Determination of a Consistent Time for the Extratropical Transition of Tropical Cyclones. Part I: Examination of Existing Methods for Finding “ET Time”

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(Manuscript received 3 August 2009, in final form 23 March 2010)

ABSTRACT

As a tropical cyclone moves poleward and interacts with the midlatitude circulation, the question of whether it will undergo extratropical transition (ET) and, if it does, whether it will intensify or dissipate, is a complex problem. Several quantities have been proposed in previous studies to describe extratropical transition including frontogenesis, 500-hPa geopotential heights, and cyclone phase-space parameters. In this study, these parameters are explored for their utility in defining an ET time using the Navy’s Operational Global Assimilation and Prediction System gridded analyses. The 500-hPa geopotential heights and frontogenesis currently do not have objective numerical definitions. Therefore, this study attempts to establish and examine threshold values that may be used to objectively define the ET time. Cyclone phase space already has numerical threshold values that can be examined.

Results show that the 500-hPa geopotential height open wave distinguishes 81 of 82 cases, but it fails to discriminate between transitioning ET and recurving non-ET cases and cannot be determined automatically. The 2D scalar frontogenesis distinguishes 77 of 82 cases but does not discriminate between transitioning ET and recurving non-ET cases. Finally, phase space successfully distinguishes 81 of 82 cases for the “ET time” defined by the asymmetry parameter but is only successful at capturing transitioning ET and recurving non-ET cases properly for 60 of 82 cases. All of the definitions are found to have disadvantages that preclude them from providing consistent guidance for when extratropical transition of a poleward-recurving tropical cyclone is occurring.

1. Introduction

Recently, there has been an increase in the research regarding the transition of tropical cyclones (TCs) into extratropical cyclones, called extratropical transition (ET), as they move poleward and interact with midlatitude circulations. It has been found that many of these ET cases result in powerful extratropical cyclones, which are sometimes even stronger and/or more intense than the former TC. These extratropical cyclones often pose a threat similar to that of TCs, but they do not receive the same attention and prove to be a challenge to forecast.

The physical processes by which a deep warm-core TC moves poleward, loses tropical characteristics, and interacts with a cold-core trough or preexisting extratropical cyclone is typical of ET (DiMego and Bosart 1982a,b; Foley and Hanstrum 1994; Harr and Elsberry 2000; Klein et al. 2000; Hart and Evans 2001). The poleward propagation of the storm brings it into an environment that is considerably different from the tropical environment in which the TC originally spawned. Some of the environmental changes include an increase in vertical wind shear associated with increasing midlatitude westerlies and baroclinicity, stronger meridional temperature gradients, a decrease in sea surface temperatures (SSTs) with an increase in the SST gradient, and an increase in the Coriolis parameter (Jones et al. 2003). The effects of these environmental changes generally act to increase the translation speed of the storm while decreasing the maximum wind speed and increasing the radius of gale-force winds. The increase in the size and speed along with increased environmental westerly vertical shear causes the decaying TC to become very asymmetric.
and contributes to the generation of large waves and swell (Jones et al. 2003).

Tropical cyclones that undergo ET are often difficult to forecast, especially for numerical models (McTaggart-Cowan et al. 2001; Ma et al. 2003; Evans et al. 2006; Anwender et al. 2008). Because a clear understanding of the interaction between TC and midlatitude features does not exist, it is difficult to forecast the ensuing intensity and strength of the fully transitioned storm. It is also problematic to accurately forecast the speed and location of the storm because small errors in the initial location of the TC can result in large errors in the 24- and 48-h numerical weather prediction forecasts. As TCs propagate farther into the midlatitudes and interact with a preexisting extratropical cyclone, it can be difficult to distinguish between the TC and the extratropical cyclone (Hart and Evans 2001). These basic forecasting issues make it challenging to forecast the location of the high winds along with precipitation and the oceanic response to the transitioned cyclone (Jones et al. 2003).

Using a combination of satellite-derived data and operational analyses, Klein et al. (2000) found that TCs undergoing ET all exhibit a common series of structural changes. They proposed a conceptual model of the ET process by dividing it into two stages—transformation and reintensification. The transformation stage begins when the TC begins to show signs of asymmetry, particularly on the west side where a dry slot forms and the deep convection decreases significantly. In addition, the tropical cyclone becomes sheared and the warm core weakens. These changes are due to the interaction between the TC and background midlatitude environment, including the increasing temperature gradient with colder temperatures to the north and increasing upper-level westerlies. The transformation stage ends when the TC becomes embedded in the baroclinic zone, and the reintensification stage begins when the tropical cyclone remnants begin to strengthen as part of an interaction with an upper-level, midlatitude trough. Not all TCs that complete the transformation stage go on to the reintensification stage, and those TCs that do not quickly weaken and dissipate.

The structural changes during the transformation stage of extratropical transition are fairly consistent from case to case and can be easily viewed in satellite imagery. Thus, the end of the transformation period could be the definition of a single, consistent time to focus the entire ET process around. Although this definition for an ET time can be viewed via satellite imagery, the classification for when the TC is fully “embedded” within the baroclinic zone is open to interpretation and could include definitions of environmental low-level temperature or midlevel geopotential heights, for example.

In this study, the end of the transformation stage of extratropical transformation is defined as the centering “ET time,” and the parameters that have been discussed in the existing literature are assessed for their utility in consistently identifying this time. Although there has been a recent increase in the study of physical processes associated with TCs as they transition into extratropical cyclones, there is still no methodology for determining ET time that 1) is widely recognized and easy to apply, 2) is consistent across all cases of ET, or 3) provides results that are consistent across different datasets and even perhaps different basins. Such a definition would have utility for the operational community by providing a standardized time to designate extratropical transition. There would also be several benefits for the research community, including a consistent designation in the best-track records for ET with associated criteria that are physically based but easily understood. The existing definitions of ET include, but are not limited to, descriptions of the structural evolution of the TC during extratropical transition using satellite-derived data (Klein et al. 2000), analyses (Sinclair 2002; Foley and Hanstrum 1994), global gridded datasets (Ritchie and Elsberry 2001, 2003, 2007; Demirci et al. 2007), the progression of an axisymmetric warm-core system to an asymmetric cold-core system via phase space (Hart 2003; Evans and Hart 2003), and frontal cyclogenesis (Harr and Elsberry 2000).

An objective definition for the ET time is provided by Demirci et al. (2007) in which they proposed that the TC is properly embedded in the baroclinic zone (i.e., end of transformation stage) when the TC becomes an open wave in the 500-hPa geopotential height analyses. In most cases during the overlapping period of the two studies, this time coincides closely with the end of transformation stage as determined by Klein et al. (2000) using satellite imagery. In addition, the open-wave time provides an objective way to define ET time that can be viewed using gridded datasets by nonexperts.

Harr and Elsberry (2000) use the 3D frontogenesis calculated by Schultz and Doswell (1999), which was an extension of the Keyser et al. (1988) study for the 2D vector frontogenesis, to explain some of the dynamic processes associated with transitioning TCs. Their case study storms (Typhoons David and Opal from 1997) are chosen such that each one is entering a baroclinic zone and encountering either westerly or southwesterly flow. Typhoon David propagates poleward ahead of a trough (southwesterly flow) and Typhoon Opal moves slightly poleward and eastward into a trough that is downstream to the TC at earlier times (westerly flow). The calculation of frontogenesis is split into two parameters—scalar and rotational frontogenesis. The Harr and Elsberry (2000) hypothesis is that the scalar frontogenesis will be...
similar for both cases, whereas the rotational parameter will be different, which is consistent with the results found in Schultz and Doswell (1999). This is because the scalar parameter is mostly related to the divergence and deformation patterns, and the rotational parameter is mostly associated with the relative vorticity patterns. Harr and Elsberry (2000) further found that the addition of scalar frontogenesis in the northeast and northwest quadrants of the transitioning TC increases dramatically for both cases and that this may be used as an indicator of the ET time.

A robust method that is becoming well accepted in the community is that of cyclone phase space (Hart 2003; Evans and Hart 2003), which examines the cyclone type as a continuum. By examining three parameters—lower-tropospheric asymmetry, lower-tropospheric thermal wind, and upper-tropospheric thermal wind—the phase and structure of cyclones can be defined. The thickness asymmetry parameter takes into account the storm speed and direction and the areal average of geopotential height to either side of the storm motion at some radius. A threshold value of the thickness asymmetry parameter, to determine whether the storm is tropical or extratropical, has been suggested as 10 m (Evans and Hart 2003), with mature TCs having asymmetry values less than 10 m and developing extratropical cyclones having asymmetry values much greater than 10 m. Mature, or occluded, extratropical cyclones may exhibit an asymmetry parameter that is also less than 10 m. This threshold asymmetry value was compared to the Klein et al. (2000) criteria by Evans and Hart (2003) and found to be generally exceeded at, or just subsequent to, the end of the transformation stage. The asymmetry parameter is the first numerical definition for ET time that includes both dynamical aspects of ET and is presented in an easy-to-understand format.

In this paper, we examine the validity of the existing definitions in the literature for defining the ET time using compositing and other statistical methods. In section 2, the data and methods will be described, section 3 provides an analysis of the results, and a summary and conclusions are presented in section 4.

2. Data and methods

The data used are the Navy Operational Global Atmospheric Prediction System (NOGAPS) analyses on a 1° latitude–longitude grid at 13 levels between 1000 and 50 hPa as acquired from the Master Environmental Library (available online at http://mel.nrlmry.navy.mil). Eighty-two recurring TCs from the western North Pacific and North Atlantic Oceans from 2003 through 2006 are included in the dataset. For the purposes of the study the Demirci et al. (2007) definition of ET time is used as a first-guess ET time. This is defined as the time at which the TC becomes an open wave in the 500-hPa geopotential height analyses using a contour interval of 20 m (Demirci et al. 2007). Using the best-track data provided by the Joint Typhoon Warning Center (JTWC) for the western North Pacific and the National Hurricane Center (NHC) for the North Atlantic, the center of each TC at 12-h intervals for 3 days prior and 3 days subsequent to the ET time (13 times in all) are found in the analyses. Because the TC is artificially boused into the NOGAPS data based on knowledge of the existing TC (Goerss and Jeffries 1994), the center is easy to find while the TC is still considered tropical. The TC bogus vortex is composed of synthetic observations that are a result of the combined cyclone-scale vortex and the large-scale environment (Goerss and Jeffries 1994). The synthetic observations are added at 13 locations in the horizontal grid—one at the TC center and one in each cardinal direction (east, west, north, and south) at three different radii (220, 440, and 660 km)—for six vertical levels (1000, 925, 850, 700, 500, and 400 mb; Goerss and Jeffries 1994). Once the maximum wind drops below 34 kt, the TC vortex is no longer boused, and the location estimates are improved upon by manual examination of the sea level pressure and low-level wind fields. In addition, because some TCs are absorbed by the pre-existing extratropical cyclone, there is no longer a closed contour in the mean sea level pressure analyses indicating the TC. In these cases, the center of the TC being absorbed is slowly merged into the preexisting extratropical cyclone.

After each storm center is determined, the data are converted to an 83° by 73° storm-centered grid for all times and these grids are used to calculate the frontogenesis and phase-space parameters in a TC-centered framework. The scalar frontogenesis parameter includes the addition of three terms [see Eq. (9a) in Schultz and Doswell (1999) or Eq. (6a) in Harr and Elsberry (2000)], which are the divergence, deformation, and tilting terms. Each of the terms is multiplied by the negative inverse of the horizontal potential temperature gradient. Because of the finite differencing used to calculate the frontogenesis, the resulting grid size is reduced to 81° by 71°. The phase-space parameters include the thickness asymmetry and the lower- and upper-level thickness asymmetry values as defined by Eqs. (2), (5), and (6), respectively, in Hart (2003) using a 500-km radius from the storm center.

The 82 TCs included in the dataset are chosen because they exhibit a recurring track in which the storm began to move poleward and eastward toward or within the midlatitudes. Note that some of these storms do not actually undergo ET. However, they are included in the dataset to determine if the parameters can distinguish
them from TCs that really do undergo at least the transformation stage of ET (Klein et al. 2000). The dataset also includes some storms that make landfall, particularly in the Atlantic hurricane basin. Although the land may have additional impacts on the ET processes, Atlantic landfalling storms are still included.

The 2003 through 2006 seasons are chosen because there are enough recurring TCs (i.e., 82) during that period to separate into reasonable groupings. The three main scenarios include TCs that undergo ET and reintensify or strengthen, TCs that undergo ET and then dissipate, and TCs that recurve but do not undergo ET. Many studies examined TCs that reintensify during ET, but the typical TC that undergoes ET has an expanded wind field with generally a lower maximum wind (e.g., Jones et al. 2003), which means that it is possible for storms to strengthen and not intensify during ET. In addition, poleward-moving storms move into a lower pressure environment, which means that a lower central pressure does not necessarily mean the storm has intensified if the environment also decreased by the same amount. Therefore, storms are grouped into either reintensifying or strengthening storms or dissipating storms depending on the difference between the central pressure and the environmental mean pressure averaged over the grid, calculated as

$$\Delta P = \frac{1}{n \times m} \sum_{i=1}^{n} \sum_{j=1}^{m} P_{i,j} - P_{\text{central}}.$$

If $\Delta P$ increases by more than 3 hPa after reaching a minimum, the storm is considered a reintensifying or strengthening case. Conversely, if $\Delta P$ either increases by less than 3 hPa or does not reach a minimum and continues to decrease, the storm is considered a dissipation case. These criteria yielded 58 TCs that strengthened after undergoing ET, 8 TCs that underwent ET and weakened, and 16 TCs that did not undergo ET.

The strengthening–reintensifying cases are further broken down into several types based on additional criteria. One criterion is based on Harr and Elsberry (2000) where TCs can interact with a preexisting midlatitude trough to the northwest or northeast. Most of the re-intensifying TCs (i.e., 42) are accelerated to the north by a pre-existing midlatitude trough (Fig. 1b). The track for the average non-ET case diverges. Figure 1a shows that, in general, reintensifying TCs that undergo ET with an upstream trough have a slightly more northerly motion into the preexisting midlatitude cyclone than TCs that rapidly accelerate eastward and undergo ET with a downstream trough (Fig. 1b). The track for the average non-ET case is quite different from the other three categories. Although the TC can be accelerated to the north and east, it is generally being steered by the subtropical ridge rather than a trough. In some cases, the TC continues to curve around the ridge and moves back to the south (Fig. 1d).

3. Results

a. 500-hPa geopotential height fields

The dataset for each individual case is initially centered on the time at which the TC becomes an open wave in the 500-hPa geopotential height analyses (Demirci et al. 2007). Figures 2 and 3 show the composite geopotential height fields and standard deviations for the cold-core and warm-seclusion ET cases that interact with an upstream trough and reintensify. For both composites, the west side of the TC is clearly beginning to interact with the east side of the trough, which slopes from southeast to northwest. The major differences can be seen after ET time where there is a high amplitude trough at +48 h in both composites (Figs. 2d and 3d), but there is also a closed low for the warm-seclusion ET composite (Fig. 3d). This is indicative of the potential for rapid intensification with the warm-seclusion cases found by Shapiro and Keyser (1990). However, at later times in the composites, the standard deviations are also much higher than at earlier times. The standard deviation is greater at the remnant TC center for the cold-core ET case composite because the timing of reintensification in the 500-hPa heights varies. The standard deviations near the composite TC for the warm-seclusion ET case after
the open-wave ET time remain low until later times because of the fast reintensification of warm-seclusion ET events and the time it takes for the resulting extratropical cyclone to mature or become occluded.

Based on the Harr and Elsberry (2000) study, TCs that interact with a trough or preexisting extratropical cyclone to the northeast and undergo ET should encounter strong westerly midlevel flow (as opposed to the upstream trough ET cases, which encounter southwest–northeast flow). Figure 4 shows the composites for the downstream trough ET cases along with the standard deviation. It appears that before the composite TC becomes an open wave in the 500-hPa geopotential heights, it moves into a stronger zonal flow indicating that the midlatitude westerlies are dominating the TC motion into the trough to the northeast. However, the standard deviations are greater in the northeast quadrant of the composite TC (as opposed to the northwest quadrant for the upstream trough ET cases), which suggests that the midlevel flow is varying more on that side of the TC. In addition, the downstream ridge has less amplitude, which suggests that the upper-level TC anticyclonic outflow has had less impact on the downstream flow than for the upstream trough cases. Subsequent to the ET time, the composite pattern looks similar to that for the upstream trough cases. This is because the TC has advected to the east side of the trough, and although the overall pattern is less meridional, similar reintegration processes are occurring (Harr and Elsberry 2000).

The post-transition dissipation cases are not separated into upstream and downstream trough interactions because the majority of the nine cases are upstream trough cases. The composite pattern for the dissipating cases (Fig. 5) has some similarities to the upstream trough reintensifying case (Fig. 2) with the southwest–northeast flow on the west side of the TC present indicative of the presence of an upper-level trough to the northwest. However, the ridge to the east of the TC is stronger in the dissipating cases (cf. Figs. 5 and 2) and the remnants of the TC do not embed as deeply in the midlatitude flow. In addition, the standard deviations to the north of the TC are much higher for the dissipating cases, indicating considerable variability in the location and timing of any upper-level troughs that might be present.

Finally, the composites for the TCs that recurve into the midlatitudes, but do not undergo ET, are shown in
Fig. 6. The composite flow on the TCs is more zonal than the upstream trough ET cases and there is little evidence of an upper-level trough near to the TC after ET − 24 h (Figs. 6a,b). The ridge that is initially present to the east of the TC rapidly flattens (Figs. 6c,d) and the remnants of the TC do not embed deeply in the midlatitude flow. In some cases the TC even moves back to the south out of the flow at ET + 48 h, which contributes to the higher standard deviations near the TC at this later time. At all times, there are higher standard deviation values well to the north of the TC center, which most likely indicates varying strength and structure of the midlatitude circulation.

All but 1 of the 82 TCs meet the Demirci et al. (2007) open-wave definition for ET. However, 16 of the 82 do not actually undergo ET but are TCs that recurve under the influence of the subtropical ridge toward the baroclinic zone and then move back south. Thus, the success rate using the open-wave definition for all of the recurring TCs in the dataset is 98.8%. However, the open wave does not distinguish those TCs that approach the baroclinic zone but do not undergo the transition stage. It would be ideal to be able to not only determine a consistent ET time for all recurving TCs, but to also be able to discriminate, at a minimum, the reintensifying cases from the dissipating and non-ET cases. Figure 7a shows the averaged 500-hPa height values at the storm center for each group, with the heights slowly decreasing as the TC approaches the trough and remains a closed wave. As expected, the value for upstream and downstream trough post-transition reintensification ET cases decrease the most post-transition, with the warm-seclusion ET cases lower than those of the other scenarios throughout the period. The values after transition for warm-seclusion ET cases are also consistent with their generally more rapid intensification, with the steepest drop in 500-hPa
values within the first 24 h and lowest values at later times. The dissipating and non-ET groupings show very slight decreases in the average central 500-hPa geopotential height values near the end of the time series, consistent with their general movement poleward, but a lack of reintensification.

To confirm that these cases really do either strengthen or dissipate relative to their environment, Fig. 7b shows the difference between the grid-averaged 500-hPa geopotential heights and the central 500-hPa geopotential height for each group where $\Delta h$ is calculated using Eq. (1) in a manner similar to that for $\Delta P$. If $\Delta h$ increases, then the post-ET system is strengthening, and if $\Delta h$ decreases, then the system is weakening. For the three reintensifying groups it can be seen that from −48 to 0 h the TCs are generally weakening as would be expected during the transition stage. After ET time, the warm-seclusion ET cases strengthen most rapidly while the other upstream cases also strengthen significantly. The downstream trough cases also strengthen but are delayed for about 12–24 h as the TC advects eastward around the base of the downstream trough. Both the dissipating ET and the non-ET cases weaken relative to their environment through at least +36 h after which the non-ET cases show some sign of strengthening as they move south back into the tropics (Fig. 7b).

Figure 7c shows the standard deviations of the 500-hPa height values for each group in Fig. 7a. They are smaller prior to the ET time but begin to increase after the ET time, especially for groups 1–4, which all interact with a trough. This is because, for all the cases that interact with a trough, there is considerable variability from case to case in the structure of the midlatitude circulation. The standard deviations increase earlier in the time series for the warm-seclusion ET cases because they begin to strengthen earliest. The standard deviations increase later in the time series for the downstream trough ET cases because of the time taken to advect around the base of the trough before strengthening occurs. This suggests that maybe the greatest variability is in the actual

![Fig. 3. As in Fig. 2, but for TCs that undergo warm-seclusion ET with an upstream trough and reintensify.](image-url)
interaction with the trough for all groupings. The dissipating ET cases also show an increase in the standard deviations from about ET time to +24 h. This is the time period when the individual TC has the closest approach to a nearby trough. The standard deviations for the non-ET cases remain relatively low through most of the time series because the TCs do not move close to a trough at any stage. There is a slight increase in the standard deviation values at the very end of the time series because some TCs reintensify as tropical entities while others dissipate.

Thus, there appears to be a coherent pattern in the average time series of 500-hPa heights for all the groups. However, there is increased variability (as shown by the standard deviations) during the actual trough interaction because the timing, structure, and speed of the trough vary considerably from case to case. Furthermore, although there is value in terms of choosing a consistent 500-hPa “pattern” as the ET time, there is little dynamical value to the definition of an “open wave.” In addition, the issue of how well the TC vortex is represented in the analysis will affect how accurately the ET time is determined from case to case and analysis system to analysis system. For example, one of the TCs in this dataset interacts with a trough but never becomes an open wave. In some cases, it is also difficult to determine whether the TC becomes an open wave because of baroclinic affects or simply because the storm is weakening.

On the other hand, the 500-hPa geopotential height open-wave definition for ET time is objective and provides a consistent result. In addition, the results above show that there could be some numerical differentiation between ET (66 cases total) and non-ET cases (16 cases). Table 1 shows the results of a true–false test based on several criteria for this differentiation. The first criteria is the Demirci et al. (2007) open-wave definition, which is successful (positive and true) for all but 1 ET case but unsuccessful (negative and false) for all non-ET cases because the definition should reject these cases (negative and true). Two other possible discriminators are proposed.

![Figure 4](image_url)

**FIG. 4.** As in Fig. 2, but for TCs that undergo ET with a downstream trough and reintensify.
based on the central 500-hPa value dropping by either more than 100 m or just dropping in general from the open-wave time to 48 h. These definitions reject more of the non-ET cases as negative and true (15 and 8, respectively). However, they also accept less of the ET cases as positive and true (47 and 61, respectively). Most of the positive and false ET cases for the drop over 100 m come from the post-transition dissipation ET cases, which indicates that it may be appropriate to include the dissipating ET cases with the non-ET cases. The new result would yield a slightly lower rejection rate for the negative cases (21 of 24) while increasing the positive and true rate (46 of 58). Conversely, for the second criteria of any drop in geopotential height, the rejection rate of the negative cases drops dramatically (from 8 of 16 to only 9 of 24) and only slightly improves the positive and true rate (from 61 of 66 to 55 of 58). Therefore, a more acceptable discriminator for the ET time would be the use of a geopotential height drop at 500 hPa greater than 100 m within 48 h.

b. Frontogenesis

Harr and Elsberry (2000) examine the frontogenesis evolution of cyclones interacting with a preexisting trough to the northwest and northeast, consistent with the flows found by Schultz and Doswell (1999), and they hypothesize that scalar frontogenesis can be used to ascribe the ET of TCs. More specifically, the hypothesis is such that the addition of scalar frontogenesis in the northeast and southwest quadrants of the cyclone will show a distinct increase, which could potentially indicate the ET time. The 3D scalar frontogenesis is calculated for extratropical flow by Schultz and Doswell (1999), where the spatial patterns show considerable noise and little coherence. However, the 3D scalar frontogenesis is also calculated by Harr and Elsberry (2000), and the spatial patterns are generally smooth and coherent. In general, the tilting term should dominate positive frontogenesis for a mature or symmetrical tropical cyclone while the deformation and divergence terms should be negligible (Schultz and Doswell, 1999).
Doswell 1999). As the encroaching trough approaches, the contribution from tilting should decrease while the deformation and divergence contributions increase.

For this study, the frontogenesis parameter is calculated as the combined averaged scalar frontogenesis in the northeast and southwest quadrants within 500 km of the TC. Figure 8 shows the average and standard deviation time series of the three contributing terms to scalar frontogenesis and the total scalar frontogenesis. The scaling for the divergence and deformation is slightly less than one order of magnitude lower than the scaling for the tilting term and total scalar frontogenesis. The average tilting (Fig. 8e) is clearly contributing the majority of frontogenesis to the total scalar frontogenesis (Fig. 8g), especially at early times while the TC is more mature and symmetric and the divergence (Fig. 8a) and deformation (Fig. 8c) are small. At later times, when the tilting contribution decreases, the divergence and deformation both increase. However, the magnitude of the increase is not enough to entirely offset the tilting contribution even at these later times. Also it does not appear that the scalar frontogenesis terms have any distinguishable pattern that may be used to separate the upstream and downstream reintensifying ET cases, the posttransition dissipation ET cases, and the non-ET cases. Furthermore, the standard deviations (Figs. 8b,d,f,h) also show that there is very large case-to-case variance due to the variance in storm intensity (tilting) and proximity to the midlatitude trough (deformation and divergence).

The average divergence and deformation figures show that it may be more appropriate to examine the 2D scalar frontogenesis of Keyser et al. (1988). Figure 9 displays the average and standard deviation of the 2D scalar frontogenesis not including the tilting contribution. Before the TCs become open waves, the 2D scalar frontogenesis is close to zero, which is expected. As the TCs approach the open-wave ET time, the frontogenesis for the downstream trough reintensification ET cases, the post-transition dissipation ET cases, and the recurving non-ET cases begins

Fig. 6. As in Fig. 2, but for TCs that recurve into the midlatitudes, but do not undergo ET.
to increase (Fig. 9a). The upstream trough reintensification ET cases show an increase after the open-wave ET time. For all cases, the standard deviations (Fig. 9b) increase dramatically after the open-wave ET time, as well. The only pattern that appears to distinguish the reintensification cases from the dissipation or non-ET cases is that the average 2D frontogenesis is higher at 36 h. A further examination of the 2D scalar frontogenesis reveals that a threshold value of 0.05 K (100 km)$^{-1}$ (3 h)$^{-1}$ captures 77 of the 82 cases and can be used as a centering time. Figures 9c and 9d show the recentered average and recentered standard deviations. Although the patterns for each scenario in Fig. 9c are similar to those found in Fig. 18 of Harr and Elsberry (2000) for 3D scalar frontogenesis, the standard deviation values represent extremely high case-to-case variability at all times. Thus, the mean values are not a good representation for each group, and it is difficult to define a practical parameter threshold to distinguish the reintensification cases from the dissipation or non-ET cases using the 2D scalar frontogenesis.

c. Phase-space asymmetry parameter

Another method for determining the transition of a TC into an extratropical cyclone is the use of phase-space diagrams (Hart 2003; Evans and Hart 2003; Hart et al. 2006). The proper progression for ET using phase-space diagrams (Evans and Hart 2003) should start with a symmetric warm-core structure (thickness asymmetry close to 0 and positive low-level thermal wind values) that is a reflection of the tropical structure of the TC. As the storm enters the midlatitude environment, the thickness asymmetry ($B$) will begin to rise and the thermal wind parameter ($V_L^T$ for 600–900 hPa and $V_U^T$ for 300–600 hPa) will decrease because of the encroaching midlatitude westerlies, which act to shear the upper levels of the TC and make the TC more asymmetric. During ET, $B$ values should increase as the TC becomes asymmetric warm core (Hart 2003; Evans and Hart 2003; Hart et al. 2006). Finally, $V_L^T$ decreases below zero, and ET is completed. In many cases, $B$ values decrease again late in the life cycle, indicating that the cyclone has matured and begun to occlude. Evans and Hart (2003) determined that a TC is no longer tropical at a value of $B$ greater than or equal to 10 m and the ET evolution is complete when the $V_L^T$ becomes negative.

Figure 10 shows the average and standard deviations of $B$ and the average and standard deviation of $V_L^T$ centered on the first time that $B$ is greater than 10 m.

TABLE 1. Performance success of 500-hPa geopotential heights at defining ET onset and completion.

<table>
<thead>
<tr>
<th>500 hPa</th>
<th>ET onset</th>
<th>ET completion</th>
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<tbody>
<tr>
<td></td>
<td>Open wave</td>
<td>$\Delta &lt; -100$ within 48 h</td>
</tr>
<tr>
<td>Positive*</td>
<td>Success</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>Fail</td>
<td>19</td>
</tr>
<tr>
<td>Negative**</td>
<td>Success</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Fail</td>
<td>8</td>
</tr>
</tbody>
</table>

* Positive (ET) = 66 cases.

** Negative (non ET) = 16 cases.
Each of the ET groups in Fig. 10a exceeds and remains above the $B = 10$ m value until the end of the time series. The average $B$ value for the non-ET cases just exceeds the 10-m threshold, but only at the ET time. This indicates that the non-ET cases do not become as asymmetric as the ET scenarios. The standard deviation values for each scenario in Fig. 10b also remain low prior to ET time for all scenarios and begin to rise at ET time, indicating more variability among the cases in all scenarios after this time.

The maximum $B$ values for the upstream cold-core reintensification and the downstream trough reintensification cases occur at $+36$ h. This indicates that these cases remain very asymmetric in structure throughout
much of their life, beginning to resymmetrize as occluded extratropical cyclones late in their life cycle. The $B$ parameters for the post-transition dissipation cases continue to slowly rise throughout the time series, indicating that these cases never develop into extratropical cyclones and gradually dissipate. Conversely, the maximum $B$ value for the upstream trough warm-seclusion ET cases is reached much earlier, at +12 h, and then decreases through the rest of the time series almost back to $B = 10$. This is indicative of the rapid reintensification and structural resymmetrization inherent in warm-seclusion cases (Figs. 10a and 7a,b). In addition, the maximum value for the downstream trough reintensification cases is much higher than in the other scenarios because of the strength of the gradient between the midlatitude westerlies and the steering ridge, which causes a higher asymmetry. It appears from this analysis of the average $B$ values for each scenario that there could be some features that discriminate the various cases from each other.

Phase space includes low-level $V_L^T$ and upper-level, $V_U^T$, thermal wind parameters, along with $B$ to determine the completion of ET. When centering the five scenarios on a centering time of $B > 10$ m, the defining characteristic for the thermal wind parameters are that in all cases, the upper levels of the storm become cold cored at, or just subsequent to, the 0-h time (Fig. 10c). The low-level thermal wind parameter becomes negative (develops a cold core) approximately 12 h after the upper-level thermal wind parameter for all cases except the warm-seclusion case (Fig. 10c). This thermal wind development from the top down is indicative of a strengthening cold-core structure appropriate for the reintensification cases. The exception is the warm-seclusion cases in which the low-level thermal wind remains positive, indicating that a low-level warm core remains and even strengthens throughout the time series even as the upper-level becomes relatively weakly cold cored (Figs. 10c,e). This is the expected signal for warm-seclusion transitions in which the lower vortex may become weakly cold cored (five of the nine cases do become weakly cold core) but then reintensifies as a shallow warm-core system in the lower levels and cold cored in the upper levels (Hart 2003; Evans and Hart 2003; Hart et al. 2006).

Interestingly, the average evolution in phase space for the recurving non-ET case is such that these storms begin and complete ET by phase-space definitions (i.e., they become asymmetric and cold core in the upper levels, then become cold core in the lower levels as one would expect for a reintensifying ET storm). However, these cases should not be following the traditional ET path through phase space. Instead they should retain most of the warm-core structure, especially in the low levels, and exhibit a much smaller change in symmetry. Furthermore, the phase space shows no differentiation between
the cold-core reintensifying ET cases and the post-transition dissipation ET cases even though the average low- and upper-level thermal wind values of the post-transition dissipation ET cases remain positive about 12 h longer than the other scenarios. For all cases, the standard deviations of the thermal wind parameters are a similar order of magnitude to the average, indicating high variability from case to case within each scenario (Figs. 10d,f).

Based on the average plots discussed, the phase space appears to be a consistent method for determining the ET onset and completion. However, it does not distinguish cold-core intensifying TCs from dissipating TCs and only the $B$ parameter distinguishes the recurving non-ET cases. Based on the Hart (2003) and Evans and Hart (2003) definition of $B = 10$ m, a success table is developed for the thickness parameter $B$. All of the ET cases have such a time (positive and true), and all but one of the non-ET cases also have a time at which $B$ is greater than 10 m (negative and false). This shows that while $B$ may be a good way to determine the beginning of ET, it may not be a good parameter for discriminating ET from non-ET cases. The completion of ET is when the low-level thermal wind parameter $V^L_T$ becomes negative while $B$ remains greater than 10 m and $V^U_T$ is also negative (Hart 2003; Evans and Hart 2003). The success of this completion definition is very high (middle columns of Table 2) for the ET cases, but not so successful for the non-ET cases. The last column is labeled proper ET in Table 2. The reason for the large discrepancy between the “ET progression” and “proper ET” columns is because the storm can again become symmetric ($B < 10$ m) before becoming cold core and this would not be considered a proper ET progression through phase space.

![FIG. 10. Average and standard deviation of (a),(b) thickness asymmetry (m); (c),(d) low-level thermal wind (m s$^{-1}$); and (e),(f) upper-level thermal wind (m s$^{-1}$) centered on the first time that the thickness asymmetry is >10 m.](image-url)
Table 2 shows that 50 of the 66 ET cases (76%) are positive successes and follow “proper ET progression.” This is better than the results from Hart et al. (2006) in which they find that roughly 70% of their ET cases resulted in cold-core evolutions. Furthermore, Table 2 shows that the negative success rate, in this circumstance “proper non-ET progression,” is 63%. In addition, as expected, only five of nine warm-seclusion cases become cold core in the lower levels while remaining asymmetric. Of those five cases, four of them become cold core in the lower levels before undergoing the warm-seclusion intensification, whereas the other case undergoes the warm seclusion prior to becoming cold core in the lower levels. The other four warm-seclusion cases either do not become cold core in the dataset examined in this study or become cold core after occlusion (i.e., $B$ and $V_L^T$ correctly characterize these cases), which is consistent with the difficulties of properly characterizing warm-seclusion ET cases found by Hart (2003), Evans and Hart (2003), and Hart et al. (2006). Of the recurring non-ET cases, 6 of 16 cases (37.5%) incorrectly undergo the proper ET evolution in phase space. Therefore, it appears that phase space discriminates the ET cases from the non-ET cases if the ET time is designated using the ET completion time in phase space, but not if the ET time is designated as the first time that $B$ is greater than 10 m.

4. Conclusions

A variety of methods for defining the life cycle of extratropical transition of tropical cyclones can be used to define the time at which a TC is no longer tropical. The methods proposed by previous authors described include an open wave in the 500-hPa geopotential height analyses (Demirci et al. 2007), scalar frontogenesis (Harr and Elsberry 2000), and a phase-space asymmetry parameter value of 10 m (Hart 2003; Evans and Hart 2003). Each method has potential advantages and disadvantages.

The time at which a TC becomes an open wave in the 500-hPa geopotential height analyses coincides with the Klein et al. (2000) end of transformation stage time and is generally easy to determine objectively. All but one case had begun ET by this definition. However, the recurring non-ET cases also begin ET by this designation and therefore the open-wave definition fails to discriminate the ET from the non-ET cases at ET onset. It is possible to set a threshold height change within 48 h of the open-wave time that defines ET completion and distinguishes ET from non-ET cases. However, because the task of determining “open wave” time is currently not automated, the 500-hPa open-wave definition is limited in its usefulness.

Scalar frontogenesis may be used to dynamically characterize the TC–trough interaction while providing an objective, numerical value (and therefore potentially automated) for determining an ET time. However, it is complicated to calculate and the results tend to lack continuity, making it difficult to set reasonable thresholds for scalar frontogenesis to either determine an ET time or distinguish reintensifying from dissipating cases. At early times, the 3D scalar frontogenesis is dominated by the tilting contribution surrounding the TC, and at later times the deformation contribution is greatest but at a lower order of magnitude than the tilting contribution at early times. Overall, the 3D scalar frontogenesis pattern is noisy, and it is difficult to extract a coherent signal. The 2D scalar frontogenesis is also examined to determine if neglecting the tilting contribution provides a more coherent signal for the ET time. Although there appears to be a pattern more similar to that found by Harr and Elsberry (2000) in which the frontogenesis increases dramatically, there is considerable case-to-case variability, making it problematic to set a threshold for ET.

Using cyclone phase-space evolution, the asymmetry parameter $B$ was examined along with the thermal wind parameters as a means of defining the time at which a TC is no longer tropical. Similar to the open-wave definition, the phase-space asymmetry parameter definition, which would provide an “ET onset” time, results in all but one TC beginning the transformation stage of ET, when in reality none of the non-ET cases should, and thus does not discriminate between ET systems and non-ET systems. The phase-space asymmetry parameter also provides no way of distinguishing between cases that re-intensify or dissipate post-transition. However, the results
of this study actually indicate that more TCs undergo “proper ET” in phase space than was stated by Hart et al. (2006), suggesting that a discriminating factor for ET is the completion of ET in cyclone phase space. The problem with this definition, similar to that for “open wave,” is that determining that ET has happened after it has happened has little utility for forecasting, although it does have considerable utility in a hindcast mode for determining whether ET really occurred.

The task of identifying a useful, consistent, automatic, and timely “ET time” is still to be accomplished. Thus, future work will be committed to 1) distinguishing a dynamically relevant ET time, 2) distinguishing recurring ET TCs from recurring non-ET TCs, and 3) distinguishing dissipating ET TCs from intensifying ET TCs during the period the TC is actually undergoing ET. In addition, the dataset of recurring TCs will be increased so that more subclasses of ET TCs can be included in the analysis while using a new set of gridded analyses that do not include a TC bogus. Such subclasses include rapid, slow, weak, moderate, and strong intensifiers, to name a few. Also, there may be some potential in automating the Klein et al. (2000) satellite-based ET metrics to establish a more consistent ET time that will be easier for the operational community to use in situ.

Acknowledgments. We would like to acknowledge the efforts of two anonymous reviewers whose comments have resulted in a considerably improved manuscript. We would also like to acknowledge the communications we have had with Dr. Bob Hart regarding the calculation of phase-space parameters and Dr. Jeffrey Goerss regarding the NOGAPS TC vortex bogus insertion. NOGAPS analyses were downloaded from the Master Environmental Library (MEL, available online at http://mel.nrlmry.navy.mil). This work has been supported by the National Science Foundation under Grant ATM-0730079.

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