P1.16 WARM-SECLUSION EXTRATROPICAL CYCLONE DEVELOPMENT: SENSITIVITY TO THE NATURE OF THE INCIPIENT VORTEX

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1. INTRODUCTION

The development of intense warm-core seclusion (Shapiro and Keyser 1990) extratropical storms can occur from several different precursor disturbances. These include tropical cyclones that have undergone extratropical transition, maritime extratropical cyclones with both cold-core baroclinic and shallow diabatically generated warm core backgrounds (Moore and Montgomery 2004), and polar lows. With the most intense, bomb-like deepening (Sanders and Gyakum 1980) or rapid intensification is triggered by a tropopause fold or frontal fracture (Browning et al. 1997), in which statically stable, high potential vorticity spills into the middle troposphere slightly upstream of the surface low. With the inclusion of copious amounts of latent heating provided by warm western boundary ocean currents, the growth rate of baroclinic instabilities may be significantly enhanced by latent heat processes (Emanuel et al. 1987). Another facet of the problem involves the impact of distant mobile upper-level troughs (Molinari and Vollaro 1989) interacting with tropical cyclones as well as low-level cyclonic extratropical circulations. Four separate storm systems that culminate in a mature warm seclusion are numerically modeled using the PSU/NCAR MM5 model and analyzed to better understand the brief time period in which the tropopause fold is triggered and the overall thermal structure of the system begins to warm as the pressure drops rapidly. A central question to address concerns whether the mechanism for triggering rapid cyclogenesis and the subsequent warm seclusion development is dependent upon the origin of the incipient cyclonic vortex.

2. CASE STUDIES AND NUMERICAL MODEL

Two extratropically transitioning tropical cyclones, Hurricane Irene (Oct. 1999) and Typhoon Koppu (Sept. 2003) are modeled and analyzed alongside two storms of extratropical origin, one in the North Eastern Pacific (Oct. 26-30, 2000), and one in the Eastern Atlantic (Oct. 25-31, 2004) that impacted Southern England. For brevity, a short mention of each case is provided. The tropical cyclones both transitioned quickly to extratropical cyclones and rapidly re-intensified into extratropical cyclones. Irene traveled along the eastern US seaboard, underwent ET (merger), and subsequently bombed. TY Koppu followed a similar lifecycle as Irene, but near Japan, and was not as intense post-ET. The Pacific extratropical cyclone origins were cold-core at all levels (not shown) while the Atlantic system developed akin to diabatically generated low-level warm cores described by Moore and Montgomery (2004).

The model used in this study is the high-resolution non-hydrostatic, 5th generation Pennsylvania State University-NCAR Mesoscale Model (MM5, Grell et al. 1994). Two successive runs were conducted for each system, one at 36 km and the second at 12 km with the boundary conditions provided by the coarser run. The model initial and lateral conditions are the ECMWF TOGA Operational Analysis 1.125° except for the Atlantic system in which the NCEP GFS 1°x1° operational forecast was used in conjunction with Reynolds Daily sea surface temperatures (SSTs). The 36 km domains contained 29 sigma levels with 9 sigma levels within the Planetary Boundary Layer (PBL) while the 12 km domains contained 42 sigma levels with 3 added to the near surface. Additional model parameters include the Grell cumulus scheme, Reisner II microphysics (Reisner et al. 1998) and Blackadar PBL. The outer domain was integrated for 48-72 hours while the inner domain centered upon the tropopause fold period was 36-48 hours.

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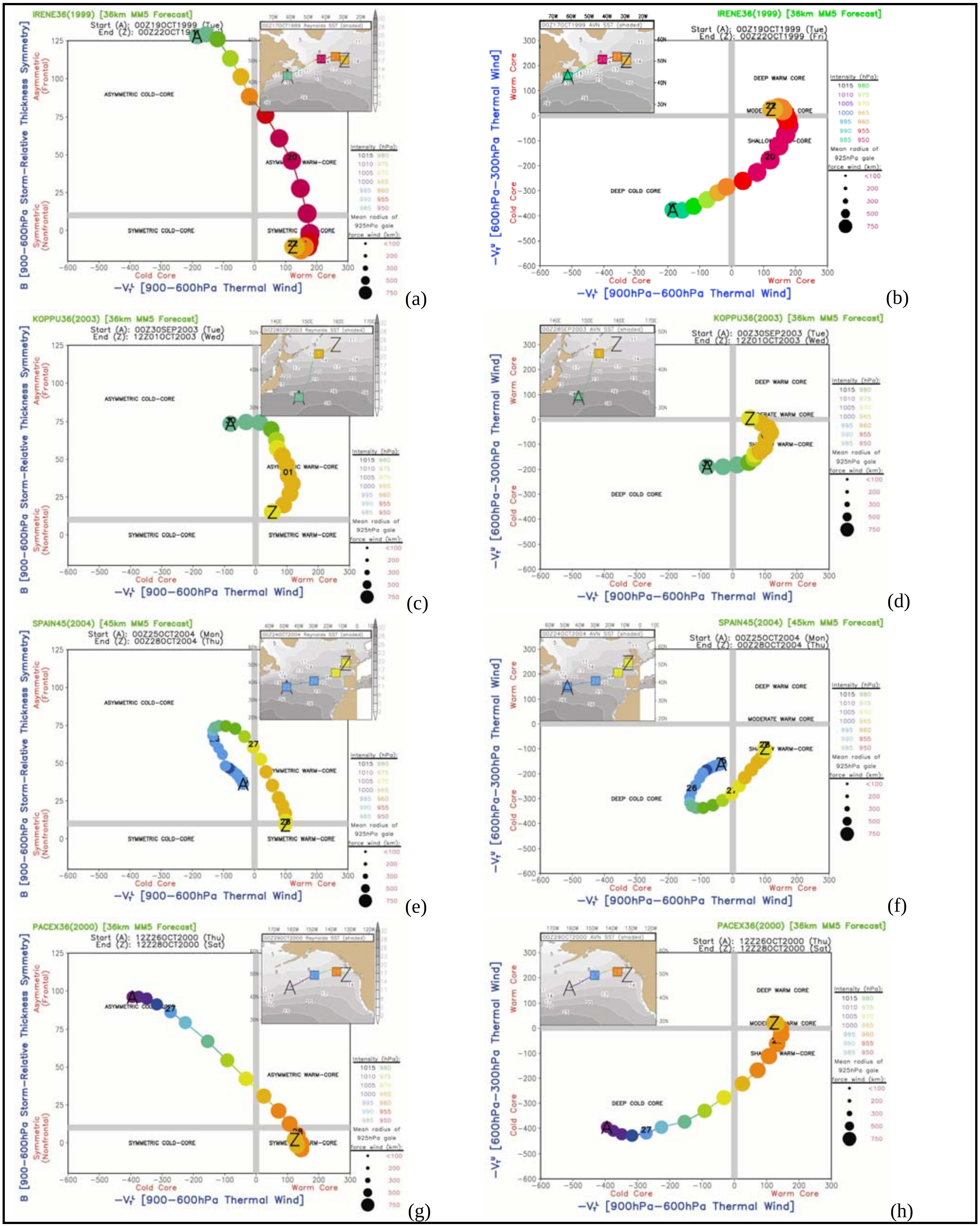

Figure 1. Cyclone phase space (Hart 2003) from MM5 model output of (a)-(b) Hurricane Irene (1999) (c)-(d) Typhoon Koppu (2003) (e)-(f) Atlantic extratropical cyclone (Oct 2004) (g)-(h) Pacific extratropical cyclone (Oct 2000).

3. METHODS

An important tool for analyzing tropical and extratropical cyclone structure has been the potential vorticity framework. The evolution of the storm structure is analyzed in conjunction with the cyclone phase space (CPS, Hart 2003) trajectories calculated from MM5 model output. The temporal and spatial resolution afforded by the numerical model is used advantageously in the portrayal of the three-dimensional frontal and thermal structure on the CPS. Particular attention is paid to the point on the trajectory where the cyclone begins to (re) develop warm core thermal structure usually concomitant with rapid pressure drop. As of potential use for frontal fracture analysis, the use of eddy momentum flux convergence (EFC) has served useful for diagnosing trough interactions with tropical cyclones (Molinari and Vollaro 1990, Hanley et al. 2001).

$$EFC = -\frac{1}{r^2}\frac{\partial}{\partial r} r^2 \overline{u_L{}' v_L{}'} \quad (1)$$

Positive values of EFC indicate that azimuthal eddies are acting to increase the angular momentum especially in the outflow layer with TC-trough interaction. Hart and Evans (2005) points out that during extratropical transition, the evolution from warm-core symmetric to cold-core asymmetric is primarily driven by the eddy angular momentum flux of the trough, with the eddy heat flux associated with the trough playing a much lesser role. However, after ET, with the coupling of decaying TC with a low-level baroclinic zone, the generation of convection associated with thermal advection (i.e. warm frontogenesis) plays a more important role with increased eddy heat fluxes due to baroclinic instability during cyclogenesis. At the same time, well away from the surface, vertical shear associated with the midlatitude circulation destroys the vertical coherence of the TC vortex usually blowing the positive PV anomaly downstream leaving a low-level warm core. Around this remnant TC signature, convection may continue to fire and precondition the downstream environment to become more favorable for potential extratropical cyclogenesis (August-Panareda et al. 2004). At this post-ET juncture, to ascertain the scale matching inherent with “trough coupling” and the increased static stability and lowered Rossby penetration depth associated with the tropopause fold, Vis5d animations of each system clearly show the origin of the PV intrusion and the evolution of the vortex and trough scale.

4. RESULTS

The EFC calculations for Irene (1999) at successive 2-hour time periods encapsulating the PV intrusion are shown in Fig. 3. Previously presented values of EFC > 10 (m s^{-1}) day^{-1} at 200 hPa were used by DeMaria et al. (1993) to indicate a trough interaction with tropical cyclones mainly located in hardly baroclinic environments. The EFC values for extratropical environments where the upper-level jet is nearby are considerably higher, at time reaching 50 – 100 (m s^{-1}) day^{-1} at between 200-400 hPa depending upon the height of the tropopause and jet location. The thin extension of high EFC values extends inward and downward from a major reservoir at jet level. The importation of angular momentum is primarily concentrated at midlevels at radii near the storm center with noticeable low-level contributions likely corresponding to the chevron shaped band of strong winds coined the “sting jet” (Browning 2004). A three-dimensional view (Figure 2) of the 2 PVU potential vorticity surface colored with vertical motion indicates a descending intrusion behind the main diabatic core of the rapidly intensifying cyclone.

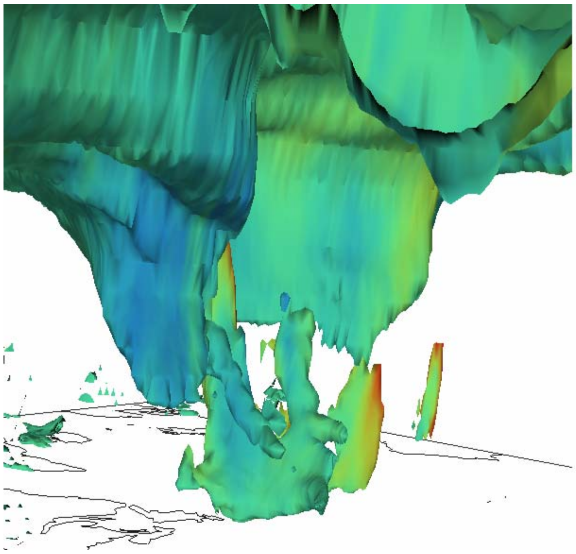

Figure 2. Potential vorticity Vis5d rendering of the 2 PVU isen-surface (colored with ascent (red) descent (blue-green) at 10z Oct. 19, 1999 during the frontal fracture period. Note the narrow protrusion descending from the main trough located on the SW flank of the diabatic core. This is separate from the main trough and acts as a lightning rod for rapid intensification.

Typhoon Koppu (2003) completed extratropical transition and developed into an intense warm-core seclusion over a period of three days. The conversion to cold-core asymmetric structure occurred rapidly on September 30 and reached maximum cold core structure shortly thereafter (Figure 1bc). The vertical shear associated with an upstream trough and interaction with a pre-existing frontal system rapidly destroyed the upper-level warm core structure of the typhoon. Yet a significant remnant PV tower associated with continued convection was enveloped by a very thin PV intrusion slightly upstream out the main trough.

The Atlantic cyclone studied originated in the central Atlantic is a prime example of a shallow warm-core disturbance dependent upon latent-heat dynamics (e.g. Lothar storm 1999 studied by Wernli et al. 2001), which grows moderately until interaction with a similar PV intrusion as Irene. This point is demonstrated on the CPS (Figure 1f) as the point where the dramatic turn in the trajectory from deep cold core to shallow warm core begins in earnest. Large descent associated with the tropopause fold is in direct contrast to the vigorous ascent driven by diabatic processes, especially convection with the formation of the cloud head. With an infusion of eddy angular momentum at mid- to low-levels provided by the PV intrusion, rapid spinup and pressure drop occurs in conjunction with the eddy heat fluxes associated with the convection. The incipient vortex paralleled the edge of the upper-level trough and only was the PV fold triggered when the secondary circulation driven by diabatic processes was significant enough to achieve the descent necessary. The Pacific cyclone studied confirms this general scenario. Each of the systems studied concluded in a large scale, LC2-type cyclonic wrap-up (Thorncroft et al. 1993) with the storm center advected along the tip of the upper-level PV intrusion.

5. CONCLUSIONS

The final result of the individual cyclone lifecycles was a warm-core seclusion, yet the trajectory taken was considerably different. However, a commonality is the necessary transition from warm-core to cold-core and then back again. Even with the extratropical cyclones, which relied on latent heat processes away from upper-level influences, the evolution of a thermal advection dipole decidedly made the systems more asymmetric. The critical point at which the storm developed a strong enough low-level circulation to trigger an upstream secondary circulation and a subsequent descending tropopause intrusion occurred at maximum asymmetry and cold-core depth. Thus, in marine environments, where latent heat is readily accessible, many cyclones develop along a shallow zone of isentropic lift for several days with modest results. It is only when the scale of the cyclone is finally noticed by the upper-level trough that rapid development occurs. It appears the major hurdle for warm seclusion development is achieving enough of a scale to be noticed with the cyclonic wrap-up occurring shortly thereafter.

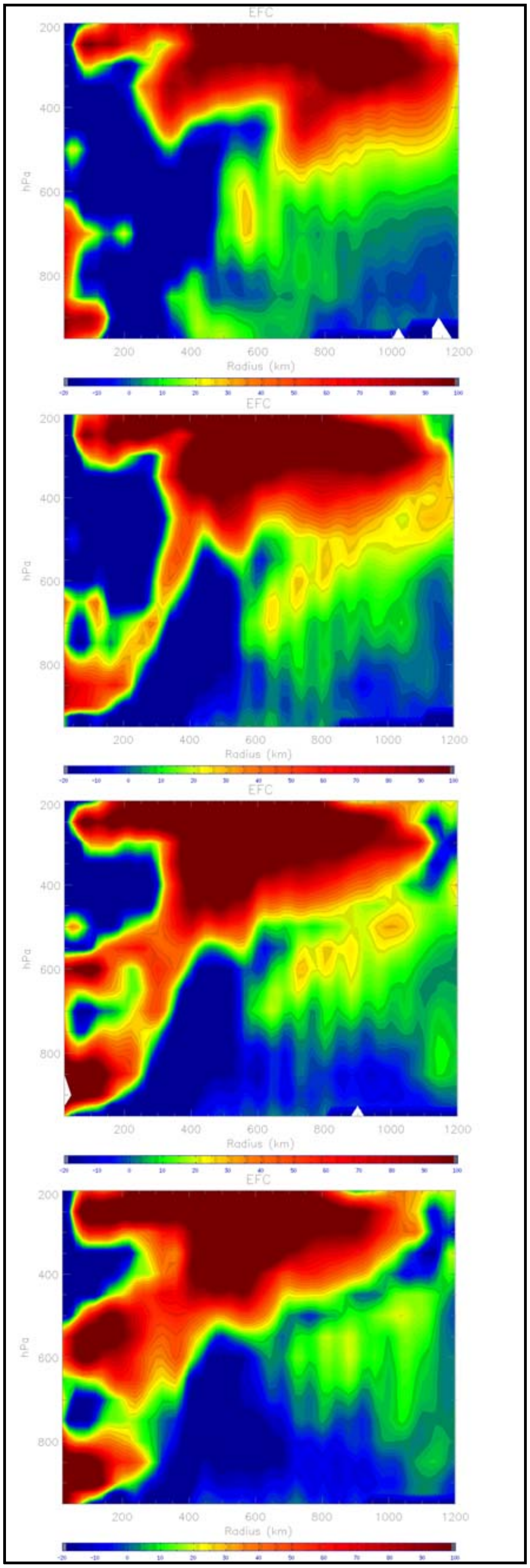

Figure 3. Eddy momentum flux convergence (EFC) at 06z, 08z, 10z, 12z, during the frontal fracture period on October 19 for Irene (1999). Abscissa is radius in km. Away from storm center and ordinate is vertical level from 200-950 hPa.

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