13.1 THE ROLE OF LATENT HEAT RELEASE IN THE FORMATION OF A WARM OCCLUDED THERMAL STRUCTURE IN AN INTENSE CONTINENTAL CYCLONE

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1. INTRODUCTION

The occlusion process effectively describes a cyclone's transition from a baroclinic to an equivalent barotropic disturbance. This process was first described by Bjerknes and Solberg (1922), and has traditionally been viewed in terms of differential frontal propagation, or frontal "catch-up." The conceptualization they introduced depicts two theoretical methods of occlusion: (1) cold occlusion, in which the primary cold front overtakes and *undercuts* the warm front, and (2) warm occlusion, in which the cold front overtakes and *ascends* the warm front.

Recently, Martin (1998a) documented the occurrence of the frontal catch-up mechanism in an observed cyclone. That study documented the development of a warm occluded structure at mid-tropospheric levels as a cold frontal zone encroached upon, and subsequently ascended a warm-frontal zone. Formation of the warm occluded structure was closely associated with the development of a cutoff cold air mass and its concomitant positive PV anomaly aloft. This anomaly rotated cyclonically during its evolution, and assumed a "treble clef" shape (Fig. 1a). This treble clef upper-level PV distribution was characterized by an isolated, low-latitude high-PV feature that was connected to the high-latitude reservoir of high PV by a rather thin filament of high PV. Concurrent with the appearance of the treble clef upper tropospheric PV anomaly was the development of a three-dimensional sloping "canyon" in the topography of the 309 K θ_e surface. This feature was first labeled the trowal (<u>tr</u>ough <u>o</u>f <u>w</u>arm air <u>al</u>oft) by Galloway (1958), and is a characteristic component of the warm-occluded structure (Martin 1998, 1999).

The relationship between the trowal and the upper-tropospheric treble clef PV shape was shown to be a consequence of the underlying thermodynamic structure associated with a positive PV anomaly at the tropopause level. Figure 1b depicts the characteristic thermodynamic structure associated with the horizontal juxtaposition of two upper-level PV anomalies of unequal magnitude separated by a relative minimum in

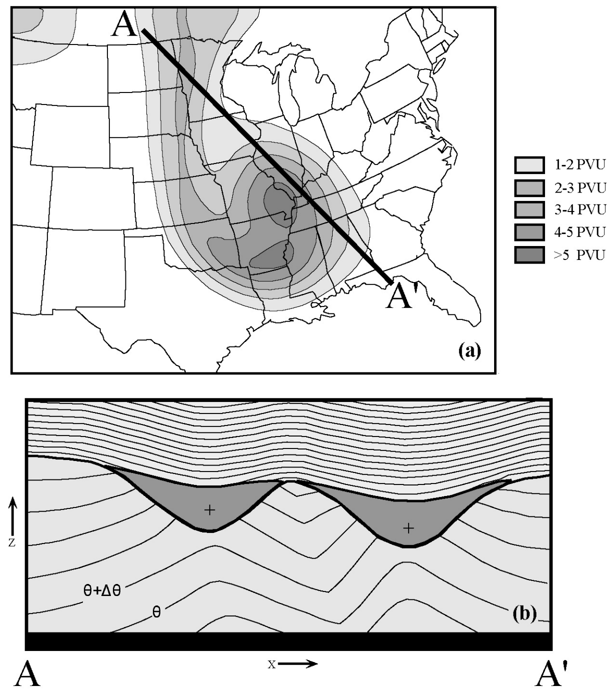

Figure 1: Depiction of treble clef PV signature and underlying thermal structure (a) 9 km PV 1800 UTC 19 January 1995; PV is labeled in potential vorticity units (1 PVU = 10^{-6} m^2 s^{-1} K kg^{-1}). (b) Cross-section along A-A' depicting the representative thermal structure associated with a treble clef shaped upper tropospheric PV structure. Thin lines represent isentropes θ; thick lines enclose positive PV anomalies in the lower stratosphere. Adapted from Martin (1998a).

PV. Notice that beneath the relative minimum in upper-level PV, there lies an axis of maximum θ, and that this axis separates two distinct regions of tropospheric baroclinicity. This configuration is identical to the structure of a classical warm occlusion and is a hydrostatic consequence of the treble clef-shaped, upper-level PV structure. Thus, the formation of a treble clef-shaped tropopause PV anomaly is the unambiguous signature of the development of an underlying warm occluded thermal structure. Consequently, examination of the manner in which latent heat release (LHR) affects the development of the upper-tropospheric treble clef-shaped PV anomaly is equivalently an examination of the role of LHR in promoting the development of a warm occluded thermal structure. Here, we use the relationship between the trowal and the treble clef-shaped upper-tropospheric PV structure to diagnose the effect of condensational heating on the development of a warm occluded thermal structure in a particularly intense continental mid-latitude cyclone.

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2 METHODOLOGY

The cyclone of interest occurred over the central United States on 10-11 November 1998. This storm was characterized by surface winds in excess of 80 miles per hour, 25+ foot waves on Lake Superior, and copious amounts of snowfall in the occluded quadrant, northwest of the cyclone center. A successful full-physics numerical simulation of this storm was performed using version 3.3 of the fifth generation PSU/NCAR Mesoscale Modeling System (MM5). A companion simulation, devoid of the effects of condensational heating, was used to assess the effect of LHR on the formation of the warm-occluded thermal structure.

As the upper-tropospheric PV evolution is central to our analysis, we considered the local rate of change of PV at that level. A three-dimensional distribution of PV can be modified by advection and/or diabatic heating according to:

$$\frac{\partial PV}{\partial t} = -\vec{\mathbf{V}} \cdot \vec{\nabla} PV - \frac{1}{\rho}\left(\vec{\boldsymbol{\eta}}_a \cdot \vec{\nabla}\dot{\theta}\right) \qquad (1)$$

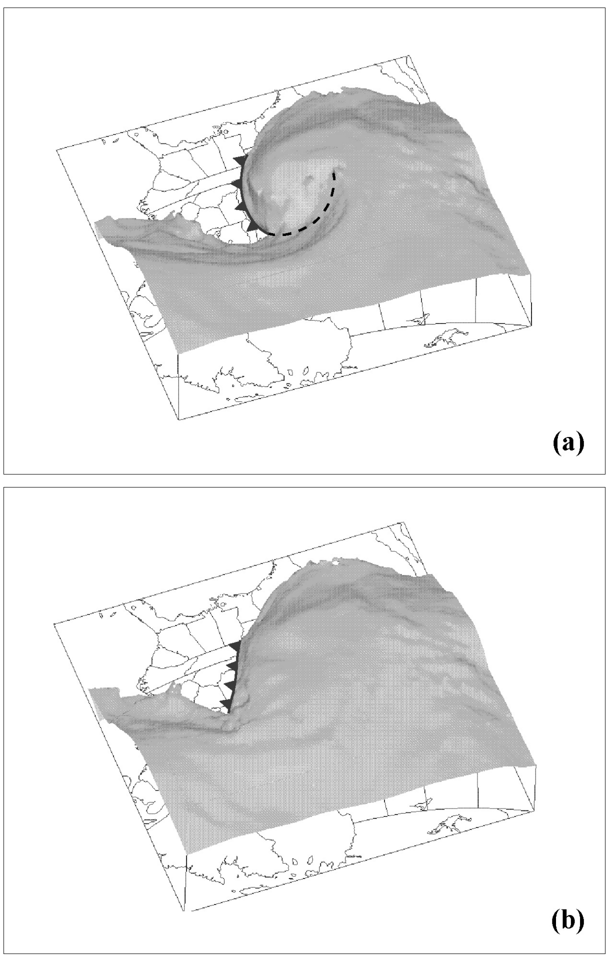

Figure 2: Northeast elevation of the 312 K saturated equivalent potential temperature surface valid at 1800 UTC 10 November 1998. Shown are the trowal (dashed line), and cold frontal positions. (a) represents output from the full-physics MM5 simulation, and (b) output from the MM5 simulation without LHR.

where $\vec{\boldsymbol{\eta}}_a$ is the three-dimensional vorticity vector, and $\dot{\theta}$ is the rate of diabatic heating. Following the formulation employed by Cammas, et al. (1994), we calculated the local non-advective time tendency of PV. In addition, we performed a piecewise PV inversion on the model output, following Davis and Emanuel (1991), in order to isolate the upper-tropospheric advective PV tendency associated with the LHR-produced PV anomaly. In this manner, we explicitly accounted for the role of LHR in both physical processes described on the right-hand side of (1).

Figure 2a (2b) shows the 312 K saturated equivalent potential temperature (θ_{es}) surface valid at 1800 UTC 10 November 1998 from the full-physics (no-LHR) MM5 simulation. This isosurface provides a depiction of the warm and cold-frontal surfaces, as well as the trowal, which can be seen in the three-dimensional canyon between the two fronts. Note that the trowal is clearly present in the full-physics simulation (Fig. 2a), and almost completely absent in the case without LHR (Fig. 2b). The near non-existence of the warm-occluded thermal structure in the no-LHR simulation provides us with the motivation for our analysis.

3.SYNOPTIC EVOLUTION

In the interest of brevity, we present here a shortened description of the evolution of the trowal structure and attendant upper-tropospheric PV distribution. In Figs. 3a-3c, the development of the trowal is depicted in the topography of the 312 K equivalent potential temperature surface. The evolution of the treble clef PV structure is shown using PV in the 320-330 K isentropic layer, which spans isobaric surfaces from 400 to 240 hPa. Thus the PV in this layer is upper-tropospheric PV. At 0600 UTC 10 November (Fig. 3a), a significant positive PV anomaly was located over the western United states. Associated with this upper-tropospheric wave, a fairly modest surface cyclone was located over far northwestern Missouri. At this time, the minimum sea-level pressure was 986 hPa, and the storm was in the early stages of development, as evidenced by the position of the frontal surfaces and in the juxtaposition of the sea-level pressure minimum with the eastern edge of the upper-tropospheric PV gradient. By 1800 UTC (Fig. 3b), the sea level pressure minimum had moved northeastward over western Wisconsin, and had deepened explosively to 967 hPa. At this time, a trowal structure was evident in the 312 K equivalent potential surface, the axis of which stretched from northeast Wisconsin to western Minnesota. This structure lay directly underneath a relative minimum in tropopause-level PV. By 0600 UTC 11 November (Fig. 3c), the trowal and associated treble clef structure were fully developed. The axis of low PV in the treble clef notch was nicely collocated with the trowal, and stretched from southwestern Ontario to northwest Wisconsin.

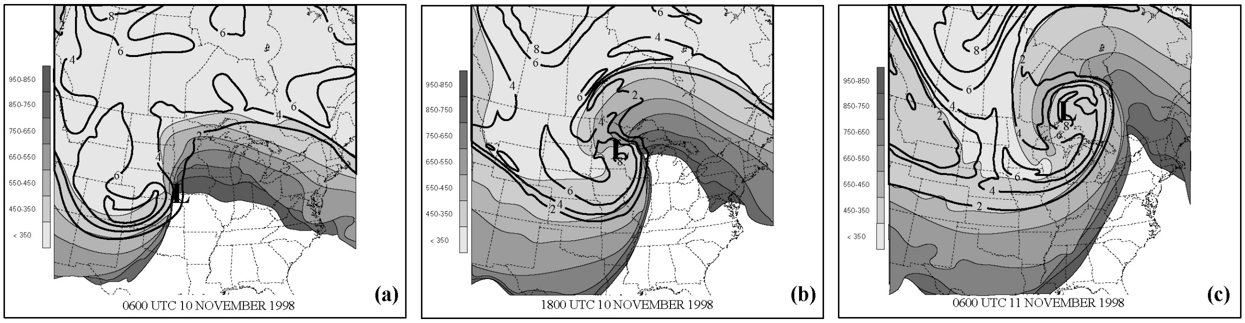

Figure 3: Evolution of the upper-tropospheric PV distribution and underlying trowal structure. Solid lines depict PV in the 320-330 K isentropic layer, while shaded contours represent the topography of the 312 K equivalent potential temperature surface. (a) corresponds to the six hour MM5 forecast valid 0600 UTC 10 November 1998, (b) the 18 hour MM5 forecast valid 1800 UTC 10 November 1998, and (c) the 30 hour MM5 forecast valid 0600 UTC 11 November 1998.

4. RESULTS AND CONCLUSIONS

An examination of circulation associated with LHR-induced PV revealed little kinematic influence on the upper-tropospheric PV distribution. At the tropopause-level, the flow associated with this anomaly was of insufficient strength and incorrect orientation to produce the PV trough characteristic of the treble clef PV structure. We conclude that advection of the upper-tropospheric PV by the circulation induced by latent heating in the middle-troposphere was not the process of primary importance in the development of the treble clef PV structure.

In depicting the influence of the lagrangian rate of change of PV due to latent heating on the treble clef PV structure, we first show that a region of significant PV dilution is persistently collocated with the reduced upper-tropospheric PV anomaly. Low values of PV associated with the formation of the treble clef PV notch were consistently advected northward out of the region of dilution by flow associated with the total PV perturbation.

Further analysis employed an hourly probe along a single representative trajectory to depict the explicit process by which parcels in the trowal airstream experienced a decrease in their PV. We show that air parcels in this trajectory started in the lower troposphere, ascended through a region of latent heating and subsequent PV dilution, experienced reduction of PV to values near zero, and finished in the treble clef notch at the level of the tropopause.

A similar diagnosis was performed on the storm of 1 April 1997, a maritime cyclone that developed a cutoff upper-tropospheric PV anomaly and was associated with copious precipitation along the warm front. This storm has been investigated in prior work on the trowal (Martin 1999) and was found to be associated with significant quasi-geostrophic forcing for ascent in the trowal region. Preliminary results indicated that, although this storm much differently than the storm of 10-11 November 1998, the primacy of LHR in producing the treble clef PV structure was similar. When subjected to companion simulations with and without LHR, the simulation without latent heating contained only a hint of the impressive trowal structure that developed in the full-physics simulation. Based on these two cases, we suggest that the influence of latent heating may be an integral part of the development of the occluded structure in many cases of extratropical development.

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