P1.42: THE THERMODYNAMIC EVOLUTION OF EXTRATROPICALLY TRANSITIONING TROPICAL CYCLONES

Clark Evans
NCAR Earth System Laboratory, Boulder, CO
evans@ucar.edu

Robert E. Hart
Florida State University, Tallahassee, FL
rhart@fsu.edu

1. Introduction

The extratropical transition (ET) of tropical cyclones (TCs) is a well-studied phenomenon encompassing the transition of an initially warm-core, upright TC into an initially cold-core, tilted, baroclinic extratropical cyclone (Jones et al. 2003). An ET event brings about a number of changes within a TC, including but not limited to the development of frontal structures; expansions and asymmetric evolutions to the wind, wave, and precipitation fields; and a transition from tropical to extratropical cyclone energetics. The effects of ET events are significant and broad-reaching, ranging from effects upon short-term synoptic-scale weather patterns and the degradation of forecast skill (e.g. Harr et al. 2008; Archambault 2010) to contributions to global-scale phenomena (e.g. McTaggart-Cowan et al. 2007).

Among the changes brought about by the ET process, the transition of the TC from a warm to cold thermal structure is one that is less understood. The study of Sinclair (1993) is the only known work to date that directly addresses this problem while other works – Hart et al. (2006), McTaggart-Cowan et al. (2003; 2004) – pose hypotheses as to the physical and dynamical processes behind this evolution. These works suggest that adiabatic cooling near and the horizontal advection of cold air atop the transitioning cyclone's center of circulation overcome weak diabatic heating due to convection and precipitation. A net cooling rate of 3-5 K day^{-1} results, intensifying as ET progresses, bringing about the observed thermodynamic structure evolution of the transitioning cyclone. However, due to the relative coarseness of the data used in the study of Sinclair (1993) and the untested nature of the hypotheses of Hart et al. (2006) and McTaggart-Cowan et al. (2003; 2004), a comprehensive understanding of the factors influencing the thermodynamic evolution of a transitioning cyclone remains elusive.

As a result, the aim of this work is to conclusively quantify the factors that influence the thermodynamic evolution of a transitioning TC. In doing so, thermodynamic budgets from high resolution numerical model simulations are used in conjunction with observations and theory to physically describe this evolution. A full description of the methodology employed in this study may be found in the following section. Results from this work may be found in Section 3, followed by a discussion of the results and their implications in Section 4. Conclusions are presented in Section 5 and are followed by acknowledgments and references.

2. Methodology

A case study methodology is utilized in this work owing to its applicability to an observed ET event. The primary case selected for study is the ET of TC Bonnie of 1998 (Pasch et al. 2001). TC Bonnie was a fairly typical north Atlantic TC, forming in the basin's main development region, reaching peak intensity as it began recurvature, and ultimately undergoing ET over the open waters of the northern Atlantic Ocean. More importantly, the ET of TC Bonnie also represented a fairly typical north Atlantic ET event.The ET of TC Bonnie was characterized by no land interaction, no merger with another extratropical cyclone during ET, and the gradual decay of the vortex after ET with a cold-core thermal structure. This evolution, as noted by Hart et al. (2006), accounted for approximately 75 % of north Atlantic basin ET events during 1998-2003, thus fostering confidence in the applicability of the findings from this case to the larger ET paradigm as a whole. Studies of other tropical, extratropical, and ET events are also conducted to conclusively describe the temporal evolution of the thermodynamic structure of a transitioning TC.

To study these cases, a numerical simulation approach is employed. We note that the lack of an in situ thermodynamic data set from a transitioning TC means that true verification of the model simulation-based results presented in this study is currently impossible. Simulations are carried out using a triply nested domain (36/12/4 km) within the non-hydrostatic Penn State/NCAR Mesoscale Model version 5 (MM5; Grell et al. 1995). Focus in the results presented below is on the output from the 4 km simulation immediately prior to, during, and after the ET event.

The primary means of analyzing the output from these simulations is through the use of thermodynamic budgets, as in the study of Zhang and Bao (1996). These budgets conform to a modified form of the MM5 thermodynamic equation from Dudhia (1993), given by:

$$\frac{\partial T}{\partial t} = -v \bullet \nabla T + T(\nabla \bullet v) + \left.\frac{\partial T}{\partial t}\right|_{parameterizations} \quad (1)$$

In (1), “parameterizations” include temperature tendencies from convection (36 and 12 km only), diffusion, microphysics, planetary boundary layer, radiation, and shallow convection. The first term on the right hand side of (1) is a three-dimensional advection term while the second term is a divergence or adiabatic cooling term. Specifics regarding the computation of each term of (1) and slight variations in (1) from the form given by Dudhia (1993) may be found in Evans (2009).

3. Results

3.1 Symmetric Evolution

In describing the total thermodynamic evolution of the ET of TC Bonnie, we first describe the symmetric or azimuthally-averaged evolution. Figure 1 depicts the vertically-integrated, azimuthally- and radially-averaged (inside 500 km) total temperature tendency from the 4 km simulation. At the start of the simulation, as the TC still exhibits a warm-core structure and is traversing the western periphery of the Gulf Stream, a steady-state thermal structure of the vortex is observed. As the cyclone begins the ET process early on the 29th of August, however, weak cooling begins to erode the warm-core structure. At and after the time where ET nears its completion early on the 30th of August, this cooling further increases in magnitude, corresponding well to the lower tropospheric thermal wind trajectory of the simulated cyclone within the cyclone phase space of Hart (2003; not shown).

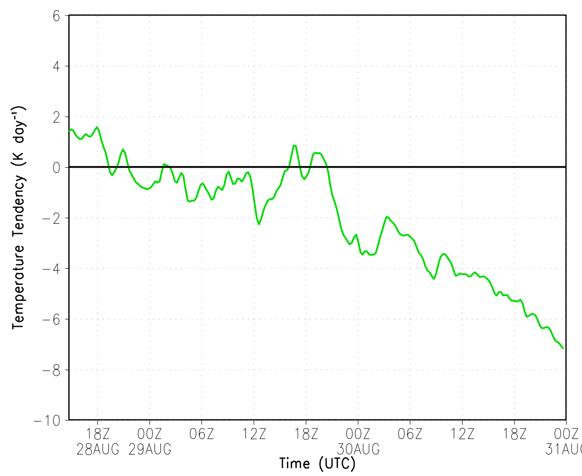

Figure 1: Vertically-integrated, spatially-averaged (inside 500 km radius) total temperature tendency (K day^{-1}) from the 4 km TC Bonnie MM5 simulation between 1200 UTC 28 August 1998 and 0000 UTC 31 August 1998.

The net result is a temporally-integrated cooling of approximately 6 K, a magnitude that is consistent with the 2-3 K day^{-1} rate shown by Sinclair (1993).

The dynamical/adiabatic and parameterized/diabatic contributors to this total temperature tendency are depicted in Figure 2. A dynamical cooling rate of approximately 10 K day^{-1} is offset early in the simulation by a diabatic heating rate of approximately 10 K day^{-1}. As ET progresses, however, the magnitude of the diabatic heating decreases, resulting in the observed net inner-core cooling shown in Figure 1. The contributors to these dynamical and parameterized temperature tendencies are depicted in Figure 3. A near balance between the microphysical and divergence/adiabatic cooling tendencies is observed, leading to the total temperature tendency increasingly resembling that due to advective processes as ET progresses. The importance of cold thermal advection is in line with the hypotheses of Sinclair (1993) and McTaggart-Cowan et al. (2003; 2004).

The temporally-integrated vertical structure of the thermodynamic evolution is shown in Figure 4. Net cooling of the inner core of the transitioning TC is maximized aloft and in the boundary layer with minimal changes in the middle troposphere. As was observed with the vertically-integrated evolution in Figure 3, the vertical structures to the adiabatic cooling and microphysical tendencies nearly balance, resulting in advectional and radiational cooling

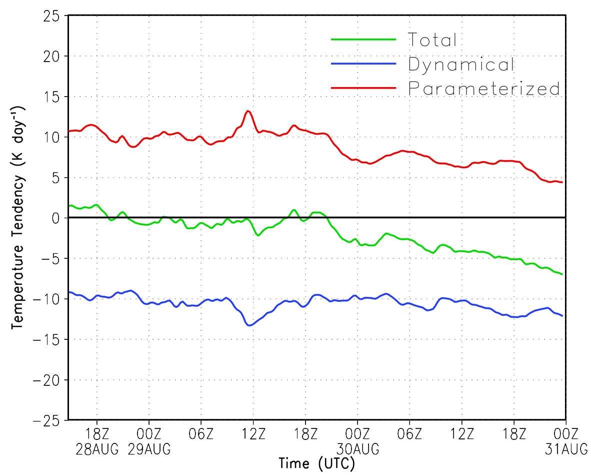

Figure 2: As in Figure 1, except for the total (green line), dynamical (blue line), and parameterized (red line) temperature tendencies.

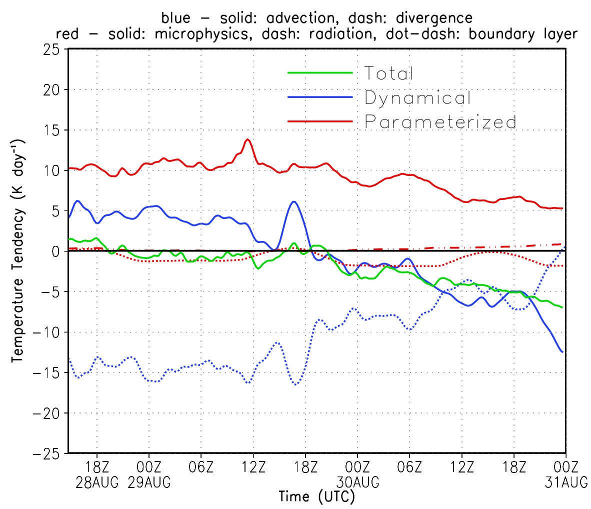

Figure 3: As in Figure 2, except for the significant components to the total, dynamical, and parameterized temperature tendencies.

dominating the vertical structure of the total thermodynamic evolution (not shown).

The radial structure to the azimuthally-averaged evolution is depicted in Figure 5. Weak heating inside of 100 km radius is noted through the middle of the ET process. Weak cooling between 50-150 km radius begins near the onset of ET around 0000 UTC on the 29th of August and gradually expands both radially inward and outward as ET progresses and ultimately completes on the 30th of August. Note that much of this cooling is found inside the radius of maximum winds of the transitioning cyclone, or inside

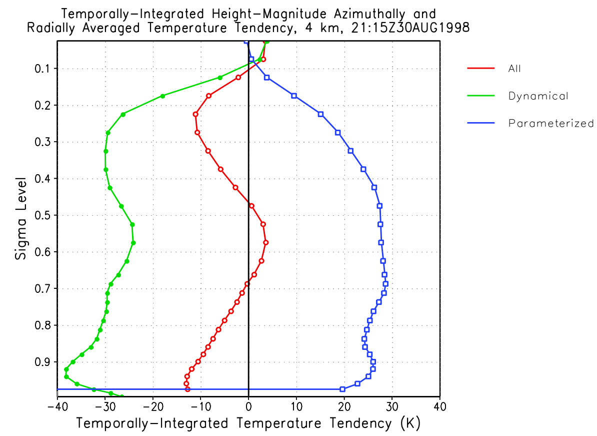

Figure 4: Vertical structure to the temporally-integrated (until 2115 UTC 30 August 1998), spatially-averaged total (red line), dynamical (green line), and parameterized (blue line) temperature tendencies (K day^{-1}) from the 4 km TC Bonnie MM5 simulation.

of 175-200 km radius during and after the ET process, providing evidence to support the hypothesis of this cooling driving the outward movement of the radial wind maximum posed by Evans and Hart (2008). The adiabatic/dynamical and diabatic/parameterized contributions to this radial structure are depicted in Figures 6 and 7, respectively. Both the dynamical cooling and diabatic warming gradually expand outward as the cyclone's circulation expands during the ET process with a slight preference for cooling increasing as ET draws to a close.

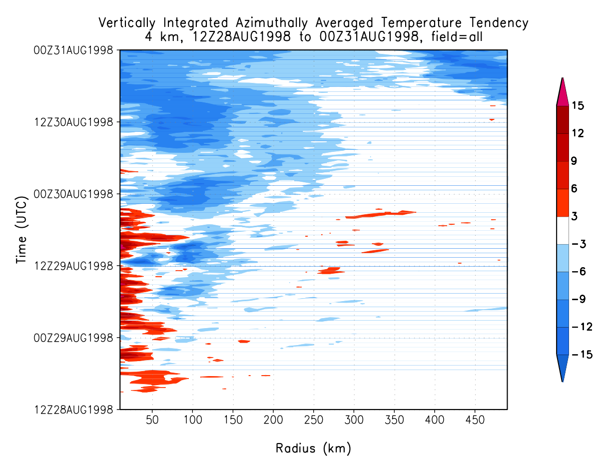

Figure 5: Vertically-integrated, azimuthally-averaged total temperature tendency (K day^{-1}) radial structure between 1200 UTC 28 August-0000 UTC 31 August 1998.

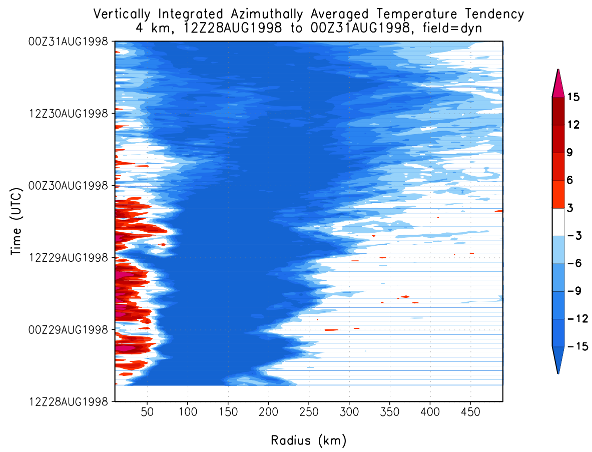

Figure 6: As in Figure 5, except for the dynamical component to the total temperature tendency.

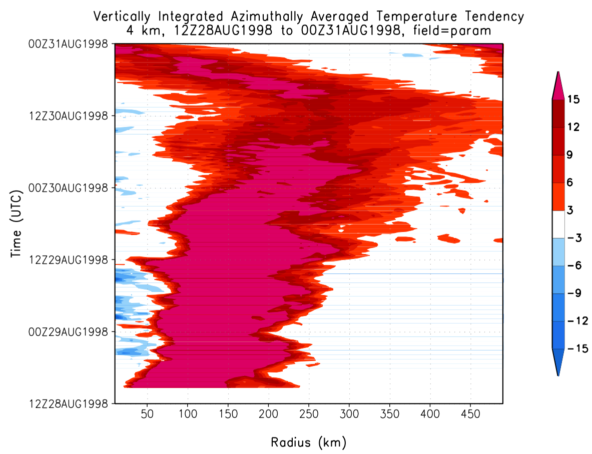

Figure 7: As in Figure 5, except for the parameterized component to the total temperature tendency.

As before, latent heat release due to condensation in areas of precipitation dominates the diabatic heating contribution but is again nearly balanced by adiabatic cooling. Note that the impacts of weak 1-2 K day^{-1} radiational cooling near the center of the transitioning cyclone are more apparent in this view than in the spatially-averaged fields presented previously (not shown).

3.2 Asymmetric Evolution

We now turn to describing the significant asymmetric component to the total thermodynamic evolution. First, the asymmetric thermodynamic structure obtained during the ET process is examined (Figure 8). Near the beginning of ET (Figure 8a), the vertically-averaged potential temperature field is approximately 0.5 K warmer upstream of the vortex as compared to downstream. As ET completes (Figure 8b), this anomaly has grown to approximately 3 K and has rotated cyclonically around the vortex to a position due south of the vortex's center of circulation. This asymmetric structure is also depicted by the evolution of the thermal asymmetry parameter (B) in the cyclone phase space trajectory of TC Bonnie, highlighting an increasingly asymmetric thermal structure to the vortex in the lower-to-middle troposphere that favors warmer conditions in the right-of-track hemisphere (not shown).

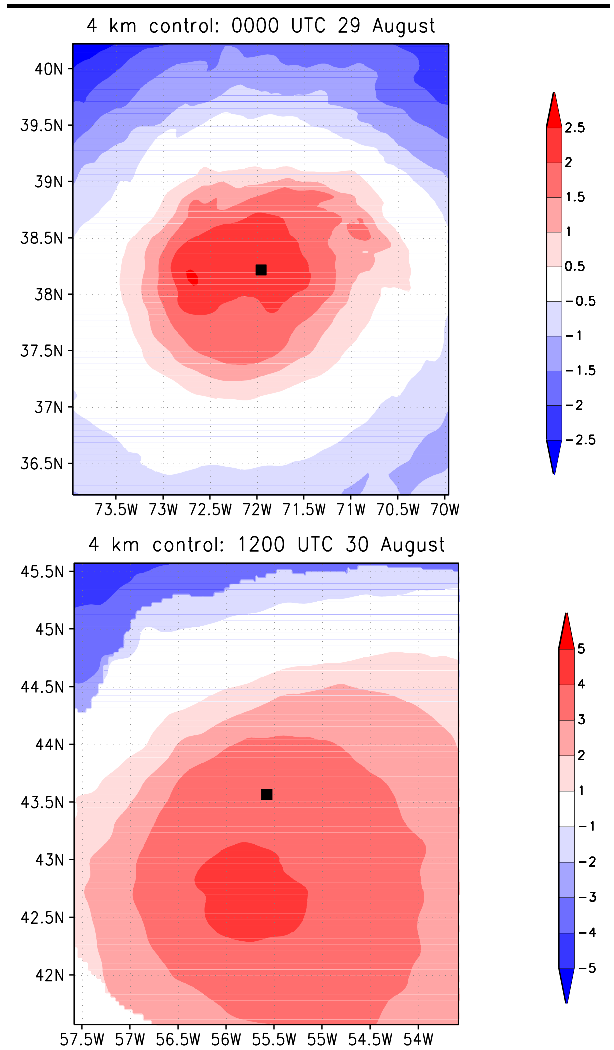

Figure 8: (a, top): Vertically-averaged potential temperature anomaly (K) from the vertical (1000-300 hPa) and spatial mean at 0000 UTC 29 August 1998 from the 4 km TC Bonnie MM5 simulation. (b, bottom): As in (a), except at 1200 UTC 30 August 1998.

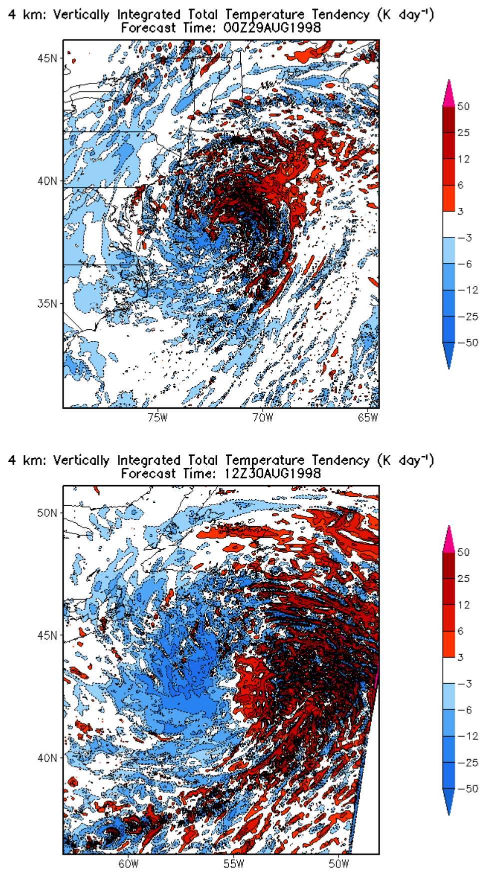

Figure 9: Spatial structure to the total temperature tendency (K day-1) at (a, top) 0000 UTC 29 August 1998 and (b, bottom) 1200 UTC 30 August 1998 from the 4 km TC Bonnie MM5 simulation.

Next, the vertically-integrated spatial structure to the total temperature tendency is depicted in Figure 9. At the beginning of ET (Figure 9a), the total temperature tendency field exhibits a wavenumber one pattern with net heating (cooling) found downshear (upshear) of the vertical wind shear vector. This opposes the anomaly structure observed in Figure 8a. This wavenumber one structure is maintained through ET (Figure 9b) as the spatial extent of both the heating and cooling tendencies expands radially outward from the center of circulation at the surface. This structure, even after the completion of ET, continues to be out of phase with the anomaly structure observed in Figure 8b, the causes behind which are uncertain. Contributions from the diabatic and adiabatic components to this evolution are depicted in Figures 10 and 11 respectively. Latent heat release due to condensation, as obtained from the microphysical parameterization, dominates the diabatic tendency (not shown). The heating associated with these precipitation processes downstream of the cyclone in its “delta rain” region (Klein et al. 2000) is largely offset by dynamical cooling primarily associated with adiabatic cooling processes (not shown). Outside of this region, dynamical warming and cooling processes dominate the total thermodynamic evolution’s structure with warming (cooling) observed downstream (upstream) of the cyclone. This pattern closely resembles that which arises due to horizontal advection and is obtained out of the balance between horizontal advection and the vertical advection and adiabatic cooling terms (not shown).

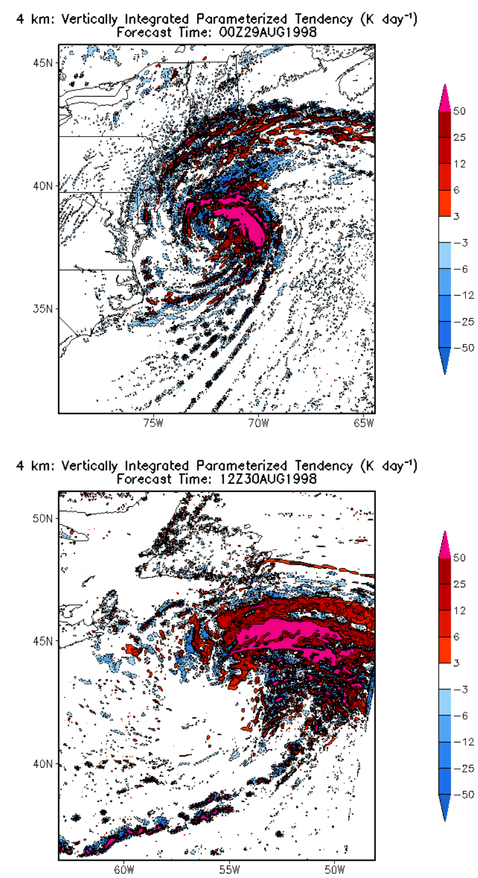

Figure 10: As in Figure 9, except for only the parameterized component to the total temperature tendency.

This balance favoring advection and adiabatic cooling processes serves to confirm the hypotheses posed by the previous works listed in Section 1 as well as that of Jones (1995). Further discussion of these results in the

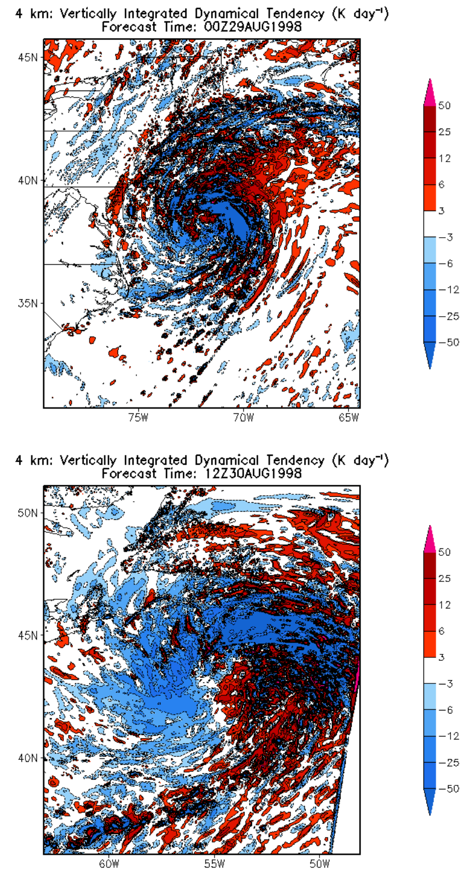

Figure 11: As in Figure 9, except for only the dynamical component to the total temperature tendency.

context of the work of Jones (1995) is presented in Section 3.4.

Future work aims to more conclusively describe the asymmetric component to the thermodynamic evolution by partitioning the total temperature tendency and its components into right-of-track and left-of-track components. This will allow for the quantification of the vertically-tilted asymmetric thermodynamic structure that develops as a result of the ET process and insight into the causes behind the thermodynamic evolution and trajectory a cyclone takes through the cyclone phase space of Hart (2003).

3.3 Physical Discussion

The thermodynamic evolution associated with the ET process described in the previous two sections is believed to be a natural outgrowth of the factors that influence or accompany ET as a whole. We now consider the physical mechanisms associated with the ET process and apply them to understand the tendencies contributing to the cyclone's thermodynamic evolution. Latent heat release contributing to this evolution largely arises out of condensational warming in the diffluent "delta rain" region found downshear of the cyclone. As ET progresses, this latent heat release both moves radially outward from the center of circulation and decreases in magnitude. This is due in part to the suppression of convection and precipitation in the upstream semicircle of the cyclone due to descent along its developing dry intrusion (Browning 1999; Figure 5 of Klein et al. 2000) as well as to the downstream movement of the diffluent 'delta rain' region as the cyclone's circulation expands. Supporting evidence for this evolution is provided by the evolution of the area-integrated cloud water and precipitation rate fields from the 4 km simulation (not shown). Next, as a TC undergoes ET, the magnitude of the surface heat fluxes that it draws from the underlying oceanic surface significantly weakens (Jones et al. 2003). During the tropical phase, these fluxes, as transported vertically by convection, are more than sufficient to overcome the cooling effects of adiabatic cooling. During the transition and extratropical phases, however, this is no longer true, though the magnitude of the adiabatic cooling also weakens as convection and precipitation decay (e.g. Figure 3). Finally, from a dynamical perspective, the evolving conveyor belts or air streams (Browning 1999) associated with the transitioning TC exhibit both significant vertical and radial structure (Klein et al. 2000), allowing for the transport of thermal energy both radially and vertically about the cyclone. While still a tropical cyclone, this transport favors the horizontal transport of warmer air, presumably from the tropics (not shown). As the cyclone undergoes ET, however, this balance progressively favors the horizontal and vertical transport of colder air as the cyclone enters a cooler mid-latitude environment and its cold conveyor belt and dry intrusion mature (e.g. Figure 8a of Evans and Hart 2008). In the following section, we expand upon the idea that the thermodynamic evolution is a natural outgrowth of the factors that influence ET as a whole by considering the impacts of vertical shear on this evolution.

3.4 Contribution from Vertical Shear

The idealized works of Jones (1995, 2000a,b) depict the impacts of vertical wind shear on TC-like vortices, particularly in terms of their vertical or secondary circulations. Associated with these vertical circulations are spatial and vertical asymmetries in the potential temperature fields of the vortices, as depicted in Figure 12 of Jones (2000b). Since the structural evolution associated with an ET event can be described as the result of a TC's interaction with vertical wind shear, it stands to follow that the thermodynamic structural evolution observed during an ET event may be significantly modulated by the direct and indirect effects of vertical wind shear upon the vortex.

The results presented to this point describe the thermodynamic evolution of the TC Bonnie vortex as it underwent ET in a full physics framework. Conversely, the idealized works of Jones (1995; 2000a,b) describe the evolution of the vortices in a hydrostatic, adiabatic framework. To aid in understanding how the processes described by the Jones (1995; 2000b) works are manifest in the total thermodynamic evolution obtained from the full physics simulation, a "fake dry" MM5 simulation is conducted at a horizontal grid spacing of 4 km. The only difference from this simulation to the "control" 4 km simulation is that the temperature tendencies associated with microphysical and shallow convective processes are not allowed to influence the total temperature tendency. As opposed to conducting a simulation where microphysical and shallow convective parameterizations are not employed, this method has the advantage of allowing the simulated moisture fields to evolve in a physically realistic manner (G. Bryan 2010, personal communication). Owing to these changes, the thermodynamic evolution of the transitioning TC captured by this simulation is comprised almost exclusively of shear-related dynamical processes with minor contributions from shortwave and longwave radiation.

The vertically-integrated, spatially-averaged temperature tendency fields from this "fake dry" simulation are depicted in Figure 12. A net cooling of 2.1 K during the simulation period is observed, approximately 35% of that observed in the control simulation. Apart from the radiative cooling rate of 1-2 K day^{-1}, the component contributors to this evolution are weaker in magnitude than their counterparts in the control simulation. This leads to a weaker thermodynamic asymmetry in this simulation than in the control case (not shown). Given that the vortex in this simulation is much weather than in the control simulation (not shown), this is consistent with the idea that the thermodynamic response required to maintain balance is weaker for a weaker vortex under constant vertical shear conditions than

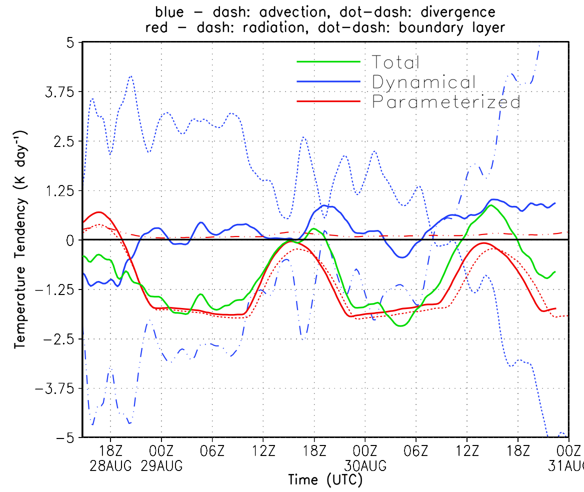

Figure 12: As in Figure 3, except for the 4 km "fake dry" MM5 TC Bonnie simulation.

for a stronger vortex (Jones 1995). As implied by the previous statement, however, the most striking difference between the control and "fake dry" simulations appears in the evolution of the intensity and structure of the vortex itself. In the "fake dry" simulation, the simulated TC Bonnie vortex rapidly undergoes ET and weakens, becoming indistinct from the mid-latitude flow on the 29th of August (not shown). The differences between the vortices in the two simulations are well-captured by vertical cross-sections of potential vorticity with a substantially weaker and shallower vortex in the "fake dry" simulation as compared to the control simulation (not shown). This implies that in an environment of moderate to strong vertical shear, diabatic heating is required to maintain the vortex through the ET process, in line with the findings of Davis et al. (2008).

Additionally, Jones (1995) explored the viability of three hypotheses posed by Raymond (1992) relating to the development of potential temperature asymmetries associated with vortices in vertical shear. Under adiabatic conditions, they found that the key factors driving the development and evolution of potential temperature asymmetries about the vortex were the vertical tilt of the vortex, modulated at first by environmental shear and later by internal vortex interactions, and cyclonic vortex flow through the potential temperature anomalies that arise out of the vortex's tilt. Vertical and horizontal temperature advection, respectively, are shown to be the means by which these anomalies are achieved. Jones (2000b) noted that an additional mechanism, one related to the thermal wind structure of the vortex, may also play a role in modulating these asymmetries. Current work is aimed at quantifying the roles of these mechanisms along with the role of the vortex's interaction with the environmental potential temperature gradient in contributing to the total thermodynamic evolution observed during the ET of TC Bonnie.

Preliminarily results show that the magnitude and movement of the potential temperature asymmetries observed in the control simulation are similar to that shown by Jones (2000b; c.f. Figure 8 to their Figure 12). Furthermore, similar qualitative patterns in the vertical (cooling downstream, warming upstream) and horizontal (warming downstream, cooling upstream) temperature advection patterns are noted in the control case to those implied by Jones (2000b). Indeed, the evolution of the thermal advection contribution to the total temperature tendency closely mirrors that of the total temperature tendency as a whole during the ET process (Figure 3). These findings all suggest that a large portion of both the asymmetric and net thermodynamic evolution during ET may be explained solely by the effects of vertical wind shear upon the vortex, i.e. that the thermodynamic evolution is largely an adiabatic rather than a diabatic process (akin to the findings of Wang et al. 1993). That said, non-insignificant contributions to the total thermodynamic evolution from diabatic processes are still observed and, as the results from the "fake dry" simulation show, are necessary to allow the vortex to be maintained through the ET process. Furthermore, significant differences appear with the structure of the secondary/vertical circulation of TC Bonnie as described by Evans and Hart (2008) as compared to the idealized vortex in Jones (1995), particularly in terms of its vertical extent. A more detailed analysis is currently being pursued and is expected to provide clearer insight into precisely how much of this evolution can be attributed to the effects of vertical wind shear alone.

4. Discussion

4.1 Sensitivity to Horizontal Grid Spacing

Operationally, most forecasts of ET events are conducted at a horizontal grid spacing of 20-40+ km, much coarser than the horizontal grid spacing of 4 km employed in the primary simulations performed in this work. Though the thermodynamic evolution appears to largely be modulated by synoptic-scale influences that govern the ET process as a whole, the diabatic heating contribution is represented within the simulated cyclone as a parameterized process and thus potentially introduces sensitivities in the evolution to the horizontal grid spacing employed within the model simulation. To quantify this effect, the budget output from the 36 and 12 km simulations of TC Bonnie is analyzed and compared to that from the 4 km simulation. Before delving into the results, it should be noted that the 12 and 4 km simulations are initialized as nests of the 36 km and 36/12 km simulations, respectively, meaning that each simulation is not fully independent from the others. Thus, it is possible that the differences shown below may not capture the full degree of variability that could potentially arise out of horizontal grid spacing differences alone.

Figure 13 depicts the total, dynamical, and parameterized contributions to the total temperature tendency from the 36, 12, and 4 km simulations of TC Bonnie. Qualitatively, the same general evolution is observed at 12 km and 36 km grid spacing as at 4 km grid spacing: a gradual increase in the simulated cooling rate as the dynamical cooling contribution remains fairly steady and the parameterized diabatic heating contribution slowly weakens. There is some tendency, however, for the parameterized diabatic heating rate to be weaker with coarser grid spacing, resulting in a slightly faster acceleration of the net cooling rate during the ET process on the 29th and 30th of August.

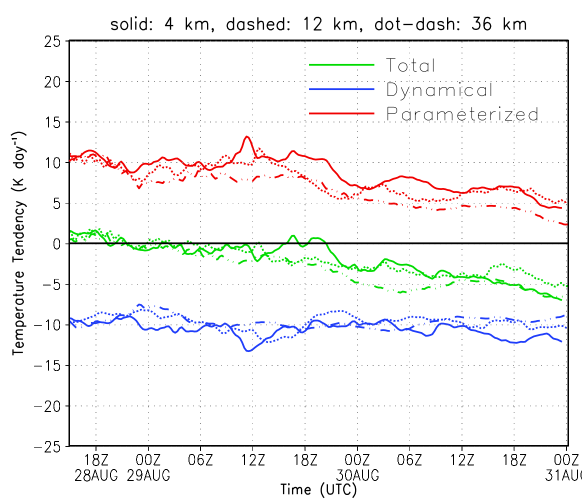

Figure 13: As in Figure 2, except for the 36 km (dot-dash), 12 km (dashed), and 4 km (solid) MM5 TC Bonnie simulations.

The primary contributors to these tendencies are found to be the same at 12 km and 36 km as at 4 km with minor quantitative differences observed primarily with the diabatic heating rate due to microphysical processes (not shown). These differences presumably arise due to grid spacing-dependant differences associated with the scale and intensity of model-simulated updrafts in regions of saturation (i.e. precipitation). Additionally, note that the vertical, radial, and spatial structure to the thermodynamic evolution and the simulated cyclone's trajectory through the cyclone phase space during ET are all qualitatively and quantitatively similar in the 36 and 12 km simulations to that from the 4 km simulation (not shown).

As a consequence, the additional detail in each field afforded by the convection-permitting 4 km simulation does not appear to significantly impact the total thermodynamic evolution of the vortex. The implication that this evolution is largely adiabatic rather than diabatic in nature, as noted in Section 3.4, implies that this should be the case. This also provides further evidence supporting the hypothesis of Hart et al. (2006) that the primary influences upon the thermodynamic evolution of the transitioning TC appear to be associated with the interaction between the TC and the mid-latitude vertically sheared environment. If this is the case, it stands to follow that as long as a numerical model can accurately depict and forecast this interaction, it can accurately forecast the thermodynamic evolution of the transitioning cyclone. Note, however, that this says nothing about the ability to forecast the downstream evolution as a TC undergoes ET, shown by Jones et al. (2003) and references therein to be a significant challenge associated with ET events.

4.2 Broader-Scale Impacts Upon Weather & Climate

While the focus of this work is on the inner core thermodynamic evolution, significant downstream effects of an ET event due to both transport and latent heat release are also observed. From this work, this is shown clearly by the Hovmoller plot of the vertically-integrated microphysical temperature tendency (not shown) and vertical structure of the area-averaged equivalent potential temperature differences between the downstream and upstream hemispheres of the cyclone (Figure 14). Additionally, the works of McTaggart-Cowan et al. (2007), and, to a lesser extent, Hart (2010) and Archambault (2010) provide further evidence showing the potential larger-scale impacts of heat transport and release associated with ET events. The results from these works naturally motivate further research into the four-dimensional synoptic-scale thermodynamic evolution of the environment outside of the inner core of transitioning TCs.

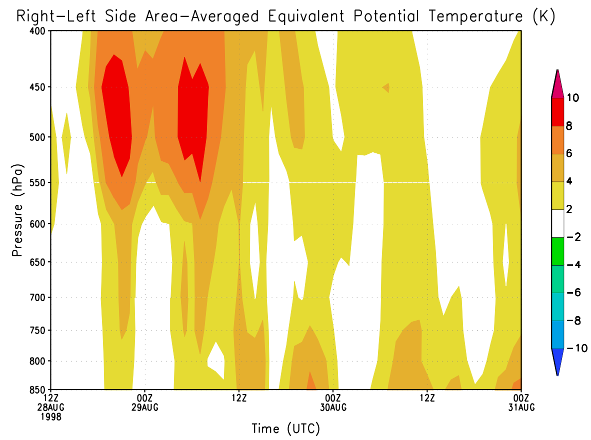

Figure 14: Difference in the area-averaged (inside 175 km) equivalent potential temperature (K) field between the right and left hemispheres of TC Bonnie between 1200 UTC 28 August-0000 UTC 31 August 1998 as obtained from the 4 km MM5 simulation.

Understanding this thermodynamic evolution is hypothesized to be critical to not only improving short-term numerical weather prediction forecasts downstream of transitioning TCs but to understanding the longer-lasting impacts of a transitioning TC on both regional and global weather and climate. Future work will explore these topics and attempt to clarify the role of TCs in modulating global energy blaance using a variety of case study, idealized, and climatic modeling approaches.

5. Conclusions

In this work, the factors contributing to the thermodynamic evolution of an extratropically transitioning TC have been identified. The observed net cooling of approximately 6 K is largely driven by horizontal and vertical temperature advection process, in part supporting the hypotheses and findings of Jones (1995; 2000b), Sinclair (1993), and McTaggart-Cowan et al. (2003; 2004). These processes are found to be associated with the developing conveyor belts or air streams of the transitioning cyclone, are nearly tropospheric-deep, and are maximized inside of the radius of maximum winds of the cyclone. Non-trivial contributions to the total temperature tendency arise due to adiabatic cooling, akin to the hypotheses of Hart et al. (2006) and Sinclair (1993); radiative cooling, particularly atop the center of circulation of the cyclone; and latent heat release due to condensation in the "delta rain" region of the transitioning cyclone. In all, this evolution is believed to largely be adiabatic in nature, akin to the hypothesis of Wang et al. (1993), and a natural outgrowth of the factors influencing ET as a whole. More specifically, preliminary results suggest that much of the thermodynamic evolution/structure that arises during ET may be due to the fundamental evolution of the vortex in a vertically sheared flow by means of the mechanisms proposed by Raymond (1992) and explored by Jones (1995; 2000a,b).

Findings from the TC Bonnie case are utilized in conjunction with the thermodynamic budget evolutions from four additional cases – another case similar to TC Bonnie, north Atlantic TC Ivan of 1998; an ET event featuring a warm-seclusion (e.g. Shapiro and Keyser 1990) evolution after ET, north Atlantic TC Danielle of 1998; a strengthening, purely tropical cyclone, north Atlantic TC Georges of 1998; and a strengthening, purely extratropical cyclone, a north Atlantic oceanic cyclone of mid-November 1998 – to develop a schematic of the contributors to the thermodynamic structure of a transitioning TC (Figure 15). During the tropical phase (Figure 15b), warming associated with latent heat release, surface fluxes, and advective processes dominates over adiabatic and radiative cooling. As the cyclone begins to undergo ET (Figure 15c), a relative balance between these warming and cooling contributions is achieved. This balance is largely maintained through the ET process (Figure 15d) before giving way to a preference for cooling as ET completes (Figure 15e). It should be noted that the ET process, whether cold-core or warm-seclusion in nature, brings about a shift in the contribution from advection processes from warming to cooling and a reduction in the magnitude of diabatic heating from both latent heat release aloft and surface heat fluxes. During the extratropical phase (Figure 15f), advective cooling processes dominate, gradually diminishing in magnitude due to the occlusion of the cyclone after ET. Further work is needed to clarify the differences between a cold-core and warm-seclusion extratropical cyclone or ET event as well as to extend the evolution shown in Figure 15 to the entire lifecycle of all types of cyclones.

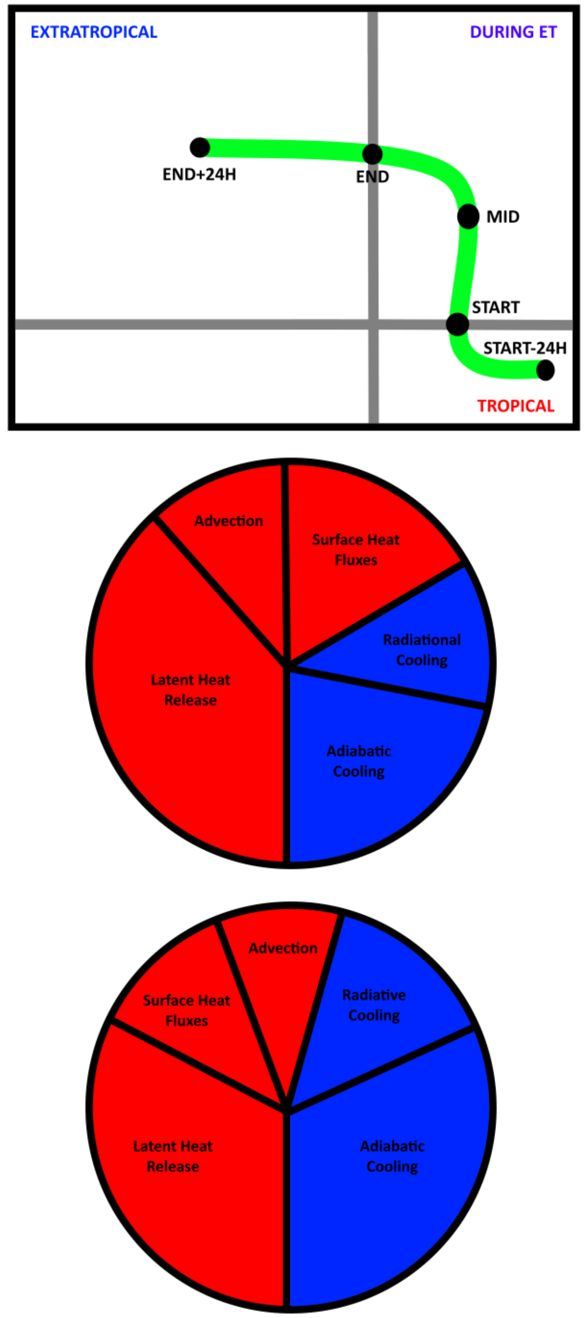

Figure 15: (a, top) Schematic of a typical ET trajectory through the cyclone phase space of Hart (2003) with important milestones labeled. (b, middle) Schematic depicted the relative magnitudes of the principal heating (red) and cooling (blue) components to the total temperature tendency at "START-24H" on the schematic in (a). (c, bottom) as in (b), except at "START" on the schematic in (a).

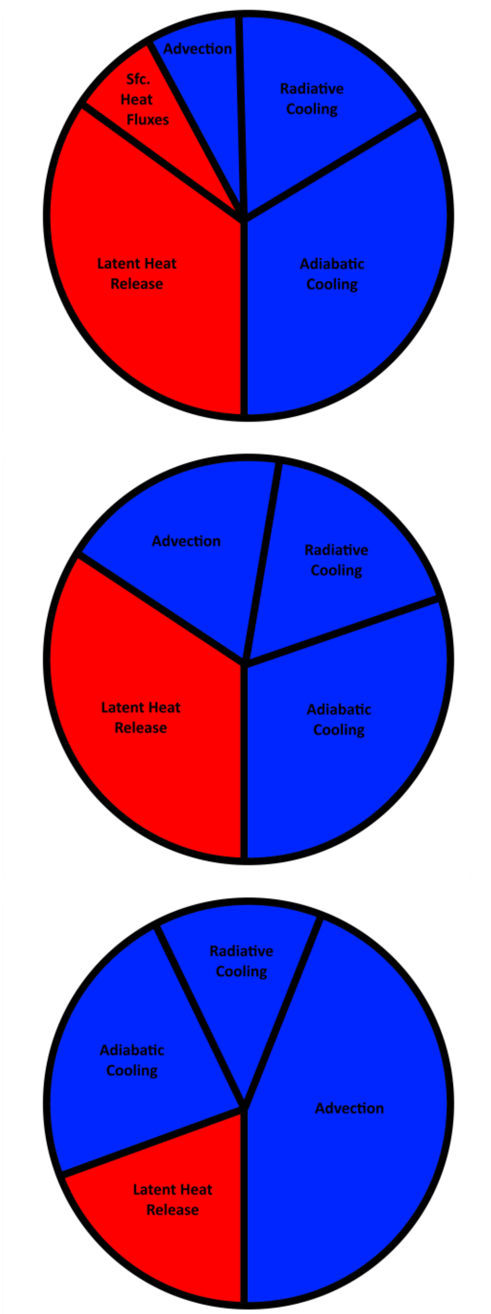

Figure 15, cont: (d, top) as in (b), except at “MID” on the schematic in (a). (e, middle) as in (b), except at “END” on the schematic in (a). (f, bottom) as in (b), except at “END+24H” on the schematic in (a).

Acknowledgments

We gratefully acknowledge thoughtful discussions on this topic with George Bryan, Chris Davis, Greg Holland (all NCAR), Paul Reasor (NOAA/AOML/HRD), Lance Bosart (SUNY-Albany), Jim Elsner, T.N. Krishnamurti, and Paul Ruscher (all FSU). All images were created using the GrADS 2.0a7.1 software package. NCAR is sponsored by the National Science Foundation.

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