Interpretation of satellite imagery of a rapidly deepening cyclone

By M. V. YOUNG, G. A. MONK and K. A. BROWNING

Meteorological Office, Bracknell

(Received 12 August 1985; revised 4 November 1986)

SUMMARY

Model output and observational data are used to interpret, in detail, satellite images of a distinctive cloud system several hundred kilometres long which was observed before and during rapid cyclonic development that occurred over England. Conceptual models are forwarded which account for the structure of the major cloud areas and upper-level moisture fields (as observed by water vapour imagery) immediately prior to and following the onset of vigorous cyclogenesis.

The cloud system corresponded to what R. B. Weldon refers to as a baroclinic leaf cloud and was characterized by 'ana' cold frontal ascent. The baroclinic leaf lay within an area of enhanced ascent ahead of a major upper-level trough. A jet streak which originated upstream, propagated rapidly around the base of the upper trough. A tongue of dry air centred on the left flank of this jet streak lay immediately upstream of the leaf cloud and had a major influence on its subsequent development. This intrusion of dry air was well represented by the Meteorological Office fine mesh model, which showed it as a pronounced tongue of recently descended air with high potential vorticity, which originated in the upper troposphere and lower stratosphere. Rapid cyclogenesis occurred as the dry intrusion overran low-level air of high $\theta_v$ within a warm conveyor belt at the southern tip of the leaf cloud. Interaction of the dry intrusion and baroclinic leaf cloud is shown to be particularly important in accounting for the detailed distribution of weather. It also suggests a way of pinpointing the location and timing of vigorous cyclogenesis.

1. INTRODUCTION

Weldon (1979) introduced the term 'baroclinic leaf' to refer to the characteristic leaf-shaped cloud pattern often observed in satellite imagery during the early stages in the development of a mid-latitude cyclone. Weldon's schematic portrayal of the evolution of a baroclinic leaf cloud system is shown in Figs. 1(a)–(e). He refers to the first two of these patterns (Figs. 1(a) and (b)) as a straightforward baroclinic leaf. After several hours, a baroclinic leaf may evolve into a comma cloud (Figs. 1(d) and (e)) which indicates cyclogenesis is taking place. A baroclinic leaf is distinctive in satellite imagery. Its poleward boundary is sharply defined and, though it may be convex, straight or even concave, it more usually has an S-shape of shallow amplitude as shown in Fig. 1(a). With the passage of time, the trailing part of the boundary is eroded as shown in Figs. 1(b) and (c) and a cloud-free slot (dry slot) penetrates into the cloud system to give the comma pattern.

A cloud-free slot of the kind shown in Fig. 1 is due to the intrusion of dry air originating upstream of the cloud system in a region of a tropopause fold. Reed and Danielsen (1959) were the first to suggest that tropopause folding and cyclogenesis are related. More recently, in a discussion of the Presidents' Day storm, Uccellini et al. (1985) linked an explosive cyclogenesis event with the arrival in the lower and middle troposphere of stratospheric air that had originated in an upstream tropopause fold, by slantwise descent along isentropic surfaces. They demonstrated how satellite water vapour imagery could be used to identify the stratospheric extrusion as it entered the developing system. In a paper on satellite image interpretation, Smigielski and Ellrod (1985) noted that the appearance of a dark band (due to dry air) behind a moist S-shaped pattern in the water vapour imagery usually precedes surface development and deepening. They also stated that this dark band, formed by strong subsidence, becomes elongated and larger as cyclogenesis continues. Such dark bands as observed in the water vapour imagery have been referred to as 'dry intrusions' (e.g. Rodgers et al. 1985).
The present study was stimulated by a series of NOAA infrared pictures that showed the appearance and evolution of a baroclinic leaf cloud as a deepening depression approached the British Isles. METEOSAT imagery over a limited area close to the British Isles enabled a detailed analysis to be made during the period of most rapid deepening. In this paper we establish the relationship of the baroclinic leaf cloud during rapid cyclogenesis to the dynamics of the larger scale environment with special reference to a major intrusion of dry air. We also clarify some aspects of the sub-synoptic-scale structure of the leaf and its relationship to the surface weather. The cyclone described in this paper deepened by 30 mb in 15 hours at a latitude of 50°N and met the criterion for a 'bomb' defined in Sanders and Gyakum (1980). The cyclogenesis appeared similar to that shown in Petterssen (1956) in which the initial wave was induced along a cold front ahead of an approaching upper-level trough.

2. SYNOPTIC OVERVIEW

(a) Satellite imagery

The baroclinic leaf cloud described in this paper developed on 26 November 1983: it approached southern Britain from the Atlantic during the period 06 to 24 h (all times GMT). Initially, two distinct baroclinic leaves, labelled C and C' in Fig. 2(b), grew out of a broad, rather uniform belt of cloudiness associated with a baroclinic zone (Fig. 2(a)).
The forward leaf C' ran north-eastwards and dissipated whilst leaf C, the cloud feature discussed in this paper, became a distinctive feature (Fig. 2(c)) and underwent considerable reorientation as the southern portion (H in Fig. 2(d)) accelerated eastwards and began to be eroded. Considerable high cloud formed in the warm air adjacent to leaves C and C'; however, a cloud-free slot was situated ahead of the hook-shaped southern tip (H) of the leaf cloud (Fig. 2(d)). During the cyclogenetic phase some 12 hours after leaf formation, the overall cloud cover expanded, the cloud leaf C forming the head of a vast comma.

The full disc METEOSAT water vapour image available in the METEOSAT Image Bulletin (ESA) for 12 h 26 November suggested a small dry area to the rear of the leaf.
C. During the next 12 hours it elongated into a distinct tongue, a 'dry intrusion', and lay immediately poleward of the baroclinic zone with its forward portion extending into the cyclogenetic region (close to H in Fig. 2(d)).

Also shown in Fig. 2 is the tail portion of a partly convective cloud mass in the shape of an indistinct comma (K) to the west of the baroclinic leaf; it was close to but remained separate from the baroclinic leaf C.

(b) Surface and upper air analysis

Surface analyses for 06, 12, 18 and 24 GMT, 26 November, are shown in Fig. 3. These are broadly similar to analyses appearing in the Meteorological Office Daily Weather Summaries and the Deutscher Wetterdienst European Bulletin but have been slightly redrawn by the authors to incorporate all available data. (The main differences lie in the frontal analysis over Europe and southern Britain.) Before 00 h 26 November, a vast low pressure complex extended from Scandinavia to the central Atlantic. However, during

![Synoptic analyses](image-url)
26 November, pressure in mid-Atlantic was rising as polar air plunged southward behind an eastward moving upper trough. The leading edge of the polar air at the surface was

Figure 4. Subjective 300 mb analyses for (a) 12, (b) 24 GMT on 26 November 1983. Solid contours are geopotential height in decametres, and dashed lines are isotachs in m s$^{-1}$ in the vicinity of jets J1 and J2. Jet maxima are shown by bold arrows.
marked by a cold front which in the infrared imagery was associated with the indistinct comma cloud mass labelled K in Fig. 2(c).

Surface analyses were not simple on the 26 November; broadly speaking, however, a series of minor waves lay between Scandinavia and the Azores in association with a baroclinic zone. One wave, marked LE in Fig. 3, underwent rapid development and lay beneath the baroclinic leaf as it crossed southern Britain on 26 November. The most rapid deepening occurred between 20h on 26 and 03h on 27 November, when central pressures fell by 19 mb accompanied by the formation of an intense low-level circulation. During this time LE travelled rapidly at 23 m s\(^{-1}\) from 255°.

The 300 mb analyses at 12 and 24h on 26 November 1983 (Figs. 4(a) and (b)) show two distinct jet streams, J1 and J2. Jet J1 was centred near 300 mb with its entrance region lying close to the main baroclinic cloud leaf (C). Jet J2 originated well to the rear of the mid-Atlantic upper-level trough (Fig. 4(a)), and propagated at 35 m s\(^{-1}\) around the base of the trough to reach and overtake the southern tip of the baroclinic leaf (Fig. 4(b)) during the stage of most rapid cyclonic development. The distinct tongue of dry air seen in the water vapour imagery appears to have been associated with this jet, and was adjacent to the leaf during its formation late in the morning of the 26 November. The approach of jet J2 and the associated dry intrusion, will be seen in later sections to have played a crucial role in the evolution of cloud and precipitation near the developing depression and perhaps in accelerating the deepening process itself.

(c) Fine mesh model output

The Meteorological Office operational fine mesh forecast model was used to provide dynamical insight into the evolution of the satellite imagery during cyclogenesis. It is a limited area 15-level sigma coordinate model with 75 km resolution near the British Isles. All model diagnostics referred to in this paper are derived from the forecast based on 00h on 26 November. Figure 5 shows forecasts of sea level pressure, and the upper-level jet axis at intervals of six hours. Surface frontal positions shown in Fig. 5 are our interpretation, inferred from the model forecast surface pressure, wind fields and 850 mb wet-bulb potential temperature, \(\theta_w\). The surface cyclogenesis associated with LE was evident on a sufficiently broad scale to be well handled by the model; likewise the upper air pattern. The position of LE was 3° too far east throughout the forecast, as was the position of the baroclinic leaf as inferred from the 300 mb fine mesh relative humidity forecasts. The deepening rate of LE was also slightly too slow. However, the positions of jet J2 and the associated region of very dry air were correctly handled by the model, at least at \(T + 24\) when they were observed by the dense radiosonde network of western Europe and METEOSAT water vapour imagery. The model performance was thus considered sufficiently realistic for detailed diagnosis up to 24 hours, although by 24h on 26 November more weight was placed on observational data when the system reached the relatively data-rich region of the British Isles.

3. Structure of the baroclinic leaf and dry intrusion prior to rapid cyclogenesis

In this section, we use a combination of model output and limited observational data to identify:

1. the structure of the baroclinic leaf C and its associated cold front;
2. the structure of the dry intrusion; and
3. the relationship between the baroclinic leaf cloud and the dry intrusion.
Although we allude to the evolution of the system from 06 h, this section focuses primarily on data at 18 h, at the beginning of rapid cyclogenesis.

(a) The baroclinic leaf cloud

Fields of humidity and vertical motion from the fine mesh model have been analysed in the vicinity of the baroclinic leaf. The leaf was clearly evident in the model as a deep layer of high humidity undergoing large-scale ascent. The 500 mb fields at 06 and 18 h are shown in Figs. 6(a) and (b). Model output indicated that the strong ascent and high humidities present at 500 mb within the leaf extended throughout the troposphere. The baroclinic leaf also lay within a broad region of warm advection. (In Fig. 6(b), the region of high humidity beyond the crosses over north-west England and northern Ireland has not been considered as part of the baroclinic leaf, since it was not associated with organized ascent according to the model nor with significant upper-level cloud in the satellite imagery.) Regions of moist air at 700 and 300 mb defined by relative humidity greater than 90% are shown in Fig. 7, together with the position of the surface cold front.
Figure 6. Model-derived forecast fields of vertical motion and humidity for 500 mb valid at (a) 06 and (b) 18 GMT, 26 November 1983. Areas of moist air, identified by relative humidity greater than 90%, are lightly stippled and enclosed by a dashed line. Areas of ascending (−) or descending (+) motion with a magnitude greater than 5 mb h⁻¹ are enclosed by continuous lines, with areas undergoing ascent emphasized by dense stippling. In (b) the small crosses represent the northern limit of the baroclinic leaf cloud.
(SCF) as suggested by the model. Figure 7 shows that in most places the rear edge of the moist air sloped rearwards into the cold air with increasing height, a relationship that had been true since the beginning of the model forecast period; however, at 18 h dry air aloft was beginning to overrun the SCF south of 45°N. Thus, using the terminology of Bergeron (1937), since the moist air was ascending with 'rearward sloping ascent' (Browning 1985), the cold front had an 'ana' structure north of 45°N, whilst towards the southern tip of the leaf the front was 'split' (Browning and Monk 1982) with the upper front running ahead of the surface front, and the warm air exhibiting 'forward sloping ascent'.

Trajectories of a number of air parcels lying within and behind the baroclinic leaf cloud at 18 h were computed manually from model horizontal wind and vertical velocity fields at three-hourly intervals, and examples of these are shown in Fig. 8. Moist ascending air within the leaf is shown by solid lines: dry descending air behind it is shown by dashed lines. Maximum rates of ascent of the air parcels within the leaf, averaged over the 12-hour period ending at 18 h, were of the order of 10-15 mb h⁻¹. Corresponding rates of descent behind the leaf averaged 5 mb h⁻¹.

An isentropic analysis was performed using model output for 18 h on the 310 K potential temperature surface, winds being computed relative to the velocity of both the southern tip of the leaf and the propagation velocity of jet J2. This shows clearly that the air within the leaf was flowing south to north roughly parallel to its rear edge (Fig. 9). This flow corresponds to what Harrold (1973) described as a warm conveyor belt (WCB). The isentropic relative flow analysis is very crude because it assumed the system was in a steady state, which our system clearly was not; and additionally, dry-bulb potential temperature (θ) was used, rather than the wet-bulb potential temperature (θw) as would have been appropriate for ascending moist air. However, the analysis served to demonstrate the broad pattern of the relative flow. The trajectory and isentropic analyses support one another in showing the presence of moist slantwise ascent of air.
parcels whilst moving through the leaf cloud within the WCB.

(b) The dry intrusion

(i) Overall structure. The dry intrusion was clearly identifiable as early as 06h in the model relative humidity analysis as a zone of very dry air in the upper troposphere lying immediately poleward of jet J2. The relationship of the dry intrusion to the jet J2 at 18h is clearly demonstrated at 300mb in Fig. 10(a) whilst Fig. 10(b) shows that the dry intrusion was also characterized by a tongue of high potential vorticity (PV) along the northern side of the jet suggesting the air to be of stratospheric origin (Hoskins et al. 1985).

A vertical section north to south at 18°W across the dry intrusion, shown in Fig. 10(c), reveals a baroclinic zone within which a tongue of dry air extends from the stratosphere to the lower troposphere. Within the dry intrusion, the magnitude of PV suggests that stratospheric air was present down to 370mb, presumably as a result of recent slantwise descent in the vicinity of the jet. The true extent of the intrusion of stratospheric air was probably not resolved by the fine mesh model. A number of observational studies, such as Uccellini (1986) and those reviewed in Keyser and Shapiro (1986), indicate that narrow tongues (typically 100–200 km in width) of high PV originating within tropopause folds penetrated as low as 700mb in not dissimilar synoptic situations.

(ii) Structure at the jet exit region. Within the exit region of J2, the dry intrusion had a distinctive shape, resembling a ‘hammer head’ lying perpendicular to and across
the jet axis (Fig. 10(a)). At upper levels the hammer head structure is also reflected in the field of \( \psi \). On the 315 K surface shown in Fig. 10(b) a tongue of high \( \psi \) extends across the left exit of the jet; whilst higher up on the 330 K surface a tongue of high potential vorticity is observed across the right exit of the jet, dashed in Fig. 10(b).

The isentropic analysis in Fig. 9 explains how the hammer head structure arose. It shows that, relative to the motion of the exit of jet J2, there is a bifurcation of the flow at the exit: air at the jet left exit turns cyclonically and ascends whilst air in the right exit region turns anticyclonically and descends. The existence of diffuent flow at the leading edge of the dry intrusion, accompanied by ascent within the northern branch and subsidence within the southern branch, was confirmed by a back trajectory analysis (Fig. 11) which was carried out on a series of air parcels which lay within the hammer head at 24 h 26 November. The subsidence within the right-hand branch, of the order of 7 mb h\(^{-1}\) as deduced from parcel trajectories, was observed to be in a region of marked negative vorticity advection (not shown). The ascent of the order of 4 mb h\(^{-1}\) within the left-hand branch was forced by a tongue of locally strong positive vorticity advection embedded within a region of cold advection. In an earlier study of a cyclogenetic event over the east coast of the United States, Danielsen (1966) demonstrated diffuent divergent trajectories of mostly descending air on the 305 K surface using 36-hour trajectories as in the present study. He found that south of the jet axis, the air was of
Figure 10. (a) Relative humidity at 300 mb as derived from the fine mesh model forecast at 18 GMT, 26 November 1983. Areas of relative humidity less than 40% are hatched, and those greater than 90% are stippled. The area assumed to represent the baroclinic leaf cloud is heavily stippled. The axis of jet J2 is represented by a bold arrow. The location of surface fronts derived from the model are shown conventionally. AB is the line of the cross-section in Fig. 10(c).

(b) Potential vorticity (pv) on the 315 K isentropic surface as derived from the fine mesh model forecast.
valid at 18 GMT, 26 November 1983. Potential vorticity is shown as solid lines, values greater than 2 PV units being hatched. Also shown is the southern boundary of the region where PV is greater than or equal to two on the 330 K surface (thick dashed lines), drawing attention to a narrow tongue of high-PV air at the right exit of J2 which matches that occurring at the left exit on the 315 K surface. PV has been calculated on the isentropic surface using the equation $PV = -g(\theta \partial/\partial p)(\xi + f)$, where $\theta$ is the potential temperature, $p$ is pressure, $\xi$ the relative vorticity calculated on the $\theta$ surface, and $f$ the Coriolis parameter. The units used are those suggested by Hoskins et al. (1985) whereby values less than 1.5 represent tropospheric air, and more than 4.0, stratospheric air. Intermediate values characterize a transitional zone.

(c) Vertical section across the dry intrusion along the line AB in Fig. 10(a). The PV contours of 1.5 and 4 units are shown as bold continuous lines. Dashed lines are isotachs showing the westerly component of the wind speed in m s$^{-1}$ for values greater than 50 m s$^{-1}$. Thin continuous lines are isentropes. Dry air with relative humidity less than 40% is hatched. The dry intrusion is characterized by a tongue of low humidity and high PV emanating from higher levels.

Figure 11. Tracks of four air parcels between 06 and 24 GMT 26 Nov. 1983 (dashes — labelled 1 to 4) within the dry intrusion, computed as in Fig. 8. Relative humidity isolines of 40% and 90% (continuous) are used to define the dry intrusion at the beginning and end of the period. (Due to descent of most parcels, isolines are shown at 400 mb at 06 GMT and 500 mb at 24 GMT.) Moist areas (greater than 90% humidity) are stippled. The dry areas enclosed within the 40% isoline are labelled D. Initial and final pressures of each parcel are labelled, whilst the table gives the pressure of each parcel, signified by a different symbol, at 6-hour intervals. Diffusent motion is inferred within the head of the dry intrusion. Parcel 4 ascends as it moves north within the cyclonic branch of the gyre. Parcels 1, 2 and 3 all descend, parcel 1 moving forward along the axis of the dry intrusion whilst 2 and 3 progress into the anticyclonic portion.
Figure 12. Conceptual model derived from fine mesh model isentropic relative flow analyses on the 310 K surface at 18 GMT, 26 November 1983. Two major flows are depicted: the warm conveyor belt (WCB) which ascends rearward above the cold front giving rise to the baroclinic leaf cloud (stippled), and the diffluent flow within the dry intrusion. The left-hand (northern) part of the flow within the dry intrusion represents high-rv air of stratospheric origin ascending at the left exit of the jet J2. The right-hand part represents low-rv air of tropospheric origin which descends at the right exit of the jet. The length of the dashes forming the boundaries of these two flows gives an indication of the height of the flow, short dashes being in the lower troposphere and long dashes being in the upper troposphere. The axis of the jet J2 is shown as a bold, solid line, and the confluent asymptote separating the dry intrusion from the WCB is shown as a bold, dashed line.

tropospheric origin. North of the jet, stratospheric air was present, part of which began to ascend near the tip of the dry slot of the depression.

(c) The relationship between the baroclinic leaf cloud and the dry intrusion

The significant air motions within the leaf cloud and dry intrusion, discussed above, are summarized in Fig. 12. The broad WCB originates at low levels ahead of the surface cold front (SCF) before ascending to form the leaf. The sharp western edge of the leaf marks a confluent asymptote which forms the upper cold front (UCF) at the boundary

Figure 13. Major air flows associated with baroclinic leaf cloud based on Weldon (1975). The two deformation fields shown are schematic: in reality they are superimposed on a general flow from left to right so that the flows at 'b' and 'd', rather than being from right to left, may merely have a minimum component from left to right.
Figure 14. (a) Successive positions of the axes of the model-derived jet J2 and dry intrusion in relation to the observed baroclinic leaf cloud at 06, 12, 18 and 24 GMT, 26 November 1983. The axis of jet J2, as inferred from the fine mesh model, is shown by solid arrows. The dry intrusion, as marked by the axis of minimum relative humidity, is shown as dot-dashed lines. Positions of the baroclinic leaf (heavily stippled) are inferred from polar orbiting satellite data. Positions of the southern tip of the baroclinic leaf at the actual times of the satellite images are marked by crosses. The sudden apparent change in direction after 1550h is due to erosion of the southern end of the leaf cloud as the dry intrusion overran it. (b) Forecasts of potential vorticity on the $\theta = 315$ K surface, as derived from the fine mesh model valid at 06, 12, 18 and 24 GMT, 26 November 1983. Isopleths and shading are as in Fig. 10(b). The axis of maximum potential vorticity on the $\theta = 315$ K surface is shown as a bold continuous line, whilst the southern branch of the axis on the $\theta = 330$ K surface is shown dashed. Note the persistence of the hammer-head shape at the forward part of the dry intrusion.
between the dry subsiding air and the moist ascending WCB. Confluence of these two flows of very different origin was also suggested by the trajectory analysis shown in Fig. 8. The model suggested in Fig. 12 closely resembles that shown in Weldon (1975), reproduced in Fig. 13, which indicates the main motions associated with a baroclinic leaf prior to cyclogenesis. Carlson (1980) also described a case of cyclogenesis where a WCB and a dry tongue originating upstream came together at a major axis of confluence.

Figure 14(a) demonstrates that the relative positions of the dry intrusion and cloud leaf in the conceptual model in Fig. 12 were maintained throughout the evolution of the leaf, at least until the onset of the most rapid cyclogenesis at 18 h. Furthermore, the progress of the dry intrusion is demonstrated elegantly on successive potential vorticity forecasts in Fig. 14(b). It can be seen from Figs. 14(a) and (b) that the hammer head was already forming at 06 h, several hours before leaf formation. The leaf formed within a region of general cloudiness as the head of the dry intrusion associated with jet J2 approached the baroclinic zone associated with J1 from the north-west.

The character of the cold frontal zone in the region of the baroclinic leaf cloud began to change significantly immediately prior to rapid cyclogenesis. At 18 h, in Fig. 12, part of the dry intrusion is beginning to overtake the SCF; a process that subsequently accelerates, leading to the important changes in the character of the cold front referred to in section 3(a), and possibly associated with the onset of rapid cyclogenesis.

4. THE EVOLUTION OF THE LEAF DURING CYCLOGENESIS

During the rapid cyclogenesis that took place between 18 h 26 November and 03 h 27 November, air with high PV at the head of the dry intrusion overran much of the southern section of the leaf and associated SCF. Dramatic changes that occurred in the frontal structure and associated weather, are perceived as having occurred in three separate stages which are discussed below.

Stage 1: Pre-overrunning, before 18 h (Fig. 15(a)). This is the stage discussed in the previous section. The UCF, defined by the leading edge of the dry intrusion aloft, was lagging behind the SCF, with rearward sloping ascent of high-θ_w air occurring within the leaf cloud where the WCB was ascending over the cold air. Although the UCF was just beginning to overrun the SCF near the southern tip of the leaf by 18 h, overrunning did not take place over the northern section of the SCF until considerably later. Indeed, as the northern part of the SCF came within range of the U.K. radar network at 19 h, several line convection elements (James and Browning 1979) were observed along it. According to Browning (1985), line convection often occurs in association with the rearward sloping ascent encountered at an ana cold front.

Stage 2: Initial overrunning, 19–22 h (Figs. 15(b) to (e)). This period was characterized by air at the head of the dry intrusion overrunning all but the most northern section of the SCF, leading to partial overrunning above the high-θ_w air within the WCB. Descending air in the dry intrusion at the exit of jet J2 led to rapid decay of cloud in the southern section of the leaf such that the tip of the leaf cloud progressively retreated north. Whilst this was taking place a new cloud band was developing with its rear edge along the leading edge of the dry intrusion some 100 km east of the SCF (Figs. 15(c) to (d). (This stage of the development as portrayed on the imagery departs from the equivalent stage suggested by Weldon and demonstrated in Figs. 1(c) and (d). In Weldon's example the cold frontal cloudband was part of the original leaf whereas in the present study, the cloudband ahead of the upper cold front formed from an amorphous area of upper cloud within the warm air.)
Figure 15. Sequence of sketches for 26 November 1983 showing the overrunning process in the vicinity of the baroclinic cloud leaf at one-hour intervals during rapid cyclogenesis. Upper cloud boundaries derived from METEOSAT infrared imagery are scalloped. Cloud areas colder than \(-35\,\text{°C}\) are stippled, with denser stippling within the baroclinic leaf, much of which is colder than \(-35\,\text{°C}\) (the inner boundary of the leaf is shown by a dashed line). Growing convective tops are stippled heavily. The leading edge of the dry intrusion aloft, shown by the double line, is taken from the water vapour imagery in (a) and (g), and inferred from changes in cloud pattern in the remaining pictures. The location of the driest air aloft as inferred from the imagery is hatched in (a) and (g). Surface warm and cold fronts are shown conventionally. The locations of radar-detected line convection associated with the surface cold front, at or within 15 minutes of the time of each sketch, are indicated by a thickened line along the front. The surface low is marked by a cross, the central pressure being given in millibars. The bold plus sign shows the location of the maximum pressure fall during the previous hour.

At first the dry intrusion suppressed the cloud tops everywhere where it overran the SCF. The dry air extended ahead of and just to the north of the tip of the cloud leaf, leading to the formation of a 'dry slot' in the satellite imagery. Soon, however, deep convection broke out within the dry slot. As is shown later, the air within the dry intrusion was not only much drier than that within the WCB but also had a relatively low $\theta_w$. The new cloud boundary that began to form ahead of the SCF appears to have been due to the growth of convective cells that originated at the leading edge of the potentially unstable zone associated with the dry intrusion. Thus, this new cloud boundary corresponded to an upper cold front (UCF) marked by a distinct horizontal discontinuity in $\theta_w$. Danielsen (1966) first remarked upon this process in connection with severe storm development at the leading edge of stratospheric extrusions. Indeed, fine mesh model products in the present study show that the leading edge of the PV anomaly on the 330K surface was situated immediately upwind of the cloud boundary corresponding to the UCF. This as we shall see later could have provided the ascent necessary for convective development at the UCF. Within the dry slot, the air within the left branch of jet J2 was ascending particularly strongly and this led to widespread convection breaking out after 21 h. The greatest pressure falls measured over periods of one hour were in this region, just south of the deepening depression centre. By 22 h, air at the head of the left branch of the dry intrusion (see double line in Fig. 15(e)) was approaching the depression centre, and at the same time the depression was reaching its maximum rate of deepening.
Figure 16. Plots of surface wind and precipitation over the British Isles and northern France for 24 GMT, 26 November 1983, along with upper cloud areas derived from METEOSAT infrared imagery. Cloud areas with tops colder than \(-25^\circ\text{C}\) are stippled. Isopleths of wet-bulb potential temperature, \(\theta_w\), greater than \(10^\circ\text{C}\), derived from the surface observations are dashed. Note the sharp discontinuity of \(\theta_w\) at the surface cold front near the depression centre. This was inferred using autographic records from stations in southern England and the Channel Islands.

Stage 3: Mature overrunning, after 22 h (Figs. 15(f) and (g)). Overrunning by the dry intrusion ahead of the SCF continued such that by 24 h (Fig. 15(g)) the UCF was 200 km ahead of the SCF in places. Detailed evidence for this is given in Fig. 16, which shows that the rear edge of the upper cloud deck with its accompanying continuous rainfall is well ahead of the SCF on which an almost instantaneous fall in \(\theta_w\) of around 3 K occurred. The only exception to this general picture of overrunning was just to the south-west of the depression centre, where rearward sloping ascent of the WCB air was maintaining upper cloud at the southern end of the remnant of the leaf cloud. Radar observations indicated the presence of line convection elements at the SCF until about 22 h (Fig. 15(e)) when they finally decayed. Line convection is due to forced vertical ascent of boundary layer air due to a cold density current encroaching into a region of negligible convective instability. The disappearance of the line convection is thought to have coincided with destabilization at and immediately ahead of the SCF as colder, dry air at the base of the dry intrusion began to overrun the warm moist air of the WCB. Ahead of the SCF, in the dry slot, development of extensive anvil cirrus led to the
disappearance of the dry slot as a single upper cloud deck formed which merged with, and became indistinguishable from, the boundary of the original baroclinic leaf cloud.

As shown in section 3 the dry air behind the UCF was characterized by high $\text{pv}$. Thus, during stages 2 and 3, when cyclogenesis was most intense, high values of $\text{pv}$ were being advected over the low-level baroclinic zone associated with the SCF. Hoskins et al. (1985) describe how the arrival of a positive $\text{pv}$ anomaly aloft is often accompanied by surface cyclogenesis which can be particularly marked when there is a warm anomaly or baroclinicity present near the surface and may be further accentuated if the low-level air is moist. This may well account for the rapid cyclogenesis in the present case study. This is supported by the fact that the area of maximum hourly pressure falls (see + symbols in Figs. 15(d) to (g)) was not ahead of the main surface low centre, but at the leading edge of the dry intrusion, ahead of a minor secondary centre in the region of vigorous convection.

5. MESOSCALE STRUCTURE OF THE DEVELOPING CYCLONE

(a) Observational data

This section is concerned with the observations, mostly at 24 h, which are used to construct a schematic model showing the distribution of cloud and rain in relation to the previously diagnosed major air flows.

Figure 17(a) shows the cloud distribution at 24 h in relation to low LE and the surface frontal analysis. Between 22 and 24 h, the baroclinic leaf had become almost indistinguishable from the cloud developing ahead of it (Figs. 15(e) to (g)). Over the Irish Sea, a band of slightly lower cloud tops gradually emerged from beneath the western edge of the leaf after about 23 h. This was possibly associated with the development of a cold conveyor belt (Harrold 1973) as a relative easterly wind field was established at lower levels to the north of the intensifying cyclonic circulation.

The extent of the dry intrusion at 24 h may be partially inferred from the water vapour image in Fig. 17(b). The water vapour channel is sensitive to moisture within a deep layer of the atmosphere, centred near 400 mb (Eyre 1981). In Fig. 17(b), the dry air is seen as a broad tongue lying immediately north of the jet axis. However, the hammer head configuration sketched in Fig. 9 was not well resolved at this later time. This is because the left branch was eroded following transfer of moisture upwards by deep convection, whilst the right-hand branch was partly obscured by the presence of thin cirrus.

Radar rainfall and gauge data were analysed over the U.K. during passage of the baroclinic leaf cloud. Between 22 and 24 h when most of the leaf was over the radar network, radar analyses suggested a gradual reduction in precipitation intensities from south to north through the leaf. Rainfall rates near 4 mm h$^{-1}$ occurred over southern England in the vicinity of the southern tip of the leaf, whereas over northern England a typical rate was 1 mm h$^{-1}$. Over southern England, both gauge and radar data resolved a change from weakly to strongly convective precipitation in the region ahead of the surface cold front as the front progressed from west to east across the country. This was associated with the development of deep convective cloud within the dry slot ahead of the SCF as described earlier.

Figure 18(a) shows a vertical section across the cold front along the line drawn in Fig. 17(a). The frontal structure by this time is that of a split cold front (Browning and
Figure 17. METEOSAT imagery for 24 GMT, 26 November 1983. (a) METEOSAT infrared image. The approximate cloud top temperature in degrees Celsius corresponding to the colours are as follows: white, colder than -45; red, -35 to -45; dark blue, -25 to -35; pale blue, -15 to -25; green, -5 to -15; yellow, +5 to -5; black, warmer than 5. Surface fronts are shown conventionally and the rapidly deepening depression centre is marked LE. The straight line shows the position of the cross-section in Fig. 18(a). B, T, U and S denote the locations of the radiosondes plotted in that cross-section. (b) METEOSAT water vapour image covering the same area as Fig. 17(a). The colour sequence, black, green, blue, red, white, represents increasing amounts of moisture centred around 400 mb, black being driest, white moistest. The axis of jet J2 at 300 mb is shown as a bold arrow. The broad band of dry air is shown lying north of the jet axis.
Figure 18. (a) A vertical section for 24 GMT, 26 November 1983 along the line across northern France and Belgium shown in Fig. 17(a). The dashed lines are isopleths of $\theta_e$, and solid lines relative humidity, regions of greater than 90% humidity and/or cloud being stippled. The scalloped cloud edge represents the upper cold front. Locations of radiosonde ascents are Brest (B), Trappes (T), Uccle (U), and St Hubert (S). Cloud top height information was inferred from METEOSAT infrared imagery, whilst the sharp discontinuity in $\theta_e$ at upper levels was inferred from water vapour imagery. (b) Tephigram for Trappes at 24 GMT, 26 November 1983, the location of which is shown by T on Figs. 17(a) and 18(a). Note the shallow moist zone below 700 mb capped by dry air.
Monk 1982), with the cold front (UCF) being marked by a pronounced drop in $\theta_w$, but only a small drop in temperature (of the order 1 degC in this case). The Trappes ascent at 24 h, shown in Fig. 18(b), was positioned immediately behind the UCF and some 150 km ahead of the SCF. It indicates the dry air with low $\theta_w$ at the head of the dry intrusion above 700 mb, and the shallow moist zone with high $\theta_w$ that lay within the WCB beneath. Just ahead of the UCF, there was a deep zone of almost constant $\theta_w$ where the infrared imagery indicated the growth of convective cells.

After 24 h, the depression moved out of the region for which we have detailed satellite imagery, and into the relatively data-sparse North Sea. Thus, mesoscale analysis during the remainder of the cyclogenetic and mature phases was not possible. However, at the surface, the central pressure reached 961 mb by 03 h on 27 November and, as development slowed, a minimum of 954 mb occurred at 12 h. The region of maximum hourly pressure fall was trackable until 03 h when it lay over the northern Netherlands ahead of the depression centre. The baroclinic leaf had by then become totally absorbed into the vast region of upper cloud above the WCB, whilst slightly warmer tops associated with the top of the emerging cold conveyor belt became a significant cloud feature to the west of the system.

(b) The conceptual model

Information extracted from the above observations, together with model back
trajectory analyses and isentropic analyses using observational data and model output, have been used to construct the conceptual model in Fig. 19. Three major air flows are shown in relation to the major cloud boundaries: they are the dry intrusion, a warm conveyor belt (WCB), and a cold conveyor belt. For simplicity the WCB is split into two conveyor belts, namely W1 and W2. W1 is that portion of the WCB lying beneath the dry intrusion whilst W2 is that part lying ahead of the upper cold front. The cold conveyor belt is associated with the area of medium-level cloud emerging west of the overlying baroclinic leaf after 23 h. The overall precipitation pattern has largely been discussed above; however, we note here that the precipitation within the shallow moist zone (shown by comma symbols) was generally light and intermittent. This was especially so remote from the low centre where, as shown in Fig. 18(a), the WCB was less than 3 km deep (see Trappes ascent, Fig. 18(b)).

The conceptual model in Fig. 19 describes the major airflows and surface weather throughout the rapid deepening phase of the depression. Although the system was clearly evolving, the overall relationship of the component air masses to each other remained essentially unaltered.

6. DISCUSSION

We have seen in the preceding sections how the appearance and subsequent evolution of signatures of two distinct features in satellite imagery—the baroclinic leaf and the dry intrusion—were related to dynamical processes which had a dramatic effect in increasing the rate of deepening of a wave depression and in influencing large-scale and local weather over southern England late on the 26 November 1983.

Inspection of all METEOSAT imagery in the vicinity of the British Isles since summer 1984 indicates that the dry intrusion/baroclinic leaf couplet occurs frequently. As suggested by Weldon (1979), baroclinic leaves are not necessarily indicators of cyclogenesis although many do appear prior to the deepening of a surface low. Cyclonic rotation of the leaves normally occurred, although not always with overrunning as in this case study. Often the SCF remained beneath the upper cloud shield, although in such cases the upper cloud in the south-west quadrant usually thinned and sometimes dissipated.

Dry intrusions were always found to be present when significant surface cyclogenesis occurred within a marked baroclinic zone. Water vapour imagery often showed the area of dry air to be hammer-head shaped. Sometimes, however, only a narrow tongue of dry air was present. In such cases it originated immediately next to a jet stream, with the leading edge forming a dry slot within the developing cyclonic system. Occasionally, very narrow distinct dry tongues were associated with explosive deepening, for example on 17 October 1984 when a decrease of central pressure of 24 mb in six hours occurred off western Ireland giving storm force winds. NOAA-6 infrared imagery indicated the formation of a narrow dry slot on 13 August 1979, prior to rapid development of a very vigorous storm (the Fastnet storm), suggesting that a marked dry intrusion was already present.

Other authors have studied air flows in maturing cyclones, for example Danielsen (1966, 1967), Weldon (1975, 1979), Carlson (1980), Uccellini et al. (1985) and Uccellini (1986). A theme common to all of these studies was the influx of dry air in the upper troposphere into the rear of the developing system, associated in some cases with a marked jet streak. An analysis of a wave depression over the U.S.A. by Carlson (1980) showed the presence of a dry, historically descending flow of air into the rear of the
system. Uccellini et al. (1985) demonstrated that the explosive cyclogenesis of the 'Presidents' Day storm' was linked to the eastward movement of a marked dry tongue in the water vapour imagery which appeared some 12-24 hours earlier. They showed that the dry tongue was associated with stratospheric air, identified by high $pv$, which descended along isentropic trajectories to as low as 700 mb. Although water vapour imagery was not presented, Uccellini (1986), in an analysis of the QE II storm, shows that an intense frontal zone was present to the rear of the storm prior to cyclogenesis, with dry air extruded from the stratosphere extending within a tropopause fold to below 700 mb. Using ALPEX data, Buzzi et al. (1984) observed high ozone concentrations characteristic of stratospheric air, within a descending tongue of dry air following cyclogenesis in the lee of the Alps. The above studies confirmed the results obtained by Danielsen (1966, 1967) which were made before the widespread availability of satellite imagery.

The storm studied in the U.S.A., lee cyclogenesis, and the case described in this paper are related through the observations of marked intrusion of stratospheric air into the troposphere. However, the environments ahead of the dry intrusions were rather different. In our study a baroclinic zone extended throughout the troposphere whilst the Presidents' Day storm occurred when a marked short wave upper trough approached a low-level baroclinic zone due to a coastal front (Bosart 1981). Lee cyclogenesis occurs when an existing upper-level disturbance overruns the warm low-level air of the Mediterranean. Hoskins et al. (1985) in their review of $pv$ stated that cyclogenesis is likely as a region of high $pv$ aloft overruns a low-level baroclinic zone. This applies to all of the above three situations.

The appearance in water vapour imagery of an anomalously dry area adjacent to an upper jet, which then elongates into a dry intrusion and approaches a region of enhanced baroclinicity, should be noted by forecasters. In a data-sparse region, the position of the jet itself may be inferred from water vapour imagery (Weldon 1985) as may the approximate position of a shallow wave. Such observations may provide valuable additional information on the likely location and timing of cyclogenesis. Further evidence of cyclogenesis or an intensification of the rate of cyclogenesis may be inferred from the development of convection near the depression centre. Bosart alluded to the possible role of CISK in the sudden increase in the rate of the deepening as widespread convection broke out at the beginning of the Presidents' Day event. In the present case the onset of convection located just south of the depression was related to the most rapid pressure falls in that area. Morris (1971) in a discussion of the quasi-geostrophic omega equation in a case of rapid cyclogenesis off south-west England, argued the importance of convection from the surface contributing to the rate of deepening of the low.

Although rapid cyclogenesis almost invariably culminates in a comma-shaped cloud pattern, the histories of the systems as observed in satellite imagery are not necessarily similar. Mullen (1983) summarized four synoptic scenarios that may lead to rapid cyclonic development that meets the criterion for a bomb. The present case study represents one of these scenarios, which Mullen describes as occurring when a mobile upper trough advances towards the trailing edge of a surface cold front. Rapid deepening of the induced frontal wave then proceeds. This resembles the 'meridional trough cyclogenesis' category described by Weldon (1975). The cyclogenesis described by Bosart (1981) and Uccellini et al. (1985) corresponds to another of Mullen's classes, whereby a cold air low becomes the dominant feature accompanied by the development of an 'instant occlusion'. Mullen also described a hybrid of the two, in which a cold air low and a frontal wave amalgamate into a double-centred vortex, both separate features meeting the criterion for a bomb. Mullen's fourth category occurs when a polar air cyclone undergoes rapid deepening
without the merger of its associated comma cloud and the main frontal band: examples of such systems have been studied by Reed (1979).

The ascent within the moist air which gives rise to the upper cloud canopy and precipitation (and sometimes to a baroclinic leaf cloud) was described by Danielsen (1966) and demonstrated in terms of a warm conveyor belt by Harrold (1973). Carlson (1980), Browning and Hill (1985), and now we in the present study, propose conveyor belt models to explain the precipitation distribution. We believe that the synoptic-scale processes, observable through the medium of satellite imagery and crystallized in the two conceptual models shown in Figs. 12 and 19, are present in many cyclogenesis events, and that such models may be usefully applied by a forecaster to anticipate local weather. The conceptual models may be used in isolation from or more usefully in conjunction with numerical forecast models. For example, the precise location of a jet streak may be inferred from the dry intrusion which may then be used to refine the output of a forecast model.

We have stated above that some baroclinic leaf/dry intrusion events occur with dry air overrunning the surface cold frontal zone whilst others do not. We cannot say at the present time whether further studies will demonstrate that satellite imagery may be used to predict the final relationship between the baroclinic leaf and dry intrusion. Nevertheless it is likely that the application of a small number of conceptual models, illustrating distinct phases in the evolution of the system, will be valuable to the forecaster for anticipating the surface weather.

7. Conclusion

NOAA imagery, enhanced METEOSAT imagery, and numerical model output have provided a major information source in this study of the structure and evolution of a distinctive leaf-shaped cloud system which was observed before and during rapid cycloonic development over southern Britain. This so-called baroclinic leaf cloud developed from a general area of upper-level cloudiness some 8-10 hours before the most rapid cyclogenesis. It lay in a region of enhanced ascent ahead of a major upper trough and was maintained by a warm conveyor belt flow undergoing rearward sloping ascent, originating at a sharp surface cold front.

The position of formation of the leaf cloud and its subsequent motion were closely related to the location of an upper tropospheric jet streak which originated upstream of the leaf. A so-called dry intrusion has been identified as an important feature of this jet. This is a region of air of low humidity lying along the jet, much of which has undergone recent slantwise descent from the stratosphere, splaying out in a hammer-head configuration at the exit region. It was evident in numerical model humidity and potential vorticity fields in the middle and upper troposphere, and its location was identified as a distinct dry tongue in satellite water vapour imagery.

The developing cycloonic system has been represented in terms of two conceptual models both of which indicate two primary airflows: an ascending moist warm conveyor belt flow which gives rise to the leaf cloud, and a subsiding dry air flow constituting the dry intrusion (Fig. 19). A change in relationship between the two airflows as part of the dry air overruns air within the warm conveyor belt, is simply described by the models, which also explain the changes in surface weather near the developing low and surface cold front. As the dry intrusion and its attendant upper-level potential vorticity anomaly propagated eastwards overtaking the surface cold front and part of the warm conveyor
belt to the south of the leaf, two major events occurred:

1. Rapid deepening of the cyclonic circulation took place as the dry intrusion was advected over warm moist air at the surface (Hoskins et al. 1985).

2. A split front structure of the kind described by Browning and Monk (1982) formed rapidly, the forward edge of the dry intrusion constituting the upper cold front.

The formation of the split front led to an overall change in the precipitation pattern owing to the formation between the upper cold front and the surface cold front of a shallow moist zone (SMZ) surmounted by the overrunning dry intrusion. The SMZ was characterized by light rain and drizzle. However, ascent of the dry air within the left-hand branch of the dry intrusion led to destabilization above the northern portion of the SMZ and development of vigorous convection within the dry slot of the developing cyclone.

This study draws attention to three features on satellite imagery that could have applications in forecasting:

1. The distinctive 'baroclinic leaf cloud', which is seen as a useful precursor of cyclonic development.

2. The 'dry intrusion', seen as a 'dark band' on water vapour imagery and often producing a 'dry slot' in the cloud imagery, at whose forward edge heavy convective outbreaks are liable to occur.

3. The 'split front', with its characteristic precipitation distribution.

Acknowledgments

We are indebted to Harry Otten for bringing this case to our attention and supplying the NOAA satellite pictures. We also thank Brian Hoskins and Glen Shutts for comments and suggestions regarding the use of potential vorticity charts, Michael McIntyre and Toby Carlson for their comments on the first manuscript, and many staff of the forecasting research and dynamical climatology branches within the Meteorological Office for their assistance with the computer programming.

References


Hoskins, B. J., McIntyre, M. E. and Robertson, A. W. 1985 On the use and significance of isentropic potential vorticity maps. *ibid.*, 111, 877–946

James, P. K. and Browning, K. A. 1979 Mesoscale structure of line convection at surface cold fronts. *ibid.*, 105, 371–382


