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RAINFALL FORECASTING FOR RIVER AUTHORITIES*

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Summary. Synoptic criteria are derived as a basis for forecasting rainfall amounts in various river catchments in the hilly districts of north-west England and north Wales, with particular reference to amounts likely to cause flooding. The results of the forecasts are compared with subsequent rain-gauge measurements.

Introduction. River authorities in the United Kingdom have varying requirements for forecasts of the amount of rain expected to fall in a specified period of time. The most common one is that they wish to be warned in advance of rainfall likely to cause flooding. To attempt this the forecaster needs to know the minimum rainfall conditions which are likely to cause flooding if all other factors are favourable. The assessment of other factors such as antecedent precipitation, soil moisture deficit, and the like, is left to the river authority hydrologist. Some river authorities also require forecasts or warnings of smaller amounts of rain for the purpose of regulating river flow by releases from storage lakes and reservoirs. The forecaster needs to have ready access to rain-gauge readings taken in the river catchments, preferably whilst the rainfall is still in progress, or soon after the event, so that he can quickly check the validity of the assumptions on which his forecast was based.

Warnings of major falls have been issued for the Langdale valley in the heart of the English Lake District, for the upper end of the Eden valley which lies between the Lake District hills and the northern Pennines, and for the Gwynedd area of north Wales, which includes the catchments of the Conway, Mawddach, Wnion and Dovey (Figure 1). A study has also been made of flood occasions in catchments of the Lancashire River Authority other than the Langdale valley. A criterion that can be said to be common to all these catchments is that before there is much risk of flooding, more than 35 mm, or about 1½ inches, of rain has to fall within a limited time. The time of the fall is more difficult to specify, but for a total fall of, say, only 36 mm the time should not be longer than 12 hours. In the short steep catchments of the Langdale valley it has been found that the 36 mm has to fall in not more than 6 hours. The 6-mm-per-hour rate appears to be critical for similar catchments in other hilly districts, such as those of north Wales. On the other

* Presented at the Royal Meteorological Society discussion meeting on 16 February 1972.

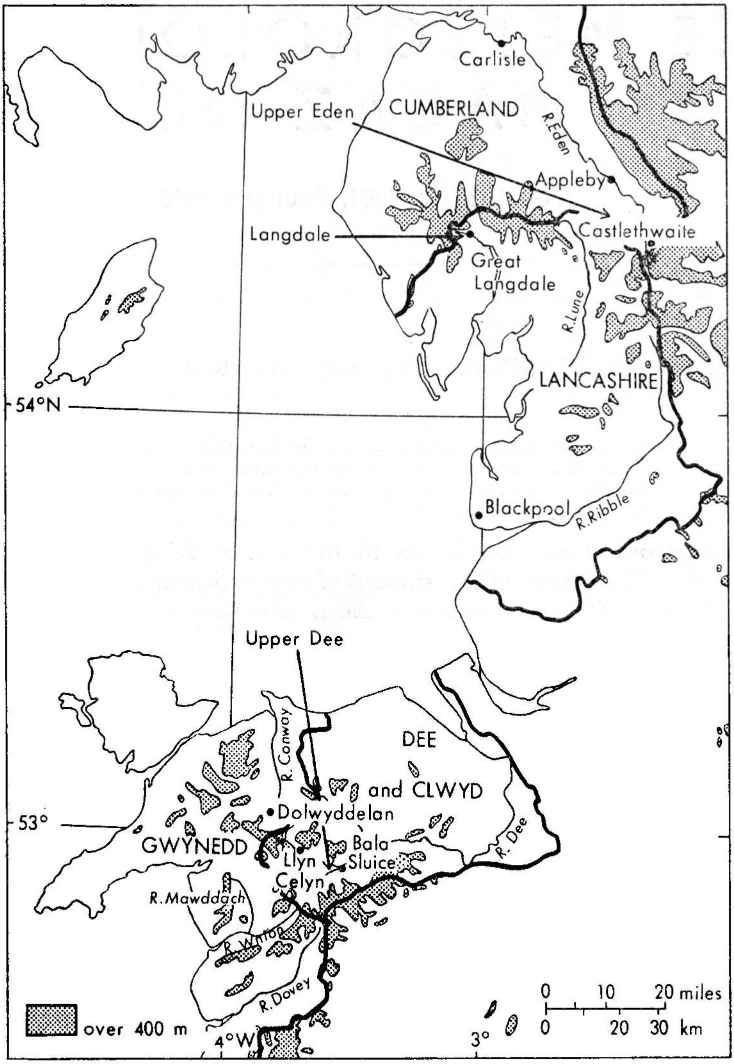

FIGURE 1—FORECAST DISTRICTS, RIVER AUTHORITY AREAS AND RAIN-GAUGE SITES

hand, in the less steep catchments of the broader river valleys, such as those which open out on to the Lancashire plain, there is some evidence that rain falling at rates of only 3 to 4 mm an hour may give rise to flooding if it is sufficiently prolonged for more than 35 mm to accumulate.

Warnings of smaller amounts of rain have been issued to the Lancashire River Authority in connection with a programme of river gauging in the Lake District. Experimental forecasts of rainfall amount, specified in three ranges, have been prepared for the upper part of the Dee catchment in north Wales.

Orographic rainfall. The problem of forecasting rainfall amount in these catchments is concerned with assessing the effect of neighbouring high ground on the general rainfall pattern. Moist airstreams approaching the Langdale valley, for example, from a westerly or south-westerly direction first encounter high ground rising to a general level of about 600 metres with peaks rising to between 750 and 1000 m. A similar comment may be made about the Conway valley in north Wales, lying on the east side of Snowdonia. If the effect of the high ground is assessed on the basis of rainfall readings taken at intervals of 24 hours, there may be a tendency to assume that the so-called 'orographic contribution' is spread over a long period of time at an even rate of 1 or 2 mm per hour. A study of hourly rainfall values, taken either from autographic records or from readings of interrogable gauges, shows that this is seldom the case, but rather that the added rainfall is concentrated into shorter periods when rates of 6 mm an hour are quite common. When the hourly amounts are looked at in relation to synoptic charts, it is seen that the higher rates of rainfall are frequently associated with the approach of warm and cold fronts, particularly cold fronts.

The synoptic situation of 6 January 1971, Figure 2, has been chosen to illustrate the variability of the orographic contribution of the Lake District hills, on an occasion when one might have expected a long period of steady orographic rain superimposed on fairly small amounts of frontal rain. Between 18 GMT on 6 January and 06 GMT on 7 January the low-level wind flow, as reported by the Aughton radar ascents, at levels between 900 mb and 700 mb, approximated closely to 230 degrees 50 knots (1 kt $\approx$ 0·5 m/s). The warm air mass was almost saturated up to the 760-mb level with a lapse rate close to the 11 °C saturated adiabatic. Conveniently, both warm and cold fronts passed through the three reporting stations, Great Langdale (54° 26′N, 03° 03′W, 170 m above MSL), Carlisle on low ground some 65 km to the north, and

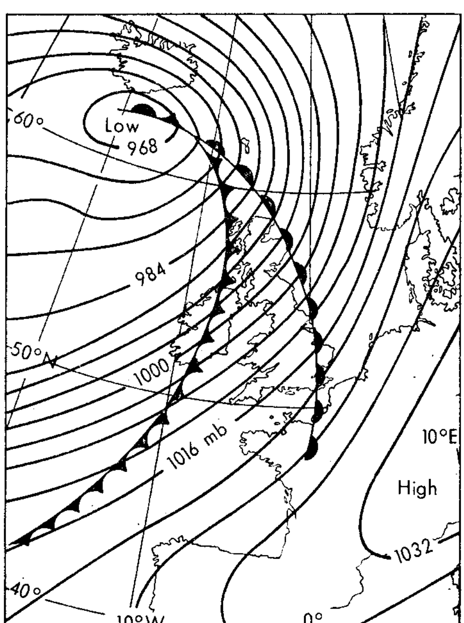

FIGURE 2—SURFACE CHART AT 00 GMT ON 7 JANUARY 1971

Blackpool some 80 km south of the hills, at roughly the same times (the only significant difference being that the warm front reached Blackpool about an hour earlier than it reached the other two stations). At Great Langdale the warm front passed at 1925 GMT on 6 January, and the cold front at 0545 GMT on 7 January 1971.

Figure 3 shows the rates of rainfall obtained from autographic recordings of tilting-siphon rain-gauges at each of the three stations, the area under each graph representing the amount falling in a particular period of time. Table I estimates the additional rainfall at Great Langdale in excess of a

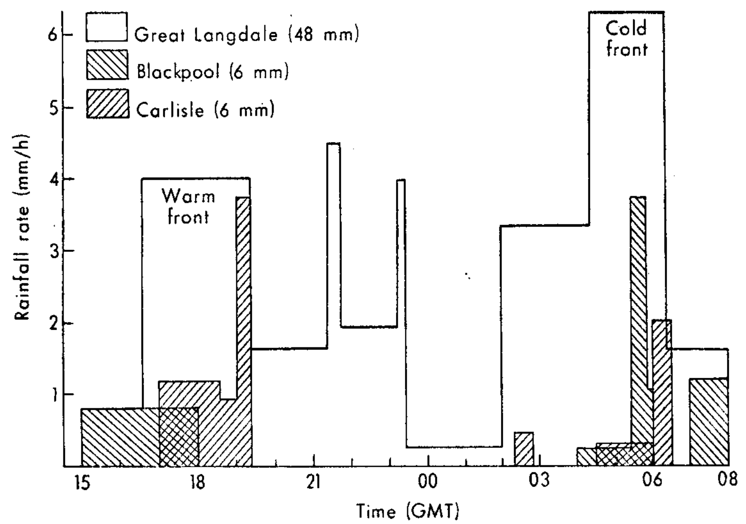

FIGURE 3—DISTRIBUTION OF RAINFALL ON 6 AND 7 JANUARY 1971

mean of the amounts falling at Carlisle and Blackpool, over periods of time which correspond to the steps on the Great Langdale histogram of Figure 3. The most significant periods of orographic rainfall are the three in heavier type (ignoring the two short bursts in the warm sector). Their importance

TABLE I—OROGRAPHIC RAINFALL AT GREAT LANGDALE ON 6/7 JANUARY 1971

Zone	Times	Period	Excess	Rate of excess
	GMT	*hours*	*mm*	*mm/hour*
Ahead of warm front	1500–1635	1·6	0·6	0·4
Warm frontal zone	**1635–1925**	**2·8**	**10·0**	**3·6**
Warm sector	1925–2125	2·0	3·1	1·6
Warm sector	2125–2150	0·4	1·8	4·5
Warm sector	2150–2320	1·5	2·9	1·3
Warm sector	2320–2330	0·2	0·8	4·0
Warm sector	2330–0200	2·5	0·6	0·2
Ahead of cold front	**0200–0420**	**2·3**	**7·8**	**3·4**
Cold frontal zone	**0420–0620**	**2·0**	**12·2**	**6·1**
Behind cold front	0620–0800	1·7	1·8	1·1
Whole period	1500–0800	17·0	41·6	2·4

lies in the requirement for a forecast of the period, as well as the amount, of the peak fall. On this occasion the peaks were so well separated as to constitute no risk of flooding. For floods to occur the peak figure of the cold frontal zone needs to be maintained over a longer period. Often the peaks on the two frontal zones amalgamate so that the warm frontal rainfall cannot be identified in the long period of heavy rain that occurs ahead of the cold front. Some of the peak rates that have been noted are given underneath Figures 4 and 9.

Occluded fronts seldom show such marked increases in rainfall as any of the warm and cold front examples above. This points to the importance of the release of water droplets by the lifting of warm moist air in the lowest layers of the atmosphere (where the water content is usually greatest). The mechanism which often gives rise to very high rates of rainfall on the approach of a cold front and, less frequently, on the approach of a warm front is not fully understood. Two factors may be worth a mention. Raindrops, falling from a higher level in the frontal zone, will scour out the smaller cloud droplets released by forced uplift over the mountain escarpment. This effect appears to increase the frontal rainfall on both the windward and leeward sides of the mountains. However, the maximum rainfall, and presumably the maximum intensity, usually occurs over a limited distance immediately to the lee of the first mountain barrier. This is a region where the air, in rising up to and past this barrier, achieves its maximum vertical component of velocity, and hence its minimum horizontal component. Here raindrops falling through a rising column of air are given the maximum opportunity for collision with smaller droplets. If, because of the vertical motion, there is some reduction in the horizontal flow, then, in a given time, these raindrops fall into a relatively smaller ground area. The lapse rate of the saturated air is usually neutral, so there is no reason why air which has acquired a vertical motion should not continue to ascend some distance beyond the first mountain barrier.

A calculation before the event of the amount of rain likely to fall in a limited time in a particular area, not only involves assumptions about the efficiency and magnitude of these processes, but also requires forecasts of the rainfall pattern upwind of the mountains, and forecasts of humidity, temperature and wind at different levels in the air masses crossing the mountains. The forecaster does not attempt such a calculation. Instead he attempts to identify and forecast a limited number of synoptic conditions which are normally found to be associated with the specified rainfall.

Langdale valley. This was the first area for which an attempt was made to relate heavy rainfall to synoptic conditions. The reasons are largely historical, but the day-to-day investigation has been greatly assisted by the excellent recordings of the Great Langdale rain-gauge, which have been made available soon after the event, by the rainfall observer, Mr P. G. Satow. Rainfall values which have been obtained from time to time from other gauges in the Lake District suggest that the Great Langdale gauge is fairly representative of rainfall events in central Lakeland. The results obtained for this area have laid the foundation for attempts to forecast rainfall amount in other areas where a requirement has arisen.

Mr Satow first sorted through his autographic records for the 10-year period 1954–63, and extracted 35 occasions of particularly heavy rainfall. When the periods during which the heavy rain occurred were looked at in relation to *Daily Weather Reports*,* it was found that on 30 of these occasions

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

the rainfall was clearly associated with the passage of a warm front, or a cold front, or both. On two other occasions the rainfall appeared to be associated with thundery developments. Table II lists the 10 most outstanding occasions of prolonged heavy falls, each of which satisfies the criterion of a fall of more than 50 mm at a mean rate of at least 8 mm an hour.

TABLE II—OUTSTANDING OCCASIONS OF PROLONGED HEAVY RAINFALL AT GREAT LANGDALE 1954–63

Year	From Date	From Time GMT	To Date	To Time GMT	Duration *hours*	Rainfall *mm*	Mean rate *mm/hour*
1954	15 Jun	0920	15 Jun	1910	9·8	98	10·0
1954	2 Dec	0045	2 Dec	0815	7·5	73	9·7
1958	25 Jan	0155	25 Jan	1055	9·0	84	9·3
1958	12 Oct	2210	13 Oct	0500	6·8	64	9·4
1960	26 Feb	1640	26 Feb	2255	6·3	51	8·1
1961	3 Aug	1540	3 Aug	2110	5·5	73	13·3
1962	15 Jan	1420	16 Jan	0030	10·2	85	8·4
1962	12 Feb	0010	12 Feb	0655	6·7	73	10·8
1962	10 Aug	2300	11 Aug	0800	9·0	113	12·6
1963	25 Sept	2100	26 Sept	0500	8·0	80	10·0

Figure 4 shows the Great Langdale recording on the night of 10 to 11 August 1962 when serious flooding occurred, as it almost certainly did on all the other occasions, except on 25 January 1958 when the precipitation was in the form of snow. Floods which sweep down the valley floor constitute a serious threat to grazing stock on adjacent farm lands, particularly if the phenomenon occurs in the hours of darkness. It may be interesting to note that on 6 of these 10 occasions the heavy fall occurred during the night hours, and another 3 were in the late evening.

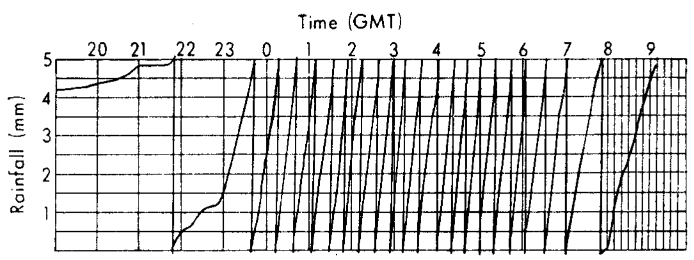

FIGURE 4—DIAGRAMMATIC REPRESENTATION OF HYETOGRAM AT GREAT LANGDALE, 10–11 AUGUST 1962

Commencing at 23 GMT, 10 August, 9 hours rain fell at the rate of 13 mm/h.

All 10 occasions were found to be associated with the same synoptic weather type, namely the easterly passage across the Lake District of the warm sector of a depression enclosing moist air of subtropical origin. Figure 5 illustrates diagrammatically the development of such a depression over the Atlantic between 12 GMT on 6 April and 12 GMT on 9 April 1965. On 9 April 1965 the first of the warnings of heavy rainfall for the Langdale area was issued, and in fact 37 mm fell in the 6-hour period commencing at 18 GMT. Figure 6 shows the vertical distribution of temperature and humidity in the warm air as sampled by the radiosonde released from ocean weather station J, 52°30′N 20°W, at 00 GMT on 9 April.

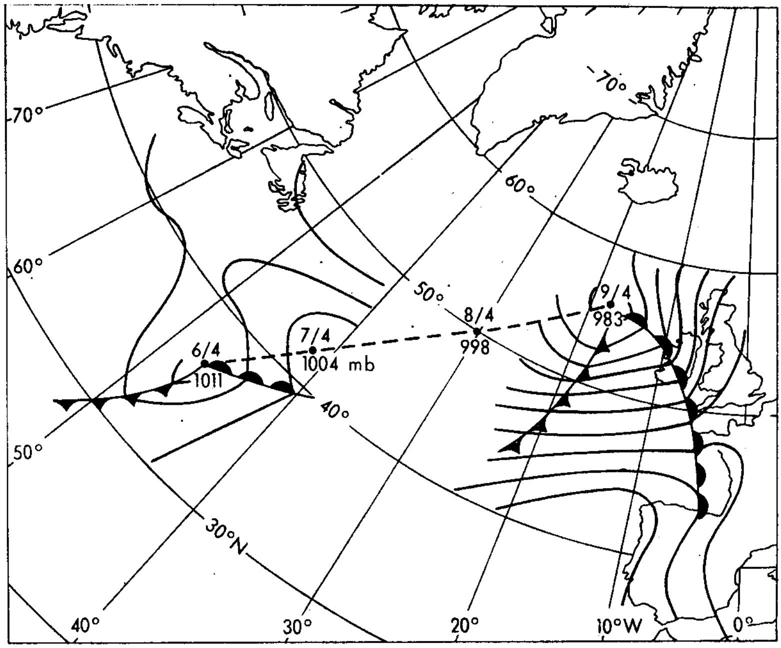

FIGURE 5—TRACK AND DEVELOPMENT OF DEPRESSION 6–9 APRIL 1965
Positions and depths shown at 12 GMT. Isobars are at 4-mb intervals.

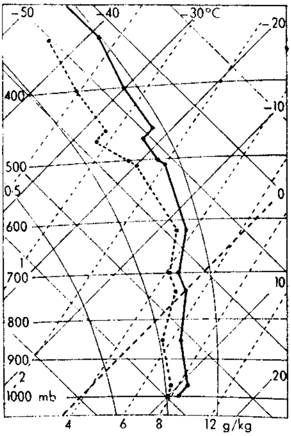

FIGURE 6—UPPER-AIR SOUNDING FOR OCEAN WEATHER STATION 'J' AT 00 GMT ON 9 APRIL 1965

.———. Temperature .- - - - -. Dew-point

Figure 7 illustrates somewhat similar Atlantic developments during the period from 12 GMT, 29 October to 12 GMT, 31 October 1965. In the event, however, the heavy rainfall was confined to a 4-hour period from 1315 to

1715 GMT on 31 October when only 29 mm fell, considerably less than the minimum requirement for a prolonged heavy rainfall warning. The Valentia (south-west Ireland) ascent (Figure 8) for 12 GMT on 31 October provided the first clue to the difference from the occasion of 9 April 1965. This was the first sampling of the temperature and humidity of the more southerly of the two warm air masses in its passage across the Atlantic. Until this sounding was available, the very dry air above the 800-mb level had remained unsuspected.

For prolonged very heavy rainfall in the Langdale valley two alternative sets of criteria have been developed. If 36 mm or more is to fall at a rate of at least 6 mm per hour, one or other set is normally satisfied. The first requires the following three conditions to be satisfied :

(a) A depression moves eastwards, or northwards, across an arbitrary line joining the southern tip of Iceland to Cornwall before it starts to fill.

(b) The warm sector of the depression is occluding, but is not fully occluded as it approaches the Lake District.

(c) Relative humidity in the warm air is high from the surface up to the 650-mb level.

The first condition is perhaps the easiest to forecast. The second is much more subjective because of the difficulties of identifying the position of the 'triple point' on the surface chart. It is most important, however, that the surface warm air has not entirely occluded by the time the fronts reach the Cumberland coast, or prolonged heavy rainfall will not occur. The third

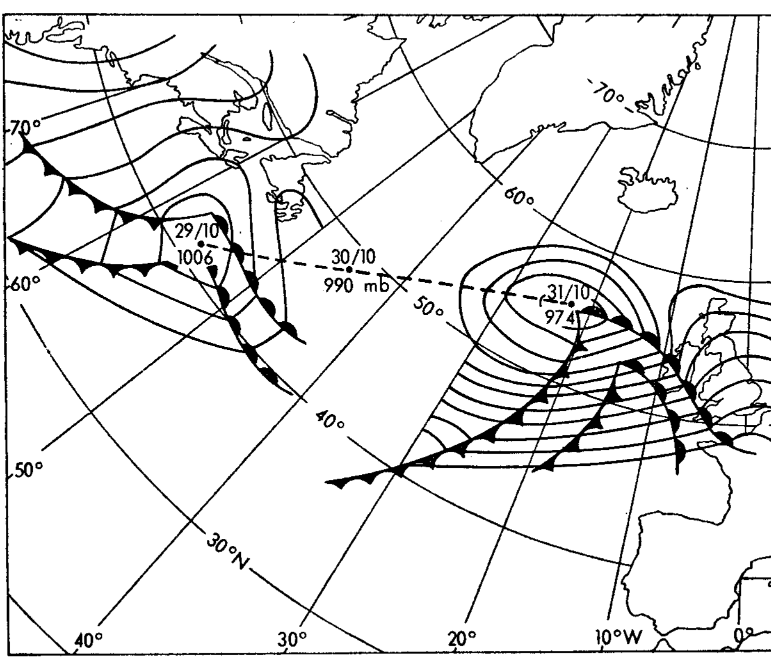

FIGURE 7—TRACK AND DEVELOPMENT OF DEPRESSION 29–31 OCTOBER 1965
Positions and depths shown at 12 GMT. Isobars are at 4-mb intervals.

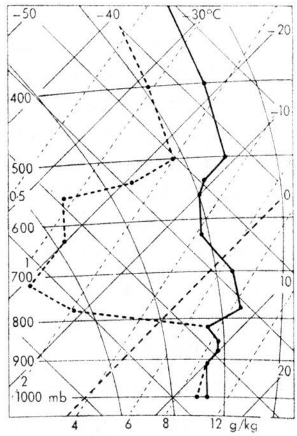

FIGURE 8—UPPER-AIR SOUNDING FOR VALENTIA AT 12 GMT ON 31 OCTOBER 1965

.———. Temperature .– – – –. Dew-point

condition is the most difficult to forecast. The warm air may cross the Atlantic without being sampled by a radiosonde, the distribution of humidity in the vertical often exhibits a latitudinal variation within the warm sector and, perhaps most important, large-scale developments, which so often take place near the British Isles, may result in a rapid increase in the depth of the saturated layer. The forecast that relative humidity is expected to approach saturation throughout much of the layer from the surface to 650 mb may be very subjective.

Many other parameters have been looked at from time to time in an attempt to obtain a more precise definition of the conditions which produce the heaviest falls. Amongst these are wind components normal to the mountain range, surface temperature, surface dew-point, rate of pressure fall, the dew-point depression at the 700-mb level, and the relationship with upper-level jet streams. The 700-mb wet-bulb potential temperature looked promising, but experience suggests that only a minimum value is required, above which there is no direct correlation with the rainfall. Some of these variables are already implicit in the three specified conditions.

The alternative set of criteria is :

(a) An active cold front often with small waves becomes slow moving as it approaches the Lake District.

(b) Relative humidity in the warm air ahead of the cold front is high from the surface up to the 700-mb level.

(c) The geostrophic wind speed ahead of the front is 35 knots or more from a south-westerly direction, the arc from 190 to 250 degrees true being the most favourable.

Neither set of criteria covers the thunderstorm occasion, when large falls may occur in a short period of time. In this area the association of intense thundery activity with flooding appears to be infrequent, though floods which followed prolonged thundery activity during the evening of 13 August 1966 were noteworthy in both the Langdale and Borrowdale valleys.

The Lancashire River Authority engineers intimated at one stage that, in addition to warnings of prolonged very heavy rainfall, they would also be glad to receive warnings of less intense falls. The minimum condition specified was 4 hours of heavy rain, defined in accordance with the standard definition of rain falling at more than 4 mm per hour. This condition is satisfied by many cold fronts, and by warm fronts — but not necessarily by occluded fronts — which approach the Lake District from a general westerly, south-westerly, or southerly direction, provided that certain criteria for humidity and low-level wind flow are achieved. These may be summarized :

(a) Relative humidity of the air ahead of the cold or warm front is high throughout the layer from the surface up to the 700-mb level (there should be no relatively dry layer).

(b) Geostrophic wind direction lies in the arc 150 to 270 degrees.

(c) Geostrophic wind speed is normally 35 knots or more, but the minimum rainfall conditions may be achieved with a lower speed of, say, 25 knots if this is accompanied by pressure falls of about 4 mb per 3 hours.

Gwynedd River Authority area. In a 2-year period commencing November 1966 during which warnings of prolonged very heavy rainfall were issued to the Authority, it was found that the synoptic criteria developed for the more intense falls in the Lake District applied equally well here. This is not surprising in that the mountainous area of north Wales is one of three in the British Isles which have similar contours and a similar exposure to moist south-westerlies (the third being the North-west Highlands of Scotland). The rainfall limits specified for the issue of warnings were similar to the Langdale figures of 36 mm or more at a rate of at least 6 mm per hour, but in addition it was suggested by the Authority that a fall of 50 mm in a 24-hour period might be enough to produce flooding on its own, regardless of the detailed rates of fall. In the event all the 9 major occasions that occurred in the 2-year period appeared to satisfy both specifications.

Figure 9 shows the surface chart for 06 GMT on 27 February 1967, an occasion when the first set of criteria for prolonged very heavy rainfall, as listed under the Langdale valley heading (page 40), was satisfied. This occasion was selected as one on which the rainfall produced by the warm and cold fronts of a single depression fell in the standard rainfall day. Rainfall values for the 24-hour period commencing 09 GMT on 27 February 1967 were obtained for about 500 climatological stations extending from the Scottish border to central Wales. Figure 10 shows isohyets drawn from the plotted values. Values over 75 mm were reported by 3 stations in the Lake District, and one station in Snowdonia reported over 100 mm. This situation is also of interest in producing the highest rate of prolonged frontal rainfall that has been noted. An interrogable tipping-bucket rain-gauge at Dolwyddelan, 366 m above MSL, in the Upper Conway, collected 76 mm of rain in the 4¼ hours commencing 1215 GMT on 27 February, a mean rate over this period of 18 mm per hour. At the same time other gauges in the Gwynedd area were obtaining rates of 10 to 11 mm per hour over periods of between 5 and 7 hours.

Figure 11, the surface chart for 18 GMT on 1 October 1967, illustrates an occasion when the second set of criteria for prolonged heavy rainfall was

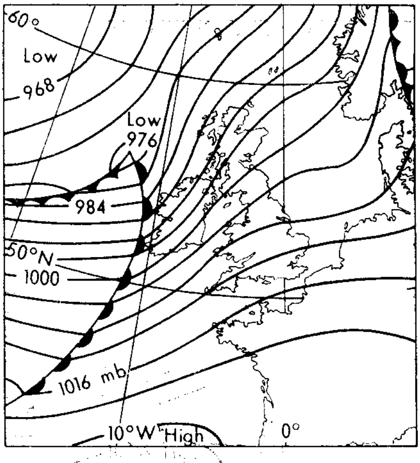

FIGURE 9—SURFACE CHART AT 06 GMT ON 27 FEBRUARY 1967

4 hours rain at 18 mm/h in Upper Conway, 5 hours rain at 10 mm/h in Langdale.

satisfied in respect of the Gwynedd area. The slow-moving cold front with waves, shown just west of the area, produced a reading of 99 mm in the Dolwyddelan gauge in the 13-hour period commencing at 12 GMT on 1 October. Flooding was reported from the Conway valley next morning. This cold frontal zone also produced one of the largest falls, 35 mm in 10 hours, noted in the Upper Dee area.

Upper Eden area. Rainfall warnings for the upper end of the Eden valley have been issued to the Cumberland River Authority since March 1969. The Authority requires advance warning of the likelihood of flooding in Carlisle and Appleby. The minimum rainfall conditions likely to cause this were not known, but the Authority agreed that it should be alerted on occasions when 38 mm or more is expected in any period of 24 hours or less. The synoptic conditions likely to produce 38 mm of rain in this very sheltered area are still not fully tested, because in the 3 years since March 1969 this figure has only been achieved on three occasions, and no flooding has occurred. They may be summarized in two sets, the first requiring three conditions to be satisfied :

(a) An active cold front, often with waves, becomes slow moving as it approaches the area.
(b) Relative humidity in the warm air ahead of the cold front is high from the surface up to the 700-mb level.
(c) The geostrophic wind speed ahead of the front is 45 knots or more from a general south-westerly direction, 210 to 250 degrees probably being the most favourable.

Figure 12, the surface chart for 18 GMT on 12 February 1971, illustrates an occasion when these criteria were achieved. A tipping-bucket gauge at Castlethwaite (244 m above MSL) recorded just 38 mm in the 9-hour period commencing 13 GMT on 12 February. This was the only occasion in 1971 on which the specified minimum amount was reported at any of three gauges

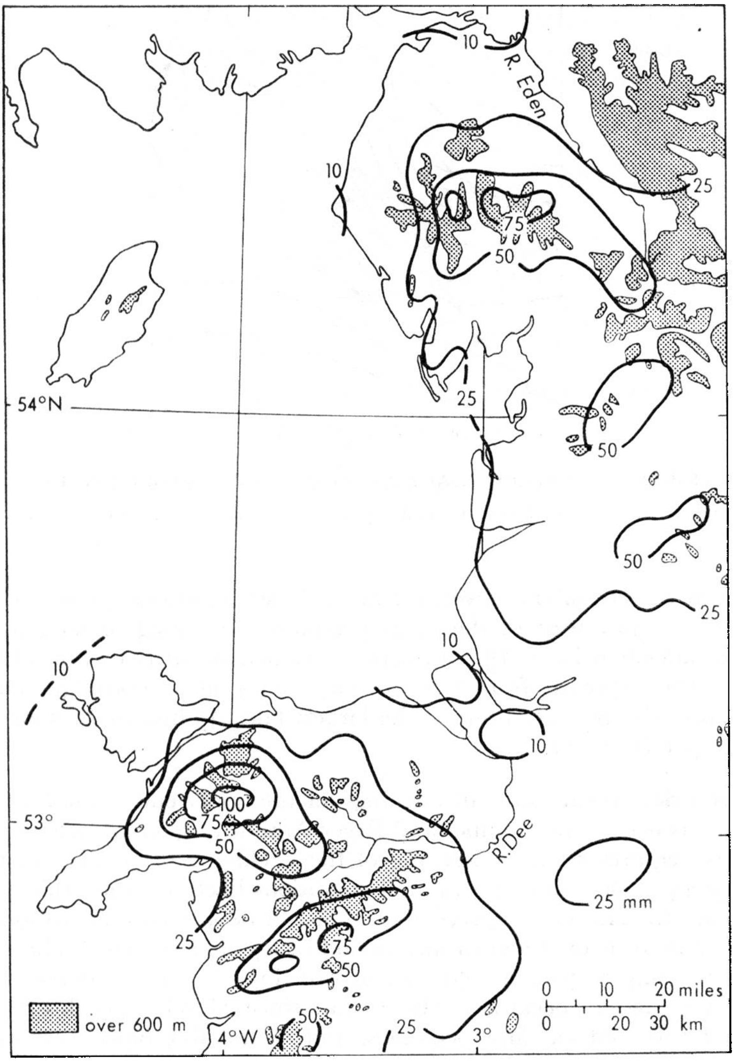

FIGURE 10—RAINFALL DAY 27 FEBRUARY 1967

Correction : Stippling denotes height over 400 m, not 600 m as shown.

in the catchment area. The criteria listed above are almost identical with the second set for major falls in the Langdale valley.

An attempt was made to modify the first set of criteria for the Langdale valley by adding a fourth condition :

(d) Geostrophic wind speed is 50 knots or more.

The assumption was that very strong winds would carry appreciable rain as far beyond the first mountain barriers as the Eden valley. Although this does occur, the amount appears to fall short of the 38-mm figure.

Instead the second set of criteria relate to the condition of almost continuous showers, produced by uplift over the hills of a strong south-westerly unstable

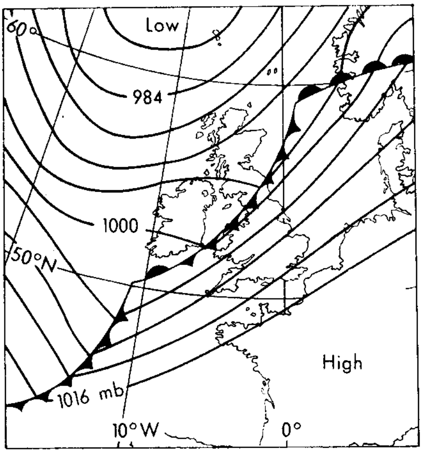

FIGURE 11—SURFACE CHART AT 18 GMT ON 1 OCTOBER 1967
13 hours rain at 7 mm/h in Upper Conway, 10 hours rain at 3·5 mm/h in Upper Dee.

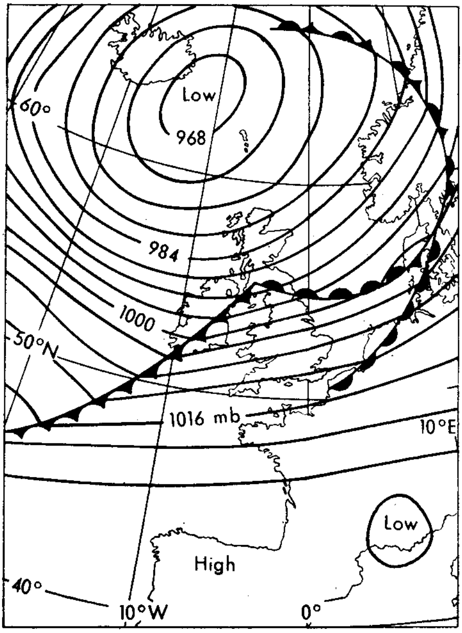

FIGURE 12—SURFACE CHART AT 18 GMT ON 12 FEBRUARY 1971
9 hours rain at 4 mm/h in Upper Eden.

airstream, and carry over into parts of the Eden catchment. The conditions may be summarized :

(a) An unstable south-westerly airstream, with instability extending to the 600-mb level, is maintained over the area for 9 hours or more.
(b) The gradient wind speed is 45 knots or more from a direction between 210 and 250 degrees.

These conditions were satisfied on 9 September 1970 (not illustrated) when the Castlethwaite gauge collected 67 mm in a 37-hour period commencing at 09 GMT on 9 September, and indicated rates of fall of 4 mm per hour for short periods.

Lancashire River Authority area. A flood warning scheme being developed by this Authority requires warnings of heavy rainfall covering all catchments in their area. A preliminary study has been made of the incidence of flooding over the area as a whole during the period 1964 to 1970 inclusive. On each occasion of appreciable flooding, evidence has been found from the autographic record of one rain-gauge or another of a fall of 35 mm or more. On the majority of occasions this fall occurred in a period of between 8 and 12 hours. The 28 occasions when floods were reported may be classified in relation to the prevailing synoptic weather type :

Occluding warm sector of a developing depression	7
Slow-moving cold fronts	7
Unstable west to south-west airstreams	5
Thunderstorms	5
Open-wave depression developing to north of area	1
Quasi-stationary frontal zone	1
Deepening depression over area	1
Trough in a warm sector	1

This analysis is encouraging in that the first three types are those already identified for other areas. The thunderstorm problem remains, since, on the basis of this very limited evidence, on average not more than one thunderstorm occasion, out of the many that occur each year, causes significant flooding in any part of the Authority's area. When the occasion does arise, the results may be quite spectacular, such as on 8 August 1967 when the village of Wray, near Lancaster, was partly swept away by flood waters.

Upper Dee area. This area lies to the east of the main mountain ranges of north Wales, and does not normally experience the more intense rainfalls of Gwynedd. The Water Resources Board are mounting a large-scale experiment to control the flow of the River Dee by using the regulating reservoirs of Bala Lake and Llyn Celyn. A high-powered radar has been set up to measure areal rainfall as it occurs, and it is expected that there will be a requirement for forecasts of the amount of rain expected to fall in a specified period. Over a period of several years, experimental forecasts of rainfall amount covering periods up to 24 hours ahead, have been written out in the three ranges 5 to 15 mm, 15 to 30 mm, and more than 30 mm, and subsequently compared with actual rain-gauge readings. A number of empirical forecasting rules have been developed in an attempt to identify the synoptic features associated with different rainfall amounts. The ones summarized below specify differing criteria for forecasts of amounts of 15 to 30 mm. Their similarity with criteria found in other areas will be noted.

(a) A developing wave, on either a cold front or a warm front, is expected to pass near to the area in the form of an open sector of moist air. The wave tip usually moves with an easterly component between latitudes 52°N and 54°N.

(b) An active cold front, often with waves, is expected to become slow moving across the area.
(c) An occluding warm sector of a developing depression is expected to cross the area. Relative humidity in the warm air mass should be high up to the 700-mb level.
(d) A moist south-westerly airstream of 45 knots or more and unstable to the 600-mb is expected to be maintained for some time. Rainfall accumulates at a rate of about 2·5 mm per hour on average.
(e) Thunderstorms, or thundery rain, are expected in association with a slow-moving trough or with weak pressure gradients.
(f) An active warm front is expected to approach the area.

Autographic records of gauges at Bala Sluice (164 m above MSL) and at Llyn Celyn (271 m above MSL) are subsequently analysed for the time of the forecast. If the mean of these two values falls within the range forecast the forecast is regarded as correct. The results of forecasting amounts of 15 mm or more are given in the next paragraph. It has seldom been possible to forecast amounts of more than 30 mm, as distinct from the 15- to 30-mm range. Similarly there are difficulties in forecasting the smaller amounts in the 5- to 15-mm range, these forecasts being correct only on about half the occasions.

Results. Table III lists the number of occasions on which the specified rainfall conditions were achieved, the number of these that were correctly forecast, and the total number of forecasts issued.

TABLE III—NUMBER OF OCCASIONS OF SPECIFIED RAINFALL AND THE NUMBER CORRECTLY FORECAST

Area	Period	Specified rainfall	Observed	Forecast correctly	Total forecast
Langdale	1 year 1965–66	24 mm at 4 mm/hour	11	8	18
Langdale	2 years 1966–68	36 mm at 6 mm/hour	13	5	13
Langdale	4 years 1968–72	16 mm at 4 mm/hour	50	38	77
Gwynedd	2 years 1967–68	36 mm at 6 mm/hour or 50 mm in 24 hours	9	7	16
Upper Eden	3 years 1970–72	38 mm in 24 hours	4	3	14
Upper Dee	2+ years 1970–72	15 mm	57	47	78

The results indicate that if a number of significant occasions are not to be missed, a good many more warnings must be issued than will be justified by the event. The first two entries for Langdale in Table III illustrate this. After receipt of the first year's warnings the recipient said he was being warned too often when floods did not occur. The result of attempting to be more selective in the two years that followed was that warnings were not issued on eight occasions. On the other hand, warnings for the Upper Eden are regarded as quite successful despite the relatively large number of alerts, which, with experience, is now decreasing.

Concluding remarks. The procedure of empirical forecasting of rainfall amount involves a number of meteorological variables which in themselves are often difficult to forecast. The decision whether or not to issue a warning is often very subjective, and the overall accuracy is quite sensitive to the requirements of the recipients. River authorities use the warnings as a first alert and then arrange to monitor rain-gauge and river-level recordings as the rain progresses. On some occasions the river levels may be so low that no immediate action is necessary. Sometimes the forecaster is able to modify his original warning in the light of later information on the synoptic charts and of actual rain-gauge readings from the catchment areas.

Acknowledgement. I am indebted to Mr P. G. Satow for supplying the Great Langdale rainfall recordings, and to the Lancashire River Authority for permission to publish Figure 4.

551.5(09):06

A SHORT HISTORY OF THE FORMER HOMES OF THE METEOROLOGICAL OFFICE

By L. JACOBS

At the end of a new phase of building at Bracknell with the Operational Instrumentation Branch buildings at an expanded experimental ground (Beaufort Park, originally 30 acres and now 90), the Richardson Wing,[1] and the College at Shinfield Park,[2] it is fitting to put on record the history of the former homes of the Meteorological Office.

A general history of the Meteorological Office was included in the special issue[3] of the *Meteorological Magazine* to commemorate the centenary of the Office in 1955. Few details are given here, however, of the exact locations of the Office and the dates of occupation. The annual reports of the Office from the first one, dated 23 May 1855 and issued in January 1856, have been studied and several of the sites mentioned have been visited and recent official photographs have been taken.

The Office was first established as part of the Board of Trade in January 1855 with Admiral FitzRoy as Director and only three other staff members. Strangely enough although the address Parliament Street, London SW, is given in all the early reports there is only one mention of the building being Number 2. The minutes of the Meteorological Committee are quite specific in quoting Number 2 as the address, so it appears that Shaw[4] is wrong in quoting the address as Number 1. The only description of the location of the Office that can be traced is in 'The clerk of weather' by Wynter,[5] who states :

'If the lounger is on his way to the Abbey, as he gets towards the end of Whitehall, he sees before him, on his left hand, looking down King Street,

PLATE I—A MODERN PHOTOGRAPH OF THE PREMISES AT 63 VICTORIA STREET

See page 49

PLATE II—THE BUILDING IN EXHIBITION ROAD

See page 50

PLATE III—THE BELL-PUSH STILL IN SITU IN DECEMBER 1971

See page 50

PLATE IV—VICTORY HOUSE, KINGSWAY

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To face page 49

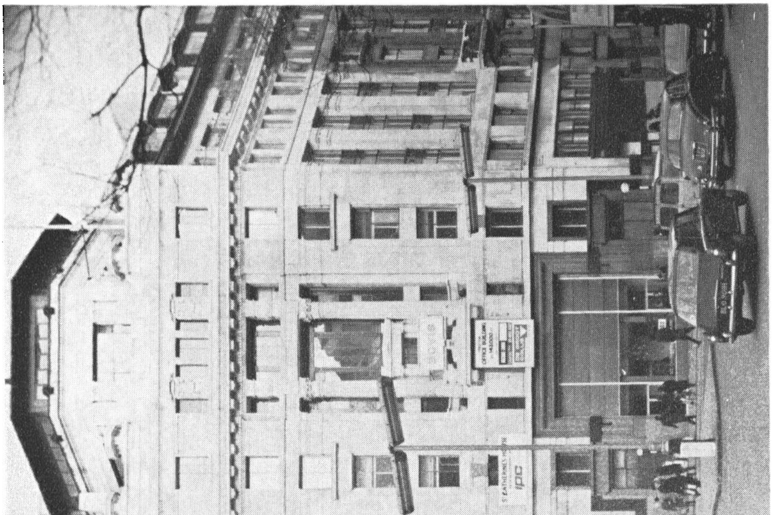

PLATE V—ADASTRAL HOUSE, KINGSWAY

See page 50

an over-hanging bow window; here is the den or cave of the magician who takes under his care the four winds, and foretells rain or snow with certainty.'

King Street is not on a London street map of 1912 but is on such a map of 1851; this latter map shows that the southern end of Whitehall had in the centre of the present road another row of buildings starting from about the present site of the Cenotaph and extending to the southern end of Whitehall. Looking from the Cenotaph to the southern end of Whitehall, King Street ran on the right-hand side of this central row of buildings, while Parliament Street was on the left of this row of buildings; Number 2 was almost exactly where the Cenotaph is now. It is puzzling that Wynter speaks of seeing the Office 'on his left, looking down King Street' as this would imply that the Office faced on to King Street; perhaps it did and extended right through from Parliament Street to King Street.

No mention has been traced of the details of the rooms occupied by the Office at Number 2 Parliament Street; it is, however, possible that some of the unexamined FitzRoy papers held in the Meteorological Office archives may mention them. It is interesting, however, to find that in the first annual report, mentioned above, it is stated that 'at present the rooms allotted to the Meteorological Office are so filled that additional persons would be detrimental. Space is wanted for packing and storing instruments, as well as for keeping records accessively; but, with more accommodation and additional assistance our fast accumulating materials may be overtaken, and their results promptly published'.

Clearly the Office outgrew whatever accommodation was allotted to it by the Board of Trade in Parliament Street. Shaw[4] indicates that the Office indeed had to move out: 'In 1869 the Department was dispossessed of its quarters in 1 [see remarks above regarding this being an error for 2] Parliament Street, belonging to the Board of Trade and hired for itself the residential flat then known as 116 Victoria Street'. While there was no mention in the minutes of the Meteorological Committee of this 1869 move it is recorded that the meeting of 24 May 1869 took place at 2 Parliament Street while the next meeting on 7 June 1869 was at 116 Victoria Street. On 12 December 1888 the minutes give the meeting address as 116 Victoria Street while the next meeting, that on 9 January 1889, is at 63 Victoria Street; this, at first sight, indicates a change of location in Victoria Street but Shaw[4] firmly states 'from 1869 to the present time [1910] the Office has occupied the premises at 116 which was renumbered 63 Victoria Street'. Descriptions of this Office at 63 Victoria Street are given, amongst others, by Lempfert.[6]

A modern photograph of the site and the building is given in Plate I which shows the narrow balcony on the second floor of Number 63 referred to[7] in the following extract: 'various weather reports stand out in bold lettering from an upper balcony, signifying that this office has telegraphic connection with various important positions on our coast'. This balcony is clearly the one referred to by Bench.[8] Although in 1902 an article[7] stated that the Office had 'capacious chambers in Victoria Street', Sir Herbert Maxwell's Committee, the first to investigate the Office, pronounced in 1903 'the premises at 63 Victoria Street unsuitable for the work that had to be done in them . . .' (Shaw[4]). This led to discussion in 1906 on the future location of the Office

(Report of the Meteorological Committee for the year ending 31 March 1906, Appendix I); it was eventually agreed to design a new building in Exhibition Road, South Kensington, specially for the Meteorological Office on the upper floors and with a district Post Office on the ground floor. The transfer of the Office staff to the new premises was completed on 15 November 1910 and the Meteorological Committee invited a large party to an 'at Home' in the new building on 1 December. Details of the accommodation are given in the Sixth Annual Report of the Meteorological Committee for the year ending 31 March 1911, and the frontispiece is a photograph of the new Office viewed from the north-east. Plate II shows the building, still standing in December 1971, and, it appears, with the original four trees still in front of it. Plate III, also taken in December 1971, shows that the push button of the bell of the Meteorological Office still exists outside the main door; the Office vacated this accommodation in November 1939.

Owing to the general expansion of the Office it was necessary to find additional accommodation in 1919; it was agreed (Fifteenth Annual Report for the year ending 31 March 1920) that space would be provided for the Directorate, the Forecast Branch and the Marine Division on the third to fifth floors of the Air Ministry, Adastral House, Kingsway (Plate V), and the move took place in stages from 1 July to 18 November 1919. The remainder of the Office stayed at South Kensington until November 1939 when it moved with the Marine Division to Wycliffe College, Stonehouse, Gloucestershire. The Adastral House contingent moved to nearby Victory House in Kingsway (Plate IV) in April 1938, then occupying the top three floors and the famous 'Air Ministry roof'. There was an overflow of staff from Victory House to the nearby Public Trustee Office in November 1957; meanwhile in 1945 the marine, climatological and instruments branches and the library had moved from Stonehouse to Harrow. The forecasting section left its position under the 'Air Ministry roof' at the end of August 1939 and went to a temporary home in Birmingham; in February 1940 it moved to its permanent war-time home at Dunstable.

The first section of the Office to move to the new Headquarters at Bracknell was the Directorate from Victory House in February 1961 and the main move from Harrow, Dunstable and the Public Trustee Office took place in the autumn of that year.

This present version is condensed from a fuller account.[9]

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551.543:551.577.36:551.589.5(420+429)

CYCLONIC-TYPE RAINFALL AND ATMOSPHERIC MEAN-SEA-LEVEL PRESSURE OVER ENGLAND AND WALES

By E. N. LAWRENCE

Summary. For days of cyclonic type of atmospheric circulation over the British Isles region' the long-term monthly and annual averages of the daily rainfall amount over England and Wales (combined) for 5-mb ranges of MSL pressure and the corresponding frequencies of these ranges were calculated for the period 1950–69 (20 years).

The results show that the annual average rainfall amount increases approximately linearly with decreasing pressure from 1020 to 980 mb. The amplitude of the annual variation has a flat minimum from 1005 to 1020 mb and similarly, the ratio of this amplitude to the average has a minimum at around 1010 mb. There is a small systematic change with pressure in the date of the annual maximum average daily rainfall amount, from early November to October, as pressure increases from 985 to 1010 mb (baroclinic lows); when pressure is about 1015 to 1020 mb (thermal lows), maximum average daily rainfall amount tends to occur in summer (July–August).

The average annual frequency of cyclonic-type days is at a maximum with pressures around 1005 mb; in winter, maximum frequencies occur at 995–999 mb, and in summer at 1005–1009 mb; the amplitude of the annual variation of frequency is at a maximum with pressures of 1005–1010 mb. The ratio of the annual amplitude to the annual total frequency for a 5-mb range of pressure has a minimum at 995–999 mb. For pressures below 995 mb, the annual maximum frequency occurs in winter (November–December or January) while for pressures greater than 995 mb, the maximum frequency occurs in summer (July–August); there is a sharp discontinuity around 995 mb.

The results are discussed in relation to sea temperature and land–sea orientation.

Introduction. The register of daily synoptic types for the British Isles region[1] has two 'wet' types with comparatively large frequencies, namely the 'straight' westerly type and the cyclonic type. For the purpose of improving estimates of individual monthly values of areal rainfall over England and Wales from synoptic-type rainfall averages,[2] averages for 'straight' westerly-type days were obtained for 5-mb ranges of MSL pressure.[3] In the present work, similar rainfall averages are obtained for cyclonic-type days.

Method. To ascertain objectively the daily pressure over England and Wales on cyclonic-type days during the period of 20 years from 1950 to 1969, the pressure (to the nearest millibar) was read from the midday chart of the *Daily Weather Report** for the central point of 53°N 02°W.

For these days, the direct estimates of daily areal rainfall amounts over England and Wales[2] were processed to obtain for each calendar month the average daily rainfall amount for 5-mb ranges of pressure (e.g. 990–994, 995–999, 1000–1004 mb, etc.) and the corresponding average frequencies of these ranges (days per month).

To eliminate irregularities arising from small samples, rainfall and frequency averages for a particular month and 5-mb ranges of pressure were calculated as explained in a previous paper.[3] The resulting rainfall averages were slightly adjusted, proportionally, so that the annual rainfall for the cyclonic type is that previously estimated.[2]

The values thus obtained include some 'theoretical' categories, that is, for pressure ranges beyond the extremes actually observed in any month or in either of the two adjacent months. These 'theoretical' categories were eliminated by grouping the three pressure categories at each extreme of pressure, for each month separately. If the total of the three frequencies was less than 0·015 (0·3 over the 20 years), it was grouped with the adjacent

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

frequency and so on. Categories eliminated by this restriction are indicated by a dash in Table I, which shows the final rainfall and frequency averages.

TABLE I—AVERAGES OF RAINFALL OVER ENGLAND AND WALES FOR GIVEN RANGES OF MSL PRESSURE AND FREQUENCIES OF THESE RANGES, IN THE PERIOD 1950–69, FOR CYCLONIC-TYPE CIRCULATION

		Pressure range (mb)													
		955–959	960–964	965–969	970–974	975–979	980–984	985–989	990–994	995–999	1000–1004	1005–1009	1010–1014	1015–1019	1020–1024
Jan.	*R*	9·6	7·7	6·2	5·3	5·2	5·4	5·4	5·0	4·6	4·5	4·2	3·9	3·9	4·5
	F	0·02	0·04	0·07	0·13	0·21	0·27	0·34	0·43	0·50	0·47	0·37	0·24	0·13	0·08
	RF	0·19	0·31	0·43	0·69	1·09	1·46	1·84	2·15	2·30	2·11	1·55	0·94	0·51	0·36
Feb.	*R*	9·1	5·5	4·6	4·7	4·9	4·9	4·9	5·0	4·8	4·5	4·2	3·9	3·7	3·4
	F	0·02	0·03	0·05	0·08	0·13	0·21	0·35	0·49	0·56	0·48	0·32	0·18	0·09	0·05
	RF	0·18	0·17	0·23	0·38	0·64	1·03	1·71	2·45	2·69	2·16	1·34	0·70	0·33	0·17
Mar.	*R*	—	6·1	3·3	4·3	5·2	4·9	4·6	4·7	4·7	4·4	4·0	3·7	3·4	2·6
	F	—	0·03	0·03	0·04	0·09	0·18	0·32	0·50	0·60	0·55	0·38	0·21	0·10	0·04
	RF	—	0·18	0·10	0·17	0·47	0·88	1·47	2·35	2·82	2·42	1·52	0·78	0·34	0·10
Apr.	*R*			—	4·2	6·4	5·7	4·9	4·8	4·7	4·5	4·2	3·8	3·3	2·8
	F			—	0·02	0·05	0·11	0·21	0·37	0·58	0·70	0·62	0·40	0·17	0·06
	RF			—	0·08	0·32	0·63	1·03	1·78	2·73	3·15	2·60	1·52	0·56	0·17
May	*R*						7·2	5·8	5·2	4·9	4·6	4·3	3·8	3·4	2·7
	F						0·07	0·12	0·31	0·64	0·97	1·05	0·78	0·38	0·14
	RF						0·50	0·70	1·61	3·14	4·46	4·51	2·96	1·29	0·38
June	*R*						7·4	6·3	5·5	5·1	4·8	4·4	4·2	4·0	3·9
	F						0·03	0·08	0·27	0·60	0·97	1·14	0·96	0·54	0·22
	RF						0·22	0·50	1·49	3·06	4·66	5·02	4·03	2·16	0·86
July	*R*						7·3	6·5	5·9	5·4	5·0	4·8	4·7	4·8	4·9
	F						0·06	0·13	0·33	0·68	1·07	1·28	1·11	0·66	0·27
	RF						0·44	0·85	1·95	3·67	5·35	6·14	5·22	3·17	1·32
Aug.	*R*						7·7	6·9	6·2	5·7	5·3	5·0	4·8	4·8	
	F						0·10	0·19	0·40	0·75	1·16	1·37	1·16	0·90	
	RF						0·77	1·31	2·48	4·27	6·15	6·85	5·57	4·32	
Sept.	*R*			—	—	6·3	7·1	6·9	6·6	6·2	5·7	5·2	4·8	4·5	
	F			—	—	0·04	0·10	0·23	0·41	0·64	0·87	0·96	0·78	0·56	
	RF			—	—	0·25	0·71	1·59	2·71	3·97	4·96	4·99	3·74	2·52	
Oct.	*R*			4·9	6·5	7·6	7·7	7·6	7·4	6·9	6·3	5·7	5·1	4·6	
	F			0·03	0·03	0·08	0·21	0·40	0·55	0·63	0·64	0·57	0·40	0·24	
	RF			0·15	0·19	0·61	1·62	3·04	4·07	4·35	4·03	3·25	2·04	1·10	
Nov.	*R*		8·8	7·2	6·5	6·9	7·5	7·7	7·4	6·7	6·0	5·4	5·0	4·7	4·1
	F		0·03	0·04	0·09	0·19	0·34	0·51	0·61	0·61	0·54	0·41	0·24	0·10	0·04
	RF		0·26	0·29	0·59	1·31	2·55	3·93	4·51	4·09	3·24	2·21	1·20	0·47	0·16
Dec.	*R*		9·7	7·5	6·0	6·0	6·5	6·7	6·2	5·4	4·8	4·3	3·9	3·9	4·4
	F		0·06	0·07	0·13	0·24	0·34	0·42	0·48	0·50	0·47	0·37	0·23	0·12	0·07
	RF		0·58	0·53	0·78	1·44	2·21	2·81	2·98	2·70	2·26	1·59	0·90	0·47	0·31
Year	*R*	9·25	7·89	5·97	5·54	5·95	6·45	6·30	5·93	5·46	5·06	4·70	4·42	4·32	3·95
	F	0·04	0·19	0·29	0·52	1·03	2·02	3·30	5·15	7·29	8·89	8·84	6·69	3·99	0·97
	RF	0·4	1·5	1·7	2·9	6·1	13·0	20·8	30·5	39·8	45·0	41·6	29·6	17·2	3·8

R = monthly or annual rainfall averages in mm/day
F = average frequencies of the pressure ranges in days/month or days/year
RF = product of *R* and *F* in mm.

Annual variation. The monthly values of the average daily rainfall amount for 5-mb ranges of pressure (*R* mm per day) and the averages of frequency of the 5-mb ranges (*F* days per month) were harmonically analysed, as previously described.[3] Theoretical values and other values obtained before the grouping of some categories were used throughout, in order to provide complete (annual) sets of 12 calendar-month values for the analysis of the more extreme ranges of pressure. Resulting harmonic coefficients (a_n, b_n) are given in Table II.

Figures 1–6 show rainfall and frequency patterns in simplified, general form, that is, excluding 'noise'. The theoretical and other pre-grouped values were used for these figures, which are not intended to replace the averages of Table I.

Figure 1 shows the annual variation of average daily cyclonic-type *rainfall amount* over England and Wales, together with the first harmonic curves for five alternate 5-mb ranges of pressure. There were relatively few occasions

TABLE II—HARMONIC COEFFICIENTS OF (a) THE ANNUAL VARIATION OF CYCLONIC-TYPE RAINFALL AMOUNT AND (b) FREQUENCY OF CYCLONIC TYPE FOR DIFFERENT RANGES OF MSL PRESSURE, OVER ENGLAND AND WALES, 1950–69

Pressure range *mb*	Harmonic coefficients a_0	a_1	b_1	a_2	b_2	a_3	b_3	a_4	b_4	a_5	b_5
(a) Rainfall amount, *R*					*millimetres/day*						
975–979	+6·747	−1·413	−0·527	−0·216	−0·394	+0·093	−0·056	−0·027	+0·215	+0·052	−0·125
980–984	+6·530	−0·907	−0·919	−0·153	−0·517	−0·020	+0·005	−0·047	+0·146	+0·056	−0·077
985–989	+6·193	−0·438	−1·236	−0·132	−0·463	−0·110	+0·052	−0·072	+0·113	−0·009	−0·048
990–994	+5·822	−0·214	−1·201	−0·302	−0·268	−0·190	+0·120	−0·068	+0·104	−0·041	−0·002
995–999	+5·423	−0·183	−0·975	−0·394	−0·114	−0·180	+0·165	−0·017	+0·093	−0·018	+0·025
1000–1004	+5·026	−0·198	−0·768	−0·339	−0·044	−0·106	+0·155	+0·052	+0·090	+0·019	+0·020
1005–1009	+4·649	−0·231	−0·647	−0·230	+0·003	−0·083	+0·132	+0·092	+0·117	+0·044	+0·022
1010–1014	+4·313	−0·288	−0·600	−0·090	+0·063	−0·141	+0·116	+0·077	+0·139	+0·044	+0·033
1015–1019	+4·075	−0·309	−0·660	+0·151	+0·062	−0·183	+0·062	+0·069	+0·095	+0·035	+0·030
1020–1024	+3·938	−0·268	−0·838	+0·519	−0·016	−0·092	−0·050	+0·178	+0·005	+0·037	+0·028
(b) Frequency, *F*					*days/month*						
975–979	+0·089	+0·100	−0·032	+0·022	−0·028	−0·006	−0·016	−0·001	−0·002	+0·002	−0·002
980–984	+0·162	+0·135	−0·063	−0·002	−0·029	−0·026	−0·013	−0·004	+0·006	+0·003	−0·002
985–989	+0·274	+0·147	−0·088	−0·036	−0·007	−0·046	+0·002	−0·007	+0·017	+0·005	−0·004
990–994	+0·429	+0·093	−0·070	−0·043	+0·021	−0·047	+0·009	−0·009	+0·024	+0·007	−0·008
995–999	+0·608	−0·077	−0·018	−0·011	+0·030	−0·020	−0·009	−0·011	+0·030	+0·008	−0·015
1000–1004	+0·741	−0·331	+0·009	+0·046	+0·016	+0·025	−0·041	−0·019	+0·040	+0·009	−0·021
1005–1009	+0·736	−0·516	−0·005	+0·109	+0·008	+0·053	−0·055	−0·027	+0·041	+0·009	−0·022
1010–1014	+0·558	−0·485	−0·024	+0·137	+0·017	+0·040	−0·041	−0·023	+0·025	+0·007	−0·016
1015–1019	+0·295	−0·281	−0·019	+0·105	+0·016	+0·012	−0·020	−0·010	+0·008	+0·004	−0·008
1020–1024	+0·098	−0·090	−0·004	+0·048	+0·004	+0·000	−0·008	−0·001	+0·000	+0·001	−0·002

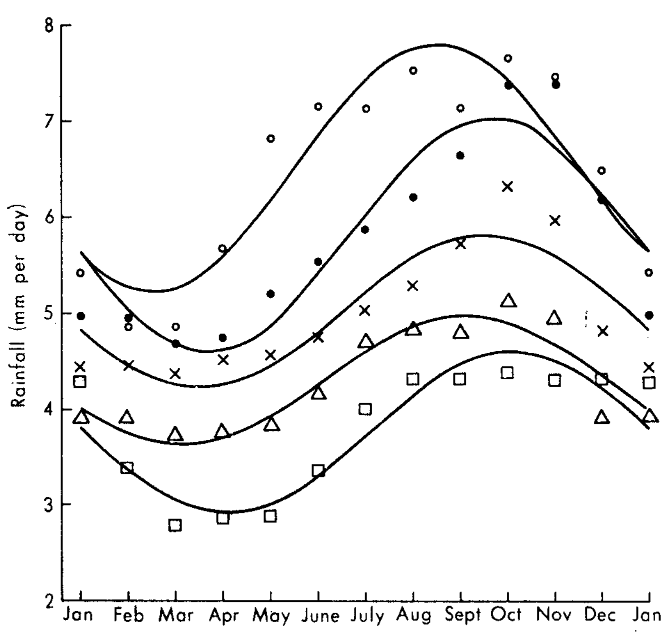

FIGURE 1—ANNUAL VARIATION OF THE AVERAGE DAILY CYCLONIC-TYPE RAINFALL AMOUNT OVER ENGLAND AND WALES FOR DIFFERENT RANGES OF PRESSURE AT MSL AND THE FIRST HARMONIC CURVES, DURING THE PERIOD 1950–69

○——○ 980–984 mb ×——× 1000–1004 mb □——□ 1020–1024 mb
●——● 990–994 mb △——△ 1010–1014 mb

of cyclonic-type days with pressures of 1020–1024 mb and so the graph and averages for this pressure range in Figure 1 are based on data which exclude that for 28 July 1969, a day of exceptionally heavy rainfall (1·54 in) and a pressure index of 1015 mb. The pressure pattern for this day was very complex: the main low was centred to the south-west of the British Isles and a 'flat' thundery 'trough' extended over much of England and Wales; the pattern might justifiably be described as 'unclassifiable'.[1,2]

Figure 2 shows the amplitude, $\sqrt{(a_1^2 + b_1^2)}$, of the annual variation of the average daily rainfall amount, and Figure 3 gives the date of the maximum average daily rainfall amount (based on the first three harmonics) for 5-mb ranges of pressure. Figures 4 to 6 (corresponding to Figures 1 to 3) show results for the *frequencies* of the 5-mb ranges of pressure.

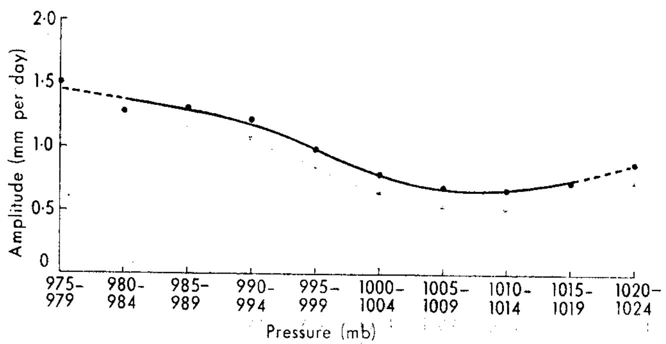

FIGURE 2—AMPLITUDE OF THE ANNUAL VARIATION OF THE AVERAGE DAILY CYCLONIC-TYPE RAINFALL AMOUNT OVER ENGLAND AND WALES FOR DIFFERENT RANGES OF PRESSURE AT MSL, BASED ON FIRST HARMONICS, DURING THE PERIOD 1950–69

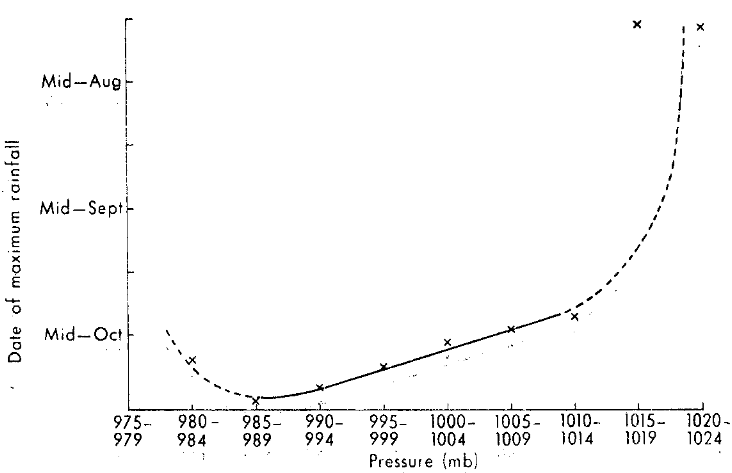

FIGURE 3—DATE OF THE ANNUAL MAXIMUM AVERAGE DAILY CYCLONIC-TYPE RAINFALL AMOUNT OVER ENGLAND AND WALES FOR DIFFERENT RANGES OF PRESSURE AT MSL, BASED ON THREE HARMONICS, DURING THE PERIOD 1950–69

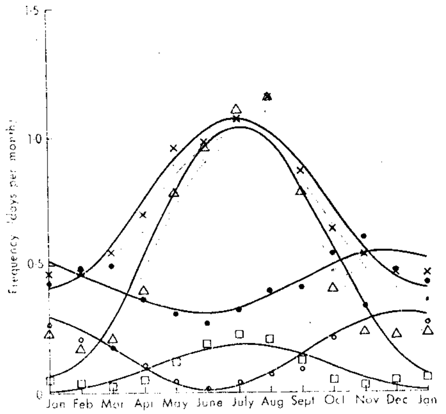

FIGURE 4—ANNUAL VARIATION OF THE AVERAGE FREQUENCY OF DAYS WITH CYCLONIC-TYPE CIRCULATION OVER THE BRITISH ISLES REGION FOR DIFFERENT RANGES OF PRESSURE AT MSL AND THE FIRST HARMONIC CURVES, DURING THE PERIOD 1950–69

○——○ 980–984 mb	×——× 1000–1004 mb	□——□ 1020–1024 mb
●——● 990–994 mb	△——△ 1010–1014 mb	

Data are insufficient to calculate results for the pressure level of 975–979 mb in Figure 3; in the graphs of Figures 2, 3, 5 and 6, the extremities, to the points for pressure levels of 975–979 mb and 1020–1024 mb, are generally less certain and are indicated by pecked lines. Also, in Figures 3 and 6, the steep gradients (shown also by pecked lines) are not intended to denote exact values in the pressure ranges concerned.

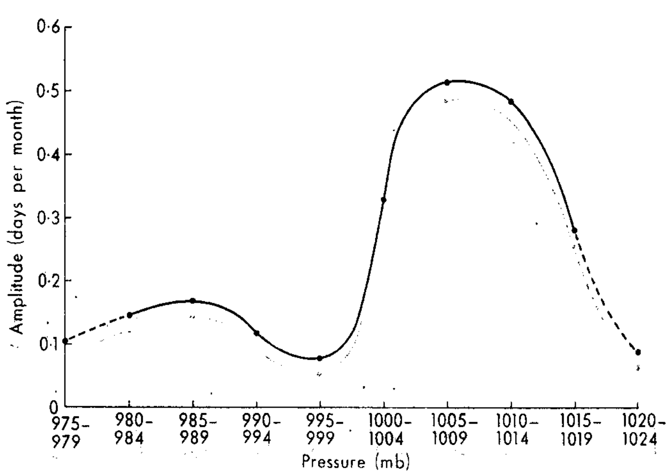

FIGURE 5—AMPLITUDE OF THE ANNUAL VARIATION OF THE AVERAGE FREQUENCY OF DAYS WITH CYCLONIC-TYPE CIRCULATION OVER THE BRITISH ISLES REGION FOR DIFFERENT RANGES OF PRESSURE AT MSL, BASED ON FIRST HARMONICS, DURING THE PERIOD 1950–69

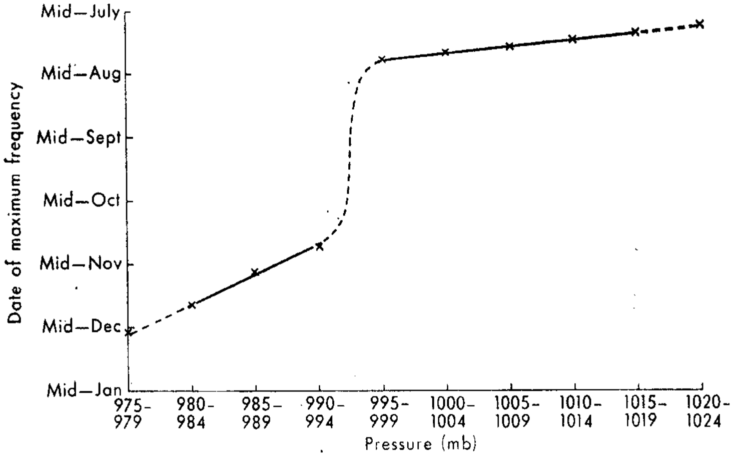

FIGURE 6—DATE OF THE ANNUAL MAXIMUM AVERAGE FREQUENCY OF DAYS WITH CYCLONIC-TYPE CIRCULATION OVER THE BRITISH ISLES REGION FOR DIFFERENT RANGES OF PRESSURE AT MSL, BASED ON THREE HARMONICS, DURING THE PERIOD 1950–69

Discussion. Results (Table I) show that the annual average rainfall amount for cyclonic-type days increases approximately linearly with decreasing pressure from 1020 to 980 mb. There is a tendency for the daily rainfall amount to level off with further decrease of pressure; this may be caused by the association of very low pressures with deep depressions at or near their maximum depth, with a large part of England and Wales well away from active fronts and with drier and colder air aloft, associated with the 'cold pool' stage of cyclonic development (cf. westerlies[3]). In some months the rainfall amount levels off (rate of decrease being less than the linear rate) as pressure rises above 1010 mb; this could possibly be due to thundery (thermal) lows in summer and to cols in winter.

The amplitude of the annual variation of rainfall amount (Table I and Figures 1 and 2) has a flat minimum from 1005 to 1020 mb, and similarly, the ratio of this (single) amplitude to the average increases from a minimum value of approximately 0·16 at around 1010 mb to a maximum value of about 0·23 with pressures below 990 mb.

There is a small systematic change with pressure in the date of the annual maximum average daily rainfall amount (Table I and Figure 3), from early November to October, as pressure increases from 985 to 1010 mb (baroclinic lows); when pressure is about 1015 to 1020 mb (thermal lows), maximum average daily rainfall amount tends to occur in summer (July–August).

The annual average frequency of cyclonic-type days (Table I) is at a maximum with pressures around 1005 mb; in winter, maximum frequencies occur at 995–999 mb, and in summer at 1005–1009 mb; the amplitude of the annual variation of frequency (Table I and Figures 4 and 5) is at a maximum with pressures of 1005–1010 mb. The ratio of the annual (single) amplitude to the annual total frequency for a 5-mb range of pressure increases from a minimum of about 0·01 to 0·02 at 995–999 mb to about 0·07 or more at 980–984 mb and at $\geqslant$ 1010 mb.

For pressures below 995 mb, the annual maximum frequency occurs in winter (November–December or January) while for pressures greater than 995 mb, the maximum frequency occurs in summer (July–August). There is a surprisingly sharp discontinuity around 995 mb (Table I and Figure 6), a result which suggests the need for further research into other characteristics of cyclones which vary with atmospheric pressure.

The autumn maximum of average daily rainfall amount (985–1010 mb, Table I and Figure 3) suggests that for baroclinic disturbances, the rainfall mechanism is closely related to sea surface temperatures in the north-west of the North Atlantic.[3,4] The summer rainfall maximum with higher pressures (thermal lows) indicates the importance of thermal convection overland. The tendency to a slightly earlier annual maximum with very low pressures (980–984 mb, Table I) may be associated with increased convection in 'flat' central low-pressure areas.

Concluding remarks. The cyclonic-type circulation over the British Isles region, like the 'straight' westerly type, has a frequency and an average daily rainfall amount which change systematically with surface pressure.

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ASSESSMENT OF CONVECTIVE DEVELOPMENT IN THE SINGAPORE AREA

By J. KONIECZNY

Summary. Convective development, or lack of it, is shown to be highly dependent on the moisture content between the 1000- and 500-mb levels and on various upper-wind parameters. Development is also related to the positive energy available, represented by the area between the environment curve and the convective path curve expected at maximum temperature.

Introduction. With an abundance of energy and moisture in the Singapore area, every day is likely to be a potential 'development' day for large-scale convection. An assessment of the amount of development, or lack of it, becomes of primary importance. The main object of this investigation was to find some rules, so that with reasonable confidence, convective development could be forecast as nil or only slight.

To find some guiding criteria in day-to-day forecasting, a number of elements were considered and evaluated. The most important factors were found to be :

(a) The positive energy available for convection.
(b) The humidity of the environment as represented by the dew-point depression.
(c) The vertical wind profile.

Data used. Only convective development over land was considered, i.e. that occurring between 0730 and 1930 local time (00 – 12 GMT). Occasions with the shear line (intertropical convergence zone[1]) in the vicinity of Singapore Island or with a sumatra-type[1] convergence zone were not considered. Assessment of convective development over the area was made from the Changi radar plots, based on the following criteria :

(A) Nil/slight — complete absence of echoes, or only isolated small echoes.
(B) Heavy — general widespread echoes or numerous large echoes.
(C) Moderate — any pattern which could not be classified as (A) or (B). These occasions were rejected.

Development (C) is fairly closely connected with development (B) on many occasions, so, if at some stage radar plots indicated the presence of development (B), these days were included in the investigation even though the development was mainly (C).

As apparently straightforward convection can turn out to be involved with lines of convergence, in practice cases are often not clear-cut, and this made objective classification of the data difficult.

Temperature and wind data were obtained from the 00 GMT (0730 local time) Payar Lebar Airport upper-air soundings. Only one ascent is available during a 24-hour period.

The period February 1965 to February 1967 was investigated. Some 258 occasions of development (A) or (B) were found and resulted in criteria which, used independently for a period of time, gave a useful indication of actual convective development in day-to-day forecasting (Table I).

TABLE I—NUMBER OF CASES OF EACH DEVELOPMENT TYPE DURING THE SOUTH-WESTERLY AND NORTH-EASTERLY MONSOON PERIODS

Development type	South-westerly monsoon	North-easterly monsoon	Total
A	66	55	121
B	71	66	137
Total	137	121	258

The selected cases were subdivided into those occurring in the north-east monsoon (approximately November to March) and those in the south-west monsoon (approximately April to October) because it was found that the 1000–700-mb layer was important in both monsoon periods but the 700–500-mb layer was relatively unimportant in the south-westerly period. This is probably because in the north-east monsoon the north or north-easterly current is deep and therefore the middle-level water content is important and would favour convection in the afternoon at maximum heating. During the south-westerly monsoon, however, the airflow is more complex, having at times only a fairly shallow south-westerly or north-westerly flow, with the height of the change-over to the main upper north-easterlies fluctuating through the middle troposphere (8000–20 000 ft*).

Analysis of Payar Lebar upper-air ascent. A measure of the moisture content of the 1000–500-mb layer was obtained by taking the sum of the temperature differences (in degrees Celsius) between the environment temperature and the dew-point at the 900, 800, 700, 600, and 500-mb levels (see Figure 1).

---

* 10 000 ft≈3 km.

A measure of the positive energy available was obtained by similar summation of temperature differences, at the same levels, between the environment temperatures and the temperatures of the theoretical convective path curve for the forecast day maximum temperature.

The following wind parameters were extracted for the two layers :

(a) Mean wind speed — an average of the arithmetical sum of wind speeds at 1000, 3000, 5000, 7000 and 10 000 ft for the layer 1000–700 mb and at 10 000, 12 000, 14 000 and 19 000 ft for the layer 700–500 mb.

(b) Maximum wind speed — highest reported speed in each of the layers.

(c) Vertical wind shear — measure of difference between the highest and lowest wind speed in the layer for each of the layers, irrespective of the heights at which the extremes occurred.

Results.

Moisture and energy parameters. Values were extracted as shown by the example in Figure 1 and then plotted on a scatter diagram, Figure 2; different symbols were used for development types (A) and (B). The zone where the two types of development occurred together was marked off by the two separation lines PJ and PN. There are insufficient data to be able to decide precisely where these lines should be or what slopes they should have. If the environment were very moist a development type (B) would be likely regardless of any other condition. This argument would lead to PN being horizontal; the data indicate that it has a slight positive slope. The line PJ is better defined by the data and is consistent with the idea that less heating will be required to produce development type (B) in a very moist environment than in a drier one.

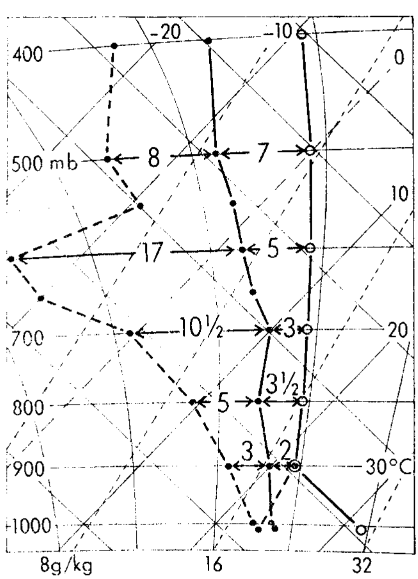

FIGURE 1—DIFFERENCES IN TEMPERATURE AT STANDARD LEVELS

. —— . Dry bulb . - - - - . Dew-point o —— o Convective parcel

The zone between PN and PJ was then subdivided into four equal sectors II, III, IV and V and the frequency of each type of development in each sector is presented in Table II; the two other sectors containing either (A) or (B) were numbered I and VI.

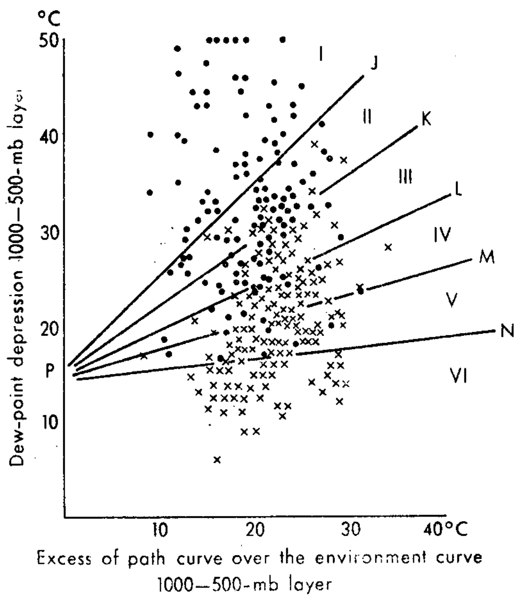

FIGURE 2—DEW-POINT DEPRESSION PLOTTED AGAINST EXCESS OF MAXIMUM TEMPERATURE PATH CURVE OVER THE ENVIRONMENT CURVE

● Nil/slight — type (A) × Heavy — type (B)

Since the surface heating is almost constant throughout the year (the average maximum temperature ranges between 28°C and 32°C[2]) the changes in the moisture content are the most likely cause for the different developments which occur. This has also been suggested by Johnson and Mörth.[3] The changes in the temperature of the environment are likely to be the other contributing factor. These changes are far greater than found for Gan by Dent and Preedy[4] and are more comparable to those found by Goldie, Moore and Austin[5] for south-east Asia.

As the south-westerly monsoon is a shallow airstream, the moisture and energy parameters were examined in the 1000–700-mb layer to see if the frequency distribution in Table II could be improved, but this gave only a marginal improvement.

TABLE II—FREQUENCY OF EACH DEVELOPMENT TYPE IN EACH REGION OF FIGURE 2

Development type	Region I	II	III	IV	V	VI	Total
			number of cases				
A	47	35	22	10	7	0	121
B	0	9	17	33	39	39	137
			percentage				
A	100	80	56	23	15	0	
B	0	20	44	77	85	100	

Wind parameters. The average values of the mean speed, maximum speed and wind shear in the 1000–700-mb and 700–500-mb layers, Table III, indicate that the wind speeds and shear are generally stronger in the lower layer when there is little or no development (type (A)). This aspect is examined in greater detail in Table IV, and in Table V the wind shear in each layer is given separately for each monsoon. During the preparation of Table III it was also noticed that a wind speed exceeding about 18–20 kt (1 kt≈0·5 m/s) at any level in the 1000–700-mb layer favoured development type (A). Table IV shows that the difference in the mean wind between the lower and the upper layer is clearly the best indicator of development (giving a Heidke's[6] skill score of 0·66). Table V shows that the wind shear in the lower layer gives some indication of a preference for (A) or (B) development in both monsoons, but in the 700–500-mb layer the shear gives a useful indication in the north-easterly monsoon only.

TABLE III—AVERAGE VALUES FOR THE WIND PARAMETERS IN THE TWO LAYERS

Development type	Layer	Average maximum *kt*	Average mean *kt*	Average vertical shear *kt*
A	1000–700 mb	16·8	12·1	16·1
B	1000–700 mb	13·3	8·1	12·2
A	700–500 mb	13·8	10·0	14·3
B	700–500 mb	13·1	9·8	12·4

TABLE IV—FREQUENCY OF EACH DEVELOPMENT TYPE WITH THE RELATIVE DISTRIBUTION BETWEEN THE TWO LAYERS OF VARIOUS WIND PARAMETERS

Development type	Mean wind $P_L \geqslant P_U$*	Mean wind $P_L < P_U$	Maximum wind $P_L \geqslant P_U$	Maximum wind $P_L < P_U$	Vertical shear $P_L \geqslant P_U$	Vertical shear $P_L < P_U$
A	106	15	102	19	88	33
B	29	108	50	87	41	96
			percentage			
A	79	12	67	18	68	26
B	21	88	33	82	32	74

*$P_L \geqslant P_U$ means wind parameter in lower layer $\geqslant$ wind parameter in upper layer.
Lower layer = 1000–700 mb, upper layer = 700–500 mb.

TABLE V—FREQUENCY DISTRIBUTION OF EACH DEVELOPMENT TYPE AND WIND SHEAR IN THE TWO DIFFERENT LAYERS FOR EACH MONSOON

Development type	Layer	South-westerly monsoon (137 cases) Wind shear $\leqslant$15 kt	South-westerly monsoon (137 cases) Wind shear >15 kt	North-easterly monsoon (121 cases) Wind shear $\leqslant$15 kt	North-easterly monsoon (121 cases) Wind shear >15 kt
A	1000–700 mb	22	44	24	31
B	1000–700 mb	52	19	50	16
A	700–500 mb	36	30	34	21
B	700–500 mb	43	28	53	13

Forecasting method. Results suggest that the moisture and energy parameters and the mean wind of the lower layer relative to the upper layer are the best indicators. The next step in the analysis would have been to take the occasions in the regions of Figure 2 where both development types can occur and examine how the mean-wind parameter would resolve them. However, at this stage the original data were no longer available and therefore this aspect was studied by assuming that the mean-wind parameter is independent of the moisture and energy parameters and multiplying the frequencies of

TABLE VI—PRODUCTS OF THE FREQUENCIES IN TABLES II AND IV (MEAN WIND)

Development type	Wind parameter	Region I	II	III	IV	V	VI
A	$P_L \geqslant P_U$*	4982	3710	2332	1060	742	0
B	$P_L \geqslant P_U$	0	261	493	957	1131	1131
A	$P_L < P_U$	705	525	330	150	105	0
B	$P_L < P_U$	0	972	1836	3564	4212	4212

* See note below Table IV

TABLE VII—PERCENTAGE RATIO OF TYPE A TO TYPE B FOR ASSOCIATED VALUES OF THE MEAN WIND PARAMETER AND THE MOISTURE AND ENERGY PARAMETER IN FIGURE 2

Development type	Wind parameter	Region I	II	III	IV	V	VI
				per cent			
A	$P_L \geqslant P_U$*	100	93	83	52	40	0
B	$P_L \geqslant P_U$	0	7	17	48	60	100
A	$P_L < P_U$	100	35	15	4	2	0
B	$P_L < P_U$	0	65	85	96	98	100

* See note below Table IV

development types (A) and (B) for each sector given in Table II by the frequencies for mean wind given in Table IV; from these combined contingency ratios, given in Table VI, percentage ratios of types (A) and (B) were calculated and are given in Table VII. Thus a forecaster only needs to calculate the three parameters and then decide from Figure 2 to which sector the temperature and energy parameters belong; the relative likelihood of types (A) and (B) is then given in Table VII against the mean-wind parameter.

Other parameters. No evidence was found that the changes in the tropopause height or changes in the transition height of the wind flow to the upper north-easterlies had any influence on type of development. Only the sea-breeze, forming convergence lines, was a significant factor and can change the development pattern from (A) to (B).

Further comments. As a result of the availability of moisture and energy over the area, development type (C) is present on nearly half of the days of the year and is more usual than either (A) or (B). Types (A) and (B) are both extremes of development and are therefore more important, the former as being a complete or almost complete absence of radar echoes while the latter constitutes the main hazard.

As development (C) falls between the two extremes, the position of the plot in Figure 2 of the obtained values of the moisture and energy parameters, especially if the wind criteria are also considered, will indicate the tendency towards one or other of the extremes.

Large changes in the environment occur from day to day, especially in moisture content, without a detectable change in air mass. These changes, which are too large to be considered as fluctuations in the air mass itself, can be attributed to the convergence/divergence flow pattern, though they are extremely difficult to forecast. Changes in the wind field are indicated in the local routine pilot-balloon data.

Conclusion. Although the synoptic situation with its convergence/divergence pattern is the main basis for forecasting likely convective development in the tropics, and in spite of the difficulties of objective classification of the cases mentioned earlier, it is considered that the criteria derived from dew-point depression/convective path curve as obtained in Figure 1, in conjunction with wind profile parameters, serve as a useful guide to convective development. An earlier version of this method was used for a considerable period at Singapore/Tengah and gave a fairly good assessment of actual observed convective development during day-time hours. Unfortunately, with only one upper-air ascent during a 24-hour period, changes in the environment, apart from purely synoptic ones, are hard to assess. The local pilot-balloon ascent can be used as a pointer to changes in the wind field. For development type (A), wind values in the 1000–700-mb layer are more applicable than values for the higher layer.

Acknowledgement. The author wishes to thank Mr J. J. Parry and Mr P. F. Abbott for their helpful suggestions and co-operation.

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NOTES AND NEWS

Retirement of Mr T. N. S. Harrower

Mr T. N. S. Harrower, Assistant Director of the Meteorological Office Branch responsible for meteorological services to the Royal Air Force and Army, retired on 31 December 1972 after 36 years service. He read mathematics and physics, amongst other subjects, at Glasgow University and, after taking his degree, was posted to Croydon to be one of the first Technical Officers in the Office to be given formal training in forecasting. Immediately after this training Mr Harrower was posted to Foynes to forecast for early transatlantic flights.

Tom served, as a Flight Lieutenant in the Royal Air Force, for most of the war years in the Middle East and was very lucky to escape with his life in the evacuation from Crete. On his return to the United Kingdom in 1944 he spent the next six years at Pitreavie where he was promoted to Principal Scientific Officer. After about seven years at London/Heathrow Airport and a similar time in branches dealing with aviation and general services he was promoted to Senior Principal Scientific Officer and took charge of the Forecasting Techniques Branch. As Assistant Director in charge of forecasting techniques he can claim that the work of his branch was largely responsible for putting the 3-level model into operational practice on KDF 9 to produce, for the first time in the Meteorological Office, numerical forecasts on a routine basis.

In 1966 Tom was posted to take charge of the Defence Services Branch where he remained until he retired. As Assistant Director (Defence Services) he controlled about one-third of the whole of the staff of the Meteorological Office. In the last few years there have been large changes in the organization of the Royal Air Force, including the withdrawal of British Forces from the Far East and the Persian Gulf and these changes have given rise to a heavy load of work in the Branch.

Tom has wide interests in scientific fields other than meteorology. He could easily have been a medical consultant or ornithologist and his ability to see, faster than most, the wood from the trees, would have ensured that he was successful in these disciplines. In addition he possesses a tenacity of purpose and his forthright way of stating his case will be missed in the Office, where undoubtedly he has been one of the characters for the last 36 years.

We all wish Mr and Mrs Harrower many years of happiness and good health in their native land to which they have returned.

V. R. C.

Conference on the observation and measurement of atmospheric pollution

The World Meteorological Organization and the World Health Organization are sponsoring a Technical Conference on the Observation and Measurement of Atmospheric Pollution in Helsinki, Finland, from 30 July to 4 August 1973. An international exhibition of meteorological and pollution-measuring instruments, sponsored by the host country will be held from 2 to 9 August 1973. The call for papers has been issued with a deadline of 1 March 1973 for submission of abstracts. Persons wishing to participate in the Technical Conference are invited to obtain further information about it from M. J. Blackwell, Meteorological Office, Met O 16, Beaufort Park, Easthampstead, Wokingham, Berks. Persons wishing to participate in the instrument exhibition are invited to obtain further information from the METEOREX 73 Exhibition Committee, P.O. Box 503, Helsinki 10, Finland.

OBITUARY

It is with regret that we have to record the death of Mr W. G. Fowler, Assistant Scientific Officer, St Mawgan, on 3 October 1972.

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