

SIXTH INTERNATIONAL WORKSHOP on TROPICAL CYCLONES

Topic 2.5 : **Physical Processes and Downstream Impacts of Extratropical Transition**

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2.5.1 Introduction

Substantial progress in the understanding of extratropical transition (ET) has been made since the period of the last report written for the IWTC-IV, in which much of the material was derived from the review paper of Jones et al. (2002).

The importance of the ET in influencing the dynamics of the atmosphere has become more evident in recent years. The occurrence of ET events over the North Pacific has been observed to coincide with periods of reduced forecast model skill (Jones et al. 2003). Harr et al. (2004) examined downstream propagation of increased ensemble standard deviation in mid-tropospheric heights from several operational global model ensemble prediction systems during the ET of typhoon Maemi (2003) that also coincided with reduced forecast skill over the Northern Hemisphere. The complex physical and dynamical processes during ET are extremely sensitive to sources and impacts of initial condition errors and forecast model uncertainty. Therefore, factors that impact forecast model error growth downstream of an ET event must be identified. For example, predictability during an ET event may exhibit large variations due to the phasing between the decaying tropical cyclone and the midlatitude circulation (Klein et al. 2002). McTaggart-Cowan et al. (2006a) have shown that the ET of Hurricane Katrina (2005), though lacking in reintensification, had an important impact on the middle-latitude flow and reduced medium-range predictability.

The purpose of this discussion is to identify crucial physical processes associated with ET, and the associated downstream impacts. Specific forecasting issues and observation strategies to improve forecasting and understanding of the ET process are discussed elsewhere.

2.5.2 Physical Processes

The poleward movement and ET of a tropical cyclone (TC) initiates complex interactions with the middle latitude environment that often results in a high-impact midlatitude weather system with strong winds, high seas, and large amounts of precipitation (Atallah et al. 2006). Although these extreme conditions severely impact the region of the ET, there are significant impacts downstream of the ET event, owing to the excitation of large-scale propagating Rossby wave-like disturbances. Although ET occurs over several ocean basins, the largest number of ET events usually occurs during the Northern Hemisphere summer and fall seasons over the western North Pacific (Jones et al. 2003). The case of supertyphoon Dale of 1996 (Kelsey and Bosart 2006) offers an excellent example of a western North

Pacific ET. Downstream impacts propagate across the North Pacific to impact North America via the forcing of anomalous cyclonic and anticyclonic circulations.

Despite the large number of western North Pacific Basin ET events, important tropical characteristics of hurricanes are often maintained in higher latitudes of the North Atlantic, as in the case of Juan (2003) (McTaggart-Cowan et al. 2006b, c) and in even in the South Atlantic as in Caterina (2004) (McTaggart-Cowan et al. 2006d). Indeed, Dickinson et al. (2006) have documented a relatively rare case of ET in the eastern North Pacific, that of Lester (1992).

Scientific issues associated with ET and downstream impacts due to ET events may be placed in a framework of mechanisms, predictability, and strategies for increasing predictability. The ET process may be characterized by complex physical interaction within three interrelated regions: the tropical cyclone core, the tropical cyclone-middle latitude interface, and the middle latitude impact region. To understand the impact of ET on high-impact downstream weather events, mechanisms responsible for the generation, intensification, and propagation of the Rossby wave-like disturbances need to be identified. All three regions of the ET process likely play important roles in the mechanisms responsible for downstream impacts due to ET. A Rossby wave response may be forced by advection of vorticity due to the divergent wind (Sardeshmukh and Hoskins 1988), which may result from the tropical cyclone core. A similar mechanism may be associated with diabatic Rossby waves (Moore and Montgomery 2005) due to upward motion along sloping isentropic surfaces that exist at the tropical cyclone middle latitude interface (Harr and Elsberry 2000). Finally, the middle latitude impact region provides the avenue by which the wave energy impacts the middle latitude circulation into which the decaying TC is moving. Furthermore, the downstream response to ET events exhibits large spatial and temporal fluctuations, which may be related to specific characteristics of each of the three ET regions.

One ongoing project most relevant to physical processes during ET is the configuration, testing, and development of a limited area model in Canada (MC2) of the Global Environmental Multiscale (GEM) code with synthetic vortex insertion employed (pre-ET) to initiate short-range numerical forecasts designed to assist in forecast production. Validation of this model includes analysis of aircraft data collected primarily from dropsondes during a handful of storms since the year 2000. The aircraft component of this work was conducted by the National Research Council (NRC) of Canada using the Convair-580 aircraft (Wolde et al. 2001) organized by Jim Abraham (MSC) and Walter Strapp (MSC/NRC).

An analysis of aircraft and dropsonde data outlining interesting physical characteristics of the rapidly-transitioning Hurricane Michael in October 2000 can be found in Abraham et al. (2004). More recently, a collaborative observing study involving two flights into the ET of Tropical Storm Ophelia in September 2005 was organized by Jim Abraham of the MSC and Sim Aberson of the Hurricane Research Division (HRD) in Miami, Florida. Some interesting findings from those flights were presented in May 2006 at a poster session at the Canadian Meteorological and Oceanographic Society (CMOS) Congress in Toronto, Ontario, Canada (Fogarty, 2006).

Primary findings from these aircraft flights indicated extreme boundary layer wind shears during the ET over cool sea surface temperatures off Eastern Canada, and a significant deepening of the usual low-level wind maximum in TCs. During the ET of Ophelia, the upper portion of the storm's circulation was sheared away by strong upper level winds accompanied by the intrusion of dry, mid-latitude air. This may have influenced the representative steering layer for the storm, making it challenging to forecast its movement. Hurricane wind speeds were also observed only 200 m above the ocean surface to the right of the storm track. This was surprising given that the storm's central pressure had risen to near 1000 hPa – but highlights the high wind potential to the right of seemingly benign ET events.

The results of these aircraft studies are used at the Canadian Hurricane Centre (CHC) to understand the behavior of hurricanes undergoing ET. The aircraft/dropsonde data also aid in validation of the

experimental in-house model for hindcast simulations. The “hurricane configuration” of the MC2 model used for hindcast sensitivity studies (Fogarty et al. 2006a,b) shows promise as a forecast tool. Equally important is the acquired knowledge from these studies that provide 4-dimensional (3D plus time) imagery of the evolution of moisture and mass fields during the ET process. Program leads Peter Bowyer, Jim Abraham and Chris Fogarty share findings with staff through training sessions, workshops, and one-on-one discussions. Output from several of the experiments demonstrating structural changes taking place during ET can also be viewed at: <http://projects.novaweather.net/work.html>.

An idealized modeling study used a dry three-dimensional primitive equation model to investigate the ET of tropical-cyclone-like vortices in developing baroclinic waves (Weindl 2004). The sensitivity of the ET to the initial location of the tropical cyclone was investigated for the two paradigms of baroclinic wave life cycles, one characterized by cyclonic wrap-up and the other by anticyclonically tilted troughs that thin and form cut-offs. It was found that for the cyclonic life cycles the tropical cyclone moved into the middle latitudes and was absorbed into the large-scale deep surface low pressure system typical of these life cycles. Because of the large difference in horizontal scale between the tropical cyclone and the middle latitude low the TC behaved rather passively, although the presence of the remnant TC PV anomaly lead to enhanced surface winds. For the anticyclonic life-cycles the sensitivity to the initial TC position was strong, with the middle latitude trough moving past the TC vortex in some cases so that no ET took place and in other cases the TC vortex interacted with the small-scale tropopause cut-off or formed a frontal wave and developed into a small scale but rather intense middle latitude low.

Singular vectors (SVs) constructed from the adjoint model of the U. S. Naval Operational Global Atmosphere Prediction System for three Atlantic hurricanes in 2004, Ivan, Jeanne and Karl, have been examined to understand interactions between them and a middle latitude trough system (Maue et al. 2006). By optimizing the perturbation energy localized in a small region centered at the 48-hour projected position of a tropical cyclone, the initial SV represents the sensitive region to the final state within the specified region for a specified optimization period. For Hurricane Ivan, the SV analysis reveals the merging of a weak middle latitude trough and Ivan to form a new trough/cut-off low. This new trough system impacted the evolutions of Hurricane Jeanne in subsequent time through the upstream flow of the trough that moves toward Jeanne. The SV associated with Jeanne at a later stage shows that Jeanne influenced the third hurricane Karl through the trough system as Karl went through ET, and became part of the trough. The most striking result is where the final disturbance shows clear signal of Karl when the optimization is confined in the vicinity of Jeanne only. This energy has to come from the trough that is present in the initial sensitivity to Jeanne as there is no signal of Karl in the same initial SVs. This study demonstrates the capability of the SV approach in providing evidence of the complicated interactions between a mid-latitude trough and tropical cyclones.

A number of recent studies have used modern models consisting of the atmosphere, ocean waves, sea spray and the upper ocean to evaluate the coupled atmosphere-ocean impacts of surface fluxes, spray evaporation and wave drag on middle latitude cyclones that include systems originating at tropical cyclones (Perrie et al. 2005; Zhang et al. 2006; Ren and Perrie 2006; Ren et al. 2004; Perrie et al. 2004; Zhang and Perrie 2006a; Perrie 2006). These studies focus on the role of air-sea fluxes on storm intensity and development, and related impacts on the structure of the atmospheric boundary layer, and on ocean surface waves and surface fluxes (Zhang and Perrie 2006b). Case studies have included Earl (1998), Daniel (1998), Gustav (2002), and Juan (2003) and two intense winter storms from 2000 and 2002.

Results suggest that sea spray tends to intensify storms whereas wave-related drag tends to diminish intensity. Sea-surface temperature depression from the upwelling induced by storm passage represents a further factor that tends to diminish storm strength. The mechanisms by which spray and wave-related drag can influence storm intensity are quite different. When wind speeds are high and sea surface temperatures (SSTs) are warm, spray can significantly increase the surface heat fluxes. By comparison, momentum fluxes related to wave-drag are important over regions of the storm where

young, newly generated waves are prevalent, for example during the rapid-development phase of the storm, and decreases in areas where the storm waves reach maturity. The peak flux enhancement values tend to occur during the storm's intensifying period, when the sea-state is young and rough, and winds are high, and spray droplet production rates are high, into the lower atmosphere. Our studies show that the collective influence of spray and waves on storm intensity depends on their occurrence in the early stages of a storm's rapid intensification phase, and their spatial distribution with respect to the storm center.

Spray evaporation causes the lower part of the atmosphere to experience cooling and moistening. This cooling process increases the air-sea temperature difference, destabilizes the surface layer, and enhances the surface layer turbulence. Thus, the convergence of mass and moisture fluxes from the surface are enhanced, particularly when the local heat flux region is close to the active storm region, as when storms are over warm Gulf Stream waters. This results in upward transport of moisture from both the surface and spray, coupled with latent heat release at the middle tropospheric levels which contributes to warming the mid-troposphere air and lowering the surface pressure. This contribution (of moistening processes) to the thermal-dynamic structure is favorable for storm intensification. By comparison, the influence of wave-drag on storm development is quite different from that of spray. Because of friction-induced kinetic energy dissipation associated with enhanced surface roughness, wave drag can induce anomalous convergence-generated upward motion around the storm center and an attendant dynamic compensation downdraft outside of the storm center, contributing to the downward mixing of upper level dry cool air. This gives a slight increase in static stability in the lower troposphere, thus suppressing convection and reducing storm intensity, and is analogous to the classical Ekman spin-down mechanism. A PV analysis can be used to show that baroclinic processes associated with surface friction induced by wave drag along the warm front also occur, and also can be the dominant mechanism to effect storm development. The inclusion of sea spray can significantly dilute the Ekman pumping effect around storm center, which relegates wave drag effects to secondary importance for storm development.

2.5.3 Downstream Impacts

Because the western North Pacific is the region in which most ET processes occur (Jones et al. 2003), it follows that downstream impacts from cyclogenesis in this region be studied. Baroclinic energy conversion in the western and central North Pacific generates a vast amount of kinetic energy that plays a key role in maintaining the storm tracks downstream over the eastern North Pacific, North America, and North Atlantic (Chang and Yu 1999; Orlanski and Sheldon 1995; Nielsen-Gammon and Lefevre 1996, Danielson et al. 2004). Cyclogenesis over the western and central North Pacific is typically triggered by dynamical influences from the surrounding area, including upper-tropospheric wave packets that propagate from East Asia, due to forcing by the extratropical transition (ET) of tropical cyclones, and by Rossby waves initiated by organized tropical convection.

The resulting extratropical storms from ET in the western North Pacific basin may have unusually strong downstream effects due to the extraordinary amount of kinetic energy generated during ET. Palmén (1958) estimated that two or three typical ET would provide the entire NH north of 30°N with the kinetic energy sufficient to maintain the general circulation against frictional dissipation.

Recent papers (Hakim 2003 and Chang 2005) have provided strong statistical evidence that the presence of wave packets on the two Asian waveguides increases the likelihood of the occurrence of deep cyclones over the western and central North Pacific. The northern waveguide crosses through Siberia, while the southern waveguide runs along the subtropical jet across southern Asia (Chang and Yu 1999; Hoskins and Hodges 2002). It has been hypothesized (Chang 2005) that wave packets originating from the northern waveguide trigger cyclogenesis, while wave packets originating from the region of the southern wave guide only enhance, but do not trigger, cyclogenesis. There are also indications that these wave packets are in turn invigorated by the cyclogenesis events, making their

impacts further downstream potentially more significant.

A case study of the extratropical transition of Hurricane Erin in September 2001 (Roebcke 2003; Roebcke et al. 2004) a sequence of forecasts has been performed using the global model (GME) of the German Weather Service (DWD). Forecasts were initialized each day between the time period 10 to 17 September. Each model run was initialized with European Centre for Medium-Range Weather Forecasts (ECMWF) and DWD analyses. It is suggested that the re-intensification as an extratropical cyclone occurred because Erin moved into a favorable location both from a PV- θ perspective since Erin was located directly to the east of a tropopause depression and from jet streak dynamics since Erin was located between the entry region of a downstream jet streak and the exit region of a smaller-scale upstream jet streak.

It is demonstrated that the forecasts are not able to predict the rapid re-intensification phase of Erin. It is suggested that the forecasts' failure can be partly attributed to the model's inability to represent the upstream jet streak well. This appears to be linked to the model's poor representation of Tropical Storm Gabrielle. From a PV- θ perspective and from trajectory calculations it is hypothesized that the outflow of Gabrielle contributed to enhanced baroclinity and a steepened tropopause in the region of the upstream jet streak. As a consequence, the upstream jet streak was enhanced and contributed to Erin's re-intensification.

The outflow of Erin is depicted as a raised tropopause downstream of Erin from a PV- θ perspective. Time series of tropopause maps and trajectory calculations suggest that the pronounced ridging downstream of Erin can be attributed to the outflow of Erin. The downstream impact of the outflow extends across the Atlantic basin and influences western Europe. The ridging downstream of Erin is underpredicted in almost all forecasts.

Full physics numerical experiments with idealized initial conditions to investigate the impact of a tropical cyclone on the middle latitude flow with focus on the downstream region of an ET-event (Riemer 2006). In this experiment, a TC interacts with the most simplified representation of the middle latitude flow regime: a straight jet. The prominent features of the interaction are a jet streak that forms in the region where the TC outflow impinges on the jet and a ridge-trough couplet on the tropopause. Both features amplify during the interaction. Beneath the left exit region of the jet streak rapid surface cyclogenesis takes place. At upper levels the ridge-trough pattern extends downstream as a wave pattern and initiates a family of cyclones. The upper-level wave pattern can be interpreted as the excitation of a Rossby wave train (RWT) by the ET event and its subsequent propagation downstream. Sensitivity experiments reveal the importance of the atmospheric states in the middle latitudes for the propagation of the RWT. Baroclinic energy conversion and diabatic processes are found to be important for the amplitude of the RWT. The results suggest that the concept of baroclinic downstream development (Orlanski and Sheldon 1995, Nielson-Gammon and Lefevre 1996) is of greater importance than the pure propagation of a (barotropic) RWT.

Piecewise PV inversion shows that the cyclonic circulation of the decaying positive PV tower of the ET system is the main contributor to ridge building. The balanced effect of the outflow layer is mainly to intensify the downstream trough. Low-level temperature and PV anomalies have only negligible impact. The effect of the outflow layer on trough formation is confirmed by sensitivity experiments using different cyclone structures. ET events of TC with a less pronounced outflow layer exhibit less meridional orientation of the downstream flow and the primary downstream system tends to a more cyclonic life cycle than in experiments with prominent outflow layers. The effect of the TC structure on the downstream region is greatest one wavelength downstream of ET. The impact on the further propagation of the RWT is more complex and depends amongst other things on moist processes in the environment (Riemer and Jones 2006).

A developing baroclinic wave is a more realistic representation of the middle latitudes and we investigate the interaction of a TC with a variety of baroclinic life cycles. Interacting with a mature

system the ET event shows only little and localised impact on the upper-level middle latitude flow pattern. Interaction with a developing wave from a localised upper-level perturbation shows significant enhancement of the ongoing baroclinic development and a downstream impact comparable to the straight jet case. These examples show that there are situations in which the middle latitude flow is more conducive for an impact of the ET system. These situations seem to be linked to the maturity of the baroclinic system (Riemer 2006).

Research at the University of Washington (R. Torn and G. Hakim) examines the sensitivity to the phasing relationship between the tropical cyclone and extratropical waves, by using an ensemble Kalman filter (EnKF) for select western Pacific ET events. Previous research has shown that small changes to the position of the TC or mid-latitude waves can significantly alter the ET forecast and thus the downstream state (e.g. Browning et al. 2000, Klein et al. 2002). One advantage of this technique is that it provides an analysis ensemble of equally likely states, and thus a way to objectively measure relationships between the tropical cyclone and extratropical circulations. Preliminary results show that the downstream impact of ET is proportional to how much the TC reintensifies as a baroclinic system. For the case of Typhoon Tokage (2004), those ensemble members that include a deepening baroclinic storm produced a downstream Rossby wave, while those ensemble members that include a weakening TC have little downstream impact. Additional research is needed to understand the physical processes that lead to the aforementioned rapid error growth in the downstream state.

2.5.4 Summary and recommendations for future research directions

A continuing science issue is to understand the origins of the varying types of extratropical transition, including being able to identify the physical mechanisms that allow a subset of these storms to reintensify explosively. Another crucial science issue is to what extent differences in mean environmental conditions across the various ocean basins can contribute to varying types of extratropical transition. Another science issue is determining what is the collective impact on the general circulation of the atmosphere of the periodic insertion of upper-level warm pools into middle and high latitudes in conjunction with the ET process. As pointed out earlier, this has impact on predictability. Factors associated with reduced forecast skill include parameterization of convection, and oceanic surface fluxes.

A continuing operational issue is the need to understand the dynamical processes control the distribution and amount of precipitation relative to the tracks of landfalling and transitioning tropical cyclones. Work is underway on transferring research knowledge on this topic to operations through collaborative efforts with Wes Junker at NCEP/HPC.

Future work should also address the sensitivity of the downstream state to the upstream state and the tropical cyclone during ET events.

Future investigation of the relative roles of fluxes and momentum transports on ET strength is needed.

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