OCCLUDED FRONTS AND THE OCCLUSION PROCESS

A Fresh Look at Conventional Wisdom

BY DAVID M. SCHULTZ AND GERAINT VAUGHAN

Comparing the 90-yr-old Norwegian cyclone model to recent research results demonstrates that descriptions of the occlusion process in textbooks need to be rewritten.

The Norwegian cyclone model is the foundation of observational synoptic meteorology. In the early twentieth century, the scientists at the Geophysical Institute in Bergen, Norway, drew upon previous research and a mesoscale observing network to create a conceptual model for the structure and evolution of extratropical cyclones and their attendant fronts (e.g., Bjerknes 1919; Bjerknes and Solberg 1921, 1922). Even 90 yr hence, the success of the Norwegian cyclone model is a testament to its ingenuity, simplicity, and basic accuracy. Elements of the Norwegian cyclone model continue to be presented in meteorological textbooks, whether for meteorologists (e.g., Palmén and Newton 1969; Wallace and Hobbs 1977, 2006; Carlson 1991; Bluestein 1993; Gordon et al. 1998; Barry and Carleton 2001; Martin 2006), introductory classes (e.g., Gedzelman 1980; Moran and Morgan 1997; Lutgens and Tarbuck 2001; Aguado and Burt 2001; Ackerman and Knox 2007; Ahrens 2008; Barry and Chorley 2010), or the general public (e.g., Kimble 1951; Williams 1997, 2009; Lehr et al. 2001). Figure 1 provides a typical example of how the Norwegian cyclone model is illustrated in one of the most recent books (Williams 2009).

Despite the durability and longevity of conceptual models such as the Norwegian cyclone model, their applicability needs to be continually reassessed. The body of conventional wisdom, or common knowledge shared among the members of the scientific community, is called a paradigm (Kuhn 1970). Weaknesses, inconsistencies, contradictions of existing theory, and observations that do not fit the paradigm [called anomalies by Kuhn (1970)] are occasionally revealed. As a growing number of such anomalies accumulate, eventually a new conceptual model that explains the anomalies arises. This new conceptual model replaces the old, and a paradigm shift occurs. Science advances.

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In this article, we examine some of the conventional wisdom that has arisen in conjunction with the Norwegian cyclone model. To limit the scope of this article, we examine just one aspect of the model: occluded fronts and the occlusion process. Likely because of the success of the Norwegian cyclone model in explaining observations of cyclones, Keyser (1986, p. 252) found that "modern case studies illustrating occluded fronts and the occlusion process are virtually nonexistent." As a result, our investigation may be hindered by the available research. Fortunately, a period of abundant research that originated from the problem of unforecasted explosive cyclone development identified by Sanders and Gyakum (1980) has yielded new insights into occluded fronts and the occlusion process (e.g., Shapiro and Keyser 1990; Kuo et al. 1992; Schultz and Mass 1993; Reed et al. 1994; Reed and Albright 1997; Market and Moore 1998; Schultz et al. 1998; Martin 1998a,b, 1999a,b; Martin and Marsili 2002; Stoelinga et al. 2002; Posselt and Martin 2004; Novak et al. 2004, 2008, 2009, 2010; Grim et al. 2007; Han et al. 2007). Therefore, we take stock of these recent results and compare them with the Norwegian cyclone model.

THE CONVENTIONAL WISDOM OF THE NORWEGIAN CYCLONE MODEL. The process by which an extratropical cyclone forms an occluded front was first described by Bjerknes and Solberg (1922) and was based upon the analyses and

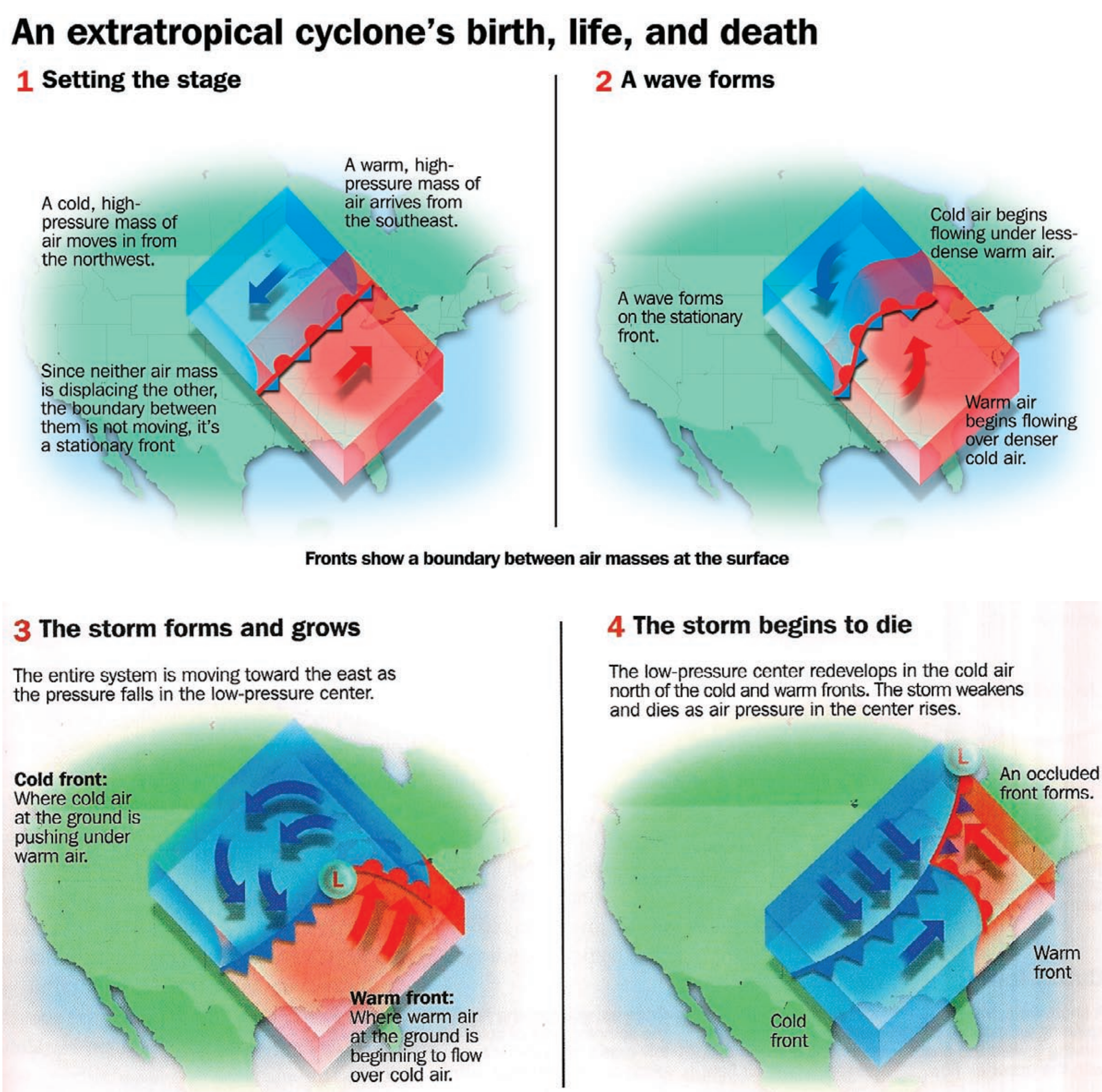

FIG. 1. The life cycle of an extratropical cyclone from an introductory textbook (excerpts from Williams 2009, 110–111).

insight of Tor Bergeron (e.g., Bergeron 1937, 1959; Godske et al. 1957; Friedman 1989, chapter 10). This work was largely responsible for the development of the conventional wisdom of the occlusion process in the Norwegian cyclone model, which is associated with the view of fronts as discontinuities in the temperature field [also called the wedge model by Keyser (1986)]. This conventional wisdom can be defined by the following four tenets:

1) The occluded front forms and lengthens as a faster-moving cold front catches up to a slower-moving warm front, separating the warm-sector air from the low center (Fig. 2).
2) Two types of occluded fronts are possible (Fig. 3): A warm-type occlusion forms if the air ahead of the warm front is colder than the air behind the cold front, whereas a cold-type occlusion forms if the air ahead of the warm front is warmer than the air behind the cold front.
3) The formation of the occluded front signifies an end to the deepening phase of the cyclone.
4) The occluded front is characterized by the prefrontal weather of a warm front (widespread clouds and precipitation) followed by the postfrontal weather of a cold front (clear skies and drying).

These four tenets define what we refer to as the "catch-up" model of the occlusion process. Textbooks typically illustrate the catch-up model by schematic horizontal maps and vertical cross sections through occluded fronts that look similar to Figs. 1–4.

TOWARD IMPROVED PHYSICAL UNDERSTANDING. Although the Norwegian cyclone model was based on fronts as discontinuities in temperature, later research (e.g., Bjerknes 1935; Bjerknes and Palmén 1937) showed that fronts were better described as discontinuities in temperature gradient [also called the zone model by Keyser (1986)]. In addition, the advances offered by baroclinic instability and quasigeostrophic and semigeostrophic theories changed the way that fronts were perceived (e.g, Hoskins 1982; Keyser 1986; Davies 1997; Schultz 2008), implying that the conventional wisdom of the Norwegian cyclone model may no longer provide the best explanation for cyclone structure and evolution.

Thus, we propose to evaluate these four tenets of conventional wisdom from the Norwegian cyclone model in light of these advances. This evaluation leads us to a new perspective on occluded fronts and the occlusion process where we define the occlusion

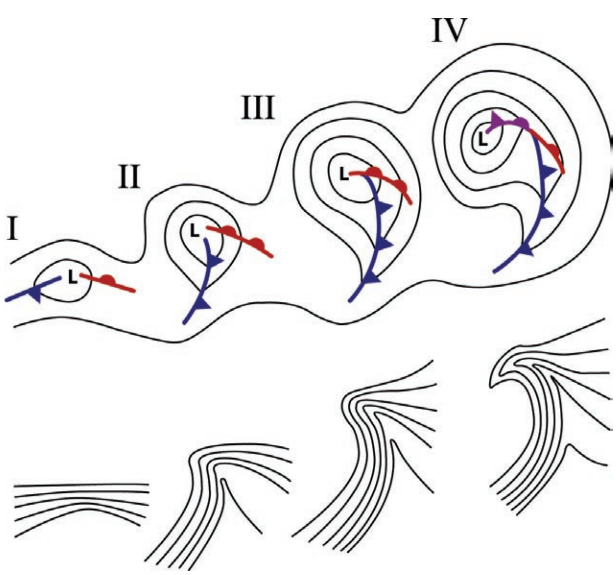

Fig. 2. Conceptual model of a Norwegian cyclone showing (top) lower-tropospheric (e.g., 850 mb) geopotential height and fronts, and (bottom) lower-tropospheric potential temperature. The stages in the respective cyclone evolutions are separated by approximately 6–24 h and the frontal symbols are conventional. The characteristic scale of the cyclones based on the distance from the geopotential height minimum, denoted by L, to the outermost geopotential height contour in stage IV is 1000 km. [Caption and figure adapted from Fig. 15a in Schultz et al. (1998).]

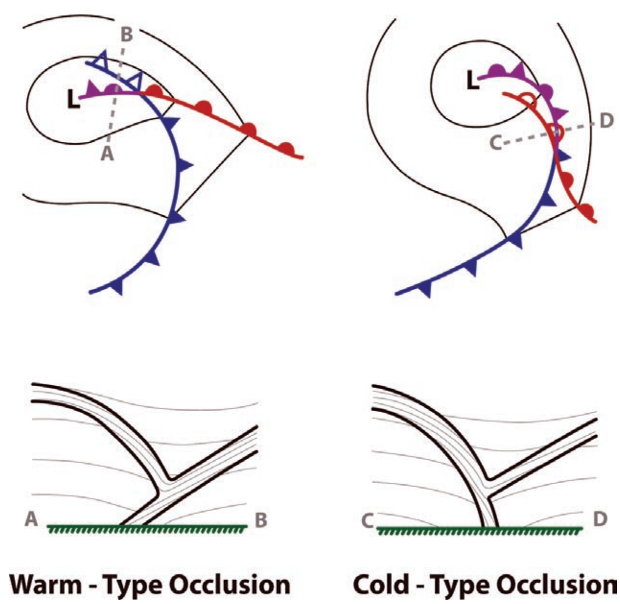

Fig. 3. (top) Schematic surface maps of sea level pressure and (bottom) schematic vertical cross sections of potential temperature through warm- and cold-type occlusions. [Adapted from Fig. 9.04 in Saucier (1955).]

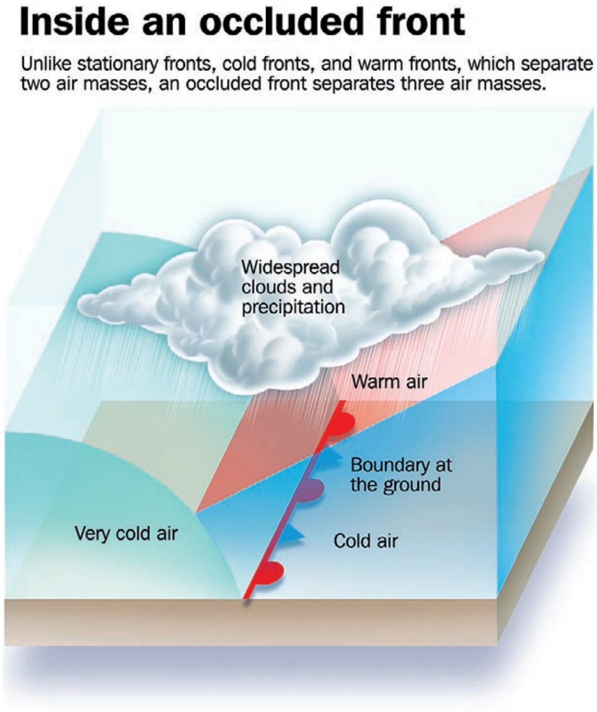

Fig. 4. An occluded front from an introductory textbook (excerpt from Williams 2009, p. 110).

process as the separation of the warm-sector air from the low center through the wrap-up of the thermal wave around the cyclone. This new perspective has the following advantages over the Norwegian cyclone model:

1) a more general, fluid dynamical perspective that extends the occlusion process into a continuously stratified fluid;
2) an improved description of the relationship between the processes responsible for the evolution of the thermal structure of the cyclone (i.e., the occlusion process) and the processes responsible for the deepening of the cyclone (i.e., development);
3) a generalization of the occlusion process across the spectrum of cyclone life cycles, particularly other cyclone models that are not generally considered to form occluded fronts (e.g., the Shapiro–Keyser cyclone model); and
4) a synthesis of various physical processes (synoptic-scale dynamics, frontogenesis, and clouds and precipitation) and conceptual models (airstream models and cyclone models) into a coherent framework for occluded fronts and cyclones.

This new perspective is developed throughout this paper, through a discussion of the four tenets of conventional wisdom and their applicability within this new perspective. This new perspective exposes the weaknesses and anomalies of the conventional wisdom, which are then resolved and explained by reference to observations, theory, diagnostics, and numerical modeling, as described in the schematic figure by Shapiro et al. (1999, their Fig. 1). The result is improved physical understanding of the occlusion process.

TENET 1: THE OCCLUDED FRONT FORMS AND LENGTHENS AS A FASTER-MOVING COLD FRONT CATCHES UP WITH A SLOWER-MOVING WARM FRONT. The key to occluded front formation in the Norwegian cyclone model is the catch-up mechanism. For the surface cold front to catch up to the surface warm front, the cold front must be moving faster than the warm front in the direction of motion of the warm front. Indeed, observed cyclones (e.g., Carr 1951; Schultz and Mass 1993; Market and Moore 1998; Martin 1998a; Locatelli et al. 2005) and model simulations (e.g., Joly and Thorpe 1989; Reed et al. 1994) of occluding cyclones support this tenet. It is undeniably true that in many cyclones the cold front approaches the warm front, eventually overtaking it. However, is catch-up the explanation for occluded front formation, or is it the consequence of an underlying dynamical process?

Consider the following analogy: Suppose you had come across an automobile accident and asked a witness, "What happened here?" and got the obvious and unhelpful response, "Two cars collided." An *explanation* would be if one car failed to brake or one car ran a red light. Information from the collision could then be used to assess which of the possible explanations are most likely (e.g., the damage patterns on the two cars can rule out some possible explanations). Simply put, catch-up producing an occluded front is the *result* of the occlusion process in the Norwegian cyclone model; it does not provide an *explanation* for how the occlusion process occurs.

To obtain insight into the explanation for occluded front formation, consider simple models of vortices that produce occluded-like structures. For example, kinematic models of a vortex advecting a passive tracer representing isotherms show that occluded-like warm- and cold-air tongues can develop when the "cold front" moves at the same speed as the "warm front" (Doswell 1984, 1985; Davies-Jones 1985; Keyser et al. 1988). Even in a nondivergent barotropic model where "isotherms" are passively advected by the flow

(Schultz et al. 1998), occluded-like warm- and cold-air tongues can develop (Fig. 5).

The thinning process that creates these tongues results from the radial gradient in tangential wind speed around the vortex, which can also be expressed as a shearing deformation (e.g., Saucier 1955, 355–363). This gradient in tangential wind speed takes the initially straight isotherms and differentially rotates them. The differential rotation of the isotherms increases the gradient (i.e., frontogenesis; Petterssen 1936), and the lengthening and spiraling of the isotherms brings the cold- and warm-air tongues closer (Fig. 5). (In contrast, a vortex in solid-body rotation would have no deformation and would not produce tongues.)

Although the spiraling isotherm pattern appears as if warm- and cold-air tongues flow toward the center of the vortex, individual air parcel trajectories in this model travel in circular orbits and never approach the center themselves. Instead, the spiral pattern exists because the axis of dilatation [the direction of maximum stretching in the fluid (Saucier 1955, 355–363; Cohen and Schultz 2005)] lies 45° counterclockwise relative to the streamlines everywhere in the vortex (e.g., Doswell 1984; Keyser et al. 1988; Schultz et al. 1998). Thus, in time, the isotherms approach the orientations of the axes of dilatation, which creates the spiral pattern.

Another characteristic of the airstreams in the kinematic and barotropic models is that the area of the cold air mass is the same as the area of the warm air mass—for all times. Because these models contain no horizontal divergence, the air is simply redistributed into symmetric warm- and cold-air tongues, and the warm-sector air is separated from the low center. However, in real extratropical cyclones, cold air expands at the expense of the warm air in the lower troposphere, which requires divergence. Such a process can be modeled using a baroclinic channel model without moisture (e.g., Takayabu 1986; Davies et al. 1991; Thorncroft et al. 1993; Reed et al. 1994; Schultz and Zhang 2007). For example, one of the simulations from Schultz and Zhang (2007) shows the development of a deep low pressure center, warm- and cold-air tongues, and the subsequent narrowing of the warm sector resulting from deformation, the horizontal convergence and ascent of the warm-sector air, and its separation from the low center (Fig. 6). The result is an occluded cyclone in horizontal maps (Fig. 6) and an occluded front in a vertical cross section (Fig. 7).

In such simulations, the warm-sector air is removed from the lower troposphere primarily through ascent over the warm front. Flow out of the warm sector by ascent over the cold front also occurs, but is of secondary importance (Sinclair et al. 2010). At the same time, the area of the cold air at the surface surrounding the cyclone expands as a result of the following two processes: the introduction of more cold air into the circulation around the low center by the cold conveyor belt (originating from the anticyclone downstream of the cyclone center) and surface divergence associated with low-level descent behind the cold front. The enlarging cold sector and the combination of the wrapping up of the thermal wave and ascent narrowing the warm-air tongue enhances

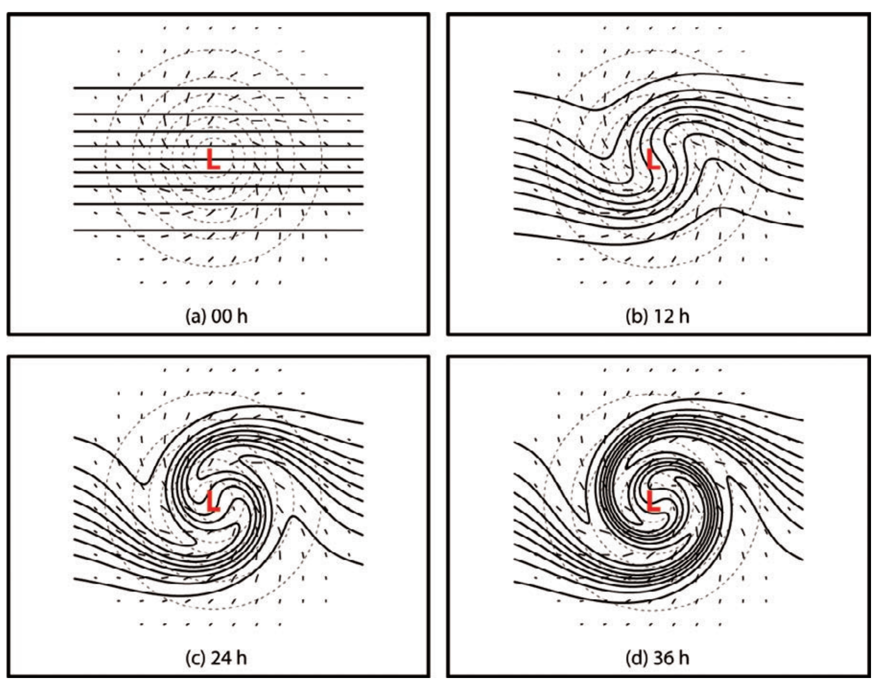

Fig. 5. Evolution of the Doswell (1984, 1985) vortex at (a) 0, (b) 12, (c) 24, and (d) 36 h. Large "Ls" represent locations of minimum streamfunction. Potential temperature (solid lines every 2 K), streamfunction (dashed lines every 1 × 10^6 m² s^{-1}), and axes of dilatation of the horizontal wind [proportional to magnitude of total deformation; separation between displayed axes of dilatation is 148 km (every fifth grid point)]. [Caption and figure adapted from Fig. 12 in Schultz et al. (1998).]

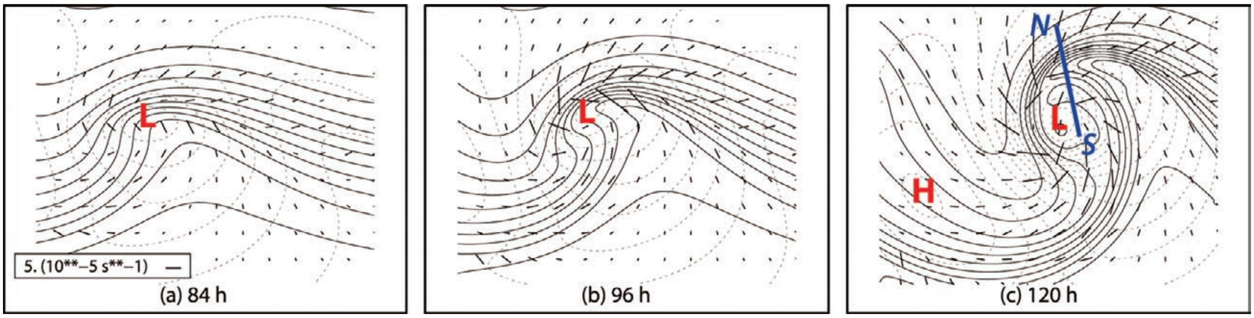

Fig. 6. Evolution of a growing baroclinic disturbance in confluent background flow at (a) 84, (b) 96, and (c) 120 h. Potential temperature every 4 K is denoted (solid black lines). The 850-mb geopotential height every 6 dam is depicted (dotted gray lines); and L and H mark the locations of the minimum and maximum in geopotential height, respectively. The axes of dilatation of the horizontal wind are marked (short black lines); their length is proportional to the magnitude of the total deformation according to scale in (a), and the separation between the displayed axes of dilatation is 300 km (every third grid point). The blue line N–S in (c) represents the location of the cross section in Fig. 7. [Caption and figure adapted from Fig. 4 in Schultz and Zhang (2007), and an animation of this graphic can be found online at http://dx.doi.org/10.1175/2010BAMS3057.2.]

the occlusion process, but does not change its essence. The essence of the occlusion process—the wrapping up of the thermal wave and the separation of the warm sector from the low center—occurs, whether in kinematic passive tracer models, barotropic models, or baroclinic models.

Although this wrap-up of the thermal wave during the occlusion process is most readily illustrated in idealized cyclone models, observations confirm that catch-up cannot be responsible for the length of some occluded fronts. Consider the oceanic cyclone in Fig. 8, which is discussed by Reed and Albright (1997). The occluded front at the surface and the cloud pattern aloft are wrapped nearly one and a half times around the low center. Such a long occluded front was formed as deformation and rotation by the cyclone's circulation lengthened the front, not as a result of catch-up (which cannot increase the total length of the fronts). Reed et al. (1994, their Fig. 4) also showed that the combined narrowing of the warm sector and the extension of the occluded front occurred by deformation of the warm-air tongue, not as a result of catch-up. These results are consistent with the technique described by Smigielski and Mogil (1995) to determine the central pressure of a marine extratropical cyclone using only satellite imagery. Their technique shows that the deeper the central pressure of the cyclone, the greater the number of rotations that the spiral cloud pattern possesses. Thus, stronger circulations produce greater lengths to the occluded fronts, greater lengths that cannot be explained by catch-up.

A different explanation for the squeezing together of the two frontal zones and the lengthening of the occluded thermal ridge was proposed by Martin (1999b, 2006). He used an expression for the rotational component of the **Q** vector partitioned into terms containing geostrophic deformation and geostrophic vorticity.

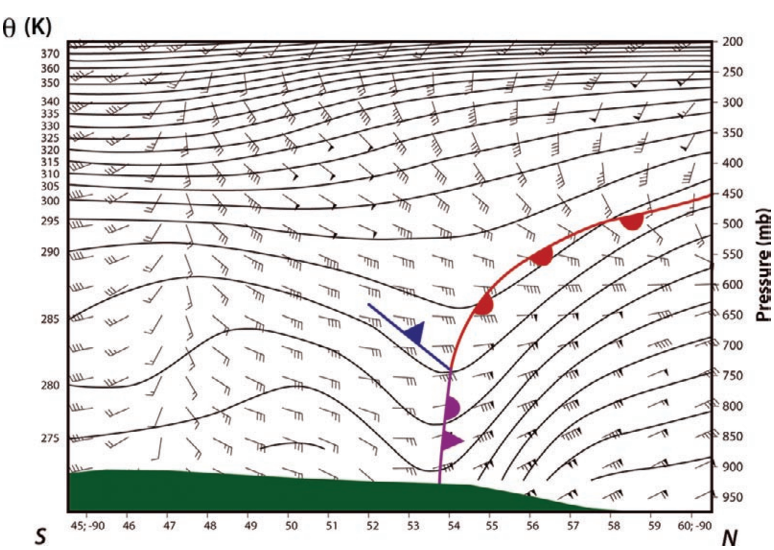

Fig. 7. North–south cross section through the warm-type occluded front in Fig. 6c. Potential temperature (solid lines every 5 K) and horizontal wind (pennant, full barb, and half-barb denote 25, 5, and 2.5 m s^{-1}, respectively; separation between displayed wind vectors is 100 km). The ground is shown (green area), and the horizontal axis is labeled in degrees latitude.

Because both of these terms were large in the region of the occluded front, Martin (1999b) concluded that quasigeostrophic ascent along the occluded front was a result of these combined terms. By involving the **Q** vector, however, Martin's (1999b) mechanism is notably baroclinic. We propose a different mechanism—that *barotropic kinematic processes* produce the structure of the occluded front, as shown by Doswell (1984, 1985) and Schultz et al. (1998). Because our argument does not require baroclinicity, wrap-up represents a more fundamental explanation for the formation of the warm tongue than that offered by Martin (1999b).

Three-dimensional structure of occluded cyclones. Despite the emphasis on what happens at the surface, occlusion is a three-dimensional process involving not only the narrowing of the warm sector, but also the ascent of the intervening warm air over the warm front. Furthermore, processes occurring aloft affect the development of the surface low center. Therefore, a holistic approach to the occlusion process must involve its three-dimensional structure.

The spiraling of the warm and cold air around each other to form the wrap-up of the thermal wave occurs not only at the surface, but aloft as well. The depth over which this wrap-up occurs is related to the intensity of the cyclone and the depth of the closed circulation (e.g., Palmén 1951, p. 610). The wrap-up of the thermal wave is related to the warm conveyor belt, the warm-sector air that is lifted aloft over the warm front (Fig. 9). The majority of air in the warm conveyor belt in a young cyclone rises aloft over the warm front, turns anticyclonically, and travels downstream (Fig. 9a). A closed circulation forms in the lower troposphere, which gets progressively deeper as the surface pressure falls. This deepening closed

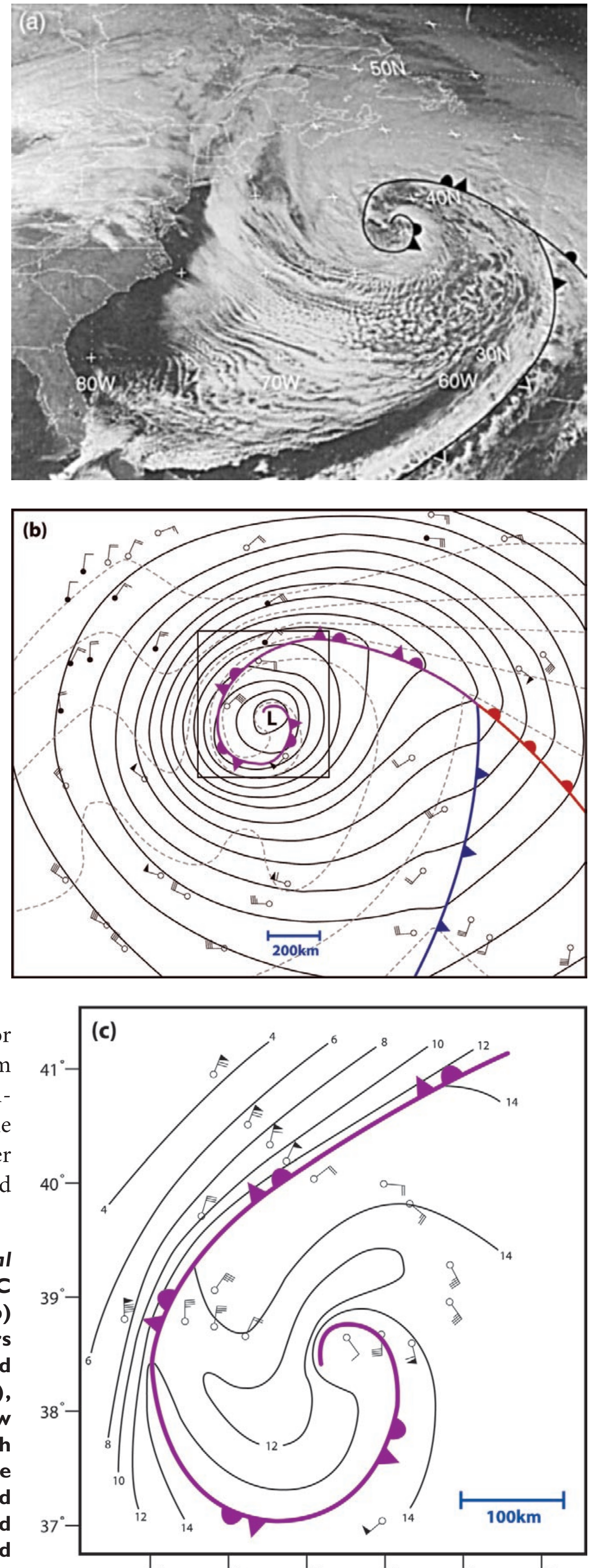

Fig. 8. (a) *Geostationary Operational Environmental Satellite* (*GOES-7*) visible satellite image at 1801 UTC 14 Dec 1988 with frontal positions superimposed. (b) Surface map at 1800 UTC 14 Dec 1988 with isobars (solid black lines every 4 mb) and isotherms (dashed gray lines every 4°C). Ship positions (open circles), buoy positions (dots), and area of expanded view (rectangle) in (c). (c) Flight section at 300 m AGL with ship, buoy, and dropsonde data added and temperature (solid lines every 2°C). In (b) and (c), horizontal wind (pennant, full barb, and half-barb denote 25, 5, and 2.5 m s^{-1}, respectively). [Captions and figures adapted from Figs. 6, 7, and 9a in Reed and Albright (1997).]

circulation is accompanied by a portion of the rising warm conveyor belt air being directed cyclonically around the low center (e.g., Browning and Roberts 1996, their Fig. 8; Bader et al. 1995, p. 305; Browning and Roberts 1994, their Fig. 10; Martin 1998a,b; Schultz 2001, 2221–2222; Fig. 9b herein). This cyclonically turning portion of the warm conveyor belt was first recognized by Bjerknes (1932) and Namias (1939), and later by Golding (1984), Kurz (1988), Browning (1990), Mass and Schultz (1993), Browning and Roberts (1994, 1996), Martin (1998b, 1999a), and Han et al. (2007). Martin (1998b, 1999a) referred to this portion of the warm conveyor belt as the trowal airstream, after the trowal or trough of warm air aloft in the occluded front (e.g., Crocker et al. 1947; Godson 1951; Penner 1955), and Bierly and Winkler (2001) referred to it as the cyclonically turning moist airstream. Note that this airstream does not need to reach the cyclone center aloft.

The intensification of the cyclonic turning of the warm conveyor belt is usually supported by an intensification of the upper-level shortwave trough or potential vorticity anomaly (Martin 1999a; Novak et al. 2008, 2009, 2010), as shown in Fig. 9b. In most baroclinic channel model simulations, preexisting upper-level shortwave troughs do not exist. Instead, they develop at the same time as the cyclone. In the real atmosphere, however, preexisting shortwave troughs do occur (e.g., Sanders 1988; Lefevre and Nielsen-Gammon 1995; Dean and Bosart 1996;

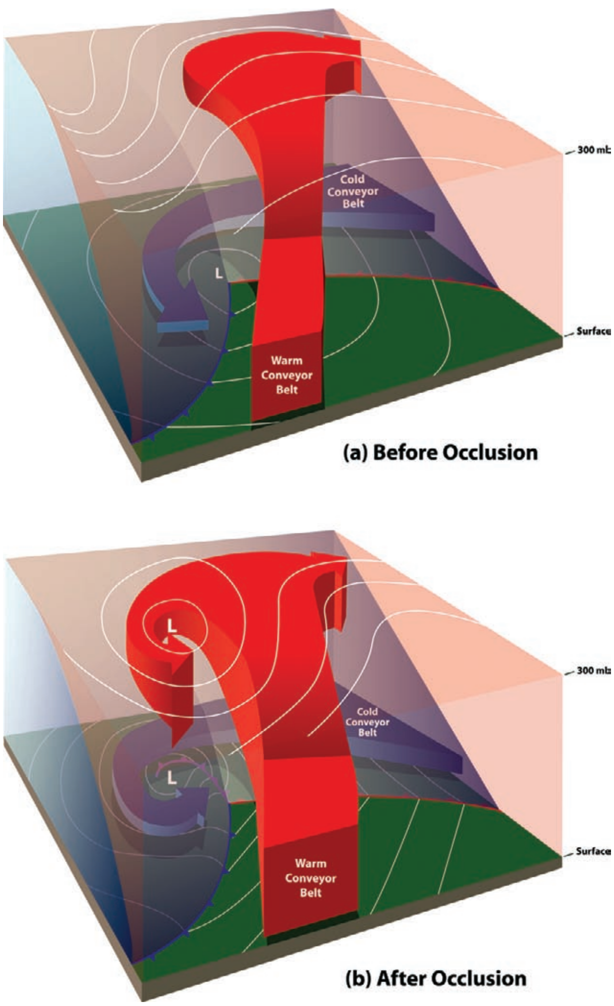

Fig. 9. Warm conveyor belt (red) and cold conveyor belt (blue): (a) before occlusion and (b) after occlusion. The interaction between the upper-level front and the surface-based cold front is not depicted. The characteristic horizontal scale of the domain is 1000 km on each side.

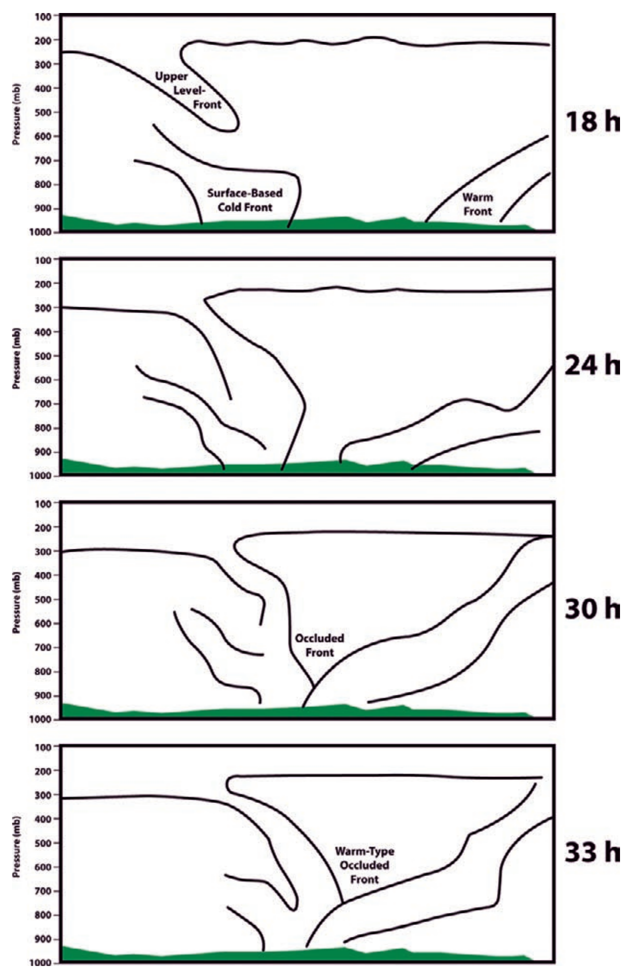

Fig. 10. Vertical cross sections of the formation of a warm-type occluded front at 18, 24, 30, and 33 h into a mesoscale model simulation initialized at 1200 UTC 14 Dec 1987. Heavy lines represent manually analyzed lines of temperature gradient discontinuities and the tropopause. The ground is shown (green area). [Caption and figure adapted from Fig. 9 in Schultz and Mass (1993).]

Hakim 2000) and are associated with cyclogenesis, especially explosive cyclogenesis (e.g., Uccellini et al. 1985; Uccellini 1986; Sanders 1987; Rogers and Bosart 1991; Lackmann et al. 1996, 1997). Occlusion is usually accompanied by the formation of a closed or cut-off low in the mid- and upper troposphere (e.g., Palmén 1951; Martin 1998a; Martin 2006, section 9.5.2). Tying the development aloft to the separation of the warm-sector air from the low center, Palmén (1951, p. 616) said, “The process of seclusion of the polar air at the 500-mb level [the formation of a closed low] thus corresponds to the occlusion process in lower layers.”

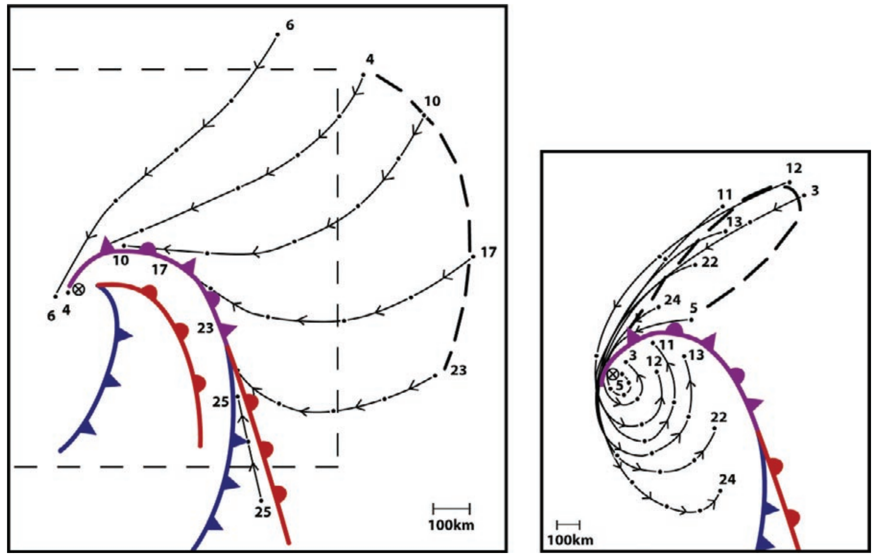

Fig. 11. The σ = 0.91 (~900 mb) backward trajectories for the period from 2200 UTC 13 Feb to 1330 UTC 14 Feb 1982, for (a) parcels to the east of the storm and far removed from it and (b) parcels closer to the surface low. Manually determined fronts for the beginning and ending hours are shown in (a) and for the ending time only in (b). The inset in (a) indicates the location of (b). Thick dashed line segments denote the locations of air that would eventually become (a) the leading edge and (b) the trailing edge of the occluded front (thick dashed line segments). [Caption and figure adapted from Fig. 8 in Kuo et al. (1992).]

These upper-level shortwave troughs are associated with upper-level fronts (e.g., Reed and Sanders 1953; Lackmann et al. 1997; Schultz and Sanders 2002), which may be involved in the occlusion process, as shown in the schematic diagram from Godske et al. (1957) and reproduced in Palmén and Newton (1969, p. 125), and in case studies by Schultz and Mass (1993), Steenburgh and Mass (1994), Locatelli et al. (2005), and Grim et al. (2007). In these four cases, the extension of the upper-level front into the occluded front structure gave the appearance of the “cold front” being lifted over the warm front (Fig. 10), although the structure did not form that way. Thus, structures that could have developed in a manner consistent with the Norwegian cyclone model might actually have developed in a decidedly non-Norwegian way.

Back-to-back fronts. Yet another demonstration that the catch-up process does not explain the occlusion process is the description of an occluded front as the “combination of the warm and the cold front” (Petterssen 1956, 217, 220) or a “back-to-back frontal zone” (e.g., Wallace and Hobbs 1977, p. 123; Market and Moore 1998), with the prefrontal weather of a warm front (clouds and precipitation) followed by the postfrontal weather of a cold front (clear skies and drying). One condition for a back-to-back front would be if the air behind the occluded front was air that was behind the cold front before occlusion and the air ahead of the occluded front was air that was ahead of the warm front before occlusion. Schultz and Mass (1993) showed that soon after occlusion and near the surface this condition was met (e.g., the front was a back-to-back front as indicated by trajectory 8 in their Fig. 12), but later and above the surface, the post-cold-frontal air originated ahead of the warm front (trajectory 23 in their Fig. 12; trajectories 5 and 17 in their Fig. 13). Cohen and Kreitzberg (1997, their Figs. 15 and 16) showed that their trajectory labeled “a” originated ahead of the cyclone and circled around the low center, ending up equatorward of the occluded front. Kuo et al. (1992) showed that as the occluded front aged, the post-occluded front air originated ahead of the warm front (Fig. 11), as did Bjerknes and Giblett (1924, their Fig. 4). In fact, these trajectories in Fig. 11 and those in Schultz and Mass (1993) and Cohen and Kreitzberg (1997) were part of the airstream called the cold conveyor belt (Carlson 1980), which originates from the anticyclone ahead of the low center, travels near the surface underneath the warm-frontal zone, and then turns cyclonically around the low center (Schultz 2001), as shown in

Fig. 9. The cold conveyor belt is the airstream that eventually surrounds the low center with cold air—it is the airstream responsible for separating the warm-sector air from the low center. With the air ahead of the warm front circling the low center and ending up behind the cold front as part of the wrap-up of the thermal wave, we question whether it is appropriate to refer to an occluded front as a back-to-back frontal zone. (More discussion of this point occurs in tenet 4 below.)

Other cyclone models. The Norwegian cyclone model is not the only conceptual model for cyclone structure and evolution. Another example is the Shapiro–Keyser cyclone model (Fig. 12; Shapiro and Keyser 1990). In this cyclone model, the northern portion of the cold front is weakened by differential rotation around the cyclone [the frontal fracture (Browning et al. 1997; Schultz et al. 1998, their Fig. 10)] and is aligned nearly perpendicular to the warm front (the frontal T bone). At stages III and IV in Fig. 12, the warm-frontal zone is advected around the low center by the cold conveyor belt to form a back-bent front [Schultz et al. (1998, p. 1770) discuss the terminology of the back-bent front], and this back-bent front eventually wraps up and around the slower-moving warmer air (Fig. 11; Kuo et al. 1992; Reed et al. 1994) forming a warm-core seclusion.

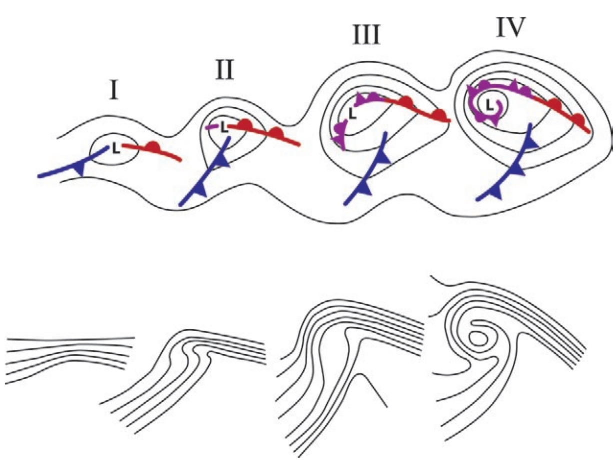

Fig. 12. Conceptual model of a Shapiro–Keyser cyclone showing (top) lower-tropospheric (e.g., 850 mb) geopotential height and fronts, and (bottom) lower-tropospheric potential temperature. The stages in the respective cyclone evolutions are separated by approximately 6–24 h and the frontal symbols are conventional. The characteristic scale of the cyclones based on the distance from the geopotential height minimum, denoted by L, to the outermost geopotential height contour in stage IV is 1000 km. Figure and caption are adapted from Shapiro and Keyser (1990, their Fig. 10.27) to enhance the zonal elongation of the cyclone and fronts and to reflect the continued existence of the frontal T bone in stage IV and from Fig. 15b in Schultz et al. (1998) to change the back-bent warm front into an occluded front and back-bent occluded front.

Stages I and II in the Shapiro–Keyser cyclone model are similar to those in the Norwegian cyclone model, except for the obtuse or right angle between the cold and warm fronts (cf. Figs. 2 and 12). With the weak northern portion of the cold front nearly perpendicular to the warm front in the Shapiro–Keyser cyclone, a narrowing warm tongue as in the Norwegian cyclone model does not develop, and catch-up does not occur (Fig. 12). By stage III in the Norwegian cyclone model, an occluded front starts to form as the cold conveyor belt wraps around the low center. In the Shapiro–Keyser cyclone model, the cold conveyor belt essentially follows the same path as that in the Norwegian cyclone model, but results in a back-bent front and warm-core seclusion. Thus, the Shapiro–Keyser cyclone model has not traditionally been viewed as forming an occluded front and undergoing the occlusion process (e.g., Shapiro and Keyser 1990; Schultz et al. 1998).

Nevertheless, if the occlusion process is more generally defined to be the separation of the warm-sector air from the low center through the wrapping up of the thermal wave, then the thermal structure and evolution of the Shapiro–Keyser cyclone can be welcomed into this more general definition. Indeed, if we consider the extension of the cold front in stages III and IV of the Shapiro–Keyser cyclone intersecting with the warm front to define the westernmost limit to the warm sector, then the portion of the warm front extending from this intersection westward can be considered to be the occluded front (drawn with the purple occluded front symbols in Fig. 12). [Additionally, portions of the occluded front extending westward from the low center could be considered to be a back-bent occlusion, as per its original terminology (Bjerknes 1930; Bergeron 1937).] Stages III and IV in both the Norwegian and the Shapiro–Keyser cyclone models exhibit an increasing distance between the warm-sector air and the low center caused by the rotation and deformation associated with the cyclonic circulation. In both cyclones, the cold conveyor belt is the airstream that wraps the low center in cold air, allowing this separation to occur. Consequently, this generalized definition of the occlusion process allows a description of occluded front formation and the occlusion process in the Shapiro–Keyser cyclone model.

Similarly, Reed et al. (1994, p. 2707) discussed the structure and evolution of an extratropical cyclone with many of the characteristics of the Shapiro–Keyser model, but concluded that there was "no reason to abandon the term 'occluded front.'" Indeed, their argument is consistent with our fluid-dynamical approach to the occlusion process that focuses on the wrap-up of the thermal wave. The precise details of that wrap-up will vary from cyclone to cyclone depending upon the large-scale flow within which the cyclone is embedded (e.g., Davies et al. 1991; Thorncroft et al. 1993; Evans et al. 1994; Wernli et al. 1998; Schultz et al. 1998; Schultz and Zhang 2007). Nevertheless, differential rotation around a cyclone will create a separation between the low center and the warm-sector air, regardless of the other details of the cyclone, such as whether the angle between the cold and warm fronts is an acute angle (as in the Norwegian cyclone model) or a right or obtuse angle (as in the Shapiro–Keyser cyclone model).

Other cyclones that do not undergo occlusion as envisioned in the Norwegian cyclone model also can be viewed as having undergone occlusion in the framework of wrap-up. For example, in describing a developing cyclone in the central United States, Palmén (1951) observed a cold front arriving from the Pacific Ocean connecting with a warm front representing the northern extent of warm, moist air from the Gulf of Mexico. The resulting structure resembled an occluded cyclone without having undergone the typical occlusion process. As Palmén (1951, 615–616) summarized,

> The three-dimensional fields of temperature, pressure, and wind . . . are, however, characteristic of every 'occluded' cyclone whether it has passed through a regular process of occlusion or not . . . . Obviously, a well-marked surface front is not so essential for the development as was generally assumed formerly.

Indeed, other similar cyclones have produced warm-type occluded fronts (e.g., Locatelli et al. 1989; Hobbs et al. 1990, 1996; Steenburgh and Mass 1994; Neiman and Wakimoto 1999). In addition, the instant occlusion process is another cyclone model in which an occluded-like structure develops from a non-Norwegian-like process (e.g., Anderson et al. 1969; Reed 1979; Locatelli et al. 1982; Mullen 1983; Carleton 1985; Browning and Hill 1985; McGinnigle et al. 1988; Evans et al. 1994). These examples are consistent with Petterssen's statement that "extratropical cyclones are born in a variety of ways, but their appearance at death is remarkably similar" (Uccellini 1990, p. 100).

Wrapping up wrap-up. To summarize this tenet, most textbooks describe the occlusion process occurring as a result of catch-up. Instead, we argued that catch-up does not explain the occlusion process, but is merely just a signature of wrap-up. Simple models of vortices, even in the absence of divergence and moisture, wrap up to produce occluded-like structures resulting from deformation and rotation around the cyclone, producing a narrowing warm tongue and an increasing separation between the low center and warm sector. Furthermore, catch-up cannot explain the length of long spiral occluded fronts. Catch-up also begs the question of why the cold front moves faster than the warm front, which, although largely true, evades the issue that *any* baroclinic zone being rotated around a cyclone will produce narrowing symmetric warm- and cold-air tongues and a separation between the low center and the warm sector. Although the catch-up mechanism precludes the formation of an occluded front in the Shapiro–Keyser cyclone model, viewing the occlusion process as the wrap-up of the thermal wave rather than the catch-up of fronts allows the occlusion process to be generalized to cyclone models other than the Norwegian cyclone models that have not generally been considered to undergo the occlusion process.

TENET 1—REALITY: The occluded front forms as a result of the wrap-up of the baroclinic zone and lengthens due to flow deformation and rotation around the cyclone.

TENET 2: TWO TYPES OF OCCLUSIONS ARE POSSIBLE, DEPENDING ON THE RELATIVE TEMPERATURES OF THE AIR ON EITHER SIDE OF THE OCCLUDED FRONT. In the Norwegian cyclone model, Bjerknes and Solberg (1922) posited that some difference in temperature between the two cold air masses would occur across an occluded front. They described the lifting of one cold air mass by the other colder one, giving the appearance of one front riding up over the other (Figs. 3 and 4). If the air behind the cold front were warmer than the air ahead of the warm front, then the cold front would ride up the warm front forming a warm-type occlusion. On the other hand, if the air behind the cold front were colder than the air ahead of the warm front, then the warm front would ride up the cold front, forming a cold-type occlusion. Stoelinga et al. (2002) called this relationship between the cross-front temperature and the resulting occluded front structure *the temperature rule*.

Not until some of the first radiosonde data were published were the first three-dimensional observations of occluded fronts available (Bjerknes 1935; Wexler 1935; Bjerknes and Palmén 1937). Much later, Schultz and Mass (1993) evaluated the temperature rule by examining all of the published cross sections of occluded fronts. They found no relationship between the relative temperatures on either side of the occluded front and the resulting structure. In fact, of 25 cross sections, only three were cold-type occlusions. Of these three, one was a schematic without any actual data (Elliott 1958), one had a weak warm front (Hobbs et al. 1975), and one could be reanalyzed as a warm-type occlusion (Matejka 1980, 86–97). Therefore, Schultz and Mass (1993) concluded that cold-type occlusions, if they even existed, were rare.

Stoelinga et al. (2002) explained why the temperature rule did not work for Schultz and Mass (1993). They showed that because occluded fronts were not zero-order discontinuities in temperature (i.e., surfaces across which temperature is discontinuous; Fig. 13a) but first-order discontinuities in temperature (i.e., surfaces across which the temperature gradient is discontinuous, but temperature is continuous; Fig. 13b), then the relative static stabilities on either side of the front, not relative temperatures, determined the slope of the occluded front (what they called *the static stability rule*). Specifically, if the air in the cold-frontal zone were less statically stable than the air in the warm-frontal zone, then the occluded front would tilt forward, forming a warm-type occlusion. On the other hand, if the air in the cold-frontal zone were more statically stable than the air in the warm-frontal zone, then the occluded front would tilt rearward, forming a cold-type occlusion. As Stoelinga et al. (2002, p. 710) emphasize, the static stability rule is "based only on principles of first-order discontinuities applied to the instantaneous potential temperature distribution in the vicinity of an occluded front, rather than on an underlying dynamical process or mechanism." Nevertheless, the static stability rule is a satisfying explanation for assessing the resulting structure of two approaching fronts. But, the static stability rule also makes a powerful prediction.

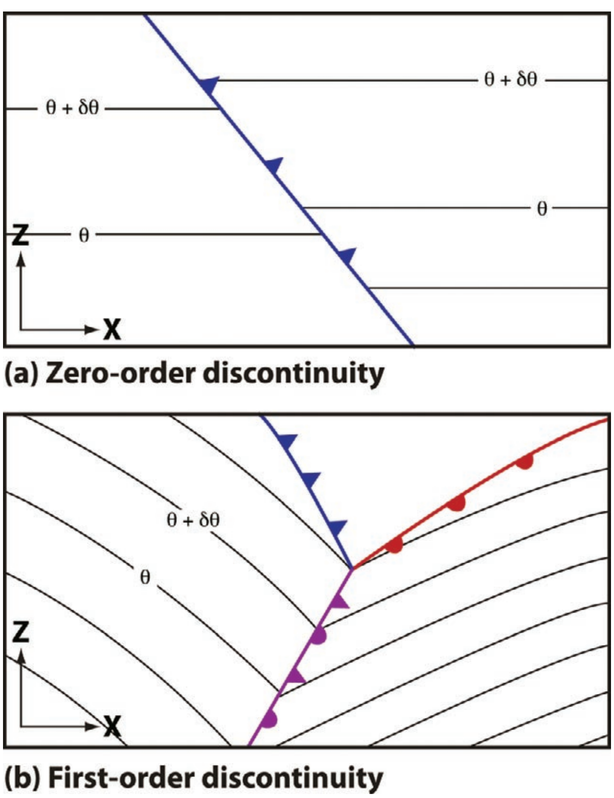

Fig. 13. Vertical cross sections of potential temperature through a (a) zero-order discontinuity and (b) first-order discontinuity. (b) Adapted from Stoelinga et al. (2002, their Fig. 6).

Cold-frontal zones are generally characterized by near-vertical isentropes (i.e., very low static stability) at the leading edge with well-mixed postfrontal air (e.g., Brundidge 1965; Keyser and Anthes 1982, their Fig. 12; Shapiro 1984, their Fig. 3; Reeder and Tory 2005; Schultz and Roebber 2008). In contrast, warm-frontal zones are generally characterized by sloped isentropes corresponding to higher static stability (e.g., Locatelli and Hobbs 1987; Doyle and Bond 2001). Given these typical differences in static stability between cold and warm fronts, the static stability rule would predict warm-type occlusions to be the most common type of occlusion. The difficulty of envisioning a cold-frontal zone that is statically more stable than a warm-frontal zone means that the static stability rule would predict that cold-type occlusions are relatively rare, if they even exist at all.

These results suggest that a reevaluation of the cold-type occlusion is warranted. Specifically, the three cold-type occlusions in Schultz and Mass (1993) had one common element: they were all occluded cyclones making landfall in western North America at the end of the Pacific storm track. At the end of storm tracks, cyclones often lack well-defined warm fronts, as mentioned by western U.S. and European meteorologists (e.g., Saucier 1955, p. 298; Wallace and Hobbs 1977, 127–128; Friedman 1989, p. 217; Davies 1997, p. 271) or possess a "stubby" warm front. The diffluence at the end of the storm tracks weakens warm fronts, as discussed by Schultz et al. (1998).

Indeed, Saucier (1955, p. 271) indicates that there is "insufficient evidence" for elevated warm fronts in many occlusions. Thus, cold-type occlusions may be more common in certain regions where warm fronts tend to be weak. However, not all landfalling cyclones in western North America are cold-type occlusions; many others are warm-type occlusions or forward-tilting cold fronts (e.g., Kreitzberg 1964; Elliott and Hovind 1964; Houze et al. 1976b; Wang and Hobbs 1983; Hertzman and Hobbs 1988; Locatelli et al. 2005; Garvert et al. 2005; Martner et al. 2007). Clearly, more remains to be learned about the climatology, structures, and formation mechanisms of warm-type versus cold-type occlusions.

In summary, few textbook authors openly question the relative rarity of cold-type occlusions as Barry and Chorley (2010, 241–242) did, although many have hinted at a controversy associated with occluded-front formation and structure (e.g., Wallace and Hobbs 1977, p. 127; Carlson 1991, p. 239; Bluestein 1993, 134, 274; Williams 1997, 49–50; Barry and Carleton 2001, p. 452; Martin 2006, p. 258). Some textbooks even have presented the reverse, saying that warm-type occlusions are less common than cold-type occlusions (e.g., Saucier 1955, p. 271; Petterssen 1956, p. 220; Moran and Morgan 1997, p. 259). Regardless of how textbooks portray occluded fronts, *if the temperature rule cannot explain the vertical structure of occluded fronts and cannot predict the predominance of warm-type occluded fronts, then the rule should not appear in textbooks*. Instead, the static stability rule better describes the predominance of warm-type occlusions and the rarity of cold-type occlusions.

TENET 2—REALITY: Two types of occlusions are possible, depending on the relative static stabilities of the air on either side of the occluded front. However, warm-type occlusions are more common, in general.

TENET 3: OCCLUSION MEANS THAT THE CYCLONE WILL STOP DEEPENING.

In the Norwegian cyclone model, occlusion was an indication of the end of the deepening phase of the cyclone because removing the warm air from the low center meant that the cyclone no longer had access to the available potential energy stored in the warm sector. Indeed, Bjerknes and Solberg (1922) said, "All cyclones which are not yet occluded, [*sic*] have increasing kinetic energy (p. 6)," and "After the occlusion the cyclone soon begins to fill up (p. 7)."

If, however, cyclogenesis is viewed as a three-dimensional process from the perspective of the quasigeostrophic height tendency equation (e.g., Holton 2004, section 6.3.1; Martin 2006, section 8.3) and its form with diabatic processes (Bluestein 1992, p. 330), then whether the warm-sector air reaches the low center at the surface, or even in the lower troposphere, is of secondary importance to the development of the low center. The terms contributing to geopotential height falls include the vertical derivative of temperature advection, vorticity advection, and the vertical derivative of the diabatic heating rate. Although temperature advection over the low center may be small in the lower troposphere near the center of an occluded cyclone, differential temperature advection, vorticity advection, and the release of latent heat during condensation in the cloud may still be occurring, causing continued height falls. Thus, the mechanism for cyclogenesis can be expressed in modern theories of cyclone development, whether using quasigeostrophic theory (Charney 1948), Petterssen–Sutcliffe development theory (Sutcliffe 1947; Petterssen 1955), baroclinic instability (Charney 1947; Eady 1949), or potential vorticity thinking (e.g., Hoskins et al. 1985; Hoskins 1997).

Observations often show that cyclones continue to deepen for many hours after the formation of the occluded front, reaching central pressures many millibars deeper than at the time of the occluded front formation (e.g., Bjerknes 1932; Brown and Younkin 1973; Sanders 1986; Neiman and Shapiro 1993; Reed and Albright 1997; Martin and Marsili 2002), a point made by several textbooks (e.g., Moran and Morgan 1997, p. 267; Lutgens and Tarbuck 2001, p. 247). For example, "The depression usually achieves its maximum intensity 12–24 hours after the beginning of occlusion (Barry and Chorley 2010, p. 237)." Indeed, no fewer than 29 of the 91 northeast U.S. cyclones for which surface analyses appear in Volume 2 of Kocin and Uccellini (2004) deepen 8–24 mb during the 12–24 h after formation of the occluded front. The most extreme example from that dataset was the cyclone of 19–20 February 1972, which deepened 32 mb in 36 h after occluded front formation (Kocin and Uccellini 2004, p. 478).

Taking a broader perspective, the occlusion process, now defined in this article as the wrap-up of the thermal wave, will occur more quickly if the cyclone has a stronger circulation (e.g., Smigielski and Mogil 1995). In fact, this idea was known previously. Saucier (1955, p 270) said, "One of Bergeron's rules in analysis: A frontal wave is occluded if the pressure difference between the cyclone center and last closed isobar is 15 mb or greater." The flip side is that a cyclone that never develops a strong circulation may never occlude. For example, Alberta clippers (cyclones that originate in the lee of the Rocky Mountains in the Canadian province of Alberta) often undergo little deepening as they progress across North America (e.g., Thomas and Martin 2007), likely because of weaker quasigeostrophic forcing and reduced moisture (Mercer and Richman 2007). Also, Alberta clippers rarely develop occluded fronts, at least over land, and at least in the traditional sense (e.g., Locatelli et al. 1989; Steenburgh and Mass 1994); sometimes they may deepen and occlude over the Atlantic Ocean. Similarly, cyclones developing in anticyclonic shear (e.g., Davies et al. 1991; Wernli et al. 1998; Shapiro et al. 1999) and the zipper lows along the eastern Atlantic coast of North America (Keshishian and Bosart 1987) remain open waves, without occluding or deepening much. Therefore, somewhat ironically, *conventional wisdom states that occlusion results in an end to cyclone deepening, whereas we now recognize that a deepening cyclone results in occlusion*.

This tenet—a critical one for operational forecasting—is summarized quite well by Carlson (1991, p. 233): "There is a conflict between the dynamic viewpoint and the Norwegian model because the former does not require occlusion for decay to begin, nor does the occlusion process seem to deal with processes occurring at upper levels." He continued (p. 239):

> . . . occlusion is not so much an overrunning of retreating cold air by advancing cold air, as in the classical Norwegian cyclone model, but the result of an evolution of the pattern involving the migration of the cyclone into the cold air, an interleafing of moist and dry air streams and a cessation of forcing (advection of vorticity and temperature).

TENET 3—REALITY: Many cyclones continue to deepen after occlusion or never occlude at all.

TENET 4: OCCLUDED FRONTS ARE ASSOCIATED WITH WIDESPREAD CLOUDS AND PRECIPITATION FOLLOWED BY ABRUPT CLEARING AFTER SURFACE FRONTAL PASSAGE. As discussed previously, the occluded front in the Norwegian cyclone model is considered by some to be a "back-to-back frontal zone" (e.g., Wallace and Hobbs 1977, p. 123; Market and Moore 1998), with the prefrontal weather of a warm front (stratiform clouds and precipitation) followed by the postfrontal weather of a cold front (clear skies). Schematic pictures in textbooks illustrate the "widespread" or stratiform clouds and precipitation associated with the occluded front (e.g., Fig. 4). Although this type of weather is possible, this conceptual model of the clouds and precipitation overgeneralizes what can really happen, ignoring the mesoscale structure of observed weather associated with different occluding cyclones (also noted by Carlson 1991, p. 239). Two examples show that the clouds and precipitation associated with occluded fronts are more complicated than conventional wisdom.

Clouds and the dry airstream. The first overgeneralization relates to the cloud boundaries associated with occluded fronts. Satellite image interpretation manuals indicate that the surface positions of fronts (including occluded fronts) can be identified by the locations of the clouds (e.g., Bader et al. 1995, 302–326 and especially Fig. 5.4.19). Indeed, Reed and Albright (1997) found agreement between the

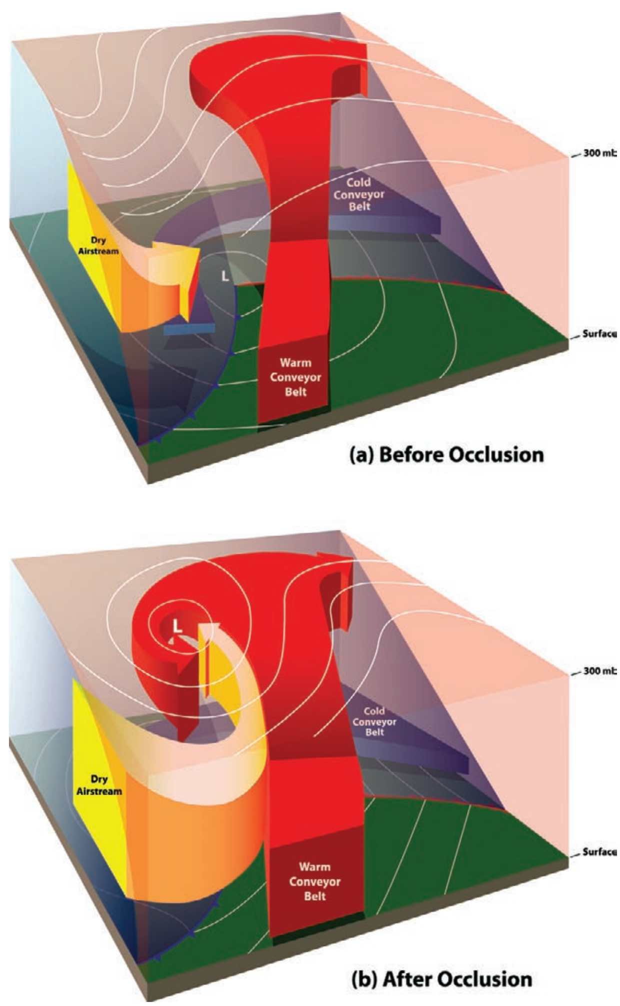

Fig. 14. Cyclone model in Fig. 9 presenting the dry airstream (yellow): (a) before and (b) after occlusion.

surface position of an occluded front and the rear edge of the spiraling cloud band on satellite imagery (Fig. 8a). However, other examples in the published literature show that the spiraling cloud band does not necessarily coincide with the position of the surface occluded front (e.g., Kuo et al. 1992, Fig. 5; Bader et al. 1995, Figs. 5.4.1 and 5.4.11; Market and Moore 1998, Figs. 2b and 11c).

One example of why the spiraling cloud band does not coincide with the front is related to the dry airstream (e.g., Danielsen 1964; Carlson 1980; Carr and Millard 1985; Young et al. 1987; Browning 1990, 1997, 1999; Wernli 1997; James and Clark 2003). The dry airstream descends on the west side of the upper-level trough, only to rise again adjacent to the warm conveyor belt after rounding the base of the trough (Figs. 14a,b). As the dry airstream ascends, it may override the lower-tropospheric frontal structure of a cyclone (e.g., Bader et al. 1995, 315–317 and Fig. 5.4.1). Given that dry airstreams are generated in the upper troposphere by secondary circulations associated with upper-level frontogenesis and jet formation (e.g., Keyser and Shapiro 1986; Young et al. 1987), any direct link to surface occluded fronts is weak. Nevertheless, Grim et al. (2007) showed that the dry airstream can be the equatorward boundary of the trowal, at least in some cases.

Figure 15 illustrates one such example where the dry airstream ran aloft over the surface positions of the cold and occluded fronts, bringing a sharp edge to mid- and upper-level clouds. Given that the clouds are produced by ascent aloft, not surprisingly, the spiraling cloud band may not be consistent with the surface position of not only the occluded front, but the cold front as well. Also, the forward tilt of a warm-type occluded front implies that the surface position of the occluded front is offset from the warm-air tongue aloft where clouds and precipitation occur. For these reasons, we should expect an often imperfect relationship between cloud boundaries and surface fronts, as demonstrated by others (e.g., Kuo et al. 1992; Mass and Schultz 1993; Han et al. 2007). As indicated by Bader et al. (1995, p. 302), "analysts should therefore be aware that it is sometimes difficult to locate the surface fronts from the [infrared satellite] images alone." Therefore, using cloud boundaries for the analysis of occluded fronts should be done with caution.

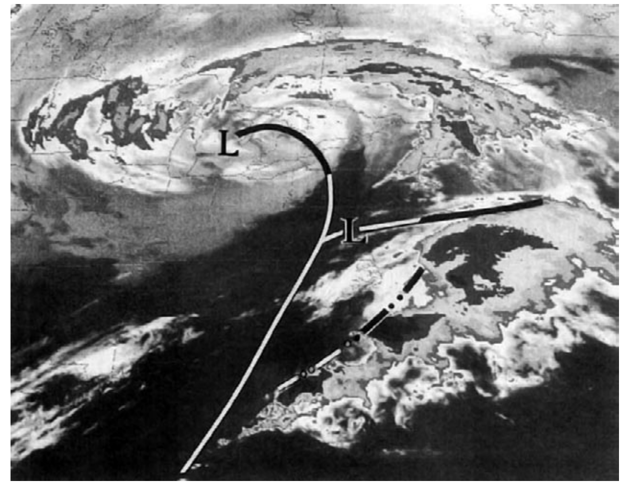

Fig. 15. Infrared geostationary satellite image with grayscale enhancement at 2301 UTC 15 Dec 1987 showing the dry airstream over the surface position of the occluded and cold fronts. The National Meteorological Center (now the National Centers for Environmental Prediction) surface frontal positions at 2100 UTC 15 Dec are shown; the location of the squall line is shown (dashed–double-dotted line). The fronts changing from black to white is for contrast with the background. [Caption and figure adapted from Fig. 19 in Mass and Schultz (1993).]

Banded precipitation. The second overgeneralization relates to occluded fronts having uniform stratiform precipitation (e.g., Fig. 4). Because occluded fronts have been viewed as the end result of cyclogenesis, occluded fronts are traditionally associated with weak vertical velocities, light and uniform precipitation rates, and minimal hazardous weather (e.g., Carlson 1991, 239 and 241). Yet, as previously discussed in tenet 3, the cyclone may continue to deepen for another 12–24 h after occluded front formation. In addition, embedded mesoscale structures favoring strong ascent may organize within the occluding cyclone. As a result, the occlusion process may indicate the start, or continuation, of hazardous weather.

Specifically, observations of occluded fronts do not necessarily show a uniform precipitation region. Instead, the prefrontal stratiform precipitation may be punctuated with a variety of precipitation bands associated with an ascent of 30–40 cm s^{-1} (e.g., Elliott and Hovind 1964), which occasionally reaches as high as 1–6 m s^{-1} (e.g., Wang and Hobbs 1983; Cronce et al. 2007), and enhanced precipitation rates (e.g., Kreitzberg 1968; Kreitzberg and Brown 1970; Hobbs et al. 1975; Houze et al. 1976a,b; Hertzman and Hobbs 1988; Saarikivi and Puhakka 1990; Bader et al. 1995, Fig. 5.4.8; Martin 1998b; Hand et al. 2004; Novak et al. 2004, 2010; Grim et al. 2007).

Although precipitation bands associated with warm fronts and occluded fronts have been recognized for a long time (e.g., Austin and Houze 1972;

Houze et al. 1976b; Hobbs 1978; Houze and Hobbs 1982), some of the most intense precipitation rates in occluded cyclones occur in association with warm air that has been wrapped around the cyclone, bringing low static stability air and elevated frontogenesis to the northwest of the low center (e.g., Sanders and Bosart 1985; Sanders 1986; Martin 1998b; Nicosia and Grumm 1999; Jurewicz and Evans 2004; Hand et al. 2004; Novak et al. 2004, 2008), as illustrated in the example of intense snowbands over Finland embedded within the comma head of the cyclone (Fig. 16). In the northwest quadrant of the cyclone, such snowbands often remain nearly stationary. Coupled with the high precipitation rates in these bands, crippling snowfalls may result from such bands, producing large socioeconomic impacts, particularly in the northeast United States. These bands occur northwest of the low center after occluded front formation (Novak et al. 2008). In fact, the climatology of bands in such cyclones by Novak (2002) showed a preference for bands in the northeast quadrant of a cyclone before occluded front formation and bands in the northwest quadrant after occluded front formation (Fig. 17).

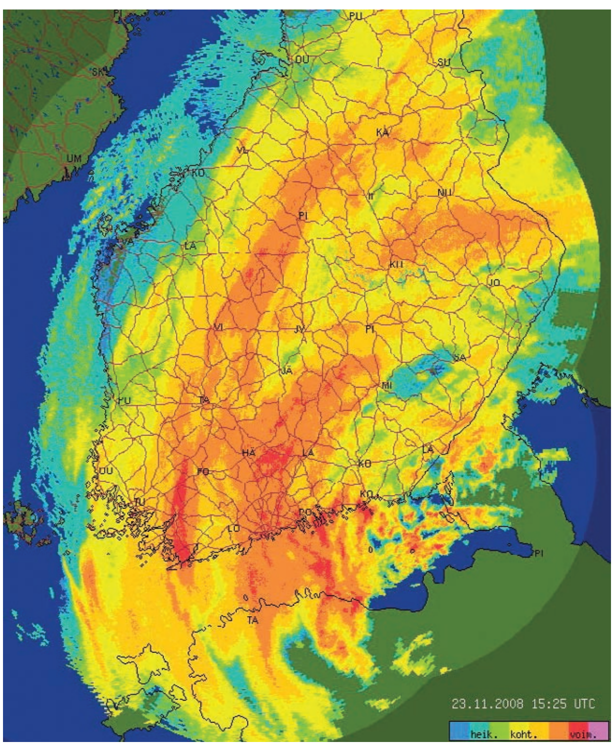

Fig. 16. Radar composite over southern and central Finland at 1525 UTC 23 Nov 2008. The surface low center is located to the southeast of this image. The scale for radar reflectivity factor (from light precipitation in blue to heavy precipitation in red) is described in Saltikoff et al. (2010). An animation of the radar imagery of this storm from 0910 UTC to 2210 UTC 23 Nov 2008 can be found online (http://dx.doi.org/10.1175/2010BAMS3057.2).

These bands in the northwest quadrant of cyclones occur in an environment that is favorable for frontogenesis (e.g., Sanders and Bosart 1985; Sanders 1986; O'Handley and Bosart 1989; Schultz et al. 1998; Martin 1998b; Market and Cissell 2002; Hand et al. 2004; Novak et al. 2004, 2008, 2009, 2010). For example, Hand et al. (2004) found that many extreme rainfall events over the United Kingdom occurred in association with frontogenesis north or northwest of the cyclone center. In the climatology of such precipitation bands, Novak et al. (2010) found that they occurred within a 700-mb trough that was the vertical extension of the surface warm-type occluded front. These bands also occurred in a region of warm-air advection and increasing advection of potential vorticity with height, with both processes favoring ascent. In addition, the warm air was often conditionally unstable or, less frequently, moist symmetrically unstable (Novak et al. 2010). Martin (1998b) and Novak et al. (2008) calculated air parcel trajectories to show that the air rising abruptly and turning cyclonically in the band was warm conveyor belt air, supporting its relationship to the occluded front and the wrap-up of the thermal wave. Han et al. (2007) found that banded precipitation in two occluded cyclones was associated with the secondary circulation associated with frontogenesis, as diagnosed by the Sawyer–Eliassen equation, and the results were in qualitative agreement with Martin (1998b) and Novak et al. (2008, 2009, 2010).

In summary, textbooks provide a relatively simple picture of the cloud and precipitation distribution accompanying occluded cyclones (e.g., "widespread" and uniform stratiform). In reality, the mesoscale structures described in this section differ from this simple picture in two ways. First, these mesoscale structures add complexity to the features described in the Norwegian cyclone model. Second, the structures depict an occluded front as a region of active frontogenesis associated with the potential for heavy precipitation. Thus, just as concepts for occluded fronts such as the back-to-back front are inadequate to justify the catch-up mechanism (tenet 1), so are they inadequate for explaining the cloud and precipitation structure of occlusions.

TENET 4—REALITY. Occluded fronts are associated with a variety of cloud and precipitation patterns, including dry slots and banded precipitation.

SYNTHESIS. This article has reexamined studies of cyclones and occluded fronts over the last

90 yr to critique the Norwegian cyclone model and synthesize the results from various physical processes (synoptic-scale dynamics, frontogenesis, and sensible weather) and conceptual models (airstream models and cyclone models) into a coherent framework. Our study has revealed that the model of occluded fronts commonly presented in textbooks needs revision. Previous research and new ideas are now synthesized into a new perspective that addresses weaknesses in the Norwegian cyclone model (e.g., Figs. 9, 14, and 17). The principal components of this new perspective on occlusions are the following:

- The occlusion process is the wrap-up of the thermal wave, narrowing the warm sector and increasing the separation between the warm sector and the low center by differential rotation and deformation around the cyclone.
- The elevated warm sector above a surface occluded front is the cyclonically turning portion of the warm conveyor belt.
- The elevated cold front in an occluded front may be an upper-level front instead of a cold front that has been lifted over the warm front.
- Air behind the cold front originates ahead of the warm front in the cold conveyor belt and is the occluding airstream.
- By viewing the occlusion process as the separation between the warm sector and the low center through the wrap-up of the thermal wave, occlusion can be generalized to a greater portion of the spectrum of cyclone life cycles.
- The formation of a cold- or warm-type occluded front depends upon the relative static stabilities of the cold- and warm-frontal zones.
- Stronger cyclones are more likely to occlude than weaker cyclones.
- The dry airstream can overrun the surface occluded front, displacing the clouds and precipitation. Therefore, caution is required if analyzing surface fronts using the locations of cloud bands from satellite imagery.
- Occluded fronts can be associated with intense frontogenesis and heavy precipitation, particularly to the northwest of the low center.

In this new perspective, the occlusion process is demoted relative to its stature in the Norwegian cyclone model. Indeed, not all cyclones even form occluded fronts. Occlusion is still part of the evolution of a developing cyclone, but the merger of the cold front and the warm front is no longer the defining moment of cyclone evolution when the brakes of development are applied. Instead, the formation of an occluded front is merely the by-product of the wrap-up of the thermal wave and the deformation of a warm-air tongue by differential rotation around the cyclone. Although we do not dispute that the catch-up mechanism occurs in many cyclones, it is not an explanation for the occlusion process.

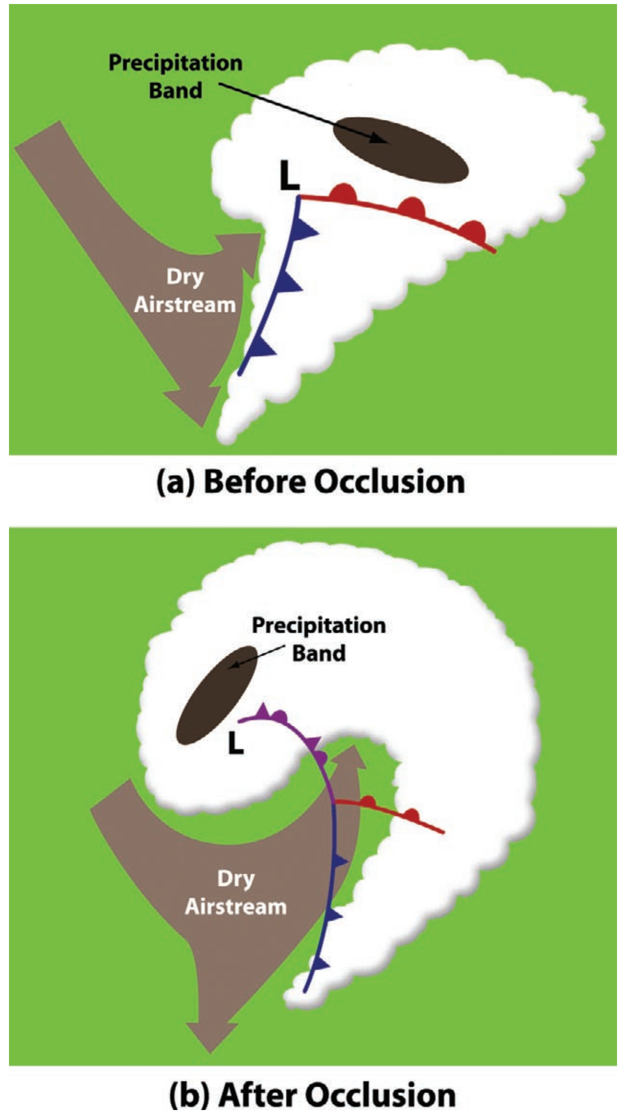

Fig. 17. Schematic depiction of the evolution of the dry airstream, clouds, and regions where precipitation bands commonly occur (a) before and (b) after occlusion.

Perhaps this emphasis on the formation of the occluded front as the key to cyclone development and structure has deep roots in the synoptic tradition of manual analysis of surface weather maps. Nevertheless, this new perspective does not require a change in our analysis techniques. Occluded fronts are still regions of wind shifts, pressure troughs, and temperature maxima, and they deserve indication on surface weather charts. But, this line on the map is not the only feature worthy of our attention. As recognized in the trowal conceptual model, other features needing recognition include regions of midlevel frontogenesis where precipitation often stops and clouds dissipate, sometimes abruptly.

Recognizing this change from the occlusion process as the mechanism for the end of cyclone development to the occlusion process as the byproduct of development goes beyond being philosophical or pedagogical, however. Newer paradigms supplant older ones because of their ability to explain the available observations better and to address anomalies within the old paradigm (Kuhn 1970). This new paradigm for occluded fronts and the occlusion process helps to resolve the following anomalies within the Norwegian cyclone model.

- Idealized model simulations of cyclones, even without convergence and moisture, can produce narrowing warm tongues resembling occluded fronts.
- The extreme length of occluded fronts that spiral around deep low centers, which cannot be explained by catch-up, is due to the deformation and rotation of the warm-air tongue around the cyclone center.
- Shapiro–Keyser cyclones, which apparently do not undergo catch-up, do undergo the occlusion process.
- The temperature rule does not explain whether a warm- or cold-type occluded front forms.
- Because cold-frontal zones tend to have neutral static stability near the surface and warm-frontal zones tend to have high static stability, warm-type occlusions are more common than cold-type occlusions.
- Cold-type occlusions feature weak or nonexistent warm fronts.
- Many cyclones, especially rapidly deepening ones, continue to deepen after occlusion.
- Many weak cyclones never produce occluded fronts before dissipating.
- Some of the most intense precipitation rates during cyclogenesis occur after occluded front formation.

Thus, *viewing the occlusion process as wrap-up rather than catch-up resolves anomalies within the Norwegian cyclone model and provides a better and more general fluid-dynamical description of the occlusion process.*

As discussed previously, the occlusion process is just one aspect of the Norwegian cyclone model needing reexamination. Other aspects of the Norwegian cyclone model have been examined by other researchers. For example, different conceptual models of cyclone evolution have been proposed for rapidly developing marine extratropical cyclones (Shapiro and Keyser 1990) and for cyclones in the central United States (Hobbs et al. 1990, 1996; Keshishian et al. 1994; Steenburgh and Mass 1994; Weisman et al. 2002; Metz et al. 2004; Schumacher et al. 2008). Mass (1991), Sanders and Doswell (1995), Sanders (1999), Kessler (2008), and Hoffman (2008) have questioned whether extant frontal analysis techniques are adequate. Finally, Keyser (1986) and Schultz (2005, 2008) have discussed the appropriateness of the Norwegian cyclone model for cold fronts. Future examinations of other aspects of the Norwegian cyclone model would be worthy endeavors.

Textbooks can be slow to adopt new ideas, but they can also be agents of change. Many geography textbooks have errors in basic scientific concepts, such as the Kelvin temperature scale (Day 2009) and heat (Day et al. 2010). Lest synoptic meteorology succumb to the same outdated fate, textbook authors need to write their textbooks using accurate and current scientific concepts, ensuring that students learn the latest thinking on a topic, even if the science is not completely resolved. The development of this new paradigm for occluded fronts and the occlusion process is one step toward a more modern approach to replace the Norwegian cyclone model.

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