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THE ROLE OF THE OCCLUSION PROCESS IN THE EXTRATROPICAL-TO-TROPICAL TRANSITION OF ATLANTIC HURRICANE KAREN

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1. INTRODUCTION

Occasionally, baroclinic cyclones in the Subtropical Western Atlantic undergo conversion to full-fledged tropical systems in a process known as extratropical-to-tropical conversion (ETC). Two widely-accepted necessary conditions for tropical cyclogenesis are: 1) tropospheric-layer shear of less than 15 m s^{-1} above the sea-level pressure (SLP) minimum and 2) sea surface temperatures (SST) in excess of 26.5^{o}C. ETC cases are relatively rare because most candidate disturbances form in proximity to the 26.5^{o}C SST line and, being of baroclinic origin and therefore also associated with cyclonic vorticity advection by the thermal wind, form in the presence of significant vertical shear. In their analysis of several ETC cases, Davis and Bosart (2003) found that most cases were marked by initial shears of 15-35 m s^{-1}. For this reason, identification of the means by which the shear is reduced above the SLP minimum in ETC events is an essential issue in understanding these storms.

Davis and Bosart (2004) hypothesized two types of transitioning systems: strong extratropical cyclones (SEC) in which a vigorous, frontal surface cyclone develops, and weak extratropical cyclones (WEC) where a frontal zone organizes convection without the formation of a robust baroclinic cyclone. In both types, diabatic heating due to latent heat release (LHR) from the cyclone's deep, moist convection rearranges the potential vorticity (PV) field into one favorable for tropical cyclogenesis by reducing shear over the storm.

The PV-shear relationship can be discerned by considering the quasigeostrophic PV (QGPV) without the Coriolis component, ***q'***,

$$q' = \frac{1}{f_o}\nabla^2\Phi + \frac{\partial}{\partial p}\left(\frac{f_o}{\sigma}\frac{\partial \Phi}{\partial p}\right) = \Lambda(\Phi) \qquad (1)$$

where Λ is an elliptic, linear operator. Taking the gradient of (1) and assuming geostrophy, a relation between the QGPV gradient and wind can be found,

$$\nabla q' = \Lambda\left[\left(\frac{\partial \Phi}{\partial x}, \frac{\partial \Phi}{\partial y}\right)\right] = \Lambda(fv, -fu)\,. \qquad (2)$$

The ellipicity of Λ infers that in the Northern Hemisphere a local maximum (minimum) in the gradient of q' would be correlated with a minimum (maximum) in meridional wind and a maximum (minimum) in zonal wind. Assuming that the largest PV gradients are around the tropopause and that near-surface winds are weak, the largest values of tropospheric shear will be collocated with the strongest upper-level PV gradient. Thus, shear will decrease over a surface cyclone if the upper PV anomaly weakens or if the cyclone moves out from under the maximum upper-tropospheric PV gradient.

The upper positive PV anomaly can be weakened by the redistribution of PV via LHR. The precursor system can be moved away from the maximum upper-tropospheric PV gradient through the process of extratropical occlusion which renders the SLP minimum beneath the inflection point (i.e. area of zero PV gradient) of the upper-tropospheric PV maximum. These two mechanisms are not necessary independent of one another as recent work by Posselt and Martin (2004) has demonstrated that LHR is a fundamental component of the occlusion process. This paper will examine the ETC of Hurricane Karen, which formed in the western Atlantic in October 2001, paying particular attention to the role that the occlusion process plays in creating an environment favorable for tropical cyclogenesis.

2. DATA

The synoptic overview of Karen utilizes the six-hourly Global Final Analysis (FNL) data set provided by NCEP. Standard meteorological variables were sampled at 50 hPa intervals from 1000 hPa to 100 hPa on a 1^{o} by 1^{o} latitude-longitude grid, in order to calculate the PV and shear over the domain. The Best Track database compiled by the Tropical Prediction Center was utilized for SLP data.

3. GLOBAL ANALYSIS

3a. Synoptic Overview

The weather systems important to the initiation of Karen began to develop at 1800 UTC 9 October 2001 (hereafter, all times refer to October 2001 and are denoted as hour/date) as a progressive trough moved across the north Atlantic. A trailing cold front from this system penetrated into the subtropics to as far south as 30^{o}N. At this same time, a new trough began to fracture off of the westerlies near the East Coast of the United States. In the next 36 hours, the new trough moved southeastward and deepened, eventually becoming stationary. Meanwhile, a surface cyclone began to develop on the tail-end of the baroclinic zone trailing the

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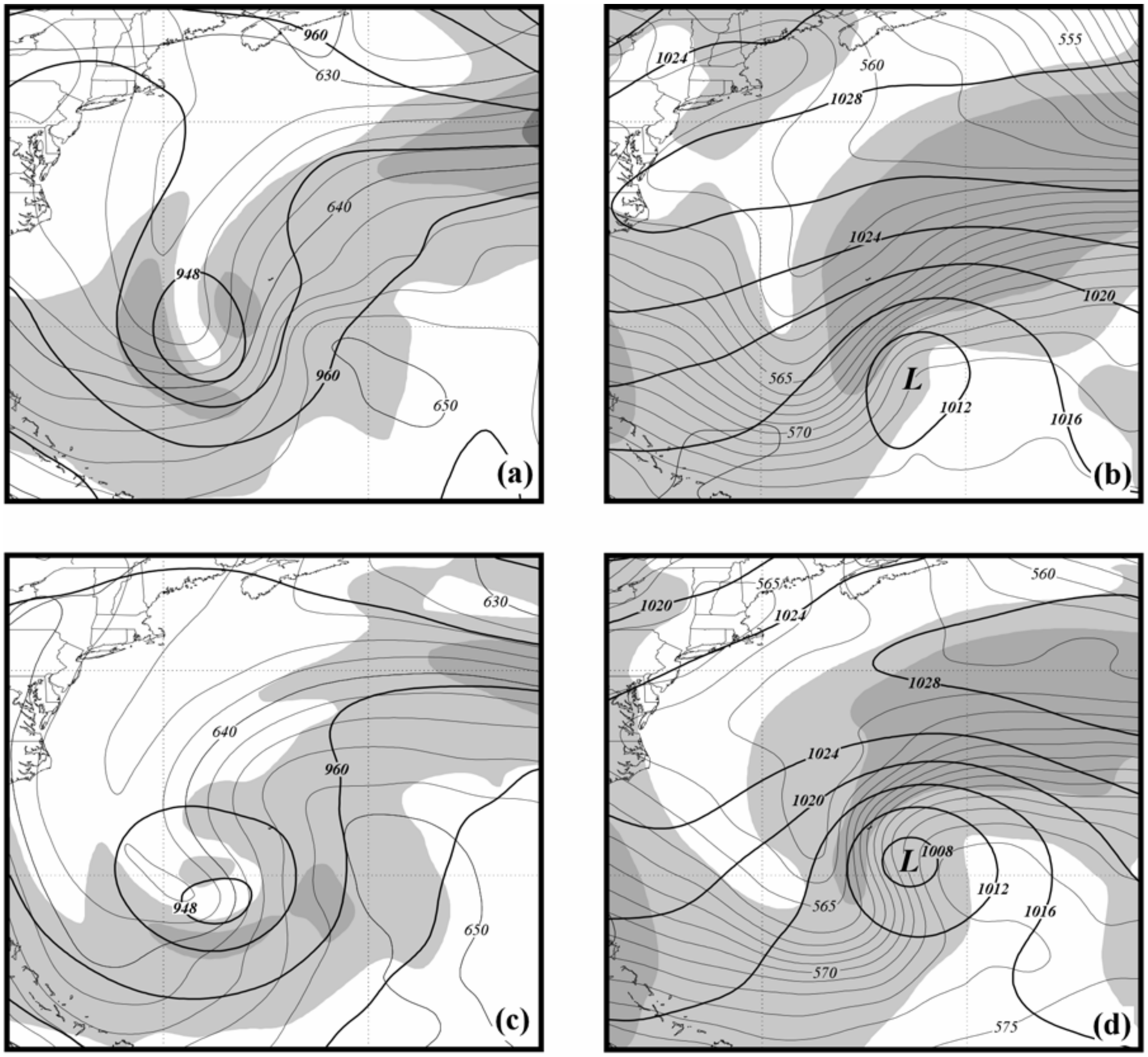

FIG. 1. (a) 300 hPa geopotential height (thick contours, dam), 200-500 hPa layer thickness (thin contours, dam), and 300 hPa wind speed (shaded at 15, 25 and 35 m s^{-1}) for 0600 UTC 11 October 2001. (b) Sea level pressure (thick contours, hPa), 500-1000 hPa layer thickness (thin contours, dam), 200-900 hPa layer vertical shear (shaded at 15 and 35 m s^{-1}), and position of surface cyclone (denoted by "L") for 0600 UTC 11 October 2001. (c) As in (a), but for 1800 UTC 11 October 2001. (d) As in (b), but for 1800 UTC 11 October 2001.

prior system such that by 06/11 the two features had moved into an alignment favorable for mutual amplification (Figs. 1a-1b). Karen's precursor was clearly non-tropical at this time as a thermal ridge was evident in the thickness field (Fig. 1b). Over the next 12 hours, the upper-level trough significantly amplified the lower-level thermal ridge and extratropical Karen began to deepen (11 hPa in 12 h). At approximately the same time (18/11), the trough became cut-off (Figs. 1c-1d) and a thickness minimum (i.e. cold dome) developed in its vicinity. In addition, a 30 m s^{-1} jet streak had moved to the south of the cut-off placing extratropical Karen in an area of 25-35 m s^{-1} shear.

From 18/11 to 06/12, Karen deepened another 10 hPa to 988 hPa and began to occlude with the surface cyclone becoming vertically aligned with the upper-level vortex. The low-thickness area located near the cut-off warmed quickly (70 gpm in 12 h) associated with sustained convection that developed to the west of the surface cyclone (Fig. 2a). The upper-level jet streak moved around the trough and was at this time east of both vortices having maintained its strong winds. Despite the area of enhanced upper-level winds directly to the east, shear over Karen decreased to 10-15 m s^{-1} (Fig. 2b) mostly due to the increased low-level winds associated with the surface vortex and their subsequent alignment with the upper cut-off. By 18/12, shear over Karen decreased to under 10 m s^{-1}, a value favorable for tropical cyclogenesis, and the system developed a lower-tropospheric warm core (Figs. 2c-2d) stretching through the entire troposphere by 06/13 (not shown). However during the formation of the warm core, Karen's SLP remained constant. At this point, Karen was, for all intents and purposes, a tropical storm.

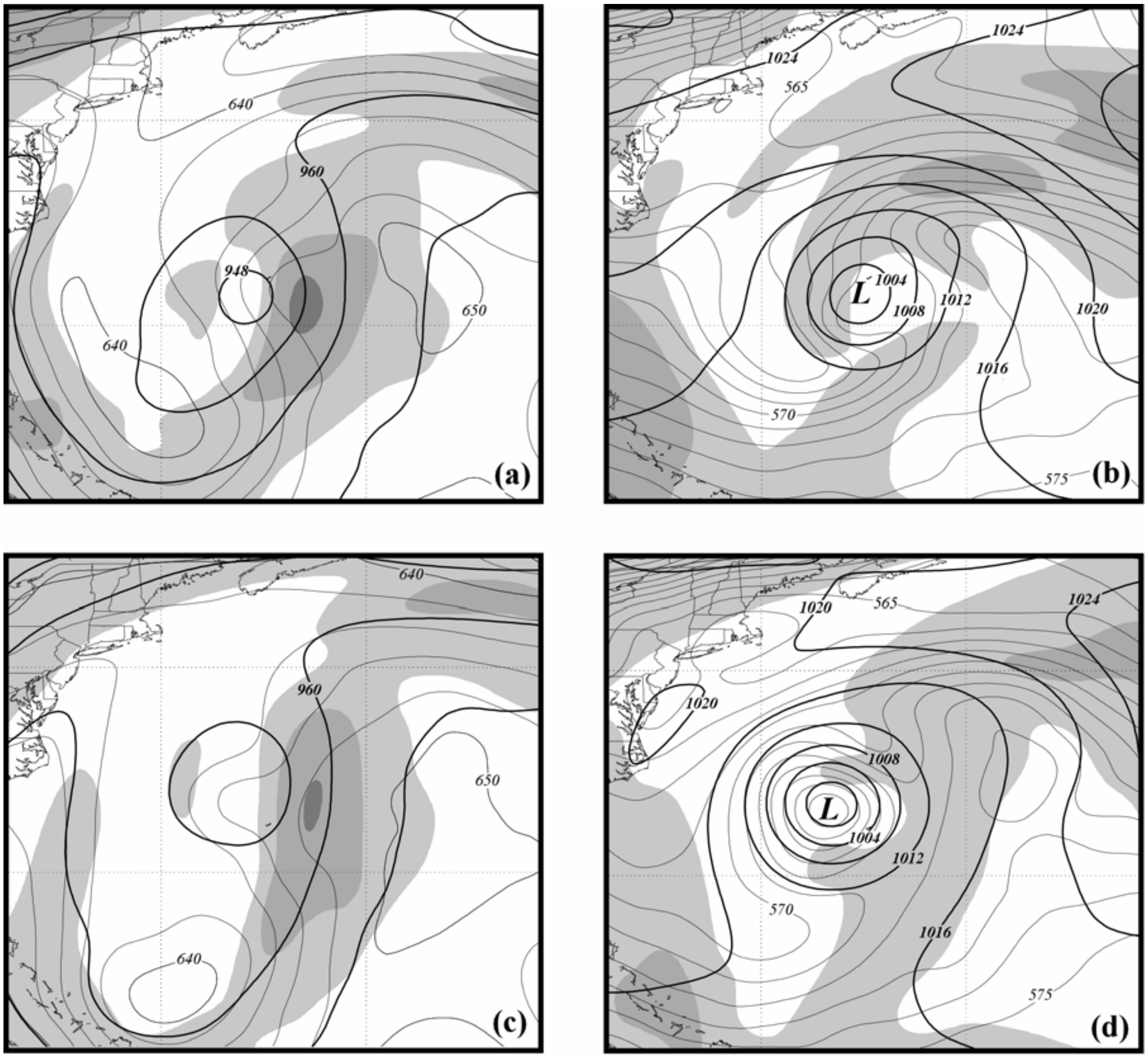

FIG. 2. (a) As in Fig. 1a, but for 0600 UTC 12 October 2001. (b) As in Fig. 1b, but for 0600 UTC 12 October 2001. (c) As in Fig. 1a, but for 1800 UTC 12 October 2001. (d) As in Fig. 1b, but for 1800 UTC 12 October 2001.

3b. Shear-PV diagnosis

As shown in the previous section, the upper trough/cut-off played a significant role in deepening the extratropical cyclone that would become Karen. Shear associated with the upper vortex was largest over Karen during the cyclone's initial deepening phase. As the cyclone occluded, the two circulations became vertically stacked decreasing shear and allowing Karen to acquire tropical characteristics. Thus, the reduction of the shear over Karen was the pivotal element leading to the ETC event.

At 06/11, the gradient of Ertel PV* (EPV) reasonably diagnosed the location of maximum upper level winds with winds in excess of 30 m s^{-1} to the southwest and northeast of the EPV maximum. Because surface winds associated with Karen at this time were weak, the area of strongest winds also corresponded to the area of largest shear (Fig. 3a). Over the next 24 hours, convection to the west of Karen's center developed and contributed to a redistribution of the PV into the "treble clef" shape characteristic of occluded cyclones (Martin 1998, Posselt and Martin 2004). By 18/11, low-level EPV drastically increased in response to LHR (Fig. 3b). While shear over Karen's center was still strong due to a persistent upper-level EPV gradient, the diabatically-generated low-level EPV anomaly and its associated counterclockwise circulation promoted the advection of low-EPV air into the center of the upper vortex. By 06/12, the PV distribution had clearly adopted the "treble clef" structure as the upper anomaly had become smaller and more circular (Fig. 3c). During this process, the upper-level EPV maximum moved quickly northeastward and its now tighter circulation became

* For consistency, here we use Ertel PV noting that QGPV us an isobaric linear form of EPV. The locations of extrema and gradients in both fields were similar.

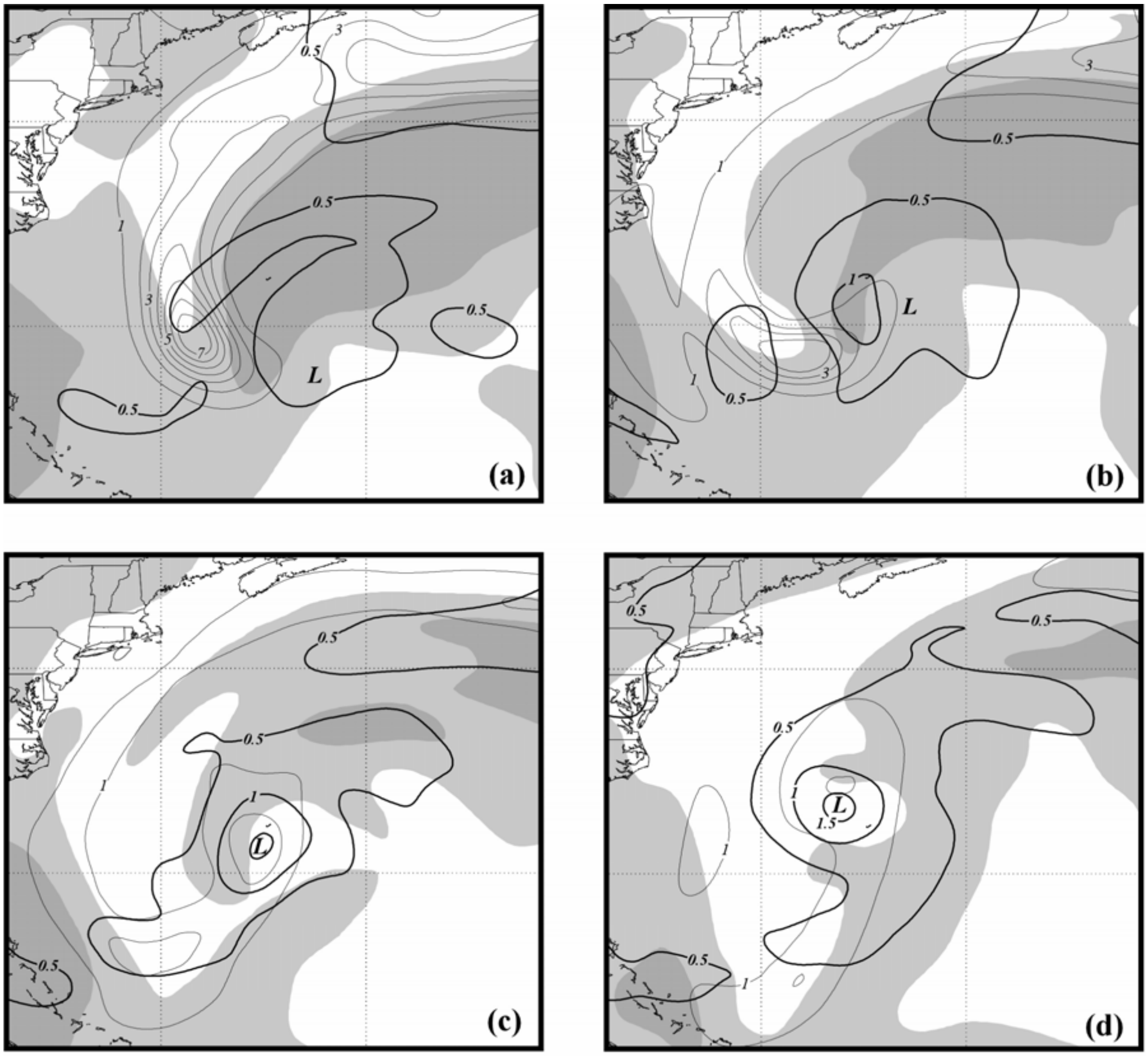

FIG. 3. Ertel PV in the 305-315 K isentropic layer (thick contours, PVU), Ertel PV in the 330-340 K isentropic layer (thin contours, PVU), 200-900 hPa layer vertical shear (shaded at 15 and 35 m s^{-1}), and position of surface cyclone (denoted by "L") for (a) 0600 UTC 11 October 2001, (b) 1800 UTC 11 October 2001, (c) 0600 UTC 12 October 2001, and (d) 1800 UTC 12 October 2001.

stacked with Karen. These transformations are the canonical results of the occlusion process as described in Posselt and Martin (2004). As the surface cyclone occluded, Karen's near-surface winds intensified and became vertically juxtaposed with the still marginally strong upper-level winds (associated with a modest EPV gradient to the east of the storm), thus reducing the shear over the SLP minimum. At 18/12, Karen had moved even further westward, away from the lingering EPV gradient, and shear over the cyclone reduced to around 5 m s^{-1} (Fig. 3d) allowing Karen to maintain a warm core and other tropical characteristics.

4. CONCLUSIONS AND FUTURE RESEARCH

Hurricane Karen formed via the interaction of an old baroclinic zone and an upper-level trough intruding into the Subtropical Atlantic. As Karen's precursor became a robust extratropical cyclone, shear over the system actually increased promoting deepening of the system through column stretching via upward vertical motion associated with cyclonic vorticity advection by the thermal wind. As Karen began to occlude (and moved closer to the upper-level vortex), diabatically-generated PV weakened the upper-level cutoff while the cyclone's near-surface winds increased. These two processes, in addition to Karen's progress toward a position beneath the inflection point of the PV-gradient field, reduced the shear over Karen to levels below which tropical cyclogenesis was favorable.

The occlusion process, characterized by both significant diabatically induced upper-tropospheric PV erosion above the SLP minimum as well as the acquisition of a vertically stacked structure, created a favorable low-shear environment for the cyclone to obtain tropical characteristics. We therefore hypothesize that the extratropical occlusion process is a sufficient mechanism for creating the environment necessary for the ETC to occur given that the storm remains over sufficiently warm water. In the context of other ETC cases, Karen was an extreme SEC system. Thus, in cases where the precursor baroclinic storm is weaker, the occlusion process may play a less important role and the ETC process may proceed as a result of other, perhaps related mechanisms.

Because the transition took only twenty-four hours to occur, future work will focus on running the Weather Research and Forecasting (WRF) model to obtain data on smaller spatial and time scales. The analysis will focus on the interaction between the surface cyclone and the upper cut-off as well as quantifying the role LHR had in the morphology of each. By analyzing these simulations, mesoscale processes that are not identifiable in the coarse global dataset will be studied to provide further insight into what role the occlusion process had in this ETC event.

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