10C.1

DETERMINATION OF A CONSISTENT TIME FOR THE EXTRATROPICAL TRANSITION OF TROPICAL CYCLONES

David E. Kofron*, Elizabeth A. Ritchie, and J. Scott Tyo
University of Arizona, Tucson, Arizona

1. INTRODUCTION

Although there has been considerable research on tropical cyclones (TCs) and extratropical cyclones, the transition of TCs as they propagate into the mid-latitudes and interact with extratropical features has received somewhat less attention. Many of these TCs become powerful extratropical cyclones, and they often pose a threat to marine interests and countries in a similar fashion as TCs.

The process by which a TC moves poleward, loses tropical characteristics, and interacts with the mid-latitude environment is called extratropical transition (ET). Some of the environmental changes include an increase in vertical wind shear associated with increasing mid-latitude westerlies and baroclinicity, stronger meridional temperature gradients, a decrease in sea surface temperatures (SST's) with an increase in the SST gradient, and an increase in the Coriolis parameter (Jones et. al. 2003). The effects of these environmental changes are generally to increase the translation speed of the storm while decreasing the maximum wind speed but increasing the size of the storm. The increase in the size and speed along with increased environmental westerly vertical shear causes the decaying TC to become very asymmetric and contributes to the generation of large waves and swells (Jones et. al. 2003). Because there is no clear understanding of how the TC and mid-latitude features interact, it is difficult to forecast the ensuing intensity of the fully transitioned storm. It is also problematic to accurately forecast the speed and location of the storm because small errors in the initial location of the TC can result in large errors in the 24 and 48-hour numerical weather prediction forecast. These basic forecasting issues make it challenging to forecast the location of the high winds and precipitation and the oceanic response to the transitioned cyclone (Jones et. al. 2003).

In order to better forecast the extratropical transition of TCs, the time at which the TC loses tropical characteristics and begins to interact with the preexisting mid-latitude cyclone or trough, called the ET time in this study, must be determined. Although there has been a recent increase in the study of physical processes associated with TCs as they transition into extratropical cyclones, there has been no advent of a common definition of ET that is consistent across all cases. Such a definition would have utility for the operational community by providing a standardized time to designate extratropical transition. There would also be several benefits for the research community, including a consistent designation in the best track records for ET with associated criteria that are physically based but easily understood.

The existing definitions of ET include, but are not limited to, descriptions of the structural evolution of the TC during extratropical transition using satellite derived data (Klein et. al. 2000), analyses (Sinclair 2002; Foley and Hanstrum 1994) and global gridded datasets (Ritchie and Elsberry 2001, 2003, and 2007; Demirci et. al. 2007), the progression of an axisymmetric warm-core system to an asymmetric cold-core system via phase-space (Hart and Evans 2003; Evans and Hart 2003), and frontogenesis (Harr and Elsberry 2000).

A potentially useful tool for determining the ET-time is potential vorticity (PV). The idea of "PV thinking" has been brought up many times (Jones et. al. 2003), however, it has not been used as a means of characterizing the evolution of a TC undergoing ET. Like phase-space, PV can be used to explain the structure of the TC and the balanced atmospheric flow surrounding the TC. The values decrease quickly out from the center, and the PV gradients relax as well. The preexisting trough that the TC interacts with has higher PV values in the upper levels because the upper level jet is dominant. Some more mature mid-latitude cyclones may also exhibit higher low-level PV values along a frontal boundary. The interaction of the TC and the trough may be best explained by examination of mid-level isentropic PV.

In this paper, we will examine the validity of the existing definitions for defining the ET-time as well as examine the potential usefulness of

* *Corresponding author address:* David E. Kofron, Univ. of Arizona, Dept. of Atmospheric Science, Tucson, AZ 85721-0081.
email: kofron@atmo.arizona.edu.

potential vorticity diagnostics to propose a new method for defining ET-time that can be easily understood and is useful to both the operational and research communities as well as sufficiently explain the dynamics of ET.

2. DATA AND METHODS

The data used are the Naval Operational Global Atmospheric Prediction System (NOGAPS) analyses on a 1° lat-lon grid at 13 levels between 1000 and 50 hPa as acquired from the Master Environmental Library (https://mel.nrlmry.navy.mil). Recurving TCs from the northwest Pacific and north Atlantic oceans from 2003 through 2006 (82 storms) are included in the dataset. For each storm, the 6 days surrounding a first guess ET time, which is defined as the time at which the TC becomes an open wave in the 500-hPa geopotential height analyses at 12-hour intervals, are included. After each storm center is accurately found, the data are interpolated to 0.5° resolution onto a 60.5° by 50.5° storm-centered grid. The interpolated data are then used to calculate the frontogenesis parameters (Equations 6a and 6b in Harr and Elsberry 2000), phase-space parameters (Equation 2 in Hart 2003), and isentropic potential vorticity (Equation 8 in Hoskins et. al. 1985).

The 2003 through 2006 seasons are chosen because the number of recurving TCs (82) is deemed a sufficient size to separate into different bins. The three main scenarios include storms that undergo ET and reintensify, storms that undergo ET but dissipate, and storms that recurve but do not interact with any mid-latitude feature and, thus do not undergo ET. The minimum central sea-level pressure determines reintensification or dissipation in the 48-hour period after the maximum central pressure is reached at the storm center. If the pressure drops by 3 mb or more, then the storm is classified as a reintensification case. Conversely, if the pressure drops by less than 3 mb or rises, then the storms are classified as a dissipation case. Of the 82 cases, 46 of them reintensified and 36 dissipated.

The 46 reintensification cases were further separated into two bins based on their interaction with a preexisting mid-latitude cyclone to the northeast or northwest. This is determined by examination of the 500-hPa analyses, as suggested by Harr and Elsberry (2000). A little more than half of the TCs (24) are accelerated by a preexisting mid-latitude cyclone to the northwest and are placed into bin1. The other reintensifying TCs (22), which are accelerated rapidly and interact with the mid-latitude cyclone to the northeast, are categorized into bin2. The average pressure drop for either of these bins is the same (10 mb).

The remaining 36 storms fall into the other scenarios in which the storms either undergo ET and dissipate (bin3) or do not undergo ET (bin4).

3. RESULTS

3.1 500 hPa Geopotential Height Fields

The dataset for each storm is centered about the time at which the TC becomes an open wave in the 500 hPa geopotential height analyses. This definition is chosen as a starting point for the experiment for several reasons. The first is that all recurving TCs generally exhibit the same pattern in the 500 hPa height fields as they begin to interact with the mid-

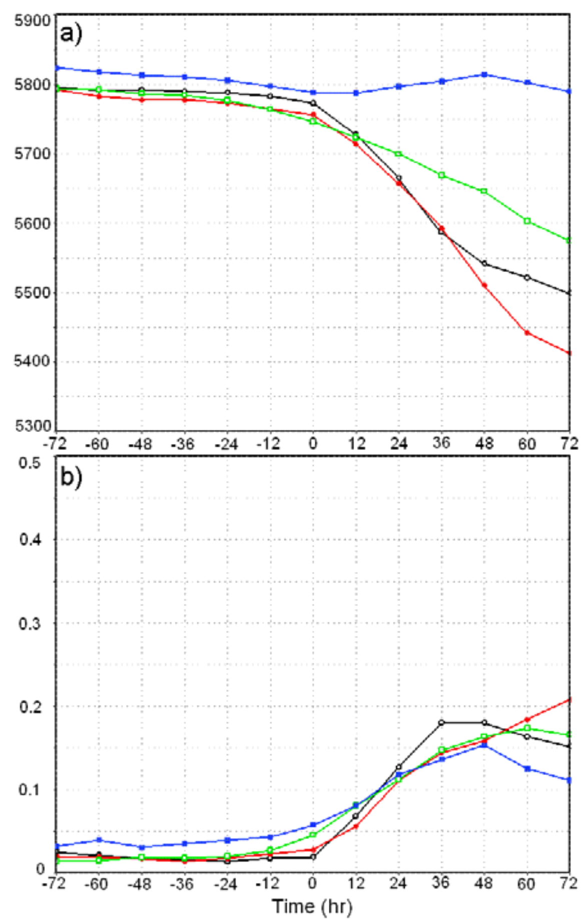

Figure 1: Bin1 (black), bin2 (red), bin3 (green), and bin4 (blue) 500 hPa geopotential height a) averages (m) and b) normalized standard deviations.

latitudes. The average of each bin mentioned earlier is shown in Figure 1a. All of the bins exhibit the same general decrease in 500 hPa height value at the storm center through the first time that TC becomes an open wave (0 hr). The most likely reason for the decrease is the movement of the TCs into the mid-latitudes where the environmental heights decrease with latitude. The more significant decrease in height values after the 0 time is a result of the interaction of the TC and the mid-latitude trough, but the amount of decrease can vary greatly (Figure 2a).

The other reason for choosing this definition is that it is easy to see when the wave becomes open in the analyses. After the TC becomes an open wave, however, the decrease in 500 hPa heights can vary greatly, as shown by the normalized standard deviation plots in Figure 1b. The normalized deviations are low for all four bins up to the 0 time and begin to increase dramatically after the 0 time, which indicates a larger spread in 500 hPa height values.

3.2 Frontogenesis

Harr and Elsberry (2000) suggest that frontogenesis can be divided into two parameters – scalar and rotational frontogenesis (EQ 1a and 1b). The case study of two TCs that interact with a trough to the northeast and northwest indicates that the patterns for rotational frontogenesis are different while the patterns of scalar frontogenesis are similar. This is because scalar frontogenesis is dominated by divergence and deformation, which promotes warm frontogenesis to the northeast and cold frontogenesis to the southwest, whereas rotational frontogenesis is dominated by deformation and relative vorticity, which supports the amplification of frontogenesis in opposite locations around the storm for the two baroclinic situations. The hypothesis from Harr and Elsberry (2000) is that scalar frontogenesis may be used to explain the interaction of the TC and the mid-latitude system, however, there is no quantitative measure provided as a basis. Figure 2a shows the average difference between the cylindrical average in the northeast and southwest quadrants at each time for each of the four bins plotted at times relative to the time at which the TC becomes an open wave in the 500 hPa height analyses. There does not appear to be a coherent pattern in the area-averaged scalar frontogenesis. The image of the normalized standard deviation (Figure 2b) also supports the lack of a coherent pattern.

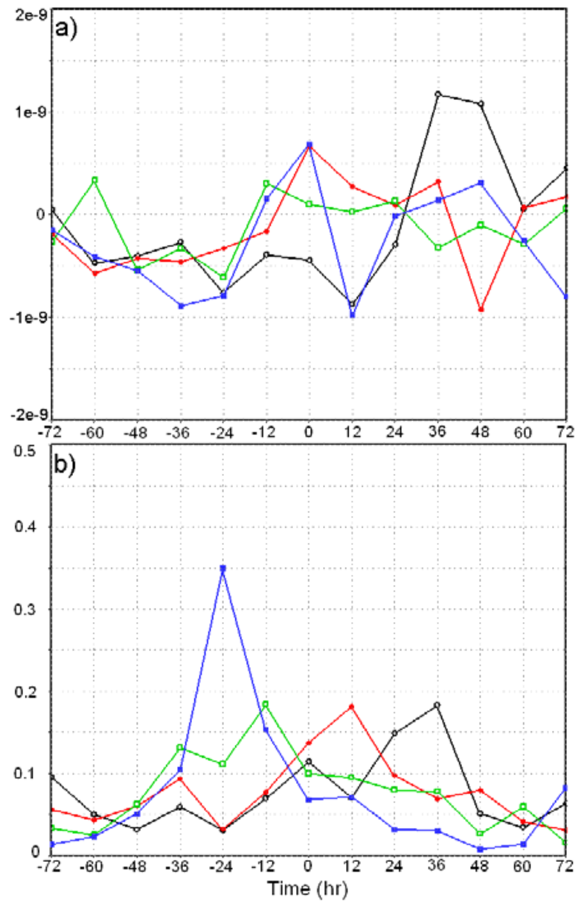

Figure 2: Bin1 (black), bin2 (red), bin3 (green), and bin4 (blue) scalar frontogenesis a) averages (K/m/s) and b) normalized standard deviations.

3.3 Phase-space Asymmetry Parameter

Another method for determining the transition of a TC into an extratropical cyclone is the use of phase-space diagrams (Hart and Evans 2003; Evans and Hart 2003). Although there are three parameters calculated to produce the diagrams, which include an asymmetry parameter and upper and lower level thermal wind parameters, Hart and Evans (2003) only use the asymmetry parameter to determine the time at which the TC changes from tropical to extratropical. The other two parameters are used to examine the core temperature, either warm or cold core, of the TC. The asymmetry parameter, B, is defined as the difference of the averaged 900-600 hPa thickness on the right and left side of the TC motion. The radius from the center of the TC used to calculate B in this study is 5° latitude, but Hart and Evans (2003)

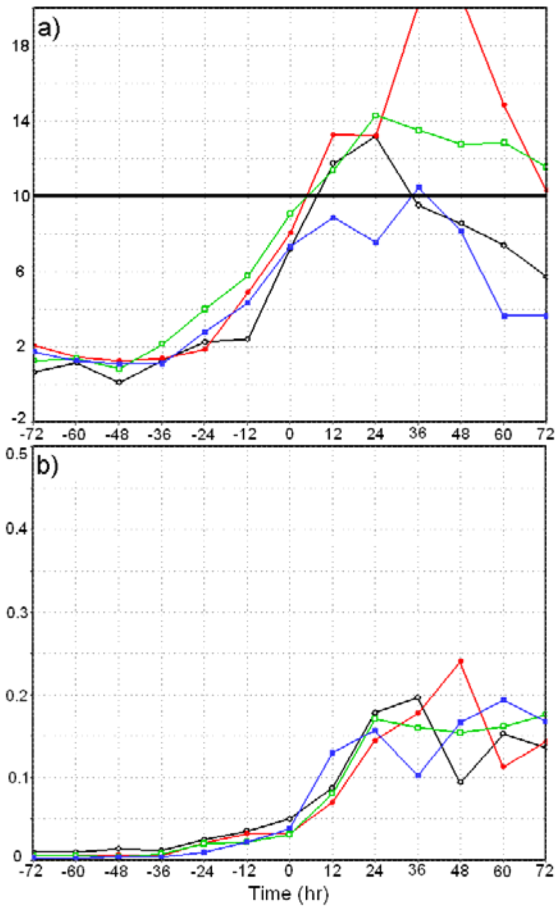

Figure 3: Bin1 (black), bin2 (red), bin3 (green), and bin4 (blue) phase-space asymmetry parameter a) averages (m; purple line is at 10 m) and b) normalized standard deviations.

mention that there are any number of radii that may be appropriate. Because a mature TC is generally close to axisymmetric, it has a lower value of B and may even be negative at times. As the TC propagates into the mid- latitude westerlies, however, the shape of the TC generally becomes asymmetric and causes the B value to increase dramatically. As an extratropical cyclone begins to occlude, the B values may decrease as the TC becomes more symmetric.

Evans and Hart (2003) further examined the asymmetry parameter and determined that the TC is no longer tropical at a value of 10 m or higher for B. A comparison of the asymmetry parameter for each of the four bins is displayed in Figure 3a. The average of each of the first three bins in which the TC interacts with a mid-latitude trough have B values that exceed the 10 m value and do so at roughly the same time as compared to the time at which the TC becomes an open wave in the 500 hPa height analyses. Also, the values decrease at later times as the TC is absorbed into the preexisting mid-latitude cyclone for the first three bins. Thus, the B parameter may discriminate when a mid-latitude trough is present as part of the recurving TC, but it does not discriminate dissipating from intensifying cases. The average of the TCs that do not interact with a mid-latitude trough (bin4) exceeds the 10 m mark at a later time, but many of the storms never exhibit an asymmetry value high enough to be considered ET by the Evans and Hart (2003) definition. The storms that do exceed the 10 m value for bin4 are considered ET cases incorrectly.

Figure 3b is the normalized standard deviation of the asymmetry parameter B at the times relative to the TC being an open wave in the 500 hPa analyses. The values near the beginning of the curve are most likely low because most of the storms are tropical and symmetric. As the storm propagates to the north, it becomes more asymmetric at a rate that will vary more from storm to storm because of the different translational speeds or the strength of the baroclinic region it enters. This variance appears even before the storms become open waves in the 500 hPa height fields.

3.4 Potential Vorticity

The final method examined to determine the ET time is a possible new way of defining a specific ET time that has been mentioned in previous studies (Jones et. al. 2003) but never researched to find a quantitative measure for finding the ET time. This method is by use of Ertel's potential vorticity. Assuming geostrophic balance and by use of the invertibility principle in the absence of diabatic and frictional processes, the balanced atmospheric flow in and around the TC can be found. TCs, however, are not in geostrophic balance and there are diabatic and frictional processes, but PV can be used to explain the basic structural changes as the TC enters into the mid-latitude regions. Lackmann (2002) showed that the PV values near the center of the TC decrease with height in the atmosphere and have a much higher PV gradient at the inner core of the storm. As the TC approaches the mid-latitudes, the PV structure can be expected to evolve in a fashion similar to the 500 hPa height fields. Figure 4 shows the composite evolution of the bin2 cases over a 48-hour period. The TC enters into the mid-latitudes as a closed contour feature. As the storm begins to shear, the maximum value at the

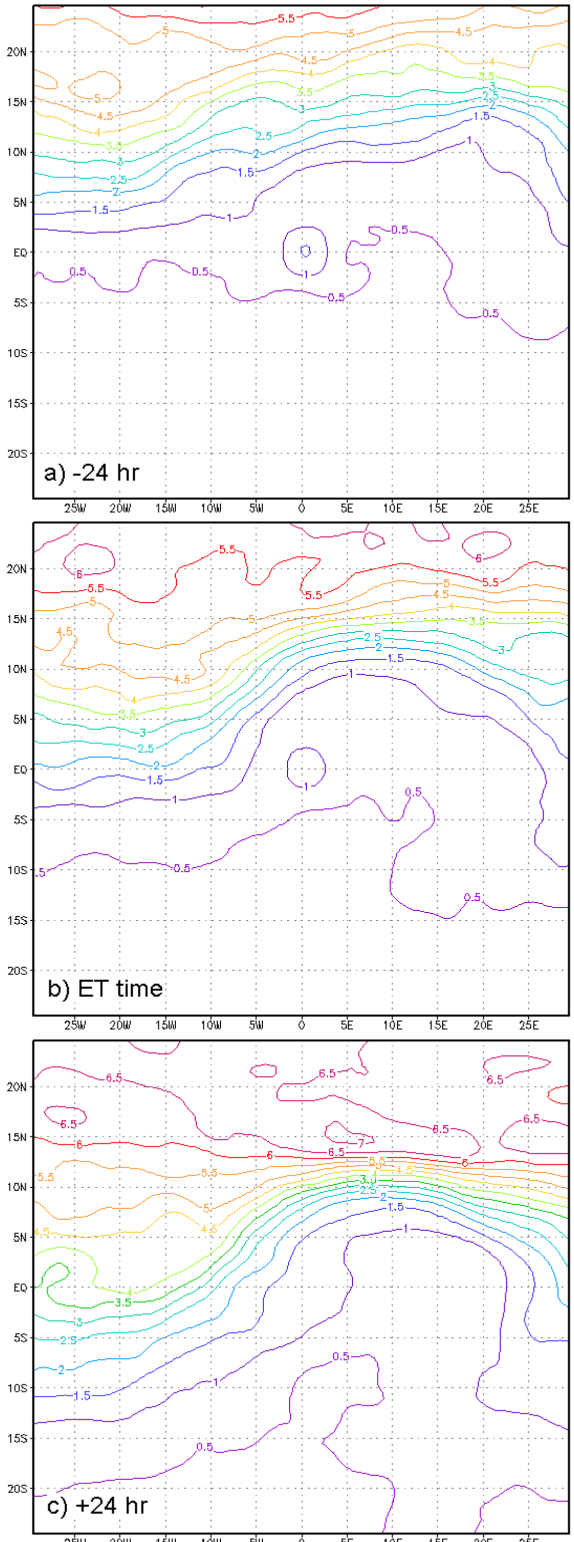

Figure 4: Composite averages of bin2 cases for the evolution of PV along the 335 K potential temperature isentrope at a) –24, b) 0, and c) +24 hours relative to the time at which the TCs are open in the 500 hPa geopotential height analyses.

center of the TC decreases near the ET time as determined by the open wave time in the 500 hPa height analyses. Finally, the TC becomes absorbed into the PV shield to the north that is associated with the trough.

The area-averaged values of PV are calculated within a radius of 5 degrees from the center of the TC. Figure 5a shows these PV values averaged for each scenario at each time relative to the time at which the TC becomes an open wave in the 500 hPa height analyses. There is a clear decreasing trend in the PV values as the TC begins to weaken and enter the mid-latitudes for all bins. As the TC is absorbed by the preexisting mid-level low in the first three bins at times after reaching a minimum, the PV increases dramatically. The line representing the scenario in which the storm interacts with the trough and dissipates (bin3) does not increase in value as much as the first two bins where the storm reintensifies. For the scenario in which the recurving TC never enters

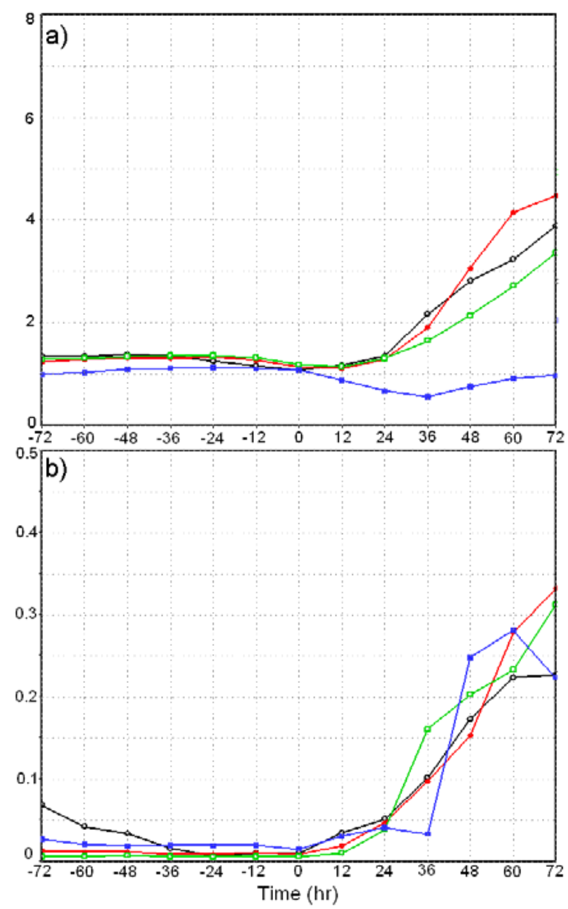

Figure 5: Bin1 (black), bin2 (red), bin3 (green), and bin4 (blue) isentropic potential vorticity (335 K) a) averages (PVU) and b) normalized standard deviations.

the baroclinic region (bin4), the values reach a minimum at a later time and then show signs of a slight increase possibly because the TC regains tropical characteristics and reintensifies as a tropical system.

The plots of the normalized standard deviation of the averaged PV values at each time (Figure5a) show that the storms deviate less near the corresponding minimum times from Figure 5a. The values after the minimum PV time deviate greatly because the end result during the reintensification or dissipation stage varies greatly even with each scenario. Also, the deviation at early times (-72 hr) for the scenario in which storms interact with a northwest trough (bin1) is higher, which may indicate that TCs with a higher range of initial PV intensity may interact with northwest troughs and reintensify. Because of these factors and the low deviations near the time at which the PV is a minimum, it can be hypothesized that the circularly averaged PV values at the center of the TC can be used as a means of defining the time at which the TC is no longer tropical, and therefore, the ET time.

4. DISCUSSION AND CONCLUSIONS

A variety of methods for defining the life-cycle of the extratropical transition of tropical cyclones can be used to define when a TC is no longer tropical. The methods described include the time at which the TC becomes an open wave in the 500 hPa geopotential height analyses, scalar frontogenesis as a means for describing the environmental changes surrounding the TC, the time when the phase-space asymmetry parameter reaches a value of 10 m or higher, and the time when the circularly averaged PV value reaches a minimum prior to a distinct rise.

The advantages to using the time at which the TC becomes an open wave in the 500 hPa height analyses as the ET time are that it is easy to see in the fields and easy to understand. However, there are also disadvantages, which include the lack of dynamical significance to explain the tropical-extratropical interaction and the fact that some storms never become open waves in the analyses. There are also advantages and disadvantages to using scalar frontogenesis. The advantages include dynamical significance and a tendency to explain the large-scale environment surrounding the TC well; the disadvantages include a lack of consistency from case-to-case and that frontogenesis is difficult to understand and calculate. So, these two methods are most likely not the best for describing and defining the life cycle of ET.

The phase-space asymmetry parameter and potential vorticity perform much better. The asymmetry parameter is generally easy to understand and explains some of the structural change involved in the tropical-extratropical interaction in a mostly consistent manner. The parameter, however, can be difficult to calculate and is not necessarily reliable for TCs that are not well represented in the gridded analysis. It also does not separate the intensifying from the dissipating storms after the ET time. Potential vorticity, on the other hand, can be used to separate the cases after ET time. The circular average at the center of the TC also has a consistent pattern for all cases, although some of the TCs that never interact with the preexisting extratropical low reach a minimum value later or never at all. These cases can be separated from the dataset as storms that do not undergo ET. The other advantages to using PV are that it is easy to calculate and generally easy to understand.

Future work on this topic will include a larger dataset of recurving TCs and a more in-depth statistical analysis to better validate that PV is better used as a method for defining the ET life cycle. Also in the future plan is a storm track and intensity forecast model, which may be based on potential vorticity.

Acknowledgements: This work was supported by the National Science foundation under grant ATM-0730079.

5. REFERENCES

Demirci, O., J. S. Tyo, and E. A. Ritchie, 2007: Spatial and Spatiotemporal Projection Pursuit Techniques to Predict the Extratropical Transition of Tropical Cyclones. *IEEE Trans. Geo. Remote Sensing*, **45**, 418-425.

Foley, G. R. and B. N. Hanstrum, 1994: The Capture of Tropical Cyclones by Cold Fronts off the West Coast of Australia. *Wea. Forecasting*, **9**, 577-592.

Evans, J. L. and R. E. Hart, 2003: Objective Indicators of the Life Cycle Evolution of Extratropical Transition for Atlantic Tropical Cyclones. *Mon. Wea. Rev.*, **131**, 909-925.

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. and J. L. Evans, 2003: A Cyclone Phase Space Derived from Thermal Wind and Thermal Asymmetry. *Mon. Wea. Rev.*, **131**, 585-616.

Hoskins, B. J., M. E. McIntyre, and A. W. Robertson, 1985: On the Use and Significance of Isentropic Potential Vorticity Maps. *Quart. J. R. Met. Soc.*, **111**, 877-946.

Jones, S. C., P. A. Harr, J. Abraham, L. F. Bosart, P. J. Bowyer, J. L. Evans, D. E. Hanley, B. N. Hanstrum, R. E. Hart, F. Lalaurette, M. R. Sinclair, R. K. Smith, and C. Thorncroft, 2003: The Extratropical Transition of Tropical Cyclones: Forecast Challenges, Current Understanding, and Future Directions. *Wea. Forecasting*, **18**, 1052-1092.

Klein, P. M., P. A. Harr, and R. L. Elsberry, 2000: Extratropical Transition of Western North Pacific Tropical Cyclones: An Overview and Conceptual Model of the Transformation Stage. *Wea. Forecasting*, **15**, 373-395.

Ritchie, E. A. and R. L. Ellsberry, 2001: Simulations of the Transformation Stage of the Extratropical Transition of Tropical Cyclones. *Mon. Wea. Rev.*, **129**, 1462-1480.

---, and ---, 2003: Simulations of the Extratropical Transition of Tropical Cylones: Contributions by the Midlatitude Upper-Level Trough to Reintensification. *Mon. Wea. Rev.*, **131**, 2112-2128.

---, and ---, 2007: Simulations of the Extratropical Transition of Tropical Cyclones: Phasing between the Upper-level Trough and Tropical Cyclones. *Mon. Wea. Rev.*, **135**, 826-876.

Sinclair, M. R., 2002: Extratropical Transition of Southwest Pacific Tropical Cyclones Part I: Climatology and Mean Structure Changes. *Mon. Wea. Rev.*, **130**, 590-609.