TOWARDS A BETTER UNDERSTANDING OF AND ABILITY TO FORECAST THE WIND FIELD EXPANSION DURING THE EXTRATROPICAL TRANSITION PROCESS

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1. INTRODUCTION

Extratropical transition (ET), the process by which an initially warm-core tropical cyclone (TC) transitions into an extratropical cyclone, is a process that highlights the response of a TC to increased baroclinic forcing in the way of increased temperature and moisture gradients, vertical wind shear, and decreased sea surface temperatures. Synoptically, the response of the TC is marked by a transition to an asymmetric appearance in satellite imagery, including asymmetric evolutions of the precipitation and wind fields (Jones et al. 2003). In particular, the TC wind field is known to expand outward during ET, with a greater radius of maximum winds observed within the extratropical cyclone.

Despite synoptic knowledge of the evolution of the wind field during ET, little is known about the dynamical processes that control the related structural changes. An increased knowledge of the processes controlling the wind field evolution is critical from both meteorological and societal standpoints, particularly in terms of improving forecasts of the wind field evolution in order to protect life and property, both on land and in the open seas.

Two theories have been informally used to describe the wind field expansion of TCs undergoing ET. The first is the consequence of absolute vorticity conservation in an increasing latitude environment. However, this theory is readily discounted since the wind field expansion still occurs even when transitioning TCs move zonally across the Atlantic. The second theory concerns the outward movement of eyewall parcels to larger radii as the eyewall convection weakens. While this process undoubtedly happens, it cannot explain the wind field expansion given the constraint of absolute angular momentum conservation. Unless the wind profile is inertially unstable, outward movement of parcels will always result in their deceleration as they move outward.

This work is designed to present findings towards an improved understanding of the wind field evolution during the ET process. Methodology behind the analyses performed is presented in Section 2. Analyses of momentum fields and budgets, thermodynamic properties, and synoptic conditions are presented for a case of an extratropically transitioning TC in the North Atlantic Ocean in Section 3. Based upon the observed findings, conclusions are drawn and hypotheses developed proposing a mechanism leading to the observed wind field evolution during ET in Section 4, with areas of future work extending upon these conclusions and hypotheses noted in Section 5.

2. METHODOLOGY

In order to account for the majority of post-ET evolutions, a post-ET cold-core TC is desired for analysis. Further, a storm undergoing transition sufficiently far away from land is desired so as to largely negate the effects of friction upon the process. Finally, due to the resolution of the available operational analysis data, a storm that is reasonably well-depicted in both the tropical and extratropical phases by the data is needed. Based upon these criteria, North Atlantic basin TC Bonnie of 1998 was selected for analysis. Operational analysis data are obtained from the Aviation (AVN; Kanamitsu 1989) model 1° analyses between 0000UTC 26 August 1998 and 1200UTC 30 August 1998, near the time of completion of the ET process per the cyclone phase space of Hart (2003; Figure 1).

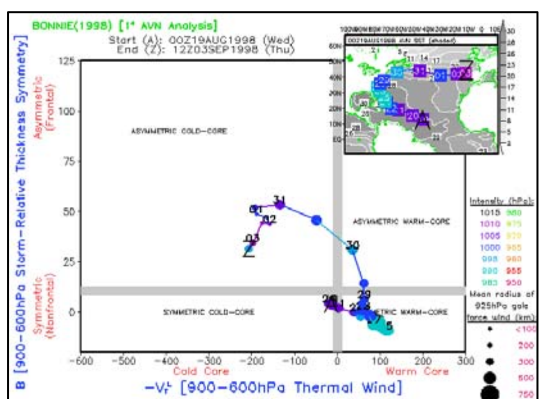

Figure 1: Cyclone phase space depiction of the evolution of TC Bonnie in the North Atlantic. A full description of the parameters shown may be found in Hart (2003).

Absolute angular momentum (per unit mass; units: $m^2\ s^{-1}$) values were calculated within the azimuthally-averaged storm cylinder out to a radius of 1000km as a function of the wind speed of the storm, as follows:

$$M = r^2(\Omega \sin\phi + w) \qquad (1)$$

where all symbols have their standard meteorological definition except for ***w***, the rate of rotation of the storm cylinder and equal to the wind velocity divided by the radius. Potential vorticity (PV; units: 10^{-6} K m^2 kg^{-1} s^{-1}) is calculated within and around the storm vortex utilizing the isentropic PV formulation:

$$IPV = -g\eta \frac{\partial \theta}{\partial p} \qquad (2)$$

where all symbols have their standard meteorological definition.

Eliassen-Palm (E-P) fluxes are calculated within the storm vortex cylinder utilizing the storm-relative, cylindrical coordinate framework of Molinari et al. (1995). Comprised of eddy heat and momentum fluxes, the E-P flux and its divergence are ideal measures of the effects of the midlatitude environment upon the storm. Specifically, the formulation used in this work is given as follows:

$$F_L = [-r\overline{(\sigma u_L)' v_L'}, \overline{p' \psi_\lambda'}] \qquad (3)$$

$$\nabla \bullet F_L = -r^{-1}(r^2 \overline{(\sigma u_L)' v_L'})_r + (\overline{p' \psi_\lambda'})_\theta \qquad (4)$$

where σ is the pseudodensity and equivalent to -dp/dθ, ψ is the Montgomery streamfunction, primed quantities denote differences from the azimuthal mean, barred quantities denote azimuthally averaged values, subscripts of L denote storm-relative flow, and all other subscripts denote derivatives. Equation (3) gives the components of the E-P flux, while equation (4) gives the E-P flux divergence, a quantity that is directly related to an eddy PV flux (Molinari et al. 1995). These calculations are performed over a cylindrical grid with twenty vertical levels (dθ = 4K), thirty radial points (dr = 50km), and twelve azimuthal angles (dλ = π/6 radians).

It should be noted that all analyses are performed with the isentropic vertical coordinate rather than the pressure vertical coordinate so as to better depict the scales of both the TC and the associated midlatitude trough as they interact during the transition process. Further, all calculations are done within a storm-relative framework, where the component of motion has been removed from the wind field of the storm. This is done to discount the effects of storm motion acceleration upon the evolution of the wind field and to maintain consistency with the E-P flux calculations. Special focus is given to the environmental factors affecting the storm lifecycle, given the relative weaknesses of the operational analysis data to resolve the inner core features of a tropical cyclone.

3. RESULTS

3.1 *Potential vorticity diagnostics*

Cross-sections of isentropic potential vorticity (PV) are depicted in Figure 2 (a) 36hr prior to the completion of transition and (b) at the completion of transition, highlighting the midlatitude environment into which the storm was moving as well as the external influences upon the transitioning storm.

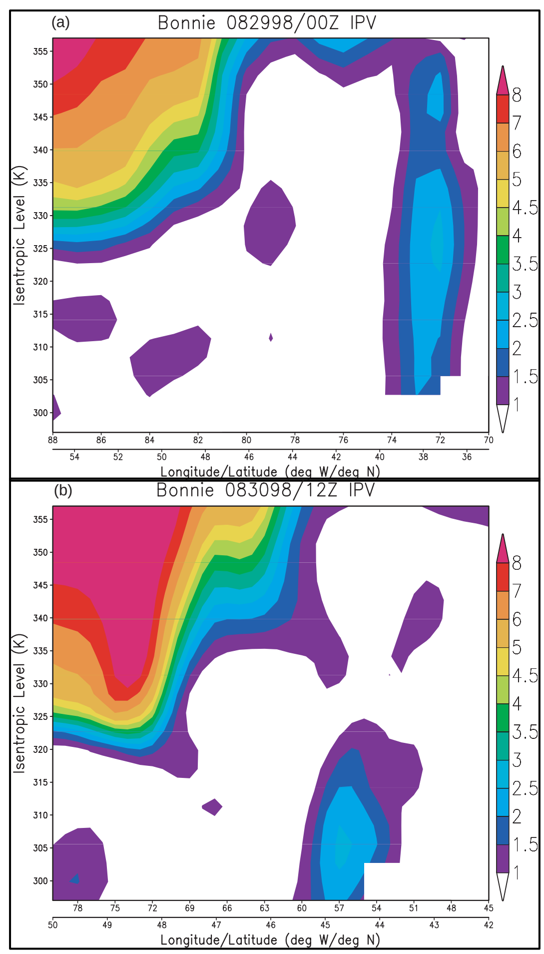

Figure 2: Isentropic PV cross-sections at **(a)** 36hr prior to the completion of transition and **(b)** the time of the completion of transition.

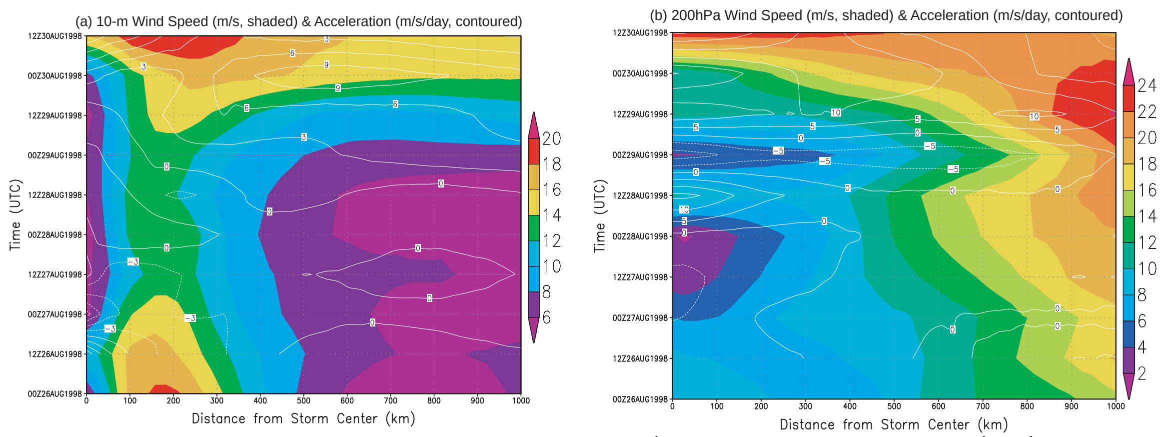

Figure 3: Storm-relative time progression of the wind speed (shaded; m s^{-1}) and its acceleration (contoured; m s^{-1} day^{-1}) at **(a)** 10-m and **(b)** 200hPa. Plots are given at radii out to 1000km from the center of the storm with the initial times at the bottom of each plot.

Thirty-six hours prior to the completion of transition, a longwave midlatitude trough is noted to the northwest of the TC with a weak shortwave trough noted on its eastern periphery near 46°N, 80°W. At this time, however, the TC is largely intact vertically, as depicted by the vertical tower of PV near 38°N, 72°W.

At the completion of transition, the impacts upon the TC by the midlatitude trough and environment are evident. The distance between the shortwave trough and tropical cyclone has narrowed to the point where the two features are now nearly coincident. The upper-level structure of the tropical cyclone has eroded in response to the environmental forcing, leaving a lower-level vortex that tilts slightly to the north and west with increasing height, a feature of extratropical cyclones. After ET, the former TC continues towards the east over the North Atlantic Ocean, occluding and dissipating over the following days (as depicted in Figure 1).

From these analyses, it is apparent that the extratropical longwave trough provided the impetus to affect structural change upon the TC as a whole. Further analysis is required to understand the specific impacts upon the TC, however, and its impacts upon the TC wind field will now be examined.

3.2 *Momentum and wind field diagnostics*

Figure 3 depicts the time evolution of the wind field and its acceleration out to a radius of 1000km from the center of the storm at (a) 10m and (b) 200hPa. As the storm nears the completion of transition, an increase in the magnitude of the wind speed is noted, first at outer radii and progressing closer to the center of the storm shortly thereafter. The increase in wind speed is noted aloft about 6-12hr prior to the increase near the surface, suggesting the initial response of the storm to the midlatitude environment occurs at upper levels in advance of the approaching trough. The magnitude of the increase in winds is greatest aloft, something that is clearly shown by the time evolution of the non-storm-relative (i.e. normal) wind profile at 200hPa (not shown). It should be noted that the operational analysis data does not capture the deceleration of the wind field at inner radii as is seen during the transition process.

The distribution of absolute angular momentum through the storm cylinder and its difference from the vertical mean out to a radius of 1000km are depicted in Figure 4 at (a) 72hr prior to the completion of transition, (b) 36hr prior to the completion of transition, and (c) the time of ET completion. In the three days leading to transition, the destruction of the warm core of the TC vortex is clearly evident, where the profile of wind speeds decreasing with height (as evidenced by negative differences from the vertical mean at upper levels in Figure 4a) near the center transitions to one of wind speeds increasing with height (as seen by the positive differences from the vertical mean at upper levels in Figure 4c; see also $-V_T^L$ in Figure 1). The movement of these positive differences is also highlighted by increasing absolute angular momentum values aloft within the storm vortex, further highlighting the impacts of the midlatitude trough upon the TC as seen in figure 2. As before, the response aloft in both the momentum and vertical difference fields occurs shortly prior to that at the surface (not shown).

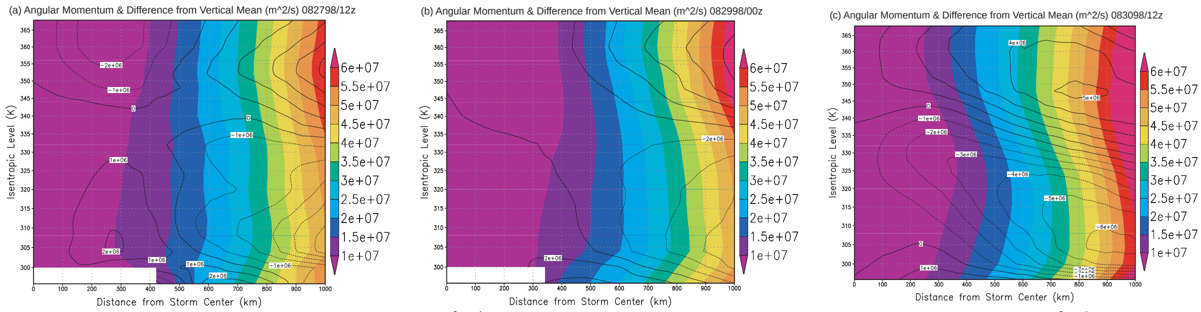

Figure 4: Absolute angular momentum (shaded; $m^2\ s^{-1}$) and its difference from the isentropic vertical mean (contoured; $m^2\ s^{-1}$) at **(a)** three days prior to the completion of transition, **(b)** 36 hours prior to the completion of transition, and **(c)** completion of transition.

3.3 *Eliassen-Palm diagnostics*

As previously mentioned, the E-P flux and its components give a comprehensive view of the dynamical (eddy momentum flux) and thermodynamical (eddy heat flux) factors influencing the TC as it undergoes ET. Since its divergence is directly related to an eddy PV flux, as noted by Molinari et al. (1995), it can also serve as a means as quantifying the direct impacts of the shortwave trough (Figure 2) upon the outer storm circulation.

Cylindrical views of the E-P flux divergence and its scaled components, the eddy momentum and heat fluxes, are presented in Figure 5 at (a) 36hr prior to the completion of transition and (b) at the completion of transition. Outward directed arrows denote inward cyclonic eddy angular momentum flux, while downward directed arrows denote outward eddy heat flux. It should be noted that despite the scaling employed within the figures, the momentum flux is generally two to three orders of magnitude larger than the heat flux; thus, these figures provide a representation of their relative components to the ET process and not their actual relative values.

Prior to the completion of transition (Figure 5a), a small region of positive PV flux is noted within the 324-332 K isentropic layers at radii of 1300-1500km. This is largely driven by vertical changes in the magnitude of the eddy heat flux, as depicted by the upward-pointing arrows at and above these levels. Given that this occurs just as the midlatitude trough is beginning to approach the warm-core TC (as seen in Figures 1 and 2), this denotes the initial impacts of the midlatitude trough upon the TC vortex, with the greatest impact felt as a slight weakening of the upper-level warm-core of the tropical cyclone due to inward-directed eddy heat flux at upper levels. This is in concurrence with the transition of the warm-core vortex into a cold-core vortex as depicted in Figure 4 with the time evolution of the radial profile of differences in momentum from the vertical mean.

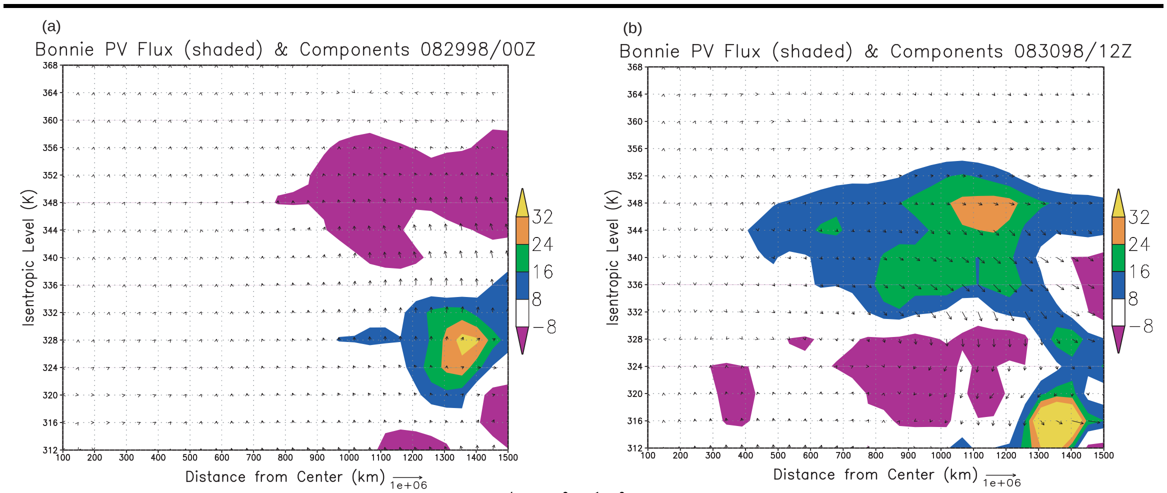

Figure 5: E-P flux divergence (shaded; increment of $8x10^4$ Pa $m^2\ K^{-1}\ s^{-2}$) and its scaled components at **(a)** 36hr prior to the completion of transition and **(b)** the time of the completion of transition. The eddy heat (vertical arrows; units: Pa $m^2\ s^{-2}$) and momentum fluxes (horizontal arrows; units: Pa $m^3\ K^{-1}\ s^{-2}$) are scaled according to Molinari et al. (1995; their figure 3).

By the time of the completion of transition (Figure 5b), however, inward cyclonic eddy momentum flux forcing dominates the environment of the storm at upper levels, leading to a large region of positive PV flux in the 332-348 K isentropic layer at radii of 600-1300km. The impact of the observed momentum fluxes is felt primarily in the secondary circulation of the transitioned TC, as the cyclone attempts to compensate for the destructive momentum forcing via an enhancement to all branches of its secondary circulation. This occurs in a manner similar to TC Elena in 1985 (Molinari et al. 1995), but at lower isentropic levels (as noted in the cold-core composite of Hart et al. 2005), leading to structural change of the cyclone. This is quantified once again by outward-directed eddy heat flux at outer radii.

4. CONCLUSIONS

A case of an extratropically transitioning TC in the North Atlantic, Bonnie of 1998, was selected for analysis. Analyses of the dynamical and thermodynamical properties of the storm were presented in an attempt to gain insight into the expansion of the wind field during the ET process.

The wind field was observed to accelerate within the outer circulation both near the surface and at upper levels in conjunction with an approaching midlatitude trough. This acceleration occurred first at outer radii, progressively moving inward through time, and occurred at upper levels shortly prior to occurring near the surface. Angular momentum profiles clearly depict the destruction of the warm core structure of the vortex with the approach of the midlatitude trough and further quantify the acceleration of the outer wind field. Eddy PV flux forcing, primarily dominated by cyclonic eddy momentum flux forcing at upper levels, was observed to move to progressively inner radii with the approach of the trough. Based upon the results presented by Molinari et al. (1995) and later applied to the ET process by Hart et al. (2005), this external forcing served to promote the enhancement of the secondary circulation of the transitioning TC. Adiabatic cooling in the vertical branch of the secondary circulation brought about the transformation into a cold-core vortex, while the relatively low isentropic level of the external forcing indirectly brings about the destruction of the upper-level TC vortex.

5. RESEARCH IMPLICATIONS

Based upon the results presented, a theory towards the expansion of the TC wind field during ET is proposed. As noted by Molinari et al. (1995), the effect of enhancing the secondary circulation within a TC leads to an increase in surface wind speeds, as shown with the rapidly intensifying TC Elena in 1985 in their work. For a storm undergoing ET, however, the environmental factors promoting rapid intensification are not present; specifically, the midlatitude trough does not narrow to match the scale of the TC vortex, nor are the underlying surface conditions favorable for tropical development (e.g. the wind-induced surface heat exchange mechanism of Emanuel (1986) is cut off). The result of the external forcing is thus to promote structural change within the transitioning TC and exacerbate the weakening process of the inner core of the TC over cooler waters.

As a consequence of the transitioning cyclone’s response to the extratropical environment and forcing, however, a means for understanding the expansion of the TC wind field during ET may be developed. As the PV and momentum fluxes move progressively inward from outer radii at upper levels with the approach of the trough, the wind field accelerates in response to these features and their impact upon the cyclone’s secondary circulation. This occurs first at outer radii and upper levels, moving to progressively inner radii and lower levels and is consistent with the wind field evolution depicted with Bonnie. Within the inner core of the TC vortex, however, wind speeds weaken during the ET process. This is a result of unfavorable underlying surface conditions for tropical development, consistent with the cut off of the WISHE mechanism over cooler waters.

As this occurs during the ET process, the acceleration of the outer wind field and deceleration of the inner wind field combines to effect a change in the environmental balance of the TC, taking it out of gradient and cyclostrophic wind balance and into geostrophic wind balance. Parcels no longer are stratified to momentum surfaces and are instead stratified to isentropic surfaces. Geostrophic adjustment processes occur at outer radii within the storm vortex to account for the increased environmental forcing, with the net effect of the adjustment process and environmental forcing upon the TC circulation being a flatter wind profile and increased radius of maximum winds.

This process is consistent with the hypotheses presented by Molinari et al. (1995) and Hart et al. (2005) as well as the results seen here with TC Bonnie. It should be stressed, however, that further analysis is needed to provide additional support for this hypothesis, as is outlined below.

6. FUTURE WORK

Further studies with regards to the hypothesis presented here are needed, ideally with high-resolution mesoscale modeling to better capture the inner-core processes that may play a role in the wind field evolution. Additional cases of transitioning storms of different post-transition evolutions (e.g. the composites of Hart et al. 2005) are needed to extend the results to all transitioning storms. Finally, as a means of improving the ability to forecast the wind field evolution, the potential vorticity diagnostic results presented here can be extended upon with piecewise PV inversion analysis (e.g. McTaggert-Cowan et al. 2001) to obtain the precise asymmetric wind field and better understand its evolution.

6. ACKNOWLEDGEMENTS

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