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## FORECASTING LARGE 24-HOUR RAINFALL TOTALS IN THE DEE AND CLWYD RIVER AUTHORITY AREA FROM MARCH TO AUGUST

By C. A. S. LOWNDES

**Summary.** The synoptic type was noted for some 45 days when the 24-hour rainfall was more than 1·5 inches at any station in the Dee and Clwyd area of Wales during March–August 1911–68. Of the 26 days classed as cyclonic, 15 were associated with thunder; of the 14 days classed as westerly, only one was associated with thunder. A detailed study was made of a selection of stations and criteria were obtained for indicating large rainfall totals. For westerly types the criteria were similar to those previously obtained for the winter half of the year and the criteria were successfully tested on independent data. Criteria were also obtained for the cyclonic types and applied to independent data with limited success.

**Introduction.** An investigation is being undertaken by the Dee and Clwyd River Authority and the Water Resources Board into river regulation and there is therefore a special interest in forecasting rainfall in the drainage area of Lake Bala and the Chester Dee. Figure 1 shows the position of the Dee and Clwyd River Authority Area and includes stations mentioned in this report. In an earlier paper,[1] criteria were obtained for indicating 24-hour rainfall totals of 2 inches or more in the Dee and Clwyd area in the months September to February. For these six months the large rainfall totals were nearly all associated with westerly types as defined by Lamb,[2] in particular with the warm sector of deepening depressions or waves.

The present report is concerned with the forecasting of large 24-hour rainfall totals over the same area for the other six months of the year, March to August. For these months, the synoptic types associated with large rainfall totals were more varied and complex. For this reason, a relatively large number of occasions of heavy rainfall were needed for an adequate study of the synoptic types involved and it was found necessary to reduce the threshold value from 2 in to 1·5 in. As in the previous paper, rainfall amounts are given in inches and heights in feet, although the units now used are millimetres and metres. In the years 1911–68, for the months March–August, the dates of occasions when any station in the Dee and Clwyd area recorded at least 1·5 in of rain were extracted. Only readily available data were used, so that not all occasions were included. The synoptic type was noted for each of the days extracted. Of the 45 days, 26 were classed as cyclonic, 14 as westerly, 2 as easterly, 2 as south-easterly and 1 as north-westerly. Of the 26 days

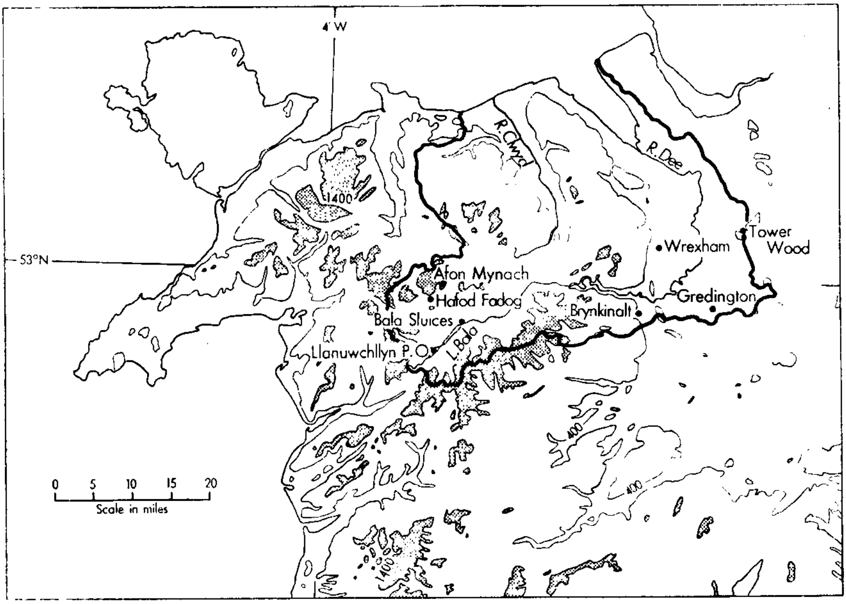


FIGURE 1—THE DEE AND CLWYD RIVER AUTHORITY AREA

The 400-ft contour is shown and areas above 1400 ft are shaded. The boundary of the area is indicated by a thick line.

classed as cyclonic, 15 were associated with reports of thunder. Of the 14 days classified as westerly, only 1 was associated with reports of thunder or observations of atmospherics.

A detailed investigation was made of (i) seven of the westerly situations (numbered from 1 to 7 for convenience in this article), (ii) five of the cyclonic situations associated with thunder, numbered from 8 to 12 and (iii) five of the cyclonic situations not associated with thunder, numbered from 13 to 17. The dates and highest rainfall values were as follows:

(1) 6 June 1948, 1·53 in, (2) 3 April 1949, 1·85 in, (3) 2 April 1962, 3·50 in, (4) 23 August 1962, 1·73 in, (5) 26 August 1962, 1·74 in, (6) 7 July 1964, 2·10 in, (7) 19 March 1968, 3·15 in, (8) 31 May 1924, 5·31 in, (9) 18 July 1926, 2·47 in, (10) 11 August 1948, 1.83 in, (11) 3 July 1957, 1·50 in, (12) 18 July 1964, 1·61 in, (13) 18 August 1956, 2·31 in, (14) 9 March 1963, 1·50 in, (15) 8 May 1965, 2·13 in, (16) 21 June 1965, 1·65 in, (17) 1 April 1966, 2·08 in.

As in the months September to February, nearly all the highest rainfall totals for the westerly occasions were recorded at Afon Mynach (1200 ft), the highest of the stations, indicating the importance of the orographic effect in westerly situations throughout the year. For the cyclonic situations associated with thunder, all but one of the highest rainfall values were recorded at stations at heights between 300 ft and 500 ft, indicating the relative unimportance of the orographic effect. For the cyclonic situations not associated with thunder, all but one of the highest rainfall values were recorded at stations at heights between 570 ft and 1200 ft, suggesting that on most occasions the orographic effect was of some importance. One example of the detailed descriptions of the westerly types, that for occasion (4), is given below.

**Westerly types — the situation on 23 August 1962.** The rainfall for the 24 hours ending 09 GMT on 24 August at some of the stations in the Area was (i) Afon Mynach, 1·73 in, (ii) Llanuwchllyn P.O., 1·35 in, (iii) Hafod Fadog, 1·31 in and (iv) Bala Sluices, 1·06 in.

Figure 2 shows the surface chart for 12 GMT on 22 August when a partly occluded depression (988 mb) was centred south of Greenland. By 06 GMT

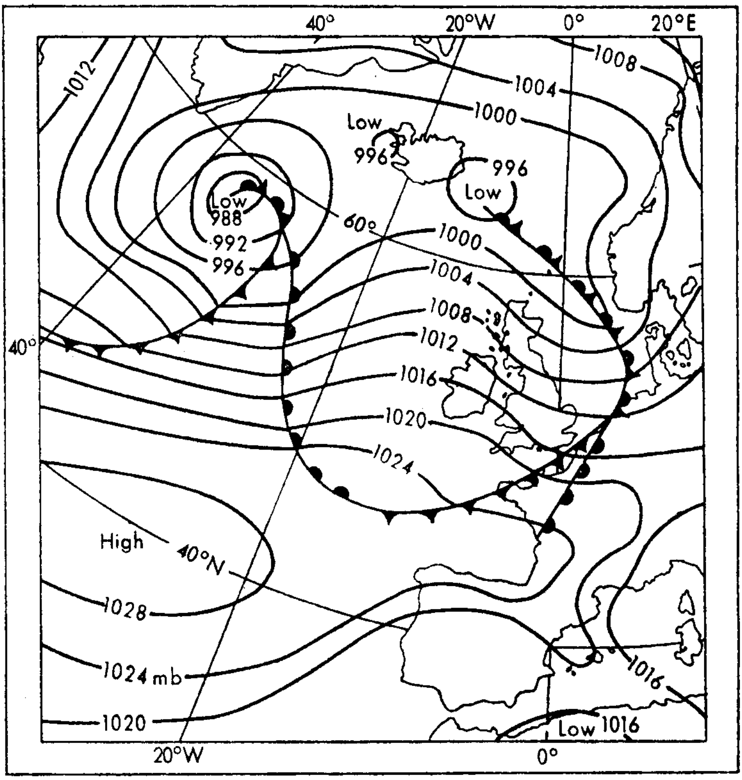


FIGURE 2—SURFACE CHART FOR 12 GMT, 22 AUGUST 1962

on the 23rd (Figure 3) the depression had moved eastwards to a position south of Ireland, having deepened to 984 mb. The associated warm front had reached western Ireland. Continuous slight rain was reported in Ireland by 03 GMT when 3-hour pressure falls of 3–4 mb had occurred over Ireland and falls of 1–2 mb over Wales, ahead of the warm front. Rain began at 09 GMT over north Wales. By 18 GMT (Figure 4) the depression was slow moving to the north-west of the British Isles and had deepened to 980 mb. The point of occlusion had moved eastwards just north of Scotland to the northern North Sea. The warm front now extended over the North Sea and south-east England and the cold front was lying across southern Scotland and southern Ireland, its easterly movement having been delayed by a small wave which moved eastwards across the Atlantic and dispersed to the south-west of Ireland by 16 GMT. Pressure falls of 3 mb were reported over Wales in the warm

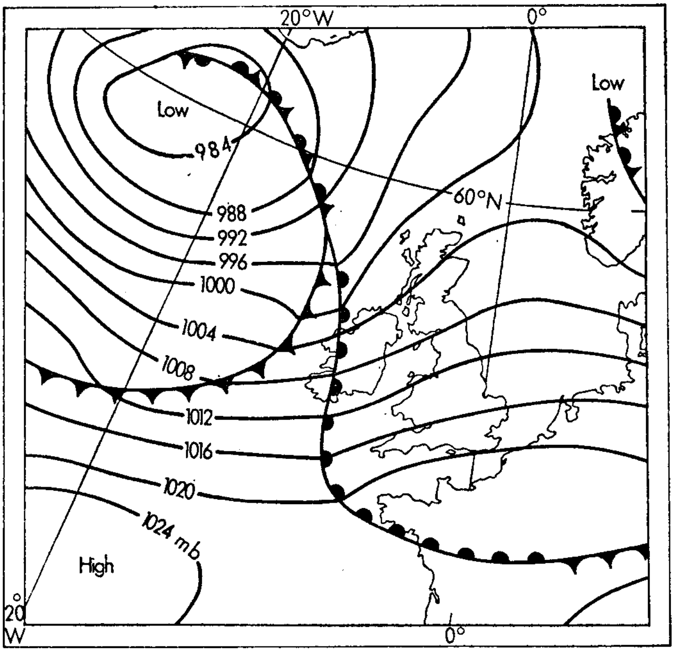


FIGURE 3—SURFACE CHART FOR 06 GMT, 23 AUGUST 1962

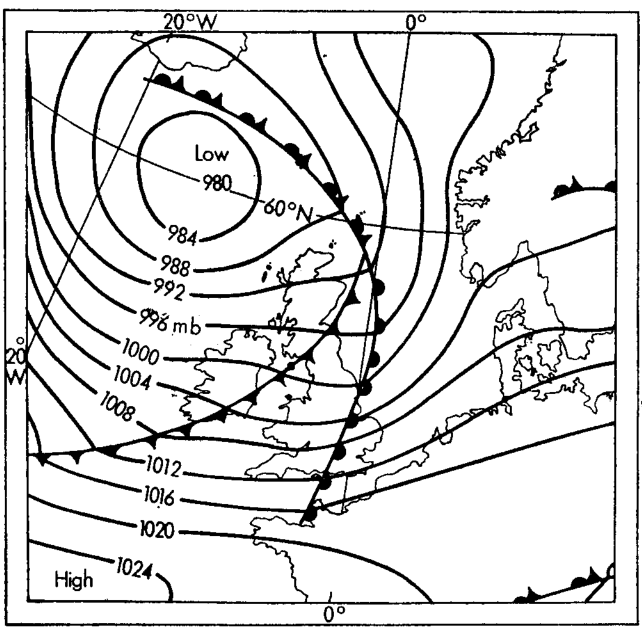


FIGURE 4—SURFACE CHART FOR 18 GMT, 23 AUGUST 1962

sector. The surface geostrophic wind in the warm sector in the vicinity of the Area was 260°/50 kt. The surface dew-point in the warm sector was 4 degF (2 degC) above the normal,[3] i.e. above the average for the time of year. The cold front had moved east of the Area by 21 GMT. For the rest of the rainfall day there were showers and bright intervals over Wales. The depression moved slowly eastwards to a position north of the British Isles by 09 GMT on the 24th and filled slightly from 980 mb at 18 GMT on the 23rd to 982 mb at 09 GMT on the 24th. There were no reports of thunder or observations of atmospherics over the Area during the rainfall day.

The 500-mb chart for 12 GMT on the 23rd (Figure 5) suggested the presence of a west-south-westerly jet stream with its exit over Ireland. The Benwell criteria[4] for heavy rainfall over the Area were not satisfied but it was considered to be a borderline occasion. The Area was situated to the right of the jet exit rather than to the left.

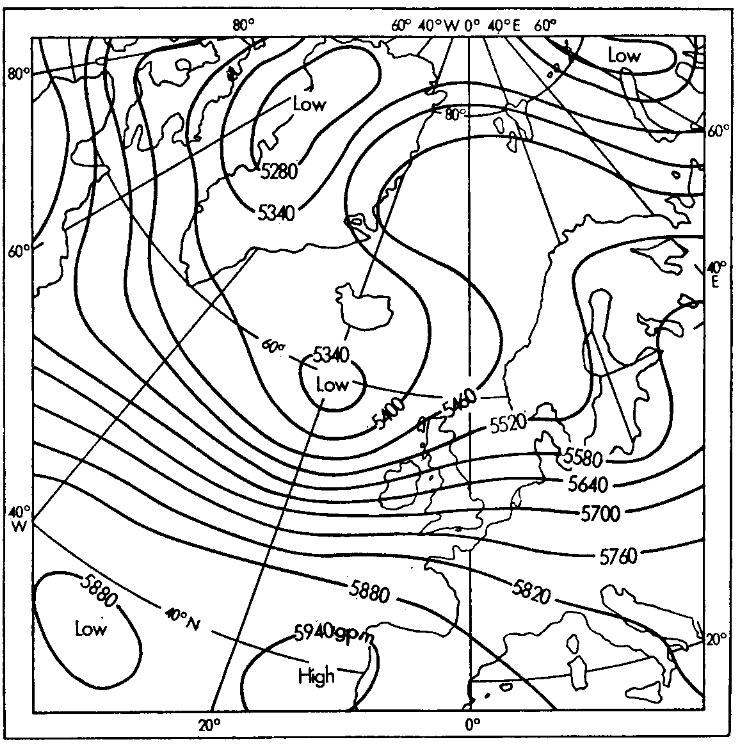


FIGURE 5—500-mb CHART FOR 12 GMT, 23 AUGUST 1962

**Westerly types — the tracks of the depressions.** Figure 6 shows the tracks of the depressions, wave-depressions and waves for occasions (1) to (7) listed in the introduction. The reference numbers of the occasions are used for numbering the tracks. The depressions or waves approached the British Isles from the north-west, west and south-west. In general, they moved north-eastwards across northern England or southern Scotland, or eastwards across northern Scotland or to the north of Scotland. On occasion (3) the rain was partly associated with an occluding depression (3a) and partly with a wave on the cold front (3b). On occasion (7) the rain was partly associated with a wave (7a) and partly with a wave-depression (7b).

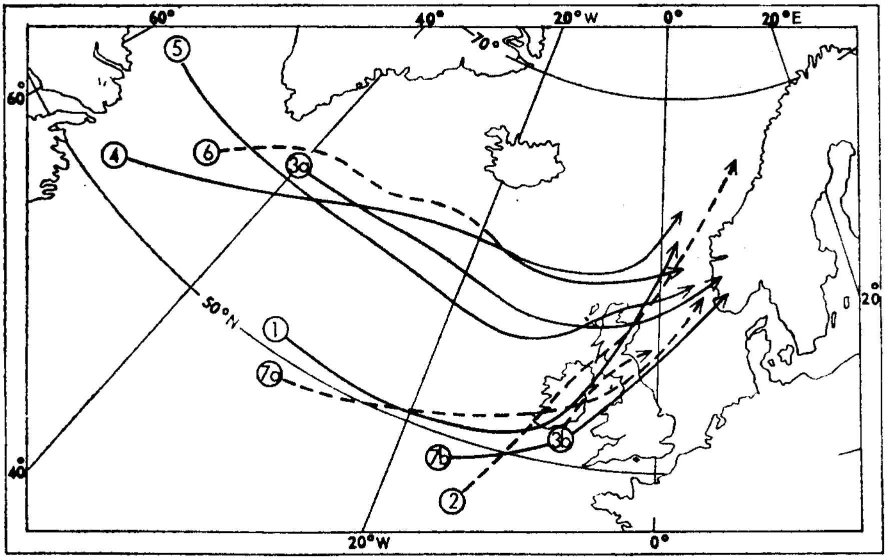


FIGURE 6—WESTERLY TYPES—TRACKS OF DEPRESSIONS AND WAVES

——— Track of depression. – – – Track of wave.

**Westerly types — a summary of the seven occasions.** The seven occasions showed some similarities as follows :

(i) The rainfall was associated on all occasions with a warm sector which moved eastwards across the Area. On occasion (2) the tip of a wave moved north-eastwards across Ireland and Scotland and on occasion (3b) one moved north-eastwards from southern Ireland across southern Scotland. On occasion (7a) the tip of a wave moved north-eastwards across Ireland and northern England. On occasion (1) the tip of a wave-depression moved north-eastwards across Ireland and Scotland and on occasion (7b) one moved north-eastwards from south of Ireland across the north coast of Wales and northern England; there was no occlusion. On occasions (4) and (6) the point of occlusion of a depression moved eastwards just north of Scotland and on occasions (3a) and (5) one moved eastwards across the north of Scotland and across central Scotland respectively.

(ii) With the exception of occasion (3a) the associated depression or wave deepened until 18 GMT on the actual day. On occasion (3a) the depression deepened until 00 GMT on the actual day, then showed no change during the next 24 hours.

(iii) On all occasions the lowest pressure at the centre of the associated depression or at the wave-tip during the rainfall day was between 964 mb and 984 mb.

(iv) With the exception of occasion (7a) there was a maximum 3-hour pressure fall of between 3 mb and 6 mb ahead of the warm front. On occasion (7a) there was a fall of only 2 mb. On all occasions there was a maximum 3-hour pressure fall of between 3 mb and 5 mb in the warm sector.

(v) The surface dew-point in the warm air ranged from the normal to 9 degF (5 degC) above the normal.[3]

(vi) On all occasions the surface geostrophic wind speed in the warm sector was between 40 kt and 70 kt and the direction between 220° and 260°.

With the exception of occasions (4) and (7a) the Benwell criteria[4] for heavy rainfall over the Area were satisfied. Occasions (4) and (7a) were considered to be borderline occasions.

**Westerly types — criteria for indicating 24-hour rainfall totals of 1·5 in or more in the Dee and Clwyd Area in the months March to August.**

(i) A deepening partly occluded depression, wave-depression or wave moves towards the longitude of the British Isles, keeping south of Iceland, from directions between north-west and south-west.

(ii) The point of occlusion or the wave-tip moves eastwards across or north of the British Isles, to the north of Wales and south of the Shetlands, i.e. a warm sector crosses the Area.

(iii) The depression or wave continues to deepen until 18 GMT on the 'rainfall day', i.e. 09 GMT *(d)* to 09 GMT *(d + 1)*.

(iv) The central pressure or the pressure at the wave-tip falls to 984 mb or less during the rainfall day.

(v) There are 3-hour pressure falls of 3 mb or more ahead of the warm front and in the warm sector in the vicinity of the Area.

(vi) The surface dew-point in the warm sector is not below the normal[3] in the vicinity of the Area.

(vii) The surface geostrophic wind speed in the warm sector is 40 kt or more and the direction is from 220° to 260° inclusive in the vicinity of the Area.

The above criteria were satisfied on all occasions except (3a) and (7a). The Benwell criteria[4] for heavy rain over the Area were satisfied on all occasions except (4) and (7a).

**Westerly types — a comparison of the criteria with those obtained for the months September to February.** Criteria (ii) and (v) satisfy the corresponding criteria obtained for the months September to February.

Criterion (i) requires the depressions or waves to approach the British Isles from directions 'between north-west and south-west' compared with 'between north-west and west-south-west'.

Criterion (iii) requires the depression or wave to continue to deepen until 18 GMT compared with midnight on the 'rainfall day'.

Criterion (iv) requires the central pressure to fall to 984 mb or less compared with 988 mb or less.

Criterion (vi) requires the surface dew-point in the warm sector to be normal[3] or above compared with 6 degF (3 degC) or more above the normal.[3]

Criterion (vii) requires the surface geostrophic wind direction in the warm sector to be from 220° to 260° compared with 230° to 280°. The wind speed is required to be 40 kt or more for both periods.

There is little difference between the two sets of criteria with the exception of criterion (vi) in which the large positive anomaly in the surface dew-point required in the winter half of the year is not required in the summer half.

The Benwell criteria[4] for heavy rainfall over the Area were much more successful than in the winter half of the year. However, in both periods, the requirement that the Area should be below the left exit of the jet stream at 500 mb was the subject of rather critical decisions. The relative success of the criteria in the summer half of the year was due to the Area being situated, on average, below the centre of the exit, whereas in the winter half, the Area was situated, on average, below the right exit.

**Westerly types — a test of the criteria on independent data.** A test of the criteria was carried out for days classified as westerly in the months March to August for the five years 1964–68. These periods included two of the seven occasions on which the criteria were based, i.e. 7 July 1964 and 19 March 1968. Excluding these occasions, of the 222 days there were 4 on which the criteria were satisfied.

The dates and highest rainfall values recorded were as follows : (i) 9 April 1965, 1·47 in, (ii) 22 March 1968, 1·95 in, (iii) 23 March 1968, 3·61 in and (iv) 1 April 1968, 1·62 in. All but one of the highest rainfall values were recorded at Afon Mynach (1200 ft) the exception being occasion (i) when 1·47 in was recorded at Llanuwchllyn P.O. (570 ft). All four days were associated with rainfall totals of 1·5 in or more. Of the 216 days when the criteria were not satisfied, there were 2 with rainfall totals of 1·5 in or more, i.e. 26 June 1966 (1·47 in) when a warm-front wave and a shallow wave-depression crossed Scotland, resulting in a very wide warm sector crossing the Area, and 19 August 1968 (2·08 in) when the warm front was associated with thunderstorms.

If the two occasions on which the criteria were partly based were included, the criteria would have indicated six of the eight occasions with totals of 1·5 in or more which actually occurred in westerly situations. No occasions with less than 1·5 in would have been indicated.

The Benwell rules[4] indicated heavy rain over the Area on occasions (i), (iii) and (v) but the requirement that the left exit of the jet stream at 500 mb should be over the Area was the subject of rather critical decisions. On all these three occasions the Area was situated below the centre of the exit rather than below the left exit.

**Westerly types — the result of reducing the number of criteria.** It is obvious that the seven criteria are highly correlated and it might therefore be possible to reduce their number without seriously affecting their success as rainfall indicators. It was found that the number could be reduced to four by excluding (iv), (v) and (vi), resulting in the addition of only one day, 17 June 1965, when the rainfall total was 1·10 in, to the indications.

**Westerly types — conclusions.** About one-third of daily rainfall totals of 1·5 in or more in the Dee and Clwyd River Authority Area were associated in the summer half of the year with westerly types, in particular with the warm sector of deepening depressions or waves. Seven criteria for indicating totals of 1·5 in or more were obtained for the months March to August. In a test on independent data, four out of the six occasions with 1·5 in or more which actually occurred in the westerly situations were indicated. No occasions with less than 1·5 in were indicated. The number of criteria could be reduced to four without seriously affecting their success as rainfall indicators.

**Cyclonic types.** One example of the detailed descriptions of the cyclonic types, that for occasion (12), is given below.

**The situation on 18 July 1964.** The rainfall at some of the stations in the Area for the 24 hours ending 09 GMT on 19 July was (i) Tower Wood, 1·61 in, (ii) Wrexham, 1·58 in, (iii) Brynkinalt, 1·54 in and (iv) Gredington, 1·50 in.

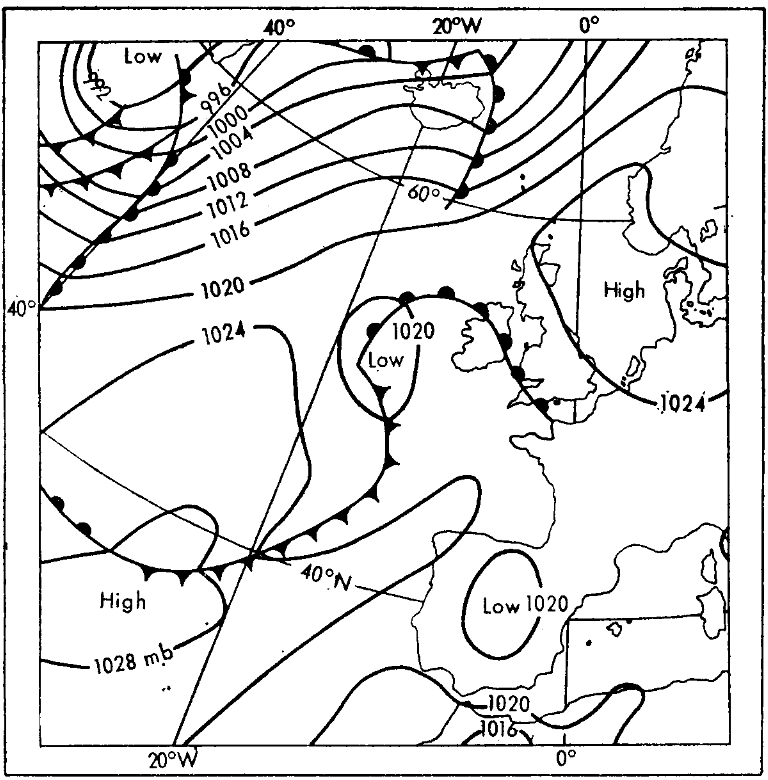


FIGURE 7—SURFACE CHART FOR 12 GMT, 17 JULY 1964

Figure 7 shows the surface chart for 12 GMT on 17 July when a depression (1020 mb) was centred to west of Ireland and an anticyclone (1024 mb) over the North Sea. By 00 GMT on the 18th (Figure 8) the depression had moved eastwards to the South-west Approaches with no change in pressure. The associated cold front was approaching Biscay and Spain. Three-hour pressure falls of 1 mb were reported in south-west England where thunderstorms had occurred. By 12 GMT (Figure 9) the depression was centred over south Wales, having deepened to 1016 mb with the cold front over north-west France and Biscay. Pressure falls of 1–2 mb had occurred over Wales and southern England. Widespread thunderstorms had occurred over Wales

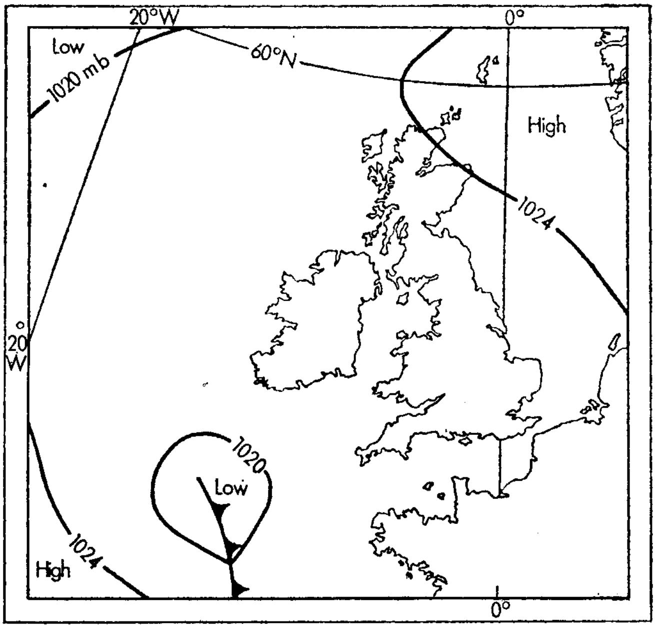


FIGURE 8—SURFACE CHART FOR 00 GMT, 18 JULY 1964

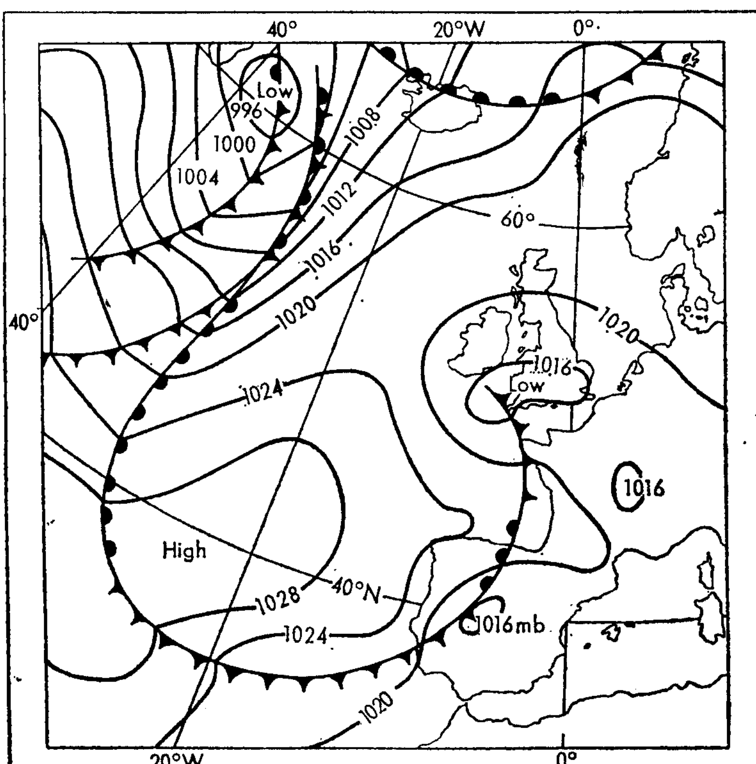


FIGURE 9—SURFACE CHART FOR 12 GMT, 18 JULY 1964

between 03 GMT and 09 GMT and over most of England by 09 GMT. By 00 GMT on the 19th (Figure 10) the depression had moved north-eastwards across Wales to northern England, having further deepened to 1012 mb. The cold front had moved eastwards across southern England to the North Sea. Pressure falls of 2 mb had occurred over Wales where further thunderstorms had been reported. The depression continued to move north-eastwards to the North Sea by 09 GMT, having further deepened to 1010 mb. The surface geostrophic wind over the Area during the rainfall day was light and variable.

The 500-mb chart for 00 GMT on the 19th (Figure 11) showed a large trough over the British Isles with a low over the Irish Sea. The trough moved eastwards across the British Isles whilst the low moved from south-west of Ireland, across Ireland and Wales to eastern Scotland from 12 GMT on the 17th to 12 GMT on the 19th. There were no winds of 70 kt or more in the region of the British Isles. The Benwell criteria[4] for heavy rainfall over the Area were not satisfied.

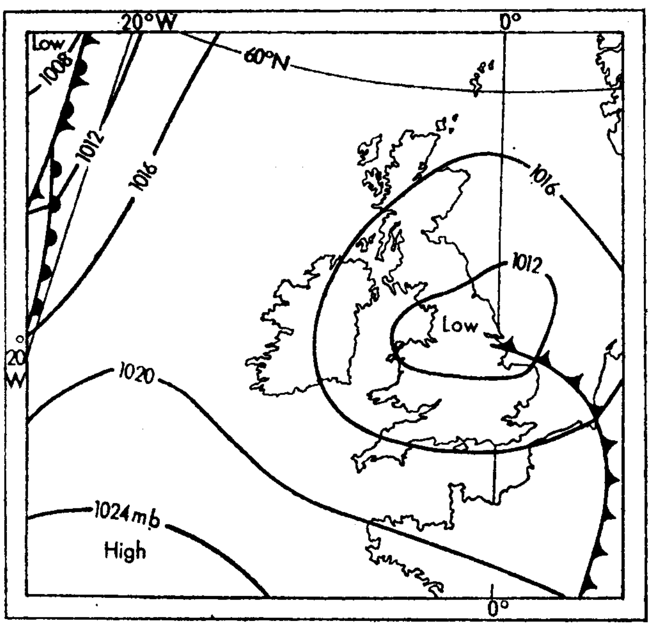


FIGURE 10—SURFACE CHART FOR 00 GMT, 19 JULY 1964

**Cyclonic types associated with thunder — the tracks of the depressions.** Figure 12 shows the tracks of the depressions for occasions (8) to (12) listed in the introduction. The reference numbers of the occasions are used for numbering the tracks. The depressions finally approached the British Isles from the south or south-west and moved northwards, north-eastwards or eastwards across Wales or England.

**Cyclonic types associated with thunder — a summary of the five occasions.**

(i) On occasion (8) a depression moved northwards from France across eastern England, with Wales coming within the cyclonic circulation. It is

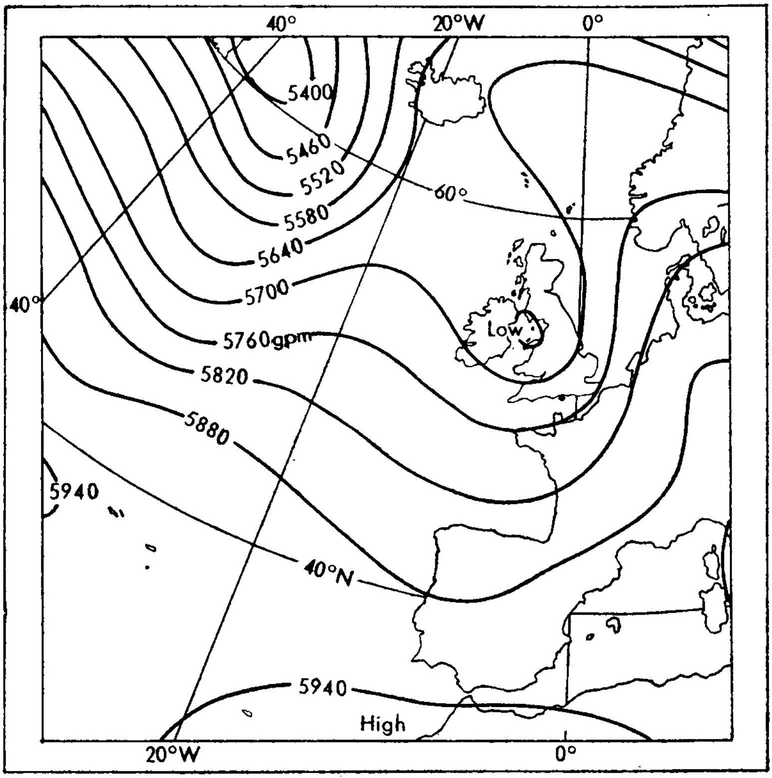


FIGURE 11—500-mb CHART FOR 00 GMT, 19 JULY 1964

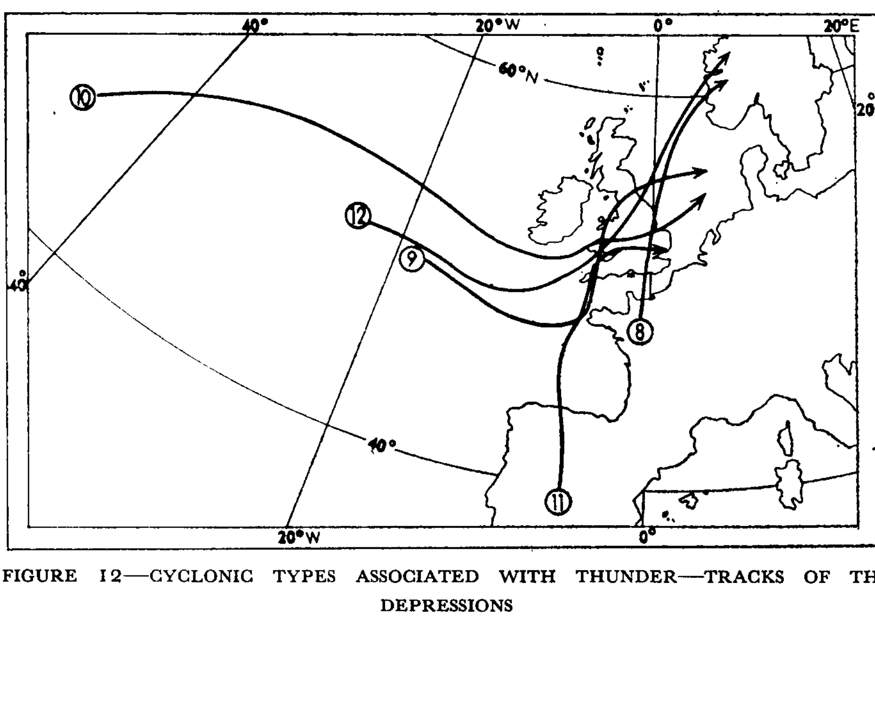


FIGURE 12—CYCLONIC TYPES ASSOCIATED WITH THUNDER—TRACKS OF THE DEPRESSIONS

not known whether any fronts were involved. On occasions (9), (10), (11) and (12) a depression from the south-west or south moved across Wales. On occasion (9) it is not known whether any fronts were involved. On occasions (10), (11) and (12) the depressions were associated with fronts, none of which crossed the Area. On occasion (10) a partly occluded depression crossed south Wales, the occlusion moving across south Wales and southern England and a secondary cold front moving southwards across Ireland and south Wales. On occasion (11) a wave-depression crossed south Wales and on occasion (12) a depression with an associated cold front crossed south Wales. Thus, on at least three of the five occasions, no fronts crossed the Area.

(ii) When approaching the British Isles, the depression deepened on all five occasions but on four of them the deepening was very slight. When crossing the British Isles, the depression deepened on three of the five occasions. On one occasion there was no change in pressure and on one occasion the depression filled.

(iii) The lowest pressure at the centre of the depression during the rainfall day ranged from 999 mb to 1010 mb.

(iv) The maximum 3-hour surface pressure fall over Wales during the rainfall day ranged from 1 mb to 3 mb.

(v) The surface geostrophic wind over the Area during the rainfall day was on all occasions either variable or light and variable.

The Benwell criteria[4] did not indicate heavy rainfall over the Area on occasions (10), (11) and (12) when there were no jet streams at 500 mb in the region of the British Isles. There were no 500-mb data for occasions (8) and (9).

**Cyclonic types not associated with thunder — the tracks of the depressions.** Figure 13 shows the tracks of the depressions and waves for occasions (13) to (17) listed in the introduction. The reference numbers of the occasions are used for numbering the tracks. The depressions approached the British Isles from the south-west or west. On three occasions a depression moved eastwards or north-eastwards across Wales and on one occasion a wave moved eastwards across north Wales. On one occasion a depression moved north-eastwards across eastern Ireland to southern Scotland.

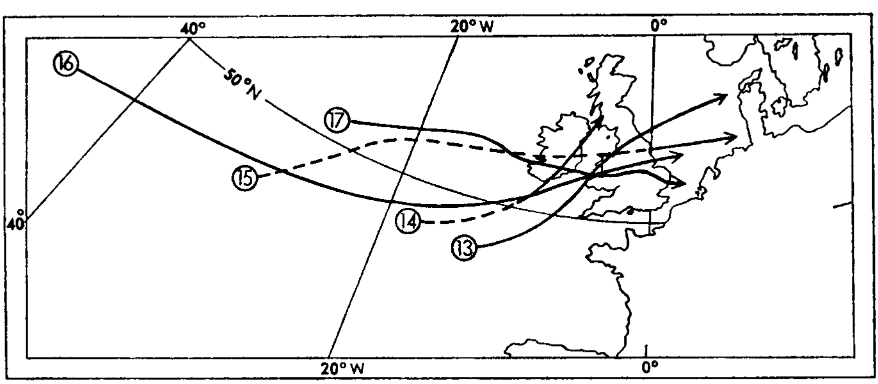


FIGURE 13—CYCLONIC TYPES, NOT ASSOCIATED WITH THUNDER—TRACKS OF DEPRESSIONS AND WAVES

——— Track of depression. - - - - Track of wave.

**Cyclonic types not associated with thunder — a summary of the five occasions.**

(i) On occasion (14) a partly occluded depression moved north-eastwards from south of Ireland across eastern Ireland to Scotland, with Wales coming within the cyclonic circulation. The occlusion moved north-eastwards across Wales. On occasions (13), (15), (16) and (17) a depression or wave moved eastwards or north-eastwards across Wales. On occasion (13) a wave-depression moved north-eastwards across Wales, becoming partly occluded with the occlusion crossing the Area. On occasion (15) a wave moved eastwards across north Wales, the tip of the wave crossing the Area. On occasion (16) a partly occluded depression moved eastwards across Wales but the fronts did not cross the Area. On occasion (17) a partly occluded depression moved eastwards across south Wales. The associated occlusion did not cross the Area but a cold front associated with a polar low to the north of Scotland was quasi-stationary over the Area for most of the rainfall day. Thus, fronts crossed the Area on four of the five days.

(ii) When approaching the British Isles, the depression deepened on three of the five occasions and on one occasion filled very slightly. The wave showed no change in pressure.

When crossing the British Isles, the depression at first deepened then filled on one occasion, filled on two occasions and showed no change on one occasion. The wave deepened.

(iii) The lowest pressure at the centre of the depression or at the wave-tip during the rainfall day ranged from 968 mb to 1002 mb.

(iv) The maximum 3-hour surface pressure fall over Wales during the rainfall day ranged from 3 mb to 6 mb.

(v) The surface geostrophic wind over the Area during the rainfall day was variable or light and variable on four of the five occasions.

The Benwell criteria[4] indicated heavy rainfall over the Area on occasion (15) but the criteria were not satisfied on the other four occasions, mainly because of the absence of jet streams at 500 mb in the region of the British Isles. Occasion (15) when the tip of a wave moved across the Area was on the borderline between the westerly (warm sector) type and the cyclonic type.

**A comparison of the cyclonic types associated with thunder with those not associated with thunder.**

(i) On the thundery occasions, the depression approached the British Isles from the south or south-west and on at least three of the five occasions no fronts crossed the Area. On the non-thundery occasions, the depression approached the British Isles from the south-west or west and on four of the five occasions a front crossed the Area.

(ii) On the thundery and on the other occasions, the depression either deepened or showed only slight changes in central pressure when approaching the British Isles, and deepened, showed little change or filled when crossing the British Isles.

(iii) The thundery depressions were generally less intense than the others, the lowest central pressure averaging 1001 mb for the thundery occasions and 991 mb for the others.

(iv) The thundery depressions were associated with relatively small 3-hour pressure falls over Wales, the maximum 3-hour fall averaging 2 mb for the thundery occasions and 4 mb for the others.

(v) The surface geostrophic wind over the Area was mainly variable or light and variable on thundery and on non-thundery occasions.

(vi) On the thundery and on the other occasions the Benwell criteria[4] for heavy rain over the Area showed little success, mainly because of the absence of jet streams of 70 kt or more at 500 mb in the region of the British Isles. It is interesting to note that the westerly (warm-sector) types were nearly all associated with jet streams of 70 kt or more at 500 mb.

**Cyclonic types — criteria for indicating 24-hour rainfall totals of 1·5 in or more in the Dee and Clwyd Area in the months April* to August.**

(i) A depression finally approaches the British Isles from directions between west (tracking south of 54°N) and south.

(ii) As it approaches the British Isles, the depression deepens or shows only slight changes in central pressure, i.e. it is not obviously filling.

(iii) The depression moves eastwards, north-eastwards or northwards across Wales, or eastwards, north-eastwards or northwards across England, tracking south or east of Wales.

(iv) If the depression does not cross Wales, the cyclonic circulation of the depression extends over Wales.

(v) The central pressure falls to 1010 mb or less during the rainfall day.

**Cyclonic types — a test of the criteria on independent data.** A test of the criteria was carried out for days classified as cyclonic in the months March to August for the five years 1964–68. On many occasions, the rainfall associated with the movement of a depression across the British Isles was spread over two 'rainfall days'. On these occasions, the highest rainfall total at any station over the two rainfall days was obtained, together with the duration of the rain estimated from hourly synoptic charts. On most occasions, the rain over the two days fell in less than 24 hours and was used as the 24-hour rainfall total. On a few occasions, the rainfall fell over a period of more than 24 hours and the two-day total was reduced in proportion to provide an estimated 24-hour total.

It soon became clear that there was no evidence that the criteria would be of use in March and the investigation was restricted to the months April to August.

The test periods included three of the occasions on which the criteria were based, i.e. 18 July 1964, 21 June 1965 and 1 April 1966. Excluding these occasions, of the 145 days there were 10 on which the criteria were satisfied. The dates and highest rainfall values recorded were as follows: (i) 17 May 1965, 1·16 in, (ii) 23 July 1965, 2·55 in, (iii) 31 July–1 August 1966, 1·05 in, (iv) 6 August 1966, 0·18 in, (v) 14–15 May 1967, 1·73 in, (vi) 27–28 May 1967, 1·06 in, (vii) 13 July 1967, 2·50 in, (viii) 1–2 July 1968, 2·59 in, (ix) 14 July 1968, 2·03 in, (x) 16 August 1968, 0·48 in.

* In a test of the rules on independent data it became clear that the criteria would be of no use in March.

Of the 10 occasions, 6 were associated with thunder, i.e. occasions (ii), (vi), (vii), (viii), (ix) and (x). Of the 10 days, 5 were associated with rainfall totals of 1·5 in or more, 3 with 1·0–1·4 in, and 2 were associated with totals of less than 1·0 in. Of the 135 days when the criteria were not satisfied, there were 4 with rainfall totals of 1·5 in or more, i.e. (i) 8 May 1965 (2·13 in) when a wave moved eastwards across north Wales, the wave-tip crossing the Area, (ii) 13 July 1965 (1·65 in) when a wave moved north-eastwards across Wales and later another moved north-eastwards across the Midlands, (iii) 12–13 August 1966 (1·50 in) when a depression moved northwards just west of Wales and (iv) 25 May 1968 (1·94 in) when a thundery trough with an associated occlusion moved north-eastwards across Wales.

If the 3 occasions on which the criteria were partly based were included, the criteria would have indicated 8 of the 12 occasions with totals of 1·5 in or more which actually occurred in cyclonic situations and also 3 occasions with 1·0–1·4 in and 2 occasions with less than 1·0 in.

**Cyclonic types — conclusions.** About one-half of daily rainfall totals of 1·5 in or more in the Dee and Clwyd River Authority Area were associated in the summer half of the year with cyclonic types, of which over one-half were associated with thunder. Five criteria for indicating totals of 1·5 in or more were obtained for the months April–August. In a test on independent data, five out of the nine occasions with 1·5 in or more which actually occurred in the cyclonic situations were indicated, together with three occasions with 1·0–1·4 in and two occasions with less than 1·0 in.

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# AN EMPIRICAL APPROACH TO FORECASTING GRASS MINIMUM TEMPERATURES AND THE PROBABILITY OF GRASS MINIMA BELOW 0°C IN EASTERN ENGLAND

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**Summary.** Depressions of the grass minimum temperature below the air minimum temperature at 10 stations in eastern England were examined for the period 1961–65. Depressions were obtained for various categories of night-time conditions defined according to weather, state of ground, cloud amount and geostrophic wind speed. Various statistical parameters were computed for the depression associated with each category. For 16 of the categories ogives were drawn showing the percentage of occasions when the depression was greater than a specified value. Each ogive was used to estimate the probability of occurrence of a specified depression under the conditions of the category. Finally a table was produced to give, for each specified forecast air minimum, an estimate of the probability of occurrence of a grass minimum below 0°C. The probabilities of various forecast errors in the specified forecast were combined, as necessary, with the probabilities of the depressions required to give a grass minimum below 0°C.

**Purpose of the investigation.** During the period October 1961–September 1965 Tinney and Menmuir collected and analysed detailed observations from 13 stations in eastern England and the Midlands in order to provide data for use in forecasting air minimum temperatures and grass minimum temperatures. They completed the first part of the investigation[1] but circumstances prevented them from investigating grass minimum temperatures. The observations collected by Tinney and Menmuir have been used by the present authors to investigate the depression of the grass minimum temperature below the air minimum temperature at 10 of the stations. The 10 stations are :

| | | | | |
|---|---|---|---|---|
| Wyton | Waddington | Finningley | Marham | Mildenhall |
| Wittering | Cottesmore | Bassingbourn | Lindholme | Scampton. |

Locations and heights above sea level are given in Figure 1 of the paper by Tinney and Menmuir.[1]

There is considerable evidence that the night minimum temperature is generally lower at the tips of long grass than of short grass,[2] as all 10 sites are standard Meteorological Office enclosures in open exposures on airfields with broadly similar routines for cutting the grass, the data are probably as homogeneous as any which are likely to become available. As has been shown by Gloyne[3] and others, minimum temperatures on bare soil and on concrete roads are usually not so low as grass minima.

The investigation had a twofold purpose : to examine the observed depression of the grass minimum temperature below the air minimum temperature at screen level and also to evolve a method of combining the results with the forecast air minimum temperature in order to obtain the probability of a grass minimum below 0°C for a given forecast air temperature.

**Depression of grass minimum temperature below air minimum temperature.** The simplest approach to forecasting the grass minimum temperature would be to average all the depressions of grass minimum temperature below air minimum temperature and to subtract this value from the forecast air minimum temperature, but this would be very rough and ready because of the large scatter of observed depressions about the mean. Better results would be obtained if the observations were separated into various categories distinguished from each other by weather, state of ground, cloud amount and wind speed, and if statistics were compiled for each category. This has been done in Table I and for easy reference each category has been designated by a letter in the right-hand column of the table.

Occasions when a front passed a station during the period between sunset and sunrise were excluded from the analysis for that station and occasions when fog occurred during the night were excluded from all categories except the last.

Wind speeds were expressed in terms of geostrophic wind rather than surface wind because Tinney and Menmuir used geostrophic wind speeds when they assembled the data and Craddock and Pritchard[4] also used geostrophic winds.

The ranges of cloud amount were chosen as follows : 0–2/8 was chosen to include radiation nights, 6/8–8/8 was chosen to include nights which were predominantly overcast and 3/8–5/8 resulted from the choice of the other two; only low and medium cloud were taken into account.

Analysis of variance[5] showed that at the 5 per cent level there was no significant year-to-year variation between the mean depressions at any station, and the average of four years could therefore be regarded as representative in all the categories in Table I.

Although the *t*-test[6] showed that at the 5 per cent level the mean depression within a category at any one station was in most cases significantly different from the mean depression in the same category at another station, it will become evident later in the paper that this makes very little difference in practice and therefore, in order to obtain figures representative of eastern England as a whole, the data from all the stations within each category were treated as a single population.

Category P originally comprised three parts corresponding to three ranges of wind speed, but analysis of variance showed that there was no statistically significant difference between the parts at the 5 per cent level and so they were compounded into a single category.

Category Q consisted of the occasions when rain was falling for a substantial part of the night. This is a rather subjective definition but it gave rise to no difficulties in practice. Analysis of variance showed that all cases of rain falling could be combined, irrespective of wind speed. There were only 46 cases of snow falling during the night and this total is too small for statistical analysis, so it was assumed that, since all the cases of falling rain were from one population, all cases of falling snow would also come from a single population.

Cases of no precipitation but with the ground covered with snow were examined next, and again analysis of variance showed that at the 5 per cent level the variation with geostrophic wind speed is not significant. Nor is there any statistical difference between 0–2/8 and 3/8–5/8, but there is a statistically significant difference between 0–5/8 and 6/8–8/8; this explains the choice of categories S and T.

The final category U comprises only those fogs which formed early in the evening and persisted throughout the night; 21 GMT was taken as an arbitrary criterion for acceptance in this category. No attempt was made to separate these cases according to wind speed and, since the total number in the category was only 74, too few for statistical analysis of individual stations, this category was treated as though it consisted of a homogeneous population.

The results are summarized in Table I which is based on a total number of 6599 cases. As the distributions are not normal, there is no simple way of expressing, in terms of the standard deviation $\sigma$, the percentage of observations lying within various limits on each side of the mean. Percentages on each side of the median can however be easily calculated from the actual tabulations, and the 25 per cent limits and 45 per cent limits on each side of the median are shown in Table I. These correspond to ranges of 50 per cent and 90 per cent respectively.

**Comments on Table I.** Hogg[7] investigated those depressions of the grass minimum temperature below air minimum which produced ground frosts*

* The definition of ground frost changed on 1 January 1961 from a grass minimum reading of '30·4°F or below' to '32°F or below' and on 1 January 1963 to 'below 32°F'.

TABLE I—SUMMARY OF DEPRESSIONS OF GRASS MINIMUM TEMPERATURES BELOW AIR MINIMUM TEMPERATURES FOR 10 STATIONS IN EASTERN ENGLAND (OCTOBER 1961–SEPTEMBER 1965)

| Weather | State of ground | Cloud amount (oktas) | Geostrophic wind speed (knots) | Number of cases | Mean depression | σ | Median | 25 per cent limits (lower) | 25 per cent limits (upper) | 45 per cent limits (lower) | 45 per cent limits (upper) | Category |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | degrees Celsius | | | | | | | |
| No precipitation, No fog, No snow cover, $T_{min} \geqslant 0°C$ | dry | 2 or less | 0–12 | 366 | 3·35 | 1·33 | 2·8 | 2·0 | 4·0 | 1·3 | 4·7 | A |
| | | | 13–24 | 584 | 3·08 | 1·31 | 2·8 | 2·0 | 3·7 | 1·4 | 5·0 | B |
| | | | ⩾25 | 182 | 2·70 | 1·06 | 2·3 | 1·9 | 3·1 | 1·2 | 3·9 | C |
| | moist or wet | 2 or less | 0–12 | 69 | 3·09 | 1·33 | 2·6 | 1·7 | 3·5 | 1·2 | 4·7 | D |
| | | | 13–24 | 380 | 2·63 | 1·15 | 2·5 | 1·7 | 3·4 | 1·4 | 4·3 | E |
| | | | ⩾25 | 370 | 2·43 | 0·87 | 2·2 | 1·7 | 2·9 | 1·3 | 3·3 | F |
| | dry | 3–5 | 0–12 | 228 | 3·26 | 1·13 | 2·9 | 2·1 | 4·2 | 0·9 | 5·3 | G |
| | | | 13–24 | 379 | 2·67 | 1·32 | 2·4 | 1·7 | 3·6 | 1·0 | 5·1 | H |
| | | | ⩾25 | 143 | 2·36 | 1·06 | 2·1 | 1·5 | 3·0 | 0·7 | 4·8 | I |
| | moist or wet | 3–5 | 0–12 | 118 | 2·89 | 1·07 | 3·0 | 1·7 | 3·7 | 1·2 | 4·7 | J |
| | | | 13–24 | 290 | 2·50 | 1·59 | 2·1 | 1·5 | 3·4 | 0·9 | 4·8 | K |
| | | | ⩾25 | 287 | 2·32 | 0·96 | 2·0 | 1·5 | 3·1 | 0·8 | 4·1 | L |
| | dry | 6–8 | 0–12 | 366 | 1·67 | 1·25 | 1·4 | 0·7 | 2·4 | 0·2 | 3·5 | M |
| | | | 13–24 | 544 | 1·52 | 1·12 | 1·2 | 0·6 | 2·1 | 0·2 | 3·0 | N |
| | | | ⩾25 | 214 | 1·37 | 0·87 | 1·1 | 0·7 | 1·8 | 0·3 | 2·5 | O |
| | moist or wet | 6–8 | All wind speeds | 893 | 1·63 | 1·08 | 4·3 | 0·8 | 2·1 | 0·4 | 2·9 | P |
| Rain, No snow cover, $T_{min} \geqslant 0°C$ | moist or wet | 6–8 | All wind speeds | 863 | 0·73 | 0·49 | 0·5 | 0·4 | 1·3 | 0·0 | 3·4 | Q |
| Falling snow | snow-covered | 6–8 | All wind speeds | 46 | 0·57 | 0·18 | 0·5 | 0·4 | 0·8 | 0·0 | 1·5 | R |
| No precipitation, No fog | snow-covered | 0–5 | All wind speeds | 142 | 2·47 | 1·30 | 2·3 | 1·0 | 4·1 | 0·2 | 5·6 | S |
| | | 6–8 | | 61 | 1·47 | 1·29 | 1·2 | 0·4 | 3·0 | 0·1 | 4·7 | T |
| Fog by 21 GMT, $T_{min} \geqslant 0°C$ | no snow cover | Sky obscured | All wind speeds | 74 | 0·42 | 0·24 | 0·2 | 0·0 | 0·6 | 0·0 | 1·6 | U |

on radiation nights at 7 places in south-west England. The basis on which he selected his cases was different from that described in the present paper and therefore a subsidiary investigation was made using data which could be compared with Hogg's. This showed that the mean depression for the 7 places in south-west England on radiation nights with ground frosts was greater by about 1 degC than the corresponding figure for the 10 stations in eastern England. A note of warning must therefore be sounded; Table I applies specifically to eastern England and its use should not be extended to other parts of the country without good reason.

Type of soil, proximity of buildings and lie of the land have all been examined but no systematic explanation has been found for the different depressions at different stations. The correlation coefficient for daily values of the depressions in category A for Lindholme and Finningley, 5 miles apart on flat ground, was 0·7. That for Scampton and Waddington, 9 miles apart on the Lincolnshire Wolds but with the Witham gap between them, was 0·5. The coefficient for Bassingbourn and Wyton, 21 miles apart, was also 0·5, but the coefficient for Mildenhall and Honington, 13 miles apart, was only 0·2. There is therefore no simple way of transferring results obtained at one station to somewhere else in the neighbourhood and, unless actual observations are available from the place in question, the best that can be done is to use mean values for the area.

There is evidence that depressions on radiation nights are larger in spring and summer than in autumn and winter, but the seasonal means are within about 10 per cent of the annual means.

To summarize, tables corresponding to Table I could be constructed for each of the 10 stations but the extreme departure from any one of the means is about 1·5 degC at one station and all the others are within 1 degC. The seasonal variation is at most about 0·3 degC. These figures are within the tolerances acceptable to forecasters. Moreover when the table of probabilities discussed in the next part of this paper was worked out, it was found that these departures from the means made no more than a 5 per cent difference to the probabilities and therefore Table I constitutes a good working guide to the approximate depression of the grass minimum temperature below the air minimum temperature in eastern England.

**The probabilities of grass minima below 0°C occurring with a given forecast night minimum air temperature.** In a previous paper[8] the authors showed that the errors in forecasting night minimum air temperatures by the method of Saunders[9,10] in a year's test with data from 10 stations were normally distributed with a standard deviation of 1·89 degC and a mean of −0·3 degC. The percentage of errors lying within various ranges can therefore be obtained from tables and the results are shown in Table II. Ogives, showing the percentage of occasions in 1961–65 when the depression of the grass minimum temperature below the air minimum temperature was greater than a specified depression, were plotted for categories A–P and one of these ogives (the curve for category A) is shown in Figure 1. If the assumption is made that Table II can be applied to the data of 1961–65 it is possible to combine the information in Table II with the information in each of the ogives in turn to calculate the probability of a grass minimum

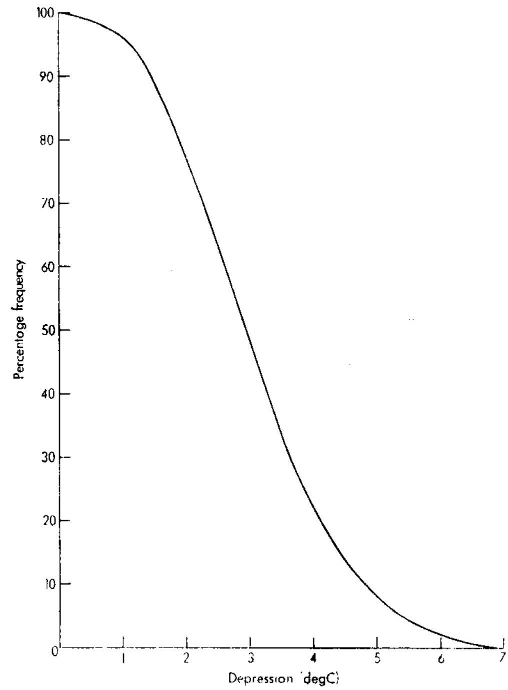


FIGURE 1—OGIVE, FOR CATEGORY A, SHOWING PERCENTAGE OF OCCASIONS WHEN THE DEPRESSION OF THE GRASS MINIMUM TEMPERATURE BELOW THE AIR MINIMUM TEMPERATURE WAS GREATER THAN CERTAIN SPECIFIED VALUES

below 0°C for each category corresponding to a specified forecast air minimum temperature. The method can best be explained by an example taken from category A, so that Figure 1 can be used in the calculations.

Suppose the forecast air minimum to be +2°C and that the forecast is based on the method of Saunders[9,10] as tested by Steele, Stroud and Virgo.[8]

If the assumption is made that Table II (based on average values of mean error and standard deviation) can be applied to a selected sample of forecasts of 2°C, the percentage probability that a forecast of 2°C is correct within ±0·5 degC can be read from Table II as 20·6 per cent. The actual air minimum will be +2°C and thus a depression greater than 2 degC is needed to give a grass minimum below 0°C. The assumption is then made that the average distribution of depressions in the 1961–65 sample can be used to represent the distribution in a selected sample, e.g. the correct forecasts of air minimum of 2°C in category A conditions. From Figure 1 depressions greater than 2 degC occur on 77 per cent of occasions in category A conditions, and thus grass minima below 0°C occur on 77 per cent of the 20·6 per cent of forecasts of 2°C which are correct, i.e. the percentage probability of a grass minimum below 0°C with a forecast air minimum of 2°C is 15·9 per cent if only the correct forecasts are considered.

Now suppose the forecast air minimum to be 1 degC too cold. This happens on 19·6 per cent of occasions (Table II). The actual minimum will be 3°C. A depression greater than 3 degC is needed for a grass minimum below 0°C and from Figure 1 this occurs on 48 per cent of occasions. The

TABLE II—PERCENTAGE PROBABILITY OF ERRORS IN FORECASTING NIGHT MINIMUM AIR TEMPERATURE

| Error | Percentage probability* | Error | Percentage probability* |
|---|---|---|---|
| No error† | 20·6 | | |
| 1 degC too warm‡ | 16·5 | 1 degC too cold | 19·6 |
| 2 degC too warm | 10·0 | 2 degC too cold | 14·1 |
| 3 degC too warm | 4·6 | 3 degC too cold | 7·7 |
| 4 degC too warm | 1·7 | 4 degC too cold | 2·9 |
| 5 degC too warm | 0·5 | 5 degC too cold | 1·7 |
| 6 degC too warm | 0·1 | 6 degC too cold | 0·1 |

* Based on a normal distribution with mean − 0·3 degC and standard deviation 1·89 degC, as obtained in the 1967–68 sample.
† 'No error' is defined as a forecast minimum within ±0·5 degC of an actual minimum.
‡ An error of '1 degC too warm' is defined as a forecast minimum of 0·5 to 1·5 degC warmer than the actual minimum.

percentage probability of a grass minimum below 0°C in this case is therefore 19·6 × 0·48 = 9·4 per cent. The process is repeated degree by degree until the probability of a grass minimum below 0°C is, for all practical purposes, zero. Now consider cases when the forecast air minimum of 2°C is too warm. The forecast will be 1 degC too warm on 16·5 per cent of occasions and on these occasions the actual air temperature will be + 1°C. A depression greater than 1 degC is needed to give a grass minimum below 0°C; from Figure 1 this occurs on 96 per cent of occasions and the probability is 16·5 × 0·96 = 15·8 per cent. When the forecast is 2 degC too warm which occurs on 10·0 per cent of occasions the actual air temperature will be 0°C and all depressions will give a grass minimum below 0°C. The probability in this case is 10·0 × 1·00 = 10 per cent. Similarly when the forecast is 3 degC too warm, which occurs on 4·6 per cent of occasions, and the actual air temperature is − 1°C all depressions give a grass minimum below 0°C and the probability is 4·6 × 1·00 = 4·6 per cent. The process is continued degree by degree until the forecast temperature is 5 degC too warm; thereafter probabilities are too small to be worth considering.

Finally all these separate probabilities are added together to obtain the total probability of a grass minimum below 0°C for a forecast air minimum temperature of 2°C. The same procedure is applied for forecast air minima below 0°C. Consider a forecast air minimum of − 2°C and let the category be A. If the forecast error is in the range 2 degC too cold to 6 degC too warm all depressions give a grass minimum less than 0°C (the probability of an error greater than 6 degC is negligible). The probability for this range is, therefore, (1·7+4·6+10·0+16·5+20·6+19·6+14·1) × 1·00=87·1 per cent.

If the forecast is 3 degC too cold, which happens on 7·7 per cent of occasions, the actual air minimum will be +1°C and depressions greater than 1 degC will give a grass minimum less than 0°C. From Figure 1 depressions greater than 1 degC occur on 96 per cent of occasions and the probability is, therefore,

$$7{\cdot}7\times0{\cdot}96=7{\cdot}39 \text{ per cent.}$$

Similarly the probabilities for forecasts 4, 5 and 6 degC too cold are (2·9×0·77), (1·7×0·48) and (0·1×0·22) per cent making a total probability in the range 3 degC too cold to 6 degC too cold of

$$(7{\cdot}7\times0{\cdot}96)+(2{\cdot}9\times0{\cdot}77)+(1{\cdot}7\times0{\cdot}48)+(0{\cdot}1\times0{\cdot}22)=10{\cdot}46 \text{ per cent.}$$

The total probability of a grass minimum below 0°C in category A when the forecast air minimum is −2°C is

$$87{\cdot}1+10{\cdot}46=97{\cdot}56\approx 98 \text{ per cent.}$$

The results for forecast air minimum temperatures between +8°C and −4°C for the various categories discussed above are given in Table III.

TABLE III—PERCENTAGE PROBABILITY OF A GRASS MINIMUM BELOW 0°C FOR CERTAIN FORECAST NIGHT MINIMUM AIR TEMPERATURES

| Category* | Forecast air minimum (°C) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | +8 | +7 | +6 | +5 | +4 | +3 | +2 | +1 | 0 | −1 | −2 | −3 | −4 |
| | | | | | | | *per cent* | | | | | | |
| A | 1 | 3 | 8 | 16 | 29 | 45 | 62 | 77 | 88 | 95 | 98 | >99 | |
| B | 1 | 3 | 8 | 16 | 29 | 45 | 63 | 77 | 88 | 95 | 98 | >99 | |
| C | <1 | 2 | 5 | 11 | 21 | 37 | 55 | 72 | 86 | 94 | 98 | >99 | |
| D | 1 | 3 | 7 | 14 | 26 | 40 | 57 | 73 | 87 | 94 | 97 | >99 | |
| E | 1 | 2 | 6 | 13 | 24 | 39 | 56 | 73 | 85 | 93 | 97 | >99 | |
| F | <1 | 1 | 3 | 8 | 17 | 32 | 51 | 69 | 84 | 93 | 97 | >99 | |
| G | <1 | 3 | 8 | 15 | 28 | 44 | 61 | 76 | 87 | 94 | 98 | 99 | >99 |
| H | <1 | 2 | 5 | 11 | 21 | 35 | 53 | 70 | 84 | 92 | 97 | 99 | >99 |
| I | <1 | 1 | 4 | 8 | 17 | 31 | 48 | 66 | 81 | 91 | 97 | 99 | >99 |
| J | <1 | 2 | 5 | 12 | 23 | 39 | 57 | 73 | 86 | 94 | 98 | 99 | >99 |
| K | <1 | 1 | 4 | 9 | 19 | 33 | 50 | 67 | 82 | 91 | 97 | 99 | >99 |
| L | <1 | 1 | 3 | 7 | 15 | 29 | 47 | 65 | 81 | 91 | 96 | 99 | >99 |
| M | <1 | 1 | 3 | 6 | 13 | 24 | 38 | 56 | 72 | 85 | 93 | 98 | >99 |
| N | | 1 | 1 | 4 | 10 | 20 | 34 | 52 | 70 | 86 | 93 | 97 | >99 |
| O | | 1 | 1 | 3 | 8 | 17 | 32 | 50 | 69 | 84 | 93 | 97 | >99 |
| P | | 1 | 2 | 4 | 11 | 21 | 34 | 55 | 72 | 86 | 94 | 98 | >99 |

* The categories are here assumed to be defined by forecasts of the various variables including air minimum.

**Comparison with Lawrence's work.** Lawrence[11] investigated the forecasting of grass minimum temperatures under clear skies and light winds. Following Faust[12] he used a quantity $H=T+E/2$, where $T$ and $E$ are the dry-bulb temperature and dew-point at 1500 GMT on the previous afternoon. As this takes no account of the state of the soil, he introduced as an additional variable the number of consecutive preceding days up to a maximum of 10 on which the reported rain was nil or a trace. He tested data for Dunstable and found a standard deviation of 1·70 degC. He also found that he could reduce his standard deviation to 1·65 degC if some allowances were made for soil temperature at 4 inches. Very few stations possess soil thermometers; none exist at any of the 10 stations from which the data used in the present investigation were obtained, and therefore the appropriate figure for a comparison of the two methods is 1·70 degC.

This standard deviation relates to the method alone; errors in forecasting whether the night in question will be a radiation night are not included. Steele, Stroud and Virgo[8] obtained a value of $\sigma_n=1{\cdot}35$ degC for the error inherent in the method for obtaining air minimum temperatures. The standard deviation of the depression of the grass minimum below the air minimum for radiation nights in Table I (categories A and D) is 1·33 degC. These two standard deviations can be compounded; they give 1·89 degC as the standard deviation of the error inherent in the method described in the present paper applied to forecasting of grass minima on radiation nights. This figure is about the same size as that obtained by Lawrence, though not quite as good. On the other hand, radiation nights constitute only a small fraction of the total number of nights included in Table I.

**Discussion.** It is hoped that Table I will serve as a general forecasting guide to the depression of the grass minimum temperature below the air minimum temperature in various circumstances in eastern England. For certain purposes forecasters are asked to state the probability of the occurrence of a grass minimum below 0°C so that the user can weigh the cost of taking precautions against the possible loss which he might suffer if he failed to do so. It is hoped that Table III will be a useful tool for forecasters issuing this kind of forecast in eastern England. The table has been worked out to the nearest 1 per cent. It is unlikely to be used in this form, but any forecaster who wishes to do so can round off the figures to the nearest 10 per cent or any other value which suits his purpose. When this is done, the statistically significant differences between stations mentioned earlier should be of no consequence and the table should be representative of eastern England as a whole.

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# AN INVESTIGATION INTO THE DEPRESSION OF THE GRASS MINIMUM TEMPERATURE BELOW THE AIR MINIMUM TEMPERATURE AT COTTESMORE

By A. G. SILLS

**Summary.** A simple diagram was constructed from data for April 1967 to mid-July 1968 for Cottesmore to assist in forecasting the depression of the grass minimum below air minimum when the cloud amount and geostrophic wind speed over the night are given. The diagram gave successful results with independent data and results compared favourably with those obtained by the method of Steele, Stroud and Virgo.

**Introduction.** In a paper by Steele, Stroud and Virgo[1] depressions of the grass minimum temperature below the air minimum temperature in 1961–65 for 10 stations in eastern England were analysed, the mean depressions being calculated for various categories according to weather, state of ground, cloud cover and geostrophic wind speed. Means for each of the 10 stations were calculated and those for Cottesmore are shown in column *(a)* of Table I. The capital letters in column *(g)* identify the categories used by Steele, Stroud and Virgo. These mean depressions together with forecasts of air minima based on the method of Saunders[2] were used to forecast grass minimum temperatures at Cottesmore during the period of the observations (1961–65). This method produced some poor forecasts in various categories. The purpose of the investigation described in this paper was therefore to find an improved method of forecasting for Cottesmore the grass-minimum depression below air minimum temperature.

**Method.** It was apparent from a superficial analysis of grass minima that cloud and wind were of major importance. A scatter diagram was therefore plotted, with the 1800–0900 GMT mean low-cloud amount and mean geostrophic wind as variables, using data for the period April 1967 to mid-July 1968. Only low cloud, base 8000 ft or less, was considered and sky obscured was counted as 8/8. Best-fit isopleths of grass-minimum depression below air minimum were drawn and Figure 1 was produced.

The main features of the diagram are :

(i) the insignificance of geostrophic wind with 8/8 cloud;
(ii) the increase in the depression when cloud is broken, i.e. 7/8 or less;
(iii) the importance of geostrophic wind with little or no cloud.

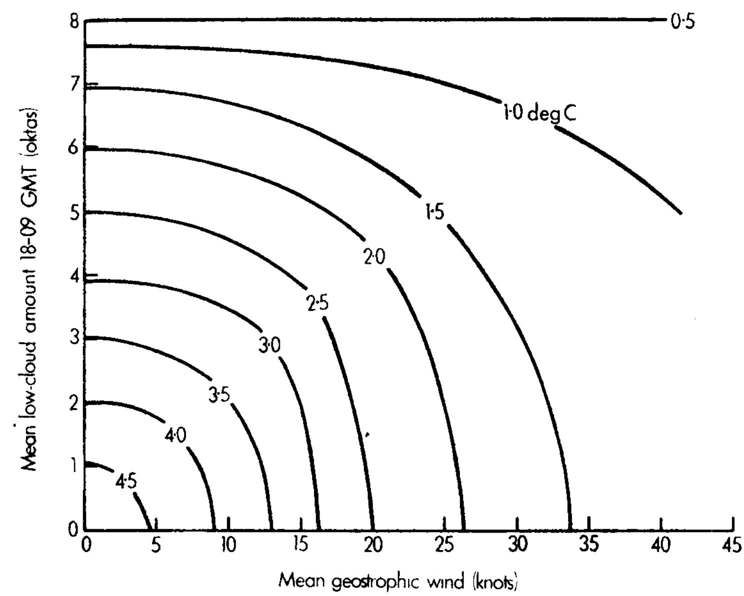


FIGURE 1—ISOPLETHS OF GRASS MINIMUM DEPRESSION BELOW AIR MINIMUM TEMPERATURE AT COTTESMORE

**Tests of the method.** To assess the errors inherent in the diagram method, actual observations were used to derive depressions from the diagram for each of the categories for which there were observations, and these depressions were checked against actual depressions. There were 262 grass minima available in the period covered by the diagram (April 1967 to mid-July 1968) but only 184 fitted into the categories A to Q defined by Steele, Stroud and Virgo. Mean errors and root-mean-square errors are listed in Table I.

For comparison the 'Cottesmore mean' depressions calculated for each category in 1961–65 are also listed in Table I along with the corresponding mean errors and root-mean-square errors obtained when checking the 'Cottesmore mean' against actual depressions in the 1967–68 period. In Table I the 'Cottesmore mean' method is checked against independent data whilst the diagram method is checked on dependent data. The diagram method shows smaller mean errors in 8 out of 12 categories and also smaller root-mean-square errors in 8 categories and in the sample taken as a whole.

TABLE I—COMPARISON OF ERRORS BETWEEN ACTUAL GRASS MINIMUM DEPRESSIONS AND THOSE DERIVED FROM THE 'COTTESMORE MEAN' AND THE COTTESMORE DIAGRAM

| 'Cottesmore mean' depression | Number of cases | Using 'Cottesmore mean' Mean error | Using 'Cottesmore mean' Root-mean-square error | Using Cottesmore diagram Mean error | Using Cottesmore diagram Root-mean-square error | Category |
|---|---|---|---|---|---|---|
| *(a)* | *(b)* | *(c)* | *(d)* | *(e)* | *(f)* | *(g)* |
| *degC* | | | *degrees Celsius* | | | |
| 3·01 | 11 | −0·15 | 0·78 | +0·34 | 0·80 | A |
| 2·98 | 7 | +1·04 | 1·18 | +0·70 | 0·97 | B |
| | | No observations within category | | | | C |
| | | No observations within category | | | | D |
| 2·13 | 11 | +0·15 | 0·48 | +0·50 | 0·58 | E |
| 2·19 | 10 | +0·60 | 0·57 | −0·08 | 0·29 | F |
| 3·00 | 10 | −0·53 | 0·67 | −0·40 | 0·57 | G |
| 2·02 | 4 | −0·35 | 0·75 | −0·73 | 0·91 | H |
| | | No observations within category | | | | I |
| | | No observations within category | | | | J |
| 2·18 | 13 | −0·36 | 0·98 | −0·52 | 0·93 | K |
| 1·96 | 13 | −0·25 | 0·42 | +0·19 | 0·52 | L |
| 1·81 | 8 | +0·16 | 0·86 | −0·07 | 0·64 | M |
| 1·23 | 6 | −0·18 | 0·79 | −0·10 | 0·78 | N |
| | | No observations within category | | | | O |
| 1·47 | 50 | +0·21 | 0·79 | −0·18 | 0·65 | P |
| 0·47 | 41 | −0·17 | 0·68 | +0·07 | 0·52 | Q |
| | | | *Weighted means* | | | |
| | 184 | −0·01 | 0·72 | −0·05 | 0·53 | All |

For a further test the diagram was applied to all 262 observations and estimates were obtained for the depression on all occasions including those which did not fit into the categories used in the Steele, Stroud and Virgo method. These included nights with snow cover, precipitation, air-mass change, etc., and results are shown in Table II*(a)*. Note that 87 per cent of the errors were within ±1 degC. The median value of the depression during 1967–68 was 1·6 degC (extremes 0·0 and 4·8 degC). The relatively small

TABLE II—MEAN ERROR AND DISTRIBUTION OF ERRORS USING THE COTTESMORE DIAGRAM FOR ALL CASES DURING TWO PERIODS IN 1967–68

| | Number of cases | Mean error | Root-mean-square error | Distribution of errors within certain limits (degC) ±0·5 | ±1·0 | ±1·5 | ±2·0 |
|---|---|---|---|---|---|---|---|
| | | *degC* | *degC* | | *per cent* | | |
| *(a)* April 1967–mid-July 1968 | 262 | +0·06 | 0·70 | 60 | 87 | 97 | 99 |
| *(b)* Mid-July–December 1968 | 100 | +0·06 | 0·73 | 65 | 90 | 96 | 98 |

range of depressions is probably associated with physical characteristics of Cottesmore, such as topography or type of soil. The 'Cottesmore mean' depression for all categories 1961–65 was also 1·6 degC, and when this mean depression was used over the 1967–68 observations, 78 per cent of all errors were within ±1 degC.

A check of the diagram method using independent data for mid-July–August 1968 is shown in Table II*(b)*. Results are similar to those in Table II*(a)* but the period of the independent test is rather short for firm conclusions to be drawn. The check suggests that the diagram method is capable of giving good results at a particular station, provided that the air minimum can be forecast accurately.

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# THE VARIATION OF VERY LOW CLOUD BASE WITH TIME AND DISTANCE AND WITH HEIGHT

By N. E. DAVIS

**Summary.** The record of the cloud-base recorder at Wyton is used to determine the correlation coefficient between the lowest cloud base at one time and the lowest cloud base at periods of from 1–15 minutes later. The correlation coefficients vary considerably from one set of observations to another but on average fall to about 0·50 after 15 minutes. The standard deviation of the difference between the lowest cloud base at one time and the lowest cloud base at periods of from 1–15 minutes later is also determined. The standard deviation increases to about 100 feet after 10 minutes.

An estimate is made of the correlation coefficient between the lowest cloud base at one point and the lowest cloud base at another point up to 3 miles distant. The corresponding standard deviation of the difference is about 100 feet at a distance of about 2 miles.

A comparison with some earlier work by Harrower indicates that the standard deviation of the difference between the lowest cloud base at one time and the lowest cloud base $t$ minutes later is of the form

$$\sigma = 4h^{\frac{1}{2}}t^{\frac{1}{2}}$$

where $\sigma$ is measured in feet and $h$ is the mean height of the cloud base in feet.

**Introduction.** Dunaeva[1] described an experiment in which simultaneous observations of low-cloud height, visibility, temperature, dew-point and wind were made every 15 minutes following the appearance of cloud with a base at or below 300 metres. Dunaeva found that the correlation coefficient, between the cloud base at one time and the base 15, 30, 45, 60, 75 and 90 minutes later, varied quite considerably from one set of consecutive observations to another.

The present paper uses records from the cloud-base recorder which records the height of the base of the cloud immediately overhead at approximately 1-minute intervals.

**Choice of data.** The record of the cloud-base recorder at Wyton (52°21′N 00°07′W) was examined and four occasions were chosen for further study. As the height of the cloud base was to be extracted at exact minute intervals (by interpolation from the cloud-base recorder values at approximately 1-minute intervals) the quality of the record had to be exceptionally good (smoothing between readings to cover a doubtful record would defeat the object of the study). Only cases with 8/8 cloud cover could be considered. As the cloud-base recorder gave only the height of the cloud immediately overhead, the recorder did not record anything if a hole (however small) was immediately overhead. Further, the 8/8 cloud cover had to have a continuous base. If, for example, the cloud cover consisted of a uniform sheet of 8/8 cloud at 800 feet with 3/8 or 4/8 thin cloud at 200 feet, i.e. with a distinct gap between the 2 layers, then the recorder would sometimes record 200 feet and sometimes 800 feet. If a minute interval fell midway between a 200-foot reading and the following 800-foot reading, an interpolated value of 500 feet would be incorrect as there was no cloud at this level at all and yet no other value could be ascribed. Finally, for the first part of the investigation, only cases in which the cloud base descended at some time or other during the period to below 300 feet were considered. This last restriction was deliberately chosen so that the investigation would be confined to cases in which the cloud base was varying at about the minimum permitted height for aircraft landing.

The last two restrictions in the event were nearly mutually exclusive as turbulence generated by the ground frequently breaks the lowest cloud into patches.

The four cases chosen were:

| | |
|---|---|
| 0301–0500 GMT on | 8 July 1967 |
| 0201–0300 GMT on | 13 July 1967 |
| 0001–0200 GMT on | 28 July 1967 |
| 1001–1100 GMT on | 23 August 1967 |

**Variation of cloud height with time.** Values of the height of the lowest cloud were read every minute throughout the periods given and the correlation coefficient $r_t$ between the height of the lowest cloud and the height of the lowest cloud $t$ minutes later was calculated for each of the four occasions for all values of $t$ from 1 to 15. These values are given in Table I. If we consider these four occasions as a representative sample of the variation of very low cloud base with time, then the four occasions can be combined together to give an estimate of the average correlation coefficient. This estimate is given by the last line in Table I and diagrammatically in Figure 1.

TABLE I — CORRELATION COEFFICIENT BETWEEN HEIGHT OF LOWEST CLOUD AND HEIGHT OF LOWEST CLOUD $t$ MINUTES LATER

| Date | $t$ minutes | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1967 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 8 July | 0·67 | 0·58 | 0·55 | 0·57 | 0·54 | 0·48 | 0·45 | 0·53 | 0·53 | 0·41 | 0·40 | 0·36 | 0·29 | 0·28 | 0·23 |
| 13 July | 0·87 | 0·86 | 0·78 | 0·73 | 0·68 | 0·66 | 0·67 | 0·60 | 0·61 | 0·56 | 0·55 | 0·55 | 0·51 | 0·58 | 0·49 |
| 28 July | 0·52 | 0·34 | 0·28 | 0·29 | 0·28 | 0·25 | 0·20 | 0·20 | 0·19 | 0·12 | 0·03 | 0·09 | 0·05 | 0·24 | 0·19 |
| 23 Aug. | 0·94 | 0·87 | 0·84 | 0·82 | 0·82 | 0·84 | 0·83 | 0·83 | 0·80 | 0·78 | 0·77 | 0·75 | 0·73 | 0·74 | 0·69 |
| Four series combined | 0·83 | 0·75 | 0·72 | 0·72 | 0·70 | 0·68 | 0·63 | 0·67 | 0·66 | 0·61 | 0·58 | 0·56 | 0·52 | 0·55 | 0·51 |

The mean height of the lowest cloud base over the periods given were 316 feet on 8 July, 221 feet on 13 July, 377 feet on 28 July and 428 feet on 23 August with standard deviations of 100, 35, 79 and 152 feet respectively.

The main feature of Table I is the large range of correlation coefficients from 0·52 to 0·94 after 1 minute and 0·77 to 0·03 after 11 minutes. On 23 August the general cloud base rose throughout the hour of record and the high correlation is due to this relatively long-period change. On 28 July the general

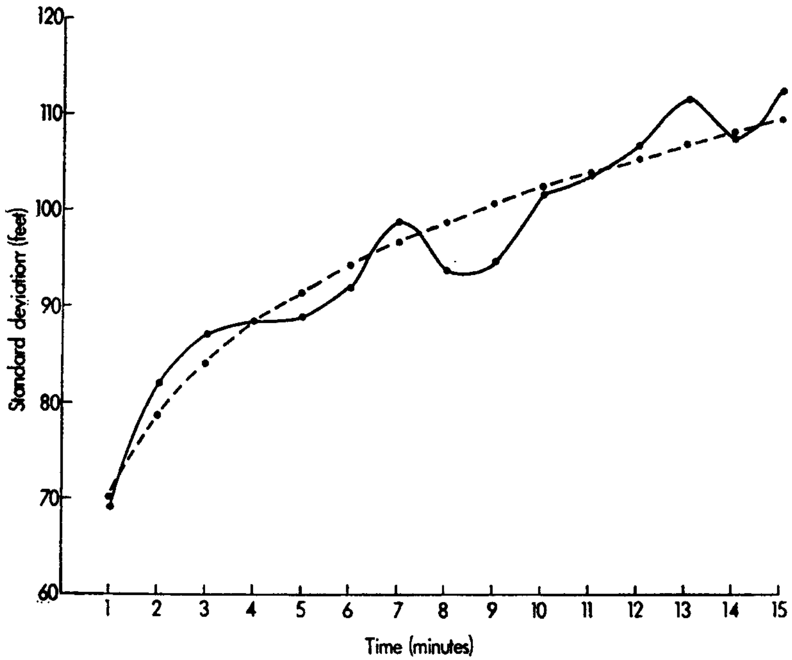


FIGURE I — STANDARD DEVIATION OF THE DIFFERENCE BETWEEN HEIGHT OF LOWEST CLOUD AND HEIGHT OF LOWEST CLOUD $t$ MINUTES LATER

·——· Combined examples. · – – – · $\sigma = 70t^{\frac{1}{6}}$

cloud base remained constant throughout the two hours of record but the minute-by-minute values oscillated in an almost random manner about the general average. The period of sampling — 1 hour for 13 July and 23 August and 2 hours for 8 and 28 July — is only 4 to 8 times greater than the largest period of correlation (15 minutes), so that long-period changes are in general cut out and the correlation coefficient is thus reduced.

The nearness of the ground probably damps down all medium eddies and enhances those with periods of a few minutes or less. A closer examination of the data of Table I shows that oscillations in the correlation coefficient occur with approximate periods as shown in Table II.

TABLE II — PERIODS OF OSCILLATIONS IN CORRELATION COEFFICIENT COMPARED WITH CORRESPONDING CLOUD HEIGHT

| Date 1967 | Mean cloud height | Period of oscillations in correlation |
|---|---|---|
| | *feet* | *minutes* |
| 13 July | 221 | 3½ |
| 8 July | 316 | 4–4½ |
| 28 July | 377 | 4½ |
| 23 Aug. | 428 | 5 |

This table appears to indicate that the nearness of the ground does have an effect on eddies at cloud base level.

The aviator, however, is not concerned with the correlation coefficient but with the variation in cloud base from the time a decision is made to land to the actual moment of landing. To this end, in Table III is given the standard deviation,

$$\sigma = [\Sigma(d_t - M_t)^2/n]^{\frac{1}{2}}$$

of the difference, $d_t$, between the cloud height at one time and the cloud height $t$ minutes later, where $M_t$ is the mean difference over the period considered.

TABLE III — STANDARD DEVIATION OF THE DIFFERENCE BETWEEN HEIGHT OF LOWEST CLOUD AND HEIGHT OF LOWEST CLOUD *t* MINUTES LATER

| Date 1967 | *t* minutes 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | *feet* | | | | | | | |
| 8 July | 81 | 92 | 95 | 94 | 97 | 103 | 107 | 99 | 97 | 108 | 109 | 112 | 118 | 117 | 123 |
| 13 July | 17 | 18 | 23 | 25 | 27 | 27 | 27 | 30 | 29 | 31 | 32 | 32 | 33 | 31 | 34 |
| 28 July | 78 | 92 | 96 | 96 | 97 | 99 | 102 | 103 | 104 | 108 | 114 | 111 | 114 | 103 | 106 |
| 23 Aug. | 51 | 74 | 83 | 87 | 87 | 83 | 84 | 87 | 91 | 95 | 97 | 99 | 101 | 101 | 109 |
| Four series combined | 69 | 82 | 87 | 87 | 89 | 92 | 99 | 94 | 95 | 102 | 105 | 107 | 112 | 108 | 113 |

Figure 1 shows the curve for the combined set of observations, and also the curve

$$\sigma = A\,t^{\frac{1}{4}} \qquad \ldots (1)$$

(where $A = 70$ when $\sigma$ is measured in feet and $t$ in minutes). The best-fit curve $\sigma = At^{\frac{1}{4}}$ is obtained by straight line regression of log $\sigma$ on log $t$ over the 15 combined values of $\sigma$ in Table III. The correlation coefficient between log $\sigma$ and log $t$ over these 15 values is 0·80.

Apart from 13 July, after about 10 minutes the standard deviation of the difference increases to some 100 feet. This means that if a decision were made on the basis of a report 10 minutes old, the cloud base would already have changed by more than 100 feet on some 30 per cent of occasions. If a landing were made 15 minutes after the report, the change on some 30 per cent of occasions would be 110 feet. To some extent this variation is enlarged by the method of measurement. The cloud-base recorder gives only the base of the cloud immediately overhead. If for example there were 8/8 of cloud at 300 feet and 4/8 cloud at 200 feet, the cloud-base recorder would show oscillations between 200 and 300 feet according to whether there was a cloud cell at 200 feet immediately overhead or not. On the other hand a trained meteorological observer would report a steady state of 8/8 at 300 feet and 4/8 at 200 feet. Nevertheless, for a landing aircraft, if the cells and holes at 200 feet were sufficiently large, the cloud base would effectively fluctuate between 200 and 300 feet.

**Variation of cloud height with distance.** As low-cloud base height is known to be variable, the decision to proceed with landing an aircraft is frequently made on final approach some 2 or 3 miles from the airfield on the basis of the cloud actually experienced at that point. The question therefore arises regarding the variation of cloud base with distance. The mean surface wind speed for each of the occasions in Table I was extracted from the Wyton observations, 50 per cent was added and the result was assumed to be the mean speed at the cloud level. By using this mean speed, and by assuming that the variations in cloud base are effectively carried along in the airstream without change, the correlation coefficients with respect to time in Table I were converted into correlation coefficients with respect to distance for each of the occasions. These values are given in Table IV. In Table V are given the standard deviations of the difference between the cloud base at one place and the cloud base at another at distance *d*.

TABLE IV — CORRELATION COEFFICIENT BETWEEN CLOUD BASE HEIGHT AT ONE POINT AND CLOUD BASE HEIGHT AT ANOTHER POINT AT DISTANCE *d*

| Date | Distance *d* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1967 | 1000 ft | 1000 yd | 1 mile | 2000 yd | 1½ miles | 3000 yd | 2 miles | 4000 yd | 3 miles |
| 8 July | 0·66 | 0·56 | 0·49 | 0·46 | 0·54 | 0·43 | 0·38 | 0·29 | 0·22 |
| 13 July | 0·87 | 0·80 | 0·68 | 0·66 | 0·64 | 0·60 | 0·56 | 0·55 | 0·50 |
| 28 July | 0·48 | 0·29 | 0·23 | 0·20 | 0·16 | 0·04 | 0·06 | 0·24 | 0·00 |
| 23 Aug. | 0·96 | ·085 | 0·82 | 0·82 | 0·83 | 0·83 | 0·81 | 0·78 | 0·73 |

TABLE V — STANDARD DEVIATION OF THE DIFFERENCE BETWEEN HEIGHT OF LOWEST CLOUD AT ONE POINT AND HEIGHT OF LOWEST CLOUD AT DISTANCE *d*

| Date | Distance *d* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1967 | 1000 ft | 1000 yd | 1 mile | 2000 yd | 1½ miles | 3000 yd | 2 miles | 4000 yd | 3 miles |
| | | | | | *feet* | | | | |
| 8 July | 82 | 95 | 101 | 104 | 97 | 107 | 110 | 118 | 120 |
| 13 July | 17 | 22 | 27 | 27 | 28 | 30 | 31 | 32 | 34 |
| 28 July | 82 | 96 | 100 | 102 | 105 | 113 | 113 | 103 | 120 |
| 23 Aug. | 46 | 79 | 88 | 87 | 83 | 85 | 90 | 94 | 101 |

The correlation coefficients with respect to distance show a wider variation than those with respect to time but in view of the approximate method used this is not surprising.

In 1955, an experiment was carried out at London/Heathrow Airport in which simultaneous observations of cloud height by means of two cloud searchlights were made at two points on the airfield some 1·8 miles apart, whenever there was more than 4/8 cloud below 1500 feet. A total of 251 observations when the cloud base was below 1000 feet were analysed by Harrower (unpublished). The mean difference in cloud height between the two sites was 16 feet and the standard deviation about the mean was 143 feet. This value is somewhat greater than those above and it suggests that, as Harrower used cloud bases up to 1000 feet, the standard deviation of the difference between the cloud base at two nearby points or at the same point some minutes later depends to some extent on the general level of the base of the cloud. The constant $A$ in equation (1) would appear to depend on $h$, the mean height of the cloud.

A re-examination of the records at Wyton was made and a further six cases in 1967 were extracted in which cloud was 8/8 with base between 500 and 2500 feet. Table VI gives the correlation coefficient between height of lowest cloud and height of lowest cloud $t$ minutes later and Table VII gives the standard deviation in feet of the difference between the height of the lowest cloud and height of lowest cloud $t$ minutes later for these six cases.

In Table VI the range of correlation coefficient is even larger than in Table I. On 21 October the general cloud base rose from 670 to 1400 feet during the hour of sampling. On 2 August, on the other hand, the cloud base during the hour of sampling varied rapidly and erratically about the mean level of 1838 feet.

TABLE VI — CORRELATION COEFFICIENT BETWEEN HEIGHT OF LOWEST CLOUD AND HEIGHT OF LOWEST CLOUD *t* MINUTES LATER

| Date 1967 | *t* minutes | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 2 Aug. | 0·03 | −0·03 | −0·00 | 0·42 | −0·04 | −0·21 | 0·05 | 0·13 | −0·13 | −0·27 | −0·09 | 0·01 | −0·10 | −0·32 | 0·26 |
| 21 Oct. | 0·97 | 0·92 | 0·88 | 0·85 | 0·83 | 0·84 | 0·84 | 0·84 | 0·78 | 0·79 | 0·75 | 0·70 | 0·70 | 0·73 | 0·74 |
| 1 Nov. | 0·61 | 0·43 | 0·36 | 0·23 | 0·19 | 0·18 | 0·21 | 0·35 | 0·38 | 0·39 | 0·49 | 0·35 | 0·25 | 0·13 | −0·01 |
| 30 Nov. | 0·49 | 0·36 | 0·51 | 0·19 | 0·32 | 0·45 | 0·23 | 0·14 | 0·22 | −0·05 | −0·13 | 0·19 | −0·02 | 0·03 | 0·08 |
| 3 Dec. | 0·59 | 0·53 | 0·41 | 0·30 | 0·28 | 0·08 | 0·05 | −0·06 | −0·05 | −0·05 | −0·08 | −0·05 | 0·01 | 0·07 | 0·10 |
| 14 Dec. | 0·32 | 0·23 | 0·14 | 0·25 | 0·16 | −0·18 | −0·01 | −0·01 | 0·05 | −0·04 | 0·00 | 0·06 | 0·16 | 0·05 | 0·13 |

TABLE VII — STANDARD DEVIATION OF THE DIFFERENCE BETWEEN HEIGHT OF LOWEST CLOUD AND HEIGHT OF LOWEST CLOUD *t* MINUTES LATER

| Date 1967 | Mean height | *t* minutes | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| | | | | | | | | *feet* | | | | | | | | |
| 2 Aug. | 1838 | 155 | 162 | 162 | 123 | 164 | 180 | 149 | 144 | 166 | 177 | 153 | 144 | 154 | 166 | 126 |
| 21 Oct. | 1124 | 46 | 71 | 85 | 96 | 100 | 95 | 94 | 94 | 106 | 104 | 113 | 122 | 122 | 116 | 114 |
| 1 Nov. | 675 | 75 | 89 | 95 | 104 | 106 | 107 | 105 | 94 | 91 | 87 | 80 | 91 | 98 | 106 | 115 |
| 30 Nov. | 1186 | 39 | 42 | 38 | 47 | 41 | 40 | 45 | 48 | 46 | 50 | 52 | 44 | 48 | 46 | 46 |
| 3 Dec. | 1462 | 66 | 72 | 80 | 87 | 88 | 101 | 103 | 109 | 106 | 106 | 108 | 106 | 105 | 97 | 97 |
| 14 Dec. | 2118 | 194 | 207 | 220 | 207 | 220 | 263 | 245 | 244 | 239 | 250 | 245 | 241 | 227 | 243 | 234 |

Table VII does show a tendency for the standard deviation to increase with the height of the mean cloud base and equation (1) can be written approximately as

$$\sigma = 4\,h^{\frac{1}{2}}t^{\frac{1}{6}}$$

when $\sigma$ and $h$ are measured in feet and $t$ in minutes.

It may be concluded that standard deviation of the difference between the height of low cloud at one point and the height of low cloud at the same point *t* minutes later, rises to 100 feet after about 10 minutes when the mean cloud base is 500 feet or below and to about 200 feet after about 10 minutes when the mean cloud base is about 2000 feet. Furthermore the standard deviation of the difference between the height of low cloud at one point and the height of low cloud at another point *d* miles away rises to 100 feet when *d* is about 1½ miles and the mean cloud base is 500 feet or below and to about 150 feet when *d* is about 1½ miles and the mean cloud base is about 1000 feet.

Minimum landing conditions for aircraft should not only specify the height of the cloud base but should also take note of the variability. A situation with an average height of 300 feet and a standard deviation of 200 feet is potentially more dangerous than one also with an average height of 300 feet but with a standard deviation of only 20 feet. An automatic cloud-base recorder with its minute-by-minute readings, though it does not give the actual cloud base the aircraft will find on landing, does give, in general, the average height of the cloud base and an estimate of the variability can be obtained by the observer from the range of the recorded heights over the last 15 or 20 minutes, using the formula[2] connecting range and standard deviation.

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## CORRECTION

*Meteorological Magazine,* September 1969, p. 296. The name of the reviewer should read R. MURRAY.

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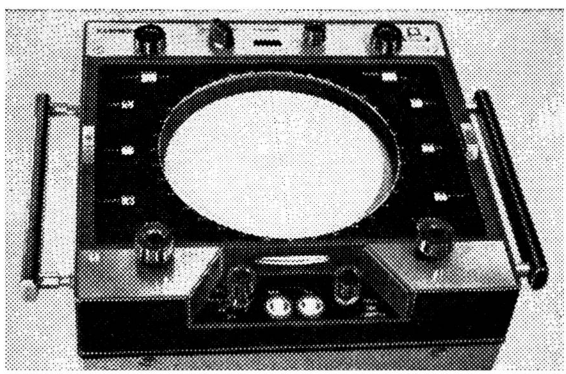

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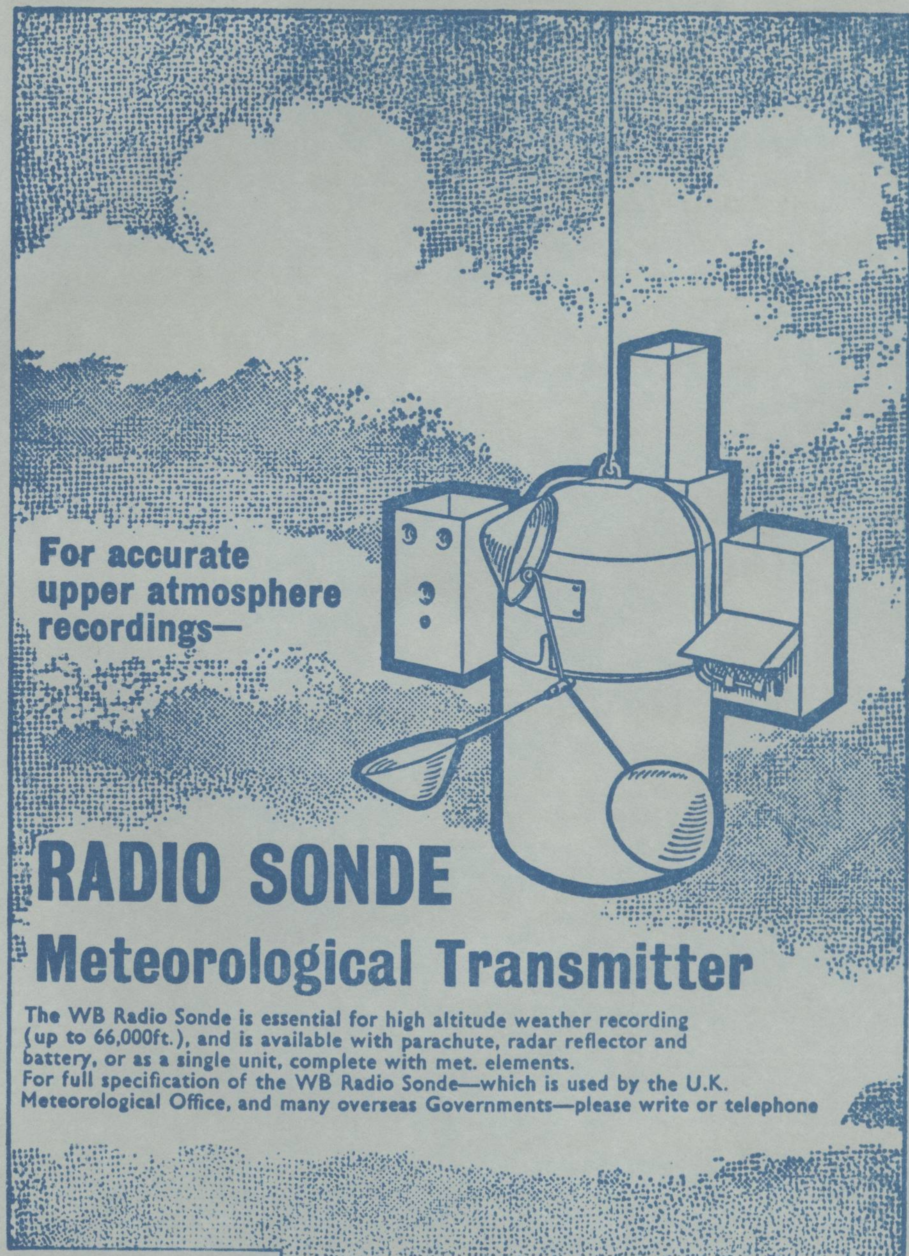
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