Extratropical Transition of Western North Pacific Tropical Cyclones: An Overview and Conceptual Model of the Transformation Stage

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ABSTRACT
Extratropical transition (ET) in the western North Pacific is defined here in terms of two stages: transformation, in which the tropical cyclone evolves into a baroclinic storm; and reintensification, where the transformed storm then deepens as an extratropical cyclone. In this study, 30 ET cases occurring during 1 June–31 October 1994–98 are reviewed using Navy Operational Global Atmospheric Prediction System analyses; hourly geostationary visible, infrared, and water vapor imagery; and microwave imagery. A brief climatology based on these cases is presented for the transformation stage and the subsequent cyclone characteristics of the reintensification stage.

A three-dimensional conceptual model of the transformation stage of ET in the western North Pacific Ocean is proposed that describes how virtually all 30 cases evolved into an incipient, baroclinic low. The three-step evolution of the transformation of Typhoon (TY) David (September 1997) is described as a prototypical example. Four important physical processes examined in each of the three steps include (i) environmental inflow of colder, drier (warm, moist) air in the western (eastern) quadrant of David’s outer circulation that initiates an asymmetric distribution of clouds and precipitation, and a dipole of lower-tropospheric temperature advection; (ii) the interaction between TY David and a preexisting, midlatitude baroclinic zone to produce ascent over tilted isentropic surfaces; (iii) systematic decay and tilt of the warm core aloft in response to vertical shear; and (iv) an evolution of David’s outer circulation into an asymmetric pattern that implies lower-tropospheric frontogenesis.

The beginning and end of the transformation stage of ET in the western North Pacific is defined based on the interaction of the tropical cyclone circulation with a preexisting, midlatitude baroclinic zone. In particular, cases that complete the transformation stage of ET become embedded in the preexisting, midlatitude baroclinic zone, with the storm center in cold, descending air. Cases that begin transformation but do not become embedded in the baroclinic zone fail to complete transformation and simply dissipate over lower sea surface temperatures and in an environment of vertical wind shear. Use of the conceptual model, together with satellite imagery and high-resolution numerical analyses and forecasts, should assist forecasters in assessing the commencement, progress, and completion of the transformation stage of ET in the western North Pacific, and result in improved forecasts and dissemination of timely, effective advisories and warnings.

1. Introduction
Tropical cyclones in the western North Pacific that complete extratropical transition (ET) can become powerful, midlatitude storms capable of causing significant damage to coastal and maritime interests. Extratropical transition is a complex, four-dimensional evolution in which meteorological features on various horizontal and vertical scales interact over a range of temporal scales. The thermodynamic and dynamic characteristics of a mature tropical cyclone are well researched, as are the physical processes responsible for extratropical cyclogenesis. By contrast, the transition from tropical cyclone to extratropical cyclone is poorly understood and incompletely researched. Furthermore, numerical weather prediction (NWP) models often fail to forecast accurately the onset of ET and the subsequent evolution of the resulting midlatitude cyclone and, thus, may have significant motion and intensity errors. Any effort that improves the description, understanding, and definition of ET would provide forecasters with better tools for diagnosing and forecasting ET, and lead to dissemination of more effective advisories and warnings.

Matano and Sekioka (1971) defined two characteristic types of ET in the western North Pacific based only on surface pressure analyses. A complex transition occurs when a preexisting midlatitude front or trough interacts with a tropical cyclone to produce a new extratropical cyclone on the front. A compound transition results when a midlatitude cyclone approaches and appears to merge with a tropical cyclone such that the tropical cyclone is transformed into an extratropical cyclone. Brand and Guard (1978) added a third type of transition in which the tropical cyclone dissipates after recurva-
t. Later, the critical role of upper-tropospheric divergence and positive vorticity advection (PVA) in the extratropical reintensification of tropical cyclones was identified and discussed in several papers (DiMego and Bosart 1982; Sinclair 1993; Foley and Hanstrum 1994; Klein 1997; Harr et al. 2000), thus illustrating the three-dimensional character of ET. In the case of Hurricane David, Bosart and Lackmann (1995) described how the tropical cyclone altered an environment of weak, pre-existing baroclinicity to permit extratropical redevelopment. Browning et al. (1998) discussed the evolution of Hurricane Lili into an extratropical, warm-core cyclone through interaction with a stratospheric potential vorticity (PV) anomaly, and subsequent intrusion of cool, dry air that encircled the warm, moist air over the circulation center.

The sequence of events that occur during ET have been examined and described using satellite imagery, NWP analyses, and radar reflectivity patterns. Klein (1997) studied cases of ET in the western North Pacific that occurred during July–October 1994–96. He indicated that virtually all of these cases appeared in infrared (IR) imagery and NWP analyses to transform from a warm-core vortex into a baroclinic, extratropical cyclone in the same sequential fashion, and called this the transformation stage of ET. He also defined a second stage called reintensification, in which the transformed tropical cyclone either reintensifies if the upper troposphere is favorable for extratropical cyclogenesis [i.e., upper-tropospheric divergence and PVA are superposed above lower-tropospheric baroclinicity as described by Bosart and DiMego (1982), Sinclair (1993), and Foley and Hanstrum (1994)], or dissipates. Shimazu (1998) reviewed conventional radar reflectivity patterns during 16 typhoons that struck Japan. In all seven cases in which a typhoon approached a midlatitude frontal zone, a triangular-shaped “delta rain region” was observed north of the storm center.

A tropical cyclone that translates poleward into the midlatitudes may interact with upper-level troughs and the polar jet, particularly during the autumn. Harr et al. (2000) discussed how the character and phasing of midlatitude synoptic patterns affect ET in the western North Pacific. They defined two characteristic synoptic patterns (northwest and northeast) based on the location of the upper-level PV maximum in the midlatitudes relative to the tropical cyclone at transition time [first synoptic time at or after the Joint Typhoon Warning Center (JTWC), Pearl Harbor, HI, designates the storm as extratropical]. Storms in the northwest pattern tended to deepen more quickly in the 36 h following transition time, and moved in a more meridional fashion, than those in the northeast pattern, which reintensified more slowly and moved more zonally.

One of the objectives of this study is to develop a conceptual model of the transformation stage of ET in the western North Pacific that describes how vertical wind shear and lower-tropospheric, horizontal temperature and moisture gradients in the midlatitudes interact with a tropical cyclone that is translating poleward over lower sea surface temperatures (SSTs) to transform the tropical cyclone into a baroclinic, extratropical storm. Cases occurring during 1997–98 have been added to the Klein (1997) database so that this study includes 30 cases of ET occurring in the western North Pacific from 1 June through 31 October during 1994–98. Although ET can occur at anytime of the year, this study focuses on the months June through October to address specific threats posed to maritime interests by tropical cyclones undergoing ET. Many transocean voyages during this period are planned at higher latitudes, which minimizes distances while avoiding tropical cyclones. However, an ET may lead to an unexpectedly strong midlatitude cyclone during these months, thus posing a threat to safe navigation at higher latitudes.

Section 2 describes the data and method used to examine the 30 cases of ET that occurred during this five-year period. In Section 3, a brief climatology based on these cases is presented for the transformation stage and the subsequent cyclone characteristics of the reintensification stage. A conceptual model of the transformation stage of ET, based on detailed analysis of these 30 cases, is presented in section 4. The step-by-step transformation of TY David is presented as an example of how the transformation stage of ET proceeds according to the proposed conceptual model. In section 5, the conclusions of this study are summarized, and areas of future research are discussed.

2. Data and analysis procedures

a. Definitions

Use of the terms transition and transformation during discussions of ET in the literature often produces confusion. The objective here is to describe ET as an evolution that occurs over a period of time and involves a specific sequence of physical processes that can be observed and described by satellite imagery and NWP analyses. In this study, ET begins with commencement of the transformation stage and concludes when the reintensification stage is completed. The commencement of ET does not occur when JTWC designates the storm as extratropical.

Based on Klein (1997) and review of all 30 ET cases that occurred in the western North Pacific from 1 June through 31 October during 1994–98, the transformation stage of ET is defined to begin when visible, (IR), and water vapor imagery suggest an asymmetric appearance of clouds and, especially, a widespread decrease of deep convection in the western quadrant of the tropical cyclone. Simultaneously, the outermost edge of the tropical cyclone circulation is impinging on a preexisting midlatitude baroclinic zone or front on the northern or northwestern side. Transformation is defined to be completed when the storm has the characteristics of a baro-
clinic cyclone in both satellite imagery and NWP analyses, and the center of the storm is embedded in cold, descending air. If the storm then deepens as a baroclinic cyclone, this reintensification stage is defined to begin at the synoptic time when the transformed storm has achieved its highest central sea level pressure (SLP) at or after the completion of transformation. The reintensification stage is defined to conclude at the synoptic time when the reintensifying storm has achieved the deepest SLP before either filling or holding steady in the next analysis. If the tropical cyclone does not complete both the transformation and reintensification stages, it will be classified as a “decayer.” In this period, 14 tropical cyclones that became extratropical failed to complete ET and were classified as decayers. In section 4c, (Supertyphoon STY) Ivan is presented as an example of a decayer, and its characteristics are contrasted with those of storms that complete ET.

**b. Method**

All tropical cyclone tracks and intensities are from the JTWC poststorm (“best track”) analyses. While cases occurring in 1994–95 were studied using Geostationary Meteorological Satellite (GMS-4 and -5) imagery only at 12-h intervals (0000 and 1200 UTC), cases occurring in 1996 (1997–98) were examined using GMS-5 imagery at 3-h (1 h) intervals. During 1997–98, the polar-orbiting Special Sensor Microwave/Imager (SSM/I) passes over tropical cyclones during ET were also available. Archived Navy Operational Global Atmospheric Prediction System (NOGAPS) analyses and forecasts with 2.5° lat–long resolution were available at 12-h intervals throughout the period studied. After 1 September 1996, 1° lat–long NOGAPS analyses and forecasts at 6-h intervals were also available. Water vapor winds were included as a data source in the NOGAPS analyses after 1 June 1996. Each analysis began no less than 72 h before the tropical cyclone became extratropical according to JTWC, and continued until at least 24 h after the transition appeared to be complete.

**3. Climatology of ET occurring from 1 June through 31 October during 1994–98**

In the period from 1 June through 31 October during 1994–98, 30 out of 112 (27%) tropical cyclones in the western North Pacific completed ET as defined above (Table 1). Thus, an average of six completed transitions occurred annually of the 22 tropical cyclones that were observed during 1 June–31 October 1994–98. The annual and monthly distributions of ET cases are depicted in Table 2. Nearly half of all transitions (14 out of 30) occurred during September.

Characteristics of ET cases that occurred from 1 June through 31 October during 1994–98 are depicted in Fig. 1 and listed in Tables 1 and 3. Of these 30 ET cases, 25 were recurring tropical cyclones, while the remaining 5 translated poleward in a reverse-oriented monsoon trough. Riehl (1972) determined that most recurving tropical cyclones had achieved their peak intensity at or within 24 h of recurvature. The 25 ET cases that were recurvers commenced the transformation stage an average of 18 h after recurvature, with an average intensity of 85 kt (peak intensity for all 30 ET cases is 105 kt). Only 1 of the 30 completed ET cases had a peak intensity of less than typhoon intensity. Other recurring tropical cyclones failed to complete ET and were classified as decayers (the example of STY Ivan is presented in section 4c) as defined earlier.

The SLP in the NOGAPS analysis of the tropical cyclone at the commencement of ET is not representative of the actual central SLP, since the resolution of the NOGAPS analyses is too coarse to permit accurate depiction of the tropical cyclone inner core. Thus, the central SLP of the tropical cyclone recorded at commencement of ET was based on the JTWC best track analyses. By the end of transformation, the SLPs in the NOGAPS analyses were in better agreement with those reported by JTWC. Therefore, the SLPs in the NOGAPS analyses at the completion of transformation and the end of reintensification are recorded. The average duration (in h) of each of these stages, as well as the total duration of ET, are given in Table 3.

Based on the satellite imagery and these NOGAPS analyses, the transformation stage is described in three sequential steps (section 4). The mean and standard deviation of the SLP at each step, and the time elapsed between steps, are depicted in Fig. 1. After completing reintensification, 11 cases achieved an SLP that was below 980 mb, 15 cases achieved a final SLP between 980 and 1000 mb, and 4 cases had an SLP above 1000 mb. The 11 deepest cases included 6 cases of rapid deepening, which is defined here as a minimum 12-mb decrease in central SLP for a period of at least 12 h (Carlson 1991). Even for these small samples, the 11 cases that reintensified below 980 mb were statistically deeper, based on a Student’s t-test at a 99% confidence level, than the 15 cases that achieved a final SLP between 980 and 1000 mb.

At the time ET commenced, the size of the tropical cyclone was defined using two criteria: length (in km) of the major and minor axes of the outermost closed sea level isobar, and of the 1000-mb relative vorticity contour equal to $1 \times 10^{-5}$ s$^{-1}$. Based on both criteria, the size of the tropical cyclone did not appear to play a distinctive role in its ET (Table 3). That is, the initial size of the tropical cyclone had no correlation with the duration of any stage of ET, or the total duration of ET. No effect of size could be detected in that these storms were as likely to redévelop below 980 mb as they were to achieve a final intensity between 980 and 1000 mb.

Peak intensity (kt) of the tropical cyclone or the SLP of the tropical cyclone at the beginning of the transformation stage (based on JTWC best-track analyses) also do not appear to play a distinctive role in deter-
mining the final SLP of storms that complete ET (Table 1). Of the 11 deepest cases of reintensification, 6 were typhoons (TYs) and 5 were supertyphoons. Some weak typhoons (e.g., TY Peter and TY Stella, with peak intensities of 65 kt) became powerful baroclinic cyclones after completing ET, while some supertyphoons (e.g., STY Ward and STY Ryan) did not reintensify significantly. Since only one tropical storm completed ET, it is more likely that a typhoon will be able to survive vertical wind shear and poleward translation over lower SSTs during transformation and eventually complete ET.

Of the 30 ET cases, 13 translated into a northwest pattern (Fig. 2a) and 17 translated into a northeast pattern (Fig. 2b) according to the definitions of Harr et al. (2000). Storms in the northwest pattern (Fig. 2a) generally exhibited a more meridional track, while most of those in the northeast pattern (Fig. 2b) had an anticyclonic curvature that resulted in a more zonal track. The type of the synoptic pattern (northwest or northeast) that a tropical cyclone translated into is defined at or just after transition time. During the transformation stage of ET, tropical cyclones that eventually translated into a northeast pattern exhibited the same characteristics in NWP analyses and satellite imagery as those that later translated into a northwest pattern. In terms of size (km), peak intensity (kt), or intensity of the tropical cyclone at commencement of transformation, no significant differences were found between ET cases translating into a northwest pattern versus those that translated into a northeast pattern.

**Table 1.** List of tropical storms (TS), typhoons (TY), and supertyphoons (STY) that completed ET during 1 Jun–31 Oct 1994–98.

<table>
<thead>
<tr>
<th>Name/commencement of ET</th>
<th>SLP at start of transformation stage (mb)/duration (h) of transformation</th>
<th>SLP at completion of reintensification stage (mb)/duration (h) of reintensification stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1200 UTC 23 Jul 1994</td>
<td>984/997/36</td>
<td>990/48</td>
</tr>
<tr>
<td>1200 UTC 2 Sep 1994</td>
<td>996/997/24</td>
<td>994/12</td>
</tr>
<tr>
<td>1200 UTC 16 Sep 1994</td>
<td>933/981/60</td>
<td>969/48**</td>
</tr>
<tr>
<td>1200 UTC 9 Oct 1994</td>
<td>939/998/36</td>
<td>981/24**</td>
</tr>
<tr>
<td>0000 UTC 16 Sep 1995</td>
<td>898/980/48</td>
<td>959/24**</td>
</tr>
<tr>
<td>0000 UTC 19 Sep 1995</td>
<td>954/988/72</td>
<td>987/12</td>
</tr>
<tr>
<td>0000 UTC 22 Sep 1995</td>
<td>910/1003/60</td>
<td>998/12**</td>
</tr>
<tr>
<td>1200 UTC 20 Oct 1995</td>
<td>916/999/48</td>
<td>1002/12**</td>
</tr>
<tr>
<td>0000 UTC 9 Jul 1996</td>
<td>967/994/60</td>
<td>986/12</td>
</tr>
<tr>
<td>0000 UTC 3 Aug 1996</td>
<td>972/1004/72</td>
<td>1001/24</td>
</tr>
<tr>
<td>0000 UTC 14 Aug 1996</td>
<td>949/987/36</td>
<td>985/24</td>
</tr>
<tr>
<td>0000 UTC 2 Sep 1996</td>
<td>972/986/36</td>
<td>975/24**</td>
</tr>
<tr>
<td>0000 UTC 18 Sep 1996</td>
<td>980/998/72</td>
<td>974/60</td>
</tr>
<tr>
<td>0000 UTC 21 Sep 1996</td>
<td>962/984/48</td>
<td>978/12**</td>
</tr>
<tr>
<td>1200 UTC 30 Sep 1996*</td>
<td>962/995/48</td>
<td>977/48**</td>
</tr>
<tr>
<td>0000 UTC 24 Oct 1996</td>
<td>938/997/36</td>
<td>991/12</td>
</tr>
<tr>
<td>0000 UTC 13 Jun 1997</td>
<td>938/996/36</td>
<td>993/24</td>
</tr>
<tr>
<td>1200 UTC 18 Jun 1997</td>
<td>954/990/48</td>
<td>989/12</td>
</tr>
<tr>
<td>0000 UTC 27 Jun 1997</td>
<td>976/986/48</td>
<td>977/24</td>
</tr>
<tr>
<td>1200 UTC 7 Aug 1997</td>
<td>980/996/60</td>
<td>993/24</td>
</tr>
<tr>
<td>0000 UTC 21 Aug 1997</td>
<td>984/999/48</td>
<td>984/36</td>
</tr>
<tr>
<td>1200 UTC 3 Sep 1997</td>
<td>949/993/36</td>
<td>996/12**</td>
</tr>
<tr>
<td>0000 UTC 18 Sep 1997</td>
<td>976/988/36</td>
<td>966/36</td>
</tr>
<tr>
<td>0000 UTC 28 Sep 1997</td>
<td>927/984/48</td>
<td>974/12</td>
</tr>
<tr>
<td>0000 UTC 22 Oct 1997</td>
<td>927/997/60</td>
<td>967/56</td>
</tr>
<tr>
<td>0000 UTC 5 Sep 1998</td>
<td>984/814/48</td>
<td>975/24</td>
</tr>
<tr>
<td>0000 UTC 15 Sep 1998</td>
<td>976/980/48</td>
<td>963/36**</td>
</tr>
<tr>
<td>1200 UTC 21 Sep 1998</td>
<td>954/1004/36</td>
<td>1003/12**</td>
</tr>
<tr>
<td>1200 UTC 15 Oct 1998</td>
<td>962/987/36</td>
<td>984/36</td>
</tr>
</tbody>
</table>

* Yates commenced ET in Sep 1996 but completed both stages of ET in Oct and thus is considered an Oct case.
** In these cases, the reintensification stage did not begin when the transformation stage was completed. In these cases, the SLP recorded at the end of transformation continued to increase or hold steady, then decreased once the reintensification stage began. For this reason, some cases feature SLPs at the end of transformation that are actually lower than those recorded at the end of reintensification.

**Table 2.** Number of ET cases occurring per month and year during 1 Jun–31 Oct 1994–98.

<table>
<thead>
<tr>
<th>Year</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>1995</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>1996</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>1997</td>
<td>3</td>
<td>0</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td>1998</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

Total No. of ET cases 3 2 5 14 6 30
Total No. of tropical cyclones by month 6 22 31 30 23 112
FIG. 1. Schematic of the evolution of ET in the western North Pacific based on 30 cases that occurred from 1 Jun through 31 Oct during 1994–98. The times on the abscissa are subsequent to the beginning of the transformation stage. Means ± standard deviation of SLP are listed for each step of transformation, and for the conclusion of the reintensification stage, with the number of cases observed in each of the three outcomes of reintensification depicted parenthetically.

Thirty-six hours after completion of the reintensification stage, the 13 northwest cases were statistically deeper (at a 95% confidence level) than the 17 northeast cases. Thus, it should be possible for a forecaster to anticipate both the track and intensity of ET based on the pattern into which the tropical cyclone is translating as it completes the transformation stage.

4. A conceptual model of transformation of western North Pacific tropical cyclones in ET

a. Typical satellite imagery

Klein (1997) suggested that the transformation stage of virtually every ET case could be described by a common sequence of IR images. The IR images during the transformation stage of ET in the cases of STY Violet and TY Opal (Fig. 3) and STY Ginger and TY Stella (Fig. 4) illustrate features common to all of the cases. In all four cases, a marked decrease of deep cloudiness and rainbands outside the inner core in the western quadrant of the tropical cyclone occurs in the earliest IR image (step 1 of the transformation stage) of the sequence (Figs. 3a, 3d, 4a, and 4d). The result is an asymmetric appearance of clouds and deep convection compared to the more symmetric structure during the mature stage of the tropical cyclone. Dry slots also appear be-

![Timeline of events during Extratropical Transition in the Western North Pacific](image_url)

**FIG. 2.** Storm tracks of the 30 cases of ET occurring from 1 Jun through 31 Oct during 1994–98. Tracks depict the path of (a) 13 cases that translated into the northwest pattern and (b) 17 cases that translated into the northeast pattern of Harr et al. (2000), from the commencement of the transformation stage until completion of the reintensification stage.

<table>
<thead>
<tr>
<th>Trait</th>
<th>Mean value (std dev)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Peak intensity during lifespan as a tropical cyclone</td>
<td>105 kt (31)</td>
</tr>
<tr>
<td>2) Size (major and minor axes) at commencement of transformation</td>
<td>1524 km (470), 1255 km (337)*</td>
</tr>
<tr>
<td>3) SLP at commencement of transformation (JTWC best track data)</td>
<td>1273 km (414), 947 km (228)**</td>
</tr>
<tr>
<td>4) SLP at completion of transformation (NOGAPS analyses)</td>
<td>957 mb (25)</td>
</tr>
<tr>
<td>5) Duration of transformation</td>
<td>46 h (12)</td>
</tr>
<tr>
<td>6) SLP at completion of ET (NOGAPS analyses)</td>
<td>984 mb (12)</td>
</tr>
<tr>
<td>7) Duration of reintensification</td>
<td>28 h (15)</td>
</tr>
<tr>
<td>8) Total time elapsed during ET</td>
<td>81 h (27)</td>
</tr>
</tbody>
</table>

* Based on diameter of outermost closed isobar at sea level.
** Based on diameter of closed contour of $1 \times 10^{-5}$ units of relative vorticity at 1000 mb.

**TABLE 3.** Characteristics of 30 ET cases from 1 Jun through 31 Oct during 1994–98.
Fig. 3. Infrared imagery of the transformation of STY Violet at (a) 0332 UTC 21 Sep, (b) 1832 UTC 21 Sep, and (c) 1232 UTC 22 Sep 1996, and TY Opal at (d) 1232 UTC 18 Jun; (e) 0432 UTC 19 Jun; and (f) 1232 UTC 20 Jun 1997. Notice the change in scale and domain in each imagery frame. The direction of storm motion is depicted by arrows to the right of the storm.

Between rainbands in the southern quadrant, and the cloudiness there is reduced compared to the eastern and northern quadrants.

In the second IR image (step 2 of the transformation stage) of each sequence (Figs. 3b, 3e, 4b, and 4e), deep convection has nearly ceased in the southern quadrant and is greatly reduced in the eastern quadrant as well. However, a large area of multilayer cloud with embedded deep convection appears in the northern quadrant and extends around to the western quadrant. Cirrus outflow interacts with the polar jet to produce what Bader et al. (1995) called a cirrus “shield” that features a sharp edge, which implies confluence between this outflow from the transforming storm and the polar jet. The average interval between steps 1 and 2 is 30 h (Fig. 1), with a range of 12 to 60 h in these 30 cases.

The transformation of all four storms is nearly complete in the third IR image (step 3 of the transformation stage) of each sequence (Figs. 3c, 3f, 4c, and 4f), which typically occurs after another 18 h, with a range from 12 to 36 h. The deep convection of the inner core of the storm has been eroded west of the circulation center. Notice the erosion of inner-core deep convection to produce dry “gaps” in what was once the eyewall. In the outer circulation of the storm, little deep convection is evident anywhere except for that embedded in the large area of multilayer cloud north and east of the storm center. A band of convective clouds extends from the western part of this multilayer cloud region and begins to turn southward in the western quadrant of the storm. The cirrus shield described in Figs. 3b, 3e, 4b, and 4e is clearly visible, and the cloud patterns to the north and east of the storm center suggest the commencement of warm frontogenesis. By contrast, the cloud patterns south of the storm center suggest that at most only weak cold frontogenesis has begun. This is consistent with the conclusion of Harr and Elsberry (2000) that cold frontogenesis is typically less vigorous than the warm frontogenesis that occurs during ET.

b. A conceptual model of the transformation stage of ET

Recall that the appearance of the transformation stage of ET in satellite imagery was not affected by whether a tropical cyclone later translated into a northwest or northeast pattern. Since a representative, three-step sequence of IR imagery (Figs. 3 and 4) can be identified
that is similar for each of the 30 ET cases studied, it is hypothesized that the physical processes responsible for that appearance are also similar in these ET cases. A conceptual model (Fig. 5) is proposed that describes virtually every case of ET that occurs over the western North Pacific Ocean. The transformation stage of ET is divided into three steps that are recognizable in satellite imagery and features important, sequential physical processes. Even during the June–October period studied, a recurving tropical cyclone in the extreme western North Pacific may encounter a region of considerable baroclinity with a northeast–southwest orientation parallel to the east Asian coast. If the tropical cyclone recurves farther to the east, it will approach a more east–west-oriented zone farther to the north over the open Pacific Ocean. It is the interaction of the TC circulation with the baroclinic zone and its associated vertical wind shear that initiates the transformation stage of ET. Consequently, some differences in ET timing may occur if the tropical cyclone moves poleward closer to the coast and interacts with the southwest–northeast baroclinic zone, instead of recurving farther eastward where the baroclinic zone is more east-west.

Twelve of the 30 ET cases either made landfall or translated close enough to land (Fig. 2) that the tropical cyclone outer circulation interacted with land, including three cases depicted in Figs. 3 and 4 (STY Violet, TY Opal, and TY Stella). Despite the interaction with land, the transformation of these three storms appears similar to that of STY Ginger (Fig. 4a), whose track remained far from the coast of Japan. One important exception is that the eastern half of the inner core of STY Ginger remains fairly well organized, with spiraling rainbands that imply continued deep convection. In the 12 cases whose tracks passed over or close to land, interaction with the terrain appeared to weaken the inner core sufficiently so that it appeared less well organized than in the remaining 18 cases. This was the only difference in the satellite imagery or NWP analyses noted between cases that interacted with land, and those that did not. Presumably, this similarity is because the physical processes during the transformation stage were of a large enough spatial scale that they were relatively unaffected by the small size of the Japanese islands (only one case of ET studied here achieved landfall over continental Asia, and three others passed close enough to China so that their outer circulations briefly interacted with land).

In step 1 (Fig. 5), the tropical cyclone commences the transformation stage as it translates poleward over lower SSTs (not shown), and its outer circulation begins to impinge on a preexisting midlatitude baroclinic zone. As interaction with the baroclinic zone begins, colder,
Fig. 5. Conceptual model of transformation stage of ET in the western North Pacific, with labeled areas as follows: 1) environmental equatorward flow of cooler, drier air (with corresponding open cell cumulus); 2) decreased tropical cyclone convection in the western quadrant (with corresponding dry slot) in step 1, which extends throughout the southern quadrant in steps 2 and 3; 3) environmental poleward flow of warm, moist air is ingested into tropical cyclone circulation, which maintains convection in the eastern quadrant and results in an asymmetric distribution of clouds and precipitation in steps 1 and 2; steps 2 and 3 also feature a southerly jet that ascends tilted isentropic surfaces; 4) ascent of warm, moist inflow over tilted isentropic surfaces associated with baroclinic zone (dashed line) in middle and lower panels; 5) ascent (undercut by dry-adiabatic descent) that produces cloudbands wrapping westward and equatorward around the storm center; dry-adiabatic descent occurs close enough to the circulation center to produce erosion of eyewall convection in step 3; 6) cirrus shield with a sharp cloud edge if confluent with polar jet.

drier, environmental equatorward flow (labeled 1 in Fig. 5) exists to the west of the tropical cyclone. Thus, little deep convection is evident in the outer circulation of the western quadrant of the tropical cyclone, and a dry slot forms in the southwestern quadrant (labeled 2 in Fig. 5), with decreased deep convection. As this cooler, drier air is heated and moistened by surface fluxes from the relatively warm ocean, open-cell cumulus may be observed. Environmental poleward flow to the east of the tropical cyclone (labeled 3 in Fig. 5) advects warm, moist air into the southern and eastern quadrants of the tropical cyclone, which maintains deep convection in these quadrants. Thus, an early indicator of transformation is an asymmetric appearance of tropical cyclone cloud patterns, similar to that observed in Figs. 3 and 4. This environmental, poleward flow turns cyclonically and interacts with a preexisting baroclinic zone (labeled 4 in Fig. 5) to produce ascent over tilted isentropic surfaces.
surfaces. Since the storm is also beginning to interact with vertical wind shear associated with the polar jet, a cirrus shield (labeled 6 in Fig. 5) is observed in IR imagery.

In step 2 (Fig. 5), the tropical cyclone is located just equatorward of the baroclinic zone. Cyclonic rotation of the baroclinic zone to a southwest to northeast orientation (even if not already preexisting) occurs as environmental flow of cooler, drier (warm, moist) air continues west (east) of the storm (labeled 1 and 3, respectively). This produces a dipole of lower-tropospheric, cold (warm) temperature advection to the west (east). Notice also the expansion of the dry slot (labeled 2 in Fig. 5) into the southern quadrant. Environmental poleward flow of warm, moist air east of the storm advances to the baroclinic zone and ascends over tilted isentropic surfaces poleward of the storm (labeled 4 in Fig. 5). Some of these ascending parcels turn cyclonically and then descend into the western quadrant (Fig. 5c, step 2). The (presumed dry adiabatic) descent west of the storm center is the subsidence branch of a vertical motion dipole in combination with the ascent to the east. At the same time, other parcels continue their ascent to the midtroposphere and turn anticyclonically to the northeast (labeled 5 in Fig. 5). Finally, narrow bands of convection may extend southwestward from the northern quadrant to a point west of the storm center, which is generally in a region of cooler, drier environmental inflow and descent that otherwise inhibits deep convection.

During this step, the storm is affected by vertical wind shear associated with the baroclinic zone, and a cirrus

Fig. 6. Step 1 of transformation of TY David depicted in (a) IR imagery, (b) visible imagery, and (c) water vapor imagery at 0332 UTC 18 Sep, and (d) 85-GHz SSM/I imagery at 2259 UTC 17 Sep 1997.
shield with a sharp cloud edge (labeled 6 in Fig. 5) appears as the warm, upper-tropospheric outflow of the transforming storm becomes confluent with the polar jet, which is still well poleward of the storm at this time. However, the onset of vertical wind shear to the south of the jet begins to "ventilate" the storm by advecting the top of the upper-tropospheric warm core downstream (Fig. 5c, step 2). Even though the 500-mb westerlies approach and wrap around the weakening midtropospheric warm core, deep convection persists in the tropical cyclone inner core.

Step 3 (Fig. 5) is the logical conclusion of the continuation of the physical processes described in step 2 as the storm center becomes embedded in the baroclinic zone. Vertical wind shear increases, SST values under the storm decrease, cold (warm) advection produced by equatorward (poleward) environmental flow west (east) of the storm, and the interaction of the tropical cyclone circulation with the baroclinic zone to produce ascent over tilted isentropic surfaces to the north, and then (dry adiabatic) descent to the northwest and west, all continue as described in step 2. Although increased vertical wind shear is believed to be responsible for continued advection downstream of the remnants of the upper-tropospheric warm core, a weaker lower-tropospheric warm core remains over the surface center (shaded, in the lower-right panel of Fig. 5c). Meanwhile, dry-adiabatic descent west of the storm center of parcels that have previously ascended the baroclinic zone progressively weakens tropical cyclone inner-core convection.
and eventually produces eyewall erosion in the western and southern quadrants.

The transformed tropical cyclone now resembles an extratropical cyclone in that a large swath of multilayer cloud exists on the poleward side that resembles a warm front, with a weaker cloud band to the southeast that resembles a cold front. Ascent northwest of the storm center is undercut by (dry adiabatic) descent and produces a swath of clouds that now extends from the large region of multilayer clouds north and east of the storm center and wraps around toward the western side of the storm. The environmental poleward flow of warm, moist air on the east side ascends over the baroclinic zone and joins the strong southwesterly jet aloft that resembles a warm conveyor belt of an extratropical cyclone (Carlson 1991).

An example of TY David (September 1997) will be presented in section 4c to illustrate the physical processes described in the conceptual model (Fig. 5). In section 4d, the example of STY Ivan (October 1997), which did not complete ET according to the definitions of section 2a, is presented to show that the conceptual
model can also be used to differentiate between storms that finish the transformation stage and decayers.

c. Typhoon David (September 1997)

At 0332 UTC 18 September (Fig. 6a), TY David is translating north-northwest over decreasing sea surface temperatures (not shown) as it approaches the Kuroshio that branches eastward from Honshu, Japan. Compared to previous satellite imagery (not shown), the amount of deep convection has decreased in the western quadrant (Fig. 6a), and the resulting distribution of clouds and rainfall (with continued deep convection in the remaining quadrants) has become more asymmetric. Notice also the dry slot forming in the southern quadrant and wrapping around into the eastern quadrant. Visible imagery (Fig. 6b) reveals open-cell cumulus in the western quadrant and clearly depicts the location of the baroclinic zone. In this case, the island chain to the northwest may have locally added to the modified airflow characteristics in that quadrant of the circulation. Water vapor imagery (Fig. 6c) confirms that the environmental flow to the west of David is dry and that the western quadrant is drier than the other quadrants at the same distance from the center. However, an SSM/I pass at 2259 UTC 17 September (Fig. 6d) indicates the deep convection in the inner core of the storm is still quite symmetric.

The imagery in Fig. 6 can be supplemented with the NOGAPS analysis of 1000-mb streamlines and equivalent potential temperature \( \theta_e \) at 0000 UTC 18 September (Fig. 7a) to confirm that the transformation stage of ET has begun. The outermost part of TY David’s circulation is just beginning to impinge on a preexisting baroclinic zone that is oriented from southwest to northeast in the Japan Sea. Whereas the large-scale environmental flow to the west of TY David is advecting cooler, drier air with low values of \( \theta_e \) equatorward into David’s circulation, the flow pattern is also locally being modified by the islands. Meanwhile, a poleward flow to the east of TY David maintains the inflow of warm, moist air into the eastern quadrant of the storm. As a result, tropical cyclone convection persists in the eastern and northern quadrants, and the storm exhibits an asymmetric pattern of deep convection (Fig. 6). Thus, TY David has commenced step 1 of the transformation stage of ET according to the conceptual model in Fig. 5.

Vertical west-to-east cross sections through the storm center of \( \theta_e \) and winds (Fig. 7b), and PV and vertical motion (Fig. 7c) from the NOGAPS analysis, depict the predominantly tropical characteristics of TY David at 0000 UTC 18 September. Cross sections of hydrostatic Ertel PV are prepared using

\[
PV = -g(\zeta + f)(\partial \theta / \partial p).
\]
Cross sections of vertical motion ($\omega$) are prepared using NOGAPS model-derived vertical motion. It is acknowledged that the 1° lat–long resolution of these cross sections is insufficient to depict accurately the actual distribution of $\theta_e$ and PV in the inner core of the storm. However, these analyses provide a qualitative description of the physical processes occurring beyond the inner core of the storm during transformation and should provide a quantitative description of physical processes occurring on a scale greater than 300 km. At 0000 UTC 18 September, the NOGAPS analysis depicts a distinct warm core that extends up to 200 mb above David (Fig. 7b). The 365-K isentrope of $\theta_e$ below 850 mb indicates that a warm, moist pool of lower-tropospheric air is associated with TY David. Notice also that the maximum winds are located in the lower troposphere, immediately on either side of the storm center. Two PV maxima, one near the surface and one associated with the upper-tropospheric warm core, are analyzed (Fig. 7c), and upward vertical motion exists on either side of the storm center below 500 mb. An area of descent is also evident between 400 and 250 mb west of the storm center. This subsidence, combined with the intrusion of cooler, drier air into the western quadrant (Figs. 6 and 7a), is believed responsible for the drastically reduced cloudiness in the western quadrant and the formation of the dry slot southwest of the storm center (Fig. 6).

Since TY David has begun to interact with a pre-existing baroclinic zone (Fig. 7a), it is worthwhile to examine the vertical wind shear associated with this lower-tropospheric baroclinicity. Vertical wind shear was calculated at 0000 UTC 18 September by azimuthally averaging the $u$ and $v$ wind components (m s$^{-1}$) along a circle of 300-km radius, centered on the storm, at all mandatory levels from 850 to 200 mb (Fig. 7d). The change in wind direction from southeasterly in the lower and midtroposphere to south-southwesterly in the upper troposphere is consistent with David’s imminent recurvature through the subtropical ridge. Although very little vertical shear exists between 850 and 400 mb, the wind shear from 400 to 200 mb is nearly 7.5 m s$^{-1}$ from the southwest.

Over the next 24 h, TY David recurved and began to translate north-northeastward until the center was less than 100 km from the lower-tropospheric baroclinic zone. Step 2 of David’s transformation can be inferred from IR and SSM/I imagery. The same features noted in the satellite IR imagery at 0332 UTC 18 September (Fig. 6) can again be readily identified at 2332 UTC 18 September (Fig. 8a). An extensive dry slot is present in the southern quadrant (Fig. 8a), and evidence of dry air is suggested in the SSM/I imagery at 2246 UTC 18 September (Fig. 8b) even in the innermost circulation of the storm. Deep convection in the inner region appears to be eroding, particularly west and south of the storm center. A large cirrus shield (Fig. 8a) indicates a strong upper-tropospheric outflow that is interacting with the polar jet (Bader et al. 1995). A large region of multilayer cloud with embedded convection immediately north of the storm is evident in both the IR and SSM/I imagery (Fig. 8). Notice that the triangular-shaped region of convection north of the storm center resembles the delta rain region described by Shimazu (1998). A distinct cloud band northwest of the storm that extends around the storm into the western quadrant is also evident in Figs. 8a and 8b.

The NOGAPS analysis of 1000-mb streamlines and $\theta_e$ at 0000 UTC 19 September (Fig. 9a) depicts continuing equatorward (poleward) environmental advection of cooler, drier (warm, moist) air that has penetrated...
At 0000 UTC 19 September, cold (warm) advection (Fig. 9b) is clearly evident west (northeast) of the storm associated with the equatorward (poleward) environmental air inflow with low (high) values of \( \theta_e \) described earlier. On the larger scale, the lower-tropospheric temperature advection has maximum (minimum) values northeast of the storm at 40°N, 145°E (west of the storm at 35°N, 136°E), where the environmental \( \theta_e \) gradient is the strongest. The warm advection region corresponds well with the swath of multilayer cloud region (Fig. 8) developing north and east of the storm. By contrast, the cold advection region west of the storm corresponds well with the dry region in Fig. 8. A smaller scale warm–cold advection dipole is found to the east of David as the tropical cyclone circulation interacts with the adjacent thermal pattern.

Two important characteristics can be observed in the 500-mb analysis at step 2 of the transformation stage. During step 1, David’s surface center is located beneath concentric, closed 500-mb contours and is equatorward of the 5820-m contour associated with a short-wave trough to the northwest of the storm (Fig. 10a). During step 2 (Fig. 10b), the closed contours associated with David 24 h earlier have combined with the approaching 500-mb trough so that David appears to be in an open wave. Furthermore, the streamlines associated with this short-wave trough have wrapped around the circulation of David, which indicates that David has become embedded in the 500-mb westerlies. This open wave in the 500-mb isobars was evident during step 2 of the ET transformation stage in 26 of the 30 (87%) ET cases studied. If a 500-mb isobars interval of 30 m is selected (not shown), a closed contour above David’s surface center suggests that the warm core is still present. This is consistent with the persistence of inner-core convection in Fig. 8. Nevertheless, forecasters should anticipate this open wave and streamline pattern in 500-mb isobars during step 2 of the transformation stage provided the standard interval of 60 m is used.

A southwest–northeast vertical cross section through the storm center (Fig. 11a) indicates that the closed 360-K \( \theta_e \) contour that defined the upper-tropospheric warm core at 0000 UTC 18 September (Fig. 7b) has been dispersed, and the lower- and midtropospheric warm core has been weakened. Also evident in Fig. 11a is advection downstream of the tropical cyclone warm core (as defined by the 350-K contour) above 700 mb, and vigorous southerly winds northeast of the storm center below 400 mb (Fig. 11a). A southwest–northeast vertical cross section of PV and NOGAPS model-derived vertical motion (Fig. 11b) indicates that ascent is analyzed northeast of the storm center (Fig. 11b), which suggests that these air parcels ascend the tilted isentropic surfaces that are nearly east–west oriented (Fig. 9a). This flow turns cyclonically (Fig. 9a) and descends (presumably dry adiabatically) into the western quadrant.

Fig. 12. Hodograph of azimuthally averaged \( u \) and \( v \) wind components (m s\(^{-1}\)) around a circle with radius 300 km from the storm center, at mandatory levels between 850 and 200 mb at (a) 0000 UTC 19 Sep and (b) 1200 UTC 19 Sep 1997. Notice the different wind scales on the abcissa and the ordinate in each case.
southwest of the storm center (Fig. 11b). This air thus has lower values of $\theta_e$, and subsequent advection into the southern quadrant close to the storm center is considered to be responsible for the erosion of deep convection observed there (Fig. 8). Even though the upper-tropospheric warm core has been dispersed, a PV maximum is located between 250 and 150 mb (Fig. 11b). Also evident is a slight tilt to the northeast (relative to the storm center) with height of the PV contours above 250 mb. Weakening of the lower-tropospheric winds is reflected in absence of the lower-tropospheric PV maximum that was present 24 h previously. Notice also the PV maximum above 150 mb southwest of the storm, which is an upper-tropospheric reflection of the approaching short-wave trough northwest of David in the 500-mb analysis (Fig. 10b).

As during step 1, environmental vertical wind shear was calculated at step 2 (Fig. 12a). The wind shear from 850 to 250 mb has increased in 24 h to nearly 9 m s$^{-1}$, and the winds at each level are from the southwest. According to the moist numerical simulations of Frank and Ritchie (1999) and Ritchie and Elsberry (1999), vertical wind shear should produce a tilt downstream of isentropic surfaces and contours of PV, and a vertical motion dipole with maximum ascent (descent) located downshear and left (upshear and right). Thus, it is sug-
gested that this vertical shear flow is responsible for the advection of the upper-tropospheric warm core downstream (Fig. 11a) and the slight tilt downshear of the PV contours above 250 mb (Fig. 11b). It is also believed that this shear contributes to the descent analyzed southwest of the storm center. However, a descent maximum at 900 mb (Fig. 11b) is located where streamlines are believed to descend dry adiabatically as they turn cyclonically into the western quadrant (Fig. 9a). Since David is simultaneously interacting with vertical wind shear collocated with lower-tropospheric baroclinity, it is difficult to determine how much of the analyzed descent is due to vertical wind shear (Frank and Ritchie 1999) or lower-tropospheric baroclinic effects.

During the third step in the ET transformation, David continues to translate poleward. At 1232 UTC 19 September, significant deep convection is no longer evident in the outer western, southern, and eastern quadrants (Fig. 13a). Instead, the remnants of TY David now more closely resemble a midlatitude cyclone, with a large swath of multilayer cloud that implies warm frontogenesis has commenced north and east of the center, but little evidence to suggest that cold frontogenesis may have commenced south of the center. Brightness values in the 85-GHz SSM/I image (Fig. 13b), which are a proxy for rainfall from deep convective clouds, suggest greatly reduced rain rates in the southwestern portion of the inner core of the storm. However, the remnants of the delta rain region that were evident 12 h earlier may be identified in Fig. 13b slightly northwest of the storm center. Also evident in both Figs. 13a and 13b is the distinct cloud band farther north and west of the storm center that was first described in step 2. The region of deep convection north of the storm center is to the left of the vertical wind shear direction (Fig. 12b). This location is consistent with the numerical simulations of Frank and Ritchie (1999) and Ritchie and Elsberry (1999) that have maximum values of ascent left of the direction of the vertical wind shear, even though the shear in this case is concentrated in the lower troposphere below 400 mb.

As in the previous two steps of David’s ET transformation, the 1000-mb analysis at 1200 UTC 19 September (Fig. 14a) again depicts equatorward (poleward) advection of cooler, drier (warm, moist) environmental air toward the inner core of the storm. Although the remnants of David’s circulation center are clearly within the baroclinic zone, a small bulge of higher \( \theta_e \) air remains associated with the center in the NOGAPS analysis. During the past 12 h, the \( \theta_e \) gradient in the baroclinic zone east of the storm center from 145° to 155°E has increased. Ascent of the poleward environmental flow over tilted isentropic surfaces is analyzed east and north of the storm (not shown), and (dry adiabatic) descent is implied where this flow turns cyclonically into the western quadrant and toward the inner core of the storm. These processes are responsible for the lack of deep convection in the western, southern, and eastern quadrants, and the erosion of convection in the southwest quadrant of the inner core (Fig. 13b).

Calculations of lower-tropospheric frontogenesis by Harr and Elsberry (2000) suggest that vigorous warm frontogenesis and weak cold frontogenesis should be anticipated in most cases of ET. In this study, significant frontogenesis was typically not observed until step 3 of the transformation stage. The satellite imagery in Fig. 13, NOGAPS analyses of 1000-mb \( \theta_e \) and streamlines (Fig. 14a), and calculations of 850-mb temperature advection (Fig. 14b) provide supporting evidence that lower-tropospheric frontogenesis may be commencing in step 3 of TY David’s transformation. Notice the large values of warm (cold) advection (Fig. 14b) to the northeast (southwest) of the storm center.

Contributions to 900-mb frontogenesis may be examined using the Miller frontogenesis equation adapted by Carlson (1991):

\[
\frac{d}{dt} \left( \frac{-\partial \theta}{\partial y'} \right) = \frac{\partial u}{\partial y'} \frac{\partial \theta}{\partial x'} + \frac{\partial v}{\partial y'} \frac{\partial \theta}{\partial y'} + \frac{\partial \omega}{\partial \phi} \frac{\partial \theta}{\partial \phi}
\]

In this expression, the first (second) term on the right side represents contributions to lower-tropospheric frontogenesis due to horizontal wind shear (confluence) in the \( y' \) direction normal to the frontal zone in the direction of the cold air, and the third term on the right represents contributions due to vertical motion (“tilting” term). In this analysis, the diabatic term is not

![Fig. 14. Streamlines and equivalent potential temperature values at 1000 mb, and 850-mb temperature advection, as in Figs. 9a and 9b except for 1200 UTC 19 Sep 1997.](image-url)
Fig. 15. Calculations of 900-mb frontogenesis (interval $10 \times 10^{-10}$ K m$^{-1}$ s$^{-1}$, except for the $-1 \times 10^{-10}$ K m$^{-1}$ s$^{-1}$ contour), with solid (dashed) contours depicting frontogenetic (frontolytic) regions, and 900-mb streamlines at step 3 of the transformation of TY David based on (a) confluence and (b) shear contributions at 1200 UTC 19 Sep 1997, and (c) vertical south–north cross section of potential temperature (solid contours, 5-K interval) and NOGAPS analyzed vertical motion, with dashed (shaded) contours depicting ascent (descent) at a $2(1) \times 10^{-3}$ mb s$^{-1}$ interval.

calculated. Based on Carlson (1991), it was expected that the confluence (horizontal shear) term would be the leading term where warm (cold) frontogenesis had commenced. The objective of this analysis is to illustrate how a forecaster could confirm quantitatively the frontogenesis implied in satellite imagery at any step of the transformation.

Notice that a maximum in 900-mb frontogenesis due to the confluence term (Fig. 15a) exists in a region of 900-mb streamline confluence and widespread, strong warm advection (Fig. 14b) that corresponds well to the region labeled “possible warm frontogenesis” in Fig. 13a. In Fig. 15b, a maximum of 900-mb frontogenesis northwest of David is in a region of horizontal shear in the 900-mb streamlines, which corresponds well to the distinct cloud band northwest of the storm center in both IR and SSM/I imagery (Fig. 13). Notice that the shear term contributions (Fig. 15b) do not indicate significant cold frontogenesis south of David.

A south–north cross section along 150°E (Fig. 15c) depicts a direct circulation (with an ascent maximum at 48°N) in the region where warm frontogenesis is indicated in the satellite imagery. Although the contribution of the tilting term is frontolytic in this location [$-1.5 \times 10^{-9}$ K (m s)$^{-1}$ at 900 mb], the diabatic term (not calculated) is expected to be frontogenetic due to the latent heat release associated with the ascent of the warm, moist, poleward-flowing parcels that ascend these isentropic surfaces (Fig. 14a), as in the calculations of Harr and Elsberry (2000). A similar distribution of warm frontogenesis, with either weak or nonexistent cold frontogenesis, was observed during step 3 in nearly all of the ET cases studied. Thus, forecasters should anticipate this result during step 3 and may use digital fields from numerical analyses as in the above calculation to confirm the onset of warm frontogenesis (and little to weak cold frontogenesis).

With lower-tropospheric frontogenesis commencing, it is useful to consider what, if any, tropical characteristics remain in the remnants of David. An east–west vertical cross section through the storm center at 1200 UTC 19 September (Fig. 16a) indicates the continued existence of a pool of high $\theta_e$ air (>345 K) between 700 and 400 mb associated with the original tropical cyclone warm core. Although the central values have decreased relative to the tropical cyclone warm core
(>360 K) that existed 36 h earlier (Fig. 7b), the environmental values have also decreased so that a distinct warm pool remains. The cold dome of isentropes west of David 12 h earlier has advanced eastward so that the storm center is in air with low values of $\theta_e$ that have undercut the higher $\theta_e$ air above. Wind speeds increase with height above 850 mb in the western half of the cross section, which according to the thermal wind equation is consistent with the location of the cold dome. Notice also the southerly jet east of the storm between 700 and 400 mb, as well as the backing (veering) of winds west (east) of the storm center. This is consistent with the dipole of lower-tropospheric maximum (minimum) temperature advection directly east (west) of David (Fig. 14b).

In Fig. 16b, descent west of the storm has undercut ascent at the storm center, and the maximum descent corresponds to the intrusion of lower $\theta_e$ that is the leading edge of the cold dome to the west (Fig. 14a). A PV maximum in the upper troposphere west of the storm is associated with the short-wave trough northwest of the storm. The connection of PV contours associated with David to those of the upstream, upper-tropospheric PV maximum (Fig. 16b) suggests that David is about to couple with the short-wave trough. The PV values associated with David have decreased in the past 12 h and are tilted to the east. Vertical wind shear at 1200 UTC 19 September (Fig. 12b) indicates southwesterly flow at all levels, and an 850–250-mb vertical wind shear in excess of 20 m s$^{-1}$, which is more than double the value observed 12 h earlier. These larger values of wind shear are believed to be the cause of the continued downstream advection of the top of the warm core (Fig. 16a), as well as the increased tilt of the PV contours downshear (Fig. 16b). This tilt is consistent with that in Hurricane Isidore simulated by DeMaria and Huber (1998) using the Geophysical Fluid Dynamics Laboratory model at $\frac{1}{6}$ lat–long resolution. Again, it is difficult to separate how much of the analyzed ascent east of the storm center is due to the tilting of PV contours (Frank and Ritchie 1999) or lower-tropospheric baroclinic effects.

Visualization software (Vis5D) was used in conjunction with NOGAPS 1° lat–long analyses and 6-h NOGAPS forecasts of three dimensional winds to produce four geographic trajectories of air parcel motion through David from 0000 UTC 18 September through 1200 UTC 19 September (Fig. 17). Trajectory 1 depicts southerly flow originating in the eastern quadrant of David that ascends as it progresses poleward and then turns to the east. Notice the resemblance of this trajectory to a warm conveyor belt of an extratropical cyclone (Carlson 1991), and its relationship to the multilayer cloud region in Fig. 13, the warm advection region in Figs. 9b and 14b, and the southerly jet in Figs. 11a and 16a. This trajectory represents the poleward transport of warm, moist environmental air around David's circulation at outer radii, and its ascent over tilted isentropic surfaces of the baroclinic zone north of David. Trajectory 2 originates north and east of the storm center, wraps cyclonically around the center of circulation, and then ascends and turns to the northeast. The path of this trajectory corresponds with the distinct cloud band northwest of the storm at 0000 UTC 19 September (Fig. 8). Thus, it is believed that this cloud band is produced when parcels in the eastern quadrant travel poleward, turn cyclonically north of the storm center while ascending over tilted isentropic surfaces in the baroclinic zone, then turn to the northeast and ascend over undercutting cold, dry air descending northwest of the storm center.

Trajectory 3 in Fig. 17 originates in the baroclinic zone northwest of the storm center and descends as it travels equatorward into the western quadrant. The path of this trajectory is consistent with the dry regions in water vapor imagery (Fig. 6c), the descent west of the storm center at 0000 UTC 19 September (Fig. 11b), and the cold advection regions in Figs. 9b and 14b. Thus, this trajectory represents the equatorward advection of cooler, drier environmental air to the west of David. Trajectory 4 originates in the southern quadrant, turns
cyclonically through the eastern quadrant, ascends slightly in the northern quadrant, then continues cyclonically into the western quadrant and descends, finally turning to the east far to the south of the translating storm. The path of this trajectory in the western quadrant of David is consistent with the descent in Fig. 11b and the continued cold advection west of David (Fig. 9b).

At 1200 UTC 19 September, the center of David is located in cold, descending air. Thus, the transformation of TY David is complete based on the definitions presented in section 2. Notice the appearance of fronts and erosion of inner-core tropical cyclone convection (Fig. 13); the advection downstream of a weakening, upper-tropospheric warm core (Fig. 16a); and the undercutting descent into the storm center (Fig. 16b) that is associated with an advancing cold dome. Given this baroclinic structure, convection is no longer hypothesized to be the primary energy source of David, which has become an extratropical cyclone. Reintensification begins almost immediately, as the remnants of David couple with an upper-level trough to its northwest and rapidly redeepen to 966 mb (not shown).

d. Supertyphoon Ivan (October 1997)

As in the case of TY David, all of the other 29 cases of completed ET that occurred from 1 June through 31 October 1994–98 eventually became embedded in a pre-existing, midlatitude baroclinic zone. Thus, it appeared that interaction of a tropical cyclone with a midlatitude baroclinic zone was an essential component in each step of the transformation stage of ET. During that period, 14 tropical cyclones were designated extratropical by JTWC that subsequently failed to complete ET; that is, they did not complete both the transformation and reintensification stages. Satellite imagery of these dissipating extratropical storms often resembles the first two steps in the sequence of the transformation stage (as depicted in Figs. 6 and 8 in the case of TY David).

STY Ivan is not classified as an ET case because it failed to complete the transformation stage of ET according to the definitions in section 2. At 1232 UTC 24 October 1997 (Fig. 18a), satellite IR imagery suggests that STY Ivan may be in step 2 of the transformation stage of ET. Notice the asymmetric cloud patterns characterized by the lack of tropical cyclone convection in the western and southern quadrants, and the presence of cloud bands that extend west and south from the northern quadrant. A weak cirrus shield also extends from the overrunning cloud bands over the multilayer cloud swath northeast of the storm center. Ivan is interacting with a baroclinic zone associated with a pre-existing cold front located 750 km to the northwest (Figs. 18a and 18b). Vertical cross sections through the center of the storm at 1200 UTC 24 October (Fig. 18c and 18d) reveal that the original tropical cyclone warm core is evident only below 400 mb and that a PV maximum is located above the storm center in the lower troposphere, with ascent (descent) well to the east (west) of the storm center. Vertical wind shear from 500 to 200 mb of 9 m s\(^{-1}\) appears to be responsible for advecting the warm core downstream (Fig. 18c), and for the tilt of PV contours to the east above 300 mb (Fig. 18d).
All of these features are similar to those analyzed during step 2 of the transformation of TY David.

The NOGAPS 200-mb analysis at 0000 UTC 25 October (Fig. 19a) indicates upper-tropospheric streamline confluence above Ivan, and an area of convergence. By 1200 UTC 25 October (Fig. 19b), Ivan has translated east and moved away from the baroclinic zone to the northwest. Notice that the significant dipole of cold and warm advection evident in Fig. 19b is not associated with Ivan, but with the cold front to the northwest. At this time, Ivan appears in IR imagery to be weaker (Fig. 20a) than it was 12 h earlier, as no vigorous convection appears anywhere in the storm circulation. No cirrus shield is evident, which suggests that the outflow of Ivan is not interacting with a maximum in the polar jet. The lower-tropospheric pool of high \( \theta_e \) air associated with Ivan’s center 12 h earlier has weakened (Fig. 20c). Unlike TY David (Fig. 14a), Ivan does not translate into or become embedded in the baroclinic zone to the northwest (Figs. 20b and 20c). Notice also that the surface streamline pattern associated with Ivan (Fig. 20b) does not exhibit a closed circulation. Unlike TY David (Fig. 14a), little or no ascent of warm, moist poleward flow over tilted isentropic surfaces is analyzed in the north or east quadrants of Ivan’s outer circulation.

Vertical, west-to-east cross sections through the storm center at 1200 UTC 25 October (Figs. 20c and 20d) indicate that a weak remnant of the warm core remains in the lower troposphere below 500 mb and is being advected downstream. Unlike David (Fig. 16a), Ivan’s center is not embedded in an advancing cold dome, but remains in a pool of higher \( \theta_e \) air. Undercutting descent is not observed at the storm center (Fig. 20d), and only a shallow, closed PV contour below 850 mb remains at the storm center. A broad area of descent is above the storm center, which is consistent with the 200-mb convergence analyzed 12 h earlier (Fig. 19a) and the lack
of deep convection anywhere in the storm circulation (Fig. 20a).

Even though the IR imagery at 1232 UTC 24 October (Fig. 18a) resembles step 2 of the transformation stage, Ivan fails to complete ET as defined in section 2. Ivan does not become a baroclinic low and is in strong westerly flow with vertical wind shear values in excess of 13 m s\(^{-1}\) from 500 to 200 mb, so it simply dissipates over lower SSTs (not shown) and beneath upper-tropospheric convergence. Unlike TY David, Ivan does not translate poleward into a baroclinic zone, and its center never becomes embedded in a cold dome. Instead, Ivan was steered zonally and moved away from lower-tropospheric baroclinity (Figs. 19b and 20b) so that interaction with a preexisting, midlatitude baroclinic zone did not occur. Thus, ascent of warm, moist, poleward flow over tilted isentropic surfaces is not observed. With the exception of two storms (STY Winnie during August 1997 and TY Waldo during September 1998) that dissipated over land, the remaining 11 cases designated as extratropical by JTWC that failed to complete ET behaved similarly to Ivan. The example of STY Ivan thus suggests that satellite imagery can be used in conjunction with NWP analyses and vertical cross sections to distinguish decayers from real ET cases based on the conceptual model (Fig. 5) of the transformation stage of ET.

5. Summary and conclusions

A brief climatology of ET in the western North Pacific has been prepared based on a study of 30 cases that occurred from 1 June through 31 October during 1994–98. Following Klein (1997), ET is described in terms of a transformation stage during which the tropical cyclone interacts with a preexisting, midlatitude baroclinic zone and is transformed into a baroclinic low, and a reintensification stage, where that transformed storm then deepens as an extratropical cyclone. A timeline for the evolution of these ET cases is depicted in Fig. 1. Eleven cases of deep reintensification (below 980 mb) are statistically deeper at a 99% confidence level than cases of moderate reintensification (between 980 and 1000 mb).

A conceptual model is proposed (Fig. 5) that describes the three-step transformation stage of nearly every ET case that occurs in the western North Pacific. Transformation is defined to begin (step 1) when the outer circulation of the tropical cyclone begins interacting with a preexisting, midlatitude baroclinic zone or front, while simultaneously exhibiting an asymmetric appearance of clouds and precipitation that result from a widespread decrease of deep convection in the western quadrant of the tropical cyclone outer circulation. Transformation is defined to end when the storm has become embedded in a preexisting, midlatitude baroclinic zone, such that the surface center is in cold, descending air that has undercut overrunning ascent above and east of the storm center (step 3 of the conceptual model in Fig. 5). Reintensification begins when the transformed storm deepens after achieving its highest central SLP at or after the completion of transformation. Reintensification concludes when the transformed storm has achieved the deepest SLP before either filling or holding steady in the next analysis.

Only 4 of 30 ET cases (13%) in the period resembled the compound transition described by Matano and Sekioka (1971). Each of these cases completed the transformation stage of ET and became a baroclinic cyclone as described by the conceptual model (Fig. 5) before they later “merged” (according to the model of Matano and Sekioka 1971) with a preexisting, midlatitude cyclone. Thus, no difference has been found in this sample between the compound and complex cases defined by Matano and Sekioka (1971) during the transformation stage of ET. The primary advantages of this model compared to that of Matano and Sekioka (1971) are that it is (i) three-dimensional; (ii) descriptive of virtually every ET case occurring in the western North Pacific; (iii) can be used to explain how a tropical cyclone evolves into an recipient midlatitude, baroclinic low during the transformation stage of ET; and (iv) combines satellite imagery with NWP analyses and cross sections to assist forecasters in assessing the commencement, progress, and completion of ET transformation stage.

As in the conceptual model of Matano and Sekioka
Fig. 20. As in Fig. 18 except for (a) 1232 UTC 25 Oct and (b)–(d) 1200 UTC 25 Oct 1997.

(1971), and as described in the case of Hurricane Agnes (DiMego and Bosart 1982), this model highlights the importance of an interaction between the tropical cyclone and preexisting, midlatitude baroclinity in the lower troposphere. This conceptual model demonstrates the key role of the equatorward advection of cold, dry air (Matano and Sekioka 1971; Brand and Guard 1978; Browning et al. 1998) into the western quadrant outer circulation of the tropical cyclone and describes how vertical wind shear affects the storm during transformation, based on Frank and Ritchie (1999) and Ritchie and Elsberry (1999). It also describes how frontogenesis (Harr and Elsberry 2000) commences during the third step of transformation. This conceptual model (Fig. 5) is based on observations that every ET in the western North Pacific completed the transformation stage in the same basic, three-step manner, regardless of interactions with land or the synoptic pattern (northwest or northeast) that the storm translates into as transformation concludes. It also describes the physical processes that occur (and their appearance) during each step of the transformation of a tropical cyclone into a baroclinic low.

Implied in the conceptual model are new definitions of when both stages of ET begin and end that involve the interaction of the tropical cyclone circulation and midlatitude baroclinic zone. Thus, a forecaster using this model would require 1° lat–long resolution NWP analyses and forecasts in addition to hourly geostationary satellite imagery (including visible, IR, and water vapor channels), microwave imagery, and radar data (when the storm either passes over or close to land). Specifically, the forecaster should prepare and examine streamlines, isentropes of $\theta_e$, and temperature advection in the lower troposphere, 500-mb winds and isoheights, 200-mb winds and isoheights, and vertical cross sections of winds, $\theta_e$, PV, and vertical motion. It is further suggested that this model may be useful in other ocean basins, where recurving tropical cyclones may also interact with preexisting lower-tropospheric baroclinicity and vertical wind shear, although the model would have to be adapted to the characteristics (coastline, currents, climatological tropical cyclone storm tracks, etc.) unique to these other ocean basins.

One key element missing from this conceptual model
is a detailed analysis of inner-core processes during ET. The resolution of the NOGAPS 1° latitude–longitude analyses is insufficient to describe in detail the physical processes occurring in the tropical cyclone inner core. Reanalysis of selected case studies and numerical simulations using a nested, mesoscale model such as the Coupled Ocean–Air Mesoscale Prediction System should provide sufficient resolution to describe more fully the evolution of the inner circulation of the tropical cyclone during ET.

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