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HANDBOOK

OF

WEATHER FORECASTING

METEOROLOGICAL OFFICE

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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 4

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FURTHER METHODS OF ANALYSIS

4.1. STREAMLINE AND ISOTACH ANALYSIS

In temperate latitudes forecasters are normally experienced at deducing the wind field from maps of the pressure field, but in low latitudes where the geostrophic relation is not closely obeyed, isobars do not give a good representation of the wind. In these regions a direct analysis of the wind observations is required. Also at high levels (say 100 millibars or above) pressure-height data tend to become less accurate and more sparse than wind data, and here, too, it may be desirable to analyse the wind field directly.

Several methods of wind analysis are possible; that which uses streamlines and isotachs is the best for most purposes. "Streamlines" are lines which are everywhere tangential to the wind direction. Instantaneously the air flows along the streamlines, but if, as is normally the case, the streamline pattern is changing, then the air trajectories do not coincide with the streamlines. "Isotachs" are isopleths of wind speed. Both series of lines are required to represent the wind field completely, and both are normally shown on the same chart.

Some analysts have attempted to depict wind speed by spacing the streamlines so that the distance between them is inversly proportional to the wind speed, and the relation is analogous to that between isobars and the geostropic wind speed. This is not, however, a satisfactory method, since if convergence of the streamlines is taking place, adjacent streamlines must become closer together, but the wind speed may be decreasing rather than increasing. In what follows, therefore, no attempt will be made to relate the spacing of the isobars to the wind speed, and this important difference between streamline/isotach charts and the more familiar isobaric charts must be constantly borne in mind until facility is gained in the practical use of streamline charts.

Figure 4.1 shows a typical streamline chart on which are depicted most of the patterns which will be met in streamline analysis. The streamlines should be marked with arrows to show the direction of the wind. At the top of Figure 4.1 is a broad westerly airstream with roughly parallel streamlines. At A and B are anticyclones in the northern hemisphere; A represents a centre at which there is no inflow or outflow, but a commoner occurrence is shown at B where there is an anticyclonic outdraught. At C is a depression with a cyclonic indraught. At B and C more than one streamline is shown meeting at a point; where two streamlines meet at an angle to one another the wind must be calm. However for a surface chart B may be taken as representing a region in which air is descending and flowing out laterally. Similarly at C convergence and upward motion is indicated. If Figure 4.1 depicts the wind flow at an upper level, then the air outflowing at B may be supplied by descent from above or ascent from below.

A, B, and C are all singular points, where the direction of flow is indeterminate and the wind speed zero. Another type of singular point, N, corresponds to a col, and is called a neutral point. This is drawn conventionally to show air flowing towards the singular point from two directions and away from it in two others.

The lines marked DEF, QPC on Figure 4.1, where streamlines merge, are called asymptotes. Along QPC the neighbouring streamlines move closer and closer to

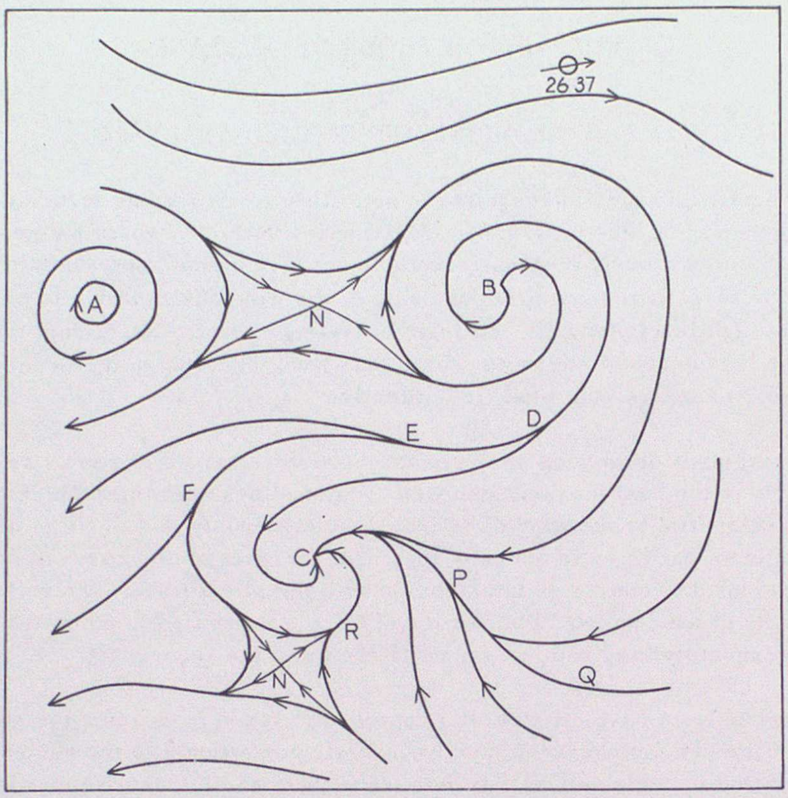

FIGURE 4.1 *Typical streamline chart*

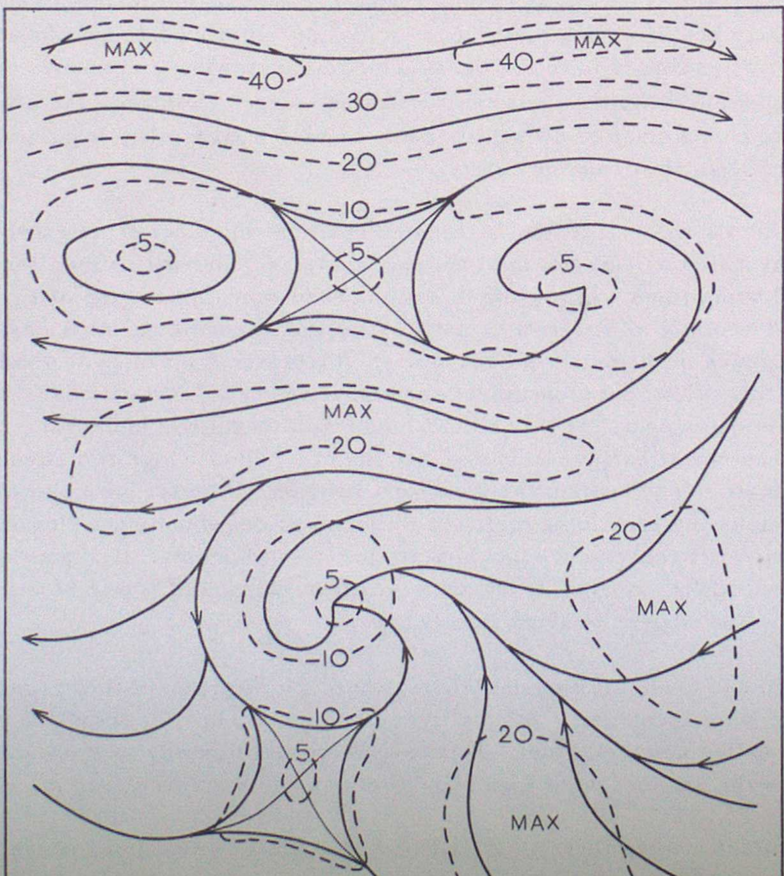

FIGURE 4.2 *Streamline chart with isotachs added*

the asymptote. Theoretically they should never actually meet a true asymptote, but for ease of drawing the nearby streamlines are normally shown as merging with the asymptote. Similarly along DEF the streamlines diverge from the asymptote. Where two streamlines merge they must be drawn as having a common tangent; they cannot meet at an angle unless the wind is calm. It should be noted that it does not necessarily follow that along QPC, for instance, horizontal mass convergence is taking place though it may often do so. If the wind speed increases along QPC sufficiently rapidly the tendency for the mass of air to increase because of inflow from the sides may be more than offset by a more rapid removal of air downwind. This is very likely the case at R, near the neutral point. In a similar way the line DEF may or may not be associated with horizontal mass divergence according to the pattern of wind speeds.

Figure 4.2 shows the same situation as Figure 4.1, but with the isotachs added. The following features are often present in the isotach pattern, and a knowledge of them will often aid the analysis in regions of sparse data:

(a) The centres of maximum speed are usually elongated and lie roughly along the streamlines.

(b) The isotach spacing is often much closer on the flanks of the maxima than at their ends, and therefore the isotachs on the sides are also roughly parallel to the streamlines.

(c) A speed minimum occurs at every singular point (since the speed here is zero by definition).

(d) Speeds are generally relatively small in areas of sharp curvature in the streamlines.

(e) In the vicinity of a neutral point the isotachs are roughly elliptical, but farther from the centre the shape often resembles a four-pointed star.

The drawing of streamlines is facilitated if the data are plotted with wind direction arrows drawn centrally over the station circles, together with figures indicating the direction and speed. An example is shown in the top right-hand corner of Figure 4.1. The arrow should be plotted with the aid of a protractor; sufficient accuracy is rarely obtainable freehand.

Until facility has been gained in drawing streamlines it is helpful to make use of an intermediate series of lines, namely "isogons" or isopleths of wind direction. These can be drawn fairly easily, interpolating as necessary, in the same sort of way that isobars are drawn. Isogon patterns will, however, differ in an important respect from isobaric patterns. Where there is a singular point in the streamlines (corresponding to a pressure centre or col) the isogons for all directions will meet in a point, the wind direction being indeterminate at this point. The first step in an isogon analysis is to locate the singular points; sketching in the isogons for 90°, 180°, 270° and 360° is often an aid to this. Then the remaining isogons at 30° intervals can be drawn. Figure 4.3 shows a chart with isogons drawn.

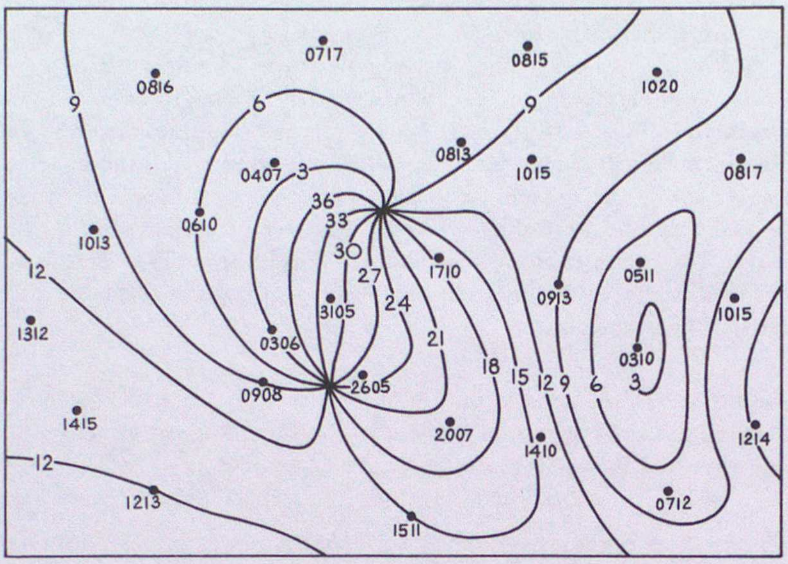

FIGURE 4.3 *An example of isogon analysis*

In order to proceed to a streamline analysis, a series of short parallel lines (about ¼ inch in length) should be drawn at approximately ¼-inch intervals along each isogon; the direction of the short lines should correspond to the indicated value of the isogon. Parallel rulers are invaluable for this work. The map is now covered with what are in effect short direction arrows and drawing streamlines to suit them is then not difficult. An inflexion in the streamlines occurs whenever the tangent to an isogon is in the direction represented by that isogon. Figure 4.4 shows the chart of Figure 4.3 with streamlines drawn.

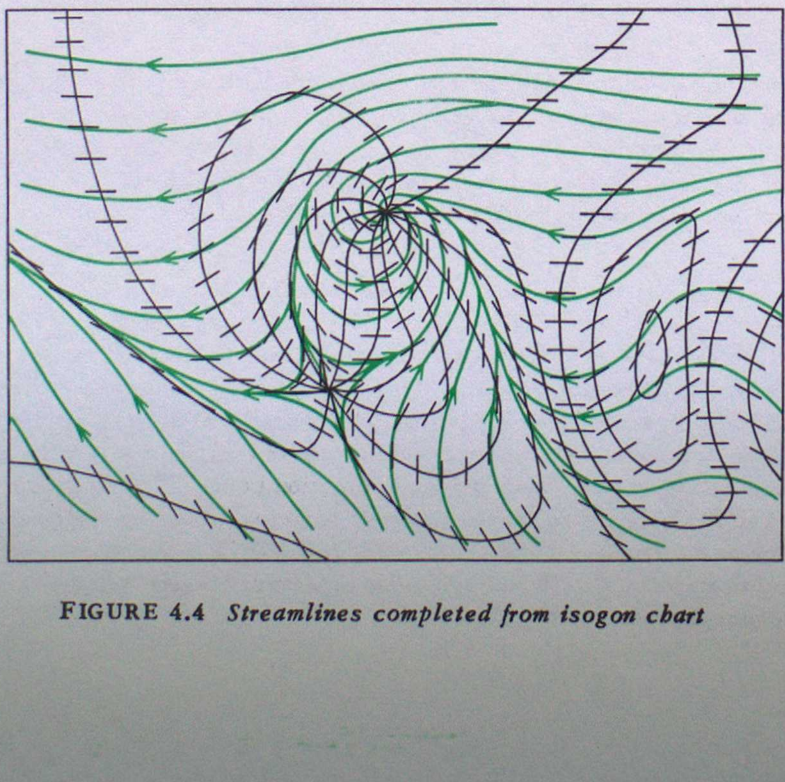

FIGURE 4.4 *Streamlines completed from isogon chart*

Further Methods of Analysis

The isogon method of drawing streamlines is somewhat tedious and with a little experience the analyst should not have difficulty in drawing the streamlines direct, making use only of the plotted wind directions at the observing stations. Any tendency to attempt to show streamlines passing through every station should be resisted. In drawing isobaric charts an analyst allows for departures from the geostrophic relation, and reported winds frequently blow partially across the isobars as drawn. This habit must not be carried over to streamline analysis; the streamlines should be drawn at all points tangential to the observed winds and to numerous imaginary interpolated wind arrows. Changes in direction of streamlines should not be too abrupt. When drawing streamline charts it will usually be found advantageous to work outwards from anticyclones (where outdraughts are likely) and inwards towards depressions. Use should be made of the principle of continuity both in time between successive charts and vertically between charts for adjacent levels. In general, a simple pattern is more likely to reflect the truth than an unduly complicated one.

The analysis is completed by drawing the isotachs, either as dotted lines or in a different colour, and perhaps suitably shading the areas of maximum and minimum wind speed, or marking with heavy dashed lines the cores of jet streams. The common features of isotach patterns described earlier in this section will provide a useful guide when drawing isotachs.

More detailed information on streamline analysis is given in an excellent manual by Palmer[1*], and there are a few additional hints in a companion manual by Ramage[2]. Both these refer particularly to tropical meteorology. Saucier[3] (pp.303-312) also has a section on streamlines.

4.2. AIR TRAJECTORIES

Most forecasters will require at some time or another to estimate the trajectory of a parcel of air over a period of time. This cannot be inferred reliably from a streamline chart, which gives a picture of the direction of movement of all particles at one time. If a series of streamline charts are available an air trajectory can be built up in steps taken from each. Petterssen[4] (pp.27-32) and Saucier[3] (pp.312-316) describe somewhat complicated methods of interpolating between charts, but a simple and satisfactory approximation can readily be obtained as follows. Suppose that charts are available at six-hourly intervals 0600, 1200 G.M.T. etc., and that trajectories commencing at 0600 G.M.T. are required. It is then assumed that the 0600 G.M.T. chart is typical of the air motion during the period 0600 to 0900 G.M.T., the 1200 G.M.T. refers to 0900–1500 G.M.T. and so on. The position of the parcel of air at 0900 is found by measuring along the streamline the distance that will be travelled in three hours according to the wind speed in that region. If the wind speed is changing or the streamlines are rather curved, it may be necessary to proceed in hourly steps. The 0900 G.M.T. position is then transferred to the 1200 G.M.T. chart and the movement for the six hours 0900 to 1500 G.M.T. is found in a similar way, the process being repeated as required. For most purposes a smooth freehand curve joining the 0600, 0900, 1500 G.M.T. ..... positions will give an adequate representation of the trajectory. A slight refinement can be introduced by recording the 0600, 1200, 1800 ..... positions on the trajectory chart and interpolating trajectories that are tangential to the 0600 streamlines at the 0600 G.M.T. point, and tangential to the 1200 streamlines at the 1200 G.M.T. point, and so on.

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

Specially drawn streamline charts will not often be available, but in the free atmosphere in middle and high latitudes the contours on constant pressure charts can be used as streamlines. If there is evidence that the winds depart from the pressure pattern significantly, some account should be taken of this, possibly by sketching in some streamlines in the area concerned. Wind speeds can be obtained from the geostrophic wind or, if curvature is likely to be important, from the gradient wind. It should not be forgotten that it is the curvature of the trajectory not of the isobar which enters into the gradient wind equation and these are not the same if the pressure system is moving. Methods of allowing for this in estimating the gradient wind are described in Chapter 13, Section 13.5.2.

Surface trajectories are more difficult to compute unless proper streamline charts are available, and over land local effects will make these difficult to construct. A rough approximation can be obtained by using sea-level isobars, and assuming that the surface wind is some fraction of the geostropic speed and backed a certain amount from the geostrophic direction. Forecasting rules are given in Sections 13.9.1 and 13.9.2 and relevant relations are given in Sections 13.5.1 and 13.5.2. On the meso-scale, however, streamline analyses of the actual surface wind may reveal significant convergence zones in the vicinity of local storms, sea-breezes, and systems of like magnitude.

The methods of constructing trajectories which have been described apply to forecast as well as actual trajectories, use being made of forecast instead of actual wind charts. The accuracy of forecast trajectories will, of course, depend on the accuracy of the prebaratics or prontours used. Freeman[5] has given some figures of the accuracy attained in forecasting 24-hour trajectories over the British Isles. As would be expected the larger errors occur, in general, with the longer trajectories and with the longer forecast periods.

All the trajectories so far considered have been horizontal ones. If vertical motion is taking place, a parcel of air can be carried to another level where the motion, particularly the wind speed, may easily be different. The three-dimensional trajectory of a parcel of air may diverge widely from a trajectory computed on the assumption of purely horizontal motion. In so far as the motion is dry adiabatic, use can be made of isentropic charts in evaluating three-dimensional trajectories – see Section 4.5.

4.3 VERTICAL CROSS-SECTIONS

4.3.1. *General*

Analysis by means of vertical cross-sections can be a valuable aid to obtaining a three-dimensional picture of the synoptic situation. It is rarely practicable to produce vertical cross-sections as routine, but the occasional drawing of one is most helpful in gaining an insight into the vertical structure of fronts and jet streams. Investigations into selected synoptic situations are often aided by the construction of cross-sections.

The most useful form of cross-section chart is one which is graduated in a logarithmic scale of pressure for the vertical axis, and in a suitable scale of miles on the horizontal axis. The height scale is then nearly linear and should be about 100 or 200 (or occasionally 400) times the horizontal scale.

The horizontal line along which the section is to be drawn should be chosen so as to lie close to as many upper air ascents as possible and will usually be chosen to be roughly perpendicular to the front which is the main feature of interest. The direction of the horizontal axis should be taken so as to produce fronts which slope in the customary way, that is warm fronts sloping upwards to the right; this will usually be achieved by plotting the more westerly end of the section on the left-hand side. Alternatively a line running approximately north-south or east-west may be appropriate. Stations which are off the direct line are usually projected perpendicularly on to it, though sometimes better results may be obtained by projecting along a line parallel to the front, rather than perpendicular to the plane of the section.

Vertical lines should be drawn on the cross-section to represent correctly the positions of the upper air stations. Selected data should then be obtained from the relevant tephigrams and transferred to the section. As well as values for reported significant points it is often helpful to plot at the correct pressure levels interpolated values of selected isopleths, for example, 10°C, 0°C, −10°C etc. isotherms. There is a fairly wide choice of parameters which may be analysed and they will be considered in turn below, under the general headings of temperature, humidity and wind. It is rarely satisfactory to include more than two sets of isopleths on one cross-section, so for a complete analysis, more than one section will usually be required.

4.3.2. *Analysis of temperature*

Temperature (T) is usually the first parameter considered when cross-sections are being constructed. A complete temperature analysis will be greatly assisted by investigating at the same time the distribution of potential temperature (θ), values of which may be readily obtained from the tephigram (see Chapter 3, Section 3.2). Isopleths of potential temperature are also lines of constant entropy and are referred to as isentropes.

The tephigrams should be examined for any stable layers, which normally are reported by significant points, and these should be marked on the section. In the free troposphere stable zones lie nearly along isentropic surfaces and stable layers with similar potential temperatures on neighbouring ascents can be joined to mark a stable zone on the section. In the stable zones there will be a concentration of isentropes and the isotherms will slope steeply. Stable zones may be of two general types. In a zone which is nearly horizontal, the isentropes will also be nearly horizontal, as will the isosteres (lines of equal density), and both will be parallel to the isobars; this state is said to be barotropic. A barotropic stable zone could result from the development of a subsidence inversion for instance. In a sloping stable zone the isentropes will cross the isotherms at an angle (the isobars and isosteres will also cross each other) and a baroclinic state is said to exist. The degree of baroclinity can be measured by the number of intersections per unit area. Since a front is a region of marked baroclinity the sloping stable zones on the cross-section can be used to delineate frontal zones. It should be noted, however, that for very steeply sloping zones marked stability is not required to produce a baroclinic state. Frontal zones can therefore be extended to regions without pronounced stability, provided the slope of the zone is steep.

The boundaries of a frontal zone are normally drawn on cross-sections as discontinuities with kinks in the isotherms. Although the isentropes will cluster along the zone, some will cross the boundaries and kinks should also be drawn in the isentropes. The sense in which the kinks must be made is shown in Figure 4.5. The kinks in isotherms and isentropes are in opposite senses.

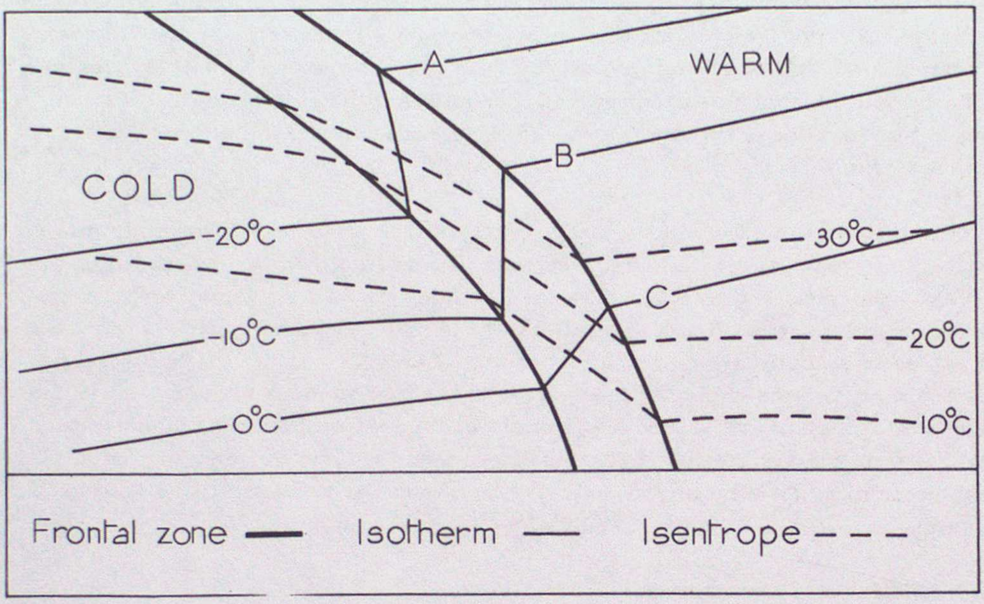


FIGURE 4.5 *Drawing of a frontal zone with discontinuities at the boundaries*

In Figure 4.5, the drawing of isotherm A at the front corresponds to an inversion on the tephigram, B to an isothermal layer, and C to a slow decrease in temperature with height.

The remaining important feature of the temperature field is the tropopause. The pressure at the tropopause is reported in upper air messages, and the position of the tropopause can be marked on the section. Where the tropopause is roughly horizontal it is usually well marked, but in regions where it has a pronounced slope, its exact height cannot always be identified with certainty, and it may not exist as a clear-cut discontinuity. It may be more correct to draw separate tropopauses at different levels (as shown in Figure 7.31 of Chapter 7). Figure 4.6 shows how isotherms and isentropes should kink at the tropopause. Again the kinks are in opposite senses.

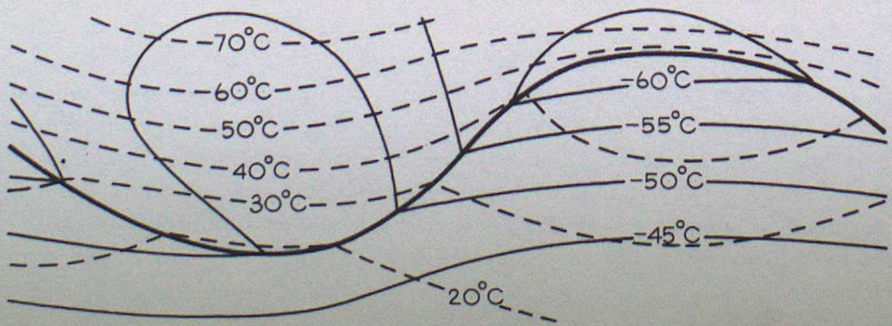


FIGURE 4.6 *Isotherms (——) and isentropes (- - -) at the tropopause (——)*

Further Methods of Analysis

Figure 4.7 is a north-south cross-section through a well marked cold front which lay along the north French coast on 11 January 1955, and shows an analysis of temperature (black lines) and potential temperature (green lines). The baroclinity is clearly concentrated on the frontal zone, though the warm air above the front is also slightly baroclinic; the cold air is almost barotropic. On this occasion the frontal surface extended right up to the tropopause, but this is not the only configuration possible. The frontal zone may bend back to the earth's surface to cut off a dome of cold air or may become indeterminate at a level below the tropopause.

When those parts of the cross-section that lie between upper air ascents are being drawn, care should be taken to ensure that the isotherms and isentropes are mutually consistent, and therefore intersect at the correct pressure level (the value of which is readily obtained from a tephigram). The two sets of lines should be adjusted as necessary until a coherent picture is obtained.

4.3.3. *Analysis of humidity*

There is a choice of several parameters which can be used to analyse humidity on a vertical cross-section, the most useful being depression of dew-point, humidity mixing ratio or wet-bulb potential temperature. In general, humidity patterns will be more complicated than temperature patterns, and often small centres and large gradients of humidity will be present. Freeman[6] has given some striking examples of this in an analysis of some fronts investigated by the Meteorological Research Flight.

Depression of dew-point is most useful in delineating regions of dry air; such regions often occur in the upper parts of frontal zones. Figure 10.4 in Chapter 10 shows a humidity analysis for the same situation as is depicted in Figure 4.7. No difficulties will be found in drawing isopleths of dew-point depression using the normal techniques of scalar analysis. If sufficient data are available it is convenient to depict cloud formations and precipitation on the humidity cross-section. Isopleths of relative humidity would show a pattern rather similar to that for dew-point depression, but as relative humidity is not easily obtainable from a tephigram, it is a less convenient parameter.

Humidity mixing ratio is a good measure of absolute humidity and also shows up dry regions graphically. In Figure 4.8 the black lines are isopleths of humidity mixing ratio; an approximately logarithmic scale is required for this parameter and the values chosen (0.1, 0.2, 0.5, 1, 2, 4, 8 gm/kg) form a convenient set. Away from the frontal zone the humidity lines are roughly horizontal with the cold and warm air masses clearly distinguished; for instance, the 0.5 gm/kg line is near 700 millibars in the cold air and near 450 millibars in the warm air. In the frontal zone the dry region has resulted in considerable distortion in the humidity lines and the pattern suggests that the patch of 0.2 gm/kg air at 800 millibars probably subsided from about 500 millibars. If isopleths of dew-point were drawn they would exhibit a similar pattern to those for humidity mixing ratio.

Wet-bulb potential temperature is a more conservative parameter than many and is valuable in air-mass analysis. Values at selected points can be derived from the tephigram without difficulty. At temperatures below −40°C humidity is not normally reported, but at these temperatures the moisture content of the air is then so low that no appreciable error results in assuming that the air is saturated.

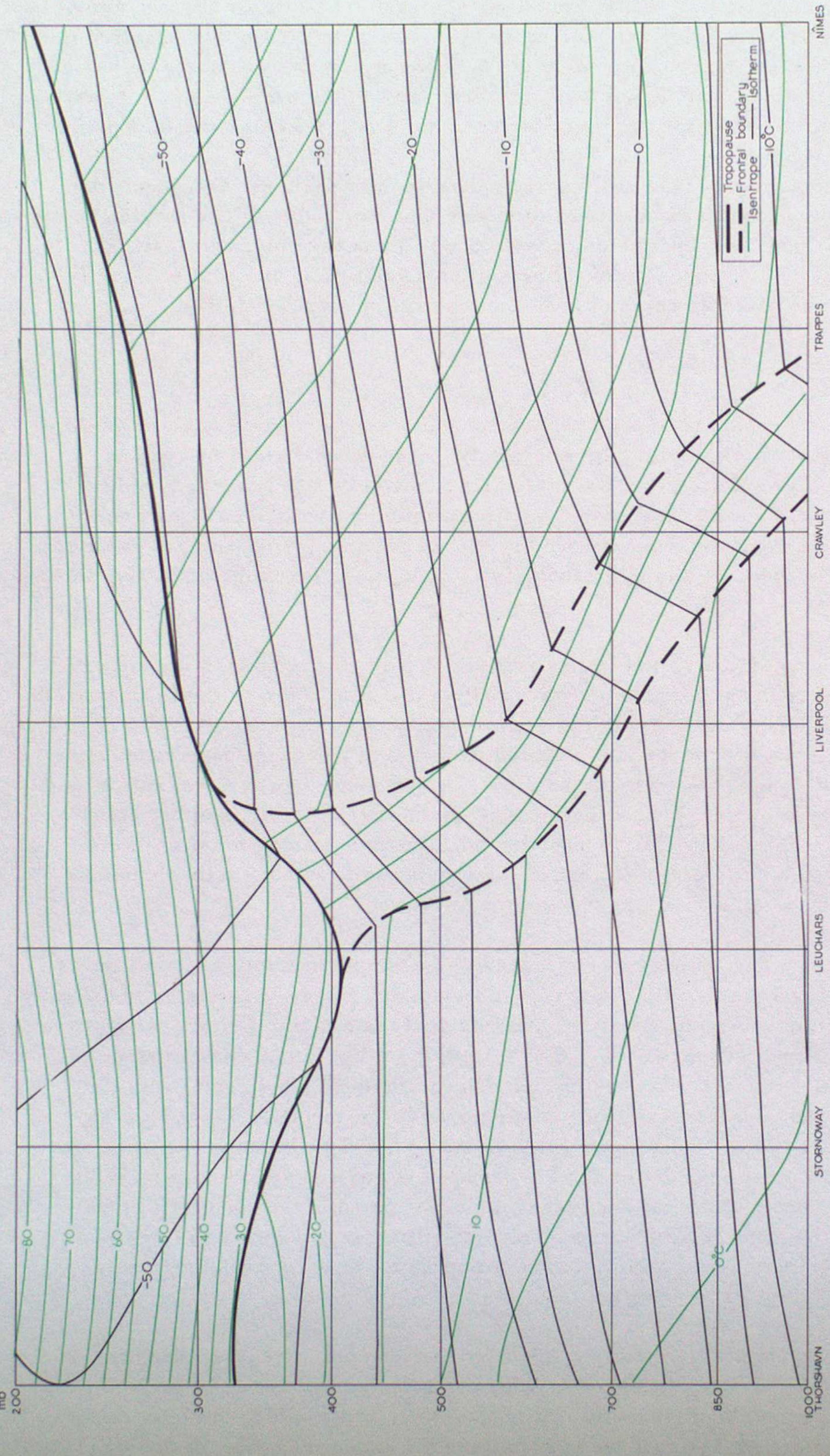


FIGURE 4.7 *Vertical cross-section of the atmosphere from Thorshavn to Nîmes showing temperature and potential temperature, 1400 G.M.T., 11 January 1955*

FIGURE 4.8 *Vertical cross-section of the atmosphere from Thorshavn to Nîmes, showing wet-bulb potential temperature and humidity mixing ratio, 1400 G.M.T., 11 January 1955*

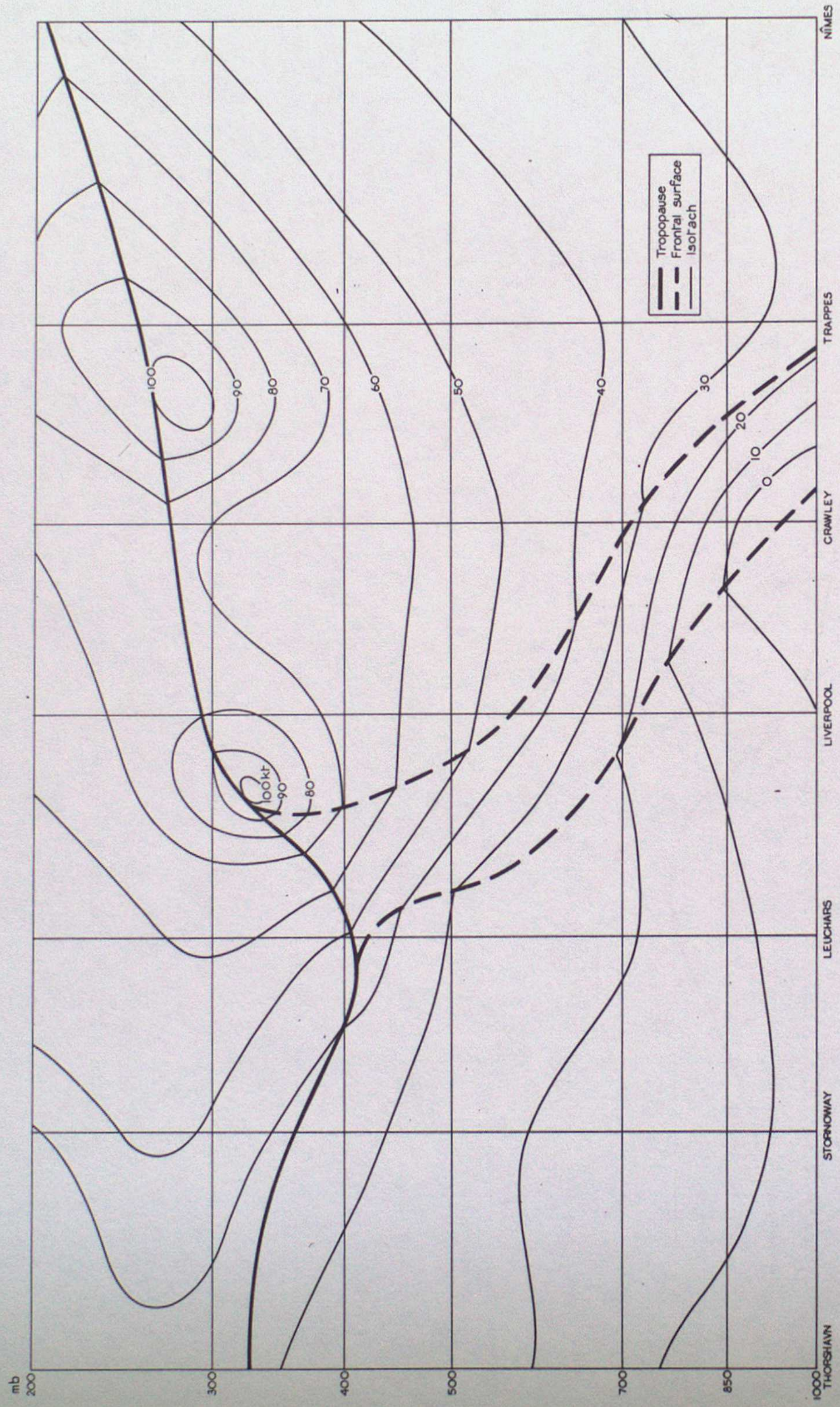


FIGURE 4.9 ***Vertical cross-section of the atmosphere from Thorshavn to Nîmes, showing isotachs of wind speed perpendicular to the plane of the section, 1400 G.M.T., 11 January 1955***

At such low temperatures there is an approximate one-to-one correspondence between wet-bulb potential temperature and potential temperature and the two sets of isopleths are parallel to one another. In the stratosphere and upper troposphere, this will normally be the case, as can be seen by comparing Figures 4.7 and 4.8. The concentration of wet-bulb potential temperature lines along a frontal zone is more marked than is the case for isentropes, while in the lower troposphere away from fronts, the wet-bulb potential temperature varies little within an air mass; hence its value in analysis. This feature shows up well in Figure 4.8. Where the wet-bulb potential temperature lines do cross discontinuities, the kinks will be in the same sense as those on isentropes.

4.3.4. *Analysis of wind*

The analysis of wind on vertical cross-sections is usually carried out by drawing isopleths of wind speed (isotachs) perpendicular to the plane of the section. After the component in this direction of each reported wind has been computed and plotted on the section, the analysis is straightforward.

Figure 4.9 shows the wind analysis for the same situation as is depicted in Figures 4.7 and 4.8. If the frontal boundaries and tropopause are drawn as discontinuities then kinks should be drawn in the isotachs as shown in Figure 4.9. The sense of the kinks is the same as that in the isentropes. Since a frontal zone is shown by a rapid transition in temperature it will also be a region of marked wind shear and the isotachs will tend to be concentrated along the line of the frontal zone. The jet-stream core will normally show up as one or more closed isotachs surrounding a maximum in the wind speed. The situation on 11 January 1955 (shown in Figure 4.9) is somewhat unusual in having a double jet stream. One core appears in the usual position, in the warm air near the tropopause and above the upper end of the frontal zone. There is also a second jet in the upper troposphere above the surface position of the front. This jet is associated with the moderate baroclinity which was present in much of the region above the main frontal zone.

If observed winds are lacking or sparse an analysis can be made of the geostrophic wind component normal to the section. This might be done by drawing isopleths of contour height of the pressure levels, but these lines are so nearly horizontal that this form of analysis is impracticable. However, if the departure of the contour heights from the ICAO standard atmosphere, that is, the *D* factor, is plotted a straightforward analysis can be carried out. Use can be made of analysed constant pressure level charts to provide supplementary data at those levels between sounding stations. The geostrophic wind normal to the section can be found by using an ordinary geostrophic wind scale (for suitable latitude and chart scale) to measure the gradient of the *D* lines along a pressure level. Winds can be measured at numerous points and entered on the section, and isotachs can then be drawn. Although in the free atmosphere the geostrophic wind is a good approximation to the actual wind, the two are rarely identical and differences are to be expected between the patterns of the isotachs for the two sets of winds.

Matthewman[7] has devised a scale for computing the geostrophic wind normal to a cross-section from the slopes of the isentropes. Full directions for constructing and using the scale are given in the article.

4.3.5. *Time sections*

A variant of the vertical cross-section which is sometimes useful is the time section. In this the vertical axis represents height or pressure on a logarithmic scale and the horizontal axis refers to time instead of distance. The technique of time-section analysis is more valuable in tropical regions or other areas of sparse data than in temperate latitudes with adequate networks, but even here the occasional preparation of a time section can be instructive, in that it displays graphically the continuity of the changes that are taking place in the atmosphere.

As with line cross-sections, a wide variety of parameters can be analysed on time sections and the techniques for both are very similar. For wind, however, the component of the wind normal to the section obviously cannot be used, and on time sections the observed wind speed and wind direction are best analysed directly by drawing isotachs and isogons (lines of equal direction) respectively. The remarks in Section 4.1 on isogon analysis apply also to time sections. If the time section is primarily concerned with parameters other than wind and isopleths of wind are not going to be drawn, a good method of displaying the wind on the section is by plotting wind arrows and feathers according to normal conventions and taking the upward vertical as north.

In temperate latitudes where the motion of weather systems is predominantly from west to east it is best to prepare time sections with the time axis increasing from right to left. Warm and cold fronts will then appear on the section sloping the customary way. A crude indication of cloudy areas can be obtained by shading the regions of the section where humidity is high (dew-point depression is less than 3°C say,) but there will obviously be many discrepancies. Surface and aircraft observations can be used to add some precision to the cloud picture. The passage of upper troughs and ridges is of interest and some form of pressure (or contour-height) analysis may be required. Isopleths of the *D* factor are probably best for this, or 12-hour pressure-height changes can be plotted. The inclination to the vertical of the axis of upper anticylones and depressions often shows up graphically on vertical sections.

The suggestions made in the foregoing paragraphs do not exhaust the possibilities of representing the weather on vertical-section charts. Other parameters can be used and a variety of methods of pictorial representations can be devised to suit particular problems and situations. Cross-sections are commonly used for the presentation of forecasts and forecasters will find the preparation of sections using synoptic data an instructive exercise.

4.4. FRONTAL CONTOUR CHARTS

4.4.1. *Construction of frontal contour charts*

The three-dimensional structure of frontal surfaces can be depicted by the frontal contour chart. This consists of a base map on which are drawn a series of lines showing the position of the intersection of the frontal surface with selected pressure surfaces. Contours for the standard levels, namely 1000, 850, 700, 500 and 300 millibars, will normally be drawn and these may often usefully be supplemented by 600 and 400 millibars. The upper boundary of the frontal zone, that is, the lower limit of the warm air mass, is usually taken as defining the frontal surface.

Further Methods of Analysis

The tephigrams for all relevant upper air ascents should first be examined and the upper limit of the frontal zone determined on each. Where the front is well marked this will not be difficult; there will be a much more stable lapse rate in the frontal zone than in the warm air above. Wet-bulb potential temperature is one of the best air mass markers, and the wet-bulb potential temperature in the warm air near the front should be noted; this value can be expected to be roughly the same on each ascent. This fact can be used to ensure that the same front has been selected on each ascent and also as an aid in locating the frontal boundary on ascents where the change in lapse rate is not well marked. The effect of latitude and land and sea surfaces will, however, tend to introduce gradual spatial changes in the wet-bulb potential temperature representative of the air mass. The values of the pressure at the frontal boundary and the wet-bulb potential temperature at this level should be plotted on the base chart for each upper air ascent that intersects the frontal surface.

Instead of the wet-bulb potential temperature, the saturated wet-bulb potential temperature (the value of the saturated adiabatic through the dry-bulb temperature) may be used to mark the air masses. At higher levels it will differ little from the wet-bulb potential temperature (because of the low saturation vapour pressure) but lower down marked subsidence can produce significant differences between the two.

Hodographs can be used as an aid to frontal contour analysis. The vertical wind shear through a baroclinic zone is parallel to the associated front. The direction and magnitude of the wind shear through the frontal zone should be plotted on the base map for each upper wind ascent. Steep cold fronts should be well defined on the hodograph, but may not show up so clearly on the tephigram. Conversely shallow warm fronts will be delineated better by the tephigram than by hodograph.

Vertical cross-sections can be used to pinpoint the position of the selected frontal contours along the lines of the sections. The surface position of the front should be marked on the map and the frontal contours drawn to fit the plotted data. The contours as drawn define the position of the front at various upper levels and in order to ensure consistency these frontal positions should be entered on the appropriate upper air contour chart, where the position of the front should fit troughs in the contours and differences in temperature in the two air masses. The position should also be consistent with advection from the previous chart. By making use of all the various upper air charting procedures a coherent and detailed picture of the structure of the frontal systems can be built up.

4.4.2. *Features of frontal contour charts*

A frontal contour chart for 3 December 1960 is shown at Figure 4.10, and the corresponding 1000–500-millibar thickness chart at Figure 4.11. The differing slope of the surface at various parts of the front shows up clearly. Along the cold front from the Baltic to the Balearics there is a steep slope whereas along the warm front from Portugal to Ireland the slope is smaller. The slope of the slow-moving cold front over the Atlantic is also small.

In addition to the regions of fairly even slope, frontal surfaces may develop cold domes and warm pools. Figure 4.10 shows an incipient cold dome over the Pyrenees, being formed by the more rapid advance of warm air over France than over Spain. On this occasion the cold dome was only a transitory feature and fairly quickly warmed out. Had it been farther south and larger it might well have persisted as a cut-off

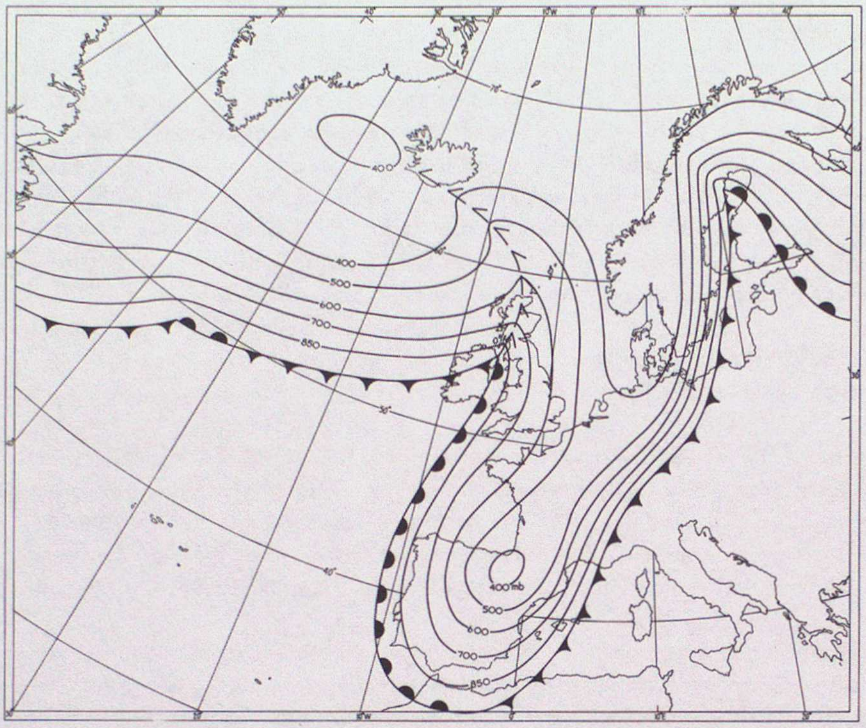


FIGURE 4.10 ***Frontal contour chart, 0001 G.M.T., 3 December 1960***

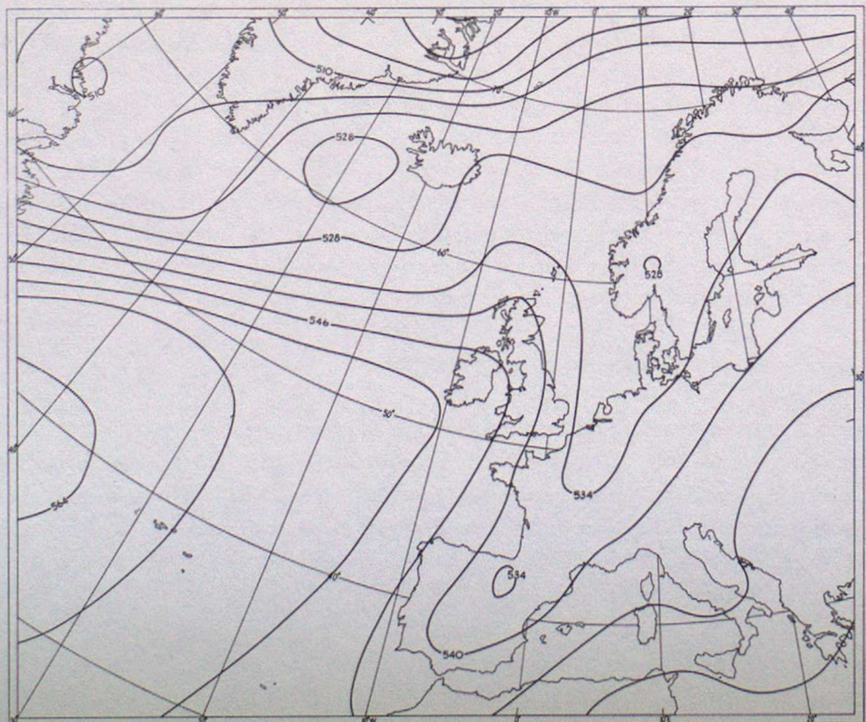


FIGURE 4.11 ***1000-500-millibar thickness chart (decametres)***
0001 G.M.T., 3 December 1960

feature after the wave over Ireland had passed away to the east. The profile of a front during the early stages of the formation of a cold dome is shown in Figure 4.12. Godson[8] and Crocker[9] and others give good descriptions of the formation and dissolution of cold domes.

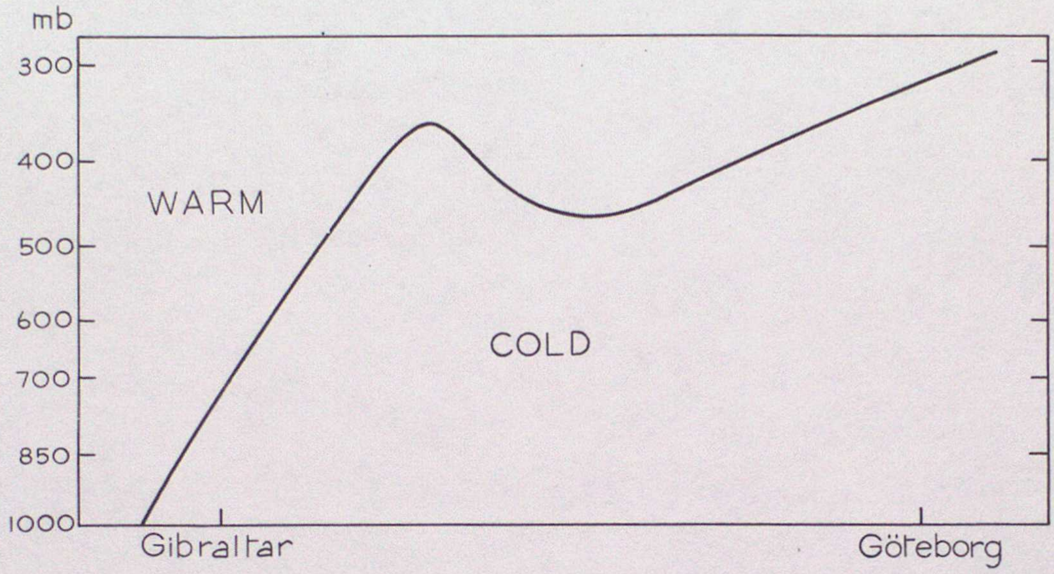


FIGURE 4.12 *Vertical section from Morocco to Denmark on 3 December 1960, showing frontal surface with a small cold dome*

Warm pools can be formed in an analogous way. On 3 December 1960 a small warm pool had been cut off near Iceland by cold air sweeping eastwards south of the slow-moving depression which was centred to the west of Iceland. The presence of cold domes or warm pools will mean that upper air charts on which frontal positions have been drawn may have a somewhat unfamiliar appearance. The chart for 400 millibars on this occasion is shown at Figure 4.13. The cold dome and warm pool appear as detached closed fronts.

Frontal contour analysis has been much used in Canada and the analysts there have found that at any rate in their area the structure of occlusions rarely shows a significant difference between the two cold air masses at the surface. The important feature is the "trough of warm air aloft", for which the abbreviated title of "TROWAL" has been given. On Figure 4.10 a TROWAL extending from Scotland to Iceland has been marked by a series of inverted ticks. It is the line joining the crests of the frontal wave at the various upper levels. A TROWAL is an upper front; its passage is often marked by a positive pressure tendency discontinuity at the surface and a change in precipitation from a frontal to a showery type with a clearing of upper cloud. There may be little temperature change at the surface. Harley[10] has described a trowal which moved south-eastwards across the British Isles when there was nothing but arctic air at the surface.

Frontal contour charts have not been extensively used in the United Kingdom, but they can be a valuable tool in conjunction with other methods of analysis in carrying out a detailed investigation of an interesting synoptic situation. The 1000-500-millibar thickness chart bears a good deal of resemblance to the frontal contour chart, as may be seen by comparing Figures 4.10 and 4.11, and for day-to-day use the thickness chart alone will generally be considered adequate.

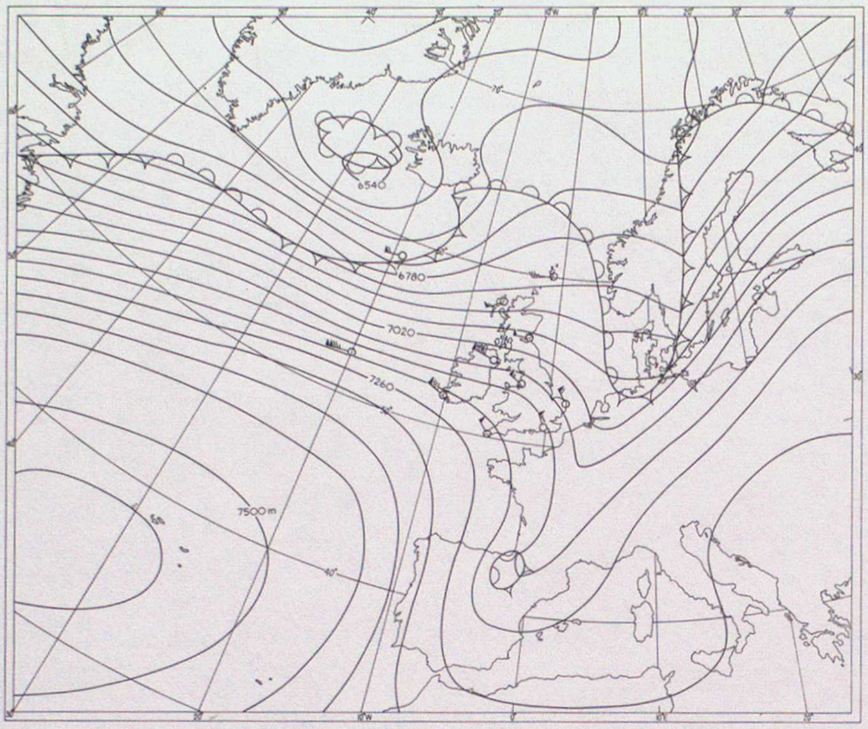


FIGURE 4.13 *400-millibar contour chart, 0001 G.M.T., 3 December 1960*

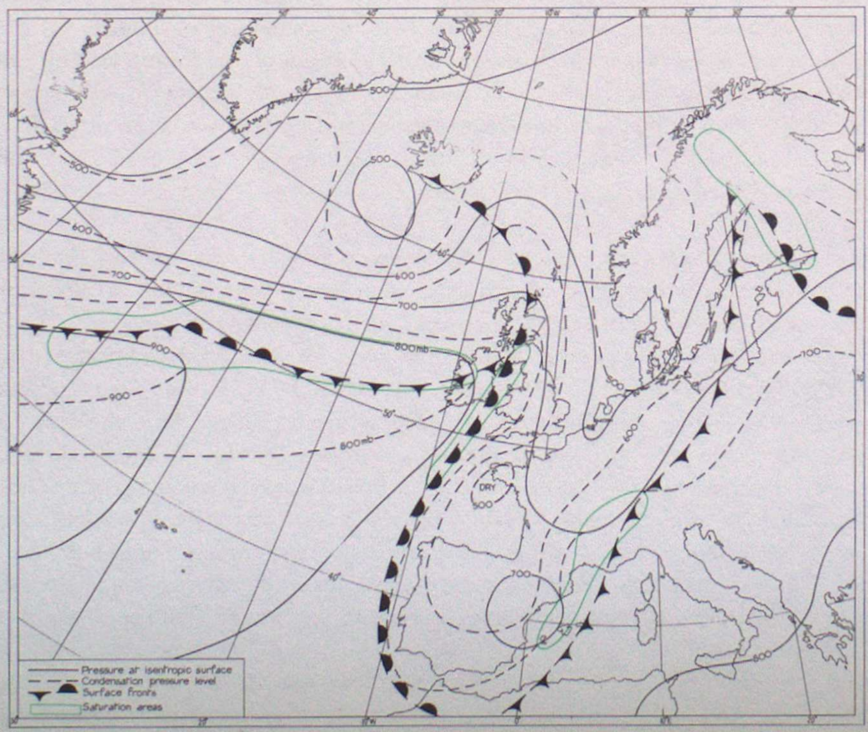


FIGURE 4.14 *Isentropic chart for 20°C, 0001 G.M.T., 3 December 1960*

4.4.3. *The three-front model*

In an attempt to maintain greater continuity of frontal analysis in space and time, Canadian meteorologists have developed the "three-front" model, which has been described by Anderson, Boville and McClellan[11] and Galloway[12,13,14]. For the extratropical regions of North America and the North Pacific and Atlantic Oceans four air masses separated by three fronts are recognized. They are listed in Table 4.1 together with typical values of wet-bulb potential temperature (θ_w), which are quoted from a paper by Penner[15]. A much more detailed classification applicable to the British Isles has been given by Belasco[16] and is quoted in Section 14.8.1.

TABLE 4.1

Front	*Air mass*	*Wet-bulb potential temperature (range for mid-troposphere)* *Winter*	*Summer*
	Maritime tropical (mT)	13°-18°C	15°C
Polar (P)			
	Maritime polar (mP)	8°-12°C	10°-14°C
Maritime (M)			
	Maritime arctic (mA)	2°-7°C	4°-10°C
Arctic (A)			
	Continental arctic (cA)	2°C	4°C

Fronts are defined as baroclinic zones associated with a discontinuity in gradient of temperature and wind. They are continuous in space and time though the intensity may vary. Even though the front is diffuse at the surface and possibly has little in the way of cloud or precipitation to identify it, the presence of warm air aloft to the north confirms its existence and justifies its continuance in the analysis. Short-lived features such as a line of rain not associated with an air-mass boundary are not marked as fronts. Nevertheless frontolysis and frontogenesis elsewhere do occur and the analysis is then modified accordingly. Often a vigorous disturbance will draw two of the fronts into its circulation resulting in large temperature contrasts and varying interactions between the fronts. For instance, the trowal of the polar front may produce a trough in the warm sector of the maritime front. Penner[15] and Godson[17] give other examples.

4.5 ISENTROPIC ANALYSIS

4.5.1. *Construction of isentropic charts*

An isentropic chart shows the state of the atmosphere on a surface of constant potential temperature. Except for non-adiabatic processes such as condensation or radiation, air particles will remain in an isentropic surface. The motions of the air masses can be followed on the chart if they can be identified by some other conservative parameter. Absolute humidity which is fairly conservative, is used for this purpose and the movement of the moisture pattern is charted.

The level chosen for the isentropic analysis will usually be as low as possible so as to include a large range of humidity values, but such that it is above the friction layer. If a series of analyses are to be made a level should be chosen which can, if possible, be used throughout. Seasonal changes will, of course, be necessary. In Figure 4.14, which shows a winter situation, a potential temperature of 20°C has been used. In summer, 40°C might be more suitable; the isentropic surface will slope upwards from near the ground in warm regions and may reach the tropopause in cold areas.

The complete analysis of an isentropic surface requires three series of lines to show pressure, humidity and a "stream function". These data can be obtained from a tephigram and should be plotted for each upper air station.

4.5.2. *Pressure contours on isentropic charts*

The pressure at which the selected isentrope intersects the ascent curve can be read directly from the tephigram. The drawing of the isobars on the chart may be aided if isotherms have been drawn on the normal constant pressure upper air charts. On an isentropic surface pressure lines are also lines of constant temperature (and density); on the 20°C isentropic surface the 700-millibar isobar is also the (approximate) – 8°C isotherm. Hence the –8°C isotherm, on the 700-millibar constant pressure chart is also the 700-millibar isobar on the 20°C isentropic surface. Appropriate values for other pressures and potential temperatures can readily be obtained from a tephigram. Isobars will be parallel to the vertical shear of the geostropic wind through a slice of the atmosphere centred on the isentropic surface. If hodographs of the observed winds are available they may be used to obtain estimates of the wind shear and so aid the drawing of the isobars. Spilhaus[18] has shown that the spacing of the isobars is inversely proportional to the shear-stability ratio but the computation of this parameter for routine use is somewhat laborious. The surface positions of fronts should be marked on the isentropic chart as they can be of assistance in drawing the isobars. These will tend to be parallel to vigorous fronts and will be closely packed behind a strong cold front or ahead of a strong warm front. If the data show that isobars cross the front or are widely spaced on the cold side of it, the front may be expected to be weak or frontolysing. The general similarity in the shape of the isobars in Figure 4.14 and the frontal contours in Figure 4.10 (both relate to the same occasion) may be noted.

4.5.3. *Humidity on isentropic charts*

The second set of lines on an isentropic chart depicts humidity. Humidity mixing ratio may be used, but a more useful parameter is the condensation pressure. This is the pressure at the level to which air on the isentropic surface would have to be raised for it to become saturated; the value may be readily obtained from the tephigram. The proximity of the pressure (p) lines and the condensation pressure (p_c) lines on the chart gives an indication of the degree of saturation. Regions where the air is saturated should be shaded; the p and p_c lines will be coincident in these areas and departures from isentropic motion will occur. At higher levels radio-sondes rarely record 100 per cent humidity, even where cloud can be assumed to be present. Differences between p and p_c of 20 millibars or so may often be interpreted as relating to saturated air. The condensation pressure lines are also lines of constant humidity mixing ratio and lines of constant wet-bulb potential temperature. The pattern of the humidity lines will usually show tongues of moist and dry air and the ease with which the movement and development of these tongues can be followed is one of the advantages of isentropic analysis. Common configurations are for large anticyclonic eddies of moist and dry air to form, and a moist tongue to branch at an occlusion. Namias gives a detailed discussion of isentropic moisture patterns in a chapter in the first edition of a book by Petterssen[19] (Chapter VIII, p.351). Moist tongues tend to be associated with warm air from the south and dry tongues with cold air from the north. In winter they often do little more than reflect the differences in height on the isentropic surface, the dry air being associated with ridges in the surface and the moist air with troughs. This weakness of the method is less pronounced in summer especially in continental areas when a greater variety of moisture patterns can be found at low levels.

4.5.4. *Wind on isentropic charts*

Knowledge of the wind flow on the isentropic surface is important and observed winds at the appropriate levels should be plotted on the chart. Montgomery[20] devised a "stream function" such that its isopleths bore the same relation to the geostrophic wind on the isentropic surface as height contour lines do on constant pressure maps. The form given for the stream function, ψ is

$$\psi = c_p A + \Phi$$

where A is the absolute temperature, Φ is the geopotential and c_p the specific heat of air at constant pressure. A more practical parameter can be obtained by dividing the stream function by g. In Figure 4.15 the isopleths drawn are those for Ψ defined by

$$\Psi = \frac{c_p}{g}T + z = 102.3T + z$$

where T is the temperature (in degrees Celsius) on the isentropic surface and z is the height of the isentropic surface in metres. The units of Ψ are also metres and

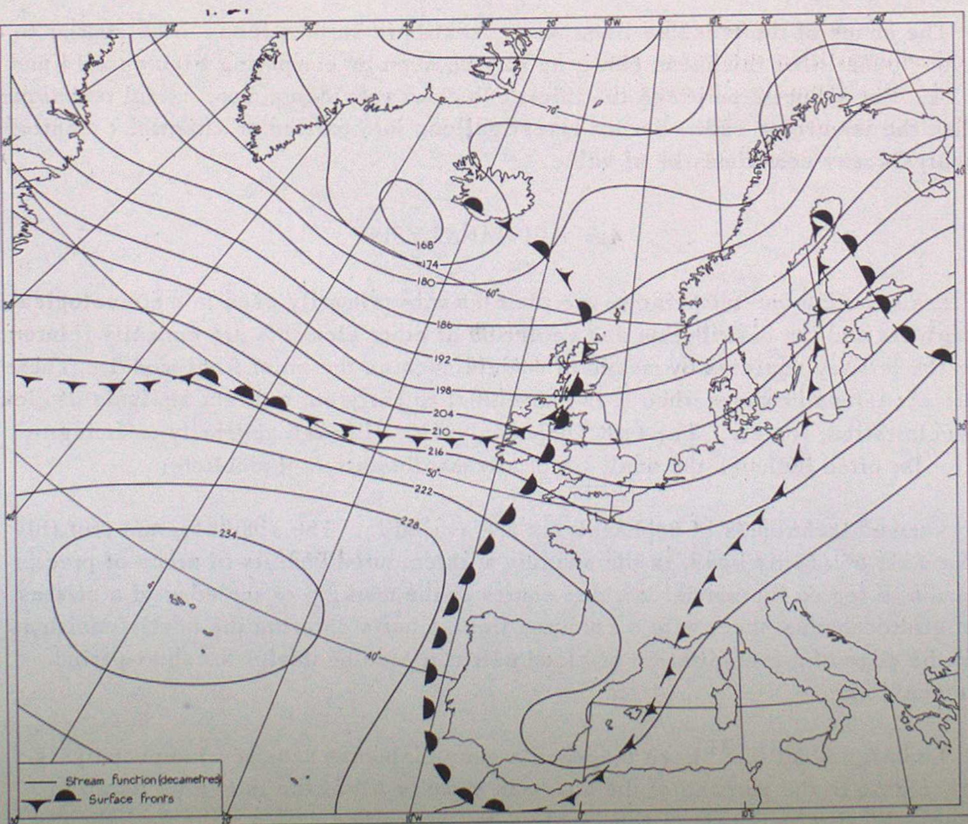


FIGURE 4.15 *Isentropic chart for 20°C showing stream function, 0001 G.M.T., 3 December 1960*

the normal geostrophic scales can be used on the Ψ-lines in exactly the same way as they are used on height contours on constant pressure charts. T can be read directly from the tephigram and z can be obtained after a little calculation by adding the thicknesses of successive layers.

The wind flow on the isentropic surface can give some indication of vertical motion and hence can be of value in forecasting precipitation or cloud clearances by subsidence. If the isentropic surface were stationary, a wind blowing from high pressure to low on the isentropic surface would be accompanied by ascent and vice versa. In general the isentropic surface is itself moving and the motion of the air is not then parallel to the isentropic surface. However where the wind is strong it is probable that the displacement of the isentropic surface will be at a lower speed than that of the air and the relative motion will still produce ascent when the winds blow towards lower pressure on the isentropic surface.

4.5.5. *Usefulness of isentropic charts*

Isentropic analysis was used extensively in America during the early 1940s, and many of the parameters required were included in coded upper air messages, but this practice ceased in about 1945. The time required to construct an isentropic chart and the consequent delay in its completion restrict its value as a synoptic tool, though some forecasters have found that charts for a limited area can be drawn sufficiently quickly and can be of value in forecasting convectional activity which can be much dependent on moisture patterns. However, convection with its associated condensation and precipitation is not a dry-adiabatic process and thus introduces a non-conservative element into the analysis.

The shape of the pressure lines on an isentropic surface tends to be similar to the 1000-500-millibar thickness chart, as may be seen by comparing Figures 4.14 and 4.11. For synoptic purposes the thickness chart provides a more useful technique than the isentropic chart, but for investigations into particular situations isentropic analysis may sometimes be of value.

4.6 NEPHANALYSIS

Pressure, wind and temperature are the elements primarily used in meteorological analysis and the distribution and evolution of other elements are normally related to the primary analysis by means of models such as the polar front model. There are occasions however when it is convenient to carry out a direct analysis of cloud, precipitation, fog etc. The term "nephanalysis", although generally referring to clouds, often includes the analysis of any manifestation of moisture.

Various techniques of nephanalysis are available. The simplest, and probably the most commonly used, is the shading with coloured pencils of areas of precipitation or fog on the normal working charts or the marking of the edge of a stratus or stratocumulus sheet with a coloured line. Charts showing the hourly positions of the edge of a precipitation or cloud belt can also be useful for short-period forecasting.

Ludlam and Miller[21] have proposed a more elaborate scheme of nephanalysis. According to the purpose of the analysis some or all of the isopleths listed in Table 4.2 can be drawn. Each isopleth can be marked with a suitable indicator and drawn with a distinctive colour or type of line.

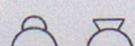
TABLE 4.2

Indicator used to label isopleth	*Colour*	*Isopleth*
0	Purple	Edge of region with cloudless skies
1*h*	Blue	Cumulus or cumulonimbus system, tops reaching *h* km
2*h*	Blue	Cumulonimbus system, tops reaching (10+*h*)km
3	Brown (pecked)	Edge of region of 5/8 or more stratocumulus
41	Brown	Edge of region of fog
42	Brown	Edge of region of 5/8 or more stratus
5	Red (pecked)	Edge of region of 1/8 - 4/8 upper cloud
6	Red (continuous)	Edge of region of 5/8 or more upper cloud
61	Red (continuous)	Edge of cirrus system
62	Red (continuous)	Edge of altostratus system
70	Green	Edge of precipitation system or nimbostratus
7*pp*	Green	Precipitation rate *pp* mm/hr
80	Green	Edge of shower system
8*pp*	Green	Shower precipitation, rate *pp* mm/hr (based on 15 min.period)
9*tt d*	Green	Severe storm region, maximum lightning discharge rate *tt*/min., maximum hailstone diameter *d* cm

All available information should be used, pilots' reports, reconnaissance flights, sflocs, radar presentation – all can help to complete a nephanalysis. In regions where normal observations are plentiful nephanalysis will not often add a great deal to the wide-scale analysis that will not be provided by conventional methods. In regions where quantitative data are sparse or unrepresentative, cloud observations may provide the most reliable basis for analysis and prediction.

This is the situation in many tropical regions and it is here that regular nephanalysis is most likely to be valuable. Palmer (and others)[1] have described a slightly different technique to Ludlam's. Upper cloud is delineated in a somewhat similar way; solid lines are used for the edge of 5/8 or more and pecked lines for smaller amounts, but different colours are used for high and medium clouds and the regions of medium clouds are shaded in the appropriate colour. The distribution of low cloud, showers, thunderstorms and rain is, however, shown by scattering suitable symbols in the relevant areas. Varying amounts of the symbols are blacked in to indicate the amount of cloud cover. A possible set of symbols is shown in Table 4.3.

TABLE 4.3

	1/8 – 3/8	Sc or St		1/8 – 3/8	Large Cu or Cb
	4/8 – 6/8	Sc or St		4/8 – 6/8	Large Cu or Cb
	7/8 – 8/8	Sc or St		7/8 – 8/8	Large Cu or Cb
	1/8 – 3/8	Small Cu			
	4/8 – 6/8	Small Cu			

The labour of marking the symbols on the chart is considerable unless a set of rubber stamps is available. When carefully analysed such a chart provides a graphic representation of the weather and can be valuable for briefing aircrews.

Both techniques have advantages and disadvantages and the complexity of Ludlam's numerous isopleths must be weighed against the labour and subjectivity of Palmer's scattered symbols. The methods which have been briefly described should however provide ideas from which individual forecasters can develop nephanalysis techniques suited to their particular needs.

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