

SYNOPTIC COMPOSITES OF THE EXTRATROPICAL TRANSITION LIFECYCLE OF NORTH ATLANTIC TCs AS DEFINED WITHIN CYCLONE PHASE SPACE

Robert E. Hart¹ and Jenni L. Evans²

¹The Florida State University, Tallahassee, FL

²The Pennsylvania State University, University Park, PA

1. Introduction

The cyclone phase space (CPS, Hart 2003; Evans and Hart 2003) summarizes the various types of mesoscale to synoptic-scale cyclones into a multi-dimensional continuum. One of the major cyclone lifecycles well-diagnosed within the phase space is the conversion of a symmetric, warm-core cyclone into an asymmetric, cold-core cyclone (extratropical transition). The return period of transitioning or transitioned tropical cyclones is comparable to, or higher than, the return period of purely tropical cyclones in many coastal areas of the middle latitudes (Fig. 1). Therefore, diagnosis and understanding of the ET lifecycle is critical to understanding the climate of the middle latitudes, and the potential threat due to these systems.

The evolution of 15 extratropically transitioning cyclones from 1998 to 2002 will be examined through a composite mean of the CPS evolution, variability about that composite mean CPS trajectory, and composites of the synoptic patterns at various key milestones throughout the ET trajectory. Storms are partitioned into post-transition intensifiers and weakeners; comparison of their synoptic evolution distinguishes key factors affecting post-transition evolution. A preliminary examination of the post-transition impact of synthetic (bogus) vortex insertion during the tropical phase concludes these analyses.

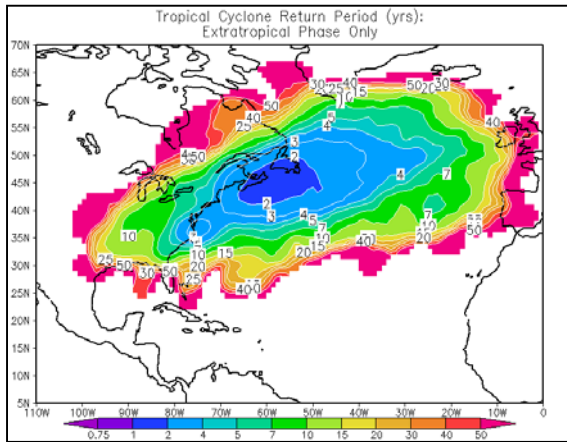


Figure 1: Return period (years) of an extratropically transitioned tropical cyclone passing within 300km of a given location, from 1950-1999 NHC best-track dataset.

Corresponding author address: Robert Hart, Florida State University, Department of Meteorology, 404 Love Building, Tallahassee, FL 32306-4520. Email: rhart@met.fsu.edu

2. Methodology

Operational NCEP AVN and Navy NOGAPS 1° analyses are used to calculate CPS trajectories for each of the 15 storms considered. The objective starting (T_B) and ending (T_E) times for extratropical transition (as defined by Evans and Hart 2003) are used as reference points for compositing the entire ET cyclone phase trajectory. Two additional points are also examined: T_B-24 (24hr prior to the start of transition), and T_E+24 (24hr after the end of transition). Compositing of synoptic fields is done using storm-relative coordinates, although no accounting for storm motion (coordinate rotation) is performed. The storms used in this study, and their post-transition (T_E to T_E+24h) intensity tendency, are listed in Table 1.

Storm Name	Year	Δ MSLP from T_E to T_E+24
Bonnie	1998	Weakened
Danielle	1998	Strengthened
Earl	1998	Weakened
Mitch	1998	Strengthened
Floyd	1999	Weakened
Gert	1999	N/A
Irene	1999	Strengthened
Alberto	2000	Neutral
Gordon	2000	Strengthened
Isaac	2000	Neutral
Michael	2000	Weakened
Allison	2001	Strengthened
Michelle	2001	N/A
Gustav	2002	Weakened
Isidore	2002	Neutral

Table 1: List of storms, their year of occurrence, and the immediate post-transition intensity change that occurred. A MSLP pressure change over the 24hr period of $-(+)$ 4hPa was required to classify as strengthening (weakening). N/A indicates available operational analyses ended prior to T_E+24h or the storm was absorbed by a preexisting cyclone or trough.

3. Mean ET Phase Evolution & Variability

For all fifteen cyclones, the mean CPS values of T_B-24 , T_B , T_E , and T_E+24 were determined to define the mean phase trajectory for extratropical transition (Figure 2). These calculations were based upon grids from the operational NCEP AVN analysis. While there is model/analysis dependence, the NOGAPS-based composite was qualitatively similar (not shown). One day prior to the start of transition (T_B-24), the cyclone has

achieved its strongest warm-core structure, on average. This also indicates that a typical transitioning cyclone has been weakening for only 24hr before transition begins (in agreement with Hart and Evans 2001), suggesting that most tropical cyclones are still relatively intense when first becoming frontogenetic. The mean transitioned cyclone reaches the strongest cold-core structure (including associated significant baroclinic tilt; Hart 2003) approximately 24hr after transition completes (T_E+24).

While the evolution from warm-core symmetric to cold-core asymmetric (with a period of hybrid status) is well-defined by the 15-member composite trajectory (Figure 3). The variability in the tropical phase occurs primarily in the strength of the warm-core (parameter $-V_T^L$), rather than the thermal asymmetry (parameter B). The variability about the mean value of B about the point T_B is necessarily minimal, since this point has been defined a priori (Evans and Hart 2003). Once transition completes, variability increases dramatically, becoming a maximum 24hr after transition. This variability illustrates the large range of cyclone structure that can occur once ET has completed (Figure 4). The factors dictating the type of post-transition evolution are under investigation.

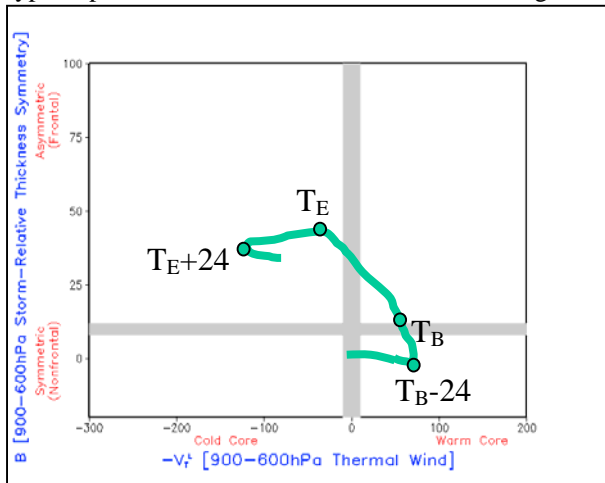


Figure 2: 15-cyclone composite mean cyclone phase trajectory.

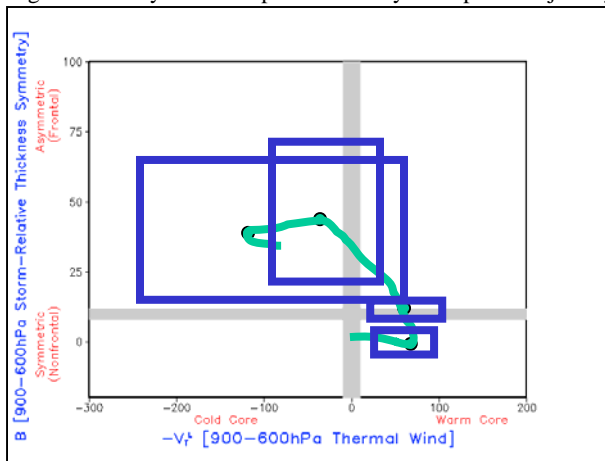


Figure 3: One-standard deviation variability about the mean trajectory shown in Figure 2.

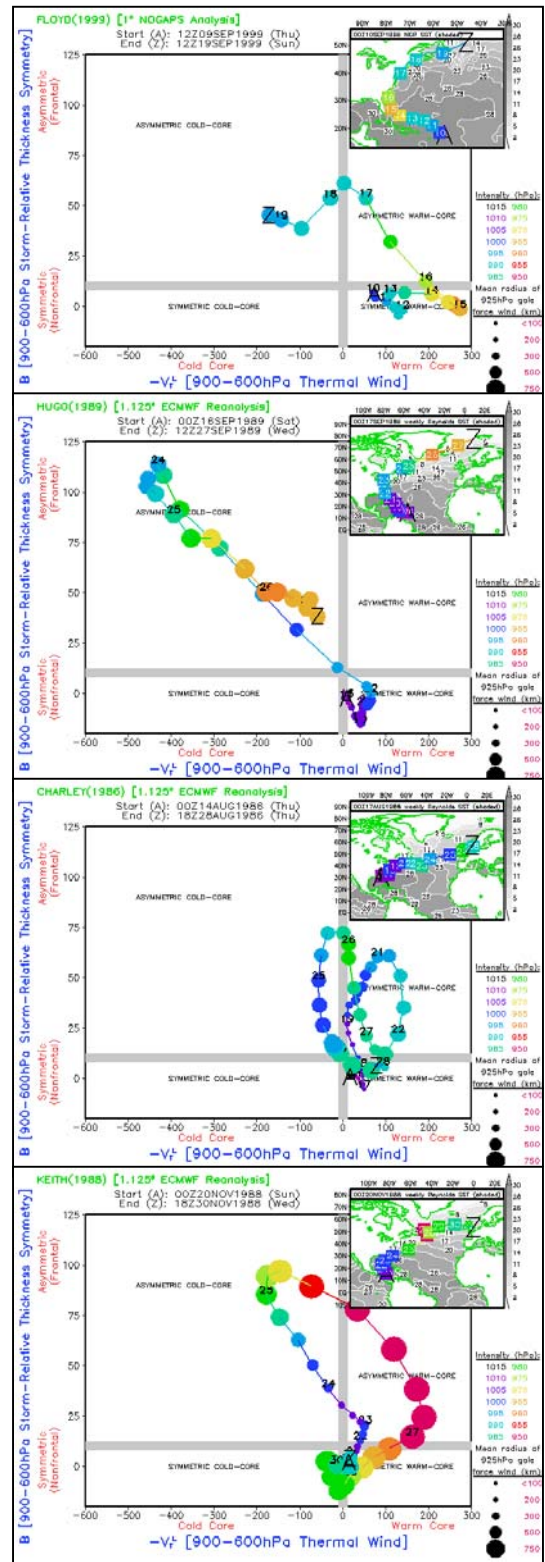


Figure 4a-d: Four examples (including some outside the analyzed data period) of the type of variability exhibited in the post-transition phase, and quantified in Figures 2 and 3. Percentages indicate preliminary estimates of fraction of ET distribution undergoing that post-tropical evolution from a larger ECWFM/NCEP reanalysis dataset. a) Floyd (1999), non-intensifying cold-core development (40%); b) Hugo (1989), Explosive cold-core development (25%); c) Charley (1986), extended hybrid existence (20%); and d) Keith (1988), Explosive warm-seclusion development (15%).

4. Synoptic composites

Synoptic composites of the mean 500hPa, 700hPa, K-index, and meridional PV/potential temperature-cross section are shown below for each of the four ET lifecycle milestones (T_B-24h , T_B , T_E , T_E+24h) discussed in Section 3. Since there is a highly varying range of latitude, longitude, and month of occurrence in the 15 events, the composite mean 500hPa anomaly from the 30-year NCEP/NCAR reanalysis (Kalnay et al. 1996) climatology is also provided. These composites are shown to illustrate the evolving mean structure associated with transitioning cyclones, and the environmental features that are driving those cyclone changes. Note the figures precede the discussion for each case.

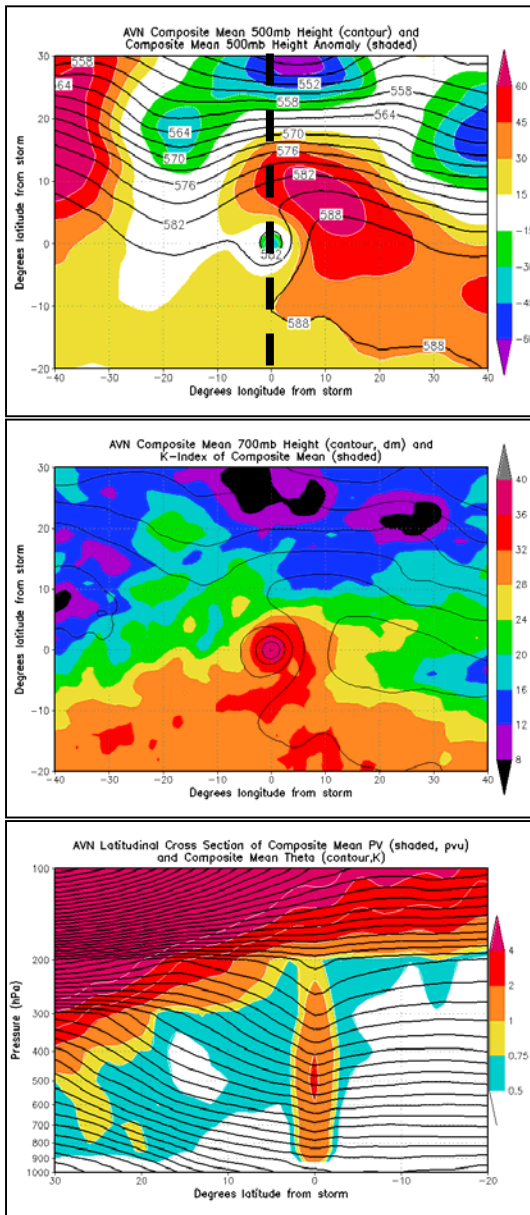


Figure 5: Composite mean for time T_B-24h for a) 500hPa height (contour) and anomaly from 30-year mean (shaded); b) 700hPa height (contour) and K-index (shaded); c) latitudinal cross section of PV & theta, location along the dashed line in (a).

a. T_B-24hr : Tropical phase

One day prior to the start of transition (Figure 5), the cyclone is near peak warm-core intensity (in terms of cyclone phase; Figure 2), and has yet to be influenced by or interact with the upstream trough. There is no noticeable tilt of the tropical cyclone at this point, but the cyclone does appear to mark the weak division between two distinct air masses (note the changing slope of the potential temperature lines either side of the TC in Figure 5c). Further note that the maximum level of potential vorticity at this time is in the middle troposphere (600-500hPa), while it is at a considerably lower height by the time T_B (Figure 6). This is more likely to be an indication of the accuracy of cyclone representation within the operational analyses than of the true cyclone. As the cyclone moves poleward and transition begins, the cyclone experiences a growth in size and is thus more accurately resolved by the 1° operational analyses.

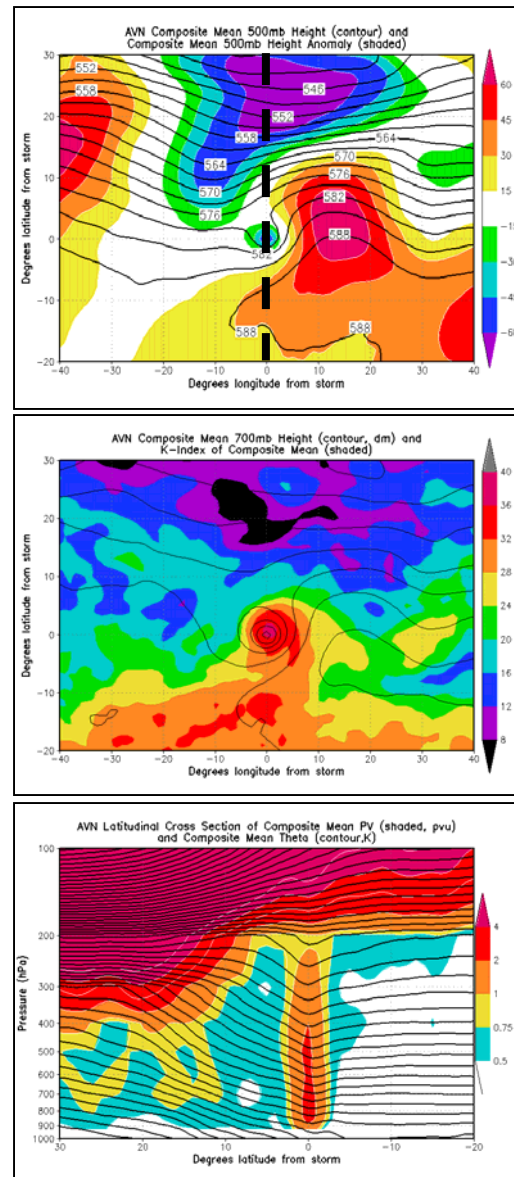


Figure 6: As in Figure 5, except for time T_B .

b. T_B : Transition begins

At this point the value of B has first exceeded 10m, representing the formation (or introduction) of a significant temperature gradient across the cyclone. At 500hPa, the upstream trough has amplified considerably (both in terms of absolute magnitude and climatological anomaly; Figure 6a), and the tropical cyclone is now positioned approximately 8-10° from the trough axis, a distance consistent with Hanley et al. (2000) for trough-TC interaction. The downstream ridge, which has been moving poleward with the TC, is now being halted by the advancing trough and has lead to dramatically increased gradients northeast of the TC. The impact of shear is first being noticed on the TC, with location of most unstable air now displaced northeast of the height minimum (Fig. 6b).

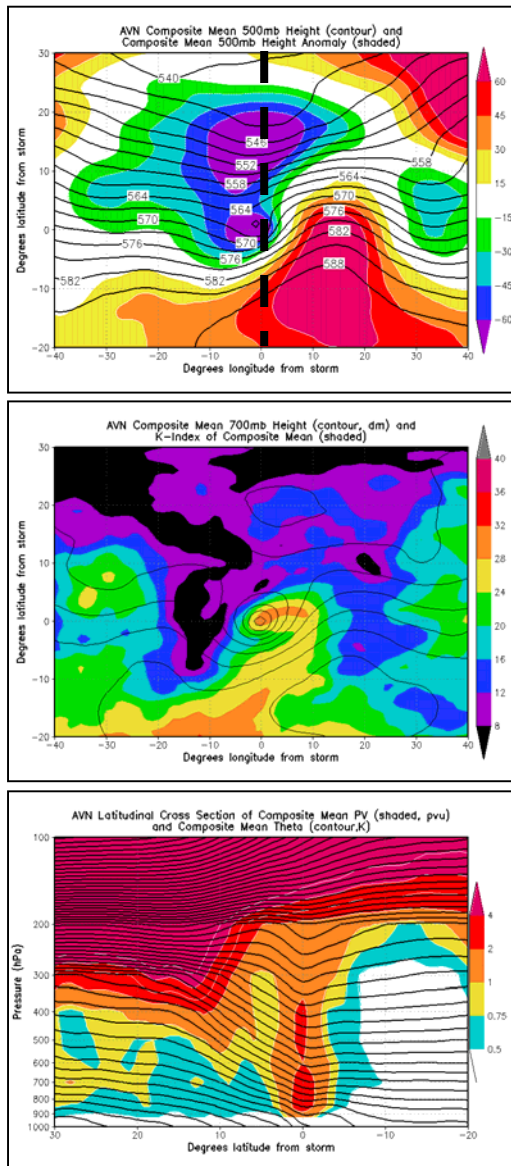


Figure 7: As in Figure 5, except for time T_E .

c. T_E : Transition ends

Once the cyclone has reached a thermal wind structure that signifies cold-core tropospheric structure ($-V_T^L < 0$), transition is declared to have completed (T_E , Figure 7). At 500hPa, the TC has clearly merged with the trough in such a position that there is a slight negative tilt of the trough axis (Fig. 7c). There remains substantial unstable air over and downstream of the cyclone, and a large amount of dry, cool air has advected equatorward just west of the cyclone (Fig. 7b). The tropopause has lowered considerably just upstream of the cyclone, apparently the result of both the poleward movement of the cyclone and the constructive interaction between the cyclone and the trough. The increase in size of the cyclone is also apparent in the meridional PV cross section (Fig. 7b).

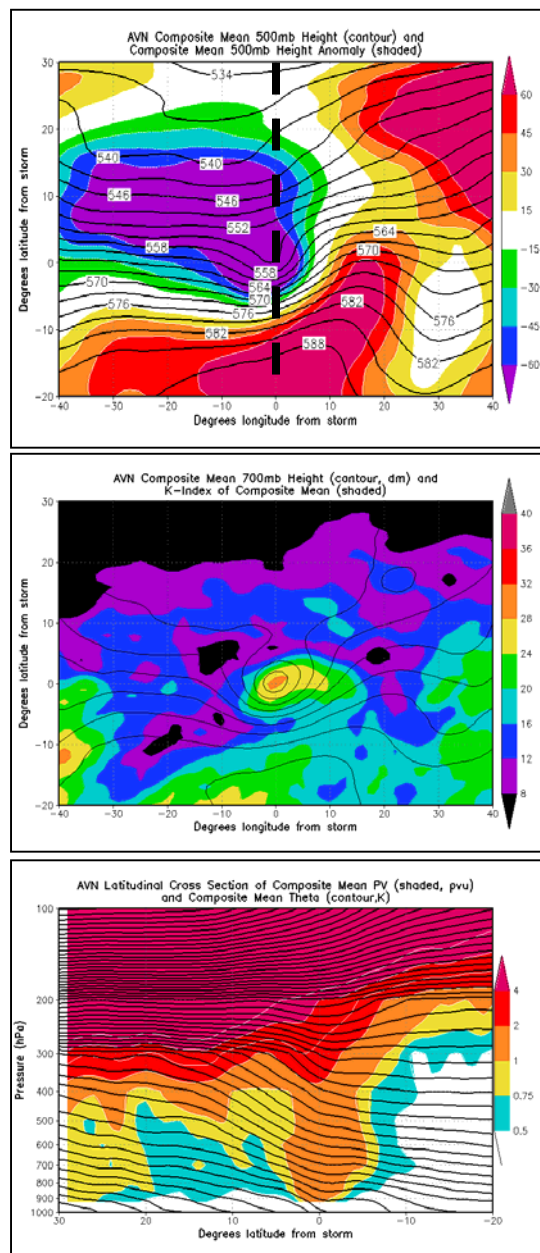


Figure 8: As in Figure 5, except for time T_E+24 hr.

d. T_E+24 hr: Post-tropical

As the cyclone has continued to evolve into a tilted baroclinic system, the TC-remnant low-level PV anomaly has been weakened and the size has continued to expand. The mid-level unstable TC remnant air remains at the baroclinic cyclone core, consistent with cases examined by Thorncroft and Jones (2000). The trough at 500hPa is negatively tilted, and this has aided the growth of the downstream ridge. Dry air to the west of the cyclone at T_E has begun to wrap around the southern side of the cyclone by T_E+24 hr. When the dynamics favor explosive development, the cool, dry air to the west wraps around the cyclone center so quickly that the warm, moist TC remnant becomes trapped, leading to a warm seclusion (Fig. 4d; see also Shapiro and Keyser 1990).

5. Intensity change subcomposites

The fifteen ET events are further partitioned based upon the MSLP minimum change between the time T_E and T_E+24 . The composited analyses (Figure 9) are for the start of transition, T_B . Given the number of events in each category, the results shown here are only preliminary. However, further examination using a longer dataset with more events is ongoing and reveals patterns similar to those shown here.

The cases where the cyclone weakened after transition (Fig. 9a) exhibited, in the mean, the strongest tropical cyclone structure and the shortest distance between the trough and the cyclone itself. These are generally the cases where the TC attained such high intensity that when rapidly entering the middle latitudes, weakening was the only possible recourse since the time of year precludes baroclinicity of sufficient magnitude to support such low MSLP (the rapidly moving cyclone may have exceeded any maximum potential baroclinic intensity). The short distance from the trough also may be too short for baroclinic development, and also positioning the cyclone in a region of higher wind shear.

Storms that have mostly unchanged intensity just after transition completes are associated with, on average, the strongest and most amplified middle latitude trough. The TC is slightly further from the trough axis, but still not sufficiently distant for optimal interaction. The TC intensity at T_B is also weakest of the three composites, further decreasing the potential for constructive interaction. The strongly positive tilt of the upstream trough suggests that wind shear over the TC would be considerably less than in Fig. 9a, arguing for advection of the TC by the mean flow without significant interaction

A transitioned TC that undergoes intensification between T_E and T_E+24 (Fig. 9c) interacts with a trough that is neither exceptionally strong nor amplified. The separation distance at T_B between the trough and TC is the largest of these subsets, and the orientation of the downstream ridge prevents the cyclone from outrunning the trough. The preliminary results shown here confirm the arguments of ideal scale-interaction necessary for constructive vortex interaction (Kimball and Evans 2002).

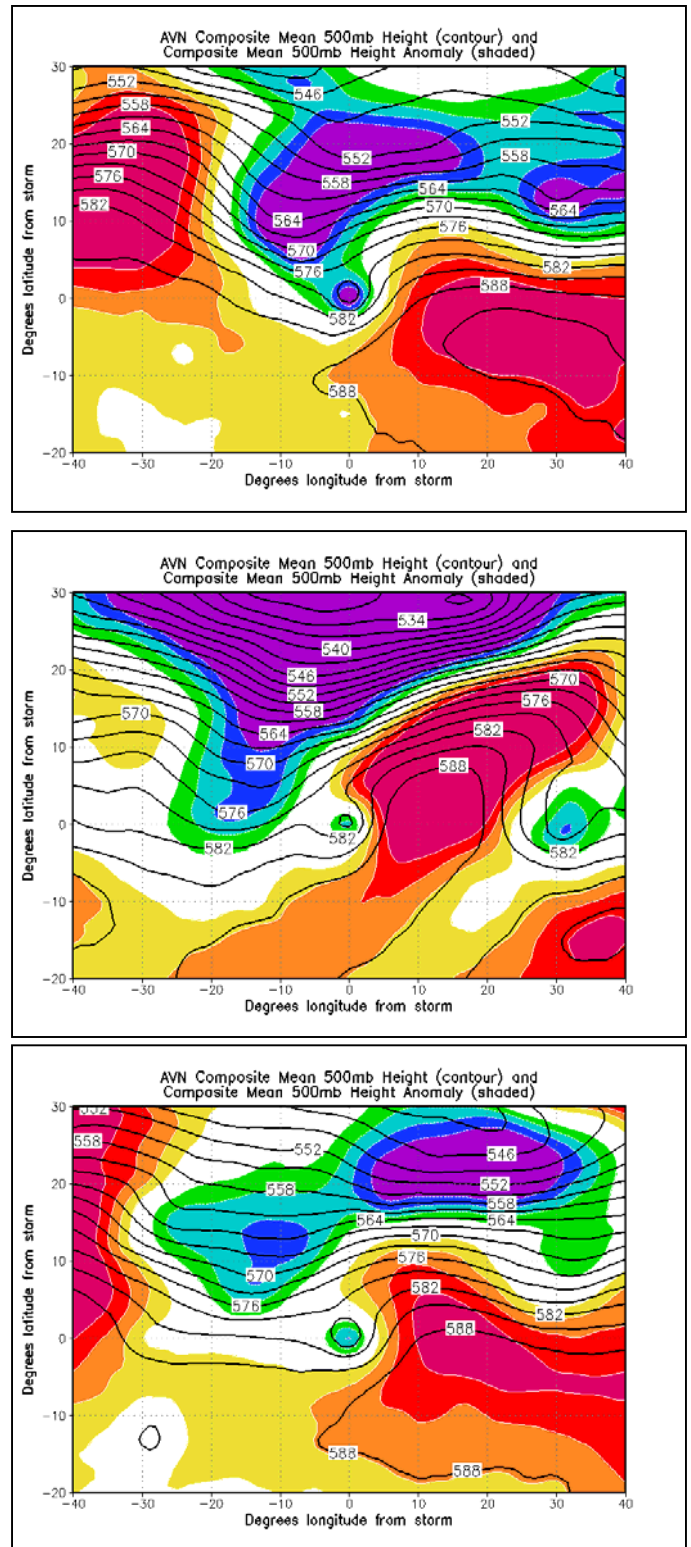


Figure 9: Composite mean 500hPa height (contour) and anomaly from the 30-year NCEP/NCAR reanalysis mean (shaded) at the start of transition (T_B) for a) cyclones that weakened more than 4hPa between T_E and T_E+24 hr; b) cyclones that did not change intensity by more than 3hPa; and c) cyclones that strengthened by at least 4hPa. The number of cases for each subset is 5, 3, and 5, respectively. See Table 1 for a listing of the storms comprising each group.

6. Potential impact of bogus.

In regions of the globe where there are minimal observations, the model first-guess (usually 12hr forecast from the previous run) plays an enormous role in dictating the future analyses. Further, the post-tropical impact of a bogus (synthetic) vortex insertion during the tropical phase of a cyclone is a question that has remained unanswered in this context. This significance cannot be overstated, since the use of an unrealistically symmetric, warm-core vortex too far after T_B may contaminate the resulting post-tropical lifecycle. By comparing a 2000-2002 subset of operational analyses at the time T_E+24 (when bogussing has long ceased) among two operational centers, we can begin to address this issue.

During the period 2000-2002, the NCEP AVN used primarily vortex relocation to initialize a TC, such that only observations and model physics were allowed to change the structure of the vortex. Conversely, during the same period, the Navy NOGAPS used a strong bogussing routine to initialize TCs. If there is a significant impact at latter times by utilizing the bogussing technique, it would be apparent in the structure of the analyzed cyclone at T_E+24 and beyond. As shown in Figure 10, the NOGAPS-based analyzed vortex at T_E+24 is fundamentally of different structure than that analyzed in the AVN. While the differences are striking and argue that the bogus is influencing the cyclone structure at later times—well after bogussing itself has ceased—the sample size of eight storms (Table 1) also argues that further examination is required.

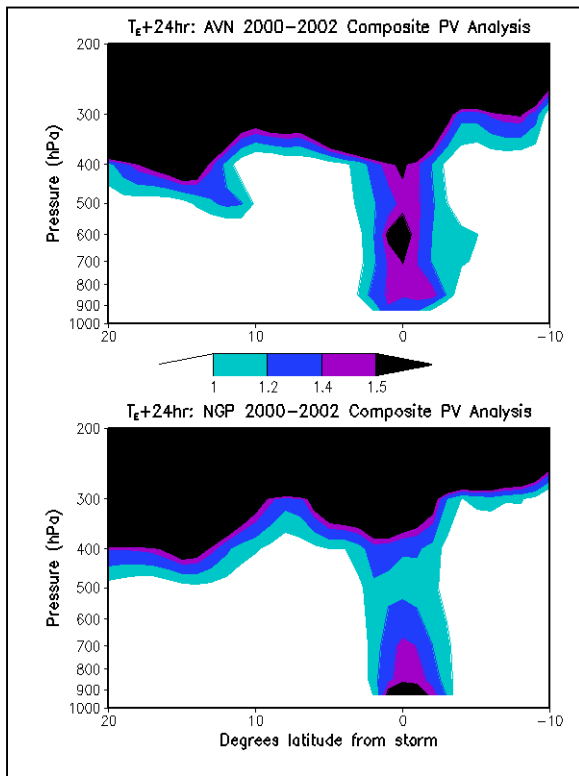


Figure 10: Comparison of analyzed PV cross section at T_E+24 hr for a) 2000-2002 AVN subcomposite and b) 2000-2002 NOGAPS subcomposite.

7. Concluding Summary

A well-defined 15-member ensemble mean trajectory through cyclone phase space is defined for extratropical transition in the North Atlantic. Variability from this mean trajectory is small in the tropical phase, and then increases dramatically once extratropical transition has completed. The TC reaches peak warm-core intensity within the CPS around or just after T_B-24 h. The unstable cyclone core remains through transition to T_E . Low-level PV maximum is weakened but expands outward, and upper level PV maximum grows downward over and just upstream of surface cyclone, from T_E to T_E+24 hr. Complex structural differences in the TC and its environment exist between events where cyclones weaken, remain neutral, or intensify after transition. TC intensity, trough intensity and tilt, and separation distance all modulate the post-tropical intensity change. It remains to be answered what dictates the structure of the resulting post-tropical cyclone: cold-core, hybrid, or warm-seclusion, although there has been considerable examination of this question in recent case studies (Harr et al. 2000; McTaggart-Cowan et al. 2003).

Since a model first guess is heavily influenced by the previous short-term forecast, the inclusion of a synthetic vortex prior to and during ET can significantly alter the resulting analyses after bogussing has ceased. If a synthetic vortex improves model analysis and forecast representation of reality, it is uncertain at what point between T_B-24 hr and T_E bogussing should be ceased to maximize forecast skill of cyclone structure and intensity.

8. Acknowledgements and References

The first author was partially supported by a UCAR Visiting Scientist Position arranged through NCEP, and by Penn State Univ. Dept. of Meteorology.

- Evans, J.L. and R. Hart, 2003: Objective indicators of the extratropical transition lifecycle of Atlantic tropical cyclones. *Mon. Wea. Rev.*, **131**, 909-925.
- Hanley, D., J. Molinari, D. Keyser, 2001: A Composite Study of the Interactions between Tropical Cyclones and Upper-Tropospheric Troughs. *Mon. Wea. Rev.*, **129**, 2570-2584.
- Harr, P., R. L. Elsberry and T. Hogan, 2000: Extratropical transition of tropical cyclones over the western North Pacific. Part II: The impact of midlatitude circulation characteristics. *Mon. Wea. Rev.*, **128**, 2634-2653.
- Hart, R., 2003: A cyclone phase space derived from thermal wind and thermal asymmetry. *Mon. Wea. Rev.*, **131**, 585-616.
- Kimball, S. K., J.L. Evans, 2002: Idealized Numerical Simulations of Hurricane-Trough Interaction. *Mon. Wea. Rev.*, **130**, 2210-2227.
- McTaggart-Cowan, R., J.R. Gyakum, M.K. Yau, 2003: The Influence of the Downstream State on Extratropical Transition: Hurricane Earl (1998) Case Study. *Mon. Wea. Rev.*, **131**, 1910-1929.
- Shapiro, L. J., and D. Keyser, 1990: Fronts, jet streams, and the tropopause. Extratropical Cyclones: The Erik Palmén Memorial Volume, C. W. Newton and E.O. Holopainen, Eds., *Amer. Meteor. Soc.*, 167-191
- Thorncroft, C. and S. C. Jones, 2000: The extratropical transitions of Hurricanes Felix and Iris in 1995. *Mon. Wea. Rev.*, **128**, 947-972.