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A STATISTICAL ANALYSIS ON THE DIFFERENT FEATURES OF TC EXTRATROPICAL TRANSITION OVER LAND AND OCEAN

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Abstract: The extratropical transitions (ETs) of tropical cyclones (TCs) over China and the ocean east to 150°E are investigated by the use of best-track data and JRA-25 reanalysis spanning 1979–2008. The ET events occurring north of 25°N and in the warm season (from May to October) are extracted from the reanalysis to emphasize the interaction between TC and midlatitude circulation. Statistical analysis shows that 18.5% of the warm-season TCs go through land ETs north of 25°N in the western North Pacific. And 20.5% of the ET events occur over the ocean east of 150°E. Most (62.2%) ET TCs over China gradually die out after ET, but more (70.7%) ocean ET cases have post-ET reintensification. The evolutions in cyclone phase space and the composite fields for land and ocean ETs, as well as the ET cases with and without post-ET reintensification, are further analyzed. It is found that most TCs with ET over China and those without post-ET reintensification evolve along the typical ET phase path as follows: emergence of thermal asymmetry → losing upper-level warm core → losing lower-level cold core → evolving as extratropical cyclone. The TCs undergoing ETs over ocean and those with post-ET reintensification form a high-level cold core before the ET onset. The TCs with land ET have long distance between the landing TC and a high-level trough. That makes the TC maintain more tropical features and isolates the TC flow from the upstream and downstream jets of the midlatitude trough. The structure of circulation leads to weak development of baroclinicity in land ET. On the contrary, shorter distance between ocean TC and high-level trough makes the high-level trough absorb the TC absolutely. Under that baroclinicity-favorable environment, strong cold advection makes the TC lose its high-level warm core before ET onset. The composite fields confirm that the TC with ocean ET has stronger baroclinic features. Generally, the TC at land ET onset is located to the south of the ridge of the subtropical high, which tends to prevent the TCs from interacting with midlatitude circulation. But for the ocean ET, the situation is just the opposite. Similar analyses are also carried out for the TCs with and without post-ET reintensification over both land and ocean east of 150°E. The results further prove that the TC with stronger baroclinic characteristics, especially in the circumstance favorable to its interaction with high-level midlatitude systems, has more opportunity to reintensify as an extratropical cyclone after ET.

Key words: tropical cyclone; extratropical transition; JRA25; cyclone phase space; thermal structure; upper-level jet; reintensification; cyclone filling

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1 INTRODUCTION

The mechanism of the formation of tropical cyclone (TC) is completely different from that of the extratropical cyclone. However, under some conditions, the TC can evolve and even reintensify as the extratropical cyclone. The transition process between the two kinds of systems is called extratropical transition (ET) of TCs. In the ET process, the TC loses its features of tropical convective system into baroclinic frontal structure. Due to the mixed characteristics of the convective and frontal systems, the ET has greatly different evolution process and mechanism from both TCs and extratropical cyclones[1-7]. That results to huge challenge for the ET

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prediction[8-11].

Many factors have impact on the ET process, such as the baroclinity area, midlatitude system, low sea surface temperature (SST), landing mainland and so on. Qualitative methods are presented to defined the different stages of the ET process based on satellite imagery[12-14]. At more recently, quantitative method describing the structural evolution of TC in ET process is presented by Evans and Hart[15]. This objective method uses three structural parameters to construct a cyclone phase space (CPS) to describe the cyclone as well as the ET evolution[15]. Based on CPS analysis, important statistical features of the ET events are found in North Atlantic[6, 16] and Southwest Pacific[17]. In the western North Pacific, detailed case analyses[18,19] and conceptual model study[12] can also be found. Further numerical work[20] has proved that the interaction between midlatitude circulation and TC is a key factor for the reintensification of the TC remnant flow.

Landing TC with ET has direct impact on the activity of human being and often brings huge disaster to the coastal and even inland regions. For example, the notorious torrential rain that took place in August 1975 in Henan province in China was produced by a reintensified landing TC after ET. Most TCs die out after they land on the continent as their main energy source, the warm ocean, is no longer available. Under some specific circumstances, however, the landing TCs may develop and reintensify as extratropical cyclones after interacting with midlatitude systems. Although TC numerical modeling has greatly increased our understanding of the TC as a tropical system in the past 30 years, the knowledge of the ET, especially the development of the cyclone after ET, is still far from enough. Furthermore, the environmental difference between the land and ocean ETs is a key factor influencing the post-ET development of TC. In previous works[20-22], the ET features are summarized based on samples with the population belonging to a single class that includes both land and ocean ET events, though the environments during land and ocean ET and their relations to the post-ET developments are still not studied in detail. As a result, it is necessary to obtain the common features of development and structure of the TCs after ETs. The TC track data and high-quality reanalysis provided us a chance to extract the climatic features of the ETs from the history of TCs. Therefore, this work focuses on the structure of the landing ET and its relation with midlatitude circulation, as well as the difference between the land ET and ocean ET based on a sample with large population. The features of intensity and circulation structure during ET are also discussed by classifying the ET events into two categories, i.e. the TCs with only the cyclone filling process and those with the reintensifying process after ETs. The ET cases occurring in the past 30 years are analyzed. Because the ET cases occurring in a long period of time are analyzed, some characteristics with better statistical reliability than in previous work are expected to be obtained.

With consideration of the above discussion, the paper is organized as follows. First, the data and methodology used in the study are introduced in Section 2. Then, a brief climatology of the ET events over China and the ocean is presented in Section 3. In the subsequent section, the ET cases are further examined based on the evolution of TC in the CPS. The circulation fields obtained from composite analysis are also investigated in that section. At the end of the paper (section 5), the work is concluded and some discussions are also presented.

2 METHODS OF TC TRACKING AND ET DESCRIPTION

In order to examine the feature of TC after ET, we extend the information of the TC best-track data to higher latitudes using the grid data of the JRA-25 reanalysis from Japan Meteorological Agency (JMA)[21]. The best-track data used here are at 6-h intervals from U.S. Navy’s Joint Typhoon Warning Center (JTWC). The best-track data spanning 1945–2008 are used to track the TC motion. And the structures of TC and midlatitude circulation are examined using JRA-25 reanalysis covering the period from 1979 to 2008 with a horizontal resolution of 1.25°×1.25° at 23 standard pressure levels. The 6-hourly dataset is used in this analysis. The dataset of JRA-25 reanalysis used here was produced from spectral model output with a spectral resolution of T106 and 40 vertical layers[23].

The methodology of cyclone detection and tracking used here is the same as that presented by Zhong et al.[21], which combined the best-track data and track data obtained via the methods presented by Hart[24]. This method can make TC locating and tracking easier when several local mean sea level pressure (MSLP) minima occur in the same searching area. Because the TCs landing on China sometimes leave too far from its genesis region, there is usually a lack of the best-track around and after ETs. Furthermore, since the reintensification of the TC remnant flow after ET is very important for the understanding of the whole ET process, extending the TC ‘observation’ to higher latitudes by using grid data is helpful for our ET analysis. Using the cyclone tracking method mainly considering TC motion speed and direction variation presented by Hart[24], many TC tracks are prolonged reasonably beyond what the best-track covers. Detailed discussion about TC tracking and statistics of the TCs can make a reference to Zhong et al.[21].

Based on the 6-hourly track data obtained from grid data, we can easily calculate the diagnostic fields focusing on TC from reanalysis. The definition of ET onset is a key factor to analyze the ET process. A simple parameter ***B*** describing the TC asymmetry is used to defined of ET onset. As one of the three parameters for constructing the CPS, the asymmetry parameter can be written as [15, 22]

$$B=\overline{\left(Z_{600}-Z_{900}\right)}_{warm}-\overline{\left(Z_{600}-Z_{900}\right)}_{cold}, \quad (1)$$

where Z_{600} and Z_{900} are 600- and 900-hPa geopotential height and the overbars represent the areal mean over the semicircles with 500 km radius on the warm/cold side of the average thermal wind vector[22]. The meaning of this parameter is explicit, i.e. B being close to zero for the storm with typical TC feature and large positive values for that with asymmetric frontal feature. As in Evans and Hart[15] and Sinclair[22], the ET onset is defined as the first time level of the period satisfying $B > 10$ m in eight or more successive 6-hourly (i.e. persisting longer than 48 hours) analyses[21].

The CPS is a helpful tool for our understanding of ET process. Aside from the asymmetry parameter mentioned above, the other two parameters used to construct CPS are the lower-layer (900–600) hPa scaled thermal wind[24]

$$\left.\frac{\partial\left(\Delta Z\right)}{\partial \ln p}\right|_{900hPa}^{600hPa}=-\left|V_T^L\right| \quad (2)$$

and upper-layer (600–300 hPa) scaled thermal wind[24]

$$\left.\frac{\partial\left(\Delta Z\right)}{\partial \ln p}\right|_{600hPa}^{300hPa}=-\left|V_T^U\right|. \quad (3)$$

In Eqs.(2-3), the variable

$$\Delta Z=Z_{MAX}-Z_{MIN}, \quad (4)$$

which is the maximal height difference within a radius of 500 km around the cyclone center. The physical meaning of the two parameters is the thermal structure at different level, i.e. cold or warm core of the cyclone [19]. And the negative $-V_T^U$, i.e. the lower-layer cold core, is considered as the indicator of the completion of ET event.

3 BRIEF CLIMATOLOGY OF ET EVENTS OVER CHINA AND OCEAN

3.1 *Basic statistics*

Using the data and methods described in previous sections, a total of 318 ET cases were found from 1979 to 2008. In these cases, 298 (93.7%) ET events occurred in the latitudes north of 25°N, where TCs have great probability of interacting with midlatitude circulation. In that subset of the ET sample, there are 84.3% (200) ET cases occurring in the warm season (from May to October), in which TCs can acquire much energy to sustain in high latitudes. Because the aim of this study is to investigate the features of the ET events interacting with midlatitude circulation, only the ET events occurring to the north of 25°N and in the warm season are considered. The landing TCs are defined as those entering the area to the northwest of the irregular line in Figure 1. In the subset of warm-season ET events north of 25°N, 40% (50) of the 200 TCs were observed landing China. Furthermore, a total of 37 TCs in the 50 cases have land ET process and the remaining 13 landing TCs undergo ET over the ocean although they have landed China before ETs. In fact, in the area north of 25°N, almost all (97.4%, 37 out of 38) land ET events occur in warm season. Therefore, the warm-season ET events dominate the features of those occurring in midlatitude.

Figure 1. Schematic diagram of the definition of TC landing. The TCs entering the area to the northwest of the polyline along the coast of China are considered as landing TCs.

In order to obtain the typical feature of ocean ET, the TCs that move to the west of 150°E are eliminated to rule out the influence of landing as much as possible. Figure 2 shows the track distribution of the TCs with land ETs (black lines) and ocean ETs (gray lines). For the land ETs, almost all the TCs move in paths with recurvature and the ET locations are often near the recurvature point. But for the ocean ETs, TCs have more variable moving paths and the ET is located more poleward in comparison with the land ETs as the ocean surface supplies more energy for TC to support them to enter higher latitudes.

The intensity variation of TC after land and ocean ET is another topic of this work. Here, we define the TC reintensification (filling) as the mean sea level pressure (MSLP) of TC center decreasing (increasing) in three or more successive 6-hourly analyses after ET onset. In practice, the variation point of the time series of the TC MSLP usually does not coincide with the point of ET onset. Therefore, only if the variation point is in three or fewer successive 6-hourly analyses (i.e. 18 hours) after ET onset, the intensity variation around the variation point is considered to be caused by ET process. Based on the above definitions, there are 14 TCs reintensifying and 23 TCs filling after ET onsets of land ET cases, i.e. most TCs experiencing land ETs get weakened. On the contrary, ocean ET is prone to strengthen TC as shown by the fact that there are 29 reintensifying cases and 12 filling cases.

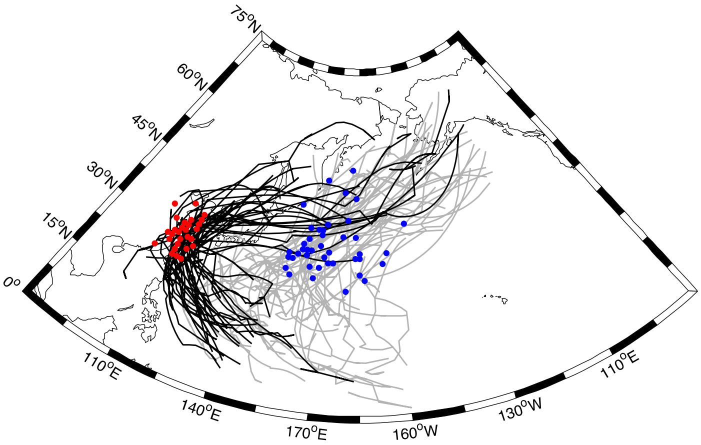
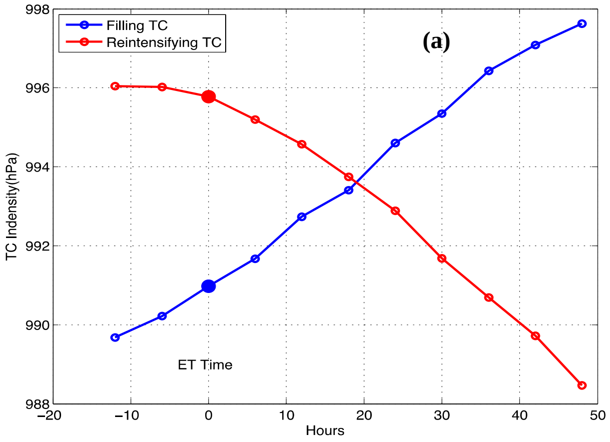


Figure 2. Distribution of the TC tracks for land ET events (black lines) and ocean ET events (gray lines), where the red/blue dots represent the locations of land/ocean ET onsets.

3.2 *Mean intensity and vertical structure*

Figures 3a and 3b illustrate temporal variations of the mean TC intensity during the period from 12 hours before ET onset to 48 hours after ET onset. It is interesting that relatively weak TCs have larger probability to reintensify after ET onset. On average, the TC with reintensification after ET is about 5 hPa stronger in the center MSLP than the filling one (shown by Figure 3a). As shown by Figure 3b, the MSLP difference at ET onset is enhanced to about 8 hPa for the land ET cases. But much less MSLP difference (about 1 hPa) is found for the ocean ET cases. That is to say, the initial intensity at ET onset is a good indicator for the post-ET development of the landing TC. For of sake of convenience, we use the abbreviations LF (OF) and LR (OR) to represent the TC with post-ET cyclone filling (i.e. without reintensification) and reintensification over land (the ocean), respectively.



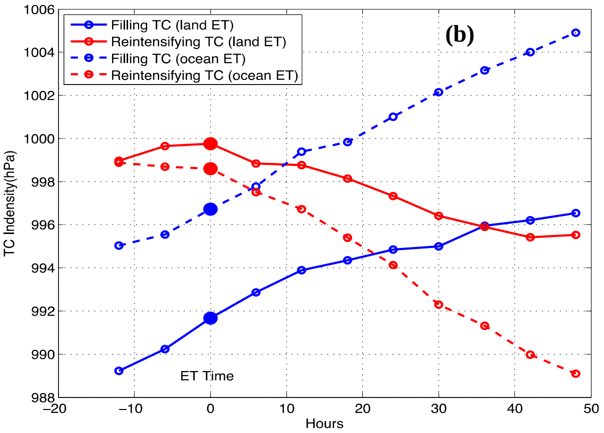


Figure 3. The intensity variation from 12 hours before ET to 48 hours after ET: (a) the mean evolution of the MSLP of TC center for cyclone filling (blue line) and reintensification process (red line) after ET onsets; (b) the same as (a) but for the land ET (solid lines) and ocean ET (dash lines) cases. The bold red/blue dots indicate the time of ET onset.

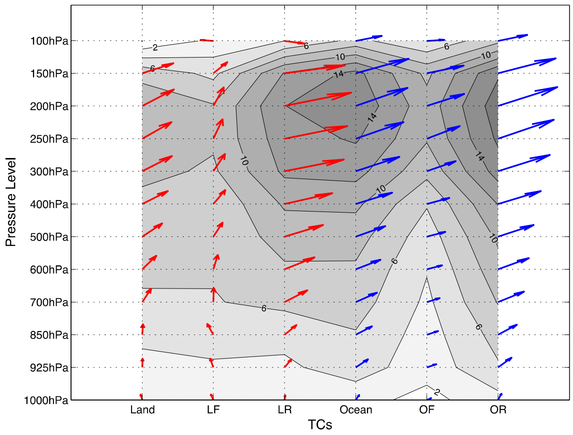
Average vertical profiles in Figure 4 are constructed over a 500-km radius circle centered on each storm’s minimum MSLP at each vertical level at ET onset. The magnitude of wind vector in Figure 4a displays the degree of symmetric circular flow around the TC center, i.e. small (large) magnitude of wind vector means that the TC has highly (weakly) symmetric circular flow, or has more tropical (extratropical or frontal) system feature. As shown in Figure 4a, all the six categories of TCs have highly symmetric flow at low levels (below about 700 hPa) and the asymmetric feature gradually becomes obvious at higher levels. The high-level asymmetric structure means that the high-level flow of TC is affected by the baroclinic flow at the ET onset. A noticeable feature is that the TC at ocean ET onset displays more asymmetric structure than that at land ET onset. This feature suggests that the ocean ET process has stronger interaction with midlatitude circulation. Similarly, the TC with post-ET reintensification has stronger extratropical feature. On the contrary, the LF has highly symmetric flow structure almost throughout the whole thickness (1000-100 hPa). But for the LR, the flows above 600 hPa are affected by strong westerlies, showing much more obvious baroclinicity. That is, the TC having more extratropical feature at ET onset is more likely to strengthen as an extratropical system after ET process. The vertical profiles of relative vorticity (Figure 4b) show that the positive relative vorticity of the LF and OF at lower levels extends to higher altitudes than those of the LR and OR. For the OF, the uppermost level at which the TC maintains positive vorticity can even be 100 hPa. The strong barotropic tropical convective features found in the LF and OF suggest that the TC has relatively less probability to be strengthened as a frontal system if it maintains too much tropical features at ET onset.

In the mean divergence profiles (Figure 4c), the strongest high-level divergent layer is between 250 hPa and 150 hPa. The TC at land ET onset has stronger lower-level convergent and high-level divergent flow. This may be attributed to the property of the lower surface, i.e. greater friction of land surface can produce a stronger convergent flow in the boundary layer than over the ocean surface. This feature is also displayed in the profiles of vertical velocity. The effect of boundary layer friction may result in a stronger and thicker updraft layer of the TC at land ET onset (Figure 4d).

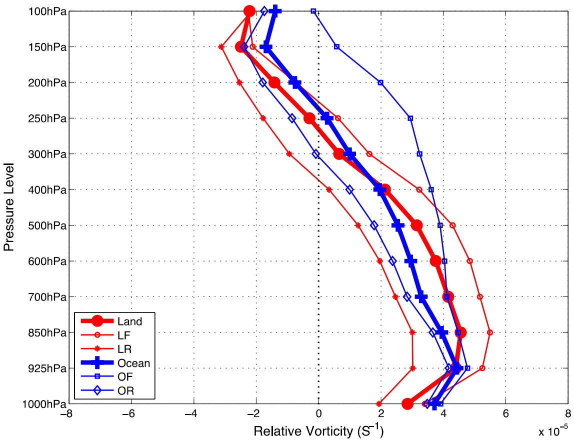
4 ET EVOLUTIONS AND ASSOCIATED CIRCULATION STRUCTURES OVER LAND AND OCEAN

4.1 *Difference of TC evolution between land and ocean ETs*

The method based on the cyclone phase space is a powerful tool to illustrate the life cycle of the TC, especially a good indicator of the ET process because the thermal structure of cyclone can be easily described in the CPS[16, 23]. The objectively defined three-dimensional cyclone phase space derived from thermal wind and thermal asymmetry was presented by Hart[24]. According to the definition of ET completion presented by Hart[24], TC is considered to have completed ET if only its lower-level warm core was replaced by a cold core.



(a)



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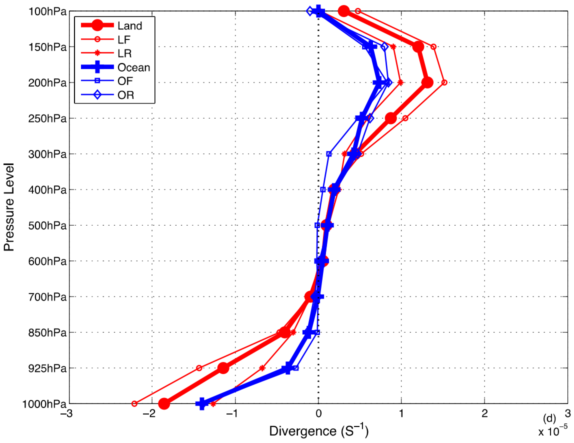
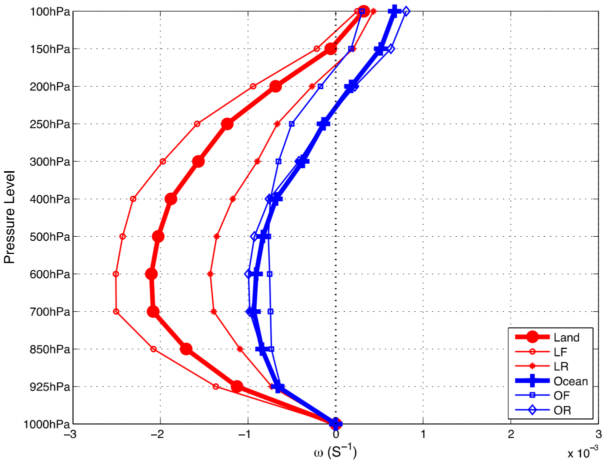


(c)



(d)

Figure 4. The mean properties for different categories of TCs possessing ET during 1979–2008: (a) mean wind vector and wind speed (in m/s) at different *p*-levels; (b) mean vertical profiles of relative vorticity; (c) TC center MSLP at different vertical levels; (d) same as (b) but for mean divergence. The mean properties are averaged over a 500-km-radius circle centered on TC MSLP minimum at different vertical level.

The tacks in Figure 5 illustrate the evolution of individual TC (gray track) and their composite mean path (black track) spanning the time period from 12 hours before ET to 48 hours after ET. Each arrowhead in the phase diagram represents one 6-hourly analysis and the blue (red) dot represents the position of the ET onset (mean ET onset). Figures 5a and 5b are the phase diagrams of the land ET. As shown in the mean paths of Figures 5a and 5b, the TC undergoing land ET maintains its high-level (600–300 hPa) and lower-level (900–600 hPa) warm cores (positive V_T^L and V_T^U) at ET onset. As the ET develops, the landing TC first loses the high-level warm core and then the lower-level warm core. In comparison with land ET, the TC over the ocean loses the high-level warm core when the symmetry of circular flow is destructed (i.e. ET onset, $B \geq 10m$) (as shown in Figures 5c and 5d). Furthermore, ocean ET reaches the lower-level cold core more rapidly than land ET. That is to say, the TC with ocean ET takes shorter time to complete the ET process. By comparing Figure 5a with Figure 5c, TC tracks in the former can reach relatively larger values in the first and the third quadrant, which indicates that the TC with land ET has stronger high- and lower-level warm cores before ET and weaker cold core after ET completion. As Figure 5b shows, the land ET can only reach relatively smaller B values than ocean ET. Based on the above analysis, we can deduce that the TC having strong tropical feature at the initial state of ET can hardly evolve into a weak extratropical system after ET completion.

Figures 6 and 7 present the phase diagrams for the LF, LR, OF and OR. Comparing the panels for LF and OF with those for LR and OR, the feature similar to that obtained from Figure 4a can be found. The TCs with post-ET reintensification have stronger baroclinicity at and after ET onsets. That can be indicated by the more asymmetric (larger *B*) flow structure (Figures 6d and 7d), and the stronger cold core at high and low level after ET completion (Figures 6c and 7c). Especially for the LF and LR (Figures 6a and 6c), losing high-level warm core earlier makes the LR have high-level cold core before the ET onset. That implicates high-level cold air invasion at the early stage of ET is beneficial for the TC to develop as an extratropical cyclone after ET.

4.2 *Circulation structures during land and ocean ETs*

To highlight the key environmental factors during ET onset, detailed composites of circulation at *p*-levels are presented in this subsection. The composite fields are obtained by calculating the mean fields over an area in which the TC center is 30° away from the north boundary, 25° away from the south boundary, and 30° away from both the east and west boundaries. The composite fields for the land ET onsets at the vertical levels of MSLP, 850 hPa, 500 hpa and 200 hPa are presented in Figures 8a–8d. At the land ET onset, TCs are averagely located about 2° to 3° southeast to a tilted westerly upper-level (200 hPa) trough. The weak northeastern environment flow around the TC center drives the TC under it to move slowly into the upper-level trough. The weak upper-level veering flow indicates that the TC moves at the position just near the recurvature point of the moving path as shown in Figure 2. A strong downstream upper-level jet is found to the northeast of the TC. Holland and Merill[25] proposed that the downstream subtropical jet reduced inertial stability in the outflow region and generated a divergent area poleward and eastward of TC center[17]. In Figure 8a the divergent area associated with the upper-level jet and that of TC outflow merge as one divergent center. The strong divergence bridges the jet and TC and enhances the outflow of TC. The strengthened outflow and increasing instability there may be a factor for the reintensification of TC after ET onset. In the upstream of the high-level trough, another jet is also found to the northwest of the TC. That jet enhances the interaction between trough and TC by transporting more cold air from high latitudes into TC. This is more clearly reflected by upstream flow traversing contours of 500-200 hPa thickness (Figure 8b). At the level of 500 hPa, the relation between TC and midlatitude trough is displayed more clearly. Although the outflow of TC at 500 hPa has emerged with the downstream jet, the TC still maintains its circular flow and has relatively uniform thickness in the TC impact area, which makes the upstream cold air hardly approach the TC center. That is why the phase diagram shows that the TC maintains the high-level warm core at the land ET onset (as shown by Figure 5a).

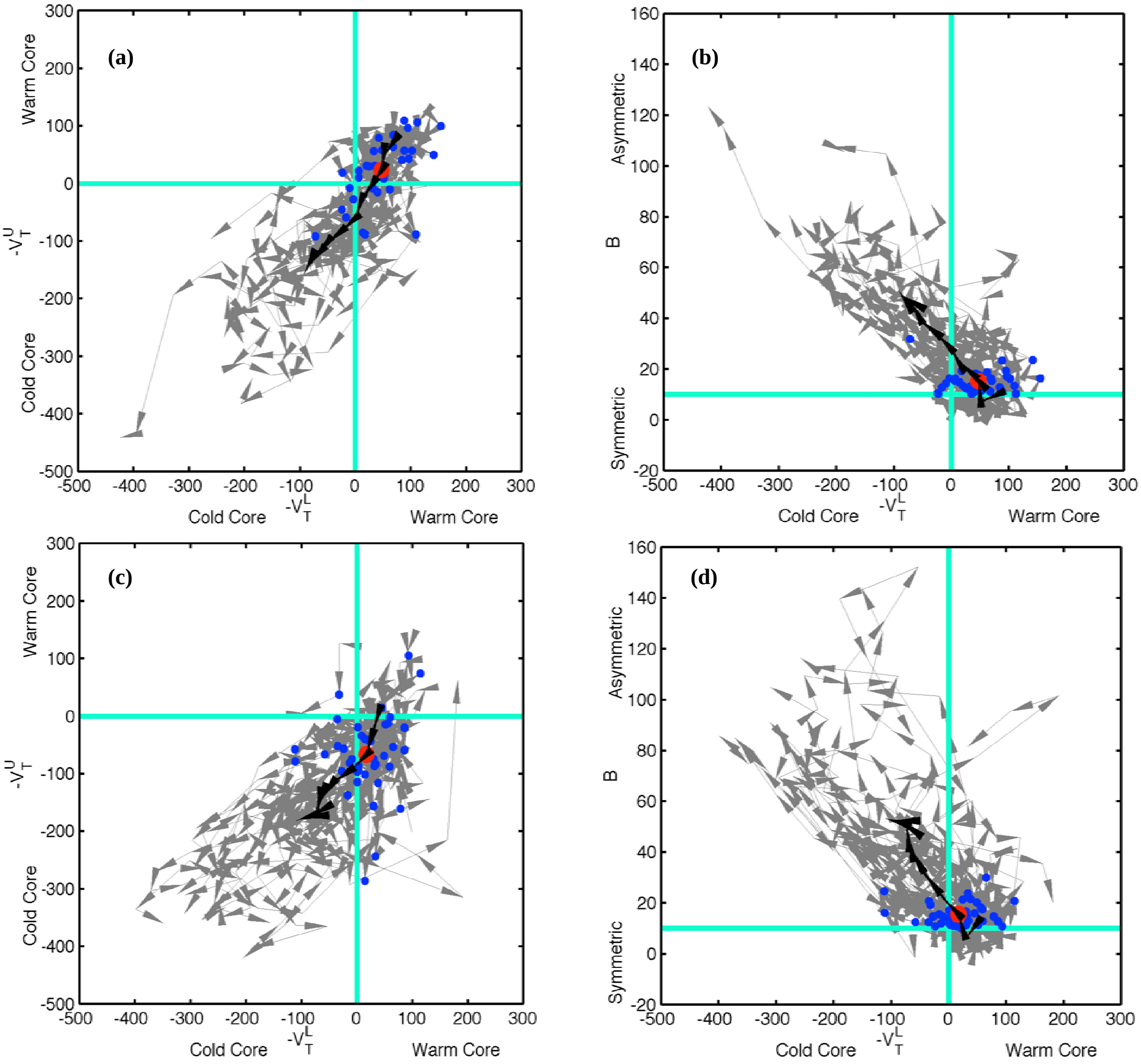


Figure 5. The phase diagrams of land ET (a, b) and ocean ET (c, d) events derived from JRA-25 during 1979–2008. The phase parameters B, V_T^L and V_T^U are respectively the thermal asymmetric parameter, upper- and lower-level scaled thermal wind. The gray tracks are the evolution paths of the TCs and the arrowheads point towards the data at subsequent time levels. Black tracks are the mean paths from composites. The blue (red) dots represent the positions (mean positions) of ET onsets.

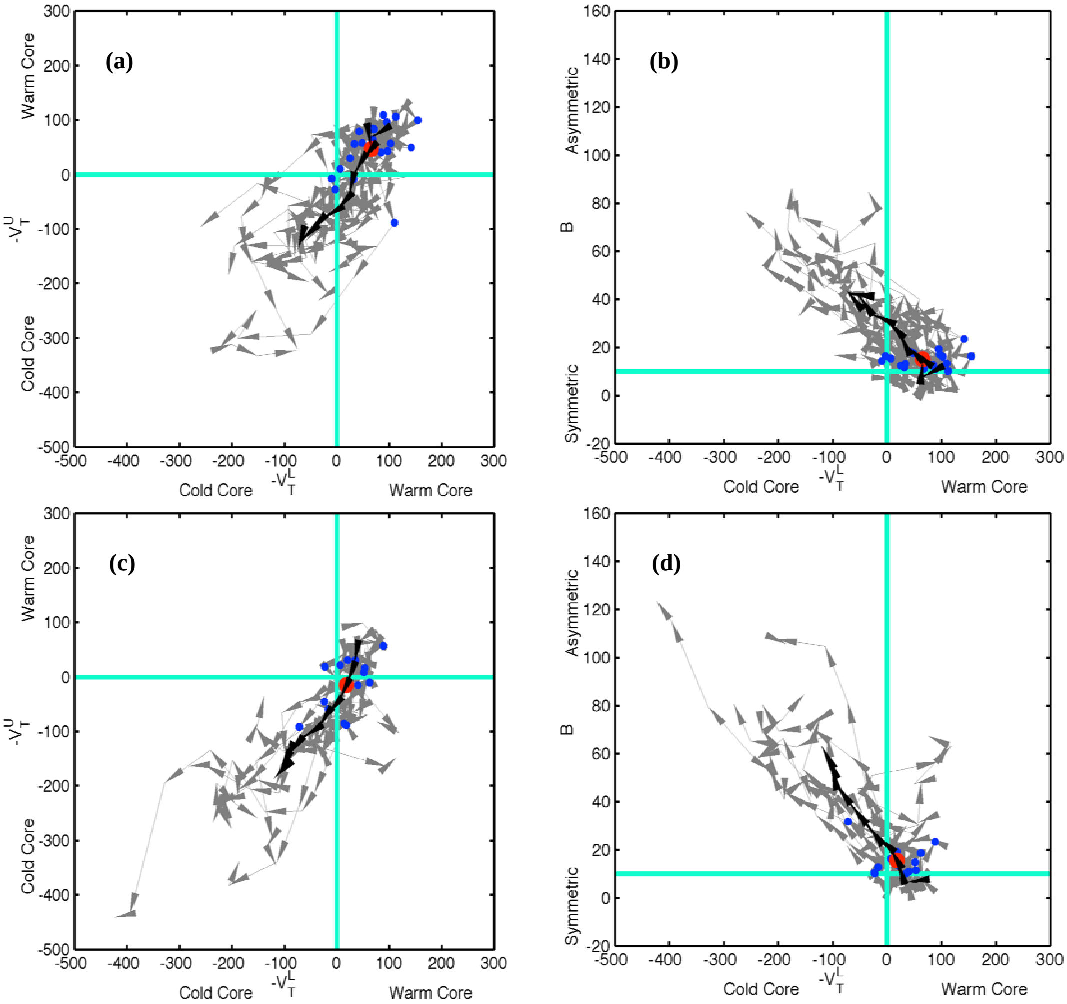


Figure 6. Same as Figure 5 except that figures (a) and (b) are for the landing TCs with post-ET cyclone filling (LF), and (c) and (d) are for those with post-ET reintensification (LR).

When it comes to ocean ET (Figures 9a and 9b), the TC is averagely located upstream of a high-level ridge. Relatively more straight flows upstream of the TC center produced a weak jet there. Because warm ocean surface can support TCs moving into higher latitudes (as shown in Figure 2), the TC moves poleward and is absorbed in the large-scale midlatitude trough. At the same time, a strong upper-level veering flow drives the TC to move rapidly northeastward. Due to the stronger interaction between the TC and midlatitude circulation, the inflow and outflow of TC both emerge with the upstream and downstream environmental flows. The circular flow of the TC is destructed and completely embedded in the midlatitude trough. Different from the land ET (Figures 8a and 8b), the strong upstream cold advection in the TC inflow area indicates that the high-level thermal structure of TC has high degree of interaction with midlatitude large-scale circulation. As a result, the strong upper-level cold air flows into the TC and forms a high-level cold core at the ocean ET onset, just as shown in Figure 5c. In comparison with the land ET, the ocean ET generates stronger baroclinicity due to the absorption of TC into large-scale circulation and the thermal advection driven by large-scale upstream and downstream flows.

At the lower level (Figures 8c and 8d and Figures 9c and 9d), almost symmetric closed isolines around the TC center are found in both 850 hPa potential height field and MSLP field. Both in the land and ocean ETs, the TC is located to the west of a subtropical ridge, i.e. the subtropical high. However, the relative position of TC to the subtropical ridge is different in land ET and ocean ET. At the land ET onset, the average position of TC center is located southwest to the ridge, which results in the recurvature of the moving path. For the ocean ET, the TC is often to the northeast of the ridge at ET onset. That results in more variable paths as shown in Figure 2. The relative positions of TCs to the subtropical high (Figures 8c and 9c) generate lower-level jets to the west of TC centers. Particularly for the ocean ET, a strong lower-level jet stretches from south to east along the southern and eastern edge of the TC. Forced by upper-level divergence northeast to the TC center shown by Figures 8a and 9a, the ascent center slightly migrates to the area under the equatorward entrance of an upper-level subtropical jet because of the weak stability there. Due to the northeastward shifting of the divergent center in Figure 9a, the strong ascent migrates more northeastward for ocean ET than land ET. With the coexisting stronger gradient of 500-1000 hPa thickness to the north of the TC, stronger warm advection can be found in the region northeast to the TC center. That suggests possible warm frontogenesis commencement in that region. Because for stronger baroclinicity in ocean ET, the region with larger integral cloud water covers much larger area than that in land ET. The shape of cloud water pattern is similar to the northeast part of the cirrus "shield" formed by interaction between a transformed TC and a polar jet[12].

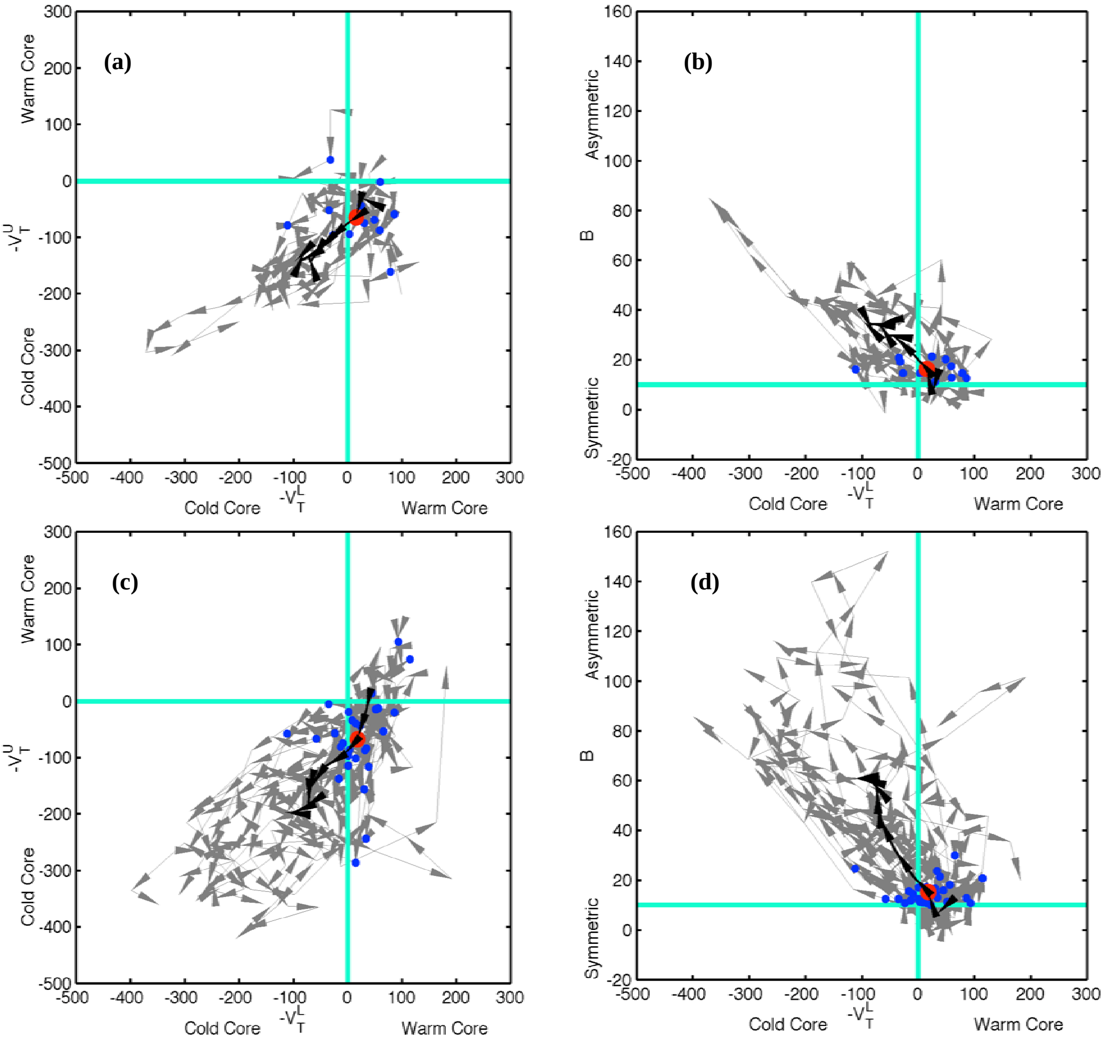
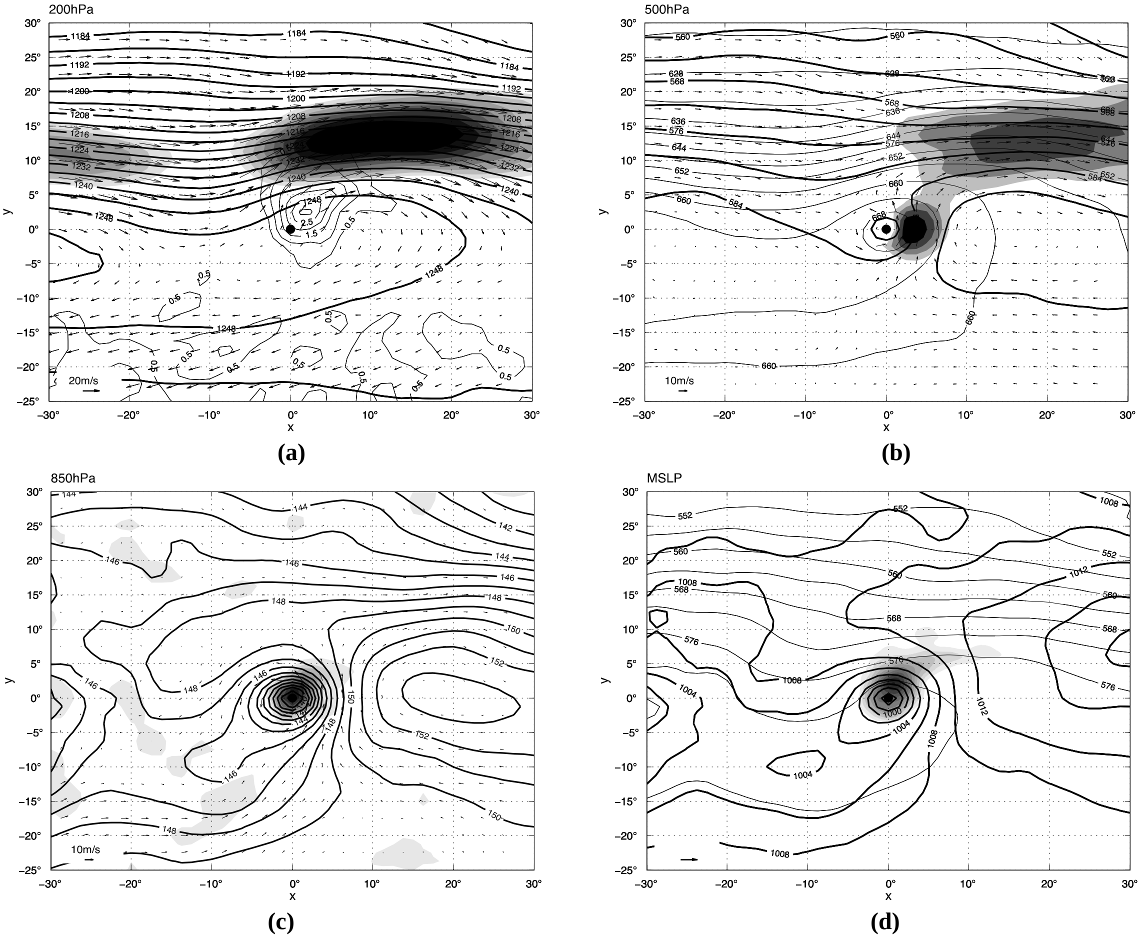


Figure 7. Same as Figure 5 except that panels (a) and (b) are for ocean TCs with post-ET cyclone filling (OF), and (c) and (d) are for those with post-ET reintensification.

The above analysis is also carried out for the LF, LR, OF and OR, respectively, to find the characteristics that determine the development of the TC after ET. Figure 10 illustrates the composite circulation patterns for the LF and LR. The figures of the ocean ET are omitted here due to the similar features as land ET. At 200 hPa (Figures 10a and 10b), the LR is closer to the high-level downstream jet than the LF. Although the LF is more intense and generates stronger high-level divergent area at ET onset, the LR is more strongly impacted by the high-level trough, which is shown by the more northeastwardly shifting of the divergent area. Distinct difference between the two types of TCs can be found in the fields at 500 hPa (Figures 10c and 10d). In the impact area of the LF (Figure 10c), the circular flow and almost uniform high-level thickness prohibit the high-level cold air from entering the TC. Furthermore, since the LF still maintains strong tropical feature, its outflow does not merge with the downstream jet. Those high-level structures have the effect of preventing the TC from obtaining much baroclinic energy. On the contrary, the flow of the LR is absolutely absorbed by the high-level trough (Figure 10d). Especially, the inflow and outflow of the LR merge with the upstream and downstream flow of the trough, which enhances the thermal exchange between TC and trough. The strong advection of cold air at the high-level provides more baroclinic energy for the TC evolving as an extratropical cyclone after ET. For the lower-level circulation shown by Figures 10e to 10h, the relative position of the TC to the subtropical high is still the most noticeable characteristics. The mean location of the LF (Figures 10e and 10g) is to the south of the ridge of the subtropical high, which prohibits the TC from interacting with the midlatitude system in the higher latitudes at ET onset. But for the LR, the environmental condition is more favorable to the interaction between the TC and the midlatitude circulation since the TC is located to the north of the ridge of the subtropical high. As a result, the distributions of the ascent and the cloud water of the LR indicate stronger extratropical features than those of the LF.



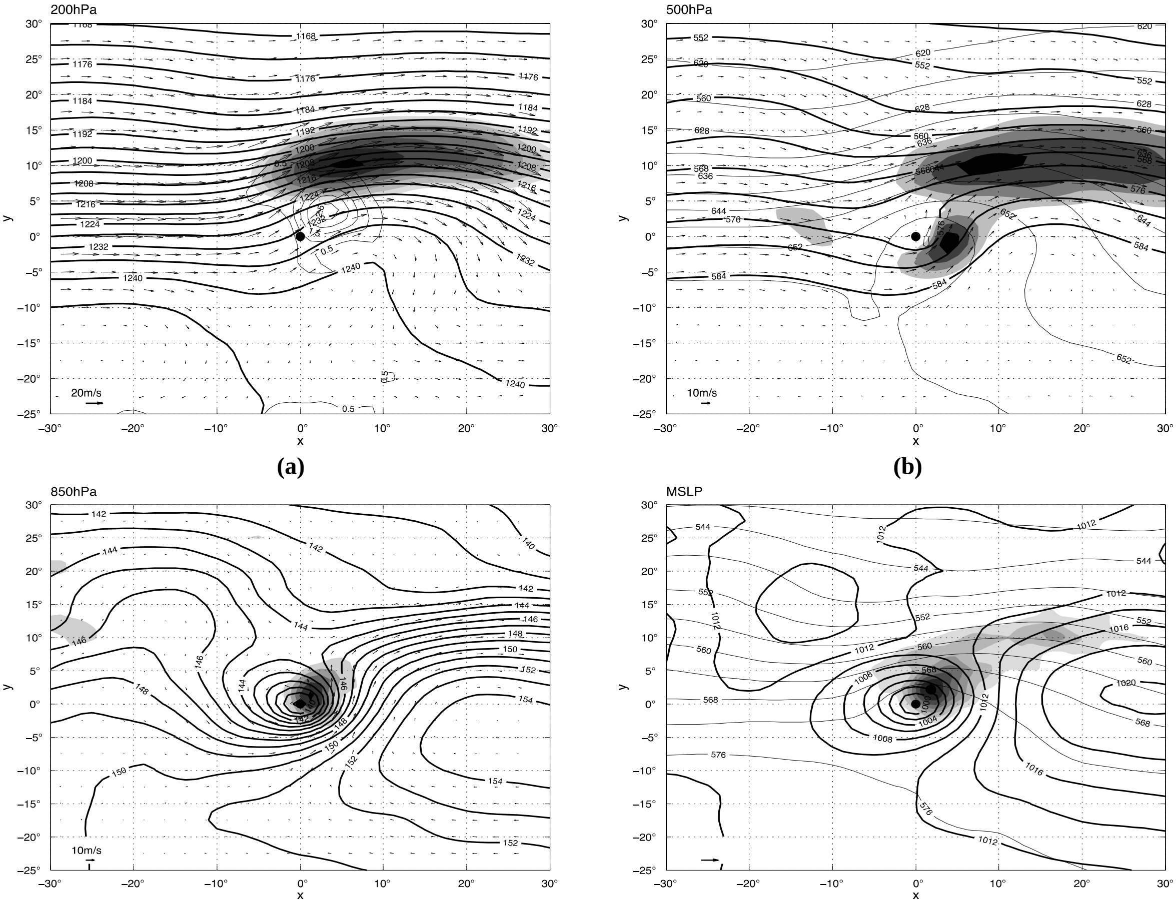
(a) (b)

(c) (d)

Figure 8. The composite fields at land ET onset: (a) 200 hPa geopotential height in dam (thick line), divergence (in 10^{-5} s^{-1}) greater than 0.5×10^{-5} s^{-1} (thin line), and wind vector (in m s^{-1}) with isotach greater than 25 m s^{-1} shaded; (b) 500 hPa geopotential height in dam (thick line), 500–200 hPa thickness (in dam), and wind vector (in m s^{-1}) with isotach greater than 10 ms^{-1} shaded; (c) 850 hPa geopotential height in dam (thick line), wind vector (in m s^{-1}), and vertical *p*-velocity ω (in 10^{-3} Pas^{-1}) with ascent region ($\omega<-0.5\times10^{-3}$ Pas^{-1}) shaded; (d) MSLP in hPa (thick line), 1000–500 hPa thickness (in dam), and 1000–100 hPa vertically integral cloud water (in 0.1g/kg) with values greater than 0.08 g/kg shaded. The black dot in the figure indicates the TC location at the ET onset.

5 CONCLUSIONS

Based on the reanalysis data spanning from 1979 to 2008, the study presents a comparative analysis between the tropical cyclones (TCs) with extratropical transition (ET) process over China and those over the ocean east to 150°E. In order to emphasize the interaction between TC and midlatitude circulation, the analysis focuses on the ET events with onsets north to 25°N in the warm season (from May to October). In that subset of ET events, there are 18.5% (37 out of 200) cases having land ET and 20.5% (41 out of 200) cases having ocean ET east to 150°E. The statistical analysis further demonstrates that most (62.2%, 23 out of 37) TCs die out without any reintensification process after land ETs. But for the ocean ET, most (70.7%) TCs reintensify as extratropical cyclones after ET. From the statistics of TC tracks, most TCs with land ETs recurve near the ET positions. The TCs with ocean ETs move in more variable tracks and have more poleward ET onset positions.



(a) (b)

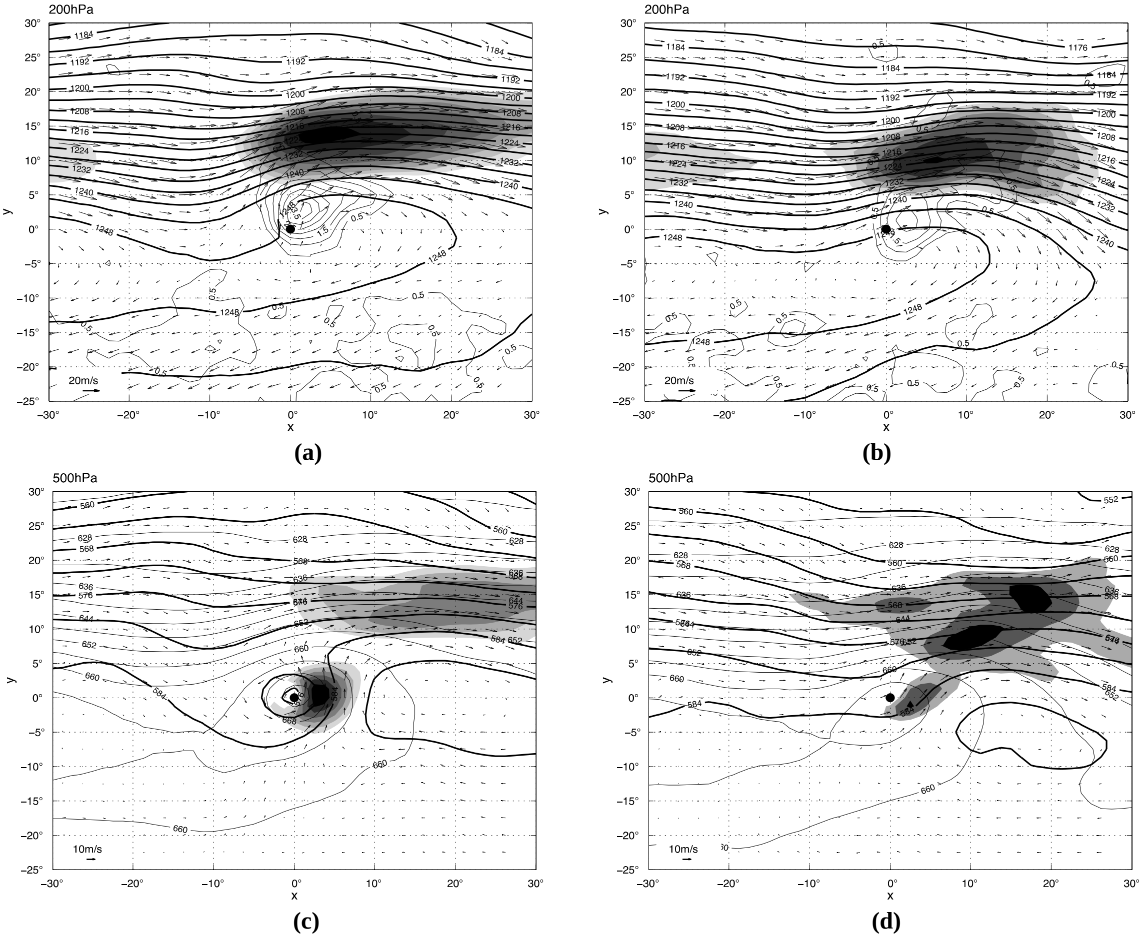
(c) (d)

Figure 9. The same as Figure 8 but at ocean ET onset.

Based on the statistics obtained in cyclone phase space (CPS), the developments of TCs, especially evolutions after ETs, are compared between land ET and ocean ET, as well as the land/ocean ET with and without post-ET reintensification. It is found that the mean phase evolution path of land ET is in typical transition steps as follows. The TC first shows thermal asymmetry, then loses the upper-level warm core, and finally completes the ET as the lower-level cold core replaces the warm core. But the ocean ET loses the high-level warm core when the asymmetry of TC flow becomes significant. This difference is also found when the same comparative analysis is carried out for the evolutions of TCs with and without post-ET reintensification. That is just the reason why more TCs with ocean ETs can reintensify as extratropical systems. For the post-ET evolution, the TC undergoing ocean ET evolves with much more obvious extratropical characteristics. Similarly, the land ET cases with post-ET reintensification also mostly lose their high-level warm cores before ET onsets. That is to say, only the TC with stronger baroclinic structures, such as stronger high-level cold core and more asymmetric flow, can evolve into a more energetic extratropical cyclone.

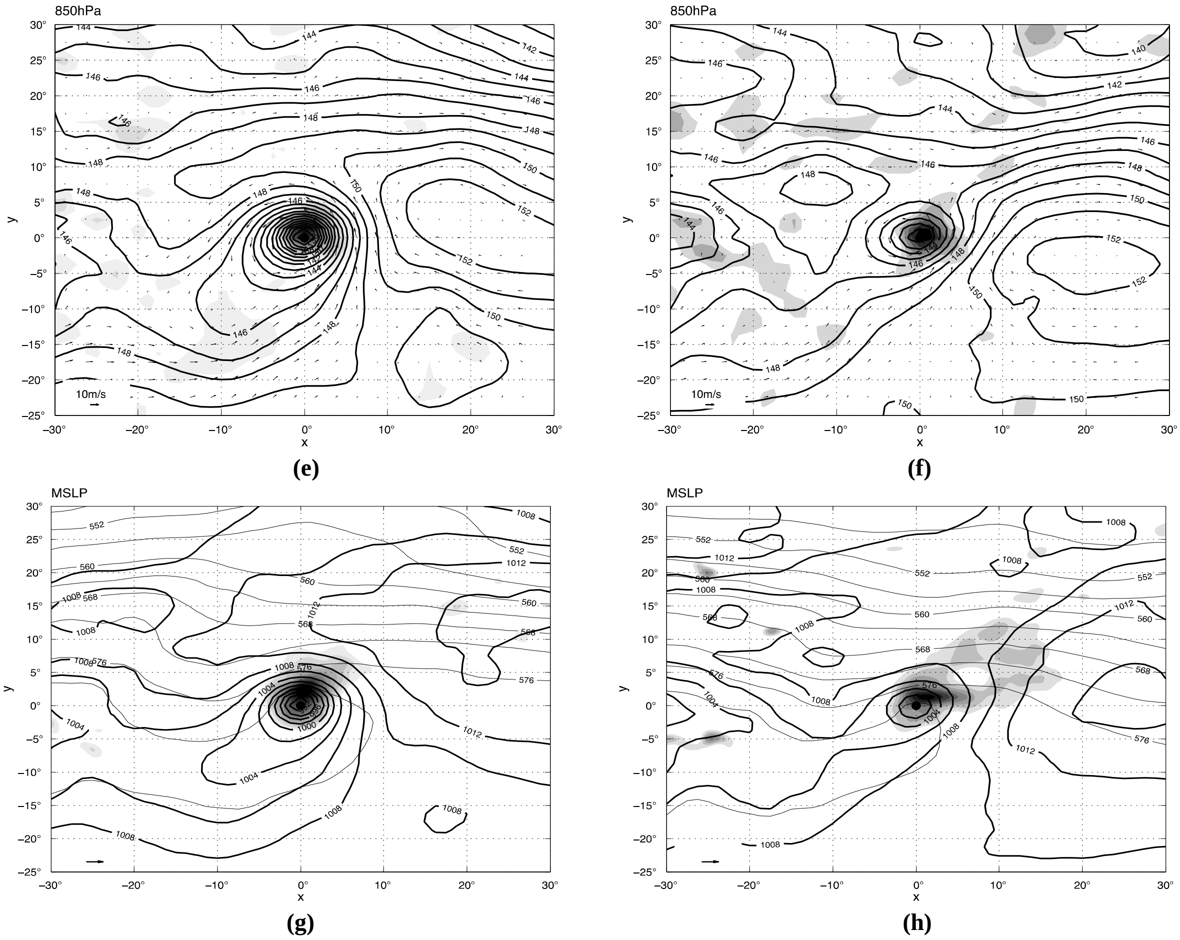
Through compositing circulation at ET onsets for different types of TCs, the TC flow and its relation to the midlatitude circulation are presented to explain the development characteristics shown in CPS. Generally, the TC with land ET is more distant from the midlatitude high-level troughs. At the land ET onset, the TC maintains tropical characteristics better, such as isolated symmetric circular flows. That structure prevents the TC inflow and outflow from merging with upstream and downstream jets or flows, which further prohibits high-level thermal advection from going into the TC. The weak high-level exchange between TC and midlatitude circulation inhibits the growth of the baroclinicity over TC. At the low level, most TCs at land ETs are located to the south of the ridge of the subtropical high, which prevents the TC from deeply interacting with midlatitude circulation. Inversely, most TCs with ocean ETs are absorbed by the high-level trough because the warm ocean supports TC to move into higher latitudes. And the inflow and outflow of the TC merge with the upstream and downstream jets of high-level trough, which enhances the high-level thermal advection. Therefore, the TC has a high-level cold core before ocean ET onset. Moreover, because the TC is often located to the north of the ridge of the subtropical high, the distributions of ascent and cloud water of the ocean ET show stronger extratropical (frontal) features than land ET. The difference mentioned above is enhanced when the same comparative analysis is carried out between the TC with and without post-ET reintensification. In fact, the landing TCs with cyclone filling after ETs, i.e. the LFs, determine the mean structure at land ET since most TCs have no reintensification processes after land ETs. On the contrary, the structure of TC at ocean ET possesses similar features as those of the TC with post-ET reintensification because most TCs with ocean ETs reintensify after ET. In a word, if the TC reintensifies after ET, it often has stronger extratropical characteristics and merges with midlatitude circulation better no matter where ET occurs.

The conclusions above drawn from the ET samples during the past 30 years can provide some implications to the predication of post-ET evolution, especially intensity variation of landing TC. The key factors determining the post-ET intensity variation include the high-level cold core or warm core, the distance between TC and high-level trough, the high- and lower-level thickness gradient and the relative position to the ridge of the subtropical high. Although, from the statistical meaning, those factors are significantly distinct for different types of ET cases, further work is still needed for the forecast of the ET, especially for the land ET evolution. The dataset used in this work is too coarse in both spatial and temporal resolution to explore the evolution of the detailed three-dimensional structure of TC during ET process. The statistical analysis in this study covers only some fragments of the ET process, which can hardly tell the whole story of the processes of land and ocean ET. That prevents us from understanding the detailed physical processes of the ET evolution. Furthermore, there is no way to discuss the impact of the boundary layer associated with land or ocean surface on the ET by the use of present dataset. Those problems may be addressed through high-equality mesoscale numerical work in future.



(a) (b)

(c) (d)



(e) (f)

(g) (h)

Figure 10. The composite fields at land ET onset for different types of TCs. The four panels in the left column are composite fields for the landing TC with post-ET cyclone filling (LF), and the meanings of the composite fields are the same as those in Figure 8. The panels in the right column are composite fields for the landing TC with post-ET reintensification (LR).

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