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HANDBOOK

OF

WEATHER FORECASTING

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PREFACE

The Handbook of Weather Forecasting was written mainly for distribution within the Meteorological Office to provide forecasters with a comprehensive and up-to-date reference book on techniques of forecasting and closely related aspects of meteorology. The work, which appeared originally as twenty separate chapters, is now re-issued in three volumes in loose-leaf form to facilitate revision.

Certain amendments of an essential nature have been incorporated in this edition but, in some chapters, temperature values still appear in degrees Fahrenheit. These will be changed to degrees Celsius when the chapters concerned are completely revised.

CHAPTER 6

PREBARATIC AND PRONTOUR CHARTS

CONTENTS

CHAPTER 6

PREBARATIC AND PRONTOUR CHARTS

LIST OF DIAGRAMS

CHAPTER 6

P R E B A R A T I C   A N D   P R O N T O U R   C H A R T S

6.1. INTRODUCTION

Although a number of individual forecasters experimented with the drawing of forecast charts during the 1920's and probably earlier, in "The Construction and Use of prebaratic Charts"[1] * it is indicated that the routine preparation of forecast surface charts was not commenced in the Meteorological Office until 1925. This was in the nature of an experiment (the charts were not used at that time for operational forecasting). The experiment was not continued but some individual forecasters continued to prepare occasional forecast charts. The preparation of routine surface and upper air forecast charts for operational use in the Meteorological Office was commenced in the early 1940's.

Forecast charts prepared in a central office can be transmitted to distant offices either by means of coded messages or by facsimile. By such transmissions, the views of forecasters at meteorological centres can be economically transmitted to a wide clientele. Such transmissions are of great value to outstations without the resources or time to prepare their own forecast charts as routine. Apart from their obvious value in depicting general developments over a substantial area for 24 hours or so ahead, they also contribute to the shorter-period more local forecasting. For example, experience indicates that it is easy for a forecaster, interested in a relatively small area, (for example, when forecasting the clearance of a front from an area) to concentrate unduly on that part of the chart without taking due account of movement and development around the fringes of the smaller area. The more general forecast chart over a large area and for a probably longer period ahead assists the outstation forecaster to take a better perspective.

In the Central Forecasting Office of the Meteorological Office, forecast charts are prepared for a substantial part of the North Atlantic Ocean, Europe and adjacent areas for a period 24 hours ahead of the time of the chart on which they are based. By the time these forecasts can be issued and displayed at distant stations, the forecasts are valid for a period about 19 hours ahead in the case of sea-level charts and about 12 to 14 hours ahead for upper air charts. The period of validity and time of issue represent a compromise between speed, accuracy and user requirements. However, it is unlikely that considered forecast charts for such an area could be prepared by forecasters using orthodox hand techniques, and issued as routine in any period much less than about four hours after the time of the last complete chart. Of course some account can usually be taken of observations which may be received subsequently, but before the issue of the forecast chart. For general purposes the 24-hour period seems a good working value but, for specialist use, some variations may be required. For example, for long flights it may be

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*The superscript figures refer to the bibliography at the end of this chapter.

desirable to have a variable time-scale so that the forecast chart is made up to be valid at the epoch of time when the aircraft is expected to be over a given area of the chart. Such charts are usually called composite forecast charts. Further, when a forecast chart is prepared for use solely in the office of preparation, it may be valuable to prepare a skeletal forecast surface chart for a very restricted area for as little as six or even three hours ahead. In such a short time, very little development on a synoptic scale can occur and these forecast charts are usually little more than a direct linear extrapolation of current trends as revealed by a recent series of charts. Although the concept of linear extrapolation is simple, short-period forecast charts can be very useful and should not be ignored for very short-term forecasting. The preparation of forecast charts for upper levels for such short periods ahead is scarcely practical with the limited staff available at most outstations, but useful forecasts of upper winds (for periods up to about 12 hours) can usually be made by extrapolation of trends and movements of systems as revealed by recent observations (see Chapter 13). The preparation of very short-period forecast charts for upper levels is consequently seldom attempted except perhaps at major forecasting offices with sufficient staff.

It would be very useful for many purposes if reliable prebaratics could be prepared for periods more than 24 hours ahead and much current research is directed towards this end. There are, however, important difficulties arising from the fundamental character of atmospheric motions. These have been discussed by Sutcliffe [2,3] and can be illustrated by the behaviour of a young depression which can grow from an undetectable distortion of the pressure field to a mature storm in 48 hours or even less. Although dynamical theory gives useful indications of the areas in which new depressions may form, it seems unlikely that the positions and times at which a new centre will appear can be given with any worth-while accuracy - the positions and times of formation of new depressions are probably influenced materially by events too small in amplitude or scale to be properly detected by the observational network. Accordingly, a prebaratic cannot be expected to give with much accuracy the positions, intensity and shape of depressions and other features not in existence nor detected on the analysed charts at the time the prebaratic was prepared. The life-cycle of the depression thus sets a limit in the range of 36 to 48 hours for which detailed prebaratics can be prepared.

It may be possible to depict for longer periods ahead some features which have a longer life-cycle (for example, long waves, blocking anticyclones etc.). Prebaratics for longer periods may therefore have some value if it is realized that the detail of the smaller-scale weather systems can have little accuracy. It is reasonable to attempt to predict the position of the large upper air troughs and ridges and the tracks of depressions but not their detail, shape or timing. Such longer-period prebaratics form the basis of medium-range forecasting at the Central Forecasting Office for three or four days ahead.

In the last few years the development of electronic computers, with a capacity for making a large number of computations at high speed, has revived interest in the possibility of calculating the future state of the atmosphere by a consideration of the dynamics of the problem. A generation ago Richardson showed how such a computation should lead to a forecast. His calculations failed for a number of reasons but, even if they had proved successful, it would have been exceedingly difficult to introduce such a system on an operational basis due to the sheer weight of numerical computations involved. The speed of modern computers has now largely removed this obstacle, and computations based on simplified theories of barotropic or barclinic atmospheres have shown that forecast charts can be calculated within a period which will render them of operational value. A computer is now available in the Dynamical Research Division of the Meteorological Office and tests and experiments are being carried out. There is a need for the manual preparation of forecast charts until machine-made forecast charts are introduced and, even after the introduction of the latter, it seems likely that some hand-made forecast charts will be needed for some types of requirements. No attempt will be made in this chapter to give a detailed account of the theory and practice of computing forecast charts but, for a general introductory account, the reader may refer to a paper by Knighting.[4]

Although the present era may be one of a transition from the preparation of forecast charts by forecasters to their numerical computation, a section setting out the procedures for man-made forecast charts will serve a useful purpose and have a reasonable life. It is emphasized in this introductory account that the approach is essentially a practical rather than a theoretical one. Although there must be much empiricism, at the same time an effort will be made to incorporate results from theoretical concepts, some of which were considered in Chapter 5. Some of the methods can scarcely be applied as routine at the smaller outstation, but even there during slack periods an attempt at compiling occasional forecast surface and upper charts will seldom fail to be an instructive exercise for the practical forecaster. In the following treatment the preparation of forecast charts will be discussed in the next few sections. The techniques described will be those currently practised in the United Kingdom. There are variations in other countries but to keep the treatment to a reasonable length and within the compass of the bulk of forecasters in the field it seems desirable to restrict the treatment to the United Kingdom methods. There would be little point in describing these techniques of preparing forecast charts without giving some information and guidance on meteorological developments which may occur. A truly comprehensive account of all possible synoptic developments is clearly impossible since, in the meteorological sense, history never repeats itself precisely. At the other extreme, bald, simple statements undoubtedly over-simplify. For example, to state that a wave depression will move with four-fifths of the speed of the geostrophic wind in the warm sector is an over-generalization and over-simplification. Any attempt to catalogue all possible variations must fail and would confuse. Nevertheless some guidance must be given. The account in the later sections of this chapter is an attempt to strike a concordant and useful note between the extremes of over-simplification and over-elaboration.

6.2. IMPORTANCE OF ANALYSES

Essential prerequisites to the preparation of successful forecast charts are careful analyses and considerations of a series of surface and upper-level charts. It is important to stress, particularly to inexperienced forecasters, that analyses do not end with the construction of suitable isopleths which fit the available observations and are reasonable from the aspect of continuity. This is only the first stage of analysis and is really nothing more than a mapping of scalar or vector quantities. It is most important that the latest charts and the preceding series should be meticulously examined so that the analyst can obtain a time and space appreciation of movement and development. The analyst should also study the charts so that he obtains an understanding of the situation which is satisfactory from the geometrical, kinematical, statical, dynamical and physical viewpoints. This is an exacting task which can seldom be completed in entirety on the forecast bench, even when a long time can be devoted to analysis. It certainly cannot be reached by a hurried and ill-considered drawing of a few isopleths.

When considering analysed charts with a view to the preparation of forecast charts it is important that contemplation should be concentrated on important things. Contemplation is a time-consuming process and the practising forecaster has usually little time to spare. There is, of course, no invariant rule on how the time available for analysis should be allocated. Nevertheless it will usually be found advantageous to take the broad view first. This will involve a consideration of the major synoptic systems, usually several hundreds of miles in horizontal dimension, which form a vital part of the long-wave pattern over the chart area. For the charts drawn at most outstations, this will mean considering generally one or two, but seldom more than three, major features on any one occasion. Within the broad flow pattern associated with these major features there will usually be found a number of smaller features of sufficient size to be important on the synoptic scale, for example, a few hundred miles in extent and with a lifetime of at least several hours. In the short term, behaviour of these smaller synoptic systems is often closely controlled by the larger systems so that, when making an assessment and judgement of past events, forecasters must examine both the long-and short-wave patterns and their inter-relations.

To achieve a more complete understanding of the charts currently being analysed, forecasters will often find it helpful to estimate, from the preceding series of charts, the features and their positions which could be expected on the current charts. Some features will usually have behaved in a manner very close to the short-term estimate and these features may be regarded as confirming the view up to date. On the other hand, some features will almost certainly have behaved rather differently (for example, moved at a different speed or in a different direction, failed to intensify when they were expected to intensify, and so on). In some synoptic situations it is clear from the general situation, and the pressure and wind fields in particular, that development is favoured in one area of the chart more than another. Observations and changes from chart to chart in these areas must be carefully studied so that the earliest possible warning of impending change is obtained. It is often of almost equal importance to observe when incipient changes fail to materialize or develop, even though the area is a favourable one. All these features will repay very careful study and an attempt must be made to explain the different behaviour and then to understand the reasons for it. The forecaster will thus concentrate attention on those areas where development is somewhat different from the pattern previously expected. At this stage, the forecaster will find it helpful to shorten both the time and distance scale of his search for understanding. Time must be found for the detailed examination of individual observations and their time changes within the area(s) where the unexpected may be happening. For example, changes in upper-cloud type or variations may yield a valuable clue as to the processes which are occurring.

With experience and good judgement, forecasters will find that it is usually possible to apportion the time available for consideration of the analysis in a reasonably satisfactory manner in order to perform these various tasks. The proportions are not, of course, fixed. In those situations with a well established and dominant long-wave pattern, the forecaster can often proceed, after a quite short time, to a greater consideration of the short-wave pattern and developments in limited areas. On another occasion where the long- and short-wave patterns are interacting in a complex manner, which sometimes occurs during a change of synoptic type, the greater part of the time for consideration may be most profitably spent on the larger-scale developments. The ability to identify the important areas on any particular chart is obtained by a combination of theoretical knowledge, practical experience and wise judgement. This is a very great asset in the preparation of forecast charts which achieve a continuing high standard of accuracy.

In addition to taking a view which is balanced and at the same time unbalanced (in that it is often concentrated on the smaller but meteorologically more important areas of the chart) the forecaster should be as objective as possible. This is undoubtedly difficult to achieve. During the analytical stages the forecaster can scarcely fail to form a view on what he thinks is going to happen. It is only human to examine the data in the hope that these views will be confirmed. In many cases they undoubtedly will be but there are others, and unfortunately they are not so few as some would like to believe, when much of the observational data do not confirm the view. A small minority of observations may be "forced" into the pre-determined view on a few occasions without incurring the penalty of serious errors (that is, the discordant observations are to some extent unrepresentative of the synoptic situation). However, when a substantial number of observations are at variance with the previously expected development(s), substantial errors may be made if the forecaster persists in his previous deductions. It is most important to be aware of this. Over an area which has a close network of observations one or two isolated misfits - although naturally causing the forecaster some misgivings - should not normally be interpreted as a justification to change a concept (on the time and distance scale of prebaratic/prontour charts) which is otherwise supported by the vast majority of the observations. Where the observing network is sparse a decision of major importance may have to be taken on a single observation. The ability to take the correct decision in these situations is an essential attribute of the forecaster who achieves a sustained high accuracy in the preparation of forecast charts. In this respect, as with the apportioning of the available time for considering the synoptic situation, the successful forecaster possesses a complex combination of a good theoretical understanding of atmospheric processes, a wide synoptic climatological knowledge, long experience and sound judgement.

It is pertinent to remark in this section that, when developments are running contrary to expectations, they may do so for several hours. On some occasions such developments are the harbingers of a change in synoptic type. Until it is clear in what way the atmosphere is developing, it is often very difficult to take a consistent view from chart to chart. There is a sort of indeterminancy about the observations, which are capable of two (if not more) interpretations.
During such periods the preparation of forecast charts is difficult and the consistency between successive sets may be poor. Perhaps the best possible advice is to take as broad and unified a view as possible of the synoptic situation and developments over the areas of the analysed and forecast charts. It is easy to become obsessed with a relatively small deviation from the expected developments. Here again, the ability to take a balanced view and to make a wise judgement is a very valuable attribute.

6.3. MECHANICS OF THE PREPARATION OF FORECAST CHARTS

It was made clear in the introduction that the basic method to be described would be that currently in general use in the United Kingdom. In essence the method consists of preparing a forecast surface chart (prebaratic) and of building upwards from the lower to an upper pressure level by the successive graphical addition of forecast values of isopleths of thickness, for the various layers between the fixed pressure levels. Forecast charts for these upper levels are termed prontours. The order of this procedure does not mean that a "prebaratic" is produced without consideration of upper air conditions, nor that an upper air forecaster may not have a valuable contribution to make to the prebaratic and the nature of the possible developments from a consideration of upper air patterns alone. It is important to realize that the fields of contours at the different levels in synoptic systems evolve together as a whole, and a satisfactory set of forecast charts must also form a consistent entity. In many cases, experienced forecasters preparing prebaratics can visualize the nature of the likely evolution of the upper air as well as the surface conditions, and can produce a prebaratic which will lead to acceptable prontours. Occasionally, however, after a start has been made on the prontours, a particular prebaratic may appear to be leading to unlikely prontours. After further consideration of the surface and upper air charts, some adjustment to the prebaratic may be necessary, even at this late stage, in order to ensure that the surface and upper air forecast charts may develop together as one entity.

In regard to the partial thicknesses to be used for building to upper levels, the use of 1000-700, 700-500, 500-300 and 300-200-millibar thicknesses in succession probably leads to forecasts of the best internal consistency. However, in view of the use made of the 1000-500-millibar thickness for assessing development, etc., some forecasters prefer to consider the layer from 1000 to 500 millibars in a single operation, particularly if relatively little operational use is to be made of the 700-millibar prontours. At 200 millibars some forecasters prefer to forecast the prontour directly from the 200-millibar analyses but the use of thickness technique seems to yield slightly better results. At levels above 200 millibars, where the wind patterns are sometimes fairly slack and the systems often slow-moving, the forecasting of prontours directly from the analyses is generally preferable to the use of thicknesses. Some forecasters consider that it is often better to prepare the 100-millibar prontour directly from the analyses and before the 200-millibar prontour, so that the 200-millibar prontour may be constructed in the light of expected developments at both higher and lower levels. The use of isotachs is sometimes helpful in delineating wind speeds, particularly when winds are strong (see Chapter 13 for a brief discussion of isotachs).

It seems likely that the following procedure will lead to satisfactory prontours.

Level	Method
700 mb. prontour	Grid 1000 mb. prontour with 1000-700 mb. forecast thickness.
500 mb. prontour	Grid 1000 mb. prontour with 1000-500 mb. forecast thickness or, if 700 mb. prontour is available, grid 700 mb. prontour with 700-500 mb. forecast thickness.
300 mb. prontour	Grid 500 mb. prontour with 500-300 mb. forecast thickness.
200 mb. prontour	Grid 300 mb. prontour with 300-200 mb. forecast thickness. or Forecast 200 mb. prontour directly from analyses.
150/100 mb. prontour	Forecast (150 mb./100 mb.) prontour directly from analyses.

(Where alternatives are shown, the writers preference is to the method first indicated).

6.3.1. The preparation of a "prebaratic"

Take a blank chart of suitable scale and as a first step mark lightly in pencil the probable positions of any large-scale synoptic surface features, which are relatively slow-moving, and estimate their central pressures using time continuity and general dynamic ideas on development. At this stage it is also useful to make a few spot estimates of pressures at the forecast time, particularly for places where pressure changes are expected to be relatively small. This latter process is not usually very difficult and follows fairly easily from a study of tendency fields on earlier charts. On occasions when confidence in these quasi-stationary large systems is high, it may be advantageous to sketch in lightly a few tentative isobars. The next stage is to consider the more mobile systems. These may move around a major system and be thermally steered, and a fair estimate of their track can be made by considering their present position and structure, and also the present and future position and thermal characteristics of the steering system. On some occasions the mobile system may move and develop in such a way as to interact with and modify the larger system. If new systems seem likely to form, either on fronts or in air masses, tentative estimates must be made of their future positions and central pressures and these should be entered lightly on the chart. With these estimates and the earlier estimates of the quasi-stationary systems it is usually possible at this stage to visualize the broad outlines of the pressure field. Some of the isobars may be tentatively sketched in at this stage, but it is not essential to do so. A view must now be taken on the probable location of any fronts on the actual chart taking account of frontogenesis or frontolysis. Where fronts and synoptic systems are closely linked together, the location of a centre of low pressure may provide a fix at one part of the front, and it may be possible to obtain another fix where the front is expected to move but little during the forecast period. From a consideration of the flow patterns, the existing gradient across the front and a tentative estimate from the skeleton "prebaratic" so far prepared, a preliminary estimate can be made of movement at right-angles to the orientation of the front. Care must be taken that frontal positions and shapes are not too slavishly modelled on textbook patterns. There are variations which it is legitimate and useful to portray in prebaratics. It is sometimes difficult, for example, to decide to what extent an occlusion may spiral out of a depression, or a warm front be held up by ageostrophic motion - leading to more rapid occlusion. On some occasions an unexpected southward plunge of cold air in the rear of a depression may occur and carry a cold front to lower latitudes in that area. This will produce a marked concavity in the outline of the cold front on the forecast chart. In estimating frontal movements, account must be taken of actual speeds and future gradients and a suitable mean obtained.

When estimating movement, forecasters are strongly recommended to measure displacements or gradients on current and past charts, using either suitable transparent scales or dividers. Future movements should then be estimated numerically and the distances measured out on the forecast charts. Scales which give six-hour movements are available but, if speeds are estimated in knots, the distance travelled in six hours can be very readily stepped out using dividers, for example, at a speed of 28 knots a movement corresponding to 2.8 degrees of latitude will occur in six hours. The use of quantitative estimates is recommended because this will help the forecaster in keeping a clear picture of the modifications to movement which have been introduced. Experience shows that if more rough-and-ready methods are used it is easy to introduce variations different from those that were intended, that is, accelerations or decelerations may be unreasonably large.

The forecaster is now in a position to complete the frontal patterns and draw some tentative isobars. Care should be taken in drawing forecast isobars over the sea. Where pressure fields over extensive sea areas have been well established on a series of charts, pressure changes should be carefully estimated so that unreasonable changes are not unwittingly introduced. This type of error is easily made and the point needs care. It is almost inevitable that the first sketch will not inspire much confidence nor look like a synoptic chart. Gradients may not match expected frontal movements, a major synoptic feature may have been extended to swamp large areas of the map. On some occasions it will be found that attention has been so concentrated on depressions that there is literally no room on the map for the small mobile high (or ridge) which is so often a feature between mobile depressions. In some such cases it may even be preferable to draw the highs or ridges first and the depressions in the spaces. After the consideration of the first sketch of the prebaratic is the time for a vigorous but judicious use of the rubber, adjusting positions, pressures, fronts and isobars here and there to produce a plausible picture. Inexperienced forecasters should not be too despondent at the amount of erasing which may have to be done. It is often helpful, on a sort of trial and error basis, to put in lightly one or two possible variations, examine the whole critically and then finally settle for what appears the most probable. This trial basis often enables the forecaster, having seen the overall picture, to eliminate some possibilities which were previously worrying him.

It is also important to examine gradients critically. In the first attempt it is usually found that gradients have been made unduly tighter or slacker and, after a consideration of likely pressure changes, some adjustment is usually called for - this does not mean that variations must be so smoothed out that gradients are uniform over large areas, but very tight or slack gradients need good justification.

Where a light-slope (a transparent surface illuminated from below) is available and single-sided charts are used it is often helpful to superpose the prebaratic chart on one or two recent analysed charts (if the prebaratic is on the same map scale as the working chart). This throws into high relief the relative movements of pressure systems and fronts and shows, very clearly, variations in the direction and strength of pressure gradients. This device often brings clearly to the forecaster's mind those things for which the changes so far introduced appear about right or noticeably overestimated or underestimated. Modifications can often be made on the light-slope. Many experienced forecasters prefer to draw their prebaratics directly over a number of analysed charts on a light-slope. This is largely a matter of preference. Although the inexperienced forecaster may find the multiplicity of lines and time scales rather confusing, the method has distinct advantages, but there may perhaps be a tendency at times to rely too much on extrapolation of recent trends.

Following this further consideration of the prebaratic chart, final amendments to pressure distributions and frontal positions can be made.

Little reference has been made to the upper air pattern since it is the mechanics only which are being described in this section. More will be said about the use of upper patterns in later sections.

6.3.2. The preparation of prontours

Once the prebaratic has been decided upon it is possible to commence the preparation of prontours by upward building. The 1000-millibar prontour is obtained directly from the isobaric pattern on the prebaratic by a similar procedure to that described in Chapter 2, for obtaining 1000-millibar contours from the mean sea level isobars, that is, isopleths of $\pm$ 60 metres, $\pm$ 120 metres, etc. are drawn where the sea-level pressure is expected to exceed (or fall short of) 1000 millibars by units of 7, 7½ or 8 millibars according to the low-level temperatures expected (it is not normally necessary to attempt any allowance for the effect of water vapour content in this operation). It is advantageous to mark the mean sea level locations and heights at the centres of the pressure systems, and also to mark the surface frontal positions. The next stage is to draw, on this 1000-millibar prontour, forecast isopleths of thickness from 1000-700 or possibly 1000-500 millibars. To do this, a procedure somewhat analogous to the preparation of the prebaratic is followed. First locate those parts of the chart where little change in thickness is expected and either mark in lightly some estimated thicknesses, or, alternatively, sketch in short segments of selected isopleths. In the parts of the chart where mobility is expected, a first estimate of thickness is obtained by pure advection with the speed of the geostrophic wind at right-angles to the thickness, suitably averaged over the forecast interval. Simple advection is usually an overestimate of the movement of thickness lines, the overestimate often being by a factor of two. The location and orientation of fronts also provide a guide since, for mobile systems, thickness patterns relative to frontal locations frequently show fairly small changes over 24 hours. After making an estimate based on advection, modifications for cooling or warming, from whatever cause, must be assessed and incorporated into the thickness pattern. It is necessary to estimate to what extent the mobile system will be steered by the thermal pattern and to what extent the system will engage with and distort the pattern. This latter process at times leads to substantial changes not only in the value of the thicknesses but also to the configuration of the thickness lines.

(These aspects were considered in Chapter 5 and will be further considered in Section 6.8 of this chapter.)

The 1000-millibar prontour and the forecast thicknesses are then "gridded" together to obtain a prontour for the level 700 (or 500) millibars. This first gridding will usually reveal "kinks" in contours, abnormal curvatures or variations in gradient, which experience indicates are unreal. It follows that, as with the prebaratic, time should be allowed at this stage for contemplation of the pattern, its abnormalities, etc. It should be remembered, however, that there are now three families of curves on the chart, the 1000-millibar prontour (that is, effectively the prebaratic), the forecast thicknesses and the prontour for the upper level. An adjustment to one set of isopleths brings corresponding adjustments to one or perhaps both of the other sets. It is at this stage where hydrostatic and dynamical consistency of the forecast through the lower part of the troposphere can be readily considered, and indeed this is one of the strong practical reasons why the thickness techniques are well suited to current needs. Where surface and upper forecasts are being prepared by separate forecasters, as at the larger forecast centres, this is a stage at which further joint discussion of the forecast should occur - provided the operational time-table permits. Where one forecaster alone is preparing all forecast charts, the consideration of surface and upper levels as a unified whole can be done whilst the forecaster is preparing the various isopleths and during the gridding process. It is, as it were, a continuing process. From this contemplation some (usually minor) adjustments can be made to one or more sets of isopleths of the forecasts made so far, to ensure that the features show a consistent and logical development from recent analysed charts and this is usually the last opportunity for further modification. This is generally imposed by the operational time-table although a good case could be made for reconsideration of the whole forecast when the prontours for all the upper levels to be prepared are available. This, however, is seldom operationally practicable.

Prontours for levels above 700 (or 500) millibars can be prepared by the further graphical addition of successive partial thicknesses (that is, 700-500, 500-300 and 300-200-millibar layers). Some forecasters find it advantageous to delineate the forecast location of upper fronts on the forecast chart at the base of the level being considered, but the practice is not widespread in the United Kingdom and many outstations do not have the facilities to prepare the necessary time and space cross-sections from observational data to make such a process anything beyond a pure rule-of-thumb extrapolation from the surface location or a stereotyped application of textbook models. In the layers which are expected to contain the tropopause care is needed when delineating forecast thicknesses, owing to the changes in horizontal and vertical temperature gradients around the tropopause. No very satisfactory practical method of allowing for this has so far been devised. The remarks in Chapters 7 and 13 on wind and temperature distributions may assist in making reasonable estimates.

At levels above the tropopause the temperature changes are controlled more by vertical motion than by horizontal advection. In forecasting the thickness pattern at levels above and including the tropopause the main guide is persistence and extrapolation of any decided trend revealed by preceding charts so as to maintain the same relationship between the thickness pattern and the troughs, ridges and other features of the upper flow pattern.

Analysis of upper air data shows that upper contours are usually smooth curves exhibiting gentle variations from cyclonic to anticyclonic curvature. In general, prontours which appear as a series of short segments with very pronounced changes of curvature over distances of a few tens of miles, sometimes so abrupt as to be almost discontinuities (as for isobars at fronts), are likely to be in error. On a first gridding such ungainly and unlikely prontours are sometimes obtained over a relatively small area of the chart when endeavouring to join up the appropriate intersections and also to avoid touching intervening isopleths. These difficulties are sometimes encountered near the centres of low-pressure areas with tight gradients and steep curvature, and also with tight thermal gradients. Experience shows that, in many cases, quite minor amendments to the position of one or occasionally two sets of isopleths in the area concerned will so modify the intersections that fairly smooth and plausible prontours can be obtained. Further, these minor amendments are usually well within the variations on the theme of pure advection and are also physically plausible. In some cases where amendments to the lower-level prontour and the thickness fail to produce an acceptable upper prontour pattern it may be found advantageous to smooth the upper prontour to see what changes in the thickness would have to be made. At other times when there is strong confidence in the thickness pattern some amendment to the 1000-millibar (or lower-level) prontour may be called for in order to obtain likely upper prontours. There is no fixed procedure but this type of consideration and adjustment is sometimes a useful approach to the problem of obtaining good prontours in difficult situations. In the attempt to produce reasonably smooth isopleths it is very easy to overdo the smoothing which leads to too smooth a pattern without the variety which the atmosphere nearly always exhibits. This point needs care in practical work. The happy mean is something which forecasters can obtain only after a fair amount of bench practice.

These are the processes by which mutually consistent surface and upper-level forecasts can be prepared. It is desirable to mention the direct forecasting of upper-level charts (usually 500 millibars or above). Upper flow patterns are usually smoother than those at the surface. After the establishment of regular routine radio-sonde ascents to high levels which permitted a systematic routine three-dimensional analysis of the atmosphere, it was hoped that better forecasts might be achieved by considering upper flow patterns, rather than surface data. This has not so far been proved for the 24-hour forecast except for the 100-millibar pressure level. The forecasting of upper contours and thickness values and their subsequent graphical subtraction to obtain the 1000-millibar (that is, surface) pattern is the technique currently employed in forecasting by means of the electronic computer. The direct forecasting of upper levels has its exponents and the following brief comments are made.

6.3.3. <u>Some other methods of preparing forecast charts</u>

6.3.3.1. <u>Direct forecasting of upper air charts.</u> In theory, methods of extrapolation, experience and dynamical reasoning such as are used to derive the surface prebaratic might be applied at any other level. However, it is found in practice that extrapolation is easiest to apply to the surface chart and the forecaster generally has most experience in regard to this level. If charts for several levels are drawn independently (as is the practice in some meteorological services) it is difficult to maintain consistency unless thickness charts are also drawn and used as a check.

However, recent work on numerical forecasting has demonstrated that the flow at the 500-millibar level does behave as if the motion were non-divergent and largely independent of levels above or below. There is therefore some justification for attempting to forecast the 500-millibar prontour independently from other levels. This technique has been widely used in America and an informative monograph on related techniques has been prepared by Riehl[5] and collaborators.

In preparing a prontour for the 500-millibar level, consideration is first given to the long-wave pattern. The distance between consecutive troughs and ridges is measured and compared with the stationary wavelength for Rossby waves (see Chapter 5 Section 5.8) given by the formula:

$$L_s = 2\pi\sqrt{\frac{U}{\beta}}$$

If the wavelength is shorter than the stationary wavelength eastward movement is looked for, and extrapolation probably gives the best estimate of the speed. If the wavelength is longer than the stationary wavelength retrogression is likely; this is often brought about by the development of a new trough to the west of the old one.

In predicting the 500-millibar contours particular attention should be given to changes in amplitude of the large-scale troughs and ridges which should be extrapolated when possible. Certain typical processes can often be recognized at an early stage and the development predicted to continue along the lines of the recognized model. Among these are the formation of a "cut-off low" (see Chapter 5 Section 5.3.4 and Chapter 12 Section 12.5.3) and the development of a "blocking high" (see Chapter 5 Sections 5.3.5 and 5.3.6 and Chapter 12 Sections 12.5.1 and 12.5.2). Meridional extension described in detail in Section 6.8 of this chapter is another such process.

Examples of typical evolutions of the 500-millibar flow pattern are given by Smith[6] in Meteorological Report No. 21. Reference may also be made to some empirical rules for the computation of the movement of cold lows at 500 millibars over the United States which have been propounded by Bailey and Hilworth[7].

6.3.3.2. <u>Some graphical methods</u>

6.3.3.2.1. Fjørtoft's method. In a paper, "On a numerical method of integrating the barotropic vorticity equation", Fjørtoft[8] described a simple graphical technique which can be applied to the construction of prontours at about the 500-millibar level. The method is based on the treatment of the flow as non-divergent. Thus the local rate of change of vorticity ζ is balanced by the change due to advection of the absolute vorticity. Expressed mathematically this may be written:

$$\frac{\partial}{\partial t}(\zeta + l) = -\mathbf{V}\,.\,\text{grad}\,(\zeta + l), \qquad \ldots (1)$$

where V is the wind vector, l is the Coriolis parameter and t denotes time.

For geostrophic flow the vorticity ζ may be expressed approximately in the form:

$$\zeta_Q = (h_A + h_B + h_C + h_D - 4\,h_Q)/4\,G\,,$$

where G , which is a function of grid length, chart magnification factor and the Coriolis parameter, can be obtained from a specially prepared chart such as that shown in Figure 6.1, h indicates the contour height of whatever pressure surface is being dealt with and the suffixes refer

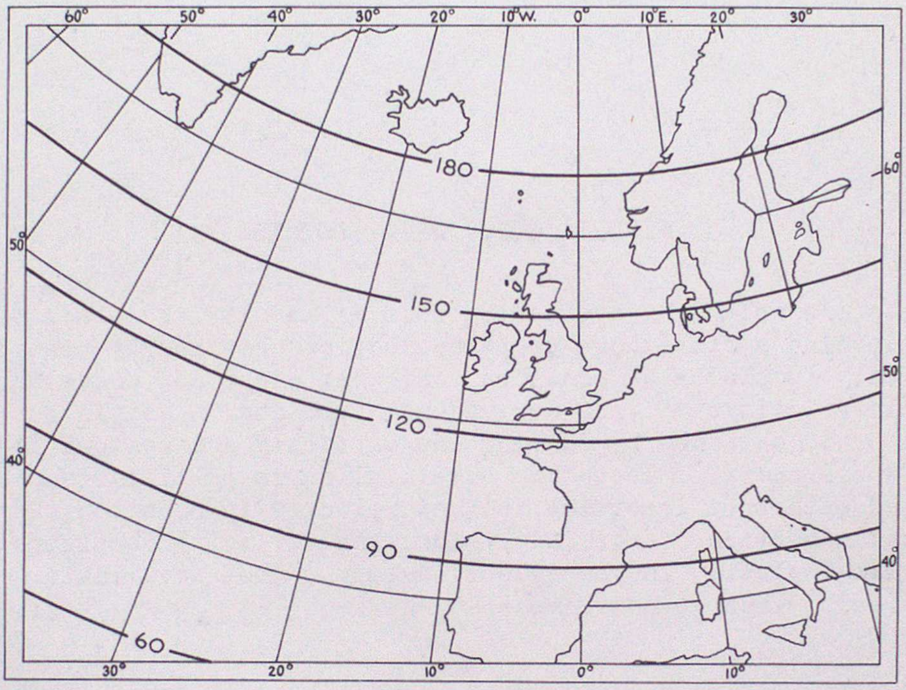


FIGURE 6.1 G CHART IN METRES FOR GRID LENGTH OF 600 MILES

to positions in the network of points shown in Figure 6.2.

It is convenient to write $\bar{h} = \frac{1}{4}\,(h_A + h_B + h_C + h_D)$, so that ζ_Q becomes $(\bar{h} - h_Q)\,/\,G$.

To a close approximation equation (1) may now be written:

$$\frac{\partial}{\partial t}\,(h_Q - \bar{h} - G) = -\,V.\ \text{grad}\,(h_Q - \bar{h} - G)\,. \quad . \quad . \quad . \ (2)$$

The practical problem is that of calculating $(h_Q - \bar{h} - G)$ over the contour chart, then moving this vorticity pattern on with the geostrophic wind for some suitable time interval and finally recovering the contour heights from the new vorticity field.

The application of the methods of finite differences to solve equation (2) approximately is legitimate only if the time intervals are made sufficiently small so that adequate approximations to the value of the geostrophic wind during the forecast period are obtained. Since the geostrophic wind changes with time, the time intervals have to be fairly short, say one or two hours. Thus if a 24-hour forecast is being prepared and hourly intervals are used then the computations must be made for each step and repeated for the succeeding period using the new values obtained for the various quantities in the preceding step. Since the work involved in the computations for each step would take about two hours, the step-by-step application of equation (2) to 24-hour forecasting (involving 24 sets of computations) is not a practical proposition.

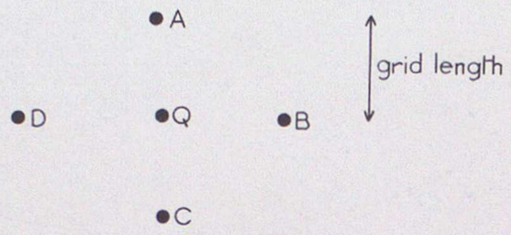


FIGURE 6.2. GRID POINTS

Fjørtoft's method of overcoming this difficulty is to add to the geostrophic wind a fictitious geostrophic flow obtained by considering the vorticity isopleths as pressure contours; in other words the geostrophic velocity, V , is derived not from the h_Q field but from the field $(\bar{h} + G)$ obtained by summing the vorticity and contour fields over the whole chart. That this substitution is justifiable may be ascertained either by inserting the new velocity in equation (2) or by noting that advection of vorticity along the vorticity isopleths must be zero and its inclusion in the advection term cannot invalidate equation (2). Thus we now have:

$$\frac{\partial}{\partial t}(h_Q - \bar{h} - G) = -V_1 \cdot \text{grad}\,(h_Q - \bar{h} - G), \quad . \; . \; . \; (3)$$

where V_1 is the geostrophic flow derived from the field $(\bar{h} + G)$.

Now $\bar{h}$, being the mean of four contour heights separated by appreciable distances, will vary more slowly with time than h_Q. Therefore, it is argued that V_1 will also vary slowly with time and may be considered constant for reasonably long time steps. Experience and practical convenience suggest that, with a grid length of 600 miles, a time step of as much as 24 hours may be used.

Having moved on the vorticity field with the winds, V_1 , the difference between the initial and final vorticity fields gives the change, $\Delta(h_Q - \bar{h})$, in $(h_Q - \bar{h})$, and since $\bar{h}$ is presumed to vary slowly with time, this change is approximately equal to Δh_Q ,the field required to predict the new contour field.

Most of the work involved in the practical application of Fjørtoft's method entails the addition or subtraction by gridding of fields of isopleths. The steps involved are:

(i) Copy the contour field on to a sheet of tracing paper.

(ii) With this second copy placed on the original chart but displaced the equivalent of 1200 miles east, and with another sheet of tracing paper on the top, add by gridding the two sets of contours. Only even-valued isopleths need be drawn, then halving the value of these isopleths yields a contour chart of $\frac{1}{2}(h_B + h_D)$.

(iii) Repeat (ii) for a southward displacement of 1200 miles, to obtain the field of $\frac{1}{2}(h_A + h_C)$.

(iv) Add, by gridding, the fields of $\frac{1}{2}(h_A + h_C)$ and $\frac{1}{2}(h_B + h_D)$ and halve the sums to obtain the $\bar{h}$ field. Notice that this $\bar{h}$ field covers a smaller area than the original pressure-contour field and is located in the middle of the larger field, as shown in Figure 6.3.

(v) Add, by gridding, the $\bar{h}$ field and the G field (from Figure 6.1) to obtain the field of $(\bar{h} + G)$.

(vi) Subtract, by gridding, the field of $(\bar{h} + G)$ from the h_Q field to obtain the vorticity field $(h_Q - \bar{h} - G)$.

(vii) Advect, for a 24-hour period, the field of $(h_Q - \bar{h} - G)$ with the "geostrophic flow" determined by the $(\bar{h} + G)$ field, regarded as contours, to obtain the forecast field of $(h_Q - \bar{h} - G)$.

(viii) Subtract the initial field of $(h_Q - \bar{h} - G)$ from the forecast field of $(h_Q - \bar{h} - G)$ to obtain the field of $\Delta(h_Q - \bar{h})$, which, on the assumption that $\Delta \bar{h}$ is relatively small, approximately equals Δh_Q.

(ix) Add the Δh_Q and initial h_Q fields to obtain the 24-hour forecast contour field.

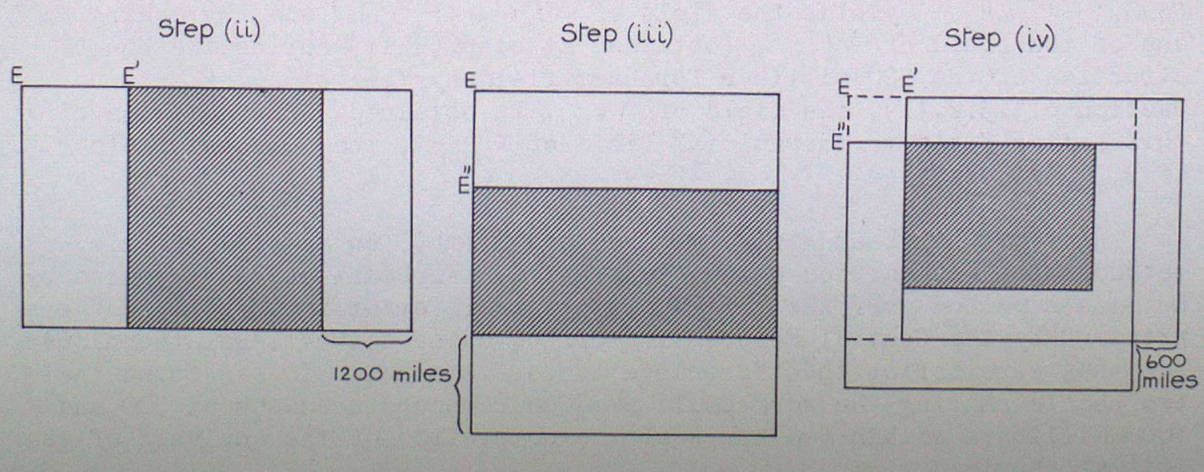


FIGURE 6.3. STEPS IN FJØRTOFT'S METHOD OF CONSTRUCTION OF 500-MILLIBAR FORECAST FIELD

E' and E" denote positions of the corners of the gridded charts relative to that of original contour chart, E, gridding being carried out over the shaded areas.

Experience at using the method suggests that, while the quality of the forecast chart obtained depends to some extent on the care taken in gridding and particularly in the advection steps, the time taken to complete the process depends largely on the efficiency of organization; all the charts drawn should be clearly labelled to avoid confusion and any system of colours used to distinguish various fields needs to be planned in advance.

6.3.3.2.2. Estoque's method. The application of Fjørtoft's graphical method has been extended by Estoque[9] to a baroclinic model atmosphere whose behaviour is determined by the 1000-500-millibar thickness and the 500-millibar fields. The 24-hour forecast chart for the 500-millibar field is constructed by the method described in Section 6.3.3.2.1. To obtain the changes expected in the 1000-millibar field Estoque made additional assumptions concerning the baroclinity of the atmosphere and deduced the following equation

$$\frac{\partial}{\partial t}(h_{500} - B h_{500} - h_{1000}) = - V_{(h_{500} - B h_{500})} \cdot \text{grad}\,(h_{500} - B\, h_{500} - h_{1000}), \qquad \ldots (4)$$

where h_{500} and h_{1000} are the heights of the 500 and 1000-millibar contour surfaces at the point in question, $V_{(h_{500} - B h_{500})}$ is the geostrophic wind vector obtained from the field of $(h_{500} - B\, h_{500})$ and B is a factor which depends on the grid length, chart magnification factor, the Coriolis parameter and the potential temperatures of the atmosphere at 500 and 1000 millibars.

B varies between 0.62 at 30°N. and 0.39 at 70°N. and may be approximated as 0.5 over a whole chart covering latitudes near the British Isles. Taking B as 0.5, then equation (4) becomes

$$\frac{\partial}{\partial t}(\tfrac{1}{2} h_{500} - h_{1000}) = - V_{(\frac{1}{2} h_{500})} \cdot \text{grad}\,(\tfrac{1}{2} h_{500} - h_{1000}).$$

This equation can be solved graphically by advecting the field of $(\frac{1}{2} h_{500} - h_{1000})$ with half the geostrophic flow obtained from the 500-millibar contours to obtain the forecast field of $(\frac{1}{2} h_{500} - h_{1000})$. Subtraction of this forecast field from the initial field of $(\frac{1}{2} h_{500} - h_{1000})$ yields the field of $\Delta(\frac{1}{2} h_{500} - h_{1000})$ and, by making use of the field of Δh_{500}, (obtained at step (viii) during the construction of the 500-millibar forecast field by the method of Section 6.3.3.2.1.), the field of Δh_{1000} is obtained. By addition of this latter field to the initial field of h_{1000}, the forecast field of h_{1000} is obtained.

A report has been given by James and Smith[10] on a trial of this method which was carried out at Dunstable. Forecast charts prepared by Estoque's method over the trial period were inferior to those which were prepared by the Central Forecasting Office using conventional techniques, but they were better than forecasts of persistence. It was found that two people sharing the work could produce 24-hour forecasts at 500 and 1000 millibars within two hours of the completion of the analysis of the initial charts.

6.4. SOME GENERAL CONCEPTS

It is quite clear that a description of the mechanics for producing forecast charts is not sufficient to enable a forecaster to prepare useful forecast charts. It is necessary that sound and reliable estimates of movements and developments shall be made. This of course is the crux of the forecasting problem and, although some formal rules would be most useful, it has not so far been possible to demonstrate or commit to paper some invariant rules (such as are known in other branches of physics and mathematics) which the forecaster can use without modification, discretion or judgement. There are some underlying principles but, in every case, there is inter-action between the synoptic systems, and the forecaster must exercise judgement to a greater or lesser degree in the manual preparation of prebaratic and prontour charts on the forecast bench. No series of data, analogues, examples of synoptic types and empirical rules could possibly be exhaustive and, at the same time, useful for the outstation forecaster. The rest of this chapter has been designed to give an account of various facts, theories or empirical ideas which should be in the armoury of practical forecasters. Experience allied with this knowledge should enable reasonably satisfactory forecast charts to be prepared on most occasions when they are required.

6.4.1. Extrapolation

High on the list of a forecaster's weapons is extrapolation. Movement, accelerations and changes in shape and intensity of synoptic systems can usually be determined from a sequence of analysed charts with good accuracy over a land area with a dense reporting network, and with fair accuracy where the reporting network is somewhat less dense. (In areas devoid of observations little can be done except to use semi-intuitive rule-of-thumb methods, for example, move systems which enter the area with plausible speed and direction, make reasonable assumptions about decay or development including the formation of new systems. It is of paramount importance to watch the observations received from the boundary regions of the sparse area for the first sign of the emergence of any systems). The crude methods of extrapolation are very simple and consist purely of an extension forward in time of the observed tracks, movements (making allowances for observed accelerations or decelerations) and development. The experienced forecaster then makes ad hoc qualitative adjustments to these extrapolations. In doing this use is made of synoptic models (including analogues), climatological knowledge and an understanding of the dynamics of atmospheric motion and of pressure systems.

Much reliance is often placed on extrapolation for forecasting for periods of not more than about 24 hours ahead and fair results often follow. Nevertheless extrapolation must not be used blindly. The forecaster should always ask himself whether the extrapolation leads to charts which bear a reasonable resemblance to analysed charts of similar situations. Extrapolation may be used both on surface and upper air charts. At upper levels primary attention is usually devoted to ridge and trough lines and systems of closed isopleths. When extrapolations of both surface and upper air features are carried out separately it is important to understand that these are only approximations to the physical changes occurring and it follows that the extrapolations may not be hydrostatically consistent. (The systematic application of thicknesses to build upward from a lower level is well able to cope with this but if forecasters attempt a direct forecast of a chart for an upper level then, as a minimum, a number of spot checks for hydrostatic consistency must be carried out).

It is quite clear that simple extrapolation will not lead by itself to the prediction of changes which are not already in progress at the time the forecast is prepared. On some occasions a consideration of the long-wave pattern is helpful. A computation may indicate whether a long-wave feature is likely to be progressive, retrogressive or stationary and this may assist in forecasting the more gradual changes in speed and direction of movement of synoptic systems. At times, changes in speed and/or direction of movement are abrupt and virtually discontinuous on the synoptic time-scale. There may, of course, also be sudden changes in the rate of development of systems. When any or all of these abrupt changes occur they are likely to lead to large errors in forecast charts. As examples, a depression may abruptly follow a different track and accelerate; there may be a sudden (but sustained) fall of pressure leading to a very extensive and deep depression or a surge of pressure may set in and be maintained which leads to a very substantial change in the situation during a 24-hour period. When consideration of synoptic models and dynamics are applied to surface and upper charts some estimate of the likelihood of such abrupt changes can sometimes be made. The successful anticipation of such changes is one aspect where the skill of the good forecaster is well demonstrated. The foreknowledge of the occasions and areas where extrapolation will fail is of great value and it is in the exercise of this type of judgement that the forecaster demonstrates real skill.

It is, of course, a natural desire of many forecasters to show such skill and bring off a successful forecast of this type of change. It is emphasized that such changes are fairly uncommon and that care and restraint must be exercised when assessing such changes. If the unusual or unheralded change is forecast there should be good supporting evidence on the charts that such changes are at least a possibility. If the forecaster indulges unreasonably in whims and hunches in forecasting the unusual he will more often than not be wrong and, after the event, realize that he had allowed himself to be blinded by a limited part of the chart when the greater (if not overwhelming) evidence pointed to the validity of a simple extrapolation of existing trends leading to a dull, prosaic, but, nevertheless, more accurate forecast.

These may seem rough and ready methods of extrapolation but the necessary skills are readily acquired and applied in practice. There are more sophisticated formulae available. As long ago as 1933 Petterssen[11] published some formulae for the computation of movements. For a derivation of the formulae the reader should refer to the original paper or to the textbook due to Petterssen[12]. The formulae are merely quoted here.

The velocity of an isobar is given by $-\dfrac{\frac{\partial p}{\partial t}}{\frac{\partial p}{\partial x}}$

The velocity of an isallobar is given by $-\dfrac{\frac{\partial^2 p}{\partial t^2}}{\frac{\partial^2 p}{\partial x \partial t}}$

The velocity of a front is given by $-\dfrac{\frac{\partial p}{\partial t} - \frac{\partial p'}{\partial t}}{\frac{\partial p}{\partial x} - \frac{\partial p'}{\partial x}}$

In the case of a front the primed symbols refer to the air in the rear of the front. In the above formulae the axis may be chosen in any direction which intersects the "line", that is, not necessarily at right-angles to it. In applying these formulae forecasters must be thoroughly familiar with the meaning of the symbols. These are:

$\frac{\partial p}{\partial t}$ = barometric tendency per unit period of time

$\frac{\partial p}{\partial x}$ = increase of pressure p per unit length along the x-axis

$\frac{\partial^2 p}{\partial t^2}$ = the change in barometric tendency per unit period of time

$\frac{\partial^2 p}{\partial x \partial t}$ = increase in barometric tendency per unit of time per unit length along the x-axis.

Similar expressions hold for movement along a y-axis and may be used to calculate speeds in the direction of the y-axis. In many cases it is not necessary to know where a particular point of a line will move to but rather the location in space of the (iso) line so that a single calculation along one axis may often suffice.

The movements of a trough or ridge line is given by

$$-\frac{\frac{\partial^2 p}{\partial x \partial t}}{\frac{\partial^2 p}{\partial x^2}}$$

Here the x-axis must be chosen at right-angles to the trough or ridge line. $\frac{\partial^2 p}{\partial x^2}$ is the change in slope of the pressure profile along the x-axis.

The movement of cyclonic and anticyclonic centres and cols is given by $-\frac{\frac{\partial^2 p}{\partial x \partial t}}{\frac{\partial^2 p}{\partial x^2}}$ in the direction of the x-axis and $-\frac{\frac{\partial^2 p}{\partial y \partial t}}{\frac{\partial^2 p}{\partial y^2}}$ in the direction of the y-axis.

In applying these latter two formulae the origin of the axes should be located at the centre of the system and the x-axis and y-axis should be chosen to coincide with the longest and shortest axes of symmetry. These axes will not, in general, be rectangular.

When velocities are determined along skew axes the velocities must be compounded to obtain the resultant velocity. This is best done graphically (rather than algebraically) in the following manner. Mark off along each skew axis from the origin the component of velocity (OA and OB) and at the end of each vector erect a line perpendicular to the respective axis. Then the vector joining the origin to the intersection of the two perpendiculars (that is, OC) represents the resultant velocity. This is shown in Figure 6.4.

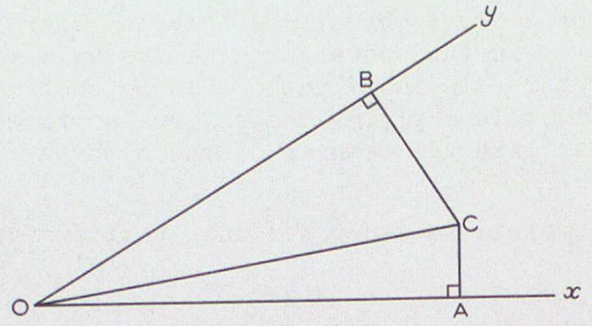


FIGURE 6.4. RESULTANT VELOCITY FROM COMPONENTS ALONG SKEW AXES
OA = velocity along Ox, OB = velocity along Oy, OC = resultant velocity.

Although the formulae are mathematically exact their application to synoptic charts does not lead to forecasts of the same exactitude. This arises from a number of causes. The formulae refer to instantaneous time/space derivatives and, from synoptic charts, it is possible to determine only finite difference approximations to these quantities. Further, the selection of the "unit" of distance along an axis requires good judgement. It should also be noted that the formulae for cyclonic centres and troughs do not apply when the co-ordinate axes intersect well defined fronts.

For further details regarding the practical application of these (or similar) formulae the reader may refer to the textbook by Byers.[13]

If a satisfactory estimate of the speed of a centre, trough, ridge or front can be made from positions on successive synoptic charts then there is usually no practical advantage to be gained by the use of the Petterssen formulae. There are, however, some occasions when the trough or ridge line is so ill-defined or so placed between reporting stations that its position cannot be determined with much precision and measurements of movement are vague or unreliable unless they are taken over so long an interval as to make them unrepresentative. Speeds calculated from the Petterssen formulae may then prove more accurate than those obtained by direct measurement.

The successful practical application of the Petterssen formulae requires some skill and proficiency which can be acquired with a little practice and forecasters inexperienced in their use should attempt the computations on a trial basis at times when their formal training or the operational tasks permit this to be done.

From a differentiation of the velocity formulae expressions for accelerations can be found. However, these include third derivatives of the pressure field, the accelerations come out as small differences between relatively large terms and the formulae give inconsistent results. They are of no practical value and are not listed here.

Formulae for the movement of long waves were given in Chapter 5.

6.4.2. Dynamical aids

The concepts of thermal steering and of the developmental thickness patterns were considered in Chapter 5. Little more need be said here in general beyond stressing the importance and persistence of the self-maintaining systems described in Chapter 5 Section 5.16. This is tantamount to saying that when a cyclone (anticyclone) moves into an area favourable for cyclonic (anticyclonic) development the system is likely to strengthen, and to weaken when a cyclone (anticyclone) moves into an area favourable for anticyclonic (cyclonic) development. It is important that the latest analysed thickness charts should not be interpreted as a static pattern since there is an inter-action between the long- and short-wave features which may, even within a period of 24 hours, lead to a substantial change in the pattern which must be allowed for in the forecast charts.

It should be mentioned in this section that the upper air patterns sometimes yield a clue to the sudden change in direction and/or speed of pressure systems and thus indicate those occasions when extrapolation may lead to a poor forecast.

6.4.3. The use of synoptic models and analogues

A synoptic model whose life-cycle is widely known and described in most textbooks of meteorology is the wave depression with a warm sector which developes into a deep system, occludes and finally fills. There are several other basic models and there are large numbers of variations on each model - not to mention the somewhat different behaviour of subsequent members of the same family of systems. Many forecasters make use of their knowledge - based partly on theory, but also on the results of experience - of the behaviour of certain combinations of systems. As each forecaster's interpretation of what does or not constitute a particular sort of configuration varies, it is clear that some improvements in the application of models (and analogues) to forecasting might accrue if some objective means of classifying the models were used. Several attempts at this have been made and much effort (notably in the United States) has been expended on compiling analogues but with only relatively little success so far as an outstation forecaster is concerned.

Some account must be taken of the larger-scale seasonal variations. For example, in winter the north-west of Europe is cold and may be often overlain with a cold trough while a warm ridge extends northwards in the eastern North Atlantic. When these features are well marked and the warm ridge is well to the west of the British Isles there is a marked tendency of depressions to turn south-eastwards towards north-west Europe but it should be emphasized that, even so, such movement is abnormal (that is, less than half do so). In the summer, when the continent is warm, thermal steering tends to keep depressions moving in a general northeasterly direction. These are but two examples of the sort of variations which may be linked with seasonal features. It follows then that in an application of synoptic models (or analogues) some account must be taken of seasonal variations. This sort of reasoning stresses the importance to the forecaster of a working knowledge of synoptic climatology.

6.4.4. Synoptic climatology

Without being too concerned about the precise definition of synoptic climatology it may, for the purpose of this handbook, be regarded as describing the totality of the weather, resulting from or at least physically related to some aspect of the atmospheric circulation as conveniently portrayed on a synoptic map. In this way is established a relation between weather and circulation and as an extension it follows that statistics of synoptic systems, their tracks, central pressures, air-mass characteristics etc. are all closely linked in any such studies. Synoptic climatology as a term is relatively young, having been coined by Jacobs[14] in 1942 but there is little doubt that, as a general concept, forecasters have for long used a general knowledge of synoptic behaviour in the forecasting of atmospheric systems and their movement. The acquisition of such knowledge has been a long process resulting partly as a by-product from daily experiences of forecasting the weather. There is almost a complete absence of published literature dealing explicitly with the synoptic climatology of north-west Europe. Some facts and figures regarding pressure systems near the British Isles have been included in Chapter 12. They should prove useful in a general sort of way but their application to one system on any one occasion must be made with care and circumspection.

6.4.5. Summary

At this juncture it is useful to summarize the approach to the preparation of forecast charts. A broad view of the synoptic situation should first be taken, starting with the larger slow-moving (or static) major synoptic systems or pseudo-permanent features. Using these features as 'anchors' for the smaller-scale ones the forecaster should make his estimates of movements. Estimates of the extent of development or decay must also be made. In any or all of these tasks the forecaster may use extrapolation (of both surface and upper features) thickness patterns for steering and development, synoptic models and climatology. These concepts may be used in the variety of combinations which seem to the forecaster most likely to lead to a correct forecast for the particular situation under consideration.

In the following four sections some information on a variety of atmospheric features is presented in a way and form which should enable the forecaster to elaborate on the broad view to some extent. A considerable amount of the content of Section 6.5 to 6.8 has been taken from the "Handbook of technical Forecasting", Chapter 1 - "The Construction and Use of prebaratic Charts".[1] That chapter was mainly the work of Douglas.

In describing some of the varieties of modes of behaviour of synoptic systems it is not possible to start ab initio and proceed in a strictly logical sequence to develop an argument and describe the main types of development and movement. This arises partly from the complexities of the atmosphere, partly from lack of theoretical understanding and partly from lack of adequate observations of the state of the atmosphere at any one time. There is a great deal of empiricism in forecasting so that it seems permissible to fashion the Sections 6.5 to 6.8 in a manner and sequence which is likely to be most helpful to the practical forecaster. Individual sub-sections are developed in as logical a sequence as possible.

6.5. DEPRESSIONS AND TROUGHS NEAR THE BRITISH ISLES

6.5.1. Warm sector depressions

The warm sector depression is usually an intermediate stage which follows the formation of a small wave on a cold front but precedes any subsequent development into an occluded depression. It is not therefore particularly logical to start with the warm sector depression; nevertheless, it is practical to do so partly because of its familiarity to most forecasters.

6.5.1.1. Movement. At the outset it should be stated that when a sequence of actual observations and analysed charts enables an assessment of the actual speed and direction of movement to be made with reasonable accuracy, that assessment should form the primary basis for short-period forecasting, making allowances for probable changes in speed and direction. When actual values cannot be determined due to an open network or because the wave is newly formed an estimate of probable movement must be made. This is often particularly difficult to do for flat newly-formed waves.

Sawyer[15] found that the 24-hour movement of a newly-formed wave depression was within $\pm$ 20° of the direction both of the warm sector isobars and of the 1000-500-millibar thickness lines over its centre when it was first identified. An older empirical rule was that the movement was in the direction of the isobars in the warm sector. Hoyle[16] has made a further investigation of the speed and direction of motion of simple warm sector depressions associated with almost straight and undistorted thickness lines. The results indicated that values of the 1000-500-millibar thicknesses, suitably meaned over an area centred on the depression, gave close estimates of the movement. For non-occluded warm sector depressions over the North Atlantic which have a simple and conventional thermal structure with no closed circulation at 500 millibars, Hoyle found that

(i) they move in good agreement with steering by the 1000-500-millibar thermal wind and

(ii) better results are obtained by measuring the mean thermal wind over an area than by reading a spot value at the centre of the depression. In his investigation Hoyle calculated the west-east and south-north mean components from the difference in thickness between points 300 miles north and south and 300 miles west and east of the centre. If desired, a special scale may be constructed to give the value of these components directly from a thickness chart. However, there is no serious difficulty in using a standard geostrophic scale to determine the components. The calculated components are combined to yield a resultant velocity.

(iii) Simple warm sector depressions over the Atlantic move with the direction of, and slightly over four-fifths the speed of the thermal wind (meaned as in (ii)) with a probable error of less than 5 knots in speed and less than 10° in direction.

(iv) Although these figures refer to measurements of the thermal wind simultaneous with the measured motion of the depression and not to the reliability of thermal steering at any instant as a guide to the motion of a depression over the subsequent 24 hours, Hoyle considered that the technique of forecasting pre-thickness charts was sufficiently well developed for them to be used with reasonable confidence in conjunction with the existing thickness pattern to estimate the future 24-hour motion of a depression when thermal steering was believed to be the right principle to apply. (Austin[17] found that a depression which was being thermally steered normally continued to be so and that the converse held to a lesser degree).

When the actual speed and movement cannot be directly assessed it is suggested that Hoyle's method should be applied whenever the calculations can be made. If they cannot the motion should be estimated as being in a direction midway between that of thickness lines and the warm sector isobars with a speed about four-fifths of the geostrophic wind in the warm sector. The speed is often between 30 and 40 knots and variability from the four-fifths geostrophic value is large.

When the 1000-500-millibar thickness pattern becomes appreciably distorted over the warm sector depression as it evolves, the application of Hoyle's results will probably lead to unreliable estimates of future movement. It is unfortunate that reliable rules for forecasting the movement of such depressions quantitatively have not been propounded in terms of synoptic parameters readily deduced or calculated from routine charts. A subsequent stage in the evolution of a warm sector depression is one of occlusion, often after a period of deepening. Still later there is a stage of filling. Depressions which are deepening markedly tend to turn to the left of their track but in "The Construction and Use of prebaratic Charts"[1] it is noted "that this is not a reliable forecasting rule. There is an awkward mutual relationship between the thermal structure of a depression, its motion and its size and intensity. Fast movement does not favour much modification of the thermal field. This is due mainly to the fact that if a depression is moving faster than the lower air mass the period of its influence on those layers is reduced. Any slight slowing down favours distortion and therefore deepening and more distortion".

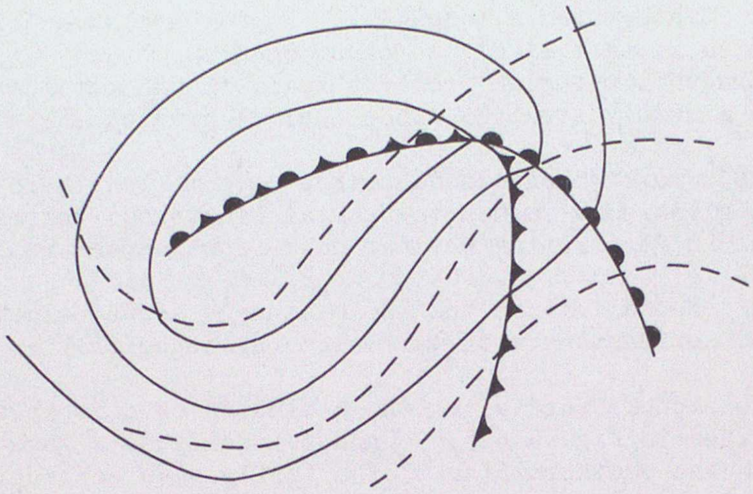
During the process of occlusion of depressions near the British Isles the centre of the depression normally remains at the end of the occlusion. Much of the occlusion then moves forward faster than the centre of the depression and the point of occlusion is gradually displaced from near the centre toward the periphery of the depression. However, on some occasions the centre moves along the occlusion, remaining at the meeting of the warm and cold fronts. Pressure tendencies and the recent track of the centre give an indication when this is likely, and a thickness pattern favourable for the formation of break-away lows at the tip of the warm sector is a useful indication that low pressure is to be expected at the triple point (see Chapter 5, Section 5.14).

Very deep depressions tend to become slow-moving or stationary and, near the centre of an old depression, the occlusion may display considerable curvature and even circumvent the centre. Such depressions are unlikely to move much until they have largely decayed but further break-away depressions may form on fronts, usually near the periphery of the depressions.

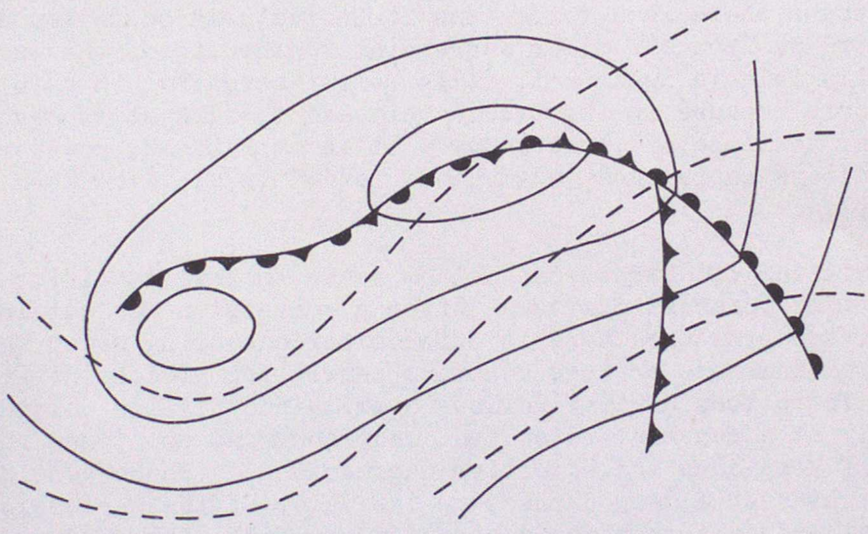
In the case of filling depressions there is a tendency for the centre to move to the right of the thickness lines. Deep occluded depressions with little thermal pattern over their central areas tend to move in the direction of the strongest current around them.

On some occasions a complex development occurs. This might be classed as movement or cyclogenesis and is illustrated schematically in Figure 6.5.

The figures illustrate a forward development which is more pronounced in Figure 6.5(b) and leads to a separate centre. If there are two such centres the foremost one often soon becomes the main centre owing to the filling up of the old one. Processes similar to (a) or (b) show up as a complex movement of an apparently discontinuous nature which can seldom be forecast accurately in detail for periods of 24 hours ahead. Once the process is seen to be occurring allowance can be made but, beforehand, precise forecasts of this type of development are difficult. Over areas where information is sparse, the double centre may be unnoticed at first and often only becomes apparent from a sudden forward movement of the centre of lowest pressure.



(a)



(b)

FIGURE 6.5. FORWARD DEVELOPMENT OF A DEPRESSION

(a) as an elongation,

(b) as a separate centre, which is often soon the only centre owing to rapid filling of the old one.
The continuous and broken lines are surface isobars and 1000-500mb. thickness isopleths respectively.

6.5.1.2. Development and decay of warm sector depressions. There is no infallible rule for forecasting development or decay. An old rule is that wave depressions deepen in accordance with the barometic tendency in the warm sector. Observed tendencies are undoubtedly a most powerful tool but the thickness pattern is also very useful. Some waves move with but little change of intensity for some time but may suddenly deepen when they move through thickness patterns favourable for development. In "The

Construction and Use of prebaratic Charts"[1], it is stated that: "A wave may first appear in the cyclogenetic region ahead of the thermal trough and then run away from it without becoming a major feature, at least till much later, after it has moved a long way. Rapid development into a large and deep depression is most likely to occur when an already existing wave runs into the cyclogenetic region from the rear, though considerable deepening can occur in a nearly straight steep thermal gradient."

Sawyer's[15] work which was described at some length in Chapter 5 Section 5.14 gives some values to frontal length and thermal wind which should assist in forecasting whether cold-front waves are likely to develop.

Douglas[18] found that on the whole it pays to be bold in deepening well authenticated depressions with warm sectors, especially in higher latitudes.

The extension forward along the occlusion of a depression has already been illustrated in Figure 6.5. On some occasions a wave develops and moves through the southern flanks of a fairly deep depression. When this occurs there is often a "sympathetic" troughing along a line from the tip of the wave towards the central region of the other depression. In many of these cases there is a temptation to indicate an occlusion extending from the trough from the older depression to the tip of the wave. Although historically this is incorrect, it is sometimes useful in both analysis and prognosis because in the trough rain and cloud systems develop which are similar to those of occlusions. It is emphasized, however, that this does not always happen and judgment is needed in deciding when to apply the concept.

The filling of depressions seldom leads to serious difficulty in the preparation of forecast charts. After a depression has attained its lowest surface pressure there is often a period during which the central pressure remains more or less constant before the process of filling commences. There then usually follows a sustained filling, although not necessarily at a constant rate, for many hours and sometimes for days in the case of very deep and extensive depressions. Where a cold pool is located right over a deep depression the decay of the depression is usually gradual and, although the depression may fill, the cold pool sometimes retains its identity as an upper feature. In some cases in the later stages of filling, the depression may start moving and carry its cold core with it. The direction and speed of motion is then controlled by the large-scale upper current in which the system is embedded.

It should perhaps be remarked that some warm sector depressions fail to develop and may even fill although they have an open warm sector. Such a process may be expected when the depression moves into an anticyclogenetic field - that is, a mutually destroying combination.

6.5.2. Waves on warm fronts

Waves on warm fronts are much less common than waves on cold fronts. In addition although warm-front waves may have a short-lived phase of rapid deepening, they seldom (if ever) develop into large systems so that from the point of view of isopleths on surface or upper charts the errors incurred when these are not forecast are relatively small. However, in the short term, the weather associated with the wave may be substantially different from that deduced from a prebaratic which does not indicate such a wave. These warm-front waves tend to be accompanied by rather narrow fast-moving belts of fairly intense and considerable precipitation, extensive low cloud and strong surface winds - more particularly on the cold side of the warm front.

Sawyer's[19] study of warm-front waves which was described in Chapter 5 will yield a clue as to when the 1000-500-millibar thickness pattern is favourable for the formation of a warm-front wave, so that the forecaster may be on the alert. It should be remembered that the existence of a suitable thickness configuration is not sufficient evidence always to justify a forecast of a warm-front wave. When a wave occurs on a warm front it is usually a single one but if the generating pattern is persistent there may very occasionally be a second. The wave usually moves fast and has a relatively short life as it generally soon runs into an anticyclogenetic area where it decays. Anticyclonic building often occurs in the warm air in the rear of the wave. Warm-front waves which affect the British Isles usually form in the north of the central or eastern Atlantic and occasionally as far away as the area between Iceland and Greenland.

At the surface, warm-front waves usually have a very narrow isobaric pattern, elongated in the direction of the front. They rarely contain more than one or two closed isobars and often resemble pronounced v-shaped troughs down the front. The effect of these waves on the upper flow is usually very transient and little can be done to indicate their effect on upper forecast charts. At high levels the winds are usually strong and quasi-parallel to the surface warm front when waves are likely. For most practical purposes the relatively slight and transient variations which occur in the upper flow during the passage of a warm-front wave are of little concern to aerial navigation.

6.5.3. Cyclogenesis associated with occlusions

The warm-front waves forming on the right of a thermal confluence associated with an occluding depression have already been described in Section 6.5.2. In addition the forward extension of depressions by secondary development on the occlusion has been illustrated schematically in Figure 6.5.

Sawyer[19] has illustrated the characteristic isobaric and thickness patterns accompanying the formation of a secondary depression at the triple point on warm and cold occlusions. An account of this work was included in Chapter 5, Section 5.14.2.

6.5.4. Non-frontal depressions

Depressions, which develop from waves on fronts, usually lose most of their frontal characteristics during the later processes of filling and decay. In these closing stages of their life they approximate to deep vortices often extending through much, and sometimes all, of the troposphere. Some remarks on these later stages were included in parts of Section 6.5.1.

There are some depressions which do not originate on fronts. For example, sometimes an old decaying depression moves across the east coast of North America to the North Atlantic where it may be rejuvenated. When this occurs there is usually a cyclogenetic area indicated on the upper air patterns but there may be no pre-existing well marked frontal system.

As the process of deepening goes on, it is usually possible to insert a pattern of fronts into such depressions but that pattern is often complex and is difficult to forecast with much accuracy before the shape and orientation can be reasonably determined from a sequence of analysed charts.

The region ahead of an upper trough is a well favoured region for deepening and, when an old depression and an upper trough are in suitable juxtaposition, that area of the charts should be watched with special care for signs of deepening and development which sometimes occur suddenly and at a rapid rate. It is stated in "The Construction and Use of prebaratic Charts"[1] "when there is simultaneous development on two quasi-parallel frontal systems, or of a polar air and a frontal depression, often amalgamating later to one system, it takes place ahead of the upper (thermal) trough. Some of the deepest systems are of this type, and if there is a polar air and frontal depression, it is the frontal system which usually absorbs the other."

Other types of non-frontal lows are those forming entirely in polar air. Sumner[20] has shown theoretically that the existence of a very small degree of instability in depth will permit small-scale cyclonic development to proceed rapidly. In a statistical and synoptic study Sumner[21] has found that cold pools may be associated with any type of surface pressure distribution, but more commonly with a (fairly shallow) surface depression, especially when situated over the sea. Also, when cold pools are travelling in a stream with a fairly straight run of isobars more or less midway between a large high and a large low there is a marked tendency for the isobars to become cyclonically curved. It is difficult to indicate in any formal way when depressions should be forecast to form in association with cold pools. One important group is the formation of polar-air depressions over the sea which occurs mainly in the winter half of the year. These are naturally more numerous over extensive sea areas but, on occasions, a secondary depression has formed when a cold pool was situated over the quite restricted area of the English Channel.

The formation of a new polar-air depression is difficult to forecast with any accuracy for a 24-hour period ahead and, even for short-period forecasts, the weather associated with such systems is difficult to assess. In summer, rainfall may be continuous and of heavy instability type leading to notable falls of rain and, at times, to severe flooding. In winter, the water content is less and the amount of precipitation is usually less but, if the freezing level is low, precipitation may be in the form of snow or sleet leading to dislocation of traffic.

Another important type is the shallow non-frontal depression which forms at times over large land masses during the summer. The initial appearance of this type of depression can usually be associated with cyclogenetic areas as indicated by the thickness or upper air charts. However, the thermal gradients are weak and the initial shape of the depression is usually ill-defined. Thunderstorms frequently develop as a result of the convergence into the developing depression and subsequently amalgamate into rain areas which may assume frontal characteristics. The location of the thunderstorms and rain areas is probably often controlled by the distribution of humidity, surface temperature and stability and does not necessarily coincide with the area of greatest cyclonic development suggested by the thickness chart. In the later stages, the depression centre tends to become associated with the rain area in a manner more like the typical frontal depression and a frontal structure may be indicated on prebaratics.

Of particular concern to forecasters in Great Britain are depressions of this type which form over France in the summer months. They usually form ahead of a thermal trough approaching across the Bay of Biscay, but the lee effect of the Pyrenees and Cantabrian mountains may contribute when a southerly wind exists over Spain. When development of such a system is expected a close watch should be kept for the development of thunderstorms over France or the Bay of Biscay.

6.5.5. Miscellaneous effects and rules

6.5.5.1. The dumb-bell effect. It is well known amongst practising forecasters that two lows, in relatively close proximity, tend to rotate around each other and the complex is sometimes referred to as a dumb-bell depression. The two depressions do not, however, retain a fixed distance apart and there is also usually a general, if slow, translation of the complex superimposed on the rotational motion. The precise path to be followed by the lows is rather difficult to forecast. In general, the smaller one rotates around the larger which is usually the slower-moving but, on occasions, the relative importance of the two lows may change during the period of the forecast. When this occurs, the paths followed by the lows become very complicated. Nevertheless, when two lows are firmly interlocked, the rough and ready application of the dumb-bell effect often leads to satisfactory forecasts of the tracks of the centres. Care must be taken not to apply the method when one (usually the smaller more recently formed) of the lows may break and move away from the complex. This results in two distinctly separate lows each moving on a track which is not closely controlled by the proximity of the other system, but the smaller system may be steered by the thermal pattern associated with the periphery of the larger system. The distinctive dumb-bell effect is, however, missing.

6.5.5.2. Lee depressions. These are well known features which form in the isobaric patterns in the lee of high ground. Formation on a moderate scale over the British Isles is almost unheard of. However, vestigial traces of lee depressions can sometimes be observed on analysed large-scale and detailed charts. They can sometimes be traced in the lee of the Welsh mountains, with winds having a mainly westerly component, and in the lee of the Pennines or the Scottish mountains. Their intensity is usually so slight that no allowance should normally be made in forecast surface charts but it may be possible to take some account of their possible presence when interpreting forecast charts in terms of surface wind.

There are, however, a number of areas near western Europe where lee depressions commonly form on a scale of size which is important in the preparation of forecast charts. The following areas are well known and recognized:

East and west of Greenland
East and west of the Norwegian mountains
South of the Alps, including the Gulfs of Genoa and Lions
West of Portugal
North of the Cantabrian mountains
South and north of the Atlas mountains
The Adriatic (as a trough either to the east of the Apennines or to the west of the Dalmatian and Albanian mountains)
South-east of Spain (often only a weak trough)
South of Iceland
South and north of Turkey.

6.5.5.3. Very elongated depressions. Very elongated depressions tend to move in the direction of their longer axis. If the larger negative tendencies are not on that line the depression will tend to move in a direction between the longer axis and the isallobaric descendent.

6.5.5.4. Deepening and filling. Depressions are deepening or filling according to whether the zero isallobar is behind or in front of the centre of the isobaric system at mean sea level.

From an examination of some sixty depressions over western Siberia, Europe and the North Atlantic during the period 1954-56 Shabel'nivoka[22] has deduced some criteria between the deepening or filling of these depressions and the temperature contrasts. The chosen depressions were those which deepened by more than 5 millibars in the time interval of 12 hours between synoptic charts. Weak depressions associated with a small pressure gradient and little vertical extent were excluded from the study. Shabel'nikova determined the temperature gradient over a distance of about 1000 kilometres perpendicular to the frontal zone from the decrease in thickness over that distance and expressed the result in units of one decametre change of thickness per hundred kilometres. In about 10 per cent of the cases the zone of more or less uniform gradient of thickness did not extend to 1000 kilometres and the decrease in thickness was determined and averaged over a somewhat smaller distance of 800 or 900 kilometres.

For the change in thickness as determined from the 1000–500-millibar thickness pattern Shabel'nikova found the following results.

Thickness change dm./100 km.	Depressions deepening per cent	Depressions filling per cent
> 2.0 units	78	9
1.5 to 2.0	18	35
< 1.5	4	56

These figures show that an existing depression usually deepened if the 1000-500-millibar thickness change was greater than 2 units but usually filled if the thickness change was less than 1.5 units. When the thickness change lay between 1.5 and 2.0 the results were less conclusive.

It is not known how reliable these criteria would be as forecasting rules but the results have been included since it should be useful to have the data readily available. If the results are applied to forecasting it is suggested that they be used rather tentatively and that forecasters should remember that the values were determined from cases where noticeable deepening (5 millibars in 12 hours) had occurred and that weak depressions were excluded from the investigation.

6.5.6. Troughs

6.5.6.1. Frontal troughs. Straightforward frontal troughs move with the speed of the cold air at a few thousand feet . With regard to the amount of troughing along the front, forecasters should be wary of varying it substantially from a recent actual analysis unless there is good evidence of change or substantial indications that changes will commence during the forecast period.

In a considerable number of cases, however, frontal troughs can by no means be classified as straightforward. On some occasions the isobaric trough may be to the rear of the surface front and on others be somewhat ahead of it. The motion and the weather are usually complex. Theoretical or schematic models of such configurations are not available and it is not possible to give any advice on how to deal with them systematically.

Isobaric troughs which produce much weather and precede or succeed warm fronts in the British Isles are relatively rare. Isobaric troughs to the rear of cold fronts may, at times, be due to an incipient wave on the cold front or the formation of a polar-air depression. Isobaric troughs forming ahead of cold fronts are more frequent in summer than in winter and some remarks on them are included in Section 6.5.6.2.

6.5.6.2. Non-frontal troughs. Across many non-frontal troughs there is a moderate thermal wind and estimates of their movement and development cannot yet be made from models or systematic procedures. Extrapolation and three-hour pressure tendencies are probably the best guide. It is perhaps pertinent to remark that in some cases, notably in southerly types in summer, there is a marked tendency for the rain-producing clouds to move forward of the lower-level trough; the trough effectively moves with the speed of an upper layer and this is normally faster than the slack low-level winds sometimes occurring in warm southerly types in summer. The extrapolation of upper troughs (at say 700 millibars) may be helpful in determining their motion. In warm southerly types in summer, particularly when a cold front approaches from the west, pre-frontal troughs are liable to develop in north Spain, the Bay of Biscay or France. These troughs usually move between about north and north-east and bring unstable medium cloud with thundery rain in advance of the cold front approaching from the west. The main thermal contrast is often associated with the cold front in the west, but the bulk of the rain and cloud system arrive with the upper trough ahead of it. In some cases the cold front is almost rainless.

6.6. ANTICYCLONES AND RIDGES NEAR THE BRITISH ISLES

The absence of any theory for anticyclogenesis which is comparable with frontal theory for cyclogenesis is one reason why the problem of forecasting anticyclogenesis is generally more difficult than that of cyclogenesis. Further, most cyclogenesis soon leads to closed isobaric systems at low levels but sustained building of pressure may lead only to an intensified ridge development. Also the processes leading to the formation of depressions often seem to occur at a quite rapid rate and to be concentrated in a restricted area, whereas anticyclogenetic processes seem to occur at a slower rate, but often are sustained for longer periods than those for cyclogenesis, and to take place over more extensive areas. It seems that the inherent instability in the general circulation of the atmosphere leads to the rapid and vigorous growth of depressions but to the rather slower growth, but more sustained persistence, of anticyclones over the chart areas with which forecasters in the United Kingdom are frequently concerned.

In Chapter 5 it was shown how dynamical concepts and the use of 1000-500-millibar thickness patterns lead to the recognition of areas where anticyclogenesis is favoured. From these results the forecaster can derive a practical working insight of the probable movement and intensification of both the classical warm anticyclone and the mobile cold anticyclone embedded in the baroclinic zone and migrating with the travelling low-pressure systems in a pseudo-recurrent sequence. In spite of the knowledge of the association between various thickness patterns and anticyclonic building and decay, the initial formation and final decay of anticyclones are difficult problems to solve on the forecast bench. For existing anticyclones much reliance can often be placed on persistence and extrapolation is usually a particularly powerful tool. Tendencies are also extremely valuable but they do not indicate a rise of pressure in advance of its commencement. Further, after a spell of falling pressures some anticyclones are rejuvenated so that simple extrapolation of such tendencies will lead to erroneous forecast charts. There is little doubt that accurate forecasting of initial formation and final decay of major anticyclones is difficult to achieve.

The existence of a thickness pattern favourable for anticyclogenesis in association with travelling pressure systems may lead to a variety of developments. Such developments range from the formation of a migratory cold anticyclone at one extreme, through the development of a feeble, small and transient ridge, to a temporary filling (or cessation of deepening) of a depression as it moves through the thermal pattern.

In attempting to systematize an approach to the forecasting of anticyclones and ridges it is convenient to start with the problem of the existing anticyclone.

6.6.1. Existing anticyclones

When, on the latest analysed charts, well established and extensive high-pressure areas already exist in locations where they may affect the pattern over the forecast area during the period, the forecasting problems are mainly of movement and changes in shape and intensity. Close attention should be paid to barometric tendencies and characteristics on a sequence of recent synoptic charts. The pressure variations are often particularly valuable in estimating the trends for the shorter term. It should be remembered, however, that tendencies in well established highs are often relatively small and that the semi-diurnal pressure waves (maxima occur at about 1000 and 2200 and minima at about 0400 and 1600 local time) may materially enhance or detract from the change in pressure attributable to anticyclonic building or decay. Allowance for the semi-diurnal waves of pressure should therefore be made when interpreting observed barometric tendencies and characteristics.

A description of Sawyer's[23] work relating the types of anticyclone with various thickness patterns over them was given in Chapter 5. Some typical movements and changes in central pressure were given and if these are considered in relation to the existing trends and 1000-500-millibar thickness configurations together with tentative estimates of the thickness pattern some assessments of probable changes are possible.

Where the thickness patterns over an existing anticyclone do not fit readily into Sawyer's[23] classification the dynamics of the problem can be taken into account in a qualitative manner by examining the thickness patterns over the area. It will be recalled from Chapter 5 that the left flank of a confluence and the right flank of a diffluence in the thickness pattern are anticyclogenetic. It is important, however, to draw attention to a distinction between them. Any moving system overtaking a confluence is accelerated and any tendency for the self-generating process is checked whereas, when overtaking a diffluence, a system is retarded and the self-generating process is enhanced. There is often a pronounced thermal ridge in association with a diffluence and the right flank is markedly anticyclogenetic.

Some cold, initially mobile anticyclones slow down and gradually evolve into warm slow-moving anticyclones with associated changes in the thickness pattern. This evolutionary process is well known and widely recognized and applied in practice by experienced forecasters. In the application of Sawyer's[23] work to practical forecasting the stage of the life history of the anticyclone must be considered. This consideration coupled with the changes in thickness pattern may yield a clue as to the occasion on which a cold anticyclone may transform into a warm one.

Once a warm slow-moving high is well established its persistence with only slow changes of pressure and little movement can usually be relied upon until persistent falling pressures occur. Ultimately, of course, it must decay. The process of decay will usually take at least 48 hours before it is complete but there are often false alarms. For example, steady falls of pressure may be sustained for several hours, sometimes 24 hours or more, and the anticyclone seem to be decaying but there may then follow a period of further building - and during this re-building period there is often considerably more movement than previously. In some cases the period of diminishing pressure may be associated with the advance of a cold front towards the anticyclone and in the rear of this cold front there may be a building ridge or anticyclone. The cold front continues to advance and often ultimately to move through the old high which continues to decay. The high to the rear of the cold front continues to build and also to advance and, at times, appears to amalgamate with and absorb the older high. The combined high-pressure area usually comes to rest or becomes slow-moving in a position close to that previously held by the preceding high. The broad synoptic pattern is, as it were, re-established and the old high is rejuvenated - although historically it is in some respects a new centre formed by amalgamation of the old system with the new advancing and building system. The sequence is widely recognized and applied by experienced forecasters but a full and satisfactory theoretical account has yet to be produced.

In addition to this rejuvenation and pseudo-persistence of warm highs due to the advance of cold air down their eastern flank from the north, warm anticyclones may be reinforced by the northward movement of warm air along their western flank. The circulation of a high which is established through much of the troposphere tends, in itself, to lead to the southward advection of cold air on its eastern flank and the northward advection of warm air on its western flank. When there is a deep, often slow-moving depression well away to the west, with a belt of winds with a substantial southerly component through much of the troposphere, then a very pronounced thermal ridge may be built up over the western parts of the high, leading to a strengthening of the old high, which then tends to extend northwards and, at times, may move bodily north or north-east. It is important that a substantial isobaric or thermal gradient continues to exist for a sufficient time to effect the northward transport of large masses of warm air and that there should be adequate horizontal separation of the centres of these major high- and low-pressure areas. A figure of 1000 miles is tentatively suggested. If the centres are too close it seems as if, on some occasions, there is inadequate space between them for the northward transport of large volumes of warm air. On other occasions where the low is fairly close to the high-pressure area there is a tendency for the low and the high to engage and for the low to move through the area occupied by the high (or parts of it) leading to the decay of a substantial portion of it.

On the subject of the rejuvenation of warm anticyclones and the northward advection of warm air, it is remarked in "The Construction and Use of prebaratic Charts"[1] that:

"A rise of sea-level pressure in a warm sector or an inadequate fall ahead of a warm front (in extreme cases even a slight rise) is an indication of this kind of development, which leads to fine hot spells in summer".

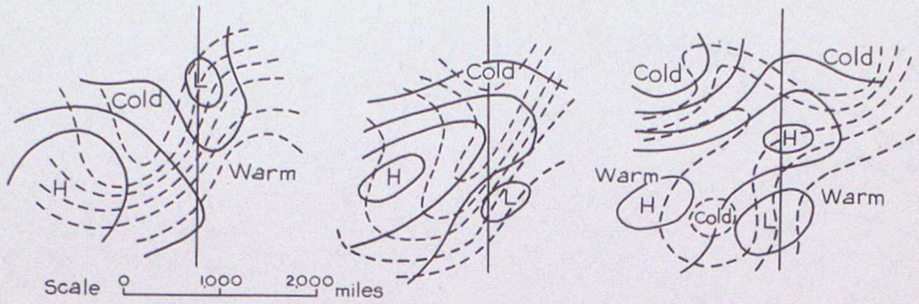
6.6.2. Formation of new anticyclones

So far the treatment has been concerned with the modification to pre-existing anticyclones. There are, from time to time, new centres formed and some remarks on them will now be made. Sutcliffe[24] has examined the formation of new anticyclones - a new anticyclone, for this purpose, was defined as the emergence of a centre of relatively high pressure on the surface chart not continuous with any pre-existing centre (but omitting weak short-lived cells in a ridge situation). Some 42 cases were found for the period 1950-51 over the area of western Europe, the eastern and central Atlantic. From a classification of the anticyclones with respect to the 1000-500-millibar thickness pattern over them Sutcliffe came to the conclusion that there are probably only two modes of breakdown of the zonal westerlies which lead to new anticyclonic centres. One of these modes may be termed the simple sinusoidal oscillation. This is, in effect, the pattern associated with an unstable wave depression developing between the thermal trough and ridge and high pressure building between the thermal trough and the succeeding thermal ridge. The other mode was termed the anticyclonic disruption.

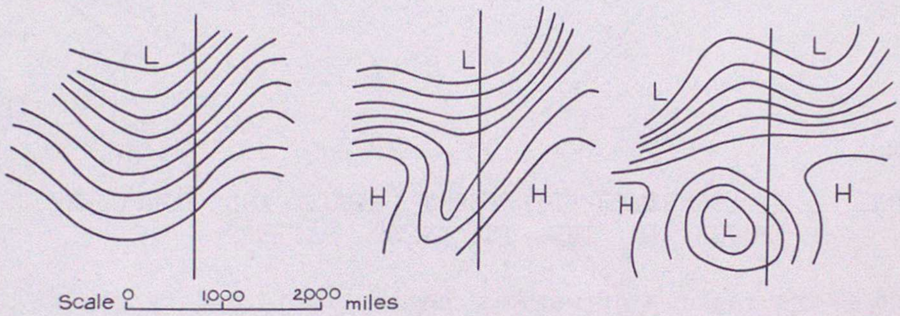
Out of 42 cases Sutcliffe found 25 cases of new anticyclonic centres forming in association with simple sinusoidal oscillations. The synoptic patterns fell into two distinct classes. In the one case the belt of baroclinic westerlies was bounded on the south by the subtropical anticyclone; with this type of situation there were only four occurrences of formation of new anticyclones. In the other case the synoptic patterns showed generally lower pressure to southward of the belt of baroclinic westerlies; there were 21 cases of new anticyclonic development of this class. The very few cases of new anticyclones, when the Azores anticyclone lies south of the westerlies, was surprising. Although the other class is apparently much more favourable, neither is reliable as a forecasting rule since the appropriate thickness and isobaric patterns occurred many times more frequently than the new anticyclonic centres. When the patterns did exist, they usually led to substantial ridge development but without a distinct closed centre of high pressure.

Of the remaining 17 cases of development of new anticyclonic centres, some eight were too complex to fall into a reasonably simple classification but the remaining nine exhibited the common feature which Sutcliffe termed anticyclonic disruption and has described in some detail. The following account is modelled largely on his text.

From time to time the oscillation of the baroclinic westerlies, although for the most part consisting of a number of wave-like distortions passing between cold troughs and warm ridges, builds up to large amplitudes, the current and the wave pattern disrupt, the stream divides and two distinct wave-like distortions move at different speeds rapidly becoming out of phase. Geometrically the disruption may be imagined as taking place by relatively faster progression of one of the wave-forms. One of the wave-forms moves at higher latitudes and the other at lower latitudes. The more rapid movement of the northerly wave-form is the more common and definite process which leads to disruption and anticyclonic building between the high- and low-latitude system. However, at times the southerly system moves more quickly eastwards and undercuts a higher-latitude ridge between the northerly and southerly systems. A schematic representation of a sequence of charts leading to anticyclonic disruption was given and described by Sutcliffe.[24] This is reproduced in Figure 6.6 and described below.



Surface isobars = full lines; 1000-500 mb. thickness = broken lines



500 mb. contours

FIGURE 6.6 SCHEMATIC MODEL OF ANTICYCLONIC WAVE DISRUPTION

Progression to north, stagnation and cutting off to south with surface ridge building across the neck.

The process is characterized by the lagging behind of the low-latitude upper trough followed by complete disruption and the cutting off of a low-latitude upper low generally with a cold pool and also a low-latitude surface depression; at the same time high pressure builds across the neck of the cut-off.

Although nine separate anticyclonic centres formed in the two-year period in association with the process of anticyclonic disruption, it should be noted that the process more commonly leads only to a ridge development or a displacement across the neck of a pre-existing high from the west. (There were 33 such occurrences in one year alone).

Although from a practical point of view the investigation was of limited value for the forecasting of new anticyclonic centres, an account has been included in the handbook since the processes often lead to ridge development. Thus forecasters may be reasonably confident in forecasting building pressure but there is little clue as to when to forecast a separate centre.

Another type of pattern which sometimes leads to the formation of a new anticyclone is a deep depression well to westward which throws up an extensive warm tongue to high latitudes, that is, the cyclogenesis occurs to westward of a diffluence, the deep depression is, or becomes, slow-moving and pressure builds in the anticyclogenetic region of the diffluence. This situation leads sometimes to a blocking high, that is, a warm high situated in rather higher latitudes than normal.

Haworth and Houseman[25] have drawn attention to a particular 1000-500-millibar thickness pattern which is favourable for anticyclogenesis. The thermal pattern is really a combination of a diffluent ridge and a confluent trough as shown schematically in Figure 6.7.

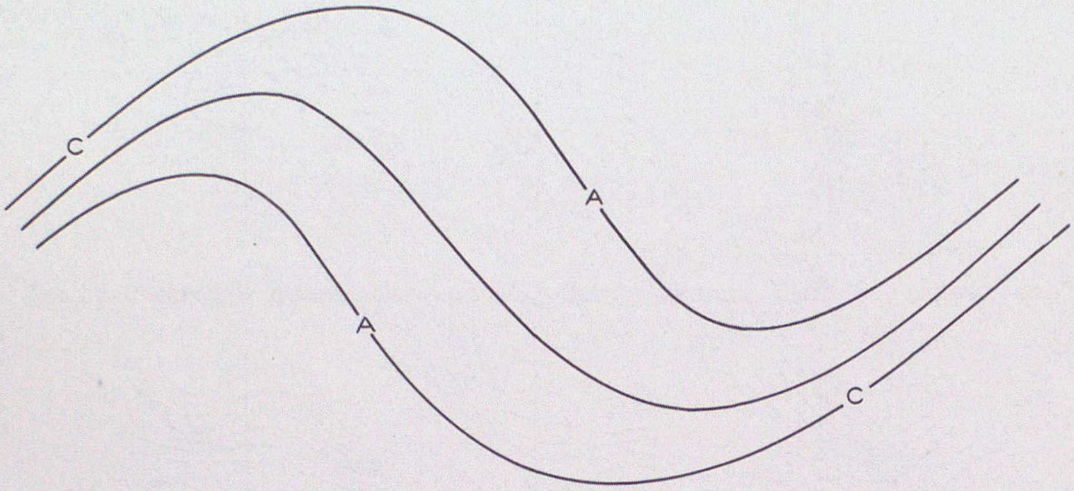


FIGURE 6.7. COMBINED DIFFLUENT RIDGE AND CONFLUENT TROUGH IN THE THICKNESS PATTERN

A and C are regions of maximum anticyclonic and cyclonic development respectively

In this case the warm side of the diffluence and the cold side of the confluence are favourable for anticyclogenesis. Haworth and Houseman remark that the pattern must persist and argue that depressions approaching the diffluence tend to slow down whilst those forming in the confluence accelerate so that the separation between the depressions increases, thereby leaving room for a disruption of the mobile westerlies. If the advection pattern implies that the diffluent ridge - confluent trough configuration will be maintained (or enhanced) for a reasonable period (for example, 24 hours or so) then anticyclonic building is likely to occur. A number of synoptic examples of actual anticyclogenesis are cited but no statistics are given which enable an estimate to be made as to how often the pattern is in fact followed by anticyclogenesis. Nevertheless this brief account has been included as forecasters may find it useful. The following remarks regarding practical use are taken verbatim from the authors'[25] account:

"Practical application to forecasting.- To use the diffluent ridge confluent trough for forecasting the formation of a new anticyclone, the following factors must be kept in mind:-

(i) Advection such as to keep the pattern in existence over a sufficiently long period.

(ii) Sharp diffluence on the ridge and confluence on the trough with sharp ridge and trough lines.

(iii) Orientation of the thickness lines in the A - A region [on Figure 6.7] should be near to the west-east direction and the thickness lines in the C areas should be near to the south-north direction.

(iv) The whole pattern should have a high mean latitude, say above 50°N.

"If any one of the above conditions is not fulfilled, the intensity of the resulting anticyclogenesis will be reduced. A new anticyclone will not usually develop unless conditions (i), (ii) and (iv) are fulfilled, but other symptoms of anticyclogenesis, e.g. filling depressions, weakening fronts, will be manifest.

"Characteristics of the development of anticyclones.-

(i) A depression on the thermal ridge is deflected to the left with much deepening, advecting warm air northwards.

(ii) A depression on the confluent trough moves north-east, advecting cold air southwards.

(iii) Any new depression developing on the confluent trough moves south-east at right angles to the thermal pattern and fills.

(iv) An anticyclone develops with marked tendency for two ridges orientated from A to A a little down the thermal pattern from the A - A axis.

(v) The large-amplitude pattern so generated gives a slight weakening of the anticyclone and then a re-build.

(vi) If a new model pattern is generated on the western side of an old high with a weakening pattern, then the tendency is for the centre to be transferred to the new A - A in the next 24 hr. and for this to become the major system.

(vii) The orientation of the A - A axis governs the future shape of an existing high even when a decline is indicated.

(viii) If the confluent trough weakens or the diffluent ridge becomes confluent the pattern is destroyed and the anticyclogenesis will be markedly reduced."

Miles[26] has made a useful synoptic study of the factors associated with the formation and persistence of all surface anticyclones spending more than one day in the Scandinavian region during the winter half of each of the twelve years 1946 - 57 inclusive. His main findings may be summarized:

(i) Somewhat less than a fifth of the anticyclones appearing in the region persisted beyond three days.

(ii) Nearly all of the strong anticyclones developed some 600 nautical miles to the east of a large-amplitude thermal ridge. Continued growth of this ridge for at least twenty-four hours after the anticyclone appeared in Scandinavia was usually required for persistence of the anticyclone.

(iii) Several other factors which appear to be relevant to the persistence of these anticyclones have been elucidated. The strength and position of the major thermal troughs upwind to 110°W longitude, the strength of any warm anticyclones to the south and south-west of Scandinavia and the maintained growth of the large-amplitude thermal ridge appear likely to have the greatest prediction value.

Some of the detailed conclusions of Miles's study seem likely to be useful on the forecast bench and the following extract is reproduced. (D = first day the surface anticyclone was over Scandinavia; D-1 and D+1 are the preceding day and the succeeding day respectively).

"The formation of winter anticyclones over Scandinavia is found to occur usually in association with a large thermal ridge which first forms over or just to the west of Iceland and then extends north to north-eastwards across the Norwegian Sea. Occasionally, cells of high pressure appear over Scandinavia associated with deep cold air with a more or less zonal circulation pattern over the Atlantic, but they do not grow above about 1020 millibars and rarely last more than a day or two. In October and March, anticyclones occur in association with blocking situations over east Europe and west Russia, that is, the original blocking anti-cyclone is centred to east or south-east of the Scandinavian region.

"Besides the large thermal ridge in the neighbourhood of Iceland on day D-1 the following factors leading to its further growth are usually present:

(i) Deep surface low about 60°N. and between 30° and 45°W. (that is some 20° longitude west of the thermal ridge).

(ii) Well marked southerly current at 500 millibars north of 50°N. and between longitudes 20° and 35°W.

(iii) The east Atlantic high-pressure cell displaced north-eastwards towards the English Channel.

For the persistence of the resulting anticyclone the following conditions are usually required to be satisfied on D day.

(iv) A single thermal trough in the Atlantic-American sector with a negative thickness anomaly greater than 20 decametres and located east of 70°W. (A second trough west of 70°W. is allowed if its negative anomaly is less than 20 decametres).

(v) The absence of a closed-contour high exceeding 570 decametres at 500 millibars in the region between 40° and 55°N., and 25°W. and 10°E.

(vi) The closed anticyclone over Scandinavia west of 20°E. on first appearance.

(vii) The main warm advection not further west than about 20°W. longitude.

"A rule based on (iv) and (v) for D day would have correctly predicted the persistence of ten out of twelve persistent highs in the period November to February and wrongly predicted two of eighteen non-persistent highs to be persistent. At D+1 a further criterion that the total thickness at Bear Island should have increased by six decametres or more between D and D+1 would have confirmed the earlier prediction of persistence in nine out of the ten and corrected the previous indication of persistence in one of the two non-persistent cases.

"Non-persistence arose most often (about two-thirds of all cases) as a result of movement east or south-eastwards out of the Scandinavian region. The eastward movement could be attributed to continued mobility (and occlusion) of the thermal ridge, and the south-eastward movement to thermal steering on the forward side of the thermal ridge, when this was being maintained by a warm blocking high near the British Isles. Decline of the anticyclone accounted for about a third, and this could sometimes be attributed to the intensification of a trough in the zone 0°-20°E as a result of fresh ridge growth well west of Iceland.

"The strength of the Scandinavian anticyclone on the day of its first appearance offers no guide to persistence. The mean central pressure for the non-persistent cases was 1030 millibars compared with 1028 millibars for the persistent ones."

6.6.3. Weakening of anticyclones

The decay of a large well established anticyclone usually takes a considerable period - two or three days is probably about the norm but there are substantial variations. The rate of weakening is not usually steady and over a few hours there may be variations in tendency which are disconcerting to the forecaster. For example, negative tendencies - sometimes as high as two millibars per three hours - may persist almost unchecked for perhaps 24 hours and it appears that the anticyclone is in the final stages of decay when subsequently there is a rejuvenation, the high rebuilds (or a new building high becomes dominant and effecively absorbs the old high) and is re-established as a long-lived slow-moving feature. Some of the types of rejuvenation already described may assist the forecaster in deciding whether such a process may revivify a decaying high.

On a few occasions a high decays quite rapidly. Sawyer[23] has indicated one type of thermal distribution when central pressure sometimes decreases rapidly. In this pattern the anticyclone was associated with a diffluent thermal ridge but a thermal trough was advancing towards the anticyclonic centre. Douglas has also commented in a similar vein and remarked that the weakening of anticyclones is usually slow until an external influence, usually an upper trough, comes into the picture .

6.6.4. Ridges

Much of the text on anticyclones is applicable to the forecasting of ridges. In Section 6.6.2 it was seen that many of the anticyclogenetic areas often lead to the formation of ridges rather than closed anticyclones. An estimate of the extent of such ridging is very important when preparing forecast charts but accurate numerical estimates are difficult to make. The assessment of ridging ahead or in the rear of fronts has a marked effect on the estimated future position of these fronts. If the estimate is seriously in error substantial errors in forecasts of weather and in timing are likely to occur. For example, strong ridging in the rear of a cold front usually leads to a pronounced penetration of the front, whilst strong ridging ahead of the front in a warm sector will effectively hold the front back. It is readily seen that both under- or over-estimates can lead to substantial errors in both frontal configurations and positions. It is unfortunately true that accurate quantitative estimates of ridge building are almost as difficult to make as are forecasts of new anticyclones.

It is pertinent to remark that ridges sometimes decay much more rapidly than anticyclones. This is particularly true of the more mobile smaller ridges. Such ridges often bring a few hours of clear dry weather in spells of generally unsettled weather and the successful forecasting of such ridges is therefore of some considerable practical importance. When a ridge following a depression suddenly collapses the succeeding depression usually advances quickly bringing a renewal of wet weather. At times the thickness pattern may yield a clue but this is not always so. The intensity of the ridge does not seem directly related to its ability to persist for some quite feeble patterns can persist and be traced over many charts. Broad, extensive ridges of a quasi-barotropic character and apparently joining up extensive anticyclones are, however, often persistent features of a chart over several days.

6.7. FRONTS NEAR THE BRITISH ISLES

6.7.1. General

When attempting to deal with fronts in the preparation of forecast charts it is important that the forecaster should examine the frontal structures in the right perspective.

A careful examination of a very detailed and densely plotted chart on a large scale will usually reveal some evidence of minor fronts or lines of demarcation of weather which are often not fronts at all. These systems may maintain their identity and exhibit a coherent pattern of configuration and movement on a sequence of detailed charts. They can accordingly be identified and tracked on charts and extrapolation of movement is often of very great value for very short-period forecasting. However, these minor features, even when identified, can seldom be satisfactorily predicted in detail for as long as 24 hours in advance. The insertion of these minor fronts (or discontinuities) on analysed charts undoubtedly complicates the pattern. For the preparation of forecast charts for periods of about 24 hours ahead it is important, as previously stressed, that the forecaster should take a broad view. He must therefore concentrate on the major fronts associated with strong contrasts, pronounced cyclonic shear and marked thermal patterns. A multiplicity of fronts on a chart is often a positive hindrance to a forecaster when preparing 24-hour forecast charts. For this purpose it is therefore useful to mark in only the major frontal surfaces. Where there is a strong but broad baroclinic zone with some evidence for multiple fronts it will usually be found preferable to locate one front as accurately as possible rather than deal with multiple fronts. Thus when considering analysed charts prior to the preparation of prebaratics some simplification of frontal structures may be desirable so that the forecaster can concentrate on the major features. With the limited time usually available for the preparation of forecast charts such concentration on major aspects will usually lead to more accurate forecasting for 24-hour periods.

Apart from the confusing picture which a multiplicity of fronts on an analysed chart conveys to the forecaster preparing a prebaratic the person receiving and using a prebaratic with a similar multiple frontal structure will have considerable difficulty in interpreting the chart in terms of weather. There is much difficulty in interpreting even major fronts accurately in terms of weather, and experience shows that the minor fronts are usually of value to the forecaster only for the shorter-term forecast, when some success can be obtained by advection and extrapolation of currently reported weather at the minor front, modified slightly at times to make allowance for topography, diurnal variations etc. Occasionally, however, the omission from a prebaratic of a minor front or double frontal structure may seem likely to lead the recipient to misinterpret the prebaratic in terms of weather. In such cases, it may then be preferable to include multiple fronts. However, the point can often be adequately covered in any plain-language message accompanying the prebaratic and, in general, it is probably preferable to deal with major fronts on prebaratic charts.

6.7.2. Warm fronts

The motion of warm fronts can usually be satisfactorily forecast by taking it as two-thirds of the geostrophic wind speed measured at the front in a direction at right-angles to the orientation of the surface front. The geostrophic wind is readily obtained from the surface isobars (see Chapter 13) and must be suitably time-averaged throughout the forecast period. For periods up to 24 hours it is usually satisfactory to measure the geostrophic wind speed on the latest actual and on the tentative forecast surface chart and then to make some approximate interpolations for intervening periods of suitable duration, for example, six-hourly periods. A statistical investigation of the success achieved by using the two-thirds rule has been carried out by Matthewman[27] who found that it is difficult to improve on it by statistical regression equations. There was some slight improvement if the speed was taken as two-thirds of the component (normal to the front) of the geostrophic wind at 900 millibars measured in the cold air some 75 miles ahead of the front. Matthewman found that the speed of a warm front was very close to the component of the actual wind in the cold air below the frontal zone and above the friction layer, say at 900 millibars. If such an observation is available it can be used as an estimate of the frontal speed (for short periods). Statistically Matthewman found that this gave an algebraic mean error of less than one knot and a root mean square error of less than six knots. It is only over dense observing networks that such observations are likely to be generally available but forecasters should use them whenever they are. A direct wind observation is very valuable because it takes implicitly into account the effect of ageostrophic motion in the cold air. It is difficult to obtain a reliable estimate of ageostrophic motion from actual synoptic charts but it is possible to recognize it qualitatively. The ageostrophic motion at right-angles to a front is $1/2\ \Omega\sin\phi$ times the acceleration of the air parallel to the front and is directed towards the front when the acceleration increases the cyclonic shear. (In such cases the front is on the left of an observer looking in the direction to which the air is accelerating). If the velocity is in knots and the acceleration is in knots per hour then, in latitude 50°, the ageostrophic motion (at right-angles to the front) is $2\frac{1}{2}$ times the acceleration. Although ageostrophic components normal to a warm front are generally larger than at a cold front (Matthewman found for some 18 well marked warm fronts values ranging approximately from 2 knots to 35 knots with a mean of about 15 knots) nevertheless it is the errors in estimating the geostrophic wind speeds at right-angles to the front which lead to the largest part of the error in forecasting the movement of warm fronts for periods as long as 24 hours.

Where there is large ageostrophic motion of the cold air towards the front, rainfall amounts are usually large and the front slows down. When a cold front advances at the normal geostrophic speed towards such a warm front the combined effect leads rapidly to occlusion. Commenting on some values of ageostrophic components obtained by Miles[28] Douglas has remarked that when the ageostrophic motion in the cold

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HINKEL, C.H. and SAUNDERS, W.E.[38] Speed of movement of warm fronts on the Atlantic. *Met. Mag., London*, **84**, 1955, p.241 and **85**, 1956, p.375, found that over the ocean five-sixths of the geostrophic speed should be used.

air towards the front exceeded about 17 knots, then in nine out of the ten cases used by Miles[28] the relevant part of the front was occluded within 24 hours, and usually within 12 hours. On the whole the ageostrophic motion exceeded one-third of the geostrophic especially when the former was outstandingly high.

The following extract from "The Construction and Use of prebaratic Charts"[1] should be valuable:

> "Qualitative estimates affecting the position of warm fronts on prebaratics
>
> Generally speaking the recent motion of the front and the isobaric configuation, the tendency field and the rainfall enables a good qualitative estimate to be made of the ageostrophic motion. It is useful to have in mind the acceleration of the air just ahead of the warm front as it moves along the front, generally into the region of stronger gradients towards the centre of the depression. In the case of a fast-running open wave much of the relative motion of the cold air into the depression is due to the motion of the depression, and if this is deepening there is an additional steepening of the gradient. In some cases there are subsidiary factors such as anticyclonic building ahead of the front, but in this case subsidence weakens the temperature gradient aloft, and if subsidence is prolonged the front will weaken, with a rise of pressure over it."

6.7.3. Cold fronts

Most cold fronts move with a speed almost equal to the component geostrophic wind at right-angles to them and an estimate of their future position, based on a suitable time-average between the speed deduced from the isobaric patterns on the latest actual and tentative prebaratic charts, often forms a good forecast. Even this simple rule must be used with discretion and there are certain points which should be mentioned.

Firstly, where there is very little pressure gradient on one part of a front it is sometimes difficult to make reliable estimates of movement. However, such a cold front often has a turning point beyond which it returns to act as a warm front. A forecast of the position of such a turning point will provide a convenient 'anchor' for one part of the front. If no development is in progress, the turning point runs along its own isobar with the speed of the warm air which is the geostrophic speed when the curvature effect is too small to be appreciable. This is shown schematically in Figure 6.8.

In many cases the isobars are straight or nearly straight and the method is easy to use. Where there is a considerable length over which the cold front is quasi-stationary then the movement of both ends of this part must be forecast. In practice, in such situations, the forecast problem is often difficult because of the possibility of wave development. Development upwind of the turning point must be considered. For example, if a wave depression upwind is deepening and the warm sector isobars become backed, then the cold front near the turning point does not progress so far, that is, it becomes retrograde. In the opposite sense anticyclonic building in the cold air will result in a rather greater progression of the cold front. The final estimate of the movement of the front depends in a complex way on developments and changes in the synoptic patterns.

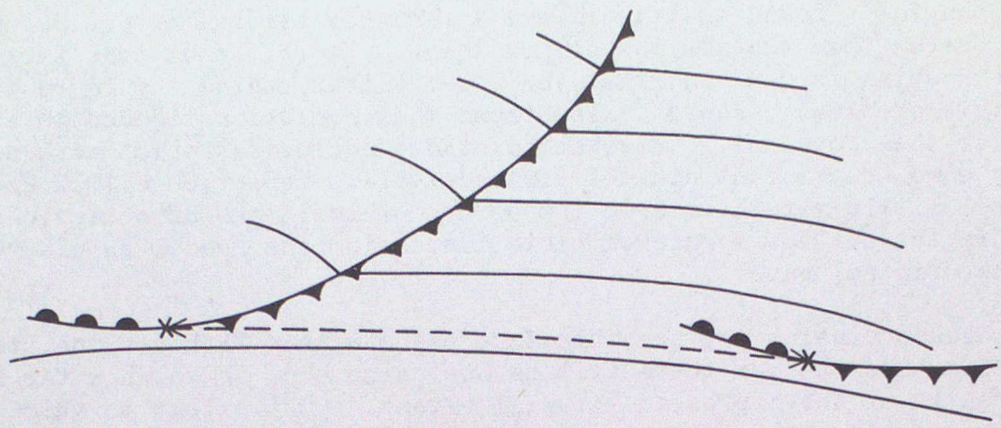

FIGURE 6.8. COLD FRONT BECOMING QUASI-STATIONARY IN THE POSITION SHOWN ON THE RIGHT OF THE DIAGRAM

As in the case of warm fronts, some account must be taken of ageostrophic motion. When the isobars are strongly curved, as in deep depressions, the effect of cyclonic curvature is to reduce the wind speed across the front below the geostrophic value. Although in such cases the cold front often moves at sub-geostrophic speed, the occlusion process usually proceeds and the forecasting of the movement of the depression centre may present the greater forecast problem.

When there is anticyclonic building to the rear of a cold front, its motion tends to be super-geostrophic. It is not usually practicable to obtain a close numerical estimate of the ageostrophic speed from current working charts but, at times, it may amount to as much as 10 knots and, in very well marked cases, sometimes more. Super-geostrophic motion of cold fronts may also occur, notably in summer at the end of hot spells. These cold fronts are often upper cold fronts and a pseudo or actual air-mass boundary may extend right down to the surface if there is a descending squall. In many such cases the main cold air comes in at about 4,000 to 8,000 feet but if there are heavy thunderstorms the cold air in a squall may descend from great heights.

6.7.4. Occlusions

If an occlusion has a substantial depth of warmer air behind it then it acts and moves as a warm front. It should be noted, however, that some occlusions which appear to be warm at the surface act as cold fronts at upper levels. The depth of warm air necessary to make an occlusion act as a warm type is not known precisely but experience suggests that a depth of warm air extending above 800 millibars is probably necessary in many cases.

With cold occlusions the rules for movement of cold fronts apply and it is often found that the sharper the isobaric trough at a cold-type occlusion the more likely it is to be moving at its geostrophic speed. Some occlusions move at super-geostrophic speed and the remarks in Section 6.7.3 on that aspect of cold fronts also apply to cold occlusions. The majority of occlusions near the British Isles move like cold fronts.

Douglas[18] found that there was a tendency for summer occlusions to move faster than the air masses low down. He felt that this fact was worth keeping in mind and that the 700-millibar charts should be useful for this problem. Jones[29] also found that occlusions tended to arrive earlier than forecast. However, of those occlusions which were not early some 40 per cent did not arrive at all. (Section 6.10.2.2. contains a little more detail on the errors of positions of occlusions on prebaratics but for a more complete discussion the reader should refer to the original paper.[28])

When occlusion may possibly take place within 24 hours the problems are to decide whether there will be occlusion and, if so, how far from the centre of the depression it will extend. The extent to which a warm sector is occluded depends on the motion of cold and warm fronts. Thus a first estimate of the extent of occlusion is obtained from the predicted motion of the warm and cold fronts. After this has been done it is usually necessary to make some adjustments to produce a plausible chart and there is a certain amount of empiricism in the final decision. The extent of occlusion depends to a considerable degree on the ageostrophic motion of the warm front and on the rate of deepening of the depression. With very deep depressions, once the occlusion process commences it is often nearly complete within 24 hours or, at least, it has extended to a point a few hundred miles from the centre of the depression.

The formation of a spiral occlusion is favoured by an intense rotation and by a slow speed of movement of the depression. This process is not always carried far enough, either on current or forecast charts, and both should be critically examined to make sure that no absurdly large ageostrophic motion is involved. Such an occlusion often behaves as a warm front but the ageostrophic motion is not likely to be much in excess of 20 knots except very near the centre of the depression. It can be considered qualitatively in relation to rainfall and other factors. If the occlusion can no longer be followed in a logical sequence and if no definite frontal characteristics are visible, it is best to drop the occlusion even if it is raining, unless the rain is on a very well defined belt.

The introduction of a back-bent occlusion, either on an actual or a forecast chart, should have historical justification involving the movement of the centre of the depression along the occlusion or at least an undoubted process of occlusion with the centre remaining at the point of occlusion, a process which can be defined in terms of air masses. Most back-bent occlusions are quite short but there may be a trough extending much further. It is a mistake to call these troughs occlusions. In a few cases there may be a development of a real cold front, that is, an air mass boundary or a squall line travelling at the correct speed, as shown on successive charts, and, in such cases, the end of a short back-bent occlusion may be joined to a longer cold front. A special kind of long trailing occlusion can be formed behind a breakaway depression or by the kind of development when a double centre forms and the leading centre deepens and becomes the major feature. The long occlusion may weaken quickly if there is a big rise of pressure behind a breakaway and no large initial temperature difference between the two sides, but in the case of a warm-occlusion type of breakaway the temperature contrast at the trailing occlusion is often larger than at the cold front.

6.7.5. Frontogenesis

It is readily shown that the velocity field is frontogenetic or frontolytic according as the isotherms lie within 45° of the axis of dilatation or not (for example, see Petterssen[11]). Sawyer[30] has made an investigation of the relationship between fronts and frontogenesis and concluded that:

> "The large scale circulation around depressions and anticyclones inevitably contain regions of confluence and when these are associated with a temperature gradient perpendicular to the axis of dilatation frontogenesis results. This frontogenesis leads to a vertical circulation which causes the ascent of warm air and the descent of cold air and the formation of an inclined frontal zone.
>
> "Synoptic evidence suggests that such frontogenesis is in progress in association with most active fronts and it seems likely that they owe their characteristic features to it."

In most synoptic situations of this type fronts already exist and although Sawyer's work helps in understanding why such fronts should continue to exist or be produced in the frontogenetic areas it does not directly aid an assessment of the chances of frontogenesis. Nevertheless it is valuable in that it sets a scale on which to look for frontogenesis in the first instance. The velocity and isotherm fields should be kinematically favourable before large-scale frontogenesis is forecast. If convergence is also occurring in that area then the chances of frontogenesis are considerably enhanced. If in addition to these two features a depression forms in the area the typical frontal surfaces seem to be established in a few hours. However, the mere formation of a depression without a classical frontal structure is not a signal to introduce on the prebaratic new fronts in a stereotyped way. There should always be also good physical, kinematical and dynamical reasons before frontogenesis is predicted.

In a number of cases, what purports to be frontogenesis is the rejuvenation of an old front which may have been dropped from previous analyses. The problem of the retention of old inactive fronts is a difficult one to solve in practice. Those analysts who invariably retain all fronts or only one are extremists and are likely to be wide of the mark. Some middle course is usually preferable.

The following sequence of events sometimes leads to the appearance of a new frontal link. When, in the rear of a cold front, the cold air is shallow, spreads out and is warmed from below, the region of strong temperature contrast is often at the boundary of the deeper cold air, where there is little or no subsidence. If further cyclogenesis occurs (usually upwind or to west of the shallow cold air) subsequent development and movement may take place as if the frontal link were located at the boundary of the deeper cold air. This is shown schematically in Figure 6.9.

There are certain preferred geographical regions for frontogenesis. The best known is near the eastern seaboards of the major continental land masses in mid-latitudes in winter. In such areas the temperature differences between air over adjacent land and sea are often large and strong fronts occur. Of direct interest to forecasters in the British Isles is the formation of a strong polar front off the eastern seaboard of North America.

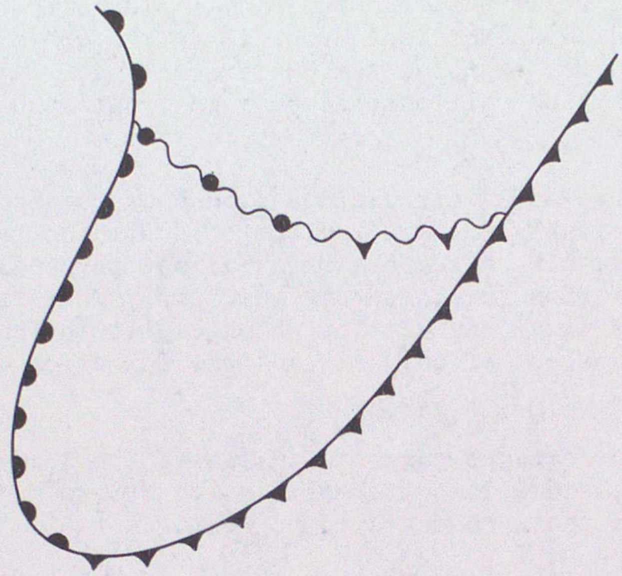

FIGURE 6.9. FRONTOLYSIS OF AN OLD FRONTAL SYSTEM, WHEN THE SUBSIDING COLD AIR BECOMES SHALLOW, WITH FRONTOGENESIS FURTHER NORTH

Frontogenesis is not a frequent occurrence near the British Isles. When it does occur it is often due partly to land and sea distribution. However, owing to the irregular coastline such fronts are often local or complex and are not readily incorporated into forecast charts. For the weather of the British Isles the most important of such fronts occur in the southerly thundery type in summer.

6.7.6. Frontolysis

Frontolysis is not usually a factor which leads to serious errors in forecast charts but it may cause large errors in the weather to be inferred from such charts. As with frontogenesis there should be good kinematical, dynamical and physical reasons leading to an expectation of frontolysis. The mere commencement of building of pressure on either side of a front is not a sufficient condition to forecast frontolysis. For example, between a warm and cold high the upper flow may remain parallel to an intervening frontal surface which retains its identity and often becomes an active feature when the next depression approaches, an occurrence which is not usually long delayed in typical mobile situations. In this case, even though pressure is rising, the thermal contrast near the front is often maintained. When there is persistent and prolonged rising pressure around a frontal surface the associated subsidence will usually destroy the front. Further, if a front gets into an anticyclonic flow pattern and is at a large angle to the upper flow there is often little thermal contrast in depth across the front and subsidence will usually destroy such weak frontal characteristics as may exist. If such events have persisted for several hours and seem likely to continue it would be wise to forecast frontolysis and drop the front.

6.7.7. Frontal changes introduced on prebaratic charts

Reference has been made in Section 6.7.1 to the occasional need to simplify a complex frontal analysis. When this has to be done there will be no strict historical continuity between the fronts on the actual and forecast chart. Where a plain-language statement can accompany a prebaratic a suitable comment on the change can be made so that the user of the prebaratic is fully aware both of the change and the reasons for it. Occasionally it may be desirable to change a frontal linkage particularly where an old linkage lies in a frontolytic region and a new one is being forged in a frontogenetic region. It is not possible or profitable to attempt to catalogue all the various possibilities of change or to indicate when changes should be introduced. In general, historical continuity is very valuable and it should not lightly be abandoned for a somewhat doubtful new system. Nevertheless, strict historical continuity sometimes results in a configuration of multiple fronts which is geometrically awkward and perhaps finally of a character which is at variance with synoptic experience. To persist in maintaining for too long such an array of fronts without some simplification or to fail to insert new frontal systems which are clearly borne out by the observations brings considerable attendant disadvantages. The forecaster must exercise a great deal of judgment and common sense in deciding when changes should be introduced.

6.8. THICKNESSES NEAR THE BRITISH ISLES

6.8.1. General

In Chapter 5 Section 5.12 there were included some data concerning the movement of thickness lines and the methods by which some adjustments could be made to the values obtained by straightforward advection. When these are applied even with great care and diligence it is often found that the upper-level charts obtained by gridding reveal inconsistencies in gradients or directions, or there may appear to be an unreasonable change in gradients. Further, the intersections of the lower chart and the thickness isopleths may lead to a very awkward and unnatural pattern of contours of the upper isobaric surface, particularly near the centres of depressions where the lower isopleths may be strongly curved and also at times near fronts, more particularly those with which is associated a marked trough at lower levels. On the synoptic scale and on the scale of chart with which most forecasters work, irregular contours (of an isobaric surface) which exhibit very sharp curves (almost kinks at times) and very marked variations in wind speed over distances of say 100 miles or so in the direction of the current are almost certainly likely to be wrong and to require some adjustment. Some remarks were included in Section 6.3.2. on the way in which adjustments to the three families of isopleths could be made to produce mutually consistent and synoptically acceptable patterns. The following additional remarks should also be helpful.

It is widely known that the axes of upper features associated with surface features do not lie vertically above the lower features. For example, in a newly-formed wave depression the slope of the axis of the vortex or incipient vortex is towards the cold air and the rear of the wave. In general, it slopes towards the north-west. After passing the mature stage the axes of the vortices at various levels frequently approach the vertical and, when they do so, the system is usually slow-moving. It is not possible to quote numerical values of these separations for quantitative use in forecasting but forecasters should make some allowance for this in a qualitative manner. In a similar way the vortex associated with an anticyclone usually slopes towards the south and west. The upper centres of old depressions and old anticyclones are usually only slightly displaced towards the colder or warmer air, that is, the axis of the vortex is almost vertical.

Experience indicates that upper highs tend to rotate on clockwise paths and upper lows on counter-clockwise paths - but the motion is neither uniform nor circular in general.

Well established thermal lows and highs are usually persistent features of the synoptic chart for two or three days. The elimination of such a thermal feature from forecast charts for periods of 24 hours should be made only when there is very good evidence for such a change. Such features do, of course, weaken at times and may later decay completely. At other times after a period of weakening there follows a reinforcement of the feature by a fresh influx of either cold or warm air. A consideration of the major flow patterns will sometimes yield a clue concerning the complete decay or rejuvenation of the thermal feature.

Non-adiabatic heat processes (for example, radiation) are factors which require consideration but, at the time of writing, these can only be allowed for in a general qualitative way.

The effect of the underlying surface is also important when assessing the movement of thickness lines. This aspect was considered in Chapter 5. Cold surfaces lead to relatively quick (sometimes super-geostrophic) advection of cold air thickness and to a relatively slow (sub-geostrophic) advection of warm air thickness. As an example of the control exerted by a cold surface, Lamb[31] has shown that the average 1000-500-millibar thickness at the windward limit of extensive snow and ice is 17,300 feet (about 5270 metres). Movement of thicknesses of 17,400 feet (5300 metres) or greater over extensive snow-covered ground is subject to certain restrictions but there are many sorts of cooling processes involved.

When the underlying surface is warm in relation to the lower tropospheric air, convection from the surface plays a large part in increasing the thickness. For example, if cold air which is unstable from the surface upwards is advected across a warmer sea, vigorous convection effectively transports heat upwards through the unstable layer and increases the thickness of that unstable layer to a value close to that appropriate to a wet adiabatic through the sea surface temperature.

As a check on the movement of thickness lines forecasters should refer to Meteorological Reports No. 13[32] which contains some extreme positions of thickness lines which occurred in a five-year period. Similar charts are included in Chapter 12, Section 12.8. Reference to such charts will prevent an extreme position being unwittingly exceeded.

It should also be remembered that warm highs and cold lows act very effectively as steering systems. Small-scale features which approach these stable (usually extensive) steering systems cannot readily penetrate through them. The smaller-scale systems are usually caught up in the peripheral circulations of the large systems which they then tend to circumnavigate - undergoing development and decay in various parts of their track, in accordance with customary ideas concerning cyclogenesis and anticyclogenesis.

When jet streams are known to be occurring or are forecast to occur the general discussion in Chapter 7 Section 7.3 should be of some value in preparing prontours. In a monograph on forecasting in middle latitudes prepared by Riehl and others[5] are included the following statements which may also be of some general assistance:

"Where the hemispheric westerlies are above average in low latitudes, velocity maxima along the jet stream in middle latitudes occur with preference in long-wave troughs, and velocity minima in long-wave ridges.

"When the hemispheric westerlies are above average in high latitudes, velocity maxima along the jet stream in middle latitudes occur with preference in long-wave ridges, and velocity minima in long-wave troughs".

In the region of the British Isles the tropopause is usually located between about the 300- and 100-millibar levels and it is necessary to take this into account when preparing upper charts for those levels which intersect the tropopause. No systematic and wholly satisfactory way of doing this by means of the thickness technique has yet been devised. The difficulty arises from the changes in temperature gradients in the region of the tropopause. Some allowance based on a general qualitative assessment can usually be made on forecast charts but considerable care should be exercised in regions where the tropopause slopes sharply or there are breaks in the tropopause surface. The discussion of the tropopause in Chapter 7 Section 7.4 should be of some help.

6.8.2. Meridional extension of thermal troughs

The variations in the long-wave pattern and their interaction with short-wave patterns have already been referred to in Chapter 5. These are undoubtedly difficult problems to solve on the forecast bench. A valuable synoptic study of the southward meridional extension of thermal troughs has been made by Miles[33] and the following account is based on his work. Meridional extension was defined as follows:

If two 1000-500-millibar thickness lines (drawn at intervals of 60 metres) moved southward 5° latitude or more in 24 hours, then meridional extension of the thermal trough was said to have occurred. Meridional extension of a thermal trough was found to be nearly always accompanied by a substantial fall of surface pressure to the south-east of it. This may be reflected either in the south-east movement of a surface depression or in the formation of a new low-pressure centre to the south-east of the parent depression. If the cold front with which the thermal trough is associated has moved well to the east before the thermal trough extends, the pressure falls will produce a trough in the polar air. In all the cases investigated by Miles meridional extension led to the onset of colder weather over a zone some 15° to 20° longitude wide.

Some 102 cases of meridional extensions between longitudes 20°W. and 20°E. which occurred during the years 1953-56 were investigated. During meridional extension the thermal trough usually showed a marked slowing down, decelerating on average about 6° longitude per $(\text{day})^2$ during the evolution. The mean displacements were 16° longitude for the day before the onset of meridional extension, 12½° longitude in the first 24 hours following its onset and 6° longitude in the next 24 hours. Most thermal troughs undergoing meridional extension reached near-stagnation within

48 hours of the onset of extension. Miles used this 48-hour position of the thermal trough to define the longitude at which meridional extension was regarded as having taken place. At the same time (that is, 48 hours after onset) the 500-millibar contour trough was usually a few degrees east of that longitude (5° longitude or less in 90 per cent of all the cases). By using the longitude of the thermal trough 48 hours after the onset and the latitude of the most southerly thickness line to undergo meridional extension (as defined), Miles devised a grid over which changes in surface pressure were computed. This is shown schematically in Figure 6.10.

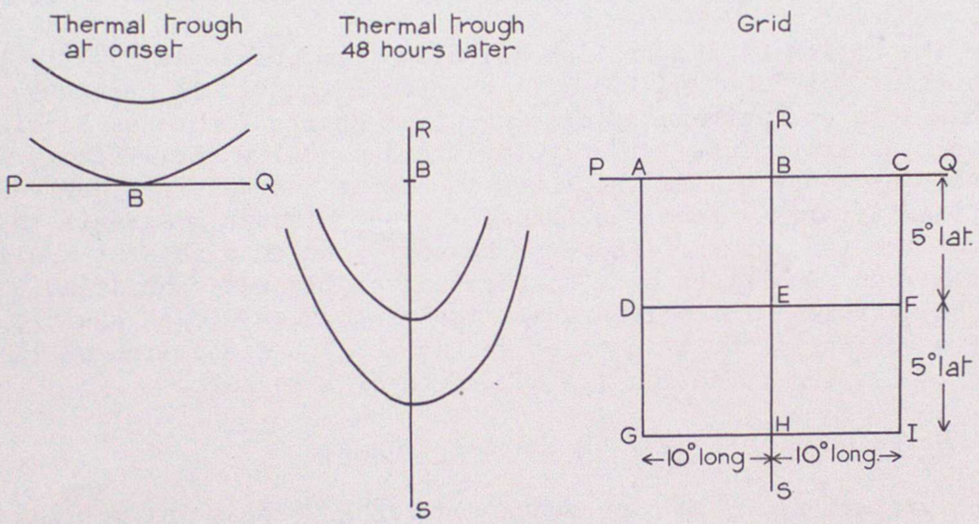

FIGURE 6.10. SCHEMATIC ILLUSTRATION OF THE GRID OVER WHICH SURFACE-PRESSURE CHANGES WERE COMPUTED

The grid was located by placing the axis RBEHS on the longitudinal axis of the thermal trough 48 hours after the onset of meridional extension and the line PABCQ was located at the latitude tangential to the southerly part of the thickness line of maximum displacement at the onset of its meridional extension. Pressure changes were then computed for grid points 10° of longitude on either side of the thermal trough 48 hours after onset and 5° and 10° latitude south of its latitude at the time of onset. The values obtained by Miles for the surface pressure changes and the mean isallobars in the first and second 24 hours following the onset of meridional extension are shown in Figure 6.11.

It will be seen that in the first 24 hours the largest falls occurred in and to the east of the longitude which the trough occupied 48 hours after onset. The heaviest falls occurred to south-east of the thermal trough which, during this period, was on average just over 10° longitude west of the line BEH in Figure 6.10 in the middle of this period. In the following 24 hours the falls occurred further south-east and rises were occurring over the northern part of the thermal trough.

Meridional extension was frequently associated with an amplifying upwind ridge. About 90 per cent of the occurrences were preceded by an increase in amplitude of a 500-millibar contour ridge upwind. On average the meridional extension began 24 hours after the beginning of the growth (as previously found by Austin[34]). It is noteworthy that during the first 24 hours while the ridge was extending northwards (mean amount 6° latitude) the contour troughs were usually relaxing (mean negative extension 3° latitude). In the following 24 hours while the ridges extended north another $3\frac{1}{2}$° latitude on average, the troughs underwent a mean extension of 6° of latitude, with a further 6° in the next 24 hours. The growth of the contour ridge was nearly always accompanied by an approximately equal growth of the thermal ridge some 10° longitude further west.

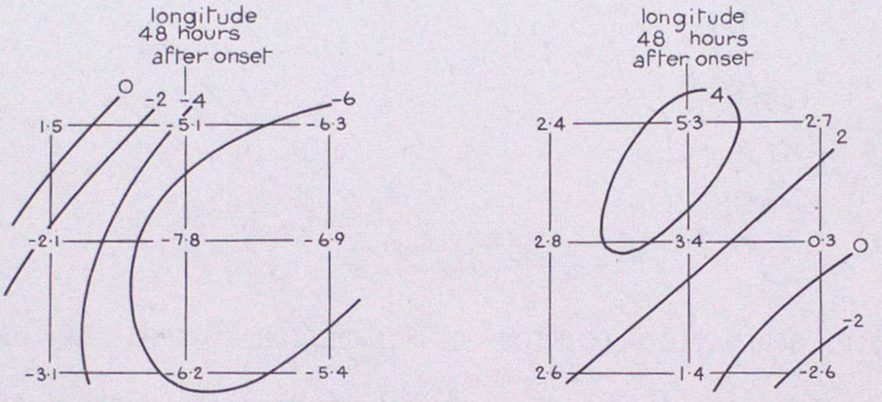

FIGURE 6.11. MEAN SURFACE PRESSURE CHANGES AND ESTIMATED MEAN ISALLOBARS FOR PERIODS OF 24 AND 48 HOURS OVER THE GRID DEFINED IN FIGURE 6.10.

The association of meridional extension with the amplifying upwind ridge pointed to the importance of a southerly component on the west side of the ridge. As the maximum southerly component seemed likely to occur at an inflexion point in the flow, Miles examined the individual cases and found that a well marked inflexion point could be readily recognized in the 500-millibar contours for 71 cases of meridional extension. In 11 other cases there were double inflexion points due to wave trains at different latitudes. No inflexion point could be readily identified in the remaining 20 cases which were mostly made up of anticyclonic southerlies and cases where the air moved into a confluence from a wide area. For the 71 cases with which a single inflexion point was recognized, Miles found that the longitude of the thermal trough 48 hours after onset of meridional extension was located, in the mean, 55° longitude downwind from the longitude of the inflexion point at the time of onset (with a standard deviation of 11° longitude). For the 11 double inflexion points the mean spacing was 63° longitude and this was principally due to the northern member of the pair. There was also a tendency for spacing to increase with latitude for single inflexion points. For the seven single inflexion points north of 57°N. the mean spacing was 66° longitude. However, some 80 per cent of the inflexion points occurred between 47° and 57°N. and for these there was little relation between latitude and spacing.

An examination of wind directions at the inflexion points emphasized the importance of the southerly component. About two-thirds of the wind directions lay between 180° and 219°. There were six cases (of single inflexion points) where the direction of the wind exceeded 220°, but even for these, the mean southerly component amounted to 42 knots.

The inflexion points were most often located just to the west of the axis of the thermal ridge as shown in Figure 6.12(a). In those cases much of the southerly component was present in the airstream near the surface. In a smaller number of cases the inflexion points were located as in Figure 6.12(b) and the southerly component arose from the thermal wind.

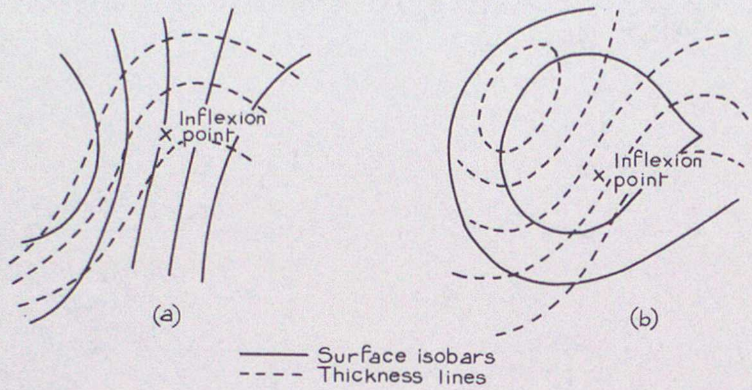

FIGURE 6.12. SCHEMATIC LOCATION OF INFLEXION POINTS ON UPWIND RIDGE

These characteristic inflexions appeared on the forward sides of upper troughs usually in association with cyclogenesis as indicated in Figure 6.13.

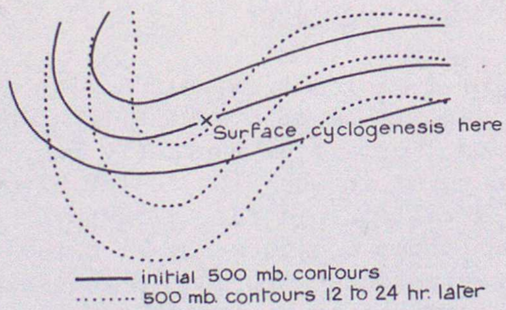

FIGURE 6.13. SCHEMATIC ILLUSTRATION SHOWING THE CHANGES IN UPPER TROUGHS (AND LOCATION OF SURFACE CYCLOGENESIS) OCCURRING DOWNWIND OF CHARACTERISTIC INFLEXION POINTS

At first the amplitude of the new ridge-trough pattern might be little more than 5° latitude from the trough. In the following 24 to 48 hours the amplitude increased at an average rate of 5° latitude per day and the separation from the upwind trough at an average rate of about 5° longitude per day, often with further backing of the wind at the inflexion point.

Miles also found that there was an association between the location of meridional extension and the upwind surface anticyclone. The longitude of the meridional extension (48 hours after onset) occurred, in the mean, some 32° longitude (with a standard deviation of 11° longitude) downwind from the centre of the anticyclone at the time of onset.

The anticyclones were usually centred further north than the average high-pressure cell in the east Atlantic. Ninety per cent of them were north of latitude 40°N. at time of onset compared with a latitude between 30° to 35°N. for the average high-pressure cell. It was quite usual for the axis of the upwind anticyclone to change from west-east to north-south as meridional extension progressed, that is, there was development northwards ahead of the growing upper ridge.

Taking the wind speed and direction at the inflexion point, Miles determined the longitude of the downwind trough using the concept of constant absolute vorticity (C.A.V.). He found that the meridional extension usually occurred substantially to the west of that indicated by the C.A.V. trajectory.

The synoptic situations in which meridional extensions occurred were described as follows by Miles:

"About a half of the cases occurred in a zonal type of situation. They appear to have been initiated either by vigorous cyclogenesis (about 60° longitude upwind) ahead of a moderate or large-amplitude contour trough or by a fairly sudden increase in the amplitude of this trough. These developments were followed by the growth of a downwind ridge and then by M.E. [meridional extension] of the existing downwind trough or the formation of a new trough from the existing zonal flow. When the amplitude of an existing trough exceeded 5° latitude before M.E. it was nearly always at least 30° longitude downwind of the I.P. [inflexion point] at time *t* [the time of onset]. Troughs of this amplitude usually suffered negative extension or led to cut-off cold pools in low latitude if nearer than about 30° longitude to the I.P.

"About a third of the cases occurred in already meridional situations as a relaxing trough followed by a new amplifying ridge from the west moved through the existing long-wave ridge. M.E. of this trough then occurred after it had led to the partial (or in some cases the complete) collapse of the old ridge and the new one had taken its place. A few occurred downwind of "blocks", in a region of strong westerly flow aloft, and a few slightly upwind of "blocks", that is, they were associated with the southern part of the splitting upper flow. Two summer cases appeared to be due to the propagation south-eastwards of a marked north-north-westerly flow over Greenland at 500 millibars.

"There were three interesting occurrences of M.E. following anticyclonic disruption of a fairly large-amplitude thermal trough. The northern part of this trough moving east faster than the southern part underwent a little negative extension at first but began to extend positively when about 40° longitude away from the southern part. On a number of occasions M.E. occurred a day or two earlier in an area occupied by a quasi-stationary warm anticyclone."

On the question of forecasting the occurrence and location of meridional extension of thermal troughs Miles wrote as follows:

"(a) Occurrence: The growth of a ridge upwind would appear to give the most reliable advance indication of the onset of M.E., but it seems likely that an I.P. with wind direction less than [i.e. between 150° and] 225° commonly appears in the early stages of the ridge growth, and may sometimes give an earlier indication. There is a rather variable interval between the first appearance of such an I.P. and the onset of M.E. It is most often between 12 and 24 hours, with 15 per cent of these intervals less than 12 hours and about

20 per cent 36 hours or more. This interval appears not to be closely associated with either the latitude or the strength of the southerly component at the I.P. or the rate of movement of the growing ridge at time *t* [the time of onset].

"This matter of the precise timing of the onset of M.E. is important because there are often no other signs of its happening right up to the moment of onset.

"(b) Location: The best forecast of location when there is a single upwind I.P. is probably 55° longitude downwind of it. If *t* can be correctly determined such a forecast could be expected to have a root-mean-square error of 11° longitude. When the main concentration of thickness lines is initially north of 55°N. there is evidence that spacings greater than 60° longitude are nearly as likely as those below this value, though in the five months April to August only once was a spacing greater than 60° longitude measured. All spacings show a tendency to be some 5° longitude shorter in the summer months.

"When there is a strong anticyclone north of 40°N. and other indications of M.E. then a forecast that it will occur 30° longitude downwind from the position of the centre at time *t* may also be expected to have a root-mean-square error of 11° longitude. In the absence of an I.P. and a strong anticyclone, a location 45° longitude downwind from a growing thermal ridge is probably a useful forecast."

A test made on the data for 1957 showed that:

"(i) a forecast of M.E. whenever an I.P. [wind direction 150° - 225° and speed ≥ 40 knots in the 500-millibar flow ahead of the upwind trough] occurred would have been correct on about 70 per cent of occasions, and

"(ii) the longitude of the trough 48 to 72 hours later would have been forecast with a root-mean-square error of 15° longitude from considerations of the longitude of this I.P. and that of the surface anticyclone just downwind of it."

This work of Miles should be of practical value to forecasters.

6.9. GENERAL REVIEW OF FORECAST CHARTS

When the series of forecast charts for the various levels have been prepared, it is very important that the forecaster should review them critically before they are put to operational use. In some respects this review is often difficult to carry out satisfactorily on the forecast bench, for lack of time. It is good advice to defer making the forecast as long as possible so as to be able to use the latest available information but, assuming there is a definite time by which the forecast charts must be available, this deferment inevitably cuts into the time left for the consideration of the forecast and the mechanical processes of preparation. Practical forecasters are usually working under this sort of handicap and, where the time of starting the forecasts can be modified slightly, it may be advantageous on some occasions to await later observations (usually surface - mainly because of the infrequent upper air information), make a final decision on the developments and carry out the upward building steps more speedily. However, some forecasters produce better forecasts when they work to a slower and standard routine. In some respects the decision on the speed of working may be determined partly by the characteristics of the individual forecaster and partly by the operational timetable, but the general type of synoptic situation is also a factor at times.

This is likely to be so in particularly mobile situations where rapid development may occur. In such cases the advantage of a later observation from a station in a vital or outlying area may well outweigh attendant disadvantages incurred by having to complete the set of forecast charts more quickly.

It is not really practicable to give a comprehensive list of all the ideas and concepts which forecasters should apply to all sets of forecast charts. A few points are recapitulated and should help the inexperienced forecaster.

It is important that the forecaster should first take a sufficiently broad view of the general synoptic pattern over a sufficiently large area. Some forecasters tend to consider only the system(s) which will affect the forecast area during the period. Such a limited view may lead to serious errors. Although it might be argued that nothing less than a hemispherical view is required in many cases, limitations of staff, time and information preclude this at almost all forecast centres with the possible exception of a national or very large centre. For 24-hour forecasting near north-west Europe an area which includes the greater part of the North Atlantic, Europe and western Russia, the Mediterranean and north-west Africa will be found to be adequate in most cases. An inspection of a sequence of charts at several levels over such an area will usually reveal, in a qualitative manner, the current long-wave pattern and the shorter-wave travelling features. Most outstations do not have the facilities for computations on long-wave features (for example, as recommended by Riehl[5]) and must rely on the guidance of the Central Forecasting Office in regard to the changes in the very large-scale features of the flow. The interpretation of the C.F.O. forecast can be assisted by some qualitative considerations. In this respect it is extremely useful to identify any semi-persistent and quasi-permanent synoptic features which extend through much of the troposphere. These often provide useful "anchors" around which the travelling systems may be arranged and they will often prevent a forecast chart from going "far wrong". However, the process must not be applied indiscriminately. There is a complex action and interaction between long- and short-wave features; neither is completely immune from the other, both are constantly in a state of flux and at times substantial changes in the long-wave pattern must be legitimately forecast. The compilation of the value of the stationary "Rossby" wavelength may be helpful in determining whether features will progress or retrogress. Miles[33] has indicated some ways in which the meridional extension of thermal troughs may be forecast and an understanding of the onset or cessation of blocking is also valuable. However, the successful forecasting of changes in the long-wave pattern (or general synoptic type) is a very difficult problem for the outstation forecaster to achieve with his (usually) quite limited resources. If the changes can be spotted and reliably inferred in the early stages of growth, then a successful forecasting of their continued development is an easier problem. Extrapolation is then a powerful tool. However, simple extrapolation has serious pitfalls as these changes in the long-wave pattern themselves exhibit a sort of oscillation as decay and rejuvenation occur over periods which can often be measured in days. Experience is extremely valuable and perhaps that experience can be most quickly and satisfactorily acquired by a systematic study of the synoptic situation and use of the known rules (empirical, physical or any other) in as objective a manner as possible - the whole process to be followed by a retrospective and unbiassed examination of the developments which subsequently occurred. These are time-consuming processes and, although forecasting must often be done to a tight timetable, the backward examination can usually be done during some convenient "slacker" period. The forecaster should learn much of synoptic value from this sort of procedure. Conscientious and systematic application of these ideas will build up an experience of a proficiency for dealing with synoptic situations and their evolution which should materially improve ability to prepare accurate forecast charts on many occasions.

6.10. LIMITATIONS, ACCURACY AND USE OF PREBARATICS

6.10.1. Limitations

One of the advantages of a prebaratic is that it compels the forecaster to come to a definite decision about future developments. An attendant disadvantage is that the forecaster cannot pictorially express either his confidence in or his doubts about the forecast which he has finally decided upon. Further, when he suspects that synoptic developments are not quite what they appear to be, he cannot incorporate vague suspicions into a prebaratic. It is, however, often possible to issue a plain-language statement to accompany the prebaratic (and prontours). This plain-language statement is a very valuable adjunct because it enables the forecaster to indicate, by a suitable choice of words, the confidence which he has in the prebaratic and the areas in which the forecast may be in error, either in synoptic development or in timing. The personal characteristics of forecasters are also involved. For example, although some bold confident forecasters preparing forecast charts may habitually over-estimate their probable accuracy, others, of a somewhat more diffident and hesitant nature, may be ever conscious of the nicety of judgment involved in the decision regarding synoptic developments and, at times, may be unduly influenced by a possible, but rather unlikely, development. Somewhat analogous difficulties occur amongst forecasters who receive a set of forecast charts, either by facsimile or prepared from coded messages. The experienced forecaster, who has sufficient time and information, may have formed a firm opinion of future developments. If the prebaratic indicates rather different development the confident forecaster may be unduly critical and sceptical of the prebaratic but the more diffident, less decisive or inexperienced forecaster may perhaps readily amend his previous ideas and accept the prebaratic. Forecasting is a very complex process and, so long as the preparation of analysed and forecast charts depends on qualitative and subjective procedures, there are bound to remain not inconsiderable differences between analyses and prognoses prepared independently by different forecasters using the same data, and these differences must, in some way, have some bearing on the frame of mind in which one forecaster views and considers forecast charts prepared by another. This is, of course, highly subjective and indeterminate but an objective assessment of the probable accuracy of forecast surface charts can be obtained by considering the errors in prebaratics.

6.10.2. Accuracy

The differences between prebaratics and subsequent actual charts have been compiled at the Central Forecasting Office and studied by several workers.[18, 29, 35] The statistics are interesting and worthy of detailed study. However, for the practical forecaster, it is perhaps more important to get some orders of magnitude established in general statements. This is done below. Any additional detail required should be obtained by reference to the original papers.

6.10.2.1. Errors in the 24-hour forecast of positions and central pressures of depressions and anticyclones. A check[35] carried out at the Central Forecasting Office indicated that for depressions the mean errors in the positions of the centres were mainly within the range 200 to 250 miles with a mean error of about 5 millibars in the central pressure. For anticyclones the corresponding errors were rather smaller being about 190 to 240 miles and 2 millibars respectively.

6.10.2.2. Errors in the forecasts of frontal movements. For 24-hour forecasts of the surface chart the mean error in the positions of fronts was about 100 nautical miles; the error in timing was about 5 hours. The work of Jones[29] indicated that the distance and timing errors were least for fronts with an initial gradient of between 15 and 25 knots across them. The errors to be expected were somewhat larger (than 100 miles and 5 hours) for occlusions and for fronts which were accelerating or decelerating quickly or had large initial gradients. Unpredicted ageostrophic movement of the fronts contributed less than a fifth of the large errors and most of the errors were ascribable to errors in forecasting the pressure field. A few were due to incorrect analysis of the original chart owing to lack of observations or to failure to forecast a geostrophic movement of the front.

For 18-hour forecasts Douglas[18] found rather smaller errors in frontal positions. He thought the error would increase more or less proportionally as the period of the forecast increased from 18 to 24 hours. The later work of Jones indicated that the increase was rather greater than this. For shorter periods the errors should be smaller.

6.10.3. Uses

The general magnitudes of errors in prebaratics impose their restrictions on the manner in which forecast surface charts should be interpreted. For example, if on a 24-hour forecast chart for midday a front was shown near the forecast area under consideration and with an expected gradient across it, it would be inadvisable to say that frontal passage was expected precisely at midday. Rather, the forecaster should interpret the prebaratic to himself and to the layman as implying a frontal passage at some time during mid-morning or afternoon and the best timing estimate at that time as being about 12 o'clock. Estimates of timing can be kept continually under review in the light of later information and, as the forecast period approaches, the estimate of time should become considerably more accurate. (When using centrally prepared prebaratic charts in conjunction with later observations considerable interpolation will be necessary as the period of validity of the prebaratic will have advanced beyond the period of the "locally required" forecasts.)

Apart from the problem of timing, some prebaratic charts may contain pressure or frontal systems whose existence, development or location may be rather problematical. On a number of such occasions some reference to these will have to be included in any plain-language statements issued. These must always be carefully considered when interpreting forecast charts even in a very general way. Many other examples could be quoted of the need for care in interpreting forecast surface charts. As in so many other aspects of forecasting judgement is needed. There is no hard and fast rule. In some cases the trust and confidence in both the type of synoptic development and in the predicted detail may be justifiably high. In other cases, although the type of development is most probably accurate, confidence in detail may be low. When the synoptic situation is complex or a possible change in the large-scale synoptic pattern is being established but with still some possibility of the previous pattern being re-established, caution is clearly necessary and a considerable latitude in interpreting prebaratics is called for. In such circumstances it may prove a disservice to the customer to attempt too detailed and precise a forecast. Even in the very general interpretation of prebaratic charts the good forecaster will demonstrate his wisdom and skill in selecting the occasion for boldness and precision and that for caution and indeterminancy.

When the forecast surface chart is completely correct its interpretation in terms of weather presents a serious problem which seems likely to remain with forecasters for a long time. For example, the pattern and weight of rainfall associated with fronts is quite variable in time and space and from front to front. Further, the distribution of cloud may be patchy and this may be linked with important variations in visibilities and temperatures. There are also orographic influences to be considered. Sometimes these are local and on a small scale which can scarcely be taken into account when preparing a forecast chart for a substantial area. Nevertheless, the local variations are often of vital importance for accurate forecasting of local weather. The interpretation of forecast charts in terms of weather is undoubtedly difficult. The texts in Chapters 8 to 11 should prove helpful.

6.11. LIMITATIONS, ACCURACY AND USE OF PRONTOURS

6.11.1. Limitations

The method of preparing forecast upper charts described in this chapter consists mainly of an upward building from the forecast surface map by the successive addition of partial thicknesses. Thus the surface forecast map is of paramount importance and it follows that limitations of the surface forecast must be incorporated in some complex way in upper-level maps. However, the correspondence between lower- and upper-level errors is not in a one to one ratio. Although thicknesses will be forecast to be statically and dynamically consistent with the lower-level forecast maps there is often a subjective element in the adjustment of thicknesses. Further, some element of direct forecasting of upper patterns may well be built into the final forecast upper air map. This may arise from the concept of future upper air patterns obtained by the upper air forecaster and is often incorporated during the adjusting processes after the first trial gridding when the upper map is clearly an unlikely picture. When the forecaster proceeds to mould the prontours to give a pattern in which the changes from the recent sequence of actual charts represent developments which are reasonable from the historical, statical, dynamical and general synoptic points of view he probably uses subjectively some element of direct forecasting of prontours. This is quite clearly a very qualitative subjective process so that surface errors could not be expected to be precisely mirrored at upper levels. Nevertheless, where thicknesses are "tied" to frontal surfaces, cold lows, warm highs etc. it is inevitable that the location of upper features will follow fairly closely the surface features and, if errors are incurred at the surface, some similar sort of error is likely at upper levels.

6.11.2. Accuracy

At the time of writing the main purpose for which prontours are used is to forecast the winds at upper levels. The methods of obtaining forecast winds from upper charts and some comments on their accuracy are included in Chapter 13.

6.11.3. Uses

Many of the remarks about the interpretation of forecast surface charts apply in a general sort of way to forecast upper air charts. Where marked wind shear in the vertical or horizontal is indicated along a fairly narrow band it is clear that especial care must be exercised when forecasting winds near the band and, in a 24-hour forecast, it would generally be unwise to recommend a minor shift of track by say as little as 50 miles horizontally or 5000 feet vertically to attempt to avoid or take advantage of a strong wind belt. Likewise if geostrophic winds were computed as 100 knots (say) then the charts should be interpreted as strong winds with a probable mean value of 100 knots. It should also be remembered that at middle and upper tropospheric levels the strong winds (as in jet streams) and their variations are very difficult to forecast with precision, in regard to location, timing or speeds. Relatively narrow elongated areas of high wind speeds are sometimes embedded in a broad strong baroclinic flow. These areas of strong winds fluctuate in regard to size, movement and peak wind speed. Interpolation for heights intermediate between the standard pressure levels for which prontours are prepared must be done with care.

The question of the interpretation of upper-level charts in terms of weather will not be discussed at length but this is a problem which will probably have to be tackled. The preparation of forecast charts by numerical processes using an electronic calculating machine is a proved reality. The techniques currently used produce upper flow and mean thickness patterns which, by subtraction, yield a surface forecast chart. However, fronts, so far, have to be inserted by inspection and synoptic experience. Thus, there is an "a priori" case for a technique for the direct interpretation of upper charts in terms of weather. Little systematic work on this subject is so far available. However, some general information on the aspect of the interpretation of upper air charts in terms of cloud has been included in a study by Visscher[38]. Precision in regard to area covered by clouds, amount and levels of cloud was not attempted. What was attempted was the establishment of relations between observed cloudiness and upper air patterns and thicknesses so that these relations might be of value in forecasting weather from forecast upper charts. Over areas covering considerable parts of the United States (for example, the states of California, Arizona, Utah and Colorado) some success in forecasting "clear" or cloudy conditions was obtained. Carlstead[37] has described a model, suitable for use with a computer of large capacity, for the numerical prediction, for periods up to about 36 hours ahead, of middle (about 700 millibars) cloudiness and areas and amounts of precipitation. Only a few specimen forecasts were illustrated. The probable accuracy of forecasts based on the model was not assessed and some limitations of the model were described by Carlstead.

Some remarks on the association of clouds and precipitation with jet streams are contained in Chapter 7, Sections 7.3.2.4 and 7.3.2.5. Some rules (included in Chapter 16, Section 16.6.4) for forecasting cirrus clouds indicate that the characteristics of tropospheric flow are among the factors which must be borne in mind. Thus jet streams and the characteristics of the upper flow as shown by prontours enter somewhat indirectly into a forecaster's assessment of the probable weather. However, more research is required before forecast upper charts can be directly interpreted with acceptable accuracy in terms of weather.

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61

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