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Downstream Development during the Extratropical Transition of Tropical Cyclones: Observational Evidence and Influence on Storm Structure

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1. Introduction

The multi-scale interactions and system-structure transformations make ET a difficult scientific and forecast problem. The high impact of ET events on shipping and coastal communities is a strong motivation for improved understanding and prediction (Jones et al., 2003). The role of trough interaction has long been identified as a critical feature driving ET (Brand and Guard 1978; Harr and Elsberry 2000; Hanley et al. 2001; Hart and Evans 2001; Klein et al. 2002; Ritchie and Elsberry 2001, 2003). However the precise nature of the trough interaction remains somewhat unclear. Evans et al. (2000) and Jones et al. (2003) have shown that the global long-wave pattern predictability becomes dramatically decreased when a TC moves into the middle latitudes. This decrease in predictability is likely associated with the TC-trough interaction, but also possibly with the difficulty in prediction of components of the developing high-amplitude, long-wave pattern (eg, prediction of the source perturbation and then the wave propagation). An important aspect described in Ritchie and Elsberry (2007) is the phasing between the storm and the upper trough, which can change the degree of interaction between the two weather systems. We will provide evidence that it may be better to view ET as the interaction of a TC with a Rossby wave, since the initial interaction is with the ridge portion of the wave, similar to the remote trough interaction, described by Hanley et al. (2001). The storm then eventually interacts with the trough and upper jet of the wave.

To partially avoid the ET definition issue, we will use the case studies in Davis et al. (2008) and Fogarty et al. (2006) to illustrate some of the processes we think are occurring during ET. The key characteristics of ET are summarized in the conceptual models of Klein et al. (2000) and Davis et al. (2008) and include: large 200-850hPa wind shear; increase in size of the TC vortex; transition from warm to cold core; development of thermal asymmetries; enhanced vertical mass flux; movement from favourable, low-shear TC environment to a favourable extratropical environment often at the equatorward, entrance to an upper jet. We will illustrate that all these characteristics are consistent with the conceptual model that we propose here.

A key question is: “How does the Tropical Cyclone survive the very large environmental vertical wind shear it experiences as it moves towards the favorable, equatorward entrance region of the jet, located on the eastern flank of the upper trough?” Davis et al. (2008) propose that (i) resistance to shear depends critically upon diabatic processes, and (ii) resistance can be achieved by either altering vortex structure, forming a new vortex center, or by baroclinic cyclogenesis. They also find that diabatic processes systematically offset the effects of shear and that the vertical mass flux is larger during ET than during the mature hurricane phase. Results from our study are consistent with these findings. Our extension is to document the Downstream Development, DD events that commence prior to ET and describe how these can influence the behaviour of the vortex and embedded convection. Specifically, we suggest that the DD event can (a) establish favourable conditions of a developing low level cyclonic environment, which can capture the storm, (b) influence the ascent field within the storm and hence the behavior of embedded convection and vertical mass flux, (c) develop a new vortex center, which can be independent of, or rapidly merge with the TC vortex, and (d) produce enhanced horizontal low-level moisture flux to influence convection and the vertical mass flux.

2. Observational analysis

Observed tracks and intensities of three ET events and one non-ET event (Rita) are shown in Fig. 1. We will mostly focus here on Maria as an illustrative example. We use 6-hourly NCEP re-analysis data (2.5°×2.5°) to understand the different synoptic characteristics between ET and non ET cases.

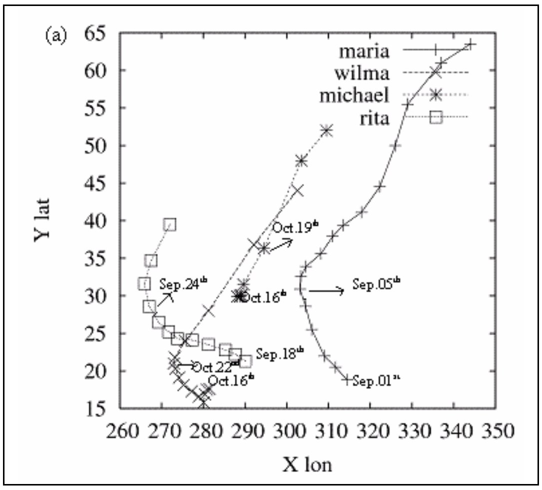

Figure 1. Tracks of three ET Hurricanes (Maria, Wilma, Michael) and one non-ET Hurricane (Rita). Approximate time of ET and recurvature (Rita) are indicated by the arrows and corresponding times.

a. 200hPa and 850hPa wind field

For Hurricane Maria the evolution from pre-ET to post-ET is shown in Figs. 2 (200 hPa) and 3 (850 hPa). During ET and recurvature, the troughs at 200 hPa over high latitudes have moved eastwards and deepened, so that the flow has become markedly more meridional with large-amplitude troughs and ridges. Meanwhile the hurricane has moved northward and begun to approach the upper trough, but is still located within the region of the upper ridge. At 850hPa, two anticyclones strengthen to the east and west of the TC (Fig. 3). The anticyclone to the east is producing warm and moist advection (not quantified here). The flow from the southeast originates over the warm tropical oceans at low latitudes. The development of the anticyclone to the west of the hurricane is producing cold and dry advection from the north. Such patterns of warm, moist advection to the east and cold, dry advection to the west have been documented in many ET events (eg, Klein et al., 2000) and are likely to (i) assist in forcing asymmetries in cloudiness, and (b) establish a large-scale, low-level cyclonic environment for the hurricane to move into. We suggest that these evolving large-scale patterns are crucial for ET, are related to the evolving DD event, and are consistent with observed structural changes.

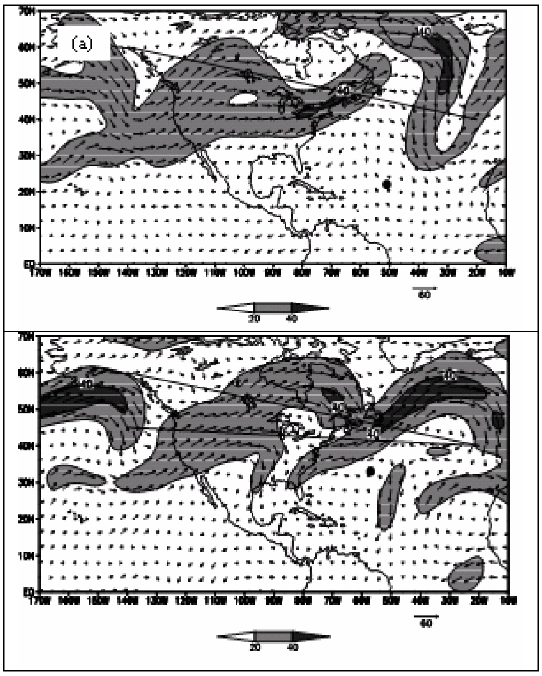

Figure 2. ET 200 hPa wind analyses for pre- and post-ET Maria, indicated by the black dots. Units are m/s and 20 m/s and 40 m/s isotachs are shaded.

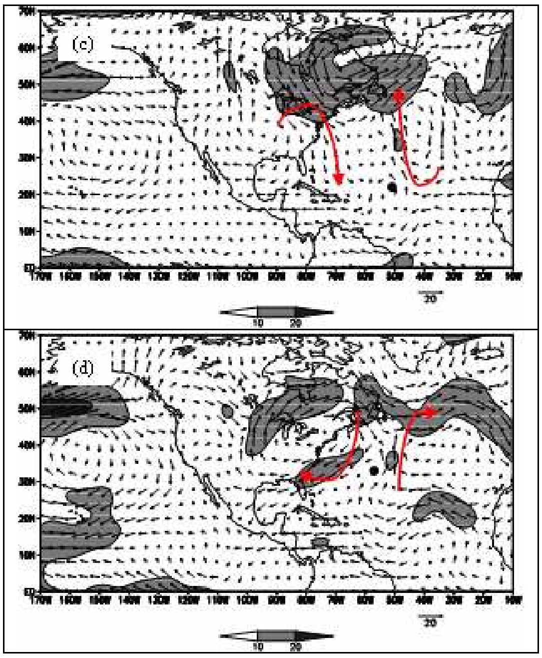

Figure 3. ET 850 hPa wind analyses for pre- and post-ET Maria, indicated by the black dots. Units are m/s and 20 m/s and 40 m/s isotachs are shaded.

b. Vertical structure changes during ET

To illustrate the vertical structure changes during ET, Fig. 4 shows cross-sections of potential vorticity (PV) for Maria along the skewed lines drawn in Fig. 2.

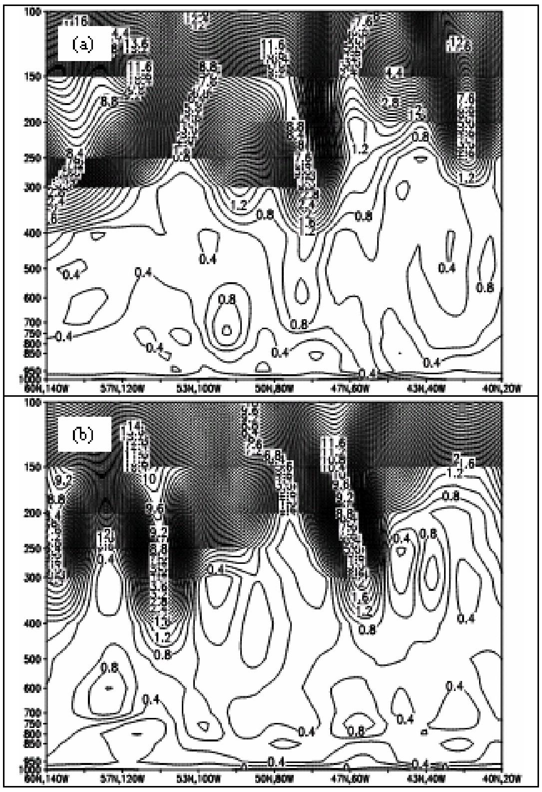

Figure 4. Pre- and post-ET vertical cross sections of Potential Vorticity for Hurricane Maria, along the lines shown in Fig. 2.

The amplification of large-scale troughs and ridges is clearly evident from pre-ET to post-ET. The trough upstream of Maria moves east and deepens as it and Maria approach one another. Strong ascending motion (not illustrated here) is observed around the hurricane from pre- to post-ET. At this time, it is not possible to tell if the increased ascent is associated with the large-scale trough or with latent heat release associated with the active moist processes occurring in the storm.

c Amplification and Propagation of Rossby Waves during ET

Based on the above discussion, a crucial aspect of ET appears to be the downstream amplification and propagation of an upper tropospheric Rossby wave train. To illustrate the wave pattern and development associated with ET, we use time-longitude sections (Hovmoller diagrams) of stream function anomaly at 250 hpa. Note that this choice of variable highlights the smoothed, large-scale structures of vorticity and thus is particularly appropriate for illustrating the downstream development of troughs and ridges discussed above. Figure 5 shows for Maria, Hovmoller diagrams of stream function anomaly for a 10-day period prior to and during the ET. On the diagram the location of the hurricane at ET is marked by the black dot. The arrow sloping from bottom left to top right indicates the propagation and amplification of troughs and ridges, marked by T's and R's.

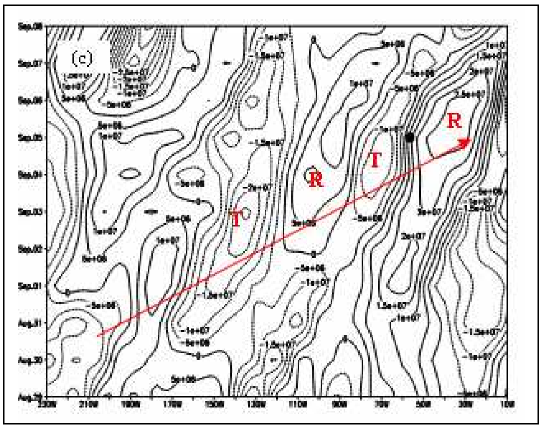

Figure 5. Time-longitude section of Stream Function Anomaly at 45N on 250hPa level for Maria. The arrow shows the propagation direction of the trough/ridge wave train. The black dot is the position of the hurricane at ET time.

Downstream development is clearly evident with troughs and ridges developing eastward in time. For ET cases, the storm is located on the eastern flank of the upper trough. For the non-ET case, the storm is located just to the west of the ridge axis and some 1500 km from the upstream trough axis (not illustrated). The group propagation (Cg) of the wave train for each case is of the order of 30 m/s, while the phase speed (Cp) of the individual troughs and ridges is approximately 6 m/s. Comparison of theoretical values of Cp and Cg, based upon barotropic, linear dynamics does not give good agreement with the estimated/observed values. The reasons for the difference remain unclear, however we speculate that the assumption of barotropic flow in a clearly baroclinic environment, and the presence of large diabatic effects may alter the behaviour of waves from that predicted by linear barotropic dynamics.

2. Simulations

To further illustrate the influence of the downstream development, we have designed numerical experiments with the Australian Bureau of Meteorology's Operational Limited

Area Prediction System, LAPS (Puri et al., 1997), and its configuration for TC applications, TC-LAPS (Davidson and Weber, 2000). We use the latter configuration, which employs vortex specification and dynamical nudging to initialize the vortex, to make a 0.15^0, 29 level simulation for Maria. This simulation is used to check that the model can re-produce the observed characteristics of the ET. In this way we verify that the initial and boundary conditions contain the necessary information to produce the ET. Then to isolate the environmental flow changes from the effects of the vortex and associated diabatic processes, we run a dry, coarse resolution (1.5^0, 29 level) simulation with the Maria circulation removed from the initial condition. In this way only the large-scale environmental features are preserved. We will call this the Large Scale Environment, LSE simulation. By comparing the two simulations, we can at least to a first approximation understand how the environmental flow changes might be influencing the behaviour of the vortex.

Global reanalysis data are used in all simulations. The vortex specification and nudging initialization are described in Davidson and Weber (2000). Figure 6 shows observed and simulated tracks and central pressures from the TC-LAPS simulation. The skill in both the simulated track and intensity is clearly evident. The simulated structural changes during ET are not illustrated, but can be summarised as follows. At t = 0, the storm is isolated from midlatitude influences and moving northwestwards in weakly sheared flow (implied from the wind field at 200 hPa, Fig. 2). At t = 72 hours, the storm is embedded in a very large low-level trough, consistent with its increased size during ET, and moving in strongly sheared flow. A frontal-like structure is evident in the ascent field, which is becoming asymmetric about the circulation center with the main region of strong ascent developing to the north of the circulation. Note that even though the shear is strong (and strengthening) at t = 72 hours (of the order of 15 m/s), the system continued to intensify.

Results from the LSE simulation are illustrated in Fig. 7, which shows the mean sea level pressure field at simulation times, t = 0 and 48 hours. The black dot in the figure marks the observed location of the storm. Note that at t = 0, the Maria vortex has been removed from the initial condition and that at subsequent times there is no tendency for the circulation to re-appear in the simulation. During the simulation and as observed, a large scale trough builds just west of Maria, while a ridge develops to its east and northeast. Maria's motion towards the northwest is consistent with the development of these two features. Even though the simulation is dry, the trough and eventually a low pressure system develop to the northwest of Maria. The simulation is able to reproduce the observed ridge-trough-ridge structure through dry, baroclinic and downstream development processes discussed earlier. We suggest that the development of such structures, which appear to be mostly associated with the dry dynamics, is crucial for the ET of Maria. They provide favourable large-scale conditions for the maintenance of the Maria vortex and eventually the transition and/or merger of the vortex with a developing extratropical low.

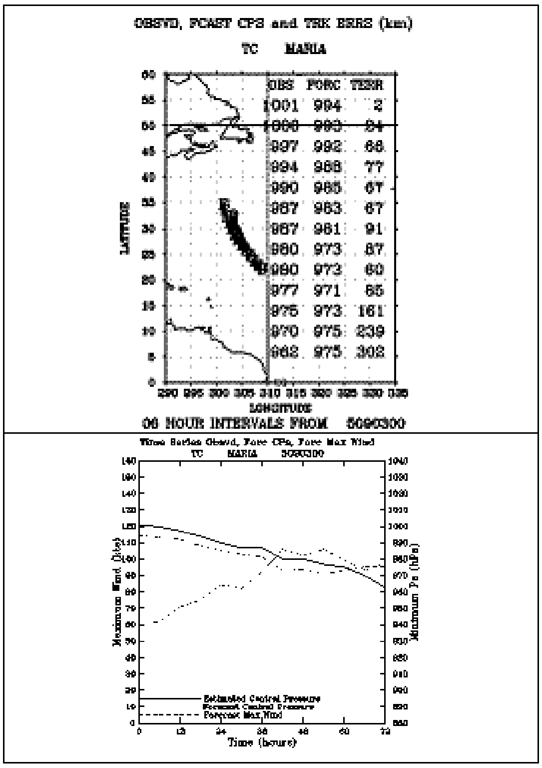

Figure 6. Forecast and observed tracks and intensities for Hurricane Maria from base time 00UTC 3 September 2005.

Figure 8 shows time-height series of vorticity and vertical motion over a 300km-radius circle following the Maria circulation. Left panels are from the TC-LAPS simulation, right panels for the LSE simulation. The time series of vorticity (upper, left panel) shows a period of slow, low-level intensification for approximately 48 hours, then a short period of weakening, followed by a period of intensification over a deep layer, after 60 hours. At upper levels, a strengthening in the anticyclone is evident in the time series. The vertical motion field shows considerable variability. Minima in the ascent field occur between 24 and 36 hours, and 48 and 60 hours of simulation time. In general terms, these periods correspond with decreased intensification rates evident in the vorticity time series. The right panels in Fig. 8 are from the LSE simulation along the observed track. The time series of vorticity suggest that Maria was moving through a weakly anticyclonic environment as it tracked to the northwest until it eventually encountered the developing cyclonic environment after 60 hours of simulation time. The time series for omega shows an understandable initialization problem during the first 12 hours of the simulation, but after that shows an interesting variability in the ascent field. The LSE is characterized mostly by descent but with maxima and minima, which in general correspond with maxima and minima in the vertical motion field from the TC-LAPS simulation. That is, the LSE appears to modulate the ascent field in the full physics, high-resolution simulation.

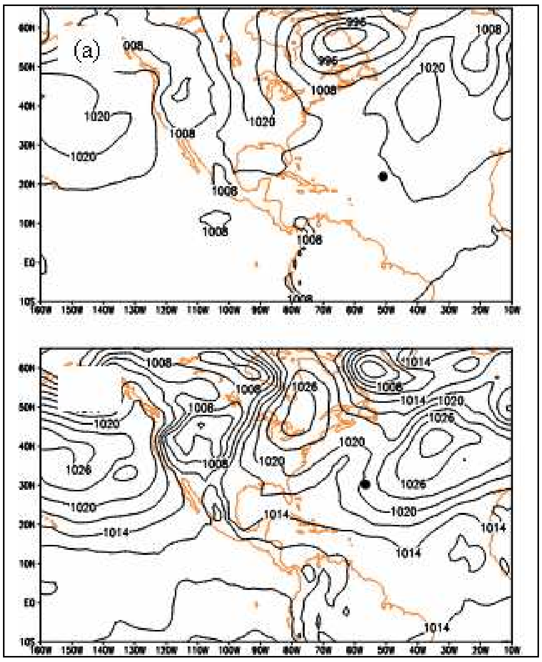

Figure 7. Mean sea level pressure at t=0 and t=48 hours, from the “without vortex” simulation for Maria. Base time is 00UTC 3 September 2005. The black dot is the observed position of Hurricane Maria at each time.

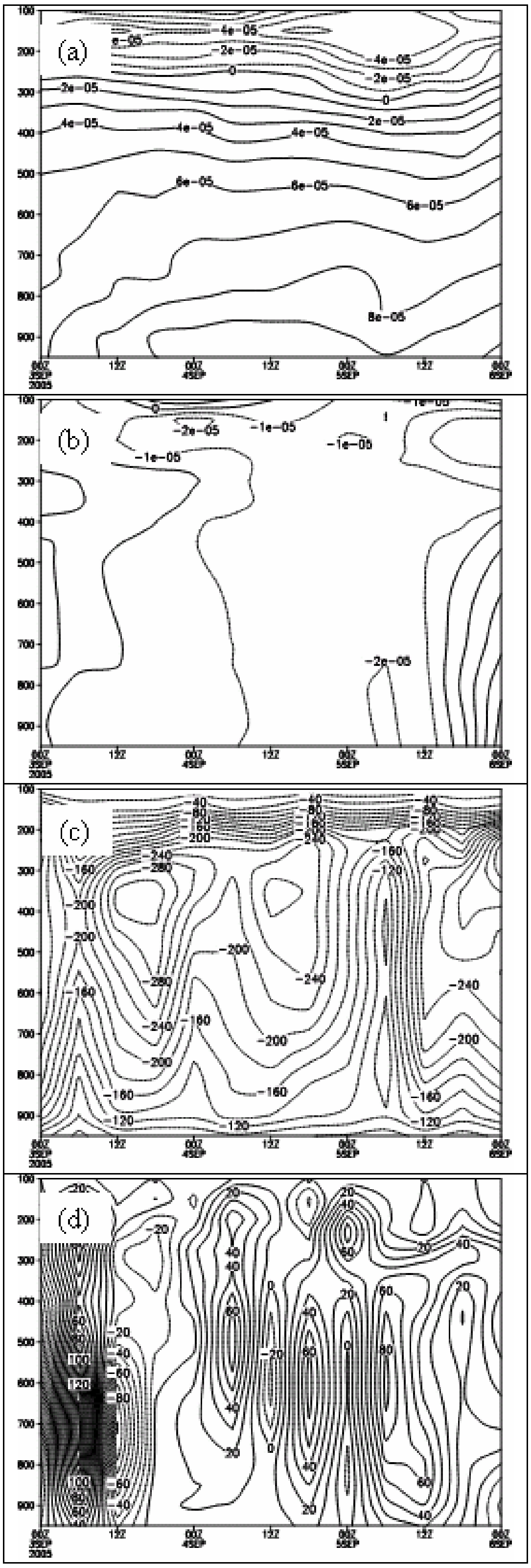

Figure 8. Time-height series over a 300km radius circle of vorticty and omega following the Maria vortex. (a) and (c) from a 0.15^0, full physics simulation, with vortex specification at t = 0. Contour intervals are 1x10^{-5} s^{-1} and 20hPa/day. (b) and (d) from a 1.5^0, dry

simulation, with vortex removed at t = 0. Contour intervals are $1x10^{-5}$ s^{-1} and 10hPa/day

To understand how the structural changes described above might influence the behavior of the vortex, Fig. 9 shows time-height series of equivalent potential temperature, θe, from the LSE experiment.

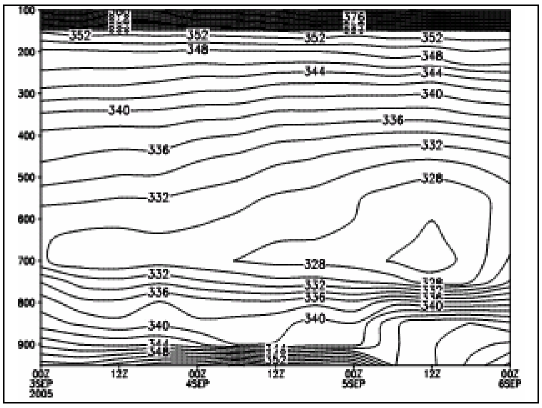

Figure 9. Time-height series over a 300km radius circle of theta-e following the forecast Maria vortex in a 1.5^0, DRY simulation, with vortex removed at t = 0.

The most interesting aspect is the evolution of boundary layer θe which shows increasing values along the storm track, then a breakdown during times when strong descent occurs in the LSE between 48 and 60 hours of simulation time (presumably as ET commences), and then another increase in θe that coincides with transition and merger.

From these experiments, we infer that during ET (i) enhanced low-level horizontal moisture flux, and (ii) enhanced surface fluxes during periods of modulation by descent in the LSE, both act to increase boundary layer θe , which offsets the vertical moisture flux associated with convection during the transition process. We thus suggest that such changes are consistent with the enhanced vertical mass flux diagnosed by Davis et al. (2008). Even though Maria was moving through a weakly anticyclonic LSE, the enhanced moisture flux and vertical mass flux may be processes that act to preserve the storm circulation. We note that these changes are ultimately linked to the downstream development processes associated with ET events.

3. Conclusion

Observational evidence suggests that during ET, Downstream Development (DD) frequently occurs at upper levels. This is seen as a wave train of amplifying troughs and ridges developing eastward in time. Associated with this process, a critical flow change is the development of large-scale, low- to mid- level anticyclones to the east and west of the storm, and a large scale trough located between the two anticyclones. This developing trough envelops (captures) the storm, seemingly holding it upright and allowing it to withstand increasing wind shear, until it reaches the favourable equatorward entrance region of the upper jet. The wrap-around flow appears to be one reason for the often-observed increase in size of storms undergoing ET. Enhanced low level, horizontal moisture flux from the southeast occurs as the anticyclone develops to the east of the storm (not illustrated here). We suggest that this, and its impact on convection, may be one reason for preserving the TC circulation as it tries to withstand the effects of increasing environmental wind shear.

Although the observational evidence for downstream amplification is strong, there is not good agreement between the observed values of group velocity of the wave train and phase speed of synoptic systems, and values predicted from linear, barotropic dynamics. We can only suggest that baroclinic and diabatic processes are altering the behavior of the waves predicted from linear barotropic dynamics. We suggest that understanding theoretical aspects of the observed behavior would be a very worthwhile pursuit.

We have run numerical experiments to try and isolate the influences of environmental flow changes from the effects of the TC vortex and its embedded convection. A full physics, high-resolution simulation of the ET of Maria shows considerable skill in reproducing many of the observed features of the ET, including track, intensity and structure changes. To isolate the LSE, we have run coarse resolution, dry simulations with the Maria circulation removed from the initial condition. This simulation indicates that the development of the low level anticyclones and capturing trough are mostly associated with the dry dynamics of the maturing DD event. There is also evidence that the LSE modulates the ascent field of the storm during ET, and that the temporary inhibition to ascent (and convection) can possibly act to moisten the boundary layer and hence energize later convective bursts.

We plan to extend this study by (i) investigating aspects of the structural changes of the transitioning storms in high-resolution simulations, (ii) generalising the results over other basins (west north Pacific, southern hemisphere), and (iii) studying the dry dynamics of the downstream amplification process which seems so crucial for ET.

References

Brand, S., and C. P. Guard, 1978: Extratropical storm evolution from tropical cyclones in the western North Pacific Ocean. Tech. Rep. TR 78 02, Naval Environmental Prediction Research Facility, 20 pp. [Available from Naval Research Laboratory/Marine Meteorology Division, 7 Grace Hopper Avenue, Stop 2, Monterey, CA 93943-5502.].

Davidson, N. E. and H. C. Weber, 2000: The BMRC high-resolution tropical cyclone prediction system: TC-LAPS. *Mon. Wea. Rev.*, **128**:1245–1265.

Davis, C. A., S. C. Jones, and M. Riemer, 2008: Hurricane vortex dynamics during Atlantic extratropical transition. *J. Atmos. Sci.*, **65**:714–736.

Evans, J. L., R. E. Hart, and C. S. Velden, 2000: Improved data assimilation in the study of Hurricane Floyd (1999). Preprints, *24th Conf. on Hurricanes and Tropical Meteorology*, Fort Lauderdale, FL, Amer. Meteor. Soc., 126–127.

Fogarty, C.T., R.J. Greatbatch and H. Ritchie, 2006: The Use of a Vortex Insertion Technique to Simulate the Extratropical Transition of Hurricane Michael (2000). *Wea. Forecasting*, **22**, 480-500.

Hanley, D., J. Molinari, and D. Keyser, 2001: A composite study of the interaction between tropical cyclones and upper-tropospheric troughs. *Mon. Wea. Rev.*, **129**:2570–2584.

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.

Harr, P. A., R. L. Elsberry, and T. F. 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. E. and J. L. Evans, 2001: A climatology of the extratropical transition of Atlantic tropical cyclones. *J. Climate*, **14**:546–564.

Jones, S. C., Coauthors 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**:373–396.

Klein, P. M., P. A. Harr, and R. L. Elsberry, 2002: Extratropical transition of western North Pacific tropical cyclones: Midlatitude and tropical cyclone contributions to reintensification. *Mon. Wea. Rev.*, **130**:2240–2259.

Puri, K., G. D. Dietachmeyer, G. A. Mills, N. E. Davidson, L. Logan and R. Bowen, 1998: The new BMRC limited area prediction system, LAPS, *Aust. Meteor. Mag.*, **47**, 203 - 223

Ritchie, E. A. and R. L. Elsberry, 2001: Simulations of the transformation stage of the extratropical transition of tropical cyclones. *Mon. Wea. Rev.*, **129**:1462–1480.

Ritchie, E. A. and R. L. Elsberry, 2003: Simulations of the extratropical transition of tropical cyclones: Contributions by the midlatitude upper-level trough to reintensification. *Mon. Wea. Rev.*, **131**:2112–2128.

Ritchie, E. A. and R. L. Elsberry, 2007: Simulations of the extratropical transition of tropical cyclones: Phasing between the upper-level trough and tropical cyclones. *Mon. Wea. Rev.*, **135**:862–876.