Reexamining the Cold Conveyor Belt

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ABSTRACT

Despite the popularity of the conveyor-belt model for portraying the airflow through midlatitude cyclones, questions arise as to the path of the cold conveyor belt, the lower-tropospheric airflow poleward of and underneath the warm front. Some studies, beginning with Carlson’s analysis of the eastern U.S. cyclone of 5 December 1977, depict the cold conveyor belt moving westward, reaching the northwest quadrant of the storm, turning abruptly anticyclonically, rising to jet level, and departing the cyclone downstream (hereafter, the anticyclonic path). Other studies depict the cold conveyor belt reaching the northwest quadrant, turning cyclonically around the low center, and remaining in the lower troposphere (the cyclonic path). To clarify the path of the cold conveyor belt, the present study reexamines Carlson’s analysis of the cold conveyor belt using an observational and mesoscale numerical modeling study of the 5 December 1977 cyclone.

This reexamination raises several previously unappreciated and underappreciated issues. First, airflow in the vicinity of the warm front is shown to be composed of three different airstreams: air-parcel trajectories belonging to the ascending warm conveyor belt, air-parcel trajectories belonging to the cyclonic path of the cold conveyor belt that originate from the lower troposphere, and air-parcel trajectories belonging to the anticyclonic path of the cold conveyor belt that originate within the midtroposphere. Thus, the 5 December 1977 storm consists of a cold conveyor belt with both cyclonic and anticyclonic paths. Second, the anticyclonic path represents a transition between the warm conveyor belt and the cyclonic path of the cold conveyor belt, which widens with height. Third, the anticyclonic path of the cold conveyor belt is related to the depth of the closed circulation associated with the cyclone, which increases as the cyclone deepens and evolves. When the closed circulation is strong and deep, the anticyclonic path of the cold conveyor belt is not apparent and the cyclonic path of the cold conveyor belt dominates. Fourth, Carlson’s analysis of the anticyclonic path of the cold conveyor belt was fortuitous because his selection of isentropic surface occurred within the transition zone, whereas, if a slightly colder isentropic surface were selected, the much broader lower-tropospheric cyclonic path would have been evident in his analysis instead. Finally, whereas Carlson concludes that the clouds and precipitation in the cloud head were associated with the anticyclonic path of the cold conveyor belt, results from the model simulation suggest that the clouds and precipitation originated within the ascending warm conveyor belt.

As a consequence of the reexamination of the 5 December 1977 storm using air-parcel trajectories, this paper clarifies the structure of and terminology associated with the cold conveyor belt. It is speculated that cyclones with well-defined warm fronts will have a sharp demarcation between the cyclonic and anticyclonic paths of the cold conveyor belt. In contrast, cyclones with weaker warm fronts will have a broad transition zone between the two paths. Finally, the implications of this research for forecasting warm-frontal precipitation amount and type are discussed.

1. Introduction

One approach to understanding midlatitude cyclones is to consider the four-dimensional airflow through such storms. Conceptual models of such airflow represent kinematic descriptions of the paths of air parcels through cyclones. Dynamics, however, cannot be entirely divorced from such models, as proposed airflow models should be consistent with the current understanding of the dynamics of midlatitude cyclones (e.g., poleward-moving, rising warm air is consistent with quasigeostrophic reasoning and the conversion of available potential energy to kinetic energy within the cyclone).

Although models of airflow through midlatitude cyclones have existed since the nineteenth century (e.g., references within Kutzbach 1979; Cohen 1993; Wernli 1995), the essence of our modern interpretation was perhaps best distilled by Carlson (1980) in his study of the central U.S. cyclone of 5 December 1977. His conceptual model based on that storm, the conveyor-belt model, describes three airstreams that affect the structure of clouds and precipitation: the dry airstream, the warm conveyor belt, and the cold conveyor belt. Subsequently, the conveyor-belt model was applied to other cyclones by other investigators, and the model became quite influential and enjoyed popularity. Occasionally,
Section 1. Previous literature

In this section, the development of the conveyor-belt model is placed in historical perspective. First, airstream models that preceded Carlson’s (1980) conceptual model are reviewed briefly in section 2a, followed by a more thorough discussion of the elements of the conveyor-belt model portrayed by Carlson (1980) in section 2b. Finally, the influence of the conveyor-belt model on later research is discussed in section 2c, along with some criticisms that have arisen in section 2d.

a. Early airstream models

Airflow models have a long history as reviewed by Kutzbach (1979, chapter 6), Cohen (1993, section 2.8), and Wernli (1995, section 1.3). Surface air trajectories were first computed by Shaw (1903) for the 26–27 February 1903 storm that devastated the British Isles. Shaw laid basic principles for the construction and interpretation of air-parcel trajectories (Shaw 1903; Shaw and Lempfert 1906; Shaw 1911, chapter 7). His work also illustrated convergence of cold easterly flow encircling the low center and poleward-moving warm air in the northeastern quadrant of the storm [e.g., Shaw and Lempfert (1906; figure reproduced in Kutzbach 1979, p. 182)], questioning a previous hypothesis that midlatitude cyclones had symmetric inflow. Such surface convergence implied ascent of the poleward-moving warm air over the cold easterly flow, leading to precipitation. Bjerkenes (1919) presented a schematic illustrating similar airflow (Fig. 1a).

A drawback to these early models is that they did not depict airflow very far above the surface. The development of upper-air networks and isentropic analysis allowed quantitative means to assess vertical motion (e.g., Rossby et al. 1937; Danielsen 1961; Green et al. 1966), as reviewed in Gall and Shapiro (2000). Bjerkenes (1932, Fig. 13) computed storm-relative moist-entropic flow rising anticyclonically into the base of an altostratus deck above a warm-frontal surface. He also noted the apparent inconsistency of this airflow turning anticyclonically despite being part of a larger cyclonic circulation. Namias (1939) showed streamlines along isentropic surfaces, showing the ascending warm air over the warm front and the dry descending air behind the cold front. The dry, descending air was further explored by Palmén and Newton (1951) in a cold-air outbreak over the central United States and by Danielsen (1961, 1964, 1966) in extratropical cyclones over the United States. Eliassen and Kleinschmidt (1957) presented isentropic streamlines relative to the moving surface low center (hereafter, storm-relative isentropic analysis) at different levels through a column of points within a warm-frontal zone: the air underneath the warm-frontal surface \( S_1 \) and \( S_2 \) in Fig. 1b) gently rose as it encircled the low center, while air above the warm-frontal surface \( S_3 \) and \( S_4 \) in Fig. 1b) rose abruptly, as described in earlier studies (e.g., Namias 1939).

Browning and Harrold (1969), Browning et al. (1973), and Harrold (1973) focused on the warm ascending airstream. Specifically, they found that a drier midtropospheric flow capped the warm ascending air, generating potential instability as these two airstreams ascended over the warm front. They also found that cool dry air descended from the downstream anticyclone and flowed underneath the warm-frontal zone. PalmeÁn and Newton (1969, Fig. 10.20) illustrated three airstreams through midlatitude cyclones. They featured the warm ascending air over the warm front, the dry descending air behind the cold front, and midtropospheric air entering the cyclone from the west (reminiscent of the midtropospheric cyclical trajectories of Whitaker et al. 1988). These studies provided the elemental airstreams...
that were integrated and extended in the development of Carlson’s (1980) conveyor-belt model.

b. The conveyor-belt model

Integrating previous literature and storm-relative isentropic analysis of the central U.S. cyclone of 5 December 1977, Carlson’s (1980) conveyor-belt model comprised three elemental airstreams: the dry airstream, the warm conveyor belt, and the cold conveyor belt (Fig. 2).

1) Dry airstream

The dry airstream originates in the upper troposphere and lower stratosphere and descends on the west side of the upper-level trough (Fig. 2). Rounding the base of the trough, this airstream fans out, ascending over the warm/occluded front and descending behind the surface cold front as illustrated by Danielsen [1964; reproduced in Browning (1999, Fig. 9)] and Carlson (1980, Fig. 10). Because of its importance in convective destabilization and cyclogenesis, the dry airstream has been the subject of explorations by, among others, Carr and Millard (1985), Young et al. (1987), Durran and Weber (1988), Kurz (1988), Wernli (1995, 63–64; 1997, p. 1694), Bader et al. (1995, section 5.2), and Browning and Roberts (1996) have argued that, during the early stages of cyclogenesis, if the upper-level flow is an open wave (no closed flow), then the warm conveyor belt rises to the upper troposphere and turns anticyclonically downstream of the cyclone. Later in the evolution of the cyclone (e.g., occlusion), if the upper-level flow is characterized by closed flow, some of the warm conveyor belt air may turn cyclonically around the low center [the so-called trawl airstream of Martin (1999)]. Thus, the deep cloud mass composing the head of the comma-shaped cloud pattern, at least in some cases, is due to the cyclonically turning portion of the warm conveyor belt [see also Reed et al. (1994)]. It is interesting to note that Bjerknes (1932) suggested that, if the rising warm sector air was unstable, cyclonic flow would be favored over anticyclonic flow, perhaps indicating some

FIG. 1. Early models of airflow through midlatitude cyclones: (a) schematic airflow of warm air (open arrows) overriding cyclonically turning cold air (solid arrows) (Bjerknes 1919, Fig. 6) and (b) storm-relative isentropic streamlines at different levels through a point northwest of the warm front of a cyclone (Eliassen and Kleinschmidt 1957, Fig. 35). Notation along the streamlines is found in the legend on the bottom right of the figure.
measure of the depth of the cyclone (and, thus, closed flow).

3) COLD CONVEYOR BELT

In contrast to the dry airstream and the warm conveyor belt, relatively little research has explored the cold conveyor belt, its properties, and its path through the cyclone. Air in the cold conveyor belt originates in the lower troposphere of the downstream anticyclone and passes underneath the warm-frontal zone (Fig. 2). Thus, the warm front separates the warm and cold conveyor belts. Potential vorticity is created in the cold conveyor belt beneath the area of latent heat release in the ascending warm conveyor belt. The increasing potential vorticity within the cold conveyor belt is transported westward toward the lower-tropospheric cyclone center. As demonstrated by Stoelinga (1996) and Rossa et al. (2000), the diabatically generated potential vorticity can enhance the cyclonic circulation about the surface cyclone without appreciably affecting the location and overall structure of the cyclone.

Since any precipitation generated within the warm conveyor belt must fall through the cold conveyor belt, the temperature and humidity of the cold conveyor belt can play an important role in controlling the type and amount of precipitation reaching the surface. Three examples follow. First, if the cold conveyor belt is characterized by a shallow layer of subfreezing air, sleet, and/or freezing rain may occur. Second, low-level cooling in the cold conveyor belt due to melting of snowflakes may cause a changeover from rain to heavy snow (e.g., Kain et al. 2000). Finally, if the cold conveyor belt is relatively dry, evaporation/sublimation of hydrometeors will reduce the amount and intensity of precipitation reaching the ground; in some cases, only virga may be observed. On the other hand, if the cold conveyor belt is nearly saturated, precipitation reaching the surface could be substantial.

The literature suggests that the cold conveyor belt takes one or both of two paths after passing underneath the warm-frontal zone. Studies prior to 1980 show the cold conveyor belt turning cyclonically around the low center, remaining in the lower troposphere behind the cold front (e.g., Fig. 1), hereafter the cyclonic path. Carlson’s (1980) analysis departed from earlier research in that the cold conveyor belt turns sharply anticyclonically and rises to the upper troposphere, hereafter the anticyclonic path (Figs. 2 and 3). This rising air produces the structure termed the cloud head, which, in some cyclones, emerges from underneath the polar-front cloud band (e.g., Böttger et al. 1975; Monk and Bader 1988; Bader et al. 1995; Dixon 2000). Since 1980, conceptual models of the airflow through cyclones tend to incorporate both interpretations (e.g., Carlson 1987; Browning 1990, 135–136; Carlson 1991, 318–319). Thus, the popularity of Carlson’s (1980) conceptual model seems to have led to general acceptance of the anticyclonic path of the cold conveyor belt, a concept that was hitherto undescribed in the literature.
c. Influence of the conveyor-belt model on later research

A testament to the substantial value and influence of Carlson’s (1980) conveyor-belt model, it has appeared in review articles (e.g., Browning 1986, 1990, 1999) and textbooks (e.g., Kocin and Uccellini 1990, 67–74, 78; Carlson 1991, section 12.4; Bluestein 1993, section 1.6.2; Bader et al. 1995, section 3.1). The conveyor-belt model also has served as a starting point for exploring cyclone structures and evolutions that do not fit into the Norwegian cyclone model. For example, such airstream analyses have been performed for cyclones conforming to the evolution described by Shapiro and Keyser (1990) (e.g., Kuo et al. 1992; Reed et al. 1994; Browning and Roberts 1994), split fronts (e.g., Browning and Monk 1982; Young et al. 1987; Kuo et al. 1992; Mass and Schultz 1993), cyclones affected by topography (e.g., Hobbs et al. 1990, 1996; Steenburgh and Mass 1994; Bierly and Winkler 2001), and cyclones in different large-scale flow regimes (e.g., Evans et al. 1994; Bader et al. 1995, section 5.2). In addition, with the increasing availability of mesoscale models, calculating air-parcel trajectories has become a more accurate method than storm-relative isentropic analysis to envision the airflow through cyclones, thus giving the conveyor-belt model a modern perspective.

d. Criticisms and ambiguity of the conveyor-belt model

Despite enjoying popularity, the simple picture of the conveyor-belt model has been criticized in the past for the following reasons. Schultz (1990, p. 219), Kuo et al. (1992), and Reed et al. (1994) argued that airstreams in cyclones do not resemble flat conveyors or three-dimensional tubes with well-defined boundaries. Instead, Wernli (1997) described airstreams as coherent flexible tubes that evolve over time rather than being steady-state entities. Mass and Schultz (1993), Reed et al. (1994), and Bader et al. (1995, p. 213) showed that the three-conveyor-belt model may be an oversimplification of the airflow through some cyclones because more than three airstreams may be needed to describe the variety of individual air-parcel trajectories. Grotjahn and Wang (1989) showed that surface fluxes of heat and moisture can modify the airflow through marine cyclones; specifically, the cold lower-tropospheric air from the downstream anticyclone (i.e., cold conveyor belt air)
can gain heat and moisture by traveling over warmer water, thus becoming “warm conveyor belt air,” a process recognized by Shaw (1911, p. 213). Some studies of marine cyclones were unable to identify a well-defined cold conveyor belt (e.g., Reed et al. 1994; Browning et al. 1995) or found no sharp boundary between the warm and cold conveyor belts (e.g., Kuo et al. 1992; Browning and Roberts 1994). Tung (1990) and Mass and Schultz (1993) found no evidence for the anticyclonic path of the cold conveyor belt. A final concern is ambiguity about what the conveyor belts actually represent: streamlines, trajectories, streak lines, or some combination of the above.

Classically, airflow is represented by one of three methods: streamlines, trajectories, or streak lines. A streamline is a line tangent to the instantaneous velocity of the fluid at every point, a trajectory is the path of a material parcel of fluid through some time period, and a streak line is a line along which the fluid elements constituting the line have passed through a particular point in space over some time period (e.g., Huschke 1959). These three are equivalent only when the flow is steady state.

In schematic airflow models, it may not be clear that what is being depicted is uniquely associated with streamlines or trajectories. A steady-state assumption is typically invoked implicitly in conveyor-belt studies to allow for the simplification that isentropic streamlines can be considered trajectories. The steady-state assumption, however, requires that the cyclone is neither changing its intensity nor its structure, generally an unlikely prospect. In addition, storm-relative isentropic analysis assumes that the local vertical velocity of the isentropic surface is zero, which may not be the case, particularly in a rapidly evolving situation. Although it is easier to calculate streamlines than trajectories, strictly, streamlines can represent trajectories only approximately.

Whereas numerically calculated trajectories appear to resolve the dilemma of objectively determining the conveyor belts, spatial and temporal resolution limits the accuracy of the calculations. Moreover, not all of the airflow in a cyclone will coincide with these aggregations of trajectories; it may be possible to find trajectories that do not belong to any ensemble of trajectories. Nevertheless, it is plausible to assume that it is possible to determine collections of sufficiently similar trajectories that their aggregation into conveyor belts will both represent the airflow properly and encompass the majority of a cyclone’s airflow. Thus, conveyor belts can be considered equivalent to the coherent ensembles of trajectories defined by Wernli and Davies (1997) and Wernli (1997), separated by the airstream boundaries of Cohen and Kreitzberg (1997). For the present study, I am assuming that the conveyor belts can be represented by collections of trajectories that follow similar paths.

The ambiguity in what airflow models represent is not limited to schematic depictions of airflow through synoptic-scale cyclones. For example, an airflow model by Lemon and Doswell (1979), a revision of an earlier such model developed by Browning (1964), was used to represent airflow in supercell thunderstorms. Although not described as such originally, the airflow models used by Browning (1964) and Lemon and Doswell (1979) for supercells are similar in spirit to the conveyor-belt model for midlatitude cyclones (e.g., Carlson 1991, section 12.5; Lemon 1998).

Despite the criticisms summarized in this section, the conveyor-belt model survives. This paper will focus on just a small number of these issues, those related to the cold conveyor belt. In particular, what is the path of the cold conveyor belt after it passes underneath the warm-frontal surface?

3. The path of the cold conveyor belt

Although it is not unreasonable to postulate the cold conveyor belt splitting and taking two different paths, in much the same manner as the dry airstream fans out behind the cold front or the warm conveyor belt splits when rising over the warm front, evidence described below questions the existence of the cold conveyor belt splitting and rising anticyclonically. Additionally, evidence suggests that the bulk of the cold conveyor belt remains in the lower troposphere and travels cyclonically around the low center. Four arguments describing the evidence for these two claims are advanced in this section.

a. Lack of evidence for the anticyclonic path

Table 1 lists 19 studies in which only the cyclonic path of the cold conveyor belt was identified. Previous literature with quantifiable airstreams or calculated trajectories that demonstrate the anticyclonic path, in fact, are rare. Many schematic diagrams of storm-relative isentropic flow exist, but these do not show the actual wind observations used to draw such anticyclonically curving streamlines (e.g., Fig. 5 in Carlson 1980; Fig. 4 in Kurz 1988; Fig. 12.18a in Carlson 1991; Fig. 8c in Browning and Roberts 1994).

In all the literature surveyed, only three studies possess numerically calculated air-parcel trajectories purported to follow the anticyclonic path of the cold conveyor belt. First, trajectory 5 in Whitaker et al. (1988, Fig. 18b) undergoes anticyclonic turning as the parcel approaches the low center and rapidly ascends to jet level. Hibbard et al. (1989) also present trajectories calculated from a model simulation of the same storm. In their Figs. 3 and 4, yellow-colored trajectories (representing those that originate in the “ocean-influenced planetary boundary layer east of the cyclone,” which suggests that they belong to the cold conveyor belt) are shown, some of which originate in the warm sector and rise over the warm front, taking a path similar to that of trajectory 5 in Whitaker et al. (1988, Fig. 18). That
Table 1. Previous literature illustrating the cyclonically turning branch of the cold conveyor belt, but not the anticyclonically turning branch.

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such air parcels originate in the warm sector indicates that they might best be labeled as belonging to the warm conveyor belt, not the cold conveyor belt. The second study showing anticyclonic cold conveyor belt trajectories examined model simulations of two oceanic explosively developing cyclones (Liu 1997). Liu found that trajectories from a narrow range of initial altitudes rose rapidly and turned anticyclonically, carrying much of the moisture in the storm. Because these air parcels entrained moisture and sensible heat fluxes, they did not remain on a moist-isentropic surface, making Liu (1997) reluctant about equating them to the cold conveyor belt. Finally, Kuo et al. (1992, their Figs. 9 and 12) examine an oceanic cyclone in which several trajectories begin in the lower troposphere, poleward of the warm front, and rise to the mid and upper troposphere while turning anticyclonically. In this case, however, strong frontogenesis in a region of strong baroclinicity occurs poleward of the original warm front. Thus, it may be argued that this air did not originate within the cold air underneath the warm-frontal zone either. These three studies indicate that defining what exactly is the cold conveyor belt in certain instances may be problematic (e.g., Grotjahn and Wang 1989).

b. Unknown mechanism to force ascent of cold stable air

For the air within the cold conveyor belt to rise to the upper troposphere would imply that air would have to pass through the stable layer that characterizes the warm-frontal zone. It seems unlikely that such cold lower-tropospheric air moving underneath the warm-frontal zone would ascend in such a rapid manner. As remarked by Shaw (1911, p. 213), “the cold air of the easterly current is very unpromising material out of which to make a rising current.” If the depiction of the anticyclonic path of the cold conveyor belt is to be taken literally, strong ascent—perhaps the strongest associated with the cyclone—must be present in this region.

Therefore, the process forcing this supposed rapid ascent in the cold conveyor belt has not been elucidated. Golding (1984), Carr and Millard (1985, p. 386), Browning et al. (1995, p. 1245), and Wernli and Davies (1997, Fig. 9), among others, show no large ascent associated with trajectories in the cold conveyor belt. Consequently, there appears to be a question about the magnitude of the vertical motion in this region of the cold conveyor belt.

c. Ambiguity of streamline analyses

Carlson’s (1980) isentropic analysis, reproduced in Fig. 3, is based on a storm-relative streamline analysis of the available radiosonde data on the \( \theta = 297 \) K surface when unsaturated and on the \( \theta_s = 12 \)°C surface when saturated. The sharp anticyclonic ascent of the cold conveyor belt as depicted occurs over Illinois, Indiana, and Michigan, in a region of strong shear of the horizontal wind on the isentropic surface. Isentropic surfaces within the cold conveyor belt from other storms
also show this region of strong shear (e.g., Fig. 12.18a in Carlson 1991; Fig. 8 in Browning and Roberts 1994).

As discussed by Schafer and Doswell (1979) and Doswell and Caracena (1988), analysis of a vector field from sparse data can be ambiguous, especially in regions of strong shear. This statement is also confirmed by Cohen and Kreitzberg (1997, their Fig. 5) who show that their integrated contraction rate, a measure of the rate at which nearby air-parcel trajectories approach each other, will be large in a region of shear. Consequently, interpreting the path of the cold conveyor belt based solely on isentropic streamline analysis can be risky.

d. Complexity and confusion

The discrepancy over the path of the cold conveyor belt leads to potential complexity and confusion. In their discussion of the variety of cyclogenesis events, Bader et al. (1995, p. 213) state: “In the cyclogenesis types described in this section, it has been found necessary to introduce a second warm conveyor belt and to reserve the term ‘cold conveyor belt’ for a third conveyor belt, confined to low levels, which appears later in the cyclogenesis.” This complexity leads to potential confusion over airstream classification (i.e., cold conveyor belt vs warm conveyor belt) and under what conditions the cold conveyor belt clearly exists and is well defined. In hopes of clarifying this situation, the 5 December 1977 cyclone studied by Carlson (1980) is revisited from a modern perspective.

4. Case study: Analysis of observations

To reexamine the storm studied by Carlson (1980), an observational analysis is performed first. At 1200 UTC 5 December 1977 (hereafter, 5/12), a surface cyclone with a central pressure around 986 hPa was centered over western Kentucky (Fig. 4a). At 500 hPa, a broad planetary-scale trough was situated over the central United States, with embedded shortwave troughs located over Minnesota and slightly to the west of the surface center (Fig. 4b).

To illustrate the cold conveyor belt, a storm-relative isentropic chart was constructed from the available soundings at 5/12. An average velocity for the surface cyclone center of 13.2 m s⁻¹ in the direction of 47° (northeast) was determined from 5/03 to 5/18. This vector storm motion was subtracted from the total wind speed at each level for each sounding to determine the storm-relative wind. A dry-isentropic chart along the \( \theta = 297 \) K surface, the same dry-isentropic surface selected by Carlson (1980, Fig. 5) for the cold conveyor belt, then was constructed (Fig. 5).

Note that this methodology differs slightly from that of Carlson (1980). His storm-relative isentropic chart was constructed from the \( \theta = 297 \) K surface, when the flow was unsaturated, but along the \( \theta_e = 12^\circ \) \( \theta_e \approx 310 \) K surface, when saturated. Because the mixing ratio (and hence \( \theta_e \) and \( \theta_w \)) varies horizontally along the \( \theta = 297 \) K surface (e.g., mixing ratios vary from 2.0 g kg⁻¹ at Cape Hatteras, NC, to 15.7 g kg⁻¹ at Tallahassee, FL, in Fig. 5), a single value of \( \theta_w/\theta_e \) cannot be assigned to a given value of \( \theta \). Thus, Fig. 5 avoids this ambiguity and is consistent with the more traditional method of constructing isentropic maps that follow a single dry-adiabatic surface. Nevertheless, the difference between these two approaches is reconsidered in section 6a of this paper. Another difference is that Carlson (1980, p. 1502) uses the phase speed of the long wave to determine the storm motion (6.7 m s⁻¹ to the east), whereas the present analysis uses the motion of the surface cyclone (13.2 m s⁻¹ to the northeast). Since this paper concerns the cold conveyor belt, a lower-tropospheric airstream, it is more appropriate to consider the flow relative to a lower-tropospheric feature like the center of the surface cyclone rather than a midtropospheric feature like the long wave.

Figure 5 shows the 297-K isentropic surface sloping upward toward the north: the pressure of the surface was greater than 900 hPa over the southern United States and less than 400 hPa over much of Minnesota and the Dakotas. Relative humidities were greater than 80% throughout Alabama, Tennessee, and the Ohio River valley. Storm-relative airflow on this isentropic surface consisted of southeasterlies and easterlies undergoing gentle ascent over the depth of 1000–740 hPa over the southeast United States, mid-Atlantic, and upper Midwest. Farther west, northwesterly flow descended down the isentropic surface from 500 hPa in Wyoming, Nebraska, and western Iowa to 980 hPa over Texas, Louisiana, and Mississippi. Another branch of the northwesterly flow curved cyclonically toward the east over Minnesota, and then spread anticyclonically toward the south over the Great Lakes, descending and meeting the southeasterly flow along a confluent asymptote. Finally, an approximately closed cyclonic circulation was centered over southern Indiana.

Other than schematic streamlines, Carlson’s (1980) analysis (his Fig. 5 or Fig. 3 in this paper) displays no data and was constructed differently from Fig. 5, so a direct comparison is not possible. In Carlson’s analysis, the low-level easterly flow turns into upper-level southerly flow, making the abrupt anticyclonic ascent from 700 hPa to above 400 hPa over Illinois. In Fig. 5, my analysis, albeit on a different isentropic surface, shows two adjacent airstreams. None of the upper-air data indicate any appreciable ascending motion over Illinois. Thus, there is considerable ambiguity in the path of the cold conveyor belt that cannot be resolved without further information (i.e., section 3c).

Although the storm-relative isentropic method provides an easy way to assess streamlines through cyclones, the usefulness of this method is limited by the availability of upper-air data, the steady-state assumption, and the conservation of potential temperature. Un-
Fortunately, the sparsity of the sounding stations limits unambiguous determination of the path of the cold conveyor belt in the crucial region of interest northwest of the surface low center. Also, in this case, the storm deepens and evolves from 5/12 to 6/12 and precipitation occurs, violating the steady-state and dry-isentropic assumptions. To make a more accurate determination of the path of the cold conveyor belt, a mesoscale model simulation was performed of this case and was diagnosed using air-parcel trajectories, which do not require these assumptions.

5. Case study: Mesoscale model simulation

To examine further the airflow through this cyclone using high spatial and temporal resolution, a mesoscale
model simulation was performed. Section 5a describes the mesoscale model used to produce the simulation of Carlson’s case, which is discussed in section 5b.

a. Model description

The Pennsylvania State University–National Center for Atmospheric Research fifth-generation Mesoscale Model (MM5), a nonhydrostatic, primitive-equation model (Dudhia 1993; Grell et al. 1994), was employed to simulate the cyclone. The simulation was initialized at 0000 UTC 5 December 1977, was ended at 0000 UTC 7 December 1977, and featured 23 variably spaced terrain-following-coordinate ($\sigma$) levels in the vertical. Here, 

$$\sigma = (p - p_{\text{top}})/(p_{\text{top}} - p_{\text{sfc}}),$$

$p$ is pressure, $p_{\text{top}}$ is the pressure at model top (100 hPa), and $p_{\text{sfc}}$ is the surface pressure. The horizontal grid spacing was 50 km over a domain of 140 by 90 points that was roughly bounded by 20° and 60°N and by 130° and 60°W. A grid spacing of 50 km captures the essence of the cyclone structure and evolution, without introducing small mesoscale structures that would result in unnecessary detail. Precipitation processes were parameterized using an explicit-moisture scheme that includes prognostic equations for water vapor, cloud water, and rainwater; cloud water and rainwater are assumed to be cloud ice and snow if the temperature is below 0°C (Dudhia 1989; Grell et al. 1994, section 5.3.1.1). The Kain–Fritsch cumulus parameterization (Kain and Fritsch 1993) was used to represent subgrid-scale convective precipitation. Other parameterizations included a multilevel planetary boundary layer (Zhang and Anthes 1982) and a radiative upper boundary condition (Klemp and Durran 1983). To create the initial conditions for the model simulation, National Centers for Environmental Prediction (NCEP) reanalyses (Kalnay et al. 1996) were interpolated to the model grid and the integrated mean divergence was removed to avoid the production of spurious gravity waves. Lateral boundary conditions were generated by linear interpolation of the reanalyses at 12-h intervals.

b. Evolution

At 12 h into the simulation (5/12), the model placed the surface cyclone center over western Kentucky (Fig. 6a), in agreement with the surface analysis from the observations at this time (Fig. 4a), although the model’s central pressure was about 5 hPa too high. The modeled 500-hPa flow captured the associated vorticity maxima over Arkansas and Minnesota (cf. Figs. 4b and 6c). At 36 h into the simulation (6/12), the surface cyclone deepened to 982 hPa with a secondary development north of Cape Cod of 987 hPa (Fig. 6b). The observed centers at this time were 990 and 986 hPa, respectively (not shown). At 500 hPa, the shortwave troughs merged to form a broad closed low (Fig. 6d). Despite the errors in the central pressures of the primary cyclone (forecast too shallow early, forecast too deep later), the locations...
of the low centers and fronts are well forecast for a model with 50-km grid spacing. Therefore, this model simulation should be adequate for addressing the issues of airflow within the cyclone.

For comparison to Fig. 5, the 297-K storm-relative isentropic surface from the model simulation is presented in Fig. 7. Although the magnitude of the storm-relative wind differs somewhat from the observations in some locations (e.g., North Carolina, West Virginia, Illinois, Michigan), the essence of the pattern is the same, illustrating tropospheric-deep descending air over the central United States, mid- and upper-tropospheric westerly flow across the northern United States and southern Canada, and ascending east/southeast flow over the southeast United States and Ohio River valley. A potentially significant difference occurs along the Great Lakes where observations at Green Bay, Wisconsin; Flint, Michigan; and Buffalo, New York, indicate northeasterly flow (Fig. 5), whereas the model simulation has weak flow from the west or east (Fig. 7). A cross section through the warm-frontal zone shows that such northeasterlies may be found at lower isentropic levels (<290 K) over the same area in a region of strong shear within the warm-frontal zone (Fig. 8). Nevertheless, this otherwise favorable comparison between Figs. 5 and 7 supports proceeding with the analysis.

6. Trajectory analysis

To explore the actual airflow within the storm, three-dimensional air-parcel trajectories were computed. The accuracy of air-parcel trajectories is limited by factors that include the spatial resolution of the model simulation, temporal resolution of model output, time step of trajectory calculation, specification of and degree of mixing (both in the model and in the real atmosphere), and strength of wind gradients. Using the approach described by Seaman (1987), trajectory calculations were performed from 60-min model output files with a 10-min time step, values consistent with the results of Doty and Perkey (1993).

a. 1200 UTC 5 December 1977

To examine flow in the vicinity of the warm front, a roughly north–south cross section across the warm front is constructed (Fig. 8). The 297-K isentropic surface (thick dashed line) is selected for comparison to Carl-
son’s choice of the dry-isentropic surface for his storm-relative isentropic analysis. Consistent with Figs. 5 and 7, the 297-K isentropic surface lies within southerlies equatorward of the surface warm-frontal position, within easterlies near the leading edge of the warm front around 700 hPa, and within westerlies above 600 hPa (Figs. 5, 7, and 8). When the air is saturated, however, ascending flow would not remain on a dry-isentropic surface, but, as indicated by Carlson (1980), would ascend more steeply moist adiabatically. Issues about which moist-adiabatic surface aside (i.e., section 4), Carlson (1980) chose the $\theta_e = 310$ K surface (approximately the $\theta_v = 310$ K surface, the thick solid line in Fig. 8). The steepness of the $\theta_e = 310$ K surface means that parcels following this surface are far removed from the cold air underneath the warm-frontal zone. Thus, the $\theta = 297$ K and $\theta_v = 310$ K surfaces are too high to be unequivocally within the cold air underneath the warm front (Fig. 8). This fact alone leads to potential confusion in interpreting the airflow.

To demonstrate this point, storm-relative forward trajectories starting along the 297-K isentropic surface within cross section AB at 5/12 and ending at 6/12 are computed (Fig. 9). Trajectories numbered 1 and 2 start in the lower troposphere below 750 hPa and rise anticyclonically during this 24-h period to above 300 hPa (Fig. 9a). The initial locations of these trajectories in cross section AB (Fig. 8), however, indicate that they began in the warm air equatorward of the warm-frontal zone, not in the cold air behind the warm front. In addition, these two trajectories resemble the storm-relative isentropic streamlines depicted in Carlson’s (1980, his Fig. 4) warm conveyor belt. Thus, in the conveyor-belt conceptual model, this strongly rising air would best be classified as belonging to the warm conveyor belt.

Trajectories 3–7 represent storm-relative, westward-moving air that originates in the lower to midtroposphere (750–600 hPa) and rises anticyclonically to about 350 hPa, a height somewhat less than that obtained by trajectories 1 and 2 (Fig. 9b). These trajectories resemble the anticyclonic path of the cold conveyor belt as depicted in Carlson’s analysis (Fig. 3 in this paper). This airstream lies within much of the warm-frontal zone along the 297-K isentrope. Finally, trajectories 8–10 represent air that originates at 550–600 hPa, sinks anticyclonically around the downstream anticyclone over New England to 600–750 hPa, and rises as it approaches the cyclone to 650–400 hPa (Fig. 9c). If these trajectories were computed forward from these locations, they would cyclonically circle the low center (not shown). Thus, these trajectories belong to the cyclonic path of the cold conveyor belt.

If some air parcels beginning on the 297-K isentropic surface belong to the warm conveyor belt, then air belonging to the true cold conveyor belt is likely to be found at a lower level (colder potential temperature).
Indeed, trajectories beginning on the 290-K isentropic surface (Fig. 10) show drastically different paths from those on the 297-K isentropic surface. All trajectories show a cyclonic turning around the low center, characteristic of the cyclonic path of the cold conveyor belt.

To compare trajectories on the $\theta = 297$ K surface to those on the $\theta = 310$ K surface, 24-h forward trajectories beginning at 5/12 are constructed along the $\theta = 310$ K surface (Fig. 11a). These trajectories break into some of the same groups previously seen on the $\theta = 297$ K surface (Fig. 9). Trajectories 21–23 resemble the cyclonic path of the cold conveyor belt, whereas trajectories 24 and 25 resemble the anticyclonic path of the cold conveyor belt (Fig. 11a). Trajectories 26–30, on the other hand, seem to be unrelated to the ascending anticyclonic path of the cold conveyor belt trajectories. If these trajectories are taken backward from 5/12 to 5/00, this distinction is made more clear (Fig. 11b). Trajectories 25–27, ascending through the midtroposphere, transition to upper-tropospheric trajectories 28–30, which ascend about 100 hPa, likely similar to the cyclical airstream noted by Whitaker et al. (1988). Thus, two noninteracting airstreams coexist on the same moist-isentropic surface in the mid- and upper troposphere.

To explore further the trajectories within the vicinity of the warm front, an inset from Fig. 8 is constructed and 24-h forward trajectories are calculated from locations starting within that inset (Fig. 12). Three different types of trajectories are classified within this inset: trajectories belonging to the warm conveyor belt, the anticyclonic path of the cold conveyor belt, and the cyclookinetic path of the cold conveyor belt (trajectory beginning locations labeled W, A, and C, respectively). Like the warm-frontal surface, the boundary between the warm conveyor belt and the cyclonic path of the cold conveyor belt slopes rearward with height and is approximately coincident with the $\theta = 310$ K surface (thick solid line in Fig. 12). Above 850 hPa, there are one or more trajectories at the boundary between the warm conveyor belt and the cyclookinetic path of the cold conveyor belt, which ascend anticyclonically. Between 700 and 750 hPa, a sharp boundary exists between trajectories belonging to the cyclonic and anticyclonic paths of the cold conveyor belts (Fig. 12). This boundary is caused by a change in the flow field with height: The flow around the cyclone is closed below 700 hPa, whereas the flow is characterized by an open wave above 700 hPa (not shown). The closed flow below 700 hPa is more likely to feature cold conveyor belt trajectories in the cyclokinetic circulation around the low, whereas trajectories turning anticyclonically, not in the closed circulation, dominate above 700 hPa.

Thus, in this inset, the anticyclonic-turning trajecto-
Fig. 9. Twenty-four-hour storm-relative forward trajectories starting on the 297-K isentropic surface in cross section AB at 1200 UTC 5 Dec 1977 (Fig. 8). Thickness of trajectory corresponds to pressure, as in legend. Trajectories numbered 1–10 at the starting and ending locations. Arrows along trajectory occur every 3 h. Sea level pressure (thin solid lines every 4 hPa) and pressure on the $\theta = 297$ K surface (dashed lines every 100 hPa). (a) Warm-conveyor-belt trajectories 1 and 2, (b) anticyclonic path of the cold-conveyor-belt trajectories 3–7, and (c) cyclonic path of the cold-conveyor-belt trajectories 8–10.

Tropical cyclones are shown to be associated with a transition between the warm conveyor belt and the cyclonic path of the cold conveyor belt. As the gradient in wind direction across the frontal zone becomes less well defined with height, the boundary between the airstreams (i.e., the zone of anticyclonic-turning trajectories) becomes broader also. It is interesting to note that the $\theta = 297$ K and $\theta_e = 310$ K surfaces lie nearly along the zone in which the anticyclonic path of the cold conveyor belt trajectories dominate. Thus, Carlson’s choice of the $\theta = 297$ K and $\theta_e = 310$ K surfaces was fortuitous in that it lay at the boundary between the warm and cold conveyor belts and his analysis of the cold conveyor belt reflected only the anticyclonic path. Other choices of isentropic surfaces would have produced analyses entirely within either the warm conveyor belt or the cyclonic path of the cold conveyor belt. Therefore, in this section, calculation of storm-relative trajectories along isentropic surfaces clarifies the results from Carlson’s (1980) analysis of the same storm.
b. 1200 UTC 6 December 1977

Twenty-four hours later (6/12), storm-relative trajectories belonging to the anticyclonic path of the cold conveyor belt do not exist on the $\theta = 297$ K surface anymore (Fig. 13). The absence of the anticyclonic path of the cold conveyor belt at this level is due to the evolving midlevel flow: whereas the 500-hPa flow was an open trough at 5/12 (Fig. 6c), by 6/12, the flow became increasingly closed, with substantial flow around the storm at midlevels (Fig. 6d). The closed circulation favors the prominence of the cyclonic path of the cold conveyor belt.

Figure 13 also shows that trajectories originating closer to the low center are more likely to curve cyclonically around the low center than trajectories originating farther east of the low center on the same isentropic surface. This observation is consistent with results from Market (1996, Fig. 4.65) and Liu (1997, 114–115).

c. Generality of conclusions

In this paper, the anticyclonic path of the cold conveyor belt is shown to be a transition zone between the more substantial warm conveyor belt and cyclonic path of the cold conveyor belt. Because this study represents only a single case, however, the generality of this conclusion can be questioned. In this section, we explore two aspects of the generality of this result.

1) THE CYCLONIC PATH OF THE COLD CONVEYOR BELT AS A TRANSITION ZONE

Table 1 presents 19 studies that did not find evidence of the anticyclonic path of the cold conveyor belt, outweighing the three previous studies described in section 3a that found anticyclonically turning trajectories (i.e., Whitaker et al. 1988; Kuo et al. 1992; Liu 1997). One explanation for why studies illustrating the cyclonic path outnumber those illustrating the anticyclonic path is that the anticyclonic path may be a relatively narrow transition zone and may be found within a small range of isentropic surfaces in the lower to midtroposphere. Thus, sampling the anticyclonic path with trajectories or isentropic analyses may be more difficult. For example, Browning and Roberts (1994, their Fig. 8) show storm-relative moist-isentropic streamlines along three
Fig. 11. Storm-relative trajectories starting on the $\theta_v = 310$ K surface in cross section AB at 1200 UTC 5 Dec 1977 (Fig. 8). Thickness of trajectory corresponds to pressure, as in legend. Trajectories numbered 21–30 at the starting and ending locations. Arrows along trajectory occur every 3 h. Sea level pressure (thin solid lines every 4 hPa) and pressure on the $\theta_v = 310$ K surface (dashed lines every 100 hPa). (a) Twenty-four-hour forward trajectories; (b) 12-h backward trajectories.

Surfaces within the transition zone between the anticyclonic and cyclonic paths of the cold conveyor belt, showing that this transition occurs over a $\theta_v$ depth of 3 K.

It may be that some cyclones possess a weak anticyclonic path of the cold conveyor belt or do not possess one at all. Tung (1990), Kuo et al. (1992), and Browning and Roberts (1994, p. 1552) found that there is no sharp demarcation between the cold conveyor belt and the overlying warm conveyor belt in the cases they examined. This is likely related to the sharpness of the warm front, which, for marine cyclones at the end of storm tracks (e.g., over the eastern ocean basins), has been characterized as weak, “stubby,” or nonexistent by western U.S. and European meteorologists (e.g., Wallace and Hobbs 1977, p. 127; Friedman 1989, p. 217; Schultz et al. 1998, 1787–1788). In the extreme case where no sharp boundary exists, trajectories may smoothly transition from one regime to another, prohibiting categorization into discrete conveyor belts. As discussed by Cohen (1993, section 2.8.5), the so-called polar trough conveyor belt of Browning and Hill (1985) and Browning (1990) may be similar to such cases, where no sharp boundary between cold air and warm air exists, merely a zone of weak warm advection. These transition trajectories likely become more numerous when the gradient in wind direction associated with the warm front is less intense than that during the 5 December 1977 storm.

That the anticyclonic path of the cold conveyor belt is a transitional airstream between the warm conveyor belt and the cyclonic path of the cold conveyor belt
suggests that the airstream identified as W2, the second warm conveyor belt (e.g., Bader et al. 1995, section 5.2), may also be the same feature. Airstream W2 is described as “composed of air having a $\theta_e$ intermediate between that of the main warm conveyor belt and the cold conveyor belt. In some cases the origin of W2 is obvious. However, in other cases, W2 probably originates near or ahead of the warm front or is the lower part of W1 that curves around the developing low” (Bader et al. 1995, p. 213). Airstream W2 also bears a striking resemblance to the cold conveyor belt in the case presented by Carlson (1987) and the cyclonically turning moist airstream of Bierly and Winkler (2001), especially during the incipient cyclogenesis. Therefore, this present study helps to clarify the role of the different conveyor-belt terminologies found in the literature.

2) THE CYCLONIC PATH OF THE COLD CONVEYOR BELT IN DIFFERENT FLOW REGIMES

A second hypothesis to explain the apparent lack of anticyclonic-path trajectories in the previous literature is that, in cyclones with a deep closed storm-relative circulation extending to the mid- and upper troposphere, cold conveyor belt trajectories would be more likely to follow the cyclonic path than the anticyclonic path. This hypothesis is consistent with the majority of the cyclones in Table 1, which are rapidly developing and well-developed marine cyclones. These results are consistent with those for the warm conveyor belt, too. For example, for open wave cyclones, more of the warm conveyor belt flow ascends anticyclonically than cyclonically. The events described by Whitaker et al. (1988) and Kuo et al. (1992) are both associated with mobile shortwave troughs, rather than closed lows in the mid- and upper troposphere, suggesting that the storm-relative flow is open. The open flow in these events explains the preference for the ascending anticyclonic path of the warm conveyor belt (e.g., Fig. 18b in Whitaker et al. 1988 and Fig. 16 in Kuo et al. 1992).

Extending this thought, the large-scale flow in which the cyclone is embedded is important in controlling the path and strength of the cold conveyor belt, and conveyor belts in general, as discussed by Evans et al. (1994) and Bader et al. (1995, section 5.2).

Additional insight can be gained by considering the cyclone from a storm-relative framework. Because more lower-tropospheric flow would be “closed” in a storm-
relative perspective when the mean storm motion is removed (e.g., Sinclair 1994, his Fig. 1), the cyclonic path of the cold conveyor belt may become even more apparent in such analyses, compared to the anticyclonic path of the cold conveyor belt.

7. Origin of cloud head

The purpose of Carlson’s (1980) paper was to explain how the cloud pattern evolved into the comma-shaped cloud head. Carlson concluded that the air in the cloud head originated in the anticyclonic path of the cold conveyor belt. Later studies of other cyclones (e.g., Mass and Schultz 1993; Martin 1999) have shown that air in the cloud head originated from the cyclonic path of the warm conveyor belt. Given the mesoscale model simulation from Carlson’s cyclone event, the origin of the cloud and precipitation for this system can be determined.

A cross section parallel to the warm-frontal zone (Fig. 14a), along the cold conveyor belt as it travels underneath the warm-frontal zone, shows that the bulk of the cloud lies above the warm-frontal zone. Two maxima of cloud liquid water are shown (Fig. 14a): the maximum over Ohio (C1) is associated with a rainwater maximum (R1), which mostly evaporates before reaching the ground (Fig. 14b). This precipitation falls through the subsaturated portion of the cold conveyor belt where relative humidities are less than 90% (not shown), allowing significant evaporation. Farther west along the path of the cold conveyor belt, a second maximum in cloud liquid water above the warm-frontal surface over Illinois (C2) is associated with a maximum in rainwater (R2) (cf. Figs. 14a,b). Backward air-parcel trajectories from these two maxima of cloud water (not shown) demonstrate that these trajectories belonged to the warm conveyor belt. Whereas Carlson’s results showed that the clouds and precipitation originated within the anticyclonic path of the cold conveyor belt, the results from the model simulation show that the clouds and precipitation originated within the ascending warm conveyor belt.

Given the popularity of the Carlson (1980) characterization of the cold conveyor belt, it is likely that some forecasters use this concept to forecast precipitation since, according to Carlson (1980), the so-called wraparound precipitation in the cloud head is attributed to the rising anticyclonic cold conveyor belt. Using this methodology, forecasting bursts of heavier precipitation would rely on watching for fluctuations in the intensity of the cold conveyor belt. The results of this paper call that approach into question because the largest ascent and generation of heavy precipitation occurs primarily in the warm conveyor belt, not in the cold conveyor belt (e.g., Figs. 9 and 14). This result is consistent with that offered by Martin (1999), who expounds on the importance of the cyclonic path of the warm conveyor belt (i.e., trowal airstream) to heavy precipitation in the northwest quadrant of cyclones, but contradicts that of Liu (1997) who showed that as much as 70% of the moisture transport in cyclones could be associated with the cold conveyor belt. Thus, there appears to be some controversy in the literature whether the air that feeds the cloud head is from the warm or cold conveyor belt (e.g., Browning and Roberts 1994; Browning et al. 1995; Liu 1997; Dixon 2000, p. 77). Instead, the usefulness of the cold conveyor belt seems to be in recognizing the potential for evaporation of falling hydrometeors from the warm conveyor belt, melting of frozen hydrometeors (e.g., Kain et al. 2000), or precipitation-type forecasting (e.g., rain, snow, sleet, or freezing rain).

This is not to say that individual cyclones that form relatively shallow cloud heads may not be caused by
the cyclonic or anticyclonic paths of the cold conveyor belt in the head of the comma cloud, but heavy precipitation rates associated with strong lifting are less likely in such a stable environment. Heavy precipitation rates are more likely to be caused by deep clouds, perhaps associated with midlevel conditional or moist symmetric instabilities formed by wraparound precipitation generated at midlevels by the cyclonic path of the warm conveyor belt. It may be that the tendency to identify the cloud head with the cold conveyor belt in oceanic cyclones is due to the tendency for the cold conveyor belt, which has a potentially large fetch over the oceans, to be nearly saturated and emerge from underneath the polar front cloud band.

In fact, this property of the cold conveyor belt raises the following forecasting issue. While the warm conveyor belt air that arrives at a given point comes from the equatorward direction, the cold conveyor belt air comes from the east. Therefore, an indication of the potential for evaporation or melting of falling precipitation into the cold air can be obtained from examination of the properties of the cold air from upstream (i.e., more east). For example, if such air is more moist farther east, then surface precipitation rates are more likely to increase with time (assuming a given precipitation rate generated in the warm conveyor belt). On the other hand, drier air being advected from farther east may indicate a lessening of the precipitation rate at the surface. This is in contrast to the air in the warm conveyor belt, for which an understanding of its properties before ascent comes from farther equatorward in the warm sector.

8. Summary

This study explored the path of the cold conveyor belt through the midlatitude cyclone of 5 December 1977, previously studied by Carlson (1980). Storm-relative isentropic analysis and air-parcel trajectories calculated from a mesoscale model simulation of Carlson’s (1980) storm showed that both the cyclonic and anticyclonic paths of the cold conveyor belt existed. The anticyclonic path represented a transition between the two more substantial airstreams in the lower troposphere: the warm conveyor belt and the cyclonic path of the cold conveyor belt. This transition zone began in the lower troposphere where the circulation around the cyclone was closed and widened with height to the point where the cyclone became an open wave. Above this point, the anticyclonic path became the dominant airstream. The prevalence of the anticyclonic path of the cold conveyor belt in Carlson’s analysis is shown to be due to his selection of isentropic surfaces at the leading edge of the warm front. Had Carlson picked a colder isentropic surface, the cyclonic path of the cold conveyor belt would have been more apparent. This serendipity also explains the relative paucity of trajectories belonging to the anticyclonic path of the cold conveyor belt in previous literature. Perhaps, in the future, renaming the anticyclonic path of the cold conveyor belt a transition airstream may be more appropriate and less confusing.

The variability of observed cyclones in different large-scale flow patterns (e.g., confluence, diffluence) has been explored previously by Evans et al. (1994), Bader et al. (1995), and Schultz et al. (1998). Whereas this study focused on the cold conveyor belt through a single cyclone, implications for the airflow in other cyclones of different strength and shape, and embedded in different large-scale flows, have been proposed and remain to be tested rigorously.

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