ANALYSIS OF THE WIND FIELD EXPANSION ASSOCIATED WITH THE EXTRATROPICAL TRANSITION OF BONNIE (1998)

Clark Evans (acevans@met.fsu.edu)
Florida State University, Dept. of Meteorology, Tallahassee, FL

1. INTRODUCTION

The extratropical transition (ET) of tropical cyclones (TCs) is the process by which a TC transforms into an extratropical cyclone. ET is caused by the interaction of the TC with the mid-latitude baroclinic environment, characterized by increased vertical wind shear; meridional moisture gradients; decreasing sea surface temperatures (SSTs) and strong SST gradients; and increasing Coriolis (Jones et al. 2003). Resultant cyclone structure changes include the development of frontal structures (Harr and Elsberry 2000); right of track enhanced wave heights (Bowyer 2000); and asymmetric evolutions of the cloud, precipitation, and wind fields (Jones et al. 2003 and references therein).

Of particular interest is the wind field expansion associated with ET events characterized by two components: the outward movement of the radius of maximum winds (RMW; Jones et al. 2003) and a flattening of the azimuthally-averaged tangential wind profile as the wind field accelerates outside the RMW. Little research has been performed into understanding this phenomenon, with most attention paid to its occurrence (e.g. Ritchie and Elsberry 2001) rather than to its underlying causes. Further, informal hypotheses proposed to explain this evolution, including an increase of the Coriolis force and the movement of air parcels outward from the cyclone's center, do not fully account for the observed evolution during ET (Evans 2006). The former theory fails due to the conservation of absolute vorticity, where increasing Coriolis implies decreasing relative vorticity and ultimately decreased wind speeds; instead, absolute vorticity is not conserved as divergence in the mid-latitudes is typically large. The latter theory fails due to conservation of angular momentum as compared to the typical structure of a vortex under conditions of gradient wind balance. Thus, a disconnect exists between observing that the wind field expansion occurs and understanding why it does so.

The aim of this work is to understand the wind field expansion as a function of features influencing the ET process as a whole. Insight from tropical and extratropical cyclone development and evolution theories is utilized where appropriate to accentuate the expansion evolution.

2. METHODOLOGY

A representative case of ET in the North Atlantic basin is selected for analysis and experimentation – TC Bonnie of 1998 (Avila 1998). TC Bonnie provides an ideal case study owing to several desired parameters: a cold-core ET event – which account for 70% of North Atlantic ET events between 1998-2003 (Hart et al. 2006) – followed by the ultimate decay of the cyclone; an identifiable wind field expansion in both operational model analyses and NHC advisories (NHC 2007); and no decay or merger with another cyclone at the completion of ET (Avila 1998, their Figure 1).

Simulations of the cyclone are performed using the non-hydrostatic Pennsylvania State University/NCAR Mesoscale Model version 5 (MM5; Dudhia 1993), revision 3.7.2, at 36 km and 12 km horizontal grid spacing. The 12 km simulation is performed as a one-way nest from the 36 km simulation data and encompasses the time period between 1200 UTC 28 August 1998 and 1200 UTC 31 August 1998, or one day prior to the start of ET through one day after the completion of ET. The model simulation results are found to reasonably approximate the TC's intensity, structure, and track with primary differences arising due to slower cyclone motion in the simulations as compared to reality (not shown). Thus, it is argued that there is sufficient agreement with respect to the observed evolution of the cyclone during ET to not negatively impact the following presented analyses.

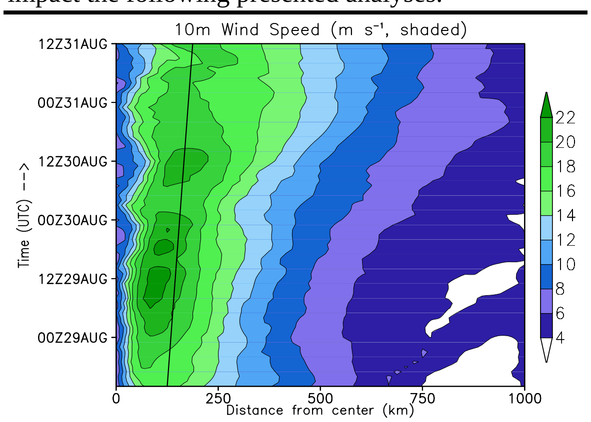

Figure 1: Azimuthally-averaged 10 m wind field (m s^{-1}) between 0-1000 km radius between 1200 UTC 28 August 1998 and 1200 UTC 31 August 1998.

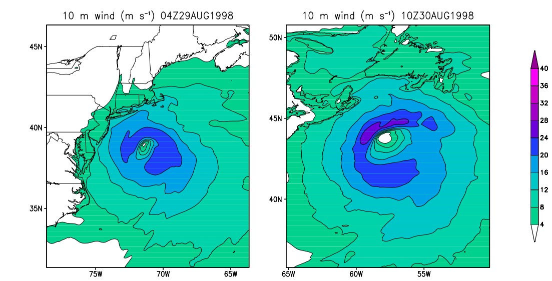

Figure 2: 10 m wind field analyses (m s^{-1}) at (a) 0400 UTC 29 August 1998, before ET, and (b) 1000 UTC 30 August 1998, at the completion of ET.

3. RESULTS

a. Evidence of expansion

Throughout the simulation period, clear evolutions of both the RMW and the acceleration of the wind field at outer radii are observed. Figure 1 depicts the evolution of the azimuthally-averaged 10 m wind field during ET. An outward displacement of the RMW of approximately 100 km is noted in conjunction with an acceleration of the wind field at outer radii (greater than 300 km radius) of approximately 4 m s^{-1} leading up to the completion of ET. A similar evolution to that at 10 m is noted on the 310 K (approximately 600-700 hPa) and 324 K (approximately 500-600 hPa) isentropic surfaces, albeit with a faster and more significant outer wind field acceleration and flattening of the cyclone's tangential wind profile (not shown).

Significant horizontal asymmetries are found within the wind field, as shown in Figure 2. At 10 m, an expansion of the storm-force (16-20 m s^{-1}) wind radii is noted in all quadrants during ET, with the most significant expansion noted to the right of the cyclone's motion. Similar evolutions are noted on the 310 K and 324 K isentropic surfaces (not shown). Note that these asymmetries are largely storm-motion independent (not shown) and that the overall wind field evolution is entirely storm-motion independent, as confirmed by the azimuthally-averaged evolution previously shown (Figure 1).

b. Outer core expansion

As a cyclone undergoes ET, it becomes increasingly asymmetric, resulting in increased radial flow both into and out of the cyclone associated with its primary circulation and potentially influencing the cyclone's wind field outside the RMW. This follows from both the conceptual model of ET of Klein et al. (2000) and the development of conveyor belt structures (e.g. Browning 1999). To attempt to quantify these structures and better understand the cyclone's circulation changes, trajectory analyses are computed in space and time (Figure 3) and clustered into three general evolutions.

These three clusters distinctly highlight the asymmetric airstreams that develop within the cyclone, including the warm conveyor belt (trajectories 3, 5, and 6), cold conveyor belt (trajectories 1 and 4), and dry intrusion (trajectory 2). Supporting evidence for these structures is provided by the atmospheric characteristics found in the simulation data with those airstreams. Specific features include descending, inflowing trajectories with lower equivalent potential temperature values behind the cyclone and low level ascent in a 25-40 m s^{-1} jet over a baroclinic zone with well-defined advection of higher equivalent potential temperature values east of the cyclone (not shown).

Given the interaction of the TC with a mid-latitude trough of low pressure and momentum source during ET events (Jones et al. 2003), it is hypothesized that these developing airstreams may transport momentum into the cyclone's circulation and lead to the observed outer core expansion. To attempt to test this hypothesis, the vertically-integrated angular momentum budget analysis of McBride (1981) is applied to the model simulation data. This budget is obtained from the equation:

$$(1) \qquad \frac{\partial}{\partial t}(m) = -\nabla \bullet \mathbf{V}m - RfV_R + RF_T$$

where m = RV_t, F_t is a frictional torque, and all other terms have their standard meteorological meanings. This equation is applied along a 500 km radius band from the center of the cyclone and averaged over a six hour period at all times.

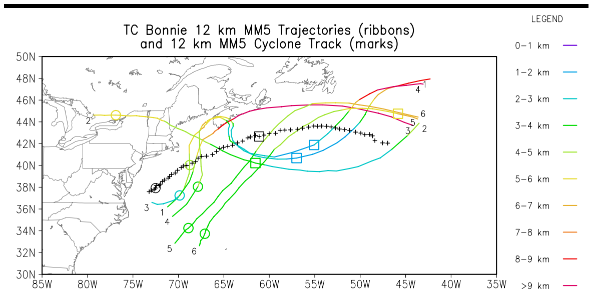

Figure 3: Trajectory analysis between 0000 UTC 29 August and 1200 UTC 31 August 1998. Color shading depicts the altitude (km) of the parcel, circles denote the parcel location at the start of ET, and squares denote the parcel location at the end of ET.

Table 1 depicts the results of the momentum budget analysis for three simulation data periods – at the start of ET (Bonnie1), at the end of ET (Bonnie2), and for a purely tropical model simulation case (TC

Case	Δt	Transport	Coriolis	Friction
Bonnie1	0.0	35.0	-9.8	-9.4
Bonnie2	0.0	27.7	-4.0	-11.7
Danielle	0.0	13.0	-2.9	-7.1
McBride D4	0.0	11.7	-3.5	-5.2

Table 1: Magnitudes of the four components (10^4 kg s^{-2}) of the angular momentum budget of McBride (1981) as applied to the 12 km simulation.

Danielle) – and the D4 "Atlantic Hurricane" composite of McBride (1981). The two Bonnie cases exhibit much greater momentum transport that not fully compensated for by increased Coriolis and frictional torques. Increased radial flow thus leads to a net import of angular momentum within the cyclone's circulation in conjunction with the outer wind field acceleration. As a result, this outer wind field evolution is a natural outgrowth of the increasingly asymmetric nature of the cyclone brought about by its interaction with the mid-latitude environment.

To understand the asymmetric wind field evolution, the horizontal momentum equation on isentropic surfaces of Shapiro (1975) is applied. This equation is given by:

$$(2) \qquad \frac{\partial}{\partial t}(\mathbf{v}) + \mathbf{v} \cdot \nabla_\theta \mathbf{v} - f\mathbf{k} \times \mathbf{v} + \nabla_\theta \psi = 0$$

where subscripts of Θ denote application on isentropic surfaces, ψ is the Montgomery streamfunction and equal to $gz+c_pT$, and boldface type denotes vector quantities. The magnitudes of each of the last three terms are directly computed while the time tendency term is calculated as the residual of the other three terms. Note that these fields are instantaneous snapshots of the cyclone. Cyclonically-directed components denote wind field accelerations per the convention on the first term in (2) and inward-directed components denote asymmetric (radial) evolutions within the wind field in these storm-centered analyses.

Figure 4 displays the magnitudes of these fields on the 310 K isentropic surface during ET. Displayed in the four panels are the advection term (upper left), Coriolis term (upper right), streamfunction term (lower left), and time tendency term (lower right). The advection and Montgomery streamfunction terms dominate the evolution, particularly where trajectories are clustered during ET (Figure 3) and where the horizontal wind fields experience their greatest changes (c.f. Figure 3 to Figure 2). This suggests that redistribution processes and the evolution of height and temperature gradients – the two varying components to the Montgomery streamfunction – beyond the RMW are causing acceleration to the wind field. Ultimately, as angular momentum is imported into the cyclone's outer circulation envelope along developing conveyor belts, temperature and height gradient fields adjust to compensate. As these belts develop via the superposition of environmental temperature and height gradients upon the transitioning TC, the net result is an acceleration of the outer core wind field and observed right-of-track asymmetry.

c. Inner core expansion

The outward movement of the RMW during ET may be viewed in a manner akin to intensifying tropical cyclones, where concentrated heating maximized inside the RMW causes it to contract (Shapiro and Willoughby 1982; Willoughby 1990). As the ET process is characterized by a transition from a warm-core to a cold-core vortex, similar yet opposite processes may be at play with the outward RMW motion. Following this, the methods of Shapiro and Willoughby (1982) and Willoughby (1990) are applied to the extratropical transition case to glean insight into this evolution.

Figure 5 depicts the azimuthally-averaged temperature tendency at 925 hPa near the completion of ET. Cooling is found within the inner core of the cyclone at this time and in the vertical mean (not shown) as the inner core cools at a faster rate than the outer core. Coincident with the inner core cooling, a weakening (strengthening) of the radial temperature gradient near and inside (outside) of the RMW is noted (not shown). This brings about the hydrostatic weakening (tightening) of the radial height gradient inside (outside) of the RMW (Figure 6). Ultimately, atmospheric and mass field adjustments occur due to the changes in the temperature field to attempt to restore and maintain hydrostatic balance.

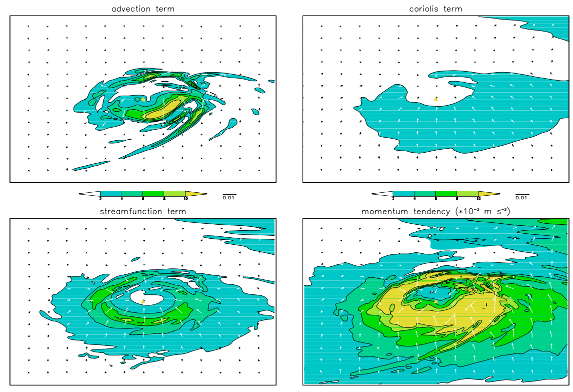

Figure 4: Analysis of the isentropic momentum equation (m s^{-2}) applied on the 310 K isentropic surface at 1000 UTC 30 August 1998. See text for a full discussion on interpreting this image.

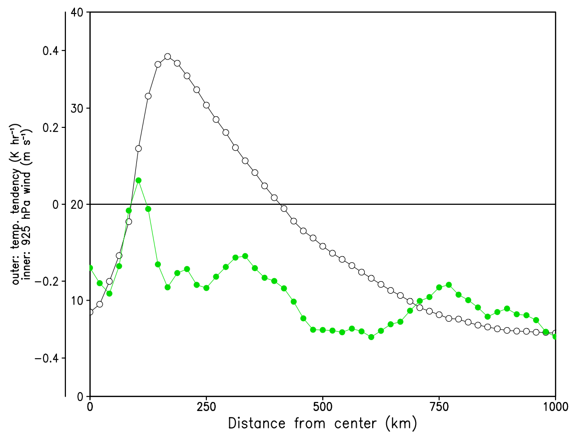

Figure 5: 925 hPa azimuthally averaged radial temperature tendency (K hr^{-1}, closed dots) and azimuthally averaged wind field (m s^{-1}, open circles) at 1000 UTC 30 August 1998.

The weakening of the radial height gradient inside of the RMW and a strengthening of the radial height gradient outside of the RMW leads to the observed outward reorientation of the RMW. With inner core cooling driving this evolution, the outward movement of the RMW associated with ET is thus a natural outgrowth of the transition into a cold-core vortex and is akin to a "reverse Sawyer-Eliassen" (Eliassen 1951) response. Further, this evolution is qualitatively similar yet opposite to the contracting eyewall intensification cases of Shapiro and Willoughby (1982) and Willoughby (1990).

d. Secondary circulation evolution

To understand the environmental influences bringing about the outward movement of the RMW plus gain further insight into the ET process as a whole, a baroclinic non-linear secondary circulation diagnostic model is applied. This model is based upon the formulation of Montgomery et al. (2006; their Section 7) and solves the elliptic PDE given by:

$$\frac{\partial}{\partial r}\left(\frac{N^2}{r}\frac{\partial\psi}{\partial r}-\frac{\bar{\xi}}{r}\frac{\partial\bar{v}}{\partial z}\frac{\partial\psi}{\partial z}\right)+\frac{\partial}{\partial z}\left(-\frac{\bar{\xi}}{r}\frac{\partial\bar{v}}{\partial z}\frac{\partial\psi}{\partial r}+\frac{\overline{\xi\eta}}{r}\frac{\partial\psi}{\partial z}\right)=\frac{\partial\bar{Q}}{\partial r}-\frac{\partial}{\partial z}(\overline{\xi F}) \quad (3)$$

where symbols used in (3) are as defined in Montgomery et al. (2006). In particular, $\bar{\xi}$ denotes the azimuthally averaged centrifugal stability, $\bar{F}$ denotes the momentum flux forcing, and $\bar{Q}$ denotes the heat flux forcing. Momentum and heat flux forcing used to force the model primarily comprise radial and vertical eddy vorticity and eddy heat fluxes, respectively.

Figure 7 depicts the flux-induced radial and vertical motion fields at 1000 UTC 30 August 1998. The secondary circulation of the cyclone is oriented such that the strongest rising motion is found along and just outside the RMW. Momentum flux forcing dominates over the heat flux forcing (not shown), a result consistent with the cold-core composite of Hart et al. (2006) with respect to their Eliassen-Palm flux formulation. A breakdown of its components shows that eddy vorticity fluxes about the RMW associated with its radial vorticity gradient dominate the momentum flux formulation (not shown).

Specifically, this momentum flux forcing induces radial flow above and below the forcing (e.g Shapiro and Willoughby 1982; Molinari et al. 1995) and leads to rising motion within the column near the RMW. The associated adiabatic cooling (Molinari et al. 1995; Hart et al. 2006) about the RMW suggests a reverse Sawyer-Eliassen (Eliassen 1951) evolution driven by the outward movement of the tightest radial temperature and height gradients. This results in changes to the location of the RMW (e.g. Figure 1) and to the regions of maximum horizontal convergence at low levels (not shown), leading to the outward relocation of the rising branch of the cyclone's secondary circulation.

4. CONCLUSIONS

Analysis of the wind field evolution associated with TC Bonnie shows that the acceleration of the outer wind field occurs due to the net import of absolute angular momentum along inflowing conveyor belt trajectories. Asymmetric compensating evolutions occur within the height and temperature fields of the cyclone's outer core as these airstreams develop, leading to the observed asymmetries in the outer wind field. Outward movement of the radial wind maximum occurs due to a secondary circulation response to relative cooling inside of the cyclone's RMW.

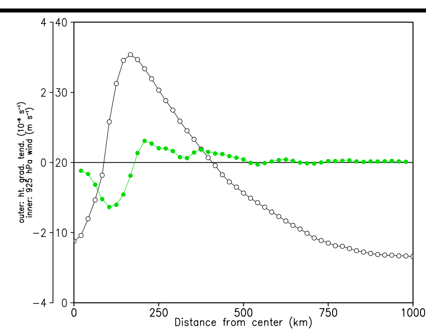

Figure 6: As in Figure 5, except closed circles now depict the 925 hPa azimuthally averaged radial height gradient time tendency (10^{-9} K m^{-1} s^{-1}).

Each evolution is a natural outgrowth of the ET process as a whole, particularly with respect to the development of frontal conveyor belt structures and inner-core cooling. The conveyor belts provide the mechanisms by which relatively warm air and momentum are transported into the outer envelope of the cyclone's circulation, particularly to the right of the cyclone's motion. The result is a significant acceleration to the lower level wind fields to the right of the cyclone's track and in the forward right quadrant of the cyclone (e.g. Figure 2) as the inner core cools. The relative integrated cooling within the inner core found with a cold-core ET event is argued to be a function of adiabatic cooling. With transitioning TCs, this adiabatic cooling is not able to be overcome in the former by surface heat fluxes over sufficiently warm SSTs (e.g. Emanuel 1986). Together, the end result of these processes is the outward movement of the RMW and flattening of the radially averaged tangential wind profile.

Finally, other post-transition evolutions than that which TC Bonnie followed are possible (Hart et al. 2006). Each potential post-transition evolution results from a unique synoptic environment with differences between each evolution largely due to the location, magnitude, and orientation of the transition-inducing feature(s) (Hart et al. 2006). As a consequence, each post-transition evolution may have a unique impact upon the evolution of the post-transition cyclone's wind field. These results may be extended in an attempt to understand these post-transition evolutions. Future work will attempt to explore these evolutions as well as tackle the broader question of the effects of material conservation changes upon the cyclone's structure.

5. ACKNOWLEDGEMENTS

This work was supported in part by a Risk Prediction Initiative grant (RPI-04-2-001) and by a Graduate Research Fellowship from the American Meteorological Society and the Office of Naval Research. The author greatly appreciates the guidance of his mentor, Bob Hart (Florida St. Univ.). The framework for the secondary circulation model was graciously provided by Paul Reasor (Florida St. Univ.) and suggested by Lance Bosart (Univ. at Albany). The author would like to thank Lance Bosart, Phil Cunningham (Florida St. Univ.), and T. N. Krishnamurti (Florida St. Univ.) for their constructive comments and suggestions. Chris Fogarty (Environment Canada) and two anonymous reviewers provided comments on the soon-to-be published manuscript from this work. All figures were created using the GrADS and Vis5d software packages.

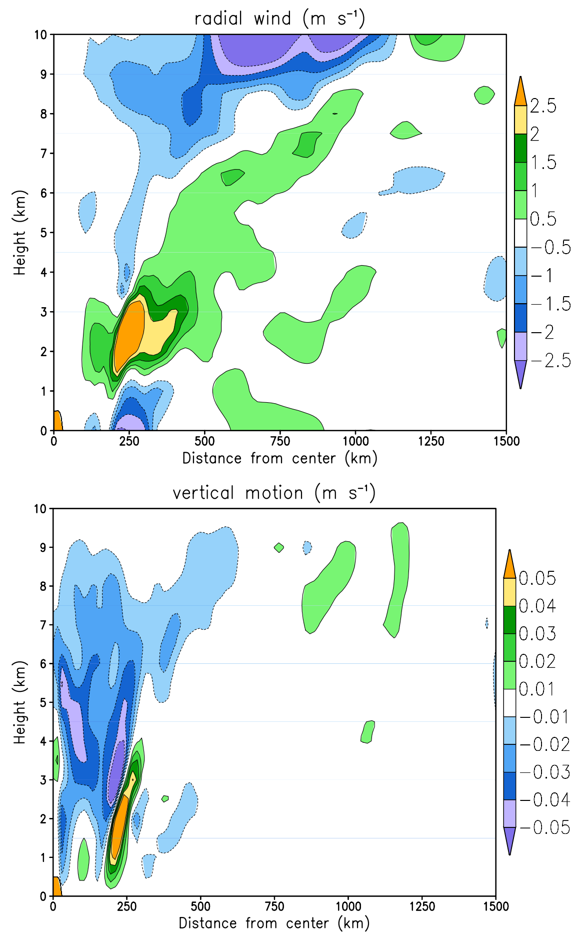

Figure 7: Radial (top, positive outward) and vertical (bottom, positive upward) motion fields diagnosed at 1000 UTC 30 August 1998 between 0-10 km in altitude and 0-1500 km in radial distance. Units on both are m s-1.

REFERENCES

Avila, L. A., 1998: Hurricane Bonnie Preliminary Report. [Available online at http://www.nhc.noaa.gov/1998bonnie.html].

Bowyer, P. J., 2000: Phenomenal waves with a transitioning tropical cyclone (Luis, the Queen, and the buoys). Preprints, *24th Conf. on Hurricanes and Tropical Meteorology*, Fort Lauderdale, FL, Amer. Meteor. Soc., 294-295.

Browning, K. A., 1999: Mesoscale aspects of extratropical cyclones: an observational perspective. *The Life Cycles of Extratropical Cyclones.* M. A. Shapiro and S. Gronas, eds., Amer. Meteor. Soc., 265-283.

Dudhia, J., 1993: A non-hydrostatic version of the Penn State/NCAR Mesoscale Model: Validation tests and simulations of an Atlantic cyclone and cold front. *Mon. Wea. Rev.*, **121**, 1493-1513.

Eliassen, A., 1951: Slow thermally or frictionally controlled meridional circulation in a circular vortex. *Astrophys. Norv.*, **5**, 19-60.

Emanuel, K. A., 1986: An air-sea interaction theory for tropical cyclones. Part I: Steady-state maintenance. *J. Atmos. Sci.*, **43**, 585-604.

Evans, A. C., 2006: Dynamics of the wind field expansion associated with extratropically transitioning tropical cyclones. M. S. thesis, Florida State University, 111pp.

Harr, P. A. and R. L. Elsberry, 2000: Extratropical transition of tropical cyclones over the western North Pacific. Part I: Evolution of structural characteristics during the transition process. *Mon. Wea. Rev.*, **128**, 2613-2633.

Hart, R. E., J. L. Evans, and C. Evans, 2006: Synoptic composites of the extratropical transition lifecycle of North Atlantic tropical cyclones: factors determining post-transition evolution. *Mon. Wea. Rev.*, **134**, 553-578.

Jones, S. C. and coauthors, 2003: The extratropical transition of tropical cyclones: forecast challenges, current understanding, and future directions. *Wea. and Forecasting*, **18**, 1052–1092.

Klein, P. M., P. A. Harr, and R. L. Elsberry, 2000: Extratropical transition of northwest Pacific tropical cyclones: an overview and conceptual model of the transformation stage. *Wea. and Forecasting*, **15**, 373-395.

McBride, J. L., 1981: Observational analysis of tropical cyclone formation. Part III: Budget analysis. *J. Atmos. Sci.*, **38**, 1152-1166.

Molinari, J., S. Skubis, and D. Vollaro, 1995: External influences on hurricane intensity. Part III: potential vorticity structure. *J. Atmos. Sci.*, **52**, 3593-3606.

Montgomery, M. T., M. E. Nicholls, T. A. Cram, and A. B. Saunders, 2006: A vertical hot tower route to tropical cyclogenesis. *J. Atmos. Sci.*, **63**, 355-386.

National Hurricane Center (NHC), cited 2006: National Hurricane Center Forecast Verification. [Available online at http://www.nhc.noaa.gov/verification/verify4.shtml].

National Hurricane Center (NHC), cited 2007: Hurricane Bonnie Advisories. [Available online at http://www.nhc.noaa.gov/1998BONNIEadv.html].

Ritchie, E. A. and R. L. Elsberry, 2001: Simulations of the transformation stage of the extratropical transition of tropical cyclones. *Mon. Wea. Rev.*, **129**, 1462-1480.

Shapiro, L. J., and H. E. Willoughby, 1982: The response of balanced hurricanes to local sources of heat and momentum. *J. Atmos. Sci.*, **39**, 378-394.

Shapiro, M. A., 1975: Simulation of upper-level frontogenesis with a 20-level isentropic coordinate primitive equation model. *Mon. Wea. Rev.*, **103**, 591-604.

Willoughby, H. E., 1990: Temporal changes of the primary circulation in tropical cyclones. *J. Atmos. Sci.*, **47**, 242-264.