CHAPTER 6

DEPRESSIONS AND RELATED FEATURES

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6.1 INTRODUCTION

A knowledge of the types of weather associated with various atmospheric circulation systems is essential both as an aid in the process of analysis and in the interpretation of prognostic charts to give the final product - the weather forecast. If the forecast period is short compared with the time-scale of synoptic developments in the area of interest, forecasts can often be made mainly on the basis of the latest observations and physical reasoning, but forecasts for more than a few hours ahead must depend to a large extent on a knowledge of the weather which has accompanied similar synoptic situations in the past. This is particularly true of depressions and troughs, since both synoptic development and weather changes may be very rapid.

The above statements are still essentially true in spite of the advances which now enable computerized models of the atmosphere to predict broad-scale cloudiness and precipitation, and they will probably remain so for many years, particularly for the detailed requirements of local weather forecasting.

The feature common to all types of depression is a region of ascending air, with divergent flow aloft and convergent flow in the lowest layers of the atmosphere. In most depressions of temperate latitudes the ascent of air is a result of baroclinic instability in the region of the polar front (see Chapter 5 - Fronts and frontal weather). The baroclinic instability is also an important factor in the development and amplification of the upper wave system which itself largely determines the formation and development of surface features. The favoured locations for frontal depressions are between an upper trough line and the next ridge line downstream, and in the right-entrance and left-exit areas of jet streams (see Chapter 2 - Dynamical ideas in weather forecasting). Other types of depression may be thermal in origin, the ascent of air being brought about by surface heating (polar lows, heat lows), or may be a result of topographical influences on the airflow (orographic lows). The compartments are not rigid, however, there often being some thermal and orographic influences at work in a frontal depression, while there is evidence of baroclinic instability in the lower troposphere in at least some polar lows.

6.2 FRONTAL DEPRESSIONS

The first attempts to depict the typical weather features associated with depressions was made in the late nineteenth century. At this time, some degree of forecasting success had been achieved from the realization that depressions moved and that certain types of weather were often associated with certain parts of the depression. Further detailed studies revealed the life cycle of frontal depressions and led to the polar-front model of Bjerknes.[1] The model has been illustrated and discussed in many text-books, and needs little comment here.

However, no long forecasting experience is needed before it is realized that most frontal depressions differ from the model to a greater or lesser extent. The model describes best those depressions which approach the longitude of the British Isles from the south-west, but is usually markedly less successful with those depressions which have been over land for any length of time. Nevertheless, the model is a useful concept: it is simple, and it is of value as an aid in the identification of frontal systems during analysis. The extent to which the observed distribution of weather varies from that of the model may provide helpful indications of how the weather might deviate from the model in the future, although a great deal of care must be exercised in using the model in this way, particularly if rapid developments are occurring or likely to occur. Upper-air charts and computer analyses and prognoses should be studied for indications of likely development areas.

The availability of satellite photographs, depicting the cloud from above has increased our knowledge and understanding of the cloud structures associated with depressions and other synoptic features, and has led to improvements in analysis and forecasting on a number of occasions.

The frontal depression usually starts life as a wave on a slow-moving front. As the amplitude of the wave increases, pressure falls and a cyclonic circulation develops with the tip of the wave near the centre of the circulation and near the region of lowest pressure. The circulation extends upwards from the surface layers as it intensifies. As the process of occlusion begins, 'squeezing' the warm air away from the surface, the rate of development often becomes slower until the depression reaches maturity and then begins to fill. The occlusion process is occasionally accompanied by the formation of a secondary low centre at the tip of the warm sector. Infrequently, a shallow low may form as a wave develops on the warm front, generally moving quickly along the warm front away from the main depression centre and not developing any marked circulation.

In suitable conditions, however, a wave may form on the cold front; sometimes minor waves or ripples form and move quickly without much development along the cold front towards the main depression centre. Most commonly however, a wave develops and forms a new depression. Depressions often appear in 'families': as earlier ones mature and decay, fresh ones start off as waves on the cold front and the process is repeated until finally cold air erupts through to low latitudes and the sequence comes to an end. The members of the family, usually from two to five in number, are separated by ridges of high pressure or by quickly-moving cold anticyclones (see Chapter 7 - Anticyclones and related features).

The life-cycle of a typical frontal depression is shown in Figure 1.

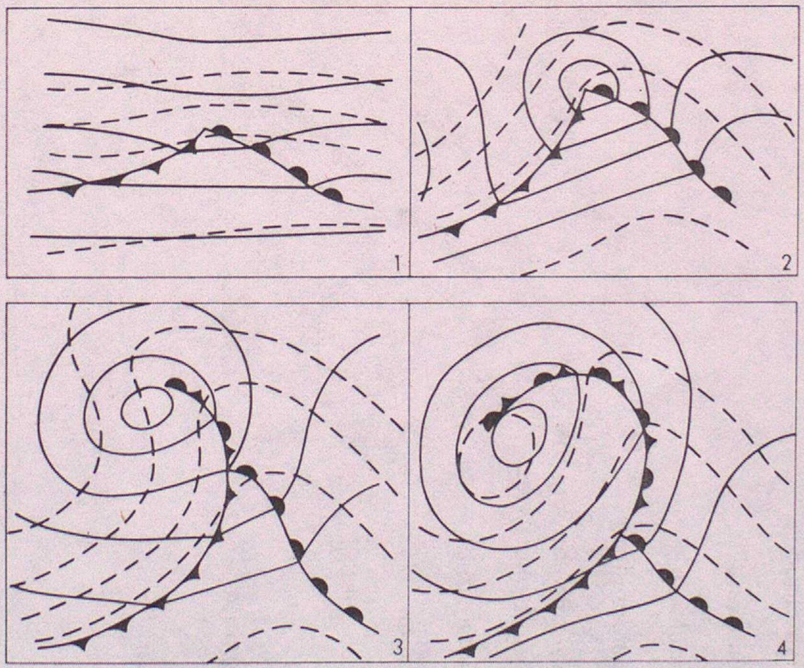


FIGURE 1. The development of a frontal depression

——— surface isobars – – – 1000–500 mb thickness

Figure 2 is a schematic nephanalysis, based on satellite photographs, showing the cloud structure, as seen from above, of two members of a typical

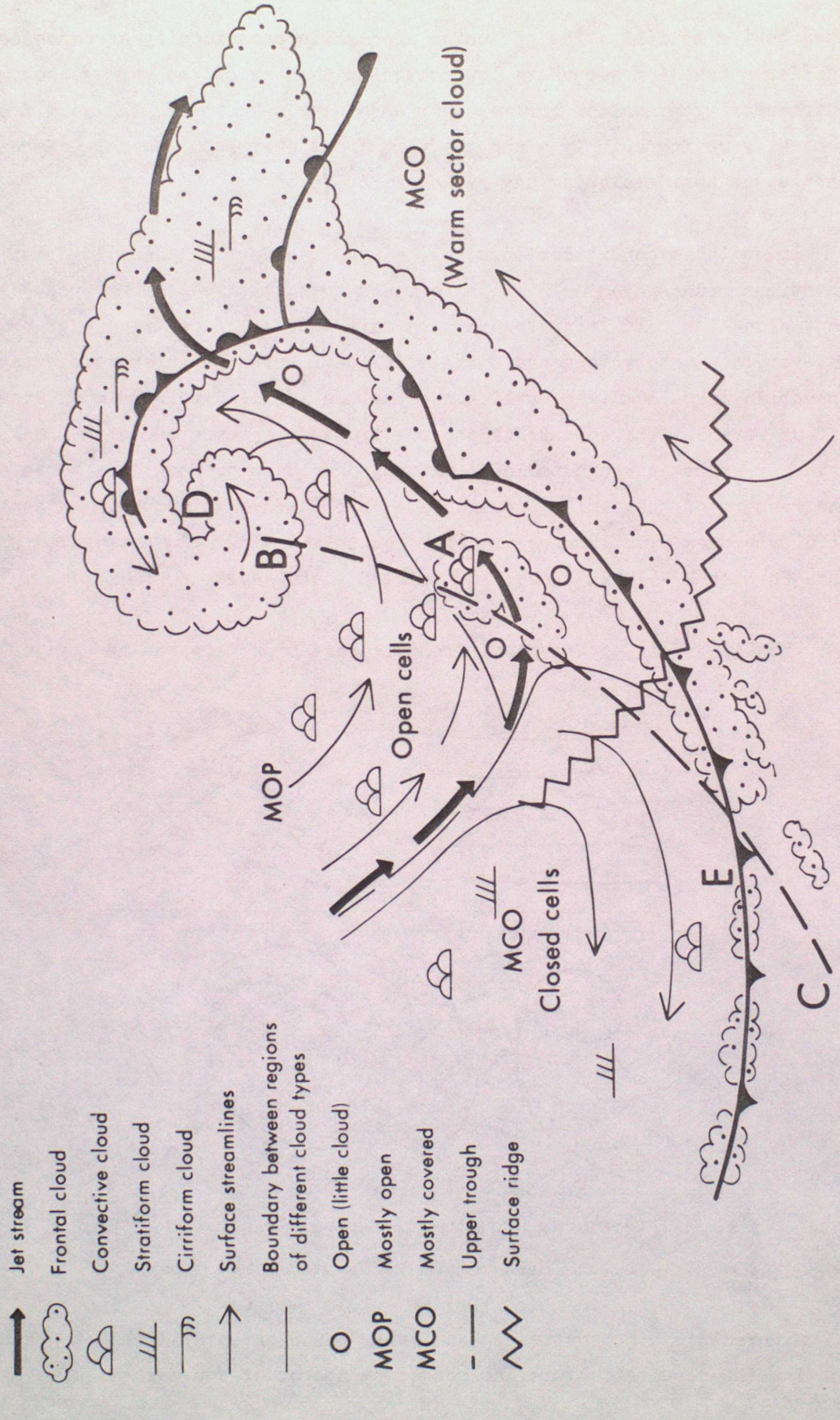


FIGURE 2. Schematic representation of cloud patterns associated with a family of depressions

family of depressions, one having reached the mature stage while the second is still in the open-wave stage. This diagram will be referred to fairly frequently in this chapter.

6.2.1 <u>The open-wave stage</u>

The slow-moving or quasi-stationary frontal zone is usually readily detectable by conventional surface analysis (Chapter 9 - Analysis of surface charts) and generally appears as a fairly narrow band of cloud on satellite photographs. The initial stage of wave formation is often more readily seen in satellite pictures than from surface observations, particularly from data-scarce oceanic regions. The wave often starts to form when an upper-level vorticity maximum develops in the cold air and approaches within five to nine degrees of latitude of the frontal zone. The upper-level vorticity maximum is indicated on satellite photographs by an area of enhanced cumulus development or comma-shaped cloud mass (A in Figure 2) ahead of an upper-level trough (B-C). At this stage the frontal cloud band broadens in the vicinity of the wave and a convex bulge develops towards the cold air. The surface position of the wave is under the bulge, near the point where the curvature of the rear edge of the cloud changes from convex to concave. No vortex pattern is yet evident in the frontal cloud, and there is a clear area between the 'comma' cloud and the front.

The details of the lower cloud structure are obscured on satellite pictures by the overlying clouds. The precipitation area associated with a 'typical' young depression is shown in Figure 3.

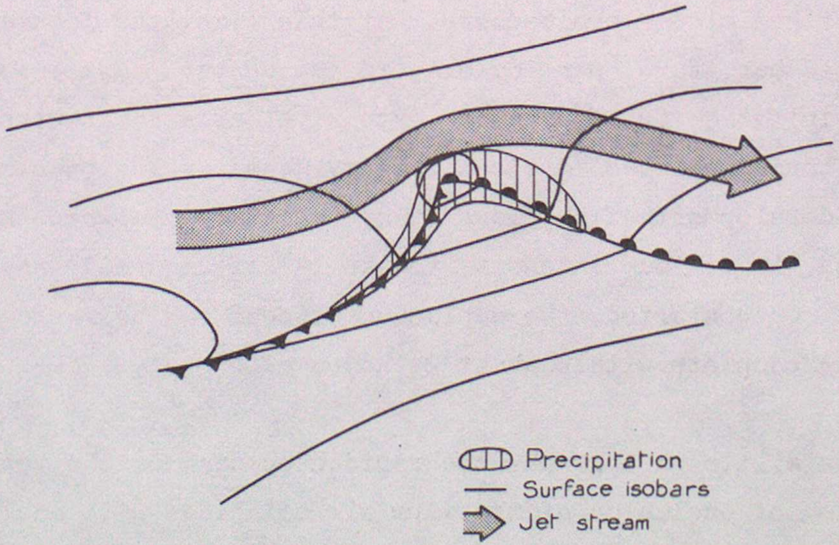


FIGURE 3. Schematic distribution of precipitation associated with a young wave depression

Most of the precipitation occurs in a band averaging some 400 kilometres wide along the track of the tip of the wave and in association with the fronts. Often the frontal precipitation is quite light at greater distances from the centre. A typical figure for the total precipitation at any point within the main band would be about 10-15 millimetres. In winter-time, when temperatures at low levels to northward of a depression are near or just below 0°C whilst those to southward are, at least initially, well above 0°C, the track of the depression may determine to a large extent whether precipitation in an area reaches the ground in the liquid or solid state.

Visibilities in the cold air mass are seldom poor. In some cases there may be hill and coastal fog in the warm air, more particularly close to the warm front. Continued development of the wave depression causes increased surface winds in its circulation and there is a tendency for any fog patches in the warm air to be lifted to low stratus. If the base of the low stratus remains very low (perhaps below 100 metres) then horizontal visibility beneath it will usually remain poor. If there should be any fog patches in the cold air due to night radiation ahead of the system, the freshening wind and formation or advection of cloud will usually lead to a fairly rapid clearance.

6.2.2 The occluding stage

The occluding stage is illustrated in (3) of Figure 1. The isobars show greater curvature than in open waves and the wind regime is of very well-marked cyclonic type not only at the surface but throughout much of the lower and middle troposphere. At this time, the fronts usually show pronounced curvature, particularly in the central parts of the depression. The precipitation is often quite extensive, as are also the areas of cloud, both in horizontal and vertical extent. When occlusion commences, the rate of development often slows down; shortly afterwards the depression may reach its maximum intensity (as in (4) of Figure 1) and then it begins to fill. Once started, the occlusion process may be rapid, often being virtually complete within about 24 hours of onset.

On satellite photographs the rapid deepening of the vortex and the initiation of occlusion of the warm air coincides with an increase in the concavity of the frontal cloud immediately to the rear of the wave, and a retraction of the upper cloud towards the warm air often occurs, revealing the lower cloud system of the occlusion. A clear area, the so-called 'dry slot', forms immediately behind the front, and the cloud system near the depression centre begins to take on a spiral appearance. The spiralling is not confined to the frontal cloud bands, but is also taken up by the cumuliform cloud lines in the cold air. The 'dry slot' remains intact as it is drawn into the vortex.

Strong subsidence is often present behind the cold frontal trough, giving rise to the 'dry slot' noted in the satellite photographs. Except when the cold front is a marked ana-front, medium and high cloud clears quickly from this region as the system moves away, and, unless the air is very cold or the underlying surface notably warm, a period without showers may follow. Heavy and frequent showers are likely as the cold air becomes deeper and less modified by subsidence, the maximum shower activity usually occurring just ahead of the axis of the associated thermal trough and to the north of the jet stream.

After occlusion commences many depressions tend to slow down, some gradually, others quite abruptly. In some cases the orientation and shape of the occlusion are fairly simple and the front may be followed systematically from chart to chart for many hours with little change in shape superposed on the pure translation of the front. In other cases the occlusion soon becomes distorted. Sometimes, under the influence of strong winds some distance from the centre of the depression, parts of the occlusion move quickly forward well in advance of both the centre and the triple point, where the gradient along the front may be weaker; it is sometimes extremely difficult to track and follow consistently the movement of such relatively old occlusions. In some such cases better forecasts may be obtained by dropping the distorted occlusion from both analyses and forecasts and treating those portions of the depression as non-frontal.

When deep depressions slow down and retain substantial pressure gradients some distance from their centres, the geometry of any occlusion often becomes complicated and the front distorted. It is clearly impossible to describe all generic shapes, but one effect, which is generally noticeable in the associated weather, is the spread of precipitation and cloud to the rear quadrants of the cyclone - notably that quadrant to the left of the track of the centre and, at times, also to those parts of the right rear quadrant which are nearer the centre. Over sea areas it is often difficult from the sparse observations to delineate such rainy areas accurately. The spread back of rain and low cloud is particularly noteworthy along the east coast of the British Isles on those occasions when depressions, after crossing the British Isles, slow down and stagnate in the North Sea and cause persistent gradient winds between north and east in eastern districts. The rain associated with such spread back is generally slight (but not invariably so) but it is usually prolonged and may aggregate to a substantial total. The pick-up of moisture from the North Sea may be an important feature leading to these persistent rains and also to the prevalence of extensive sheets of low cloud which frequently persist for a few hours after the cessation of rain. It is noteworthy that such periods of rain and extensive low cloud can persist even with sustained rises of pressure and several notable floods near the east coast of Britain have occurred under such conditions. When such an occluded depression is slowing down, it is sound practice to defer a clearance beyond the straightforward estimate of clearance based on the movement of the depression, the extent of occlusion, or rising tendencies. Clearances almost never come sooner than such estimates and are generally delayed. (See also Section 5.4.3 of Chapter 5 - Fronts and frontal weather.)

Experience indicates that the period of heaviest rain often occurs at the time occlusion takes place. The heaviest rain tends to be located near the triple point and to occur at about the time of the passage in quick succession of both warm and cold fronts. In an unpublished monograph Douglas[2] commented on an association between the occlusion process and outbreaks of rain in the depression. He remarked that 'Rain in the warm sector is generally associated with the occlusion process, and the approach of a cold front greatly increases the chance of rain, not only in the warm sector but also ahead of the warm front, unless the cold-front trough develops at the expense of the warm-front trough with excessive backing of the warm sector isobars.'

Precipitation in the warm sector is likely, and that at the fronts will be more intense, if potential instability is present. A study of the relevant tephigrams (see Chapter 10 - Upper-air ascents) will help to determine whether or not the air is potentially unstable: air is potentially unstable if the wet-bulb potential temperature decreases with height. Some indications may also be obtained from satellite photographs: if the cloud has a lumpy appearance and the tops, as indicated by infra-red photographs, are high, the presence of potential instability may be inferred. In general, by indicating the height of the cloud tops, infra-red satellite pictures give some idea of the depth of the cloud and the likely activity of the system.

In the open-wave stage and the early stages of occlusion, it often, though not always, happens that the warm front is active and the cold front inactive, or vice versa. Some methods of assessing the activity of fronts have been discussed in section 5.4 of Chapter 5 - Fronts and frontal weather.

6.2.3 The mature stage

The mature stage is reached, and development usually proceeds no further, when the 'dry slot' seen on satellite pictures has been carried round the top side of the vortex (as at D in Figure 2), suggesting that the moisture supply to the depression has been cut off. The thickness gradient over the centre usually weakens, and the speed is reduced until the low becomes slow-moving or stationary, any movement generally being in the direction of the strongest current round the centre. Although the track of the depression centre often runs to the left, upstream developments causing a veer of the cold-front jet stream can run the centre to the right.

At this stage, corresponding to the final diagram (4) of Figure 1, the cloud vortex centre and the surface and mid-tropospheric pressure centres are vertically near coincidence. The vortex may well have established itself as a feature of the planetary long-wave system, or it may have replaced or re-invigorated an already existing system. At about this time, or a little earlier, conditions are often favourable for the formation of a further wave on the frontal zone; usually a new wave will form and develop only if the cold front is more than about 2000 kilometres (1080 n. mile) long, and if the thermal wind parallel to the front is 25 knots (12 metres/second) or more. The front should be active, showing up as an unbroken band on satellite pictures; where the cloud is more broken, as at E in Figure 2, the front is inactive and waves are improbable.

As dissipation proceeds, the spiral cloud bands round the vortex become fragmented, with clear air between the bands. The cloud forming the bands is mostly shallow cumulus or stratocumulus; the unstable air is deepest near the centre of the low, and the relatively greater convection in this part of the system produces brighter and larger areas of cumulus than elsewhere in the circulation of the dissipating vortex.

6.2.4 Secondary lows on cold fronts

The general characteristics of secondaries on cold fronts cover a wide spectrum. The least definite is the very shallow minor wave which is barely detectable in the isobaric distribution, even on a large open-scale surface chart with a dense network of plotted observations, and is quite imperceptible on routine upper-air charts. In many cases the net effect on weather of such a shallow wave which does not develop is to delay the movement of the cold front in the rear of the primary depression (sometimes causing little more than a hesitation in the movement of the cold front) and to cause a corresponding delay in the clearance of the frontal high clouds. On some occasions, there is a slight spread back of cloud over areas which had cleared previously after the initial passage of the cold front. Frontal precipitation is often more prolonged near the wave and it may also be more intense. Such shallow waves usually ripple along the cold front and eventually become absorbed in the circulation of the main depression. It is sometimes difficult to track such waves consistently, even on detailed hourly charts; any particular wave may exist for only a few hours, but a number of ripples may run along the cold front in rapid succession.

At the other extreme, some secondaries on cold fronts develop quite rapidly, deepen markedly and produce extensive and clear-cut isobaric patterns. On some occasions they attain such a depth and horizontal and vertical extent that they later become of greater significance than the primary depression (see 6.2.1 to 6.2.3). With such very vigorous secondary depressions the winds often reach gale force. The strongest surface winds tend to occur shortly after the passage of the cold front and usually within 150 to 300 kilometres of the tip of the warm sector.

Secondaries on cold fronts may develop to any extent between these two extremes. Shallow waves tend to move with the mid-tropospheric flow, along the front, while deepening waves tend to move more towards the cold air.

Occasionally, in the col or minor ridge between the main and secondary depressions, visibility may deteriorate to below fog limits in restricted areas quite close to the cloudy, rainy areas. If clouds clear quickly and winds become light soon after the rain has ceased, then at night, or also during the late afternoon in winter, conditions are favourable for rapid cooling and fog may form. The fog may last for no more than a few hours, but the possibility of its formation should be borne in mind, particularly as the event might at first sight seem an unlikely one in the vicinity of marked cyclonic activity.

6.2.5 Secondary lows on warm fronts

Waves and secondary lows on warm fronts are less common than those on cold fronts and exhibit quite different characteristics. They seldom develop appreciably and usually ripple along the warm front until they finally fill up on entering an anticyclogenetic area further downstream, towards the right exit of the jet stream ahead of the warm front. Some remarks on the thermal patterns favourable for warm-front wave formation are given in section 2.3.2.2 of Chapter 2 - Dynamical ideas in weather forecasting. Jones[3] has also stated that formation is favoured when the warm front is slow-moving in the right-entrance area of a 300-millibar jet on the east side of a 300-millibar ridge. The wave usually moves along the front, at a small angle to the 300-millibar contours, towards the cold air, at a speed of about one-half that of the 300-millibar wind along the track. Of the waves studied by Jones (occurring over the British Isles on average once in three months), less than one in five had a closed isobar. Very occasionally two successive waves appear on the same warm front.

Warm-front waves are often not easy to detect initially, particularly if they form in areas where observations are sparse; even satellite photographs are usually of little value because of the extensive blanket of upper cloud ahead of the warm front. The associated weather varies, but there is often an area of enhanced precipitation - usually fairly small, about 100-200 kilometres in length parallel to the front and centred somewhat ahead of the tip of the wave.

6.2.6 Secondary lows at the point of occlusion

The conditions for the formation of a secondary low at the triple point of an occlusion have been outlined in section 2.3.2.2 of Chapter 2 - Dynamical ideas in weather forecasting. For a warm occlusion, the conditions are very similar to those for a warm-front wave; the secondary low usually moves rapidly away from the primary, and is often called a 'breakaway' low. The weather associated with such lows is very similar to that accompanying warm-front waves, but there is sometimes a noteworthy penetration of rain into the ridge ahead of the low.

Secondaries form at the triple-point of a cold occlusion in very different conditions, when there is a marked thermal diffluence ahead of the point of occlusion (see Figure 40 of Chapter 2). The low tends to move in a direction similar to that of the flow before diffluence, but biased towards the direction of the stronger branch of the diffluent flow. The rainfall of a depression is often at its greatest at about the time of formation of such a secondary low.

6.3 NON-FRONTAL DEPRESSIONS

6.3.1 Old frontal depressions

Large occluded depressions sometimes remain dominant features of the synoptic chart long after they have lost all frontal structure; sometimes they remain for several days. They are then associated with a cold pool or flat trough in the thickness pattern and the air in them is unstable. Coupled with the slow frictional convergence towards the centre in the lowest thousand metres or so of the atmosphere, this leads to irregular outbreaks of showers in the absence of any special heating from below. Such showers sometimes amalgamate into rain areas 50 or 100 kilometres in extent but the distribution and timing of such precipitation is almost impossible to predict with any accuracy, except by extrapolation of the rain areas already on the chart or inferred from radar weather echoes. In satellite pictures the mainly cumuliform cloud lines are often seen to be nearly parallel to the 1000-500-millibar thickness lines, showing that there is little variation of the geostrophic wind with height, since the cloud lines over the sea are usually parallel to the lower tropospheric winds.

6.3.2 Polar lows

The term polar low is here taken as referring to fairly small-scale and often shallow depressions or troughs (sometimes the surface isobars show only a very minor ripple) embedded in a deep cold current which has recently left northerly latitudes. These small polar lows generally move in the direction of the general lower tropospheric flow which is usually left substantially unchanged after their passage. At times, however, air which is both colder and deeper may arrive behind a larger and more vigorous polar low.

The approach of a polar low is heralded by falling tendencies (which may be only very slight), a backing and sometimes a decrease of the surface winds and a pronounced change in type, and increase in amount, of medium and high clouds. These changes in upper clouds are usually very noticeable because the preceding cold air is often virtually free from upper clouds apart from anvil cirrus clouds which are either the residue of or blown off from the tops of shower clouds. At localities near upwind coasts, the warning given by these forerunners of the approach of a polar low may be little more than one or two hours. At inland stations, in polar outbreaks with strong tropospheric winds and even with moderate winds, the warning given by upwind coastal stations may amount to but a few hours.

At times when the polar low has formed well to the north of the British Isles, observations on the west coast of Iceland, at the Faeroes, or on the Norwegian coasts enable the existence of polar lows to be inferred, although these observations may well show only the weather on the extreme periphery of such polar lows which are likely to move towards and affect the British Isles. Thus the precise location of a polar low at sea is often in doubt. Even when its position is known fairly accurately, the timing of movement for periods of say 12 to 24 hours often introduces considerable uncertainty in the forecast position.

When a polar low moves or forms over a relatively dense observational network some of these uncertainties are removed. Although showers, which may be both severe at times and frequent, are often features of a typical polar outbreak a polar low causes either a period of continuous precipitation or such extensive and frequent showers that for most practical purposes it is little different from continuous precipitation. The sky is usually almost completely covered by upper clouds and the cold, dull weather, with precipitation in the polar low, contrasts unpleasantly with the bright, showery, but at times exhilarating, weather of the pure polar outbreak.

In winter, and even in spring, polar lows may bring considerable falls of snow, particularly on high ground and at times on low ground also. The falls of snow from a polar low, being of longer duration and of greater horizontal extent than those from the showers of a simple polar outbreak, may disrupt transport and cause considerable difficulties both to the general public and to some special sections of the nation, notably farmers maintaining livestock out of doors, particularly in hilly country where there may be deep drifts.

Clearance of the sky after the passage of the polar low is often rapid and complete. Incoming solar radiation during the day may melt wholly or partially any frozen precipitation which is lying. Strong outgoing radiation may produce hard frost at night. Any subsequent hard freezing of partially melted snow often causes very great difficulties for transport.

Not all polar lows in winter cause solid precipitation, but the current temperatures in the lower troposphere should always be carefully considered. In polar lows, cooling by evaporation of precipitation may occasionally be an important factor in determining the nature of precipitation at the ground. This cooling should generally be considered when indicating the level of the $0^{\circ}C$ isotherm for aircraft flying at relatively low levels near or through a polar low.

Polar lows have usually been regarded as a result of the amalgamation of areas of vigorous small-scale convection, and this may well be true of many systems, but detailed radar studies by Harrold and Browning[4] have shown that at least some well-developed examples are formed as a result of low-level baroclinicity within the polar air. The horizontal temperature contrasts could be located on 1000-850-millibar thickness charts but did not appear to extend above 850 millibars. An area of precipitation was associated with slantwise convection, a narrow tongue of air ascending at about 10 centimetres/second. A schematic representation of the main organized air movements is shown in Figure 4.

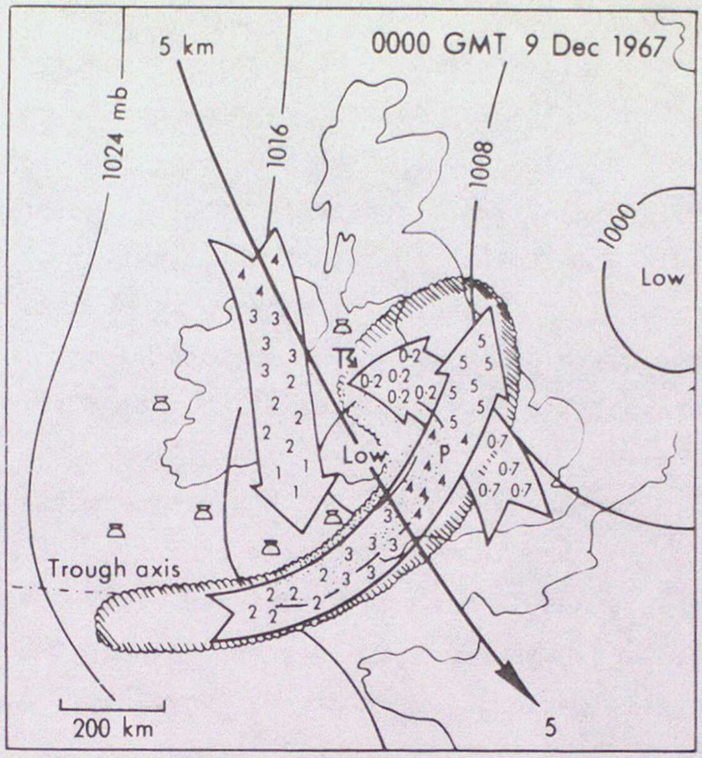


FIGURE 4. Composite diagram showing flow relative to polar low

Track of low — Area of precipitation

Major air currents. The numbers within the arrows denote height of flow in km.

Hatched lines indicate boundary of extensive cloud layer.

6.3.3 Heat lows

When heat lows over the British Isles appear on the surface chart, they usually do so in the late afternoon or evening after a day of intense solar heating. The preceding pressure distribution is usually slack although the upper winds in the lower or middle troposphere may be relatively steady in direction and light in speed (but occasionally moderate). The heat lows show up as quite shallow isobaric features on the surface chart, and seem to form preferentially over the Midlands, East Anglia and the Lincolnshire and Yorkshire plains. The weather which accompanies or immediately follows these can vary from case to case. With dry and relatively stable conditions in the troposphere, only small amounts of shallow cumuliform cloud with high bases (perhaps 1000 metres or more) will form during the day and these will disperse in the evening. In such cases the shallow heat lows usually fill up during the night and do not disturb the continuance of fine weather.

When the troposphere contains a fair amount of moisture, however, and the surface temperatures likely to be reached under the influence of daytime heating are expected to make the air unstable up to considerable heights (say 400- or 300-millibar levels), some thundery activity is likely to break out by about mid afternoon. The storms usually retain their separate identities, but occasionally a group may amalgamate to form one large storm area which may then persist as a more or less self-maintaining system for a few hours. More generally, the storms drift separately north or north-east in the light upper winds which, at about 700 millibars, are often from a southerly or south-westerly point. These storms form over the British Isles and are often clearly associated geographically with the heat lows; they are not the type which drift up from France.

It should be emphasized that the thunderstorms associated with the surface heating leading to the formation of heat lows behave rather differently as to movement from those associated with convection in a cold unstable outbreak in the rear of a depression. In the latter case there is often considerable cyclonic curvature and vorticity, and a substantial wind throughout much of the troposphere with a clear and fairly definite flow pattern which will tend to carry any storms with it, and there are probably widespread showers. The heat low is usually associated with rather weak and irregular upper winds and the showers or thunderstorms, though perhaps large, tend to be slow moving so that many areas between are unaffected and enjoy fine, hot, sunny weather.

At times when a pronounced warm spell, often with light south-east or south surface winds, breaks down, it does so as a cold front or cold trough moves slowly eastwards across western districts of the British Isles, the Bay of Biscay, France and Spain. Sporadic thunderstorms of the type described above may well occur in the afternoon and evening in association with heat lows over the British Isles, but the first break in the general weather often occurs in association with the northward movement from France or the western Low Countries of a trough in the isobars. This trough usually lies ahead of an upper trough, orientated approximately north-west to south-east, which moves into France and Britain from the Bay of Biscay, bringing substantially cooler air in the upper troposphere. The leading surface trough is often orientated approximately east-west and is usually accompanied by a fairly extensive belt of, thick, upper, unstable cloud and an area of continuous rain, some of this being very heavy and with violent and prolonged thunderstorms at times. Although there may have been a few isolated storms during the afternoon or early evening from heat lows formed over England and Wales, the skies in southern areas of England are often almost cloudless for a few hours during the late evening and earlier part of the night. This fine period is followed by an outbreak of thunderstorms, which are often extensive.

After the thunderstorms have moved away, continuous rain tends to persist in the area for some hours. The intensity of this rain is usually at least moderate just to the rear of the thunderstorms, but it tends to become less intense as the thundery trough moves farther away to the north. This type of sequence, following a hot spell, is typically a summer phenomenon, but it may occasionally occur after a hot spell quite early in spring. The generation of the troughs over France and the speed of the upper winds often seem to combine to cause these storms to reach southern districts of England towards or a little after midnight. Once they have been detected by the dense observing network over England, their movement can be deduced and the timing of their subsequent advance across other districts is not usually particularly difficult. Variations in the intensity of the rain and the outbreak of new large areas of thunderstorms within the general cloud mass and rain area are rather difficult to forecast. For very short-term forecasting, radar weather echoes can be exceedingly valuable (see Chapter 19 - Clouds and precipitation). Some other remarks on northward-moving troughs from France are included in 6.4.

6.3.4 Orographic lows

In the British Isles the height and extent of high ground are relatively small and orographic lows formed to the lee of high ground are usually insignificant on the synoptic scale when compared with those formed in the Gulfs of Lions and Genoa and to the south of the Atlas Mountains. Nevertheless, on some detailed charts it may be possible to detect orographic lows or troughs, for example, in the lee of the Welsh hills or the Scottish highlands. Such pressure systems cannot be forecast with much accuracy and their effect on general weather in the British Isles is usually almost negligible. When such features are likely to occur, some allowance may perhaps be made in forecasts of the surface wind in the regions affected. Marshall[5] has found that with a strong north-westerly flow across the Scottish highlands, surface winds at Bell Rock are, in the mean, further backed from the geostrophic than with winds in other quadrants (see section 16.5.1 of Chapter 16 - Wind). This effect could be explained by an orographic low or trough occurring on the lee side of the Scottish highlands.

However, orographic lows can occasionally be very important, as reported in the study by Aanensen[6] of the Sheffield gales of February 1962. On the 16th of that month, a general unexceptional gale in England produced extremely strong winds to the lee of the Pennines which caused great damage to buildings in Sheffield. The 0600 GMT surface synoptic chart is shown in Figure 5, while a more detailed mesoscale analysis at 0900 GMT (Figure 6) shows that the normal synoptic analysis was too simple. Mesoscale lows had formed to the lee of the Pennines, with a mesoscale high to the west, and a very tight pressure gradient between the two leading to the exceptionally strong winds. The mesoscale features appeared to be associated with a lee-wave system, mesoscale lows corr-esponding to lee-wave troughs and highs to lee-wave crests. For further details the reader should consult the original paper.[6]

6.4 TROUGHS

Some comments on the weather accompanying frontal troughs are included in Chapter 5 - Fronts and frontal weather. So far as non-frontal troughs are concerned, if a trough line is moving faster than the wind speed through it there must be convergence in the lower layers ahead of it and divergence behind. However, where the wind blows through a stationary or slow-moving trough, the reverse must be true - divergence downstream (ahead) and convergence upstream (behind). Additionally there will be some frictional convergence. Most troughs approaching the British Isles from the west move roughly with the wind speed, and convergence occurs mainly near and ahead of the trough line. However, there are occasional troughs, mainly moving west from the Continent, with convergence and bad weather in the rear. Thus it is not sound practice invariably to associate an expected improvement of weather with a surface trough line, although the surface trough line is a useful device for timing the changes in the winds. Although there may be only a belt of showers associated with some troughs, in many cases there is an area of continuous precipitation and this often seems to cease some distance ahead of the surface presssure trough - in some cases in the British Isles this distance may amount to 50-150 kilometres and occasionally may be rather more. Where the current weather can be seen to be conforming to this pattern and the winds in the lower troposphere (say around 700 millibars) seem likely to shear the rain forward of a slower-moving surface trough, some reliance may be placed on a continuation of the trend in the short term. It would,

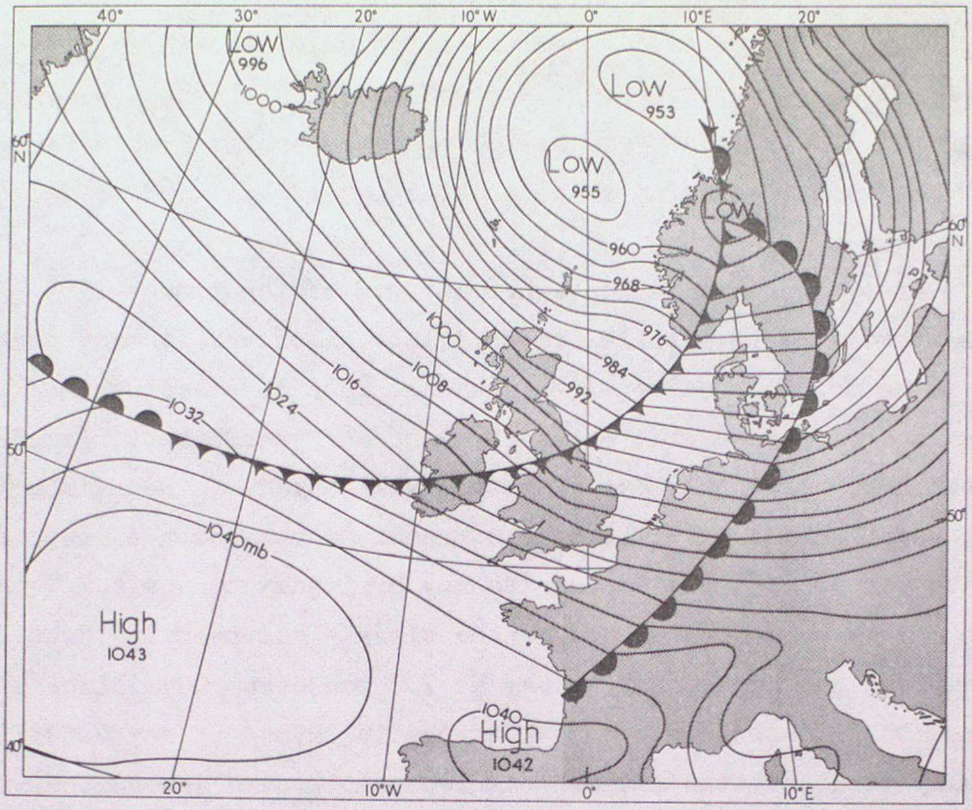


FIGURE 5. Surface synoptic chart for 0600 GMT on 16 February 1962

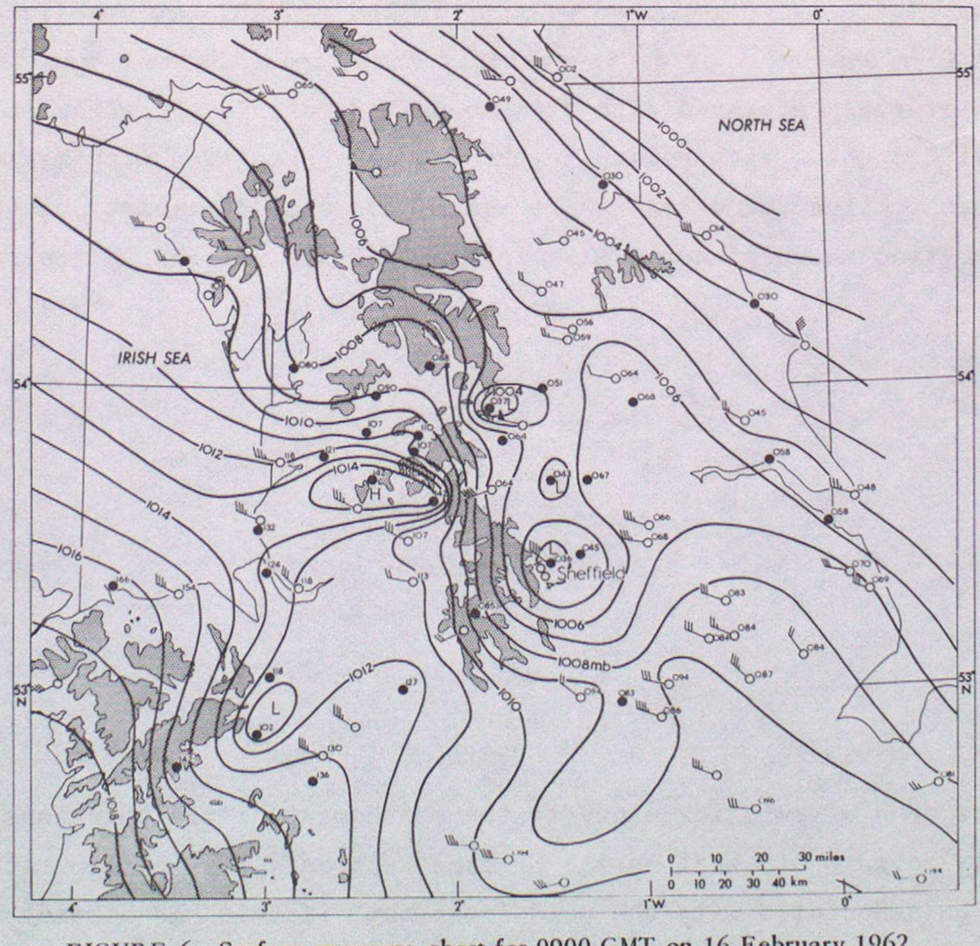


FIGURE 6. Surface pressure chart for 0900 GMT on 16 February 1962

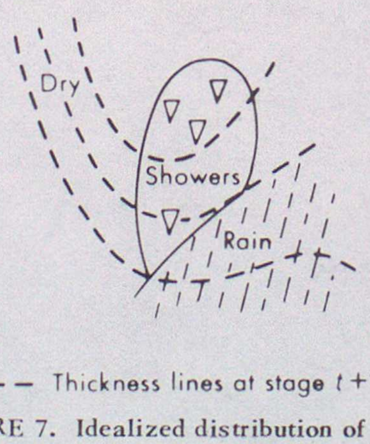
○ Meteorological Office stations ● Other stations

Land over 300 metres above MSL is shaded.

however, be unwise generally to forecast such a pattern from a set of 24-hour forecast charts, except perhaps when the forecast wind distribution seemed likely to be very reliable and to be favourable for any rain to be sheared forward of the trough line.

The area of precipitation, when forward of the trough line, is not always approximately parallel to that line, although in many cases it tends to be so. In southerly situations, when thundery weather moves northward from France, the areas of cloud and precipitation tend to be orientated approximately east-west and well ahead of the main cold trough on the chart, which often lies in a broadly north-south direction off south-western coasts and across the Bay of Biscay to Spain. This major trough may be cold-frontal and can be clearly and readily identified on both surface and upper charts (say at 700 and even 500 millibars at times). Whereas at the onset and outbreak of precipitation it may be difficult initially to detect the rather weak isobaric trough associated with the east-west belt of precipitation, a well-marked trough usually appears later.

On some occasions, thermal troughs show a tendency to relax, leading generally to improved weather in the trough, but sometimes they extend in a southerly or south-easterly direction. Miles[7] has described some features associated with this so-called meridional extension of thermal troughs. With regard to the weather associated with meridional extension, Miles found that there was a good deal of variety but that the distribution shown schematically in Figure 7 applied fairly generally.



— — — Thickness lines at stage $t+24$

FIGURE 7. Idealized distribution of weather with extending thermal troughs

The area of rain (or snow) to the south-east of the thickness trough usually moved south-east as the process went on. This precipitation might be associated with the cold front but, if this had already moved away to the east, the rain might occur ahead of a post-frontal trough.

In those cases, it sometimes appeared to result from an amalgamation of shower clouds into a continuous belt of cloud, and might be of a rather intermittent nature. In the northerly current, showers were usually restricted to an area near the axis of the thermal trough and stabilization came in, quite quickly as a rule, from the north-west.

It is important that the available upper-air charts should be carefully examined for evidence of the existence of upper troughs. The advection of an upper cold trough may increase upper instability to such an extent that there is a marked increase in the depth of convection, and this may lead to an increase in the frequency and/or severity of showers or thunderstorms. On some occasions the arrival of an upper trough may cause a baroclinic disturbance to form, or a nearby depression to deepen markedly, leading to a period of disturbed weather.

Upper troughs may often be located on satellite photographs, and indicated on nephanalyses, by changes in cloud patterns at the trough line. When an upper trough crosses a frontal cloud band at an angle, there is often a change from continuous cloud ahead of the trough to broken cloud behind it (see Figure 2, page 4).

An area of enhanced cumulus development and increased cloud cover, or a comma-shaped cloud mass often lies ahead of an upper trough. The clouds behind the trough line are less extensive and show less vertical development. At other times, an upper trough may be marked by medium and high clouds ahead and open cellular cumulus behind.

6.5 COLD POOLS

A cold pool may be defined as a mass of cold air in depth entirely surrounded by relatively warm air, and it appears as one or more closed isopleths in the thickness pattern for a fairly deep atmospheric layer.

Most cold pools form as a result of cutting-off of the cold air near the southernmost extremity of a cold trough. The latter is usually slow-moving and of large amplitude, or increasing in amplitude at the time of cut-off. The low-latitude part often slows down still further or stagnates as the higher-latitude part moves on. The cutting-off is usually accomplished by advection of warmer air across the middle of the trough, often as a result of anticyclogenesis to the west and ridge-building towards and across the trough. Sometimes the warm advection occurs round the north side of the associated surface depression. An example of cut-off low formation is shown in Figure 8.

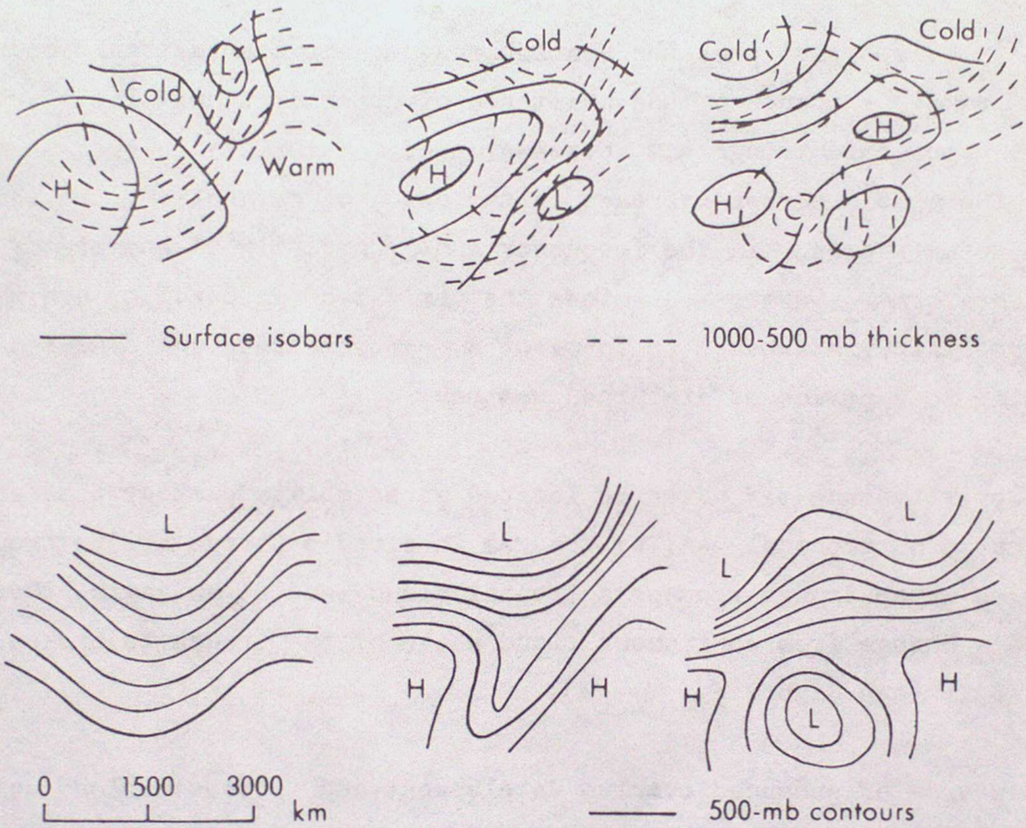


FIGURE 8. Anticyclonic disruption of a trough and formation of a cut-off low

Sumner[8] made a statistical and synoptic study of cold pools over the area between 60°W and 30°E, south of 80°N, for the five-year period from September 1946 to August 1951. He found that the cold pools in high latitudes showed no tendency to come southwards beyond 65°N and accordingly did not directly affect the weather over the British Isles. Cold pools south of 65°N were associated with a variety of surface pressure fields and a wide range of weather.

More than half of the cold pools were classified as cloudy ($\frac{3}{4}$ cover of cloud), about one-quarter as partly cloudy (between $\frac{1}{4}$ and $\frac{3}{4}$ cover), while there were relatively few cases of fine ($\frac{1}{4}$ cover of cloud), or overcast. Cold pools associated with surface lows usually had the largest amounts of cloud, whilst those associated with a surface col or a fairly straight run of isobars had the least cloud.

There was a diurnal variation in cloud amount over land, with cloud amounts most often being greater by day than at night, although in some instances this trend was reversed. The diurnal variation was present irrespective of the type of associated surface pressure system. No diurnal changes could be found over the sea, but this may well have been because of scantier coverage of observations.

On the whole there were slightly more occasions with precipitation than without. Cold pools associated with surface lows had the highest proportion with precipitation, while those with cols and straight flow at the surface had the lowest. Cold pools associated with surface highs and ridges had a surprisingly high proportion with precipitation; with highs, during the period examined, the precipitation was invariably slight snow or sleet (rain and snow), but with surface ridges all forms and intensities of precipitation occurred. General precipitation over the whole area of the cold pool was recorded on about 20 per cent of occasions, 30 per cent had precipitation in places, and the remainder had none at all. Palmén and Newton [9] discuss a number of examples reported in the literature; many cold pools were characterized by cloud and precipitation in the east and north-east sectors, while skies were mostly clear to the west. Sumner [8] found that the western part of Europe is a favoured region for cold pool formation, particularly in late spring and early summer. The life-time of individual cold pools ranges from two to ten days, with an average of three days. For about one-half of the cold pools studied by Sumner, there was no change of the associated surface type from beginning to end; the remainder showed some day-to-day changes, with a tendency for straight or slightly cyclonic flow to become more cyclonically curved. If the cold pool and surface system moved from the land to relatively warm sea in winter, there was usually a particularly noticeable increase in the cyclonic circulation at the surface.

Cold pools may come to an end by warming in situ, by moving to higher latitudes and being absorbed in the flow there, or by renewal of the trough by advection of cold air from the north.

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