13.3 CHARACTERIZATION OF EXTRATROPICAL TRANSITION USING CLUSTER ANALYSIS

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1. INTRODUCTION

The movement of tropical cyclones from their genesis regions in the tropics into the baroclinic mid-latitudes results in a variety of complex processes. The process by which the original tropical cyclone structure is replaced by a baroclinic structure is termed *extratropical transition* (ET). Tropical cyclones undergoing ET have been responsible for catastrophic inland flooding (DiMego and Bosart 1982a,b), wind-induced wildfires (Foley and Hanstrum 1994), and the sinking of ships at sea (Sekioka 1956).

While there has been an recent increase in research on ET, no quantitative definition of the process is universally accepted. The *Cyclone Phase Space* (CPS), a cyclone structure diagnostic defined by Hart (2003), is a tool that may assist in creating this definition. The three parameters spanning the CPS are the motion relative thickness asymmetry of the storm (B), 600-900 hPa thermal wind ($-V_T^L$), and 300-600 hPa thermal wind ($-V_T^U$). ET is manifested as an increase in the asymmetry of a cyclone ($\delta B>0$) and height falls (increasing with height) in the vicinity of the cyclone core [$\delta(-V_T^L) < 0$ and $\delta(-V_T^U) < 0$] (Fig. 1).

Tropical and extratropical cyclones exhibit distinctly different frontal and thermal characteristics. Thus, these storms reside in unique locations in the CPS making the CPS diagnostic well suited to investigate the evolution of cyclones during ET. Evans and Hart (2003) used the CPS to empirically define the onset (B>10) and completion ($-V_T^L=0$) of ET and found agreement between the empirically determined completion of ET (using numerical model analyses) and the time of ET declaration by the National Hurricane Center (NHC).

Quantitative definitions of ET remain in their infancy. Our goal in this study is to gain insight into the stages of ET using the framework of the CPS. To diagnose the different stages of ET, we seek

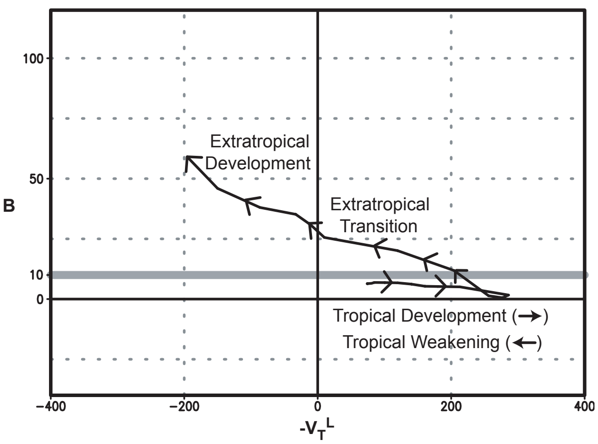

Fig. 1. Idealized CPS representation of ET; B vs. $-V_T^L$ *($-V_T^U$ not plotted for visual clarity).*

objective groupings of CPS observations representing distinct stages of transitioning cyclones in the CPS. We employ the method of non-hierarchical *cluster analysis* (CA) (Anderberg 1973) to objectively determine clusters representing these groups. Finally, we derive a synoptic climatology based on the clusters to identify synoptic patterns prevalent in each stage of ET to map out the synoptic evolution of a transitioning system.

2. DATA ANALYSIS

2.1 Dataset Used

Our dataset consists of 19 Atlantic tropical cyclones that were declared extratropical by the NHC over the years 1998-2002. CPS locations of these cyclones are generated using 12 hourly 1^o analyses from the Navy Operational Global Atmospheric Prediction System (NOGAPS). This dataset corresponds to 388 CPS observations (i.e. individual storm times). A separate dataset consisting of CPS observations from 1^o Global Forecast System (GFS) analysis fields were used for comparison.

2.2 Cluster Analysis

To discern meaningful subregions (structure types) in the CPS, we use the k-means non-hierarchical CA technique of Hartigan and Wong (1979). Non-hierarchical CA is illustrated in Fig. 2. To

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avoid unnecessarily constraining the CA groupings, we chose to generate solutions with 2-10 clusters and then apply statistical tests of significance. A bootstrap resampling technique (Gong and Richman 1995) revealed that the solutions retaining 6-10 clusters were more robust than those retaining 2-5. Next, examining the progression of the within-cluster sum-of-squares for each number of clusters pointed to seven clusters as a statistically significant “break down” of the CPS dataset. We examine this solution in section 3.

2.3 Synoptic Compositing

To create a synoptic climatology of ET in the North Atlantic Basin, we composite model analysis fields from each of the seven clusters. To form these composites, we begin with the original NOGAPS analysis fields (i.e. height, temperature, u, v, etc.) for each observation time in a cluster. Next, noting the location of the cyclone undergoing ET, we regrid the data so that the center of the cyclone is located at the center of the compositing grid. Regridding is accomplished using bilinear interpolation. After regridding all observation times for a given cluster, the fields are averaged to obtain a composite field.

3. CLUSTER ANALYSIS RESULTS

The general location of each cluster, in addition to the NHC classification of cyclones in each cluster is shown in Fig. 3; hereafter the clusters will be referred to by the numbers shown in Fig. 3. This solution partitions the CPS observations into three tropical clusters (1-3), two transitioning/hybrid clusters (4,7), and two extratropical clusters (5-6). The tropical clusters are dominated by highly symmetric (B<10) and warm-cored ($-V_T^L>0$, $-V_T^U>0$) cyclones, while the extratropical clusters are dominated by frontal (B>>10) and cold-cored cyclones ($-V_T^L<0$, $-V_T^U<0$). Cluster 1 should be interpreted with caution because numerous observations in this cluster are from cyclones that have completed transition and have begun the process of warm seclusion, which also creates a lower-tropospheric warm core ($-V_T^L>0$) (Hart 2003). Cluster 4 includes a majority of cyclones in the process of ET, while cluster 7 is a special subset of ET cases for which the transition takes place under stronger thermal gradients.

These cluster characterizations are supported by the dominant NHC categorization of cyclones in each cluster. Cyclones in clusters 2-3 are most often categorized as tropical by the NHC while the majority of cyclones in clusters 5-7 are categorized as extratropical. However there is no dominant categorization for cyclones in clusters 1 and 4. The bimodal nature of cluster 1 (tropical cyclone vs. secluded extratropical cyclone) is supported by the NHC storm summaries for the storm times present in this cluster. The lack of a dominant categorization for cluster 4 cyclones lies in the fact that NHC has no unique classification for cyclones undergoing ET. Instead, tropical cyclones are classified as tropical until ET is complete, when they are declared extratropical. Lacking an intermediate category for the transitioning phase, NHC categorizations of this phase are restricted to either tropical or extratropical (Fig. 3). Perhaps in this framework, cyclones within the cluster 4 domain of the CPS could be defined as “transitioning”, having some characteristics in common with both tropical and extratropical cyclones.

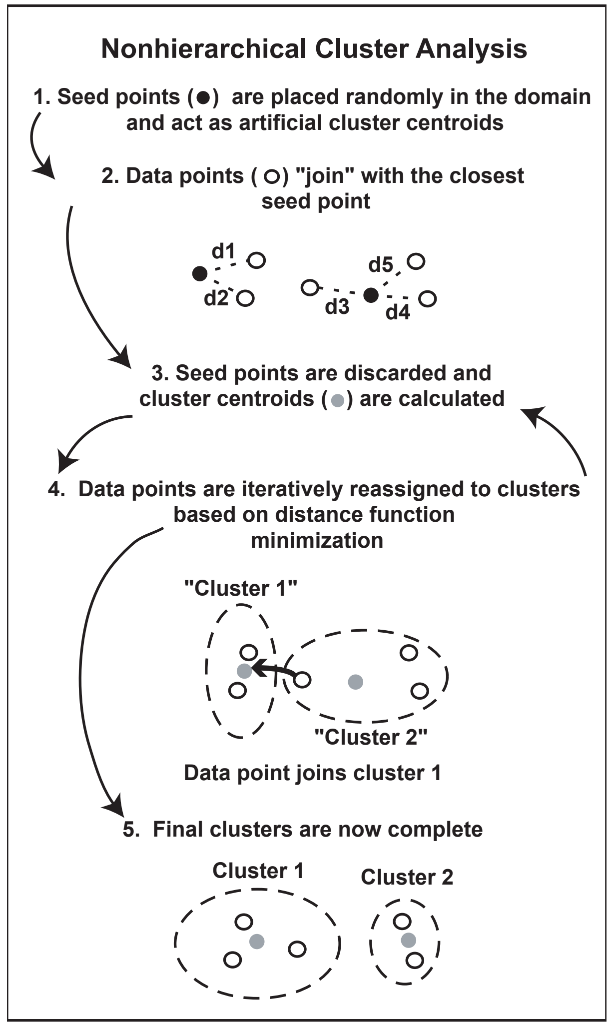

Fig. 2. Flow chart describing non-hierarchical CA.

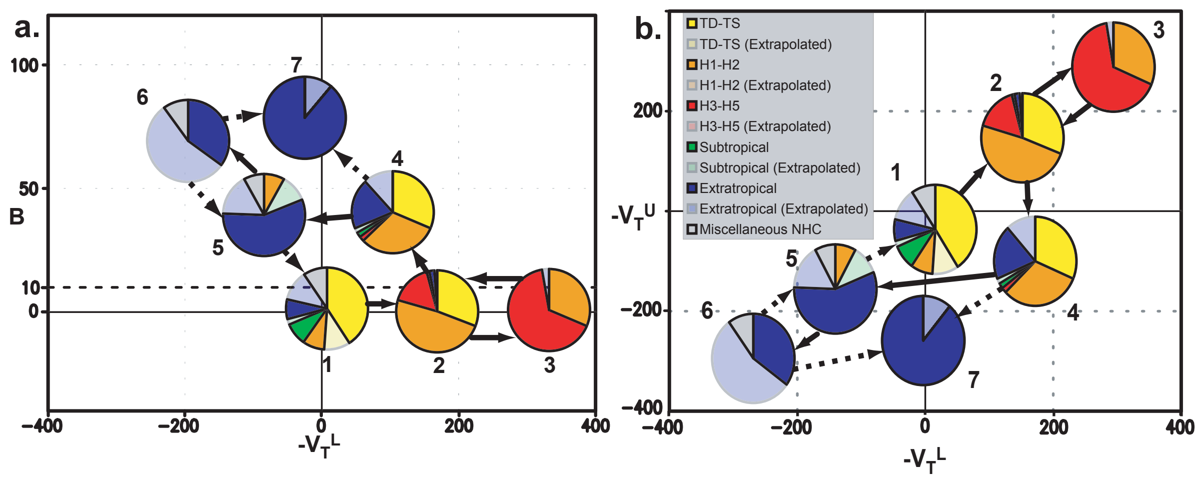

Fig. 3. Comparison of NHC classification with cluster location in the CPS (a) B vs. $-V_T^L$ (b) $-V_T^U$ vs. $-V_T^L$. Each pie represents all observations in a single cluster. Dominant path of ET evolution through the CPS is indicated by the arrows (less frequent transitions are dashed). "Miscellaneous NHC" refers to cyclones classified as "wave", "low", "merged", and "absorbed" by NHC. Extrapolated values (for times before/after NHC classification) given in faded colors.

The domain defining cluster 4 lies along the lines B=10 and $-V_T^L$=0. These are the precise boundaries empirically determined by Evans and Hart (2003) to signal the onset and completion of ET, respectively. When CA was applied to the GFS analyses the same cluster boundaries remained intact, thus providing an objective justification for the use of the clusters as meaningful indicators of the stages of the ET process.

The CPS trajectory taken by the largest number of ET cases is shown by the solid arrows in Fig. 3; less frequent paths are shown by dashed arrows. This path demonstrates that initially, a tropical cyclone strengthens as a warm core system. As the ET process commences, the storm begins to become asymmetric (i.e. frontal) and its warm core weakens. The cyclone completes ET after it becomes cold core and increasingly frontal, two characteristics of typical extratropical cyclones.

4. COMPOSITE SYNOPTIC CLIMATOLOGY

The synoptic composites from clusters 2, 4, and 6 are discussed here. These three clusters represent distinct stages of the ET process. The mean path of ET through the CPS progresses through each of these clusters sequentially. Therefore, analyzing the synoptic patterns associated with these clusters in the context of this mean path will shed light on how the environmental features surrounding the transitioning tropical cyclone evolve during ET.

A distinct tropical low-pressure system, isolated from the mean westerlies to its north is evident in the cluster 2 composite (Fig. 4a). The tropical low is approximately 25^o east of a positively-tilted upper-level synoptic-scale trough that overlies a weakness in the subtropical ridge surface pressure pattern. Cluster 2 cyclones exhibit a vertically stacked positive potential vorticity (PV) anomaly and an isentrope pattern consistent with the vertically aligned warm core associated with tropical cyclones (Fig. 5a).

In the cluster 4 composite, the tropical low pressure system is beginning to become embedded in the mean westerly flow to its north (Fig. 4b). The cyclone, now west-northwest of the subtropical ridge, is recurving. The vertical cross-section (Fig. 5b) shows that the PV anomaly associated with the tropical cyclone has developed a positive (west to east) tilt with height and is larger in horizontal extent. These changes are consistent with the increasing asymmetry (δB>0) of the cyclone. While the isentrope pattern continues to suggest a warm core, the superposition of this pattern on that of the upstream trough (now 15^o west of the cyclone) creates a region of steeply sloped isentropes west of the cyclone, conducive to heavy precipitation (Atallah and Bosart 2003).

The composite cyclone in cluster 6 is no longer a tropical system: the cyclone is now well-embedded in the mean westerlies and is approaching a larger scale surface low-pressure system to its north (Fig. 4c). A positive PV anomaly associated with the cyclone core is broader, and no longer vertically aligned but rather sloping to the west with height (Fig. 5c). A deep cold anomaly associated

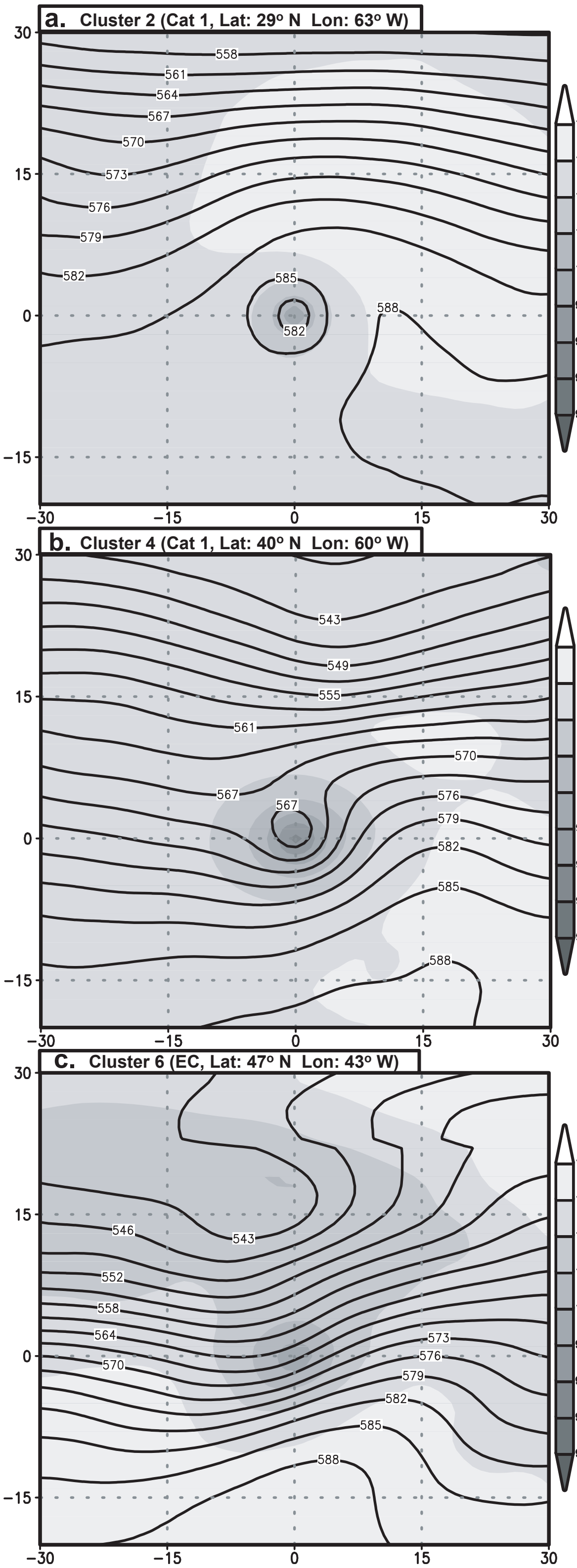

Fig. 4. Sea level pressure (shaded, hPa) and 500 hPa heights (contoured, interval 3dm); (a) cluster 2, (b) cluster 4, (c) cluster 6.

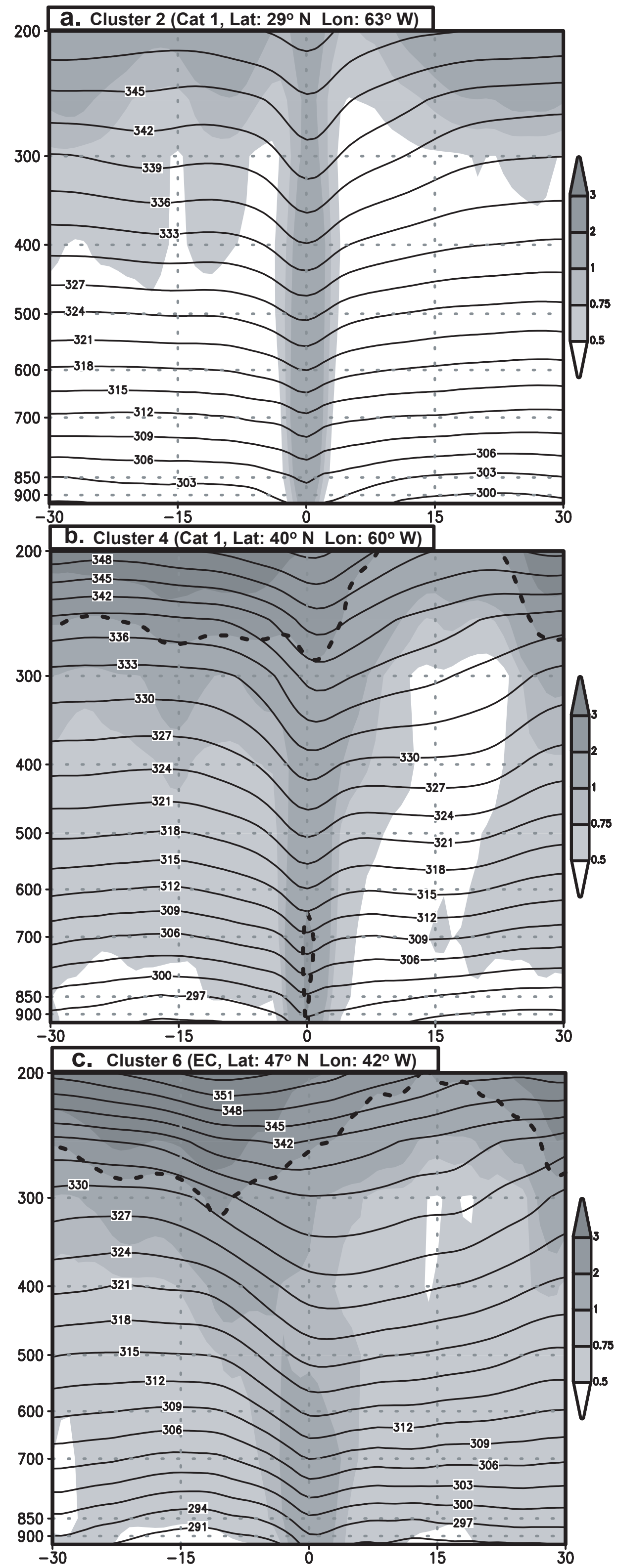

Fig. 5. Ertel's potential vorticity (shaded, PVU, 2 PVU contour dashed), potential temperature (contoured, interval 3K); (a) cluster 2, (b) cluster 4, (c) cluster 6.

with the upper level trough tilts northward with height to the west of the cyclone, with warmer air over the surface low. All of these characteristics are consistent with the structure of a mature extratropical cyclone.

The synoptic evolution implied by the composites suggests that in the “average” case of ET, the tropical cyclone initially develops in the deep tropics, south of the subtropical ridge and strengthens east of an approaching mid-latitude trough (cluster 2). The tropical cyclone reaches its greatest intensity as it rounds the base of the subtropical ridge and comes within 15^{o} of the approaching trough (cluster 3, not shown). As it recurves, the tropical cyclone core remains intact but develops a west to east tilt with height (due to interaction with increasing westerly shear) and begins to merge with the PV pattern associated with the upstream trough (cluster 4). Finally, the upstream trough becomes superposed over the tropical cyclone, their corresponding PV anomalies merge and the overall system becomes baroclinic in appearance (clusters 5 and 6). Accordingly, the newly-born extratropical system may strengthen through baroclinic effects.

5. CONCLUSIONS

A non-hierarchical CA of cyclone structures in tropical cyclones undergoing ET in the North Atlantic over the past 5 years reveals seven separate cyclone structure clusters. A synoptic composite derived using a mean path between the clusters demonstrates that each cluster represents a distinct stage of the ET process. While tropical cyclones (clusters 1-3) and extratropical cyclones (clusters 5-6) are well separated in the CPS and in the clustering results, cyclones residing in cluster 4 (i.e. those in the process of ET) have previously been categorized as either. Cluster 4 contains storms with structure characteristics of both types of cyclones, indicating that neither category completely describes cyclones of this type. The boundaries of this cluster (B=10, $-V_T^L=0$) are consistent with previously proposed quantitative definitions for the onset and completion of ET (Evans and Hart 2003), using both a NOGAPS dataset and a nearly-parallel GFS dataset. Therefore these results provide further motivation for the use of these boundaries in the operational definitions of ET.

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