Extratropical cyclone occlusion

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Abstract:	The notion of extratropical cyclone occlusion has been controversial since it was first proposed just after World War I. Recent advances in understanding the dynamics of occlusion as well as modern means of interrogating its characteristic structure are reviewed. Among the various concepts explored are 1) the use of high resolution numerical model output in revitalizing old conceptual ideas such as the trowal; 2) the role of rotational frontogenesis and its associated vertical circulation in the dynamics of the occluded quadrant; 3) the funadmental role of latent heat release in the occlusion process; and 4) the influence of the extratropical occlusion process on the development of a subset of tropical cyclones.

EXTRATROPICAL CYCLONE OCCLUSION

by

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The largest fraction of what is colloquially referred to as "weather" in the extratropics is delivered by the development and propagation of mid-latitude weather systems. These disturbances, commonly referred to as "lows" and "highs" develop in response to a fundamental instability of the westerlies, known as baroclinic instability, that arises as a consequence of the permanent but seasonally modulated pole-to-equator temperature contrast. The "lows" in this endless sequence of disturbances are known as mid-latitude cyclones. Though sporadic insights into their structure and dynamics have been accumulated for nearly 250 years, systematic study of the mid-latitude cyclone did not commence until just after World War I.

The Norwegian Cyclone Model

The relationship between the three-dimensional thermal structure and the distribution of clouds and precipitation in these cyclones was first suggested by Bjerknes and Solberg in 1922 in their conceptual model of the mid-latitude cyclone, which has come to be known as the Norwegian Cyclone Model (NCM). The genius of this conceptual model was that it placed the instantaneous structure of the cyclone into the context of an identifiable life cycle. According to the NCM, extratropical cyclones developed as infinitesimally small perturbations along a pre-existing, globe-girdling discontinuity in temperature known as the polar front which separated tropical air from polar air. Horizontal temperature advection associated with the initial perturbation converted available potential energy (APE) into eddy kinetic energy (EKE) and led to the amplification of the storm which, in turn, distorted the polar front into a cold front and a warm front and left a region of homogeneous warm air extending downward to the surface between the two fronts. This region was known as the warm sector and the air there known as warm sector air (Fig. 1a).

Occlusion

The NCM suggests that as the cyclone reaches its mature phase, with continued intensification and frontal distortion, the fronts "catch up" with one another instigating a cutting off of the cyclone center from the peak of the warm sector in what was termed the "occlusion" of the cyclone. Often a surface boundary remains after occlusion has occurred and this boundary is referred to as an occluded front. Occluded fronts were thought to occur in two varieties; the cold occlusion and the warm occlusion differentiated based upon whether the air poleward of the warm front was more dense (warm occlusion) or less dense (cold occlusion) than the air behind the cold front. Emphasis on the surface occluded boundary is, however, misplaced and distracting as consideration of a fully 3D *occluded structure* offers the most comprehensive insights into the structural and dynamical evolution of the post-mature phase extratropical cyclone. The warm occlusion process described the vertical displacement of warm sector surface air that resulted from the cold front overtaking, and subsequently ascending, the warm frontal surface. One of the main results of this process was the production of a wedge of warm air aloft, displaced poleward of the surface warm and occluded fronts.

The cloudiness and precipitation associated with the development of the warm occlusion were suggested to result from lifting of warm air ahead of the upper cold front and were consequently distributed to the north and west of the sea-level pressure minimum. Further, as a result of the gradual squeezing of warm air aloft between the two frontal surfaces, the horizontal thermal structure of warm occlusions was characterized by a thermal ridge connecting the peak of the warm sector to the geopotential or sea-level pressure minimum. In nature, this thermal ridge is often manifested as a 1000-500 hPa thickness ridge or as an axis of maximum potential temperature (θ) or equivalent potential temperature (θ_e) in a horizontal cross-section and is referred to as the occluded thermal ridge (Fig. 1b).

Structure of Occluded Cyclones

Cyclones are 3D entities and in the development stage the surface cyclone center, or sea-level pressure minimum, lies to the east of its companion upper-level cyclone center. Such a structure ensures that upward vertical motion, which occurs east of upper-level cyclones, will be located directly above the sea-level pressure minimum. This upward vertical motion not only leads directly to the production of clouds and precipitation, but also evacuates mass from the column of air thereby lowering the sea-level pressure and intensifying the circulation of the developing storm. As the cyclone approaches the occluded stage, the surface and upper-level cyclones become more vertically stacked. This reduces both the temperature contrasts and vertical wind shear in the vicinity of the surface cyclone. The displacement of the most intense upward vertical motion to the east away from the sea-level pressure minimum also inhibits additional development of the surface cyclone center. Hence, occlusion often heralds the commencement of cyclone decay.

A representative vertical cross-section perpendicular to the axis of an occluded thermal ridge reveals the characteristic thermal structure of a warm occlusion which consists of a poleward sloping axis of maximum θ_e separating two regions of concentrated temperature contrast, or baroclinicity (Fig. 2). The surface warm occluded front is generally analyzed at the location where the axis of maximum θ_e intersects the ground whereas the base of the warm air wedge between the two frontal zones (the cold and warm fronts) sits atop their point of intersection.

An alternative means of depicting the warm occluded thermal structure is by considering the topography (geometric or isobaric) of an appropriate θ_e surface selected from a vertical cross section such as that depicted in Fig. 2. In that section, the 300 K θ_e isentrope lies near the warm edge of both the cold and warm frontal zones comprising the warm occluded structure. The geometric topography of a similarly selected θ_e surface illustrates the steep slope of the cold frontal zone and the shallower slope of the warm frontal zone (Fig. 3). Also evident is a notch in the topography that pokes upward from low levels over central Illinois to northwestern Missouri. This canyon in the 309 K θ_e surface represents the region of overlap of the warm and cold fronts of the warm occluded structure.

With less sophisticated analysis tools at their disposal, scientists at the Canadian Meteorological Service in the 1940’s and 1950’s observed that the cloudiness and precipitation characteristic of the occluded quadrant of cyclones often occurs in the vicinity of the thermal ridge. This led them to regard the essential structural feature of a warm occlusion to be the wedge of warm air that is lifted aloft ahead of the upper cold front, *not* the position of the surface occluded front. These studies suggested that the location of a feature called the *trowal* (**tro**ugh of **w**arm air **al**oft) often bore a closer correspondence to the cloud and precipitation features of occluded cyclones in North America than did the often weak surface warm occluded front. The trowal conceptual model actually represents an extension of the classical occlusion model in that it draws formal attention to the wedge of warm air that is displaced poleward and upward during the occlusion process. The trowal has variously been considered a line connecting the crest of the thermal wave at successive heights as well as a "sloping valley of tropical air aloft" or, alternatively, the canyon in the 309 K θ_e surface depicted in Fig. 3. It might best be considered as the 3-D sloping intersection of the upper cold fontal portion of the warm occlusion with the warm frontal zone (Fig. 4). Compelling evidence supporting these observational findings comes from a number of recent fine-scale numerical modeling studies of occluded cyclones which have illustrated the structure and thermal evolution of, and airflow through, the occluded quadrant. These studies have identified a coherent airstream, referred to by the author as the "trowal airstream" that originates in the warm sector boundary layer, and ascends cyclonically in the occluded quadrant of the cyclone. This ascent is responsible for the production of the characteristic cloud and precipitation distribution in the occluded quadrant of middle latitude cyclones.

Dynamics of Occluded Cyclones

Although extensive investigation of the trowal was made in Canada in the 1940's and 1950's, its relationship to the distribution of clouds and precipitation in the occluded quadrant of cyclones was understood in terms of relative flow along what were considered material frontal surfaces comprising the occluded structure and not as a consequence of some characteristic dynamical process. In 1972, Morris recognized the trowal was " . . a discontinuity in the thermal advection field . ." and correctly pointed out that such a feature has dynamical significance with respect to the diagnosis of vertical motion.

Another dynamical approach to understanding the forcing for upward vertical motion in the occluded quadrant arises from considering Lagrangian changes in the potential temperature gradient vector. Given the asymmetric, frontal nature of the thermal structure of an extratropical cyclone, its evolution is the integrated result of 1) changes in the vigor of each baroclinic zone as well as 2) changes in the orientation of the baroclinic zones to one another, both of which occur continuously throughout the cyclone life cycle. Changes in the intensity of baroclinic zones are controlled by a process known as scalar frontogenesis which modulates the magnitude of the potential temperature gradient and operates on the scale of the individual baroclinic zones. This process is dynamically linked to the production of banded couplets of vertical motion that straddle the baroclinic zone (i.e. fronts) and are manifest in the front-parallel bands of clouds and precipitation commonly associated with fronts. Changes in the orientation of the frontal zones with respect to one another are a result of rotation of the potential temperature gradient vector forced by a process known as rotational frontogenesis. This physical process also has an associated vertical circulation in which couplets of upward and downward vertical motion are distributed *along* the baroclinic zones.

In 1998 Martin showed through analysis of three different cases that the characteristic occluded thermal ridge is produced by differential rotation of the warm and cold frontal baroclinic zones about the cyclone center during the cyclone life cycle. In fact, rotational frontogenesis was found to be the underlying dynamical mechanism responsible for simultaneously creating the characteristic occluded thermal ridge and for forcing the majority of the upward vertical air motions within the occluded thermal ridge of the cyclones. In light of this result, the view of the occlusion process, which had been considered to be rooted in traditional, meso-scale frontal dynamics, was reconceptualized as proceeding from the larger synoptic-scale processes that govern the progression of the cyclone through its life cycle.

Latent heat release and the occlusion process

Examination of the tropopause-level distribution of potential vorticity (PV) offers yet another means of identifying a warm occluded structure and is, in fact, a useful starting point for a discussion of the influence of latent heat release in the evolution of warm occluded thermal structures. The PV distribution at tropopause level often takes on a “treble clef” shape consisting of an isolated, low-latitude high PV feature that is connected to a high latitude reservoir of high PV by a rather thin filament of high PV (Fig. 5). This same shape appears in the isobaric or geometric height topography of the θ_e surface that lies closest to the warm edges of both the cold and warm frontal zones of the warm occluded thermal structure, particularly above about 6 km (Fig. 3). Such morphological similarity between these two fields is not case specific but instead is a general consequence of the characteristic thermodynamic structure associated with a positive PV anomaly at the tropopause in which tropospheric isentropes bend upward toward the anomaly while stratospheric isentropes bow downward towards it (Fig. 6a). Thus, regions of large tropopause-level PV sit atop relatively cold columns of air while relative minima in upper-level PV sit atop relatively warm columns of air. The characteristic thermal structure associated with the horizontal juxtaposition of two upper-level PV anomalies of unequal magnitude, separated by a relative minimum in PV, exhibits an axis of maximum θ beneath the PV minimum that separates two distinct regions of tropospheric baroclinicity (Fig. 6b). This structure precisely depicts that of a warm occlusion and is a hydrostatic consequence of the treble clef shaped upper-level PV structure. Thus, the treble clef tropopause-level PV distribution, such as in shown in Fig. 5, is a sufficient condition for asserting the presence of warm occluded thermal structure in the underlying troposphere.

If one accepts the proposition that the essential structural characteristic of the occluded cyclone is the trowal, then it follows that the occlusion process might reasonably be defined as the process(es) by which a cyclone acquires the trowal/treble clef structure. In 2004, Martin and Posselt compared companion numerical simulations of the same occluded storm; one run with a full physics (FP) package in the model code, and the other run while withholding the occurrence and associated feedbacks from latent heat release (NLHR). They employed calculations of the diabatic PV tendency and demonstrated that the initial development of the low PV notch in the treble clef structure was a direct consequence of dilution of upper tropospheric PV resulting from latent heat release in the occluded quadrant. As this dilution began to carve out the treble-clef notch, the low latitude PV feature became progressively more isolated from the higher latitude reservoir. This cutting off process, in turn, isolated the tropopause-level cyclonic circulation associated with the low latitude PV feature. As a consequence, the advection of low PV by the tropopause-level winds contributed to the rapid growth of the PV notch during the late stages of the life cycle. Though they identified a background adiabatic, kinematic tendency to produce an upper tropospheric PV treble clef in that case, the resulting NLHR treble clef structure was much weaker and slower to develop than the structure present in the FP simulation. They concluded that latent heat release plays a fundamental role in the development of the occluded thermal structure and, therefore, in the occlusion process itself. Taken as a whole, these results served to extend an emerging dynamic/conceptual model of the occlusion process by providing evidence that it depends upon the interaction of a characteristic dynamical forcing for upward vertical motion *and* the latent heat release that results from that upward vertical motion. In contrast, the cold and warm frontal structures that develop in mid-latitude cyclones are a consequence of scalar frontogenesis and are not greatly altered in their essential structural characteristics by the release of latent heat that characterizes them. The fact that the development of an occluded thermal structure appears to depend so intimately on latent heat release further highlights the fundamentally different nature of the occlusion process as compared to traditional frontogenesis. It appears increasingly clear to the author that further insight into the nature of the occlusion process will arise only when it is no longer viewed as a traditional frontal process.

Occlusion and tropical cyclones

On occasion, upper tropopsheric, middle latitude, wave disturbances can migrate sufficiently equatorward to spawn an extratropical surface cyclone in the subtropics. In such a case, the role of latent heat release is enhanced as a consequence of the greater abundance of water vapor, especially over the subtropical ocean. The interaction between enhanced latent heat release and the natural progression toward occlusion can lead to a fairly abrupt erosion of upper-level PV, a reduction in vertical wind shear and an elimination of baroclinicity. All three of these processes tend to reduce the available potential energy which, at middle latitudes, results in a gradual but decided weakening of the storm. If the subtropical storm occludes over a warm enough ocean, then the removal of the vertical shear coupled with enhanced convection offer the storm an alternative mechanism for continued development - air-sea interaction and wind induced surface heat exchange (WISHE); an energy transfer mechanism that fuels the growth of tropical cyclones. Thus, the occlusion process likely plays a role in instigating the transformation of extratropical cyclones into tropical cyclones; a process known as tropical transition. Current research seeks to better understand the physical connections between the canonical occlusion process, deep subtropical convection, and tropical transitions. These exciting developments suggest that the process of occlusion, once assumed to be relevant only for mid-latitude storms, likely plays a role in the life cycles of a broader class of cyclonic systems.

KEYWORDS: extratropical cyclone, fronts, frontal structure, occlusion, trowal

WIDELY AVAILABLE GENERAL TEXTS:

1) Jonathan E. Martin, *Mid-Latitude Atmospheric Dynamics: A First Course*, 2006.

2) Howard B. Bluestein, *Synoptic-Dynamic Meteorology in Midlatitudes, Volume II*, 1993.

3) James R. Holton, *An Introduction to Dynamic Meteorology*, Fourth Edition, 2004.

ADDITIONAL READINGS

1) Schultz, D. and C. F. Mass, 1993: The occlusion process in a midlatitude cyclone over land. *Mon. Wea. Rev*., **121**, 918-940.

2) Martin, J. E., 1998: The structure and evolution of a continental winter cyclone. Part I: Frontal structure and the occlusion process. *Mon Wea. Rev*., **126**, 303-328.

3) Martin, J. E., 1999: Quasigeostrophic forcing for ascent in the occluded sector of cyclones and the trowal airstream. *Mon. Wea. Rev*., **127**, 70-88.

4) Stoelinga, M. T., J. D. Locatelli, and P. V. Hobbs, 2002: Warm occlusions, cold occlusions, and forward tilting cold fronts. *Bull. Amer. Meteor. Soc*., **83**, 709-721.

5) Posselt, D. J., and J. E. Martin, 2004: The effect of latent heat release on the evolution of a warm occluded thermal structure. *Mon. Wea. Rev*., **132**, 578-599.

WEBSITES OF INTEREST

1) http://marrella.aos.wisc.edu/occlusion.html

This page illustrates results of the 19 January 1995 case analysis by Martin (1998) with air parcel trajectories and thermodynamic analyses.

2) http://marrella.aos.wisc.edu/trowal.html

This page illustrates a variety of trajectories that support the analysis presented in Martin (1999).

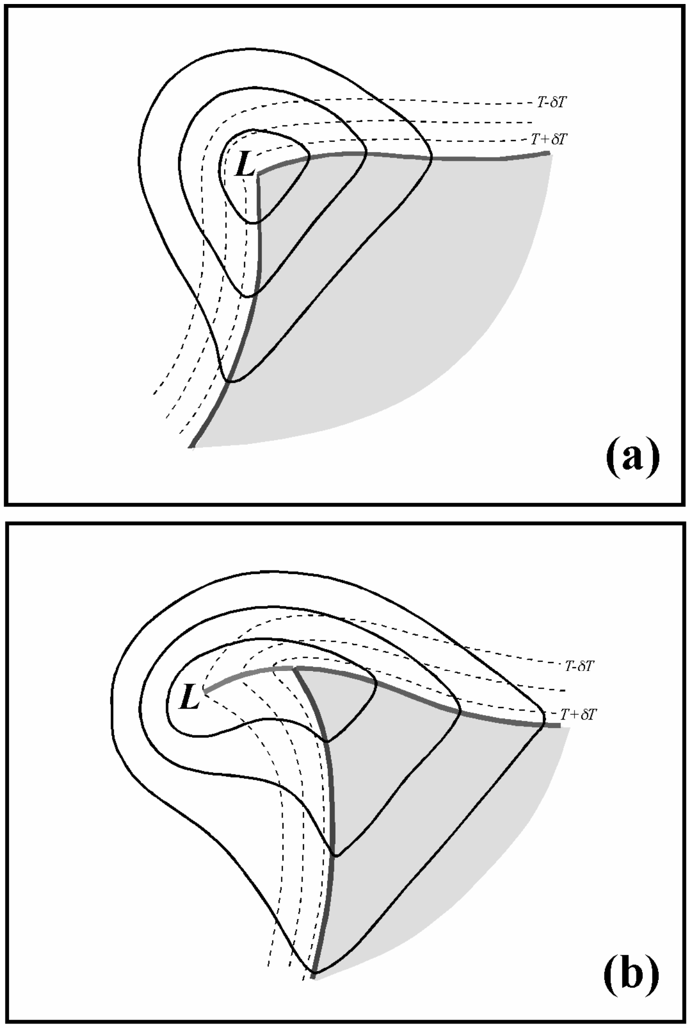


Fig. 1 (a) Horizontal view of a mature stage mid-latitude cyclone. Solid black lines are sea-level isobars, dashed lines are isotherms, thick solid lines are the cold (dark) and warm (lighter) fronts. The shaded area is the warm sector metioned in the text. (b) As for Fig. 1a but for an occluded cyclone. The thick solid line connecting the sea-level pressure minimum to the peak of the warm sector is the warm occluded front. Note the warm occluded front lies in a thermal ridge.

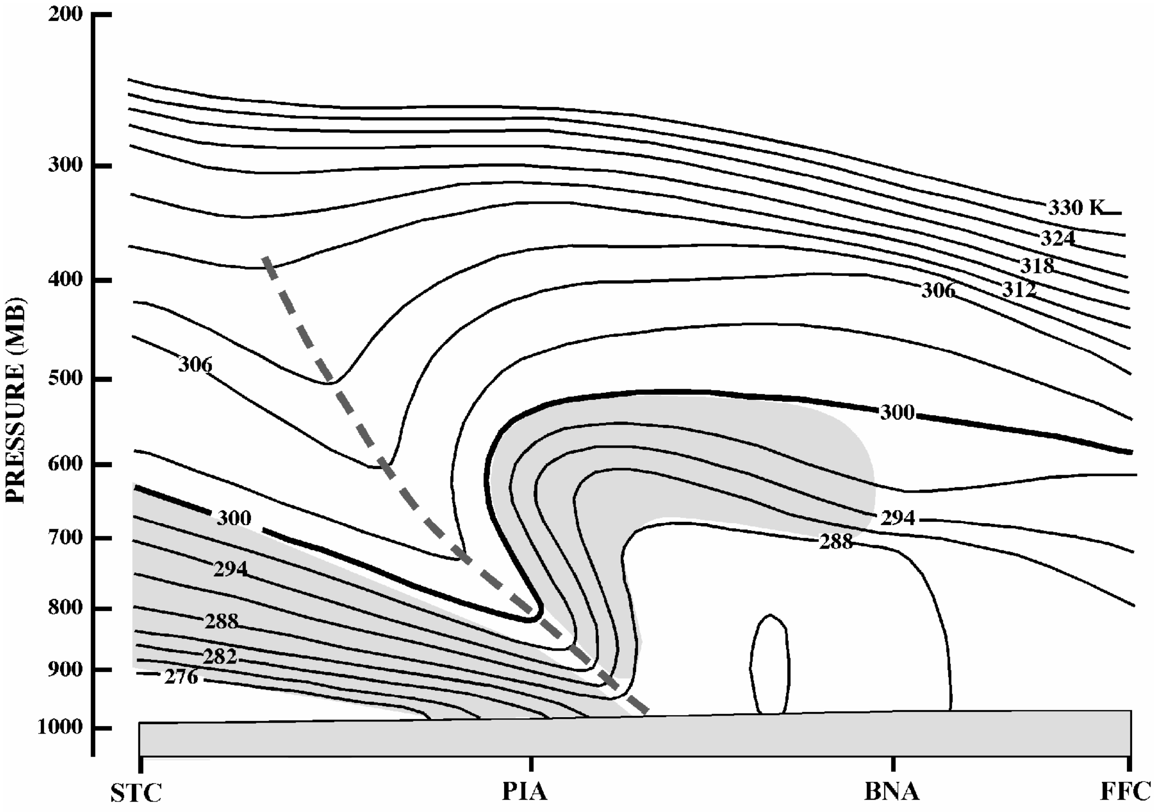
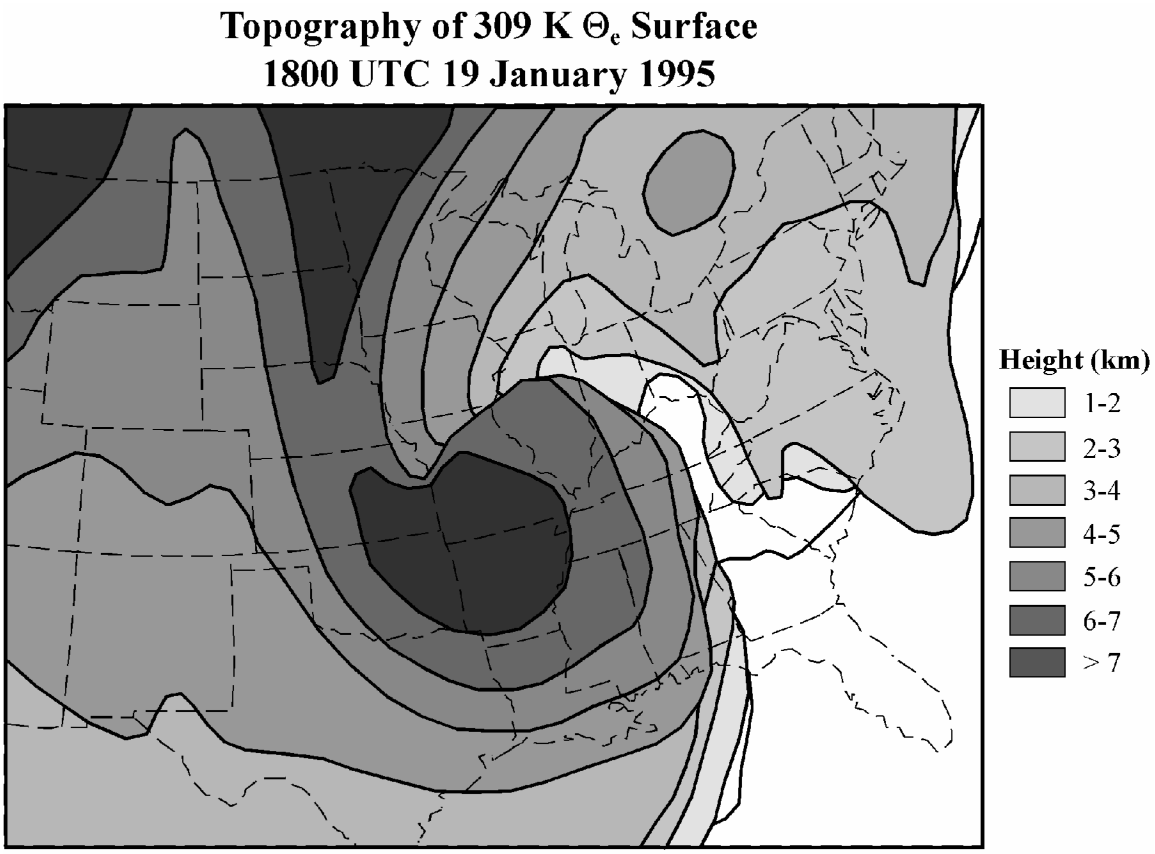


Fig. 2 Vertical cross-section from St. Cloud MN (STC), to Peoria, IL (PIA), to Nashville, TN (BNA) to Peachtree City, GA (FFC) through the occluded thermal ridge of a winter storm over North America on January 19, 1995. Solid lines are moist isentropes (θ_c) labeled in K and contoured every 3K. Gray shaded regions are the warm frontal zone (on the left) and the cold frontal zone (on the right). The thick dashed line is the axis of maximum θ_c mentioned in the text. The thick solid line is the 300K θ_c isentrope which lies at the warm edge of both the warm and cold frontal zones.



Topography of 309 K Θ_e Surface
1800 UTC 19 January 1995

Fig. 3 Geometric height topography of the 309 K θ_e isosurface from a numerical model simulation of the storm of 19 January 1995. Solid lines are height contours labeled in km and contoured every 1 km with each region shaded. Darker shading represents a higher elevation. Note the upward sloping canyon stretching from northern IL to northwestern MO as mentioned in the text. Note also the treble clef shape to the 6 and 7 km elevation contours.

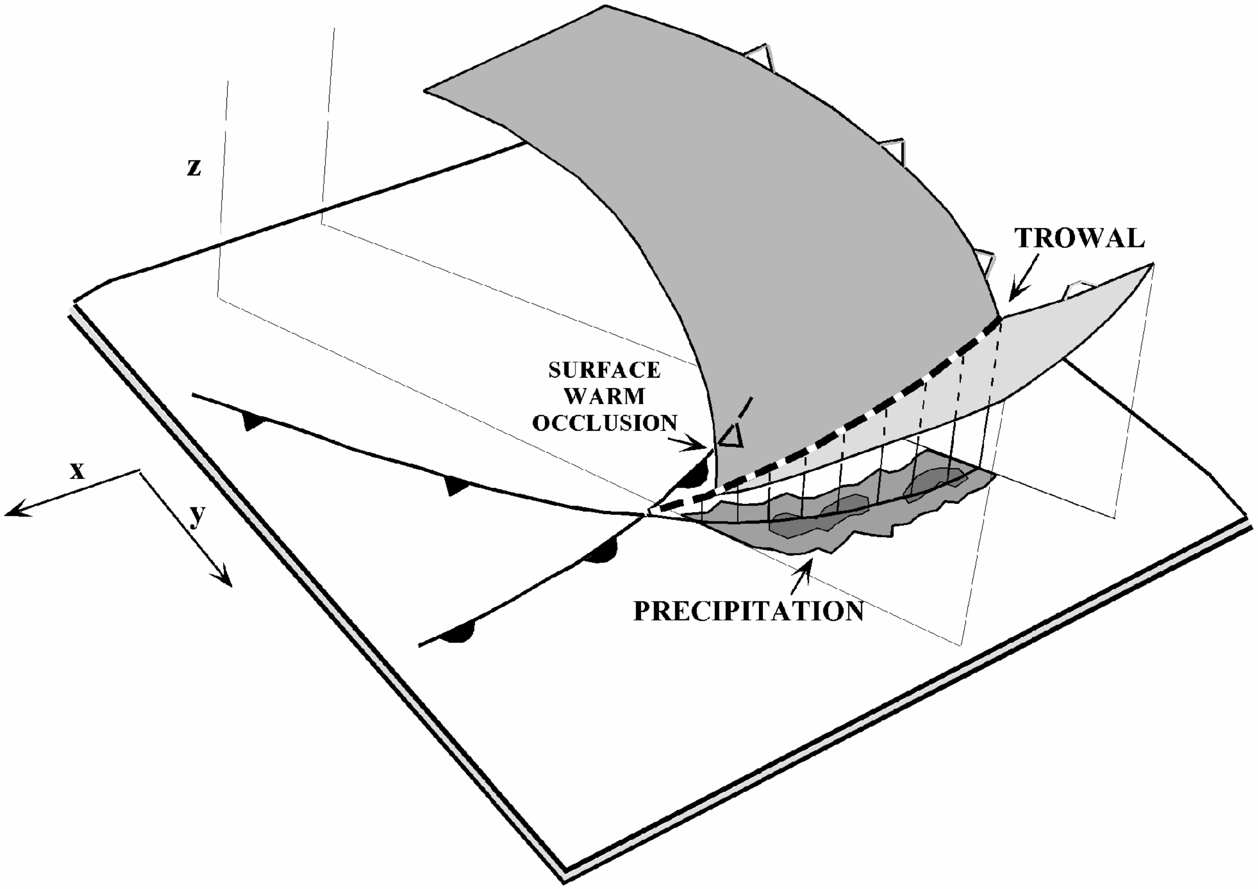


Fig. 4 Schematic of the trowal conceptual model. The dark (light) shaded surface represents the warm edge of the cold (warm) frontal zone. The bold dashed line at the 3-D sloping intersection of those two frontal zones lies at the base of the trough of warm air aloft - the trowal. The schematic precipitation in the occluded quadrant of the cyclone lies closer to the projection of the trowal to the surface than to the position of the surface warm occluded front.

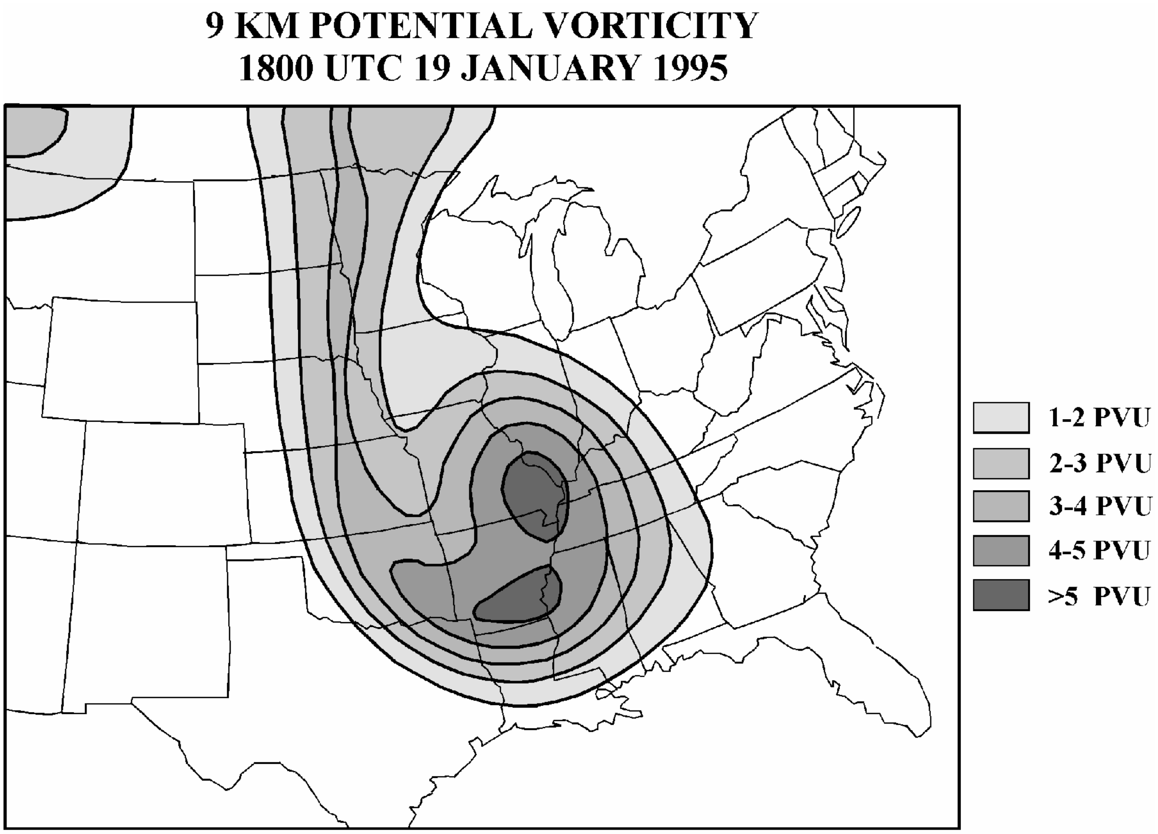


Fig. 5 9 km potential vorticity from a numerical model simulation of the 19 January 1995 storm. Potential vorticity is labeled, contoured and shaded in potential vorticity units (PVU) (1 PVU = 10^{-6} m^2 s^{-1} K kg^{-1}). Note the notch of low PV that stretches from central WI southwestward to southeastern KS. This is precisely where the trowal is located at this same time (see Fig. 3).

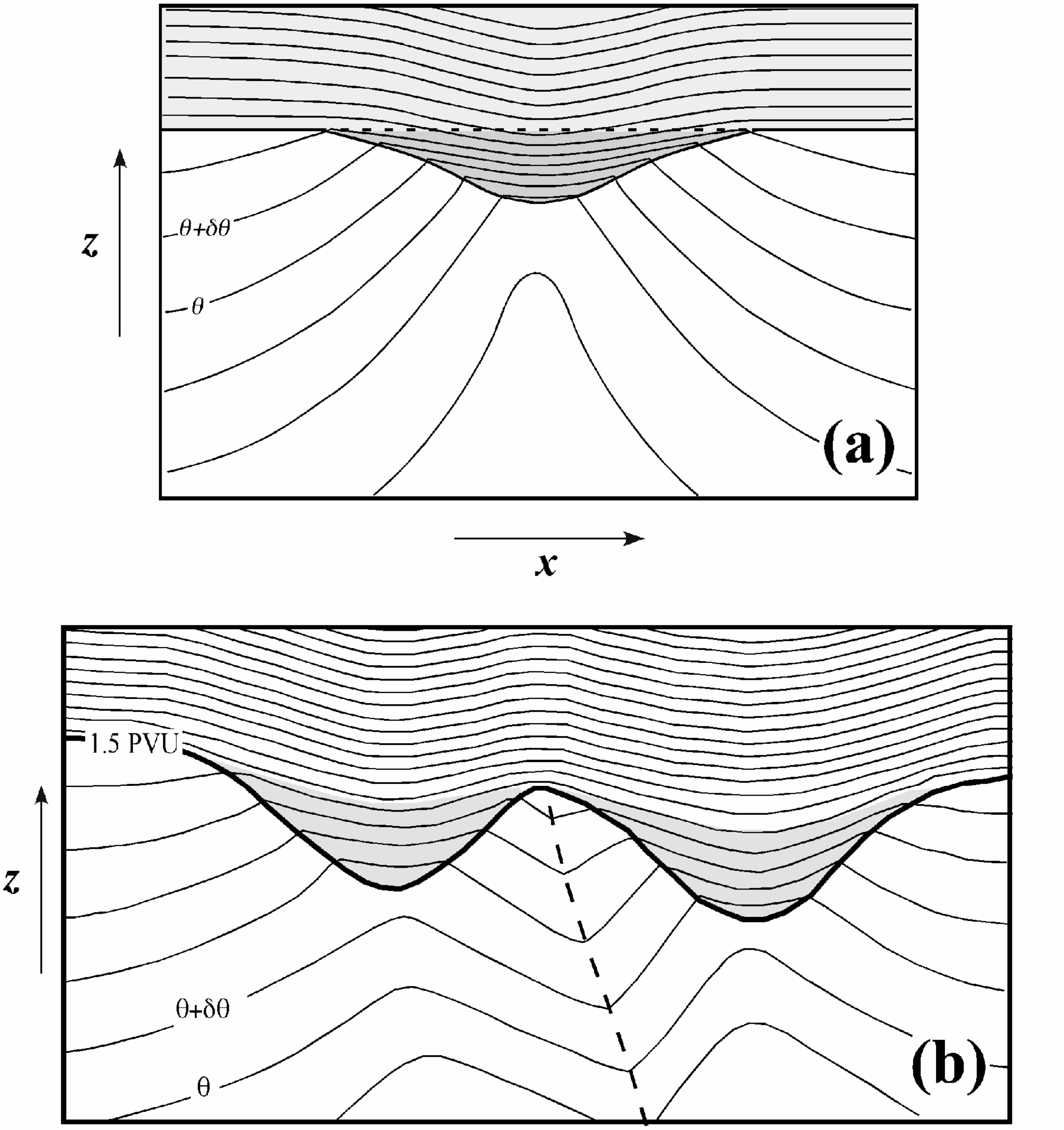


Fig. 6 (a) Schematic of the potential temperature distribution associated with a positive PV anomaly at the tropopause. Solid lines are isentropes, dark shading is the positive PV anomaly at the tropopause, light shading represents the stratosphere. (b) Schematic distribution of isentropes associated with a horizontal juxtaposition of postiive PV anomalies at the tropopause, separated by a local minimum in PV. 1.5 PVU line represents the boundary between the troposphere below and stratosphere above. The thick dashed line is the θ maximum that lies beneath the tropopause PV minimum. Note how it precisely describes the position of the trowal.