19th Conf. Weather Analysis and Forecasting
AMS, 12-16 August 2002, San Antonio, TX

7A.3 QUANTITATIVE MEASUREMENTS OF EXTRATROPICAL TRANSITION IN THE ATLANTIC BASIN

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1. Introduction

Tropical cyclones that undergo extratropical transition (ET) in the Atlantic Ocean basin can have a significant impact on life and industry on the eastern coast of North America and the western Atlantic basin. ET involves the evolution of a warm-core, vertically stacked, and quasi-equivalent barotropic cyclone into a cold-core, titled, baroclinic cyclone. ET can take between twelve hours to more than several days, depending upon the relation between the synoptic scale pattern and the tropical cyclone. In order to diagnose which tropical cyclones will complete an ET, it is necessary to examine the dynamics of the large-scale environment.

ET has recently received a lot of attention from various research groups. Klein et al. (2000), Harr and Elsberry (2000), and Harr et al. (2000) have concentrated on recurving Pacific typhoons, defining ET as a two-step process involving the transformation and reintensification stages using diagnostics including the development of warm frontogenesis. In the Atlantic basin, Thorncroft and Jones (2000) analyzed the ET of two distinctly different tropical storms from the 1995 season (Iris and Felix) from a potential vorticity (PV) perspective. Hart and Evans (2001) have developed a climatology of Atlantic ET events while Hart and Evans (2002) employ a phase-space methodology to diagnose cyclone lifecycles and strength using thickness asymmetries across the cyclone and the vertical gradient of the thermal wind.

The goal of this paper is to present several dynamical measures originally developed by Sutcliffe (1947, 1950) from a mid-latitude perspective that will help diagnose whether a tropical cyclone is a candidate for ET or dissipation in the mid-latitudes. These measures include thermal vorticity and the gradient of thermal vorticity (1000 - 200 hPa layer), as well as the advection of absolute vorticity by the thermal wind between 1000 hPa and 200 hPa. Composite cases are presented comparing the differences between hurricanes that undergo a strong and robust transition versus tropical cyclones that decay before transitioning into extratropical cyclones.

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2. Data and Methodology

The dataset used to compute all variables presented in this paper is from the NCEP/NCAR Reanalysis Dataset (Kalnay et al. 1996, Kistler et al. 2001). Although the horizontal resolution of the NCEP/NCAR Reanalysis is too coarse (2.5° x 2.5°) to determine the small-scale structure of tropical cyclones, it is well suited for diagnosing synoptic scale structure through thermal vorticity and the advection of thermal vorticity by the thermal wind. Absolute vorticity for this calculation is averaged between 700 hPa to 400 hPa. If best track data is not available for the cyclone, the 850 hPa absolute vorticity maximum was used as a surrogate for cyclone position. The NCEP/NCAR Reanalysis datasets also have the benefit of continuity from 1948-2001.

Figure 1 helps demonstrate the methods used to calculate the Sutcliffe variables for this study. Thermal vorticity, a valuable tool to measure the thermal structure (warm or cold-core) of the cyclone, is calculated between 1000 and 200 hPa over a circular area with radius of 500 km from the storm center. The gradient of tropospheric-deep thermal vorticity with respect to storm location allows insight into the interaction of the cyclone with baroclinic zones of varying intensity based on the value of the gradient. The gradient of thermal vorticity is calculated at the storm center.

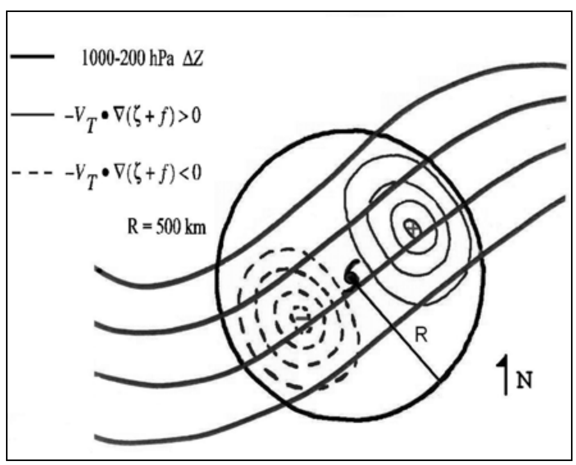

Figure 1 – Diagram illustrating methods used to calculate thermal vorticity, gradient of thermal vorticity, and the advection of absolute vorticity by the thermal wind.

The advection of mid-level absolute vorticity (700 to 400 hPa) by the tropospheric-deep thermal wind (1000 to 200 hPa) measures the forcing for large-scale ascent, based upon the original Sutcliffe (1947) theory. As tropical cyclones move into the mid-latitudes and undergo ET, a positive/negative couplet of this advection variable becomes readily apparent, as illustrated in Fig. 1. The difference between the maximum and minimum value of this variable is called the advection couplet, and is measured anywhere in a 500 km radius from the storm center along the 1000-200 hPa thickness contour through the storm center.

For the radius-theta diagrams presented in Figs. 4 and 5, distances were calculated from the cyclone center to the center of the warm and cold-core centers in 12-hour intervals. Locations of the warm and cold core centers were determined by using the Generalized Meteorological Package (GEMPAK) maxima and minima thermal vorticity values.

3. Results and Discussion

Table 1 shows the hurricanes used in the strong transition and non-transition composite cases, primarily designated by National Hurricane Center (NHC) best track analyses.

Table 1 - Hurricanes Used in Composite Cases

Strong Transition		Non Transition Cases	
Hazel	1954	Gert	1981
Agnes	1972	Chantal	1983
Eloise	1975	Bob	1985
David	1979	Elena	1985
Frederic	1979	Bonnie	1986
Hugo	1989	Gilbert	1988
Bob	1991	Jerry	1989
Bertha	1996	Emily	1993
Fran	1996	Harvey	1993
Floyd	1999	Erin	1995
Irene	1999	Dennis	1999
Michael	2000		

Figures 2 and 3 show a time series of the three variables used to diagnose transition, separated by transition classification. The three variables have also been calculated for thirteen memorable East Coast mid-latitude cyclones and are plotted as horizontal lines (storms chosen from the sample presented in Kocin and Uccellini 1990) on Figs. 2 and 3. These threshold values are representative of robust extratropical cyclones, and therefore are used as indicators that transition has occurred. Note that for the strong transition composite time series in Fig. 2, the composite tropical cyclone values exceed the mean mid-latitude values for all three variables.

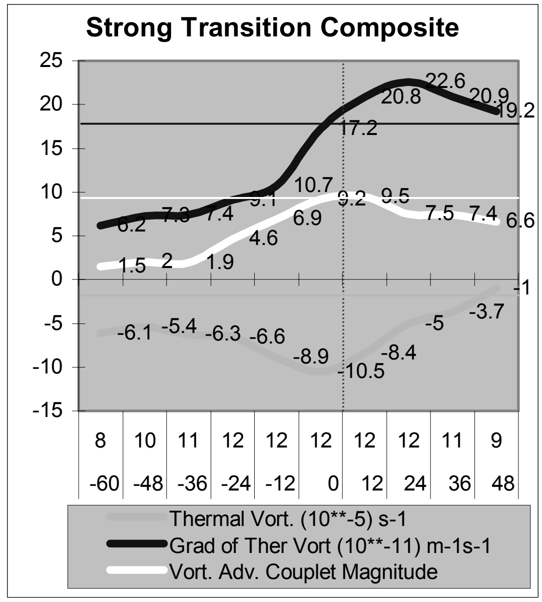

Figure 2 - Strong transition composite cases. Y-axis labeled with number of cases and time before/after NHC designated transition.

The gradient of thermal vorticity and advection couplet exceeds the extratropical values at the time of NHC-designated ET. The thermal vorticity value reaches a minimum at NHC transition time, and exceeds the mid-latitude value approximately 36 hours after transition time. The progression of thermal vorticity is most likely not a dynamical evolution, but an artifact of the NCEP/NCAR Reanalysis being more capable of analyzing the cyclone as it increases in size as it moves into mid-latitudes. Even before NHC designated transition, values of the gradient of thermal vorticity as well as the advection couplet increased from tropical values approximately 36 hours before designated transition. Therefore, the entire transition period for these 13 storms is considered to be a 72-hour period, in which the tropical cyclone evolves into an extratropical cyclone.

In comparison, the non-transition composite in Fig. 3 shows that none of the three variables used to define ET achieve values show a robust change from tropical to extratropical values over the time period used. For this composite, time equals zero when the tropical cyclone is downgraded to tropical storm status. The advection couplet fails to develop, indicative of a dying cyclone with little or no quasi-geostrophic forcing for ascent. There is no marked change in the thermal vorticity of the storm over this period, while the gradient of thermal vorticity fails to achieve the values found in strong mid-latitude East Coast cyclones. The slight increase in the gradient of thermal vorticity can partially be explained by examining the time evolution of thermal vorticity centers with respect to the storm position.

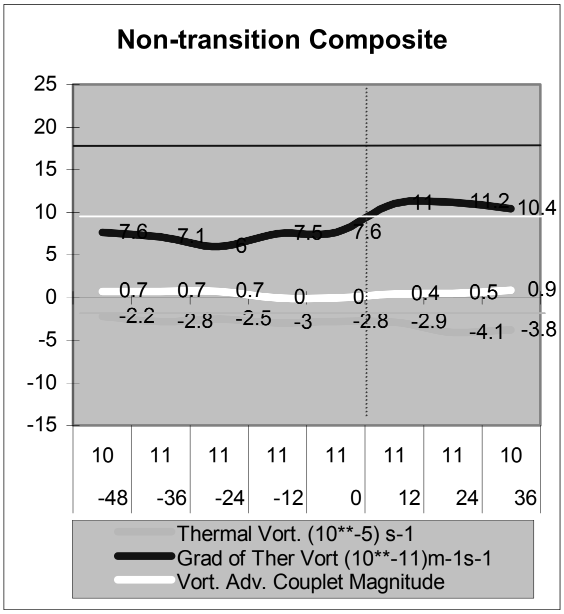

Figure 3 - Non-transition composite cases. Y-axis labeled with number of cases at time period, defined as before/after first time period after decay from hurricane status.

Figures 4 and 5 are storm relative composites for both the strong and non-transition groupings. Locations for the thermal vorticity maxima (minima) are indicated by squares (circles) for times using the same convention as noted in Figs. 2 and 3 for the strong and non-transition time series composites. The evolution of the cold-core center (squares) in the strong transition composite cases (Fig. 4) from 36 hours before to 36 hours after transition closely resembles the evolution expected of a developing baroclinic mid-latitude cyclone as shown in Sanders (1986; Fig. 4,7). During this 72-hour period, the 925-200 hPa layer wind shear increased from 17 ms^{-1} to 50 ms^{-1} with a southwesterly component, while the magnitude of the thermal wind over the center of the composite storm increased from approximately 10 ms^{-1} to over 50 ms^{-1}. The end values are typical of what one would expect over a moderate-to-strong mid-latitude cyclone.

The evolution of the non-transition composite case is a different story, as shown in Fig. 5. The cold core center at 36 hours before being downgraded from a hurricane is approximately 800 km further away than the comparable time period for the strong transition composite in Fig. 4. The cold-core center passes from the northwest to the north of the tropical cyclone at a significant distance as it decays, lacking a significant interaction evident in the strong transition composite in Fig. 3. In comparing Figures 4 and 5, it becomes obvious that one key to whether a tropical cyclone will undergo ET is the timing and location of the mid-latitude trough with respect to the tropical cyclone as it moves into mid-latitudes.

4. Acknowledgements

Research support was provided by NSF grant ATM-9912075. Dr. Lance Bosart has provided invaluable information in formulating this research, as well as Eyad Atallah and Michael Dickinson. Anantha Aiyyer and David Vollaro provided computer support to make many of the calculations possible.

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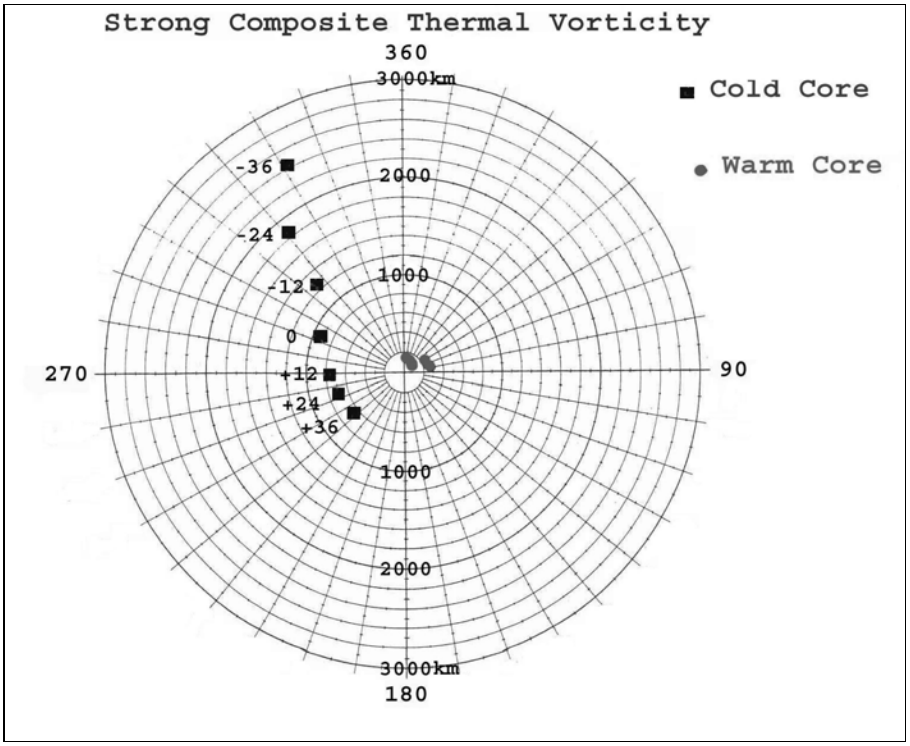

Figure 4 – Radius-theta diagram for the strong composite transitions. Dark squares indicate center of thermal vorticity maximum and distance from cyclone center at given time periods before/after NHC designated transition.

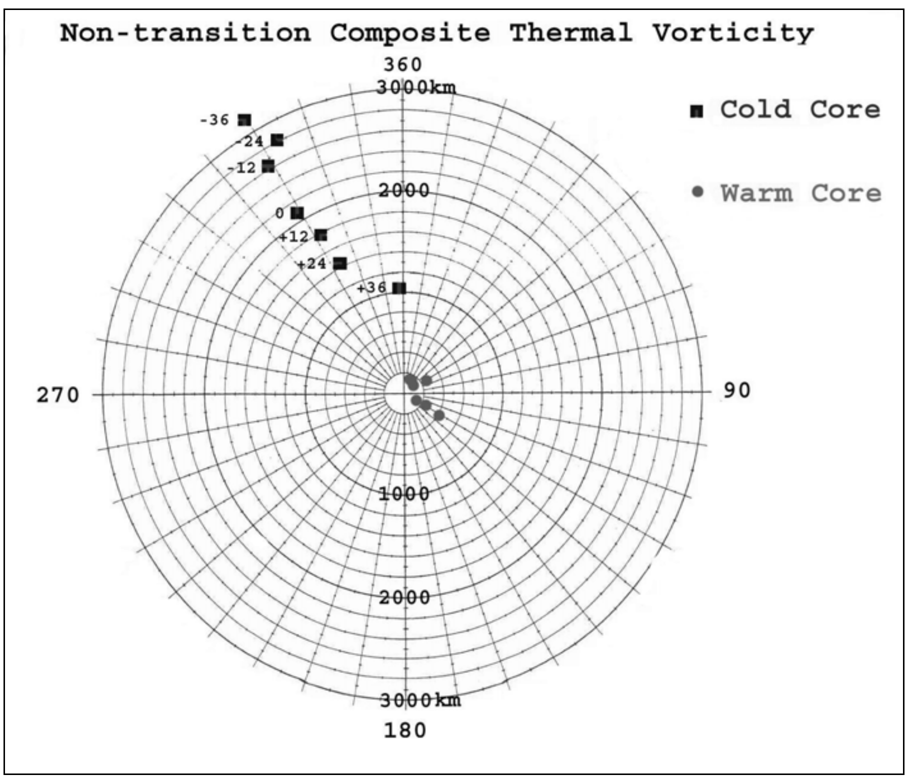

Figure 5 – Same description as Figure 4, except for the non-transition composite cases. Here, t =0 indicates first 12 hour period after the tropical cyclone has been downgraded from hurricane status.