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THE CONTRIBUTION OF A WEATHER RADAR NETWORK TO FORECASTING FRONTAL PRECIPITATION: A CASE STUDY

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SUMMARY

The recent development at Malvern of techniques for the processing and transmission of composite radar data from several sites to remote centres brings nearer the possibility of providing meteorological offices with a real-time, semi-quantitative display of precipitation distribution. A case study of frontal precipitation is presented illustrating the value of such a system for mesoscale and synoptic-scale forecasting. The case is analysed using both a subjective and an objective approach. The indications are that improvements in the forecasts can be achieved for periods of three to six hours ahead.

1. INTRODUCTION

The purpose of this paper is to investigate by means of a case study the potential value of a network of quantitative radars for providing improved forecasts of frontal precipitation. The approach we have adopted is to concentrate on the mesoscale aspects of the precipitation patterns which have reasonable persistence, rather than on individual small-scale features.

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* Formerly the Royal Radar Establishment.

It is a long time since Ligda (1957) suggested the usefulness of a radar network by producing his montage. However, it is only recently that the technology has become available to provide the automatic compositing facilities that are required if the data are to be exploited for forecasting purposes (Taylor and Browning, 1974). The techniques for processing, transmitting and displaying the radar data are being developed by the joint team from the Meteorological Office and the Royal Signals and Radar Establishment at Malvern. The intensity of the echoes from precipitation is averaged over 5 km squares and displayed almost in real time on a colour television set at a remote site. Such data, obtained from a number of radars at intervals of approximately 15 minutes, can be replayed to reveal the movement and development of the precipitation. This obviously helps in making short-period forecasts by subjective extrapolation of existing trends. Additionally the information is available in a computer-compatible format which is suitable as an input to objective forecasting schemes. Hence the technique is capable of being exploited to the benefit of both subjective and objective methods of prediction. However, these are very recent developments and, in the absence of an ample network of quantitative weather radars in Britain for this synoptic-scale study, it has been necessary to simulate one using photographs from radars providing qualitative information only and to quantify much of the data by the analysis of autographic rain-gauge records.

The particular situation considered here is the occlusion of 14 February 1975. Although this case was straightforward in the sense that it lacked major orographic effects, it nevertheless provided a good example of other difficulties with which the forecaster is frequently confronted. One was the intensification of the precipitation, caused by a small-scale perturbation of the medium-level flow, as it crossed an area devoid of regular observations. A second difficulty was that the persistence of a narrow band of convergence near to the occlusion led to an accumulation of moderate falls of rain within restricted regions which were hard to locate by routine reports alone.

2. Evolution of rainfall in relation to the surface analysis and upper-air structure

Figure 1 shows the surface analysis and principal cloud areas at 2100 GMT on 13 February 1975. The northward progress of frontal systems had become slow owing to the intensification of a ridge of high pressure from Greenland to southern Norway. The depression shown in the Atlantic had been moving north-eastwards but it was expected to turn eastwards towards the English Channel, with the occlusion bringing rain to most parts of England and Wales on the following day.

Figure 2(a) shows the total rainfall for the complete system of precipitation associated with the occlusion, from the evening of the 13th when rain reached south-west Ireland until the afternoon of the 15th when it cleared from south-east England. It can be seen that falls of from 15 mm to over 30 mm occurred in a fairly narrow band from south-west Wales to Kent, whereas comparatively little rain affected Ireland and south-west England. The movement of the precipitation is depicted by the set of hourly rainfall maps (Figures 2(b–k)). For these, radar evidence has been used to supplement data from autographic rain-gauges, particularly with regard to the existence of the bands over Ireland, the location and movement of the rain over the Irish Sea, and the intensity over

Wales and the Midlands at times when the precipitation was partly composed of snow.

Before 0200 on the 14th, none of the twenty autographic gauges over southern Ireland recorded more than 0·5 mm in any hour, with most falls being only a trace. By 0400, however, Figure 2(b) shows that small areas of moderate rain had appeared. The radar evidence is that they were organized into west-north-westerly to east-south-easterly bands which were moving slowly eastwards. Meanwhile broader bands of mainly slight rain were moving north-eastwards across the Celtic Sea. The rainfall intensified during the next three hours, both

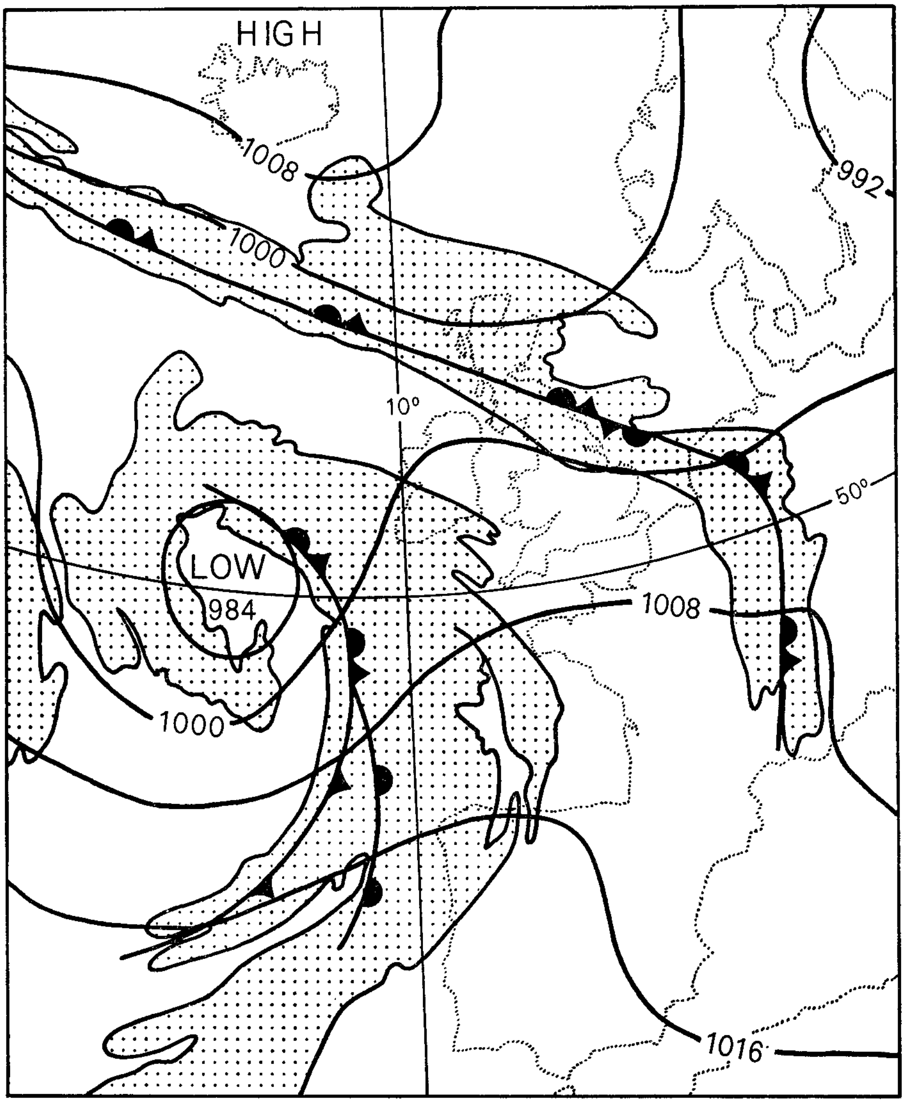


FIGURE 1—SURFACE ANALYSIS FOR 2100 GMT, 13 FEBRUARY 1975, WITH SATELLITE NEPHANALYSIS OF PRINCIPAL CLOUD AREAS

in the bands over central Ireland and near the coast of south-east Ireland. By 0700 moderate rain covered most of the Irish Sea to the south of a line from Dublin to Anglesey (Figure 2(c)). This intensification was associated with increased vertical velocity below approximately 500 mb on the southern flank of an upper trough which had moved east-south-eastwards across northern Ireland during the night. Calculations of the convergence using Bellamy triangles* show that the maximum vertical velocity was over Cardigan Bay by

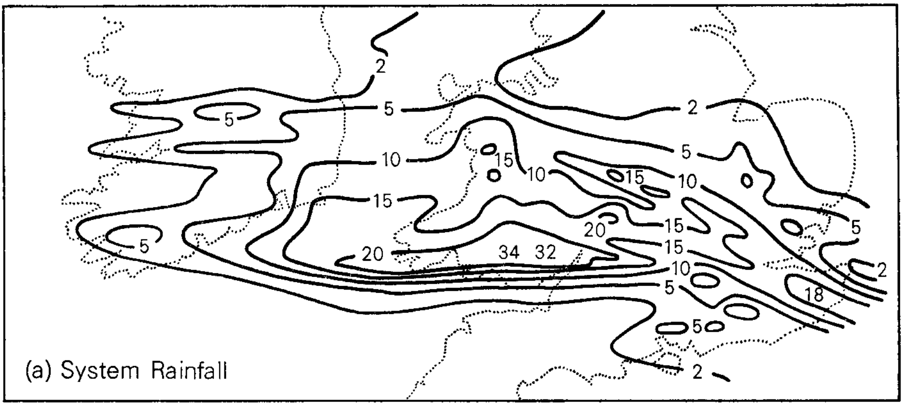


FIGURE 2(a)—SYSTEM RAINFALL (mm) COMPILED FROM DAILY TOTALS AND AUTOGRAPHIC GAUGES

the late morning and that this convergence zone extended east-south-eastwards across Wales and central England during the day (Figure 3).

From 0600 it is possible to divide the area of rain over the Irish Sea into two broad regions and to consider their history in relation to the midday upper-air analyses (Figures 3 and 4). This account is supported by a series of ascents launched by the Malvern Research Unit from a site near Pembroke and by some non-routine ascents launched by the Meteorological Offices at Aberporth, Camborne and Liverpool (Aughton). Although the intensification of the whole rain area appears to have been due to the proximity of the upper trough, the southern part was also in the region of weaker convergence associated with the occlusion. The precipitation in this region was generated by the ascent of a narrow band of warm moist air at low levels. The winds veered with height within this band from south-easterly near the surface to westerly at 700 mb, so that the eastward component through the band was small. Around the southern flank of the upper trough, slight veering of the wind above 700 mb brought cooler but still quite moist air across the top of this warm tongue, thus enhancing the potential instability which in the heavy rain extended from 750 to 600 mb. The warm air near the surface did not penetrate much further north than St George's Channel and the air at low levels over Cardigan Bay and central Wales remained cold and comparatively dry (Figure 4 (b)). The precipitation over North Wales was generated mostly between 700 and 500 mb, which levels were

* Divergence is calculated from the rate of change of area of a triangle assumed advected with the winds measured at its apexes. (J. C. Bellamy; Objective calculations of divergence, vertical velocity and vorticity. *Bull Amer Met Soc*, **30**, 1949, pp. 45–50.)

close to the axis of the stronger west-north-westerly winds which lay across central Wales. Further, the air was considerably drier to the north-west of the trough axis. Hence, as the trough continued to move across central England, the precipitation in the northern part of the rain area was carried east-south-eastwards fairly quickly and clearer weather reached North Wales by the early afternoon. In effect, the northern half of the rain area became detached from the southern half which continued to move slowly eastwards. This differential motion is evident in Figures 2(e–g), where the distinct areas have been labelled **A** and **B**.

During the evening, the air up to middle levels from southern Ireland to South Wales remained comparatively moist and unstable, and with weak convergence persisting in this region further outbreaks of moderate rain moved eastwards to the rear of area **B**, resulting in rainfall totals of over 20 mm in a narrow band across South Wales. The occlusion became quasi-stationary across southern England during the night and area **B** moved slowly along it. The rainfall analyses suggested that some new development occurred in the northern part of **B** and moved south-eastwards, but in general the area of appreciable rain remained compact as it approached south-east England (Figures 2(i–k)). Those parts of London and Kent which came under the converging paths of the cells received a total rainfall of over 15 mm.

3. The contribution of a radar network to subjective analysis and forecasting

In this case study there were a number of problems which confronted the analyst for which the existence of a radar network could have provided valuable information. They are described here in chronological order.

(a) *To establish the extent and intensity of the developing rain area before it reached Wales.*

During the night of 13/14 February, all the synoptic reports indicated that the occlusion was a weak feature. The Shannon radar at first confirmed this, revealing at 0115 only thin bands of echo moving eastwards. However, by 0515 the echoes had intensified and the bands had become broader as they moved across central Ireland (Figure 5). It is likely that a radar covering south-east Ireland would have shown the development of the rain associated with areas **A** and **B** as early as 0500 but, with only routine reports available, the passage of **A** to the south of Dublin (which remained dry throughout) prevented adequate warning of the moderate precipitation which was shortly to reach North Wales. Only Rosslare reported moderate rain as area **B** intensified. Figures 6(a–b) show the 0750 surface chart and the composite radar display for 0900, presented together for comparison of the two sets of data which would have been available at approximately the same time. Apart from clarifying the extent of the precipitation affecting Wales, the radar showed that another area of heavy rain (i.e. area **B**) was already close to the coast of south-west Wales. However, this reached Brawdy and Aberporth too late for the 0850 observations, so that it was not until 1030 by teleprinter and 1110 by facsimile that the existence of this heavy rain was established on the basis of routine observations.

(b) *To predict the northern limit of appreciable rain over England*

During the late morning, rain occurred at most of the observing stations in Lancashire. As late as 1250, Blackpool reported moderate rain (Figure 7(a)).

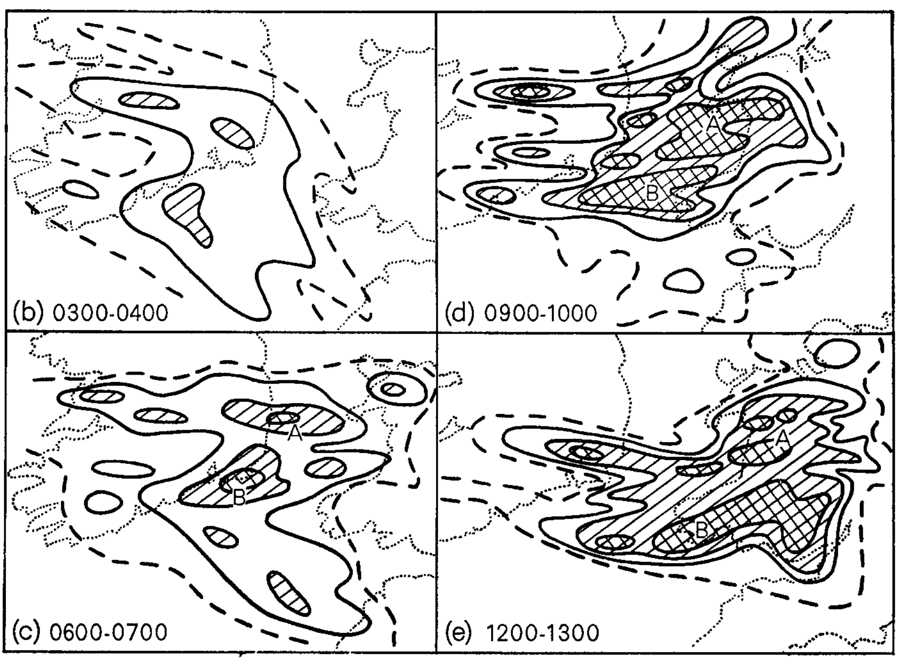
The impression given was that north-west England might still have a significant rainfall as the occlusion edged north-eastwards. However, the radar evidence was that Lancashire was being affected by a relatively small area of mainly slight rain which was moving east-south-east and that this would soon be followed by dry weather (Figure 7(b)).

(c) *To anticipate the movement of precipitation across the Midlands*

Referring again to Figure 7(a), the synoptic chart leaves much to the imagination as regards the location and movement of the heavier precipitation areas, given that the surface pressure was continuing to rise slowly over most of England. Apart from identifying these areas, the radar showed that over North Wales the rain was moving steadily east-south-east ahead of a clearance, while the rain nearer to the occlusion was moving only slowly eastwards. Thus the elongation of the rain area due to this differential motion would have been observable quite early in the afternoon by a radar network but was not apparent at any time in the routine observations, even in retrospect, owing to such factors as the large gaps which exist between reporting stations in some regions and the wide range of precipitation intensities which are possible between routine observations.

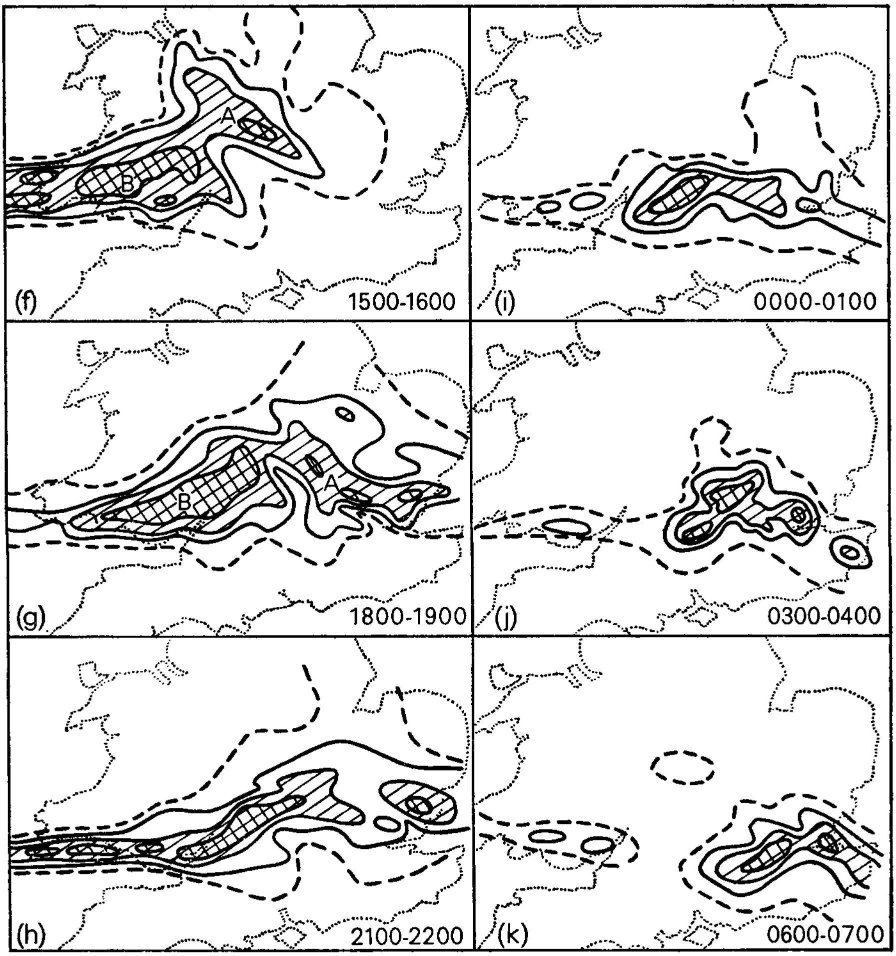
(d) *To identify small areas of rainfall of rather high intensity over south-east England*

The occlusion became slow moving across southern England during the



FIGURES 2(b–k)—HOURLY RAINFALL TOTALS AT 3 HOUR INTERVALS COMPILED FROM RADAR DATA AND OVER 100 AUTOGRAPHIC GAUGES

Contours at 0.1 mm (broken lines), 0.5 mm (full lines), 1.0 mm (hatched), 2.0 (cross-hatched). Letters A and B refer to centres of general rain areas discussed in text rather than specific cells.



FIGURES 2(b–k)—*continued*

evening. Despite the superior surface network of observations in this region, the boundaries of the main concentrations of rain became obscure as area **B** moved across the south Midlands (Figure 8). No radar evidence can be presented here, but it seems from the detailed rain-gauge analyses that cells in the northern part of area **B** may have intensified and then moved south-eastwards across the Chilterns towards Kent. At the same time the rainfall maxima in the southern part of area **B** continued to move on a more easterly course. Thus the constriction of the higher rainfall totals into a narrow band across London and Kent could probably have been anticipated, by the persistence of current trends, as early as 0300 if radar data had been available.

4. THE USE OF A RADAR NETWORK FOR OBJECTIVE RAINFALL FORECASTING

In this section we assess the potential of objective forecasting methods, using information obtained in the 14 February 1975 case study. The basic data for the forecasts were the hourly rainfall accumulations of which examples are shown in Figures 2(b–k). As already noted, these results were inferred from the available radar data, supplemented by autographic rain-gauge measurements.

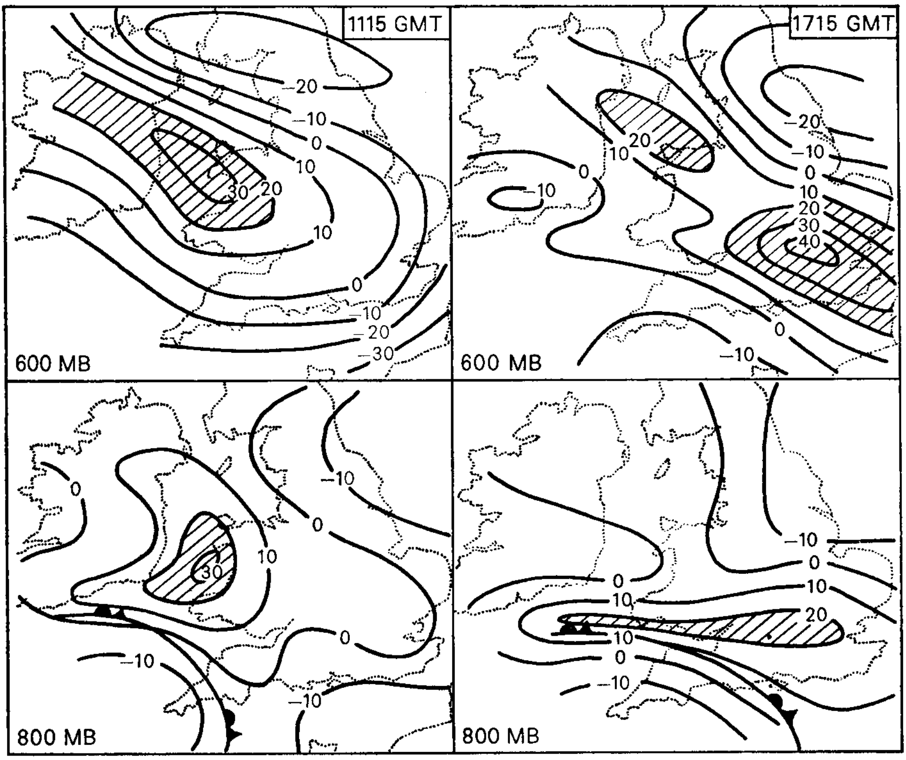


FIGURE 3—VERTICAL VELOCITY (mb h^{-1}) AT 800 AND 600 mb, AT 1115 AND 1715 GMT, 14 FEBRUARY 1975

Main areas of ascent are hatched.

We consider that these rainfall fields are of comparable accuracy to what might be obtained by a network of weather radars whose spacing was dense enough to ensure reliable quantitative coverage for the region being considered. In an actual forecasting situation the accuracy could be impaired if too much reliance was placed on radar information from beyond the effective quantitative range (about 100 km with the present generation of weather radars). For this study digitized rainfall data were available from one radar (Llandegla) for 5 km squares, but the other data sources did not always justify a resolution finer than 10 km and so the hourly rainfall fields were digitized manually on an 82 × 45 10 km grid. A logarithmic scale for rainfall intensity was used so that in the subsequent computation not too much weight was given to the heavier rain cells compared with the size and shape of the rain area as a whole. An example, for 1100–1200 GMT, is shown in Figure 9. Hourly data of this kind formed the input to a computer program which used the pattern-matching technique described by Austin and Bellon (1974) (and previously used by Leese *et alii* (1971) for obtaining cloud motions) to determine the mean pattern velocity from hour to hour. This translation velocity was found by calculating the correlation between successive rainfall fields for various spatial displacements and selecting the displacement corresponding to the maximum correlation. Forecast rainfall accumulations for up to six hours ahead were then produced by a simple extrapolation of the existing pattern with the translation velocity. About three minutes central processing time was required for each forecast on an ICL 1907F computer.

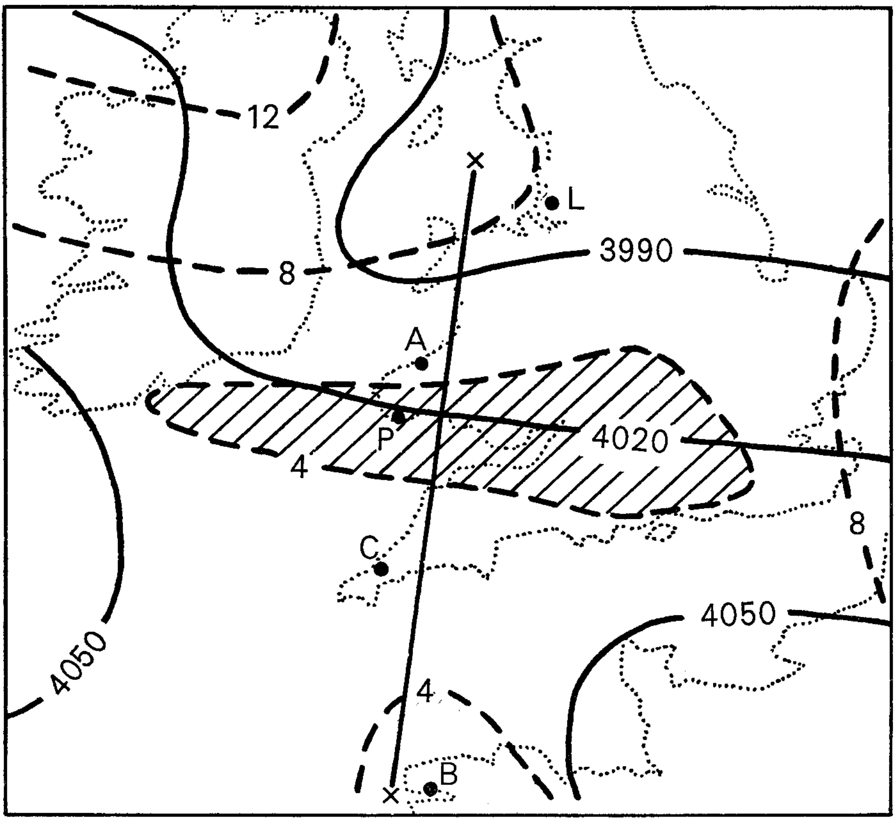


FIGURE 4(a)—600 mb ANALYSIS FOR 1115 GMT, 14 FEBRUARY 1975

——— geopotentials (gpm) - - - - dew-point depression (°C)
X ——— X location of cross section shown in Figure 4 (b)
L — Liverpool, A — Aberporth, P — Pembroke, C — Camborne and B — Brest
Main area of moist air is hatched. (Correction on p. 96).

The main results from this experiment are displayed in Table I which summarizes the outcome of six forecasts made at three-hourly intervals, using an advecting velocity determined from (a) the previous hour, and (b) the average of the previous three hours. In each case the forecasts are of the rainfall accumulated during the succeeding six-hour period and averaged over 20 km squares. The further reduction in the spatial resolution from 10 to 20 km for the purpose of forecast assessment represents a balance between smoothing out errors on the 10 km scale and retaining forecastable detail. Examples of two of the forecasts compared with the actual six-hour accumulations are shown in Figures 10 and 11. These show good general agreement in the size and shape of the rain area and in the total accumulations. However, in each case the positioning of the heavier rainfall is too far south, the reason for which will be discussed later.

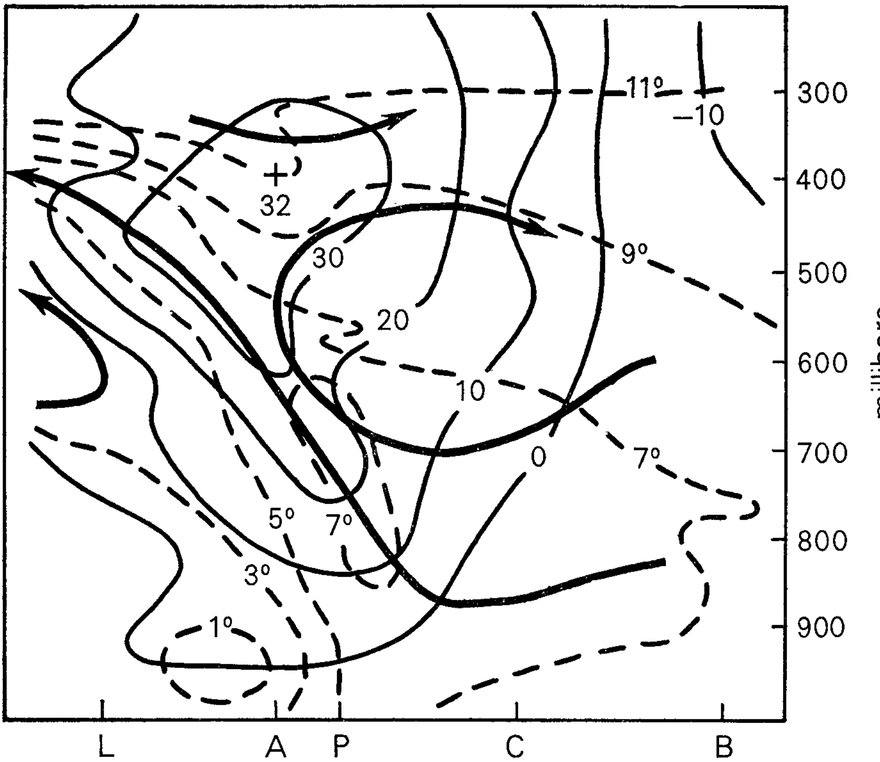


FIGURE 4(b)—1115 GMT, 14 FEBRUARY 1975: CROSS SECTION USING ASCENTS AT LIVERPOOL (L), ABERPORTH (A), PEMBROKE (P), CAMBORNE (C) AND BREST (B)

——— wind component (kn) normal to cross section, i.e. along mean direction of movement of precipitation area
– – – – wet-bulb potential temperature (°C)
Arrows represent the transverse circulation inferred assuming two-dimensional continuity in the plane of the Figure.

Listed in Table I are the absolute error averaged over all the 20 km grid squares and also the root mean square (r.m.s.) error and correlation coefficient evaluated over the same grid (unbracketed values). Since for much of the area a successful forecast of no rainfall needs little skill, the errors and correlations have also been calculated after eliminating correct forecasts of zero, and these values are bracketed in Table I. A comparison of the results in Tables I(a) and I(b) shows that averaging the objectively determined motion over three hours produced only a slight improvement compared with using the movement over the previous hour. The main improvement is in the forecast from

0600, and this is probably because early in the period the results of individual cross correlations were adversely affected by unavoidable inaccuracies in the rainfall analyses over the sea.

TABLE I—ERRORS AND CORRELATIONS FOR SIX HOUR FORECASTS OF ACCUMULATED RAINFALL MADE AT THE SPECIFIED TIMES FOR 14 FEBRUARY 1975

	Start time for six-hour forecast (GMT)	Predicted translation velocity (10 km grid lengths per hour) East	North	Mean absolute error *mm*	r.m.s. error *mm*	Correlation coefficient
(a)	0600	0	1	1·0 (1·9)	2·1 (2·9)	0·58 (0·45)
	0900	2	0	0·9 (1·7)	2·1 (3·0)	0·70 (0·61)
	1200	3	−1	1·0 (2·0)	2·4 (3·4)	0·69 (0·60)
	1500	3	0	0·5 (1·0)	1·1 (1·7)	0·91 (0·88)
	1800	2	−1	0·5 (1·9)	1·5 (2·9)	0·74 (0·59)
	2100	1	0	0·5 (2·1)	1·5 (3·1)	0·85 (0·77)
(b)	0600	$1\frac{1}{3}$	0	0·8 (1·7)	1·7 (2·5)	0·75 (0·65)
	0900	2	0	0·9 (1·7)	2·1 (3·0)	0·70 (0·61)
	1200	2	$-\frac{2}{3}$	0·9 (1·9)	2·3 (3·4)	0·76 (0·69)
	1500	$2\frac{2}{3}$	0	0·5 (1·1)	1·1 (1·7)	0·90 (0·88)
	1800	$2\frac{2}{3}$	$-\frac{2}{3}$	0·4 (1·5)	1·3 (2·4)	0·82 (0·72)
	2100	$1\frac{1}{3}$	0	0·4 (2·0)	1·4 (3·0)	0·86 (0·78)

(a) Translation velocity determined from displacement over previous hour.
(b) Translation velocity determined from average displacement for previous three hours
Bracketed values calculated after eliminating matchings of zero rainfall.

Table I shows that the average r.m.s. error in the forecast accumulation over six hours is about 2·7 mm when grid squares with correct zero forecasts have been eliminated. This is rather smaller than the actual rainfall accumulation (3 mm) averaged over all the non-zero squares and is much smaller than the peak rainfall (20 mm) accumulated in the wettest grid square. In fact, after

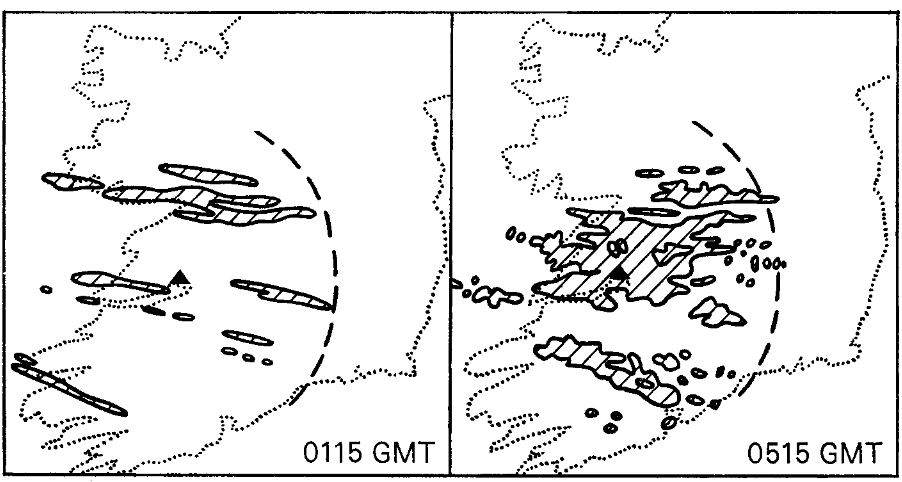


FIGURE 5—RADAR ECHOES OBSERVED AT SHANNON, 0115 AND 0515 GMT, 14 FEBRUARY 1975

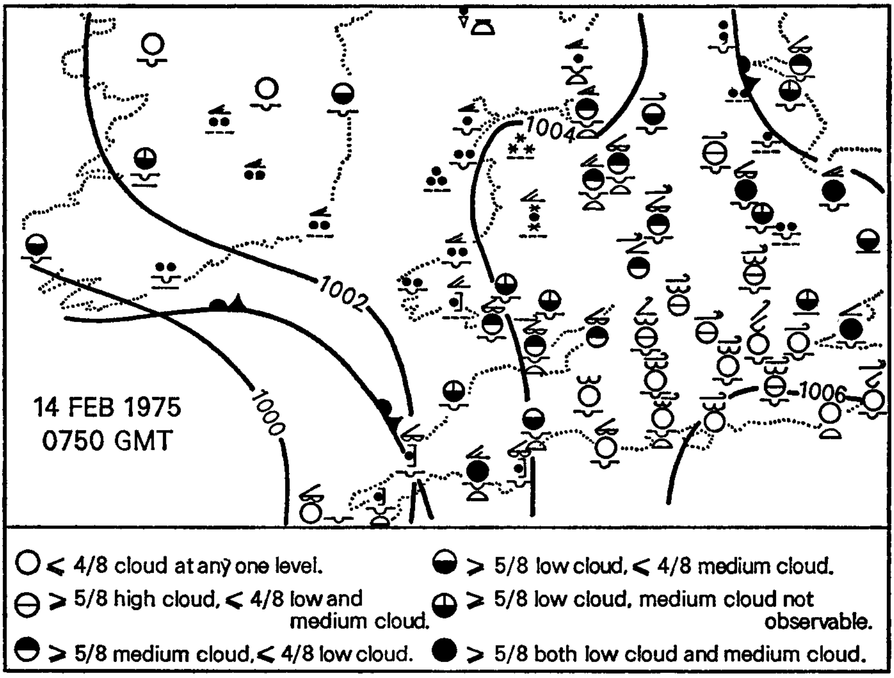


FIGURE 6(a)—SURFACE CHART FOR 0750 GMT, 14 FEBRUARY 1975

Conventional symbols for precipitation and cloud types are used.

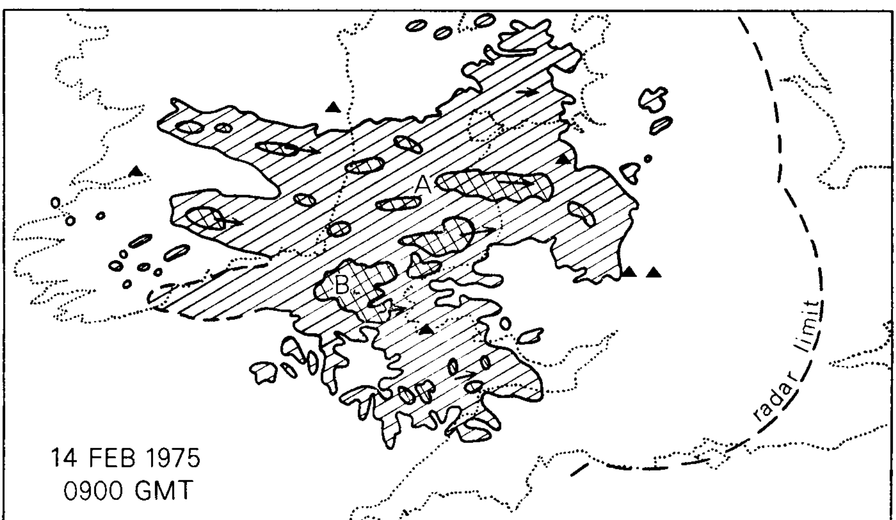


FIGURE 6(b)—COMPOSITE RADAR DISPLAY FOR 0900 GMT, 14 FEBRUARY 1975

Sites used (shown by triangles) at Shannon, Dublin, Llandegla (North Wales), Pembroke (south-west Wales), Malvern and Defford (Worcestershire). Areas of moderate and strong echoes are cross-hatched. Approximate hourly movement is indicated by arrows. A and B indicate centres of general areas referred to in text rather than specific cells.

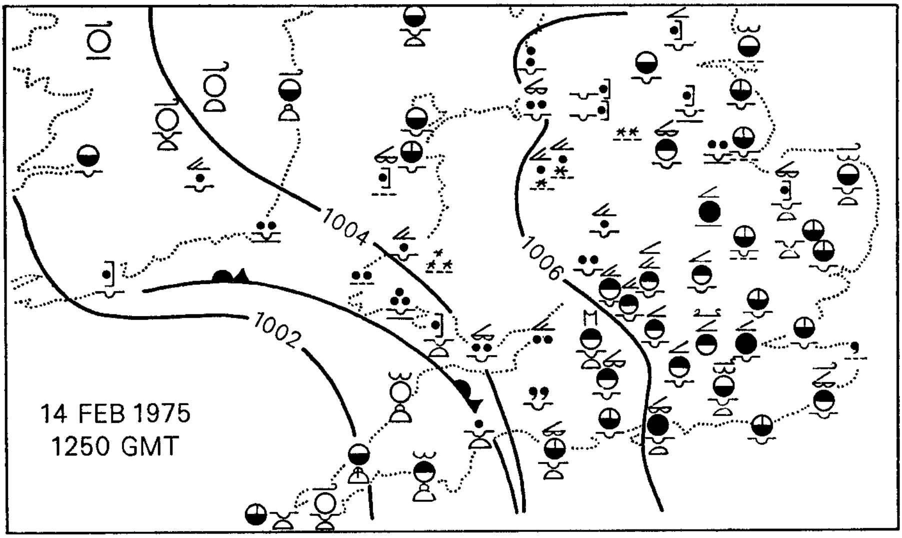


FIGURE 7(a)—SURFACE CHART FOR 1250 GMT, 14 FEBRUARY 1975
Legend in Figure 6(a) applies. (Correction on p. 96).

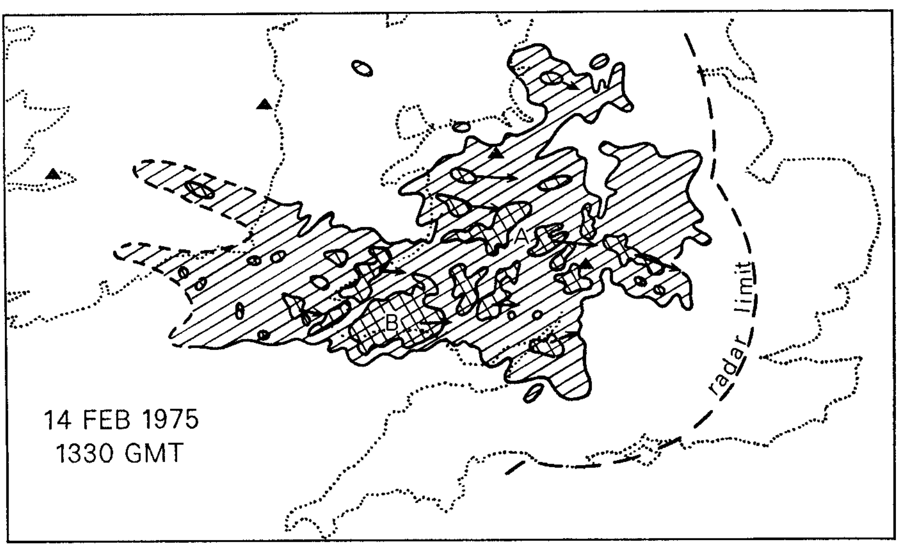


FIGURE 7(b)—COMPOSITE RADAR DISPLAY FOR 1330 GMT, 14 FEBRUARY 1975
Legend in Figure 6(b) applies.

ignoring correct forecasts of zero rain, values for 81 per cent of the remaining 2200 grid squares in the six forecasts are within 3 mm of the actual six-hour accumulation. It is therefore considered that these six-hour forecasts do give a useful, albeit crude, indication of the magnitude and distribution of the rainfall on a 20 km scale. Part of the inaccuracy is due to errors in the predicted translation velocity but, as will be shown later, most of it is caused by the neglect of development and changes in the shape of the rain area.

So far we have given no indication of the quality of the forecasts regarding the detailed trend of rainfall intensity within each six-hour period. To examine this aspect we have considered forecasts for two specific grid squares. These forecasts are illustrated in Figure 12 which compares, for the 20 km squares containing Birmingham and Oxford, the actual rainfall rate with overlapping zero-to-six-hour predictions made at three-hour intervals. The better forecasts are those for the Birmingham square, where the increase and decrease in the forecast precipitation rate correspond quite well with the actual rainfall profile although the forecast times of commencement and cessation of the rain are in error by two hours or so. Predictions for the Oxford square suffer from being on the edge of the heavier rain area for much of the period. As a consequence the rain is forecast to be slightly heavier than it actually was and to intensify earlier than in fact it did.

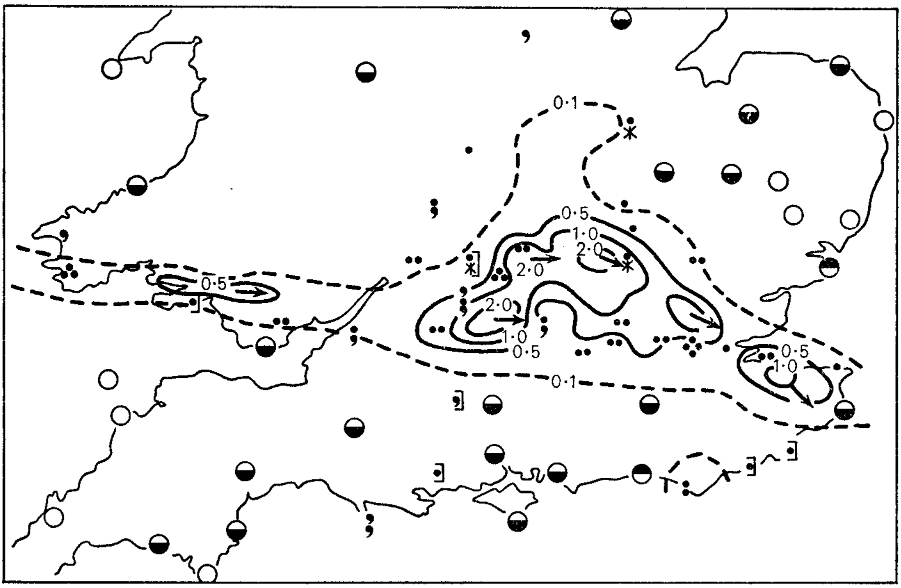


FIGURE 8—SURFACE OBSERVATIONS FOR 0250 GMT, 15 FEBRUARY 1975, COMPARED WITH TOTAL RAINFALL FOR 0200–0300

Cloud symbols are as Figure 6(a).

The objective forecasts discussed above have been obtained very simply by neglecting any development in the pattern and any distortions in the shape of the rainfall area caused by the differential motion of its different parts. We know that this will have introduced errors because, as discussed in Section 2, not only was there an overall long-term trend in the vigour of the system but also the rain areas **A** and **B** travelled with different velocities. Although this did not invalidate the overall coarse prediction, it did account for the forecasts of the peak rainfall accumulations in Figures 10(a) and 11(a) occurring about 40 km further south than the actual peak values as shown in Figures 10(b) and 11(b). These peak accumulations were associated with rain area **B** (see

PLATE I—AWARDS TO CIVIL AIRLINE CAPTAINS

From left to right: Captain W. J. Jackson and Miss Jackson, Director-General of the Meteorological Office, Mrs Jones and Captain R. A. E. Jones (see p. 93).

PLATE II—AWARD WINNERS WITH MAJOR AND MRS K. G. GROVES, AIR MARSHAL D. G. EVANS AND AIR COMMODORE D. F. M. BROWNE (DIRECTOR OF FLIGHT SAFETY ROYAL AIR FORCE)

Left to right: Mrs Groves, Mr C. L. Hawson, Major K. G. Groves, Chief Technician T. C. Maine, Air Marshal D. G. Evans, Mr D. J. George and Air Commodore D. F. M. Browne (see page 91).

PLATE III—MRS K. G. GROVES PRESENTING MR D. J. GEORGE WITH THE METEOROLOGICAL OBSERVER'S AWARD

(See page 91)

To face page 83

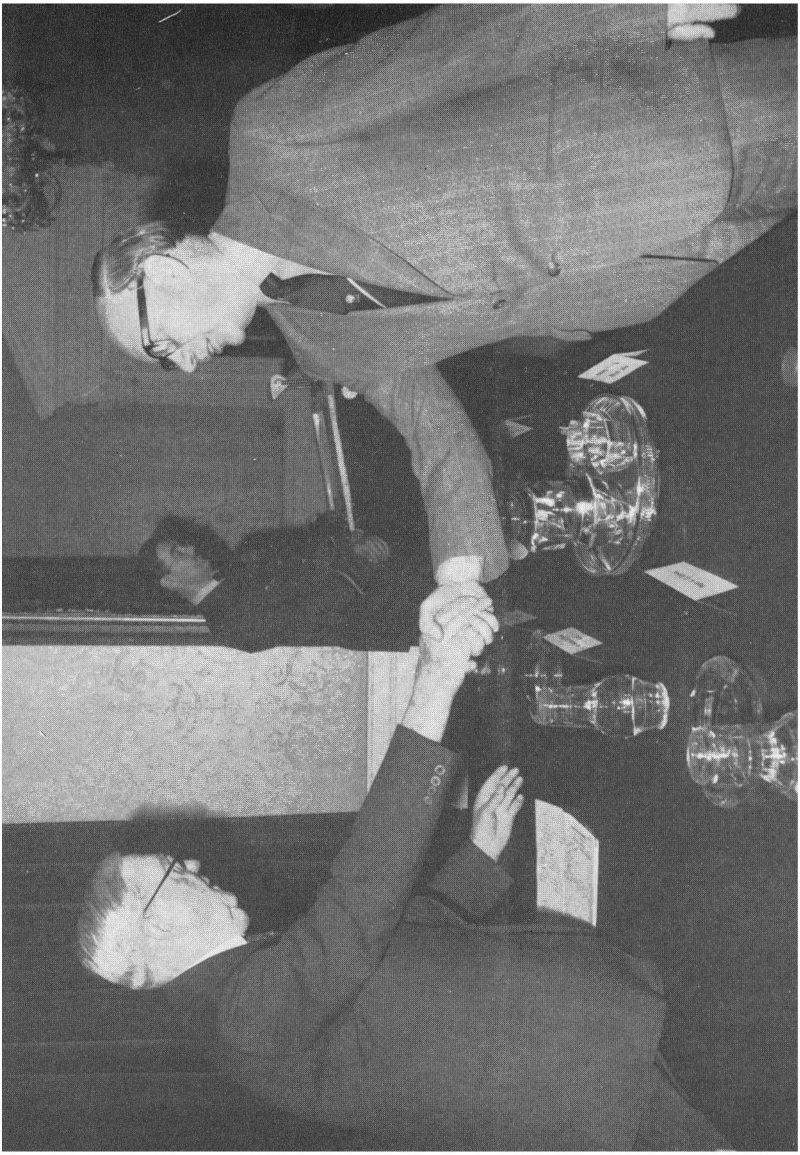


PLATE IV—MAJOR K. G. GROVES PRESENTING THE 1976 METEOROLOGY PRIZE TO MR C. L. HAWSON

(See page 91.)

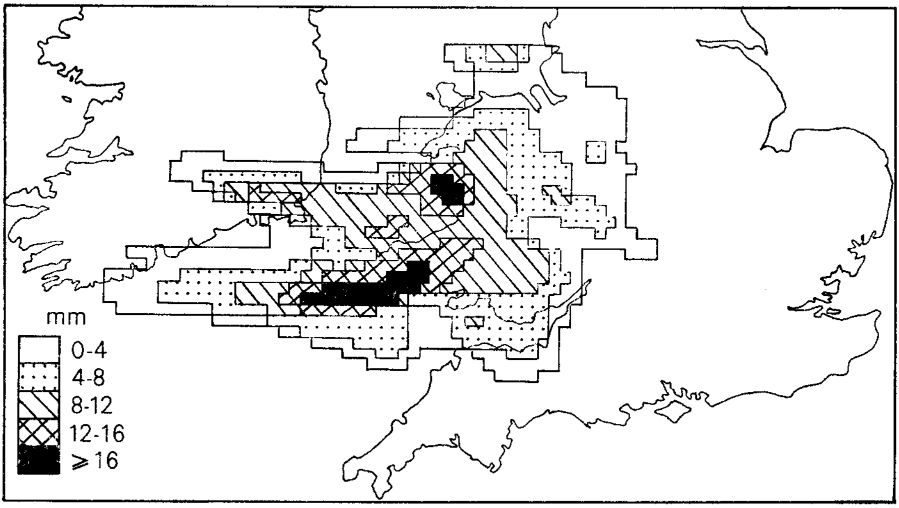


FIGURE 9—DIGITIZED RAINFALL FIELDS ON A 10 km GRID FOR 1100–1200 GMT, 14 FEBRUARY 1975

Section 2) which radar showed to have had less of a southerly component than the average for the entire rain area.

In order to isolate the errors due to distortion and development from those due simply to a non-optimal translation of the whole rain system, the results were recalculated using a number of different translation velocities at intervals of half a grid length per hour in each component. The velocities which gave the most accurate six-hour accumulations, using the criterion of lowest r.m.s. error, for each of the six forecast periods, are listed in Table II together with the corresponding errors and correlations. After eliminating correct matches of zero, the average lowest r.m.s. error for the remaining grid squares over the six periods is 2·3 mm. This value is not very much less than the average r.m.s. error of 2·7 mm from Table I(b) thereby confirming that the errors listed in Table I, although due in part to non-optimal forecast motions for the overall system, are mainly caused by effects such as development and differential movement of the various rain areas.

TABLE II—THE MOTION TO THE NEAREST HALF GRID LENGTH GIVING THE LOWEST r.m.s. ERROR, WITH CORRESPONDING ERRORS AND CORRELATIONS FOR THE SAME AS TABLE I

Start time for six-hour period (GMT)	Translation velocity (10 km grid lengths per hour) East	North	Lowest mean absolute error (*mm*)	Lowest r.m.s. error (*mm*)	Correlation coefficient
0600	$2\frac{1}{2}$	0	0·7 (1·5)	1·6 (2·3)	0·80 (0·72)
0900	2	−1	0·8 (1·5)	1·7 (2·4)	0·84 (0·79)
1200	3	0	0·7 (1·6)	1·7 (2·6)	0·89 (0·86)
1500	3	0	0·5 (1·0)	1·1 (1·7)	0·91 (0·88)
1800	$2\frac{1}{2}$	$-\frac{1}{2}$	0·3 (1·3)	1·0 (2·0)	0·90 (0·83)
2100	3	0	0·4 (1·7)	1·3 (2·7)	0·81 (0·71)

Bracketed values as in Table I

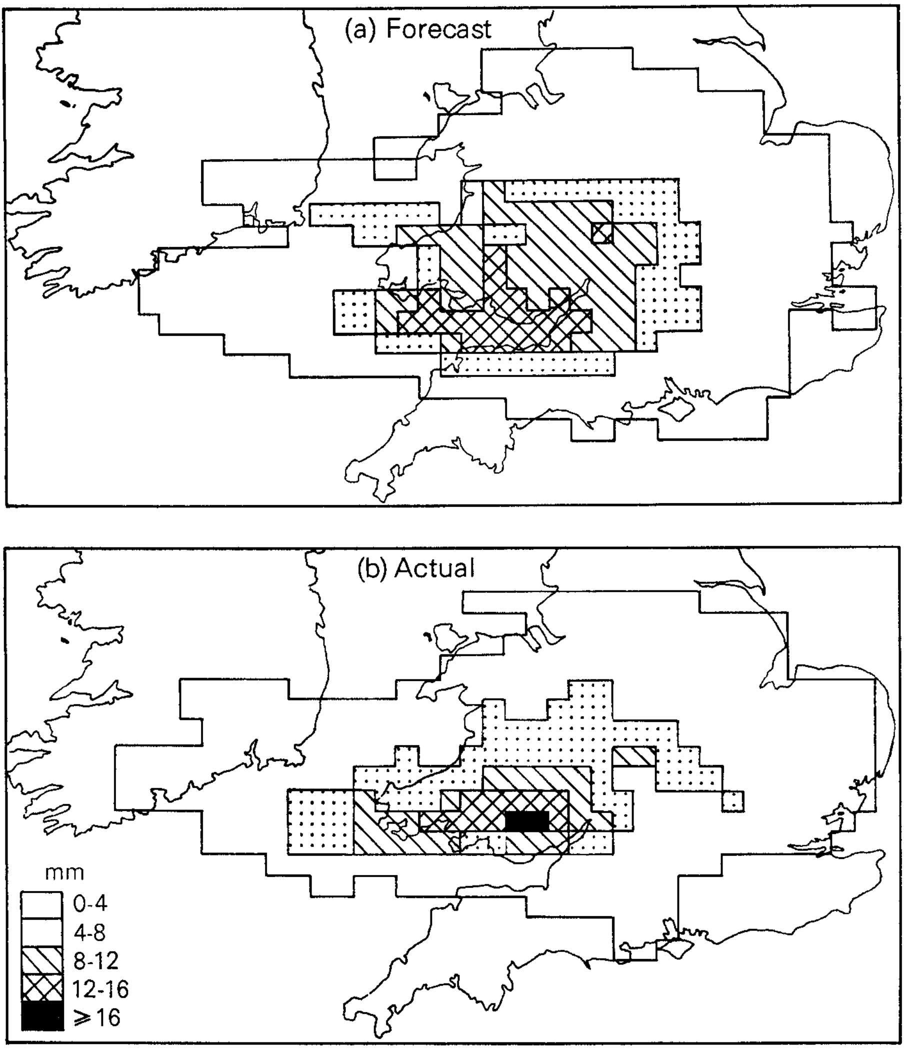


FIGURE 10—FORECAST AND ACTUAL RAINFALL ACCUMULATIONS ON A 20 km GRID FOR 1200–1800 GMT, 14 FEBRUARY 1975

Attempts to forecast the motion of separate rain areas or of different identifiable parts of large areas have been made by various workers (notably Blackmer *et alii* (1973)) who have objectively tracked such cells between successive radar pictures. An objective tracking procedure has also been developed by Ostlund (1974). There are problems with this approach in selecting an arbitrary threshold to define the cell boundaries and in dealing with splits and mergers of echoes, and we have not attempted such a procedure in this instance. Instead we have experimented with an alternative technique, dividing the total area into a number of sub-areas (which may either be fixed or move with the system

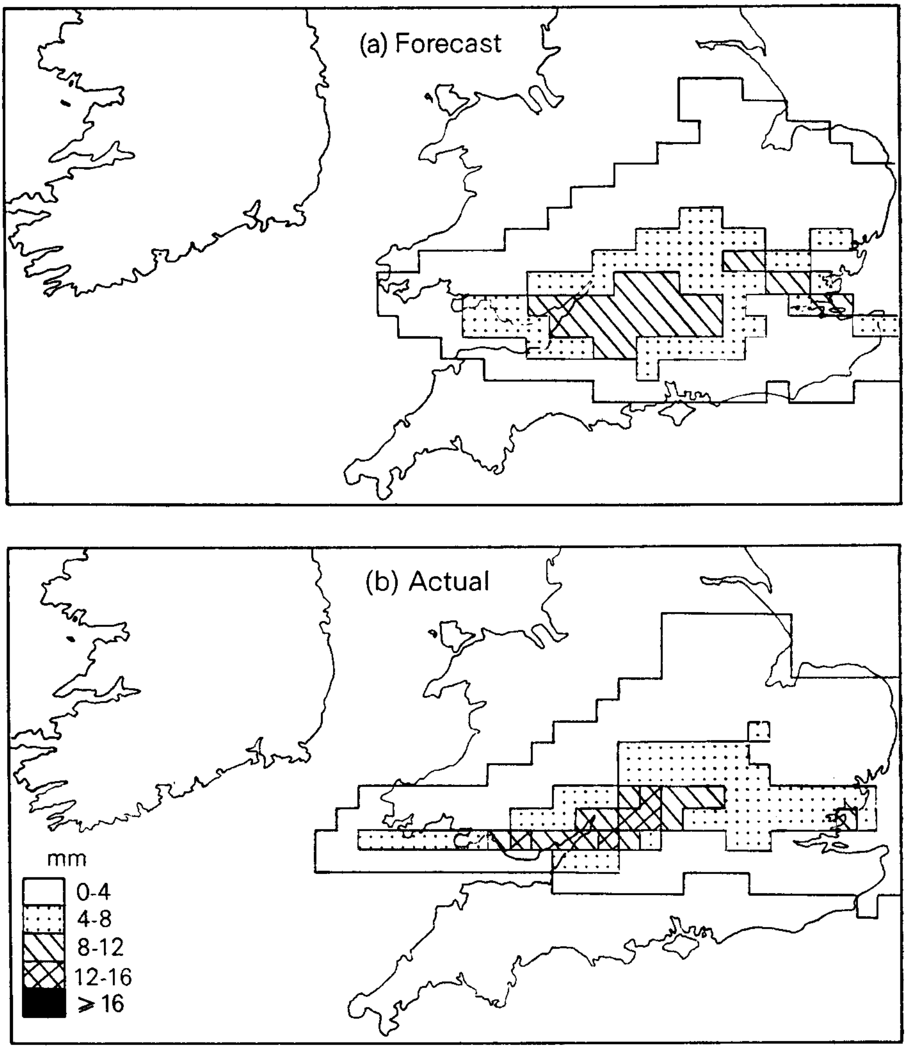


FIGURE 11—FORECAST AND ACTUAL RAINFALL ACCUMULATIONS ON A 20 km GRID FOR 1800–2400 GMT, 14 FEBRUARY 1975

velocity) and then using the basic cross-correlation method to determine a separate translation velocity for each sub-area. However, some smoothing of the forecast fields is necessary where discontinuities develop at the sub-area boundaries. In attempting to deal with the problem of development and decay we have adopted a simplified version of Schaffner's (1975) proposed forecast equation in which straightforward advection of the rain area has been supplemented by extra terms representing its linear intensification and its expansion or contraction. In the present case this method of handling development, used in conjunction with moving sub-areas, produced some slight improvements in the first two hours of the forecasts. The differing motions determined by the sub-area method confirmed the south-eastward movement in the north and the eastward translation of the southern section of the rain area discussed earlier; however, attempts to extrapolate development and differential motion beyond two hours have led to rapidly increasing errors.

Finally, it is worth while mentioning alternative ways of deriving the pattern velocity. Clearly, more weight could have been given to the motion of the heavier rain cells by correlating the actual rainfall fields (rather than their logarithmic transformation) or by ignoring values below a particular threshold. Both these methods were tried but neither resulted in improved predictions in this instance, nor was any benefit gained from interpolating within the field of correlation coefficients to obtain non-integral grid-length displacements. Another approach is that adopted by Tatehira and Makina (1974), who have produced four-hour forecasts using the 700 mb wind as the steering velocity, together with a field of development tendency. However, in the present study the height of the wind field that corresponded best with the rainfall translation varied from 800 to 600 mb and, of course, in general the optimum mid tropospheric level to use would be difficult to determine in advance.

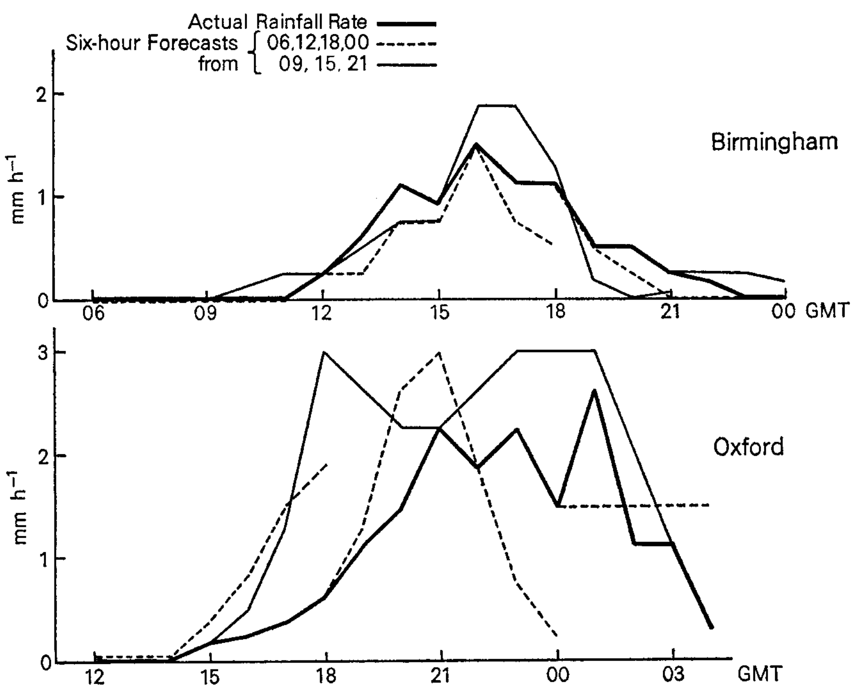


FIGURE 12—ACTUAL RAINFALL COMPARED WITH SIX-HOUR FORECASTS MADE EVERY THREE HOURS FOR THE 20 km SQUARES CONTAINING BIRMINGHAM AND OXFORD, FOR 14–15 FEBRUARY 1975

5. Conclusions

It is suggested in this case study that significant improvements in subjective analysis would have been possible given the prompt availability of data from an adequate radar network. Developing areas of moderate frontal precipitation would have been observed up to four hours before their existence was established on the basis of routine observations. Differential movement of the rain areas could have been detected while they were over the data-sparse regions of Wales and the west Midlands, and valuable information on the location of small areas of rather high intensity rainfall could have been obtained as they crossed south-east England. A simple pattern-matching technique has been used to simulate objective forecasts and these successfully reproduced the major features of the rainfall pattern for periods of up to six hours ahead.

Two of the four forecasting problems discussed in Section 3 could have been tackled by observations of echoes from isolated radars, as indeed can be the development of slow-moving storms in summer. Of course, facilities for prompt transmission of radar data are still required if meteorological offices remote from the radar are to supply forecasts for that region. However, for most mesoscale and synoptic-scale forecasts, isolated radar evidence is not sufficient. As an instance of this from the case discussed here, it is clear that the movement of the precipitation seen from Llandegla was appreciably different to that observed from Pembroke, and it required both radars to give a true impression.

We are enthusiastic about the immediate benefits that a radar network would bring to subjective forecasting. Subjective analysis is still the main tool for short-period forecasting; it depends on there being adequate surface and upper-air reports for the essential characteristics of a system to be diagnosed. Unfortunately the analyst is continually working with information which is to some extent out of date by the time it has been received, plotted and analysed, so that even the commencement of a forecast represents a projection of data acquired at least a couple of hours earlier. Further, the distribution of reports is uneven. Not only with localized showers and troughs but also in frontal systems, the areas of precipitation are often little more than a few mesoscale features which contribute the bulk of the total rainfall but cannot be resolved with the present inadequate network of observations. Hence there is all too often a failure to describe adequately the 'present' state of the weather in a given region—frequently a cause of greater irritation than later errors in the forecast itself. In addition, to the forecaster looking for confirmation of some anticipated development, the delay between its actual occurrence and the receipt of a report confirming it may so undermine his confidence as to lead to a rainfall forecast which lacks reference to what should be its chief ingredients: intensity, location and timing. A continuous display of current patterns of precipitation, even if only of a semi-quantitative nature, could become a powerful tool for the analyst, when supported by his knowledge of the dynamical influences involved and extended by conventional synoptic data.

The objective predictions in this case study gave a good indication of six-hour rainfall accumulations on a 20 km scale, but their accuracy was affected by development and differential motion of the precipitation areas. These are aspects which arise in all weather situations and are predominant in many, so that they impose limitations on the period to which the greater detail which would be possible in the analysis could be retained in the forecast. We have referred to several objective methods which endeavour to cope with these problems, but more work is required to devise adequate techniques of handling the wide variety of weather types that occur from day to day. It is likely that the availability of more continuous satellite data (e.g. METEOSAT) could be helpful in locating areas of imminent development. Further, the problem of rainfall enhancement due to topography was small in this case study, owing to light winds. This would not often be so, and for objective forecasts of orographic rain we may have to look to the development of empirical climatological rules, such as those formulated by Nicholass and Harrold (1975) for North Wales. Additionally, advected rainfall patterns could be used as input to a fine-scale numerical model such as that proposed by Collier (1975). If methods are devised of tackling these problems with a reasonable degree of success, we foresee the possibility of issuing useful objective forecasts to meteorological offices at regular intervals on the same television set as would be used to display the real-time radar data. The time taken to derive such a forecast and to display it would be as little as five minutes after the time of acquisition of the data on which the forecast was based.

Therefore we are confident that, at first as a result of more accurate and detailed subjective analysis and later perhaps by the routine dissemination of objective quantitative rainfall predictions, the establishment of a weather radar network would often lead to marked improvements in short-term forecasting. The length of the useful forecast period will depend on the characteristics of the weather system, the location of the region of interest with respect to it, and the limits imposed by the size of the radar network, but some improvement should frequently be possible for periods of three to six hours ahead.

6. Acknowledgements

The authors are grateful to the following organizations and individuals for their contributions as listed: the Irish Meteorological Service for data from the weather radars at Shannon and Dublin and for autographic rain-gauge charts; the Dee Weather Radar Project for data from the Llandegla radar; the staff from the Royal Signals and Radar Establishment for data from radars at Malvern and Defford; the Commanding Officer and staff at the Castlemartin RAC Range for use of the site; the radiosonde teams at Aberporth, Aughton and Camborne for launching non-routine ascents; the technical staff of the Meteorological Research Unit at Malvern led by S. R. Smith and the radiosonde team under D. Sumner; the voluntary observers who maintain autographic rain-gauges for the Malvern Meteorological Research Unit; the observers and authorities who provided additional rain-gauge data, including numerous meteorological offices; the Observational Requirements and Practices branch and the Agriculture and Hydrometeorology branch at Meteorological Office Headquarters Bracknell; all divisions of the Welsh National Water Development Authority; Rhondda Borough Council; the Anglian, Severn–Trent, Sussex, and Thames Water Authorities.

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THE METEOROLOGICAL MAGAZINE 1866–1977

The *Meteorological Magazine* has, in one form or another, been published for more than 111 years and we thought that our readers, particularly the new ones, would be interested in a brief history of how the Magazine came into being and of its subsequent management and organization, including an account of the various editors. The Magazine, as the official journal of the Meteorological Office, dates only from February 1920 and is really an amalgamation of *Symons's Meteorological Magazine* (published by the old voluntary British Rainfall Organization) and the official *Meteorological Office Circular.*

Symons's Meteorological Magazine

This magazine began its life in February 1866 as *Symons's Monthly Meteorological Magazine,* the monthly publication of the British Rainfall Organization, and hence owes its existence to that remarkable man George James Symons. F.R.S. Mill (1938) has given a succinct account of Symons's life, of how he resigned in 1863 from the Meteorological Department of the Board of Trade (later to become the Meteorological Office) in exasperation at the attitude of his official superiors, and of his immense achievement in creating the British Rainfall Organization virtually single-handed. Although the Magazine was started primarily to inform and unify Symons's army of co-operating voluntary rainfall observers, and was an improvement on his 'Rainfall Circulars' of the previous few years, almost from the first it carried short articles and notes on a wide variety of climatological and meteorological phenomena very much as the monthly magazine *Weather* (published by the Royal Meteorological Society) does today.

For a number of years before the end of the century Symons was helped in the task of running the British Rainfall Organization—which included editing the annual *British Rainfall* as well as the monthly Magazine—by H. Sowerby Wallis. Symons died in 1900 and on 1 January 1901 Hugh Robert Mill, D.Sc., LL.D., was appointed joint-director of the Organization with Wallis. Mill edited the Magazine until his early retirement—due to ill-health—in 1919; his life and work are well described by Glasspoole (1950) and Carter (1951). Following Mill's appointment the word 'monthly' was dropped from the title of the Magazine.

Mill's eyesight had given him trouble since 1913, and an increasing share of the responsibility for the Organization and its publications was taken by Martyn de Carle Sowerby Salter who became joint-director and joint-editor. Mill's retirement in 1919 coincided with the taking over of the British Rainfall Organization by the Meteorological Office, of which it became a Division with Carle Salter—as he was generally known—as its Superintendent. The last issue of *Symons's Meteorological Magazine* was for January 1920.

The Meteorological Office Circular

On 20 June 1916 the Meteorological Office began the publication of a leaflet called the 'Meteorological Office Circular' principally for distribution among observers. This provided a convenient means for the publication of official notices, changes in observing staff, brief reviews of recent publications and other matters of general meteorological interest. The first four numbers were edited by R. Corless, and the remainder by F. J. W. Whipple. The last issue was dated 2 February 1920.

The Meteorological Magazine

The *Meteorological Magazine* was first published in February 1920 with a cover which in addition to line-portraits of FitzRoy, Symons, Sabine and Strachey bore the words: THE METEOROLOGICAL MAGAZINE, *Symons's Meteorological Magazine Incorporating the Meteorological Office Circular.* (This design of cover was used until January 1937, the last issue of Volume 72.)

The Magazine was edited jointly by Carle Salter and F. J. W. Whipple who was Superintendent of the Climatological Division. An editorial in the last issue of the old Symons's Magazine stated 'Whilst becoming, as a matter of course, the organ of the combined meteorological services, the Magazine will, it is hoped, fully maintain its traditional character as a channel of communication between amateur meteorologists'; it is probably true to say that this hope was largely realized during the following twenty years.

In 1923 Carle Salter died at the tragically early age of 43 (see Mill (1923)), and Whipple was transferred to the British Rainfall Organization Division, becoming sole editor. In 1925 a reorganization of Meteorological Office structure took place, involving the setting up of Divisions of General Climatology and British Climatology with the British Rainfall Organization being attached to the latter. The Division of General Climatology was put under the charge of C. E. P. Brooks who was promoted to the grade of Superintendent;

his job included supervision of the Meteorological Office Library, the study of world climatology, and the Editorship of the *Meteorological Magazine.*

Brooks continued to edit the Magazine for 22 years including the period of the Second World War, although after June 1940 the need to conserve manpower led to the suspension of general publication in printed form and it was only a typescript edition—albeit with diagrams and photographs—that maintained a limited internal circulation. Proper publication was resumed with the issue for January 1947, the wartime break having given the editor an opportunity to begin his next volume with that month and not February, a mildly irritating practice that had continued ever since February 1866. In the late summer of 1947 Brooks was succeeded as Editor by G. A. Bull who was later to become Assistant Director (Support Services).

After the war, a change of policy in the editing became apparent. Before 1940, the Magazine contained short general articles on meteorology and climatology, with accounts of remarkable weather events, Meteorological Office news, accounts of personalities including retirements, obituaries, promotions and special appointments, and correspondence from members of the Office and amateurs; there was little or no mathematics and nothing that could really be described as a scientific paper suitable for a learned journal. After 1947 an increasing number of papers appeared describing the results of original investigations carried out in official time.

By the time that Bull was succeeded as Editor by R. F. Zobel in November 1960, the Magazine had largely assumed its present appearance and character, although minor changes of content and cover design still occurred from time to time. Zobel was replaced in April 1962 by A. H. Gordon who was in his turn succeeded in March 1963 by W. S. Garriock.

Garriock proved to be another long-standing editor who spent nine years maintaining the high standards of accuracy and sub-editing which had rightly become characteristic of a Magazine that acted as the official organ of an old-established Government scientific department; he retired in June 1972.

Between June 1972 and September 1974 the post of editor was filled successively by F. E. Lumb, J. G. Cottis, and J. B. Andrews; the present editor is R. P. W. Lewis.

AWARDS

L. G. Groves Memorial Prizes and Awards

The annual award of prizes took place on Friday 26 November 1976 at the Ministry of Defence, Whitehall. The Vice-Chief of Air Staff, Air Marshal D. G. Evans, C.B.E. presided and the awards were presented by Major K. G. Groves and Mrs Groves. The ceremony was attended by the Director of Services of the Meteorological Office, Mr G. A. Corby, and the Director of Research, Dr K. H. Stewart.

The 1976 Aircraft Safety Prize was awarded to Chief Technician T. C. Maine of Royal Air Force, Laarbruch, with the following citation:

'The problems associated with aircraft blocking runways as a result of a tyre-burst or brake seizure are well known in the Royal Air Force.

Speed is essential in removing the aircraft and clearing the runway to enable other aircraft to land safely, but the time taken to carry out the repair *in situ* is often considerable. Moreover, during rectification, engineering evidence of the cause can be destroyed inadvertently.

With this problem in mind, Chief Technician Maine has designed a skate, a platform on rollers, capable of being inserted under the affected wheel of the aircraft by the aircraft-towing tractor and, by a series of simple functions using the two sections of the skate, the aircraft can be quickly towed off the runway thus clearing it for use by other aircraft. The skate, which has been primarily designed for the Buccaneer aircraft, is currently in use at Royal Air Force Laarbruch. The device can be made locally and can be adapted for use with many other types of aircraft. It is in recognition of his initiative and for this practical contribution to the safety of aircraft about to land that Chief Technician Maine has been awarded the 1976 L. G. Groves Aircraft Safety Prize.'

The 1976 Meteorology Prize was awarded to Mr C. L. Hawson of the Meteorological Office with the following citation:

'For many years Mr Hawson has contributed to a wide range of research in the Meteorological Office and in particular has been responsible for encouraging research into local weather phenomena at outstations. He has given lectures on investigational techniques at the Meteorological Office College, has helped students with their training projects and on their return to outstations has continued to give active assistance in the selection and development of research work. As a result of his efforts, many excellent papers have been produced and many significant improvements made in local forecasting techniques particularly, in the last year or two, for snow and frost.

Mr Hawson is also the acknowledged expert in the Meteorological Office on winds and temperatures in the lower and middle stratosphere and on the accuracy of measurement of wind and temperature at high levels. His advice on these subjects is frequently sought by scientists from both inside and outside the Office, and is never asked for in vain.'

The Meteorological Observer's Award for 1976 was awarded to Mr D. J. George of the Meteorological Office with the following citation:

'Since 1968 members of the Meteorological Office have served aboard the Trawler Support Vessels off Iceland. These vessels are now maintained by the Ministry of Agriculture, Fisheries and Food, and provide British trawlers in the area with weather forecasts and warnings.

The meteorologists work on their own in a most difficult environment. Their duties include making regular weather observations, the frequency of which increases in hazardous weather conditions. As well as experiencing conditions of sustained severe gales and worse, the meteorologists face the special problems to be overcome in arctic seas, carrying through their programmes when the superstructure is laden with frozen spray and the meteorological screen has to be chipped free of ice so that correct readings may be taken. Mr D. J. George has completed five voyages in Trawler Support Vessels during the past four winters. He has displayed particular keenness and dedication, both in his work on station and in preparing papers for the *Polar Record* and the *Marine Obseruer* based on the observations made.'

A happy feature of the occasion was that Mr George's award was presented to him by Mrs Groves, Major Groves explaining that with the increasing part now played by women in all aspects of public life he had at last managed to persuade his wife to take a more active part in the ceremony.

Air Marshal Evans concluded the proceedings with his own congratulations to the winners of the prizes and awards, including a graceful tribute to their wives whom he was very pleased to see present. (See Plates II–IV.)

Meteorological Office awards to captains and navigators of civil airlines

Since 1954 the awards have been made annually to encourage civil airline captains and navigators to provide air weather reports. Suitably inscribed books are awarded to aircrew members who have provided the best series of reports during the year under review. Captains who have given long and meritorious service in the provision of air reports are considered for the award of brief-cases.

Last year the awards were presented by the Director-General at a ceremony in the Lodge of the Meteorological Office College at Shinfield Park, near Reading, on 19 October.

Captain W. J. Jackson of British Airways (European Division) was presented with a brief-case and Captain R. A. E. Jones of British Airways (Overseas Division), at his own request, received a selection of books. (See Plate I.)

REVIEWS

Topics in applied physics, Volume 12—Turbulence, edited by P. Bradshaw. 235 mm × 180 mm, p.p. xi + 335, *illus.* Springer-Verlag, D-1 Berlin 33, Heidelberger Platz 3, Berlin-West, 1976. Price DM 97.

There is a shortage of specialist review papers and books in the field of turbulence and it is refreshing that this book by eight authors has the stated objective of emphasizing the breadth of the subject rather than its depth. In spite of the alarming number of authors the material is carefully cross-referenced and each author appears to have paid some heed to the words of the others. As claimed by Bradshaw in the preface it has been freed as far as possible from discipline-orientated details and the approach is 'applied' rather than 'pure' with the aim of helping people who need to understand or predict turbulence in real life. Although the text assumes some familiarity with the elementary ideas of fluid mechanics and turbulence, it is sufficiently self-contained to meet the needs of research workers not experienced in the field. Much of the material is of review type and as might be hoped, the book is an extensive well-catalogued source of references.

The introduction by P. Bradshaw is a characteristically clear summary of the basic equations, quantities and ideas of turbulence which, though not unique to this book, serves to help unify the subsequent sections. The sections on External

Flows by H. H. Fernholz and Internal Flows by J. P. Johnston are built around examples in aeronautics and engineering but workers in other fields should not let themselves be put off. The material is presented in a manner which puts emphasis upon the basic processes many of which are fundamental to other disciplines.

In consequence of the material in these chapters the section on Geophysical Turbulence and Buoyant Flows by P. Bradshaw and J. D. Woods deals mainly with the effects of stable or unstable stratification. It reviews the Atmospheric and Oceanic boundary layers with clarity but brevity.

The section on the calculation of Turbulent Flows by W. C. Reynolds and T. Cebece will be of practical value to workers in all disciplines since it not only discusses the frontiers of research but also gives details of the older simpler methods. The section on Heat and Mass Transport by B. E. Launder supplements the preceding two sections by giving further discussion of Buoyant Flows and the extension of calculation methods to include these factors.

The final section on Two-Phase and Non-Newtonian Flows is a brief introduction to the complexities of these effects with emphasis on the drag reduction properties of long-chain polymer solutions.

In conclusion, this book contains a broad but unified collection of authoritative articles on 'applied turbulence'. To the meteorologist the subjects of Aeronautics and Engineering can present a bewildering wealth of references so I feel this book will be of great value in bringing within easy grasp the expertise of these fields.

P. J. MASON

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LETTER TO THE EDITOR

Satellite infra-red analyses

We refer to the discussion initiated by our recent paper, and continued by Singleton*.

We are glad that he sees some merit in our suggestions, which have arisen during the course of a broader enquiry aimed ultimately at establishing the types of satellite image contents which might be extracted automatically in formalized, operational programs for a wide range of possible applications in both meteorology and climatology.

We would like, however, to comment briefly in turn on Singleton's five reasons why our schemes for hand-drawn infra-red nephanalyses seem to him to be 'impracticable, or at best, of limited value in an operational environment'.

(a) The size filter we suggest is more important as a procedural concept than an inflexible law. Different base data and different applications might require a different threshold from the one we chose for the DMSP imagery.

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* *Meterological Magazine*, **106**, pp. 11–26.

(b) The use of a low size threshold might be expected to lead to the production of nephanalyses of special interest to local regional forecasters, since some mesoscale features would be included. Our choice of a 1° square mesh permits the mapping of features down to some 90 km across. Though the lives of a few such features might be quite short, their number and distribution would, even then, be indicative of the weather-producing processes at work. Perhaps the problem of deterioration of chart contents through facsimile transmission could be side-stepped by the transmission of enlarged sections of the national nephanalyses to regional centres as appropriate.

(c) Were satellite data considered of sufficient value, outstation procedures might be modified to permit assimilation of the contents and implications of the cloud images and cloud maps. Weather services have evolved in the past; it might be a brake to progress were present procedures to be considered sacrosanct.

(d) and (e) If satellite data were to be interpreted only in terms of conventional synoptic data—especially in regions like the North Atlantic whence conventional data are sparse, irregularly distributed and of inconsistent quality—it would seem that their usefulness might be unnecessarily curtailed. From our academic viewpoint, we would prefer satellite images to be considered as independent statements of reality, through which conventional charts might be enhanced and improved, especially where *in situ* observations are sparse. Perhaps the man best equipped to interpret a satellite image is the trained photo-analyst, not the synoptician who might tend to interpret the cloud patterns in terms of an analysis already substantially completed on the basis of possibly inadequate conventional observations. Were this thought to be the case, the satellite and synoptic analyses might be compared after their independent preparation, and the synoptic charts corrected accordingly.

Regarding Singleton's final paragraph, it seems worth pointing out that the spatial resolutions of the NOAA–SR and DMSP–HR infra-red imagery are approximately 7·5 km and 0·6 km respectively, according to official figures accepted by the Meteorological Office, not about 5 km and 0·5 km. Although a reasonable compromise between the information contents of the two types of imagery might indeed be provided by day-time analyses in CFO based on both visible (3·7 km resolution) and infra-red observations from NOAA, it is clear that any night-time charts (if drawn) and day-time charts for areas of polar night or twilight could be based only on the low-resolution infra-red data, resulting in 12-hourly charts with alternately higher and lower degrees of detail being compiled. This would seem to be distinctly unsatisfactory. With geostationary satellites (e.g. METEOSAT) soon to provide much more frequent imagery, we believe that steps should be taken to standardize the analysis and interpretation of satellite imagery so that the valuable meteorological statements this system will provide might make their own contribution to further improvements in short-term weather forecasting, especially at the meso scale. In many countries the use of satellite data has developed along decidedly *ad hoc* lines. Is this the best that can be done?

E. C. BARRETT
for E. C. BARRETT and R. HARRIS

Department of Geography
University of Bristol
Bristol

Mr Singleton comments as follows: I certainly do not regard current procedures as sacrosanct—in fact I hope that Meteorological Office outstations will regard the Barrett and Harris paper together with my note as an opportunity to consider present practices in nephanalysis and to discuss what they would like in future (Editor).

OBITUARY

It is with regret that we have to record the death on 3 November 1976 of Mr D. W. Leeson, Scientific Officer, Honington.

CORRECTIONS

The following corrections apply to the first article in this issue:

Figure 4(a): area enclosed by dotted line around Brest (B) should be hatched.

Figure 7(a): hook is missing from one of the four cirrus symbols over Ireland.

THE METEOROLOGICAL MAGAZINE

VOL. 106 NO. 1256 MARCH 1977

CONTENTS

NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire, RG12 2SZ, and marked 'For Meteorological Magazine'.

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