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SIXTH INTERNATIONAL WORKSHOP on TROPICAL CYCLONES

Topic 2.4 : **Observing and Forecasting of Extratropical Transition**

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2.4.1 **Introduction**

At IWTC-V in Cairns, Australia, researchers and forecasters agreed that a research program focusing on important physical characteristics associated with the extratropical transition (or “ET”) of tropical cyclones (TC) was needed. This research program should promote analysis of existing observational and modeling datasets to: (i) improve analyses and prediction of the structure changes, significant weather, and ocean impacts associated with ET; (ii) address uncertainties associated with numerical predictions of ET in the region of the storm; (iii) understand its far-field impacts; and (iv) coordinate any ET research program with existing programs to obtain detailed observations of the evolutionary structure of extratropical transition.

In the past four years, progress has been made in all of these areas. Contributions related to the observation and forecasting of ET are reviewed here.

2.4.2 **Towards an Operational Definition of ET**

Operational forecasting of ET remains a significant challenge. ET is still a developing research area and lacks a fully developed common language (Jones et al. 2003). Some researchers will refer to any TC that enters mid-latitudes as having undergone ET. To aid application of conceptual models, some forecasters seem to prefer to emphasize a distinction between systems that undergo significant “transformation” to a largely cold-core system (with associated structural changes) and those that undergo “capture” by mid-latitude westerlies while retaining a largely warm-cored structure. Development of consistent descriptors and definitions of the stages of ET will help progress toward operational forecasting techniques.

Any definition of ET should not only be precise enough to satisfy the needs of the operational and research communities and should be accessible to the general public as well. The lack of a concrete definition of ET that can be communicated to the general public can result in tragedy when tropical cyclone warnings are discontinued (due to the ET of the storm) but the storm makes landfall with potentially devastating societal consequences. To emphasize the importance of these storms, the Meteorological Service of Canada labels storms that have undergone ET as “post-tropical” and continues to use the storm name issued by NHC – thus, a storm such as Floyd (1999) moving into Canadian waters would be referred to as “Post-Tropical Cyclone Floyd.” Other governments have begun to consider this problem, but no uniform approach to communicating the dangers from extratropically transitioning storms to the public has been agreed among all affected nations.

Improved understanding of the processes through which ET occurs will aid in the development of a definition of ET. Thus, observational studies of ET are critical. Recent observational studies of transitioning tropical cyclones are reviewed in the next section.

2.4.3 **Observations of ET**

Due to their devastating societal consequences, a few ET case studies were published prior to the 1950s (e.g., Pierce 1939; Palmén 1958). In the 1950s Matano and Sekioka began their systematic assessments of the surface signatures of a number of transitioning storms that impacted Japan (Sekioka 1956; Matano 1958). However, intentional field studies of the process of transition would have to wait for the twenty-first century! The results of two of these ET-focused studies of Hurricanes Michael (2000) and Ophelia (2005) are reviewed here.

2.4.3.1 Hurricane Michael (2000)

Following the first International Workshop on Extratropical Transition (Jones et al. 2003), and knowing that the region around the Atlantic Provinces of Canada has the climatological peak for Atlantic ET events (Hart and Evans 2001), the Meteorological Service of Canada began planning for a field project on ET (Abraham et al. 2002; 2004). Their opportunity came with the ET of Hurricane Michael in October 2000. The Canadian National Research Council (NRC) Convair 580 (CV580) aircraft was used to conduct the first reconnaissance flight tasked for an ET event into Hurricane Michael as it underwent transition on 19 October 2000 while translating rapidly northeastward to the south of Newfoundland. On the synoptic scale, the strongest winds were to the southeast side of the storm within the precipitation region, with a strong (speed > 70 ms^{-1}) southwesterly jet in the 500-2000 m layer. The precipitation shield extended roughly 250 km to the northwest and 135 km to the east of the storm center. This asymmetric synoptic structure is consistent with the right-of-track asymmetry in the winds and the left-of-track shift in precipitation typically observed during ET.

Dropsondes, radar, and in situ microphysics measurements of temperature, wind, and cloud structures were obtained for the first time. A radar cross-section just south of the storm center revealed cloud tops near 11.5 km to the west of the center, and between 6.0 and 9.5 km east of the center. The southwest-to-northeast "tilt" of the storm center suggested by these cloud top differences was confirmed in a number of ways: first, the cloud-top circulation center was significantly displaced relative to the surface low pressure center to the southwest. The implied tilt was in excess of 80° from vertical. In addition, dropsonde wind speed and potential temperature cross-sections had a similar tilt in the wind and thermal fields. Dropsonde data also revealed relatively dry, low-level air to the northwest of the storm (even in the precipitation region). Within the jet on the southeast side of the storm, equivalent potential temperatures (ϑ_e) were similar to those in the extratropical air mass, which indicated that this air was being entrained into Michael. However, the low-level center still had relatively high values of ϑ_e consistent with tropical air. This warm air mass was most narrow near the surface and fanned outward with increasing altitude.

Microphysical measurements of the precipitation region to the northwest of the center revealed deep, horizontally uniform, stratiform clouds with no embedded convection detected. In contrast, the cloud properties east of the surface low were indicative of embedded convection, but this convection was neither strong nor deep. Exceedingly high ice water contents (and high concentrations of small ice particles) in the clouds to the west of the storm center may have important implications for the precipitation formation mechanisms and efficiency during ET.

Problems and limitations identified during the Michael flight enabled improvements to the data collection and flight planning for future missions. Since Michael (2000), the CV580 has provided the Canadian Hurricane Center with valuable data from near-land systems for Tropical Storm Karen (2001), the remnants of Hurricane Isabel (2003), and for Hurricane Juan (2003) as it made landfall near Halifax, Nova Scotia.

2.4.3.2 Hurricane Ophelia (2005)

On 16 and 17 September 2005, the NOAA U.S. Hurricane Research Division and the Canadian Meteorological Center conducted joint observational missions into Hurricane Ophelia as it was undergoing ET between Cape Hatteras, Virginia and Nova Scotia, Canada. One NOAA P-3 aircraft, a U. S. Air Force C-130-J aircraft, and an Aerosonde participated in the mission on 16 September, whereas only the P-3 gathered observations on 17 September. The P-3 released dropwindsondes in the storm environment, as well as inside and around the core of Ophelia, on both days. High resolution flight-level data, SFMR surface wind data, Doppler radar data and digital camera footage were also gathered on these flights. Special land-based rawinsondes provided by the U. S. National Weather Service were also incorporated into the post-analyses of Ophelia.

The goal of the research missions was to document the structure of a tropical cyclone as it underwent ET, and to assess the impact of observations on subsequent numerical forecasts, including verifying the impacts far downstream. These were the first joint U.S.-Canadian missions to observe a system undergoing ET, and also the first successful penetration of, and return from, a tropical cyclone by an unmanned vehicle.

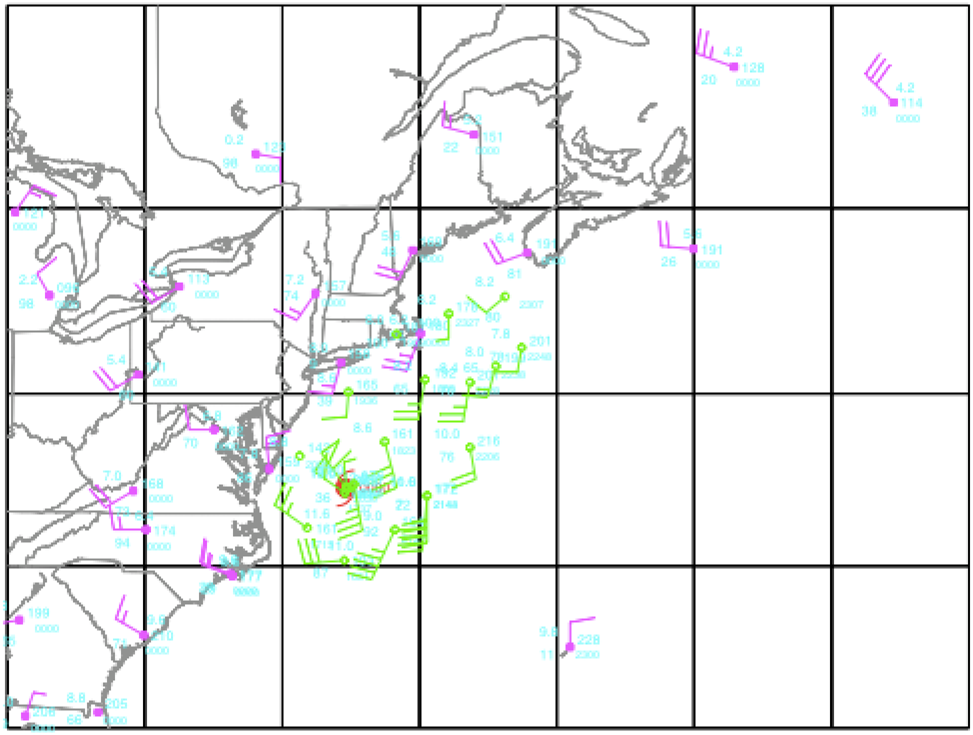

Fig. 2.4.1 700-hPa winds from 16 September 2005 research flights during the ET of Hurricane Ophelia (courtesy Sim Aberson, NOAA/HRD).

Dropwindsonde and rawinsonde observations (Fig. 2.4.1)in the environment around Ophelia on 16 September revealed a strong mid-level southwesterly flow that was beginning to impinge on the tropical circulation and a low- to mid-level pressure center over Southern Ontario (about 1200 km to the northwest of Ophelia). By the next day, this mid-level low was over Maine, and a mid-level jet was flowing over the low-level circulation of Ophelia from southwest to northeast, which resulted in only a shallow circulation below. This evolving tilt of the core is reminiscent of that of Michael on 19 October 2000.

Dropwindsonde observations in the core of Ophelia on 16 September showed that the center of Ophelia was nearly vertically aligned, with warm, moist air in the center. Dry air was beginning to impinge on the core in the mid-levels (above 700 hPa). By the next day, the core was still moist. However, the thermal soundings confirmed that the center was strongly tilted from southwest to northeast as a result of the mid-level jet and associated sheared flow impinging on the Ophelia circulation. Airborne doppler radar winds at 1800 UTC on 16 September provide further evidence of the northeastward tilt of the center from the surface through the mid-levels, then back to the southwest aloft, with maximum horizontal displacements of the center of just a few km. By 17 September, Ophelia had so few precipitation scatterers that Doppler analyses were not possible.

The inner-core data suggest a complicated structure on 16 September. Aircraft at three different levels in the vortex reported very different structures. The NOAA P-3 at about 14,000 feet reported moderate turbulence and a radius of maximum winds of just a few km. The Air Force C-130 reported a smooth flight at 10,000 feet with a much larger radius of maximum winds. Flying at 5,000 feet, the aerosonde did not penetrate to the center, but flew within the radius of maximum winds. Radar reflectivity at 1800 UTC 16 September from the NOAA P-3 exhibited a small comma-shaped feature resembling an eyewall open to the southern side, and a second band of convection to the northwest of the center. Just three hours later, the eyewall structure had deteriorated and the band to the northwest had weakened. The convection tilted upwind with height relative to the cyclonic flow in the center, but was nearly vertical in the convective band to the northwest. The convection near the center weakened with height above 1 km, whereas the convection in the band to the northwest had highest reflectivity at about 3 km altitude. By 2100 UTC, the tilt of the center was in the same direction, but the vertical displacements had nearly tripled. At mid-levels, multiple wind centers were now analyzed. The convection had disappeared by 17 September, which left a region of stratiform precipitation swirling in the low-level flow.

2.4.4 **Current Methods for Forecasting the Timing of ET**

Shortly after IWTC-V, Hart (2003) developed the cyclone phase space diagram and Evans and Hart (2003) clearly demonstrated its utility as an intuitive and objective way to define the onset and completion of the ET process. This tool highlights the structural changes of the vortex and the near-storm environment and has proved to be an excellent and relatively objective method for determining the current state of the cyclone, as well as for intercomparing the forecast evolution of the cyclone in available numerical model guidance. The accessibility of this tool has led to its use in operational centres in the U.S., Canada, and Australia.

While the cyclone phase space diagram has gained wide acceptance, its current dependence on model analyses argues against its use in isolation. Most operational centers indicate that they combine the cyclone phase space diagram with satellite guidance and conceptual models of ET (e.g., Foley and Hanstrum 1994; Fogarty 2002; Abraham and Bowyer 2002; Hart et al. 2006b). Blending of these fairly independent forms of guidance to create a forecast remains difficult and subjective.

2.4.5 **Current Methods for Forecasting ET Impacts**

A variety of specific forecasting challenges are associated with ET. Of primary concern is the reintensification – or, in some cases, (e.g., Alberto 2006) intensification – of the storm as an extratropical system. This remains a difficult problem that must be dealt with by forecasters. Another major operational concern is the changes to the surface circulation both during the ET process and once transition is complete. Redistribution of the surface winds alters the pattern of damaging winds over land and also drives ocean surface wave evolution. In addition to modifying the surface wind field, the structural changes in the storm during ET also lead to coincident modifications in the precipitation distribution associated with the transitioning cyclone. Finally, the possibility of tornadoes associated with an ET event must be considered during the tropical phase of these systems.

2.4.5.1 Surface Wind Structure

As yet, no objective product exists to provide specific guidance on the wind field redistribution and (re-) intensification during ET. However, useful operational guidelines for changes in wind structure during ET have been determined from past events (e.g., Fogarty 2002). During ET, the maximum winds generally become displaced to the equatorward side (right NH; left SH) of the storm track and the surface pressure field spreads near the storm center, which results in an expansion of the outer wind radii and an increase in the storm size. Due to the rapid storm translation speed, the right-left asymmetry across track in the peak winds is emphasized during ET. In the later stages of ET, a horseshoe shaped wind maximum in the front half of the storm domain is observed in some cases (e.g. Edson 2004).

Since the storm may decouple from the surface over the colder marine boundary layer (e.g., Abraham et al. 2004), the observed surface winds may be lower than expected. However, the degree to which decoupling occurs above the boundary layer is not readily apparent in individual events.

Operational NWP may be unreliable in forecasting broad measures of cyclone structure through ET (e.g. Evans et al. 2006) as well as the downstream cyclone development (Anwender et al. 2006), so alternate forecast strategies must be sought (Jones et al. 2003). Improved use of ocean surface winds, particularly from the NASA QuikSCAT satellite, has allowed better monitoring of the changes in the cyclone wind field as ET occurs. In a study of factors affecting gale radius evolution in warm-season cyclones, Higgs (2005) demonstrated that the storm and environmental modulators of cyclone wind structure differ for tropical and extratropical cyclones. Although two datasets (Kimball and Mulekar 2004; Moyer and Evans 2006) of significant wind speed radii in tropical cyclones currently available are internally consistent (statistically and theoretically), some systematic differences exist between these datasets (Moyer and Evans 2006). Thus, validation of products designed to forecast such surface wind changes is problematic.

2.4.5.2 Wave Field Evolution

Transitioning tropical cyclones can become very efficient ocean surface wave producers. Strong winds to the right of the track blowing in the same direction as the storm motion can create very high seas where “trapped-fetch” resonant wave growth occurs (Bowyer and MacAfee 2005). As the storm accelerates and the wind field expands during ET, the wave maximum becomes displaced farther and farther to the right of the storm track. The arrival of the wave maximum at a location typically lags the passage of the storm by 2-3 hours.

An operational modeling tool has been developed recently to compute dominant wave trajectories and significant wave heights for TCs undergoing the rapid forward translation typical of an ET event (MacAfee and Bowyer 2005, 2006). Wave forecasts from this model are available within less than one minute after the forecaster produces or changes the forecast track. This technique is not yet implemented in all regions affected by ET events.

2.4.5.3 Precipitation Distribution Changes

Heavy rainfall associated with an ET event is usually concentrated along quasi-stationary frontal zones well ahead of the transitioning storm and within a few hundred kilometers to the left of the storm track in the “delta” rain region identified by Shimazu (1998). This heavy precipitation zone is associated with the tropical cyclone outflow extending poleward from the cyclone center (Kitabatake 2002). Due to the intrusion of dry air wrapping around the southern part of the storm, precipitation is usually substantially less to the right of the storm track. Due to the import of moist tropical air to higher latitudes, the potential exists for extreme precipitation in flash floods associated with upslope flow in the vicinity of mountainous regions.

Beginning from these general guidelines, forecasters at the U.S. Hydrometeorological Prediction Center (HPC) have developed a subjective methodology for forecasting the evolution of the precipitation distribution as a storm undergoes ET (Roth 2006). When it appears that a tropical cyclone is becoming extratropical and/or fronts have moved relatively close to the storm center, the forecast region of heavy precipitation is shifted from right to left of track. While this “rule of thumb” is typically effective, storms such as Wilma (2005) and Alberto (2006) demonstrate that exceptions to this rule remain to be explained.

To provide guidance on more refined spatial detail in the quantitative precipitation forecast (QPF), the operational model track forecast that is closest to the official Tropical Prediction Center (TPC) track forecast is identified. The regions of strongest flow are identified that are: (i) in excess of 35 kt; and (ii) perpendicular to a frontal or coastal boundary or local terrain. Heavy precipitation is expected in these regions due to strong forced ascent. As with standard QPF products, favorable quadrants of upper-level jet streaks, areas of frontogenesis, and potential vorticity anomalies are also used as indicators of local QPF maxima. Conceptual models and current precipitation structure (determined from radar and satellite) are used to ensure reasonable spatial continuity in the heavy precipitation region. The diurnal cycle of precipitation will enhance core rainfall overnight and outer rainbands during day.

Storm analogs are also a useful check of a QPF forecast. Selection of an analog depends on satisfying a number of common criteria: (i) size of the current rain shield; (ii) vertical wind shear; (iii) similar storm track with similar proximity to topography; and (iv) fronts in the vicinity of the storm. An important limitation is that not all events will have a useful analog. Past events may also highlight locations susceptible to strong topographic rainfall enhancement (Roth 2006).

Past events are also used to calibrate the likely average or extreme QPFs based on observed tropical cyclone impacts over the past 15-25 years. Finally, checks are applied on the upper limits of QPF amounts, both for areal average amounts in the QPF graphics and the text QPF statement to TPC. For example, a soft cap of 2.5 inches per six-hour period is usually enforced for the 28-km forecast grid.

2.4.5.4 Tornadoes Associated with ET

Studies of Florida tornadoes associated with tropical and hybrid cyclones (cyclones having both tropical and extratropical characteristics) reveal an increased likelihood of tornadoes in hurricanes interacting with the mid-latitudes (Hagemeyer 1997, 1998). Since the hybrid cyclones studied were documented to be interacting with a midlatitude trough to the northwest and to be accelerating to the north or northeast, these storms are at least potentially beginning ET and may provide a useful model for tornado forecasting in other ET events. While tornadoes associated with the passage of a hybrid cyclone are consistently the most dangerous (all resulted in injuries and most were “killer” tornadoes), they result in longer and more active tornado outbreaks than from purely tropical cyclones and are also the rarest form of warm-season cyclone-related tornadoes documented in Florida (Hagemeyer 1997). Most of these documented tornadoes occurred in the overrunning zone very near or north of where a strong low-level jet (> 35 kt or 17.5 ms^{-1}) intersected the surface warm front, maximizing moisture convergence in a highly sheared, moist environment with diffluence at high levels. In each case, the heavy rain phase began before the severe weather phase and continued during, and well after, the tornado outbreak phase. The tornadic phases appeared to be associated with the approach of an upper short wave, an increase of the 850-500 mb wind speeds, and maximum shear and overrunning (Hagemeyer 1997).

Hagemeyer (1998) presents general guidelines (from climatological analyses of tornadic outbreaks in

Florida) for forecasting tornadoes related to the passage of a tropical or hybrid cyclone. These tornadoes tend to be stronger than "typical" Florida tornadoes. June, September and October are peak months for tornadoes associated with either tropical or hybrid cyclones, with significant hybrid cyclone tornadoes most likely in June and October (note that October is climatologically the month with the highest percentage of ET events; Hart and Evans 2001). Fast-moving tropical and hybrid cyclones are more likely to produce significant tornadoes. Outer rainbands of tropical cyclones with discernable hybrid characteristics are generally more likely to produce significant tornadoes.

Curtis (2004) discovered that 11 of 13 tornado outbreak cases associated with landfalling TCs along the Atlantic coast and Gulf of Mexico since 1960 contained clear evidence of a dry intrusion at midlevels over the outbreak area. Two distinct patterns were identified with respect to the source of the midlevel dry air. In one, a mass of dry air that impinged on much of the northern or northwestern semicircle of the storm’s outer circulation became divided into two lobes as the storm advanced, with one lobe to the northwest and the other to the northeast of the storm center. The other pattern involved ingestion of a lobe of dry air from a reservoir most often (but not exclusively) located in the eastern semicircle of the storm. Each pattern suggests the role of baroclinic processes (or increasing hybrid nature) in aiding tornadogenesis.

Significant tornadoes are most likely in association with higher reflectivity cells contained within dominant outer rainbands in the right-front quadrant of north- to northeast-moving tropical or hybrid cyclones in the Gulf of Mexico, regardless of central convection and central pressure. That is, a monotonic relationship does not exist between tornado strength and cyclone intensity (Hagemeyer 1998).

2.4.6 **Recent Research Relevant to ET Forecasting**

The ET forecast problem seems to be nearly separable into three issues: (i) the evolution of significant weather and waves associated with the storm; (ii) the possible rapid reintensification of the primary vortex; and (iii) the downstream propagation of Rossby waves generated by perturbing the midlatitude flow by the transitioning storm. As discussed above, studies of the first issue are advancing, mainly in operational centers (e.g. Roth 2006; Bowyer and MacAfee 2005).

2.4.6.1 Evolution and Simulation of the ET Vortex

The relative sensitivity of the ET process to the TC structure versus the midlatitude environment into which the storm moves has been an important focus of operationally-relevant research since IWTC-V. Recent studies on this and associated topics have engaged the problem from different perspectives (Agustí-Panareda et al. 2004; Evans and Prater-Mayes 2004; McTaggart-Cowan et al. 2004; Morgan 2004, 2006). Although each study in isolation is unable to make a general assessment of the importance of the remnant TC vortex versus the midlatitude flow, taken as a whole, this growing body of literature promises to aid in the development of conceptual models and forecasting tools that will be of significant utility to forecasters in the near-future.

The numerical modeling studies of Evans and Prater-Mayes (2004) and Ma et al. (2006) highlight the sensitivity of the numerical representation of ET to details of the model configuration and initialization. Such model sensitivities were mooted by Jones et al. (2003). Further documentation for the impact of model initial conditions on the simulation of the structure of an evolving ET is provided in Evans et al. (2006), who compare the structural evolution of the evolving storm as represented in the cyclone phase space of Hart (2003). Rather than requiring exact replication of analyzed and forecast structure, they follow Arnott et al. (2004) and cluster the identified structures into seven groups: three tropical cyclone types of increasing intensity; two hybrid forms (including the transitioning phase); and two extratropical. They find that the NOGAPS model simulations had the best 12-24 hour structure forecasts, but that the imposition of the synthetic vortex in the NOGAPS initial conditions resulted in less useful forecasts at

36 hours. In contrast, the most recent formulation of the GFS model (with vortex relocation only) was most useful at the 36-hour lead time.

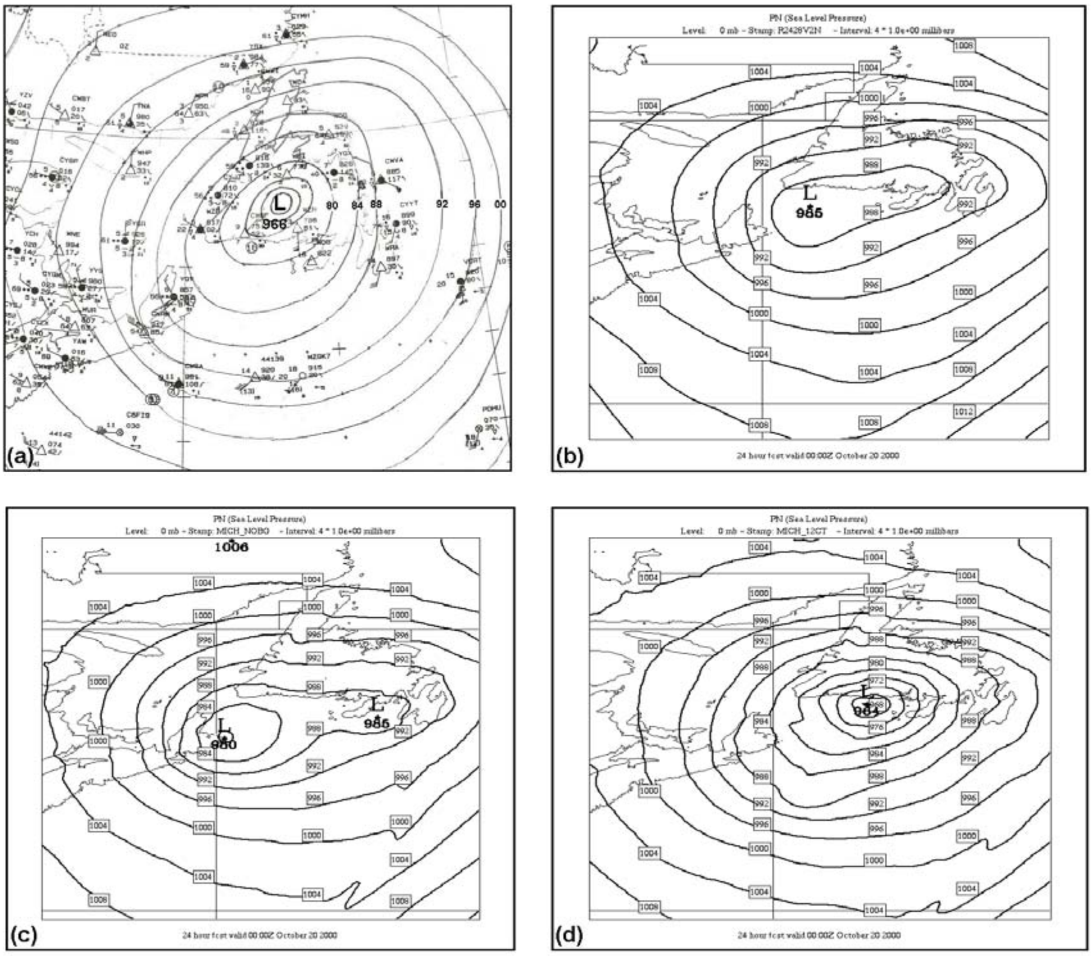

Fig. 2.4.2 Sea-level pressure (every 4 hPa) for Hurricane Michael (2000) valid at 0000 UTC 20 October 2000 based on: (a) subjective, manual analysis; (b) 24-hour GEM regional forecast; (c) 24-hour “no-vortex” simulation of the 12-km MC2 model; and (d) 24-hour simulation of the control run of the MC2 model with vortex insertion employed (courtesy of Chris Fogarty, MSC/CHC).

These results are consistent with the recent work by Fogarty et al. (2006a, b), who have demonstrated the utility of using synthetic vortex insertion in the initial pre-ET atmospheric fields during Hurricanes Juan (2003) and Michael (2000). One of the major problems with forecasting Hurricane Michael was that some numerical models were favoring the development of the baroclinic low off the coast of Nova Scotia rather than the transitioning storm that actually remained the primary low pressure center (Abraham et al. 2004). The Fogarty et al. (2006b) simulations of Hurricane Michael (2000) demonstrate that accurate specification of the tropical vortex prior to ET leads to a more faithful reproduction of the storm evolution with the baroclinic cyclone (Fig. 2.4.2). Similar to Evans et al. (2006), Fogarty et al. (2006a, b) also conclude that the use of a synthetic vortex in the initialization procedure should be limited to forecast periods less than 2-3 days and prior to ET.

Whereas the composite analyses of Arnott et al. (2004) emphasized the key, common features of a North Atlantic cyclone undergoing ET, those of Hart et al. (2006b) delineate the different synoptic factors determining post-ET evolution. The relatively small spread of trajectories in the tropical sector of the cyclone phase space contrasted markedly with the increase in trajectory variability once ET had begun, which provided justification for stratification of these 34 cases by post-ET evolution. The results of these analyses provide a basis for developing testable forecast rules for post-ET storm evolution. For example, post-ET intensifiers begin transition with a negatively tilted trough ~1000km upstream, while post-ET weakeners commence transition ~1500km east of a positively tilted trough. Hart et al. (2006b) hypothesize that the negative trough tilt in the intensifying cases permits a contraction and intensification of the eddy potential vorticity flux, while the positive tilt associated with the weakeners prevents contraction and intensification of the forcing. Identification of the relatively few ET events (6/34 in their study) that will undergo warm-seclusion is critical since such systems greatly increase the chance of post-ET wind and wave damage. Hart et al. (2006b) found that such an evolution is most likely when the scales of the interacting trough and the transitioned ET vortex are similar.

2.4.6.2 Downstream Impacts of the ET Vortex

Recent investigations have begun to address the influence of the tropical cyclone anticyclonic outflow and tropical moisture content on the excitation of standard and diabatic Rossby waves. For example, McTaggart-Cowan et al. (2006) demonstrate that a strong tropical cyclone that does not undergo significant reintensification during ET can still introduce a substantial perturbation – with associated forecast uncertainty – to the extratropics, and even back into the tropics. The growth of model error associated with the ET event has been shown by Harr (2006) and Riemer (2006) to propagate downstream at a speed between the phase speed and group velocity of the wavetrain generated. Harr (2006) further used EOF analysis and clustering to begin the development of a possible forecasting tool capable of identifying likely scenarios associated with individual ET events. Anwender et al. (2006) considered the impact of perturbations to the tropical vortex on ensemble forecasts of the downstream weather impacts of an ET event.

2.4.6.3 Potential Role of ET in Seasonal Variability

Beyond the regional and medium-range hemispheric impacts of ET, Hart (2006) has begun to investigate the relationship between recurving tropical cyclones and the subsequent winter climate. Although this work is still in its relatively early stages, it is interesting to consider the impact of anomalous recurving tropical cyclone frequency on the variability in the hemispheric meridional temperature flux at 500 hPa (Fig. 2.4.3). Preliminary results suggest that anomalous TC recurvature leads to anomalous snowcover at the start of winter that does not return to normal by winter's peak, thereby altering the albedo of the hemisphere and the radiative balance (Hart et al. 2006a).

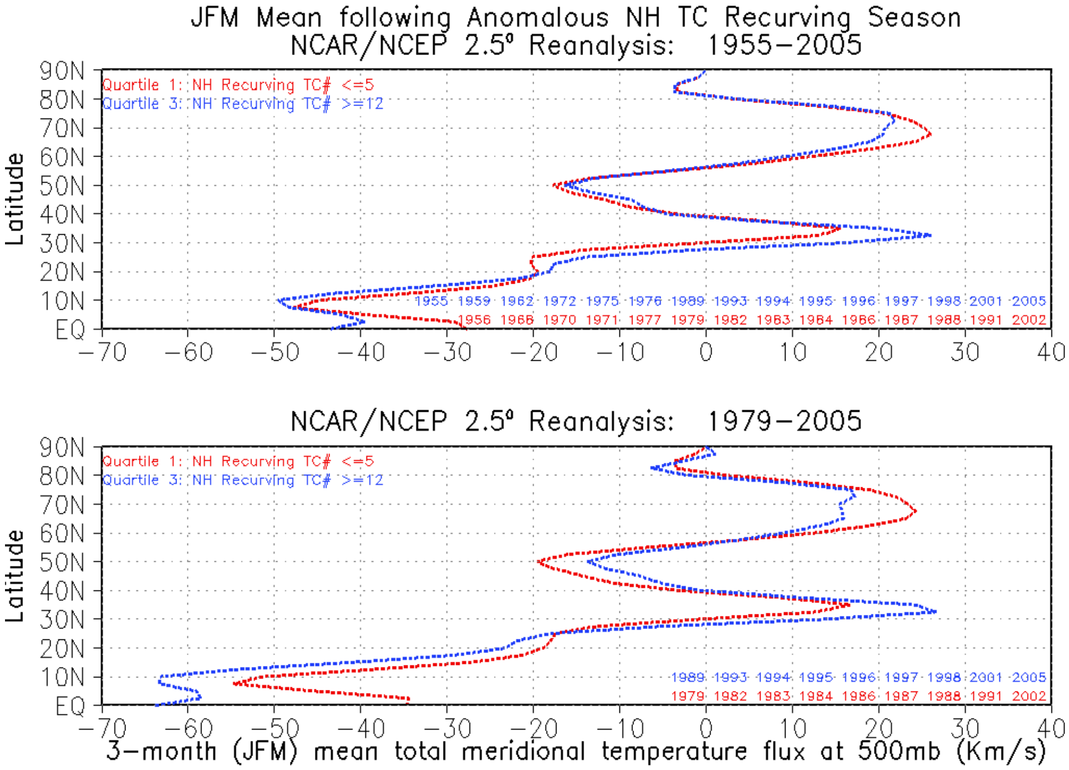

Fig. 2.4.3 The JFM zonal-mean 500mb temperature flux following five or less Northern Hemisphere recurving tropical cyclones (red) and twelve or more (blue). Top panel: 1955-2005. Bottom panel: 1979-2005. Quartiles 1 and 3 are the same for the two periods. Source of data: NCEP/NCAR reanalysis (Kalnay et al. 1996). Figure reproduced from Hart et al. (2006a).

2.4.6.4 Development of Forecast Diagnostics of Potential Interest to the Forecast Community

Since 2004, researchers at the State University of New York at Albany have been generating realtime diagnostic displays, primarily for map room discussions(http://www.atmos.albany.edu/facstaff/rmctc/DTmaps/animSelect.php.The animation-ready images are archived for approximately three months. Images are generated from the high-resolution (0.5 degree) GFS final global analysis using diagnostics computed on the sphere for enhanced accuracy. The system has been designed to be flexible to make it simple to add new images, domains, and levels upon request.

During periods of enhanced tropical/extratropical interaction (such as ET events), streamfunction, velocity potential, and quasi-geostrophic (QG) diagnostics are of particular interest. The first two quantities are useful because the flow at all latitudes is faithfully represented by the wind field components. The streamfunction field reveals the meridional extent of the midlatitude features, while the velocity potential highlights regions of large-scale ascent either driven by dynamical forcing or persistent convection. Two sets of QG diagnostics are provided: a traditional set computed using the geostrophic winds; and a second set based on the non-divergent wind field. This second method for computing the Q-vector fields has the advantage of minimizing noise in the tropics and near active convection. The intention is to use these fields to estimate the strength of the forcing that the large-scale flow is applying in the vicinity of the tropical system during both ET and tropical transition, which is the transformation of a cold-core baroclinic system to a tropical cyclone. The working hypothesis is that when the non-divergent Q-vector ascent forcing reaches a maximum near the storm center, significant constructive interaction will occur between the trough and the tropical feature. These diagnostics are still under development and review at the State University of New York at Albany, although they are freely available at the URL noted above.

2.4.6.5 ET climatology

The climatology of Hart and Evans (2001) documented the importance of ET in the North Atlantic. However, this study lacked regional detail. A climatology of tropical cyclones that have affected Canada since 1900 is presently under construction. This climatology will include the mean wind and rainfall distributions throughout various stages of ET, and the case studies of meteorological fields and impacts from historical events are intended to serve as a reference for forecasters (Fogarty, pers. comm. 2006). Detailed climatologies of this type that also incorporate the range of impacts of historic ET events would be of value in all regions affected by ET.

2.4.7 **Roadblocks for further advancements in ET forecasting**

Several pressing needs should be addressed in the future for ET diagnosis and forecasting:

(i) Improve forecasts of the timing of ET.

Given the uncertainty in current methods for identifying exactly when ET is taking place, and the importance of structure changes associated with the transition on downstream forecasts, it is imperative that research efforts focus on better observations of the event with a goal to refining conceptual models of the transition process.

(ii) Improve the analysis of storm intensity during ET.

At the Third International Workshop on Extratropical Transition in Perth during 2005, a need was identified to direct research toward the development of a satellite-based method to better observe/diagnose the ET process. One potential approach is development of a satellite-based ET identifier. Since the Dvorak IR-based method does not perform adequately as an intensity estimation tool on systems undergoing ET, some operational forecast centers have attempted local modifications that typically use only single channel analyses. Observed ET signatures from SSMI, TRMM, and AMSU instruments, or products such as high-resolution cloud-tracked winds, are all promising. However, no unified multi-spectral approach to observing ET has yet been developed. Such a tool would provide useful operational guidance.

(iii) Improve the forecast of cyclone intensity during ET, as well as verification of these forecasts.

(iv) Improve the forecast of tropical cyclone size, particularly the radii of the 34-kt, 50-kt, and 64-kt winds that are used in TC advisories and non-tropical warnings, as well as provide verifications of these forecasts;

These issues may be helped by improved numerical weather prediction. However, ET-specific statistical-dynamical techniques analogous to the tropical cyclone forecast techniques such as SHIPS and the wind radii CLIPER may be a first step.

(v) Improve the cyclone phase space diagram by direct use of observations instead of model analyses.

As a proof-of-concept, satellite-based analyses of specific case studies using microwave soundings have been performed. However, the satellite-based cyclone phase space is far from being operational.

(vi) Improve guidance for tornado outbreaks associated with a landfalling TC (whether ET or not).

(vii) Improved guidance for the precipitation structure during ET.

Explorations of the cyclone phase space as a diagnostic for surface wind radii and rainfall transitions are presently underway.

Interestingly, forecasting roadblocks identified here have much in common with the forecast needs given in Jones et al. (2003).

2.4.8 **Proposals for moving forward**

An improved understanding of the structural changes and impacts during the extratropical transition from a tropical cyclone to an extratropical cyclone will contribute to the development of improved conceptual and numerical models that will enable weather forecasters to better anticipate changes, and improve warnings associated with ET (Abraham et al. 2004). Such understanding could be gained through post-analyses of challenging forecast cases (e.g., Maria and Wilma from 2005) and focused field experiments. Field experiments in planning stages for THORPEX (such as the Pacific Asian Regional Campaign, or PARC, presently slated for 2008; Shapiro and Thorpe 2005) provide ideal fora for exploring the storm-scale evolution (including intensity, structure, and wave impacts), downstream predictability associated with ET, and for testing forecasting paradigms.

Determining the nature of the indirect effects of ET, and the physical mechanisms behind them, is an important current research topic of relevance to the forecast community. Higher resolution global analyses that assimilate an increasing number of observations will help to improve our understanding and aid in the creation of conceptual models of the impacts of ET on the larger-scale flow. Evaluations of the extent and multi-scale nature of the interactions between the remnant TC and its environment from diagnostic, modeling, and ensemble-based perspectives are promising avenues for forecast improvement.

Improvements in the availability of forecast tools and analyses to forecasters across all affected regions, and continued communication of recent results between the operational and research communities, remain vital to the advancement of ET forecasting.

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