CHAPTER 15

MEDIUM- AND LONG-RANGE FORECASTING

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15.1 INTRODUCTION

Long-range forecasting methods are necessarily very different from those of short range for a number of reasons. Short-range forecasts essentially calculate or extrapolate the weather using, as a starting point, the current chart and very recent history; many factors important over a longer period are neglected because they are difficult to deal with and are not important on a short time scale. Such a factor is the detailed radiation balance (which clearly is very different in, say, March from what it is in February). There are other such factors including a lack of observations from the tropics and southern hemisphere but the net result is that short-range methods are inappropriate for forecasts beyond a few days ahead.

Medium-range forecasting, which in Britain usually refers to 3-4 days ahead but in the World Meteorological Organization context may extend to 7 days ahead, is carried out using mainly short-range methods but incorporating some techniques rather similar to long-range methods. Long-range methods cover a very wide field but almost all rely on some kind of statistical or analogue approach.

15.2 MEDIUM-RANGE FORECASTING

15.2.1 General remarks

Medium-range forecasting is a task which demands the full application of the forecaster's knowledge, experience, skills and resources. The techniques for the production of forecast charts cover a wide range, from the mainly 'conventional' methods for the shorter periods, to the use of statistical and analogue aids for the longest periods (say, 5 to 7 days). Over a good deal of the range, computer-produced prognostic charts play a very important part in the process. The medium-range forecaster must be familiar with all these aspects of the work, and must also be able to interpret the forecast fields in terms of the expected weather.

At present (1976), medium-range forecasting is carried out on an operational basis for up to 3 or 4 days ahead, with some experimental forecasts for periods up to 7 days ahead. As the forecast period is lengthened, less precision is possible in the forecast fields or the weather. Seven days seems to be about the absolute limit at present for forecasts using mainly methods based on dynamical ideas.

15.2.2 Errors of computed forecasts

Since medium-range forecasting depends so much upon computer-produced prognoses, the errors of the final product are closely related to those of the numerical models. It is not surprising that the 'errors' of computed forecasts, however they are defined, tend to increase with the length of the forecast period. The rate of increase is not always uniform with time, however, and also varies with the synoptic situation, the numerical model and the computation methods, and the quality of the initial data-field. Figure 1 shows the root-mean-square differences between the observed and predicted geopotential at 500 millibars for forecast periods up to 96 hours.[1] The data are from the U.S. operational primitive-equation model[2] and cover ten winter seasons over the northern hemisphere.

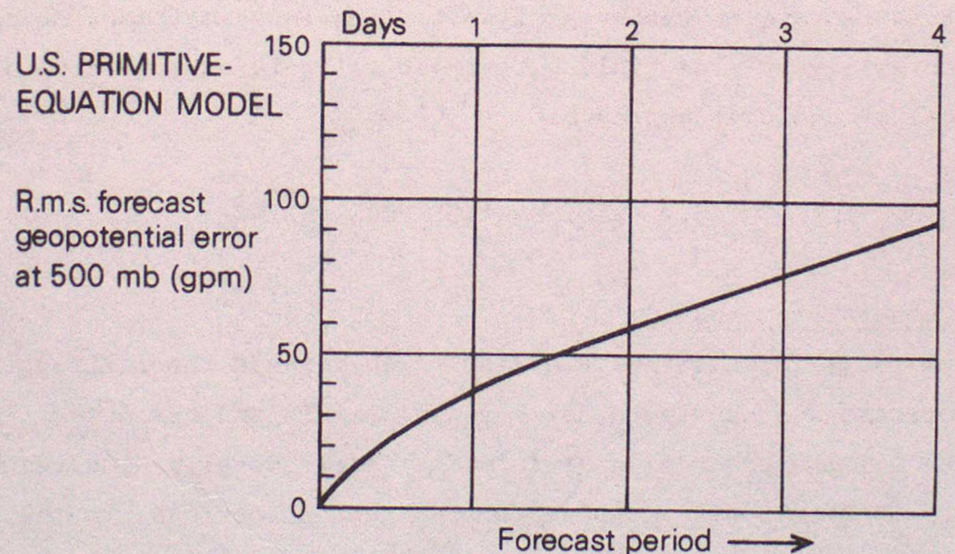

FIGURE 1. Errors of forecast geopotentials at 500 mb as a function of forecast period

Since the publication of the data of Figure 1, the U.S. primitive-equation (PE) model is terminated at 84 hours, and a barotropic model is used in the computations for longer forecast periods. The errors at 96 hours are said to be no greater than for the purely PE model. Forecast charts are issued up to $5\frac{1}{2}$ days ahead. A subjective test of the $5\frac{1}{2}$-day forecasts at 500 millibars over a three-month period for an area including the British Isles showed that a little more than half (52 per cent) could be considered 'good or fair guidance', with the remainder being classed as 'poor or bad guidance'. These markings were for the forecasts taken at face value, with no subjective attempt to allow for known or suspected errors in the model.

A feature of many, if not all, numerical models is that the surface forecasts are inferior to those for the 500-mb level. For instance, a subjective assessment of the U.S. $5\frac{1}{2}$-day surface forecasts, over the same three-month period used for the 500-mb forecast test and for the same area, showed that only 28 per cent could be considered 'good or fair guidance', the rest being classified as 'poor or bad guidance'. A subjective check of the British 10-level model forecasts for 3 days ahead, for a period of 100 days over the British Isles, indicated that only 9 per cent of the surface forecasts were superior to the 500-mb forecasts, 30 per cent were considered inferior, and the remaining 61 per cent were of about equal quality.

It is worth pointing out that in subjective assessments the superiority of the 500-mb forecasts over the surface forecasts is to some extent illusory if, as in medium-range forecasting, the ultimate objective is to forecast the weather at the surface. This is because the computer model tends to move and develop the long waves more accurately than the short waves. The long waves provide a broad similarity to the actual pattern, which consequently looks good. However, the short waves, associated with travelling depressions and mobile highs or ridges, are more closely related to the details of the timing, location and severity of the surface weather. On the other hand, the overall weather type - wet or dry, disturbed or settled, cold or warm - is often well correlated with the long-wave pattern. For the forecast periods considered in this section, therefore, the computer products are usually more successful in forecasting the general weather pattern than the details, although there are occasions when the long-wave pattern itself is transformed by a vigorous development in the short-wave pattern. Thompson[3] and Haltiner[4] have shown that the errors in the movements of the shorter waves are a result of the use of finite-difference schemes in the computations (see Chapter 3 - Background to computer models).

15.2.3 Use of computed forecasts

The implication of the subjective tests of $5\frac{1}{2}$-day forecasts cited in the previous section might suggest that these forecasts are worthless. If the errors of computed forecasts were purely random, and if a computed forecast represented the most probable solution, this inference would be correct, but in fact a very appreciable part of the error in all current computed forecasts, particularly the error in the phase and amplitude of ridges and troughs, is systematic. There is always hope of correcting, or partially correcting, systematic errors. It is to be expected that eventually ways will be found to correct most of the known systematic errors within the computer, but at present a subjective attempt is worth while in most cases, although the difficulty and the pitfalls must not be underestimated.

In the present state of the art, it is as unwise to accept a computed forecast uncritically as it is to reject it out of hand. Forecasting skill depends largely on the extent to which the truth in the computed forecast can be distilled, and the systematic errors partially corrected. Thus effective forecasting is currently a mixture of the advantage of the computer in processing the data and carrying out calculations, and the advantage of the human being in exercising judgement in the light of his meteorological experience and his study of computed-forecast errors.

Since the errors in computed forecasts generally grow with time, forecasting techniques for applying the computer products and inferring the associated weather vary with the forecast period. After the first 24 hours or so, a convenient division is into

(a) forecasts for 2 and 3 days ahead

(b) forecasts for 4 to 7 days ahead.

Under these headings the main techniques currently applied will be discussed.

15.2.4 Forecasting for 2 and 3 days ahead

The broad principles used in the production of forecast charts for 2 and 3 days ahead are little different from those of the 24-hour forecast. The main differences are that it is not possible to give as much detail as in the short-period forecasts and that the systematic errors of the computer models, and the need to make allowances for them, become greater as the forecast period becomes longer.

The first stage is to ensure that the forecasts are based on as good as possible a set of analyses. The manually produced and computer analyses are compared and any differences resolved as far as possible. It is important to consider whether any error in the computer analyses is likely to affect the computed forecasts appreciably. The forecaster, in his deliberations over the analyses, will have been made aware of the history leading to the current situation, and will already be thinking about possible future developments. These ideas will be based upon his experience of similar situations in the past, on his knowledge of the physical and dynamical principles discussed in Chapter 2, and on a study of the available computer prognoses.

The next step is to construct the forecast surface isobars, 500-mb geopotentials and thickness lines for 24 hours ahead, consistent with the broad pattern of expected developments indicated by the considerations mentioned in the last paragraph, and bearing in mind the following possible sources of error in the computed forecasts:

- (a) any significant error in the analyses;
- (b) any known general deficiency of the model;
- (c) any particular deficiency of the model as evidenced by recent errors in situations of the same general type.

The three sets of forecast isopleths must, of course, be mutually consistent. The forecast charts for 48 and 72 hours are then prepared in the same way, continuity being maintained throughout. A useful check on continuity, and on the general trend of development, can be made by drawing selected isopleths, usually 500-mb geopotentials, at 24-hour intervals on one chart.

When the forecast charts have been prepared, there remains the often difficult task of inferring the associated weather. This is, at present, an almost entirely subjective process based on the forecaster's experience of the weather, associated with similar synoptic types and his knowledge of the physical processes of the weather in the particular situation. Some guidance on this aspect of medium-range forecasting is given in Chapters 4 to 7, which deal with the synoptic climatology of various weather types.

The degree of detail appropriate to a forecast for 2 or 3 days ahead varies with the synoptic situation and is largely a matter for subjective judgement. Less precision is generally possible than in 24-hour forecasting, but the forecaster may be confident that more detail can be given in a settled situation than in a mobile one, or when a marked change of type is expected. Some elements can be dealt with more successfully than others. For example, the general level of temperature, which is fairly closely related to the thickness (see Chapter 17 - Temperature), can be forecast with confidence on some occasions, whereas forecasts of fog or frost, which often depend critically on the pressure gradient, present more difficult problems.

15.2.5 Forecasting for 4 to 7 days ahead

The 72-hour forecast, prepared in the way described in the previous section, is necessarily the starting point for a forecast for a longer period. However, the predicted pattern usually diverges from the actual situation, at least in detail, so that any extrapolation of the developments or trends for a further 24 hours or more would often lead to unacceptable errors in the forecast charts and the implied weather. Because of this, prognostic charts for 4 to 7 days ahead are not drawn at present. Instead, the main effort is directed towards visualizing the general weather type; because this is fairly closely related to the mid-tropospheric flow, the probable evolution of the 500-mb pattern is the prime target. At present (1976), 7-day forecasts are prepared only on an experimental basis. Because of this, and because the experimental techniques may be modified, only a very brief general account of the current methods will be given.

The tools used in preparing a 7-day forecast may be divided into four kinds:

(a) Computer prognoses.

(b) Continuity charts.

(c) Statistical rules.

(d) Analogues.

15.2.5.1 <u>Computer prognoses</u>. The forecast charts available are the American computer prognoses for $4\frac{1}{2}$ and $5\frac{1}{2}$ days ahead, and the more recently introduced U.K. 10-level model charts for up to 6 days ahead. The American model is baroclinic up to $3\frac{1}{2}$ days, but barotropic thereafter. It therefore suffers from the defect that baroclinic developments are not taken into consideration for most of the period of interest. However, some allowance can be made subjectively to the American prognoses for possible baroclinic effects, and for suspected systematic errors in either model in the situation prevailing. The latter type of error will have been considered when examining the computer products for the first 3 days. A variety of checks can be made, particularly if the overall synoptic type is not changing rapidly. For instance, the current computer forecasts can be compared with earlier forecasts for the same verifying time to see if there is reasonable consistency. However, a good deal depends upon the forecaster's knowledge and experience of atmospheric behaviour and of computer models.

15.2.5.2 <u>Continuity charts</u>. Continuity charts serve two main purposes:

(a) They provide a compact summary of recent and forecast developments to which the forecaster can readily refer.

(b) They help to ensure that changes from one forecast period to the next are kept within reasonable bounds.

The main problem is how to display the required data conveniently on an appropriate time scale. One solution is to draw selected geopotential values for, say, the 500-mb surface, using different colours for different observation times. For medium-range forecasting, charts at $1\frac{1}{2}$-day intervals provide an adequate series. The patterns for the six days preceding the forecast period can thus be summarized on one chart, and similar charts can be prepared for the surface and 300-mb levels. These charts are useful in showing how the current situation built up, and provide a basis for the forecaster's ideas on future developments.

Pentad mean charts can be used in a similar way on many occasions, having the advantage for this purpose that some of the detail of the daily charts is lost while the broad trend of development is largely retained. The main snag is that the latest pentad chart is centred on a time 2½ days before the current chart, but this can be overcome to some extent by constructing 'pseudo-pentad' mean charts from the central time and times 36 hours earlier and later. The series may be extended up to the time of the latest analysis, or even into the future, by using the 3-day forecast charts.

Other sometimes useful aids in the form of continuity charts are the so-called 'trough/ridge' diagrams[5] and 'meridian/time' graphs. Trough/ridge diagrams show the distribution of surface pressure, or the geopotential of an isobaric surface, as a function of time and longitude on a given latitude circle: an example is shown in Figure 2. A meridian/time diagram is similar, but shows the distribution of the property as a function of time and latitude along a given meridian. Both types of diagram are rather laborious to prepare, however, and care must be taken to avoid the temptation to use them by simply extrapolating past tendencies into the future.

15.2.5.3 Statistical rules. On some occasions one of the forecast charts, as computed or subjectively amended, suggests that a situation will arise which satisfies criteria for, say, a dry spell (Ratcliffe,[6,7] Ratcliffe and Collison[8]) or a wet spell (Lowndes,[9] Ratcliffe and Parker[10]), or for the meridional extension of a trough (Miles[11]). Such statistical rules can be of great value when they happen to apply.

15.2.5.4 Analogue aids. The use of analogues in forecasting is based upon the idea that like causes are followed by like effects. This idea is used by the short-range forecaster who searches his memory for situations in the past similar to the one with which he is dealing. It has also long been used in monthly and, more recently, seasonal forecasting (see 15.3, page 12), and has been adapted for use in medium-range forecasting.

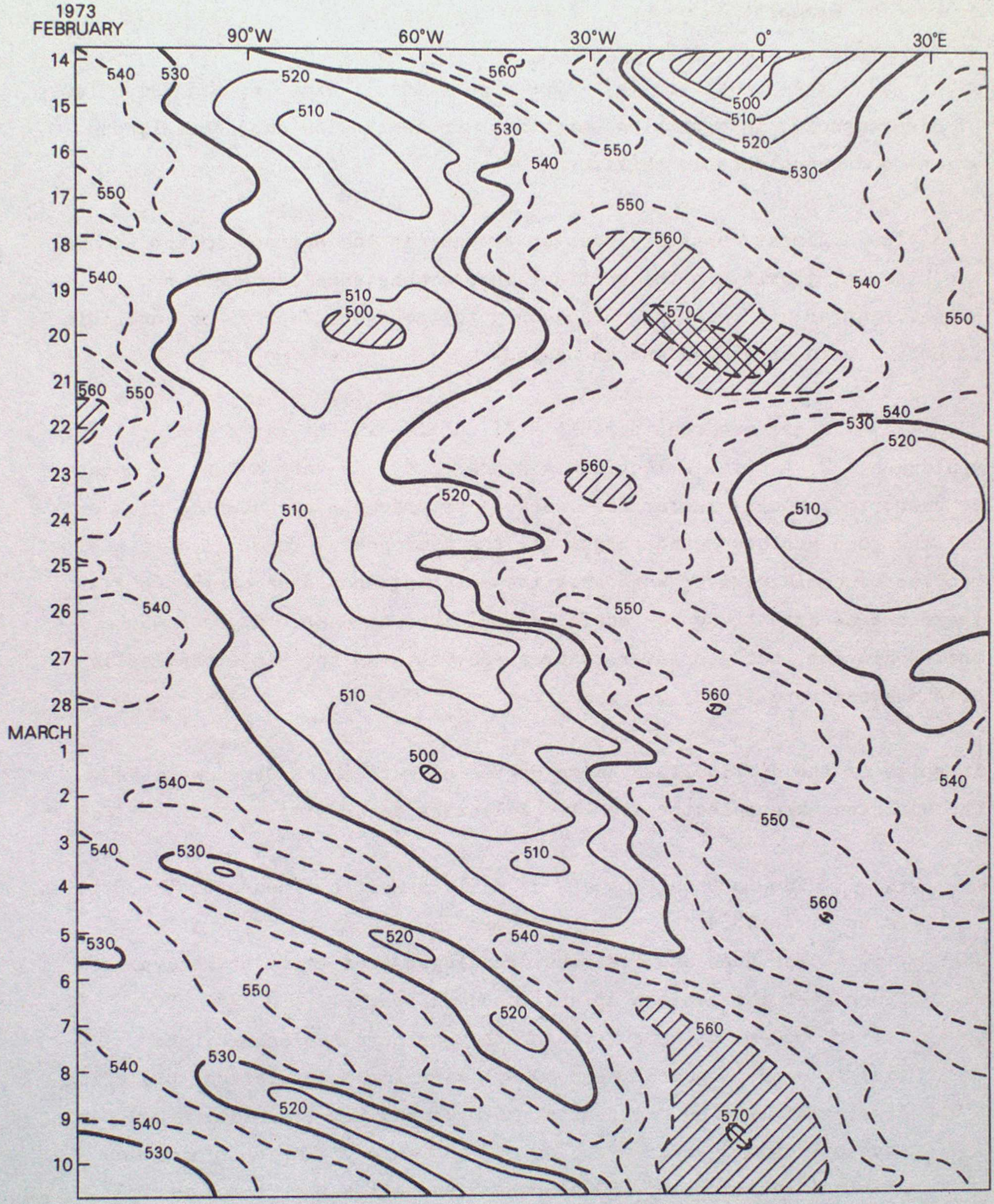

FIGURE 2. Ridge/trough diagram: 500-mb geopotentials at 55°N

Ideally, a perfect analogue is required, but a number of difficulties arise, for example:

(a) The atmosphere may never repeat itself exactly, and the effect of discrepancies is a problem which must be dealt with subjectively and which needs considerable skill.

(b) Almost certainly near-congruence at the surface is not enough, and close similarity in the vertical is probably equally necessary. Reliable upper-air records go back only to the Second World War, and this is unlikely to be a long enough period.

(c) There are considerable difficulties in the way of selecting analogues. Subjective selection is hindered by the vast amount of data to be sorted, and it is far from easy to programme a computer to pick out all the good analogues and reject all the poor ones. There is also the problem of deciding over what area the matching should be carried out: there are occasions when an analogue would be rated as good near the United Kingdom, but poor over other areas, such as the western Atlantic or eastern Europe.

In spite of the difficulties, some degree of success has been achieved. The analogues are selected from the following data sets:

(i) The Lamb catalogue[12] of daily synoptic types over the British Isles since 1861;
(ii) The Hess and Brezowski catalogue[13] of large-scale synoptic types over the eastern Atlantic and Europe;
(iii) 500-mb daily charts for the northern hemisphere; and
(iv) a catalogue of mean 500-mb maps for 5-day periods preceding dry (rainfall < 50 per cent of normal) and wet (rainfall > 200 per cent of normal) weeks over England and Wales. There is also an American catalogue of 700-mb pentad anomalies,[14] but the period covered, 16 years, is too short to be of much value.

Catalogues (i) and (ii) are searched by computer to select the best 20 or so analogues from the past data for the same time of year, the synoptic sequences being matched over a period of five days. The selected analogues are then checked by a subjective examination of historical weather maps; most of the possible analogues can be discarded at this stage, usually because the agreement is not good enough over a large enough area. The final selection of analogues usually numbers five or less.

The 500-mb analogues may be selected from catalogue (iii) by a technique based on the eigenvector analysis of Craddock and Flood.[15] It has been found best to consider the circulation over three days, giving greatest weight to the most recent day of the three.

The data from catalogue (iv) are checked subjectively: they are useful on about one-third of occasions. Even if no good analogue exists, some guidance may be obtainable if, for example, one or more nearly acceptable analogues preceded a wet week while none was followed by a dry week; the indications are that the forecast week would be unlikely to be dry, particularly if that prediction were supported by other methods.

When all the satisfactory analogues have been chosen, a 'composite' or mean chart may be constructed from the sequels for each day of the forecast period; this procedure filters out the detail and emphasizes the main, broad-scale features. Care must be taken, however, to see that the sequels form a nearly homogeneous group; it would be wrong, for example, to take the average field of a major depression and an anticyclone.

Although analogues do not provide a prime basis for a 7-day forecast, and may be misleading without careful choice and interpretation, they often serve a useful purpose in confirming the results of the other methods, or may clarify the issue when the numerical forecasts and subjective assessments leave room for doubt.

15.2.5.5 Formulation of the weather forecast. When the forecaster has considered as many aspects of the situation as practicable, and in particular has decided on those elements of the relevant computed forecasts which seem most likely to be reliable, he must then take the final step of forecasting the probable weather.

The dynamical and synoptic factors relating surface weather to the upper-flow patterns have been discussed in earlier chapters (Chapters 2, 4 to 7). In deciding on the amount of detail to put into the forecast, the meteorologist must bear in mind the errors that are likely in the prognostic charts, particularly in the movement and growth or decay of evolving systems. Unless there is a firm basis for giving a fair amount of detail, the insertion of 'frills' detracts from, rather than strengthens, the forecast. It is particularly important, though, to give as much information as possible about an expected change of type, and to attempt to forecast the timing, although errors of the order of one day are to be expected.

15.2.5.6 Conclusions. Although some elements in the 7-day forecast are less well predicted than others, the experiment has shown some degree of success. It seems unlikely that any significant improvement will stem from changes in the subjective procedures, and real progress will have to await better numerical prognoses for periods longer than three days.

15.3 LONG-RANGE FORECASTING

15.3.1 History

Britain can claim to have been about the earliest country to consider seriously the possibility of long-range forecasting. In 1878 the then 'Imperial Meteorological Reporter' (H.F.Blanford) undertook a study of monsoon rainfall in India following a disastrous famine there in 1877. This work was followed up and culminated in the discovery of the 'southern oscillation' by Sir Gilbert Walker in the 1920s. Our modern long-range methods started in the 1950s when J.M.Craddock prepared a historical series of hemispheric monthly mean-temperature-anomaly maps which have been used ever since for the selection of years analogous to the present.

A few other countries have worked in the long-range field, notably the U.S.A., the Soviet Union, Germany and Japan, and British methods have taken due account of research and practical methods in those countries. The emphasis in different countries is rather different: the Japanese, for instance, have always been interested in seasonal forecasting as the summer weather is very critical for the rice crop which is of great economic importance. In Russia longer-range forecasts have been orientated towards forecasting the dates of freezing of rivers or the break-up of ice along the north Siberian coast. In Britain and America the 30-day forecasts have probably received more attention than the longer range but in this chapter we shall consider (a) 30-day methods, (b) seasonal forecasting, and (c) possibilities of climatic forecasting.

15.3.2 30-day forecasting

Our methods of 30-day forecasting can be classified under three main headings:

(a) Anomalies of the underlying surface.
(b) Analogue methods.
(c) Statistical relationships and rules.

These methods will be briefly described and illustrated.

15.3.2.1 Anomalies of the underlying surface. Three factors are considered under this heading: snow, arctic ice and ocean surface temperatures. Snow is important mainly because of its high reflective properties, about 90 per cent of incoming solar radiation impinging on a snow surface is reflected back to space and takes no part in heat-exchange processes at the surface. Also, any incoming radiation which is absorbed as heat does not immediately raise the temperature of the snow surface above freezing because of the latent-heat requirement. For these two reasons a deep snow layer tends to lead to the establishment of a corresponding cold region in the atmosphere and may result in rather permanent upper cold troughs. In early spring and in autumn, particularly, such factors may be of importance; cold troughs can become well established in unusual longitudes, resulting in anomalies in the general circulation. For example, a deep fall of snow in autumn in the central parts of Canada may result in the Canadian upper trough occupying a preferred position at longitude 90-100°W, far enough west of normal to give a persistent downstream trough west of the British Isles with implications for the monthly forecast. Similarly a general snow cover farther south than usual over the American continent in autumn and early winter is likely to result in a more powerful than usual jet stream whose effects can be estimated for western Europe. It is in these ways that anomalous snow cover is used as an aid in long-range forecasting although little objective investigational work has yet been carried out. Anomalies of arctic ice cover can have similar effects on the general circulation; indeed the positions of the anomalies of ice and snow may largely determine the position of the atmospheric polar vortex over quite lengthy periods. Ice anomalies also have other long-term effects, especially in spring and early summer. In May 1972, for instance, the amount of ice moving from the Davis Strait into the western Atlantic was extreme; at one stage more than 100 000 square miles of ocean, normally ice-free, was covered with pack ice. The melting of this ice led to a cooling of the ocean surface which, by a rather complicated chain of reactions involving extra cyclogenesis, more cloudiness and evaporation than usual together with upwelling of cold water in the ocean, rapidly spread eastwards to give ocean temperatures about 1-2 degrees below average over the whole north Atlantic north of about latitude 45-50°N. As a result June 1972, even with predominantly south-westerly winds, averaged 1-2 degrees below normal over much of Britain, making it one of the three coldest Junes in the last 100 years. Excess ice in the Iceland region often leads to a late spring in Britain; it also aids anomalously cold northerly outbreaks over Britain in winter and spring and hence is a factor to be considered in monthly forecasting. The most important anomalies of the underlying surface are probably those in sea-surface temperature (SST) both in the Atlantic and Pacific. Sawyer,[16] reviewing the possible causes of long-term weather anomalies, came to this conclusion in 1965, subject to the provisos that SST anomalies should last for at least a month, be of considerable magnitude and cover a large area. This is not surprising since the heat capacity of the top 25 metres of ocean exceeds that of the overlying atmosphere by a factor of at least 10 and, at the same time, anomaly patterns in ocean temperature are conservative, a well-marked anomaly pattern having an average lifetime of about four months. Nevertheless, monthly and seasonal variations in sea temperature are comparable with similar variations of air temperature. For example, in July 1968 at Ocean Weather Station 'D' (44°00'N, 41°00'W), the sea-temperature anomaly was approximately equal to three-quarters of the annual variation (anomaly -5 degC; average sea temperatures in February 14°C, in July 21°C); such a large anomaly would be unusual in air temperature over land at the same latitude in summer.

In an attempt to find the effect of different Atlantic SST anomaly patterns on the weather a month ahead, a set of SST anomaly charts based on all available data has been produced for each month from about 1887 to date (almost 1000 charts). From a study of these it soon became evident that the two commonest anomaly patterns were cases with a large area of positive anomaly (WP) or negative anomaly (CP) in the area to the south and south-east of Newfoundland, approximately 40-45°N, 40-60°W. Three types of WP and three of CP were recognized with the anomaly centred near 40°W, 50°W or 60°W, and two other anomaly patterns often occurred in which most of the Atlantic north of 50°N was cold (or warm) while that south of 50°N was warm (or cold). Thus, in most months of the year, eight different SST anomaly patterns were sufficiently common over the 85 years or so of data to make up a statistical sample. For each sample, charts were produced showing (a) the mean pressure anomaly (MPA), (b) the mean temperature anomaly (MTA), and (c) the mean rainfall percentage of average, over western Europe for the following month. Figures 3(a), (b), (c) and 4(a), (b), (c) for Februarys following WP and CP Januarys respectively illustrate the type of results obtained. It is clear from these figures that a WP5 January favours low pressure with near-average temperature and above-average rainfall in Britain in February while CP5 Januarys in general precede dry Februarys, with a large positive anomaly of pressure over England. Figures 5(a) and (b) show MPAs for Mays following WP and CP Aprils respectively; again they are virtually opposite patterns near Britain. Since similar results are found at a lag of one month throughout the year, it is clear that SST anomalies are a valuable long-range forecasting tool. Nevertheless the technique has its limitations: only about two-thirds of months have a recognizable SST anomaly pattern, while in the rest the anomalies are small or the pattern notably different from any of the eight. Furthermore, results such as Figures 3 to 5 represent the mean of the sample (usually of about 8-12 individual years) and it is usual for some 10-20 per cent of cases not to conform to the sample mean, but the fact that, for most months, the indications from WP and CP cases are approximately opposite, and also that indications for one month are much the same as those for the next month for the same SST pattern, make it practically certain that the effects noted are real. The method outlined above has been used since 1969 in operational long-range forecasting with good results. It is described more fully by Ratcliffe and Murray[17] and Ratcliffe.[18] Since sea temperature appears to play such an important part in determining circulation anomalies, another method of estimating the likely pressure anomaly pattern a month ahead is to choose the three cr four best SST analogues and form a composite MPA

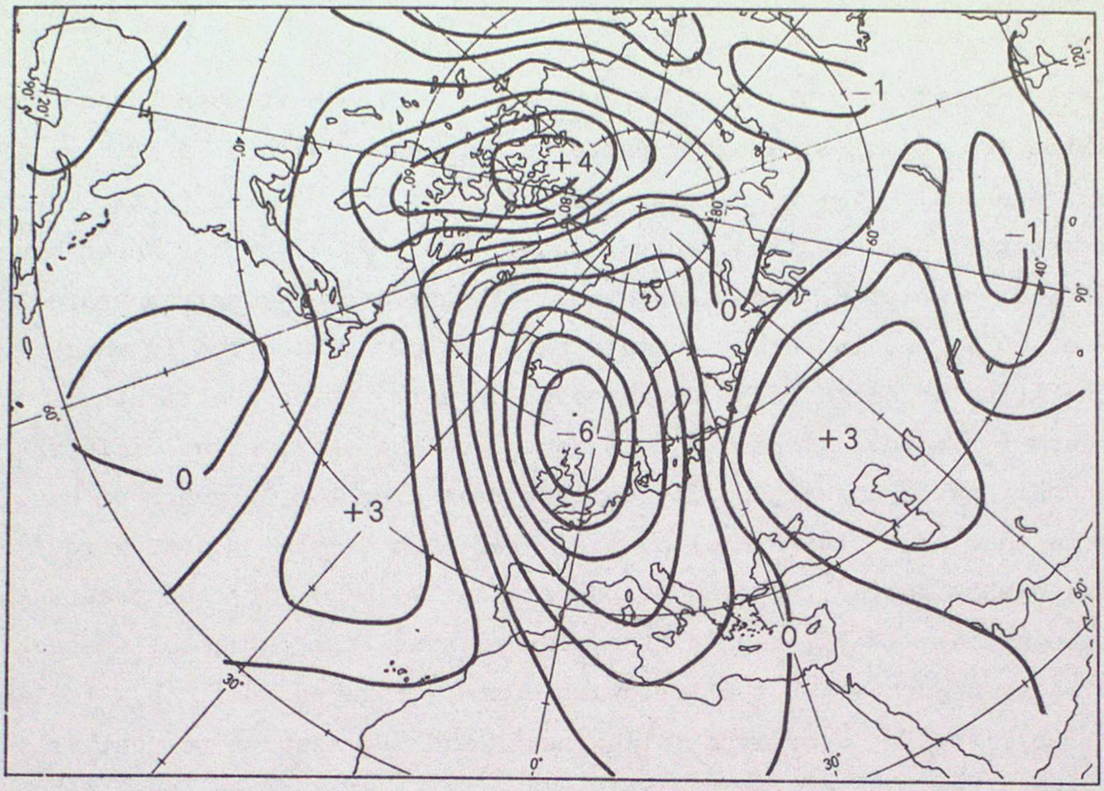

FIGURE 3(a). Mean surface-pressure anomaly (mb) for Februarys following Januarys with an Atlantic SST classification of WP5

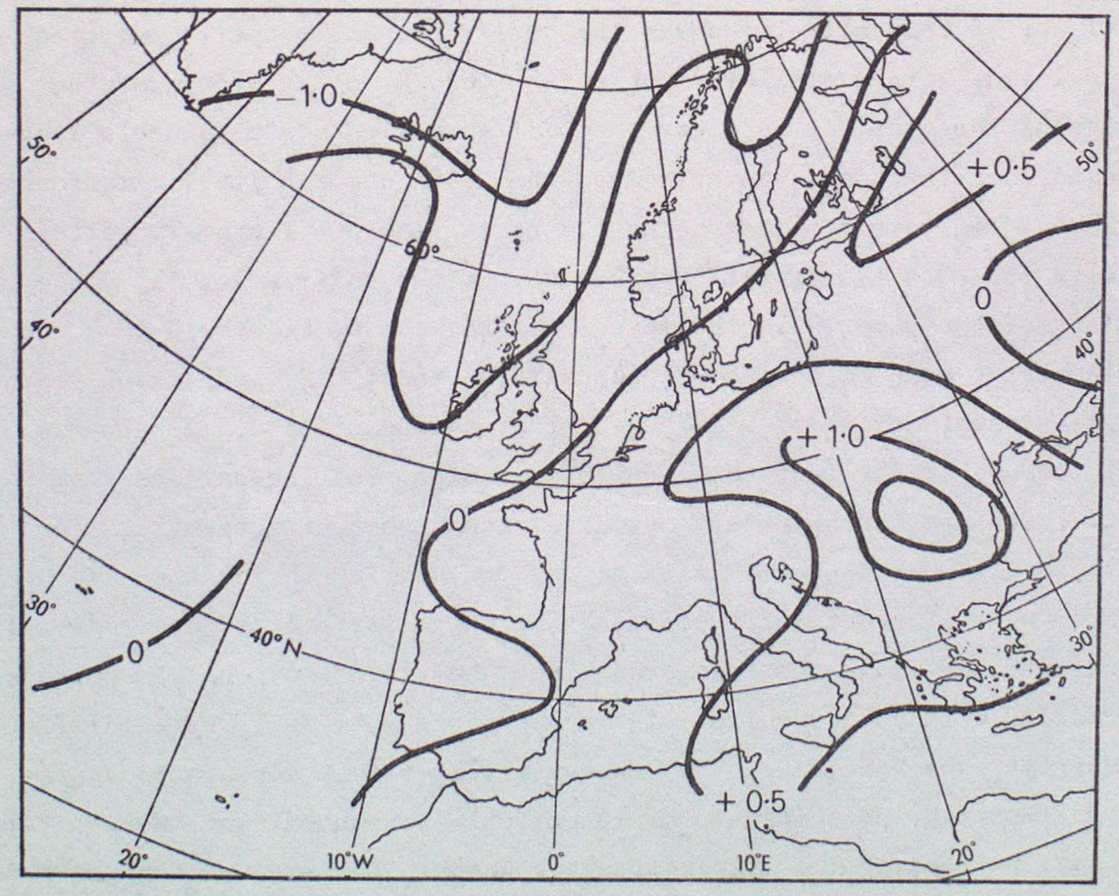

FIGURE 3(b). Mean temperature anomaly (°C) for Februarys following Januarys with an Atlantic SST classification of WP5

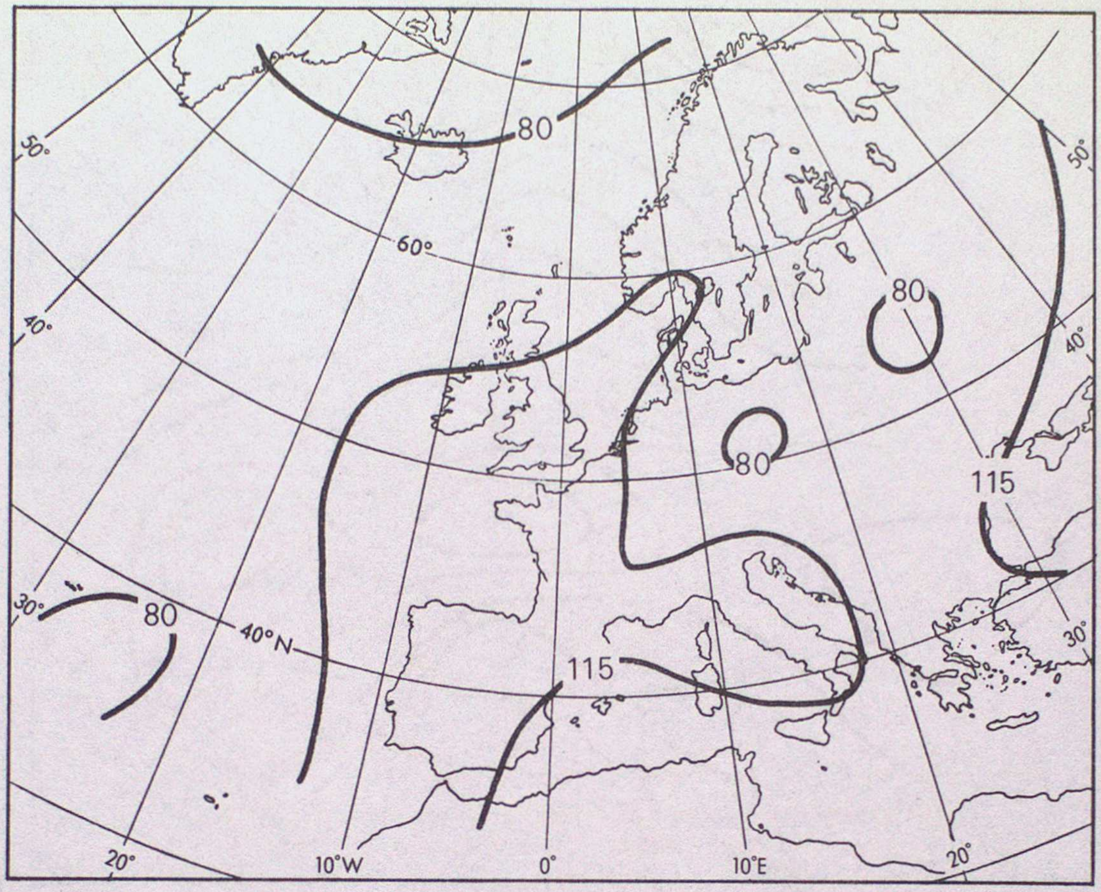

FIGURE 3(c). Mean rainfall percentage of average for Februarys following Januarys with an Atlantic SST classification of WP5

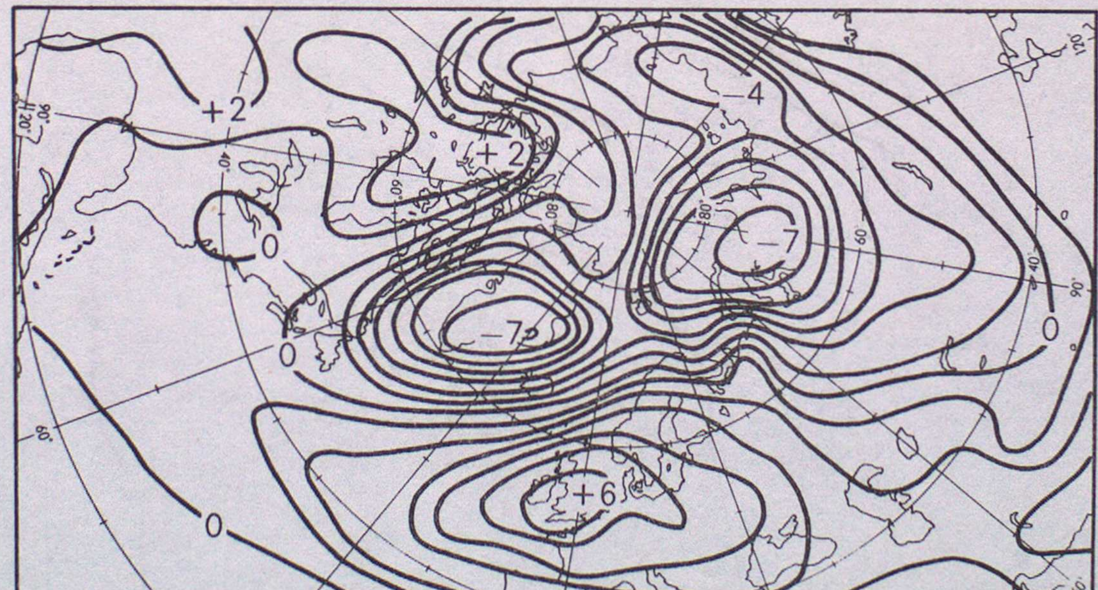

FIGURE 4(a). Mean surface-pressure anomaly (mb) for Februarys following Januarys with an Atlantic SST classification of CP5

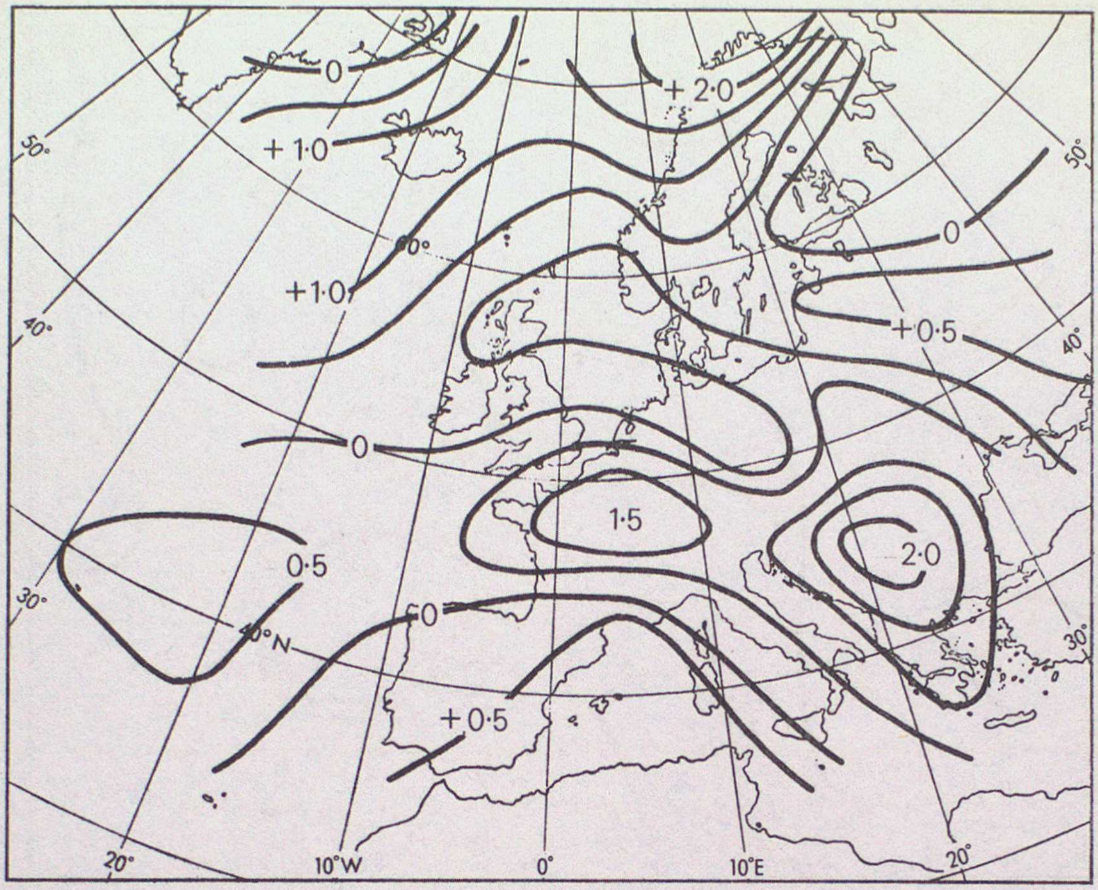

FIGURE 4(b). Mean temperature anomaly (°C) for Februarys following Januarys with an Atlantic SST classification of CP5

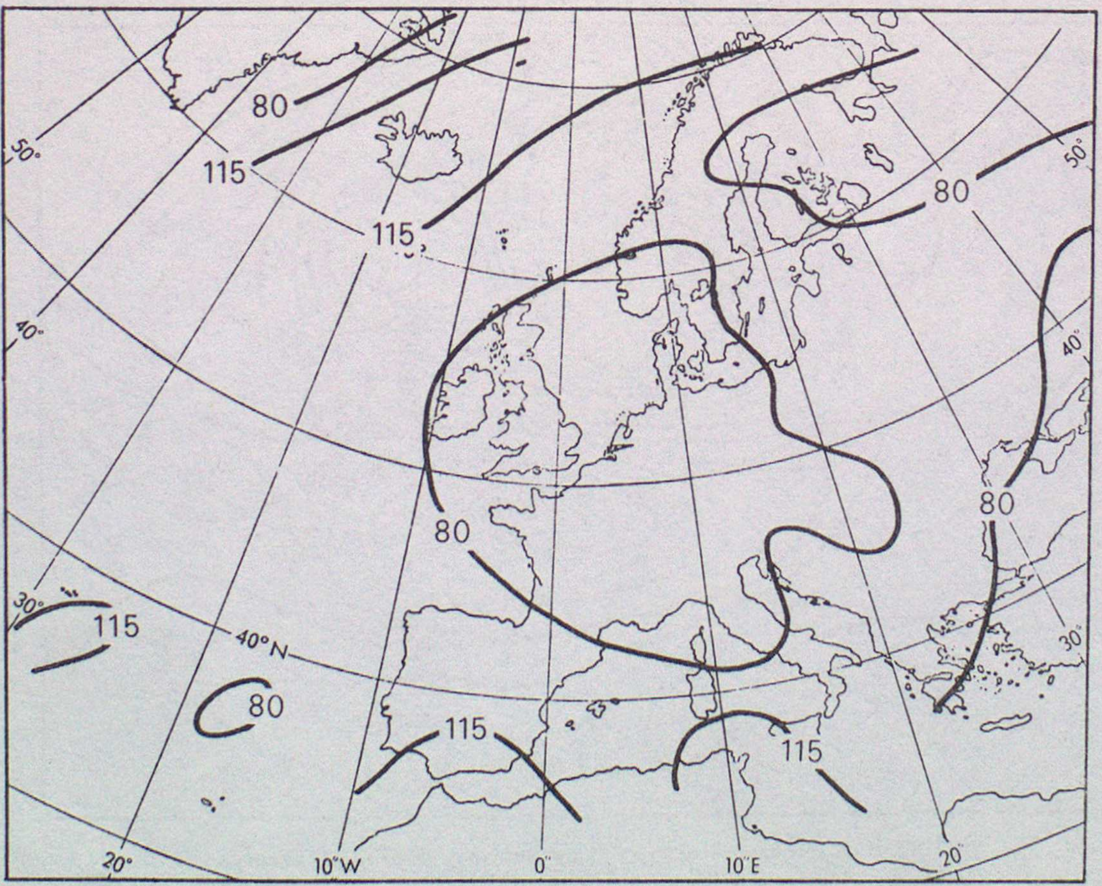

FIGURE 4(c). Mean rainfall percentage of average for Februarys following Januarys with an Atlantic SST classification of CP5

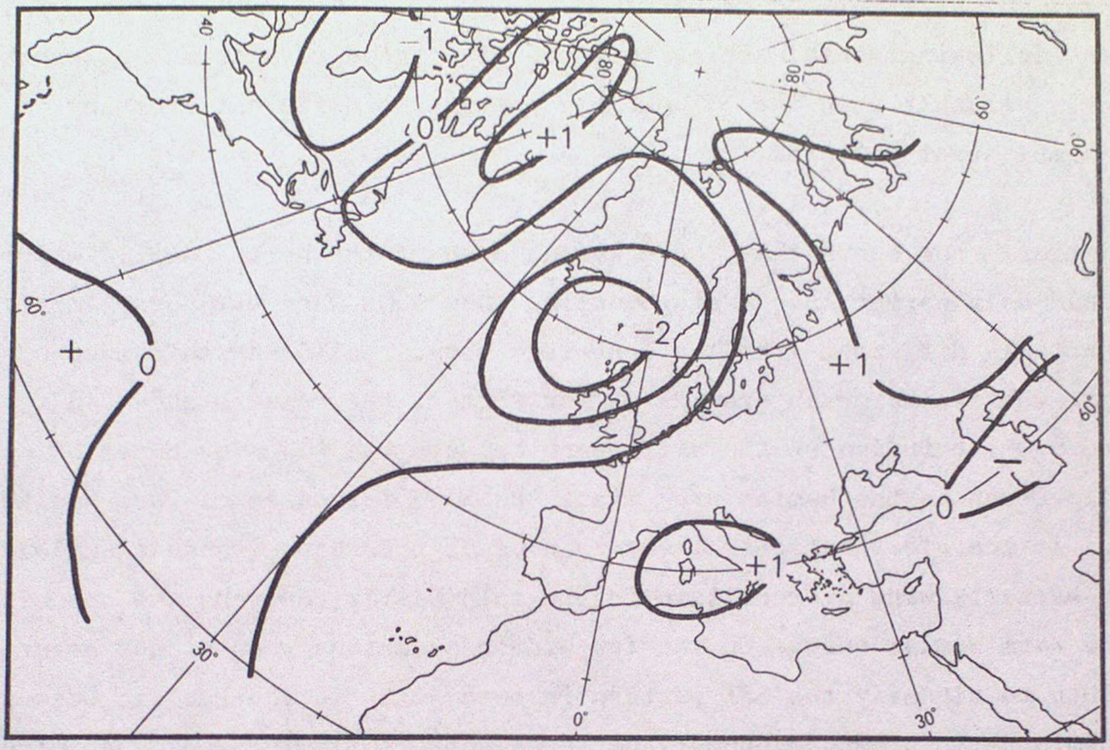

FIGURE 5(a). Mean pressure anomaly (mb) for Mays following Aprils with an Atlantic SST classification of WP5

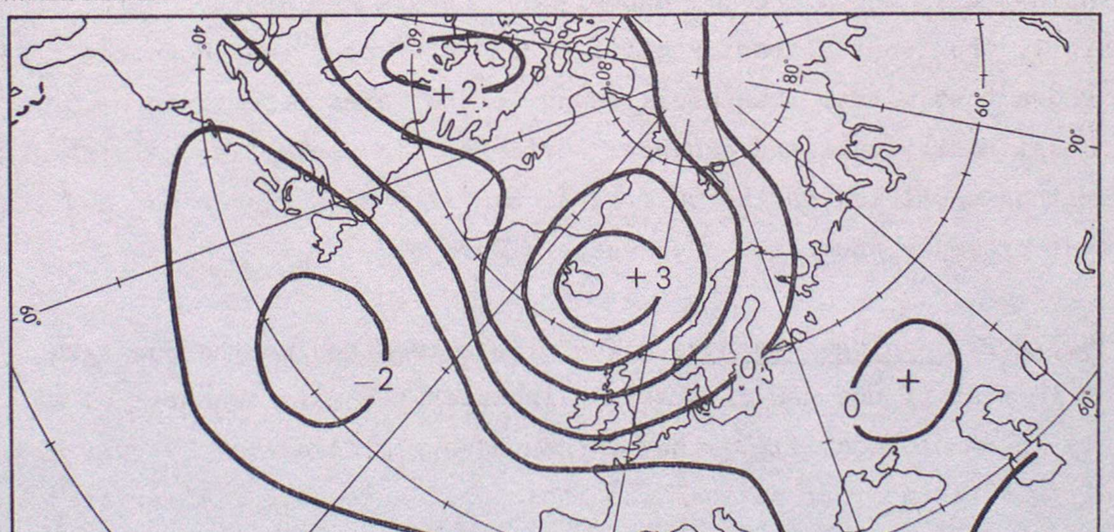

FIGURE 5(b). Mean pressure anomaly (mb) for Mays following Aprils with an Atlantic SST classification of CP5 for the following month. This, too, has given good results and is particularly valuable when the SST anomaly pattern is different from any of the normal eight patterns.

Namias[19] has shown that there was an area of the North Pacific where SSTs had been warmer than average during the 1960s when MPAs over America were notably different from the long-term mean. Following this idea up for the western European area gave, for winter, the results shown in Figure 6 which indicates the difference between the MPAs for cases of cold Pacific Ocean in the Namias area minus the MPAs for cases of warm Namias area. It therefore suggests lower than usual pressure with an anomalous south-easterly wind over Britain in the cold Namias case and the opposite in the warm Namias case. On the few winter occasions when it has been possible to classify the SST pattern in both Atlantic and Pacific Oceans, the hemispheric pressure anomaly pattern in the following month has closely accorded with that obtained by adding the expected MPAs from the two oceans, thus suggesting that, at least on some occasions, SST anomaly may largely determine the hemispheric pressure anomaly on a monthly time scale.

Another area where the SST anomaly may have some importance for Britain is the tropical east Pacific. Both Bjerknes[20] and Rowntree[21] have shown that warmer than usual ocean in that area results in a stronger than usual Hadley cell and enhanced North Pacific westerlies, giving a deeper than usual low in the Gulf of Alaska with some weaker but not insignificant pressure anomalies over western Europe.

15.3.2.2 Analogue methods. The simple idea behind the analogue method is that if one can find a year in which the main features of a monthly meteorological field (say pressure) are similar to the current field, then the weather of the next month will have some similarities to that which followed in the analogue year. It is clearly better if the underlying physics is known as in the case of SST analogues in the Newfoundland area, but in the absence of a full understanding the analogue method is useful. Six analogue methods are currently used, namely:

(i) Daily weather catalogues. Lamb[12] has classified each day's weather near the British Isles since 1860 into one of 27 different types; each day is represented by a letter (e.g., W for westerly type) so that

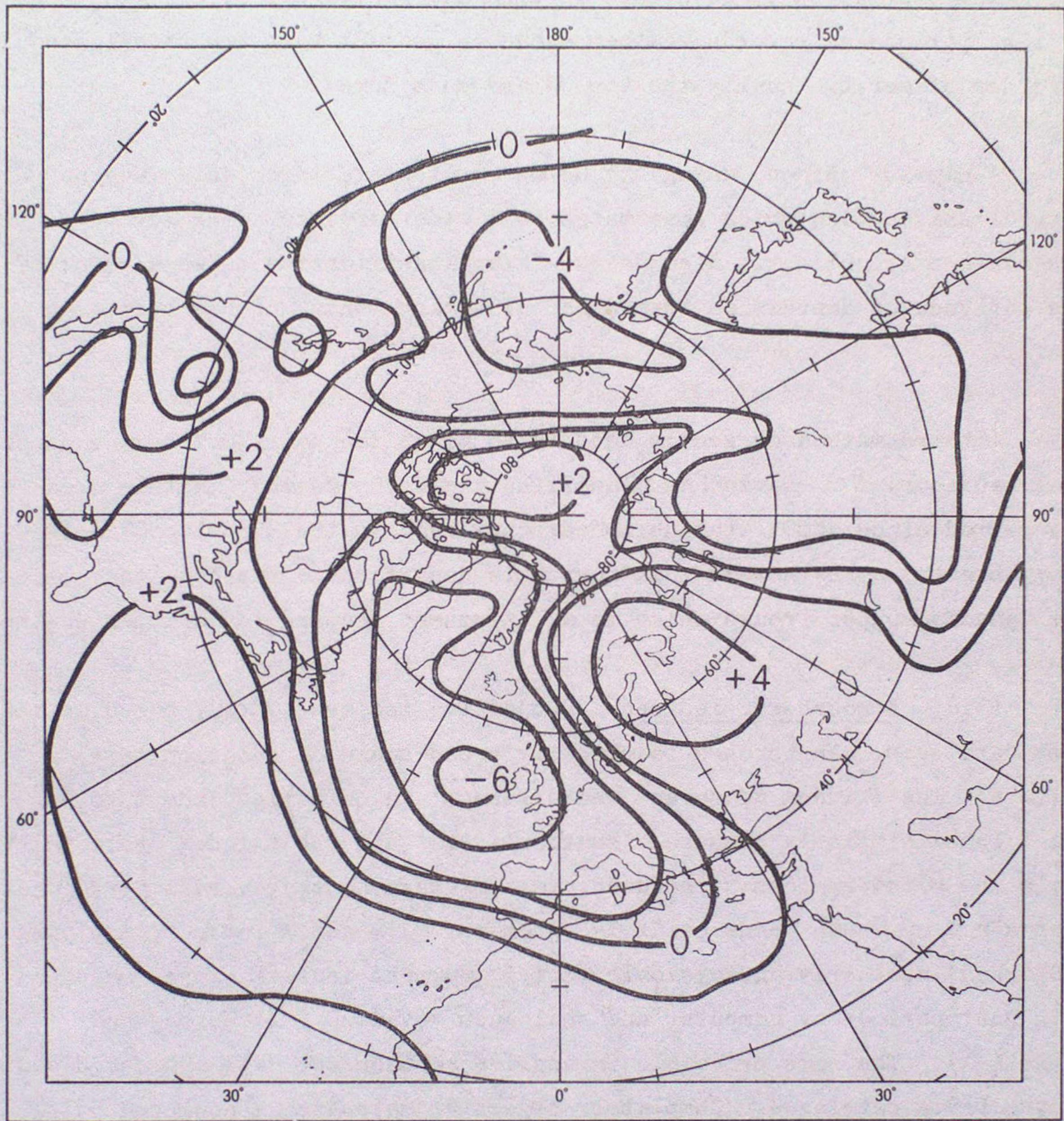

FIGURE 6. Mean pressure difference (mb), cold cases minus warm cases, in Namias area in winter

30 letters represent a month's weather. The computer has been programmed to match the current month's weather as accurately as possible, allowing for a shift of up to 15 days both forward and backward in time. The most similar periods as regards weather sequence near Britain are then listed in order of merit: usually the top 30 are considered.

A similar method, using the German Grosswetterlagen daily weather-type classification which appertains to a wider area covering Europe and the eastern Atlantic, is also used. This classification takes account of the latitude of depression tracks and of anticyclones and has been very useful.

A third method currently used is to match the daily weather sequence near Labrador. N.E. Davis has classified the daily weather in this area for the period since 1880: (unpublished; copy held in the Synoptic Climatology Branch). Weather in this region is sensitive to the longitude of the Canadian upper trough which is an important feature for British weather.

(ii) Atmospheric indices. Objective indices (*PSCM*), based on the Lamb catalogue, can be used to classify broad-scale circulation near Britain. The *P* index measures 'westerliness' in quintiles from 1 to 5, the *S* index similarly measures 'southerliness' and the *C* index cyclonicity, while the *M* index, less often used, is a measure of the overall meridionality. Thus a $P_1 S_1 C_1$ month means quintile 1 for the *P*, *S* and *C* indices, implying a blocked, northerly anticyclonic month. Current indices can be matched with past periods by computer and analogues revealed (see Murray and Benwell[22]). The same principle is applied to Labrador *PSCM* indices based on the Davis catalogue. Completely objective matching is achieved by these methods.

(iii) Monthly mean pressure anomaly and (iv) Temperature anomaly fields. Monthly mean pressure and temperature anomaly fields over the northern hemisphere are subjectively matched; the most important anomalies on the current charts being listed first of all to aid the matching process. Data for matching purposes is available back to 1873 although the temperature fields are sparse in early years.

(v) Hemispheric 500-mb fields. 500-mb data on a hemispheric scale are only available since 1945 but a statistical method of deducing the monthly mean charts for earlier years based on pressure anomalies has been developed so that, for analogue purposes, charts are available back to 1873 when the pressure data started. 500-mb analogues appear to have more predictive value than most other types and further work on 500-mb predictors is outlined below.

(vi) SST anomaly fields (Atlantic). Although SST anomaly is considered as described in 15.3.2.1 (page 13), it is still valuable to consider analogues of the monthly SST anomaly map over the whole of the Atlantic area including Biscay and the coastal waters of western Europe. These local waters are sometimes important for both temperature and rainfall forecasting in Britain.

After a subjective study of the daily weather maps, the best four or five analogous years are selected and their sequels used as guidance in preparing the 30-day forecasts. Years that show considerable resemblance to the current year over a period of several months are to be preferred to a year which suddenly appears as a good analogue. Graphs of similarity are maintained continually so that it can be seen at a glance when an analogue year appears to be approaching its peak.

15.3.2.3 Statistical relationships and rules. A large number of forecast rules (as many as 40 for some months) have been developed to give guidance on the expected weather a month ahead. Examples of this type of work are:

(i) Rules based on 500-mb anomalies. Twenty-eight years of daily 500-mb data over much of the northern hemisphere are now available on magnetic tape. The procedure adopted has been to select, say, the 8 driest and 8 wettest Septembers in the 28 years, form a mean of the 500-mb monthly charts in August preceding each class, and subtract the two means, thus defining areas which have been different in the past before dry and wet Septembers. A suitable statistical test is then carried out to estimate the significance of the areas so defined.

Figure 7 gives an example of how this method works and shows the areas in August which are apparently significantly different (5 per cent level) at 500 mb before wet and dry Septembers. The chart indicates the areas where mean preceding wet minus mean preceding dry is significant and therefore represents the significant anomaly pattern preceding wet; if the signs are reversed the pattern becomes that typically preceding dry. The next step in the method is, for each individual year in the 28-year sample, to add up the 500-mb anomalies at all points significantly negative before wet and subtract the sum of all the anomalies at grid points significantly positive before wet. The results are then ranked; ideally, years with wet Septembers should have a large negative number and years with dry Septembers a large positive number. Table 15.1 gives the ranked list of years in this case. It is then only necessary to compute anomalies at the significant points for the current year and see how the result compares with the ranked list. A value of, say, -150 would imply wet while one of, say, +300 would suggest dry. This general method is very flexible and powerful. It is currently used not only for rainfall forecasting but also for temperature forecasting and it has been adapted to cater for mid-month to mid-month periods. Figure 8 shows the significant 500-mb anomaly pattern over the period mid November to mid December preceding a warm mid December to mid January. Here the implication clearly is that a more

TABLE 15.1 August as a predictor for September rainfall

Year	Significant August 500-mb anomalies	September (wet or dry)	Year	Significant August 500-mb anomalies	September (wet or dry)
1969	315	D	1967	11	W
1947	311	D	1945	10	
1959	285	D	1961	−6	
1955	251	D	1952	−17	W
1971	148	D	1950	−54	W
1948	119		1958	−54	W
1966	113	D	1951	−77	
1949	112	D	1965	−82	W
1964	91	D	1963	−85	
1970	81		1954	−97	
1972	64		1962	−100	W
1968	48	W	1957	−111	W
1953	23		1946	−125	W
1960	13	W	1956	−145	

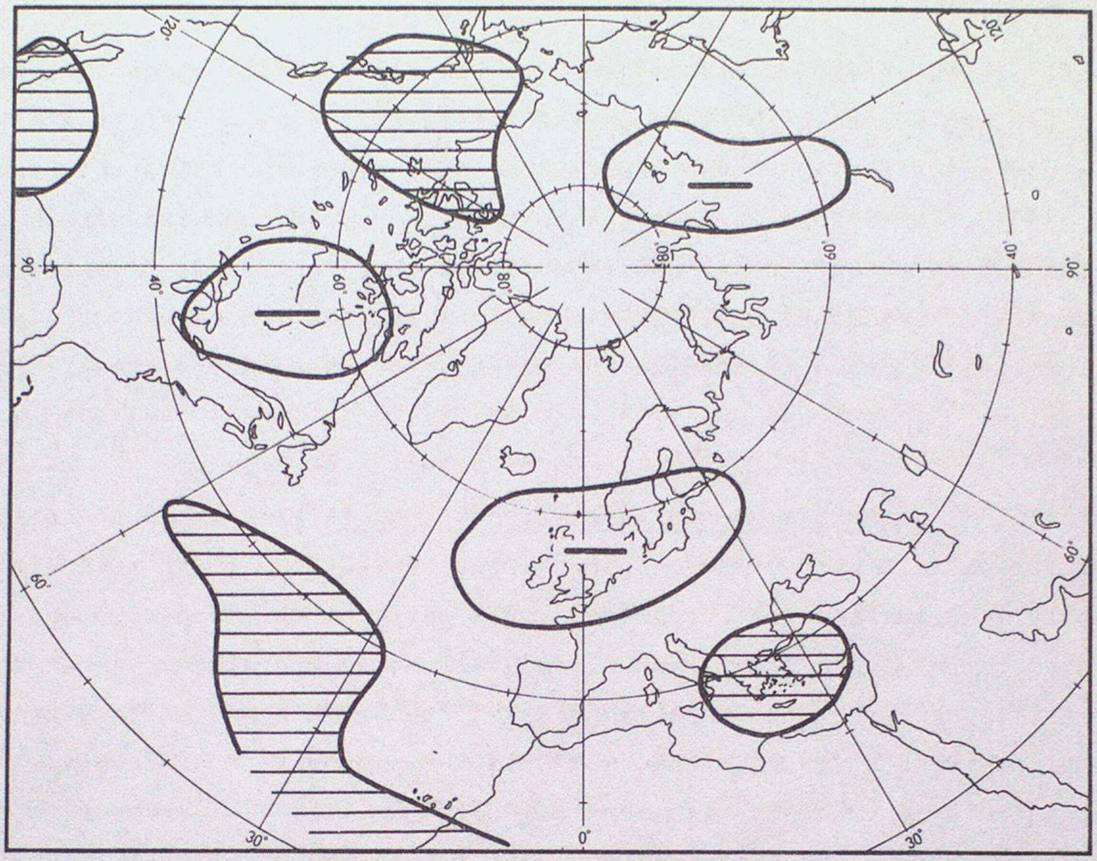

FIGURE 7. Significant (at 5 per cent level) areas of 500-mb anomaly in Augusts preceding wet Septembers

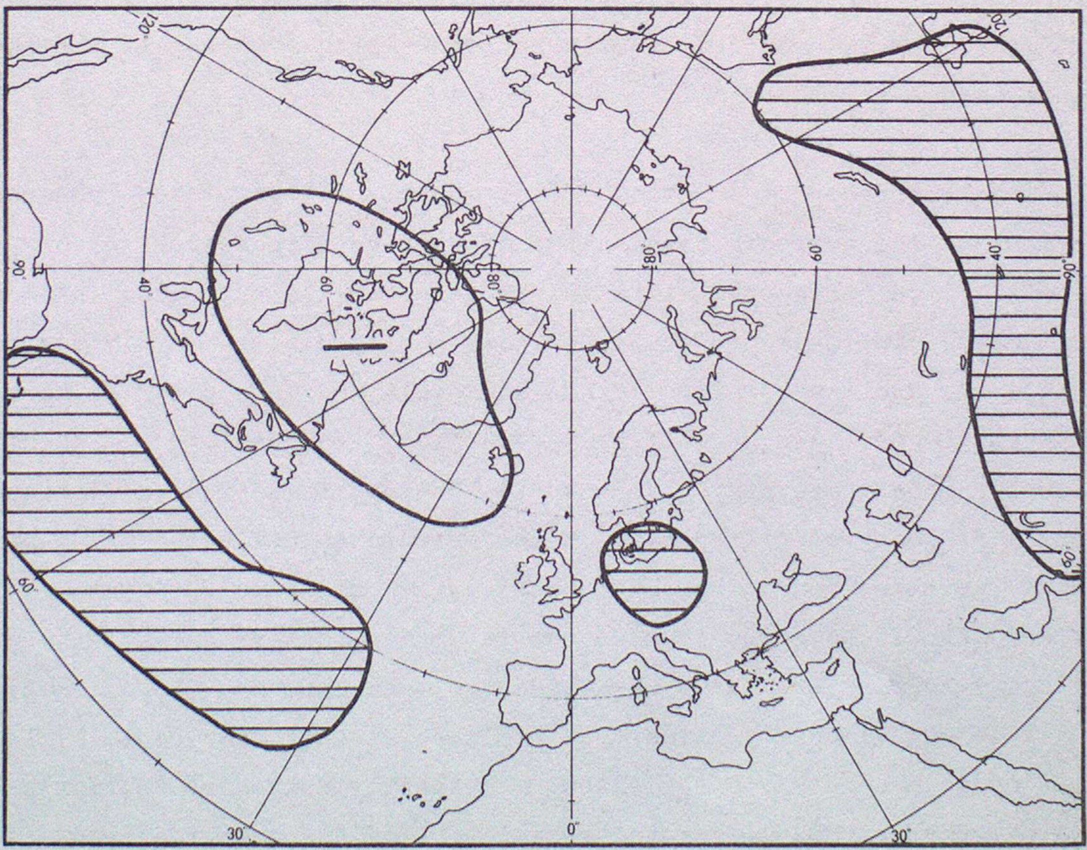

FIGURE 8. Significant (at 5 per cent level) areas of 500-mb anomaly from mid Novembers to mid Decembers before warm mid Decembers to mid Januarys

powerful than usual jet stream over the western Atlantic at about latitude 45°N favours warmth in Britain in the following 30 days. Half months in each period of the year have been ranked for both temperature and rainfall since 1945, so that it is possible to select dry/wet and warm/cold half months and carry out the procedure outlined above on the 15-day time scale instead of the monthly one. This often enables the two halves of a month to be compared or contrasted in the monthly forecast adding greatly to its value.

(ii) Rules based on surface-pressure anomaly. Broad-scale anomalous circulation in the troposphere can be represented to a first approximation by monthly mean surface-pressure-anomaly MPA patterns which in turn are intimately related to large-scale patterns in rainfall and temperature. An example of the relationship between monthly means of temperature and surface-pressure anomalies is shown in Figure 9, which is the composite of February MPA maps associated synchronously with very cold (or quintile 1) Februarys in central England. The large-scale blocking over the north-east Atlantic and Europe and the easterly anomaly of flow near the surface over England are clearly indicative of very cold weather in February over central England. Very mild (or quintile 5) Februarys are typically associated with large-scale mean monthly pressure-anomaly patterns which are roughly the reverse of those shown in Figure 9.

The long record (back to 1873) of monthly mean surface pressures over most of the northern hemisphere has been used in searching for empirical circulation predictors in the three months preceding the month of interest. The same procedure has been employed with monthly and seasonal predictions, and the detailed method was explained in a paper by Murray,[23] but it may be outlined briefly by an example of forecasting the quintiles of monthly mean temperature over central England in February. For each class of February specified by each temperature quintile the MPA chart in each of the three months before February was computed. For instance, Figure 10 shows the composite MPA map in January before quintile 1 (or very cold) Februarys. The broken line encloses the area where the pressure anomaly is significantly different from zero at the 5-per-cent level of significance according to the *t*-test. Evidently very cold Februarys tend to be preceded by above-average pressure in Iceland and Greenland and below-average pressure in the Mediterranean.

FIGURE 9. Mean pressure-anomaly pattern (mb) associated with very cold (quintile 1) Februarys in central England

Mean pressure for period 1873-1968 used. Broken lines enclose areas when MPA is significantly different from zero at 5 per cent level.

Composite maps like Figure 10 suggest that the circulation in certain areas in the three preceding months might be associated with specific temperature quintiles in February. MPA at one (or occasionally more than one) grid point within apparently significant areas were computed for each of the three preceding months from 1873, ranked and related to temperature quintiles of the following February. In many areas the same procedure was adopted for the difference in MPA between two points when this was thought to be relevant. The ranked MPA data were classified objectively (see Murray[23]) so as to obtain indicators of the type shown as (a) and (b) below.

(a) If MPA (at 45^oN 10^oE) in January <-2 mb, then frequency of February quintiles in ascending order is (13,7,8,2,3).

This gives a bias to cold and may be called a C type.

(b) If MPA (at 40^oN 00^oW) minus MPA (at 85^oN 00^oW) in January ≥ 6 mb, then frequency of February quintiles in ascending order is (0,4,6,12,5).

This may be called a W or warm type.

In any year individual indicators like (a) and (b) are not generally all satisfied. It has been found that quite simple discriminant procedures, such as the difference between the number of C-type and W-type indicators which are satisfied, give useful predictive rules. For February temperature, the overall rules based on November, December and January are summarized in Table 15.2. Even by 1 December preliminary rules are avail-

TABLE 15.2 Lag associations between February temperature and MPA indicators in November, December and January in central England

Period	$N_c - N_w$	February temp. (quintiles) 1	2	3	4	5
Nov. + Dec. + Jan.	−3	0	1	4	16	14
	= −2 to 2	2	9	7	4	3
	3	19	17	8	2	1

N_c and N_w are the number of individual predictors which indicate cold (quintile 1 or 2) and warm (quintile 4 or 5) Februarys respectively.

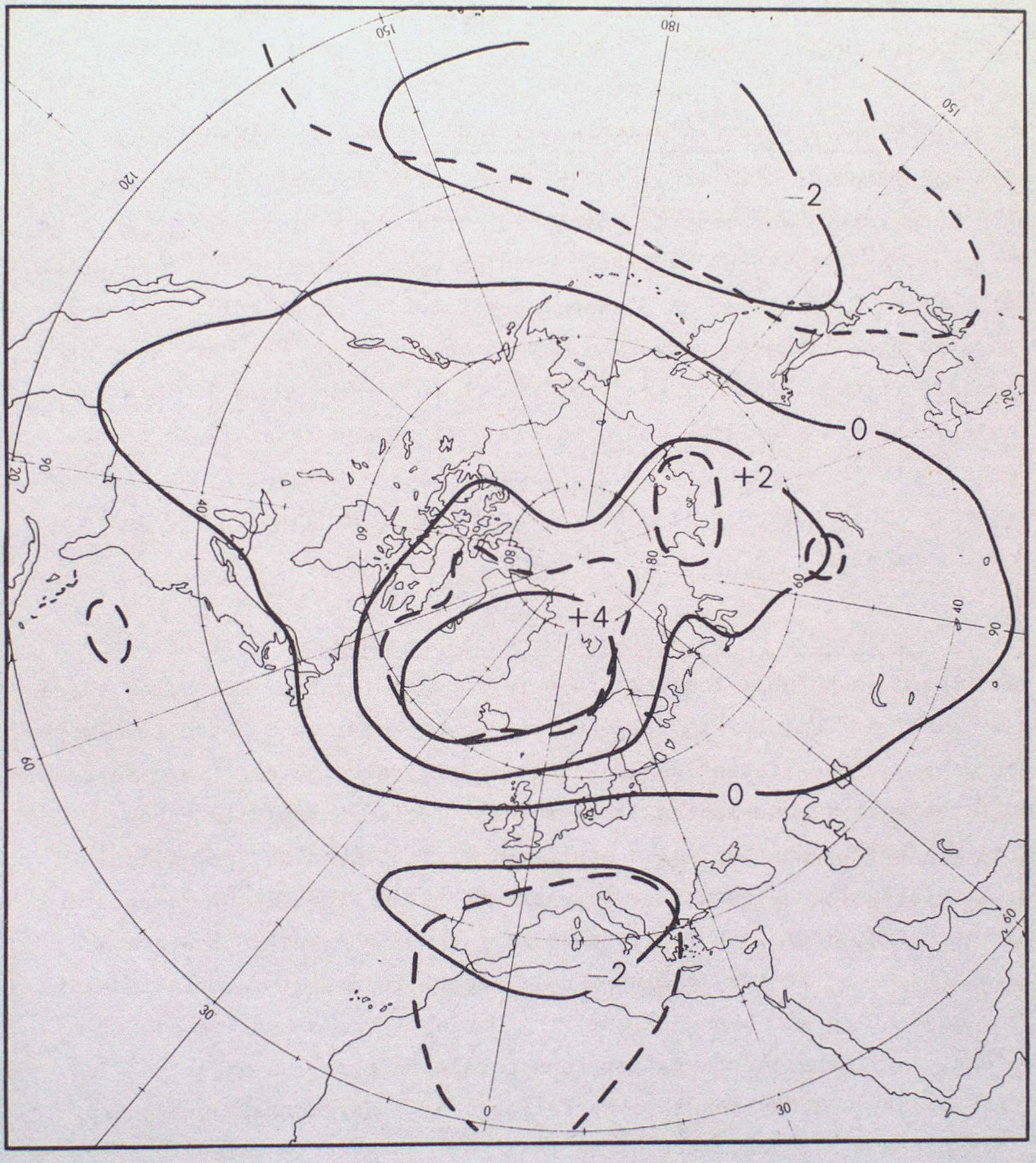

FIGURE 10. Mean pressure-anomaly pattern (mb) in January associated with very cold (quintile 1) Februarys in central England

Mean pressure for period 1873-1968 used. Broken lines enclose areas when MPA is significantly different from zero at 5 per cent level.

able, but the overall rule is generally the best. The same general method has been used in obtaining statistical relationships of use in forecasting terciles of England and Wales rainfall, and quintiles of temperature in central England for all months.

(iii) Rules based on atmospheric indices *(PSCM)*. The indices briefly described in 15.3.2.2 (ii), page 20, have good predictive value on many occasions. For example, cyclonic northerly Februarys ($S_{12}C_{45}$) have, in the past, been followed by mostly cold or very cold Marches, the latter actually being distributed as 9 cases very cold, 10 cases cold, 1 average and 2 warm, with no cases very warm. Thus that type of February suggests the probability of a cold or very cold March is almost 10 to 1. Similar valuable rules are available for both temperature and rainfall forecasts for each month throughout the year although all are not as strong as the one quoted. This work has also been extended to mid-month to mid-month periods, thus aiding mid-month to mid-month forecasting.

(iv) Rules based on persistence or anti-persistence. At some times of year there is notable temperature persistence: for example, after three warm months from December to February the chance of a warm March is almost 80 per cent and the statistics are about equally strong for a warm September after three warm summer months. The reverse (cold winter/cold March, cold summer/cold September) also applies. In fact Craddock and Ward[24] have calculated the areas in Europe where there is significant temperature persistence from one month to the next throughout the year. The probabilities of runs of wet/dry and warm/cold months in Britain continuing for another month have all been evaluated by Murray.[25] On a smaller number of occasions, anti-persistence rather than persistence may be expected: for example, a very wet May tends to be followed by a dry/normal June and a very dry September leads, more often than not, to a wet October.

These are only examples of many types of rule used in operational long-range forecasting; there are many others and some (e.g. the 500-mb anomalies) have been adapted to the 15-day or shorter time scale to enable extra detail to be given in the forecasts. When the final forecast is prepared all the above factors are taken into account, the conditions of the underlying surface, the analogues, and all the relevant forecast rules.

The 7-day forecast for the first week is also built in so that the whole forms the best possible estimate for the next 30 days, giving as much detail as possible and following on logically from the 3- to 4-day outlook.

15.3.2.4 Assessment of monthly forecasts. It is not intended here to go into details of assessment (see Ratcliffe[26]) but two important factors need to be emphasized. Firstly, temperature is always forecast in one of five equally likely categories for each of ten United Kingdom districts, and rainfall is forecast similarly as one of three categories. These elements are judged against the mean temperature anomaly and rainfall percentage obtained from some five or six observing stations representing each district. An objective scoring system is used whereby, over a long period, chance would give a zero score. A positive score is thus taken as an improvement over chance. On this basis some three-quarters of temperature forecasts and rather fewer rainfall forecasts are better than chance.

Secondly, additional information is, whenever possible, forecast in terms of anomalies. For example, a forecast that snow will be more frequent than usual is verified against the number of days of snow falling at representative stations over the country compared to the average for those stations. Three categories above, near and below average are defined for elements such as snow, gale, frost, thunder and fog, and the same objective scoring system as used for rainfall is then applicable.

Assessments are made by a panel of three meteorologists not engaged in the forecasting so that final assessments are as unbiased as possible. Over the 5 years up to 1972, 78 per cent of forecasts have been given an overall mark of at least 'moderate agreement' with the additional information being the most consistently successful.

15.3.3 Seasonal forecasting methods

Although seasonal forecasts are not issued to the public, experimental forecasts have been prepared for a number of years and the results show that considerable success can be achieved in this field. Methods are rather similar to those used for monthly forecasts but less reliance is placed on analogues since these seldom have good predictive value over such a long period. The main factors considered are as follows.

15.3.3.1 Sea-temperature analogues. It is known that SST anomaly patterns have an average lifetime of 3-4 months and patterns are more conservative in late autumn and early summer than at other seasons. In the autumn, storminess and a decline in insolation leads to the top 60 metres or so of ocean acquiring an almost constant temperature by late November so that the anomaly pattern at that season is not easily changed during the ensuing winter. A similar situation occurs in reverse by late May or early June; at this season a lapse rate of temperature from the surface downwards is established and, with less storminess than in autumn, the anomaly pattern normally lasts throughout the summer. Figures 11 and 12 show the MPA in January following WP5 and CP5 cases respectively in November. The cyclonic anomaly over Britain in the first case is typical of warm, wet Januarys while the more anticyclonic easterly anomaly of the second case is usually indicative of a cold, dry January. Table 15.3 indicates the difference in the distribution of central England temperature in summer between years in which, in May, the SST classification was WP5 and CP5. In the WP case a cool summer is probable, while the CP case favours a warm summer. In forecasting for autumn and spring SST anomaly methods have to be used with caution because these are the seasons when anomaly patterns frequently change.

TABLE 15.3

May SST classification	Central England summer temperature (quintiles)				
	1	2	3	4	5
CP5	1	1	3	4	4
WP5	3	3	7	1	1

15.3.3.2 500-mb and surface-pressure anomaly patterns. The methods described for monthly forecasting in 15.3.2.3(i) and (ii) above have been adopted for seasons. The areas which have been significantly different in the three months preceding wet/dry and warm/cold seasons have been pin-pointed both for 500-mb anomalies and surface-pressure anomalies. Rules based on the anomalies in these significant areas have then been defined for each of the four seasons. It is not necessary to consider these methods further since the principle has been described earlier, but very successful results have been achieved.

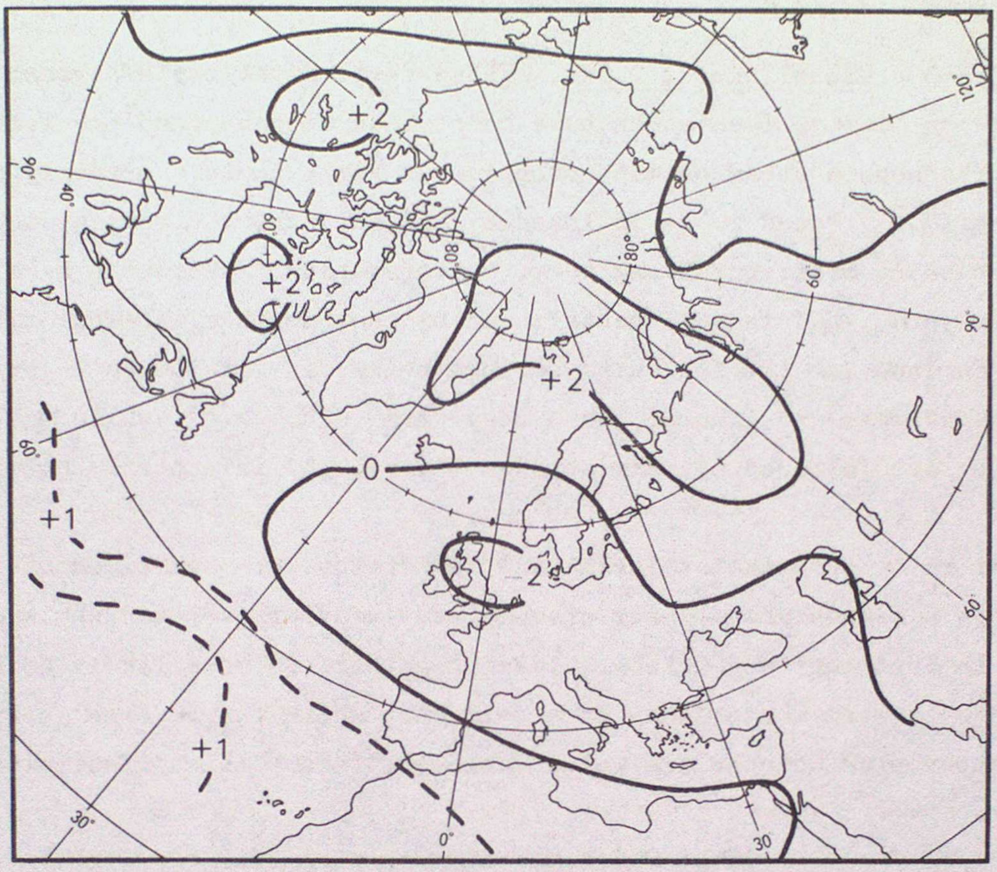

FIGURE 11. Mean pressure-anomaly (mb) in Januarys following WP5 SST classification in preceding November

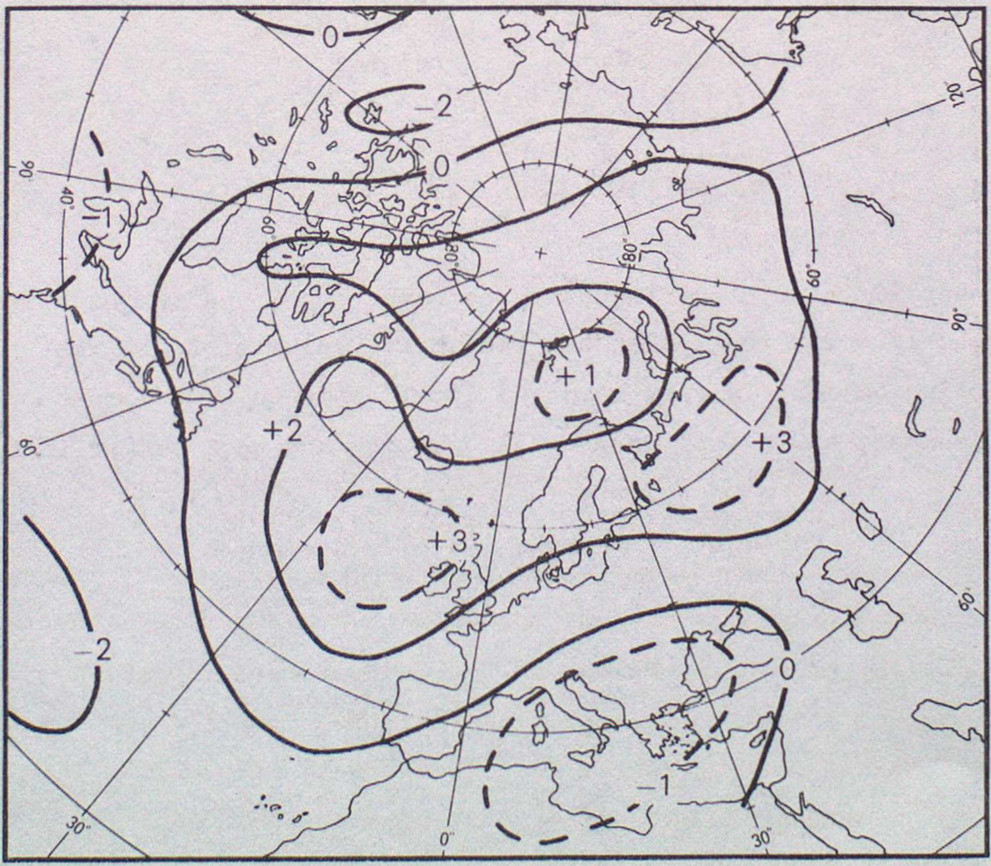

FIGURE 12. Mean pressure anomaly (mb) in Januarys following CP5 SST classification in preceding November

15.3.3.3 Miscellaneous rules. These cover a variety of types; many are based on *PSCM* indices which have been shown to have good predictive power for a season ahead on many occasions. For example, northerly cyclonic Februarys ($S_{12}C_{45}$) tend to be followed by wet springs, the springs in England and Wales being distributed as 5 dry, 6 average and 13 wet; the same type of Februarys ($S_{12}C_{45}$) tend to be followed by cool springs, the quintiles for central England for the following springs being distributed as 9 very cold, 8 cold, 4 average and 2 warm, and 1 very warm (9,8,4,2,1), while $S_{45}C_{45}$ Februarys are followed by warm springs (1,1,3,4,5) in central England.

Other rules show that rainfall and temperature are sometimes useful predictors a season ahead. For example, dry weather over the whole of Britain in September and October, taken together, is more likely to be followed by a warm winter than by a cold one, while the reverse is true if September plus October are wet. Table 15.4 shows this effect clearly.

TABLE 15.4 Relationship between September-October rainfall and temperature of the following winter

In England, Wales and Scotland	Quintile of following winter temperature				
	T_1	T_2	T_3	T_4	T_5
Dry Sept. + Oct.	2	3	3	7	7
Wet Sept. + Oct.	4	11	4	0	1

At least 20 rules of different types have been found for each season but it is probably worth mentioning the predictive value of April weather for the following summer. A very cold (T_1) April tends to be followed by a wet and cool summer, and a very warm April by a dry and warm summer (Table 15.5).

TABLE 15.5 Relationship between April temperature and rainfall and the temperature of the following summer

	Rainfall (tercile)			Temperature (quintile)				
	R_1	R_2	R_3	T_1	T_2	T_3	T_4	T_5
T_1 April	3	5	10	5	5	3	2	2
T_5 April	10	6	2	1	3	1	8	5

Ratcliffe and Collison[27] have also shown that the longitude of the European trough on the 500-mb mean map for April is important for summer-rainfall forecasting in Britain. Broadly, a trough east of 30°E favours a dry summer while one between 10° and 25°E favours a wet summer.

Three other examples of completely different methods which have been used successfully in seasonal predictions may be quoted.

15.3.3.4 Relationship between date of final stratospheric warming and summer index. In the winter stratosphere of medium and high latitudes, winds are usually westerly owing to the establishment of a cold polar-night vortex. In the summer stratosphere of these latitudes, on the other hand, temperatures are much higher owing to the continuous input of solar radiation and so an anticyclonic vortex becomes established near the pole with easterly winds in the stratosphere. The date at which this change-over from westerly to easterly winds takes place at 30 mb over Scotland varies from mid March to mid May, and the date of change-over appears to be correlated with the character of the summer to follow. A summer index (I) at Kew,* for example, based on temperature, sunshine and rainfall, shows that early dates of change-over are usually followed by good/average summers (high index) and late change-overs by poor/average summers (low index); see Poulter[28] and Table 15.6.

TABLE 15.6 Relationship between date of final stratospheric warming and summer index at Kew

Time of change-over at 30 mb over Scotland	Kew summer index (I) ≥690	689-671	≤670
Late	0	2	4
Average	2	2	1
Early	4	0	0

15.3.3.5 Relationships between October pressure patterns and winter temperatures. Strong zonal flow over the North Atlantic, with the monthly low-pressure centre in October near Iceland, usually precedes mild winters, whereas northerly or north-westerly flow over Britain, with the main monthly low-pressure centre over the Norwegian or Kara Seas, is associated with Octobers which precede cold winters in central England. These

* $I = 10T + S/6 - R/5$, where T = mean air temperature (°F), S = total sunshine (hours), R = total rainfall (mm) — for June, July and August.

associations have been confirmed in a number of ways: for example, if the October mean pressure at 65°N, 20°W near Iceland is above about 1012 mb, a cold or very cold winter is likely, whereas if the mean pressure at that point is less than about 996 mb a warm winter will probably follow. Similarly, if an anticyclone exists on three days or more in October in a defined area near Iceland, the following winter is more likely to be cold than mild and vice versa.

15.3.3.6 Relationships between late winter ice near Iceland and in the Baltic, and the start of spring in Britain. The date of onset of spring has been defined (see Davis [29]) as the date when growth starts. This may be objectively measured as the last day of a pentad in which the mean maximum temperature averages 10°C or more, provided that no later 5-day period has an average maximum temperature of less than 6°C. On this basis Table 15.7 shows the relationship between ice conditions and the date of spring at Oxford.

TABLE 15.7 Relationship between winter sea ice and onset of spring at Oxford

Final date of onset of spring	Light ice (Iceland and Baltic)	Moderate ice	Severe ice (Baltic and/or Iceland)
		Percentage	
Early	8	18	3
Average	9	16	15
Late	1	14	16

In this section it has only been possible to mention a few of the many factors considered when preparing a seasonal outlook; many others are known and used, and research on this time scale continues steadily. About 75 per cent of all experimental seasonal forecasts prepared so far have had at least 'moderate agreement' with events. Attempts to extend the time scale even further ahead, perhaps to 6 months at certain times of year, are currently being made.

15.3.3.7 Uses of long-range forecasts from 7 days to a season ahead. The economic importance of long-range forecasts is not always obvious but experience has shown that the following groups of interests are frequently able to benefit:

Fuel industry

On the 7-day time scale forecasts are useful for planning the distribution of stocks, the avoidance of any necessity for transporting large amounts of coal or fuel oil in snowy weather, for example. On the monthly time scale some oil companies try to plan the output from the refineries to conform to the expected demand; for example, if cold weather is expected in winter, the output of a refinery may be entirely given over to production of fuel oil for heating at the expense of more profitable subsidiary products which might otherwise be made. The expectation of a cold winter season can be used to plan the arrival of as many tankers as possible at the refineries at the right time.

Building industry

The amount of cement, bricks and other building material used by the industry as a whole is dependent to a considerable extent on the weather. In a mild, open winter construction continues almost at summer tempo, whereas a cold and snowy winter will result in much less work being done. A foreknowledge of temperature and rainfall categories a season ahead can be valuable in estimating the demand for many building materials. Other similar uses for which advice has been asked is for estimating the demand for underwater pumps used for pumping out foundations of buildings under construction, and by contractors attempting to plan the order in which it would be best to tackle their major projects.

Agriculture

Growers like to be able to plan their work a week ahead, jobs like fruit-picking, sowing or harvesting can be brought forward or delayed to some extent according to the weather on this time scale. A season ahead, farmers like to know whether the summer will be good or bad so that the economic value of such marginal crops as sweetcorn or outdoor tomatoes can be exploited. It is also possible to plant varieties of crops (e.g. cereals) which are likely to do best in the expected weather conditions. The probability of a cold, late spring also affects the winter pruning of fruit trees.

Industry generally

A diverse selection includes: manufacture of ice-cream which, ideally, should be eaten within a month of production, so that output is planned on expected demand a month ahead; production of salt for winter road clearance;

demand for photographic material and processing which is very sensitive to summer sunshine; production of oysters, very sensitive to winter temperatures, etc., etc.

15.3.4 Climatic change

The fact that our climate has changed over long periods of time is well known; glaciers extended well south across the British Isles some 10 000 years ago and apparently receded rather abruptly. In more recent times our climate reached an optimum around A.D.1100 when temperatures were generally a degree or so higher than today. About A.D.1600 Alpine glaciers advanced beyond previously remembered limits and did not begin to retreat again until about 1850. The years 1900-50 approximately are known from actual temperature records to have been warmer than the preceding decades, but the 1960s showed a slight cooling in most seasons from the averages in the early part of the century. What are the causes of such long-term changes and what possibility is there of forecasting trends over the next 10-30 years? It is important to realize that, even though man might conceivably be responsible for small climatic changes in the future, changes have occurred over the last 10 000 years which cannot have been caused by man. Some of the more commonly cited possible causes of climatic fluctuations are:

(a) Changes of carbon-dioxide content of the atmosphere. The carbon-dioxide content of the atmosphere is at present increasing at the rate of about 0.7 parts per million each year. In fact it was about 292 p.p.m. in the last century and increased to about 313 p.p.m. in 1960. Since carbon dioxide is a good absorber of solar radiation and a less efficient transmitter of terrestrial radiation, increased CO_2 is likely to lead to a slight general warming effect; in fact the best estimates indicate that a doubling of the present CO_2 level in the atmosphere would raise the temperature of the earth's surface by about 1.3 degrees. The steady increase of atmospheric CO_2 this century was cited as the cause of the warming between 1900 and about 1950, but it clearly cannot be the whole story since, with a continuing CO_2 increase, temperatures declined in the 1960s.

(b) Atmospheric pollution. It has been suggested that the dust content of the atmosphere is increasing as a result of man's industrial and agricultural activities and, in consequence, the overall albedo of the earth has been increased. With more solar energy reflected to space, the earth's temperature should be lowered and this effect might possibly account for the recent cooling trend. However, it is not possible to assess the atmospheric dust load or its rate of increase or to estimate accurately its effect on the radiation budget. Lamb[30] has shown, however, that major volcanic eruptions which put large quantities of dust into the stratosphere, where it may remain for several years, appear to have an effect on the overall global temperature. Clearly, therefore, long periods of time with major volcanic activity could result in some climatic changes.

(c) Changes in solar radiation. Although there is little evidence for any variation in the solar constant, the general level of solar activity varies not only over the 11-year cycle but also over periods of approximately 80-100 years and perhaps on even longer time scales. It is, however, very difficult to correlate such variations of solar activity as have occurred over the last 100 years or so with the small climatic variations apparent over the same period, and there is no general agreement on the effect of solar variations on the general circulation.

(d) Astronomical changes. Such changes include variations in the ellipticity of the earth's orbit, in the tilt of the earth's axis and in our distance from the sun at different seasons, but these changes have been calculated to effect only the longer time scales of at least 10 000 years, although they could account for the oscillations between ice ages and warm interglacial periods. The combined tidal forces of the sun and moon also undergo changes with periods of about 19 years and 1700/2000 years and these may effect such important quantities as the amount of water transferred from the Atlantic to the Arctic basin and Baltic Sea.

(e) Direct thermal effects of energy consumption. Present calculations show that thermal pollution of the environment is still on too small a scale, except in the region of large cities, to produce effects comparable with the weather anomalies which we commonly experience.

15.3.4.1 Possibilities of climatic forecasting. Present approaches to this problem are on two main lines:

(a) Attempts to ascertain the reality of past cycles such as the 80-100-years cycle apparent in solar activity, confirmed to some extent by temperature levels deduced from the Oxygen-18 samples in the Camp Century ice core from Greenland and other sources.

(b) Attempts to assess, by numerical experiments, the effects of such things as varying the CO_2 content of the atmosphere or removing the arctic ice.

Both avenues of approach are being explored in the Meteorological Office.

BIBLIOGRAPHY

1. BAUER,K.G.; Linear prediction of a multivariate time series applied to atmospheric scalar fields. American Meteorological Society, Boston, Mass. Proceedings of International Symposium on probability and statistics in atmospheric sciences, Honolulu, June 1971. 1972, pp.53-58.

2. SHUMAN,F.G. and HOVERMALE,J.B.; An operational six-layer primitive equation model. J Appl Met, Lancaster, Pa, 86, 1968, pp.525-547.

3. THOMPSON,P.D.; Numerical weather analysis and prediction. New York, Macmillan, 1961.

4. HALTINER,G.J.; Numerical weather prediction. Chichester, J.Wiley, 1971.

5. HOVMÖLLER,E.; The trough and ridge pattern. Tellus, Stockholm, 1 1949, pp.62-66.

6. RATCLIFFE,R.A.S.; New criteria concerning fine spells in south-east England during the period May to October. Met Mag, London, 94, (May) 1965, pp.129-137.

7. RATCLIFFE,R.A.S.; Criteria concerning fine spells in south-west Scotland during the period May to October. Met Mag, London, 95 (April) 1966, pp.98-105.

8. RATCLIFFE,R.A.S. and COLLISON,P.; Further criteria concerning fine spells in south-east England during the period May to October. Met Mag, London, 96, (August) 1967, pp.228-235.

9. LOWNDES,C.A.S.; Forecasting wet spells at London. Met Mag, London, 91, (Oct.) 1962, pp.284-296.

10. RATCLIFFE,R.A.S. and PARKER,A.E.; Forecasting wet spells in south-east England. Met Mag, London, 97, (Jan.) 1968, pp.1-12.

11. MILES,M.K.; Factors leading to the meridional extension of thermal troughs and some forecasting criteria derived from them. Met Mag, London, 88, (July) 1959, pp. 193-203.

12. LAMB,H.H.; British Isles weather types and a register of the daily sequence of circulation patterns, 1851-1971. Geophys Mem, London, 16, No. 116, 1972.

13. HESS,P and BREZOWSKY,H,; Katalog der Grosswetterlagen Europas [Catalogue of large-scale weather patterns over Europe]. Ber dt Wetterd, Offenbach a.M., 15, Nr.113, 1969, pp.3-13. (Translation available in the Meteorological Office Library, Bracknell.)

14. O'CONNOR,J.F.; Catalog of 5-day mean 700-mb height-anomaly centers 1947-1963 and suggested applications. Washington, National Meteorological Center. Tech Note 37, 1966.

15. CRADDOCK,J.M. and FLOOD,C.R.; Eigenvectors for representing the 500 mb geopotential surface over the Northern Hemisphere. Q J R Met Soc. London, 95, 1969, pp.576-593.

16. SAWYER,J.S.; Notes on the possible physical causes of long-term weather anomalies. WMO/IUGG Symposium on research and development aspects of long-range forecasting, Boulder, Colorado, 1964. Tech. Notes, Wld Met Org, Geneva, No. 66, 1965, pp.227-248.

17. RATCLIFFE,R.A.S. and MURRAY,R.; New lag associations between North Atlantic sea temperature and European pressure applied to long-range forecasting. Q J R Met Soc, London, 96, 1970, pp.226-246.

18. RATCLIFFE,R.A.S.; Recent work on sea surface temperature anomalies related to long-range forecasting. Weather, London, 28, 1973, pp.106-108, 113-117.

19. NAMIAS,J.; Seasonal interactions between the north Pacific Ocean and the atmosphere during the 1960's. Mon Weath Rev, Lancaster, Pa, 97, 1969, pp.173-192.

20. BJERKNES,J.; A possible response of the atmospheric Hadley circulation to equatorial anomalies of ocean temperature. Tellus, Stockholm, 18, 1966, pp.820-828.

21. ROWNTREE,P.R.; The influence of tropical east Pacific Ocean temperatures on the atmosphere. Q J R Met Soc, London, 98, 1972, pp.290-321.

22. MURRAY,R. and BENWELL,P.R.; PSCM indices in synoptic climatology and long-range forecasting. Met Mag, London, 99, (Aug.) 1970, pp. 232-245.

23. MURRAY,R.; An objective method of foreshadowing winter rainfall and temperature for England and Wales. Met Mag, London, 101, (April) 1972, pp.97-110.

24. CRADDOCK,J.M. and WARD,R.; Some statistical relationships between the temperature anomalies in neighbouring months in Europe and western Siberia. Scient Pap, Met Off, London, No. 12, 1962.

25. MURRAY,R.; Persistence in monthly mean temperature in central England. Met Mag, London, 96, (Dec.) 1967, pp.356-363.

26. RATCLIFFE,R.A.S.; Meteorological Office long-range forecasts: six years of progress. Met Mag, London, 99, (May) 1970, pp.125-130.

27. RATCLIFFE,R.A.S. and COLLISON,P.; Forecasting rainfall for the summer season in England and Wales. Met Mag, London, 98, (Feb.) 1969, pp.33-39.

28. POULTER,R.M.; The next few summers in London. Weather, London, 17, 1962, pp.253-255.

29. DAVIS,N.E.; The variability of the onset of spring in Britain. Q J R Met Soc, London, 98, 1972, pp.763-777.

30. LAMB,H.H.; Volcanic dust in the atmosphere; with a chronology and assessment of its meteorological significance. Philos Trans R Soc, London, A, 266, No.1178, 1970, pp.425-533.