METEOROLOGICAL OFFICE

TECHNIQUES AND TRAINING BRANCH MEMORANDUM No. 1

# FORECASTING PRECIPITATION - METHODS AND TECHNIQUES IN USE IN THE METEOROLOGICAL OFFICE

by

W.D.S. McCAFFERY and D.S. GILL

1964

M E T E O R O L O G I C A L   O F F I C E

TECHNIQUES AND TRAINING BRANCH MEMORANDUM No. 1

# FORECASTING PRECIPITATION - METHODS AND TECHNIQUES IN USE IN THE METEOROLOGICAL OFFICE

by

W. D. S. McCAFFERY and D. S. GILL

1964

P.11958/MAL/8/64/400

# FORECASTING PRECIPITATION - METHODS AND TECHNIQUES IN USE IN THE METEOROLOGICAL OFFICE

by

W. D. S. McCAFFERY and D. S. GILL

## 1. Introduction

Inpreparing a forecast, the forecaster must decide whether or not precipitation will occur, and if so when it will

(i) begin and end (timing), and if it will be

(ii) sporadic or continuous (time distribution),

(iii) local or widespread ( spatial distribution),

(iv) slight, moderate or heavy (intensity),

(v) drizzle, rain, hail, sleet or snow (form).

A supplementary question, which the forecaster is ill equipped to answer, is

(vi) how much rain will there be? (amount).

In seeking to answer these questions, it is not always possible to follow the same logical sequence of steps; particular situations dictate the method of approach and at times some questions barely arise, e.g. snow in summer in the British Isles. An attempt has been made in this paper to outline, without going into details, the techniques currently used by forecasters in the Meteorological Office to answer these questions and to suggest possible lines of further action.

## 2. Present methods and techniques for forecasting precipitation

The present report deals with methods and techniques in use at the Central Forecasting Office and at outstations. Details of the way in which precipitation forecasting is tackled at outstations were obtained as a result of replies to a Headquarters inquiry into forecasting methods and techniques in use at Meteorological Office outstations. There are certain differences between methods used by forecasters at the Central Forecasting Office and most forecasters at outstations, which are a reflection of different interests, C.F.O., in the main, being interested in developments over a wide area for an appreciable time ahead, while the outstation forecaster is often concerned with a detailed short-period forecast for a limited area. In general, however, the forecaster first asks the question; "Will precipitation occur in my area of interest during the period for which I am forecasting?" The answer will be "yes" if any of the following conditions apply.

(i) An active front, which will remain active, or an inactive front which will become active, or frontogenesis, is expected in the area at some time during the forecast period.

(ii) Some other active surface or upper air feature (e.g. trough or polar low) which will remain active, or an inactive feature which will become active, is expected in the area.

The general nature of the pressure pattern or predicted pressure pattern is also relevant, with a high correlation between wetness and cyclonic patterns.

(iii) The airmass expected over the area will be unstable enough to produce showers, or outbreaks of instability rain during the period of the forecast.

P.11958/MAL/8/64/400

In attempting to answer the general question posed above, the forecaster is usually led to consider also the questions of intensity, time of commencement and duration of precipitation. These aspects will be discussed together for each of the three cases mentioned above.

## 2.1 Frontal precipitation

The first task of the forecaster is to identify the fronts on the current synoptic chart. In the case of an active front this is relatively easy, using the simple concepts of the Norwegian frontal models. An inactive front is more difficult to identify, especially over sea areas, and its positioning on the chart depends greatly on past history and a close scrutiny of hourly observations from individual stations. For their first charts each day, smaller outstations, which are not open for 24 hours, rely heavily on analyses from C.F.O.

The forecaster must then decide how far the front is going to move during his forecast period. Here the main guidance at outstations comes from C.F.O., but as some stations have pointed out, the C.F.O. prebaratic is for 24 hours ahead, while their interest is often in 6 or 12 hour periods. A simple halving or quartering of the distance between present and forecast positions is not good enough, as the front is often in the process of slowing down or accelerating. The most popular methods of moving fronts for these short periods are; cold fronts at geostrophic wind speed component perpendicular to the front, warm fronts at 2/3 of the geostrophic wind speed component perpendicular to the front, or full geostrophic wind speed component perpendicular to the front measured 75-100 nautical miles ahead of the front [1,2]. There are other minor variations in the exact proportions of geostrophic wind speed component used and allowance is made, at least qualitatively, for changes of pressure gradient along the fronts. Full geostrophic wind speed, (or expected geostrophic wind speed taking into account any process which would lead to a change of strength of zonal component) is allowed for in the movement of a warm front when the associated surface pressure trough is weak, particularly when the front is moving round the northern flank of a high pressure area with a tendency for anticyclonic curvature of the isobars in the warm sector. In these cases there is usually appreciable westerly flow aloft and rain can spread well ahead of the surface warm front.

Having decided on the movement of the front, the forecaster must consider whether the activity of the front will change or not. The most common solution at present is to correlate the activity of the front with the deepening or filling of its associated depression, which in turn is linked to consideration of the thickness and isallobaric patterns and the position of the depression in relation to the jet stream and the long-wave pattern. Several forecasters forecast rain areas to increase if the rain area moves into a convergence zone at any level, or if a trough in the 300 mb. pattern catches up with the surface front (Bradbury,3). Changes in cyclonic curvature of surface isobars and identification of ana and kata cold fronts (Sansom, 4) are found helpful. The only technique mentioned by outstation forecasters for deciding on the increase or decrease in activity of warm fronts is the use of the hodograph (Parker, 5) for deciding whether upsliding motion is taking place, though strictly this merely highlights what is already occurring. Allowance is made qualitatively for topography.

Complete frontogenesis (i.e. the formation of a new front), or frontolysis (weakening of a front to the point of disappearance) are not usually significant in short term forecasts, but must be considered in longer period forecasts up to 24 hours or more. Differential thickness advection, leading to the creation of baroclinic zones, or the strengthening or weakening of already existing zones, is probably the main aid. Ideas of frontogenetical fields as discussed by Petterssen (6) are useful, as well as a knowledge of surface and upper air models associated with frontogenesis or frontolysis, or typical situations leading to frontogenesis in preferred regions. The weakening of the southern parts of a front following anticyclonic disruption of the associated upper trough is well known. Other examples are warm front wave development or intensification of warm front rainfall at the right entrance to a developing thermal jet, (Jones 7) and the frontogenetic effects induced by the thermal differences between land and water in both summer and winter. The work of Lowndes (8, 9) on wet spells at London is indicative of the forecaster's philosophy that on the broad scale precipitation may be regarded as a function of the amplitude, shape (confluent or diffluent) and speed of translation of upper troughs. Indeed the behaviour of the upper flow and its effects on surface development - roughly cyclonic in association with upper troughs and anticyclonic in association with upper ridges - may be the main concern of forecasters engaged in predicting the general character of the weather, for 24 to 48 hours ahead, over an area the size of the British Isles, leaving the approach outlined in the three numbered statements above, to be followed by forecasters attempting more detailed forecasts, for limited areas, for periods of time up to about 12 hours.

In practice, the work of Sutcliffe and Forsdyke (10) and of Sawyer (11) is heavily relied on, as well as ideas, discussed briefly by Smith (12), on the relationship between surface and upper air charts. Beyond associating cyclogenesis with raininess, details of timing, intensity, amount of rain and area affected by a predicted new development are necessarily somewhat vague. For a depression already in existence and forecast to move eastwards over or near the British Isles, studies by Sawyer (13) are a useful aid.

## 2.2 Non-frontal precipitation (excluding instability precipitation)

Given the presence of a non-frontal precipitation area, identification of the feature causing it is considerably easier than trying to forecast the development of precipitation from a feature not actually producing precipitation. Features causing non-frontal precipitation may be subdivided into those connected with surface charts and those with upper air charts.

(a) In general, surface features such as troughs and polar lows tend to be less conservative than fronts, the main method being to move the rain areas with the 700 mb wind, a method which is sometimes used with frontal rain.

(b) Cold pools and troughs in the thickness pattern and troughs on upper flow charts are useful indications of the probability of instability rain, showers or thunderstorms.

## 2.3 Instability precipitation (showers and thunderstorms)

For estimating instability, the TØ gram is used by forecasters throughout the Office. Most use the parcel method of estimating Cu. cloud tops in showers and the slice method for estimating Cu. cloud tops away from showers. Methods of estimating the frequency and intensity of showers and thunderstorms are varied, but fall into two main classes. One class uses the forecast of cloud produced from the TØ gram, classifying shower activity by depth of cloud, depth of cloud above the 0 deg C isotherm, or temperature of cloud tops and in some cases a combination of these parameters. The second class uses instability indices, of which there are many. Showalter's, Galway's, Rackliff's, Miller and Starret's, and Jefferson's are all mentioned. An additional instability index, by Boyden (14) was published too late to have been used by outstations before forwarding their reports. SFLOC'S are mentioned by almost all forecasters in connection with thunderstorm forecasting, the normal method of use being to plot continuity charts. Except for the use of radar in very short range forecasts, there is no technique which enables a forecaster to say exactly when any specific place will have a shower.

## 2.4 Form of precipitation

Having produced an answer of yes to the general question, "will precipitation occur?" the forecaster is faced with the problem of what form the precipitation will take; drizzle, rain, sleet, snow, or hail. The problem of rain, sleet or snow is common to all precipitation producing situations in winter; drizzle occurs only in stable conditions (or from shallow convective strato-cumulus in winter) and hail in unstable conditions.

P.11958/MAL/8/64/400

Turning first to the problem of rain, sleet or snow, sleet is treated as a borderline case between rain and snow and the problem becomes one of differentiating between rain and snow. Most forecasters use a 1000-500 mb thickness figure of 5280 m and below, as indicating occasions where snow is more likely than rain; many also consider the height of the 0 degree C wet bulb temperature (Handbook of Weather Forecasting, 15). Refinements in the relationship between snowfall and thickness parameters (Lamb, 16, Murray, 17), are also discussed in the Handbook of Weather Forecasting and of these, the most used is the possibility of snow occurring with 1000-500 mb thickness greater than 5280 m after a prolonged cold spell or when there is extensive snow lying. Papers by Lumb (18, 19) on the downward penetration of snow give guidance on occasions when prolonged or heavy rain may turn to snow. At Little Rissington, a high level station, forecasters prefer locally derived critical thickness figures for the 1000-850 mb and 1000-700 mb thickness.

Hail is usually forecast whenever cumulonimbus or thunder is forecast. One suggested technique was to forecast hail when the parcel method of convection gives cloud tops of 15,000 ft and the path and environment curves are at least 5 deg C apart, for most of the convective range. Numerical or objective methods for forecasting hail have not been developed for use in the British Isles and forecasters seem reluctant to try techniques developed for use elsewhere. A pilot test by Findlater (20), of a method due to Pappas, was not considered sufficiently encouraging for a more comprehensive test of the technique to be attempted.

For forecasting drizzle, apart from a knowledge of air mass characteristics and their modification due to topography, the only criterion is that due to Mason and Howorth (21) repeated in the Handbook of Weather Forecasting (para. 16.7.2). No techniques are in use for distinguishing between shallow Sc which will produce drizzle and that which will not.

## 2.5 Amount of precipitation

Apart from general considerations of increase or decrease in the activity of precipitation areas already present, no methods are in use for forecasting amounts of precipitation. An experiment carried out in Met.O.2 attempted to forecast the amount of rain expected to fall at Kew from organized rain areas during the day. Even when, for the purpose of analysis of the results, the rainfall was divided into 3 broad ranges, only 40% of the forecasts issued at 0600 hours for the rest of the day were in the correct range. In an unpublished report, Jones (22) has related present weather code figures to hourly rainfall amounts. Although the spread on either side of the mean value is very large, the error in a predicted amount of rain is reduced when the forecast is for several hours rain meaned over several stations, rather than a forecast of amount at one place. There remain the initial difficulties of forecasting the duration of rainfall, the intensity, (light, moderate or heavy), and the area over which it will fall. On the usefulness of maps of rainfall distribution in specific situations, forecasters agree that the maps provide mainly background information. It has been suggested that if it became possible to allow in rainfall forecasts for the effects of a simple topography, then the maps could be used to apply the results in areas which are topographically more complicated.

Considering the aspects listed in the introduction, it may be said that in respect of precipitation from stable cloud, especially stable frontal cloud, the forecaster is better equipped to say when precipitation will start and when it will cease, than to say how intense it will be. For precipitation from unstable cloud, especially unstable non-frontal cloud, the reverse is true. He has methods of distinguishing between rain and snow, though with a large degree of uncertainty in borderline cases. He is less certain of distinguishing between rain and hail or rain and drizzle. There are no recognized techniques for forecasting amounts of precipitation. The forecaster leans heavily on observations of present weather, modifying the status quo by extrapolation in space and time.

P.11958/MAL/8/64/400

In all precipitation forecasts, an important element is the available moisture. This is usually examined by study of the appropriate T/Ø-grams, though some forecasters use charts depicting moisture content, (e.g. as dew point depression at some level), to try to see more clearly changes in time and space. There is, however, no fully satisfactory or agreed method for dealing with this highly significant parameter.

2.6 Summary

Summarizing, it can be said that the following general methods are in use at present;

frontal and non-frontal analysis of surface charts,

analysis of upper air charts, especially of the 1000-500 mb thickness charts,

T/Ø-gram analysis,

hodographs,

and that the following more specific methods are used in certain circumstances,

instability indices and sferic reports,

thickness parameters (for forecasting snow),

moisture content charts.

A summary relating forecast aspect to type of precipitation is at Annex A and a diagrammatic summary of the steps followed in precipitation forecasting is at Annex B.

3. Methods not at present in general use

Replies from stations to the Headquarters letter requesting information on methods and techniques in use, varied greatly in detail, and not all methods or techniques may have been included. Nevertheless a search of British and recent foreign literature reveals very few available methods or techniques which are not already being used, or have been tried and found wanting. Some omissions, real or apparent, are discussed below.

Little use appears to be made of the published results of meso-meteorological studies, which indicate the existence of coherent systems on a scale of tens of miles, (rather than the hundreds of miles appropriate to the normal synoptic working chart). Wallington (23) has published details of the cellular or banded structure of precipitation associated with fronts. Pedgley's (24) study of a thundery situation over England leads to a meso-synoptic model of a thunderstorm high similar to that found by Fujita (25) in America and discussed by Petterssen in his book Weather Analysis and Forecasting second edition, volume II. Detailed analysis as described by these authors is not possible operationally, but with some knowledge of what may be expected, it is possible to analyse rainfall patterns to a limited extent using hourly observations currently available in the British Isles. Charts transmitted hourly over the facsimile network are not suitable for this work, owing to the limited number of stations which can be plotted. This could be overcome either by broadcasting a chart of precipitation only, or by outstation forecasters adding to the facsimile charts, all available precipitation reports from their area of interest. Although it may be possible to forecast for only a very limited time ahead by simple extrapolation of the existing patterns, a first requirement is greater knowledge of the way the atmosphere behaves on this scale.

A recently published article by Findlater (26) discussing the sea-breeze front, (another meso-scale synoptic model) utilises a technique of surface wind analysis by streamlines and illustrates the importance of this meso-synoptic feature in initiating convective activity. The use, in temperature latitudes,

P.11958/MAL/8/64/400

of a technique to analyse the surface wind flow, a method also used by Ludlam (27) and Ludlam and Macklin (28) is a welcome departure from the strait-jacketing effects of an analysis based only on the Norwegian frontal model and isobars at 2 mb intervals. Current teaching at the Meteorological Office Training School includes instruction in various methods of surface chart analysis such as have been discussed by Sawyer (29) and in M.O.674 (30).

A mode of development, now generally accepted by workers in the field and available as a short range forecasting tool, but not apparently widely used by forecasters, is the recognition in thundery situations of the tendency for rain areas to move somewhat to the right of the upper wind flow (e.g. Browning, 31) because the dynamics of the storm area causes the birth of new storm cells at the right and the decay of older storm cells at the left of the leading edge of the storm area.

A technique, useful in deciding whether or not there will be precipitation from stratiform (low) cloud is due to Singleton (32). A scatter diagram was plotted of precipitation or no precipitation determined by cloud base and cloud thickness and a line was drawn on the diagram such that 80% of the plotted points above the line were of precipitation. Although the method is very similar to that of Mason and Howorth (19) already mentioned, the fact that it does not contain the indeterminate layer present on their diagram makes it easier to use.

Coles (33) states that when unforeseen developments occur at the surface, the flow patterns at 300 and 200 mb often seem to be the controlling factor. A preliminary examination of a selection of fronts, indicates that the 300 to 100 mb thickness pattern, which can be used to estimate the divergence at 300 mb, may be a useful aid in distinguishing between wet, moderately wet, and dry fronts.

The general relationships which exist between upper flow patterns and surface developments have already been mentioned, with specific reference to an article by Jones (7). In this, the author, after examining the 300 mb contour patterns associated with 28 warm front waves over a period of six years, formulates a rule for forecasting the formation of warm front waves when the front is near the right entrance to a jet stream and to the east of an upper ridge.

A few forecasters have expressed interest in a method described by McElmurry (34) for forecasting the movement of rain towards a blocking anti-cyclone. Carefully drawn streamlines at 700 mb over the area of interest are used to find a line of confluence between the airflow carrying the rain and the drier air circulating round the anticyclone. The rain is forecast not to move beyond this line and will become stationary or retreat according to criteria involving wind directions in the two air streams.

Few forecasters in the British Isles have directly enjoyed the benefits of the information available from weather radar. The correct interpretation of the radar pictures requires skill and experience, but given this and also using height-range information, a true picture of precipitation reaching the ground can be obtained. With further experience this information can be utilised to give detailed forecasts for at least a short time ahead. It is also possible to obtain by radar methods, some information on rainfall intensity, but research into this is still at an early stage. More readily available, are hourly totals of rainfall amount, such as used to be reported by Eire. The difficulties are mainly those of communication, by already overloaded teleprinter channels, and those caused by the uneven distribution of stations in the reporting network.

## 4. Present research into precipitation forecasting

Research into quantitative rainfall forecasting is being actively pursued in the Meteorological Office. Various methods of estimating rainfall amount from vertical velocities have been tested by Benwell (35, 36, 37), but the results, when applied to this country, have been disappointing, even when tested on actual rather than forecast data. A check has also been made of the relationship between amounts of rainfall and vertical motion computed as part of the numerical forecasting process (Benwell, 38). The relationship between the occurrence of moderate or heavy rain and vertical motion forecast to reach or exceed 2 mb/hr, is statistically significant at the one per cent level, but the rain probability from forecast vertical velocities, as at present computed numerically, is similar to the probability from surface pressure change and not yet a satisfactory forecasting tool. Improvements are being sought by following two main lines of attack. One method is to bring into the calculations temperature and humidity at 100 mb levels up to 100 and 400 mb respectively. Amounts of excess water are computed for each 100 mb layer and hence accumulated rainfall totals are predicted. Another method is to study the small scale dynamics of fronts by means of numerical models, using a grid length of about 60 miles and information from 10 levels in the vertical. This research is designed to increase knowledge about fronts rather than to find any immediate practical operational use.

A study has been started of the pressure distribution associated with cases of noteworthy falls of rain over a fairly large area of country, i.e. occurring at several stations rather than one or two. The aim is to find any critical parameters which will distinguish between cases where heavy rain occurs and those where it does not. Using regression methods, a study has also been made of the correlation between rainfall amount at warm fronts and various parameters such as geostrophic wind direction ahead of the front, orientation of the front and frontal contrast. Using independent data a correlation coefficient of 0.67 has been obtained by this method.

Vorticity at the 300 mb level is being examined to see if there is any relationship between vorticity at this level and the amount of rain occurring at the surface. Significant relationships exist, but for forecasting more than a few hours ahead it is necessary to forecast the 300 mb chart, which is at least as difficult as forecasting the rainfall.

Research into the forecasting of hail at ground level, has now reached a stage where a probability of occurrence can be given, provided the necessary predictors can themselves be predicted. Some work has also been done on the advection of patterns of precipitable water and on orographic rainfall in southwest England. A synoptic investigation into the degree of showeriness is in progress and research into snowfall has produced five one-term predictors which each give better results than the 1000-500 mb thickness.

Using the Cardington rain-gauge network, an examination is being made of the representativeness of the rainfall measured at a point for determining the areal rainfall round the point. A similar investigation is being made in a hilly district. (Winchcombe in the Cotswolds.) The results of recordings made in showery weather and analysed over two-minute intervals, should serve to increase knowledge of the variability of rainfall in space and time.

Experiments are in progress at the Meteorological Office radar research unit on the determination of rainfall intensity by radar methods; this is possible in principle, but has many practical difficulties, not least being the existence of suitable sites in areas of interest and, of course, the cost of providing complete cover over a very large area.

## 5. Future developments

Precipitation forecasting is still weakest in respect of amount, although major difficulties exist in other aspects also. At present, the best that can be done by a forecaster, is to attempt, rather inadequately, to distinguish between light, moderate and heavy precipitation. A major requirement, therefore, is research designed to improve our knowledge of the dynamics of rainfall and to find techniques which are capable of producing reliable quantitative forecasts. Some of the largest amounts of rainfall are caused by convection, and although instability indices give a good indication of when thunder will not occur, when the indices are favourable for large scale overturning it is often difficult to decide whether, in fact, this will occur or not, and if so, precisely when and where and how much rain (and hail and thunder), will be produced.

P.11958/MAL/8/64/400

The factors of importance in the mechanism of rain production are presumably vertical velocity, humidity and instability. These have not yet been fully integrated into a satisfactory numerical model and indeed, even if such a model were available, unless the numerical grid length was reduced by a factor of three or four from the 180 nautical miles or so, now normally used in numerical objective forecasting, the computed forecasts would represent an average over a considerable area, missing the smaller scale detail which it is desirable to obtain. It is therefore unlikely that numerical methods will provide a completely acceptable forecast for all purposes within the near future, if at all.

The methods and techniques for dealing with other aspects of precipitation forecasting, discussed in the preceding pages, should not be allowed to obscure the fact that the forecaster relies heavily on present weather observations. Even with the present network of hourly reporting stations in the British Isles, there are large gaps or areas of uncertainty in the picture presented to the forecaster of the weather as it now is. The picture is further blurred by current reporting procedures, which allow for large variations in rainfall, both in time and intensity, to be reported by the same code figures. These difficulties can be overcome to some extent, by the use of radar methods which can now give a good representation of the rainfall patterns as they occur. In the future it will no doubt be possible to determine rainfall intensities also by radar methods and proposals exist for developing electronic methods of automatically computing and registering accrued rainfall over an area. This will inevitably take time and may in any case not always be physically possible or economically desirable. In the meantime, the case is strong for improving facilities for forecasting based largely on extrapolation of existing patterns with time. An improvement in the reporting network is needed, particularly in the more sparsely populated, hilly districts of Britain. Automatic weather stations are possibly the answer to this problem. From the improved network, the biggest single advantage would probably come from including hourly rainfall totals in the data made available synoptically to the forecaster. An examination of peaks in the rainfall totals may make it possible to disentangle the effects of orography which make difficult the recognition of meso-scale systems moving across the British Isles.

As well as attempting to increase the forecasters' knowledge of what rain is actually occurring, techniques are needed for adequately depicting humidity patterns at various levels, and their changes with time, and for integrating this knowledge into other techniques used in precipitation forecasting, for instance into more reliable methods for forecasting hail and thunder.

On the broad scale it seems likely that the best indications of general raininess or dryness will come from the use of more sophisticated numerical methods in which forecast vertical velocities are linked with available moisture to provide general forecasts for areas larger than the grid length used in the calculations.

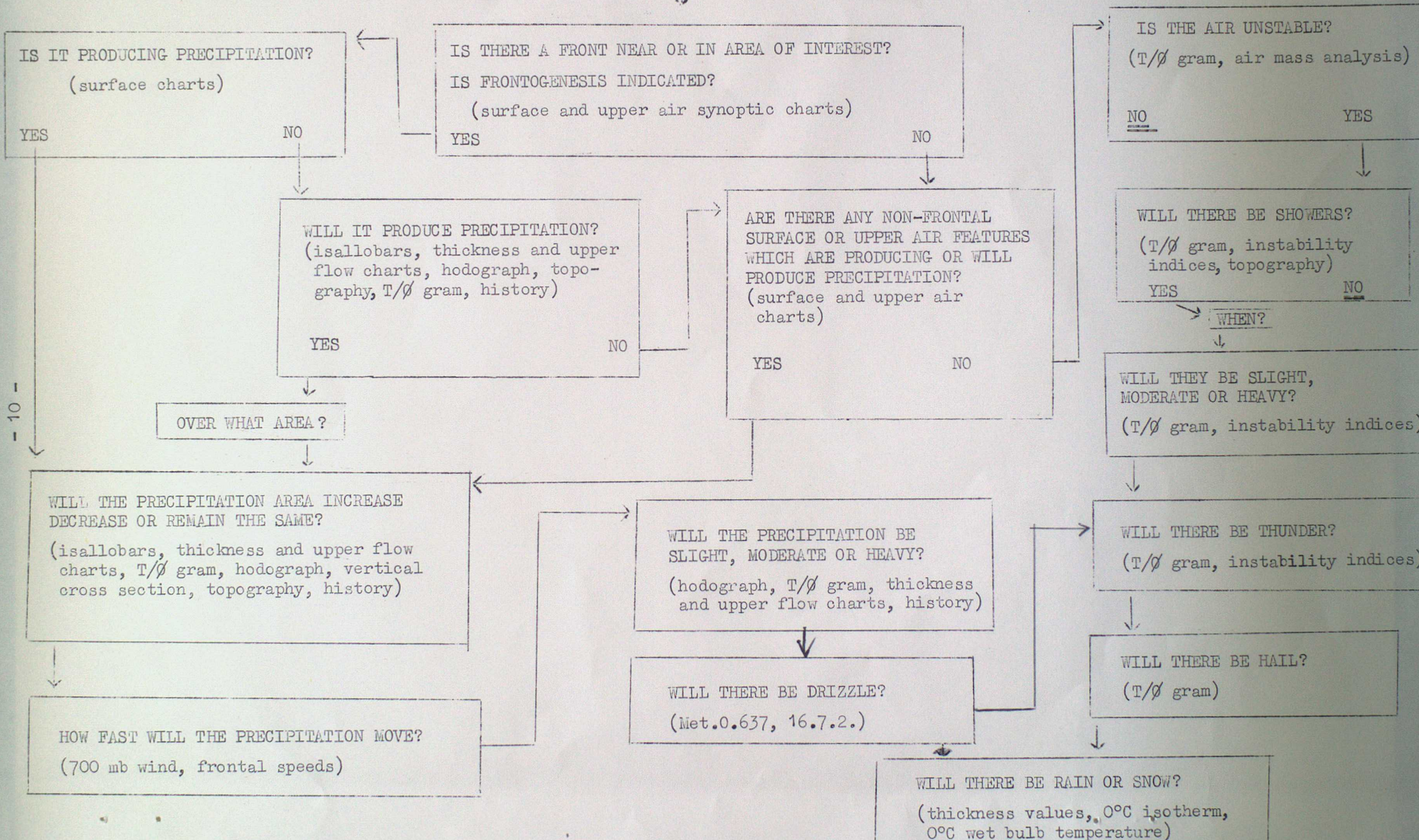
P.11958/MAL/8/64/400

ANNEX A

PRECIPITATION FORECASTING - SUMMARY

| Forecast Aspect / Type of precipitation | Timing (beginning and ending) | Time Distribution (sporadic or continuous) | Space Distribution (local or widespread) | Intensity (light, moderate or heavy) | Form (drizzle, rain, hail, sleet, snow) | Amount |
|---|---|---|---|---|---|---|
| Frontal | Speed of front and width of rain band; wind at 700 mb; extrapolation. | Degree of frontal activity; frontogenesis, or frontolysis; size of forecast area; length of forecast period; present weather observations. | Width of and degree of frontal activity; frontogenesis or frontolysis; size of forecast area; length of forecast period; present weather observations. | Frontal activity; frontogenesis and frontolysis; moisture content; degree of (convectional or potential) instability; orography; present weather observations. | Type of front and degree of activity; degree of instability; thickness parameters; height of 0°C wet bulb temp; orography; present weather observations. | Rough estimate from "x hours at y mm per hour", y being given some mean value for light, moderate or heavy rain. |
| Non-frontal (excluding "showery" precipitation) | Extrapolation; wind at 700 mb; propagation of severe storms to the right of the winds. | Size and degree of organization of associated surface or upper air features; present weather observations. | Size and degree of organization of associated surface or upper air features; present weather observations. | Moisture content; depth of and degree of (convectional or potential) instability; orography; present weather observations. | Air mass characteristics; thickness parameters; height of 0°C wet bulb temp; orography; present weather observations. | As above. |
| Showery | Time of day related to degree of instability and diurnal temperature variation; maximum shower frequency over sea and onshore coasts sometimes at night. | Shower frequency affected by orography and air mass characteristics; present weather observations. | Orographic influences; time of day and season; depth of and degree of instability; moisture content; present weather observations. | Depth of and degree of instability; moisture content; maximum surface temperature; orography; present weather observations. | As above. | Impossible to estimate. |

# RAPID REFERENCE GUIDE TO PRECIPITATION FORECASTING



## REFERENCES


1. MATHEWMAN, A.G.; Speed of Warm Fronts. Met.Mag. London, 81, 1952, p.266.

2. HINKEL, C.H. and SAUNDERS, W.E.; Speed of Warm Fronts on the Atlantic. Met.Mag. London, 84, 1955, p.241.

3. BRADBURY, T.A.M.; Development of rain ahead of an upper trough. Met.Mag. London, 91, 1962, p.71.

4. SANSOM, H.W.; A study of cold fronts over the British Isles. Quart. J.R.Met.Soc., London, 77, 1951, p.96.

5. PARKER, A.E.; Relationship between upper wind structure and rainfall at fronts. Met.Mag. London, 78, 1949, p.247.

6. PETTERSSEN, S.; Weather analysis and forecasting, 2nd Edition. New York, McGraw-Hill Book Co. Inc. 1956, Vol.I, p.203.

7. JONES, D.C.E.; Formation of waves on warm fronts in the vicinity of the British Isles. Met.Mag., London, 91, 1962, p.297.

8. LOWNDES, C.A.S.; Wet spells at London. Met. Mag., London, 91, 1962, p.98.

9. LOWNDES, C.A.S.; Forecasting wet spells in London. Met.Mag., London, 91, 1962, p.284.

10. SUTCLIFFE, R.C.and FORSDYKE, A.G.; The theory and use of upper air thickness patterns in forecasting. Quart.J.R.Met.Soc., London, 76, 1950, p.189.

11. SAWYER, J.S.; Formation of secondary depressions in relation to the thickness pattern. Met.Mag., London, 79, 1950, p.1.

12. SMITH, C.V.; Synoptic evolution of 500-millibar flow patterns. Met.Rep. London, No.21.

13. SAWYER, J.S.; Rainfall of depressions which pass eastward over or near the British Isles. Prof. Notes Met.Off., London, Vol.VII, No.118.

14. BOYDEN, C.J.; A simple instability index for use as a synoptic parameter. Met.Mag., London, 92, 1963, p.198.

15. Handbook of Weather Forecasting. Met.Off. London, Met.O.637. para. 16.7.6.1.

16. MURRAY, R.; Rain and snow in relation to the 1000-700 mb and 1000-500 mb thickness and the freezing level. Met.Mag., London, 81, 1952, p.5.

17. LAMB, H.H.; Two-way relation between the snow or ice limit and 1000-500 mb thickness in the overlying atmosphere. Quart.J.R.Met.Soc., London, 81, 1955, p.172.

18. LUMB, F.E.; Relation between the terminal velocity and the dimensions of snowflakes. Met.Mag., London, 90, 1961, p.344.

19. LUMB, F.E.; Downward penetration of snow in relation to intensity of precipitation. Met.Mag., London, 92, 1963, p.1.

20. FINDLATER, J.; A pilot study of Pappas' hail forecasting technique. Met.O.8 report, unpublished.

21. MASON, B.J. and HOWORTH, B.P.; Some characteristics of stratiform clouds over North Ireland in relation to their precipitation. Quart.J.R. Met. Soc., London, 78, 1952, p.226.

22. JONES, D.E.; Present weather and hourly rainfall. Met.O.12 Tech. Note, Unpublished.

23. WALLINGTON, C.E.; Mesoscale patterns of frontal rainfall and cloud. Weather, 18, 1963, p.171.

24. PEDGELEY, D.E.; A meso-synoptic analysis of the thunderstorms on 28th August 1958. Geophys. Mem., London, 14, No.106.

25. FUJITA, T.; Results of detailed studies of squall lines. Tellus, Stockholm, 7, 1955, p.405.

26. FINDLATER, J.; Sea breeze and inland convection. Met.Mag., London, 93, 1964, p.82.

27. LUDLAM, F.H.; A case study of thunderstorms on an occasion of small wind shear. London, Imperial College of Science and Technology, Dept. of Met., Technical (Scientific) Note No.11.

28. LUDLAM, F.H. and MACKLIN, W.C.; The Horsham hailstorm of 5th September 1958. Met.Mag., London, 89, 1960, p.245.

29. SAWYER, J.S.; Meteorological analysis - a challenge for the future. Quart.J.R.Met.Soc., London, 90, 1964, p.227.

30. Meteorology for gliding - notes for forecasters. (M.O.674) London, H.M.S.O., 1959.

31. BROWNING, K.A.; Cellular structure of convective storms. Met.Mag., London, 91, 1962, p.341.

32. SINGLETON, F.; Aircraft observations of rain and drizzle from layer clouds. Quart.J.R. Met.Soc., London, 86, 1960, p.195.

33. COLES, V.R.; Some empirical research in short range forecasting. Met.Mag., London, 91, 1962, p.89.

34. McELLMURRY, T.M.; Forecasting rain with low stratus in the Midlands of England. Bull.Amer. Met.Soc., Lancaster, Pa., 42, 1961, p.817.

35. BENWELL, G.R.R.; Quantitative precipitation forecasting methods, part 1, test of Wilson's method. Met.O.12 Tech. Note No.18, 1963.

36. BENWELL, G.R.R.; Quantitative precipitation forecasting methods, part 2, test of Estoque's method. Met.O.12 Tech. Note No.19, 1963.

37. BENWELL, G.R.R.; Quantitative preceipitation forecasting methods, part 3, test of Harley's method. Met.O.12 Tech. Note No.21, 1964.

38. BENWELL, G.R.R.; Quantitative precipitation forecasting - examination of the relationship between rainfall and the vertical velocity field obtained from the three parameter model developed by the Dynamical Research Branch (Met.O.11). Met.O.12 Tech. Note, No.22, 1964.