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DYNAMICS OF THE WIND FIELD EXPANSION WITH EXTRATROPICALLY TRANSITIONING TROPICAL CYCLONES

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1. INTRODUCTION

Extratropical transition (ET) events bring about many profound changes in the overall structure of a tropical cyclone (TC), such as in precipitation distributions, oceanic wave fields, and the structure and areal extent of the cyclone's wind field. Many of these structural changes have been the subject of previous research, such as that into features manifest during the transformation stage of ET by Klein et al. (2000) and Ritchie et al. (2001) or after ET has completed such as by Hart et al. (2006). However, the expansion of the wind field observed during ET events has remained an as yet unresearched phenomenon, with much of the discussion in the literature focusing solely on its occurrence and not upon why or how it occurs.

To date, two informal theories toward understanding the wind field expansion have been proposed. The first details the expansion as a function of the outward movement of air parcels from the center of the cyclone as the core of the hurricane collapses and cyclostrophic balance evolves to gradient balance. However, under constraints of absolute angular momentum conservation, unless the wind profile is inertially unstable, the outward movement of parcels will result in their deceleration (as a function of r^{-2}). The second theory details the expansion as a function of an increase in the Coriolis parameter and absolute vorticity conservation. However, absolute vorticity conservation implies that the vorticity far exceeds the divergence of the wind, which is not necessarily the case in the midlatitudes. Further, transitioning storms moving zonally still experience an expansion of the wind field, such that the observed change in the Coriolis parameter cannot account for the observed expansion. Thus, a gap exists in the understanding of this topic. The current research meshes tropical cyclone maintenance theories with baroclinic development ideas in an observational and dynamical modeling perspective to formulate an understanding of this wind field expansion process.

2. METHODOLOGY

Experiments are performed utilizing a typical ET evolution event, North Atlantic TC Bonnie (1998), as a case study. The non-hydrostatic Penn State/NCAR Mesoscale Model Version 5 (MM5; Dudhia 1993) is used to simulate the storm at 36km, 12km, 4km, and 2km resolution during the transition lifecycle (26-31 August 1998) as determined operationally by the NHC and using the cyclone phase space of Hart (2003). The model forecast of Bonnie is deemed to be sufficiently valid upon a comparison of forecast and observed surface synoptic fields and cyclone structure (e.g. Figure 1). Diagnostics are carried out utilizing an angular momentum and isentropic potential vorticity (PV) framework so as to understand the factors directly influencing the evolution of the wind field.

3. RESULTS

The wind field evolution associated with Bonnie through the ET process is noted in Figure 2. A clear expansion is noted primarily after timestep 30 (corresponding to 1800 UTC 30 August 1998, or 30 hours after initialization). A broad and subdued radial wind maximum is

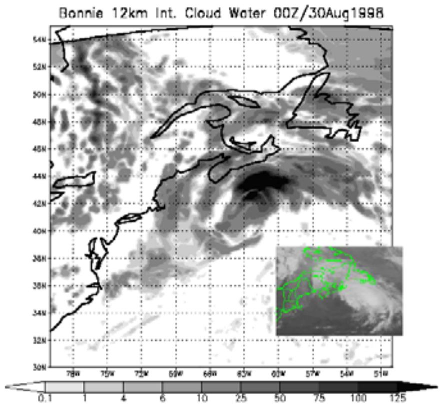

Figure 1: Integrated cloud water (units: cm) from the 12km MM5 simulation of Bonnie at 0000 UTC 30 August 1998 with a non-rotated satellite inset for comparison.

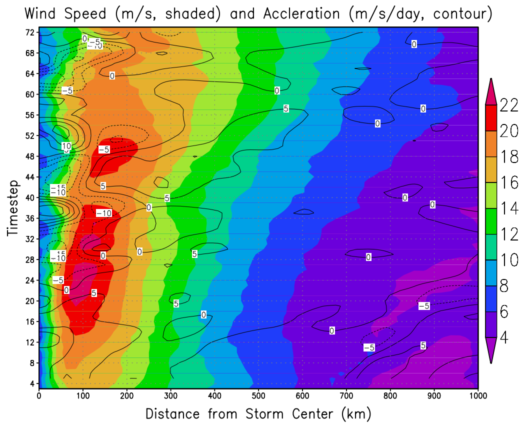

Figure 2: Radial plot to 1000km of the time evolution from 1200 UTC 28 August (bottom)-1200 UTC 31 August 1998 (top) of the wind field (shaded; m/s) and its acceleration (contoured; m/s/day) from the 12km MM5 Bonnie simulation.

noted at the completion of ET by Figure 3. The gradual decay of the inner wind field at later time steps is noted in association with the outward expansion of the wind field, implying a move into a region into unfavorable conditions for tropical cyclone maintenance. The timing of the wind field expansion – primarily after the completion of the transformation stage – agrees with the results of Ritchie et al. (2001). Indeed, an analysis of sea surface temperatures (SSTs) and vertical wind shear (not shown) shows that the storm traversed sub-20°C SSTs and >30 m s^{-1} 850-200hPa wind shear during the ET process. Given the dependence upon SSTs in the WISHE process (Emanuel 1986) and previous studies highlighting strong vertical wind shear as destructive upon TCs, it is likely that the cyclone is not developing from a tropical standpoint save for brief reintensification at early time steps as the TC moved from land to water.

In addition to the wind field expansion not resulting from the outward movement of parcels (confirmed by an informal trajectory analysis; Figure 5) or an increased Coriolis parameter (Coriolis magnitude increases by only 3.67% during the 24hr surrounding transition between 42-44°N), it is not a function of the mean zonal wind or increased translational speed adding into the wind field of the storm. The analyses presented here take into account these and all other non-dynamical influences upon the wind field of the cyclone. Furthermore, analysis of the 10m surface wind field outside of the storm from between 30-45°N shows no substantial increase in the mean zonal wind across the path of the cyclone (not shown). With no horizontal steering anomaly existing across the tropical cyclone, the factors at play in association with the expansion of the wind field in the context of these results are likely dynamical in nature.

Despite the decay of the inner core of the transitioning TC, some process is at play to bring about an outward expansion of the wind field 200-900km from the center of the cyclone. It is known that for a TC to even undergo ET, the distance between the regions favorable for tropical cyclone development and for baroclinic development must be sufficiently close such that the TC does not entirely decay before ET (Hart and Evans 2001). Using the Eady baroclinic growth rate (formulation from Hart and Evans 2001) as a proxy for the latter condition, Bonnie did move into a region sufficient for baroclinic growth during the ET process (Figure 4). To first order, it appears that the processes involved with the observed wind field expansion are of a baroclinic nature.

Such processes are likely associated with the external forcing upon a transitioning TC, generally in the form of a PV or cyclonic angular momentum source such as an upper-level trough of low pressure. Such forcings alter the secondary circulation balance in the cyclone from parcels following angular momentum surfaces to one where they follow isentropic surfaces as the storm encounters baroclinic gradients. This is highlighted by the trajectory analysis depicted in Figure 5, with isentropic descent (blue and pink trajectories) along the western side of the transitioning TC (e.g. Maue 2004 and references therein). Isentropic descent, both from the outside environment into the storm (blue trajectory) and within the storm's circulation itself (pink trajectory) as the accelerating storm does not allow the parcel to accelerate outward in the secondary circulation (unlike the green trajectory), serves to transport higher values of angular momentum from upper to lower levels, a process not possible as a TC due to its inherent structural characteristics.

To attempt to quantify the potential influences upon the transitioning TC of the baroclinic environment, the Eliassen-Palm (EP) flux and its related heat and momentum flux components are computed using the framework of Molinari et al. (1995). The EP flux divergence is a direct measure of the eddy PV flux forcing acting upon the storm. Figure 6 depicts the PV flux forcing and its components at 0600 UTC 30 August 1998, approximately six hours before the completion of ET and corresponding to the commencement of the wind field expansion over 250-600km radii. Substantial PV flux forcing is noted in the outflow layer of the storm (340-348 K isentropic levels) at radii greater than 400km. This forcing is largely dominated by an eddy cyclonic momentum flux, as denoted by outward directed arrows in this layer, the source of which is an upper-level trough of low pressure located to the northwest of the storm well prior to the completion of ET (Figure 6). This exhibits the culmination of a gradual inward progression of the external forcing from larger radii as the storm undergoes ET and highlights the expansion of the wind field as being a direct result of said external forcing.

Correlations to TC development can be drawn to understand the influence of this momentum forcing upon the transitioning TC. Molinari et al. (1995) draw upon the work of Shapiro and Willoughby (1982) to suggest that the rapid intensification of a TC under external forcing is due to the enhancement of the TC's secondary circulation to account for the momentum source. Molinari et al (1995) further extend upon these works to show that the external forcing brings about adiabatic cooling within the inner core of the cyclone to restore thermal wind balance, maximized at lower isentropic levels as compared to that seen with TC development.

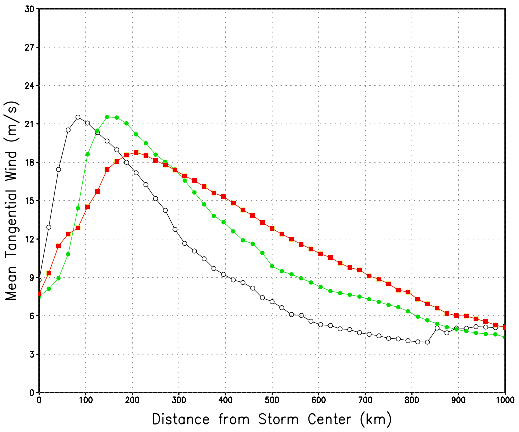

Figure 3: Tangential wind (m/s) profile at 0600 UTC 29 August 1998, prior to ET (black); at ET at 1200 UTC 30 August 1998 (green); and at 1200 UTC 31 August 1998, after ET (red), from the 12km MM5 Bonnie simulation.

Merging the two theories together, it is apparent that the external forcing both serves to bring about both inner-core structural change during ET as well as the expansion of the wind field. This is consistent with baroclinic energetics, as the momentum and PV sources noted within the EP diagram are an outgrowth of conditions favorable for baroclinic growth.

Put succinctly, the expansion of the wind field during ET is a function of the decay of the inner core of the tropical cyclone due to unfavorable underlying conditions for TC development and the enhancement to the cyclone's broader secondary circulation due to momentum and PV sources as the cyclone moves into a region favorable for baroclinic development. The weakening of the inner core brings about a flatter wind profile (as seen in Figure 3), while the baroclinic enhancement to the remnant TC circulation serves to complete the transition of the cyclone to an extratropical cyclone whereupon classical theories for cyclone development (e.g. baroclinic energetics, quasi- and semi-geostrophic diagnostics, and so on) are applicable. This baroclinic enhancement to the cyclone's secondary circulation results from the extraction of high values of angular momentum from the baroclinic environment (e.g. in the form of the fluxes noted in Figure 6) and their entrainment into the cyclone's circulation via isentropic descent at all levels along the western side of the circulation, ultimately serving to enhance the outer wind field. Weakening of the inner wind field is believed to be accomplished by a weakening of surface fluxes of heat and moisture over cooler SSTs and the loss of

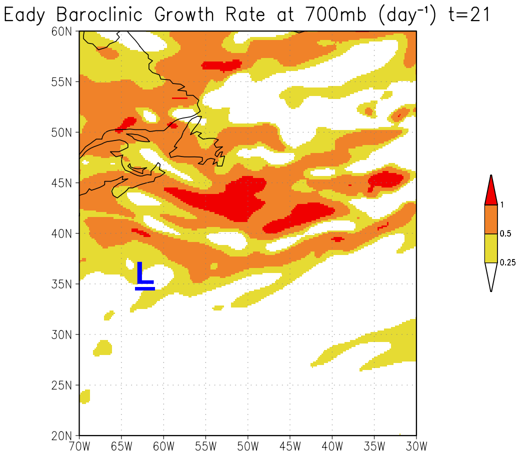

Figure 4: Eady baroclinic growth rate at 0000 UTC 29 August 1998 in the environment ahead of Bonnie during and after ET.

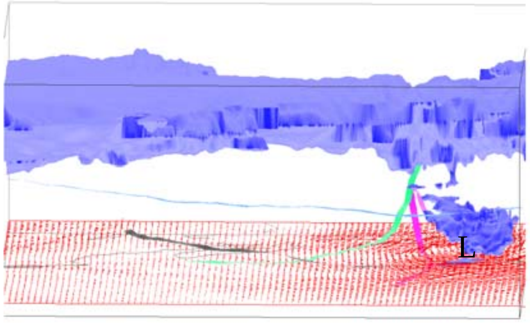

Figure 5: Vis5D trajectory analysis (ribbons) and the 30 m s^{-1} zonal wind isosurface (shaded) at 20:20 UTC 30 August 1998 from the 4km MM5 Bonnie simulation. The 'L' indicates the surface center.

angular momentum in the upward and outward branch of the cyclone's secondary circulation. The magnitude of the observed acceleration in the outer core is on the order of 2-5 m s^{-1}, while the overall magnitude of the weakening of the inner core for this case is of about the same magnitude. With a relatively slow drop off of the wind profile in the tropical stage, this 2-5 m/s increase has the effect of dramatically increasing the gale and storm force radii during ET.

4. FUTURE WORK

The results presented here will be expanded upon to include analyses of potential source and sink terms from the primitive momentum equations. Additional high-resolution trajectories will be computed to gain a better understanding of the shift in inertial balance within the transitioning TC from cyclostrophic to gradient and geostrophic balance and its potential implications toward the wind field expansion process. Sensitivities in the analyses will be explored to confirm the robustness of the results, specifically in terms of the post-ET evolution (into one of the paradigms of Hart et al. 2006) of the storm and how it potentially relates to the continued evolution of the wind field after ET. Such analyses will be presented in conjunction with the presentation at the conference.

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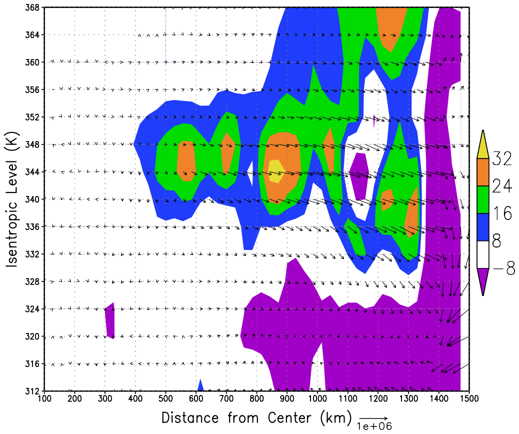

Figure 6: PV flux (units: 8x10^{-4} Pa m^2 K^{-1} s^{-2}; shaded) and its components (momentum flux: units of Pa m^3 K^{-1} s^{-2}, horizontal arrows; heat flux: units of Pa m^2 s^{-2}, vertical arrows) at 0600 UTC 30 August 1998 from the 12km MM5 Bonnie simulation.

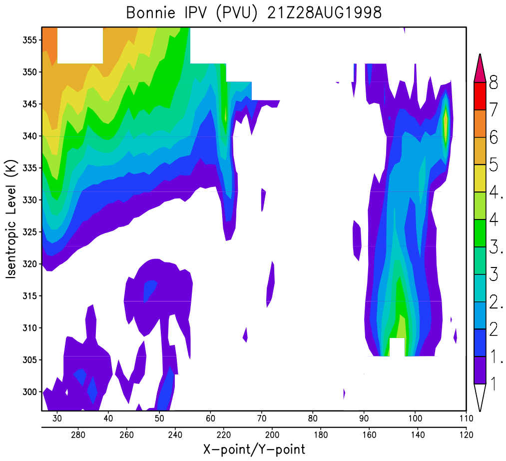

Figure 7: Isentropic PV (units: 10^{-6} K kg^{-1} m^2 s^{-1}) cross-section from northwest to southeast across Bonnie at 2200 UTC 28 August 1998, before ET the wind field expansion, from the 12km MM5 simulation.

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