-gauges at P9, P1, P4, P13, S1 and S2 the ratio of the standard deviation to the mean amount collected, i.e. the coefficient of variation, was 0·5 per cent. Applying the value of 2·57 for Student's *t* for 5 degrees of freedom, it follows that it would be expected that, owing to site effects (see Introduction), on not more than 5 per cent of occasions would the total in a standard 5-inch gauge placed at random on the site differ from the mean total collected by the standard 5-inch gauges by more than $\pm$ 2·57 $\times$ 0·5 = $\pm$ 1·3 per cent. Any gauge on the site which shows a departure of more than 1·3 per cent from the mean of the 5-inch gauges may be regarded as having significantly different collection characteristics from the standard gauge. That is, the significantly above, or below, normal ratio for such a gauge is to be ascribed to the gauge itself, rather than to the particular position it occupies on the site.

On this basis, then, it may be seen from the 'per cent of MS' columns in Tables I–III that the flush gauge, the 150-cm² collector CA and the 750-cm² funnel with rim at 30 cm collected significantly more rain than would have been expected from a 5-inch Mk 2 rain-gauge with rim at 30 cm in the same position, while the tipping-bucket rain-gauge at P5 collected significantly less.

Raising the rim height of the 750-cm² collector by 15 cm to 45 cm above the ground evidently reduces the significant over-collection of this gauge by 1–1½ per cent; at 45 cm the 750-cm² funnel collects an amount insignificantly different from the mean amount collected by the standard 5-inch rain-gauges.

As the design and rim height of the standard 5-inch Mk 2, the flush and the 750-cm² glass-fibre rain-gauges are such as effectively to eliminate errors due to splash-in of rain-water from the surrounding ground or from the outer sides of these gauges, it follows that the shape and size of the 750-cm² collectors, and the exposure with rim at ground level of the flush gauge are rather more effective than that of the standard Mk 2 rain-gauge in reducing losses of catch due to wind and turbulence effects. Other investigations have also shown a relatively high efficiency of catch for flush gauges with effective anti-splash surrounds.

However, although the collector CB behaved indistinguishably from a standard Mk 2 rain-gauge (Table II*(b)*), the CA version overall collected some 5 per cent more than even the flush gauge (Table II*(a)*). It is believed that the slightly nearer to horizontal inclination of the wide bevel just below the rim, together with the smaller obstruction created by the reduced gap

TABLE II—COMPARISON OF RAIN-GAUGES AT EASTHAMPSTEAD SEPARATED INTO TWO PERIODS *(a)* IN WHICH GAUGE CA WAS USED AND *(b)* IN WHICH GAUGE CB WAS USED

		(a) 22 August 1969 to 12 June 1970, $n = 76$				*(b)* 13 June to 30 September 1970, $n = 31$			
	Site position	Rainfall *mm*	Per cent of F	Per cent of P9	Per cent of MS	Rainfall *mm*	Per cent of F	Per cent of P9	Per cent of MS
150 cm^2									
CA	P8	377·6	104·68	109·42	110·05	—		—	—
CB	P8	—	—	—	—	198·8	95·35	99·00	99·75
SS	P7	349·2	96·81	101·19	101·78	198·2	95·06	98·71	99·45
SM	P10	343·2	95·15	99·45	100·03	200·0	95·92	99·60	100·35
SM	P11	347·2	96·26	100·61	101·19	201·2	96·50	100·20	100·95
750 cm^2									
Rim at 30 cm	P2	353·0	97·86	102·29	102·88	204·3	97·99	101·74	102·51
Rim at 45 cm	P6	348·1	96·51	100·87	101·46	202·1	96·93	100·65	101·40
5 inch									
Flush	F	360·7	100·00	104·52	105·13	208·5	100·00	103·83	104·62
Standard	P9	345·1	95·67	100·00	100·58	200·8	96·31	100·00	100·75
Standard	P1	342·3	94·90	99·19	99·77	198·3	95·11	98·75	99·50
Standard	P4	343·7	95·29	99·59	100·17	199·1	95·49	99·15	99·90
Standard	P13	344·4	95·48	99·80	100·38	200·5	96·16	99·85	100·60
Standard	S1	340·4	94·37	98·64	99·21	198·8	95·35	99·00	99·75
Standard	S2	342·7	95·01	99·30	99·88	198·4	95·16	98·80	99·55
Mean standard	MS	343·1	95·12	99·42	100·00	199·3	95·59	99·25	100·00
Standard deviation		1·7				1·1			
Coefficient of variation		0·5%				0·5%			

n = number of rainfall events

TABLE III—COMPARISON OF RAIN-GAUGES AT EASTHAMPSTEAD FOR THE PERIOD IN WHICH THE TWO DISTANT-READING TIPPING-BUCKET RAIN-GAUGES WERE INSTALLED, 2 DECEMBER 1969 TO 29 SEPTEMBER 1970

	Site position	Rainfall	Per cent of F	Per cent of P9	Per cent of MS
750 cm^2		*mm*			
Rim at 30 cm	P2	386·7	97·50	101·90	102·74
Rim at 45 cm	P6	381·0	96·07	100·40	101·22
At 45 cm with tipping bucket	P12	372·4	93·90	98·13	98·94
At 45 cm with tipping bucket	P5	361·0	91·02	95·13	95·91
5 inch					
Flush	F	396·6	100·00	104·51	105·37
Standard	P9	379·5	95·69	100·00	100·82
Standard	P1	375·0	94·55	98·81	99·63
Standard	P4	376·7	94·98	99·26	100·08
Standard	P13	378·4	95·41	99·71	100·53
Standard	S1	373·6	94·20	98·45	99·26
Standard	S2	375·2	94·60	98·87	99·68
Mean standard	MS	376·4	94·91	99·18	100·00
Standard deviation		2·2			
Coefficient of variation		0·6%			

Number of events = 71

between bevel and rim of the CA model allowed raindrops coalescing after impact with the windward side of this bevel to be blown upwards across the small obstruction, over the knife-edged rim, and into the gauge. Whatever the explanation, the results show that a visually almost undetectable change in the shape and design of a rain-gauge collector can have a large influence on its efficiency, and that exterior outward-sloping surfaces below the knife-edge rims are liable to cause errors due to splash-in or blow-in.

The 750-cm^2 tipping-bucket rain-gauge at P5 registered significantly less rainfall than its counterpart at P12 (Table III). However, several failures of the counter on the gauge at P5 occurred. Rainfall events during which the P5 counter was positively known to be inoperative have not been included in the comparative data in Table III. Nevertheless, it is probable that on some rainfall events included in this table, tips of the buckets had occurred but not been registered on the counter before it became obvious that the counter had failed. For this reason, the data for the tipping-bucket rain-gauge at P5 are regarded as suspect, and are not considered further. The cause of the counter defects has since been diagnosed.

In Table III the difference between the cumulative rainfall collected by the 750-cm^2 funnel at 45 cm at P6 and that registered by the similar collector at 45 cm at P12, but fitted with a tipping bucket, of 2·3 per cent is unlikely to be due to the chance effect of the positions chosen for these two gauges on the site. The apparent overall loss of up to about 2 per cent when the rainfall is metered by the tipping-bucket device rather than collected in a bottle may be due to the cumulative effect of evaporation from a partially filled bucket between successive rainfall events. To minimize any small loss due to evaporation, a shallow tray, normally automatically containing a layer of water through discharge from the tipping buckets, can be fitted at the base of the support tube; this maintains a near-saturated atmosphere around the buckets in the support tube between rainfall events. However, an anti-evaporation tray should not be used unless the tipping-bucket rain-gauge is also fitted with an anti-condensation shield, for reasons which follow later.

For cumulative rainfall events totalling around 400 mm or more, where each event is defined as a 24-hour rainfall of at least 1 mm, the ratios in Tables I–III show that the glass-fibre 150-cm² gauges with rims at 30 cm and the 750-cm² tipping-bucket rain-gauge with rim at 45 cm collect within 1·2 per cent of the mean of the standard 5-inch gauge. However, the ratios found will not necessarily be valid for other periods in which the average wind, turbulence and raindrop size distribution during precipitation may not be the same. Neither will they necessarily apply at other locations where again the exposure and wind régime may be different. Without many years of data, it does not seem possible to calculate the standard error or the confidence limits which would serve as a measure of the reproducibility of these ratios for large aggregate amounts such as annual rainfall. From the work of Poncelet, involving five years of data, it can be estimated that the standard error of ratios for conventional rain-gauges derived from one year's aggregate rainfall is about 1 per cent. At Easthampstead, the ratios could also differ by about 1 per cent depending on the exact spot chosen on a given suitable site to install the standard 5-inch reference gauge. So, for measuring rainfall in the U.K. for long-period climatological purposes, a change of reference rain-gauge from the 5-inch Mk 2 copper gauge to the 150-cm² glass-fibre or to the 750-cm² collector at 45 cm with calibrated tipping buckets is unlikely to introduce any additional systematic errors in mean annual or longer-period rainfall statistics.

Although difficult to maintain as a network rain-gauge, there is little doubt that rainfall measured by a carefully looked after flush gauge with proper anti-splash surround is a closer approach to the true rainfall than that measured in a standard rain-gauge with rim exposed above the ground, and unprotected by a turf wall. Where, for hydrological or other special purposes, best estimates of true annual point rainfall are required and it has not been feasible to have a flush or turf-wall gauge installed and maintained, it might be desirable to increase the annual rainfall as measured in a standard gauge exposed at 30 cm by some percentage increment C. For aggregates of daily falls equalling or exceeding 1 mm in the year 25 June 1969–30 June 1970 at Easthampstead, Table I indicates that the appropriate value for C is about 4 per cent. For the aggregate of all occasions of daily measured rainfall exceeding a trace (excluding snow) in the two-year period May 1968–April 1970 at Kew, C is 7 per cent. If F is the monthly rainfall measured in the flush gauge at Kew, and S that in the nearby standard rain-gauge, then the regression equation of F on S for the 24 months of available data, with S ranging from 2·9 mm (September 1969) to 123·7 mm (September 1968) is :

$$F = 1{\cdot}05S + 1{\cdot}09 \pm 2{\cdot}0 \text{ (S.E.)},$$

where S.E. is the standard error.

For the mean monthly rainfall of 52·09 mm measured at Kew in the standard 5-inch gauge over this period, the most probable measurement in the flush gauge calculated from the above regression equation would be 55·78±2·0 mm (S.E.), or 107·0 per cent ±3·6 per cent (S.E.) of that in the standard gauge. Thus, the standard error of the correction factor C for Kew is in magnitude about half that of the factor itself, so that applying a correction factor to a particular month's rainfall measured by a standard rain-gauge might introduce as large an error as it was intended to remove. For aggregation over years, rather than 30 days, the factor is likely to be much more stable, though variations of at least 1 per cent from year to year are to be expected.

Dew collection. On radiation nights, the amount of condensation on the collecting surfaces of the glass-fibre rain-gauges is likely to be greater than on copper Mk 2 rain-gauges, where surfaces will be maintained at a higher equilibrium temperature owing to better conduction of heat from the ground in which the copper base of these rain-gauges is embedded. This expectation is borne out by results over the period 22 August 1969–13 November 1969, chosen purposely because it included many clear, calm nights with heavy dewfall. For cumulative collections of daily amounts of less than 1 mm (mostly dew), counting traces as each equivalent to 0·025 mm, over this period the ratio of the mean amount collected in the five glass-fibre gauges to the mean of the six copper gauges was 136·2 per cent, whereas in the same period for amounts equalling or exceeding 1 mm (mostly rain) the ratio was 102·5 per cent. However, on the 'less than 1 mm' occasions, not all the water collected in the bottles came from dew which had formed on the exposed outer collecting surfaces of the glass-fibre funnels. Appreciable quantities of condensation droplets have been seen to have formed on the interior surfaces of these funnels on radiation nights; the drops could amalgamate and run down into the collecting bottles or be metered through the tipping buckets. A laboratory experiment was carried out to determine the possible rate of accumulation of this interior condensation. The open lower end of the support tube of a 750-cm^2 rain-gauge was left standing in a sink of water at 18–19°C, so maintaining a near-saturated atmosphere within the interior of the rain-gauge. The exit of the collecting-funnel spout was sealed, and the funnel maintained full of crushed ice. Under these ideal conditions for maximum interior condensation, a spurious dewfall of 0·14 mm was collected in the bottle in 6 hours. A collection of interior condensation at half this rate for 8 hours during each of the 24 or so radiation nights which occurred in the period 22 August 1969–13 November 1969 would have accounted for the additional 34 per cent collected by the glass-fibre rain-gauges in this period.

In the U.K. the fraction of the annual, or longer-period, total measured precipitation which constitutes dew is rather small, so that in this context the additional amounts of spurious dew collected by glass-fibre rain-gauges is probably negligible. But for monthly or shorter periods of rainfall, dew may sometimes form a significant part of the total measured precipitation. Where glass-fibre rain-gauges are to be used for measuring monthly or shorter periods of rainfall, or where they are to be used with a tipping-bucket device and anti-evaporation tray in the support tube, a condensation deflector can be fitted to the interior of the funnel. This deflector is so designed as effectively to divert droplets running down the interior of the funnel and spout from passing into the collecting bottle or the tipping bucket.

Performance of tipping-bucket rain-gauges. In addition to the daily measurements from the rain-gauges at Easthampstead, data were also available from 750-cm^2 tipping-bucket and adjacent 5-inch standard rain-gauges read six times a day at three of the outstations (Bristol/Filton, Glasgow Airport and Edinburgh/Turnhouse Airport) where tipping-bucket rain-gauges are in operational use for reporting hourly rainfall amounts. An analysis of these data is contained in Table IV, in which N stands for the

TABLE IV—PERFORMANCE OF TIPPING-BUCKET RAIN-GAUGES AT OUTSTATIONS

Station	Period	N_1	N_2	N_3	G_1	G_2	G_3	T_1 and T_2	T_3	R_1	R_2	R_3
Filton	Nov. 1969	40	2	31	81·1	81·15	80·0	80·79	79·37	99·62	99·56	99·22
	Dec.	49	5	33	53·6	53·73	52·3	52·98	51·16	98·85	98·62	97·81
K = 0·203 mm/tip	Jan. 1970	72	8	47	93·6	93·80	91·9	92·16	89·73	98·46	98·25	97·63
Rim height 30 cm	Feb.	48	7	30	57·8	57·98	56·6	57·45	55·42	99·39	99·09	97·91
	Mar.	37	8	18	25·0	25·20	23·5	26·19	23·55	104·75	103·92	100·20
	Apr.	52	5	32	53·4	53·53	51·5	55·01	52·58	103·02	102·78	102·09
	May	27	5	17	37·4	37·53	36·7	37·76	36·95	100·96	100·62	100·67
	June	29	5	21	47·6	47·73	47·2	46·49	46·08	97·66	97·41	97·63
	July	35	3	25	70·5	70·58	68·1	70·24	68·82	99·63	99·52	101·05
	Aug.	46	12	26	53·9	54·20	52·5	51·77	50·14	96·04	95·51	99·51
	Sept.	27	3	23	85·0	85·08	84·4	85·46	84·24	100·54	100·45	99·81
	Oct.	40	5	29	30·1	30·22	28·5	30·25	27·81	100·49	100·07	97·58
	Nov. '69–Oct. '70	502	68	332	689·0	690·70	673·2	686·55	665·85	99·64	99·40	98·91
	1970											
Turnhouse	15 Dec.–14 Jan.	29	26	20	35·5	36·15	34·1	37·54	34·27	105·74	103·83	100·50
	15 Jan.–14 Feb.	84	33	35	44·2	45·03	42·5	46·51	42·43	105·23	103·30	99·84
K = 0·204 mm/tip	15 Feb.–14 Mar.	65	34	20	39·7	40·55	38·1	41·82	38·76	105·34	103·13	101·73
Rim height 30 cm	15 Mar.–14 Apr.	70	38	24	25·5	26·45	24·8	29·99	27·54	117·60	113·38	111·05
	15 Apr.–14 May	85	51	20	38·2	39·48	35·9	41·00	36·92	107·33	103·86	102·85
	15 May–14 June	54	37	9	12·3	13·23	10·9	14·28	12·24	116·10	107·98	112·29
	15 Dec.–14 June	387	219	128	195·4	200·88	186·3	211·14	192·16	108·06	105·10	103·15
	1970											
Glasgow Airport	15 Dec.–14 Jan.	35	11	23	59·2	59·48	57·4	59·99	57·17	101·34	100·87	99·59
	15 Jan.–14 Feb.	98	32	53	90·4	91·20	87·7	92·92	89·69	102·79	101·89	102·27
K = 0·202 mm/tip	15 Feb.–14 Mar.	64	23	26	53·5	54·08	51·0	56·56	52·72	105·72	104·60	103·38
Rim height 45 cm	15 Mar.–14 Apr.	85	46	29	47·3	48·45	45·6	51·51	48·68	108·90	106·32	106·75
	15 Apr.–14 May	79	35	31	76·2	77·08	74·4	78·98	76·36	103·65	102·47	102·63
	15 May–14 June	40	28	9	24·8	25·50	24·4	27·47	27·07	110·77	107·73	110·93
	15 Dec.–14 June	401	175	171	351·4	355·78	340·5	367·43	351·69	104·56	103·27	103·29

N Number of pairs of rain-gauge readings. G Aggregate of readings from the nearby standard 5-inch rain gauge.

T Corresponding totals registered by the tipping-bucket rain-gauge. R Percentage ratio of tipping-bucket to standard 5-inch rainfall totals. Suffix 1 — Traces ignored. Suffix 2 — Each of N_2 trace readings is counted as 0·025 mm of rain. Suffix 3 — In each pair of readings more than 0·2 mm was read in the 5-inch rain-gauge.

K Calibration constant.

number of pairs of rain-gauge readings, G the aggregate of readings from the nearby standard 5-inch rain-gauge, T the corresponding totals registered by the tipping-bucket rain-gauge, and R the percentage ratio of tipping-bucket to standard 5-inch rainfall totals.

When the cumulative rainfall is obtained by summing the readings obtained from a 5-inch rain-gauge read and emptied six times a day, the total is likely to be an underestimate if individual trace readings, that is, readings of less than 0·05 mm of rain, are ignored. Because all amounts of precipitation, however small, pass into, and in aggregate are metered by, the tipping buckets, the ratio of tipping-bucket to 5-inch rain-gauge totals will be greater when traces recorded in the 5-inch gauge are ignored than when an appropriate rainfall equivalent, such as 0·025 mm, is accorded to them. In Table IV, suffix 1 refers to data where traces have been ignored, suffix 2 to readings, aggregates and ratios where each of the N_2 trace readings has been counted as equivalent to 0·025 mm of rain, and suffix 3 to ratios and aggregates derived from the N_3 pairs of readings in each of which more than 0·2 mm was read in the 5-inch gauge. Where, as at Filton, the average number of trace readings per month was only about six, the difference between the overall ratios R_2 (counting traces as 0·025 mm) and R_1 (ignoring traces) is no more than 0·2 per cent. At Turnhouse, however, where trace readings were recorded about six times more often, the difference amounts to 3 per cent.

The problem of how to deal with trace readings in the standard gauge when evaluating aggregate total measured rainfall for that gauge for comparison with the total rainfall that has been counted as having passed through a tipping-bucket gauge is largely removed when, as in Tables III and V*(a)*, only occasions when the daily fall in the 5-inch gauge exceeds 1 mm are aggregated. For data obtained from standard gauges read six times daily, such as in Table IV, the problem is similarly largely overcome by only aggregating individual readings of more than 0·2 mm. The figures in columns headed with a suffix 3 in Table IV refer to such data. It can be seen that overall the tipping-bucket rain-gauge at Filton, with a field calibration of 0·203 mm per tip, registered 98·9 per cent of the rainfall in the nearby standard 5-inch rain-gauge, the same as the 98·9 per cent registered by the instrument at P12 at Easthampstead (Table III) in relation to the mean of the nearby six standard rain-gauges there. However, the rim of the Filton 750-cm^2 collector is mounted at 30 cm, whereas that at Easthampstead was at 45 cm. Table IV shows the overall ratios for the Turnhouse and Glasgow tipping-bucket gauges were much the same, at 103·2 per cent and 103·3 per cent respectively, despite the rim of the former's being at 30 cm and the latter's at 45 cm. Bearing in mind that these ratios are bound to vary to some extent from one climatic régime to another, the results indicate that at least for measuring large overall amounts of rain the tipping-bucket rain-gauge is as efficient as, or perhaps slightly more efficient than, the standard Mk 2 manually read gauge.

Variability for monthly rainfall. The mean of the 12 monthly ratios R_3 for Filton is 99·3 per cent and the standard deviation about this mean is 1·5 per cent, with extreme departures of +2·7 per cent in April and −1·6 per cent in January, June and October 1970. The regression equation of T_3 on G_3 for the 12 months of data for Filton in Table IV is :

$$T_3 = 0{\cdot}99\ G_3 + 0{\cdot}03 \pm 1{\cdot}1\ \text{(S.E.)}.$$

TABLE V(*a*)—VARIABILITY OF RAIN-GAUGES AT EASTHAMPSTEAD FOR DAILY RAINFALL*

Comparative rain-gauge	Site position	Data period	N	E	P per cent
5 inch					
Standard	S2	25/6/69–30/6/70	89	$Y = 0.997S - 0.016 \pm 0.293$	99.5 ± 2.9
Standard	P4	25/6/69–30/6/70	89	$Y = 0.992S + 0.013 \pm 0.265$	99.4 ± 2.6
Flush	F	25/6/69–30/6/70	89	$Y = 1.009S + 0.146 \pm 0.486$	102.4 ± 4.9
750 cm²					
Rim at 30 cm	P2	25/6/69–30/6/70	89	$Y = 1.001S + 0.092 \pm 0.394$	101.0 ± 3.9
Rim at 45 cm	P6	25/6/69–30/6/70	89	$Y = 0.999S + 0.039 \pm 0.339$	100.3 ± 3.4
Rim at 45 cm	P6	2/12/69–30/6/70	57	$Y = 0.999S + 0.017 \pm 0.310$	100.1 ± 3.1
Rim at 45 cm with tipping bucket ($K = 0.207$ mm/tip)	P12	2/12/69–30/6/70	57	$Y = 0.977S + 0.081 \pm 0.451$	98.5 ± 4.5
150 cm²					
SM	P11	22/8/69–12/6/70	76	$Y = 1.012S - 0.025 \pm 0.276$	100.9 ± 2.8
CA	P8	22/8/69–12/6/70	76	$Y = 1.075S + 0.085 \pm 0.724$	108.4 ± 7.2

Y Amount collected in comparative rain-gauge. S Amount collected in standard 5-inch rain-gauge at P9.
N Number of daily rainfalls each measuring at least 1 mm in the standard rain-gauge at P9.
E Regression equation of Y on S for daily rainfalls, $\pm$ the 95 per cent confidence limits of Y.
P Most probable percentage ratio Y/S, $\pm$ the 95 per cent confidence limits, for a rainfall of 10 mm in the standard rain-gauge.
K Calibration constant.

TABLE V(*b*)—VARIABILITY OF 750-cm² TIPPING-BUCKET RAIN-GAUGES AT OUTSTATIONS FOR DAILY RAINFALL*

Location of 750-cm² tipping-bucket rain-gauge	h cm	K mm/tip	Data period	N	E	P per cent
Turnhouse	30	0·204	15/12/69–15/6/70	45	$Y = 0.989S + 0.202 \pm 0.449$	100.9 ± 4.5
Glasgow Airport	45	0·202	15/12/69–15/6/70	60	$Y = 1.030S + 0.004 \pm 0.892$	103.0 ± 8.9
Filton	30	0·203	6/11/69–31/8/70	100	$Y = 0.966S + 0.127 \pm 0.742$	97.9 ± 7.4

Y Amount collected in 750-cm² tipping-bucket rain-gauge. S Amount collected in nearby standard 5-inch rain-gauge.
h Height of rim above ground.
K Calibration constant.
N Number of daily rainfalls each totalling at least 1 mm in the nearby standard rain-gauge, where each daily rainfall is the aggregate of measurements exceeding a trace made at 3- or 6-hourly intervals.
E Regression equation of Y on S for daily rainfalls, $\pm$ the 95 per cent confidence limits of Y.
P Most probable percentage ratio Y/S, $\pm$ the 95 per cent confidence limits, for an aggregate daily rainfall of 10 mm in the standard rain-gauge.

* Rain days each with a total of at least 1 mm measured in the standard 5-inch rain-gauge (P9 at Easthampstead, nearby at outstations).

For the mean monthly value of G_3 of 56·1 mm, the most probable value that would have been recorded by the tipping bucket, calculated from the above regression equation, is 55·5 mm $\pm$1·1 mm (S.E.) or 98·9 per cent $\pm$2·0 per cent (S.E.) of G_3. Thus it appears that the ratio for any particular month at Filton can be expected to depart from the overall value by more than $\pm$2 per cent in 3 or 4 months in the year. But the variability of the monthly values of the ratio must depend on the variability of the monthly climatic régimes, and 12 months are probably insufficient to sample this adequately. Furthermore, for a month with very low rainfall, the value of the ratio has but little significance. Although there are only 6 months' data available for each of the stations in Scotland, at all three stations there is an indication that the ratio may tend to have a maximum value in the early summer months, and a minimum in the winter months.

Variability for daily rainfall. Clearly the performance of a rain-gauge cannot be regarded as acceptable solely on the basis that overall it collects close to 100 per cent of the rainfall measured in a standard gauge; it is necessary also to be assured that for individual small totals such as typically are measured during an average wet day the departures from the overall 100 per cent figure are not normally excessive.

To derive a relative measure of the extent of variation in the ratio of the amount Y collected by a particular rain-gauge to the amount S measured in a nearby standard rain-gauge for daily rainfall events, the regression equation of Y on S was calculated for the various rain-gauges shown in Tables V *(a)* and *(b)* for all daily rainfall totals of amounts of 1 mm or more in the standard gauge, and from the residual sum of squares the 95 per cent confidence limits of the regression were computed. Considering a rain day on which 10 mm of rain were measured in the standard 5-inch gauge, the amount Y that most probably would have been measured by a comparative gauge was calculated using the appropriate regression equation, and the percentage ratio of this amount to the 10 mm in the standard gauge was derived, with the 95 per cent confidence limits of this ratio. These ratios and their 95 per cent confidence limits are expressed in column P of Tables V *(a)* and *(b)*, and serve as an index of the variability of the various rain-gauges' relative collection efficiencies for a typical (rather heavy) day's rainfall. The smaller these confidence limits are, the more precise and reproducible are the daily rain-gauge measurements compared with those of a standard 5-inch rain-gauge.

The minimum attainable value for the confidence limits is set by the variability of the measurements from one standard rain-gauge compared with those from another nearby; if the rain-gauges being compared are identical in shape and exposure, this 'natural' variability cannot be reduced by altering their shape or design. From Table V *(a)*, containing the results for rain-gauges at Easthampstead, it can be seen that, relative to the standard 5-inch gauge at P9, the identical 5-inch rain-gauges at S2 and P4 have the lowest variability, at between 2½ and 3 per cent, and this standard is also attained by the 150-cm² rain-gauge at P11. The 750-cm² collectors are slightly more variable, with confidence limits between 3 and 4 per cent, while the flush gauge and the tipping-bucket gauge at Easthampstead collect within 4½ to 5 per cent of the expected ratio. Increasing the height above the ground of the rim of the 750-cm² collector from 30 cm to 45 cm does not increase its variability.

while including a tipping-bucket device to meter the rain-water rather than collecting and measuring it from a bottle makes the 750-cm² rain-gauge about 1½ per cent less consistent, with 95 per cent confidence limits of $\pm 4 \cdot 5$ per cent. The 750-cm² tipping-bucket rain-gauge is incapable of discriminating to within ± 1 tip, or for a rainfall of 10 mm to within ± 2 per cent, corresponding to a 95 per cent confidence limit of $\pm 1 \cdot 3$ per cent. Thus, erratic tipping of the buckets due to friction in the bearings, etc., contributes insignificantly to the total variability of the tipping-bucket rain-gauge.

The large range of $\pm 7 \cdot 2$ per cent for the confidence limits of the 150-cm² rain-gauge CA is no doubt due to the varying incidence of errors due to splash-in or blow-in, as already discussed.

Table V *(b)* contains a similar analysis of the outstation tipping-bucket rain-gauge performance from the point of view of ratio variability. However, each day's rainfall equalling or exceeding 1 mm in the 5-inch gauge was not obtained from a single once-daily reading, as at Easthampstead, but was the aggregate of six readings, some of which could have been of a trace. The traces were ignored in obtaining the daily aggregate of the 5-inch gauge readings; consequently the ratios and the variabilities in Table V *(b)* can be expected to be slightly greater than those for the Easthampstead tipping-bucket rain-gauge in Table V *(a)*, to an extent dependent on the frequency and regularity of occurrence of trace readings at these outstations on occasions of aggregate daily rainfalls of 1 mm or more. In fact the range of the 95 per cent confidence limits for the ratio at Filton and at Glasgow is about 3 or 4 per cent greater than that found for the tipping-bucket rain-gauge at Easthampstead. Nevertheless, even at Glasgow, on 95 per cent of occasions of a daily rainfall aggregating 10 mm, the amount registered by the nearby 750-cm² tipping-bucket rain-gauge with rim at 45 cm above the ground would not lie outside the range 11·2–9·4 mm. Random errors (relative to a standard rain-gauge) giving this range of daily rainfall are probably acceptable for the purposes to which measurements of daily rainfall are put.

Conclusions. Some general conclusions which follow from these trials and analyses are :

(i) The Meteorological Office 150-cm² and 750-cm² glass-fibre funnels are in general indistinguishable from the Mk 2 copper rain-gauges in their overall collection characteristics; they do, however, collect more condensation precipitation (dew or hoar-frost), especially if not fitted with anti-condensation shields.

(ii) The Mk 2 5-inch rain-gauge itself collects less rainfall when its rim is at the standard height of 30 cm above the ground than when mounted flush with an anti-splash surround.

(iii) Two outwardly almost identical versions of a commercially available 150-cm² rain-gauge have markedly different performance characteristics.

(iv) The field-calibrated 750-cm² tipping-bucket rain-gauges, with rims at 30 cm or 45 cm, collect overall about the same as, or rather more than, the Mk 2 standard rain-gauge; they are proving reasonably reliable in the field, but their collection efficiency when measuring daily rainfall is rather variable. However, where a daily-read standard climatological rain-gauge is installed nearby, the rainfall over intermediate periods within the day obtained from a tipping-bucket gauge fitted with a counter or event recorder may readily be apportioned to ensure that the daily aggregate agrees with that measured by the standard gauge.

OBITUARY

It is with regret that we record the death on 29 April 1971 of Mr J. B. Anderson, Experimental Officer, Met. O. 7.

REVIEW

Seventh annual report of the Water Resources Board, presented by the Water Resources Board, Reading. 245×150 mm, pp. vii+104, *illus.*, H.M. Stationery Office, London, 1971. Price: 70p.

The successive annual (and other) reports issued by the Water Resources Board at Reading, since that organization came into being following the Water Resources Act 1963, have always been of interest to those in the Meteorological Office who are in any substantial sense concerned with hydro-meteorology. Very close links have in fact been established between certain groups on the staff of the Board and within the Office, and it is more than likely that those links will be continuously strengthened in the future. (It naturally follows that the Office is normally mentioned in the annual reports of the Board and vice versa.)

The present report is of quite exceptional interest because of what it says about the future in the context of water resources management and its organization at the national and regional levels. The final chapter out of seven and 4 of the 15 appendices, totalling in numbers of pages very slightly more than a quarter of the printed text and tables, are directly relevant to this matter, whilst some other parts of the report, in particular Chapter 5 on (present) Research, are of course by no means entirely irrelevant.

The occasion for such emphasis on future organization is that the Central Advisory Water Committee is due to report soon on this very big problem, and during the year under review the Water Resources Board was among those (one must assume very prominently) who submitted papers and discussed them with the Committee. The Water Resources Board is in no doubt at all about how much needs to be done to consolidate and advance the very big step forward achieved through the Water Resources Act 1963, and also in no doubt about how soon all this needs to be done. The writing is direct and forceful, the recommendations are firm and completely unambiguous, and the result is good pleasurable reading, highly recommended to all, compulsory for many.

To take a small but significant example: on page 50 in a specific recommendation on a financial need, there occurs the beautifully straightforward phrase 'for dealing with dirty water'. A report of lesser calibre might have worried like a neurotic mongrel at 'monitoring, evaluation and regulation of dangerous or unacceptable levels of pollution', taking more than twice the length to drive home less than half the meaning. It would be wrong to give anyone a valid excuse for not reading this report, and the sample quotations from Chapter 7 which follows are not intended to provide a major helping of the real meat, but only a sniff at its flavour :

'The Water Resources Act 1963 is based on a principle which is fundamental to the proper management of water resources: that one authority should be responsible for all the water resources in a catchment, whether the water is on the surface or in the ground, and for all aspects of managing those resources . . . Experience over the past five years, however, has shown that the Act did not take this principle far enough . . . The national water authority should be as comprehensive in its responsibilities as river authorities are . . . The technical staff of the river basin authorities must be strengthened to match their additional responsibilities . . . If our premises are sound . . . then the organization for achieving what will be needed must be established without delay. A major revision of the Water Resources Act 1963 could hardly become law in less than two years from now with another two years thereafter to appoint the new authorities and for them to get into business, say in 1975. If this were only an interim stage, it would be at least 1980 before there could be any possibility of proceeding to the second and final stage which could not then come into operation until the mid 1980s at the very earliest. *That would be too late.*' (Reviewer's italics; five words amongst the most important in the report.) ' . . . We await with keen interest the report of the Central Advisory Water Committee.'

Since the above review was written the Central Advisory Water Committee report has appeared and, against the firmness of the Water Resources Board annual report, is something of an anticlimax. With so much at stake in terms of the future health and amenities, economy and prosperity of our community, the next step on the road to a new Act is now awaited with keen interest — the Government White Paper.

A. BLEASDALE

AWARD

We note with pleasure that the sixteenth International Meteorological Organization Prize for outstanding work in meteorology and international collaboration has been awarded for this year to Dr J. G. Charney, Professor of Meteorology at the Massachusetts Institute of Technology, Cambridge, U.S.A., by the Executive Committee of the World Meteorological Organization.

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THICK AND DENSE FOG AT LONDON/HEATHROW AIRPORT AND KINGSWAY/HOLBORN DURING THE TWO DECADES 1950–59 AND 1960–69

By T. KELLY

Introduction. In a previous study,[1] a comparison was made between London/Heathrow Airport, Croydon and Kingsway regarding the occurrence of persistent and semi-persistent thick and dense fog during the period 1947–56. This period was dictated by the closure of Croydon Airport. The study is now brought up to date by considering the fifties and sixties at Heathrow and Kingsway/Holborn* only. As before, 'persistent fog' lasted for 24 hours or more and 'semi-persistent fog' lasted for 12 hours or more, the latter including the former. At Heathrow, a sequence of hourly observations of fog was regarded as being continuous if the visibility rose above the prescribed limits (see below) at single hours only in an otherwise unbroken sequence. (E.g. on 3 October 1953, thick fog was observed at Heathrow at the following times : 00, 01, 03, 04, 05, 06, 07, 09 and 10 GMT. This was considered to be an unbroken period of 11 hours duration.) At Kingsway/Holborn, observations made every three hours (starting at midnight GMT) were used, each observation of fog being assumed to represent a three-hour period of fog. The prescribed limits were such that a visibility of less than 50 metres (55 yards) was defined as dense fog and a visibility of less than 200 metres (220 yards) was defined as thick fog, the latter including the former.

All the basic data were extracted from the original *Daily registers* with the kind permission of the Chief Meteorological Officer, Heathrow, and the Senior Meteorological Officer, London Weather Centre.

Persistent and semi-persistent thick fog. All occasions of semi-persistent thick fog during the 20 years under consideration are listed in Table I.

The detail of Table I is summarized in Table II, which gives the total number and duration of semi-persistent thick fogs during the early and late fifties and sixties.

---

* The London Weather Centre moved from Kingsway to High Holborn on 9 January 1965.

TABLE I—PERIODS OF SEMI-PERSISTENT THICK FOG 1950–69

		Heathrow P* date/time GMT	E† h	Kingsway/Holborn P date/time GMT	E h
1950	Jan.	26/20–28/01	30		
	Nov.	25/07–25/19	13		
	Nov.	26/07–27/09	27	26/12–27/06	21
1951	Jan.	29/20–30/11	16		
	Oct.	15/22–16/11	14		
	Dec.	13/18–14/11	18	13/21–14/09	15
1952	Dec.	05/16–08/12	69	05/09–05/18	12
	Dec.			06/09–08/09	51
	Dec.	26/22–27/21	24		
1953	Jan.	19/06–20/11	30		
	Mar.	02/21–03/10	14		
	Nov.	17/00–17/12	13		
	Nov.	25/16–26/04	13		
	Dec.	17/22–18/18	21	18/03–18/15	15
	Dec.	20/21–21/09	13		
1954	Nov.	17/22–18/12	15		
	Nov.	19/20–20/09	14		
1955	Jan.	21/16–22/09	18		
	Oct.	11/20–12/11	16		
	Dec.	01/18–02/11	18		
1956	Jan.	04/07–06/11	53	05/06–06/09	30
	Dec.	18/23–19/22	24	19/03–20/03	27
	Dec.	20/01–20/24	24		
1957	Dec.	03/18–05/02	33	04/00–04/09	12
	Dec.	05/07–05/20	14		
1958	Jan.	30/03–31/10	32		
	Oct.	27/20–28/08	13		
	Oct.	28/19–29/08	14		
	Nov.	16/19–17/07	13		
	Nov.	25/00–25/11	12		
	Dec.	03/23–05/01	27		
	Dec.	24/12–25/08	21		

		Heathrow P date/time GMT	E h	Kingsway/Holborn P date/time GMT	E h
1959	Jan.	13/21–14/16	20	14/00–14/15	18
	Jan.	28/17–30/11	43	29/03–29/24	24
	Feb.	16/22–17/14	17		
	Feb.	17/17–18/12	20		
	Feb.	18/20–19/11	16		
	Nov.	07/00–08/10	35		
	Nov.	12/09–13/01	17		
	Dec.	01/07–02/08	26		
1960	Jan.	06/22–07/11	14		
	Jan.	07/20–08/09	14		
	Jan.	26/01–26/12	12		
	Oct.	17/01–17/12	12		
	Dec.	17/23–18/12	14		
1961	Mar.	09/21–10/08	12		
	Oct.	15/02–15/14	13		
	Dec.	15/00–15/21	22		
1962	Oct.	16/23–17/11	13		
	Dec.	03/18–07/13	92	04/09–06/03	45
	Dec.			06/12–06/24	15
1963	Dec.	26/18–27/11	18	26/21–27/09	15
1964	Nov.	01/20–02/08	13		
1965	Jan.	24/23–25/12	14		
1966	Nov.	24/02–24/22	21		
1967		None			
1968		None			
1969	Dec.	09/01–09/13	13		

* P = period observed. † E = estimated duration.

TABLE II—NUMBER AND DURATION OF SEMI-PERSISTENT THICK FOGS 1950–69

	Heathrow		Kingsway/Holborn	
	Number	Duration *hours*	Number	Duration *hours*
1950–54	16	344	5	114
1955–59	23	526	5	111
1960–64	12	249	3	75
1965–69	3	48	0	0

This table shows that, during the fifties, the incidence of semi-persistent thick fog increased at Heathrow and changed little at Kingsway. At both stations, there was a remarkable decrease during the sixties, the semi-persistent fog 'season' at Heathrow being from 15 October to 10 March. There was one occurrence of persistent thick fog, this being in 1962. Kingsway/Holborn only experienced three semi-persistent thick fogs in the early sixties and two of these were during the period of persistent thick fog at Heathrow. There was none at Kingsway/Holborn during the late sixties.

Persistent and semi-persistent dense fog. All occasions of semi-persistent dense fog are listed in Table III. Here again, there is a spectacular reduction during the sixties and, at both Heathrow and Kingsway/Holborn, the last recorded semi-persistent dense fog during the period under investigation, occurred in December 1962. During the sixties, this was the only occurrence at Kingsway/Holborn and semi-persistent dense fog only occurred three times at Heathrow, all in December. Two of these were during the persistent thick fog of December 1962.

TABLE III—PERIODS OF SEMI-PERSISTENT DENSE FOG 1950–69

		Heathrow				Kingsway/Holborn	
		Period observed date/time GMT	Estimated duration *hours*			Period observed date/time GMT	Estimated duration *hours*
1950	Nov.	26/12–27/04	17	1950		None	
1951		None		1951		None	
1952	Dec.	06/01–07/13	37	1952	Dec.	06/09–08/03	45
1953		None		1953		None	
1954		None		1954		None	
1955		None		1955		None	
1956	Jan.	04/08–05/02	19	1956	Dec.	19/06–19/15	12
	Jan.	05/05–06/03	23				
1957	Dec.	04/15–05/02	12	1957		None	
1958	Nov.	16/19–17/06	12	1958		None	
1959	Feb.	18/20–19/07	12	1959		None	
	Nov.	12/10–13/01	16				
1960		None		1960		None	
1961	Dec.	15/09–15/20	12	1961		None	
1962	Dec.	03/20–05/24	53	1962	Dec.	04/21–05/06	12
	Dec.	06/12–07/06	19				
1963–69		None		1963–69		None	

Thick and dense fog occurrence. In order to see whether, in common with the decrease in semi-persistent fog, there had been a general decrease in the frequency and duration of all thick and dense fog at the two stations, Tables IV, V, VI and VII were produced, giving, month by month, the number of occasions and the total duration of all cases of thick and dense fog. Since single hourly breaks were ignored at Heathrow, it will be appreciated that the totals given for duration of fog in the tables can exceed the actual number of hours at which fog was reported (e.g. in Table IV, the visibility was 200 metres (220 yards) or more at 40 of the 1968 hours of thick fog in the fifties and 36 of the 1007 hours of thick fog in the sixties).

TABLE IV—NUMBER OF OCCASIONS/TOTAL NUMBER OF HOURS OF THICK FOG AT HEATHROW 1950–69

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Yearly total
1950	7/48	2/8	6/34		2/5	2/9	1/1			3/13	3/43	4/9	30/170
1951	3/25	3/7	3/18			1/1			3/14	9/61	1/5	6/33	29/164
1952	1/7	4/23	3/12			1/3		5/5		5/16	2/15	5/114	26/195
1953	9/74	3/16	10/46	1/8	2/7				4/29	10/48	8/47	9/68	56/343
1954	1/3	3/14			1/3	1/1	1/1	3/12	2/10	1/4	5/32	5/21	23/101
1955	6/41							2/6	1/7	4/38	6/24	4/38	23/154
1956	4/56		1/2		1/4		1/2		2/9	9/54	6/19	6/65	30/211
1957	2/11	3/9	2/10	1/4				1/2	1/3	7/32		7/53	24/124
1958	3/34	2/6	1/2			2/4		1/1	1/6	6/40	9/62	11/94	36/249
1959	4/68	5/62	2/12	1/1					1/2	4/12	4/63	3/37	24/257
Total	40/367	25/145	28/136	3/13	6/19	7/18	3/4	12/26	15/80	58/318	44/310	60/532	301/1968
1960	5/42	3/9	1/2		1/2				3/8	6/21	2/6	7/27	28/117
1961	1/4	5/5	4/24						5/12	7/46	4/18	5/35	31/154
1962	5/14		1/4							9/54	4/10	5/101	24/183
1963	3/21	1/1	2/4	1/1					4/12	1/1	5/28	8/40	25/108
1964	9/50	3/15			2/3	1/4			2/7	5/11	6/33	4/25	32/148
1965	1/14		2/6	3/10					5/15	8/38	2/14	1/4	22/101
1966		1/1	3/10		2/8	1/1		2/3	5/15	2/15	2/29		18/82
1967	1/1	2/7				1/2		1/1	2/5		1/5	3/7	11/28
1968		2/2				2/3				1/4	3/8	1/11	9/28
1969	3/7		2/11		1/5				1/1	6/11		4/23	17/58
Total	28/153	17/50	15/61	4/11	6/18	5/10		3/4	27/75	45/201	29/151	38/273	217/1007

TABLE V—NUMBER OF OCCASIONS/TOTAL NUMBER OF HOURS OF DENSE FOG AT HEATHROW 1950–69

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Yearly total
1950	4/9	1/3	4/15							2/4	4/20	2/3	17/54
1951			1/5						1/7	7/19		3/16	12/47
1952	1/1	2/8	2/6							2/2	2/9	7/62	16/88
1953	4/10	3/5	4/19	1/4					1/3	5/19	2/9	2/9	22/78
1954									1/1		2/4	1/7	4/12
1955	1/1							1/4		2/8	2/7	3/12	9/32
1956	2/42									5/10	4/10	3/7	14/69
1957		1/2	1/2						1/1	3/21		2/20	8/46
1958										2/8	8/30	6/14	16/52
1959	4/23	5/25	1/2							1/1	5/41	4/8	20/100
Total	16/86	12/43	13/49	1/4				1/4	4/12	29/92	29/130	33/158	138/578
1960	3/4	1/4								2/4			6/12
1961			2/16							3/7	1/1	2/18	8/42
1962	1/5		1/2							2/6		6/80	10/93
1963				1/1					1/1		4/12	4/13	10/27
1964	3/10	1/3								1/1		1/2	6/16
1965	1/1			1/1						3/7	1/4		6/13
1966									2/2		2/3		4/5
1967											1/2		1/2
1968										1/1		3/5	4/6
1969	1/1		1/1							1/1		1/2	4/5
Total	9/21	2/7	4/19	2/2					3/3	13/27	9/22	17/120	59/221

In an attempt to show the general trend, Tables VIII and IX were produced, giving the five-year totals for the early and late fifties and sixties. Also included in these tables are the average yearly duration, the average yearly number of occasions of thick and of dense fog and the overall average duration.

Comparison of Table VIII with Table II suggests that, at Heathrow, the late fifties were not particularly notable for the number of occasions of fog formation, with slightly fewer than in the early sixties but once the fog had formed, there was a greater tendency for it to persist than during any of the other five-year periods considered. There was a great reduction in the incidence of both thick and dense fog during the late sixties (Table VIII).

At Kingsway/Holborn, Table IX shows that there, though there were fewer of them, the thick and dense fogs of the early sixties had a slight tendency to be more persistent than those of the late fifties. Again, the late sixties show a great reduction in both the number and duration of both thick and dense fogs.

TABLE VI—NUMBER OF OCCASIONS/TOTAL NUMBER OF HOURS OF THICK FOG AT KINGSWAY/HOLBORN 1950–69

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Yearly total
1950	1/9		2/12								3/30	1/6	7/57
1951	2/12								1/3	3/18		2/18	8/51
1952			1/6							1/3	2/9	5/81	9/99
1953	2/6	1/3	2/18						2/6	1/6	1/3	4/27	13/69
1954	1/3							1/3			1/3	1/3	4/12
1955	5/15									2/12		1/6	8/33
1956	2/36								2/6	4/15		3/33	11/90
1957										1/6		2/21	3/27
1958	2/12									3/9	3/15		8/36
1959	4/48	4/15	1/3							2/6	3/9	4/18	18/99
Total	19/141	5/18	6/39					1/3	5/15	17/75	13/69	23/213	89/573
1960	4/21			1/3						1/3			6/27
1961			3/12							1/6		1/9	5/27
1962										3/15		3/63	6/78
1963	2/6										2/12	2/18	6/36
1964	2/9				1/3					1/3	3/18	1/3	8/36
1965	1/3									4/18	1/3		6/24
1966	1/3								2/6	1/3			4/12
1967													0
1968												1/3	1/3
1969	1/3		1/3							1/3			3/9
Total	11/45		4/15	1/3	1/3				2/6	12/51	6/33	8/96	45/252

TABLE VII—NUMBER OF OCCASIONS/TOTAL NUMBER OF HOURS OF DENSE FOG AT KINGSWAY/HOLBORN 1950–69

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Yearly total
1950	1/9		1/3								3/18		5/30
1951	1/3									1/3		1/6	3/12
1952											1/6	5/69	6/75
1953			1/3						1/3	1/3		5/15	8/24
1954								1/3					1/3
1955												1/6	1/6
1956	1/6									2/6		2/15	5/27
1957										1/3		1/6	2/9
1958	1/3									1/3	1/3		3/9
1959	2/9											2/12	4/21
Total	6/30		2/6					1/3	1/3	6/18	5/27	17/129	38/216
1960	1/6												1/6
1961													0
1962												3/30	3/30
1963											1/3	1/6	2/9
1964													0
1965	1/3									1/3			2/6
1966													0
1967													0
1968												1/3	1/3
1969													0
Total	2/9									1/3	1/3	5/39	9/54

TABLE VIII—AVERAGE FOG OCCURRENCE AT HEATHROW

	Total duration	Average yearly duration	Number of occasions	Average yearly number	Overall average duration
1950–54	*hours*	*hours*			*hours*
Thick	973	195	164	33	6
Dense	279	56	71	14	4
1955–59					
Thick	995	199	137	27	7
Dense	299	60	67	13	4
1960–64					
Thick	710	142	140	28	5
Dense	190	38	40	8	5
1965–69					
Thick	297	59	77	15	4
Dense	31	6	19	4	2

TABLE IX—AVERAGE FOG OCCURRENCE AT KINGSWAY/HOLBORN

	Total duration	Average yearly duration	Number of occasions	Average yearly number	Overall average duration
1950–54	*hours*	*hours*			*hours*
Thick	288	57	41	8	7
Dense	144	29	23	5	6
1955–59					
Thick	285	57	48	10	6
Dense	72	14	15	3	5
1960–64					
Thick	204	41	31	6	7
Dense	45	9	6	1	7
1965–69					
Thick	48	10	14	3	3
Dense	9	2	3	1	3

The forecasting problem. This can be stated simply, as follows. When will fog form and, having formed, when will it clear? It is not intended here to go into the theory and classification of fog formation but merely to present information which might help forecasters to decide whether, in any given situation, thick or dense fog is climatologically likely to occur in the London area and at Heathrow in particular.

Table X shows all the occasions of thick fog which occurred at Heathrow during the sixties. Using dates as abscissae and times as ordinates, each figure in the table gives the duration of the thick fog which formed at the stated hour. Where thick fog had been recorded already on any given day, subsequent figures are in bold (e.g. on 23 November 1962 fog was observed at 00, 01, 02, 03, 04, 07 and 08 GMT; hence the 2 plotted at 07 GMT is bold). Where there were two or more thick fog formations at the same hour and date in different years, the first occasion is under the correct date and subsequent cases are off-set to the left, with brackets surrounding them (e.g. in three years thick fog formed at 05 GMT on 21 September).

Discussion. As there was such a reduction in the incidence of fog in the sixties, compared with the fifties, only the former will be discussed. Thick fog and dense fog will be treated separately.

(i) *Thick fog.* At Kingsway/Holborn there were only four occurrences of fog during the last three years of the decade. During the whole decade there was no thick fog during the months of February, June, July and August, only one case each in April and May, two in September and three in March. The thick fog season at Kingsway/Holborn is, therefore, October to January and even then, Table VI shows that thick fogs became comparatively rare and short-lived towards the end of the decade. Kingsway/Holborn was free from semi-persistent fogs after December 1962.

A glance at Table X shows that, at Heathrow, thick fog is unlikely to occur in the month of July. There is only a slight chance of it occurring in April, May, June and August and then only for an hour or two near sunrise. The main thick-fog season lasts from September to March, inclusive, and there was roughly four times more fog (formation and duration) at Heathrow than at Kingsway/Holborn. The main thick-fog months are now treated separately.

September. Table IV shows that September was the only month in which the number of thick fogs during the sixties exceeded that during the fifties, though the total duration was less during the sixties. All the thick fogs were first reported between 01 and 08 GMT. All the thick fogs had cleared by 11 GMT and the majority by 09 GMT.

October. The range of hours over which thick fog was first reported was greater in October than in September. On 15 October 1961, thick fog was first reported at 02 GMT and lasted until 14 GMT. The visibility then fell below the thick fog limit at 17 GMT and, except at 20 GMT, remained below the limit until after midnight. With the exception of this particular case of fog re-formation, thick fogs only formed* between the hours of 20 GMT and 08 GMT and most of them had cleared by 10 GMT. Note that thick fog was *observed* at Heathrow at all hours except 15 and 16 GMT in the sixties.

November. In November, thick fog was observed at all hours of the day and on 24 November 1966 a thick fog, which formed at 02 GMT, lasted until after 22 GMT. On 10 November 1964, there was a thick fog until 06 GMT and the visibility fell below the thick fog limit again at 16 GMT. Apart from this case, thick fog did not form between the hours of 09 and 18 GMT, inclusive. The majority of thick fogs cleared before 09 GMT.

December. On 26/27 December 1963, thick fog was reported from 18 to 11 GMT and formed again at 15 GMT. With this exception, thick fog did not form between 12 and 16 GMT, inclusive, though it was *observed* at all hours. The thick fog which formed at 18 GMT on 3 December 1962 persisted for 92 hours and was the longest persistent fog of the decade.

January. The majority of thick fogs cleared by 11 GMT. On days when thick fog had not been reported previously, the thick fog limit was not reached until 21 GMT but on days when it had been reported previously it re-formed as early as 17 GMT. There were no reports of thick fog between 13 and 16 GMT inclusive.

February. All morning thick fogs cleared before 11 GMT and no thick fogs formed between 10 GMT and 18 GMT, inclusive. Thick fog was not observed at either 00 GMT or 20 GMT. The longest duration was 7 hours from 03 GMT to 09 GMT on 14 February 1961.

March. There was only one period of semi-persistent fog. It lasted for 12 hours, starting at 21 GMT on 9 March 1961, after thick fog in the morning from 02 to 08 GMT. Thick fog was never observed between 12 and 20 GMT, inclusive.

(ii) *Dense fog*. Table VII shows that during the sixties dense fog formed at Kingsway/Holborn only 10 times compared with 38 during the previous decade. None was reported in any of the months from February to September, inclusive. There was one isolated observation in each of the months of October and November, each giving a nominal duration of three hours of dense fog. Six of the other occurrences were in December and three in January. This small sample suggests that dense fog is not likely to form in central London before midnight or to last much after 09 GMT. After 1962, there were only five dense fogs at Kingsway/Holborn and only one of these (in December

* 'Formed' is sometimes used in this article to mean 'was first reported' or 'was first observed'. Thus fog which 'formed' at 20 GMT might, in fact, have formed at any time after 19 GMT.

TABLE X—THE DURATION IN HOURS OF EACH OCCASION OF THICK FOG WHICH OCCURRED AT HEATHROW DURING THE DECADE 1960–69

September

Time GMT	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
00																														
01																					4	1								
02																								1				6		
03																		1					4						6	
04																									6					
05																			[4	6	3]	4	[1	6]		5				
06									1					1																
07		1								1				3		3	2					1		1			1			
08																			1											
09																														

October

Time GMT	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
16																															
17															8																
18																															
19																															
20																						1									
21																										9					
22																															
23									9							13	11														
00									11							11							1						4		
01															3		12											1		11	
02						[4	4	1]			1			[3	13]														6		
03																				1											
04		6			2				1													4	1								
05				1	[4	1]						5	1					1					7								
06					4	2															5					5					
07		2												3													2				
08					1												1				[3	1]									
09																															

November

Time GMT	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
16										4																				
17																														
18																														
19									6																					
20	13					3																					10			
21																		11			1	1								
22																												1		
23									3																					
00																							5							
01						9	1		5	6											5									
02				8							6													21						
03																			5							8				
04									7																1					
05										1			1																	
06																														
07	2			2																			2							
08																														3
09																														

December

Time GMT	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
15																											8				
16																															
17																													1		
18			92								4															18		1			
19										4																					
20	1																	4			3										
21									5																						
22										10																					
23		11											2			4	14														
00							4			2					22		1														
01	3								13							4								7			1				
02								1	3																			1			
03																															
04																											4				
05																			7							3					
06																						2									
07																															
08												3																			
09									1														2								
10																															
11	1							2						4																	

TABLE X—*continued*

January

Time GMT	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	
16																																16
17																					4											17
18	2																									1						18
19																																19
20							14																									20
21																			9													21
22					[1	14]														3					1							22
23			10			5															4			14								23
00																								[10	9]			4				00
01	5																									12						01
02																																02
03								4																								03
04			1		3																9								2			04
05				1								1																				05
06																																06
07																						3										07
08				5																												08
09																								2								09

February

Time GMT	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	27	27	28	29	
18																														18
19								1																						19
20																														20
21						3																								21
22																	1													22
23																									4					23
00																														00
01						4												6												01
02																														02
03						2																		5						03
04														6															5	04
05								6																						05
06			1														1													06
07																														07
08								1											1											08
09					2															1										09

Time GMT	March 4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	April 5	8	27	29	
20																						20
21						12																21
22								2														22
23																						23
00																		1				00
01																						01
02						7															6	02
03	6	1																				03
04	4				6																	04
05						4													3			05
06						5																06
07						1				3							3			1		07
08			4										1									08
09																						09
10				2																		10

Time GMT	May 3	4	9	13	28	30	June 3	14	15	24	30	August 16	17	25	
02															02
03	5					1								1	03
04			4	4					2	4	1				04
05		2					2	1					2		05
06					2										06
07												1			07
08															08

1963) extended over more than one consecutive three-hourly observation. Thus, dense fog, like semi-persistent thick fog, is now a rare phenomenon at Kingsway/Holborn.

At Heathrow, the reduction in the number and duration of dense fogs from the fifties to the sixties was not as spectacular as that at Kingsway/Holborn. Table V shows that the number and duration of dense fogs were each reduced by about 60 per cent in the second decade. Most of the dense fogs occurred during October, November, December and January. There were also a few dense fogs in February, March, April and September, the most serious being in 1961 when dense fog was observed from 02 to 07 GMT on 9 March and re-formed at 22 GMT and lasted until 05 GMT on 10 March with another observation at 07 GMT.

Singularities. As can be seen from Table X, during the sixties the greatest number of years in which thick fog formed at Heathrow on the same date in different years was four. These dates were 21 and 24 September, 22 October, 9 November and 9 March. During the fifties, the dates on which thick fog formed during four or more years on the same date were different. There were six years in which thick fog formed on 15 October and five years in which it formed on 12 October during the fifties. There is, therefore, little evidence of any singularities on particular days, though a glance at Table X suggests the possibility that some periods — especially during January and February — have been more favourable to thick fog than others, i.e. there was little or no fog between 9 January and 18 January, 30 January and 3 February, 9 February and 13 February, etc.

Effects of smoke control. The decrease in occurrence of fog in the London area has been attributed to the introduction of smoke control. Brazell[2] gives details of the number of hours of fog at Kingsway, Heathrow, Kew and Croydon for the years 1947 to 1962, inclusive, and discusses the effect of smoke control. The reduction in dense fog (see Table IX) at Kingsway during the late fifties, compared with the early fifties, suggests that the scourge of smog was being defeated already by smoke control in central London. As smoke control areas were extended, this improvement continued and, by the early sixties, the incidence of thick fog was being reduced. This trend continued during the late sixties.

At Heathrow, situated in an area where smoke control was not applied extensively until the early sixties, the improvement in the early sixties was only marginal. There was, however, a significant improvement during the the late sixties, suggesting a direct relationship between the extension of smoke control areas and the reduction in the number of formations and the duration of both thick and dense fog. Not only has the number and total duration been reduced but the average of the duration of the individual periods of fog has also been reduced (see Table IX).

Conclusion. At Kingsway/Holborn, dense fog is unlikely to occur at any time of year. Thick fog occurs most often between October and January, inclusive, but, once formed, will only last for an hour or two.

At Heathrow, the formation of both thick and dense fog is possible. Dense fog is not likely to occur during May, June, July or August and there is only a very slight chance of it occurring in April, the main dense-fog season being between October and January, inclusive. Thick fog is not likely in July but there is a slight chance of it occurring during April, May, June and August. The main thick-fog season is from September to March, inclusive.

If, as seems likely, the introduction of smoke control areas has been a major factor affecting the reduction in the frequency and opacity of fog at Heathrow, then, even during the winter half of the year, thick or dense fog will only last for a few hours, though there is still a slight chance that thick fog will be semi-persistent during November, December and January.

Acknowledgements. I wish to thank Mr J. Mearns for his invaluable help in assembling, calculating and checking the data used and also for the large amount of typing in which he has been involved. My thanks are also due to Mr I. Jenkins of London Weather Centre and Mr J. Richardson of Heathrow for their confirmation of monthly totals and help in answering queries regarding doubtful observations.

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Author's note. Since the completion of the above article, the following data have been received from Messrs Jenkins and Richardson at London Weather Centre and Heathrow respectively, giving the observations of thick and dense fog — hourly at Heathrow and 3-hourly at Holborn — during 1970.

		Thick		Dense	
		Period observed date/time GMT	Estimated duration *hours*	Period observed date/time GMT	Estimated duration *hours*
Holborn	Jan.	28/03–28/06	6	28/03–28/06	6
	May	09/06	3		
	Nov.	27/03	3		
Heathrow	Jan.	22/21	1		
		25/21–25/23	3		
		27/04	1		
		27/22–28/09	12	27/22–28/09	12
	Apr.	09/04–09/05	2		
	May	14/05–14/06	2		
	Sept.	28/05–28/06	2		
	Oct.	08/04–08/09	6	08/04	1
		12/06	1		
		18/07–18/08	2		
	Nov.	27/01	1		
	Dec.	13/05–13/07	3		
		13/09–13/12	4		
		13/15	1		
		14/09–14/13	5		

These observations are consistent with the conclusions of the foregoing article. The only notable event was the semi-persistent dense fog at Heathrow on 27/28 January, this being the first such occurrence since December 1962.

551.510:551.513.1:523.4

MOTIONS IN PLANETARY ATMOSPHERES: A REVIEW

By R. HIDE, F.R.S.

Introduction. The study of planetary atmospheres is concerned with their origin and evolution, the chemical composition of their main gaseous components, the nature and distribution of large particles in suspension, the mean temperature and pressure of the lower boundary and the nature of that boundary, the nature of small-scale turbulent motions, the nature of energy sources and the nature of large-scale organized motions. Each of these topics is closely linked with most of the others, and any subdivision of the subject of planetary atmospheres into separate areas is inevitably somewhat artificial. Nevertheless, it is of interest in connection with the interpretation of cloud photographs — such as those now being acquired by the International Planetary Patrol[1] — to discuss large-scale organized motions.

Hydrostatic equilibrium. Stable hydrostatic equilibrium of a fluid in a steady gravitational field is possible when

$$\nabla_H \rho = 0 \qquad \ldots (1)$$

and

$$\frac{\partial \rho}{\partial z} - \left(\frac{\partial \rho}{\partial z}\right)_{ad} < \Gamma_{crit}, \qquad \ldots (2)$$

where ρ denotes density, $\nabla_H \rho$ is the horizontal density gradient, $\partial\rho/\partial z$ is the (upward) vertical density gradient, $(\partial\rho/\partial z)_{ad}$ is the adiabatic density gradient.[2] Γ_{crit} represents effects due to damping caused by radiation, viscosity, thermal conductivity, etc.[3] and does not differ significantly from zero in the problems discussed below. The nature of the hydrodynamical flow that occurs when equation (1) and/or equation (2) are not satisfied depends on a wide variety of parameters, and the investigation of such flows constitutes a major part of the subject of 'geophysical fluid dynamics'.[3,4] Hydrodynamical flow occurs in planetary atmospheres because heat sources are present, so that the rather special conditions required for stable hydrostatic equilibrium cannot be met.

Heat sources. It is generally supposed that solar radiation is largely responsible for motions in the atmospheres of Venus, Earth and Mars. Define a dimensionless parameter

$$\tau = \overline{T}/\Delta T, \qquad \ldots (3)$$

where $\overline{T}$ is the mean temperature of the atmosphere and ΔT is the drop in $\overline{T}$ that would occur during one period of rotation if the heat source were suddenly cut off. When $\tau \ll 1$, as in the case of Mars,[5,6] the atmosphere has such a small thermal capacity that it is able to respond everywhere — even at the lowest levels (where the density is highest) — to the diurnal cycle of heating and cooling, so that a 'thermal tide' is a major feature of large-scale motions at all levels. When, on the other hand, $\tau \gg 1$, as in the case of Venus and Earth, the diurnal cycle of heating and cooling has little effect on large-scale motions in the bulk of the atmosphere, although strong thermal tides would occur at very high levels, where the density is low, if solar radiation is absorbed there, and may account for the 100-hour circulation of Venus inferred from ultra-violet observations[7] and for the so-called 'super-rotation' of the Earth's high atmosphere.[8] The parameter τ has little relevance for the atmospheres of the giant planets if, as now seems likely, internal heat sources are more important than solar radiation.

Rotational effects. The angular speed of rotation, Ω, of a planet enters the two dimensionless parameters :

$$R = U/L\Omega, \qquad \ldots (4)$$

a Rossby number[4] and

$$M = L\Omega/c, \qquad \ldots (5)$$

a 'rotational Mach number.[9,10] Here L is a characteristic horizontal dimension which, for large-scale motions, can be set approximately equal to the radius of the planet, U is a typical horizontal 'wind' speed relative to the rotating planet, and c is the speed of sound in the atmosphere. For all the planets $RM < 1$ (i.e. wind speeds are typically subsonic). For Venus $R \gg 1$ (and $M \ll 1$), so that dynamical effects due to rotation are small, while for Earth, Mars, Jupiter and the other giant planets (Saturn, Uranus and Neptune) $R \ll 1$ and rotational effects predominate. In the case of Earth and Mars, because M is not much greater than unity the shortest time scales associated with large-scale horizontal motions are typically not much greater than a few 'days' (1 day $= 2\pi/\Omega$ seconds), but in the case of the giant planets, for which $M \gg 1$, these time scales should be very much greater,[9,10,11] which accords with observations.[9]

Vertical stability. The vertical gradient of 'potential density', equal to the left-hand side of equation (2), is also of dynamical importance. When, as in the case of the Earth's atmosphere, this gradient is negative on average, the atmosphere is 'vertically stable', large-scale motions then being a consequence of equation (1) not being satisfied. The determination of the vertical stability of an atmosphere from first principles is a central theoretical problem, and it is now recognized that theoretical models that take into account heat transport by radiation and small-scale turbulence but neglect heat transport by the large-scale organized motions are inadequate.[12,13]

Venus, Earth and Mars.

Venus. The observation that the visible disc of Venus is covered with cloud implies that descending motions are probably restricted to localized regions. The most striking feature of thermal convection in a fluid heated non-uniformly from above is the organization of the descending motions into very narrow regions, with rising motions elsewhere,[14] and this result has been invoked to explain the cloud cover on Venus [15–18] and used as a basis for theoretical models of the deep circulation of Venus's atmosphere.[15,17,18] (See Plate I).

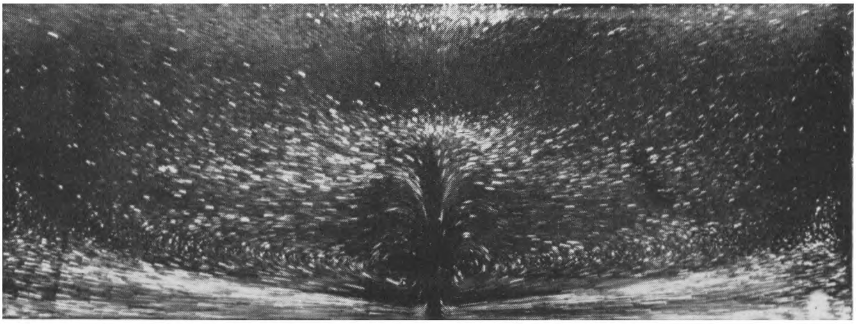
Some observers interpret the apparent motion of faint markings seen in the ultra-violet as evidence of a retrograde circulation of Venus's upper atmosphere with a period of about 100 hours.[7,19] The reality of this circulation is still in dispute, and it is important to investigate this matter further observationally. Theoretical work[13,20] on the nature of the circulation, if it exists, stems from a suggestion by Schubert and Whitehead[21] that the circulation is the rectified motion, due to non-linear effects, associated with the thermal tide in the tenuous outer atmosphere of Venus. (See also Reference 59.)

Earth. A great deal is known from direct measurements about the global circulation of the Earth's atmosphere, especially the lowest few kilometres — the troposphere — which contains most of the mass.[22] The *raison d'être* of the circulation is the convective transfer of heat from equatorial to polar regions; if the atmosphere did not circulate, differential solar heating would maintain the temperature contrast between pole and equator at several times the observed value. The Earth's rotation, as measured by the inverse of the Rossby number defined by equation (4), inhibits overturning motions in middle and high latitudes and thus constrains the flow to take the form of quasi-horizontal waves ('baroclinic waves' or 'sloping convection'[4,22]). Frontal systems and jet streams — so important in weather forecasting — are necessary concomitants of baroclinic waves, whose sharpening action is eventually regulated by the onset of small-scale instabilities,[23] which are often encountered as clear-air turbulence.

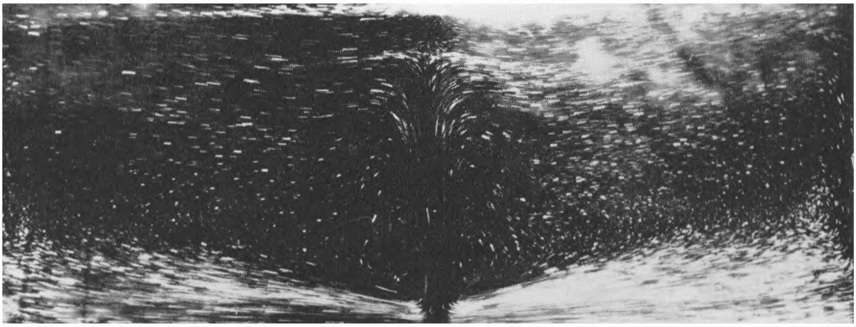
Mars. Observations bearing on motions in the Martian atmosphere are not easy to make and interpret and it will be important, therefore, to exploit theoretical models to the full. The most recent theoretical work is that of Leovy and Mintz,[6] who used the Mintz-Arakawa two-level model for integrating the primitive equations of fluid dynamics, thermodynamics and heat transfer on a high-speed electronic computer. Heating and cooling by solar and infra-red radiation were included, as were effects due to turbulent convection, although effects due to topography (which are probably quite important) were not taken fully into account.

Carbon dioxide is the main atmospheric constituent, and this was allowed to condense on the planet's surface, releasing latent heat where the surface cools to the frost-point. Two numerical experiments were performed, one for the southern Martian summer and the other for the southern autumn equinox. The solstice experiment gave strong zonal mean westerly (i.e. from the west) winds of up to 80 m/s in middle and high latitudes of the winter hemisphere (produced by the net eastward Coriolis torque that accompanied the poleward mass transfer of the condensing CO_2 polar ice-cap), baroclinic waves[4,17] in the winter hemisphere, a strong, thermally direct (i.e. hot fluid rising and cold fluid sinking) mean meridional circulation across the equator, with a strong east–west maximum near the equator and weak easterly winds over most of the southern hemisphere. The results for the equinox experiment are more like conditions in the Earth's atmosphere. In both hemispheres there are zonal mean westerly winds in the mid-latitudes with baroclinic waves in the middle and higher latitudes and easterly winds in the tropics. Large diurnal variations were found in both experiments.

Giant planets. Recent studies of motions in the atmosphere and interior of the planet Jupiter and the origin of his magnetic field include attempts to understand, in terms of hydrodynamical processes, ground-based observations of (i) the Great Red Spot and other less-persistent and generally smaller markings on Jupiter's visible surface,[10,11,24-33] (ii) the banded appearance of the visible surface[34-37] and the complicated and striking variation of rotation rate with latitude, including the pronounced equatorial jet,[24,38-41] and (iii) radio emission on decimetre and decametre wavelengths, especially the characteristic rotation periods of radio sources,[42-46] indicating the kind of theoretical advances[9,11,24,26,45-48] that should follow the acquisition of *(a)* better and more frequent photographs of the giant planets, *(b)* direct measurements of the strength and patterns of their magnetic fields, and *(c)* information about the electrical properties of their lower atmospheres and interiors. (See Plates II – IV).



(a)



(b)

PLATE I—STREAK PHOTOGRAPHS ILLUSTRATING THE STREAMLINES OF FLOW CAUSED BY DIFFERENTIAL HEATING OF THE LOWER BOUNDING SURFACE OF A NON-ROTATING FLUID

The middle half of this surface was heated and the remaining parts of the surface were cooled in a symmetrical fashion about the vertical plane through the middle of the apparatus. The other five plane bounding surfaces of the fluid were thermally insulated. The heating rate in case *(a)* was less than in case *(b)*. Note the tendency for the rising motion to occur in a narrow jet and for the horizontal flow near the bottom surface to occur in a thermal boundary layer.[14]

Theoretical models of the deep circulation of the atmosphere of Venus [15–18] stem from the theoretical considerations that led to the above experiments. When the heating and cooling take place at the upper surface, rather than the lower surface it is the descending motion that organizes itself into a jet and an ascending motion occurs throughout the remainder of the fluid. This type of circulation could account for the observation that Venus is almost completely covered with cloud.

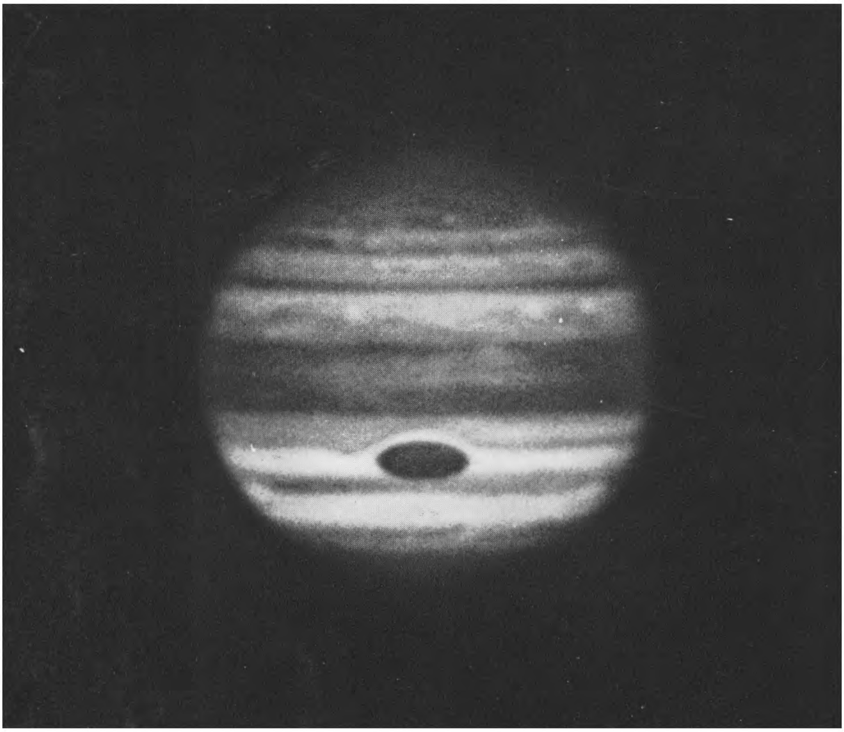


PLATE II—PHOTOGRAPH OF THE PLANET JUPITER TAKEN ON 23 OCTOBER 1964 AT 0905 UT

(Blue light, longitude 255° System 1, 21° System 2)

The Great Red Spot is a prominent feature of the southern hemisphere.

The discovery that the planet Jupiter rotates on its axis with a period of just under 10 hours was made in A.D. 1664, with the aid of one of the first telescopes capable of resolving markings on Jupiter's visible disc of dense ammonia clouds. Subsequent observations revealed that the rotation period of markings within a sharply bounded equatorial zone extending from about 10°S to 10°N is some 5 minutes less than the corresponding period for higher latitude regions of the visible disc (see Plate III). Various lines of evidence indicate that a roughly comparable equatorial current is present at high levels in the atmosphere of the planet Saturn.

Reproduced by courtesy of New Mexico State University

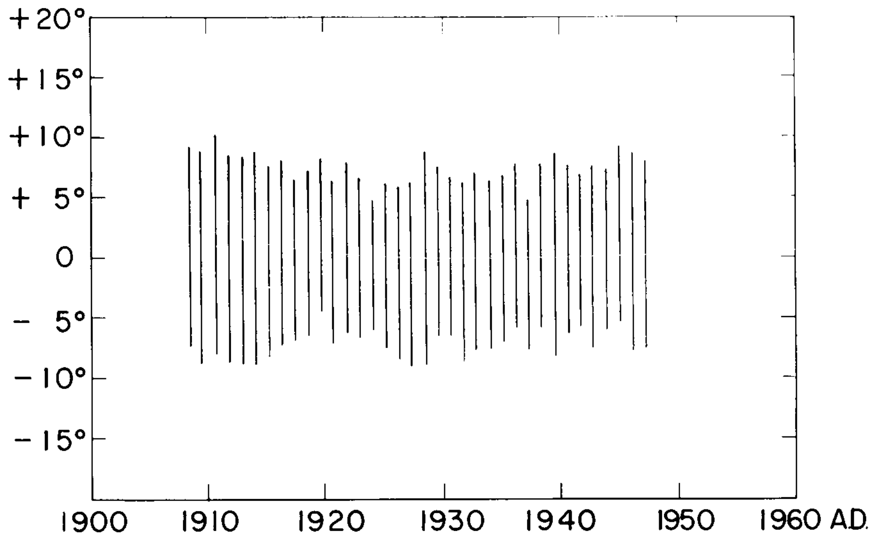


PLATE III—ILLUSTRATING APPARENT VARIATIONS IN WIDTH OF THE EQUATORIAL CURRENT OF JUPITER FROM 1907 TO 1947

Each line indicates the range of latitude occupied by the current (based on a table by Peek[49]).

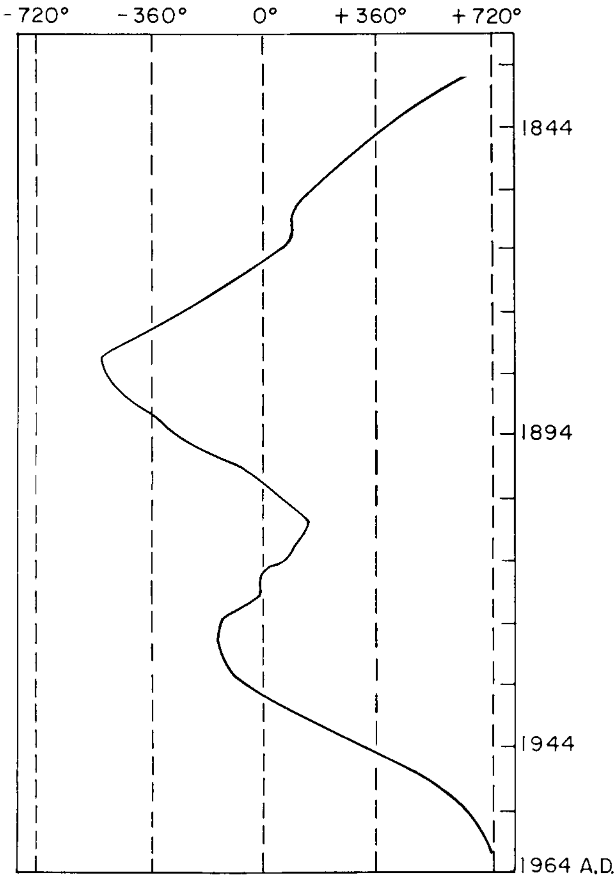


PLATE IV—WANDERINGS OF THE GREAT RED SPOT IN LONGITUDE, 1831 TO 1960

The abscissa is $\lambda_2 - 264{\cdot}3° + 28{\cdot}62°t$ where λ_2 is longitude in System 2 and t is measured in units of 399·88 days, the mean intervals between oppositions of Jupiter. The ordinate is time in years. (After Peek.[49])

According to Hide these wanderings could be a manifestation of variations in the rotation period of the underlying planet.[11 24]

Plates III and IV are reproduced by courtesy of B. M. Peek and Faber and Faber Ltd.

These studies have led to information about the deep interior of Jupiter *that may be obtainable in no other way.*[9,24,45,48,55] Horizontal and vertical transfer of angular momentum within Jupiter are implied by the existence of the equatorial jet, the motion of the Great Red Spot, and various characteristics of Jovian decimetre and decametre radio emission.[9,11,46] The (nearly) fixed latitude, but variable period, of the Great Red Spot[49] might be interpreted[46] as evidence of a gross magnetohydrodynamic torsional oscillation of Jupiter's internal layers involving a toroidal magnetic field of over 1000 gauss (but see reference 34). This field and the weak poloidal magnetic field of a few tens of gauss (at the visible surface) whose lines of force are not confined to the interior of the planet are produced in the lower atmosphere and/or in the metallic core of Jupiter,[9,46] if it is liquid, by magnetohydrodynamic dynamo action maintained by convection driven by gravitational energy release within the planet, involving a contraction in radius of the planet at the incredibly slow rate of 0·1 cm per year.[24,48,50-52] Thermal effects (due to ohmic heating) associated with quite moderate variations in Jupiter's internal magnetic field might give rise to detectable variations in the heat output from the planet,[46] but whether or not the observed variations are real and could be accounted for in this way requires further work. The importance of monitoring the total heat output from Jupiter and the other major planets cannot be over-emphasized.

The suggestion that the Great Red Spot is the end of a 'Taylor column'[25,27,28] in Jupiter's atmosphere[11] accounts for the observations in an unforced way without implying unlikely physical conditions in Jupiter's atmosphere and deep interior (contrary to conclusions advanced by Stone and Baker[29] whose discussion of the Taylor column hypothesis is based on an irrelevant theoretical model[9,26,27]). The nature of the associated disturbance deep in Jupiter's atmosphere and the interpretation of the long-period variations in the longitude of the Red Spot have been discussed by several writers.[9,11,24,31-33,45,46] The observation that the latitude of the Red Spot has not changed significantly places an important constraint on theories (a point which some writers have evidently overlooked). The short-period variations in the motion of the Red Spot[56] are small in amplitude and are most probably due to fluctuations in the position of the top end of the Taylor column relative to the bottom end.[26,33]

It is generally accepted that the banded appearance of Jupiter and Saturn reflects the influence of rotation on atmospheric motions, but no theoretical model that bears close physical scrutiny and comparison with the observations has yet been proposed. Wasiutynski[34] seems to have carried out the first theoretical investigation of this problem, in terms of a model characterized, among other things, by the assumption that, owing to internal heat sources, the lapse rate in Jupiter's atmosphere is superadiabatic. More recently, Stone[35] introduced a different model characterized, among other things, by the assumptions that differential solar heating is largely responsible for Jupiter's atmospheric motions, that the basic flow is mainly zonal, and that the lapse rate is subadiabatic and has a rather specific value.

Under these conditions the most unstable disturbances are axisymmetric and grow very rapidly, with typical growth times of a few rotation periods of the system. Stone[35] conjectures that Jupiter's banded structure reflects the presence of instabilities of this type after they have stopped growing, supposing that the main properties of the fully developed disturbances resemble those of the incipient instabilities. As the theory of fully developed disturbances has not yet been worked out, it is impossible to make a useful quantitative test of Stone's suggestion, which would seem, among other things, to imply horizontal temperature variations over Jupiter's visible disc that are considerably greater than those observed[53,54] and changes in Jupiter's appearance that would be very much faster than those observed.

Gierasch and Stone[40] cite as evidence in favour of Stone's explanation of Jupiter's banded appearance their claim that the axisymmetric disturbances invoked are capable of advecting zonal momentum toward the warmer parts of the fluid and thus provide a mechanism for driving the equatorial jet (see page 271). However, there are difficulties with these arguments. They are qualitative; only the direction and not the magnitude of the rates of momentum and heat transport have been assessed. Advective processes in directions perpendicular to the rotation axis are impossible when the flow is both geostrophic and axisymmetric,[55] for the simple reason that such processes are associated with motions perpendicular to the rotation axis, which in geostrophic flow must be supported by azimuthal gradients of pressure; such motions vanish when the pressure field is axisymmetric. It follows, then, that the advective processes invoked by Gierasch and Stone[40] must be associated with departures from geostrophy. While these departures are quite large for the rapidly-growing disturbances on which these authors base their analyses, they will be very much less for fully developed quasi-steady motions unless very strong horizontal shears develop in certain regions. It might be possible to find a reasonably efficient horizontal heat transfer mechanism by invoking strong shears, but when the spherical geometry of the system is taken properly into account, the qualitative mechanism proposed by Gierasch and Stone[40] for producing and maintaining the zonal momentum of the equatorial jet would seem to be physically impossible.[26,41]

The existence of equatorial jets in the fluid layers of rapidly rotating planets seems fairly general; Jupiter and Saturn exhibit such currents, and on Earth there is the equatorial undercurrent in the oceans and the equatorial jet in the lower stratosphere. These jets, which are now the subject of a great deal of theoretical research, are not yet fully understood. If the reasonable assumption is made that the essential vorticity balance is between horizontal advection of relative vorticity and effects due to the variation of Coriolis parameter with latitude, then $(Ua/2\Omega)^{\frac{1}{2}}$ is an approximate expression for the latitudinal width of a jet of typical flow speed U relative to a rotating planet of radius a; the expression agrees satisfactorily with observations.[24,26]

The jets in all probability represent sinks for energy and angular momentum originating at higher latitudes and advected horizontally toward the equator (but see Reference 59). Considerations of the general properties of thermally driven motions in a rotating spherical shell of fluid of outer radius a_0 and total angular momentum divided by its moment of inertia equal to Ω_0 indicate that in order to account for a westerly (i.e. faster than the basic rotation) equatorial jet without appealing to sinking motions from higher levels in the atmosphere, effects due to local azimuthal pressure gradients cannot be neglected. These pressure gradients provide the only forces (in the absence of magnetohydrodynamic effects) capable of increasing the angular momentum per unit mass of an individual fluid element to a value in excess of $\Omega_0 a_0^2$.

The fluid motions invoked by Schoenberg[57] and by Gierasch and Stone[40] in their attempts to account for Jupiter's equatorial jet, without invoking either a strong source of angular momentum deep within the atmosphere (which would conflict with the observed value of the 'radio period'[42-47]) or sinking motions in the high atmosphere above the jet, are characterized by symmetry about the axis of rotation, the concomitant pressure gradients having no azimuthal component. According to the foregoing arguments, only easterly jets could be accounted for in this way; the equatorial jets of Jupiter and Saturn are westerly.

The time scales on which non-permanent planetary-scale features undergo significant changes can be incredibly long in comparison with the time required for ordinary planetary waves to disperse the kinetic energy of a typical disturbance[9] (but not in comparison with the time required for effects arising in viscous boundary layers to produce significant dissipation, $D/(\nu\Omega)^{\frac{1}{2}}$ s, assuming that the depth of the atmosphere $D \approx 10^6$m,[9,11,46] and that the effective kinematic viscosity $\nu < 10^2 \mathrm{m^2/s}$). A completely satisfactory explanation of this discrepancy has not yet been given, but the following tentative lines along which an explanation might be sought were indicated several years ago.[9]

The usual theory of ordinary planetary waves applies to the case when M (see equation (5)) is zero, whereas M is as high as 10 for Jupiter and not much less for the other major planets, all of which rotate at hypersonic speeds with respect to the speed of sound in their outer, cooler, layers. When $M \neq 0$, the dispersion relationship for ordinary planetary waves has the form

$$\omega \approx -\beta k(1-\omega^2/k^2c^2)/[k^2+l^2+(f^2-\omega^2)/c^2], \qquad \ldots (6)$$

where ω denotes angular frequency, k and l the east–west and north–south wave numbers respectively, f the Coriolis parameter, β the rate of change of the Coriolis parameter with latitude, and c the speed of sound. This reduces when $M=0$ to the well-known 'Rossby-Haurwitz' formula, namely

$$\omega \approx -\beta k/(k^2+l^2). \qquad \ldots (7)$$

According to Hide,[9] typical periods associated with some of the oscillatory phenomena reported by Jupiter observers,[49,56] are, at several months, comparable with those expected on the basis of equation (6), but are considerably longer than those based on equation (7). Moreover, planetary waves in hypersonically rotating fluids lose their dispersive properties, as may be shown by setting $k^2+l^2 \ll f^2/c^2$ and $\omega^2 \ll k^2c^2$ in equation (6), according to which ω/k, the phase velocity, is then the same as the group velocity, $\partial\omega/\partial k$. It was in terms of this result that Hide proposed an explanation of the great duration of Jupiter's South Tropical Disturbance, which first arose in 1901 and gave way in 1939 to three prominent white spots[49] which can be seen at the present day.

Because Jupiter rotates very rapidly, atmospheric motions at the level of the visible surface of dense cloud should be highly correlated with the motions in the lower reaches of the atmosphere.[11,27] Therefore, the hypothesis that the latter motions play a significant role in the production of Jupiter's magnetic field (see page 272) can be tested by determining details of the configuration of the magnetic field and ascertaining the extent to which they are correlated with the appearance of the visible surface and with temperature variations at that level, an experiment which should be feasible as part of the projected Grand Tour programme.[58]

The central theoretical difficulty in all dynamical studies of motions in planetary atmospheres is that of understanding interactions between motions on different length and time scales. Current deficiencies in our knowledge of the scales of motion present in the atmospheres of the major planets (including the details of certain conspicuous features such as the edges of the strong equatorial currents on Jupiter and Saturn and Jupiter's Great Red Spot) will not be remedied until better photographs and thermal maps have been obtained over a long period of time. Owing to the great distance between the Earth and the giant planets, there is no observational evidence from which the scales of motion on Neptune can be deduced and indications of planetary-scale banded structure are vague in the case of Uranus, but are rather better for Saturn. There is (weak) evidence of a strong equatorial jet on Saturn (400 m/s, four times faster than Jupiter's equatorial jet), but its latitudinal width ($\approx 15°$ for Jupiter) has not yet been resolved; simple theory indicates that this width should be $\approx 30°$, and future observations will doubtless indicate whether or not this is so.

Amongst the programmes of fundamental research that will be essential if the best possible use is to be made of the data expected from the International Planetary Patrol[1] and the forthcoming Grand Tour[58] will be laboratory, mathematical, and numerical studies of the hydrodynamics and magnetohydrodynamics of rapidly rotating fluids (a strategy for which has been outlined elsewhere[26]). Interest in these difficult and still poorly developed areas of classical physics has resulted partially from observational work in dynamical meteorology, oceanography, geomagnetism and astrophysics (e.g. pulsars); and many examples of successful interactions between observational and theoretical work can be cited. Fluids that rotate at speeds not much greater than the speed of sound within them (e.g. atmospheres of Earth and Mars) differ fundamentally in their behaviour from fluids that rotate hypersonically, for example atmospheres of Jupiter and the other major planets, and it is therefore worth noting that the study of hypersonically rotating fluids remains an almost untouched area of fluid dynamics.

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TEMPERATURE DIFFERENCES BETWEEN A GROUND-LEVEL SITE AND A ROOF SITE AT NEWCASTLE UPON TYNE

By G. A. JONES

Summary. Extreme temperatures over the period June 1967 to May 1970 at a roof site at Newcastle Weather Centre were compared with those at a ground-level site at the University about 900 yards distant. The maxima at the two sites were within ± 1·5 degF on 88·2 per cent of days and showed some seasonal variation. The minima were within ± 1·5 degF on 82·9 per cent of days. The range of differences in minima was greater than that for maxima. With clear skies at night and light variable or calm winds on the Weather Centre roof the University minima are likely to be lower than the roof values. With clear skies at night and light to moderate south-west to north-west winds on the Weather Centre roof the University minima may be higher than roof values. There was a closer agreement in the extreme temperatures at the Newcastle sites than for corresponding comparisons at London and Southampton.

Introduction. Three years' temperature observations have now been recorded at the Newcastle Weather Centre roof site and these have been compared with readings at the University ground-level site, in much the same way as was done for temperatures at London[1] and Southampton.[2]

The sites. The two Newcastle sites are close to the city centre and are 900 yards* apart. At both sites the thermometers are contained in standard thermometer screens. Readings are in Celsius at the Weather Centre and in Fahrenheit at the University. The Celsius readings have been converted to Fahrenheit for convenience in comparing readings with previous work. The main results are quoted in Celsius elsewhere in the text.

The Weather Centre screen is anchored to a flat asphalt roof, 100 feet ($\approx$30 m) above street level. The roof in the immediate vicinity measures 24 feet by 15 feet and is surrounded by an iron railing, 3 feet 6 inches high. The roof, although not the highest in the city, overlooks many buildings and the screen is well exposed to the elements.

The University site is not ideally exposed but on the other hand is representative of a sort of garden environment in a tree-lined city square.

* Distances and heights are given in traditional British units. Conversion factors to metric units are : 10 yd $\approx$ 9·1 m; 1 ft = 0·3048 m; 1 kt $\approx$ 0·5 m/s.

The site is about 50 yards square surrounded by trees and enclosed by 6-foot wooden palings. The trees are deciduous, the majority being sycamores, and are about 40 feet high. The screen is near the centre of the enclosure and next to a disused concrete tennis court. The remainder of the enclosure is taken up with long grasses and scattered bushes. Around the whole square there is a road, beyond which on three sides are terraced houses. To the north-west is a large area of open ground — the Town Moor.

Maximum temperatures. The differences between the maximum temperatures (09–09 GMT), at the two Newcastle sites are shown in Table I.

TABLE I—MONTHLY AVERAGE DIFFERENCES IN MAXIMUM TEMPERATURES READ AT THE UNIVERSITY AND WEATHER CENTRE, JUNE 1967 TO MAY 1970

	Difference in maximum temperatures (University values minus Weather Centre values)		
	1967–68	1968–69	1969–70
		degrees Fahrenheit	
June	+1·3	+1·1	+1·2
July	+1·0	+0·6	+0·5
August	+0·5	+0·6	+0·2
September	+0·5	+0·1	−0·3
October	0·0	−0·2	−0·3
November	−0·2	−0·3	−0·3
December	−0·1	−0·4	−0·5
January	−0·4	−0·5	−0·3
February	−0·1	−0·1	+0·1
March	+0·7	0·0	+0·5
April	+0·9	+0·4	+0·9
May	+0·8	+0·4	+0·7

The greatest differences were mainly in the spring and summer, when the University maximum temperatures were on the average up to 1·3 degF higher than the Weather Centre readings. The autumn and winter differences showed a tendency for the University maxima to be a little lower than the Weather Centre values. March 1969 was cold and more like a winter month, so that in the spring of 1969 the difference did not become positive until April.

Table II summarizes the daily differences between the maxima at the two sites, the readings having been rounded off to the nearest whole degree Fahrenheit.

TABLE II—NUMBER OF DAYS (09–09 GMT) WITH SPECIFIC MAXIMUM TEMPERATURE DIFFERENCES, ROUNDED TO NEAREST WHOLE DEGREE FAHRENHEIT, AT THE UNIVERSITY AND WEATHER CENTRE, JUNE 1967 TO MAY 1970

Difference* *degF*	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Total	
						number of days								*per cent*
−3				1			1	1					3	0·3
−2			2	2	1	3	1	7	2	1		2	21	1·9
−1	2	7	7	22	33	26	25	25	17	7	7	12	190	17·3
0	11	27	44	35	43	52	41	55	46	49	28	23	454	41·4
+1	49	43	32	26	13	7	19	4	19	33	36	42	323	29·5
+2	21	13	6	4	1	2	6		1	3	14	12	83	7·6
+3	5	2	2		2			1			5	2	19	1·7
+4	2	1											3	0·3

* University values minus Weather Centre values.

Table II reveals that the maxima at the two sites were within ±0·5 degF on 41·4 per cent of the days and within ±1·5 degF on 88·2 per cent of the days.

Maxima differences of more than 1·5 degF occurred on 129 days and 88 of these, occurring in the spring and summer, gave higher temperatures at the University site

Minimum temperatures. Similar comparisons of minimum temperatures are set out in Tables III and IV.

TABLE III—MONTHLY AVERAGE DIFFERENCES IN MINIMUM TEMPERATURES READ AT THE UNIVERSITY AND WEATHER CENTRE, JUNE 1967 TO MAY 1970

	Difference in minimum temperatures (University values minus Weather Centre values)		
	1967–68	1968–69	1969–70
		degrees Fahrenheit	
June	0·0	+0·1	+0·2
July	+0·6	−0·3	+0·4
August	+0·2	0·0	−0·1
September	+0·5	−0·2	−0·2
October	+0·5	−0·1	+0·2
November	+0·1	−0·1	−0·3
December	0·0	−0·4	−0·2
January	+0·1	0·0	+0·2
February	−0·2	+0·2	+0·1
March	+0·3	−0·2	+0·1
April	−0·3	−0·4	+0·3
May	−0·8	−0·2	+0·2

The differences in minima were on the average well within ±1·0 degF, and unlike the differences in maxima, there were no seasonal variations.

TABLE IV—NUMBER OF DAYS (09–09 GMT) WITH SPECIFIC MINIMUM TEMPERATURE DIFFERENCES, ROUNDED TO NEAREST WHOLE DEGREE FAHRENHEIT, AT THE UNIVERSITY AND WEATHER CENTRE, JUNE 1967 TO MAY 1970

Difference*	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Total	
degF						*number of days*								*per cent*
−6						1						1	2	0·2
−5					1		1	1	1	1	2	2	9	0·8
−4	2	1	1			3			1	1	2	2	13	1·3
−3	3	2	1	5	4		3	3	3	6	7	4	41	3·7
−2	4	4	5	6	2	4	9	1	7	3	2	6	53	4·8
−1	10	10	18	14	15	13	14	13	9	8	16	9	149	13·6
0	37	30	33	27	27	45	45	42	28	37	24	30	405	36·9
+1	28	39	30	30	38	19	15	30	32	30	29	35	355	32·4
+2	5	4	5	8	5	5	6	2	3	5	7	3	58	5·3
+3	1	2						1	1		1	1	7	0·6
+4		1								2			3	0·3
+5					1								1	0·1

* University values minus Weather Centre values.

On 36·9 per cent of the days the differences in minima were within ±0·5 degF and on 82·9 per cent of the days the differences were within ±1·5 degF. The range in minima differences was greater than the range of differences in maxima. There were 4 days when the minimum at the University was more than 3·5 degF higher than at the Weather Centre and 24 days when it was more than 3·5 degF lower.

Comparison with roof sites at London and Southampton. There was a closer agreement in the extreme temperatures at the two Newcastle sites than for similar comparisons at London and Southampton. On 41·4 per cent of the days the daily differences in maxima between the two Newcastle sites lay between ±0·5 degF compared with London 25·2 per cent and Southampton 26·5 per cent. With regard to the minima, the comparable percentages for the differences between ±0·5 degF are, Newcastle 36·9, London 13·7 and Southampton 30·6 per cent.

At Newcastle the peak number of days occurred when the daily differences of maximum and minimum temperatures were 0 degF. However, at London and Southampton the peaks occurred at roof maxima about 1 degF below the values at ground level and at roof minima about 1 degF above the values at ground level.[1,2]

The height differences between the roof and ground-level sites at Southampton, Newcastle and London are 33 feet, 101 feet and 122 feet respectively, and it seems that up to 100 feet or so over cities there is no universal relationship between temperature and height. Other factors such as size and distribution of buildings, their thermal capacities, seasonal changes in vegetation in city squares, local topography and so on must be playing an important role in the heat budgets, so that each city has its own peculiar lapse rates.

Temperature extremes between the two Newcastle sites. Continuous temperature readings are available from the Weather Centre roof but extremes are read only once a day at the University, and although on a climatological basis the 24-hour extreme temperatures at roof level are close to those at ground level, there is a need for the forecaster to be aware of the odd occasions when large temperature differences may occur, especially in the minima.

The Weather Centre hourly temperatures were examined on the 11 days when the University minimum readings were lower by more than 4·4 degF and on the 11 days when they were higher by more than 2·4 degF, in order to find the probable time of the minima. A note was then made of the cloud and wind observed on the Weather Centre roof for the preceding 12 hours, together with the geostrophic wind at the main synoptic hours. The 09 GMT temperatures at the two sites were also examined.

It was found that 17 of the 22 cases were associated with less than 4/8 mean amount of low cloud. The other 5 cases had a mean of 5/8–7/8 but with breaks to less than 4/8 at times. The cases when the University site was colder were associated with light and variable breezes at roof level and sometimes calm conditions. The geostrophic winds were south-easterly or else were westerlies that became light and variable. However, it would appear that the lower minima at the University were only a temporary feature, since by 09 GMT, except for one case, the University temperatures had recovered and slightly overtaken the Weather Centre values.

In contrast, on the days when the University reported higher minima the light to moderate roof-level wind speed continued throughout the night with directions from between south-west and north-west. The geostrophic winds were from between south-west and north-north-east and varied between 15 and 44 kt. The 09 GMT readings gave higher University values on all 11 days.

From these extreme cases it appears that on some clear nights, lapse rates to at least 100 feet over Newcastle are related to the speed and direction of the wind and resulting turbulence, stable conditions being associated with calm or light and variable breezes and unstable conditions with light to moderate breezes from between south-west and north-west. This latter unstable state could be a decisive factor in preventing (or clearing) radiation fog.

It may be that on many other occasions of clear skies the wind is also an important factor but to a lesser degree, i.e. all those cases when the temperature differences between roof and ground level were less than the 2·4 degF and 4·4 degF extremes. The following tentative rules are suggested concerning Newcastle minima :

Rule 1. With clear skies at night and light and variable or calm winds on the Weather Centre roof, the University minima are likely to be lower than the roof values (6 degF (3·3 degC) lower is possible but rare) but with University temperatures recovering during daylight.

Rule 2. With clear skies at night and a persistent light to moderate south-west to north-west wind on the Weather Centre roof, University minima may be higher than roof values (3 degF (1·7 degC) higher is possible but rare).

Conclusions. The temperature differences at the two Newcastle sites over a period of three years were compared and the following results obtained :

(i) Maximum temperatures differed on the average for the month by small amounts and the differences showed a seasonal variation.

(ii) On a day-to-day basis 88·2 per cent of the roof maxima and 82·9 per cent of the minima were within ±1·5 degF (±0·8 degC) of the University ground-level values, but the range of differences in the minima was greater than that in the maxima.

(iii) Most of the differences greater than 1·5 degF (0·8 degC) gave higher maxima at the University in the spring and summer.

(iv) The differences in extreme temperatures between roof and ground level were in closer agreement than for similar comparisons at London and Southampton.

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551.509.323

A COMPARISON OF METHODS OF FORECASTING NIGHT COOLING AT SCREEN LEVEL

By W. E. SAUNDERS

Summary. Recent tests of night cooling forecasting methods are reviewed. It is shown that there is considerable spatial variation of accuracy in the use of the Saunders method, and that at present this method appears to be least accurate at stations bordering on the Fens.

In recent years, the night cooling forecasting procedure suggested by the author,[1] and afterwards adapted for widespread use by Barthram[2] and Tinney and Menmuir,[3] has been tested at a number of stations and compared with methods due to McKenzie[4] and Craddock and Pritchard.[5]

It has been thought worth while to bring these test results together to see what conclusions might be reached, and this has been done in Table I.

In Table I, the results included are those of actual forecasts made before the event, and so incorporate errors in forecasting the wind speed and cloud amount, as well as those inherent in the methods.

The tests have been numbered in order of publication for ease of reference. In order to simplify comparison, the values of root-mean-square error or

TABLE I—RECENT TESTS OF NIGHT COOLING METHODS

Test No.	Authors	Stations tested	Forecasting method: Saunders (Standard deviation)	Saunders (Root-mean-square error, degrees Celsius)	McKenzie (Root-mean-square error, degrees Celsius)	Craddock and Pritchard (Root-mean-square error, degrees Celsius)
1.	Gordon and Virgo[6]	Mildenhall	—	2·16	2·09	—
2.	Steele, Stroud and Virgo[7]	Cottesmore	1·24	—	—	—
		Lindholme	1·39	—	—	—
		Finningley	1·45	—	—	—
		Scampton	1·64	—	—	—
		Waddington	1·66	—	—	—
		Wittering	1·72	—	—	—
		Bassingbourn	2·00	—	—	—
		Mildenhall	2·06	—	—	—
		Marham	2·24	—	—	—
		Wyton	2·40	—	—	—
3.	Gordon, Perry and Virgo[8]	Mildenhall	—	—	2·14	2·30
4.	Abbott[9]	South-west England	—	1·90	—	—
5.	Ritchie[10]	Wyton	—	2·60	2·60	—

standard deviation given separately for different seasons or types of occasion in the test reports have been meaned in Table I. Generally, in this work, the differences between root-mean-square error and standard deviation are very small.

The list of standard deviations included in Test 2 is the mean of the standard deviations for clear and cloudy nights for summer and winter periods given in Tables I and II of Reference 7. Stations have been arranged in ascending order of standard deviation. The outstanding feature of this table is the wide variation between the results for the station where the highest accuracy was obtained (Cottesmore) and the station whose results were least satisfactory (Wyton).

The authors of Test 3, after referring back to Test 1, concluded that there is very little to choose between any of the three methods in practice. The author of Test 5 found it surprising, in view of the speed and simplicity of the McKenzie method, that tests should show little to choose between the methods.

However, reference to the results of Test 2, as presented in Table I, shows that one aspect which requires to be emphasized is that Tests 1, 3 and 5 all refer to two stations, Mildenhall and Wyton. These stations are at the lower end of the spectrum, where for some reason the Saunders method is decidedly less accurate than at many other stations. It may of course be that all three methods work equally well at all stations, but this is not demonstrated or implied in any of the published tests.

In Test 4, the root-mean-square error included is the mean of the root-mean-square errors for Day 1, taken from Table II of Reference 9. This is of special interest, as the technique has been used here for forecasting a mean minimum temperature for four stations. Also, these were operational forecasts issued before 09 clock time, so that maximum temperatures and dew-points at the time of maximum temperature used in the forecasts would themselves have had to be forecast, instead of actual values being used. Hence the root-mean-square error compares very well indeed with the others reported.

Reverting to Test 2, the common feature between stations where the lowest accuracy is obtained using the Saunders method appears to be their position near the edge of the Fens, as shown in Figure 1. This is certainly the case with Mildenhall and Wyton, the stations used in Tests 1, 3 and 5. Possibly, reduced accuracy at these stations might be due to a significant number of occasions when evening or night drift from the Fens renders the starting data non-representative for the station. It might be necessary to deal with these cases in the way that coastal stations with on-shore winds are dealt with. Detailed analysis of forecast errors at one of these stations might perhaps reveal what could be done to improve the results.

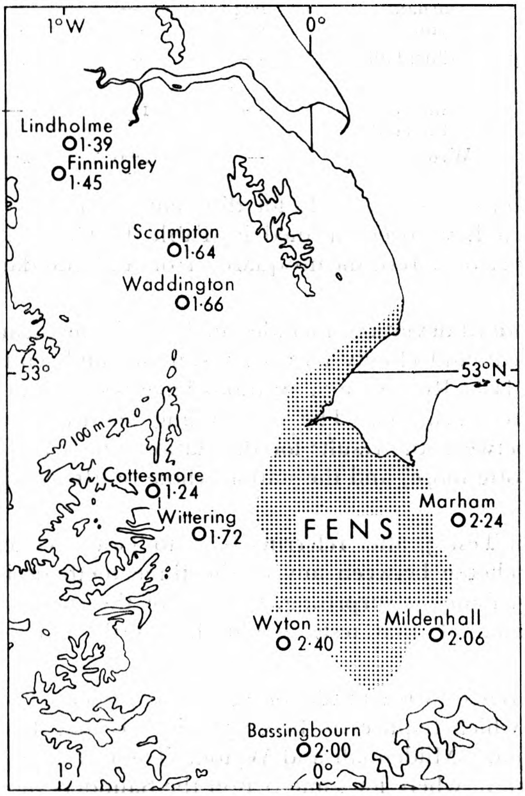

FIGURE 1—SPATIAL DISTRIBUTION OF STANDARD DEVIATION, DEGREES CELSIUS, IN TEST OF SAUNDERS METHOD BY STEELE, STROUD AND VIRGO

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OBITUARY

It is with regret that we have to announce the death of Mr R. E. Barden, Senior Scientific Assistant, Gatwick, on 26 May 1971.

REVIEW

Introduction to meteorological optics, by R. A. R. Tricker. 215 mm × 175 mm, pp. 285, *illus.*, Mills and Boon Ltd, 17–19 Foley Street, London, W1A 1DR, 1970. Price: £4·20.

Strange optical phenomena in the sky have been a source of fascination to the mind of man from the earliest times, yet even today there are some phenomena whose origin is not fully understood. The fact is that although, as Dr Tricker points out in the preface to his book, special observatories for the study of meteorological optics were set up on the tops of mountains in the last century, interest has since been diverted to other fields of study. Nevertheless, the need for both careful observation and adequate theoretical exploration of optical phenomena occurring in nature still remains.

In *Introduction to meteorological optics*, Dr Tricker endeavours to fill a gap in the literature on this subject. He not only describes the principal phenomena which have been observed, but also seeks to show how they arise and to give the relevant mathematical analysis. In doing so, he assumes that his readers have a good knowledge of algebra and elementary trigonometry, together with some knowledge of differential calculus. This seems a good level to start from, since it is sufficiently advanced to allow the author to discuss quite complicated problems, but sufficiently general to allow most readers with a scientific background to follow his argument.

The text itself is interspersed with a number of thought-provoking comments, especially on the need for careful observation. For instance, Tricker says, 'The rainbow furnishes a good example of how observation is guided by theory — and not always to the advantage of the former. The Cartesian theory proved so successful . . . . that the fact that it failed to indicate many other accompanying features' (e.g. the variable apparent width and brightness of the bow and variations in the intensity of the colours) 'was overlooked.' Again, in the chapter on the glory, Tricker remarks that some of the early drawings 'cast a very candid light on the power of man's observation.' He then reproduces a drawing made of the glory by a Spanish Captain Ulloa who observed the phenomenon from the top of a mountain in Peru in 1735.

In this drawing the glory is represented as if the observer had seen it around the shadow of a companion's head, although in fact one can only ever see a glory around one's own head!

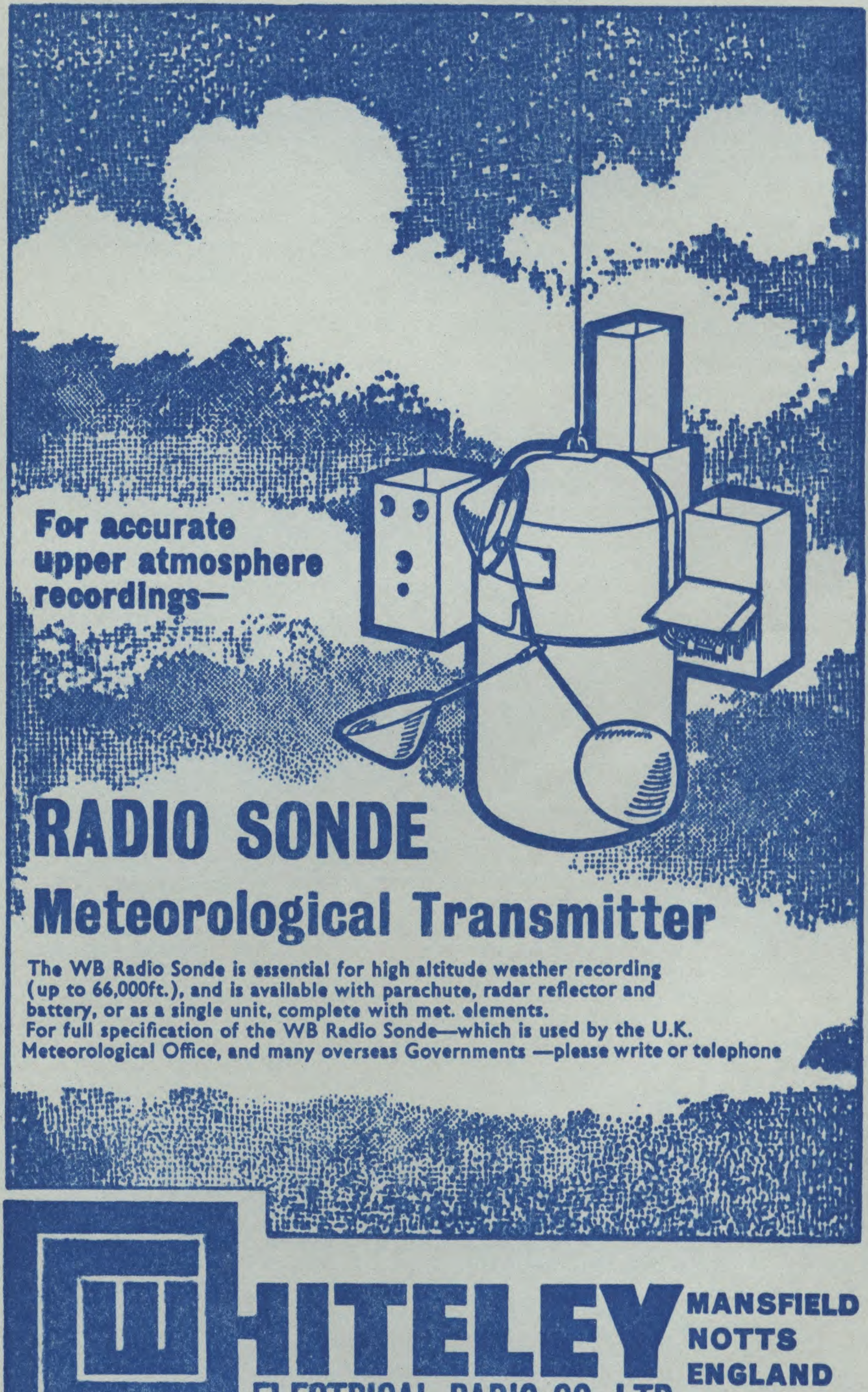
There are, however, several aspects of this book which are rather disappointing. For example, the colour plates used to illustrate the rainbow and the glory are rather insipid and many of the other phenomena are not illustrated at all. There is a lack of sub-headings which makes the text unnecessarily difficult to follow, especially in the long chapter on ice-particle haloes. There is also a chapter on the Mie theory for the scattering of light by small droplets which is rather out of place in this book since the theory is probably too difficult for the general reader, whilst the specialist would be inclined to look elsewhere for a treatment of this particular topic.

Despite these criticisms, Tricker's treatment is for the most part clear and convincing. It is perhaps only a little unfortunate that, whilst he is quick to point out the short-comings of earlier discussions of the heiligenschein, he fails to give credit to Minnaert who put forward the same explanation in his book on *Light and colour in the open air.*

The weakest part of the book is probably the section where Dr Tricker propounds a new theory for some of the unusual features of ice haloes. Here he strongly criticizes the theories given by previous workers and suggests that the explanation lies in the existence of ice crystals in the form of elongated hexagons which spin about their longest horizontal axes as they fall through the air. I am, however, not at all sure that Tricker's strictures of early theories are entirely justified. Nor does it seem likely that spinning crystals of the type he proposes exist in significant numbers in natural clouds and, even if they do, it is not clear how they differ from randomly oriented platelets.

Nevertheless, this book can be welcomed as it undoubtedly goes part way to filling a gap in the literature and should do much to encourage careful observation and to revive interest in this most intriguing branch of meteorology.

J. T. BARTLETT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AN ASSESSMENT SCHEME FOR AERODROME FORECASTS

By P. B. WRIGHT

Summary. A method is described which enables an assessment to be made, in a broad sense, of the usefulness of a set of terminal aerodrome forecasts. The test is confined to the elements of visibility, surface wind and low cloud, and the scoring system is such that an error in the neighbourhood of values critical for the landing and take-off of aircraft is marked more harshly than an error in another part of the range. The scheme also takes into account the use of PROB, TEMPO and INTER in a way which simulates the loss of value to the customer of a reduction in the preciseness of the forecast.

Introduction. This scheme is intended to assess the accuracy and usefulness of a terminal aerodrome forecast (TAF).* It has been devised in such a way that it is possible to :

(i) compare the accuracy of one set of TAFs with that of another, and
(ii) point out the occasions on which the TAFs are so badly in error that a study of the synoptic situation is called for.

Outline of the system. The assessment is confined to the elements of visibility, surface wind and low cloud. It has been assumed that conditions of visibility <4 km, wind speed $\geqslant 20$ kt,† or cloud 4–8 oktas below 1000 ft might lead to diversion of aircraft, and scales have been devised such that an error in the neighbourhood of the critical values is marked more harshly than one in another part of the range.

The scheme verifies the TAF at a particular time; it does not attempt to give an overall assessment. The method is thus akin to random sampling and tests the ability of a forecast, designed to apply to a continuous period, to predict the weather at a particular moment (or a finite number of moments) during that period. Thus, strictly, the accuracy of the forecast is not tested, but it is assessed in the way that it is often actually used by someone requiring a knowledge of the weather at specific times for planning purposes.

Briefly, the range of possible values of each element is divided into categories; a score of 10 points is awarded if the forecast weather is in the same category as the actual weather, with scores decreasing to zero as the difference between forecast and actual categories increases. The categories are chosen with relatively narrow ranges of values in the neighbourhood of the critical values quoted above. Probabilities are dealt with in such a way that a forecaster

* See : London, Meteorological Office. Handbook of weather messages (Met. O. 510b), 6th Ed. 1971 (in press) or WMO No. 9 TP4 Volume B, 1971, for details.
† 1 kt $\approx$0·5 m/s.

cannot increase his average score by simply putting additional PROBs in every forecast, although he can reduce the number of occasions on which he gets a zero score. TEMPO and INTER are treated as if they were PROB 40.

The method.

Practical details. If it is desired to assess the TAF for midnight the first step is to extract from the TAF message the forecast information referring to midnight. The forecast may be for a specific value of each element and in this case the forecast is verified as follows :

(i) *Visibility.* Find the forecast category and the actual category from Table I. Calculate the error (E_v) as forecast category minus actual category, except that E_v is zero if

(a) actual visibility is less than 6 km and difference between forecast and actual is $\leqslant$ 200 m,

(b) actual visibility is from 6 to 10 km inclusive and the difference between forecast and actual is $\leqslant$ 2 km, or

(c) actual visibility is $>$ 10 km and difference between forecast and actual is $\leqslant$ 4 km.

(ii) *Wind.* First consider wind speed and find the forecast and actual categories according to Table II. Calculate the error E_s as forecast category minus actual category, except that E_s is zero if the difference between forecast and actual values is $\leqslant$ 4 kt. Find the wind direction error E_d from Table III; if the actual wind is calm $E_d = 0$. The wind error is then given by $|E_s| + E_d$.

(iii) *Cloud.* This element is rather more difficult to assess than the others because of the complex nature of the forecasts and the possible presence of two or more layers. If only one layer is involved, find the cloud error E_c from Table IV. If two or more layers are involved the following rules should be applied :

(a) Two layers of cloud are treated as identical if their amounts differ only within one of the ranges 1 to 3 oktas or 4 to 8 oktas and their heights differ only within one of the ranges 0 to 500 ft, 600 to 1000 ft, 1100 to 1500 ft or 1600 to 2000 ft.

(b) If one layer has to be compared with two layers, compare the one with each in turn and take E_c as the larger error.

(c) If 'sky obscured' is forecast, it may be taken as equivalent to '8 oktas at 100 ft' if this seems reasonable in the particular case. If 'sky obscured' occurs, it is taken as equivalent to '4–8 oktas at 0–500 ft' if the latter was forecast. In all other cases 'sky obscured' is indeterminate.

The score. For each element, the score $= 10-2|E|$, with a minimum possible value of zero. Negative score values are counted as zero.

Gradual changes. Suppose the forecast includes the expression 'GRADU from t_1 to t_2', denoting a gradual change in the value of an element or elements during the period t_1 to t_2. When verifying for midnight, if t_2 is midnight the gradual change is assumed to have been completed. If t_1 is midnight the change is assumed not to have started. If t_1 is before and t_2 after midnight the value of the element is interpolated between the extreme values forecast.

TABLE I—VISIBILITY CATEGORIES

Visibility	Category value
⩽100 m	1
200–300 m	2
400–600 m	3
700–900 m	4
1000–1300 m	5
1400–1700 m	6
1·8–2·2 km	7
2·3–2·7 km	8
2·8–3·3 km	9
3·4–3·9 km	10
4·0–4·6 km	11
4·7–5·9 km	12
6–8 km	13
⩾9 km	14

TABLE II—WIND SPEED CATEGORIES

Speed *kt*	Category value
0–6	1
7–12	2
13–16	3
17–19	4
20–25	5
26–35	6
⩾36	7

TABLE III—WIND DIRECTION CATEGORY ERRORS (E_d)

Error in direction	Actual speed *kt*			
	⩽6	7–12	13–19	⩾20
degrees	Category error E_d			
⩽20	0	0	0	0
30–40	0	0	1	2
50–60	0	1	2	4
70–90	0	2	3	5
100–120	1	2	4	5
130–180	1	3	5	5
F/c direction variable	0	1	3	5

TABLE IV—CLOUD CATEGORY ERRORS (E_c)

Actual cloud		Forecast cloud								
oktas	*hundreds of feet*	0	1–3* 16–20†	1–3 11–15	1–3 6–10	1–3 0–5	4–8 16–20	4–8 11–15	4–8 6–10	4–8 0–5
		Category error (E_c)								
0		0	½	1½	2½	3½	2	3	4	5
1–3	16–20	½	0	½	1½	2½	1	2	3½	5
1–3	11–15	1½	½	0	½	1½	1½	1	2½	4
1–3	6–10	2½	1½	½	0	1	2½	1½	1	2½
1–3	0–5	3½	2½	1½	1	0	3½	2½	2	1½
4–8	16–20	2	1	1½	2½	3½	0	1½	2½	3½
4–8	11–15	3	2	1	1½	2½	1½	0	1½	2½
4–8	6–10	4	3½	2½	1	2	2½	1½	0	1½
4–8	0–5	5	5	4	2½	1½	3½	2½	1½	0

* Top row : oktas † Bottom row : hundreds of feet.

Qualifying statements. The forecast for midnight may include a qualifying statement, for example, 'visibility 10 km with a 40 per cent probability of 2 km'. The first value (10 km) is called the PRIMARY, the other value the SECONDARY. The definition of the error *(E)* is now modified to be the category difference between the PRIMARY and ACTUAL, and the difference *(R)* is defined similarly except that the comparison is between PRIMARY and SECONDARY. TEMPO and INTER are assumed for this purpose to be equivalent to a 40 per cent probability. The procedure is now as follows :

First calculate *R* and *E*, then find the score from Table V, VI or VII whichever is appropriate :

Table V for PROB 40, TEMPO, INTER

Table VI for PROB 30, PROB 20
PROB 40 of TEMPO or INTER

Table VII for PROB 10
PROB 30 or 20 of TEMPO or INTER

The method of derivation of these tables is given in the Appendix.

TABLE V—SCORES FOR PROBABILITY 40 PER CENT

	Primary category error *(E)*												
*R**	−6	−5	−4	−3	−2	−1	0	1	2	3	4	5	6
−4	3	4	6	7	6	5	6	4	3	3	2	0	0
−3	1	3	6	7	7	7	7	4	3	3	2	0	0
−2	0	1	5	7	7	8	9	5	3	3	2	0	0
−1	0	0	3	6	7	8	10	7	4	3	2	0	0
0	0	0	2	4	6	8	10	8	6	4	2	0	0
1	0	0	2	3	4	7	10	8	7	6	3	0	0
2	0	0	2	3	3	5	9	8	7	7	5	1	0
3	0	0	2	3	3	4	7	7	7	7	6	3	1
4	0	0	2	3	3	4	6	5	6	7	6	4	3
5	0	0	2	3	3	4	6	4	4	6	6	4	4
6	0	0	2	3	3	4	6	4	3	4	5	4	4
7	0	0	2	3	3	4	6	4	3	3	3	3	4
8	0	0	2	3	3	4	6	4	3	3	2	1	3

**R* = category difference between primary and secondary.

TABLE VI—SCORES FOR PROBABILITY 30 OR 20 PER CENT

	Primary category error *(E)*												
*R**	−6	−5	−4	−3	−2	−1	0	1	2	3	4	5	6
−4	1	2	4	5	6	7	8	6	5	3	2	0	0
−3	1	1	4	5	7	7	9	6	5	3	2	0	0
−2	0	1	3	5	7	8	9	7	5	3	2	0	0
−1	0	0	3	4	7	8	10	7	6	3	2	0	0
0	0	0	2	4	6	8	10	8	6	4	2	0	0
1	0	0	2	3	6	7	10	8	7	4	3	0	0
2	0	0	2	3	5	7	9	8	7	5	3	1	0
3	0	0	2	3	5	6	9	7	7	5	4	1	1
4	0	0	2	3	5	6	8	7	6	5	4	2	1
5	0	0	2	3	5	6	8	6	6	4	4	2	2
6	0	0	2	3	5	6	8	6	5	4	3	2	2
7	0	0	2	3	5	6	8	6	5	3	3	1	2
8	0	0	2	3	5	6	8	6	5	3	2	1	1

* See footnote to Table V.

TABLE VII—SCORES FOR PROBABILITY 10 PER CENT

R^*	Primary category error (E) −6	−5	−4	−3	−2	−1	0	1	2	3	4	5	6
−4	1	1	3	5	6	7	9	7	5	4	2	0	0
−3	0	1	3	5	6	8	9	7	5	4	2	0	0
−2	0	0	3	5	6	8	10	7	5	4	2	0	0
−1	0	0	2	5	6	8	10	8	5	4	2	0	0
0	0	0	2	4	6	8	10	8	6	4	2	0	0
1	0	0	2	4	5	8	10	8	6	5	2	0	0
2	0	0	2	4	5	7	10	8	6	5	3	0	0
3	0	0	2	4	5	7	9	8	6	5	3	1	0
4	0	0	2	4	5	7	9	7	6	5	3	1	1
5	0	0	2	4	5	7	9	7	5	5	3	1	1
6	0	0	2	4	5	7	9	7	5	4	3	1	1
7	0	0	2	4	5	7	9	7	5	4	2	1	1
8	0	0	2	4	5	7	9	7	5	4	2	0	1

* See footnote to Table V.

Further notes :

(i) If TEMPO, INTER or PROB are used, applying to a period beginning or ending at midnight, they are ignored.

(ii) If two or more qualifying statements (i.e. TEMPO, INTER or PROB) occur, they should be applied each in turn and the mean taken of the scores so calculated. However, if one of these is a PROB 10 or its equivalent, it is ignored.

(iii) For cloud it may be necessary to interpolate in Table V, VI or VII; if so, round off the score to the nearest integer above.

(iv) For cloud, ignore PROB 10. If a cloud forecast is too complicated to assess consider only the lowest layer of 4–8 oktas.

(v) For wind, first find R_s and E_s for speed and the score for speed. For direction, it will be found that a qualifying statement is rarely used in practice; if it is, ignore it. E_d can be found as usual, and twice its value is then subtracted from the score already found, to obtain the total wind score.

Discussion and comparison with other methods. Two methods for testing the accuracy of TAFs have been published; von Bezold[1] described a very thorough method of verifying all details of a TAF for a continuous period rather than at isolated moments and the qualifying statements TEMPO and INTER are verified properly. PROB is treated as if it were TEMPO. Hoppestad[2] in a similar method verifies a TAF at hourly intervals through the period of validity, thus treating TEMPO and INTER in a nearly-proper manner. He deals with probability forecasts by considering the sets of all such forecasts over a period such as three months and this is the most proper way of verifying PROBS but it implies that scores cannot be attached to individual forecasts. Both of these methods deal only with visibility and cloud height. Also, both methods can be 'played'; that is, the forecaster may increase his average score by inserting additional TEMPOs or INTERs (or PROBs in von Bezold's method).

For the purpose of testing accuracy alone the present method is inferior to the above two methods. For example, the fact that verification is made only at one moment in the period of validity may result in a low score for a forecast which was correct for most of the time, or a high score for a generally poor forecast. The method of treating TEMPO and INTER does not give the highest scores to the most correct forecasts because a forecast of '*A* TEMPO *B*' which is completely correct cannot score more than 6 and may score only 4.

For these reasons, the present method may be regarded as assessing the usefulness of a TAF, the usefulness depending on both the accuracy and the preciseness of the forecast.* A precise (that is, unqualified) forecast has its maximum usefulness when it is correct (score = 10), and a minimum when it is so far wrong that any plans based upon it cannot be carried out (score=0). On the other hand, when a qualifying statement is introduced the forecast becomes less precise and its potential usefulness is therefore reduced (except when both the primary and the secondary forecast would lead to the same action by the user): however, there is a smaller chance that the forecast will be completely useless. This variation is reflected in the scoring system, in that the maximum possible score is lower than that for an unqualified forecast, but the chance of obtaining a very low score is reduced.

Over a period, the forecaster cannot 'play' the system to his advantage. Any attempt to do so, either by being over-cautious and introducing qualifying statements when none is needed, or by omitting them when they are called for, will result in a lower average score, although it may increase the score attained by an individual forecast.

Although an individual forecast which scores only 1 is not necessarily less useful than another which scores 6, the individual scores are of interest nevertheless if interpreted in the following way :

Score 0. Wrong forecast. To be avoided if at all possible (even at the risk of lowering the average score by putting in a PROB). Each such score deserves a study of the synoptic situation to see if such a score could be avoided in future.

Score 1–3. Misleading. It should be possible to improve forecasts on most of these occasions by a more thorough knowledge of the type of synoptic situation and the probabilities involved. Hence these forecasts should be classified according to synoptic situations and carefully studied. A small percentage of these scores cannot be avoided.

Score 4–6. Dubious. This range of scores must be expected to occur quite frequently, even with much better forecasting techniques, because of the tendency of certain elements (e.g. fog and rainfall) to be discontinuous in time and space and therefore difficult to forecast except with TEMPO, INTER, etc.

Score 7–9. Satisfactory. Such scores are an expression of the inherent variability of the weather and give no cause for concern.

Score 10. Correct.

Application of the method to a sample of TAFs. The method was applied to the forecasts issued by six master diversion airfields during March 1965. The forecasts used were those issued at 17 GMT, based upon the 12 or

* Strictly, the usefulness of a given forecast depends also upon the use to which it is put, and will vary from one customer to another, but this is a complex subject and is not considered here.

15 GMT chart, and were applicable to the period 18–09 GMT. The weather forecast for midnight was verified. The frequency distribution of scores for the elements of visibility, wind and cloud is shown in Table VIII. In this table the infrequency of odd-number scores for visibility and wind is caused by the use of whole numbers for the category values.

TABLE VIII—NUMBER OF OCCURRENCES OF EACH FORECAST SCORE FOR VISIBILITY, WIND AND CLOUD

	Forecast score												
	10	9	8	7	6	5	4	3	2	1	0	Indeterminate	Total
	Number of occurrences												
Visibility	34	5	28	11	23	6	24	11	10	1	24	9	186
Wind	59	0	49	1	27	0	24	2	11	0	6	7	186
Cloud	80	11	8	19	13	12	12	4	9	1	6	11	186

Out of the total number (177) of verifiable forecasts

(i) 5 (3 per cent) were correct for all three elements. (All scores = 10.)

(ii) 39 (22 per cent) were satisfactory for all three elements. (All scores 7–9.)

(iii) 106 (60 per cent) were not misleading for any of the three elements. (All scores 4–6.)

whereas

(iv) 71 (40 per cent) were misleading for at least one element. (At least one score < 4.)

(v) 34 (19 per cent) had at least one score of zero.

Conclusions. A method has been described which enables an assessment to be made, in a broad sense, of the usefulness of a set of terminal aerodrome forecasts. The method is reasonably easy to apply, and it is suggested that similar tests could usefully be carried out at stations which prepare TAFs. Such tests might enable the synoptic situations giving rise to bad forecasts to be pinpointed and, coupled with a study of the reasons for any poor forecasts, might help to improve the service. It should be borne in mind, however, that the tests described were carried out in 1965, and that any similar study carried out at present would need to be modified to take into account the lower limits of cloud height and visibility now considered critical for diversion of aircraft. Modification of some aspects of the tests might be worthwhile, for example, it might be better to verify a given forecast at more than one time during its period of validity. A valuable addition, if a long enough run of forecasts is available, would be the compilation of a table showing the distribution of scores for each category of each element at verification time.

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APPENDIX

How Tables V–VII are produced. First suppose the forecast is for a unique value of an element. The scores obtained can be represented, for the various values of E, in a table :

TABLE IX—INITIAL SCORING ON ONE ELEMENT

	Value of E											Total
	−5	−4	−3	−2	−1	0	1	2	3	4	5	
Row A (score)	0	2	4	6	8	10	8	6	4	2	0	50

The array 2, 4, 6, 8, 10, 8, 6, 4, 2 is called 'Row A'; it is understood that all terms off the ends of the array are zeros.

Next, suppose the forecast is for 'P with a 40 per cent probability of S'. This is taken to mean that the probability of P is 60 per cent, and that of S is 40 per cent. Suppose for convenience that P and S are very widely separated, for example, $P = 15$ km visibility, $S = 800$ m. Suppose now that the actual visibility turns out to be 15 km, that is, P is correct. Instead of giving a score of 10, suppose we make the score dependent on the forecaster's confidence and award 6 points; similarly, if the actual visibility in this particular case were 800 m, the score would be 4 points. As in Table IX, we arrange an array of scores in decreasing order of magnitude on each side of both primary and secondary forecasts, such that the sum of the scores over all values of E is the same as it was before, namely 50.

To do this, and dropping now the supposition of wide separation, Row A is split into two arrays, Row B and Row C (see Table X), such that adding Row B and C term-by-term produces Row A; and such that the ratio of the highest terms of Rows B and C, and also that of the sums of the terms in Rows B and C, are both 6:4.

TABLE X—CONSTRUCTION OF SCORE FOR PRIMARY AND SECONDARY ELEMENTS

	Score											Totals
Row A	0	2	4	6	8	10	8	6	4	2	0	50
Row B	0	2	3	3	4	6	4	3	3	2	0	30
Row C	0	0	1	3	4	4	4	3	1	0	0	20

Row C is then moved horizontally relative to Row B, such that B is symmetrical about the category of P, and C is symmetrical about the category of S, where these statements are meaningful; or, in general, C is moved to the right by R steps. Rows B and C are then added together again to obtain Row D. For example, if $R = 3$, we get :

TABLE XI—ALLOCATION OF SCORE FOR PRIMARY AND SECONDARY ELEMENTS ($R = 3$)

	Score												
Row B	0	2	3	3	4	6	4	3	3	2	0		
Row C				0	0	1	3	4	4	4	3	1	0
Row D	0	2	3	3	4	7	7	7	7	6	3	1	0

Row D is then put in place of Row A in Table IX :

TABLE XII—COMBINED SCORE FOR PRIMARY AND SECONDARY ELEMENTS ($R=3$)

	Value of E											
	−5	−4	−3	−2	−1	0	1	2	3	4	5	6
Row D (score)	0	2	3	3	4	7	7	7	7	6	3	1

Table XII then indicates the score obtained, given $R = 3$, for any value of E.

This method ensures that a forecaster who 'plays safe' by forecasting two possibilities, is less likely to make a very low score, but also he is unable to score very highly.

Table V is calculated as the set of Rows D, as produced in Table XII, for different values of R.

If the probability was some value other than 40 per cent, the Rows B and C would be calculated accordingly. Table XIII shows the Rows B and C for different values of probability of the secondary element.

TABLE XIII—CONSTRUCTION OF SCORE FOR DIFFERENT PRIMARY ELEMENT SCORES AND VARIOUS PROBABILITIES OF THE SECONDARY ELEMENT

Value of probability *per cent*		Score								
50	Row A	2	4	6	8	10	8	6	4	2
	Row B	1	2	3	4	5	4	3	2	1
	Row C	1	2	3	4	5	4	3	2	1
40	Row B	2	3	3	4	6	4	3	3	2
	Row C	0	1	3	4	4	4	3	1	0
30	Row B	2	3	4	5	7	5	4	3	2
	Row C	0	1	2	3	3	3	2	1	0
20	Row B	2	3	5	6	8	6	5	3	2
	Row C	0	1	1	2	2	2	1	1	0
10	Row B	2	4	5	7	9	7	5	4	2
	Row C	0	0	1	1	1	1	1	0	0

Tables VI and VII correspond to Table V, but refer to probabilities 20 per cent and 10 per cent respectively. For probability 30 per cent, a table has not been produced; it is adequate to use Table VI.

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SURFACE WINDS AT MOMBASA, KENYA

By B. RAMSEY

Summary. An analysis of the mean hourly vector wind, scalar wind, and constancy (q), at Mombasa, averaged for each month of the year from April 1967 to March 1970, clearly shows the two well-marked periods of north-east and south monsoon, and the dominance of the latter. Constancy is high, especially in the mid-periods of these seasons, and there are some interesting features which show up in the land- and sea-breeze effects superimposed on the monsoons.

Data available. In mid-March 1967, a Dines pressure-tube anemometer was set up on the low cliff of Ras Serani, overlooking the entrance to the main harbour (Kilindini) at Mombasa (Figure 1). The site is well exposed to seaward, especially between east-north-east and south-south-west, and is about 60 feet above mean sea level. Daily anemograms have been analysed for mean hourly values of vector wind, scalar wind speed and, from these,

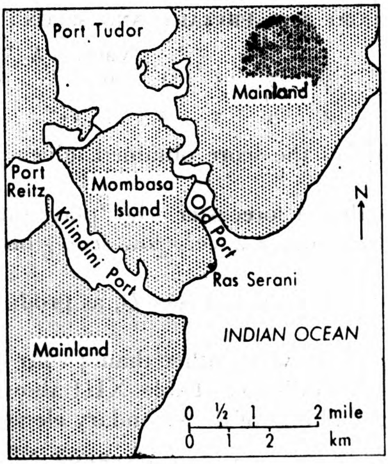

FIGURE 1—ANEMOMETER SITE, RAS SERANI, MOMBASA (04° 04′S 39° 42′E), AND ENVIRONS

constancy q^1. The instrument continues to give good service in spite of heavy exterior corrosion due to spray. The daily chart-changing has been left in the hands of the watchkeeping staff of the Signal Station, to whom thanks are due, through the Senior Harbourmaster, for providing this service.

Results. From the analysis in Table I*(a)* it is obvious that the months December, January and February cover the north-east monsoon, March and November are transitional, while April to October inclusive are entirely south monsoon months. The separate months will be discussed briefly.

January. This month shows the full development of the north-east monsoon, with q (Table I*(b)*) averaging 93 for the 24-hour period and up to 98 in the hours ending at 14 and 22 local zone time (LZT = GMT + 3). All times in the text are LZT.

February. The north-east monsoon still dominates but there are signs of a breakdown beginning. Not only are winds lighter in the afternoon than at corresponding times in January but they are less constant. This decrease in q is due to occasional incursions northward over the area by the intertropical convergence zone (ITCZ), generally associated with a large pressure rise to the south following marked cyclone activity in the Madagascar/Mauritius area. This often brings welcome rain to the area in the middle of drought conditions which are commonly associated with the dry north-east monsoon. Most unusually, this breakdown occurred in January 1970 for a few days.

March. The ITCZ frequently affects the area, especially in the latter half of the month, and on the whole gradients are lighter and more variable than those in February. Constancy is at its lowest for the whole year as periods of full north-east monsoon alternate with some fairly fresh blows from the south. The lowest hourly figure of 47 between 03 and 04 LZT is the minimum hourly value for the year. Early morning winds are still in the north-westerly quadrant, but this direction has been reached through south rather than north as in the full north-east monsoon months. The normally lighter gradients allow the land- and sea-breeze effect to dominate and afternoon winds are

TABLE 1(*a*)—MONTHLY AND ANNUAL MEAN HOURLY VECTOR AND SCALAR SURFACE WINDS, MOMBASA HARBOUR ENTRANCE 1967–70

Time	Jan.		Feb.		Mar.		Apr.		May		June		July		Aug.		Sept.		Oct.		Nov.		Dec.	
LZT	*deg*	*kt*	*deg*	*kt*	*deg*	*kt*	*deg*	*kt*	*deg*	*kt*	*deg*	*kt*	*deg*	*kt*	*deg*	*kt*	*deg*	*kt*	*deg*	*kt*	*deg*	*kt*	*deg*	*kt*
01	052	2·2 (2·5)	065	2·6 (3·4)	149	2·2 (3·8)	192	3·3 (4·7)	204	7·8 (8·7)	193	10·6 (11·1)	192	11·2 (11·5)	185	9·1 (9·7)	183	8·6 (9·0)	171	6·8 (7·2)	180	1·8 (2·8)	043	1·9 (2·4)
02	032	1·5 (1·8)	050	1·7 (2·5)	166	1·6 (3·1)	206	2·9 (4·1)	211	7·0 (7·8)	196	10·1 (10.7)	196	10·2 (10·7)	189	8·3 (9·0)	187	7·7 (8·2)	175	6·1 (6·7)	207	1·3 (2·4)	022	1·3 (1·9)
03	005	1·1 (1·3)	019	1·0 (1·7)	188	1·4 (2·8)	215	2·4 (3·6)	214	6·7 (7·5)	202	9·1 (9·7)	199	9·6 (10·0)	194	7·5 (8·3)	192	6·7 (7·5)	180	4·9 (5·7)	215	1·2 (2·3)	348	0·9 (1·4)
04	344	1·1 (1·2)	341	1·0 (1·2)	221	1·0 (2·2)	226	2·2 (3·6)	216	5·9 (6·7)	208	7·8 (8·5)	202	8·5 (9·0)	194	7·3 (8·1)	198	5·8 (6·8)	186	3·8 (5·0)	248	1·1 (1·7)	338	1·1 (1·4)
05	340	1·2 (1·3)	323	1·0 (1·2)	248	1·1 (2·0)	240	2·0 (2·8)	226	5·0 (5·6)	214	6·8 (7·7)	206	7·7 (8·2)	194	6·7 (7·5)	214	4·6 (5·4)	195	2·6 (4·6)	258	0·9 (2·1)	334	1·2 (1·3)
06	343	1·4 (1·5)	329	1·2 (1·4)	285	1·3 (2·0)	249	1·7 (2·8)	239	4·2 (4·6)	223	5·7 (6·6)	208	6·1 (6·9)	198	5·7 (6·8)	219	4·2 (5·4)	210	2·6 (4·1)	264	1·0 (1·8)	330	1·4 (1·6)
07	340	1·5 (1·6)	340	1·2 (1·5)	293	1·4 (2·0)	260	1·8 (2·7)	246	4·2 (4·5)	229	5·1 (5·9)	214	5·4 (6·2)	200	5·5 (6·7)	226	3·7 (4·9)	221	2·3 (3·9)	294	1·2 (1·7)	332	1·4 (1·6)
08	342	1·9 (2·0)	343	1·5 (1·7)	291	1·5 (2·1)	270	2·3 (2·8)	244	4·0 (4·4)	232	4·9 (5·6)	227	4·9 (5·6)	205	5·1 (6·3)	224	4·0 (4·9)	217	2·5 (4·1)	280	1·2 (1·9)	337	1·8 (2·1)
09	358	2·6 (2·8)	355	2·1 (2·7)	257	1·4 (2·2)	242	2·8 (3·4)	230	5·9 (6·2)	226	6·4 (6·8)	221	6·1 (6·5)	202	7·0 (7·4)	205	7·0 (7·3)	204	4·0 (4·8)	225	1·4 (2·0)	003	2·2 (2·7)
10	026	3·0 (3·3)	034	1·8 (3·2)	211	1·3 (2·5)	215	3·9 (4·7)	221	7·7 (8·0)	215	8·0 (8·3)	212	8·3 (8·6)	198	8·6 (9·1)	198	8·3 (8·6)	195	5·1 (5·6)	204	1·9 (2·8)	032	2·2 (2·8)
11	067	4·7 (5·3)	082	4·4 (5·7)	170	2·1 (3·6)	198	5·0 (5·7)	214	8·9 (9·4)	209	9·7 (10·0)	207	9·8 (10·1)	194	9·6 (10·1)	191	9·1 (9·5)	188	5·9 (6·3)	184	2·6 (3·4)	067	3·6 (4·5)
12	078	6·8 (7·4)	082	6·3 (7·7)	156	3·6 (5·4)	190	6·0 (6·7)	208	10·2 (10·6)	205	11·4 (11·6)	204	10·8 (11·0)	194	10·3 (10·7)	190	9·2 (9·6)	183	6·5 (7·0)	168	3·6 (3·7)	082	5·8 (6·4)
13	082	8·7 (9·1)	085	7·0 (8·6)	149	4·2 (6·6)	183	6·8 (7·7)	206	11·3 (11·6)	204	12·2 (12·4)	203	11·9 (12·0)	192	10·6 (11·0)	189	9·5 (9·8)	179	6·9 (7·5)	165	4·5 (5·4)	084	7·1 (7·9)
14	083	9·6 (9·8)	086	7·9 (9·4)	144	5·1 (7·1)	181	7·4 (8·3)	204	12·3 (12·5)	202	12·7 (12·8)	201	11·9 (12·2)	193	11·1 (11·5)	187	9·5 (9·9)	177	7·3 (7·9)	161	4·5 (5·9)	083	7·5 (8·4)
15	082	10·1 (10·5)	084	8·4 (9·7)	143	5·4 (7·6)	180	7·7 (8·7)	204	12·3 (12·5)	201	12·2 (12·5)	200	12·0 (12·2)	192	11·5 (11·9)	186	9·6 (10·1)	176	7·8 (8·5)	164	4·9 (6·0)	083	7·9 (8·8)
16	081	10·1 (10·5)	085	8·4 (9·6)	141	5·5 (7·9)	179	7·4 (8·7)	203	11·6 (11·9)	199	12·3 (12·7)	198	11·5 (11·8)	189	11·6 (11·5)	184	9·7 (10·1)	173	8·0 (8·7)	165	5·1 (6·1)	080	7·8 (8·8)
17	079	9·7 (10·0)	082	8·6 (9·6)	139	5·1 (7·8)	179	7·2 (8·3)	203	10·7 (11·0)	199	11·7 (12·0)	198	11·3 (11·6)	188	10·2 (10·7)	184	9·6 (10·0)	173	8·0 (8·6)	166	4·9 (5·8)	076	7·7 (8·8)
18	077	8·7 (9·2)	081	8·1 (9·1)	135	4·6 (6·8)	179	7·0 (8·1)	203	10·1 (10·4)	199	10·8 (11·4)	198	11·0 (11·3)	187	9·6 (10·1)	181	9·6 (9·9)	172	7·9 (8·5)	165	4·6 (5·6)	074	6·8 (7·7)
19	073	7·5 (7·8)	079	7·3 (8·1)	132	4·5 (6·3)	177	6·4 (7·6)	201	9·1 (9·6)	197	10·3 (10·7)	194	10·2 (10·6)	182	9·2 (9·7)	177	9·6 (9·9)	169	7·8 (8·3)	166	4·5 (5·5)	069	5·9 (6·7)
20	073	6·7 (6·9)	077	6·6 (7·3)	134	4·4 (6·2)	179	5·8 (7·0)	200	8·6 (9·2)	193	10·3 (10·7)	190	10·2 (10·6)	178	9·3 (9·7)	175	9·9 (10·3)	164	7·9 (8·3)	165	4·5 (5·3)	067	5·4 (6·2)
21	071	6·1 (6·4)	077	6·0 (6·9)	132	4·5 (6·2)	174	5·4 (6·5)	197	8·3 (9·1)	191	10·5 (11·0)	190	10·9 (11·2)	178	9·7 (10·1)	175	10·1 (10·6)	163	8·3 (8·7)	163	4·4 (5·2)	064	5·0 (5·8)
22	068	5·2 (5·5)	077	5·3 (6·2)	132	4·1 (5·9)	176	5·8 (6·3)	196	8·6 (9·4)	189	11·1 (11·6)	188	11·2 (11·6)	179	10·2 (10·5)	175	10·2 (10·6)	162	7·8 (8·2)	161	3·4 (4·7)	060	4·5 (5·0)
23	064	4·4 (4·6)	075	4·7 (5·6)	137	3·7 (5·6)	180	5·1 (6·2)	197	8·5 (9·2)	190	11·3 (11·8)	190	11·4 (11·6)	181	10·2 (10·7)	178	9·9 (10·3)	164	7·4 (7·8)	166	2·8 (3·6)	058	4·0 (4·5)
24	058	3·3 (3·4)	072	3·4 (4·4)	142	3·0 (4·7)	186	4·4 (5·3)	200	8·6 (9·4)	192	11·2 (11·7)	191	11·2 (11·5)	182	9·6 (10·1)	181	9·3 (9·7)	168	6·9 (7·5)	170	2·2 (3·3)	052	2·9 (3·3)

Note : Values in brackets are scalar mean speeds.

TABLE 1(*b*)—MONTHLY AND ANNUAL MEAN HOURLY CONSTANCY *q* OF SURFACE WIND, MOMBASA HARBOUR ENTRANCE 1967–70

Time LZT	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
01	86	77	55	67	89	96	98	94	96	95	63	79	83
02	82	70	59	73	89	95	96	94	94	91	70	72	82
03	87	66	52	69	90	93	96	94	92	86	52	69	80
04	94	80	47	64	89	91	95	91	87	77	69	84	81
05	87	88	58	74	88	89	93	89	85	73	53	91	80
06	93	85	70	73	91	86	89	86	80	64	69	90	81
07	93	83	78	72	95	86	88	84	77	58	72	93	82
08	95	90	76	83	89	87	87	85	83	64	66	92	83
09	92	82	63	86	94	93	94	93	94	84	76	84	86
10	90	66	55	86	96	96	96	94	97	92	76	80	85
11	88	79	63	87	95	98	99	96	96	93	81	82	87
12	93	83	69	88	96	98	98	97	96	93	77	90	90
13	96	83	65	87	97	99	99	97	96	93	83	91	91
14	98	85	74	89	98	99	98	97	96	94	78	90	91
15	97	88	72	89	97	97	98	97	96	92	82	91	91
16	96	88	70	86	96	97	97	97	96	92	86	89	91
17	97	89	68	88	96	97	98	96	96	94	86	91	91
18	95	90	69	86	95	95	98	96	97	94	83	89	91
19	96	90	72	84	94	97	96	96	97	95	84	86	91
20	97	89	72	82	93	96	96	97	97	95	84	85	90
21	97	88	71	84	91	96	97	97	97	96	87	85	91
22	98	86	69	81	91	96	97	97	97	95	79	85	89
23	96	84	65	80	93	96	98	96	97	94	77	84	88
24	96	82	59	80	91	96	98	97	96	92	69	84	87
Mean	93	83	65	81	93	95	96	94	93	87	76	86	

almost normal to the mainland coast (Figure 2). A feature missing from the north-east monsoon but present in all the southerly months, shows up for the first time in March. This is an evening *increase* in wind speed, rather than a slow decrease, and it becomes more marked as the southerly monsoon develops (Figure 3). The cause is rather obscure, but it may be related to the ending of the land- and sea-breeze effect whereby the diurnal raising of the 850-mb level inland due to heating induces a circulation which involves slight subsidence a little way out to sea, after which the normal southerly wind of the monsoon resumes its uninterrupted flow.

April. Although not very strong on the average, the south monsoon is now well established and mean hourly speeds of 23 kt are reported by the month end. As in March, night-time winds retain a marked westerly component.

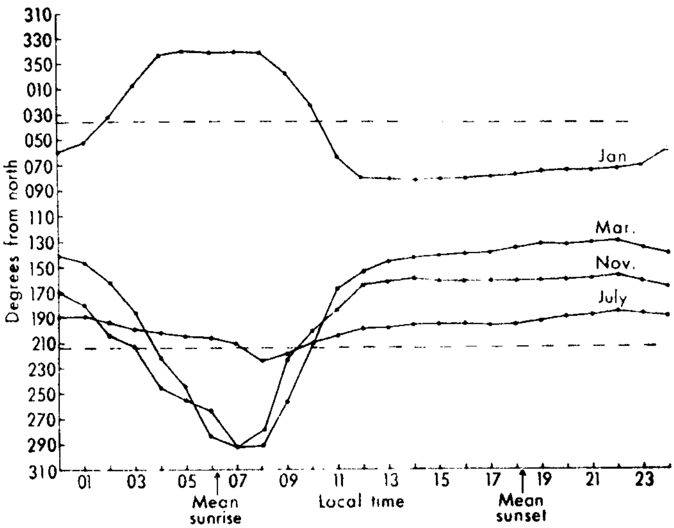

FIGURE 2—DIURNAL VARIATION OF WIND DIRECTION, MOMBASA

– – – Coastline 035–215°

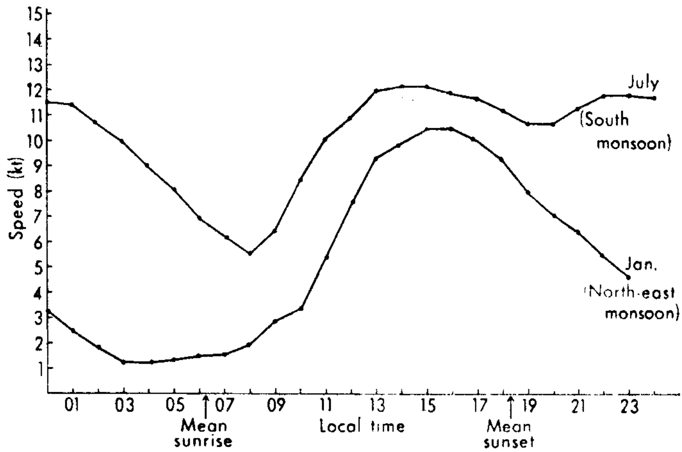

FIGURE 3—MEAN HOURLY SCALAR WIND SPEED, MOMBASA

Day-time winds are not backed so far to the south-east as in March because now the increased geostrophic wind builds up from the south. The evening increase remains slight and is an hour later. The period of maximum wind speed, 14 to 16 LZT, is about the same as in the previous three months but, as in March, and indeed in all the other southerly months, winds continue to back until the evening maximum has passed.

May. This is normally the wettest month of the year and the south monsoon is fully established. The flow is convergent on the whole as it passes northward tending to decelerate. The constancy q is much higher than in April, the monthly figure being 93 against 81, and the hourly figure reaching 98 at the time of maximum speed from 13 to 14 LZT. Early morning winds do not veer as far as they do in April and winds later in the day are further west of south than in any other month of this monsoon. This is probably due to the fact that at this time, the continental ridge is developing strongly from the south but is fairly closely adjacent to the equatorial trough which now extends from the Cape Guardafui area south-eastwards.

June. Early morning winds are nearer south than in May, and in fact, winds for the whole month are backed slightly. Highest speeds are in the hour 13 to 14 LZT, but there is a well-marked maximum from 22 to 23 LZT, two hours later than in March. Normally by the middle of the month the rains have ceased as the stream is no longer convergent but speed divergent following the release of the south-west monsoon across the Arabian Sea to India. June winds are the strongest of the year, reaching a scalar maximum of 12·8 kt from 13 to 14 LZT.

July. Winds this month are almost a copy of those for June, but still with a slight backing throughout the day and a slight decrease. Speed divergence has further increased as the Socotra area is now experiencing its strongest winds. Constancy, with a figure of 96 for the month is the highest of the year and reaches almost 100 between 10 and 11 LZT and 12 to 13 LZT. It does not fall below 87 (07 to 08 LZT) which is the highest minimum for the 24-hour period in any month.

August. This month shows a further slight backing and decrease in the strength of the south monsoon. Night winds veer least of any month and this results in the highest early morning minimum scalar speed of the year. The continued backing of the wind in the evening shows a mean component from east of south for the first time since April.

September. As the anticyclones of southern latitudes of the Indian Ocean increase their activity further to the east, and pressure begins to fall slightly over the southern parts of the interior of the continent, winds in September revert to the speeds of May but are backed by up to 20 degrees. In contrast to every month except its neighbour October, highest hourly wind speeds of the 24 hours are now at the evening maximum. Although q shows a steady fall from July, it is still remarkably high except between 04 and 08 LZT.

October. This is the last full month of south monsoon in normal years, and continues to show backing and weakening of the flow, especially by the end of the month. At this time the stream is becoming increasingly convergent as the ITCZ makes its southerly progress more apparent, and the 'short' rains may begin late in the month. As in the previous month, the strongest winds occur after dark (20 to 21 LZT) although scalar speeds at this time are the same as those in the period 15 to 16 LZT. Constancy is also highest at the evening maximum, reaching 96 in contrast to 58 from 06 to 07 LZT.

November. This may be called the other transitional month. However, there are rarely, if ever, years in which the north-east monsoon does not appear in March, whereas November may be an entirely southerly monsoon month. In 1968 the north-east monsoon did not start until 10 December. As in March, constancy drops in November to a monthly mean of 76, and the maximum speed of the day now reverts to the afternoon from 15 to 16 LZT. The early-morning breeze is once again in the north-west (normal to the coastline) as it overcomes the now weaker gradients. With the ITCZ making determined efforts to get south, this is often the second-wettest month of the year.

December. This month begins the short monsoon season of north-easterly winds, with average directions showing components from north throughout the 24 hours, and a higher constancy in the early land-breeze than in any other month. The fall in q after 08 LZT is, as in other north-easterly months, simply an indication of the varying times of onset of the sea-breeze. Afternoon mean wind directions are very like January and February but, as shows up in the south monsoon, there is a tendency for the wind to haul away from the coast as the season advances. Because December often has southerly winds at first, q is not as high as may have been expected, except as indicated above, in the period of the early land-breeze when it reaches 93 from 06 to 07 LZT.

Land- and sea-breeze effects. In this almost equatorial region, it may be expected that the land- and sea-breeze would be dominant the year round at Mombasa. Figure 2 indicates that this is true of the hotter north-east monsoon and the transition months, but much less so in the winter period of the southern monsoon.

Within a short time of the anemometer being erected, it became obvious that the land-breeze in the south monsoon was frequently not the result of a slow veer from the earlier wind of the afternoon and evening. In all months of the southerly season the wind from the sea remains more or less steady on about half the nights. On other nights, normally well after, but occasionally before, midnight, the land-breeze reaches the shore with an instantaneous change of speed and direction, almost as a front (Figure 4 is a schematic diagram of a typical trace on the anemogram). This occurs independently of the speed of the sea-wind before the change.

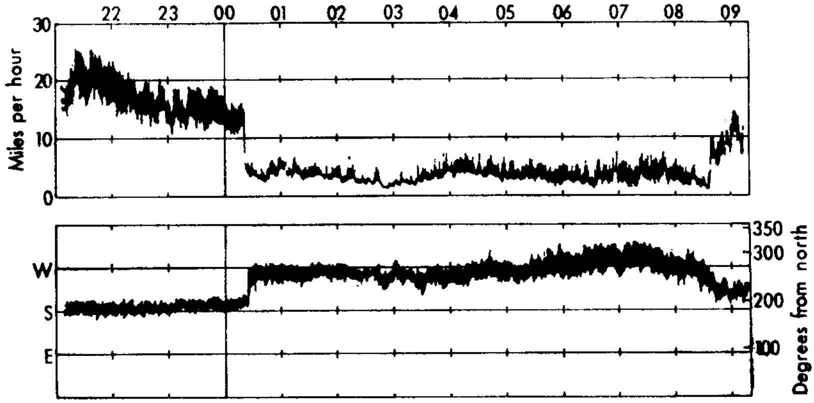

FIGURE 4—SCHEMATIC DIAGRAM OF A TYPICAL ANEMOGRAM SHOWING COMMENCEMENT OF LAND-BREEZE AT MOMBASA (SOUTH MONSOON)

An analysis was made (Table II) of the times of onset of sharp changes involved in land- and sea-breezes at the site. The table shows that in the north-east monsoon, while there is generally no land-breeze 'front', there is quite often a marked sea-breeze front. Figures 2 and 3 do not show these changes well as they are masked by averaging. The land-breeze front is thought to be due to the gradual build-up of a cold block of land-cooled air which spreads slowly towards the coast undercutting the sea-wind. Tops of palms at the time of change may still be moving under the influence of the sea-wind when the wind at the surface 70 to 100 feet below has ceased. Movement seaward is often restricted by warming over the lagoon, but on many occasions the seaward half of the lagoon is still well ruffled while the shoreward

TABLE II—AVERAGE TIMES OF SHARP LAND- OR SEA-BREEZE DISCONTINUITIES, MOMBASA HARBOUR ENTRANCE 1967–69

	Mean time (LZT) of onset of sea-breeze			Mean time (LZT) of onset of land-breeze		
	1967	1968	1969	1967	1968	1969
Jan.	No record	1039 (24)	1044 (13)	No record	0200 (4)	0049 (11)
Feb.	No record	0926 (14)	1059 (13)	No record	0110 (7)	0048 (12)
Mar.				0337 (8)	0226 (18)	0229 (19)
Apr.		No significant		0108 (20)	0050 (20)	0157 (24)
May				0136 (20)	0254 (17)	0415 (16)
June		discontinuities		0313 (22)	0323 (15)	0325 (18)
July				0446 (21)	0238 (20)	0420 (22)
Aug.		between		0220 (18)	0246 (16)	0308 (16)
Sept.				0138 (17)	0432 (24)	0306 (18)
Oct.		March and November		0249 (20)	0334 (18)	0345 (17)
Nov.				2312 (21)	0208 (12)	0108 (14)
Dec.	1035 (22)	1006 (13)	0956 (16)	No significant discontinuities		

Note : values in brackets are number of occasions.

half is smooth. The effective silence among the palms once the land-breeze has taken over is as good as an alarm clock. Why the process is not common in the early morning or night in the north-east monsoon is thought to be due to the fact that the geostrophic wind in that season is often offshore (340°) and the land-breeze forms more readily than the sea-breeze which has to 'break in' against this. The reverse holds for the south monsoon where the land-breeze is working against the geostrophic wind which is about 180° to 200°, or somewhat onshore.

Relationship with large-scale pressure changes. As noted above, there are only three months of the year when the average component for the month is from a northerly point. From Table III it may be seen that these are the only months in the year when the pressure at Lumbo, Mozambique (about 15°S 40°E) is lower than at Mombasa. That this pressure difference existed may have been assumed, but that it is so sensitive is remarkable and suggests an aid to forecasting winds in the Mombasa area. A survey of pressure changes at Tete, Mozambique, (about 16°S 33°E) confirms this and indicates that during the south monsoon a sharp rise of pressure there is very quickly followed by strong southerlies at Mombasa. The delay is about 12 hours and may be much less.

TABLE III—MONTHLY MEAN PRESSURE DIFFERENCES, MOMBASA MINUS LUMBO, MOZAMBIQUE (15°S 41°E)

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
					millibars						
−1·1	−1·0	+0·2	+1·5	+1·6	+2·2	+2·2	+1·4	+0·7	+0·5	+0·2	−0·5

Comparison with Nairobi. In a previous survey[2] winds at Nairobi were summarized in rather the same way as has been done for Mombasa, except that 850- and 700-mb winds were included as well as the surface.

There are some points of interest and comparison. The north-easterly season is much longer at Nairobi than at the coast while only five months instead of nine have components from the south. The strongest winds are from north-east and not from south, and occur in February rather than June or July. Wind speeds at Nairobi in the south-easterly season are very low, but, as was indicated at the time, that station is very much on the western edge of the strong monsoon-flow of the Indian Ocean at that time of the year, and furthermore, it is almost at the 850-mb level. Constancy at Nairobi is very similar to that at Mombasa in the north-easterly season, but, because of the weakness of the flow in the winter, q-levels at that time are very much lower than at Mombasa.

Discussion. The investigation reveals a normal reversal of the monsoons with season and in a south latitude the southerly would naturally be dominant. However, the minor features superimposed on the monsoons are of interest, especially in connection with the large-scale pressure features of the region. The phenomenon of the land-breeze 'front' is perhaps unusual and it may be a useful exercise to install a recording rain-gauge at the anemometer site to investigate the shower-forming properties of this feature in the south monsoon. The north-east monsoon sea-breeze front, in common with the sea-breeze in many parts of the world, is often accompanied by a line of large cumulus which moves inland to the sea-breeze limit and there becomes stationary and often produces thunderstorms.

Acknowledgement. This article is published by permission of the Director-General of the East African Meteorological Department.

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2. RAMSEY, B.; Low-level wind flow at Nairobi. *Met Mag, London*, **95**, 1966, pp. 47–57.

551.524.33:519.2

AN ERRONEOUS USE OF THE CHI-SQUARE TEST

By P. B. WRIGHT

Summary. When the chi-square test of association is used to compare odd- and even-numbered years with respect to the sense of the change of temperature since the previous year (i.e. whether warmer or colder), the test must be modified because the sign of the change is partially dependent on the sign for the previous year. A Monte Carlo experiment has shown that the value of χ^2 obtained by the conventional method must be multiplied by a reduction factor of 0·6 before testing for significance.

In an investigation into the possible existence of a biennial oscillation in European summer temperatures, Davis* applied the chi-square test to compare odd and even years with respect to whether they were warmer or colder than the previous year. For ease of explanation, the problem may be rephrased as follows : Define the 'link' of the year M to have the value $+1$ if the summer of M was warmer than the summer of $M-1$, and the value -1 if colder, i.e. the link defines the sign or sense of the change of temperature since the previous year. The problem then is to assess the significance of the association between the link and whether the year is odd or even; that is, the question to be answered is whether there are significantly more (or less) odd positives and even negatives than would be expected in a series of random data. Davis assessed this by applying the chi-square test in the conventional way to contingency tables such as the example below :

	Link $+1$	Link -1	Total
Odd	28	14	42
Even	14	28	42
Total	42	42	84

In this particular example, the value of chi-square was found to be 8·05, significant at better than one per cent.

Suppose a new contingency table were created by inserting every element in the above table twice. A table would be obtained with 168 items, the value of chi-square would be doubled and the significance level apparently improved. This procedure, of course, would not be used, because it is known that the additional 84 items would be completely dependent on the first 84 and so would add no further information.

* DAVIS, N. E.; The summers of north-west Europe. *Met Mag, London*, **96**, 1967, pp. 178–187.

However, the equivalent of this has already been done, albeit unwittingly, in obtaining the above contingency table in the first place. That is to say, the 84 elements in the table are not independent. This is because, in a *random* time series, the link of a given year is partially dependent on the previous link. Thus, suppose it is assumed that temperatures are randomly ordered, and suppose it is known that this year was warmer than last (although the actual values are not known), then it can be shown (see Appendix) that the probability is 0·67 that next year will be colder than this. In other words, if a given link of a random series is positive, the next link has a 0·67 probability of being negative.

It must be emphasized that the discussion here is *not* of meteorological dependence — the possible existence of persistence or cyclic behaviour. (That, after all, is what the test is trying to establish, and to do so the series is initially assumed to be random.) The dependence (or correlation) under discussion is *mathematical*.

Thus the number of independent items of data in the above contingency table is not 84, but somewhat less. This implies that the significance is less than was claimed, because the given degree of association (2 to 1) is more likely to be attained in a random sample of, say, 50 independent elements than in a sample of 84 independent elements. The problem of finding the correct value of the reduction factor by theoretical means is complex, and it is hoped to pursue this work further. An alternative approach is to perform a Monte Carlo experiment. This has been done by generating 10 000 random series each of 101 terms; the 100 links were designated 'odd' and 'even' alternately. Fuller details will be published later. The degree of association was found to exhibit a degree of scatter equivalent to that which would have been obtained using samples of 60 independent elements. Thus the correct value of the reduction factor is 0·6. (Strictly, the value given by the experiment was 0·592, with standard error of estimate 0·016.)

Hence the value of chi-square obtained by the conventional method must be multiplied by 0·6 before testing for significance. In the example on p.301, this yields the value 4·83, significant at about the three per cent level.

Appendix

To show that, in any randomly ordered series of real numbers, the probability that two adjacent links have opposite signs is 2/3.

(Let p(Z) mean : the probability that Z is true).

(i) Because the discussion is concerned only with links, it will suffice to consider the case of a random series from a population P with N values uniformly distributed in the range (0, 1). For, consider a random series from any population Q of N real numbers. Let the elements of Q be put into one-to-one correspondence with P by replacing them, in order of magnitude from the lowest, by the values

$$\frac{1}{N+1}, \frac{2}{N+1}, \ldots, \frac{N}{N+1}.$$

This transformation leaves unchanged the sign of the difference between any pair of elements. Hence the sequence of links formed from the transformed random series will be identical with the original sequence of links.

(ii) In the random series from *P*, let *A*, *B*, *C* be three successive points. Consider the links *AB*, *BC*. These links will have opposite signs if, and only if, either *B* is a maximum, or *B* is a minimum.

Let *B* have the value *t*. Then

$$\begin{aligned} p\ (B \text{ is a maximum}) &= p\ (B > A \text{ and } B > C) \\ &= t^2. \end{aligned}$$

Integrating over all values of *t*,

$$\begin{aligned} p\ (B \text{ is a maximum}) &= \int_0^1 t^2\, dt \\ &= 1/3. \end{aligned}$$

By symmetry,

$$p\ (B \text{ is a minimum}) = 1/3.$$

Hence the probability that the links *AB* and *BC* have opposite signs is 2/3.

551.582(427):551.589.5

A NOTE ON WIND DIRECTIONS ASSOCIATED WITH LOW TEMPERATURES AND PRECIPITATION IN APRIL AT RIBBLEHEAD AND SQUIRES GATE

By B. INGHAM

Summary. In order to advise on the provision of shelter for ewes at lambing-time at a farm in Lancashire a study was made of observations in April from a coastal station and a hill station in north-west England. Tables and schematic diagrams are given showing the frequency of low temperatures and cold precipitation with various wind directions and speeds. At both stations there is a relatively high frequency of easterly winds and a relatively high frequency of precipitation with these winds. Nearly half of such precipitation occurs with temperatures 3°C or below and the highest frequency of temperatures 3°C or below occurs when the surface wind is easterly.

Early in January 1971, one of the District Agricultural Advisers, based at Preston, asked for assistance in the planning of artificial shelters for ewes at lambing-time at a farm approximately 800 ft* above MSL and just above Barnacre Reservoir on the west side of the Bowland Hills in Lancashire.

Apart from rainfall, there is little or no meteorological information for the area so there was no choice but to use observations from Blackpool Airport, Squires Gate, which lies some 17½ miles to the south-west of the farm close to the sea on the edge of a fairly broad flat plain — a markedly different site from that of the farm. Four observations, at 00, 06, 12 and 18 GMT, appear in the *Daily Weather Report*†, and these observations over the period 1961–70 were used to get some idea of the frequencies of wind directions associated with low temperature and cold precipitation, for it is cold and wet rather than cold alone which imposes the most stress on ewes and young lambs.

The analysis was done in the usual way for wind direction and speed with the added refinements of division of each speed range into a selection of temperature ranges and annotations of occurrences of precipitation. Occasions

* Distances and heights are given in traditional British units. Conversion factors to metric units are : 1 foot = 0·3048 m; 1 mile ≈ 1·6 km; 1 knot ≈ 0·5 m/s.

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

of precipitation occurring at the time of observation only were counted; codings of 'weather in the past hour' were ignored. Quite a large complex table resulted from this analysis and to reduce its size the temperature classifications were reduced to two groupings, one including all temperature ranges, the other including only occasions of temperature 3°C and below. The simplified analysis is shown in Table I.

Tables of this type do not give the essentials at a glance and a series of diagrams was prepared showing the distribution of wind direction, precipitation and the occurrence of temperatures 3°C and below. Figures 1 and 2 are two examples. It should be noted that because of the discontinuous nature of the observations and the method of classification the drawing of envelopes enclosing the various values is not strictly correct but it serves very well the purpose of giving a substantially accurate picture which can be understood fairly quickly.

Figure 2, which has a zero line 0·2 cm from the centre in order to reduce crowding at the centre point, shows the distribution of wind direction, temperature and precipitation for wind speeds of 7 knots (Beaufort force 3) and above.

The relatively high frequency in April of winds with a component from the east is fairly well known but what may not be so well known is the (relatively) high frequency of precipitation with them. Inspection of Table I will show that at speeds up to 16 knots there is in fact a higher frequency of precipitation in the 080–100° grouping than for any other grouping. Moreover, nearly half of the precipitation with easterlies occurs with temperatures 3°C or below, and the highest frequency of temperatures 3°C or below also occurs when the surface wind is easterly. So it came as no surprise when during the first discussion at the farm about what should be done, and before any reference to these diagrams, the farmer said, 'It's protection against the south-east wind which blows round the shoulder of yon hill we need; we don't need to bother about the north wind — it may be cold but it's mostly dry'.

Although the occurrence of low temperatures at a station at sea level may give a good indication of the occurrence of snow on hills, it is reassuring to have independent confirmation of the correctness of such indications, especially as there were only 10 observations of snow or sleet* in the 1170 observations used in the analysis. Accordingly an analysis was made of the wind and weather at Ribblehead which stands at a height of 1023 feet above sea level and lies some 24 miles to the north-east of the farm. Apart from altitude, there is little similarity between the exposure of the farm and that of Ribblehead. The farm is virtually open to the west and south-west whereas Ribblehead lies in a pronounced col as may be seen from Figure 3.

The data analysed consisted of observations made hourly from 07 to 18 GMT for the Aprils of the six years 1961–63 and 1965–67. There were gaps on Sundays, Public Holidays and staff half-days, so that there is not a complete record of events, but it is the only available record. The wind analysis was made in the usual way with annotations for occasions of rain, snow and hail (drizzle being counted as rain, and sleet being included with snow). Coding of 'precipitation in the past hour' presented a problem — especially with regard to hail, for it seldom seems to fall at observation time — so to avoid duplication

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

TABLE I—PERCENTAGE FREQUENCIES* OF SPECIFIED WIND DIRECTIONS, SPEEDS, TEMPERATURES AND PRECIPITATION IN APRIL AT SQUIRES GATE

Speeds		350–010	020–040	050–070	080–100	110–130	140–160	170–190	200–220	230–250	260–280	290–310	320–340	Total
		Degrees from north												
		percentage frequencies												
Calm	(a)†	—	—	—	—	—	—	—	—	—	—	—	—	2·90
	(b)	—	—	—	—	—	—	—	—	—	—	—	—	0·09 (—)‡
	(c)	—	—	—	—	—	—	—	—	—	—	—	—	0·85
	(d)	—	—	—	—	—	—	—	—	—	—	—	—	— (—)
All speeds (except calm)	(a)	4·17	5·03	5·03	13·56	8·61	6·99	4·54	5·71	10·66	14·41	10·31	8·10	97·10
	(b)	0·68	0·77	0·93	3·24	1·71	1·45	1·79	1·45	2·97	2·47	1·28	0·77	19·53 (0·77)
	(c)	1·19	1·45	1·28	4·54	2·05	0·34	0·09	0·09	0·17	0·26	0·26	0·85	12·54
	(d)	0·17	0·09	0·09	1·19	0·09	—	—	—	—	0·09	—	0·17	1·85 (0·68)
4 knots or more	(a)	4·01	4·77	4·69	13·05	8·35	6·74	4·54	5·54	10·57	14·41	10·15	8·10	94·90
	(b)	0·68	0·77	0·85	3·07	1·71	1·45	1·79	1·45	2·97	2·47	1·28	0·77	19·27 (0·77)
	(c)	1·10	1·28	1·10	4·27	1·85	0·34	0·09	—	0·17	0·26	0·17	0·85	11·51
	(d)	0·17	0·09	0·09	1·19	0·09	—	—	—	—	0·09	—	0·17	1·85 (0·68)
7 knots or more	(a)	2·87	3·67	3·95	11·26	6·74	6·31	3·75	5·03	9·72	12·87	8·78	6·57	81·62
	(b)	0·68	0·68	0·77	2·90	1·62	1·45	1·45	1·36	2·64	1·96	1·11	0·77	17·39 (0·77)
	(c)	0·43	0·85	0·85	3·67	1·19	0·17	0·09	—	0·09	0·26	0·17	0·68	8·45
	(d)	0·17	0·09	0·09	1·19	0·09	—	—	—	—	0·09	—	0·17	1·85 (0·68)
11 knots or more	(a)	1·45	2·05	2·97	7·93	3·67	4·77	2·64	3·67	8·19	8·87	5·71	4·09	56·01
	(b)	0·17	0·51	0·51	2·39	0·93	1·28	1·02	1·28	2·30	1·37	0·93	0·43	13·22 (0·77)
	(c)	0·09	0·43	0·51	2·13	0·26	0·09	—	—	—	0·26	0·09	0·43	4·27
	(d)	0·09	0·09	0·09	1·11	0·09	—	—	—	—	0·09	—	0·17	1·71 (0·68)
17 knots or more	(a)	0·17	0·17	1·11	2·90	0·85	1·54	0·68	1·62	5·37	3·75	1·85	1·11	21·14
	(b)	—	0·09	0·09	0·77	0·26	0·68	0·34	0·68	1·71	0·93	0·43	0·17	6·14 (0·34)
	(c)	—	—	0·09	0·60	0·17	—	—	—	—	0·26	0·09	—	1·19
	(d)	—	—	—	0·34	0·09	—	—	—	—	0·09	—	—	0·51 (0·26)
22 knots or more	(a)	—	—	0·34	1·19	0·34	0·51	0·17	0·68	2·22	1·37	0·68	0·43	7·95
	(b)	—	—	—	0·34	—	0·26	—	0·34	0·85	0·34	0·26	—	2·39 (0·09)
	(c)	—	—	—	0·26	—	—	—	—	—	0·17	—	—	0·43
	(d)	—	—	—	0·17	—	—	—	—	—	0·09	—	—	0·26 (—)

* Percentages of 1170 observations in April 1961–70 for 00 (except 1967), 06, 12 and 18 GMT at Squires Gate (33 ft above MSL).
† *(a)* all occasions, *(b)* occasions with precipitation, *(c)* occasions with temperature ⩽3°C, *(d)* occasions with precipitation, and with temperature ⩽3°C.
‡ Values in brackets are percentage frequencies of snow.

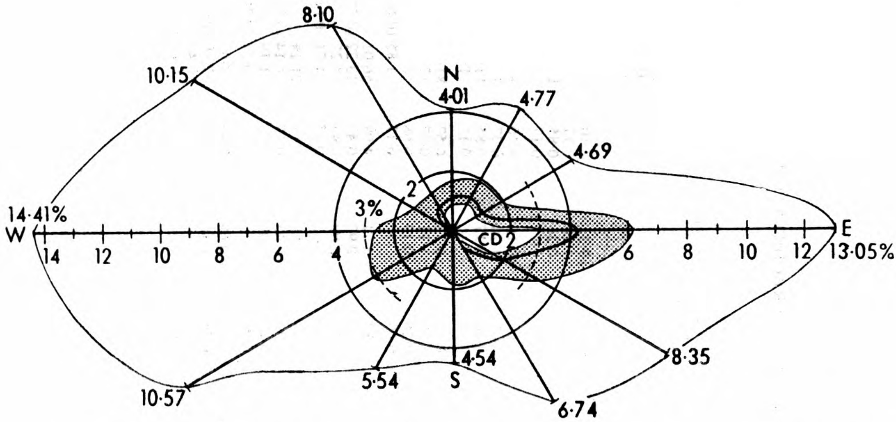


FIGURE 1—PERCENTAGE NUMBER OF OBSERVATIONS AT 00, 06, 12 AND 18 GMT, APRIL 1961–70 AT SQUIRES GATE OF WIND SPEED ⩾ 4 KNOTS, TEMPERATURE 3°C OR BELOW AND PRECIPITATION (STIPPLED AREA)

CD = Cold and dry.
Stippled area enclosed by thick line = temperature 3°C or below.

Total frequency of winds > 4 knots	94·90%	of 1170
Total frequency of winds with temperature 3°C or below	11·51%	
Total frequency of precipitation with winds > 4 knots	19·27%	
Total frequency of precipitation with temperature 3°C or below	1·85%	

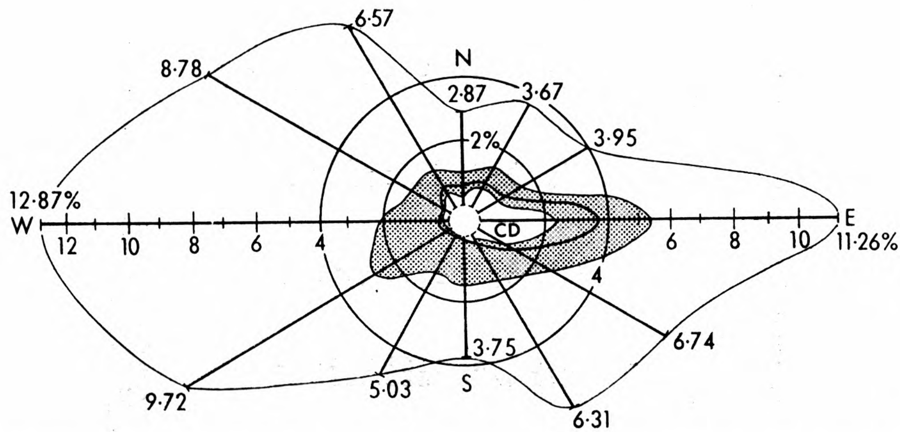


FIGURE 2—PERCENTAGE NUMBER OF OBSERVATIONS AT 00, 06, 12 AND 18 GMT, APRIL 1961–70 AT SQUIRES GATE OF WIND SPEED ⩾ 7 KNOTS, TEMPERATURE 3°C OR BELOW AND PRECIPITATION (STIPPLED AREA)

CD = Cold and dry.
Stippled area enclosed by thick line = temperature 3°C or below
Centre circle = zero line.

Total frequency of winds > 7 knots	81·62%	of 1170
Total frequency of winds with temperature 3°C or below	8·45%	
Total frequency of precipitation with winds > 7 knots	17·39%	
Total frequency of precipitation with temperature 3°C or below	1·85%	

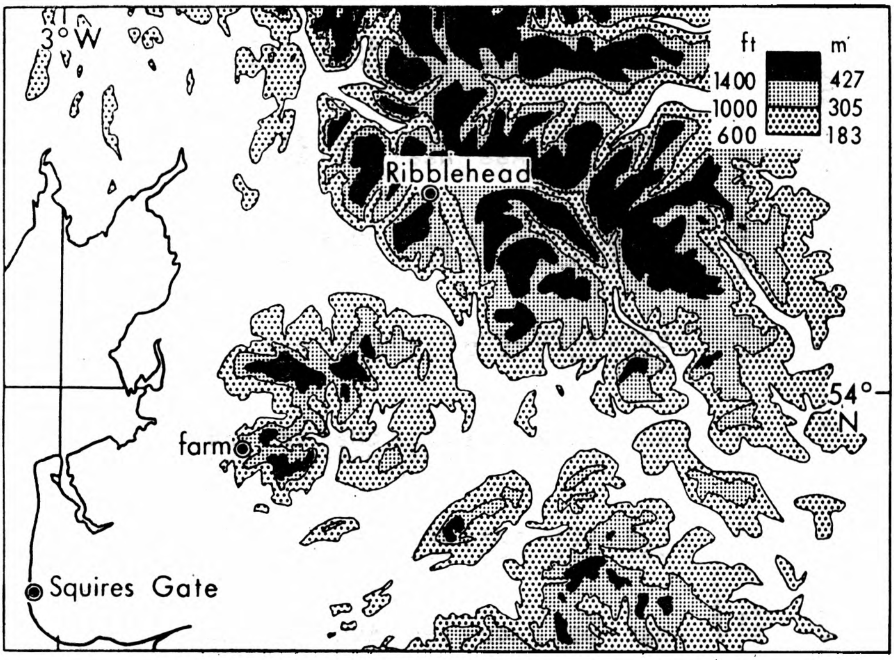


FIGURE 3—LOCATION OF THE FARM, SQUIRES GATE AND RIBBLEHEAD

in the counting of some occurrences or missing some altogether, 'past hour' codings were counted only when there was no precipitation reported at the previous hour. The complete analysis is shown in Table II. From this table diagrams such as Figure 4 may be constructed, showing frequencies of wind direction and associated forms of precipitation. Figure 4 refers to winds of 11 knots (Beaufort force 4) or more which without too much error can be considered an approximate equivalent of the 7 knots or more at Squires Gate used in Figure 2. Whereas there is a fair degree of symmetry about the east–west axis in Figure 2, there is distortion in Figure 4 which may fairly be attributed to restrictions on airflow by local topography. Comparison of the two figures suggests that when circumstances are such that the surface wind at Squires Gate might be easterly then it would probably be east-north-east at Ribblehead. It can be seen from Figure 4 that the sector 050–070° provides the greatest individual frequency of occurrence of precipitation and once again nearly half of it occurs as snow or sleet. When winds are from a westerly point, hail makes a larger contribution to the frequency of 'cold' precipitation than does snow, as can be seen from Table II; this is not unexpected.

Surface wind directions in hilly areas are subject to various constraints and in the absence of observations it is seldom possible to identify the precise direction of flow in a given set of circumstances. But if the commonest wind direction in the easterly sector can be identified then there is probably little doubt that that direction will also be the one with the greatest frequency of 'cold' precipitation and is therefore the direction against which there is greatest need for shelter.

Some surprise was expressed that the frequency of precipitation with easterly winds was as high as with westerly winds, for there is a strongly held

TABLE II—PERCENTAGE FREQUENCIES* OF SPECIFIED WIND DIRECTIONS, SPEEDS, TEMPERATURES AND PRECIPITATION IN APRIL AT RIBBLEHEAD

Speeds		350–010	020–040	050–070	080–100	110–130	140–160	170–190	200–220	230–250	260–280	290–310	320–340	Total
		Degrees from north												
		percentage frequencies												
Calm	*(a)*†	—	—	—	—	—	—	—	—	—	—	—	—	5·70
	(b)	—	—	—	—	—	—	—	—	—	—	—	—	0·29
All speeds (except calm)	*(a)*	7·33	6·34	16·05	8·37	4·54	3·55	6·22	3·60	13·20	20·05	1·63	3·43	94·30
	(b)	1·16	0·47	2·21	0·87	0·64	1·45	1·80	0·52	3·20	4·54	0·23	0·29	17·38
	(c)	0·17	0·06	1·98	1·28	0·06	0·29	0·17	0·06	0·17	0·12	—	0·23	4·59
	(d)	0·12	—	—	—	—	—	—	—	0·06	0·23	0·06	—	0·47
4 knots or more	*(a)*	6·97	6·16	15·76	8·08	4·42	3·49	6·05	3·43	12·50	19·54	1·63	3·37	91·40
	(b)	1·16	0·35	2·09	0·81	0·64	1·45	1·80	0·52	3·20	4·30	0·23	0·29	16·84
	(c)	0·17	0·06	1·98	1·28	0·06	0·29	0·17	0·06	0·17	0·12	—	0·23	4·59
	(d)	0·12	—	—	—	—	—	—	—	0·06	0·23	0·06	—	0·47
7 knots or more	*(a)*	6·34	5·24	14·31	7·15	3·60	3·02	5·29	2·91	10·29	17·45	1·16	3·20	80·00
	(b)	0·99	0·29	2·09	0·81	0·47	1·28	1·45	0·52	2·91	3·78	0·17	0·23	15·00
	(c)	0·17	0·06	1·98	1·28	0·06	0·29	0·17	0·06	0·17	0·12	—	0·23	4·59
	(d)	0·12	—	—	—	—	—	—	—	0·06	0·23	0·06	—	0·47
11 knots or more	*(a)*	4·65	4·18	12·62	5·82	2·50	1·86	3·96	1·80	7·73	15·24	0·93	2·15	63·43
	(b)	0·81	0·06	1·69	0·76	0·41	0·81	1·16	0·29	2·39	3·02	0·17	0·23	11·80
	(c)	0·17	0·06	1·98	1·16	0·06	0·29	0·17	0·06	0·17	0·12	—	0·17	4·42
	(d)	0·06	—	—	—	—	—	—	—	0·06	0·23	0·06	—	0·41
17 knots or more	*(a)*	2·85	2·21	7·85	2·85	0·58	0·64	1·34	0·35	2·85	9·31	0·35	1·28	32·44
	(b)	0·47	—	1·10	0·52	0·29	0·29	0·47	0·06	1·22	2·44	0·12	0·23	7·21
	(c)	0·17	—	1·51	1·05	—	0·17	0·17	—	0·06	0·12	—	0·06	3·31
	(d)	0·06	—	—	—	—	—	—	—	0·06	0·23	0·06	—	0·41
22 knots or more	*(a)*	0·87	1·45	4·13	1·45	0·23	0·12	0·64	—	1·40	5·35	0·12	0·58	16·34
	(b)	0·12	—	0·58	0·12	0·23	0·12	0·23	—	0·76	1·63	0·06	0·06	3·91
	(c)	—	—	0·52	0·81	—	—	0·12	—	—	0·06	—	0·06	1·57
	(d)	0·06	—	—	—	—	—	—	—	—	0·23	—	—	0·29
28 knots or more	*(a)*	0·12	0·52	1·45	0·12	0·17	—	0·23	—	0·76	2·31	0·06	0·35	6·07
	(b)	—	—	0·23	—	0·17	—	0·12	—	0·40	0·98	—	—	1·91
	(c)	—	—	0·23	0·06	—	—	0·06	—	—	0·06	—	—	0·40
	(d)	—	—	—	—	—	—	—	—	—	0·23	—	—	0·23
34 knots or more	*(a)*	—	0·06	0·52	—	—	—	0·06	—	0·23	0·58	—	0·17	1·62
	(b)	—	—	0·06	—	—	—	—	—	—	0·35	—	—	0·41
	(c)	—	—	—	—	—	—	—	—	—	—	—	—	—
	(d)	—	—	—	—	—	—	—	—	—	—	—	—	—

* Percentages of 1720 observations in April 1961–63 and 1965–67 for 07–18 GMT at Ribblehead (1023 ft above MSL) with some gaps, e.g. at weekends.
† *(a)* all occasions, *(b)* occasions with rain, *(c)* occasions with snow, *(d)* occasions with hail.

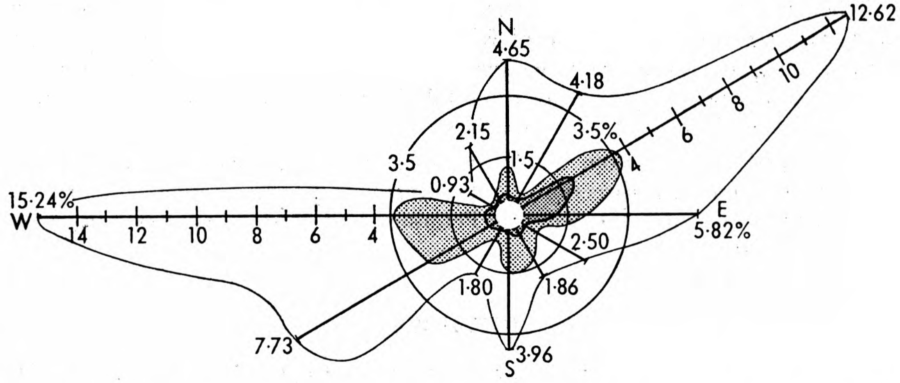


FIGURE 4—PERCENTAGE NUMBER OF OBSERVATIONS AT 07–18 GMT, APRIL 1961–63, 1965–67* AT RIBBLEHEAD OF WIND SPEED ⩾ 11 KNOTS AND ALL PRECIPITATION (STIPPLED AREA) INCLUDING SNOW AND HAIL

* Some missing — see text.
Stippled area enclosed by thick line = snow and hail.
Centre circle = zero line.

Total frequency of winds ⩾ 11 knots	63·43%	of 1720
Total frequency of all precipitation	16·63%	of 1720
Total frequency of snow and hail	4·83%	of 1720

belief that a mountain barrier affords protection from the weather to places on the lee side. In this connection, some distinction should be drawn between phenomena occurring with surface winds associated with a fairly deep established current which is changing only slowly — an example in this case is the breaking of North Sea stratus — and phenomena occurring with surface winds which form part of the circulation of a moving system. Figures from the originals of Tables I and II confirm the impression given by Figures 1 and 2 about the relative frequency of precipitation with easterly and westerly winds. If winds of 4 knots and stronger are considered, there was precipitation on a slightly higher proportion of occasions when the wind was easterly than when it was westerly (see Table III).

TABLE III—FREQUENCY* OF PRECIPITATION WITH EASTERLY AND WESTERLY WINDS IN APRIL AT SQUIRES GATE AND RIBBLEHEAD

	SQUIRES GATE Wind	SQUIRES GATE Precipitation	RIBBLEHEAD Wind	RIBBLEHEAD Precipitation
	number of occasions		*number of occasions*	
Easterly (050–130°) at Squires Gate; Easterly at Ribblehead	305	65 (1 occasion in 4·7)	410	106
Westerly (230–310°) at Squires Gate; Westerly at Ribblehead	412	79 (1 occasion in 5·2)	551	139 (about 1 occasion in 4 in both cases)

* See footnote to Tables I and II for details of observations.

When winds of 17 knots and stronger in the case of Squires Gate and 22 knots and stronger in the case of Ribblehead are considered the proportion is slightly higher in the case of westerlies but the number of actual occurrences forms such a small proportion of the total observations that too much reliance should not be placed on this comparison.

It is hoped that this note will draw attention to the features of the associations between wind direction, temperature and precipitation in the area of north Lancashire and the western Pennines and lead to similar studies in other hill areas.

REVIEWS

Forecasters' guide to tropical meteorology, Technical Report No. 240, by G. D. Atkinson. 265 mm × 200 mm, pp. xviii + 381, *illus.*, Air Weather Service (MAC) USAF, Scott Air Force Base, Illinois 62225, 1971. Price: $6. (Available to the public from National Technical Information Service, Springfield, Va 22151.)

This report, described as a *Forecaster's guide to tropical meteorology*, is not only up to date, but is just about as comprehensive a survey as could be found of the present state of the practical side of tropical meteorology. It is dated 1 April 1971, and the enormous bibliography containing 357 references dated up to and including 1970, indicates the amount of research that has gone into the preparation of the book.

The book is, on the whole, very clearly presented. Typographical errors are minimal, a rare example being the reference on page 6–25 paragraph 4 to figure 6–17 instead of 6–18. Also, typically transatlantic, much of the measurement of temperature and precipitation is in Fahrenheit and inches. The format is loose-leaf, allowing as it must for further addition resulting from the almost explosive increase in tropical work going on currently. Diagrams and tables, of which there are vast numbers, are generally clear and straightforward apart from a few minor exceptions such as some rather overcrowded charts of streamlines, isotachs and nephanalyses, but these were no doubt reduced for publication. Practically all areas of the world are dealt with, although, perhaps naturally, there is much reference to south-east Asia and the Pacific. The author is very much aware of shortcomings in tropical forecasting, especially any type of medium or long range, except in those areas which may be more easily linked with more well-documented middle-latitude areas. Data lack is still the greatest drawback, but, as he states at the end, much of the GARP effort will be directed at the tropics and he concludes 'during the next several decades tropical meteorology should be one of the most exciting and challenging areas of the atmospheric sciences'.

Very little in the report is concerned with forecasting conditions at sea, and considering the amount of the earth's surface which is water between the Tropics, this is perhaps rather an omission. The author does, however, emphasize the tremendous importance of up-to-date satellite information, and judging from some of the recent coverage of the Indian Ocean seen by the reviewer, it is obvious that APT readout should become universal at all stations of any size having responsibility for sea areas.

Oddly lacking in such a practical manual is any reference to the work of Johnson and Mörth in 1958–59 on pressure contour analysis in Africa, in spite of this having been published as long ago as 1962. Nor was there apparently any reference to Findlater's work on the cross-equatorial low-level jet. Apart from the areas near the Indian peninsula, much of the enormous area of the Indian Ocean is rather neglected. It is presumably left to readers to add their own notes in these spheres. Otherwise, the report is a must for all who are, or will be, working in, or in contact with, the Tropics.

B. RAMSEY

The physics of clouds, (second edition), by B. J. Mason. 242 mm × 165 mm, pp. xvi + 671, *illus.*, Oxford University Press, Ely House, 37 Dover Street, London W1, 1971. Price: £12.

Everybody working in the field of cloud physics is familiar with the first edition of this book, which for over a decade has been recognized as the most comprehensive and authoritative text on all microphysical aspects of the subject. A great amount of experimental research has been undertaken in this period, and the need for a revision has become clear, although the new work has in few respects demanded any drastic change of concept. The new edition extends the survey of the research literature from 1956 to about the beginning of 1970. In spite of extensive rewriting the book has increased in size by nearly 50 per cent (and in price by over 300 per cent).

The claim that it gives a detailed account of experimental and theoretical advances in the study of the microphysical processes is well justified, and in this respect the book has no rival and is an indispensable guide. It has retained exactly the same form and scope (9 chapters with the same headings) as its predecessor, and has been produced with the same care and rather old-fashioned elegance. Only in some minor respects can criticisms be raised.

The first is one not yet open to remedy, and indeed which the author straightway himself makes in his preface: it is the unfortunate absence of a secure dynamics of cloudy atmospheric motions, long sorely needed to provide a context for the microphysics and to allow its confident application to atmospheric events. This deficiency does not diminish the value of the book.

In the chapter on the artificial modification of clouds and precipitation more discussion might have been given to procedures for assessing the magnitude of the effect of seeding operations than can be compressed into two pages, for this is a problem of fundamental importance (with more general implications), not readily overcome by some programme of 'randomized' operations. Its difficulty is illustrated by the description of some particular seeding projects, but it is strange that these do not include the (weekly) periodic silver iodide emissions directed by Langmuir between December 1949 and March 1950. The possible results of this experiment, more dramatic than any so far made, provoked passionate controversy at the time, and provide an unrivalled example of the difficulty of using statistical methods to test the validity of operations for which there is no physical theory.

The chapter on radar techniques and observations has been brought up to date by the discussion of Doppler techniques and of the more recent ways in which radar echo intensity and configuration have been used to infer the form of airflow in precipitation. Most of the examples of radar displays are those used in the first edition, and do shameful injustice to those who have devised the modern data presentations, which are far more accurate and comprehensive, and even strikingly impressive as a kind of abstract art.

The chapter on the electrification of clouds, a subject to which the author himself has made many important contributions, is a particularly interesting one in view of the cursory treatment to be found in most texts and the way in which the important references are scattered about in the research literature. If the phenomena have little bearing on the motion of the atmosphere, which has come to be the predominant concern of meteorologists, they are nevertheless amongst the most spectacular of meteors and the most provocative to atmospheric physicists; apparently the number of alternative theories has increased, but still no one is much more convincing than the others.

It must be emphasized, however, that the main value of the book rests on the chapters other than the three specifically mentioned, that is, on those which concern the nucleation and growth of water drops and ice crystals in air. The extensive studies which have been made should be of great interest to physicists outside the field of meteorology, while cloud physicists will appreciate the unswerving thoroughness with which they are passed under review and conveniently referenced.

Finally, a personal reaction can be addressed to the publishers: the book would be easier to handle and to read if it had a larger page size.

F. H. LUDLAM

Global effects of environmental pollution, edited by S. F. Singer. 240 mm × 160 mm, pp. 218, *illus.*, D. Reidel Publishing Company, P.O. Box 17, Dordrecht – Holland, 1970. Price: Dfl. 40.

The concluding discussion in this volume describes the symposium which gave rise to it as a 'curtain raiser for world-wide efforts to set up a global monitoring system of crucial pollution parameters as well as for the forthcoming United Nations Conference of 1972 dealing with the problems of the human environment'. It is undoubtedly true that since then (December 1968) the scene has been rapidly filled with a mounting interest and clamour for activity in this field.

The volume collects, under the editorship of S. F. Singer, 18 papers by a group of well-known authors brought together to this symposium by the American Association for the Advancement of Science. There is a grouping of the papers into four main sections dealing with the chemical balance of gases in the atmosphere, the nitrogen cycle, effects on climate and the role of the oceans in the pollution problem. There is of course a good deal of overlapping of interest in these sections.

Meteorologists will not be surprised to find contributions here from S. Manabe — though rather surprisingly the one dealing briefly with the effects of carbon dioxide on the radiative convective equilibrium of the atmosphere appears in the group on chemical balance rather than in that on effects on climate.

In general the papers provide a rather balanced and unsensational questioning of the present inadequate state of knowledge and understanding over the whole field. It is undoubtedly possible to find issues which perhaps were not questioned sufficiently. One example which immediately occurred to the writer, in the paper on inadvertent modification of weather, is the virtual acceptance of the original claim that increased rainfall in La Porte, Indiana, was a direct result of pollution, whereas there has since been a challenging of the whole validity of the rainfall record concerned. Another, in the paper on interaction between the oceans and the land, is the contention that the main reason for recently increased acidity in the rains over Sweden is 'of course, increased industrial air pollution by SO_2'. But in a field in which many may regard printed paper as a by no means neglible source of pollution this slim rather well-produced volume will be relatively welcome, at a price (£4) which is at least consistent with the current trend.

F. PASQUILL

NOTES AND NEWS

Global Atmospheric Research Programme

Atlantic Tropical Experiment. The Global Atmospheric Research Programme (GARP) Atlantic Tropical Experiment developed jointly by the World Meteorological Organization and the International Council of Scientific Unions is an effort designed by some 25 nations to provide a basis for estimating the effects of the smaller tropical weather systems on the larger-scale atmospheric circulations and to provide comprehensive data against which the validity of numerical predictions can be tested in the tropics.

As now planned the central location of the experiment will be an area 1000 by 1000 km at a distance of about 1000 km from the west coast of Africa between latitude 5 degrees and 15 degrees north. During the months of June, July and August 1974, a fleet of some 20 ships will be equipped with modern instruments for probing the atmosphere, for making temperature and wind soundings and for flying tethered balloons each with a chain of instruments extending from the surface of the sea to 1000 m or more if possible. A geostationary satellite over South America will constantly survey the area recording both visible light and invisible infra-red rays revealing temperatures and humidities, while aircraft will be directed to these areas for more detailed studies of individual disturbances. The intention is that weather disturbances forming over the African mainland south of the Sahara Desert will be carefully mapped as they pass this network of stations over the Atlantic Ocean.

Global experiment. The Atlantic Tropical Experiment is the forerunner of an experiment to be conducted on a global scale two years later. A number of questions raised by the global experiment will by necessity have to be answered by the tropical experiment for the former to be successful in trying to understand how the atmosphere circulates and how variations of this circulation generate weather.

In 1976 an intensive observation of the atmosphere will be carried out by a series of at least six satellites, two in polar orbit and four in geostationary position, each of the latter surveying about one-quarter of the tropical and subtropical latitudes. To supplement the satellite coverage, and because in the tropics winds need to be measured directly, a series of carrier balloons with special dropsondes may be used to measure winds in tropical latitudes. Balloons will also be used in the southern hemisphere to provide critical reference observations that will permit more reliable use of satellite observations. Since vast ocean areas in the southern hemisphere are frequently covered with clouds, thereby making low-level atmospheric readings from satellite elevation less reliable, a system of buoys is also being developed to make complementary surface observations.

WMO PRESS RELEASE

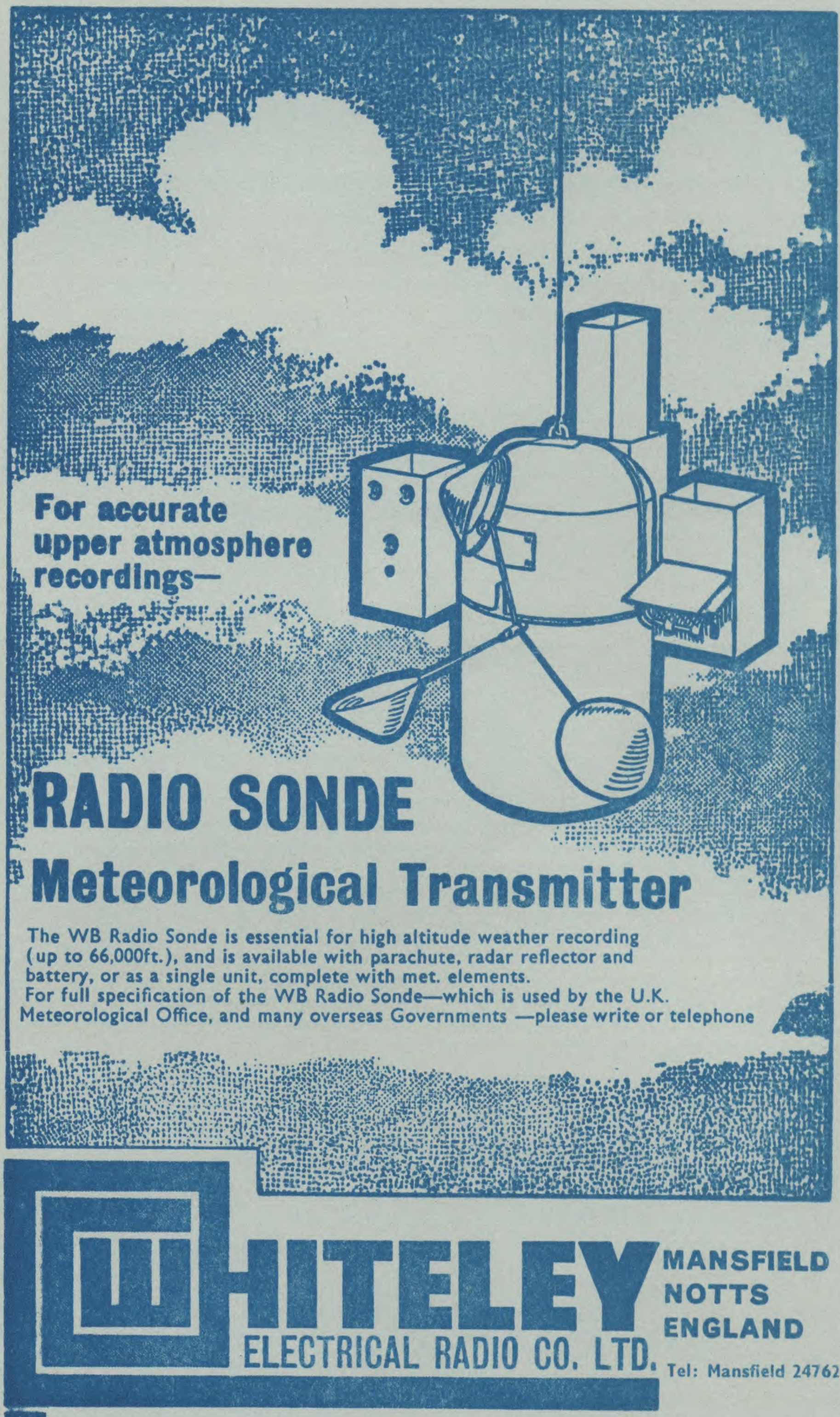
Special merit promotion of Dr R. J. Murgatroyd, O.B.E.

It is a pleasure to record that Dr R. J. Murgatroyd has been granted promotion to Deputy Chief Scientific Officer under the scheme which permits the promotion of scientists of exceptional ability in research without any consequential change in their administrative responsibilities. Promoted to Senior Principal Scientific Officer in 1957, Dr Murgatroyd was freed of administrative responsibilities in 1963 in order to enable him to pursue his important studies of the circulation of the stratosphere and mesosphere, on which subjects he is one of the world's leading experts.

Dr Murgatroyd's studies have examined the radiative heat sources and sinks in the stratosphere and above, and he has evaluated the consequent meridional circulations which, although too slow to be observed directly, are of vital importance in determining the structure of the higher atmosphere. Dr Murgatroyd has extended his studies to consideration of the mixing processes involved and has made fundamental contributions to the nature of large-scale mixing in a stratified medium such as the stratosphere.

Recognizing that a comprehensive explanation of stratospheric motion must start from the fundamental dynamical equations, Dr Murgatroyd has initiated the computer programming of the numerical simulation of the stratospheric circulation by direct numerical integration of the dynamical and thermodynamical equations. Such methods have been shown to give valid explanations of important features of the lower atmosphere. The Meteorological Office is fortunate to have a scientist of Dr Murgatroyd's wide interests and experience to exploit the potential of this approach to the understanding of the stratosphere and mesosphere.

J. S. SAWYER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THE METEOROLOGICAL MAGAZINE

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DECREASE IN THE FREQUENCY OF FOG IN CENTRAL LONDON

By I. JENKINS

Summary. Numbers of occasions with visibilities below 500, 200 and 100 metres at London Weather Centre were extracted for each of the observations at 00, 03, 06, 09, 12, 15, 18 and 21 GMT during the period July 1948 to June 1970.

At 09, 12 and 15 GMT, the number of occasions of visibility less than 500 metres was found to have decreased steadily throughout the period of the study but at 00, 03 and 06 GMT the number increased in the middle and late 1950s and only decreased in the 1960s. The ratio of the number of occasions at 06 to the number at 09 increased through unity during the period. It is suggested that these changes are connected with changes in smoke emission in central London, though not specifically with the consequences of the Clean Air Act (1956).

Introduction. A recent analysis by Brazell[1] shows that there has been a considerable decrease in the number of hours of thick and dense fog in central London and at London (Heathrow) Airport in recent years. It seemed possible that this decrease was in some way related to a decrease in pollution and it was decided to study in more detail the occurrence of fog in central London during the past 20 years or so. Observations made at London Weather Centre have been used for this study; although during the period examined the observing site was moved twice, all three sites (two in Kingsway and one in High Holborn) are within a circle of radius 200 metres, and it is believed that the fog observations have been unaffected by the moves.

Data used. The numbers of occasions when the visibility was less than 500, 200 and 100 metres (550, 220 and 110 yards) at 00, 03, 06, 09, 12, 15, 18 and 21 GMT were extracted for the years 1948 to 1970. From 1949 to 1954 the ranges in the visibility code were below 400 metres and below 600 metres but there was no code figure for below 500 metres. In this period, therefore, the numbers of occasions between 200 and 399 metres and between 400 and 599 metres were extracted separately. The number of occasions in the latter range was halved and any fractions were ignored to give an estimate of the occasions when the visibility was between 400 and 499 metres. This figure was then added to the occasions with visibilities between 200 and 399 metres to obtain the number of occasions with visibilities between 200 and 499 metres.

The period used was July to June the following year so that any foggy winter would be included in one 12-month period. Table I shows the number of occasions in each of the years examined. Five-year running means were prepared for each of the fixed hours and plotted against the middle year of the period.

Results. The graph for 09 GMT in Figure 1 is also representative of those for 12 and 15 GMT; that for 18 GMT is similar to the one for 21 GMT and that for 06 GMT resembles those for 00 and 03 GMT.

TABLE I—NUMBER OF OCCASIONS AT LONDON WEATHER CENTRE WITH VISIBILITIES BELOW CERTAIN VALUES AT FIXED HOURS, 1948–70

Time (GMT)	1948 -49	49 -50	50 -51	51 -52	52 -53	53 -54	54 -55	55 -56	56 -57	57 -58	58 -59	59 -60	60 -61	61 -62	62 -63	63 -64	64 -65	65 -66	66 -67	67 -68	68 -69	69 -70
	12-month period July to June																					
	Number of occasions																					
	(a) Below 500 metres																					
00	11	7	3	5	15	3	2	2	5	6	17	6	3	2	9	7	2	0	2	0	3	1
03	10	5	3	7	14	5	3	5	7	5	16	7	6	4	14	10	6	2	1	0	3	2
06	10	8	4	9	13	6	4	7	13	9	13	15	6	5	14	11	8	5	6	2	5	3
09	22	16	12	16	23	15	9	9	6	12	13	7	7	5	6	7	4	6	0	1	2	2
12	10	7	7	5	18	8	4	4	4	7	12	6	2	1	4	5	1	3	0	0	0	1
15	5	5	5	1	14	6	2	4	2	6	9	2	0	3	5	4	1	0	0	0	0	0
18	7	5	5	2	8	3	0	1	2	5	5	3	1	4	5	4	1	1	0	0	1	0
21	7	7	5	4	13	3	4	3	4	5	11	3	2	3	9	5	1	1	1	0	0	0
Total	82	60	44	49	118	49	28	35	43	55	96	49	27	27	66	51	24	18	10	3	14	9
	(b) Below 200 metres																					
00	3	2	1	2	7	0	0	2	2	3	6	1	1	0	4	2	0	0	1	0	0	0
03	3	2	1	3	6	2	1	3	3	2	6	2	1	0	4	3	2	2	0	0	1	2
06	3	2	1	5	5	6	1	4	6	3	6	9	1	1	5	4	3	4	2	0	0	2
09	9	8	4	3	6	3	2	3	2	3	4	2	1	2	2	3	1	1	0	0	2	0
12	3	3	5	0	5	1	1	2	1	0	2	1	0	1	3	0	0	1	0	0	0	0
15	4	1	2	0	4	3	1	1	2	0	3	1	0	1	4	0	1	0	0	0	0	0
18	4	0	1	0	2	0	0	1	1	1	2	3	0	0	3	0	1	0	0	0	0	0
21	3	1	1	1	4	0	1	2	1	1	1	0	0	0	3	2	1	0	0	0	0	0
	(c) Below 100 metres																					
00	3	1	1	1	5	0	0	1	1	2	4	1	1	0	4	2	0	0	0	0	0	0
03	3	0	1	1	5	2	0	0	2	1	3	2	0	0	1	1	1	0	0	0	0	2
06	2	2	1	2	2	2	0	3	4	3	2	4	0	1	2	2	1	4	0	0	0	1
09	5	5	2	2	2	2	1	3	2	2	2	1	0	0	1	1	0	0	0	0	1	0
12	2	3	1	0	4	1	1	2	1	0	0	0	0	1	1	0	0	0	0	0	0	0
15	1	1	2	0	4	2	1	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0
18	3	0	1	0	2	0	0	1	1	0	0	0	0	0	3	0	0	0	0	0	0	0
21	2	1	1	1	3	0	1	1	0	0	1	0	0	0	3	0	0	0	0	0	0	0

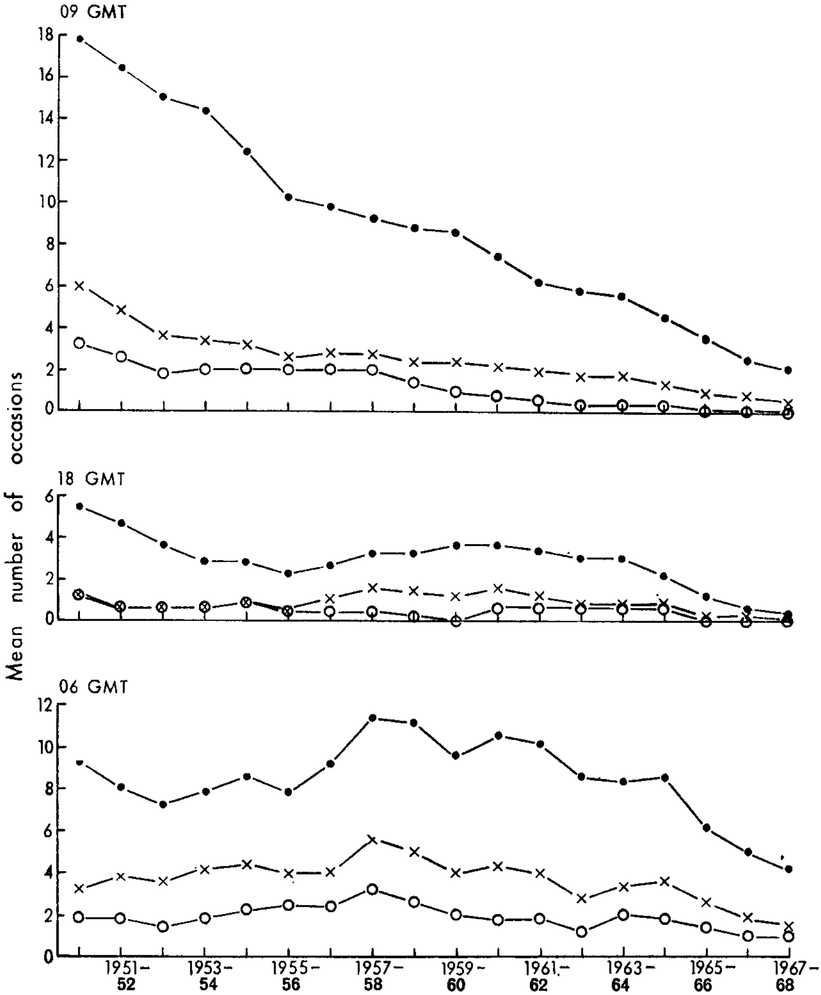

FIGURE 1—MEAN NUMBER OF OCCASIONS WITH VISIBILITY BELOW 500, 200 AND 100 METRES AT LONDON WEATHER CENTRE AT 09, 18 AND 06 GMT

5-year running means plotted on centre point of period

· ——— · below 500 m x ——— x below 200 m o ——— o below 100 m

The graphs for 00, 03 and 06 GMT show a fall in the number of occasions with visibility below 500 metres followed by a rise until the late 1950s when the number of occasions then started to fall again. The graphs for 09, 12 and 15 GMT show a steady decrease in the number of occasions with visibilities below 500 metres. The shape of the graphs for 18 and 21 GMT appears to be intermediate between those for 06 and 09, the number of occasions with visibility below 500 metres showing little change after the fall in the early 1950s until the fall in the 1960s.

The curves for visibilities less than 200 and 100 metres are broadly similar to those for visibilities less than 500 metres but the numbers of occasions are smaller.

Discussion. An investigation by Dinsdale[2] drew attention to the fact that the 5-year running means of occasions of visibility less than 440 yards at the eight synoptic hours had shown a general decrease during the 10-year period 1958–67, not only at suburban but also at rural stations. He therefore sounded a timely note of caution about interpretation of reduced fog frequencies in terms of the supposed results of the Clean Air Act (1956).

The total number of occasions of visibility less than 500 metres at the eight synoptic hours are now produced for central London (Table I). For the period 1958 to 1967, these figures are broadly similar to those produced by Dinsdale. However, examination of the detailed figures shows that the behaviour of the figures at the individual hours is not the same in each case, and the totals of the eight synoptic hours may therefore mask some important effects.

In graphs for visibilities below 500 metres at 09 and at 06 GMT (Figure 1) it is apparent that, whereas the frequency at 09 was twice that at 06 in the five-year period centred around 1950–51, by about 1956–57 the frequencies were similar. By the period centred on 1966–67 the situation was reversed and the frequency at 06 was twice that at 09. The graphs for visibilities less than 200 and 100 metres reveal a similar pattern of change, but with such small numbers the pattern is less striking. The number of occasions with visibilities below 500 metres at 06 and 09 GMT for the winter half-year (October to March) are similar to those for the complete year (Figure 2).

In the report on atmospheric pollution in Leicester[3] it was shown that during the period 1937 to 1939 the peak concentrations of smoke occur at around 08 on weekdays and 10 on Sundays and that during the hour 08 to 09 about 50 per cent more smoke was produced than at 06. If, therefore, there was a decrease in over-all smoke-emission one would expect a more marked reduction in the smoke at 09 than at 06. Pre-war Leicester and post-war London are admittedly not necessarily comparable but there is no reason to suppose that the diurnal pattern of smoke concentration is any different.

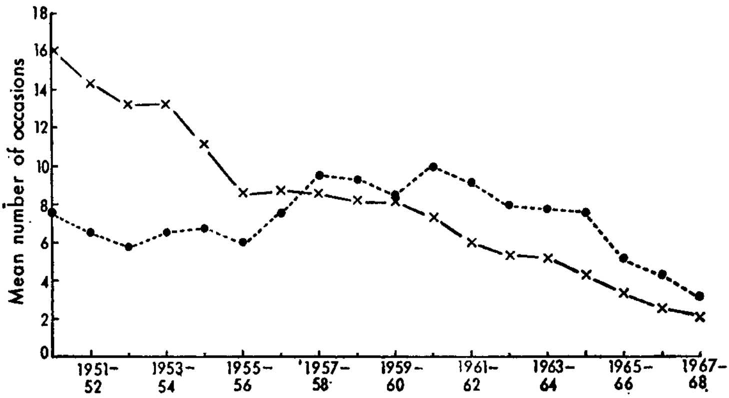

FIGURE 2—MEAN NUMBER OF OCCASIONS WITH VISIBILITY BELOW 500 METRES AT LONDON WEATHER CENTRE AT 06 AND 09 GMT FROM OCTOBER TO MARCH

5-year running means plotted on centre point of period
· - - - - - - · 06 GMT x ——— x 09 GMT

The variation in smoke concentration and estimated emission in London since 1952 was given in a paper by the Warren Spring Laboratory[4] from which Figure 3 is reproduced. It is apparent from this graph that there has been a general decline in estimated smoke-emission since 1954, i.e. from a date well before the Clean Air Act (1956) became effective.

With the data available it is not possible to establish any certain conclusions, but it seems at least possible that the change over the years in the ratio of fog frequency at 09 to that at 06 is connected with the changes in the amount of smoke emission.

In Figure 4 the estimated emission graph of Figure 3 is reproduced together with a graph of the ratio of fog frequency (less than 500 metres) at 09 GMT to that at 06 GMT; the similarity is apparent. There is, moreover, no doubt that one major effect of high smoke-concentration on fog is to delay fog clearance; the high frequency at 09 GMT in the early 1950s is, at least, partly due to this factor. The effect of a reduction in smoke concentration such as that which has taken place during the past 15 years will, however, be far more marked at 09 GMT (when concentrations are near the diurnal maximum) than at 06 GMT (when concentrations are much lower).

Many factors including wind, sunshine and temperature[5] may affect the frequency of fog over a period. Although there has been a general decrease in the frequency of fog at suburban and rural stations alike during the past 10 years or so, the changes cannot specifically be attributed to the Clean Air Act (1956) but it is suggested that the observed reduction in fog frequency in central London during the last 17 years has almost certainly been influenced by the reduction of smoke emission during the same period.

Acknowledgements are made to Mr R. J. Ogden, Senior Meteorological Officer, London Weather Centre, for his help in preparing this paper.

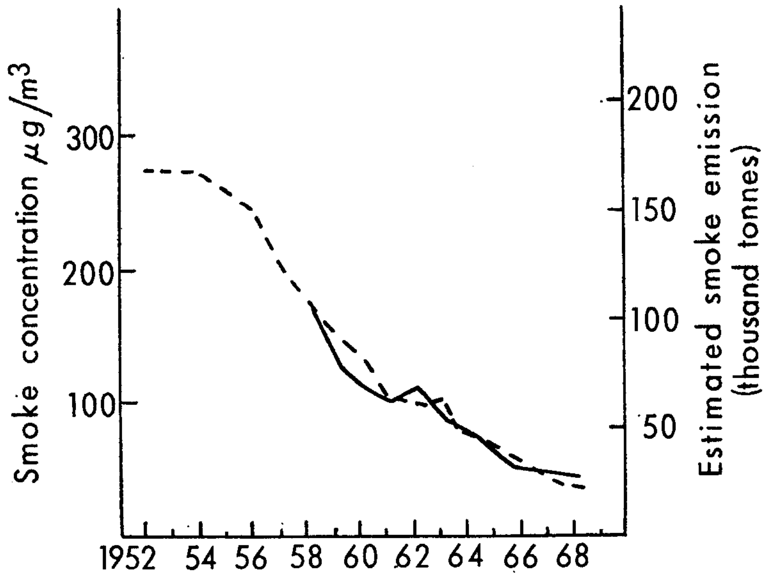

FIGURE 3—SMOKE CONCENTRATION AND ESTIMATED EMISSIONS IN LONDON

——— Average concentration - - - - - - - Emission

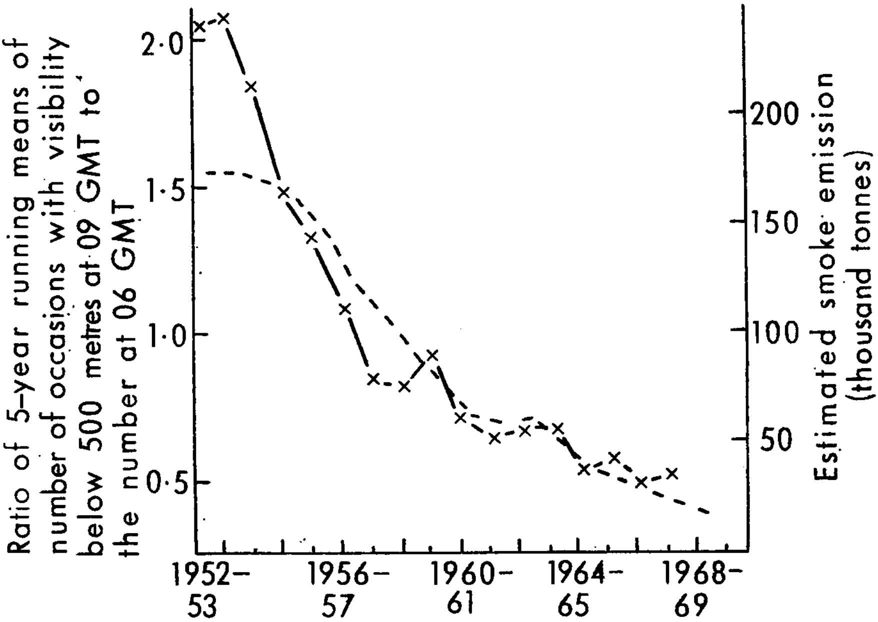

FIGURE 4—ESTIMATED SMOKE-EMISSION IN LONDON AND THE RATIO OF THE NUMBER OF OCCASIONS WITH VISIBILITY LESS THAN 500 METRES AT 09 GMT TO THAT AT 06 GMT AT LONDON WEATHER CENTRE

x ——— x Ratio of fog frequency at 09 GMT to that at 06 GMT - - - - - - - Emission

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551.508.72:551.573

A NOTE ON THE MEASUREMENT AND ESTIMATION OF EVAPORATION

By R. W. GLOYNE

Summary. This paper discusses the causes of the differences between the rate of water-loss from an evaporimeter and that from an extended, freely evaporating, area.

Some theoretical expressions of the evaporation rate from a strip and a circular area are examined to elucidate the problem. Attention is directed to the 'leading edge' or 'clothes-line' effect and to the 'oasis' effect and some field results quoted to illustrate these phenomena.

General considerations. It is now increasingly appreciated that, in a given *macro-meteorological* situation, the rate of water-loss per unit area from a device such as a pan, a small pond, or from an isolated small area can, and generally does, differ systematically in varying degrees from the corresponding rate of loss of water from an extensive, homogeneous vegetated surface.

Such differences can be attributed to one or more causes; amongst them are :

(i) Differences in the mechanisms of turbulent exchange operating on the contrasting surfaces.

(ii) Differences in the radiative and convective exchanges at the different surfaces; and the partitioning of available energy between these energy sinks.

(iii) Differences between the vertical and horizontal gradients of temperature, vapour density and wind impinging upon the several surfaces.

Although all three causes contribute towards the observed differences, the last, (iii), is the one on which attention is focused in this note.

Consider an idealized, extreme situation, viz. that of a shallow tank of water placed in a hot, arid desert.

(a) First, suppose that there is no horizontal air motion, i.e. no wind. The vapour pressure in the air immediately above the tank will initially be very low; that at the water surface will be the saturation vapour pressure corresponding to the temperature of the water surface. Water will be removed by molecular diffusion, the 'cylinder' of air above the tank will be increasingly enriched with water vapour at the expense of the water in the tank. Sutton[1] deals with this case under certain boundary conditions: lateral diffusion of water vapour is assumed to be negligibly small.

In practice, local convection currents will be present and transfer processes additional to molecular diffusion will be in operation.

The rate of evaporation will be proportional to the instantaneous vapour-concentration gradient. The drier the overlying air, the faster the rate of evaporation. If, as is postulated, the vapour is confined to the vertical 'cylinder' of air then, as evaporation proceeds, the vapour-concentration difference will decrease, and with it the rate of loss.

The rate of evaporation from the tank will generally not be the same as the rate of loss, if any, of water from the 'desert' surface, where the vapour gradient is quite different. However, the higher the vapour concentration over the desert surface, the higher the initial vapour concentration above the tank and the slower the evaporation from the tank.

(b) Now suppose there is a steady wind, then the vapour-enriched air above the tank will be continually removed and replaced by dry air; furthermore, if the surface area of the tank is sufficiently small — say a few square feet — the original low value of the vapour density will be continually re-established and evaporation will take place at the initial rate for as long as there is water to be evaporated. Once again, the rate of loss of water from the tank, i.e. from the 'evaporimeter' will generally not be the same as the rate of removal of water from the 'desert' surface, i.e. as the 'evaporation' from the desert. (*Note.* This is not to say that the rate of loss from various evaporimeters has no physical meaning nor practical significance in these circumstances.) This situation arises, although less dramatically, in most parts of the world after a drought. When the surface is dry because of drought there may be little or no loss of water from the parched earth or wilted vegetation — but a great deal from any nearby wet or continually dampened surface.

The discussion so far should clarify the distinction between *actual evaporation* (actual rate of loss of water from the surface exposed to atmospheric influences) and *potential evaporation* (the rate at which water would be lost, under the same atmospheric conditions, from a homogeneous, extensive surface (typically one of cropped grass), the surface having unhindered access to unlimited water). When, as is usually the case, the concern is with a vegetative surface, water moves from the soil to the atmosphere through the plant roots, stem and leaf to the atmosphere — the process of transpiration, and the term 'evapotranspiration' is commonly used. It is implicit in the above definition of potential evapotranspiration that there should be no horizontal gradient of temperature, vapour density and wind, and furthermore it is customarily assumed that the net radiant income defines this 'potential' or upper limit to water loss (for a further examination of this concept see Slatyer and McIlroy[2] or McIlroy[3]).

However, the point of immediate concern is that downwind from a boundary between surfaces having different physical characteristics (and water supply) there will be a marginal zone in which a progressive readjustment of the incident profiles of wind, temperature and humidity to those appropriate to the new surface will take place. If air moves from a dry to a moist surface then the rate of water-loss will be highest at the 'leading edge' and will decrease downwind: if the moist surface is that of an evaporimeter then such a surface may well be completely within this transitional zone. This effect has been aptly dubbed the 'clothes-line effect' by Chang.[4] A further effect — 'the oasis effect' — arises from large-scale advection of energy sources and sinks in the atmosphere, so contributing to the total energy available for evaporation at a given point (Slatyer and McIlroy, Reference 2, Chapter 3).

Quantitative discussion of some aspects of evaporation. A number of workers, e.g. Pasquill,[5] Sutton,[1] Rider, Philips and Bradley[6] have examined the effect of wind at, and beyond, the boundary between two adjacent surfaces possessing different levels of surface wetness, i.e. having different vapour concentration.

Let *AB* in Figure 1 be the boundary (extending indefinitely in either direction) between a dry region to the left and a saturated surface to the right; and suppose *pg* be a strip of unit width. Following Sutton[1] let :

u_m = the mean speed of a uniform horizontal wind blowing perpendicular to *AB*. Figure 1 shows u_m as $u(m)$.
x_o = the downwind distance from the boundary
q_o = the vapour concentration in the air before it reaches *AB*
q_s = the vapour concentration at the evaporating surface
E = the *total* rate of evaporation per unit cross-wind width.

Consider a rectangular 'box' of indefinite cross-wind length *AB*, of indefinite height AA' $(= z)$, but of finite downwind extent $(AD = BC = x_o)$. Under steady conditions all the water vapour leaving the horizontal surface of the elementary strip *pg* will pass horizontally through the vertical strip *gs*. Sutton shows that, in these conditions and with normal stability (adiabatic temperature lapse),

$$E = (q_s - q_o)\, B u_m^{0.78}\, x_o^{\ 0.89}, \qquad \ldots (1)$$

where *B* is a function of stability.

The effect of the progressive enrichment of the airstream by the continued evaporation of the water vapour into it is expressed by the fact that the total rate of evaporation from strips such as *pg* does not grow proportionally to the downwind distance x_o, but at a slower rate. Panofsky[7] illustrates the effect

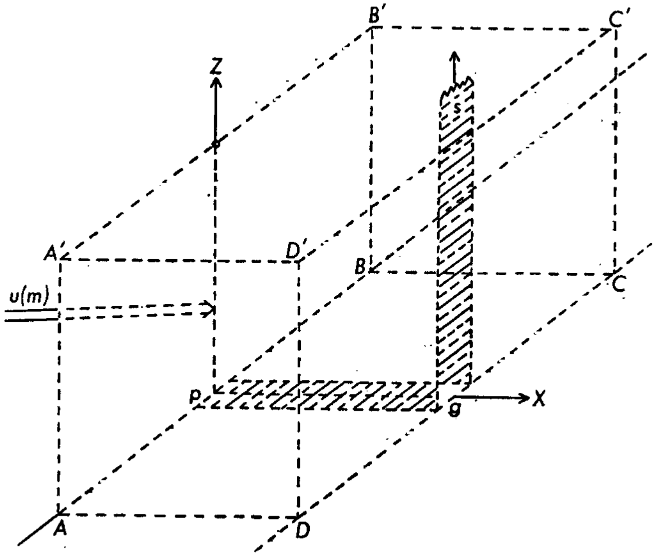

FIGURE 1—CO-ORDINATE SYSTEM FOR COMPUTATION OF EVAPORATION FROM STRIP *pg*

For additional information see text p. 324.

thus '..... evaporation depends upon the 8/9th power of the fetch. This means that, if the fetch is increased by a factor of 512 (2^9), the evaporation increases only 256 (2^8)-fold.' In the limit, Sutton notes that 'if the wetted surface extends indefinitely downwind, a stage will be reached when the air over the surface is saturated and (local?) evaporation ceases'.

Pasquill,[5] amongst others, has shown that the corresponding expression to equation (1) for a wetted circular area is :

$$E = (q_s - q_o)\ Cu_m^{0.78}\ r^{1.88}, \qquad \ldots (2)$$

where r is the radius of the circle.

Assuming a stationary meteorological situation the average evaporation per unit area (here written E(av)) will be :

for the strip : $E(\text{av}) \propto E/\text{area}$, i.e. E/x hence $\propto x^{-0.11}$,
for the disc : $E(\text{av}) \propto E/\text{area}$, i.e. E/r^2 hence $\propto r^{-0.12}$.

The change in evaporation rate averaged over the whole area (i.e. computed on a per-unit-area basis) with increasing size of the disc — defined by $r = 0.01 \times 10^n$ where $n = 1$ to 7 — can be appreciated from the following figures :

n	1	2	3	4	5	6	7
r(metres)	0·1	1	10	10^2	10^3	10^4	10^5
E(av) $\propto$	7·57	5·75	4·37	3·31	2·51	1·90	1·45

An idea of the way in which additional increments of evaporating area (corresponding to increments of x in Figure 1, and increments of r for the disc) contribute to the evaporation, is indicated by the trend of the series below in which the figures are proportional to the additional evaporation averaged over the additional area.

	Increments of x or r (cm)					
	10–10^2	10^2–10^3	10^3–10^4	10^4–10^5	10^5–10^6	10^6–10^7
For the strip : increment of E(av) proportional to	0·58	0·45	0·35	0·27	0·21	0·16
For the disc : increment of E(av) proportional to	0·57	0·44	0·33	0·25	0·19	0·14

Some practical implications and evidence from field-work. The possibility of using the formula discussed above to compute the water-loss over an extended area from that lost from a small evaporimeter has been discussed by, e.g. Green [8,9] who sought a 'correction factor' to compensate for the 'oasis effect' (more strictly perhaps the 'leading edge' effect). He suggests that beyond a radius of about 200 yd ($1{\cdot}82 \times 10^4$ cm or 182 m) the rate of decrease of average evaporation changes only slowly and it may therefore be postulated that such an area represents the idealized, indefinitely large, wetted area associated with the concept of potential transpiration. On this assumption he finds that :

$$\frac{\text{evaporation rate per unit area for } r = 11 \text{ inches}}{\text{evaporation rate per unit area for } r = 200 \text{ yards}} \approx 2{\cdot}2.$$

If the 'infinitely large' area is assumed to be defined by $r = 2 \times 10^5$ cm (a 10-fold increase), the ratio becomes 2·8.

Direct field measurements of the horizontal gradient of the actual evaporation from the leading edge are few, but Rider *et alii* (Reference 6, page 529) give some derived estimates of evaporation as an airstream moves from a (dry) tarmac surface into an irrigated, grassed area. They postulate that the true evaporation rate per unit area E (say) is that required exactly to absorb all the net radiant energy impinging on the surface at a distance (x) of 1600 cm from the leading edge. If $E(0-x)$, where x is successively 100, 400, 1600 cm, are the evaporation rates *per unit area* from strips of increasing downwind fetch of 100, 400, 1600 cm, then :

$$E(0-100) : E(0-400) : E(0-1600) : E = 3{\cdot}7 : 2{\cdot}5 : 1{\cdot}7 : 1,$$

and hence $E(0-100) : E(0-400) : E(0-1600) = 2{\cdot}2 : 1{\cdot}5 : 1.$

The corresponding ratios based upon equation (1) are 1·4: 1·2: 1·0. Millar[10] (from Australia) reports losses from lysimeters placed downwind from the leading edge of a small irrigated field adjoining a dry area; a graph in his paper indicates local evaporation rates (mm/h) averaged over about 8 hours in a single day of :

Distance from leading edge (cm)	14	167	472	1387,
Evaporation rate (mm/h)	0·78	0·74	0·71	0·70,

i.e. a much less striking contrast than that obtained by Rider *et alii.*[6] Halstead and Covey[11] computed evaporation rates for moist areas of increasing dimension situated in an otherwise completely dry area. Rather extreme initial conditions were postulated giving :

6-foot tank	0·45 cm/h
50-foot plot	0·26 cm/h
300-foot plot	0·19 cm/h
1-mile field	0·13 cm/h

Chang (Reference 4, page 141) concludes from these results that the 'clothes-line' effect extends more than 300 ft into the field. Stanhill[12] reports measurements which suggest that a 300-m fetch may be necessary (in an arid area) to avoid the 'leading edge' effect.

In his discussion of the subject Chang[4] notes research findings to the effect that the 'clothes-line' effect, even in a *humid* region, can extend to a distance of 40 times the crop height, and that an upwind 'guard-ring' of 50 metres is necessary to minimize the effect in humid climates; whilst in desert areas even a distance of 400 metres would not be too large. Referring to the 'oasis effect' proper, Chang states that this is often measurable many miles into an irrigated field in an arid climate. In Texas, Lemon, Glaser and Satterwhite[13] report an 'oasis effect' at a distance of 10 miles into an irrigated cotton field — the evaporation rate being 1·65 times that attributable to the net radiation for a 24-hour period. In a more humid climate the effect is not so great; Graham and King[14] in Ontario found that when the local surroundings of their irrigated corn were dry, the ratio between evapotranspiration and net radiation was 20 per cent higher than when the surroundings were moist.

Other research papers dealing, in particular, with the 'clothes-line' effect are by Davenport and Hudson.[15,16]

Concluding comment. The complications inherent in deriving the general evaporation (i.e. that from extended areas) from the water-loss from evaporimeters will now be obvious.

Perhaps less immediately obvious is that in field investigations in which water vapour (and indeed most other meteorological elements) are involved, the interference of conditions in any given plot by the activity in adjacent plots can seriously vitiate conclusions. In particular, such difficulties are likely to arise when randomized layouts give rise to adjacent small plots bearing crops of different geometrical characteristics (height, density, etc).

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517.9

THE DIRECT ESTIMATION OF DERIVATIVES FROM AN IRREGULAR PATTERN OF POINTS

By R. DIXON

Summary. A method is given for the calculation of finite difference estimates of derivatives in the case where the distribution of known field values is irregular. The Laplacian of a field is used by way of illustration. A simple numerical example is given.

In numerical meteorology the need frequently arises for finite difference estimates of such quantities as $\partial/\partial x$, $\partial/\partial y$, ∇, ∇^2 etc. To take the Laplacian ∇^2, for example, the simplest and best known finite difference estimate is

$$\mathbb{\nabla}^2 f = \frac{S_1 - 4f_0}{d^2}, \qquad \ldots (1)$$

where $\mathbb{\nabla}^2$ denotes the finite difference analogue of ∇^2, d is the grid length, and $S_1 = f_1 + f_2 + f_3 + f_4$ where $f_0 \ldots . f_4$ are the field values at the five regular points (Figure 1).

Another less-simple but still well-known formula which uses nine regular points (Figure 2) is

$$\mathbb{\nabla}^2 f = \frac{S_2 + 4S_1 - 20f_0}{6d^2}, \qquad \ldots (2)$$

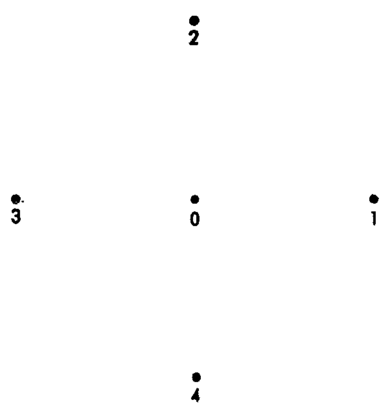

FIGURE 1—THE REGULAR FIVE-POINT PATTERN

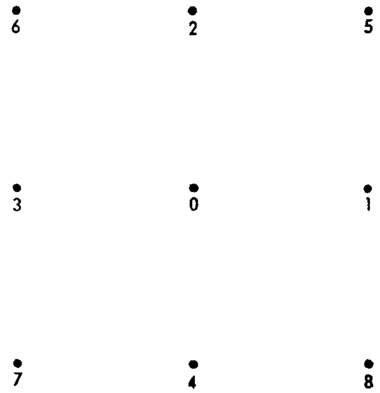

FIGURE 2—THE REGULAR NINE-POINT PATTERN

where $S_2 = f_5 + f_6 + f_7 + f_8$. S_1 and S_2 are known as the first and second symmetric sums. Other formulae involving more points may be given, but taking the nine-point pattern as a compromise between the too-simple and the too-complicated, suppose that instead of the regular pattern of Figure 2, field values are known at points of an irregular pattern (Figure 3). Such a situation might arise, for example, if the points were actual particles being followed in a fluid motion. They could be distributed regularly as in Figure 2 at time $t = 0$ and move into the pattern given by Figure 3 after an interval of time Δt. Formula (2) now no longer applies, and the problem is to obtain a formula which will serve for the irregular pattern of Figure 3.

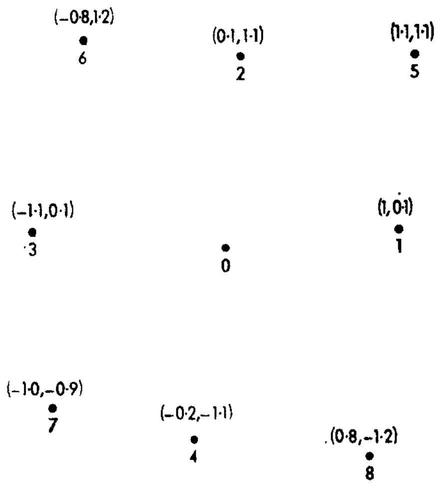

FIGURE 3—AN IRREGULAR NINE-POINT PATTERN

The method. If the point o is taken as origin then the field value f_r at any point $x_r, y_r (r = 1, 2, \ldots, 8)$ is given by Taylor's series

$$f_r\,(0 + x_r, 0 + y_r) = \left\{ \exp \left[x_r \frac{\partial}{\partial x} + y_r \frac{\partial}{\partial y} \right] \right\} f_0(0,0), \qquad \ldots (3)$$

which may be formally expanded as

$$f_r = \left\{ 1 + \left(x_r \frac{\partial}{\partial x} + y_r \frac{\partial}{\partial y} \right) + \frac{1}{2!} \left(x_r^2 \frac{\partial^2}{\partial x^2} + 2 x_r y_r \frac{\partial^2}{\partial x \partial y} + y_r^2 \frac{\partial^2}{\partial y^2} \right) + \ldots \right\} f_0. \ldots (4)$$

Equation (4) represents a set of eight equations, by giving r the values $r = 1, 2, \ldots, 8$ in turn. Now if each equation in (4) can be multiplied by a different number such that when the set is summed the terms in $\partial/\partial x$, $\partial/\partial y$, and $\partial^2/\partial x \partial y$, which do not occur in the Laplacian, disappear, whilst at the same time the coefficients of $\partial^2/\partial x^2$ and $\partial^2/\partial y^2$ in the sum equation are equal the problem is solved. The higher terms in the series are to be regarded as consigned to an error term, as is customary.

If the set of values x_r $(r = 1, 2, \ldots, 8)$ are regarded as forming an 8-component vector, denoted by $\mathbf{x}$, with similar meanings attaching to $\mathbf{1}$, $\mathbf{y}$, $\mathbf{x}^2$, $\mathbf{xy}$, $\mathbf{y}^2$ then the problem of finding the required set of multiplying numbers is the same as that of finding an 8-component vector $\boldsymbol{\psi}$ which is orthogonal to the set of vectors $\mathbf{x}$, $\mathbf{y}$, $\mathbf{xy}$, $(\mathbf{x}^2 - \mathbf{y}^2)$. This may be accomplished as follows.

Take the vector $\mathbf{y}$ and remove from it any component in the direction of $\mathbf{x}$. Then take $\mathbf{xy}$ and remove from it any components in the directions of $\mathbf{x}$ and the modified $\mathbf{y}$. Then take $(\mathbf{x}^2 - \mathbf{y}^2)$ and remove from it any components in the directions of $\mathbf{x}$ and the modified $\mathbf{y}$ and $\mathbf{xy}$. Finally, take $\mathbf{1}$ and remove from it any components in the directions of $\mathbf{x}$ and the previously modified vectors. The resulting vector is the one required. If the modified vectors are denoted by $\boldsymbol{\varphi}_2$, $\boldsymbol{\varphi}_3$, $\boldsymbol{\varphi}_4$ then the sequence of operations may be written as

$$\boldsymbol{\varphi}_1 = \mathbf{x}, \qquad \ldots 5\,(a)$$

$$\boldsymbol{\varphi}_2 = \mathbf{y} - \frac{(\boldsymbol{\varphi}_1 \cdot \mathbf{y})}{\boldsymbol{\varphi}_1^2} \boldsymbol{\varphi}_1, \qquad \ldots 5\,(b)$$

$$\boldsymbol{\varphi}_3 = \mathbf{xy} - \sum_{i=1}^{2} \frac{(\boldsymbol{\varphi}_i \cdot \mathbf{xy})}{\boldsymbol{\varphi}_i^2} \boldsymbol{\varphi}_i, \qquad \ldots 5\,(c)$$

$$\boldsymbol{\varphi}_4 = (\mathbf{x}^2 - \mathbf{y}^2) - \sum_{i=1}^{3} \left[\frac{\boldsymbol{\varphi}_i \cdot (\mathbf{x}^2 - \mathbf{y}^2)}{\boldsymbol{\varphi}_i^2} \right] \boldsymbol{\varphi}_i, \qquad \ldots 5\,(d)$$

$$\boldsymbol{\psi} = \mathbf{1} - \sum_{i=1}^{4} \frac{(\boldsymbol{\varphi}_i \cdot \mathbf{1})}{\boldsymbol{\varphi}_i^2} \boldsymbol{\varphi}_i, \qquad \ldots 5\,(e)$$

in which, for example, $(\boldsymbol{\varphi}_1 \cdot \mathbf{y})$ denotes the scalar product

$$\boldsymbol{\varphi}_1 \cdot \mathbf{y} = \mathbf{x} \cdot \mathbf{y} = x_1y_1 + x_2y_2 + \ldots + x_8y_8.$$

The sequence is the classical Gram-Schmidt orthogonalization process, which in modified forms has been widely applied in several disciplines over the past decade.

The final vector $\boldsymbol{\psi}$ is orthogonal not only to $\boldsymbol{\varphi}_1, \boldsymbol{\varphi}_2, \boldsymbol{\varphi}_3, \boldsymbol{\varphi}_4$, but also to $\mathbf{x}$, $\mathbf{y}$, $\mathbf{xy}$, and $(\mathbf{x}^2 - \mathbf{y}^2)$ since each of these is simply a linear combination of $\boldsymbol{\varphi}_1, \boldsymbol{\varphi}_2, \boldsymbol{\varphi}_3, \boldsymbol{\varphi}_4$.

Thus, if equation (4) is rewritten in vector style as

$$\mathbf{f} = \left\{ \mathbf{1} + (\mathbf{x}\frac{\partial}{\partial x} + \mathbf{y}\frac{\partial}{\partial y}) + \frac{1}{2!}(\mathbf{x}^2\frac{\partial^2}{\partial x^2} + 2\mathbf{xy}\frac{\partial^2}{\partial x \partial y} + \mathbf{y}^2\frac{\partial^2}{\partial y^2}) + \ldots \right\} f_0, \qquad \ldots (6)$$

then by taking $\boldsymbol{\psi}$ through equation (6), allowing for the fact that $\boldsymbol{\psi}$ has been so constructed that $\boldsymbol{\psi} \cdot \mathbf{x} = \boldsymbol{\psi} \cdot \mathbf{y} = \boldsymbol{\psi} \cdot \mathbf{xy} = \boldsymbol{\psi} \cdot (\mathbf{x}^2 - \mathbf{y}^2) = 0$ there results

$$\boldsymbol{\psi} \cdot \mathbf{f} = \left\{ \boldsymbol{\psi} \cdot \mathbf{1} + \frac{1}{2}(\boldsymbol{\psi} \cdot \mathbf{x}^2)\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right) + \ldots \right\} f_0,$$

yielding

$$\nabla^2 f = \frac{\boldsymbol{\psi} \cdot \mathbf{f} - (\boldsymbol{\psi} \cdot \mathbf{1})f_0}{\frac{1}{2}(\boldsymbol{\psi} \cdot \mathbf{x}^2)}, \qquad \ldots (7)$$

as the required formula. To facilitate comparisons with equation (2), (7) may be taken out of its vector guise and expressed as

$$\nabla^2 f = \frac{(\psi_1 f_1 + \psi_2 f_2 + \ldots + \psi_8 f_8) - (\psi_1 + \psi_2 + \ldots + \psi_8) f_0}{\frac{1}{2}(\psi_1 x_1^2 + \psi_2 x_2^2 + \ldots + \psi_8 x_8^2)}. \qquad \ldots (8)$$

A simple numerical example. Let the points shown in Figure 3, taken in the order 0, 1, 2, . . ., 8 have positions, with respect to the point 0 as origin, given by

(0·0, 0·0), (1·0, 0·1), (0·1, 1·1), (−1·1, 0·1), (−0·2, −1·1),
(1·1, 1·1), (−0·8, 1·2), (−1·0, −0·9), (0·8, −1·2).

The initial Cartesian base vectors required to find $\nabla^2 f$ are then

$$\mathbf{x} = (1{\cdot}0,\ 0{\cdot}1,\ -1{\cdot}1,\ -0{\cdot}2,\ 1{\cdot}1,\ -0{\cdot}8,\ -1{\cdot}0,\ 0{\cdot}8), \qquad \ldots (9)$$

$$\mathbf{y} = (0{\cdot}1,\ 1{\cdot}1,\ 0{\cdot}1,\ -1{\cdot}1,\ 1{\cdot}1,\ 1{\cdot}2,\ -0{\cdot}9,\ -1{\cdot}2), \qquad \ldots (10)$$

$$\mathbf{xy} = (0{\cdot}10,\ 0{\cdot}11,\ -0{\cdot}11,\ 0{\cdot}22,\ 1{\cdot}21,\ -0{\cdot}96,\ 0{\cdot}90,\ -0{\cdot}96), \qquad \ldots (11)$$

$$(\mathbf{x}^2 - \mathbf{y}^2) = (0{\cdot}99,\ -1{\cdot}20,\ 1{\cdot}20,\ -1{\cdot}17,\ 0{\cdot}00,\ -0{\cdot}80,\ 0{\cdot}19,\ -0{\cdot}80). \qquad \ldots (12)$$

There now follows a line-by-line application of equations (5) to determine the orthogonal $\boldsymbol{\varphi}$ vectors. The determination of $\boldsymbol{\varphi}_1$ is trivial, equation 5 *(a)* yielding immediately

$$\boldsymbol{\varphi}_1 = (1{\cdot}0,\ 0{\cdot}1,\ -1{\cdot}1,\ -0{\cdot}2,\ 1{\cdot}1,\ -0{\cdot}8,\ -1{\cdot}0,\ 0{\cdot}8), \qquad \ldots (13)$$

a vector with precisely the same components as $\mathbf{x}$. To obtain subsequent $\boldsymbol{\varphi}$ vectors in the sequence nothing more difficult than the evaluation of scalar products is required. Thus to get $\boldsymbol{\varphi}_2$, the scalar products $\boldsymbol{\varphi}_1.\mathbf{y}$ and $(\boldsymbol{\varphi}_1.\boldsymbol{\varphi}_1)$ are needed. From equations (10) and (13)

$$\boldsymbol{\varphi}_1 . \mathbf{y} = 1{\cdot}0 \times 0{\cdot}1 + 0{\cdot}1 \times 1{\cdot}1 - 1{\cdot}1 \times 0{\cdot}1 + 0{\cdot}2 \times 1{\cdot}1 + 1{\cdot}1 \times 1{\cdot}1 - 0{\cdot}8 \times 1{\cdot}2 + 1{\cdot}0 \times 0{\cdot}9 - 0{\cdot}8 \times 1{\cdot}2 = 0{\cdot}51. \quad \ldots (14)$$

Similarly it is found that

$$\boldsymbol{\varphi}_1 . \boldsymbol{\varphi}_1 = 1{\cdot}0 \times 1{\cdot}0 + 0{\cdot}1 \times 0{\cdot}1 + 1{\cdot}1 \times 1{\cdot}1 + 0{\cdot}2 \times 0{\cdot}2 + 1{\cdot}1 \times 1{\cdot}1 + 0{\cdot}8 \times 0{\cdot}8 + 1{\cdot}0 \times 1{\cdot}0 + 0{\cdot}8 \times 0{\cdot}8 = 5{\cdot}75. \quad \ldots (15)$$

Then each of the components of $\boldsymbol{\varphi}_1$ is multiplied by $0{\cdot}51/5{\cdot}75 = 0{\cdot}09$ and subtracted from the corresponding component of $\mathbf{y}$, yielding the vector $\boldsymbol{\varphi}_2$ where

$$\boldsymbol{\varphi}_2 = (0{\cdot}11,\ 1{\cdot}09,\ 0{\cdot}20,\ -1{\cdot}08,\ 1{\cdot}00,\ 1{\cdot}27,\ -0{\cdot}81,\ -1{\cdot}27). \quad \ldots (16)$$

$\boldsymbol{\varphi}_3$ is obtained from 5 *(c)* in exactly the same way, the necessary additional scalar products, evaluated in the same way as (14) and (15) being

$$\boldsymbol{\varphi}_1 . \mathbf{xy} = 0{\cdot}62,\quad \boldsymbol{\varphi}_2.\mathbf{xy} = 0{\cdot}34,\quad \varphi_2^2\ (= \boldsymbol{\varphi}_2 . \boldsymbol{\varphi}_2) = 7{\cdot}29, \quad \ldots (17)$$

giving, from 5 *(c)*

$$\boldsymbol{\varphi}_3 = (-0{\cdot}01,\ 0{\cdot}05,\ -0{\cdot}00,\ 0{\cdot}29,\ 1{\cdot}04,\ -0{\cdot}93,\ 1{\cdot}05,\ -0{\cdot}99). \quad \ldots (18)$$

To get $\boldsymbol{\varphi}_4$ the required additional scalar products are

$$\boldsymbol{\varphi}_1.(\mathbf{x}^2-\mathbf{y}^2) = -0{\cdot}41,\quad \boldsymbol{\varphi}_2.(\mathbf{x}^2-\mathbf{y}^2) = 0{\cdot}05,\quad \boldsymbol{\varphi}_3.(\mathbf{x}^2-\mathbf{y}^2) = 1{\cdot}33, \quad \ldots (19)$$

and $\varphi_3^2 = 4{\cdot}12$, the others being already known. The use of these values in 5 *(d)* then yields

$$\boldsymbol{\varphi}_4 = (1{\cdot}06,\ -1{\cdot}22,\ 1{\cdot}12,\ -1{\cdot}27,\ -0{\cdot}27,\ -0{\cdot}56,\ -0{\cdot}21,\ -0{\cdot}42). \quad \ldots (20)$$

Finally, from the scalar products

$$\boldsymbol{\varphi}_1.\mathbf{1} = -0{\cdot}10,\quad \boldsymbol{\varphi}_2.\mathbf{1} = 0{\cdot}41,\quad \boldsymbol{\varphi}_3.\mathbf{1} = 0{\cdot}50,\quad \boldsymbol{\varphi}_4.\mathbf{1} = -1{\cdot}76, \quad \ldots (21)$$

the required vector $\boldsymbol{\psi}$ is found from 5 *(e)* to be

$$\boldsymbol{\psi} = (1{\cdot}33,\ 0{\cdot}58,\ 1{\cdot}29,\ 0{\cdot}65,\ 0{\cdot}76,\ 0{\cdot}87,\ 0{\cdot}84,\ 1{\cdot}08), \quad \ldots (22)$$

Therefore, in (7) we have

$$\boldsymbol{\psi}.\mathbf{f} = 1{\cdot}33f_1 + 0{\cdot}58f_2 + 1{\cdot}29f_3 + 0{\cdot}65f_4 + 0{\cdot}76f_5 + 0{\cdot}87f_6 + 0{\cdot}84f_7 + 1{\cdot}08f_8, \quad \ldots (23)$$

$$\boldsymbol{\psi}.\mathbf{1} = 1{\cdot}33 + 0{\cdot}58 + 1{\cdot}29 + 0{\cdot}65 + 0{\cdot}76 + 0{\cdot}87 + 0{\cdot}84 + 1{\cdot}08 = 7{\cdot}40, \quad \ldots (24)$$

$$\boldsymbol{\psi}.\mathbf{x}^2 = 5{\cdot}929 \quad \ldots (25)$$

and so, using (23), (24), (25), for this example (8) becomes

$$\nabla^2 f = \frac{(1{\cdot}33f_1 + 0{\cdot}58f_2 + 1{\cdot}29f_3 + 0{\cdot}65f_4 + 0{\cdot}76f_5 + 0{\cdot}87f_6 + 0{\cdot}84f_7 + 1{\cdot}08f_8) - 7{\cdot}40f_0}{2{\cdot}9645} \quad \ldots (26)$$

The formula (26) may be tested by taking the pattern of points in Figure 3 to be in an exactly circular 500-mb contour height field given by the formula

$$f - 546 = 6x^2 + 6y^2. \quad \ldots (27)$$

The exact value of $\nabla^2 f$ in this case, by differentiation of (27), is 24.
The values for $f_0, f_1, f_2, \ldots, f_8$ obtained from (27) are
$f_0 = 546{\cdot}00$, $f_1 = 552{\cdot}06$, $f_2 = 553{\cdot}32$, $f_3 = 553{\cdot}32$, $f_4 = 553{\cdot}50$
$f_5 = 560{\cdot}52$, $f_6 = 558{\cdot}46$, $f_7 = 556{\cdot}86$, $f_8 = 558{\cdot}46$.

Using these values in (26) the value 23·986 is obtained. Of course the field represented by (27) is a very simple and symmetric one so that the error term, which has not been discussed, can be expected to be small. In practice the *f*-field would be likely to be more complicated and since its analytical form would not in general be known, only experience would show if the neglected error term was acceptable.

The method is applicable for any number of points, subject to a lower limit. In the foregoing example the only difference it would make if there were *n* points surrounding the origin point would be that all the 8-component vectors involved would be *n*-component vectors instead. It should be noted, however, that the fewest number of points for which the foregoing example could be worked is five, not counting the origin point. If there were only four surrounding points then the method would involve finding a vector to be orthogonal to four independent vectors each having four components, and this is impossible. The fact that it is possible in the regular pattern case to find a formula such as equation (1) involving only four surrounding points is a bonus associated with a regular rectilinear distribution of points. It is worth mentioning that in the case where *n* is large, the classical formulation of the Gram-Schmidt process given by (5) should not be used, as the build-up of round-off error will be excessive. A modified form such as given by Dixon and Spackman* should be used instead.

It may be noticed that the error term associated with equation (7) is of third order, whereas it is well known that the error term associated with (1) or (2) is of fourth order. This again is a bonus associated with a regular rectilinear distribution of points. A formula corresponding to (7) but having a fourth-order error term may be constructed by finding a vector orthogonal to $\mathbf{x}$, $\mathbf{y}$, $\mathbf{xy}$, $(\mathbf{x}^2 - \mathbf{y}^2)$, $\mathbf{x}^3, \mathbf{x}^2\mathbf{y}, \mathbf{xy}^2, \mathbf{y}^3$, the last four being the vectors associated with the third-order terms in the Taylor series. Note that in this case the minimum number of points, apart from the origin point, is now nine.

In working the above example on a desk calculator all numbers were carried to 10 significant digits, but for reasons of space they have been rounded and quoted to two decimal places.

Acknowledgements. I am indebted to Mr I. Jones for a valuable discussion of some mathematical points, and to Mr V. Blackman for carrying out the desk calculations.

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SYNOPTIC-TYPE RAINFALL AVERAGES OVER ENGLAND AND WALES

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Summary. Long-term monthly and annual averages of daily rainfall over England and Wales (combined) for the period 1950–69 were estimated for each type of synoptic pattern of atmospheric surface pressure. The available classification of daily surface pressure patterns was as follows : north-easterly, cyclonic north-easterly, anticyclonic north-easterly; easterly, cyclonic easterly, anticyclonic easterly; etc., together with the categories, 'cyclonic', 'anticyclonic' and 'unclassifiable'; that is, a total of 27 categories of pressure pattern over the United Kingdom. Cols were not accorded a separate category but allocated to the most

* DIXON, R, and SPACKMAN, E. A.; The three-dimensional analysis of meteorological data. *Scient Pap Met Off, London*, No. 31, 1970.

appropriate of the 27 categories stated. The daily values of areal rainfall were estimated from a network of some 30–33 stations and a conversion factor derived from the long-term averages of annual rainfall (i) over England and Wales and (ii) for the network of rainfall stations.

Accuracy of the results was assessed by *(a)* calculating individual values of rainfall (the so-called *indirect* estimates) for each month, season and year of the period 1861–1949, using frequencies of each type of daily surface pressure pattern and synoptic-type rainfall averages and *(b)* comparing these values with the *direct* estimates based on rainfall data from a large network of stations. Corrections for the application to indirect estimates *(I)*, as percentages of the long-term average, are suggested. The corrected estimate for annual *I* is given by $1{\cdot}7\,I - 70$ per cent.

The monthly rainfall averages suggest that annual variation of rainfall for a particular type is related to (1) length of land- or sea-track associated with the type and (2) annual variation of sea temperature. The rainfall averages are clearly related to isobaric curvature.

Introduction. With the ever-increasing demand for water supplies, it is becoming increasingly necessary to plan for maximum efficiency in the use of water resources. In particular, there is a need for more accurate forecasts of areal rainfall from atmospheric pressure charts. The present work describes the calculation of rainfall averages over England and Wales (combined) for different synoptic patterns of atmospheric surface pressure. The accuracy and interpretation of the results are discussed. These results together with those for other pressure levels should be useful for special case-studies of drought and the associated characteristics of the general circulation.

Method. The main surface pressure pattern for each day over the U.K. was classified[1] as one of the following 27 categories : north-easterly, cyclonic north-easterly, anticyclonic north-easterly; easterly, cyclonic easterly, anticyclonic easterly, etc. together with the categories, 'cyclonic', 'anticyclonic' and 'unclassifiable'. Cols were not accorded a separate category but were allocated to the most appropriate of the 27 categories stated.

The daily (09 to 09 GMT) values of rainfall amount for each of some 30 to 33 stations on the mainland of England and Wales were extracted mainly from the *Daily Weather Report*,* for the period 1950 to 1969 (20 years). These data were used to obtain estimates of daily areal rainfall amounts for England and Wales, as follows :

Let A = average annual rainfall over England and Wales and
$r_1, r_2, \ldots, r_n$ = average annual rainfall amounts at the 'n' stations of the network and
$\bar{r}$ = average value of $r_1, r_2, \ldots, r_n$.
If T = total rainfall for the 'n' stations on a particular day and
$\bar{T} = T/n$,

then the rainfall (d) over England and Wales for that day can be written

$$d = k\bar{T} = k'T,$$

where $k = A/\bar{r}$ and $k' = A/\Sigma r$.

The network and the values of k and k' were usually constant throughout any given year but varied from year to year.

These values *(d)* of the daily rainfall over England and Wales were then used to calculate the average daily rainfall for each synoptic type. To eliminate irregularities arising from small samples (associated with the less-frequent synoptic types), the monthly values of average daily rainfall and average frequency for each synoptic type were adjusted as follows :

Let T_m = total rainfall for the f_m days of a particular synoptic type for the month m (where $m = 1, 2, 3 \ldots 12$) during the 20-year period. Then, the

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

adjusted value (R_m) of the daily rainfall average of the particular synoptic type, for the month m is given by :

$$R_m = \frac{\frac{1}{4}T_{m+1} + \frac{1}{2}T_m + \frac{1}{4}T_{m-1}}{\frac{1}{4}f_{m+1} + \frac{1}{2}f_m + \frac{1}{4}f_{m-1}},$$

where the suffixes $(m-1)$ and $(m+1)$ indicate the adjacent preceding and succeeding months respectively. Adjusted frequencies (F'_m) were obtained from the formula :

$$F'_m = \tfrac{1}{4}f_{m+1} + \tfrac{1}{2}f_m + \tfrac{1}{4}f_{m-1}.$$

These values of the frequencies (F'_m) were then further adjusted to obtain the frequencies (F_m) as follows :

$$F_m = F'_m \times \frac{\Sigma f_m \text{ (all types)}}{\Sigma F'_m \text{ (all types)}},$$

so that ΣF_m (all types) $= \Sigma f_m$ (all types) and each of these latter expressions is equal to the total number of days in the month 'm' over the 20-year period, 1950 to 1969. The final monthly frequencies ($F_m/20$) of Table I were then obtained; seasonal and annual values may be calculated from these monthly data.

Assessment of accuracy of the results. Monthly values of rainfall were estimated for each individual month of the period 1861 to 1949 (89 years) by using the calculated daily rainfall average for each synoptic type (given in Table 1) and the *actual* frequencies of each synoptic type in any given month. These estimates of monthly rainfall are referred to as *indirect* estimates (i) and they were compared with the *direct* estimates (d) obtained from observed rainfall data, as given in *British Rainfall*.† Similar comparisons were made for quarterly, half-yearly and annual data. Table II gives the long-term averages and standard deviations of both the directly estimated and indirectly estimated series of rainfall amounts and also the correlations between the two series of estimates.

Errors $(i-d)$, expressed as percentages of the direct estimates (d), were calculated for each individual quarter, half-year and year. Their distributions are shown in Table III, from which it can be calculated, for example, that 92 per cent of indirectly estimated annual rainfall amounts are within 15 per cent of the direct estimates.

All estimates of rainfall amounts for the quarters, half-years and years were expressed as percentages of the long-term averages of direct estimates for the period 1861 to 1949. The distribution of indirect estimates, in five per cent ranges, was then obtained for each five per cent range of direct estimates. The distribution of *annual* rainfall estimates is shown in Table IV. The corresponding tables for quarters and half-years are similar.

It can be seen from Table II that indirectly estimated averages are very similar to the directly estimated averages but, as expected, standard deviations of indirect estimates are distinctly less than those for direct estimates. The latter relationship concerning variance results from the use of *averages* in the calculation of the indirect estimates: the inherent 'smoothing' process in the indirect estimation necessarily leads to estimates with lesser extremes, as shown in Table IV.

† London, Meteorological Office. *British Rainfall.*

TABLE I—SYNOPTIC-TYPE* AVERAGES OF (i) MONTHLY AND ANNUAL AVERAGE DAILY RAINFALL (R mm/day), (ii) FREQUENCY (F DAYS PER MONTH/YEAR) AND (iii) PRODUCT (RF mm) OVER ENGLAND AND WALES FOR THE PERIOD 1950 TO 1969 (20 YEARS)

		A NE	NE	C NE	A E	E	C E	A SE	SE	C SE	A S	S	C S	A SW	SW	C SW	A W	W	C W	A NW	NW	C NW	A N	N	C N	A	C	U
Jan.	R	0·4	0·8	3·9	0·5	1·8	3·9	0·3	1·4	2·7	0·1	3·2	5·5	1·1	4·2	4·2	1·0	3·8	4·6	0·8	1·6	2·3	0·7	1·4	2·5	0·5	4·9	3·7
	F	0·36	0·33	0·13	0·73	1·52	0·29	0·26	0·54	0·14	0·34	1·62	0·31	0·26	0·82	0·20	1·09	5·92	1·39	0·37	1·51	0·28	0·75	1·69	0·54	4·89	3·30	1·42
	RF	0·14	0·26	0·51	0·37	2·74	1·13	0·08	0·76	0·38	0·03	5·18	1·71	0·29	3·44	0·84	1·09	22·50	6·39	0·30	2·42	0·64	0·53	2·37	1·35	2·45	16·17	5·25
Feb.	R	0·4	1·2	1·8	0·4	1·6	3·2	0·5	1·5	3·5	0·2	3·7	6·1	0·7	3·8	4·3	0·7	3·0	4·1	0·9	1·3	2·3	0·7	1·2	2·2	0·4	4·7	4·3
	F	0·48	0·31	0·09	0·88	1·67	0·40	0·31	0·83	0·17	0·36	1·61	0·35	0·15	0·80	0·21	1·11	4·46	0·82	0·35	0·85	0·31	0·71	1·55	0·37	4·96	3·04	1·10
	RF	0·19	0·37	0·16	0·35	2·67	1·28	0·15	1·25	0·59	0·07	5·96	2·13	0·11	3·04	0·90	0·78	13·38	3·36	0·31	1·11	0·71	0·50	1·86	0·81	1·98	14·29	4·73
Mar.	R	0·2	1·3	2·1	0·3	1·9	3·1	0·6	1·6	5·2	0·3	4·0	5·3	0·1	3·6	3·5	0·5	2·7	3·1	0·6	1·3	2·0	0·5	1·1	2·3	0·3	4·5	4·0
	F	0·55	0·36	0·09	1·11	1·84	0·52	0·41	1·17	0·21	0·52	1·82	0·43	0·14	0·71	0·20	1·34	4·59	0·55	0·45	0·81	0·39	0·84	1·70	0·39	5·64	3·07	1·15
	RF	0·11	0·47	0·19	0·33	3·50	1·61	0·25	1·87	1·09	0·16	7·28	2·28	0·01	2·56	0·70	0·67	12·39	1·71	0·27	1·05	0·78	0·42	1·87	0·90	1·69	13·81	4·60
Apr.	R	0·2	1·4	2·4	0·4	2·8	3·7	1·0	2·3	6·7	0·5	3·9	4·1	0·3	3·4	3·0	0·4	2·5	3·4	0·5	1·2	1·8	0·3	1·2	2·3	0·3	4·5	3·1
	F	0·58	0·33	0·10	1·25	1·72	0·42	0·28	0·76	0·20	0·39	1·48	0·43	0·16	0·59	0·13	1·13	4·24	0·58	0·42	1·01	0·39	1·00	1·80	0·49	5·58	3·30	1·24
	RF	0·12	0·46	0·24	0·50	4·82	1·55	0·28	1·75	1·34	0·19	5·77	1·76	0·05	2·01	0·39	0·45	10·60	1·97	0·21	1·21	0·70	0·30	0·65	1·13	1·67	14·85	3·84
May	R	0·4	1·1	2·7	0·5	3·4	4·8	1·6	4·4	6·5	0·5	3·7	3·9	0·7	2·5	2·7	0·4	2·2	2·8	0·4	1·0	1·7	0·4	1·5	2·8	0·5	4·4	3·0
	F	0·58	0·34	0·08	1·37	1·61	0·37	0·23	0·55	0·15	0·24	1·18	0·37	0·24	0·51	0·06	1·11	4·38	0·87	0·46	1·07	0·34	1·04	1·88	0·48	5·59	4·46	1·44
	RF	0·23	0·37	0·22	0·69	5·47	1·78	0·37	2·42	0·97	0·12	4·37	1·44	0·17	1·27	0·16	0·44	9·64	2·44	0·18	1·07	0·58	0·42	2·82	1·34	2·79	19·62	4·32
June	R	0·6	1·5	3·3	0·5	3·4	7·6	1·1	5·4	5·5	0·5	3·5	5·3	1·3	2·6	3·8	0·6	2·0	2·6	0·3	0·9	2·0	0·4	1·7	4·4	0·7	4·6	3·6
	F	0·31	0·31	0·05	1·05	1·02	0·39	0·21	0·42	0·06	0·16	0·87	0·20	0·24	0·43	0·05	1·55	4·99	0·97	0·61	1·14	0·38	0·89	1·67	0·39	5·52	4·82	1·30
	RF	0·19	0·47	0·17	0·53	3·47	2·96	0·23	2·27	0·33	0·08	3·05	1·06	0·31	1·12	0·19	0·93	9·98	2·52	0·18	1·03	0·76	0·36	2·84	1·72	3·86	22·17	4·68
July	R	0·7	3·0	3·0	0·9	3·5	9·1	1·2	5·0	10·5	0·5	3·4	6·7	1·9	4·0	4·1	0·7	2·3	3·3	0·4	0·9	2·2	0·4	1·7	4·8	0·8	5·1	3·6
	F	0·18	0·38	0·04	0·69	0·52	0·43	0·19	0·18	0·06	0·20	0·69	0·14	0·18	0·45	0·11	1·98	5·57	1·05	0·67	1·46	0·53	0·87	1·65	0·52	5·40	5·58	1·28
	RF	0·13	1·14	0·12	0·62	1·82	3·91	0·23	0·90	0·63	0·10	2·35	0·94	0·34	1·80	0·45	1·39	12·81	3·47	0·27	1·31	1·17	0·35	2·81	2·50	4·32	28·46	4·61
Aug.	R	1·1	3·3	4·6	0·9	4·3	7·5	1·5	2·0	10·7	1·1	3·6	4·8	1·0	4·7	4·7	0·8	2·9	3·8	0·5	1·1	2·0	0·6	1·9	4·3	0·7	5·3	3·0
	F	0·33	0·43	0·05	0·48	0·45	0·34	0·23	0·25	0·11	0·32	0·91	0·23	0·15	0·54	0·15	1·83	5·61	1·23	0·53	1·30	0·42	0·62	1·52	0·58	4·89	6·03	1·47
	RF	0·36	1·42	0·23	0·43	1·93	2·55	0·35	0·50	1·18	0·35	3·28	1·10	0·15	2·54	0·71	1·46	16·27	4·67	0·27	1·43	0·84	0·37	2·89	2·49	3·42	31·96	4·41
Sept.	R	1·3	2·7	6·5	0·3	4·6	5·7	0·6	2·3	7·1	1·5	3·6	4·5	0·1	4·4	5·8	0·9	3·3	4·2	0·5	1·6	2·4	0·8	2·2	3·6	0·4	5·6	2·9
	F	0·34	0·28	0·09	0·39	0·57	0·30	0·31	0·58	0·12	0·43	1·24	0·30	0·17	0·82	0·17	1·62	5·98	1·32	0·41	1·00	0·22	0·34	1·25	0·49	5·22	4·59	1·45
	RF	0·44	0·76	0·59	0·12	2·62	1·71	0·19	1·33	0·85	0·65	4·46	1·35	0·02	3·61	0·99	1·46	19·73	5·54	0·21	1·60	0·53	0·27	2·75	1·76	2·09	25·70	4·21
Oct.	R	1·6	1·9	6·9	0·4	3·5	5·8	0·1	2·5	4·8	1·5	3·4	5·1	0·1	4·1	5·8	1·0	3·5	4·5	0·5	1·8	3·7	0·6	1·9	3·0	0·4	6·6	3·3
	F	0·33	0·16	0·09	0·47	0·78	0·38	0·38	0·71	0·17	0·44	1·49	0·32	0·18	1·08	0·20	1·65	6·25	1·25	0·36	1·09	0·22	0·37	1·41	0·36	5·81	3·77	1·28
	RF	0·53	0·30	0·62	0·19	2·73	2·20	0·04	1·77	0·82	0·66	5·07	1·63	0·02	4·43	1·16	1·65	21·87	5·63	0·18	1·96	0·81	0·22	2·68	1·08	2·32	21·88	4·22
Nov.	R	1·7	1·0	6·8	0·8	2·5	5·3	0·1	2·3	4·6	1·2	3·4	5·5	0·5	4·1	5·2	1·0	4·1	4·4	0·7	1·8	3·3	0·5	1·6	3·0	0·4	6·7	3·3
	F	0·38	0·27	0·09	0·49	0·98	0·42	0·32	0·48	0·20	0·41	1·31	0·36	0·20	0·86	0·17	1·29	6·14	1·20	0·34	1·47	0·28	0·41	1·63	0·43	4·88	3·75	1·24
	RF	0·65	0·27	0·61	0·39	2·45	2·23	0·03	1·10	0·92	0·49	4·45	1·98	0·10	3·53	0·88	1·29	25·17	5·28	0·24	2·65	0·92	0·21	2·61	1·29	1·95	25·13	4·09
Dec.	R	1·1	0·7	6·5	0·7	2·1	4·6	0·1	1·4	3·6	0·5	3·2	5·2	1·0	4·4	4·0	1·0	4·3	4·5	0·8	1·9	2·6	0·6	1·6	3·1	0·5	5·7	3·3
	F	0·33	0·39	0·11	0·53	1·21	0·34	0·28	0·43	0·16	0·44	1·37	0·34	0·29	0·68	0·16	1·06	6·68	1·48	0·39	1·85	0·29	0·57	1·69	0·57	4·38	3·50	1·48
	RF	0·36	0·27	0·71	0·37	2·54	1·56	0·03	0·60	0·58	0·22	4·38	1·77	0·29	2·99	0·64	1·06	28·72	6·66	0·31	3·51	0·75	0·34	2·70	1·77	2·19	19·95	4·88
Year	R	0·73	1·69	4·33	0·52	2·65	5·32	0·65	2·39	5·53	0·73	3·57	5·13	0·79	3·90	4·43	0·76	3·13	3·91	0·55	1·40	2·27	0·51	1·48	3·23	0·49	5·16	3·40
	F	4·75	3·89	1·01	9·44	13·89	4·60	3·41	6·90	1·75	4·25	15·59	3·73	2·36	8·29	1·81	16·76	64·81	12·71	5·36	14·56	4·05	8·41	19·44	5·61	62·81	49·21	15·85
	RF	3·5	6·6	4·4	4·9	36·8	24·5	2·2	16·5	9·7	3·1	55·7	19·1	1·9	32·3	8·0	12·7	202·9	49·7	2·9	20·4	9·2	4·3	28·8	18·1	30·8	253·9	53·9

* A = anticyclonic, C = cyclonic, U = unclassifiable.

TABLE II—DIRECT AND INDIRECT ESTIMATES OF THE AVERAGES AND STANDARD DEVIATIONS OF MONTHLY, SEASONAL AND ANNUAL RAINFALL OVER ENGLAND AND WALES DURING THE PERIOD 1861 TO 1949 AND CORRELATIONS BETWEEN THE SERIES OF DIRECT AND INDIRECT ESTIMATES

	No. of terms	Estimates of average		Estimates of standard deviation		Correlation
		Direct	Indirect	Direct	Indirect	
		millimetres				
Jan.	89	87·6	85·2	35·5	20·8	0·80
Feb.	89	66·9	65·9	33·4	21·1	0·85
Mar.	89	63·4	66·7	30·6	19·3	0·79
Apr.	89	56·4	61·7	22·0	17·4	0·74
May	89	60·3	65·0	24·7	17·3	0·75
June	89	60·4	62·3	26·4	17·8	0·85
July	89	75·4	79·6	33·0	20·6	0·87
Aug.	89	83·3	84·7	34·6	20·9	0·78
Sept.	89	75·2	76·5	35·1	21·9	0·80
Oct.	89	99·2	91·6	39·2	22·9	0·76
Nov.	89	92·2	89·8	37·4	24·9	0·82
Dec.	89	94·5	93·2	41·2	22·0	0·85
Jan.–Mar.	89	217·9	217·8	55·3	35·7	0·79
Apr.–June	89	177·0	189·1	42·6	31·8	0·84
July–Sept.	89	233·9	240·7	58·3	33·8	0·82
Oct.–Dec.	89	285·9	274·6	70·8	41·3	0·79
Apr.–Sept.	89	410·9	429·8	81·7	49·7	0·83
Oct.–Mar.	88	503·1	492·1	95·4	56·5	0·81
Apr.–Mar.	88	915·3	922·6	126·3	74·5	0·77

Errors resulting from this loss of variance may be corrected by the application of simple linear correction factors. For example, in each row of Table IV, if the value of D is compared with the median value of I in the row (I_M say), it can be seen that the difference of I_M from 100 is approximately half the difference of D from 100. This would be expected from the ratio (0·59) of the standard deviations of the indirect and direct estimates of annual rainfall in Table II. The value of 0·59 is also the ratio of the sum of the deviations,

TABLE III—PERCENTAGE DISTRIBUTION OF ERRORS* EXPRESSED AS PERCENTAGES OF DIRECT ESTIMATES OF ANNUAL AND SEASONAL RAINFALL AVERAGES OVER ENGLAND AND WALES FOR THE PERIOD 1861 TO 1949

	Negative errors *per cent*											Positive errors *per cent*						
	55–50	50–45	45–40	40–35	35–30	30–25	25–20	20–15	15–10	10–5	5–0	0–5	5–10	10–15	15–20	20–25	25–30	30–35
	Percentage frequency																	
Jan–Mar	0·0	0·0	1·1	2·2	1·1	1·1	4·5	3·4	7·9	14·6	14·6	14·6	10·1	5·6	6·7	4·5	5·6	2·2
Apr–June	0·0	0·0	0·0	0·0	0·0	1·1	1·1	2·2	6·7	9·0	11·2	11·2	20·2	4·5	15·7	7·9	5·6	3·4
July–Sept	0·0	0·0	0·0	1·1	1·1	3·4	2·2	5·6	5·6	7·9	13·5	13·5	11·2	6·7	12·4	11·2	2·2	2·2
Oct–Dec	1·1	0·0	0·0	1·1	3·4	5·6	6·7	9·0	7·9	10·1	10·1	13·5	9·0	10·1	5·6	6·7	0·0	0·0
Apr–Sept	0·0	0·0	0·0	0·0	1·1	0·0	0·0	2·2	9·0	7·9	13·5	14·6	14·6	18·0	9·0	7·9	2·2	0·0
Oct–Mar	0·0	0·0	0·0	0·0	0·0	4·5	4·5	8·0	6·8	9·1	17·0	20·5	14·8	9·1	4·5	1·1	0·0	0·0
Apr–Mar	0·0	0·0	0·0	0·0	0·0	0·0	1·1	1·1	13·6	6·8	22·7	20·5	19·3	9·1	4·5	1·1	0·0	0·0

* Indirect estimates minus direct estimates.

TABLE IV—FREQUENCY OF DIRECT AND INDIRECT ESTIMATES OF THE ANNUAL (APRIL TO MARCH) RAINFALL OVER ENGLAND AND WALES EXPRESSED AS PERCENTAGES OF THE DIRECTLY ESTIMATED AVERAGE FOR 1861/62 TO 1948/49

D*	Indirect estimates (I) *per cent*							
	85–90	90–95	95–100	100–105	105–110	110–115	115–120	120–125
				frequency				
70–75	1							
75–80	2		1					
80–85	1	7	3	1				
85–90		4	1					
90–95		3	5	3	2			
95–100		2	5	2	2			
100–105		2	4	7	1	1		
105–110		1	3	1	3	1		
110–115			1		4	1		
115–120			1	1	1	1	1	
120–125					1			1
125–130					1	2	1	
130–135							1	1

*D = direct estimates, per cent.

from 100 per cent, of I estimates of annual rainfall to that for the D estimates (Table IV data), all deviations being regarded as positive. Thus a corrected estimate for I is given by: $I + (I - 100)$, that is $(2I - 100)$ or with a greater average accuracy, by: $100 + (I - 100)/0{\cdot}59$, that is $(1{\cdot}7\,I - 70)$.

Clearly, also, part of the error of indirect estimates may be the result of long-term climatic change in synoptic-type averages. The averages for the period 1950 to 1969 may not be representative of the years from 1861 to 1949. Such long-term changes are suggested, for example, by the slightly lower indirect estimates of average monthly rainfall from October to March and the slightly higher indirect estimates of average rainfall from April to September, as compared with direct estimates (Table II).

If it is assumed that the errors (for example, as reflected in Table IV and in the averages of Table II) result only from a general long-term change in average rainfall of all synoptic types, then the average excess error in indirect estimates will be about $100\,(M - L)/L$ per cent, where L and M are the average rainfall amounts (direct estimates) in the periods 1861 to 1949 and 1950 to 1969, respectively. For example, this formula gives a value of about one per cent for annual rainfall, and the percentage excess of the indirect estimate over the direct estimate of mean annual rainfall in the period April 1861 to March 1949 (Table II) is about the same value. The magnitude of such errors is within the limits of accuracy of any of the estimates.

Part of the 'error' in the indirect estimates may be due also to errors in the direct estimates of rainfall, which are calculated from networks of rainfall stations that increased from about 58 stations in 1861 to about 70 stations around 1950. Such errors are particularly liable to occur with very low rainfall.[2]

Annual variation. The cyclonic type shows an annual wave with the driest part, on average, in spring (March to May) and the wettest part in October and November.

Westerly and westerly cyclonic types are driest (on average) around June and wettest in winter. The corresponding south-westerly and north-westerly types are driest around May and June but are wettest in late summer and autumn. North-easterlies have a somewhat similar tendency but easterlies and south-easterlies tend to be generally wetter in summer.

These patterns would appear to be related to the land–sea orientation. Atlantic types or types with long sea-track usually show a tendency to have the driest months around the time of minimum sea temperature and the wettest around the time of maximum, while those types with a longer land-track are generally wetter in summer when thermal convection is usually greater.

Isobaric curvature. The difference in wetness between cyclonic types and anticyclonic types is reflected not only in the rainfall averages for the cyclonic and anticyclonic categories but also in the decrease in rainfall within each 'directional' group of categories, from 'cyclonic' to 'straight' isobars to anticyclonic curvature.

Concluding remarks. The distribution of errors suggests that an improvement in the indirect estimates is likely to be obtained from a more detailed classification of synoptic types which would break down the more dominant, prevalent categories into smaller groups.

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REVIEWS

Biometeorological methods, by R. E. Munn. 225 mm × 152 mm, pp. xi + 336, *illus.*, Academic Press Inc. (London) Ltd, Berkeley Square House, London W1X 6BA, 1971. Price: £5·85. (Paperback edition £3·25.)

In the preface, the author defines biometeorology as the study of relationships between weather and life; he quotes examples from the fields of meteorology, hydrology, physiology, ecology, biology, medicine, geography, forestry, agronomy, engineering and, most frequently, air pollution. Whilst undoubtedly this last topic is one which falls within the very broad definition of biometeorology, it has already been discussed by A. C. Stern in the three volumes which constitute the first of this series of Interdisciplinary Monographs.

The book contains 14 chapters which review the broad subject of biometeorological methods and form an introduction to the subject. An interesting feature is the Appendix which lists 50 problems designed to test the reader, to encourage further work and to stimulate thought, but these are presented without preamble so their purpose is not immediately clear. The list of 481 references covers all the topics discussed and alone forms a valuable guide to methods. There is no mention of two important references WMO Technical Note No. 65 'A survey of human biometeorology' edited by F. Sargent and S. W. Tromp, published in 1964 and 'Medical biometeorology' by S. W. Tromp in co-operation with 26 contributors, published by Elsevier in 1963. In discussing international aspects, there is no mention of the International Society of Biometeorology and its Journal.

After an introductory Chapter 1, atmospheric sampling techniques, time and space variations and network and instrumental sampling problems are outlined in Chapters 2 and 3 largely using air pollution studies to illustrate concepts of concentration, dosage and flux. The design of biometeorological experiments in Chapter 4 is a good summary of the methods but, in the 62 pages of Chapters 5, 6 and 7, only brief descriptions of methods of using tables, graphs, charts and statistics are given. In particular, the discussions of eigen vectors and spectrum analysis give the impression that the author included these because they are fashionable and not because they are directly of use in biometeorology. Models and indices are discussed in Chapters 8, 9 and 13. These chapters are informative and useful mainly because they are illustrated by examples from human biometeorology. Apart from their use in comparison work, the value of indices in increasing our understanding of biometeorology has still to be proved. There is no doubt that the tracking methods described in Chapter 10 are invaluable tools in explaining the distribution of airborne bodies over an area and that certain conditions of ill health can be associated with certain weather events on a short time-scale of a few days. The review of evapotranspiration and water balance in the atmosphere and soil given in Chapter 11 is a handy summary of the methods but the study of past climates in Chapter 12 could have been omitted as it contributes little to the general theme of the book. Chapter 14 discusses the engineering applications in a mere 1½ pages and ignores the architectural problems altogether, whilst the four pages on economic studies merely whet the appetite for more information.

Because the topics discussed range so widely, the treatment is often superficial and uncritical. For the ordinary reader, however, it is a useful introduction to the subject and the research worker will find it valuable to have handy for the references. There are a few errors in the formulae but the book is well presented in clear type with good diagrams.

N. C. HELLIWELL

World survey of climatology, Volume 5, Climates of northern and western Europe, edited by C. C. Wallén. 300 mm × 215 mm, pp. x + 253, *illus.*, Elsevier Publishing Co. Ltd, 22 Rippleside Commercial Estate, Ripple Road, Barking, Essex, 1970. Price: £13.

This is the fifth (but the fourth, not in order of the volumes, to appear) of the 15 volumes of the World Survey of Climatology being published under the direction of Professor H. C. Landsberg. The four main chapters discuss in turn the climates of Scandinavia, the British Isles, France and the Benelux countries and the Iberian peninsula. Central and southern Europe will be covered in a later volume (Volume 6).

In an introductory chapter C. C. Wallén describes the general radiation conditions and air and sea circulations affecting the region, together with the resulting temperature and precipitation distributions. There is a muddle over Figures 5 and 6 which are maps of the frequency of cyclones with central pressure less than 1000 mb. The text leads the reader to expect winter and summer maps, respectively, but in fact Figure 5 is a summer map which is labelled 'annual", while Figure 6 is an annual map which is labelled 'summer'. These maps were originally published in 1924 and it is surprising that more recent ones could not have been found, or prepared. Their periods are not stated, nor are those of the mean temperature map (which has isotherms at unequal intervals) or the precipitation map.

The chapter on the climate of Scandinavia is written by T. W. Johannessen of the Norwegian Meteorological Institute. In 40 pages of text he gives a detailed description of the climates of Norway, Sweden, Finland and Denmark. It is interesting to learn that the 'heating season' in these countries normally begins when the mean daily air temperature falls below 11°C and ends when it rises above 9°C; this compares with official figures for this purpose of 16°C in the U.K. and 18°C in the U.S.A. Of six maps included the first two are unusual. They show the distributions for January and July of the correlation coefficients between the mean monthly air temperatures at Sula Fyr (63°51′N, 8°28′E) and at other places in Scandinavia, 1931–60. The other four maps show the mean annual potential evapotranspiration, the normal dates of beginning and end and the length of the vegetation period (daily mean temperature 6°C or above). Unfortunately there are many misprints and some errors, while statements such as 'the warm Gulf Stream passes north-eastwards close by the west coast of Norway' page 23) and 'this especially applies to autumn which is at present the warmest season of the year' (page 59) do not inspire confidence.

Chapter 3 on the climate of the British Isles is the work of Professor G. Manley formerly of the Department of Enviromental Sciences, University of Lancaster. As was to be expected perhaps from his well-known writings on the subject, a good part of his fifty-odd pages is devoted to snowfall and snow cover and to temperature variations in these islands since 1670. Only two maps are included, both for the period 1931–60, showing the distributions of days with thunder heard and mornings with snow cover. In the section on wind, and elsewhere, references are made to 'Weather in Home Fleet Waters, Vol. 2' which has not yet, in fact, been published, while no mention is made of 'Tables of Surface Wind Speed and Direction over the United Kingdom' published in 1968 and probably the most complete and recent source of information on surface winds. There are many errors and misprints which should not have escaped proof-reading.

In Chapter 4, R. Arléry of the French Meteorological Service has contributed a relatively short but well-written account of the climates of France, Belgium, the Netherlands and Luxembourg. It is illustrated by 10 maps, all 1931–60, showing the distributions of all the main climatic elements. There is a little confusion at the end arising from an apparent last-minute addition of some information on surface winds.

The final chapter dealing with the Iberian peninsula, is also relatively short and is contributed by A. Linés Escardó of the National Meteorological Institute in Madrid. It is very well illustrated by many climatic maps, those of the main elements being for the period 1931–60. Many references to conditions in the Canary Isles and Madeira seem a little out of place. The section on 'Evaporation and evapotranspiration' is puzzling. It opens with a statement that 'in practically the whole territory annual mean values of potential evaporation vary between 1000 and 2000 mm', but a map of potential annual evapotranspiration by Thornthwaite's method shows only two very small areas with over 1000 mm, while Penman's method is stated to give values which may be up to 20 per cent higher than those calculated by Thornthwaite's.

Two main criticisms may be made of the volume as a whole. The first is that although the authors are well-known climatologists who clearly know their subjects, there are many signs of hasty writing and numerous misprints and mistakes in some chapters almost suggest that proof-reading was dispensed with. The second, probably more important, is that the various chapters do not follow any common plan. To a British reader this lack of balance is particularly noticeable, as the chapter on the British Isles is the one that differs most markedly from the others. For example, the other three main chapters all give climatic tables, following a standard format, at the end. Chapter 3 does not, and it is the only one which contains no upper air data whatever. All chapters would have been easier to follow had they included a map showing the districts and places referred to in the text. Frequent reference to an atlas was necessary and even then some places could not be found.

While this volume, and indeed the whole series, must be a valuable addition to every important meteorological library, its variable standard and its price will not induce many individual climatologists to acquire it.

H. C. SHELLARD

Monsoon meteorology, by C. S. Ramage. 233 mm × 160 mm, pp. xi + 296, *illus.*, Academic Press Inc. Publishers, 111 Fifth Avenue, New York, N.Y. 10003, 1971. Price: $15.

This book is Volume 15 of the International Geophysics Series edited by J. Van Mieghem.

It is a mine of information on all aspects of the monsoon. The first two chapters are short and concerned mainly with definitions and discussion on the general causes of the monsoon, heat balance over the ocean, general distribution of rainfall, etc. The longest and most valuable chapter is Chapter 3 in which are described in considerable detail with some theory, all the major synoptic components which occur in monsoon regions; these include tropical and subtropical cyclones, monsoon depressions, heat lows, monsoon troughs, non-circulating disturbances, transequatorial flow, etc.

Chapter 4 is a short but interesting chapter on precipitation, much of it concerned with the differences between monsoon rains and thunderstorms and drawing attention to the importance of the local orography. More could have been made of the value of satellites (especially geostationary ones) in this section and a reference to the proposed GARP tropical experiment would have been appropriate since this has as one of its objectives the study of mesoscale systems on the scale between single cumulonimbus and synoptic systems which are not adequately observed by existing radiosonde networks — just the type of systems important in producing monsoon rains.

Chapter 5 on the march of the seasons considers major monsoon areas and subdivides the weather of each into seasons. It is the most coherent reading of the whole book and is a most valuable descriptive account of monsoon weather in all parts of the world in which it is observed.

The next chapter brings home the unsatisfactory state of analysis and points to the value of statistics and climatology to the forecaster in monsoon areas.

The book closes with about 20 pages on short-period forecasting with some discussion on long-range forecasting and possible relationships between the general atmospheric circulation and the monsoon. Much more could have been said on these topics, long-range forecasting in particular being inadequately discussed.

When the reputation of the author is considered, the style throughout is rather disappointing; much of the book is divided into short paragraphs which are often disconnected in their content thus making continuous reading difficult. The number of cross references is also excessive, creating a disjointed effect which is enhanced by references to diagrams, for example on page 8 one short paragraph refers to 7 diagrams scattered about the book from page 12 to page 250 and this is by no means an isolated example— almost every paragraph refers to diagrams and text in other parts of the book.

As is usual in this series, there is both a subject and an author index; I was perhaps unlucky in looking up two authors, for in each case, the page number of the reference was wrong. The bibliography runs to 11 pages and is useful and up to date; there are a few significant omissions however, notably Findlater's paper in the Quarterly Journal of the Royal Meteorological Society in April 1969 on 'Interhemispheric transport of air in the lower troposphere over the western Indian Ocean'. The author in fact in his discussions on cross-equatorial flow in the region of East Africa seems unaware of Findlater's work although there are later references in the bibliography.

Satellite pictures are a welcome feature of the book but these are rather small and the geography not always clear. Some of the diagrams, too, contain too much detail for clarity and their captions are often wordy and unclear.

Although a difficult book to review, it contains a wealth of sound information but there are some gaps in the presentation and the whole is difficult to read, though easier to use as a work of reference for students and meteorologists concerned with monsoon problems.

R. A. S. RATCLIFFE

Atmosphere, weather and climate (second edition), by R. G. Barry and R. J. Chorley. 214 mm × 140 mm, pp. 379, *illus.*, Methuen and Co. Ltd, 11 New Fetter Lane, London, EC4, 1971. Price: £2·75. (Paperback edition £1·50.)

The first edition of this book appeared in 1968 and was reviewed by Virgo.* It was clearly well received by the readers for whom it was intended, mainly geography students in the sixth form and first year at University, and the demand has apparently been sufficient to justify the publication of a second edition only three years later. The reasons for the book's popularity are not difficult to see. By attempting to describe and explain climate in terms of the properties and behaviour of the atmosphere the authors have treated the subject in a logical and up-to-date manner. Moreover, they have done so in a way which demands very little knowledge of mathematics. The style

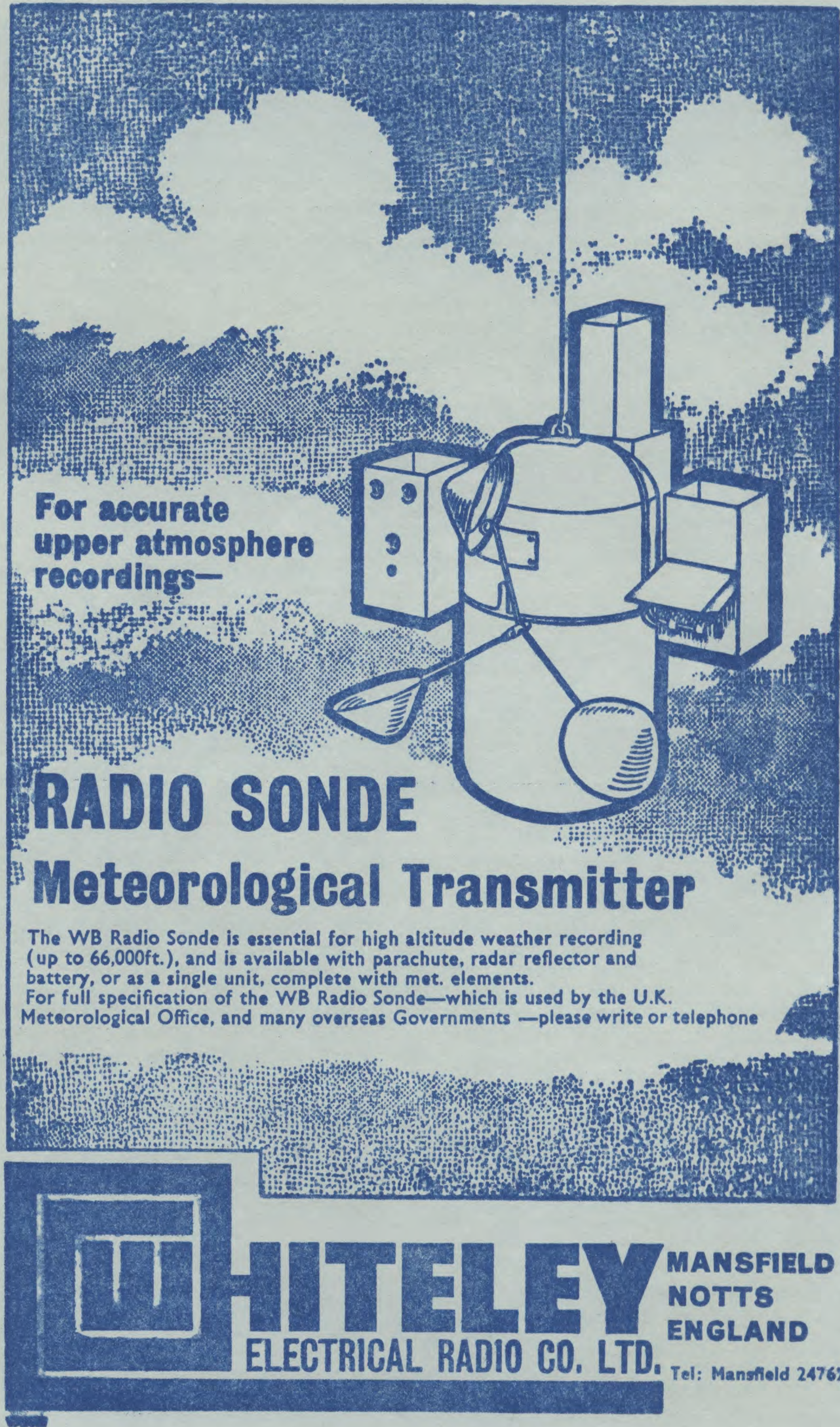
* *Met Mag, London*, **97**, 1968, p. 156.

is lively and readable, and a high level of interest is maintained throughout. Illustrations are used liberally and many numerical examples are quoted which give the reader a good idea of the order of magnitude of the quantities involved.

Unfortunately, although in the second edition the book has been improved by revisions and additions to the text, there are some defects. As must be in a book of reasonable length (and cost) covering such a wide field, much of the treatment is sketchy and, particularly in the chapters dealing with the structure and behaviour of the atmosphere, not adequate to meet the needs of the serious student of meteorology. Some sections show signs of hasty or careless preparation of the material, and too many errors are present which should have been weeded out before the first edition was published. Some of the errors are fairly obvious, while others become apparent after a little thought — the use of the formulae on pages 36 and 41, for example, will lead to ridiculous answers if c (cloudiness) and α (albedo) are expressed in 'tenths' and 'hundredths' respectively. There are just a few places where the student may be misled or confused: examples occur in the discussion of conditional instability (pages 99–100), and in the section on mesoscale phenomena (page 181), in which it is implied that the only mesoscale features of the atmosphere are severe thunderstorms.

In spite of its faults, the book is a valuable addition to the literature at a reasonable price. Its main virtues lie in the authors' sound approach to the subject and their ability to stimulate the reader's interest and encourage further study.

J. CRABTREE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MONTHLY AND ANNUAL TOTALS OF RAINFALL REPRESENTATIVE OF KEW, SURREY, FROM 1697 TO 1970

By B. G. WALES-SMITH

Summary. Values of rainfall representative of Kew have been tabulated for each month from 1697 to 1970. Details are given of the method of obtaining the representative values from the available data. Some gaps in the series have been filled by an analysis of a weather diary for Richmond.

Introduction. Routine rainfall measurements have been made at Kew from 1871 onwards. The potential value of a very long rainfall record for one station was thought sufficient to justify an attempt to estimate the annual and monthly falls on the site of Kew Observatory before 1871.

Available data. The earliest 'London area' rainfall records, known to the Meteorological Office, for a complete year are for Upminster in 1697 and from that year onwards, with an unfortunate break from 1717 to 1724 (inclusive), records for one or more London stations at a time are available. Luckily, George Smith, Proctor to Queen Anne, maintained an excellent weather diary[1] at Richmond Palace from 1713 until his death in 1745 and it has been possible to make rough estimates of monthly falls from his descriptions of weather. The numerical data used are those published by Brazell,[2] but some estimates have been made to obtain a series representative of Kew over the whole period 1697–1970. (See Appendix I.) The vast majority of the data are recorded in inches and these units have been retained in this analysis (1 in = 25·4 mm).

Analysis and adjustment of data.

1697–1716. The Upminster values have been multiplied by 12/11 = 1·0909 (the approximate relationship between the 1916–50 annual average rainfalls for Upminster and Kew).

1717–24. The Richmond diaries were used to obtain an estimate of monthly rainfall from 1717 to 1724. The diaries overlap the Upminster record from 1713 to 1716, the Fleet Street record from 1725 to 1735 and the Tonbridge record from 1736 to 1744. The Fleet Street record was accepted as an estimate for Kew, and the Tonbridge values were multiplied by 0·876 to obtain an estimate for Kew.

George Smith's diaries give a summary of each month's weather and, for most months, notes on days which the diarist seems to have thought specially important.

For the 20-year period 1725–44 George Smith's descriptions in respect of precipitation were listed, month-by-month, in abbreviated form. Thus, for example, 'Dry 3' would mean 'Dry with three rain days specifically mentioned' and 'NM4' would mean 'No precipitation mentioned in the summary but four days with precipitation listed *below* the summary'.

The Fleet Street or adjusted Tonbridge monthly estimates of Kew rainfalls were written against the descriptions for each year, month-by-month, and the descriptions were then grouped (for each month) on the basis of 'precipitation type' and rainfall amount. Amounts in each group were averaged and the number of cases per average was noted. Table I gives the final classification or 'scale.'

TABLE I—THE CLASSIFICATION OF ENTRIES IN THE RICHMOND DIARIES

	Estimated monthly rainfall	Number of cases
January	*inches*	
Very dry, very fine	0·54	2
Dry, little rain	0·78	5
NM(0–3)	0·41	3
NM>4	2·19	3
Part month stormy	1·44	2
Wet, stormy	3·03	5
February		
Extremely dry	0·10	1
Dry, fine, little or no rain	0·66	3
NM(0–3)	0·91	4
Some or occasional precipitation	1·45	6
Wintry with snow, good deal of snow	2·71	2
Wet, stormy	1·57	3
Very wet, great deal of rain	1·92	2
March		
Nil	0·05	1
Almost nil	0·10	1
Dry, generally dry	0·47	2
NM(0–5)	1·76	7
Showery	2·10	1
Some or occasional rain	1·72	4
Wet	2·65	4
April		
Very dry	0·53	1
Dry, very little rain	1·10	4
NM(0–3)	2·88	2
Showery	1·91	7
Partly showery, partly stormy	0·94	3
Some rain, thundery	2·15	2
Wet	3·47	1
May		
Exceedingly or very dry	0·47	2
Dry	0·79	2
Dry with thunder	1·63	1
Some rain	1·49	3
Showery	2·20	8
Wet, very wet	3·38	3
NM(0–3)	1·38	1
June		
Fine	0·92	1
Very little rain	1·39	3
Some rain or showers	1·83	6
Showery	2·84	5
Wet, good deal of rain	2·89	3
Extremely wet, some heavy rains	4·33	2

TABLE I—*cont'd*

	Estimated monthly rainfall *inches*	Number of cases
July		
Very dry, dry	0·97	5
Some showers of rain or hail	1·95	6
NM	0·74	1
Showery	1·89	4
Very showery, heavy rains, good deal of rain	3·98	3
Wet	0·75	1
August		
Extremely dry, very dry	0·09	2
Dry, little rain	0·30	3
Seasonable some rain, some storms, dry but some rain	1·59	4
Occasional showers	1·73	1
Showery	2·93	3
Several wet days, wet, very wet, very stormy	2·12	4
Some heavy rains	3·39	3
September		
Dry	0·34	2
NM(0–3)	1·89	2
NM≥4	2·94	1
Some rain, generally fine	1·53	5
Partly wet	3·05	4
Rainy, wet, very wet	3·41	5
Showery	1·37	1
October		
Fine, dry, little rain	1·14	4
Mostly dry	1·33	2
NM(0–3)	1·68	3
NM≥4	2·09	1
Showery, stormy	1·91	2
Some rain	2·47	2
Wet	3·01	4
Very wet	4·57	2
November		
Nil	0·40	1
Very dry	1·31	1
Dry	1·34	4
Mostly dry, some rain, partly stormy	2·02	8
NM(0–3)	1·29	4
NM≥4	3·67	2
December		
Very fine	0·53	1
NM(0–3)	1·13	4
NM≥4	1·2	2
Partly wet	1·74	6
Wet, very wintry	2·98	6
Very wet	4·27	1

The scale was used to assess the monthly falls for 1725–44 from the diaries and also to assess the monthly falls for 1713–16, a four-year period deliberately left out of the classification exercise. These monthly estimates were totalled, year-by-year, and are compared with the Upminster – Fleet Street – Tonbridge estimates for Kew in Figure 1. It will be seen that the totals for 1725–44 were 'reconstituted' quite well and that 3 out of 4 of the 1713–16 totals (plotted as crosses) were also well estimated. The year poorly-estimated was the first

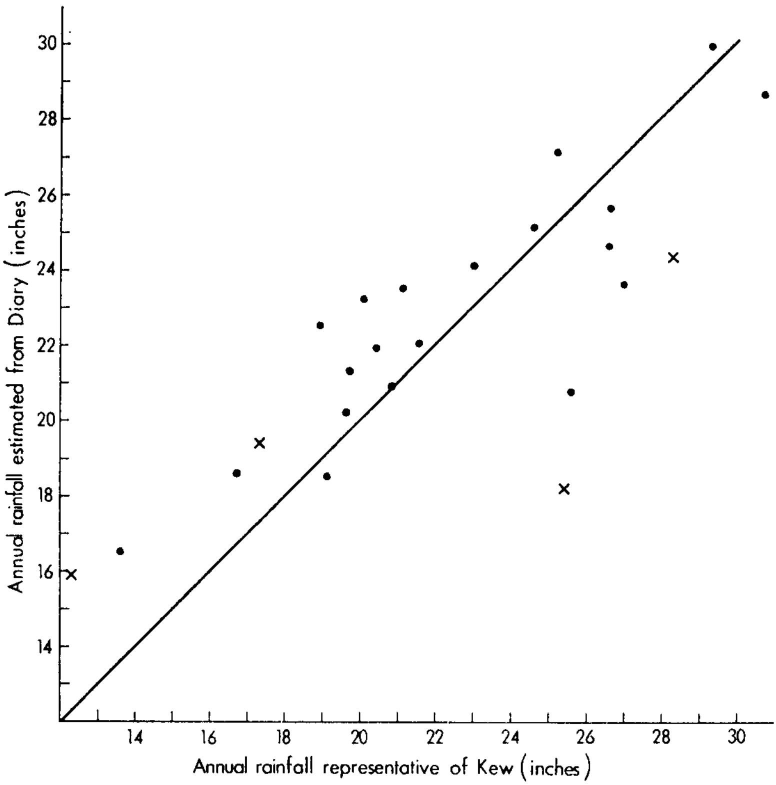

FIGURE 1—THE RELATION BETWEEN DIARY-BASED ESTIMATES AND REPRESENTATIVE MEASUREMENTS FOR KEW FOR 1713–44

x indicates totals for 4 years excluded from the Diary classification
The line represents exact correlation.

of the diary. Little more than this slight support can be given for the method except to say that these very good diaries, treated in the manner described, appear capable of identifying the majority of very wet, wet, average, dry and very dry years, correctly, in relation to average.

The next step was to use the 'scale' and the diary accounts for the period 1717–24 to estimate monthly falls and to total the monthly estimates for each year. The yearly totals are set out in Table II where they are compared with George Smith's *annual* summaries which were not used or even examined when making the scale.

It will be seen that there is an encouraging measure of agreement between the annual totals of monthly estimates and the annual summaries.

1725–35. The Fleet Street values have been accepted since

(i) they are a London record,

(ii) the correlation coefficient for the seven-year overlap with Tonbridge is very high (Figure 2*(a)*) (0·946), and

(iii) if the long-period relationship between Tonbridge *(T)* and Greenwich ($G = (24/27{\cdot}4)T = 0{\cdot}876T$) is extracted from the diagram

TABLE II—COMPARISON OF ANNUAL TOTALS OF MONTHLY RAINFALL AT KEW*

Year	Total of monthly estimates *inches*	Annual summary
1717	22·90	None.
1718	22·60	'The *sumer was very hott & dry.* extr: good grapes very little other good fruit 2d. crops white figs ripe. harvest very forward, all got in begin: Septr. *Extr: mild winter.*'
1719	17·70	'This *Sumer was very hott & dry,* good grapes, no other fruit. The Second crop of figs ripe at Michas. *very mild dry winter. water very low.*'
1720	25·80	'The *Sumer wet & green,* little good fruit. Grapes late ripe but some good. *Winter warm & wet.* no frost. mildest Season ever known.'
1721	23·70	None.
1722	18·80	'*Wet Sumer, fair fine Autumn.* very good grapes *fine fair mild dry winter.*'
1723	14·60	'*Longest Sumer ever known. very dry* good grapes 2d. crop of figs, some blew, ripe: *dry warm winter,* 3 weeks at Xtmas fine weather as April.'
1724	21·00	'*Very long Sumer* good grapes, 2d. crop figgs ripe in Septr. *great plenty all sorts fruits* especially Apples and pears tho' no good pears, *fine winter, dry till lately.*'

* Estimated from George Smith's monthly weather diary entries with the same diarist's annual weather summaries as quoted in Britton,[1] phrases relevant to the present paper being italicized.

on page 127 of *London weather*[2] and if Fleet Street and Greenwich Observatory are regarded as probably broadly comparable the dashed 'regression' line shown in Figure 2*(a)* is obtained for comparison with the calculated regression between Fleet Street and Tonbridge. The dashed line is a tolerable fit for the seven points.

1736–64. The Tonbridge values have been multiplied by 0·876. The adjustment could have been made by using the regression equation with Fleet Street but it was felt that such a relationship, based on only a seven-year overlap, was unlikely to be superior to adjustment by proportion of long averages, a well-tried method in rainfall studies. A four-year record is also available for Chelmsford (1738–41) but the long Tonbridge record was preferred.

1765–81. The Lambeth values have been accepted, being a London record without overlap. The overlap of only five years (1787–91) of South Lambeth and Somerset House (Figure 2*(b)*) gives a correlation coefficient 0·924 but it can be seen (Figure 2*(d)*) that Somerset House was poorly correlated with Greenwich (1815–40) and only slightly better correlated with Edmonton (Figure 2*(g)*) (1817–39). Greenwich and Edmonton (Figure 2*(e)*) had a correlation of only 0·753 for almost the same period (one extra year included). On this basis no use could be made of the one-year overlap of Lambeth with South Lambeth in 1782.

1782. The mean of Lambeth and South Lambeth values was accepted.

1783–91. The South Lambeth values have been accepted since

(i) they are a London record, and

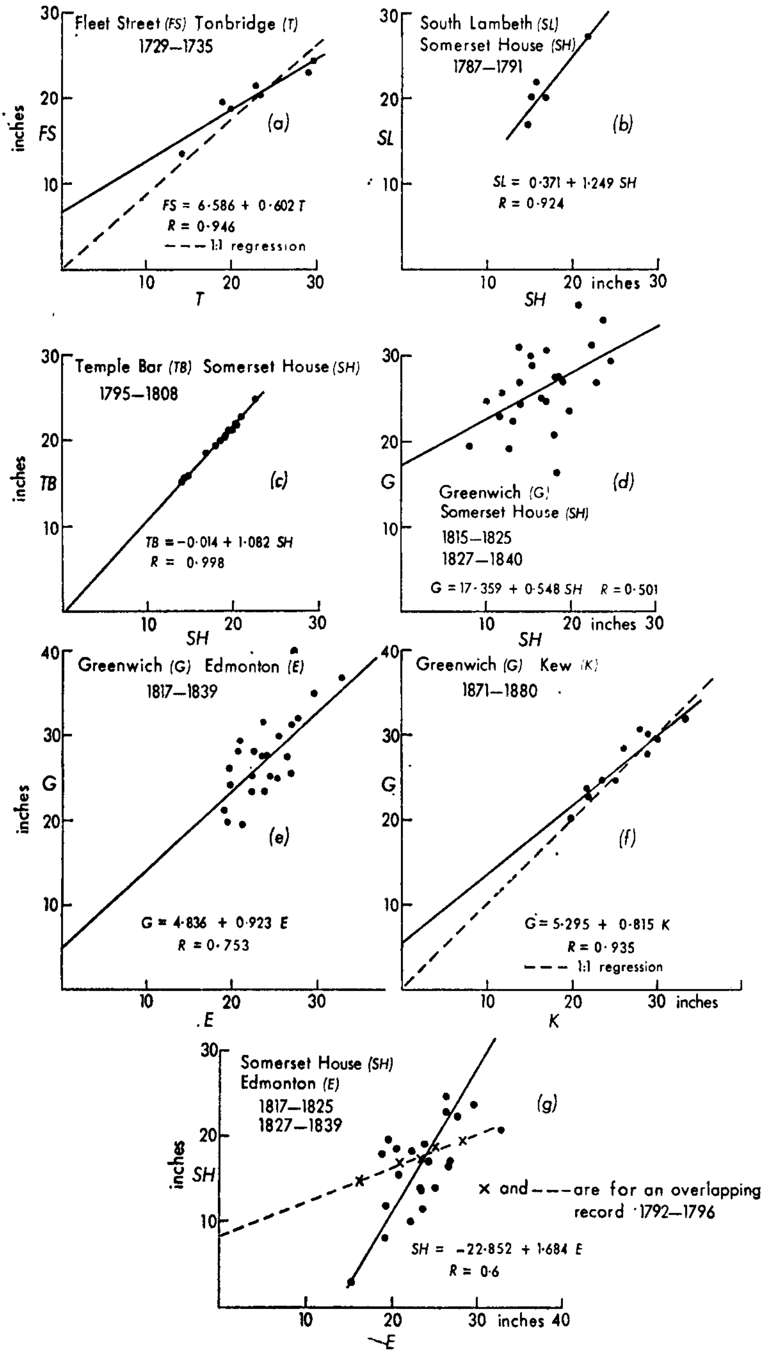

FIGURE 2—REGRESSION LINES BETWEEN VARIOUS PAIRS OF RAIN-GAUGES

(ii) for the period 1787–91 (Figure 2*(b)*) they are very well correlated with Somerset House (0·924) even though the latter record was obtained from a roof gauge!

1792–1809. The regression line for South Lambeth and Somerset House 1787–91 (Figure 2*(b)*) passes very close to the origin and there is little to choose between the slope of the line (1·249) and the direct proportion (obtained from the averages for the period) $SL = 1{\cdot}266\ (SH)$.

As may be seen from Figure 2*(c)*, Temple Bar and Somerset House annual totals were extremely well correlated during the period 1795–1808, strongly suggesting that both were good records. The Somerset House values have been multiplied by 1·266.

1810–13. The Soho Square values have been accepted since

(i) they are a London record, and

(ii) the correlations between Greenwich and Somerset House (Figure 2*(d)*) (1815–40) 0·501, between Greenwich and Edmonton (Figure 2*(e)*) (1817–39) 0·753 and between Somerset House and Edmonton (Figure 2*(g)*) (1817–39) about 0·6, show that from 1815 to 1840 if one of the records was a good one it would have to have been the Greenwich record. The values from the earlier overlapping record (1792–96), added as crosses to Figure 2*(g)*, have a very high correlation *by themselves* and a regression line $SH = 8{\cdot}3 + 0{\cdot}390\ E$ very different from the longer, later record.

The view that the Greenwich record was good is supported by the 0·935 correlation between Greenwich and Kew for the period 1871–80 (Figure 2*(f)*). All this suggests that the previously reliable Somerset House record deteriorated some time after 1808.

The four-year Soho Square record is probably to be preferred to the fragmentary Edmonton and Somerset House values for 1811–14 and gives the only available value for 1810.

The decision to accept the Soho Square totals is supported, to some extent, by considering the available choices. The Greenwich and Kew records are well correlated (0·935 for 1871–80). The correlation between Edmonton and Greenwich for 1817–39, 0·753, is not good and, if the corresponding regression (Figure 2*(e)*) is applied to the 1811 Edmonton total (27·90 in) the value is increased to 30·59 in, far higher than the corresponding Soho Square total. The correlation between Greenwich and Somerset House for the two periods 1815–25 and 1827–40 is very poor (0·501) and if the improbable-seeming regression (Figure 2*(d)*) is applied to the 1812 and 1813 Somerset House values they are tremendously increased. If, on the other hand, the factor 1·27 (approx.) is adopted, (the factor used to adjust values for Somerset House for the period 1792–1809), estimates are obtained close to the 1812 and 1813 measurements at Soho Square. The comparisons are shown in the following table.

	Soho Square	Greenwich (from Edmonton)	Greenwich (from Somerset House)	Kew (from 1·27× Somerset House)
		inches		
1811	22·66	30·59		
1812	25·80		27·41	23·22
1813	20·46		26·11	20·21

1814.* The Somerset House value was multiplied by 1·5. As already noticed, there are sound reasons to suspect that the Somerset House record was deteriorating. The factor 1·27 was accepted as reasonable for 1812 and 1813. The factors relating Somerset House to Greenwich from 1815 to 1819 are: 1815 1·73, 1816 1·98, 1817 1·90, 1818 2·21 and 1819 2·27; 1·5 is simply the mean of 1·27 and 1·73.

1815–70. The two recent 35-year annual averages for Kew and Greenwich Observatories are :

	Kew	Greenwich
	inches	
1881–1915	23·8	23·5
1916–50	23·95	24·00

The comparison for the first 10 years of the overlap (1871–80) gave the correlation coefficient 0·935 (Figure 2*(f)*) and the 10 points are almost as well fitted by the 1:1 regression line as by the calculated line. The Greenwich values have been accepted, without adjustment, as estimates for Kew.

Estimation of monthly totals for years with only annual totals or with annual and only some monthly totals. Estimates were required for the years 1704, 1706, 1707, 1709, 1710, 1711, 1712, 1713 and 1714. Monthly totals for years with only annual totals were estimated by means of the monthly percentages of annual average for Kew for the period 1916–50. Missing monthly totals for years with annual totals and some monthly totals were estimated as follows :

(i) (Annual total) — (available monthly totals) = x in.
(ii) Express x as a percentage (y) of annual total.
(iii) Subtract y from 100.
(iv) For the missing months total the monthly Kew percentages of the annual average (1916–50).
(v) Evaluate $(100 - y)$ — (total of Kew percentages for missing months).
(vi) Divide result obtained in (v) by number of 'missing months' and apply result (plus or minus) to the Kew monthly percentages before using them to apportion the residue of the annual total of rainfall between months without known totals.

For the years 1713 and 1714 monthly estimates were available from the 'scaling' of the Richmond diaries. These were expressed as percentages of their own annual totals and the percentages were then applied to the adopted annual totals to obtain monthly estimates.

The records for a few years (1776, 1782, 1784, 1785 and 1786) each contain an accumulated total for two or three months. These accumulations have been shared equally between the months except in the case of 1782 where two records were available, one complete and the other containing a three-month accumulated total.

* Brazell[2] (p. 164, Note (g)) mentions that the 1814 total recorded by another gauge, a few feet away and 11 ft 6 in lower, appears to have been 20·72 in. This fragment of evidence further supports the view that the catch of the roof gauge was seriously low. It is interesting, though probably coincidental, that 20·72/16·32 = 1·27, the factor used to adjust the 1792 to 1809 record. A fragmentary record by Luke Howard in Middlesex gives a total of 26·07 in for 1814, 1·6 times 16·32, giving some support to the choice of 1·5 as the adjusting factor for 1814.

Comparison of the estimated and measured rainfalls for Kew Observatory with general annual values for England and Wales. In the eighteenth century and the early years of the nineteenth century there were very few rainfall stations in England and Wales. Early general annual values must, therefore, be used with some caution. By the middle of the nineteenth century, however, there were over 1000 gauges in use in the British Isles. Annual general rainfalls for England and Wales are set out in Appendix II.

Monthly rainfall averages for England and Wales, expressed as percentages of monthly averages for the 35-year period 1881–1915, were published in *British Rainfall 1931*, in an article by F. J. Nicholas and J. Glasspoole.[3] The article gives the number of stations used for each year's estimates and these may be summarized as follows :

1727–66	2–4
1767–87	3–9
1788–1820	6–17
1821–49	19–28
1850–67	43–58

The annual values reproduced in Appendix II and their component monthly values have been kept up to date in the Meteorological Office under the supervision of J. Grindley and they exist as a computer print-out and as a KDF 9 magnetic-tape record.

Figure 3*(a)* compares general England and Wales values *(EW)* and the estimated Kew annual values *('K')* for 1727–1814; Figure 3*(b)* compares general England and Wales values and the Greenwich Observatory annual values *(G)* for 1815–70; Figure 3*(c)* compares general England and Wales values and the Kew Observatory annual values *(K)* for 1871–1970.

Regression equations and correlation coefficients *(R)* are :

1727–1814	$EW = 14{\cdot}446 + 0{\cdot}8089\ 'K'$	$R = 0{\cdot}6427$
1815–1870	$EW = 15{\cdot}946 + 0{\cdot}7616\ G$	$R = 0{\cdot}8032$
1871–1970	$EW = 15{\cdot}874 + 0{\cdot}8471\ K$	$R = 0{\cdot}7468$

It will be seen that all three equations are very much alike, especially the most recent pair. The improvement in the correlation is, presumably, due to (i) the use of a single (observatory) record after 1815 and (ii) the increase in density and representativeness of the England and Wales network during the early part of the nineteenth century.

Table III gives 35-year average rainfalls for (*a*) the estimated and measured values for Kew, and (*b*) England and Wales, and expresses the first set as a percentage of the second. The percentages have decreased since the 1811–45 period, presumably because of the removal of 'London and Home County bias' from the general values. Table IV examines the relationship in terms of 10-year averages and shows the same decrease of percentage. Figure 4 shows the Kew 10-year falls as percentages of 7/10 of the England and Wales values and compares the two sets of values directly.

Future plans. The monthly and annual rainfalls of Appendix I have been transferred to punched cards. An analysis scheme has been designed and programmed in FORTRAN and has provided statistics relevant to flooding, rainfall deficiency and aquifer recharge. Various other uses are being made of the series.

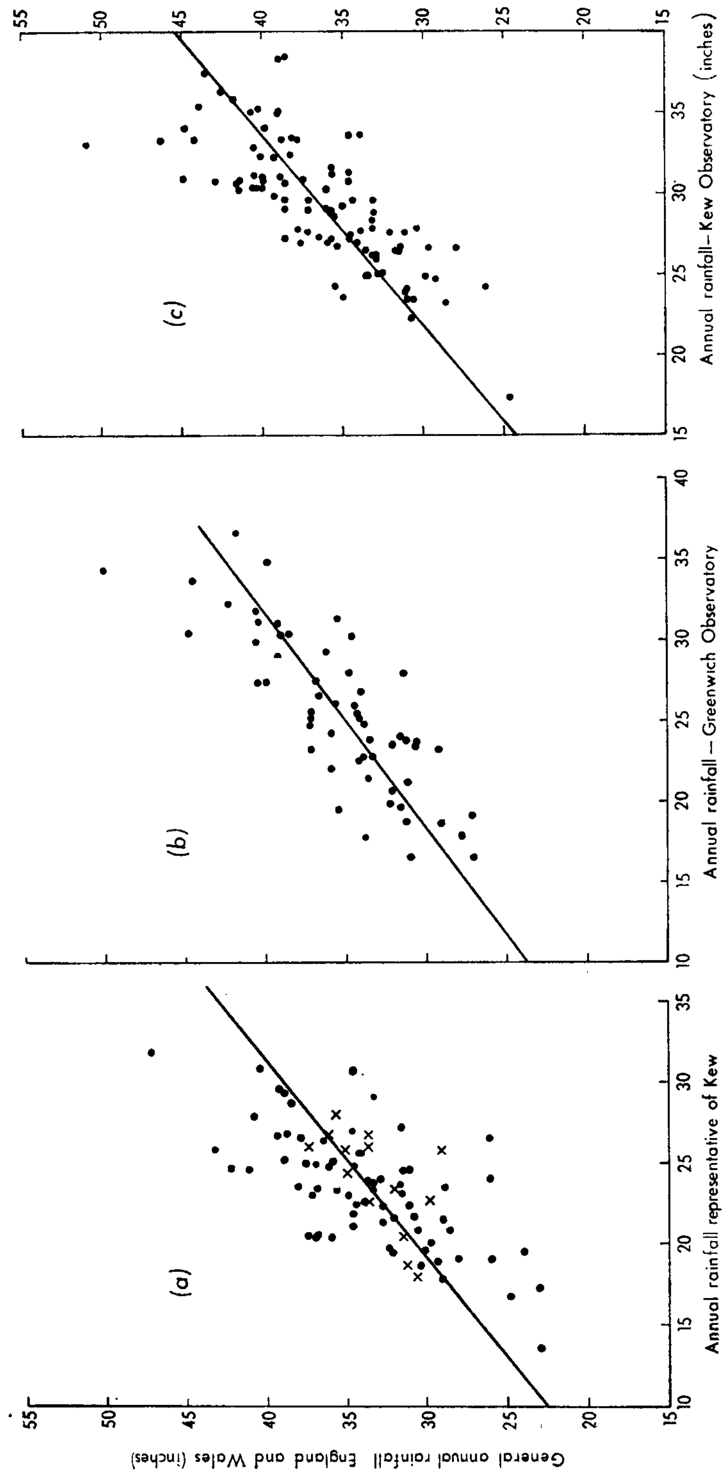

FIGURE 3—THE RELATION BETWEEN THE GENERAL ANNUAL RAINFALL FOR ENGLAND AND WALES AND THE ANNUAL RAINFALL *(a)* REPRESENTATIVE OF KEW (PERIOD 1727–1814), *(b)* FOR GREENWICH OBSERVATORY (PERIOD 1815–1870) AND *(c)* FOR KEW OBSERVATORY (PERIOD 1871–1970)

TABLE III—35-YEAR AVERAGE RAINFALL

35-year period	(a) Representative of Kew	(b) England and Wales	Percentage, (a) of (b)
1706–1740	22·46 (570·5)	—	—
1741–1775	23·79 (604·3)	33·65 (854·7)	70·7
1776–1810	23·32 (592·3)	33·43 (849·1)	69·7
1811–1845	25·80 (655·2)	35·42 (899·7)	72·8
1846–1880	24·59 (624·6)	35·82 (909·8)	68·6
1881–1915	23·79 (604·3)	35·24 (895·1)	67·5
1916–1950	23·95 (608·3)	36·53 (927·9)	65·6

Note : Rainfall amounts are given in inches with millimetre equivalents below in brackets.

TABLE IV—10-YEAR AVERAGE RAINFALL REPRESENTATIVE OF KEW OBTAINED FROM ADJUSTED AND MEASURED VALUES

Decades	Rainfall *inches*	Percentage of total for England and Wales
1701–10	21·98	—
1711–20	22·42	—
1721–30	21·74	—
1731–40	22·96	72
1741–50	21·90	73
1751–60	23·89	70
1761–70	24·95	70
1771–80	24·26	71
1781–90	22·89	69
1791–1800	23·24	67
1801–10	23·71	72
1811–20	25·95	76
1821–30	28·20	77
1831–40	23·55	67
1841–50	24·19	67
1851–60	25·00	73
1861–70	23·32	69
1871–80	26·14	67
1881–90	23·40	66
1891–1900	22·49	65
1901–10	24·13	69
1911–20	26·77	71
1921–30	24·38	65
1931–40	23·41	64
1941–50	22·63	65
1951–60	24·14	65
1961–70	23·95	67
Mean of 24 decades	24·14	
Mean of 27 decades	23·91	

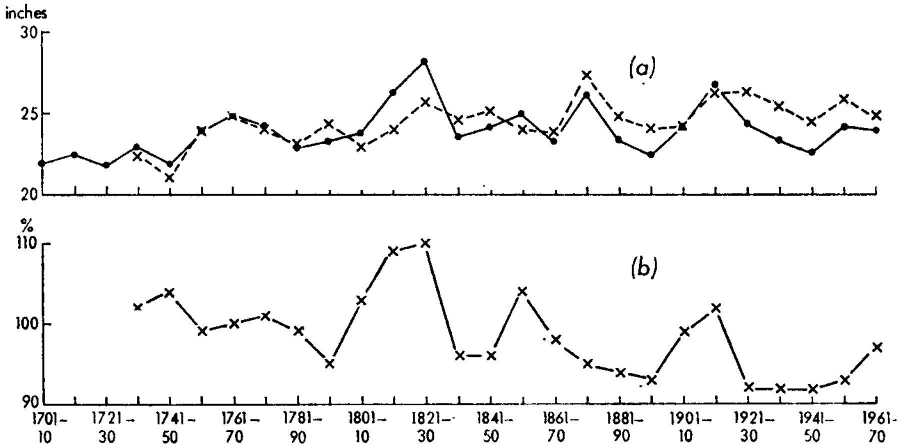

FIGURE 4—10-YEAR RAINFALLS : (*a*) KEW WITH 0·7 × ENGLAND AND WALES (*b*) KEW AS PERCENTAGE OF 0·7 × ENGLAND AND WALES

.——. Kew rainfall x – – – x 0·7 × England and Wales

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2. BRAZELL, J. H.; London weather. London, HMSO, 1968.
3. NICHOLAS, F. J. and GLASSPOOLE, J.; General monthly rainfall over England and Wales, 1727 to 1931. *Brit Rainf, 1931, London,* 1932.

Appendix I

Monthly and annual totals of rainfall representative of Kew, 1697–1970 (in inches).

1697–1716 Upminster × 1·0909

*Monthly totals for 1706, 1709–12 and for certain asterisked months in 1704, 1707 are obtained by the use of the monthly percentages of the annual average for Kew for the period 1916–50.

Adjustments to mean percentages were made where some measured monthly totals were available (see page 352).

†Monthly totals for years 1713, 1714 were apportioned from the annual totals by using the Richmond diaries.

1717–24 ‡Monthly and annual totals estimated from Richmond diaries (see page 345).

1725–35	Fleet Street
1736–64	Tonbridge × 0·876 (Note : September 1752 has only 19 days. The period 3–13 September inclusive was dropped at the change of calendar)
1765–81	Lambeth
1782	Mean of Lambeth and South Lambeth
1783–91	South Lambeth
1792–1809	Somerset House × 1·27
1810–13	Soho Square
1814	Somerset House × 1·5
1815–70	Greenwich Observatory
1871–1970	Kew Observatory

Note : In the period 1776 to 1786 values marked '+' are monthly totals obtained by sharing accumulated totals evenly between months except in 1782 when likely proportions were given by one of the two records used in the estimate (see page 352).

	1697	1698	1699	1700
January	0·79	2·40	1·95	0·86
February	0·39	0·28	1·33	1·68
March	0·59	2·05	1·23	0·34
April	1·65	1·77	0·75	1·67
May	0·70	2·64	0·59	1·52
June	1·08	1·92	0·96	1·67
July	1·35	3·73	1·45	0·93
August	3·07	1·54	1·88	1·78
September	2·29	2·65	1·77	3·25
October	1·84	2·87	2·95	3·75
November	1·23	3·69	0·43	1·15
December	2·04	1·29	1·28	2·26
Total	17·02	26·83	16·57	20·86

	1701	1702	1703	1704	1705	1706*	1707	1708	1709*	1710*
January	3·27	2·15	1·95	0·89	0·24	2·37	1·03*	3·14	2·59	1·79
February	1·93	1·60	1·41	0·48	1·21	1·70	0·59*	0·50	1·86	1·29
March	0·86	0·52	1·04	3·51	1·22	1·62	0·54*	2·21	1·78	1·23
April	0·32	2·39	2·74	1·19*	1·13	2·02	0·80*	1·05	2·21	1·53
May	2·00	1·42	4·55	1·19*	0·45	2·02	1·15	2·20	2·21	1·53
June	1·27	2·96	3·19	1·12*	0·72	1·92	1·46	2·53	2·10	1·45
July	2·08	0·96	3·27	1·63*	1·22	2·72	1·39	1·21	2·97	2·05
August	1·44	1·51	0·74	1·48*	2·37	2·48	2·38	3·22	2·71	1·87
September	1·23	1·77	3·26	1·31*	0·45	2·21	3·16	1·59	2·42	1·67
October	2·24	1·73	2·09	1·50*	3·51	2·50	1·44	0·25	2·74	1·89
November	1·80	3·07	1·59	1·66*	1·28	2·78	1·29	0·94	3·03	2·09
December	2·05	2·26	0·47	1·36*	4·76	2·29	2·65	2·15	2·50	1·73
Total	20·49	22·34	26·30	17·32	18·56	26·63	17·88	20·99	29·12	20·14

	1711*	1712*	1713†	1714†	1715	1716	1717‡	1718‡	1719‡	1720‡
January	2·30	2·32	4·18	0·38	0·95	1·89	0·90	1·80	0·80	0·40
February	1·66	1·67	3·98	1·15	0·68	0·38	1·40	0·90	1·50	2·70
March	1·58	1·59	0·69	1·31	2·75	0·43	2·60	1·80	1·80	1·90
April	1·97	1·98	1·68	1·24	2·89	1·10	1·90	1·90	1·10	1·90
May	1·97	1·98	2·08	0·61	1·03	2·08	1·30	1·60	1·20	2·20
June	1·86	1·88	2·79	1·08	3·58	1·81	1·60	1·80	1·90	1·70
July	2·63	2·66	3·94	1·39	4·38	0·98	2·00	1·20	0·90	4·00
August	2·41	2·42	1·40	1·24	4·48	0·46	2·10	0·60	2·90	2·40
September	2·15	2·16	0·56	1·24	2·01	2·16	2·00	1·60	1·00	1·90
October	2·43	2·45	1·68	1·01	3·09	3·46	2·00	2·70	1·70	3·00
November	2·69	2·70	1·40	0·77	1·88	0·97	4·00	3·70	2·00	2·00
December	2·23	2·24	1·52	0·85	0·56	1·57	1·10	3·00	0·90	1·70
Total	25·88	26·05	25·40	12·27	28·28	17·29	22·90	22·60	17·70	25·80

	1721‡	1722‡	1723‡	1724‡	1725	1726	1927	1728	1729	1730
January	1·50	0·60	1·10	3·00	0·65	3·92	2·41	3·09	0·74	0·45
February	0·90	0·80	1·80	1·00	0·10	0·64	2·06	0·63	0·79	1·23
March	1·00	2·00	0·50	1·80	0·38	1·46	2·10	2·49	1·13	3·59
April	3·00	1·00	1·00	1·00	1·97	0·68	0·53	3·47	1·60	0·67
May	1·30	1·80	0·80	1·20	2·76	1·78	3·84	1·62	1·51	1·75
June	2·80	1·40	1·00	2·00	4·05	3·39	2·85	4·61	1·20	3·75
July	1·70	4·00	3·00	3·00	0·75	4·19	0·80	4·61	1·04	2·39
August	1·60	2·30	0·30	2·20	2·70	0·08	0·07	1·67	3·04	0·02
September	2·80	0·40	0·80	1·90	2·66	4·95	1·75	1·68	3·51	2·10
October	2·50	1·80	1·30	1·20	1·23	0·98	1·72	2·29	1·42	2·46
November	3·50	1·80	1·20	1·30	1·17	1·31	0·40	2·16	2·43	1·57
December	1·10	0·90	1·80	1·40	1·65	3·61	2·57	1·00	1·95	1·50
Total	23·70	18·80	14·60	21·00	20·07	26·99	21·10	29·32	20·36	21·48

Appendix I — *continued*

	1731	1732	1733	1734	1735	1736	1737	1738	1739	1740
January	0·13	0·53	0·69	1·01	2·36	3·54	0·57	1·86	3·76	0·26
February	0·82	1·90	1·16	1·93	1·78	2·58	2·84	0·96	2·84	0·42
March	0·05	1·15	2·15	1·79	2·24	2·07	3·08	2·76	1·54	1·02
April	1·26	2·77	1·70	0·45	1·16	0·67	1·01	1·71	3·05	2·15
May	0·39	3·20	0·55	4·17	2·04	1·38	1·63	1·61	2·45	1·45
June	2·30	1·05	2·65	3·21	2·08	2·72	1·57	3·75	0·92	1·07
July	2·09	1·13	1·54	1·11	3·14	1·30	0·93	0·74	2·45	1·37
August	1·73	1·50	3·23	1·76	1·49	1·90	5·22	2·01	2·42	3·15
September	0·55	1·14	1·37	1·00	1·56	1·44	4·57	3·16	3·78	1·52
October	1·36	2·39	0·91	2·10	0·98	3·14	2·88	4·48	1·24	0·99
November	1·53	1·20	0·52	1·77	2·69	0·95	0·86	2·01	4·08	3·27
December	1·40	1·71	2·44	4·27	1·50	3·48	1·40	1·56	2·20	4·15
Total	13·61	19·67	18·91	24·57	23·02	25·17	26·56	26·61	30·73	20·82

	1741	1742	1743	1744	1745	1746	1747	1748	1749	1750
January	1·02	2·51	0·81	0·51	0·58	2·48	2·47	0·56	5·38	2·54
February	1·17	1·31	0·78	1·60	0·54	2·38	2·42	1·07	1·30	2·31
March	0·56	0·10	1·82	1·55	2·82	1·93	1·17	2·49	1·75	1·05
April	0·60	1·54	2·15	4·40	2·42	1·41	1·13	2·51	1·44	2·72
May	2·54	1·50	1·04	0·53	1·06	1·67	0·60	0·91	1·09	1·39
June	1·79	2·08	0·89	1·71	4·21	3·72	3·60	2·25	1·48	1·19
July	1·96	1·96	2·82	0·94	1·35	1·86	1·30	0·92	1·09	2·04
August	0·81	0·10	1·69	2·02	2·81	0·81	0·35	1·74	0·80	0·85
September	2·94	2·43	0·13	3·42	1·17	1·68	2·48	1·04	2·21	1·77
October	3·13	2·09	1·82	6·69	3·14	1·71	0·74	1·51	2·32	2·07
November	2·24	2·79	1·14	1·67	2·69	1·60	1·84	0·59	0·27	3·34
December	0·84	0·67	1·63	0·53	2·29	1·86	6·67	4·56	1·71	2·84
Total	19·60	19·08	16·72	25·57	25·08	23·11	24·77	20·15	20·84	24·11

	1751	1752	1753	1754	1755	1756	1757	1758	1759	1760
January	2·93	1·95	2·19	2·30	1·12	2·21	2·79	1·76	1·45	2·19
February	1·40	2·01	1·89	1·49	0·69	1·87	0·91	2·30	0·69	2·90
March	3·45	1·23	1·30	2·04	1·30	2·53	1·64	1·58	2·36	0·56
April	2·15	0·99	2·30	1·07	2·71	3·84	2·69	1·09	1·60	0·26
May	2·33	1·79	1·51	1·19	1·87	0·49	1·21	1·22	1·11	1·19
June	1·66	2·19	0·81	2·09	1·80	2·42	0·25	1·90	2·92	2·51
July	3·71	2·35	1·41	1·45	2·20	2·11	1·78	5·11	0·98	1·99
August	1·53	1·52	2·55	2·81	3·07	3·85	3·54	3·35	1·72	2·29
September	2·64	1·26	0·60	0·07	2·00	1·20	1·23	1·18	1·32	2·89
October	1·65	0·37	1·20	2·23	1·58	3·12	1·49	1·44	2·67	3·21
November	4·08	1·24	2·44	2·66	7·44	1·31	2·14	2·29	1·16	1·47
December	2·08	2·51	2·35	4·32	3·14	1·93	2·11	1·60	1·95	1·95
Total	29·61	19·41	20·55	23·72	28·92	26·88	21·78	24·82	19·93	23·41

	1761	1762	1763	1764	1765	1766	1767	1768	1769	1770
January	0·32	2·46	0·29	4·63	2·26	0·12	2·09	1·67	1·70	0·96
February	1·52	1·30	4·74	1·95	1·72	2·27	2·69	2·14	1·71	1·13
March	0·70	2·05	1·38	0·98	3·34	2·31	1·83	0·10	0·84	1·50
April	0·70	0·27	1·16	1·74	2·13	1·32	1·41	3·16	1·41	2·14
May	3·10	0·49	0·98	1·40	1·26	3·26	2·68	1·05	2·09	1·49
June	2·58	1·66	1·27	1·19	0·93	2·79	2·27	4·57	3·35	4·05
July	0·66	0·83	3·06	2·75	0·48	5·27	3·81	2·55	1·81	1·69
August	3·27	3·35	2·16	3·29	1·90	0·86	3·22	3·71	2·21	0·94
September	2·82	1·86	2·30	1·30	1·11	0·44	1·67	5·33	4·70	2·51
October	2·64	5·54	1·61	1·62	4·34	2·23	2·15	3·06	1·17	2·24
November	1·92	1·68	2·90	1·75	2·06	0·99	1·32	2·29	1·54	4·69
December	2·45	0·11	3·98	2·39	0·87	1·63	0·50	2·20	1·94	3·30
Total	22·68	21·60	25·83	24·99	22·40	23·49	25·64	31·83	24·47	26·64

	1771	1772	1773	1774	1775	1776	1777	1778	1779	1780
January	1·79	3·23	1·36	2·72	1·85	2·27+	0·97	2·31	0·25	0·77
February	0·81	3·11	1·42	2·68	2·36	2·27+	1·54	0·70	0·28	0·80
March	0·92	1·90	0·23	2·31	2·12	1·49	1·39	1·43	0·52	1·41
April	0·99	1·91	1·40	1·05	0·88	0·34	1·07	0·83	1·34	2·64
May	1·31	1·51	3·63	2·20	1·04	1·64	5·54	1·17	2·18	1·00
June	2·55	0·67	2·85	1·31	1·36	1·85	3·23	1·38	2·71	0·99
July	1·47	0·73	1·27	2·16	4·86	2·12	3·23	4·81	6·50	1·28
August	4·21	1·94	3·96	3·23	1·11	2·46	0·97	0·14	1·25	0·63
September	1·21	2·39	2·73	3·75	5·49	3·13	0·74	0·75	2·68	3·15
October	3·06	2·36	1·85	1·18	2·34	0·71	3·25	2·77	2·98	3·50
November	0·76	2·75	4·30	1·82	2·57	1·76	1·11	3·70	3·12	2·57
December	2·55	1·05	1·83	1·85	0·71	1·53	0·79	3·00	5·32	0·39
Total	21·63	23·55	26·83	26·26	26·69	22·57	23·83	22·99	29·13	19·13

	1781	1782	1783	1784	1785	1786	1787	1788	1789	1790
January	1·95	2·67	1·51	2·54	1·78	2·48	0·60	0·68	2·41	1·49
February	1·93	0·55	2·98	1·49	1·20	1·08	1·68	2·09	2·51	0·20
March	0·08	2·70	0·93	2·63	0·35	1·11	1·62	0·64	2·32	0·24
April	0·45	2·28	0·59	2·56	0·34	1·22	0·93	0·47	1·24	2·54
May	0·72	4·13	2·36	1·36	0·81	0·97	1·60	0·81	2·80	3·70
June	1·16	0·79	4·00	3·45	2·04	2·24	0·68	1·94	3·66	0·64
July	1·08	6·87	0·78	2·26	1·73	0·86	4·12	1·84	2·77	2·42
August	3·16	4·43+	2·23	2·84	3·05	1·19	0·60	4·30	1·91	2·26
September	1·95	2·28+	4·30	1·65	2·75	2·74+	0·78	3·81	1·87	0·52
October	0·32	2·16+	0·72	0·83	2·02+	2·74+	2·41	0·08	3·54	1·72
November	3·44	1·03	1·63	2·80+	2·02+	2·74+	1·51	0·62	1·24	3·40
December	1·54	0·94	1·22	2·80+	1·53	3·06	3·87	0·00	1·51	3·18
Total	17·78	30·83	23·25	27·21	19·62	22·43	20·40	17·28	27·78	22·31

Appendix I — *continued*

	1791	1792	1793	1794	1795	1796	1797	1798	1799	1800
January	2·91	2·29	1·99	0·51	0·61	2·70	1·22	1·41	1·20	3·11
February	2·29	0·90	2·00	0·82	1·58	1·44	0·28	0·87	2·83	0·33
March	0·92	2·27	1·47	1·37	2·20	0·09	0·99	0·42	0·54	0·39
April	1·57	1·96	1·38	1·77	0·63	0·38	2·35	0·66	2·11	3·66
May	0·76	2·05	1·10	2·80	0·35	2·91	1·82	2·05	2·21	1·38
June	0·60	2·05	0·54	0·49	4·23	0·68	5·34	1·21	0·70	1·27
July	2·67	2·91	2·05	0·65	1·77	2·41	1·63	3·65	3·68	0·00
August	1·26	2·62	1·66	2·04	2·35	0·67	3·53	1·94	2·80	1·86
September	0·27	2·42	3·10	3·81	0·10	1·95	5·14	3·09	3·57	3·43
October	2·33	2·38	1·44	3·59	3·22	2·28	2·53	4·34	2·77	1·63
November	3·44	0·57	2·66	4·23	3·08	1·53	1·86	3·87	2·01	4·81
December	1·44	2·24	2·29	1·29	1·23	1·66	2·04	1·09	0·44	2·11
Total	20·46	24·66	21·68	23·37	21·35	18·70	28·73	24·60	24·86	23·98

	1801	1802	1803	1804	1805	1806	1807	1808	1809	1810
January	1·56	0·19	1·95	2·11	1·91	2·33	0·62	1·34	4·09	0·26
February	0·68	1·90	0·94	1·70	1·33	0·67	1·41	0·90	2·03	1·44
March	1·41	0·51	0·57	1·95	1·11	1·68	0·24	0·21	0·92	2·54
April	0·48	1·25	1·38	2·03	2·00	0·32	0·57	2·09	3·76	1·70
May	1·91	1·52	2·14	1·58	1·08	1·29	3·63	1·42	1·03	1·04
June	1·00	2·35	4·25	0·66	4·19	0·65	1·71	0·81	1·41	0·56
July	4·46	3·57	1·73	4·70	2·75	6·19	0·42	3·11	3·49	3·78
August	1·99	0·66	0·95	3·54	4·47	2·65	2·23	1·53	1·81	2·46
September	1·59	0·85	1·16	0·00	1·94	2·43	2·45	4·78	3·16	1·98
October	1·86	2·08	0·59	2·59	1·75	1·00	0·97	4·05	0·18	1·92
November	4·16	1·28	3·09	5·05	1·00	3·23	3·10	2·21	1·38	6·08
December	3·19	1·52	3·91	0·65	2·28	3·44	0·61	0·92	2·95	2·94
Total	24·29	17·68	22·66	26·56	25·81	25·88	17·96	23·37	26·21	26·70

	1811	1812	1813	1814	1815	1816	1817	1818	1819	1820
January	1·08	1·54	0·40	1·68	0·9	2·1	3·2	1·9	2·3	1·9
February	1·26	3·70	2·42	0·79	1·3	1·6	1·3	2·0	3·0	0·6
March	0·80	2·42	0·62	1·08	2·2	1·9	2·1	3·8	1·8	1·5
April	1·12	1·34	1·44	1·95	2·7	2·1	0·1	3·3	3·1	1·6
May	2·58	2·34	3·16	2·67	2·3	2·2	4·6	2·7	3·3	4·0
June	1·82	2·54	1·12	2·34	1·9	2·4	1·4	0·7	2·5	2·3
July	3·22	2·46	2·82	1·02	1·8	4·3	4·3	0·8	2·2	4·8
August	2·26	1·92	0·88	3·01	1·8	2·5	2·7	0·1	0·4	1·9
September	1·54	0·64	1·04	1·45	1·2	2·1	0·9	4·2	3·4	2·4
October	2·52	3·86	4·74	2·41	2·6	2·8	2·6	2·1	2·3	2·9
November	2·42	2·34	1·10	2·70	1·5	3·0	2·0	2·7	3·0	2·0
December	2·04	0·70	0·72	3·38	2·3	3·1	3·8	1·4	3·8	1·8
Total	22·66	25·80	20·46	24·48	22·5	30·1	29·0	25·7	31·1	27·7

	1821	1822	1823	1824	1825	1826	1827	1828	1829	1830
January	2·4	0·6	1·5	1·0	1·1	0·3	1·2	4·3	0·4	1·7
February	0·0	1·1	3·5	2·5	1·0	1·9	0·7	1·1	1·3	2·5
March	3·9	1·5	1·5	1·9	1·4	1·9	2·6	1·0	0·7	0·3
April	2·0	2·9	2·0	2·1	2·0	1·1	1·3	2·4	4·8	3·2
May	2·4	2·1	0·8	4·2	3·3	2·7	2·6	1·7	0·6	2·2
June	2·4	0·9	1·2	3·8	0·8	1·1	0·7	2·2	1·7	2·6
July	3·1	4·5	3·6	2·0	0·1	2·6	1·4	7·0	4·2	1·9
August	2·1	2·0	3·0	4·4	2·7	1·9	1·2	4·2	4·5	3·9
September	3·7	1·5	1·0	3·5	2·8	3·4	3·9	2·6	3·6	3·5
October	2·6	4·0	4·4	2·6	3·0	1·9	4·4	1·5	1·9	0·8
November	4·7	4·1	1·8	4·3	3·2	2·8	1·3	1·0	1·4	3·4
December	5·2	2·5	2·8	4·0	3·2	1·4	3·6	2·5	0·1	1·2
Total	34·5	27·7	27·1	36·3	24·6	23·0	24·9	31·5	25·2	27·2

	1831	1832	1833	1834	1835	1836	1837	1838	1839	1840
January	1·1	1·3	1·1	3·2	0·7	1·9	2·6	0·9	1·2	2·16
February	3·0	1·6	3·6	0·4	2·6	1·8	1·7	2·0	1·5	1·09
March	2·2	1·4	1·0	0·7	2·5	2·2	0·5	1·0	1·8	0·25
April	3·4	0·4	1·2	0·5	1·2	2·7	1·3	0·5	1·5	0·09
May	1·7	1·5	0·2	1·0	3·0	1·3	1·0	1·5	1·6	1·87
June	2·1	3·3	2·2	1·5	2·4	1·1	1·0	5·1	1·9	1·37
July	3·4	0·7	1·6	5·3	0·3	1·9	1·5	2·0	3·7	1·50
August	2·0	3·4	1·8	3·3	1·2	2·6	4·6	0·9	2·7	0·99
September	2·2	0·4	1·9	0·9	4·2	3·2	1·2	2·9	5·0	2·60
October	5·5	2·5	1·3	0·4	4·2	4·2	2·5	2·0	1·9	1·48
November	2·1	1·6	2·3	1·3	2·2	2·4	1·7	3·2	4·4	2·62
December	2·1	1·2	4·8	1·1	0·4	1·8	1·4	1·8	2·4	0·41
Total	30·8	19·3	23·0	19·6	24·9	27·1	21·0	23·8	29·6	16·43

	1841	1842	1843	1844	1845	1846	1847	1848	1849	1850
January	2·11	1·02	1·35	2·42	2·40	2·82	1·38	1·20	1·50	1·20
February	1·32	1·05	2·39	2·32	0·93	1·47	1·39	2·60	2·30	1·40
March	1·35	1·90	0·51	2·30	1·51	0·88	0·77	3·10	0·60	0·40
April	1·92	0·43	1·72	0·35	0·55	3·05	0·99	3·44	1·98	2·25
May	2·06	2·09	3·75	0·30	2·21	1·50	1·40	0·40	3·70	2·30
June	2·70	0·95	1·30	1·56	1·89	0·50	1·50	3·50	0·30	1·00
July	3·60	2·96	2·42	2·18	1·85	1·50	0·67	1·98	2·90	2·82
August	2·20	1·78	3·62	1·71	3·10	4·00	1·95	4·25	0·45	1·70
September	3·95	3·99	0·46	1·19	2·12	1·79	1·56	2·38	3·25	1·35
October	5·95	1·41	4·25	4·01	1·38	5·13	2·00	3·50	2·70	1·58
November	3·70	4·25	2·30	4·50	2·40	1·52	2·00	1·20	1·50	2·18
December	2·40	0·74	0·40	0·36	2·00	1·13	2·00	2·55	2·40	1·35
Total	33·26	22·57	24·47	23·20	22·34	25·29	17·61	30·10	23·58	19·53

Appendix I — *continued*

	1851	1852	1853	1854	1855	1856	1857	1858	1859	1860
January	2·70	3·60	2·11	1·40	1·47	2·63	2·60	0·75	0·80	1·81
February	1·25	0·90	1·48	1·21	1·00	1·10	0·20	1·70	0·86	1·10
March	4·05	0·17	1·50	0·32	1·98	1·10	0·83	0·80	1·35	1·86
April	2·30	0·49	3·21	0·59	0·09	2·28	1·40	2·25	2·17	1·00
May	0·80	1·90	1·50	3·51	1·80	3·45	0·33	2·00	2·35	3·90
June	1·75	4·60	2·75	0·91	0·85	1·60	2·70	1·20	1·40	5·80
July	4·20	2·25	5·48	1·75	5·25	0·90	1·10	3·00	3·30	2·80
August	2·60	4·35	2·75	2·61	1·40	2·42	2·50	1·50	1·13	3·68
September	0·50	3·80	2·23	0·98	1·95	2·80	3·40	0·86	3·80	3·10
October	2·18	3·75	4·23	2·42	5·20	1·91	4·20	1·44	3·60	1·60
November	0·65	6·00	1·95	1·90	1·50	1·25	1·35	0·50	2·90	2·50
December	0·55	2·20	0·80	1·41	1·10	1·83	0·55	1·70	2·17	2·75
Total	23·53	34·01	29·99	19·01	23·59	23·27	21·16	17·70	25·83	31·90

	1861	1862	1863	1864	1865	1866	1867	1868	1869	1870
January	0·55	1·79	2·71	0·88	3·32	3·68	2·80	3·69	2·92	1·49
February	1·80	0·46	0·50	0·76	1·75	4·03	1·21	1·20	2·34	0·54
March	2·15	3·54	0·70	2·53	0·85	1·63	2·30	1·00	1·41	2·05
April	0·83	2·82	0·45	0·82	0·40	2·44	2·10	1·76	1·01	0·28
May	1·79	2·84	1·25	2·00	4·37	1·94	2·20	1·34	3·43	0·47
June	1·90	1·93	3·91	0·92	2·45	3·64	1·51	0·30	1·15	0·39
July	2·20	1·66	0·88	0·27	2·27	1·62	5·30	0·71	0·55	2·01
August	0·57	3·01	1·82	1·31	3·97	2·42	2·50	2·31	1·21	2·02
September	1·46	1·61	2·95	2·76	0·16	3·90	2·61	1·37	3·08	1·63
October	0·88	4·07	1·82	1·06	5·90	2·09	1·93	2·35	1·77	3·34
November	5·07	1·00	1·59	2·57	2·39	1·48	0·42	1·05	2·38	1·20
December	1·25	1·59	1·08	0·50	0·87	1·85	1·70	4·70	2·77	3·13
Total	20·45	26·32	19·66	16·38	28·70	30·72	26·58	21·78	24·02	18·55

	1871	1872	1873	1874	1875	1876	1877	1878	1879	1880
January	1·76	3·45	2·17	0·98	3·43	0·82	5·02	1·19	2·71	0·44
February	0·97	0·79	1·55	1·11	0·93	1·76	1·75	1·11	4·11	2·19
March	0·99	1·74	1·35	0·43	0·61	2·76	2·20	1·12	0·97	0·69
April	2·83	1·59	0·39	1·27	1·61	2·05	2·70	3·87	3·05	2·01
May	0·81	2·85	1·35	0·60	1·47	0·78	1·75	4·10	3·93	0·29
June	3·20	1·42	2·99	2·54	2·31	1·47	1·63	2·75	3·79	2·13
July	3·31	2·00	2·07	1·26	5·11	0·90	3·21	2·35	4·37	4·84
August	0·96	1·58	2·06	1·29	0·65	1·93	2·83	6·52	5·05	0·69
September	3·91	1·37	2·35	2·80	1·99	2·45	0·70	0·98	2·63	4·43
October	1·31	4·36	2·86	3·73	3·83	1·50	1·99	2·10	0·97	5·95
November	0·49	2·81	1·93	2·17	2·93	2·65	3·43	2·45	0·77	1·79
December	1·10	3·74	0·40	1·51	0·94	5·77	1·35	1·30	0·76	3·29
Total	21·65	27·71	21·46	19·68	25·82	24·85	28·57	29·82	33·11	28·74

	1881	1882	1883	1884	1885	1886	1887	1888	1889	1890
January	1·16	1·28	2·33	2·11	1·38	3·45	1·47	0·86	0·91	2·16
February	2·55	1·32	3·33	1·58	3·01	0·65	0·56	0·90	2·07	0·91
March	1·98	1·23	1·02	1·23	1·47	1·44	1·53	3·06	1·36	1·53
April	0·77	2·59	1·61	1·26	1·78	1·50	1·08	2·21	2·23	1·73
May	1·13	1·31	1·83	0·63	2·90	3·91	1·63	1·13	3·05	1·41
June	1·62	2·03	1·17	2·19	1·85	1·03	1·21	2·35	1·28	3·31
July	1·93	2·21	2·03	2·23	0·47	2·39	0·82	4·43	3·05	4·53
August	4·77	1·13	0·91	0·71	1·09	0·69	2·67	2·97	2·17	1·95
September	2·21	2·36	3·27	1·93	4·33	1·78	2·17	1·44	1·57	0·59
October	2·41	5·79	1·76	1·11	3·86	2·09	1·45	1·33	3·90	1·03
November	2·36	2·35	2·51	1·65	2·95	3·07	3·05	3·88	0·81	1·53
December	2·65	1·98	0·69	2·26	1·16	3·47	1·37	1·39	1·20	0·55
Total	25·53	25·58	22·46	18·92	26·25	25·47	19·02	25·96	23·59	21·23

	1891	1892	1893	1894	1895	1896	1897	1898	1899	1900
January	1·61	0·45	1·31	2·93	1·43	0·59	1·74	0·85	2·39	2·93
February	0·09	1·39	2·60	1·57	0·13	0·27	2·35	1·33	2·02	3·17
March	1·32	1·05	0·42	1·21	1·23	2·88	3·58	1·17	0·56	0·93
April	0·99	1·07	0·10	1·47	1·63	0·58	1·39	1·03	2·37	0·93
May	2·53	1·47	1·40	1·57	0·33	0·19	0·95	2·45	1·47	0·99
June	1·59	2·79	0·86	2·20	0·33	1·63	2·73	1·39	1·35	2·10
July	2·95	2·07	1·81	4·37	4·50	1·29	0·93	0·67	0·87	1·25
August	4·03	3·28	1·60	2·52	2·87	1·58	2·63	1·11	0·45	2·65
September	1·03	3·04	1·10	1·37	1·53	5·36	1·95	0·42	2·11	1·04
October	5·93	3·77	4·11	3·89	2·99	2·39	0·57	3·34	2·03	1·61
November	1·92	2·71	1·83	2·98	3·42	1·09	0·90	2·06	3·98	1·71
December	2·91	1·17	2·34	1·99	1·97	3·11	2·14	2·41	1·25	2·55
Total	26·89	24·26	19·49	28·07	22·37	20·97	21·87	18·22	20·85	21·87

	1901	1902	1903	1904	1905	1906	1907	1908	1909	1910
January	0·85	0·73	2·19	2·37	1·08	3·36	0·68	1·82	0·74	1·68
February	0·89	0·85	0·99	2·24	0·67	1·69	1·15	1·20	0·31	2·76
March	2·02	1·75	2·35	1·28	3·18	1·03	0·89	2·41	2·73	0·96
April	2·11	0·49	1·76	0·94	1·53	0·44	3·14	2·31	1·76	1·06
May	0·45	2·45	3·35	2·65	0·75	1·80	1·68	1·33	1·60	1·84
June	1·29	3·71	7·21	1·10	4·06	2·84	2·81	1·95	3·41	2·66
July	2·09	1·13	4·27	2·03	1·69	1·03	1·80	2·44	2·68	2·49
August	1·87	3·45	3·93	1·66	2·80	0·77	1·79	2·43	1·31	2·79
September	1·52	2·52	3·23	1·69	1·75	1·75	0·53	1·41	2·49	0·45
October	1·89	1·39	5·49	1·63	1·22	3·18	3·65	2·17	3·60	2·17
November	0·47	1·57	1·79	1·74	3·10	3·88	2·08	0·68	0·70	3·11
December	3·24	1·38	1·61	1·86	0·74	1·85	3·61	2·08	2·33	3·53
Total	18·72	21·44	38·17	21·19	22·57	23·62	23·81	22·23	23·66	25·50

Photograph by R. K. Pilsbury

PLATE I—TREE DAMAGED BY LIGHTNING STRIKE AT BRACKNELL

See page 373.

PLATE II—TWO PINE TREES GROWING ABOVE THEIR SURROUNDINGS

(Photographed in 1965)

Photographs by R. K. Pilsbury

PLATE III—PINE TREES AFTER A LIGHTNING STRIKE IN AUGUST 1971

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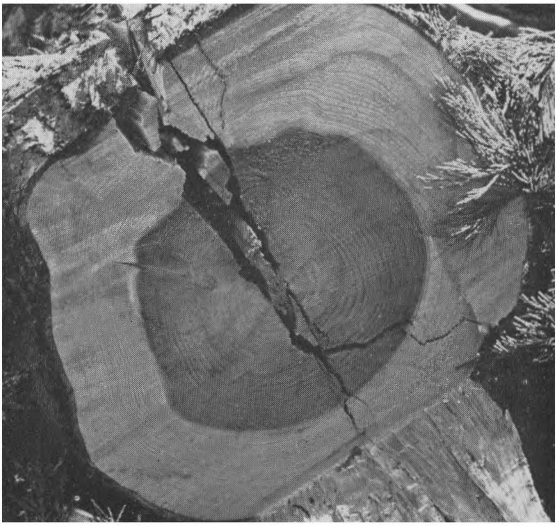
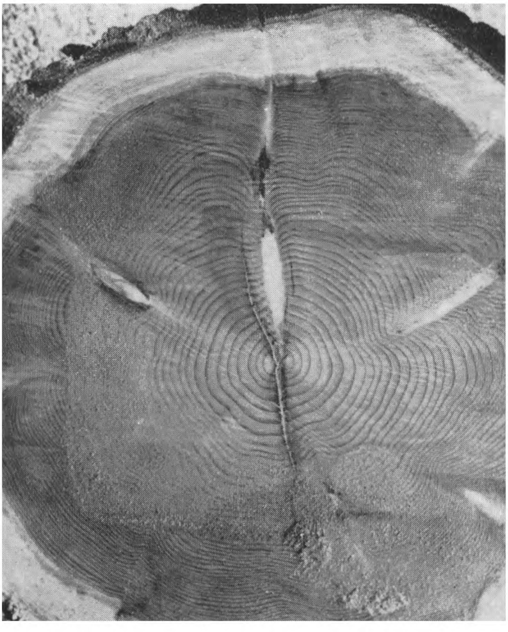


PLATE IV—CROSS-SECTION OF TRUNK AT ABOUT 70 ft



Photographs by R. K. Pilsbury

PLATE V—CROSS-SECTION OF TRUNK AT ABOUT 30 ft

At this point the split was restricted to the centre with some charring. From a count of tree rings the pine was 90–95 years old.

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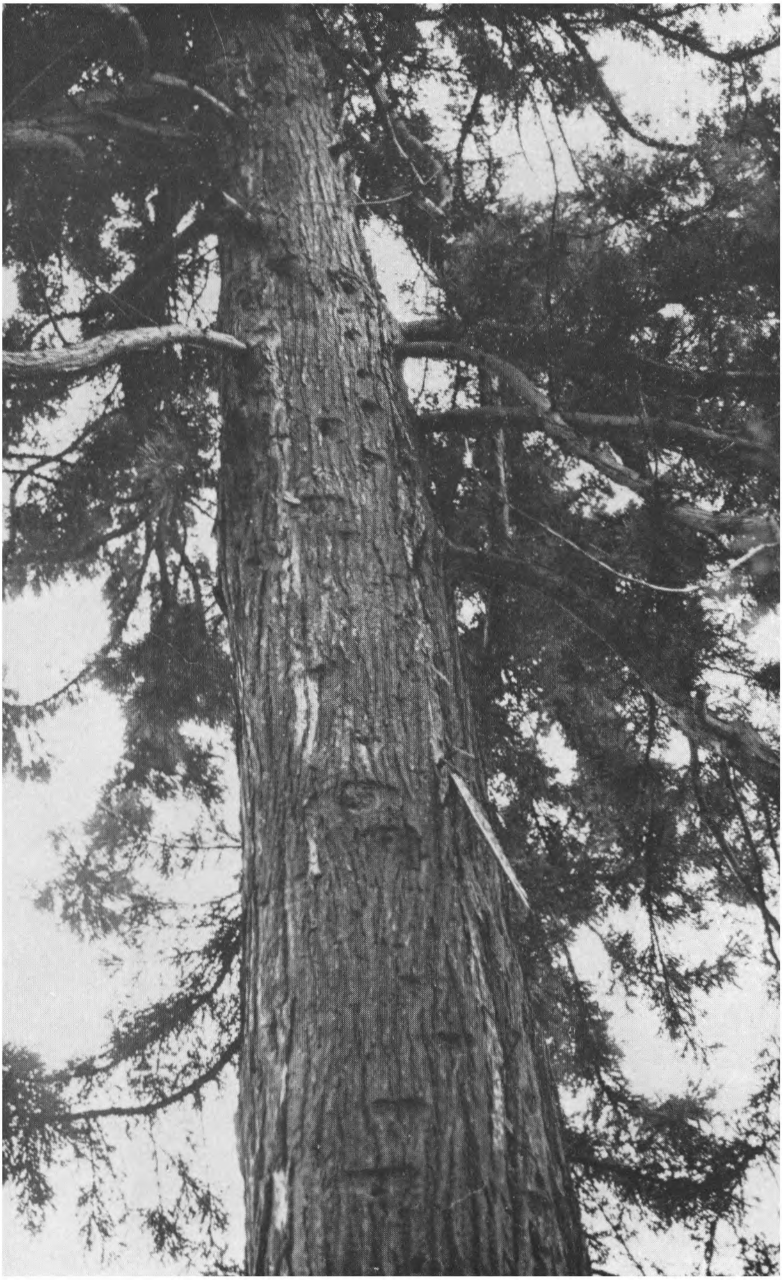

Photograph by R. K. Pilsbury

PLATE VI—BURN MARKS ON SMALLER TREE

There is a vertical burn mark on the right of the trunk with bark hanging loose. It seems that lightning jumped across from a thick branch of the damaged tree alongside.

Appendix I — *continued*

	1911	1912	1913	1914	1915	1916	1917	1918	1919	1920
January	1·19	3·46	2·56	0·55	4·19	1·22	1·13	2·94	3·53	2·17
February	1·31	1·35	0·78	2·43	3·31	3·09	0·79	0·84	2·21	0·41
March	1·31	2·72	2·09	3·94	0·80	3·95	1·74	0·90	3·06	1·17
April	1·88	0·15	2·57	0·87	1·26	1·02	2·15	3·16	2·34	2·67
May	1·55	1·29	1·77	1·75	3·16	1·66	2·04	1·82	0·36	1·51
June	1·98	3·19	0·43	2·29	0·58	2·16	3·71	1·16	1·18	3·07
July	0·83	1·68	1·91	1·93	4·21	1·39	4·50	4·78	2·65	4·40
August	0·81	5·29	1·24	1·76	3·25	3·92	4·18	1·40	2·11	1·49
September	1·36	2·14	1·89	1·00	2·33	1·62	2·06	5·71	1·45	2·45
October	3·00	2·28	3·38	1·19	1·93	3·67	3·41	1·13	0·57	1·68
November	3·40	1·67	2·26	2·98	2·37	3·91	1·32	2·10	1·05	1·32
December	4·45	2·69	0·98	6·56	5·39	2·25	1·18	2·11	3·74	1·94
Total	23·03	27·91	21·85	27·25	32·79	29·87	28·20	28·05	24·27	24·28

	1921	1922	1923	1924	1925	1926	1927	1928	1929	1930
January	2·04	2·23	1·29	2·51	1·76	2·33	1·91	3·10	0·73	2·71
February	0·19	1·87	2·81	0·41	3·20	2·28	3·40	1·40	0·51	0·58
March	1·33	1·69	2·07	0·85	0·44	0·19	2·19	1·73	0·03	1·48
April	1·06	2·60	1·57	3·39	1·98	2·66	1·78	1·41	1·07	1·87
May	0·98	1·02	2·06	2·42	1·91	1·73	1·09	1·76	1·27	3·47
June	0·20	0·98	0·25	3·45	0·04	3·39	2·53	2·24	0·88	1·31
July	0·15	3·30	3·26	3·75	3·93	1·72	3·00	2·06	2·59	1·84
August	0·99	2·07	1·57	2·50	2·58	0·58	4·07	2·59	2·16	2·82
September	1·76	1·56	1·38	2·95	2·50	1·47	4·49	1·03	0·16	2·53
October	0·44	0·75	5·33	3·63	3·07	2·04	1·27	3·63	2·73	1·07
November	1·70	1·42	1·47	2·28	1·48	5·12	2·69	1·81	4·83	3·85
December	1·30	2·83	2·05	2·84	2·67	0·24	3·71	2·35	4·43	1·82
Total	12·14	22·35	25·13	30·99	25·56	23·77	32·12	25·11	21·38	25·35

	1931	1932	1933	1934	1935	1936	1937	1938	1939	1940
January	1·07	1·61	1·34	1·20	0·89	3·91	3·76	2·23	4·31	2·47
February	1·47	0·17	2·65	0·22	2·30	1·61	4·05	0·31	0·80	1·60
March	0·32	1·29	2·17	2·12	0·37	0·90	2·76	0·26	1·00	3·39
April	3·66	2·23	0·66	1·47	2·69	1·68	1·98	0·09	2·21	1·61
May	2·48	4·03	1·83	0·44	1·39	0·51	2·15	1·30	1·39	1·21
June	1·66	0·26	1·93	1·00	3·37	3·53	1·81	0·35	1·15	1·21
July	2·91	2·45	1·74	3·19	1·63	2·35	0·95	1·02	1·79	2·69
August	4·85	1·17	0·50	1·77	1·99	0·48	2·98	2·70	3·43	0·09
September	2·09	2·32	2·72	1·26	2·55	2·81	2·03	1·94	0·91	1·37
October	0·65	5·00	1·44	0·87	1·98	1·79	2·37	2·05	4·91	2·41
November	2·14	1·01	0·94	1·76	4·35	2·79	1·38	2·60	4·43	6·76
December	0·54	0·46	0·32	4·42	2·15	1·38	3·44	3·29	0·84	1·12
Total	23·83	22·00	18·24	19·72	25·67	23·74	29·66	18·15	27·17	25·93

	1941	1942	1943	1944	1945	1946	1947	1948	1949	1950
January	2·46	2·19	4·73	1·55	1·66	1·39	1·35	3·57	1·20	0·87
February	1·93	0·88	1·44	0·67	1·39	2·26	1·19	1·43	0·88	3·16
March	3·21	1·66	0·34	0·09	0·80	1·17	4·66	0·58	0·92	0·65
April	1·72	0·81	0·73	1·31	1·13	1·91	1·68	1·24	1·47	2·44
May	1·87	3·00	1·88	0·69	2·41	3·47	1·35	2·22	2·30	1·72
June	1·93	1·42	1·28	1·51	1·76	2·78	3·17	1·67	0·50	1·85
July	4·06	1·74	1·45	1·67	2·69	3·11	1·41	1·19	1·12	3·15
August	5·89	2·21	1·40	1·97	1·26	3·74	0·40	2·87	1·50	2·33
September	0·35	1·04	2·25	2·23	1·68	3·47	1·17	1·24	0·35	2·45
October	0·76	3·43	2·52	2·71	2·08	1·33	0·15	1·83	5·24	0·57
November	2·53	1·98	1·31	3·42	0·29	4·06	1·07	1·59	2·16	4·11
December	1·56	2·19	1·39	1·19	2·69	1·95	2·14	2·02	1·47	1·58
Total	28·26	22·55	20·72	19·01	19·83	30·61	19·75	21·48	19·11	24·88

	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960
January	3·04	1·82	0·85	0·92	1·92	3·69	1·44	1·91	2·13	1·76
February	4·98	0·80	1·15	1·95	1·16	0·21	3·00	2·29	0·09	1·66
March	2·87	2·73	0·43	1·93	0·91	0·77	1·02	1·02	1·57	1·60
April	2·30	1·18	2·22	0·38	0·32	0·95	0·34	1·28	2·04	0·52
May	2·02	2·37	1·55	1·78	3·72	0·22	1·05	2·28	0·53	1·65
June	0·94	1·72	1·83	4·00	2·18	1·85	0·97	4·13	0·60	1·21
July	1·00	0·53	3·61	2·34	0·40	5·93	3·28	2·48	1·57	3·37
August	3·35	3·50	1·73	3·14	0·71	3·68	3·84	3·41	1·13	1·81
September	2·11	2·58	2·00	1·59	1·77	2·01	2·49	3·96	0·10	3·43
October	0·83	2·69	2·29	1·72	2·37	2·12	1·84	2·04	1·87	5·21
November	5·29	3·50	1·48	3·70	0·91	0·39	2·29	1·89	2·36	3·79
December	1.45	2·36	0·50	1·95	1·77	2·56	1·73	2·97	3·07	1·98
Total	30·17	25·78	19·65	25·41	18·13	24·37	23·29	29·69	17·06	27·97

	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970
January	2·44	2·81	0·83	0·53	1·95	1·24	1·24	2·28	2·55	2·26
February	2·15	0·63	0·26	0·70	0·35	2·70	2·03	0·96	1·55	1·41
March	0·16	1·35	2·30	3·27	1·83	0·43	1·43	0·91	2·19	1·70
April	2·06	1·66	1·60	3·18	1·41	3·62	1·91	2·22	0·60	2·46
May	0·95	1·56	1·85	1·67	1·37	1·91	3·87	2·52	2·09	0·80
June	1·39	0·28	1·92	3·89	1·60	2·61	2·07	2·03	1·04	1·21
July	1·20	2·33	1·29	1·95	2·15	2·74	2·20	2·83	2·95	2·59
August	2·30	2·43	2·20	1·83	2·33	3·05	1·61	3·06	3·68	2·11
September	2·14	2·84	2·34	0·41	4·20	1·09	2·25	4·82	0·11	2·23
October	2·11	2·15	1·50	1·21	0·84	3·93	3·56	2·03	0·16	0·57
November	1·82	1·99	4·50	1·34	2·85	1·31	1·37	1·50	3·17	6·18
December	3·44	2·21	0·67	1·34	3·72	2·93	2·12	2·79	1·64	1·51
Total	22·16	22·23	21·26	21·32	24·60	27·56	25·66	27·95	21·74	25·03

Appendix II

Meteorological Office estimates of general annual rainfall over England and Wales, 1727–1970 (in inches). The estimates were prepared by averaging the annual totals measured at selected stations.

1727	34·5	1780	25·9	1833	36·9	1886	41·2	1939	39·9
1728	38·7	1781	29·0	1834	31·1	1887	26·1	1940	35·6
1729	35·8	1782	40·2	1835	33·9	1888	34·5	1941	33·8
1730	28·9	1783	33·2	1836	39·7	1889	33·0	1942	33·1
1731	22·9	1784	31·5	1837	31·0	1890	31·7	1943	32·8
1732	32·3	1785	30·1	1838	31·4	1891	39·1	1944	35·3
1733	29·3	1786	34·3	1839	40·3	1892	33·1	1945	32·8
1734	40·9	1787	36·8	1840	30·8	1893	29·2	1946	41·6
1735	34·8	1788	23·0	1841	44·2	1894	38·0	1947	32·4
1736	38·7	1789	40·6	1842	33·1	1895	33·8	1948	37·5
1737	33·5	1790	32·7	1843	37·0	1896	32·8	1949	30·9
1738	26·0	1791	37·3	1844	30·5	1897	35·6	1950	40·2
1739	34·5	1792	42·0	1845	34·0	1898	30·6	1951	43·7
1740	28·5	1793	30·7	1846	36·9	1899	33·1	1952	35·5
1741	23·9	1794	35·5	1847	33·6	1900	38·4	1953	29·8
1742	28·0	1795	32·7	1848	44·5	1901	31·1	1954	42·7
1743	24·8	1796	30·3	1849	33·3	1902	29·6	1955	30·9
1744	34·2	1797	38·3	1850	31·4	1903	45·1	1956	34·2
1745	35·7	1798	31·4	1851	30·4	1904	31·4	1957	35·4
1746	31·5	1799	36·8	1852	49·8	1905	30·3	1958	40·5
1747	36·0	1800	32·8	1853	34·4	1906	35·6	1959	31·7
1748	29·7	1801	34·8	1854	27·0	1907	34·9	1960	46·1
1749	30·5	1802	31·2	1855	31·1	1908	32·0	1961	34·4
1750	26·0	1803	29·8	1856	31·9	1909	37·0	1962	31·1
1751	39·1	1804	33·5	1857	33·4	1910	39·8	1963	33·5
1752	32·1	1805	29·1	1858	27·7	1911	33·1	1964	27·8
1753	36·7	1806	37·2	1859	35·4	1912	44·0	1965	39·1
1754	31·6	1807	30·6	1860	42·1	1913	34·5	1966	40·3
1755	33·6	1808	31·9	1861	31·9	1914	38·1	1967	38·7
1756	34·6	1809	33·5	1862	36·4	1915	38·8	1968	38·6
1757	34·5	1810	36·1	1863	32·1	1916	40·1	1969	35·8
1758	34·4	1811	33·5	1864	26·9	1917	34·5	1970	35·9
1759	30·7	1812	35·0	1865	39·0	1918	37·7		
1760	35·7	1813	31·4	1866	39·0	1919	37·0		
1761	33·5	1814	35·6	1867	33·8	1920	38·4		
1762	31·9	1815	33·7	1868	35·7	1921	24·7		
1763	43·0	1816	37·3	1869	35·7	1922	37·1		
1764	37·4	1817	36·0	1870	28·9	1923	39·8		
1765	31·0	1818	34·2	1871	34·0	1924	42·3		
1766	28·8	1819	35·2	1872	50·7	1925	37·3		
1767	34·0	1820	31·2	1873	31·3	1926	35·9		
1768	46·9	1821	39·6	1874	33·3	1927	43·3		
1769	31·0	1822	34·6	1875	40·3	1928	40·4		
1770	37·7	1823	40·2	1876	41·2	1929	35·2		
1771	28·9	1824	41·6	1877	44·6	1930	41·4		
1772	37·9	1825	33·7	1878	38·8	1931	38·4		
1773	38·6	1826	29·0	1879	38·4	1932	36·3		
1774	35·3	1827	36·9	1880	39·7	1933	28·6		
1775	39·2	1828	40·3	1881	38·4	1934	33·5		
1776	33·8	1829	34·1	1882	44·7	1935	39·8		
1777	33·3	1830	36·7	1883	37·7	1936	38·4		
1778	37·0	1831	40·2	1884	31·0	1937	38·8		
1779	33·2	1832	35·2	1885	35·6	1938	34·9		

551.507.362.1:551.510.53:551.524.733

THE STRATOSPHERIC WINTER ANOMALY — A REVIEW OF ROCKETSONDE OBSERVATIONS AT SOUTH UIST (1967–71)

By G. C. BRIDGE

Summary. The British Meteorological Office has been making soundings of the stratosphere over the four winter periods between 1967 and 1971 using the SKUA rocketsonde from a height of 20 km up to 65 km, from South Uist in the Outer Hebrides. Height–time profiles of temperature and zonal wind were drawn from the rocketsonde observations and show clearly the large fluctuations which occurred at this time of year. Warming events occurred towards the end of December each year, with temperature increases over three or four days in excess of 30 degC at 45 km. Complete disruption of flow occurred simultaneously with the warming in three of the four winters investigated. Return to more normal profiles of temperature and wind was achieved by the end of February. Means and standard deviations of temperatures and zonal winds have been calculated together with a comparison with the COSPAR International Reference Atmosphere, 1965, for 60°N.

Vertical motion is considered the prime mechanism for such temperature increases, being produced by developing systems in the northern hemispherical flow which itself adopts an unstable wave number two characteristic at this time of year. External triggering from the troposphere, mesosphere, or by bursts of solar radiation is considered a possible method of initiating the development of such systems.

Introduction. The High Atmosphere Branch of the Meteorological Office has been making regular soundings of the winter stratosphere using the rocketsonde technique, from a height of 65 km down to 20 km, over the past four years, from the Royal Artillery Range at West Geirinish, on the island of South Uist in the Outer Hebrides. These soundings have been made using the SKUA sounding rocket system, which is briefly described, and the information on temperatures and winds so received, is used in preparing height–time profiles. Coded versions of available soundings appear as ROCOB data in the *Daily Aerological Report** and, if used in conjunction with similar data from other locations in the northern hemisphere, chiefly the U.S.A. and Canada, circulation patterns and temperature fields for the stratosphere over the northern hemisphere during the winter months can be constructed.

The SKUA rocket system. The SKUA is a solid-propellant end-burning type of rocket about 2·5 m in length with a detachable booster motor 1 m long. The main motor burns for approximately 33 seconds taking the rocket to around 25 km, then coasts to an apogee of 65 to 85 km depending on the launcher setting and the type of SKUA. At apogee a small charge forces off the nose cone, liberating the sonde and a parachute of 5-m diameter. The latter has metallized panels allowing it to be tracked by radar and hence used as a wind-finding sensor. The sonde, which is essentially a sensitive resistance thermometer with supporting telemetry, transmits in the 27 to 28-MHz range, the signal being detected by standard radiosonde receiving equipment, yielding a graph of temperature against time. Certain corrections[1] have to be applied, chiefly for dynamic and solar radiation heating of the temperature element. Firing at night eliminates the correction for solar radiation heating, the magnitude of which is uncertain because of variations in solar elevation, shadowing effects of the element ring and the periodic swing of the parachute and sonde.

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

The stratospheric circulation. Before presenting the results of the observations from the last four winter campaigns, a brief description of the typical annual stratospheric circulation will help to set the picture.

A large-scale anticyclonic circulation generally concentric with the north pole persists during the summer months throughout the stratosphere, with weakest flow at the equator. Temperature fields at this time of year are also rather weak and likewise tend to be concentric with the pole. Cooling by radiation loss near the pole, which occurs from August onwards, gradually breaks down the anticyclonic flow, so that by the end of the month and at high altitudes, westerlies have become established. These slowly descend through the remainder of the stratosphere, with velocities at all levels increasing to a maximum value by December. These velocities can range from around 25 m/s at 20 km to 150 m/s at 50 km in U.K. latitudes, but fall off rapidly south of about 30°N. A high cell normally appears to the south of the Aleutian Islands tending to elongate and displace the polar vortex towards Eurasia. The high is accompanied by a warming through a deep layer of the stratosphere from eastern Siberia to Alaska. At high altitudes however, the flow usually takes the form of a warm ridge situated several hundreds of kilometres to the west, giving the axis of warming a marked westward tilt in the vertical plane. Warming by descent in the right-hand exit of the westerly jet formed over eastern Siberia and northern Japan is regarded as a possible mechanism for maintaining the Aleutian warm region for most of the winter months. During the middle winter period when westerly flow is at a maximum, disturbances producing sudden warmings, frequently accompanied by disruption of flow, occur in the vicinity of western Europe.

Towards the end of March the pole, which is now receiving solar radiation once again, becomes noticeably warmer, the westerly flow at high latitudes decreases and eventually reverts to anticyclonic flow and this change slowly spreads south to affect most of the northern hemisphere by May.

In the absence of dynamical effects, the temperature structure in the stratosphere is largely the result of a delicate balance between molecular and monatomic oxygen and ozone. Ultra-violet radiation at wavelengths of around 2500 Å is strongly absorbed by ozone converting it to molecular and monatomic oxygen. The ozone mixing ratio increases with height from the tropopause to around 35 km, above which photochemical equilibrium is maintained, largely controlling the temperature at any height, and responsible for the maximum value (approximately 0°C in U.K. latitudes) prevailing at around 50 km, commonly called the stratopause.

Analysis of results. The diagrams in Figure 1 are height–time cross-sections for West Geirinish, over the winter months of the past four years. They are constructed from ROCOB data, the respective dates being marked by a black dot, but over periods of meagre observations, shown by broken lines, trends have been assessed by reference to 50, 30, or 10-mb charts as published by the Free University of Berlin.

Marked variability of stratospheric temperatures over the winter months becomes very obvious. At the start of each cross-section, temperatures of around 0°C frequently occurred in the 50 to 55-km region, as discussed earlier, with a steady decrease in temperature to a minimum of −70°C or lower at around 30 km. The height of maximum temperature appeared to descend

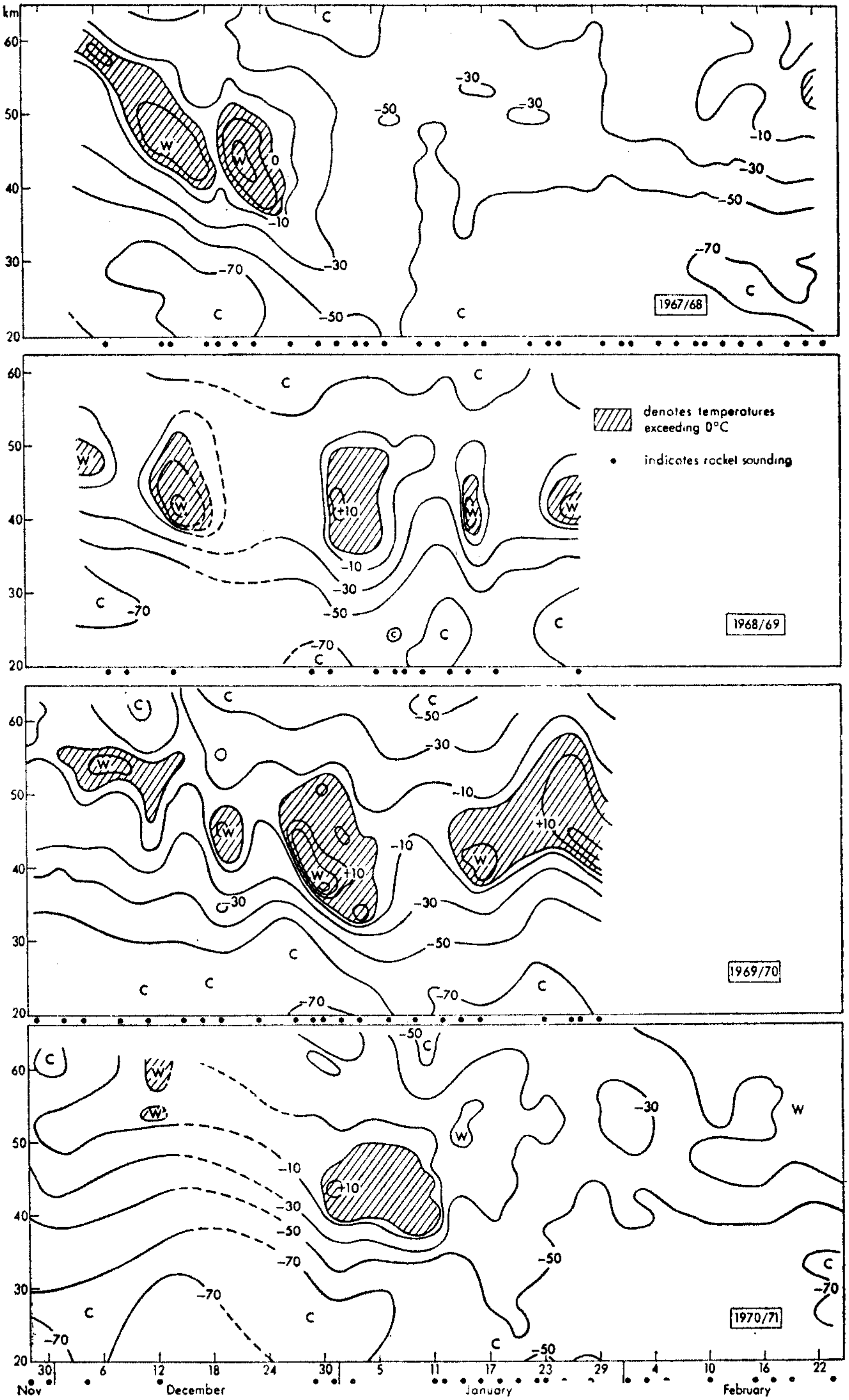

FIGURE 1—HEIGHT–TIME CROSS-SECTIONS OF TEMPERATURE (°C) AT WEST GEIRINISH FOR THE FOUR WINTER CAMPAIGNS BETWEEN 1967 AND 1971

Correction : in 1969/70, late December, the central W isopleth is + 30 not + 50.

in time, until at some point temperature rapidly increased to a value in excess of +10°C, which was then maintained for around three or four days. Cooling then occurred for the ensuing period, again fairly rapidly, as the stratosphere tried to re-establish the original profile, which, although there were further largely minor events, was achieved by the end of February. The winters of 1967–68 and 1970–71 were similar inasmuch as there appeared to be only one major warming event, each during the latter part of December. Following the warming a large portion of the lower stratosphere became near isothermal at temperatures of around −50°C, together with an unusually cold stratopause at around 55 km, then, after a period of about three weeks, a steady return to a more normal profile was observed.

The winters of 1968–69 and 1969–70 however, exhibited a different characteristic inasmuch as there were several bursts of warming, the maximum values of which were similar to other years, but without any major breakdown to follow. The height of maximum warming in all cases shown was around 40–45 km with a very large negative lapse rate of temperature below. The behaviour of the cold regions around 30 km was also similar during the winter from year to year, reaching a minimum of around −75 to −80°C about two days prior to the main warming event. They descended to around 25 km during an event but returned to their original level with a value of −65 to −70°C by the end of February. Further cold zones were found at around 60 km (in fact temperature fell steadily above this height to a minimum of around −90°C at 80 km) about nine days after the maximum warming, although during the winter of 1968–69 the effect was less marked.

Figure 2 shows the zonal wind components over West Geirinish during the last four winters, and large-scale fluctuations are again very much in evidence. It is worth remembering at this stage that these observations are for one location only and therefore no definite synoptic interpretation can be applied to them. The observations appear to sample a region of high winds circulating around the polar vortex, as speeds in excess of 150 m/s were not uncommon—mainly confined to the 50-km region. The winters of 1967–68, 1969–70 and 1970–71 exhibited a similar breakdown in flow pattern around the end of December. Wind velocity increased to a certain maximum value at about the time of the warming, with the increase spreading down through a great depth of the stratosphere, then rapidly decreased over a period of four to six days to around zero or even negative values, again over a similar depth. As the warming diminished, a recovery to the normal zonal flow pattern was achieved, though not without further less-dramatic perturbations. Reversal of flow occurred at high altitudes initially, then gradually spread down to the 25-km level over a period of about 10 days. The cross-section for 1968–69 showed none of the complete flow disruption characteristics of the other years. There may have been some tendency to disruption in early December but this was rather divorced from any warming. Westerly zonal flow persisted throughout the stratosphere fluctuating from around 150 m/s to 50 m/s at 50 km in three rather regular bursts, whilst between 25 and 35 km remarkably constant values were evident.

Cross-sections of meridional flow, not depicted in this note, showed zero or small negative values (i.e. a flow from north to south) below 35 km, but marked fluctuations of both negative and positive values above. Largest values (75 m/s) occurred at the time and level of zonal wind maximum,

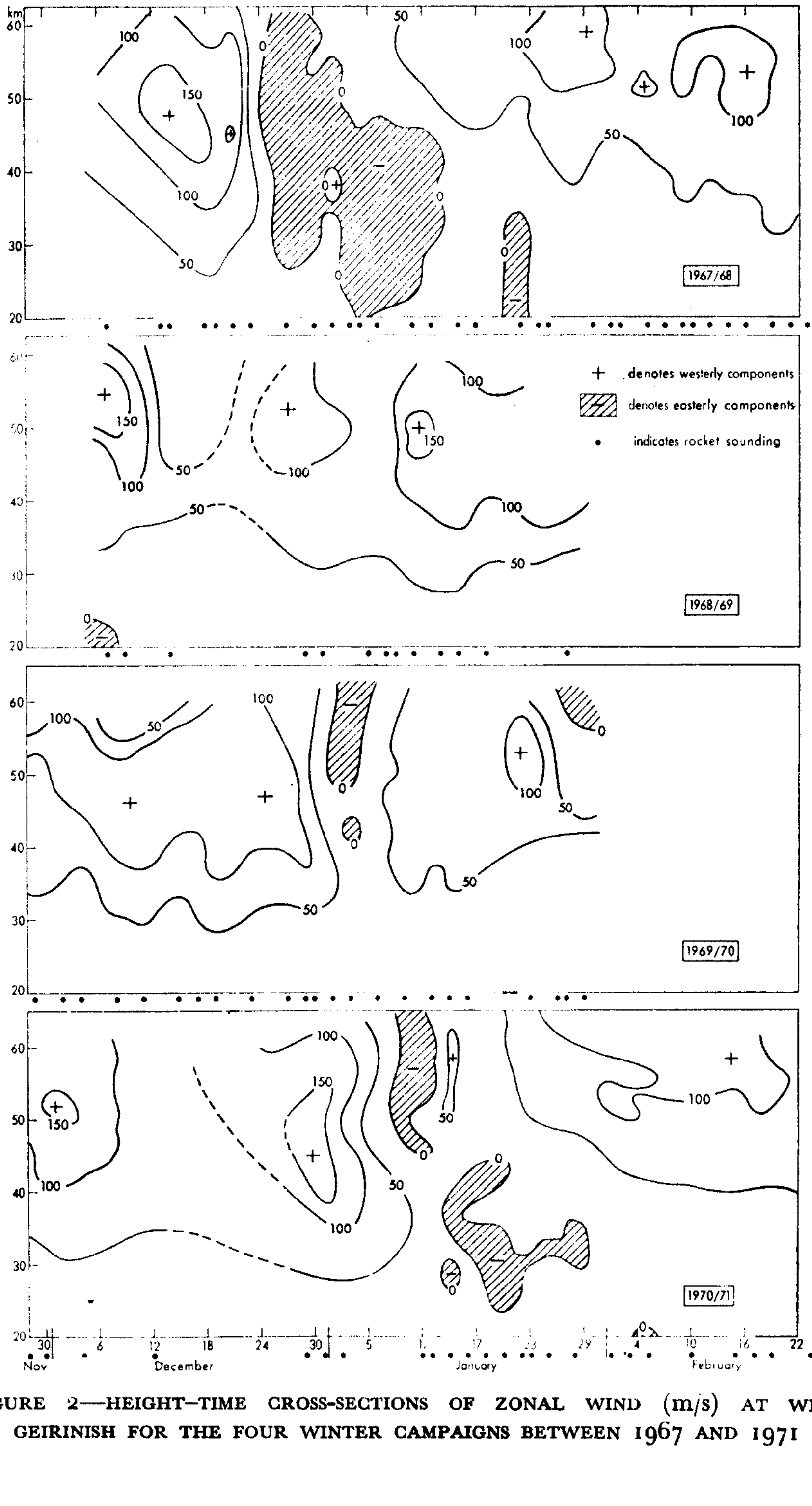

FIGURE 2—HEIGHT–TIME CROSS-SECTIONS OF ZONAL WIND (m/s) AT WEST GEIRINISH FOR THE FOUR WINTER CAMPAIGNS BETWEEN 1967 AND 1971

immediately prior to and slightly above the level of maximum warming. These values were always positive, indicating a backing in the flow preceding the event.

Table I presents mean and standard deviations of temperature and zonal wind at various heights for the three winter months, December, January and February, as well as giving a comparison with the values for 60°N as quoted in the COSPAR International Reference Atmosphere (CIRA) 1965.[2] The very large fluctuations in both temperature and zonal wind which occur in December and January are illustrated clearly by the standard deviations,

TABLE I—SUMMARY OF MONTHLY TEMPERATURES AND ZONAL WINDS AT WEST GEIRINISH FOR THE FOUR WINTER PERIODS 1967–71

Height	*N*	Temperature (degrees Celsius) Mean	*SD*	Coldest	Warmest	CIRA	*N*	Zonal wind (metres/second) Mean	*SD*	Strongest	CIRA
km											
					DECEMBER						
65	8	−27	9	−70	1	−39					
60	23	−22	13	−45	11	−46	13	81	34	117	58
55	26	−13	18	−40	10	−31	23	96	50	184	55
50	27	− 6	23	−23	12	−20	26	105	57	172	51
45	27	− 6	19	−44	29	−28	27	102	51	180	45
40	27	−20	10	−60	25	−42	27	84	41	175	38
35	27	−43	12	−72	− 4	−52	29	62	29	100	28
30	27	−65	14	−85	−27	−57	29	41	18	69	16
25	27	−73	22	−84	−49		29	27	12	38	
					JANUARY						
65	10	−39	11	−57	−23	−40					
60	30	−34	11	−54	− 8	−45	19	49	49	130	52
55	36	−23	14	−44	17	−36	29	60	43	124	40
50	37	−17	18	−47	28	−23	32	60	46	168	30
45	38	−17	23	−49	34	−33	33	49	45	144	23
40	39	−23	24	−58	16	−46	34	38	43	130	18
35	39	−39	19	−68	−22	−54	38	29	32	96	14
30	39	−53	10	−72	−27	−60	39	19	23	64	8
25	39	−62	9	−79	−41		42	15	15	42	
					FEBRUARY						
65	5	−23	10	−33	− 8	−38					
60	18	−19	9	−35	0	−40	10	87	21	131	27
55	22	−15	11	−32	18	−35	22	95	19	124	17
50	23	−18	8	−30	− 2	−23	23	91	10	111	7
45	23	−26	10	−42	− 6	−33	23	71	13	93	− 3
40	23	−45	7	−55	−29	−46	23	50	16	84	− 7
35	23	−61	5	−69	−53	−55	23	32	13	65	− 3
30	23	−67	4	−75	−61	−61	23	24	12	46	7
25	23	−66	5	−73	−57		23	15	10	34	

Note :
Height = height of the observation in kilometres.
N = total number of observations.
SD = standard deviation.
Coldest = coldest value recorded in the month during the four winter periods.
Warmest = warmest value recorded in the month during the four winter periods.
Strongest = highest wind speed recorded in the month during the four winter periods.
CIRA = COSPAR International Reference Atmosphere 1965.[2]

which indicate how little significance can be attached to a mean value during this period, especially in the 40–55-km region. Smaller variation occurs in February as more-normal flow patterns and temperature profiles become established again in the stratosphere. Quite large differences occur between the mean values and those quoted from CIRA. The latter were compiled mainly from data obtained in the U.S. Meteorological Rocket Network and relatively few soundings in other parts of the northern hemisphere. Over the whole period the mean temperatures above 40 km at West Geirinish were significantly higher than CIRA values, this difference occasionally exceeding one standard deviation, especially in December. The effect of the warm Aleutian high on the Canadian stations of Fort Greely, Primrose Lake and Fort Churchill which strongly influence the CIRA values for the latitude of U.K., probably account for the difference in values at 30 km. Large differences also appear in the values for zonal wind, especially in February. Wind reversals in December and January again render the standard deviations so large that a true mean value cannot be assessed. The Canadian observations, which seem to sample a slacker régime than that over West Geirinish in February, are responsible for the differences occurring during that month.

Discussion. There is a difficulty in trying to evaluate whether changes shown by the observations at West Geirinish are purely dynamic, advective or both, but large-scale fluctuations in temperature and wind do exist in the stratosphere during the winter months at latitudes in the vicinity of the U.K. An indicated warming of the higher stratosphere must be regarded as a sample of a large area, frequently centred over north-west Europe, but only detected several days later at 30 km by balloon observations, suggesting a gradual warming downwards through a great depth. Mean temperatures for specific layers of the stratosphere measured by satellite indicate a gradual migration of the warm area north or north-westwards towards the pole, and if, as in the case of the Aleutian warm high, there is a westward tilt with height, some of the downward motion could be attributed to movement towards the tilt.

Since the discovery by Scherhag[3] in 1952, of the stratospheric sudden warming, many such events have been investigated, but their inception is still not understood. Vertical motion has to be regarded as the prime mechanism for such temperature changes (in excess of 30 degC in three or four days), being produced by developing systems within the main flow pattern. By early December the northern hemispherical flow has a wave number one characteristic with the establishment of a high in the area of the Aleutian Islands and the displacement of the polar vortex towards Eurasia. Thereafter the vortex begins to elongate and a wave number two characteristic appears in the flow. Hirota[4] has produced a model which shows that a small disturbance injected into such a flow will rapidly develop until the flow becomes completely distorted and the number two characteristic is destroyed. Whether the injection mechanism is induced from below, that is by tropospheric events permeating through the tropopause and affecting the lower stratosphere, or from above, by disturbances in the mesosphere, is not yet understood. Another theory is that bursts of high energy solar radiation,[5] upsetting the photo-chemical balance of temperature in the upper stratosphere, may well have some influence in initiating a disturbance in a potentially unstable environment.

Detailed analysis of the circulation and temperature structure of the stratosphere can only be achieved from a network of rocket observations around the world. Unfortunately, such observations are very meagre indeed over Europe and Asia, as shown in Figure 3, and as a consequence, an assessment of the state of the stratosphere to any degree of accuracy is not possible in these areas. The advent of satellites measuring mean temperatures of discrete layers of the stratosphere offers some hope of filling gaps in the network, and hence increasing Man's knowledge of a region of the earth's atmosphere still containing many enigmas.

Acknowledgements. The author wishes to acknowledge the continued invaluable assistance of the Commandant, Royal Artillery Range, South Uist.

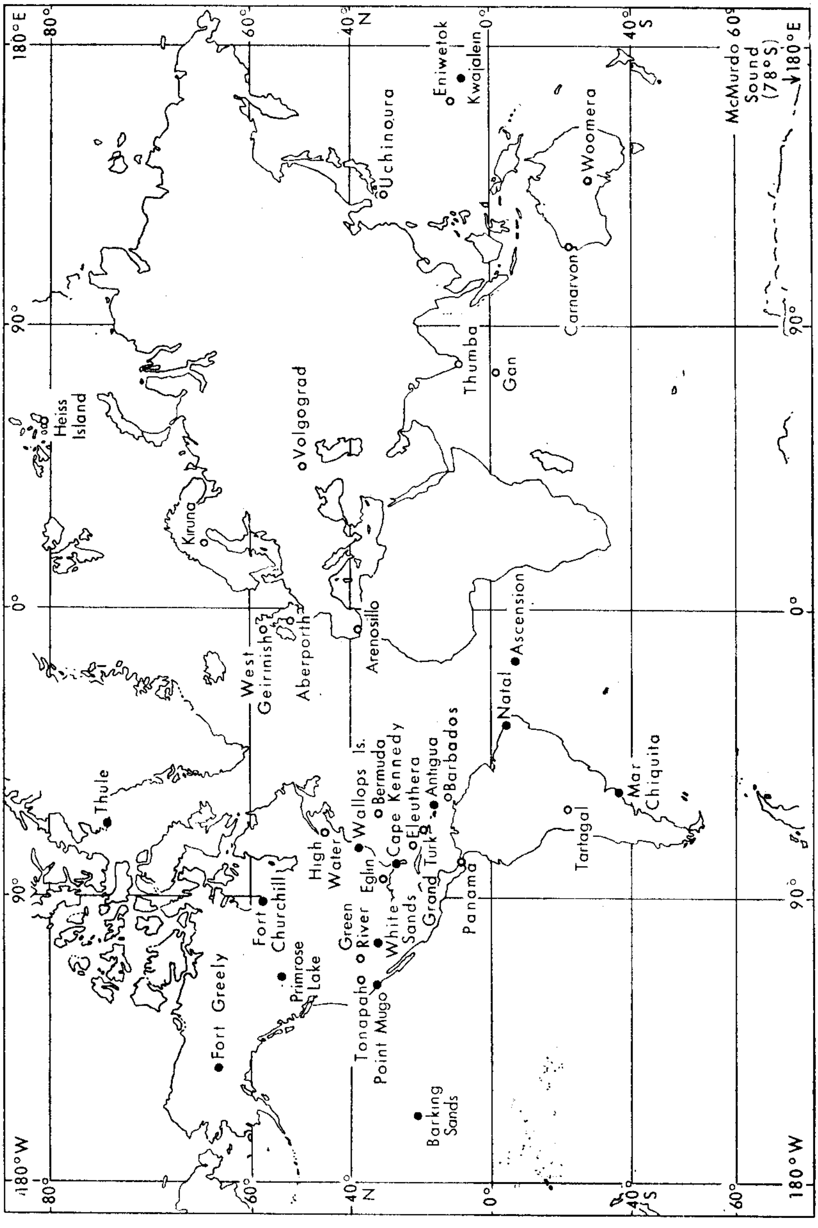

FIGURE 3—METEOROLOGICAL SOUNDING ROCKET STATIONS

● Regular reporting station (throughout the year)

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REVIEWS

Planetary atmospheres, edited by C. Sagan, T. C. Owen and H. J. Smith. 244 mm × 175 mm, pp. xviii + 408, *illus.*, D. Reidel Publishing Company, P.O. Box 17, Dordrecht–Holland, 1971. Price: Dfl.75.

The growing interest in the study of the composition, structure and circulation of planetary atmospheres is a direct consequence of better observations and advances in the theoretical and experimental study of basic chemical, physical and dynamical processes. Until a few years ago only a few astronomers were interested in the subject, but, as with other branches of planetary sciences, the study of planetary atmospheres is now developing links with its Earth Sciences counterpart, in this case meteorology, with benefits all round.

International Astronomical Union Symposium Number 40 was held in Marfa, Texas, in October 1969 on the subject of planetary atmospheres and was attended by more than 100 experts from several countries but mainly from the U.S.A. and U.S.S.R. The book under review is a collection of articles presented at the symposium, the programme of which showed a strong bias towards composition and structure, with comparatively little dynamics. The first and second parts of the book are sections of roughly equal length devoted to Venus and Mars respectively, and the third section, which is less than half the length of the first and second, deals with the outer planets, Jupiter, Saturn and Uranus. The fourth section is a six-page account of the scientific dedication of the 107-inch reflector at the McDonald Observatory.

The lack of coherence in such a wide and complicated subject at its present stage of development is reflected in this book, but some of the articles are valuable for the new observational material they contain. A meteorologist will find much to interest him, especially if he is prepared to brush up his basic chemistry and physics and to reflect a little on the underlying principles of his own field.

R. HIDE

Earthquake displacement fields and the rotation of the Earth, edited by L. Mansinha, D. E. Smylie and A. E. Beck. 244 mm × 170 mm, pp. xi + 308, *illus.*, D. Reidel Publishing Company, P.O. Box 17, Dordrecht–Holland, 1970. Price: Dfl.65.

The geographic positions of the Earth's poles of rotation undergo slight but detectable variations, including the so-called free 'Chandler wobble'. As Lord Kelvin pointed out in the last century, the difference between the observed wobble period of 14 months and the 10-month period of a perfectly rigid spheroid with the same rotation period and shape as the Earth is a measure of the Earth's mean rigidity, which is comparable with that of steel.

Geophysical interest in the Chandler wobble centres nowadays on possible excitation mechanisms. Earthquakes are associated with a redistribution of matter within the Earth and it is an old idea that this redistribution might *inter alia* produce the Chandler wobble. This idea encounters quantitative difficulties, but these were reduced considerably a few years ago when F. Press suggested that the displacement field associated with a major earthquake may extend over much greater distances — thousands of kilometres — than had previously been supposed and L. Mansinha and D. E. Smylie subsequently discovered that very large earthquakes apparently correlate quite well with changes in the centre of polar motion. A consequence of the renewed interest in the idea and in related geophysical problems was the North Atlantic Treaty Organization Study Institute held in June 1969 at the University of Western Ontario, London, Canada, on the subject of earthquake displacement fields and the rotation of the Earth.

The book under review is a collection of articles presented at the conference, the scope of which was rather wider than the title of the book implies. The first article is a brief review of observations of the rotation pole and attempts to explain them. This is followed by two articles on earthquake displacement fields, including both theory and observations. The remainder of the book falls into four main sections, on present day measurement and analysis of rotation and polar motion (seven articles), excitation of the Chandler wobble (eight articles), the observation of deformation fields (eight articles) and precise measurement of the Earth's rotation and polar motion by new methods (two articles).

Most of the articles are valuable up-to-date additions to the geophysical literature and the book contains a short subject index. Doubtless through an oversight, the alphabetical name index excludes about a quarter of the alphabet without discontinuity in pagination.

R. HIDE

Interstellar gas dynamics, edited by H. J. Habing. 244 mm × 175 mm, pp. xxiii + 388, *illus.*, D. Reidel Publishing Company, P.O. Box 17, Dordrecht–Holland, 1970. Price: Dfl.75.

Astrophysicists are interested for a variety of reasons in the dynamical behaviour of interstellar gas, and symposium number 39 of the International Astronomical Union, organized jointly by the IAU and the International Union of Theoretical and Applied Mechanics and held in September 1969 at Yalta in the Crimea, was devoted to the subject. The book under review 'is supposed to [present] what was actually reported and discussed [at the conference, but] in a polished and organised way'.

The book contains the following fifteen invited review papers: 'Review of cosmical gas dynamics' by H. C. van de Hulst; 'Some characteristics of interstellar gas in the Galaxy' by H. F. Weaver; 'Theoretical description of the interstellar medium' by G. B. Field; 'Collective plasma phenomena and their rôle in the dynamics of the interstellar medium' by B. B. Kadomtsev and V. N. Tsytovich; 'Observational aspects of galactic magnetic fields' by G. L. Verschur; 'The origin and dynamical effects of the magnetic fields and cosmic rays in the disk of the Galaxy' by E. N. Parker; 'The gas dynamics of accretion' by E. A. Spiegel; 'Mass balance of interstellar gas and stars' by E. E. Salpeter; 'Supernovae and the interstellar medium' by L. Woltjer; 'The solar wind — an example of a cosmical plasma and a stellar wind' by R. Lüst; 'Mass loss from stars' by S. R. Pottasch; 'Mass loss from eruptive stars' by A. A. Boyarchuk; 'Interstellar gains and spiral structure' by J. M. Greenberg; 'Interstellar molecules' by T. P. Stecher and E. E. Salpeter; and 'Protostars and other neutral condensations in H II regions' by P. G. Mezger. Each one of these review papers led to a lively and extensive discussion at the conference and the reports of these discussions occupy over one-quarter of the whole book.

The organizers of the conference did well in persuading so many leading workers to review their respective fields at the same meeting and the resultant book is consequently an authoritative account of this important if highly specialized subject. This reviewer has often heard astrophysicists working on fluid dynamical problems complain that dynamical meteorologists employ jargon too freely, but the meteorologist will doubtless find terms like 'elephant trunks' (the only item under 'e' in the subject index) singularly unenlightening unless he happens to be familiar with certain characteristic features of the interstellar medium. The specialist, however, for whom this book was produced will find it an indispensable addition to his library.

R. HIDE

LETTER TO THE EDITOR

Lightning strike on a tree near the Meteorological Office, Bracknell

On 19 August 1971 at 1601 GMT lightning struck one of a pair of Wellingtonia pine trees growing in front of Coppid Hall, Warfield Road, Bracknell, about 250 yd north-west of the Meteorological Office Headquarters. The top 30 ft of the tree was shattered into many pieces and the trunk was split for a further 25 ft (Plate I). The damaged tree, the highest in the neighbourhood, was about 15 ft higher than the neighbouring pine tree which is approximately 100 ft high. Plate II shows the trees as they were in 1965 and Plate III shows how the taller tree on the right appeared after the strike. The tree had to be cut down and from cross-sections of the trunk it was found that the damage extended right down to the base. Specimen cross-sections are shown in Plates IV and V.

When I examined the trees on 20 August I noticed that the other pine tree had two lightning scars on the side of the trunk facing the damaged tree stretching from a height of about 40 ft to within 10 ft of the ground (see Plate VI). It would appear that where the branches of the two trees met, just below the break, at least part of the current was transferred from one tree to the other.

The lightning strike was seen by a number of Meteorological Office staff and I quote below the most detailed one, by Mr J. C. McGovern who happened to look up from his desk a few moments before the strike. He was about 245 yd from the tree.

'On 19 August 1971 at 1600 GMT thunderstorms developed along a line from Bracknell to between Wokingham and Yateley. At 1601 GMT a lightning flash, with an earsplitting detonation, discharged from cumulonimbus, base estimated at 3000 ft.

The lightning bolt struck the furthermost of twin, conical pines on the Warfield road. For an interval of a few seconds the whole tree was enclosed in a brilliant, white light with a narrow red streak running earthwards down the trunk. The tree, particularly in the top-most section, began to shake and shiver violently; then, perceptibly, the stronger branches burst apart depositing 6–10 ft (later measured as 30 ft) of the cone on the footpath and roadway.'

At the time of the lightning there was 7/8 cloud coverage — 4/8 cumulus, estimated base 2800 ft and 3/8 cumulonimbus, bases estimated at 3000 ft. Wind conditions at the time were calm. Visibility was 3 miles with slight rain.

Mr P. Wescott was on the roof of the Office, just above Mr McGovern's room and his account is given below.

'I was on the roof, feeling quite safe, as the nearest lightning was probably $\frac{3}{4}$ mile away to the south-west. The storm was moving slowly north-westwards, with the anvil edge overhead. Only a few spots of rain occurred at the Office during the storm. The lightning was exceptional as it must have come either from the anvil or travelled outwards from the storm. The Office seemed completely surrounded by lightning with dozens of "branches" to it, with the main strike seeming to hit the tree, the top of which toppled off, having been split vertically. The thunder was a very loud bang almost instantaneous with the lightning.'

Mrs D. Hanington was only a few yards past the tree, walking northwards on the Warfield Road, when she was aware of a vivid flash over her left shoulder, a tremendous crash and a smell of burning wood. A few moments later the shattered top fell into the road a few feet behind her.

A number of eye witnesses have commented on the width of the flash — 'a fairly broad band and not very jagged' and all agree that there was either no rain or just a few small spots at the time. There are varying reports of the colour of the lightning, a number of witnesses recall it as 'blue' or 'vivid purple-blue' whilst one witness saw a red flash and not the blue colours he had seen in others, but he experienced no dazzle effect or after-image. Mrs Gaines described it as the colour of gold and said the air seemed to sizzle as she stood in Deepfield Road near the old people's bungalows. Mr Folland saw red flames 1–2 ft long licking the base of the decapitated tree head as it began to fall.

The CRDF section at Beaufort Park near Bracknell recorded 14 major lightning flashes in the area between 16 and 17 GMT.

I would suggest that the most interesting feature of this account is the report by Mr McGovern, a trained observer of many years' experience, who saw the tree 'enclosed in a brilliant white light'. I must admit that I wondered whether this was an 'after-image' effect until some weeks later I received *Weather** for September 1971, where there is a remarkable colour photograph

* ORVILLE, R. E.; Close lightning. *Weather, London*, **26**, 1971, pp. 394–395.

of a tree being struck by lightning and encased in a golden light. Possibly most of the witnesses were not actually looking at the tree at the moment of impact but their attention was drawn to it by the flash. Some of course could not see the tree as it was obscured by a neighbouring building.

Meteorological Office, Bracknell

R. K. PILSBURY

OFFICIAL PUBLICATIONS

The following publications have recently been issued :

Handbook of aviation meteorology. Second edition.

The second edition of this handbook in attempting to reflect the rapid progress that has continued in the fields of aviation and meteorology during recent years, enhances, it is hoped, the basic purpose of the book which is to provide aviators, and others interested in aviation, with a comprehensive and up-to-date guide to the branches of meteorology most suited to their interests.

Considerable rewriting has been done on vertical motion in the atmosphere, especially in relation to standing waves; on instability phenomena and precipitation; and on high-altitude flight conditions. Sections are devoted to new trends in instrumentation and to observations from space satellites, and methods of numerical forecasting in the Office are outlined. Examples have been included showing the use of computer forecasts and satellite pictures.

Although some of the original text relating to fundamental physical principles has been little affected except for minor clarifications, there are few sections of the book which remain completely unaltered.

Geophysical Memoirs

No. 114. Circulation patterns at 850, 700, 500 and 200 millibars over the eastern hemisphere from 40°N to 40°S during May and June. By P. B. Wright, B.Sc. and M. W. Stubbs, B.Sc.

This memoir presents a set of wind flow charts and vertical cross-sections to illustrate the circulation patterns of the troposphere over much of the tropics and subtropics during May and June. During this period the development of the Asian summer-monsoon system is associated with rapid changes in the circulation patterns over southern Asia and adjacent parts of the Indian Ocean. It is demonstrated that the changes that occur in the upper troposphere over areas as far apart as Africa and the western Pacific are probably part of the same development but the seasonal changes in the lower troposphere over Africa occur independently. Variations in the development during each of the years 1956–60 are discussed and it is shown that the patterns of May 1956 exhibited unusual behaviour. A biennial oscillation in several features of the circulation is described. Some relationships with changes outside the tropics are discussed.

No. 115. Mean monthly airflow at low levels over the western Indian Ocean. By J. Findlater.

This memoir contains charts of mean monthly airflow at 3000 ft (1 km) and 10 000 ft (3 km) based on data from 72 pilot-balloon and radar-wind stations known to have operated since 1930. Tabulated mean monthly winds are included for the 3000-ft, 5000-ft, 7000-ft and 10 000-ft levels.

The comprehensive network of mean values allowed streamline and isotach analyses to be made of the detailed structure of the major monsoon currents and the zones of light wind which separate them. Of particular interest is the development during the northern summer of a relatively narrow and high-speed current which circulates near the western limit of the Indian Ocean and links major synoptic features in the southern and northern hemispheres. This current crosses the equator as a southerly wind and its structure is illustrated in vertical cross-sections of mean meridional flow along the equator.

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