CHAPTER 5

FRONTS AND FRONTAL WEATHER

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5.1 INTRODUCTION

An atmospheric front is a narrow, sloping zone of transition between two air masses of differing properties, the gradient of properties across the front being much greater than the gradients within each air mass. In association with this zone of transition there generally exists a vertical circulation which not only determines the weather accompanying the front, but which is also an essential factor in the development of the front and its maintenance against dissipative effects. The dynamics of fronts is a complex subject, and it is not possible in this Handbook to give more than a very brief sketch of the main processes which determine frontal activity and weather. Some further remarks on the dynamics of fronts are given in section 2.11 of Chapter 2 - Dynamical ideas in weather forecasting; for a fuller account the reader should refer to a recent text-book, for example, Palmén and Newton.[1]

The first requirement for the development of a front is a suitable confluent flow in the lower troposphere, intensifying and concentrating the existing temperature gradients into a narrow band, a baroclinic zone. The most common and most important instance occurs in the formation of the polar front, when an outbreak of polar air moving equatorwards is brought into juxtaposition with a warm intrusion from sub-tropical latitudes. The second requirement is that there should be a suitable field of vertical motion. Without vertical motion the two air masses would form a stable system, with the warm air overlying the cold, and the air masses being separated by a sloping transition zone. However, the strong horizontal temperature contrast throughout a substantial depth of the troposphere leads, according to the thermal wind equation, to a band of strong winds in the upper troposphere - the jet stream (see Chapter 8) - which is characterized by convergence and divergence fields aloft favouring the development of surface features. Many fronts, then, owe their existence as active weather-producing systems to a complex interplay of the two processes. In other instances, however, a front may remain fairly inactive, with only slight vertical motion taking place, until it enters, or is overtaken by, an upper-tropospheric flow favourable for development; an example of this type of process will be given in Chapter 6 - Depressions and related features, illustrating the formation of a wave depression.

The major baroclinic zones of temperate latitudes are associated with the polar front, and with the polar-front jet stream, and since the vertical motion fields necessary for frontogenesis are also favourable for cyclogenesis, most active portions of the polar front are found within or near the circulation of depressions. Baroclinic zones may occur elsewhere, however, and may be set up within an 'air mass' (which must initially have some horizontal gradients of properties within it) in an area favourable for frontogenesis; the upper flow and associated vertical motion initiate the confluent flow in the lower troposphere which intensifies the temperature and humidity gradients. Such baroclinic zones may develop sufficiently to acquire frontal characteristics; they occur most commonly to the rear of a depression, where there may be fairly strong temperature contrasts within the cold air itself and where conditions may be favourable for frontogenesis. On the other hand, baroclinic zones in the cold air are often marked only by a pressure trough and an intensification of shower activity. Baroclinic zones in warm air are rarer than those in cold air, partly because temperature contrasts within the warm air mass are usually smaller than in the cold air, and partly because the upper flow fields necessary for development are weaker and occur less frequently in the warm air.

When condensation occurs to form cloud, the latent heat of condensation so released adds to the energy available for the vertical and horizontal circulations, favouring an intensification of the frontogenesis.

During the life of a front, a number of processes are at work to destroy it. Small-scale turbulence and mixing across the narrow frontal zone tend to reduce the temperature contrast, as does heat exchange between the air and the surface when the warm air moves over colder surfaces and the cold air traverses warmer surfaces. Surface friction undoubtedly produces convergence into the frontal trough and therefore has a direct effect in enhancing the vertical circulation - this is not to say that it does not also tend to slow down the flow and perhaps weaken the front or disrupt it by causing the surface contrast to be left behind. When the frontogenetic processes are no longer strong enough to overcome the dissipative effects, the front is fairly rapidly destroyed - the process is known as frontolysis.

The activity of a front, and the associated weather, are dependent to some extent on the nature of the surface over which the front is travelling. Over the ocean, conditions are often relatively straightforward, as there are no complicating orographic effects and the surface temperature changes are usually fairly gradual. On reaching land, however, other factors come into play. Increased convergence may occur near the surface in coastal areas and in mountainous or hilly regions, often leading to greater frontal activity, with thicker cloud and heavier precipitation. On the other hand, the greater surface drag experienced by the lowest layers as they flow over land may lead to a reduction in the intensity of the frontal circulation in some circumstances. Thus the effects on the front of movement from sea to land, or from land to sea, are not straightforward or easy to predict. Some fronts, particularly those which are weak or already undergoing frontolysis, will decay, while others may intensify, perhaps only temporarily, losing their vigour as they move further over the land, or perhaps maintaining their increased activity throughout their passage over the British Isles.

When the land surface is at a temperature appreciably different from that of the surrounding ocean, complicating effects arise as a result of heat transfer to or from the surface. Flow over colder ground, for example, tends to establish a stable lapse rate in the lowest layers, leading to a smaller rate of frictional dissipation of energy, but also to reduced convergence of the surface flow and reduced heat exchange with the surface. On the other hand, heating from the surface may result in increased vigour of the vertical circulation and increased frontal activity, or, if the front is weak or decaying, may lead to the dissipation of the frontal cloud or to the cloud band taking on a more convective character. The foregoing, while demonstrating that fronts are very complex entities, has emphasized the main factors which determine frontal development, activity and decay. These factors are as follows:

(a) Confluent flow, intensifying and concentrating the horizontal temperature gradient throughout a substantial depth of the troposphere.

(b) A vertical circulation, with upward motion in the vicinity of the front, divergent flow aloft and convergent flow near the surface. The convergence in the lowest layers may be emphasized by topographical effects.

(c) Dissipative factors, such as turbulence in and near the frontal zone, friction and turbulence at and near the surface, and heat exchange with the surface (usually, although heat exchange will at times work to intensify frontal activity).

Little has been said so far about the surface position of the front; at any place there is often a change of wind velocity, temperature, dew-point temperature and pressure tendency associated with the passage of the surface front. Changes in weather may be related to the position of the surface front, some types of change occurring at or near the time of passage of the front. These aspects will be discussed in more detail in two later chapters (Chapter 9 - Analysis of surface charts, and Chapter 14 - Surface prognoses).

In this section the intention has been to emphasize the dynamical factors important in determining frontal weather. The next two sections will deal with the observed structure of fronts and the associated weather characteristics.

5.2 THE STRUCTURE OF FRONTS

The classical theory of depression development and the structure of fronts, put forward by J. Bjerknes and his collaborators in the 1920s, has been described and illustrated in many standard textbooks and will not be repeated in detail here. Briefly, however, the Norwegian model envisaged three types of front, namely:

(a) Warm front, characterized by steady upgliding of the warm air above the cold air; at any place there would be a steady thickening and lowering of the cloud, with increasing precipitation, as the surface front approached. The main mass of cloud is in the warm air but, where precipitation is fairly heavy, evaporation below the frontal surface leads to saturation and stratus formation in the cold air.

(b) Cold front, with cold air undercutting the warm air, leading to more vigorous ascent than at the warm front but over a more limited area. The cloud, again mainly in the warm air mass, is often convective in character.

(c) Occluded front, where the cold front has overtaken the surface warm front and warm air is no longer present at the surface. The front is a 'cold occlusion' if the air is colder behind the front than ahead of it, and a 'warm occlusion' if the opposite applies.

The structure of actual fronts usually differs, sometimes markedly, from the model, but it is still a useful concept for forecasters to bear in mind, particularly when considering the associated surface weather features. Differences from the model are as important as the similarities when assessing the properties of a frontal system and its likely future behaviour.

After the publication of the Norwegian work in the 1920s, ideas on the nature of fronts changed little until the rapid development of aviation during and since the Second World War led to the need for, and also to the ability to carry out, more detailed studies of the three-dimensional structure and dynamics of fronts. Detailed soundings by aircraft,[2-4] mainly during the 1950s, improved our knowledge of the distributions of temperature, humidity, wind and cloud associated with fronts, while more recently Doppler radar studies, coupled with isentropic analysis (see Chapter 12 - Further techniques of analysis), have yielded a better insight into the three-dimensional airflow patterns in frontal systems. The results of these studies will be discussed in the following sections.

5.2.1 Warm fronts

Two examples of warm fronts observed by the Meteorological Research Flight, and described and illustrated by Freeman,[4] are shown in Figures 1(a) to (c) and 2(a) to (c). The comments are taken almost verbatim from Freeman's paper.

The synoptic analysis at 1400 GMT on 7 October 1955 is shown in Figure 1(a). The soundings were made along a track almost perpendicular to the front, the extreme westerly point being near the tip of a small warm-front wave moving quickly south-east. In the upper troposphere the frontal zone was about 80 kilometres wide. Below about 5000 metres the frontal zone was wider and there was evidence of a double structure. This could also be detected on the surface charts; dew-points rose in two stages, from below 10°C to 12-13°C and then to about 15°C. The frontal surface had a slope of about 1:110 and extended almost up to the tropopause (see Figure 1(b)).

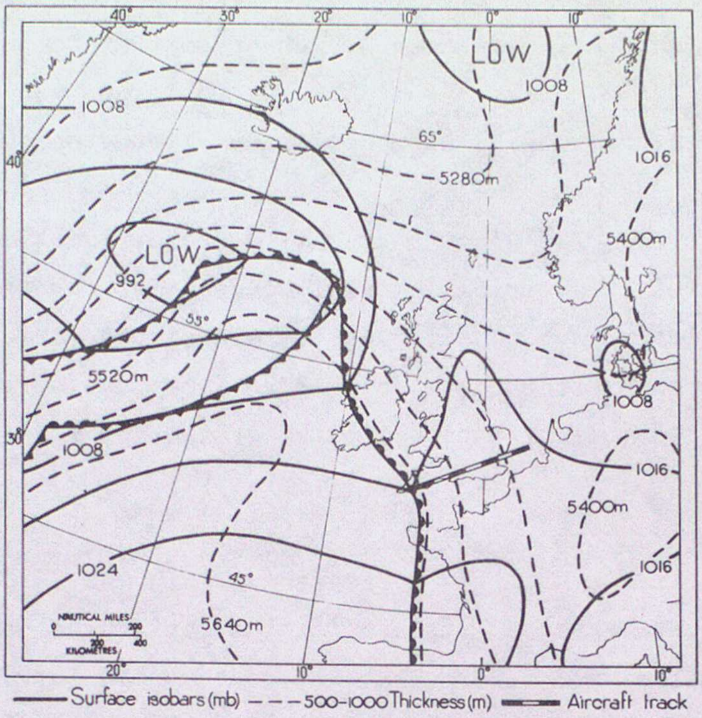

FIGURE 1(a). Synoptic chart for 1400 GMT on 7 October 1955

There was not a solid mass of cloud, as would be expected on the Norwegian model, but there were numerous layers, and even the lower part of the cloud may have been more broken than indicated in Figure 1(c). Precipitation was not reported above about 4000 metres, but rain was found at and below this level, sometimes quite near the top of a cloud layer. On the whole the cloud mass has a greater slope than that of the frontal surface. An interesting feature of the frontal zone is the region of dry air, particularly between 700 and 400 millibars.

In the second example, Figures 2(a) to (c), the flights took place ahead of the surface position of an active warm front approaching from the south-west. There was a broad frontal zone with two fairly well-marked regions of maximum temperature gradient; the upper zone may have been the remnant of an old occlusion which had moved southwards across the British Isles about three days earlier. At 4000 metres the temperature gradients were 5½ degrees in 120 kilometres and 2 degrees in 37 kilometres in the two regions. The slope of the frontal surface was about 1:200, while that of the cloud was greater, with cloud in the cold air below the frontal surface. Precipitation reached the ground as snow at the forward edge of the precipitation belt, turning to rain after about 100 kilometres.

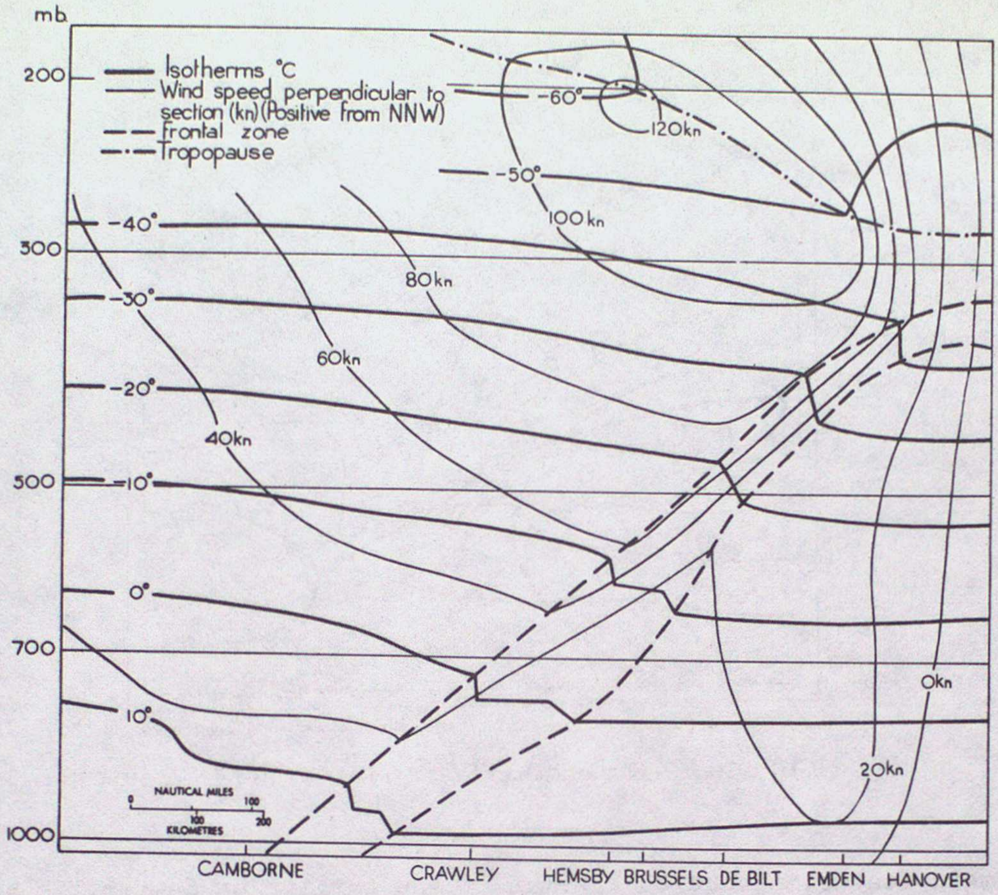

FIGURE 1(b). Vertical cross-section, Camborne to Hanover, of warm front in Figure 1(a), showing isotherms and isotachs

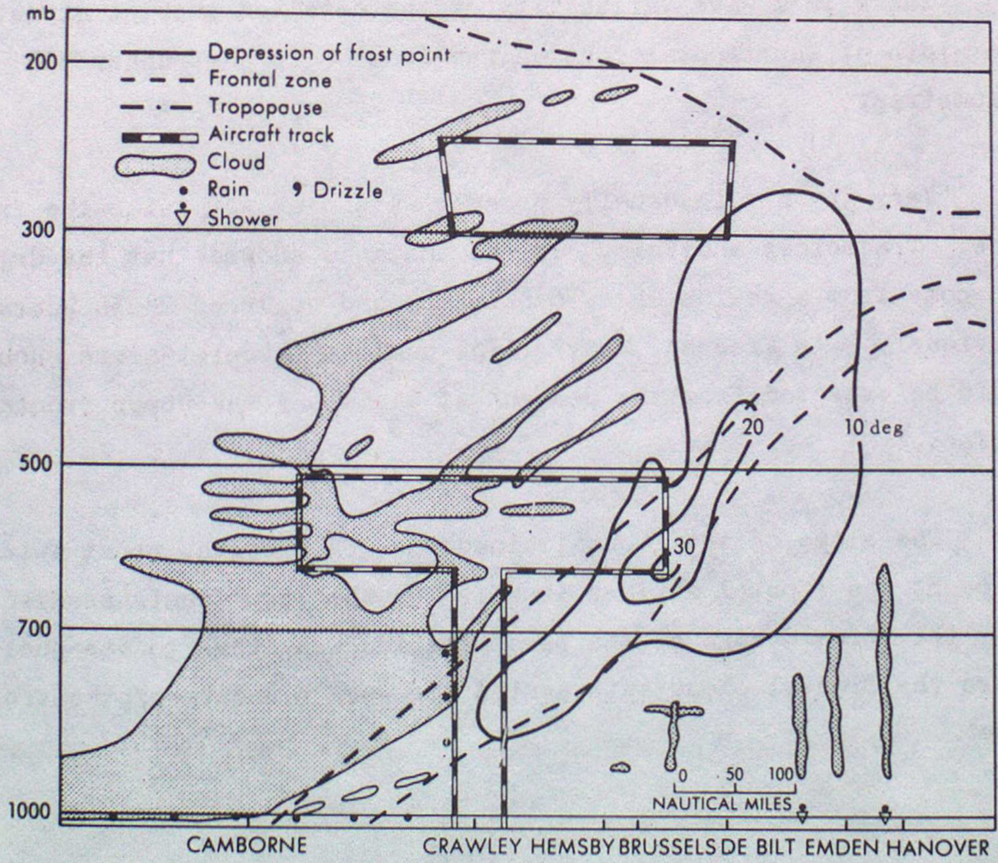

FIGURE 1(c). Vertical cross-section showing humidity and cloud

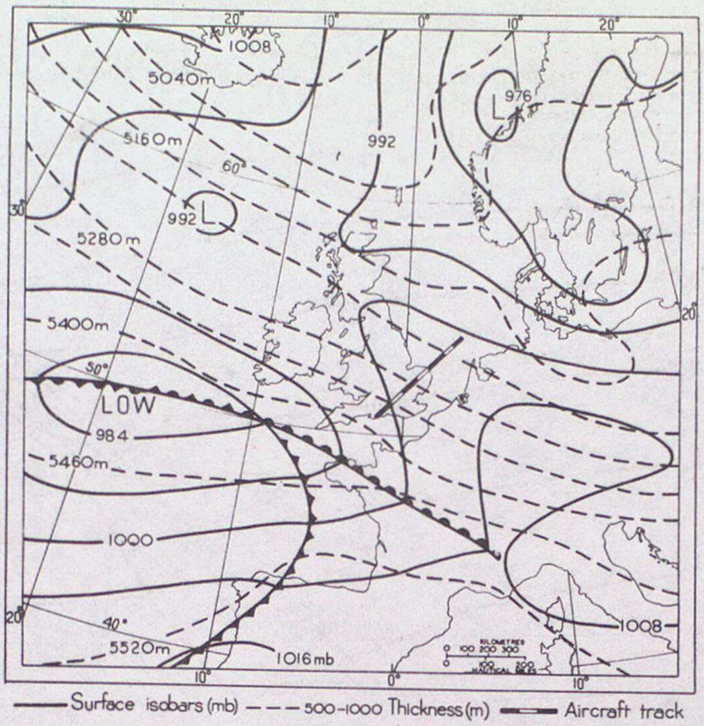

FIGURE 2(a). Synoptic chart for 1400 GMT on 13 January 1955

The main features found by Freeman,[4] and earlier by Sawyer,[2,3] are as follows:

(a) There is a wide variability of the detailed thermal structure: the width of the frontal zone varied from 40 to just under 300 kilometres.

(b) Very dry air is usually present within or very near the frontal zone. Trajectory analysis[5] of one instance showed that the dry air had come from a region where subsidence had occurred 24-36 hours previously. As Freeman[4] says, 'The humidity isopleths are such as would be expected from the descent of air along the upper frontal surface.'

(c) The slope of the frontal cloud was, on average, about twice the slope of the frontal surface itself. On the warm fronts studied, '... the forward edge of the precipitation was close to the position where the frontal cloud intersected the warm boundary of the frontal zone'.[4]

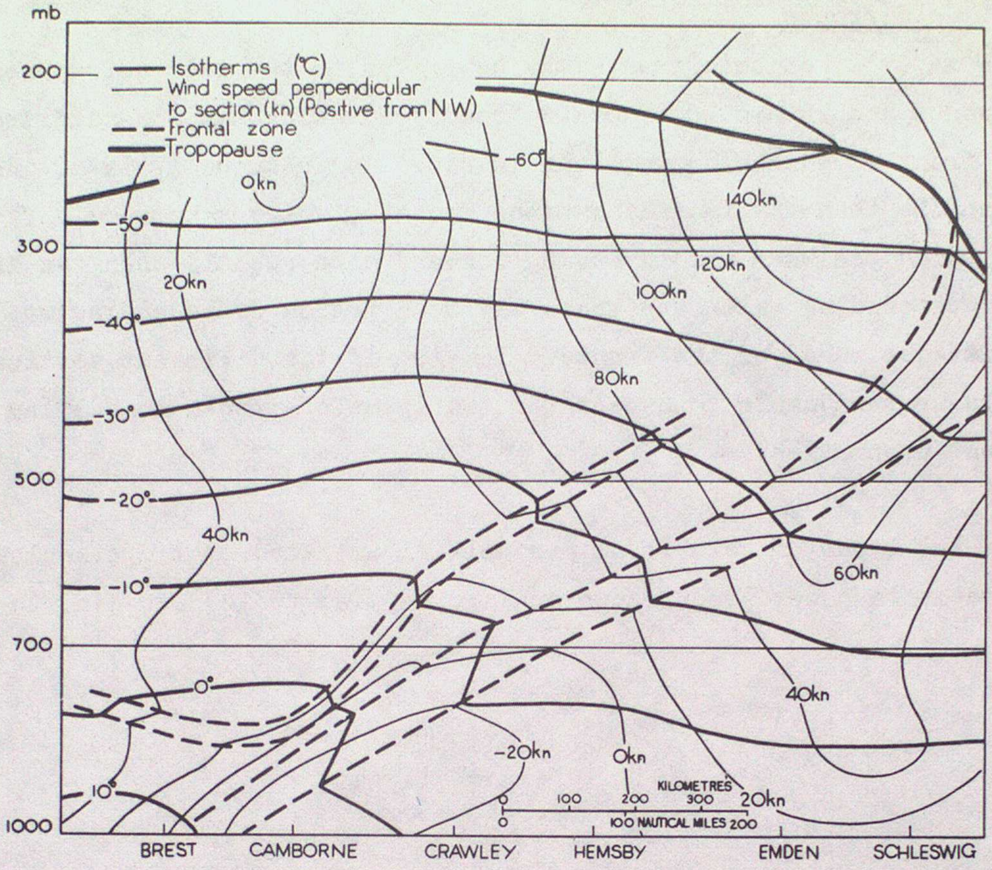

FIGURE 2(b). Vertical cross-section, Brest to Schleswig, of warm front in Figure 2(a), showing isotherms and isotachs

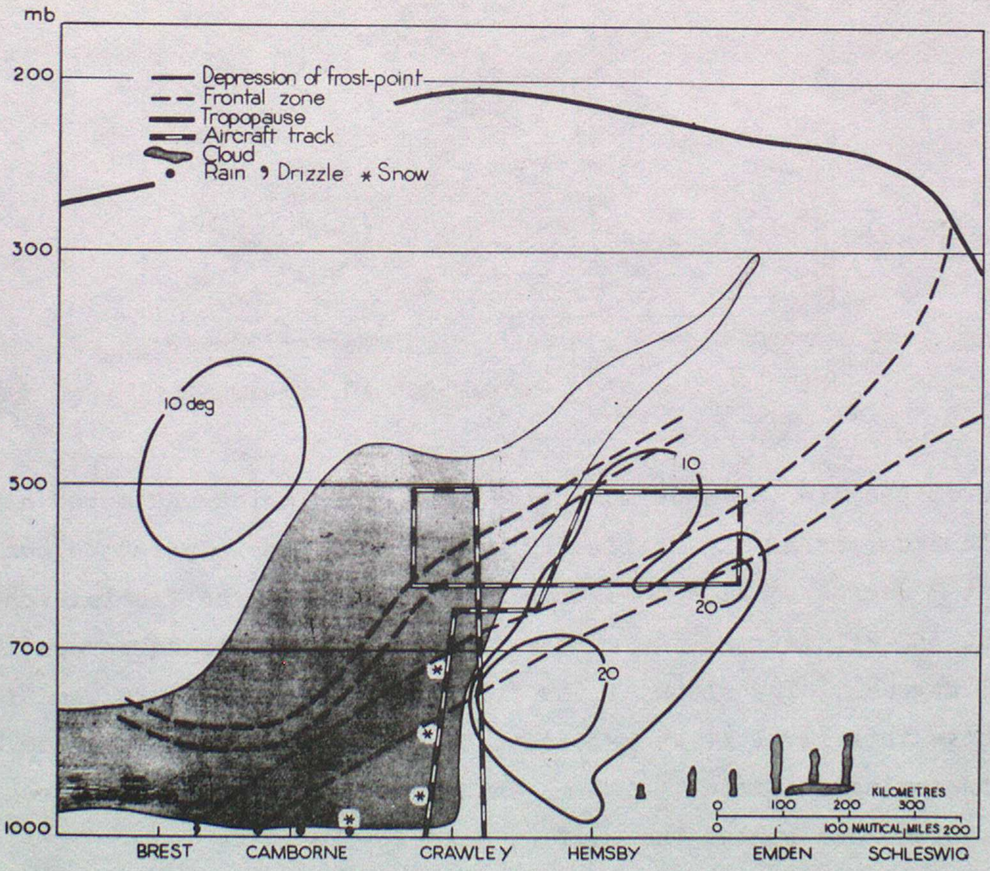

FIGURE 2(c). Vertical cross-section showing humidity and cloud

5.2.2 Cold fronts

The majority of cold fronts may be placed in two main categories, ana-cold fronts and kata-cold fronts. Broadly speaking, an ana-cold front is a cold front at which the warm air is ascending because it is moving forward less rapidly than the frontal surface beneath, while a kata-cold front is one in which the warm air is moving forward more rapidly than the front and thereby descending (although there may be a region of ascending warm air some distance ahead of the front). In view of the different vertical motions it would be reasonable to expect the two types of fronts to display quite different properties.

The two types of cold front are well illustrated by two examples taken from Freeman's paper[4] and shown in Figures 3(a) to (c) and 4(a) to (c).

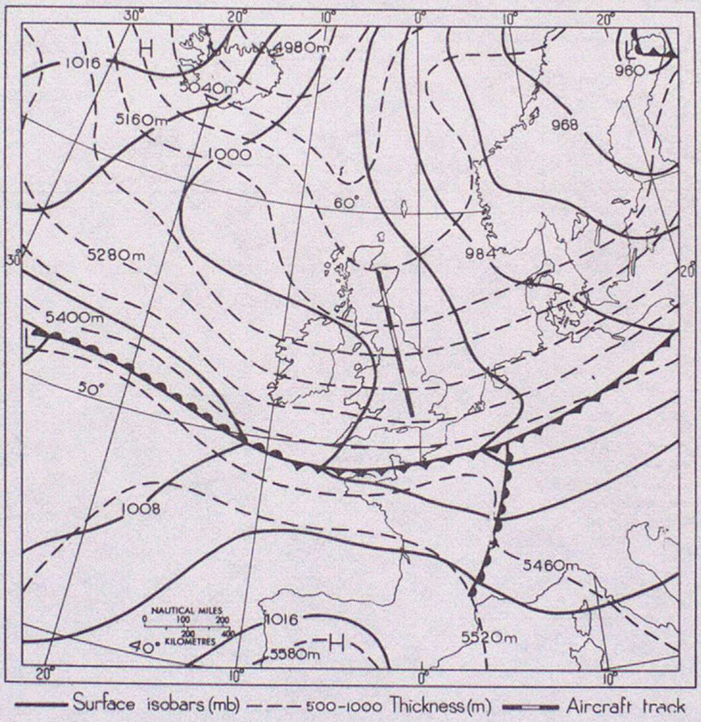

FIGURE 3(a). Synoptic chart for 1400 GMT on 11 January 1955

Figures 3(a) to (c) show an active cold front which had moved almost due southwards across the British Isles; the surface temperature contrast was about 5 degrees. At 4000 metres and 5500 metres the frontal zone was about 330 kilometres wide with a temperature difference across it of about 10 degrees. The slope of the front below 600 millibars was 1:140, while above this level it was steeper, about 1:45. This was a good example of a slow-moving ana-front, with an extensive cloud sheet and a broad precipitation belt behind the surface cold front.

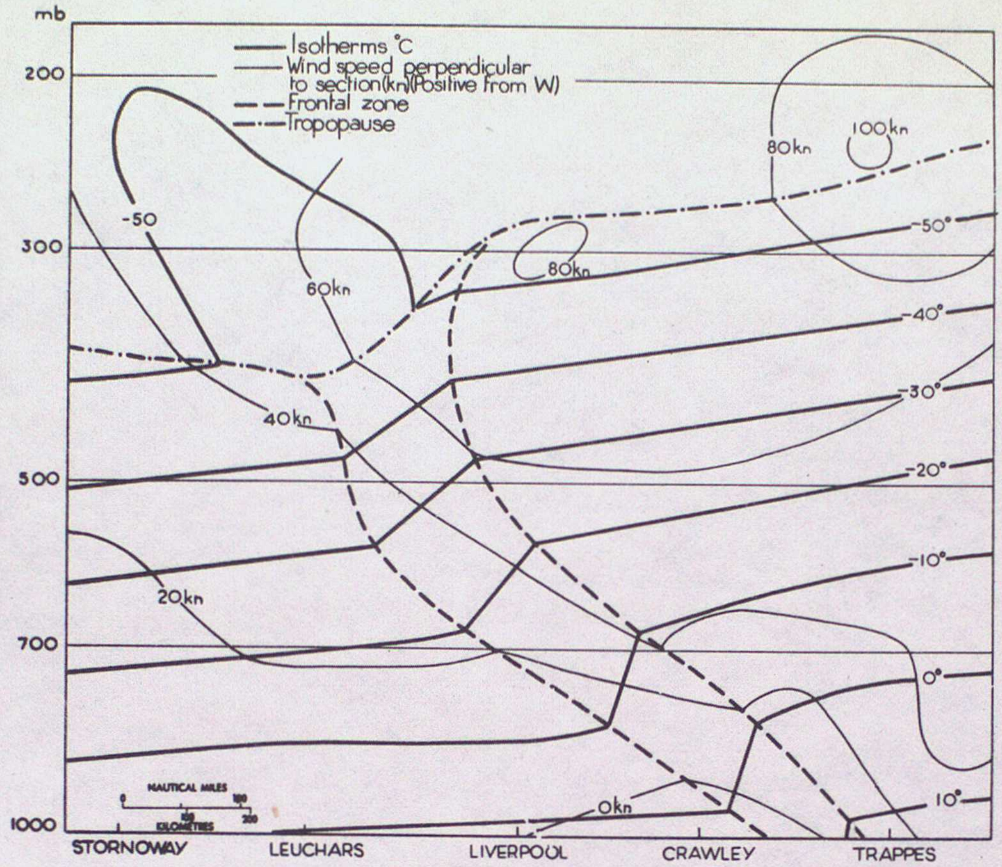

FIGURE 3(b). Vertical cross-section, Stornoway to Trappes, of cold front in Figure 3(a), showing isotherms and isotachs

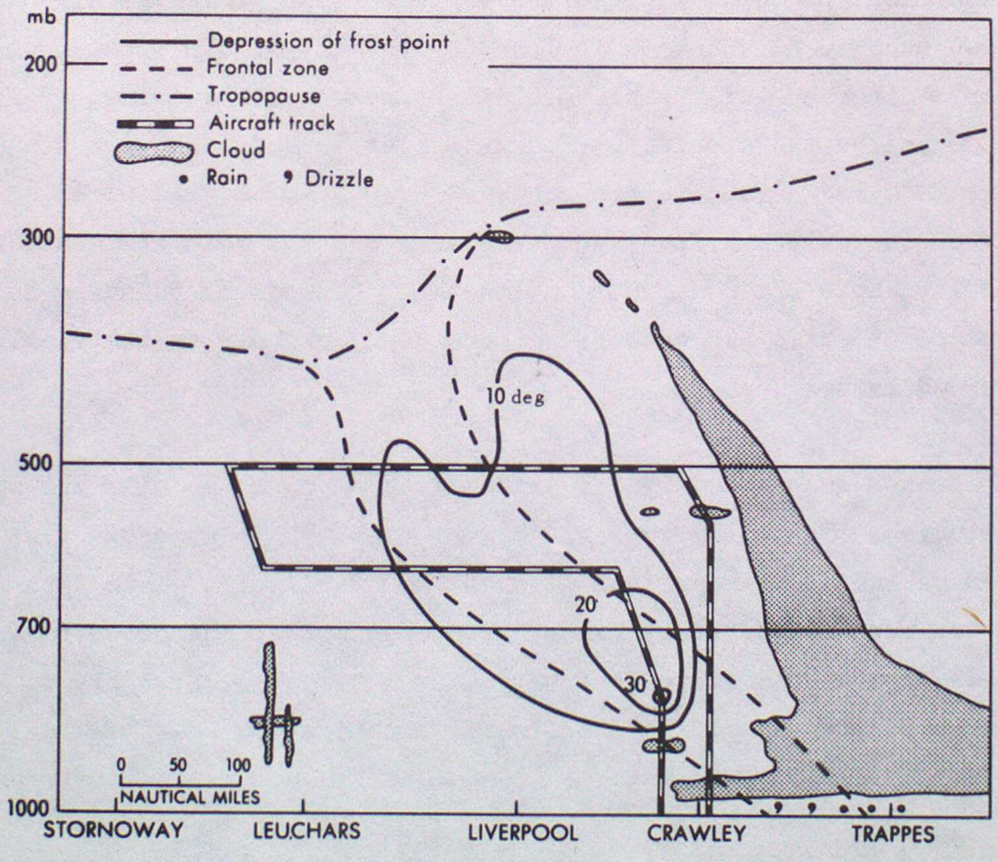

FIGURE 3(c). Vertical cross-section showing humidity and cloud

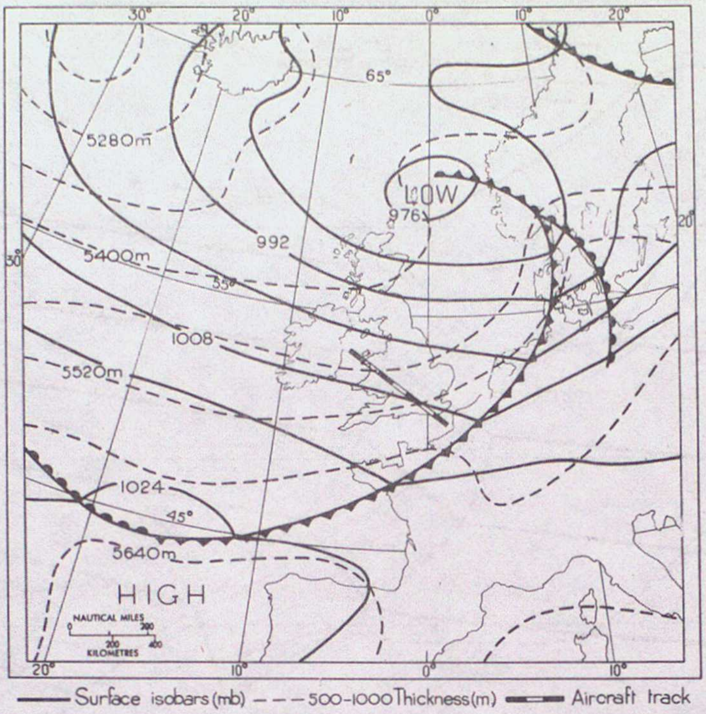

FIGURE 4(a). Synoptic chart for 1400 GMT on 16 September 1954

In contrast, the cold front of 16 September 1954 (Figures 4(a) to (c)) was a good example of a kata-cold front, with very little frontal cloud and a rapid clearance of the cloud at the passage of the front. Below about 4000 metres the frontal surface was clearly defined, with a slope of about 1:110 and a temperature contrast of 9°C in 80 kilometres. Above 4000 metres the original front was very weak and the main temperature contrast lay above the old front and probably showed the boundary between air ahead of it which had subsided a good deal, and air to the rear which had subsided rather less.

Both fronts show very dry air in the frontal zone, as with the warm fronts studied. The cold front of 16 September 1954 also shows very dry air ahead of the frontal surface at about 600 millibars. This type of feature has been discussed by Miles,[6] who found that the dry air had often been drawn from a cold region and warmed by subsidence, probably in a similar way to the dry air in the frontal zone itself.

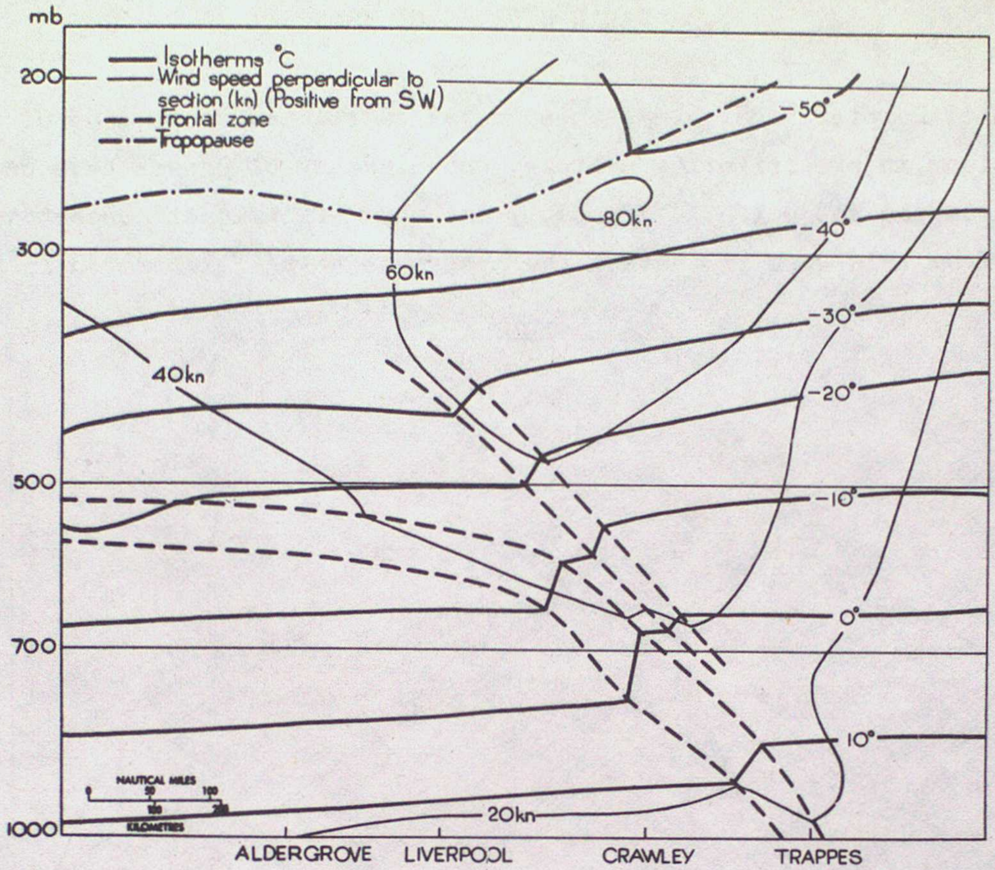

FIGURE 4(b). Vertical cross-section, Aldergrove to Trappes, of cold front in Figure 4(a), showing isotherms and isotachs

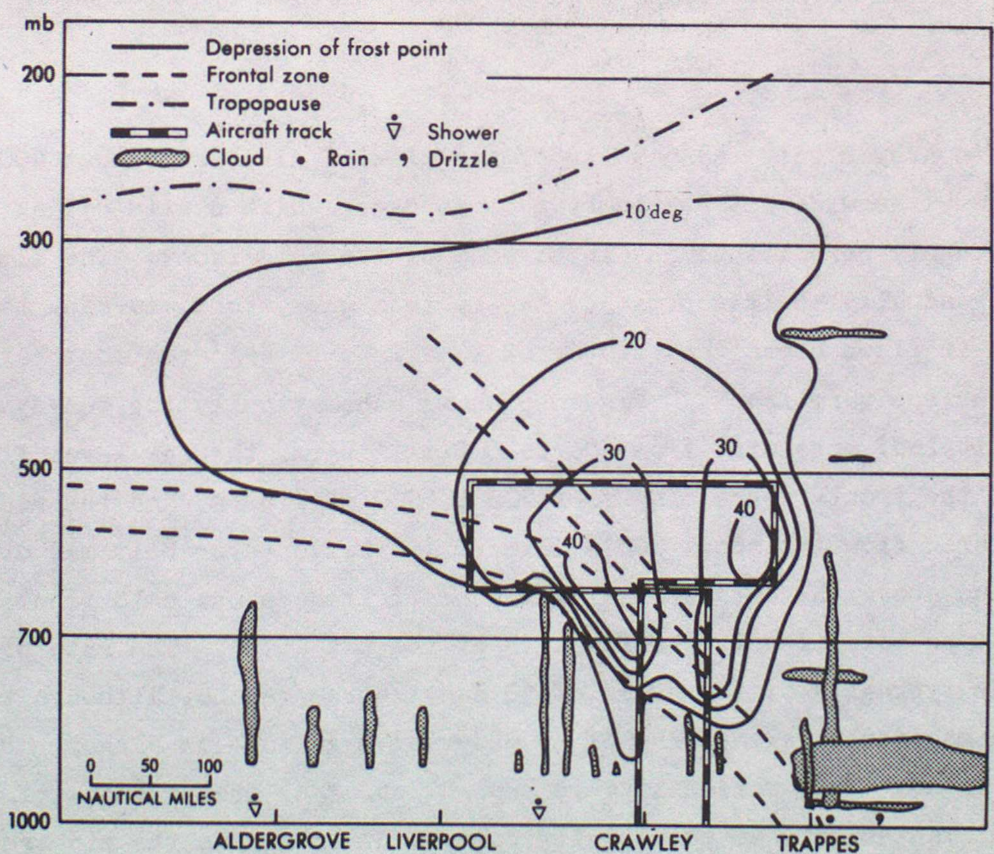

FIGURE 4(c). Vertical cross-section showing humidity and cloud

5.3 RADAR STUDIES OF FRONTS

The use of Doppler radar has enabled detailed studies to be made of the air motions in precipitating systems, and a number of papers have been written on the subject.[7-11] Probably the most significant concept to emerge from this work is that of the 'conveyor belt' illustrated in Figure 5.

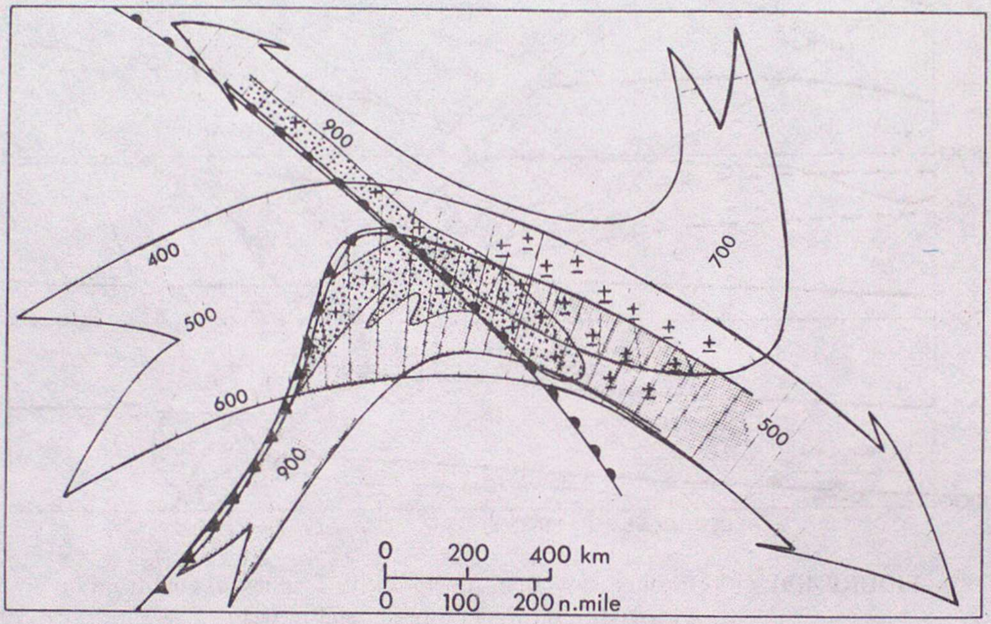

FIGURE 5. Features of large-scale flow which determine distribution of precipitation at the surface

The 'conveyor belt' is a well-defined flow of air, from about 100 to 1000 kilometres wide and a kilometre or so deep, which starts off at low levels roughly parallel to and in advance of the cold front. The flow ascends gradually as it approaches the surface warm front, turning to the right as it flows above the warm frontal surface to become almost parallel to the surface warm front. Figure 5 shows schematically the conveyor belt (stippled) ascending from 900 to 500 millibars, the low-level flow ahead of the fronts descending from 700 to 900 millibars, and the mid-tropospheric flow (at about 500 millibars). The conveyor belt may or may not ascend above the cold frontal surface; if it does the cold front is of the ana-type but, if not, the front is of the kata-type. The rate of ascent is typically of the order of 10 centimetres/second, although there may be a mesoscale variability of an order of magnitude on either side of this value. This variability is brought about by the presence of potential instability as potentially colder, drier air in the mid troposphere flows over the conveyor belt, with convective overturning taking place and producing areas of greater upward velocity and enhanced precipitation. The release of the potential instability occurs in cells typically a few kilometres across, which become organized into clusters of dimensions typically about 20 by 30 kilometres. The clusters themselves are aligned in bands parallel to the conveyor belt - parallel to the cold front in the warm sector, and parallel to the warm front ahead of it. A schematic diagram of the mesoscale vertical velocity distribution in the ascending conveyor belt is shown in Figure 6.

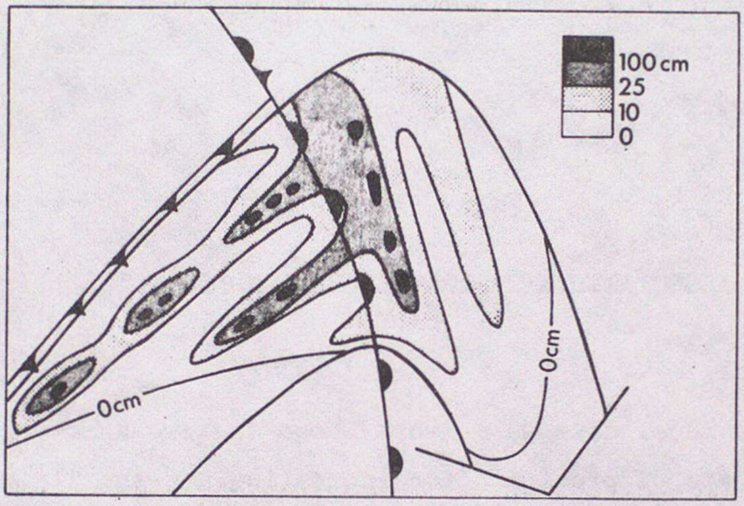

FIGURE 6. Mesoscale structure of the vertical velocity within the ascending conveyor belt

Harrold[7] showed that, in the examples studied, the rainfall pattern and amounts depended more upon the properties of the conveyor belt than on the frontal structure. Calculations of rates of rainfall based upon the dimensions, rates of flow and water contents of the conveyor belts in three examples are shown in Table 5.1; the agreement between calculated and observed values is very good.

The above does not mean that the fronts are not important; the frontal structure undoubtedly influences or determines the properties of the conveyor belt. Also, perturbations of the airflow set up by the fronts, or by orographic features, are probably responsible to some extent for the distribution and activity of the mesoscale precipitation areas when potential instability is present.

TABLE 5.1 The production of precipitation within the conveyor belt

	Inflow parameters				Calculated mean rate of rainfall at base of conveyor-belt	Actual mean rate rainfall at the ground beneath the conveyor-belt
	Width of inflow	Depth of inflow	Total flux of air through conveyor-belt	Influx of water vapour		
	km	*km*	*kg/s*	*g/s*	*mm/h*	*mm/h*
22 Mar 1968	170	2	4×10^9	2.4×10^{10}	1.0 ± 0.25	0.9 ± 0.2
18 Feb 1970	160	2.4	6×10^9	2.6×10^{10}	0.8 ± 0.2	0.5 ± 0.2
16 Oct 1967	650	2.2	25×10^9	20×10^{10}	1.5 ± 0.3	1.1 ± 0.2

5.4 WEATHER ASSOCIATED WITH FRONTS OVER AND NEAR THE BRITISH ISLES

5.4.1 Warm fronts

The classical model of a warm front shows the cloud lowering and thickening, the rate of precipitation increasing and the visibility decreasing at a given place as the front approaches, with cessation of precipitation, or a decrease to drizzle only, at the passage of the warm front. This is, on many occasions, a reasonable approximation to the truth, particularly with fronts moving towards the British Isles from the west or south-west. In detail, however, warm fronts differ considerably from one to another, even in apparently similar synoptic situations. It is difficult, therefore, to give any general guidance, based on synoptic climatology, to help in the forecasting of warm frontal weather. To obtain the best basis for a forecast, the meteorologist must study the latest observations, including those of hourly rainfall, and then assess the likely developments, making full use of available computer products, including rainfall forecasts. This aspect is discussed in Chapter 19 - Clouds and precipitation, which also describes techniques for forecasting cloud.

In spite of the difficulties, however, the following descriptive remarks may be of some use both in analysis and forecasting.

Appreciable rain is likely at a warm front if the water content of the warm air is high to the 800-millibar level or above and some ascent seems likely. If the warm air is dry above 950 millibars the front will generally give only drizzle which may be confined to the west. Douglas[12] remarks that 'in many cases the very high humidity goes up to 900 millibars or only a little higher and the situation is of a marginal type in which definite deductions are impossible at present. Where information is scarce the older air mass conceptions are sometimes useful. A warm air mass from tropical regions is more rain-producing than one which has previously subsided in the subtropical high at 40°-50°N and has not been over a really warm sea long enough to have much moisture in it. If an approaching warm front has tropical air behind it the chances of escaping rain are not high even in the south-east in summer, except in an anticyclone.'

If the synoptic situation shows that the lower tropospheric air in the warm sector is approaching this country more or less directly from tropical regions (say a general current of air below 700 millibars from a direction between about south and south-west) it would be prudent to include a forecast of warm-front rain. Rainfall amounts tend to be less when the general current of warm air arrives from a direction to the north of south-west.

If recent observations show that tendencies are consistently negative and becoming increasingly so, or if the forecast chart indicates that a substantial decrease of pressure is expected, it would be prudent to expect some increase in the extent, amount and intensity of warm-front rain. Experience indicates that a warm front often becomes more active when it approaches a pre-existing thermal band lying parallel to it.

On some occasions there are two or more bands of precipitation ahead of the surface warm front and almost parallel to it, separated by zones of less intense or no rainfall. Browning et alii[8] have described an example in detail; the movement of the rain bands was faster than that of the warm front and seemed more closely allied to the movement of the cold front. These features are consistent with the conveyor-belt ideas described in 5.3. On other occasions there may be one or more rather larger areas of heavier precipitation, moving parallel to the front in a direction away from the low-pressure centre. These areas may be up to

100 kilometres or so across; some may be associated with minor waves on the warm front, but many are not. Wallington[13] showed that hourly observations of rainfall can be used to study precipitation patterns on this scale, and a useful background to the drawing and interpretation of hourly rainfall charts has been provided by Jones.[14]

On some occasions slight rain falling from upper clouds may evaporate whilst falling through lower dry layers and the precipitation fails to reach the ground. When this happens and the front is already degenerate, the medium clouds are thinning and there may be little or no general ascent, so that such fronts may remain virtually devoid of precipitation at ground level. With active fronts associated with general ascent, continued precipitation will soon moisten the dry layer which, if it also becomes subject to general ascent, will soon have a high relative humidity as it undergoes cooling on ascent and clouds will soon form in the initially dry layers.

Orographic effects are important. Since much of the weather moves from the west towards the east and the higher ground lies more to the west than the east of the country, heavier falls of precipitation occur, on the average, in the west but there are individual exceptions. Douglas[12] has commented that experience indicates that warm-front rain weakens more readily as it spreads east when most of the rain is falling out of the lowest 3 kilometres or less. However, if there are dense masses of medium cloud extending to a high level, Douglas considers that a weakening of the rain as the front moves across the country from west to east should not generally be forecast.

5.4.2 Cold fronts

In 5.2.2 it was mentioned that there are two main types of cold front, namely those that are active or inactive (in relation to the weather which accompanies them). These cold fronts are often called ana- and kata-cold fronts respectively.

There is usually an extensive area of upper and high cloud and a substantial band of precipitation to the rear of an ana-cold front. The belt of cloud and precipitation has its major horizontal dimension aligned along the front. In the horizontal direction at right angles to the front the pall of cloud might well extend in a typical case for something like

150 kilometres to the rear. When the cold front is continuing to move away the width of the belt of precipitation often seems to be very close to that of the cloud sheet to the rear of the front. In some cases there is a short burst of heavy precipitation at the frontal passage, followed by a marked clearance of low cloud which reveals the extensive sheet of upper cloud from which precipitation, often of a light (but sometimes moderate) intensity, continues to fall. On some occasions a distinct clear-cut edge of the upper cloud can be seen near the horizon but, in such cases, rain often seems to persist almost up to the time the very edge of the cloud sheet reaches the area.

The weather accompanying kata-cold fronts is different in detail from that associated with ana-cold fronts. Air near the kata-cold-front surface is descending and this descent usually limits the vertical extent of the frontal-cloud system. In many kata-cold fronts affecting the British Isles the top of the main frontal cloud mass probably does not extend much above 3 kilometres, but isolated cumuliform tops may protrude to higher levels. Any higher medium-cloud systems are usually thin and rather patchy. Precipitation amounts are usually small and precipitation does not normally continue after the frontal passage. It either ceases abruptly at or even slightly before the time of passage of the surface front. The cloud systems usually break and clear almost simultaneously with the frontal passage at the surface and, in some cases, small breaks in the cloud system may be apparent a few miles ahead of the surface front. Where the rain ceases and the clouds tend to break somewhat ahead of the front it is usually found that the orientation of the edge of precipitation and the breaks in the cloud are closely parallel to that section of the front. The distance of this pre-frontal clearance from the actual front is variable from case to case but experience suggests that distances of 10 to 40 kilometres would probably be typical.

Some features of both ana- and kata-cold fronts have been listed by Sansom,[15] and a selection of these is given in Tables 5.2 to 5.5.

The data given in Tables 5.2 and 5.3 should enable forecasters to recognize well-marked ana- or kata-cold fronts on actual charts. The problem of forecasting whether a front will become or remain of 'ana' or 'kata' type is rather more difficult. In general cold fronts do not remain solely as a kata-front or an ana-front throughout their existence. Very

TABLE 5.2 Some characteristic surface features of ana-cold and kata-cold fronts (after Sansom[15])

Surface features	*Ana-cold front*		*Kata-cold front*
Temperature	Often a large fall which may be sudden - mean temperature drop 3 degrees.		Changes may be very slight and gradual - mean temperature drop $<$ 1 degree.
Relative humidity	High and changes slight.		Decreases and the fall may be of considerable magnitude and quite sharp.
Precipitation	Generally fairly heavy rain at the frontal passage with steady lighter rain for some time (perhaps 2-3 h) behind the front. A comparison by Sansom showed for each frontal passage an average fall of 6.5 mm.		Amounts generally very slight and frequently nil. The precipitation amounted to only 0.8 mm on average and fell immediately before or during the frontal passage. There was very little post-frontal rain.
Wind	Usually a sharp veer accompanied by a sharp decrease in wind speed.		Wind veer may be very gradual and speed changes usually slight.
Pressure field (frequency of occurrence of sharp, average or weak pressure troughs).	Sharp	7	2
	Average	2	8
	Weak	6	13

occasionally they may do so and Sansom considers that this is most likely to occur when a small secondary depression has formed on a cold front within the upper circulation of the primary depression. In such a case the cold front of the secondary will generally be a kata-cold front as the upper winds will probably have a large component across the front. The more general case of cold fronts will show a transition between 'ana' and 'kata' types both in space and time. It is difficult to generalize but it seems likely that initially the cold front of a developing depression is of 'ana' type over most of its length. Sansom found that most of the kata-fronts were occluding more actively than ana-fronts and it seemed likely that the kata-front occurred first near the centre of an occluding depression and apread outwards along its length. In the final stages of a depression when the upper circulation was well developed there might be a substantial upper flow across the cold front which would then exhibit 'kata' characteristics over substantial portions of its length. However, the formation of wave disturbances might complicate the pattern and cause segments of the front to exhibit 'ana' or 'kata' characteristics. The subsequent variation and movement of this pattern will then depend on the synoptic development of any such wave.

Sansom found no direct relation between the speed of a front and 'ana' or 'kata' characteristics. There did appear to be some slight association with the curvature of the isobars behind the cold front and a greater association with the change in curvature of the isobars in the cold air towards the front. The supporting evidence is shown in Tables 5.4 and 5.5.

Of the other features described by Sansom the following may also be of value. Rather surprisingly Sansom found that, over the British Isles, the mean speed of ana-cold fronts was slightly higher than that of kata-cold fronts. The actual mean speeds for all the cold fronts examined were:

ana-cold fronts	-	20.5 knots
kata-cold fronts	-	17.5 knots
unclassified	-	16 knots

Perhaps the type of ana-cold front most quickly and regularly recognized by forecasters is the slow-moving cold front which is about to return as a warm front. This slow movement in one direction and subsequent return towards another results in a prolonged period of cloud and precipitation in

TABLE 5.3 Some characteristic upper features of ana-cold and kata-cold fronts (after Sansom[15])

Upper features	*Ana-cold front*	*Kata-cold front*
Radio-sonde sounding started in cold air and passing through the frontal layer	No sharp temperature discontinuity. Relative humidities high at all levels. Ascent of warm air led to the high humidities, often saturated conditions, above the front.	A fairly sharp inversion of temperature or isothermal layer with very low humidities at higher levels. The inversion was primarily due to subsidence which was usually occurring in both the warm and cold air masses and the base of the inversion was normally in the cold air.
Wind sounding started in cold air and passing through the frontal layer	The component of wind normal to the front decreased slightly while the component parallel to the front increased rapidly with height. The total backing of the wind from 950 to 400 mb was about 65°. At 500 mb the mean wind direction was inclined at only 16° to the tangent to the front. The mean thermal wind between 950 and 400 mb was almost parallel to the front (actually backed by some 3½°) and corresponded to a thermal gradient of 0.7 degree per 50 km.	The components of wind parallel and normal to the front both increased with height. The total backing of the wind from 950 to 400 mb was only 20°. At 500 mb the mean wind direction was at an angle of 42° to the tangent to the front. The mean thermal wind was inclined some 30° (i.e. veered) across the front and corresponded to a temperature gradient of 0.5 degree per 50 km. (This cross-front thermal wind is an essential condition for an active kata-front and can be readily recognized.)
Relation between the component of wind normal to the front and the speed of the front	The mean speed of the front exceeded at all heights the mean component of wind normal to the front, though the difference was insignificant below 800 mb. Higher up the difference was definite which implied that both warm and cold air masses were ascending.	The mean component of the wind normal to the front exceeded the speed of the front at all levels above the lowest layers, implying that both air masses were generally descending.
Angle between the tangent to the cold front and the mean wind direction in the warm sector some 80 to 240 km ahead of the front	At 700 mb 18° At 500 mb 17°	35° 35°
Average upper wind veer at passage of front	At 700 mb 23° At 500 mb 15°	15° 5°

TABLE 5.4 The curvature of the isobars behind the cold front

	Cyclonic	Straight	Anticyclonic
	Number of cases		
Ana-cold fronts	7	3	5
Kata-cold fronts	7	3	13

TABLE 5.5 The change in curvature of the isobars in the cold air towards the front

	Increasing cyclonic or decreasing anticyclonic	No apparent change	Decreasing cyclonic or increasing anticyclonic
	Number of cases		
Ana-cold fronts	11	2	2
Kata-cold fronts	0	6	17

areas near the turning point. It is accordingly easy to form the impression that ana-cold fronts tend to be slow-moving. Sansom's figures show that this is erroneous. Although some are slow-moving the fact that the mean speed comes out higher than that for kata-cold fronts implies that a number of ana-cold fronts must have moved at quite substantial speeds. Sansom concluded that there is no direct relation between the speed of a cold front and its general behaviour.

In the region of the British Isles there is a seasonal variation in the distribution of ana- and kata-cold fronts. In summer most cold fronts crossing the British Isles are kata-fronts but there are occasional ana-cold fronts. Douglas[12] speculated that the smaller magnitude of the air-mass temperature difference may be the main reason for this, since a large temperature difference is likely to favour the undercutting of the cold air. The mean westerly thermal wind is weaker in summer than in winter and it is therefore improbable that there can be a greater tendency for forward shearing of the upper wind over a cold front. It is probable that the difference in size and character of the sea-level isobaric system in the different seasons is a factor in the problem. A persistent warm anticyclone to south-eastward is favourable for an ana-cold front at its north-western boundary and continental heating tends to eliminate such systems (in summer) at low levels. Moreover summer cold fronts are usually complicated by small lows or troughs coming up from Spain or France ahead of them.

In winter most cold fronts crossing the British Isles are of ana-cold type but there may be an occasional kata-cold front. The seasonal distribution for the British Isles as found by Sansom is given in Table 5.6.

TABLE 5.6 Seasonal distribution of cold fronts

	Winter Dec-Feb	Spring Mar-May	Summer June-Aug	Autumn Sept-Nov
Ana-cold fronts	8	5	0	2
Kata-cold fronts	1	3	10	9
Unclassified	3	4	1	4

5.4.3 Occluded fronts

In a developing depression the precipitation tends to become more intense near the tip of the warm sector and at the warm front when occlusion occurs. If a secondary depression forms at the point of occlusion there is usually a considerable area of precipitation which extends on both sides of the occlusion. Near such secondaries the precipitation is probably seldom purely of frontal origin and general low-level convergence associated with the secondary must often be a factor and, at times, may be the dominant one.

Douglas[12] has remarked that 'the air from the original warm sector can only supply rain for about 24 hours and further rain is maintained by the ascent of the warmer of the two air masses separated by the line of the surface occlusion, which has on average as well defined a trough with it as any other type of front. The lapse rate and humidity come into the problem. The thermal trough is often close behind an old occlusion and there may be an element of instability in the rain belt, though actual thunder is comparatively rare. Such rain bands are often narrow and, once the upper winds back, the risk of much forward spreading vanishes. Probably the continued supply of warmth and moisture from the sea surface to the returning cold air ahead of the occlusion plays a part in maintaining the rain belt, especially in winter when the rain often decreases after the occlusion reaches land and the trough fills up. In summer many occlusions behave as cold fronts when they reach heated land areas.'

Well within a vigorous primary depression, and away from any secondary depression at the tip of the warm sector, the precipitation associated with an occlusion is generally ahead of it. In the earlier stages of occlusion there is often a substantial pressure gradient along the occlusion so that the precipitation is in the form of a relatively fast-moving belt. However, in the later stages of occlusion, particularly with very deep slow-moving depressions, the occlusion in the region of strong winds tends to protrude ahead of the centre so that the front tends to spiral out from the centre. This forward protrusion and spiralling out from the centre usually leads to the occlusion ultimately becoming fairly closely aligned to the winds in the lower troposphere, sometimes throughout much of the troposphere. Such occlusions are slow-moving and precipitation associated with them tends to be persistent. Sometimes it is very persistent and continues even when the occlusion is difficult to identify on a detailed chart and the thermal structure is very weak. During the formation of such an occlusion a tongue of warm air is advected to the north of the centre of the depression and a tongue of cold air moves to the south and east. This leads to a reversal of the normal latitudinal temperature gradient and, although the thermal pattern associated with the occlusion may be very weak, precipitation can nevertheless be very persistent. If there is enough slowing down of the depression, rain from the occlusion can spread to westward of the centre. This is particularly noticeable in eastern districts of the British Isles on occasions when deep depressions slow down on entering the North Sea. The rain is often prolonged and on some occasions has led to historic floods. In addition rain sometimes continues for several hours even after sustained and substantial rises of barometric pressure have set in. Such long-continued precipitation is probably not entirely of frontal origin. In the later stages continued supply of warmth and moisture from the North Sea coupled with coastal convergence and/or orographic uplift are probably important factors in the maintenance of precipitation. The spread back of rain in the rear of a deep depression may occur elsewhere in the British Isles but it is then generally less well marked than in eastern districts. (See also section 6.2.2 of Chapter 6 - Depressions and related features.)

When a succession of occlusions moves eastward into Europe in winter and comes to rest on the fringes of an intense slow-moving continental cold anticyclone, the largest amounts of precipitation associated with such an occlusion generally occur in south-western districts and the precipitation is less intense as the occlusion moves eastwards. When the occlusion becomes stationary the precipitation is often feeble and may die out altogether, even though the thermal contrast across the occlusion between the maritime air to the west and the cold continental air to the east is probably greater than when the front was more active in western districts. Precipitation from such a stationary occlusion usually remains feeble and sporadic until a further trough advances from the west which sometimes invigorates the old occlusion and further precipitation occurs.

On the whole it is the existing rain area, the pressure distribution and the tendency distribution which have the greatest prognostic value when interpreting occlusions in terms of weather. These distributions should be most carefully studied in analysis and short-period forecasting.

On some occasions a long belt of precipitation forms in a non-frontal trough in a large depression. Such a belt of precipitation often exhibits the frontal characteristics of an occlusion although there may be no previous historical evidence for the evolution of an occlusion from warm and cold fronts. When such a belt of precipitation has formed some success in forecasting its movement is usually possible by inserting a pseudo-occlusion at the pressure trough (but the initial development of the rain belt in the trough is often difficult to forecast in advance). On some occasions when there is such a trough in a primary depression and a wave cyclone, which is forming towards the periphery, subsequently moves to a position near the axis of the trough in the primary depression there is an interaction between the trough and wave features which combine and subsequently move as one complex feature exhibiting, in its several sectors, weather characteristic of warm, cold and occluded fronts. This phenomenon has been observed on satellite photographs, and has been termed 'instant occlusion'.

5.4.4 Secondary fronts

When the observational data and a sequence of analysed charts show clear evidence, either at the surface or in the upper air, that the existence of secondary or multiple fronts is well founded, then there is justification for retaining such fronts on analyses and on forecasts also unless the meteorological processes are expected to lead to frontolysis. The remarks of the preceding sections of this chapter may then be applied to interpret these fronts in terms of weather.

There is, however, sometimes a tendency to identify some line of discontinuity on a weather chart (for example the rear edge of a rain area) and to regard it rather indiscriminately as a front. To identify and follow a line of discontinuity is often of great value in short-period forecasting. Experience shows that such lines retain a coherent pattern and shape, often for a few hours, as the weather moves across an area of the chart. It is legitimate to identify such lines and make intelligent extrapolation of both their movement and the change in the currently observed weather which is likely to occur with time and distance. It is wrong, however, to label such lines indiscriminately as warm, cold or occluded fronts and to associate typical weather of a model textbook front with these lines. Experience and judgement usually combine to produce a realistic and sound attitude to the use of secondary or multiple fronts in day-to-day work.

BIBLIOGRAPHY

1. PALMÉN, E. and NEWTON, C.W.; Atmospheric circulation systems. International Geophysics Series, 13, New York, Academic Press, 1969.

2. SAWYER, J.S.; The free atmosphere in the vicinity of fronts. Geophys Mem, London, 12, No. 96, 1955.

3. SAWYER, J.S.; Temperature, humidity and cloud near fronts in the middle and upper troposphere. Q J R Met Soc, London, 84, 1958, pp. 375-388.

4. FREEMAN, M.H.; Fronts investigated by the Meteorological Research Flight. Met Mag, London, 90, (July) 1961, pp.189-203.

5. POTHECARY, I.J.W.; Recent research on fronts. Weather, London, 11, 1956, pp.147-150.

6. MILES, M.K.; Wind, temperature and humidity distributions at some cold fronts over S-E England. Q J R Met Soc, London, 88, 1962, pp. 286-300.

7. HARROLD, T.W.; Mechanisms influencing the distribution of precipitation within baroclinic disturbances. Q J R Met Soc, London, 99, 1973, pp.232-251.

8. BROWNING, K.A., HARDMAN, M.E., HARROLD, T.W and PARDOE, C.W.; The structure of rainbands within a mid-latitude depression. Q J R Met Soc, London, 99, 1973, pp.215-231.

9. BROWNING, K.A. and HARROLD, T.W.; Air motion and precipitation growth within a wave depression. Q J R Met Soc, London, 95, 1969, pp.288-309.

10. BROWNING, K.A. and HARROLD, T.W.; Air motion and precipitation growth at a cold front. Q J R Met Soc, London, 96, 1970, pp.369-389.

11. BROWNING, K.A.; Radar measurements of air motion near fronts. Weather, London, 26, 1971, pp.293-304 (and 320-340).

12. DOUGLAS, C.K.M.; Preliminary monograph on forecasting rainfall and thunderstorms. (Unpublished)

13. WALLINGTON, C.E.; Mesoscale patterns of frontal rainfall and cloud. Weather, London, 18, 1963, pp.171-174.

14. JONES, D.E.; A note on the use of hourly rainfall observations. Met Mag, London, 95, (November) 1966, pp.325-332.

15. SANSOM, H.W.; A study of cold fronts over the British Isles. Q J R Met Soc, London, 77, 1951, pp.96-120.