Mesoscale analysis of a polar trough interacting with a polar front

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SUMMARY

The interaction of a polar trough with a polar front can lead to a characteristic satellite cloud pattern commonly referred to as an instant occlusion. The detailed structure and development of an event rather resembling an instant occlusion is analysed in this paper using routine data supplemented by additional radiosondes, soundings and cloud imagery from NOAA-7 and Meteosat, and radar network pictures. The event presented differs from an instant occlusion as described by Anderson and others in that a band of polar front cloud developed simultaneously with the band of cloud associated with the polar trough rather than being a pre-existing feature. Thus we refer to it under the different name of pseudo-occlusion in order to keep this distinction in mind. A conceptual model of the pseudo-occlusion is developed in which the key elements are (i) a moist, relatively warm, low-level jet associated with the polar trough, referred to as the 'polar trough conveyor belt', and (ii) a major upper-level jet streak associated with the polar front, referred to as the 'polar front conveyor belt'. The two conveyor belts intersect almost at right angles. Precipitation associated with the polar front is predominantly from stratiform cloud, whereas that associated with the polar trough is a mixture of stratiform and convective. Just on the poleward side of the upper jet the cloud top drops abruptly. Here, dry air having recently descended beneath the tropopause fold, suppresses the depth of the moist air associated with the polar trough conveyor belt. This leads to a minimum in the intensity of precipitation between the rain areas associated with the trough and the front. Although the air overrunning the trough just on the poleward side of the polar front is dry as a result of earlier descent, the air in this location is likely to have begun ascending as part of the indirect circulation in the exit region of the upper level jet streak. The polar trough low-level jet probably forms part of this circulation.

1. INTRODUCTION

This paper is concerned with the mesoscale structure and development of a phenomenon that in many respects resembles an instant occlusion. As first discussed by Anderson et al. (1969), an instant occlusion is a lambda-shaped cloud pattern seen in satellite imagery, formed when a trough associated with a small cloud vortex in the polar air excites and joins up with a wave on the main polar front cloud band. The lambda-shaped cloud pattern looks like a classical occlusion but its origin differs from that envisaged in the Norwegian model (Bjerknes and Solberg 1922).

A schematic representation of the process of instant occlusion is shown in Fig. 1(b), according to which the manner of formation is intermediate between that of a simple comma cloud and a frontal wave (Zillman and Price 1972). When the active part of a short wave trough is far from the polar front a comma cloud or vortex forms entirely within the polar air (Fig. 1(a)). The comma cloud in this circumstance is quite distinct from the frontal cloud band, which may dissipate. When the short wave trough is active in the region of the polar front a frontal wave forms, with a cloud pattern whose appearance evolves along the lines of the classical model (Fig. 1(c)). Between these extremes lies the instant occlusion in which a comma cloud links up with a deforming frontal cloud band (Fig. 1(b)). In keeping with traditional analysis procedure Zillman and Price have labelled the cloud associated with the polar vortex in Fig. 1(b) as an occlusion and the polar front band has been shown as providing the warm and cold fronts. This convention is simplistic and can be misleading since it implies an occlusion mechanism that may not be occurring.

The so-called instant occlusion process has been studied worldwide, e.g. by Zillman and Price (1972) over the Southern Ocean, by Weldon (1979) over the U.S.A., by Reed (1979) and Locatelli et al. (1982) over the north Pacific Ocean, and by Thepenier and
Figure 1. Schematic depiction of three basic sequences of vortex development evident in satellite imagery: (a) development of a comma cloud; (b) development of an instant occlusion; (c) development of a frontal wave. The figure, derived from observations over the Southern Ocean, is identical to that of Zillman and Price (1972), but it is inverted here so as to apply to the northern hemisphere. Frontal symbols indicate one scheme for representing the various evolution sequences using the tools of conventional frontal analysis. Labels I, II and III indicate, respectively, a region of enhanced convection, a decaying cloud band and a convective cloud region merging with the frontal cloud band.

Cruette (1981) over the North Atlantic Ocean. All agree that it is a common occurrence. Unfortunately, there is rather little known about the structure and evolution of instant occlusions. Thus the instant occlusion is a frequent source of difficulty in the interpretation of synoptic charts and satellite imagery. In this paper we shall present detailed analyses of the cloud, precipitation, and thermodynamic structure of a system resembling an instant occlusion that travelled over the British Isles; we then distil these analyses into a simple conceptual model the purpose of which is (a) to help the analyst understand what is happening and (b) to help him interpret his charts in terms of probable weather.

Figure 2 is a satellite cloud photograph of the particular event that is the subject of the case study in this paper. In this case all the surface frontal features were provided by the polar trough which travelled beneath, and was distinguishable from the polar front cloud band. As is often the case, however, the frontal characteristics of the polar trough were rather weak and we later suggest that perhaps a more important attribute of the polar trough was the low-level jet of air with high wet-bulb temperature which was oriented along the trough axis, beneath and at right angles to the major upper-level jet associated with the polar front cloud band. Figures 3(a) and (b) show operational Meteorological Office surface analyses three hours before and after the time of the satellite picture in Fig. 2. The cloud system of interest was associated with low Y moving in behind an older cloud system associated with low P. The operational frontal analysis is confusing in that it changes abruptly from Fig. 3(a) to 3(b). Figure 3(a) recognizes the existence of the polar trough, albeit with a falsely exaggerated curvature, which was associated with a small wave on a secondary cold front. However, in Fig. 3(b) the trough has been dropped from the analysis, the secondary front has been connected to the old cold front associated with low P and an attempt has been made to force the classical
Figure 2. Visible imagery from the NOAA-7 satellite depicting a cloud system over SW Britain at 1502 GMT on 9 September 1983. The cloud system is composed of two parts as labelled—the polar trough and polar front cloud bands. The cloud in the northern part of the picture is associated with an older frontal system.
(Courtesy of University of Dundee Electronics laboratory)

Figure 3. Meteorological Office operational surface analyses for (a) 12 GMT and (b) 18 GMT on 9 September 1983.

Frontal wave model to fit the cloud features associated with both the polar trough and the polar front.
The event described in this paper will be seen to differ from the conventional instant occlusion process described by Anderson and others in that the band of polar front cloud developed simultaneously with the band of cloud associated with the polar trough; moreover it developed some distance on the cold side of the remnants of the old cold front. In recognition of this distinction we shall refer to this event under the different name of pseudo-occlusion. The event is nevertheless similar to a conventional instant occlusion insofar as the newly developing frontal cloud band and the old frontal cloud band were both associated with the same large-scale upper-level jet, albeit with different locally intensified portions or so-called jet streaks. Perhaps the pseudo-occlusion described in the paper can be regarded in some ways as intermediate between the comma development and the instant occlusion as depicted in Fig. 1.

2. DATA SOURCES

The structure and development of the pseudo-occlusion that crossed the British Isles on 9 September 1983 has been investigated using a variety of data as follows:
(a) surface analyses from conventional stations supplemented by ship reports;
(b) upper air analyses using routine radiosonde data supplemented by extra ascents at carefully selected times from six stations in England and Wales, and using soundings from the TIROS-N Operational Vertical Sounder (TOVS) produced as described by Eyre and Jerrett (1982);
(c) detailed cloud patterns from polar-orbiting satellites as obtained from Advanced Very High Resolution Radiometer (AVHRR) imagery;
(d) sequences of cloud and rainfall patterns obtained from Meteosat and the U.K. Weather Radar Network, respectively, described by Browning and Collier (1982).

Analysis methods are mainly straightforward; where any non-standard approach is used it will be identified within the body of what will otherwise be a phenomenen-oriented presentation.

3. DEVELOPMENT OF THE PSEUDO-OCCLUSION

The first signs of the developing pseudo-occlusion were detected by satellite at 15 GMT on 8 September about 1000 km west of an old frontal system crossing the U.K. (Fig. 4(a)). At the time all that could be seen was a region of cumuliform cloud in the polar air, just south of a cold pool and co-located surface low, with a small band of layer cloud south of it which was associated with a jet streak (i.e. a localized maximum in the main upper level jet stream). The band of layer cloud was at the south-eastern end of the warm front of a depression in the western Atlantic, the front remaining stationary west of a ridge over the North Atlantic. By 05 GMT on 9 September (Fig. 4(b)) the region of cumuliform cloud had become organized into a cloud band associated with a polar trough (broken hatched shading with cumulus symbols), the northern end of the cloud band becoming wrapped around the cold pool and surface low. In Fig. 4(b) the southern end of the polar trough cloud band, near the exit of the upper jet streak, can be seen to have merged with the developing band of layer cloud associated with the main polar front to form the pseudo-occlusion. The polar front cloud associated with the pseudo-occlusion (densely hatched shading) was still distinguishable from the remnants of cloud associated with the old cold front ahead of it (widely spaced broken hatching). At this stage there was no sign of the polar front cloud band being deformed in the vicinity of the nearby polar trough. By 15 GMT on 9 September, however, there was evidence of the development of slight anticyclonic curvature of the polar front cloud band where the
polar trough joined it (Fig. 4(c)) and this was still the case at 05 GMT on 10 September (Fig. 4(d)). Meanwhile the polar trough and the polar front cloud band both had been swinging around the advancing cold pool with their orientation at the point of intersection remaining almost at right angles. Throughout the period displayed in Fig. 4 the pseudo-occlusion cloud system was catching up with the older frontal system ahead of it; in Fig. 4(d) they can be seen to have merged.

Figure 5 gives a detailed depiction of the evolving cloud pattern associated with the pseudo-occlusion during the period 10 to 16 GMT on 9 September as seen in the infrared (IR) imagery from the geostationary satellite, Meteosat. The two main regions of high cloud, associated with the polar trough and the polar front, are clearly portrayed. There is, however, a conspicuous lowering of the cloud tops southwards along the polar trough just before they are obscured by the high tops associated with the polar front; this is a significant feature which is discussed in section 4. A confusing feature in Fig. 5(a) (and to a lesser extent in Figs. 5(b) and (c)) is a tail of high cloud at the south-west end of the high cloud portion of the polar trough. This makes it appear as though the southern end
of the polar trough curves around parallel to the polar front and may have been responsible for the exaggerated curvature of the polar trough in the official analysis in Fig. 3(a). In fact this tail was a minor wisp of high cirrus parallel to the main polar front cloud band and, as we shall confirm later, the polar trough actually intersected the polar front cloud band almost at right angles in the region where low cloud can be seen occupying the gap between the high cloud associated with the polar trough and polar front. The relationships of the polar trough and the polar frontal cloud bands over the period 10–16 GMT are sketched in Fig. 5(e).

Figure 6 shows analyses of the surface wet-bulb temperature, $T_w$, (a) at the time of initiation of the pseudo-occlusion and (b) when the pseudo-occlusion was well developed. The pseudo-occlusion formed within the leading portions of the cloud masses drawn in Fig. 6(a); this area of cloud was associated with a fresh surge of high $T_w$ air behind the old cold front. Figure 6(b) shows a pattern of $T_w$ characteristic of the mature pseudo-occlusion. Key features are the narrow tongue of high $T_w$ in the polar trough extending from the Cherbourg Peninsula across south Wales to southern Ireland and the penetration of low $T_w$ air beneath the polar front cloud band as far as the Channel Islands. This is consistent with the view that the polar trough extended underneath and at right angles to the polar front cloud band. The tongue of high $T_w$ in the polar trough was well reproduced by the fine mesh model forecasts issued by the Meteorological Office. Figure 6(c) shows this tongue at 850 mb as forecast at 6-hour intervals as it approached the British Isles. This figure also shows that the tongue of high $T_w$ associated with the polar trough remained close to the exit of the upper level jet streak.

4. **Mesoscale Structure of the Pseudo-Occlusion in Its Mature Phase**

   (a) Three-dimensional thermodynamic structure

   The purpose of this section is to describe the three-dimensional structure of the entire pseudo-occlusion, with particular reference to the polar trough, both where it was situated within the polar air mass and where it was interacting with the polar front.
Figure 6. (a and b). Analyses of surface wet bulb temperatures $T_w$ at 18 GMT on (a) 8 September and (b) 9 September, 1983. The analyses over the NE Atlantic in both cases are based on measurements from ships located at the solid circles, at 18 GMT and at the open circles at 12 GMT. In (a) the areas of convective and layered cloud, parts of the leading edge of which eventually combined to form the pseudo-occlusion, are shown by cumulus symbols and horizontal hatching, respectively. In (b) the shading shows the mature pseudo-occlusion, the main area of mixed cumulus and broken hatched shading corresponding to the polar trough and the large band of dense hatching corresponding to the layered cloud associated with the polar front. In both diagrams the older cloud system to the east of the pseudo-occlusion is represented only by frontal analyses (the frontal analyses are our own and that of Fig. 6(b) differs from the corresponding operational analysis in Fig. 5(b)).

The thickness patterns in Fig. 4, derived from TOVS soundings, whilst superior in spatial resolution to those derived from routine radiosondes alone, did not reveal any very significant features associated with the polar trough even during its mature phase. This is partly because the positive temperature anomaly within the polar trough occurred almost entirely within cloudy air where TOVS IR soundings could not be obtained. It is also because the temperature anomaly was in any case quite small. In fact the anomaly in temperature was associated with an anomaly in moisture to produce a rather more significant anomaly in terms of wet-bulb temperature. Such a feature is best resolved using radiosondes but, because of the small scale of the polar trough, a rather dense network of sondes was required to study it. We achieved this economically by arranging for the release of a small number of additional sondes at carefully selected times from Aberporth, Larkhill and Malvern and by arranging for the routine 18 GMT wind-only ascents at Aughton, Camborne and Crawley to be converted to full radiosonde ascents. We then took all of the soundings made during the period 10 to 18 GMT and, displacing each one horizontally according to a system velocity appropriate to its own location, we located them in relation to the cloud pattern obtained from Meteosat at 1330 GMT. This gave a distribution of soundings as shown in Fig. 7. We would have benefited from a larger number of ascents but it is clear from Fig. 7 that a useful density of soundings was achieved in the interesting region where the polar trough intersected the polar front cloud band.

We show next a set of figures based on these ascents and other data to clarify the three-dimensional structure of these interacting features: Figs. 8 and 9 are plan views, and Figs. 10 and 11 are vertical sections along the two lines drawn in Fig. 7, one being oriented normal to and the other along the axis of the polar trough.
Figure 6. (c) Relationship of polar trough at 850 mb to upper jet at 300 mb, revealed by forecasts at 6-hour intervals from the fine mesh numerical model, initialized at 12 GMT on 8 September 1983. Arrow shows jet core at 300 mb and isolach for 60 m s⁻¹. $T_w$ at 850 mb is drawn for 10, 12 and 14 °C. Short bold line shows axis of warm air associated with polar trough. In fact the jet axis turned more sharply NE-wards than is shown by this forecast sequence (cf. Figs. 4(b) and (c)).

The polar trough was most clearly in evidence in the low troposphere (Fig. 8). Although not discernible in the 850 mb height pattern (Fig. 8(a)), it can be seen in the 1000–700 mb thickness pattern (dashed contours in Fig. 8(a)). The polar trough is revealed even more clearly in the field of wet-bulb potential temperature ($\theta_w$) at 850 mb (Fig. 8(b)) which shows a tongue of high $\theta_w$ air extending from the Cherbourg Peninsula to southern Ireland (cf. Fig. 6(b)). Winds plotted relative to the ground (Fig. 8(a)) do not reflect clearly the presence of the trough but when they are plotted relative to the moving trough (Fig. 8(b)) they show a well-defined relative south-easterly flow of the high $\theta_w$ air along the trough axis. Extending the terminology of Harrold (1973), we shall refer to this as the 'polar trough conveyor belt'.

At the middle levels, represented in Fig. 9 by an isentropic analysis for the $\theta = 30$ °C surface, part of both the polar trough and the polar front can be seen. The humidity analysis in this figure is based on fine mesh model output and satellite imagery together with radiosonde measurements at the (displaced) locations shown. The compact region of moist air extending from Wales to southern Ireland was associated with the polar trough where the moist high $\theta_w$ air was ascending towards its north-western end. This was associated with a band of relatively high cloud as shown in Fig. 5. An area of dry air existed to the north-east of the trough, separating it from the preceding frontal system. To the south-west of the trough an even larger area of dry air can be seen. As supported
by fine mesh forecast model output, some of this dry air was actually overtaking and bridging the moist air in the trough at levels above 650 mb over central southern and south-west England. Farther south, over the English Channel and northern France, Fig. 9 shows another region of moist air elongated in a SW–NE direction; this was associated with the lower parts of the band of polar front cloud which extended vertically all the way up to the main upper-level jet.

Figure 9(b) shows the distribution of vertical velocity averaged over the layer 1000 to 250 mb at a time roughly corresponding to Fig. 9(a), as inferred from the fine mesh model. The moist area associated with the polar trough was related to an area of appreciable ascent at all levels. Ascent along the polar front was strongest around 400 mb but weak below 600 mb. The dry air shown in Fig. 9(a) just south-west of the polar trough fits well with the area of descending air, which was most evident below 600 mb.

A vertical section across the polar trough where the associated moist air had begun to deepen over the Bristol Channel and Wales (Fig. 10) draws attention to the band of moist air in the trough sandwiched between dry air aloft on either side. Figure 10 shows that the air in the trough was characterized at most levels by a positive anomaly in $\theta_w$ of about 1 or 2°C. The strong low-level flow corresponding to the polar trough conveyor belt is revealed in Fig. 10 by the 15 m s$^{-1}$ isopleth which was observed as a distinct low-level jet in several of the soundings.
Figure 8. Structure of the lower troposphere in the vicinity of the pseudo-occlusion at 1330 GMT on 9 September 1983 as derived from analyses of the displaced radiosonde network in Fig. 7. (a) shows 850 mb contours (solid lines labelled in decametres) and 1000–700 mb thickness (dashed lines in decametres). Wind vectors in (a) show actual 850 mb winds reported by the radiosonde stations (each whole barb is 5 m s⁻¹). (b) shows isopleths of wet-bulb potential temperature at 850 mb drawn at intervals of 2°C. Vectors in (b) show velocities relative to the movement of the cloud band associated with the polar trough. The vectors in (b) are derived from two sources: vectors attached to solid circles are 850 mb relative winds from radiosonde stations within 300 km of the polar trough; vectors attached to solid squares are relative winds crudely inferred from the motion of mesoscale convective cloud areas as seen in the Meteosat imagery. The dashed lines are streamlines of relative flow showing air entering and flowing within the polar trough conveyor belt as it ascended from below 800 mb over SW England to above 700 mb over Ireland—see also vertical section in Fig. 11.

Perhaps the most enlightening diagrams are those in Figs. 11(a) and (b), which correspond to a vertical section along the axis of the polar trough. Here the polar trough conveyor belt is associated with the low-level jet (LLJ), which is shown ascending from SE to NW along the axis of the trough (i.e. from right to left in Fig. 11). As shown by the cross-hatched shading in Fig. 11(b) the polar trough conveyor belt was an essentially saturated flow. Because of slight potential instability owing to overrunning of dry lower \( \theta_w \) air from the south-west, convective overturning occurred within the polar trough conveyor belt as it progressed along the trough axis.

The top of the polar trough conveyor belt is seen in Fig. 11(b) (and in Fig. 9) to have been constrained below 650 mb in places where it was overlain by very dry subsided air beneath the tropopause break. Presumably this air had descended earlier as part of

Figure 9(a). Structure of the middle troposphere in the vicinity of the pseudo-occlusion at 1330 GMT on 9 September 1983 as shown by an isentropic analysis for the surface \( \theta = 30^\circ \)C using data from the displaced radiosonde network in Fig. 7 together with inferences from numerical forecast model output and from satellite imagery. Heights of this surface are plotted at 50 mb intervals. Areas of dry air (dew-point depression \( \geq 15^\circ \)C) and moist air (dew-point depression \( \leq 6^\circ \)C) are shown by stippled and hatched shading, respectively. Winds are plotted relative to the ground (each whole barb is 5 m s⁻¹).
a transverse circulation associated with the main upper-level jet. This dry air is seen in Fig. 11(b) to have been undercutting deep layer cloud which was associated with the polar front cloud band. The polar front cloud band was oriented at right angles to this section and it extended all the way up to the upper-level jet at 300 mb (Fig. 11(a)). We refer to this deep saturated flow as the ‘polar front conveyor belt’. As we shall show, the polar trough conveyor belt and the polar front conveyor belt were both generating their own distinct areas of precipitation.

Soundings in the region where the two conveyor belts intersect display a characteristic structure as shown in the example in Fig. 12. The layer from 1000 to 700 mb is the moist backed flow corresponding to the polar trough conveyor belt. The layer from 450 to 300 mb is the moist backed flow associated with the northern edge of the polar front conveyor belt. The dry veered flow in between is the air which has subsided on the
poleward side of the upper-level jet. Soundings a little farther north did not encounter the polar front conveyor belt at all and they show the dry air extending throughout the upper levels.

(b) Precipitation patterns

Precipitation patterns associated with the mature pseudo-occlusion are reproduced in Figs. 13 and 14. The figures are for different times within the period to which the preceding thermodynamic analysis applies, the precise times having been chosen to optimize the coverage achieved by the radar network.

Figure 13 shows the rainfall totals during the hour 12 to 13 GMT when the system was well observed by the Camborne radar. It shows two quite distinct rain areas. Rain area I was part of a zone of intermittent rain elongated in a NW–SE direction associated with the polar trough. The rain was heavy in places in the north of the area where convective cloud tops reached 500mb (see location Ab in the vertical section in Fig. 11(b)). Over Cornwall, however, the rain was light and was associated with cloud whose tops were held below 650mb, i.e. beneath the dry air that had subsided beneath the tropopause break (see locations C and M in Fig. 11(b)). Even farther south the rain from the polar trough petered out altogether as the tops of the cloud associated with the polar trough conveyor belt lowered to 700mb.
Rain area II, shown in Fig. 13 between England and France, was part of a band elongated in a SW–NE direction associated with the polar front. The cloud responsible for this was much deeper (see locations Cr to Br in Fig. 11(b)). There is some indication that the polar front rain was heaviest where the polar trough intersected it. The polar front cloud would have been acting as a seeder cloud and the underlying polar trough conveyor belt, although not deep enough to produce rain by itself, is likely to have provided some low-level feeder cloud. As one might expect in view of the different generating levels for the precipitation, mesoscale precipitation areas within area II were travelling at different velocities from those in area I only a little way to the north over Cornwall; those in area II travelled rapidly towards the north-east whilst those in area I travelled more slowly towards the NNE.

Figure 14 shows the instantaneous pattern of rain in relation to the major cloud system at a time, 1700 GMT, when the overall system was being observed best by the whole radar network. The purpose of this figure is to portray in some detail the kinds of mesoscale rainfall organization that characterized the different parts of the pseudo-occlusion. Most of the rain in Fig. 14 was associated with the polar trough (area I) and it was in the form of rather narrow, irregular rainbands (vertically hatched areas). In the north of the area these bands were oriented roughly west-east, parallel to the leading edge of the polar trough conveyor belt. In the south and west of area I the bands had an orientation more nearly parallel to the rear edge of the polar trough conveyor belt. Some of these bands are seen in Fig. 14 extending as far as the south coast of England beneath the northern edge of the polar front cloud band. The rain generated from the polar front cloud itself, shown cross-hatched in Fig. 14, tends to have an orientation parallel to the polar front cloud band. The distinct gap between the rain associated with areas I and II that had been evident earlier in Fig. 13 is no longer detectable in Fig. 14. This is because
The air in the polar trough was both ascending (Fig. 9(b)) and potentially unstable up to 850mb so that, even though it was capped by dry air at 650mb, it was possible for outbreaks of shallow convective rain and drizzle to develop in this region.

The visible satellite cloud picture shown in Fig. 2 clearly depicts the narrow and rather shallow lines of cumuliform cloud that were responsible for the rain bands within the polar trough. These can be seen emerging from beneath the cirriform cloud deck corresponding to the polar front cloud band responsible for the rather broader area of rain over the English Channel. It is also possible in Fig. 2 to see glimpses of the low-level cumuliform cloud lines through parts of the cirriform polar front cloud. This is consistent with Fig. 11(b) which shows a definite break in the vertical separating these two cloud masses.

5. Conceptual Model and Implications for Routine Analysis

We have analysed a case of a polar trough interacting with a polar front which gave rise to the characteristic cloud configuration (Fig. 2) resembling that of an instant occlusion. In the present case the cloud associated with the front developed simultaneously with that associated with the trough rather than being a pre-existing feature, and so we have referred to this instead as a pseudo-occlusion. Examples of similar cloud configurations are abundant: two published cases which resembled the satellite picture in Fig. 2 particularly closely can be found in plates 1 and 9 of Marshall (1982). The structure deduced from this study can be distilled into the simple model in Fig. 15. The
model consists of two orthogonal moist jets called the polar trough conveyor belt and the polar front conveyor belt. The former ascends as a low-level jet from 900 to about 700 mb as it travels polewards, the jet velocity reaching 18 ms⁻¹. The latter ascends as part of the much stronger upper-level polar front jet. Fine mesh model output suggests that the centroid of the associated moist tongue rises from about 600 to 300 mb as labelled in Fig. 15(a).

The model in Fig. 15 is similar to that of Carlson (1980) in having two conveyor belts that intersect each other (see also Harrold 1973 and Browning 1971). In Carlson’s model the two conveyor belts were referred to as the warm conveyor belt (WCB) and cold conveyor belt (CCB). The polar front conveyor belt corresponds in some respects to Carlson’s WCB. The polar trough conveyor belt, however, differs from Carlson’s CCB in that it is characterized by a relatively high wet-bulb temperature, and is thus a kind of secondary WCB below the main WCB, whereas Carlson’s CCB had its origin in the cold air ahead of a surface warm front.

The polar trough conveyor belt in the present case was characterized by weakly convective areas of cloud and precipitation which extended from the low-level jet up to 500 mb in places. Uccellini and Johnson (1979) have studied low-level jets with high $\theta_w$. 

Figure 14. Distribution of moderate rain at the surface at 1700 GMT on 9 September 1983 superimposed on the pattern of cloud. Areas of rain, shown by vertical hatching and cross-hatching, have been inferred from radars at Hameldon Hill (H), Camborne (C) and Upavon (U). The maximum ranges of this radar network are shown by circular boundaries. Principal areas of cloud have been determined from Meteosat imagery. There are three distinct regions of cloud, labelled I, II and III. Area I is associated with the polar trough; the corresponding cloud and rain is shown by broken horizontal hatching and vertical hatching, respectively. Area II is associated with the polar front, for which the cloud and rain is shown by solid horizontal hatching and cross-hatching, respectively. Area III is a minor band of convective showers in the polar air behind the main trough.
emerging on the north side of upper tropospheric jet streaks in situations of severe convective storms. Their low-level jets differed from that in the present study in that they originated farther to the south of the upper-level jet. According to Uccellini (private communication) this may be due to differences in static stability and in the slope of the isentropic surfaces in the lower troposphere. Despite their differences, both types of low-level jet have the same tendency—albeit to greatly different degrees—to generate convective instability through differential advection.

Although northern parts of the polar trough conveyor belt may be characterized by moderately deep convection, all convection in the present case was constrained below 650 mb in a zone just on the poleward side of the polar front jet by a lid of dry air that had undergone earlier subsidence. This subsidence, and the associated folding of the tropopause above it, as observed by Shapiro et al. (1982) and modelled by Hoskins and Bretherton (1972), is part of the direct transverse circulation associated with the entrance to the upper-level jet streak. Surface precipitation from the polar trough tends to be suppressed beneath such a region. Actually the polar trough was intersecting the polar front close to the exit of the upper-level jet streak. Thus, although the air aloft on the poleward side of the upper jet was dry in this region owing to its earlier descent, this air was in fact ascending as part of an indirect circulation at the jet exit. According to Uccellini and Johnson (1979) such an indirect circulation at the jet exit may have contributed to the intensification of the low-level jet. Given a sharp jet exit, a significant cross-flow ageostrophic component can develop. As pointed out by Hoskins (private communication), in order for the warm air in the polar trough conveyor belt to travel a large distance along the trough axis as part of this circulation, it is necessary that the same air within the trough should remain for a long time in the jet exit region. This is consistent with Fig. 8(b) which shows that relative to the system the wind component perpendicular to the trough is zero. In other words it is important for the development of the polar trough low-level jet that the upper-level jet streak exit which is forcing it should be both sharp and moving with the lower tropospheric winds.

The polar front conveyor belt itself is characterized by a belt of deep stratiform and cirriform cloud, with a well-defined northern edge that tends to stand out clearly in satellite pictures—it often casts a shadow in the visible imagery. This cloud belt and its associated band of precipitation are oriented at right angles to the polar trough. The
precipitation from the polar front conveyor belt is caused by ascent on the forward side of the upper trough and may be intensified in the vicinity of the intersecting polar trough by seeding of the low-level feeder cloud which, near the southern end of the polar trough, would usually be too shallow to generate rain of its own accord. The polar front precipitation quickly dies out in the leading part of the system where the associated conveyor belt flow enters the right exit region of the upper jet streak.

Figure 16. Simple analysis scheme for an instant or pseudo-occlusion. Solid line (with broken hatching) represents polar trough (with associated cloud); broken line represents the well-defined northern edge of the polar front cloud band (hatched).

We believe that the synoptic analyst may find it helpful to adopt a simple convention of the kind shown in Fig. 16 rather than attempt to force a classical occlusion or frontal wave to fit situations such as this. In the proposed scheme the polar trough is indicated in the normal way by a line drawn along the trough axis, which is associated with a wind shift and pressure recovery. If the trough develops marked temperature discontinuities then the trough line could have cold frontal symbols marked on it. The trough line should be extended beneath the edge of the polar front cloud band, at right angles if necessary. The northern edge of the latter cloud band can be indicated by (say) a broken line if the cloud appears thick enough to produce precipitation. The point of intersection of the solid and dashed lines would correspond to the triple point of the more traditional occlusion analysis. The triple point in an occluded system is a region where the precipitation can be expected to be especially heavy. In the present case study, however, the zone immediately to the north of the polar front precipitation was at times a region of suppressed precipitation intensity because the air at middle levels, though rising, was still dry following an earlier period of descent.
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