Article ID: 1006-8775(2017) 01-0015-10

ANALYSIS OF STRUCTURE EVOLUTION AND ENVIRONMENTAL CONDITIONS OF TROPICAL CYCLONES OVER THE WESTERN NORTH PACIFIC DURING EXTRATROPICAL TRANSITION

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Abstract: Fifty-eight extratropical transition (ET) cases in the years 2000-2008, including 2,021 observations (at 6-hour intervals), over the western North Pacific are analyzed using the cyclone phase space (CPS) method, in an effort to get the characteristics of the structure evolution and environmental conditions of tropical cyclones (TCs) during ET over this area. Cluster analysis of the CPS dataset shows that strong TCs are more likely to undergo ET. ET begins with the increment of thermal asymmetry in TCs, along with the generation and intensification of an upper-level cold core, and ends with the occurrence of a lower-level cold core. ET lasts an average duration of about 28 hours. Dynamic composite analysis of the environmental field of different clusters shows that, in general, when TCs move northward, they are gradually embedded in the westerlies and gradually transform into extratropical cyclones under the influence of the mid- and higher-latitude baroclinic systems. As for those TCs which complete ET, there is always much greater potential vorticity gradient in the northwest of them and obvious water vapor transport channels in the environment.

Key words: extratropical transition of tropical cyclone; cyclone phase space; cluster analysis; composite analysis

CLC number: P444 **Document code:** A

doi: 10.16555/j.1006-8775.2017.01.002

1 INTRODUCTION

When tropical cyclones (TCs) move polarward, their structure will change significantly as environmental conditions change. Some of these TCs can transform into extratropical cyclones under appropriate conditions (Elsberry[1]). The structure changes from symmetric TCs to asymmetric extratropical cyclones can be defined as the characteristics of extratropical transition (ET) (Harr and Elsberry[2]). ET occurs in the Atlantic, the western North Pacific, the Southwest Pacific and the South Indian Ocean (Jones et al.[3]). These TCs that undergo ET often bring unexpected strong rainstorm, strong wind, ocean waves and other disastrous weather to the middle and high latitudes (Foley and Hanstrum[4]; Liang et al.[5]). Chen and Ding [6] think that cold air invading a typhoon can cause or intensify baroclinic instability, and then baroclinic potential energy is converted to kinetic energy, which is the cause of TC extratropical transforming and redeveloping. Klein et al.[7] proposed a three-dimensional conceptual model of the transformation stage of ET by reviewing 30 ET cases occurring during 1 June-31 October 1994–1998 in the western North Pacific. In this model four physical processes are considered, including environmental inflow of cold/warm and dry/moist air, relationship between TC and preexisting baroclinic zone, systematic decay and tilt of the warm core aloft, and asymmetric structure development. Vertical wind shear and jet associated with baroclinic zone will also affect the structure and strength of transforming TCs (Sinclair and Revell[8]; Frank and Ritchie[9]). Mid-latitude circulation pattern plays a decisive role in the development of transforming TCs (Harr and Elsberry [2, 10]; Dimego and Bosart[11-12]; Li et al.[13]). Northwest mid-latitude circulation pattern can strengthen the coupling of TCs and midlatitude baroclinic zone, which is favorable for transforming TCs to develop into strong extratropical cyclones. Northeast mid-latitude circulation pattern can weaken the coupling of TCs and midlatitude trough, prevent transforming TCs from developing into independent extratropical cyclones. Ritchie and Elsberry[14] describe the extratropical cyclones development processes during the reintensification stage of an extratropical transition from TCs associated with different strength of upper-level troughs by using numerical simulations. They find that the final intensity of the extratropical cyclones is not only related to the strength of the upper-level trough but also related to the pattern of the general mid-latitude environment. The proper phasing of the TCs with the mid-latitude troughs

Received 2014-12-28; **Revised** 2017-01-03; **Accepted** 2017-02-15

Foundation item: National Natural Science Foundation of China (40805018); National Basic Research Program of China (2013CB430104); Special Fund for Scientific Research in the Public Interest (GYHY201106035)

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results in substantial enhancement of the upper-level divergence (Li et al.[15]). Many studies (Bosart and Lackmann[16]; Zhu et al.[17-19]; Shu and Luo[20]) have found out that the vorticity related to transforming TCs themselves, warm and humid environment, high-level anticyclone outflow are all their advantageous factors to redevelop. TCs experiencing ET and redevelopment is the result of dynamic interactions between external environment conditions and TCs themselves (Klein et al.[7]).

With the physical processes and mechanisms of ET further revealed, creating an objective standard to estimate the start and finish of ET is important to replacing the current relatively subjective judgment. Hart[21-22] and Evans[22] propose an objective diagnosis method for the process of ET named Cyclone Phase Space (CPS). It takes three parameters about thermal wind and thermal asymmetry as the coordinate of phase space, with the position in phase space a cyclone can be determined which category it is in. Previous research of ET in the western North Pacific shows that there is a certain deviation of ET between using the CPS method and the CMA-STI best-rack dataset (CMA-BTDS) (Guo et al.[23]; Song and Wang[24]). On the one hand the deviation is due to the different methods of the definition of ET, on the other hand, the modified CPS parameter threshold may be taken considering the diverse structure of TC in different ocean. In addition, there is only complete time of ET in CMA-BTDS, however, in the process of TC transforming into extratropical cyclone, there must be a transition state of cyclone, which belongs neither to TC and nor to extratropical cyclone. The CPS provides a quantitative analysis method for the characteristics of cyclone structure. By using CPS, the continuous structure evolution of ET process can be analyzed.

In this study, the CPS is used to describe the structure evolution of ET process in the western North pacific. And by using cluster analysis, the stage characteristics of ET process can be revealed, including the structure characteristics, the environmental background and the conversion between different structures.

2 DATA AND METHODOLOGY

2.1 *Data*

According to CMA-BTDS there are 58 out of 247 tropical cyclones that undergo ET in the years 2000-2008. The locations of these TCs where ET is completed are all north of 25°N, and mainly concentrate in 135°–170°E, 35°–45°N of the sea (Fig.1). 25°N can be considered as a latitude threshold through which TC may be able to complete ET. Fig.1 also shows that there are 8 ET cases which land on the Chinese mainland, with the ratio of landing being about 10%. It is smaller than the ratio of 16.63% during 1949–2007 counted by Yuan et al.[25]. The difference may be caused by the annual variation of ET case number and environmental circulation.

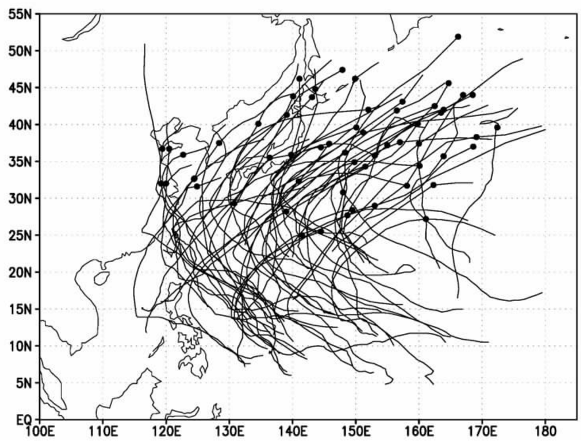

Figure 1. Tracks of all TCs that underwent ET during 2000 to 2008 in the western North Pacific, where the black solid circles are the locations defined to be extratropical cyclones in CMA-STI best-track dataset.

The CPS locations (one location is determined by three parameters) are calculated using 6-hourly 1-degree NCEP reanalysis. Based on CMA-BTDS there are 2021 CPS locations for the 58 ET cases during 2000-2008.

2.2 *Methodology*

One of the CPS parameters is B, defined as the storm-motion-relative 900-600 hPa thickness asymmetry across the cyclone, used to characterize the lower-level thermal asymmetry.

$$B = h\left(\overline{Z_{600hPa} - Z_{900hPa}}\big|_R - \overline{Z_{600hPa} - Z_{900hPa}}\big|_L\right)$$

where Z is isobaric height, R indicates the right of current storm motion, L indicates the left of current storm motion, and the overbar indicates the areal mean over a semicircle of radius 500 km. The integer h takes a value of +1 for the Northern Hemisphere and -1 for the Southern Hemisphere. According to the statistical results by Hart[21], a convenient and physically sound threshold for distinguishing the start of ET in the Atlantic is $B > 10$ m.

The other two CPS parameters are $-V_T^L$ and $-V_T^U$, defined as vertical derivative of height perturbation on isobaric surface across the cyclone within 500 km radius of two tropospheric layers of equal mass: 900 to 600 hPa and 600 to 300 hPa. Under the assumption of thermal wind balance, these two CPS parameters can indicate whether the cyclones are cold core, or warm core, or no thermal anomaly.

$$\frac{\partial(\Delta Z)}{\partial(\ln p)}\Bigg|_{600hPa}^{300hPa} = -V_T^U$$

$$\frac{\partial(\Delta Z)}{\partial(\ln p)}\Bigg|_{900hPa}^{600hPa} = -V_T^L$$

where $\Delta Z = Z_{MAX} - Z_{MIN}$ is height perturbation on isobaric surface across the cyclone within 500 km radius, U indicates upper layer, L indicate lower layer. Positive values of $-V_T$ indicate a warm-core cyclone within the layer, while negative values of $-V_T$ indicate a cold-core

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cyclone within the layer. The time when parameter B reaches a given threshold, i.e. asymmetry obviously enhances, can be considered as the start time of ET. The time when $-V_T^L$ changed from positive to negative, indicating that an absolute cold core appears at the low layer, can be considered as the complete time of ET. By now a mature extratropical cyclone has appeared. Zhang et al.[26] identify the evolution of ET for Haima (0421) using the CPS method. The result shows that the three parameters defined with the CPS method are good indicators of the ET process. Zhong et al.[27] analyzed the ET process of western North Pacific during 1979–2008 using the CPS method. They find that most ET events are shown to follow the typical phase evolution path, along which TC first shows thermal asymmetry and an upper-level cold core and then loses its low-level warm core. The CPS method can quantitatively distinguish different stages of ET process, but the parameters threshold in different regions must be determined respectively.

Taking into account the deviations between the thermal wind relation and the reality, and the asymmetry caused by movement, parameter B in the paper is modified as follows: Across the cyclone within 500 km radius with 1 azimuthal degree resolution there are 180 diameters which replace the storm motion direction in the definition of B in Hart [21]. Then 180 values of B can be calculated and the maximum value is assigned to B. It is not surprising that the value of parameter B here will be larger than that calculated by the definition in Hart [21]. After calculation of 2,021 observations the CPS parameter dataset is obtained. They occupy a wide range in CPS, so it is necessary to classify them.

Cluster analysis is an objective classification method of multiple variables for large datasets. It creates clusters of items, individuals or objects that have maximal similarity with the others in the cluster but with maximal differences between the clusters. In this paper, the 2,021 CPS parameter observations are analyzed using segment cluster analysis. After repeated tests, 7 clusters are specified as the most suitable, and the cluster results are shown in Fig.2. The count of observations of each cluster, the mean value and standard deviation of the CPS parameters and the center pressure of the cyclone of each cluster, are shown in Table 1. The percentage of strength grade cyclone defined by CMA-BTDS of each cluster is shown in Table 2. The probability of transition from a cluster to another cluster is shown in Table 3. Next section is feature analysis of each cluster.

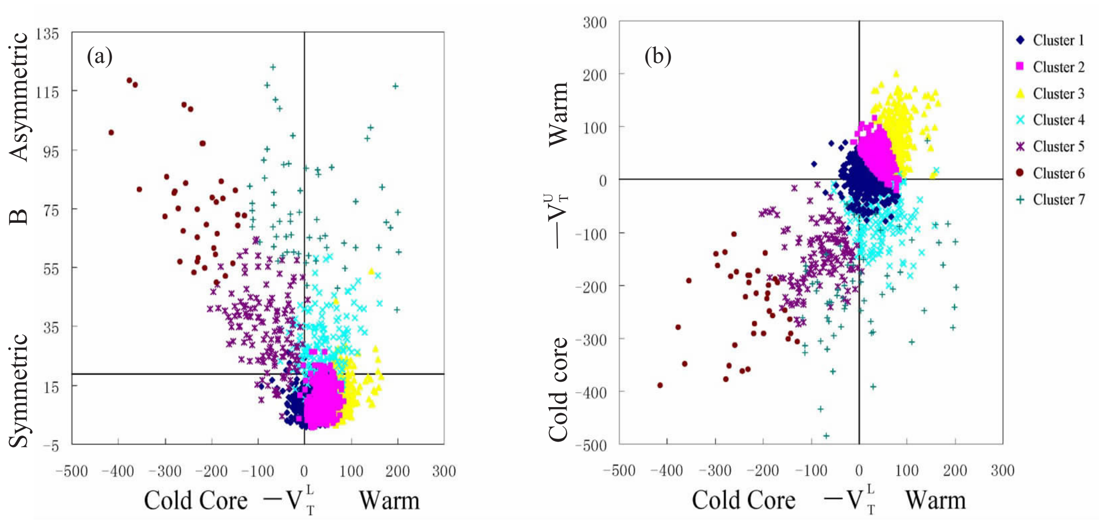

Figure 2. Scatter diagram of 2,021 CPS parameter observations by cluster analysis. a. B (in m) vs. $-V_T^L$ (in m/hPa). b. $-V_T^U$(in m/hPa) vs.$-V_T^L$. Colorful symbols represent different clusters.

Table 1. The count of observations in each cluster, the mean value of the CPS parameters and the mean center pressure of cyclones in each cluster (The corresponding standard deviation is in the bracket).

Cluster Number	Observations	B/m	$-V_T^L$ /(m/hPa)	$-V_T^U$ /(m/hPa)	Center Pressure/hPa
1	705	8.1(4.2)	15(19.7)	4.6(20.9)	989.3(16.6)
2	623	9.1(4.5)	40.2(15.2)	38.1(20.9)	971.5(22.4)
3	276	11.4(6.4)	79.3(22.5)	85.9(38.3)	954.2(18.4)
4	182	27.7(10.2)	41.5(39)	-69.6(46.9)	985.5(13)
5	137	34.5(12.6)	-80.9(47.2)	-146.5(54)	995.2(11.2)
6	37	76.3(18.1)	-232.7(66.7)	-243.3(74.7)	997.2(6.3)
7	61	75.2(17.9)	8.9(92.3)	-212.2(95)	986.4(8.6)

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Table 2. The percentage of strength grade cyclone defined by CMA-BTDS in each cluster.

Cluster Number	Weaker than Tropical Depression or Unknown	Tropical Depression	Tropical Storm	Severe Tropical Storm	Typhoon	Severe Typhoon	Super Typhoon	Transformed Cyclone
1	2.3	34.6	22.0	16.9	12.9	5.2	0.6	5.5
2	0.0	9.5	17.3	19.7	24.2	21.0	7.2	1.0
3	0.0	0.0	4.3	8.7	29.7	42.4	14.9	0.0
4	1.1	3.3	24.2	24.2	19.8	1.1	0.0	26.4
5	0.0	12.4	22.6	9.5	5.8	1.5	0.0	48.2
6	0.0	2.7	0.0	2.7	0.0	0.0	0.0	94.6
7	0.0	8.2	13.1	26.2	3.3	0.0	0.0	49.2

Table 3. The probability of transition from a cluster to others.

Cluster Number	1	2	3	4	5	6	7
1		0.696	0.012	0.190	0.070	0	0
2	0.555		0.353	0.092	0	0	0
3	0.070	0.667		0.246	0	0	0.017
4	0.228	0.015	0.015		0.424	0	0.167
5	0	0	0	0.133		0.267	0.222
6	0	0	0	0	0		0.167
7	0	0	0	0.143	0.240	0.240	

3 CLUSTER ANALYSIS OF CYCLONE STRUCTURE

3.1 *Cluster features*

According to Table 1, the 7 clusters can be divided into three categories according to their features. The first category is tropical cyclone (including cluster 1, 2, 3). This category has the characteristics as follows: cyclone intensity increases with the cluster number, $-V_T^L$ and $-V_T^U$ are positive and increase with the cluster number, the value of parameter B is small. The second category is transforming cyclone (including cluster 4, 7). This category has the characteristics as follows: the central pressure is greater than cluster 2 and 3, $-V_T^U$ is a larger negative value and $-V_T^L$ is still greater than zero, and the value of parameter B is large. The third category is transformed cyclone (including cluster 5 and 6). This category has the characteristics as follows: the central pressure increases, $-V_T^L$ and $-V_T^U$ are negative, and the value of parameter B is large.

In order to determine the ET threshold, the percentage of frequency distribution of CPS parameters in each cluster is calculated (Figure omitted). For each threshold, first of all, it must be able to distinguish between cluster 1, 2, 3 (tropical cyclone) and cluster 5, 6 (transformed cyclone). Second, it must make the proportion of clusters outside of the threshold reach a minimum. Finally, the threshold of B is determined as 19 m, and the threshold of $-V_T^L$ and $-V_T^U$ are determined as zero. According to the general evolution characteristics of cyclone structure during ET, when parameter B increases to 19 m, it can be considered that TCs start ET. When $-V_T^L$ decreases from positive value to zero, it can be considered that ET is completed. Fig.2 shows that these thresholds can distinguish the cyclone structure of the three categories well.

When transforming from TCs to extratropical cyclones, there must be a transition state, which neither belongs to TCs nor to extratropical cyclones, i.e. cluster 4 and 7. Table 2 shows that these two clusters consist mainly of tropical storm, severe tropical storm, typhoon and transformed cyclone define by CMA-BTDS. In the life cycle of 58 TCs that undergo ET in this paper, there are 52 TCs that contain cluster 4 and 7, lasting an average duration of about 28 hours and illustrating cluster 4 and 7 is a key step in ET. 93% (54/58) TCs start ET with cluster 1, 55% (32/58) TCs that undergo ET end with cluster 5 or 6, and 32% (21/58) TCs that undergo ET end with cluster 4 or 7. Ending with cluster 5 or 6 means that ET is completed, while ending with cluster 4 or 7 means ET is not completed yet. According to Table 2, 94.6% observations of cluster 6 are transformed cyclones defined by CMA-BTDS, but only 48.2% observations of cluster 5 are transformed cyclones, in addition, 22.6% and 12.4% observations of cluster 5 are tropical storms and tropical depression respectively. Fig.2 shows that in cluster 5 the characteristic of asymmetry and cold core structure of both high and low layers are weaker than that in cluster 6, so it is more likely for cluster 5 to be classified as a tropical depression or tropical storm than cluster 6.

Although each TC has its distinctive path in CPS, its structure evolution process shows certain statistical regularity. Due to the continuity of the structure evolution, in most of the time in the cyclone life cycle its structure converts to the same cluster. The transition

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probability within a cluster varies with properties of the cyclone, which is 0.77, 0.61, 0.59 with TC, transforming TC, extratropical cyclone respectively, and it also reflects the relative duration it maintains. According to the statistical direction of mutual transition between different clusters (Fig.3, see Table 3 for corresponding data), the life cycle of cyclone starts with cluster 1, i.e. weaker TC, when the warm core strengthens and central pressure drops, it converts into cluster 2, and when the warm core continues strengthen and central pressure continues to drop, it converts into cluster 3. 2/3 of cluster 3 weakens along the original path and returns to cluster 1, another 1/3 of cluster 3 converts into cluster 4 when its warm core of upper layer begins to weaken and is gradually replaced by cold core, which is earlier than with the weakening of lower layer warm core. About half of cluster 4's lower layer begins to get cold, it translates into cluster 5 when $-V_T^L < 0$. There is a part of cluster 4 that transits into cluster 1 and then weakens to disappear. When the two layers cold cores and asymmetry of cyclone in cluster 5 continue to strengthen, it transits into cluster 6. In all clusters which transit into cluster 4, cluster 3 (i.e. TCs with maximum average intensity, see Table 1 for details) accounts for the maximum ratio (46.6%), that means strong TCs are more likely to undergo ET.

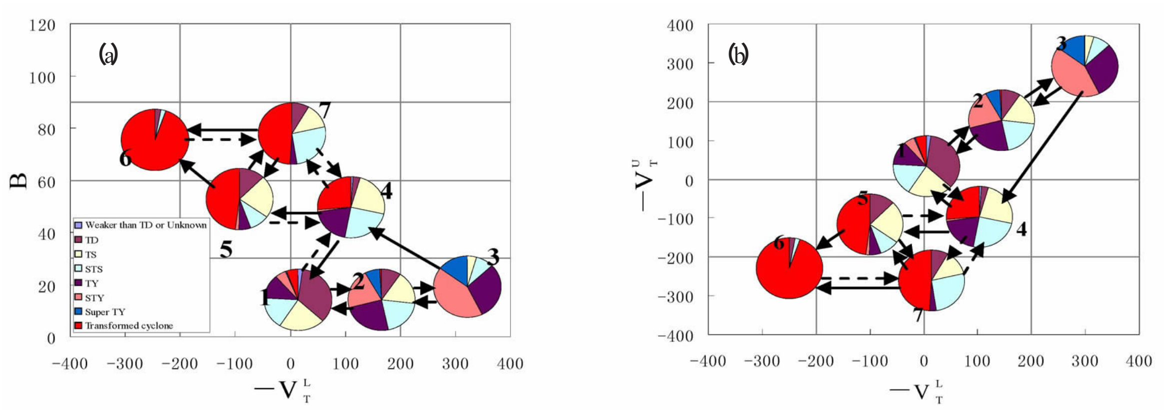

Figure 3. Statistical direction of mutual transition between different clusters. a. B (in m) vs. $-V_T^L$(in m/hPa). b. $-V_T^U$(in m/hPa) vs.$-V_T^L$. Each pie chart represents one of the seven clusters (The cluster number is shown beside the pie chart) and color sectors indicate the percentage of its containing different strength grade cyclones defined by CMA-BTDS (detail data shown in Table 2). The primary direction of cyclone evolution (the proportion more than 0.2, see Table 3) is represented by solid arrows. Secondary direction is represented by dashed arrows (the proportion more than 0.1, less than 0.2). The directions accounts for less than 0.1 are omitted.

3.2 *Case application*

According to the results of cluster analysis, the CPS path of cyclone structure which has different life cycle is analyzed and compared with that of CMA-BTDS.

3.2.1 TC TALIM (2005) WHICH DOES NOT UNDERGO ET

Tropical cyclone Talim (2005) does not undergo ET in its life cycle. From the view of its CPS path (Figure omitted), Talim always moves in a single quadrant, with $-V_T^L$ and $-V_T^U$ always greater than zero, and B always smaller than 19 m. That is, the upper and lower layers of Talim have always been in a state of warm core, and the thermal symmetry of Talim is good. The above structure characteristics are corresponding with TC that does not undergo ET. In Talim's life cycle, $-V_T^L$ increases from 16.1 to 96.1 m/hPa, $-V_T^U$ grows in fluctuations from 2.6 m/hPa to 90 m/hPa and then reduces to 2.5 m/hPa, while the value of parameter B has changed little. According to the above analysis, the intensity of Talim increases first and then decreases, without undergoing ET. According to CMA-BTDS, Talim finally weakens to become a tropical depression, corresponding with a greater-than-zero $-V_T^L$.

3.2.2 TC SUDAL (2004) WHICH COMPLETES ET

Sudal (2004), whose CPS path is shown in Fig. 4, undergoes ET and completes ET finally. When Sudal just forms, parameters B, $-V_T^U$ and $-V_T^L$ are almost zero. Since then $-V_T^U$ and $-V_T^L$ begin to increase, it indicates that the warm cores of both upper and lower layers strengthen. With central pressure dropping, Sudal strengthens and develops. After Sudal reaches its peak tropical intensity, $-V_T^U$ begins to decrease precedent of $-V_T^L$, implying warm core strength begins to decrease. During this time, the value of parameter B is always less than 19 m with little fluctuation. At 0600 UTC 15 April 2004 (as what the solid arrow points to in Fig.4a), B is greater than 19 m for the first time, indicating that Sudal begins to undergo ET. At 1800 UTC 15 April 2004 (as what the dotted arrow points to in Fig.4b),$-V_T^U$ decreases to below zero, and the upper layer warm core turns into a cold one. At 1200 UTC 16 April 2004 (as what the dashed arrow points to in Fig.4b), while $-V_T^L$ decreases to below zero, both the upper and lower layers of cyclone turn into cold core, and the ET process is completed. Afterwards the cold core continues to develop, and cyclone asymmetry gets larger. Table 4 lists the cyclone intensity grades and values of parameters B, $-V_T^L$ and $-V_T^U$ of Sudal at last

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12 points of observation time. According to Table 4, at 0600 UTC 15 April 2004, B is greater than 19 m for the first time and Sudal begins to undergo ET. At 1200 UTC 16 April 2004, $-V_T^L$ decreases to below zero and Sudal completes ET. CMA-BTDS determines that Sudal completes ET at this time too. However, in the 30 hours from the start of ET to the completion, Sudal is in a transition state between TC and extratropical cyclone.

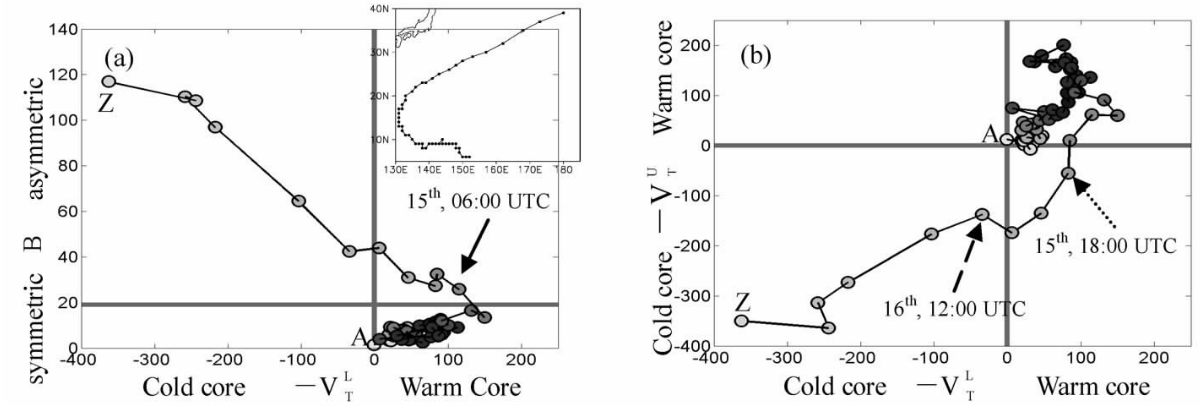

Figure 4. The CPS path diagram of TC Sudal (0018 UTC 2 April 2004 to 0018 UTC 17 April 2004). The A indicates the beginning of the plotted life cycle and the Z indicates the end. A marker is placed every 6 h. The shading of each marker indicates cyclone MSLP intensity (white, > 1,010 hPa; black, < 930 hPa). The inset at the upper right corner of Fig. 4a shows the moving track of the cyclone center.

Table 4. Cyclone intensity grade and value of parameter B, $-V_T^L$ and $-V_T^U$ of Sudal of last 12 times.

Date Time	B/m	$-V_T^L$/(m/hPa)	$-V_T^U$/(m/hPa)	Cyclone intensity grade
2004041500	13.5	149.5	60.1	TY
2004041506	25.8	115.2	61.5	STS
2004041512	32.6	84.8	10.6	STS
2004041518	27.3	82.5	-55.2	STS
2004041600	30.9	45.6	-134.9	STS
2004041606	44.0	5.8	-173.8	TS
2004041612	42.5	-34.2	-137.4	Transformed Cyclone
2004041618	64.5	-103.9	-176.8	Transformed Cyclone
2004041700	96.9	-217.3	-272.9	Transformed Cyclone
2004041706	110.3	-258.3	-313.5	Transformed Cyclone
2004041712	108.7	-243.8	-363.8	Transformed Cyclone
2004041718	117.0	-362.7	-349.7	Transformed Cyclone

4 COMPOSITE ANALYSIS OF CYCLONE ENVIRONMENT FIELD

4.1 *Environmental characteristics*

According to composite analysis of environment field of each cluster, general environmental characteristics of TCs in different stages of ET process can be obtained (Fig.5). As for cluster 1 to 3, with cluster number increasing, cyclone intensity increases, central pressure drops and warm core of upper layer strengthens. Their composite circulation situation is similar (Fig 5a). TCs are located at the southwest side of the surface subtropical high, the west of an upper subtropical high, and 25° to 15° latitude-longitude away from a northeast-southwest westerly trough. The composite analysis of cluster 4 (Fig.5b) reflects the tremendous changes while TCs move from tropical to extratropical zone. Having been embedded into the average westerly belt, TCs moved to the northwest side of the subtropical high. Because of the interaction of TC and westerly trough, the upper-level closed low pressure circulation turns into a short wave, the symmetry is beginning to collapse. The geopotential height of cyclone center on 900 hPa strengthens obviously, the cold air of the westerly belt invades the northwest side of the cyclone, and isotherm crosses geopotential height line at both east and west of the cyclone, there appears baroclinicity which is an important symbol of ET (Klein et al.[7]).

The cluster 5 and 6 represent TCs that have completed ET. Their circulation situation is similar. The upper-level short wave of the cyclone merges into the westerly trough. The cyclone of lower layer is in front of the upper trough and in the back of the upper ridge. Baroclinicity of lower layer increases obviously showing the characteristics of a frontal cyclone, and the intensity

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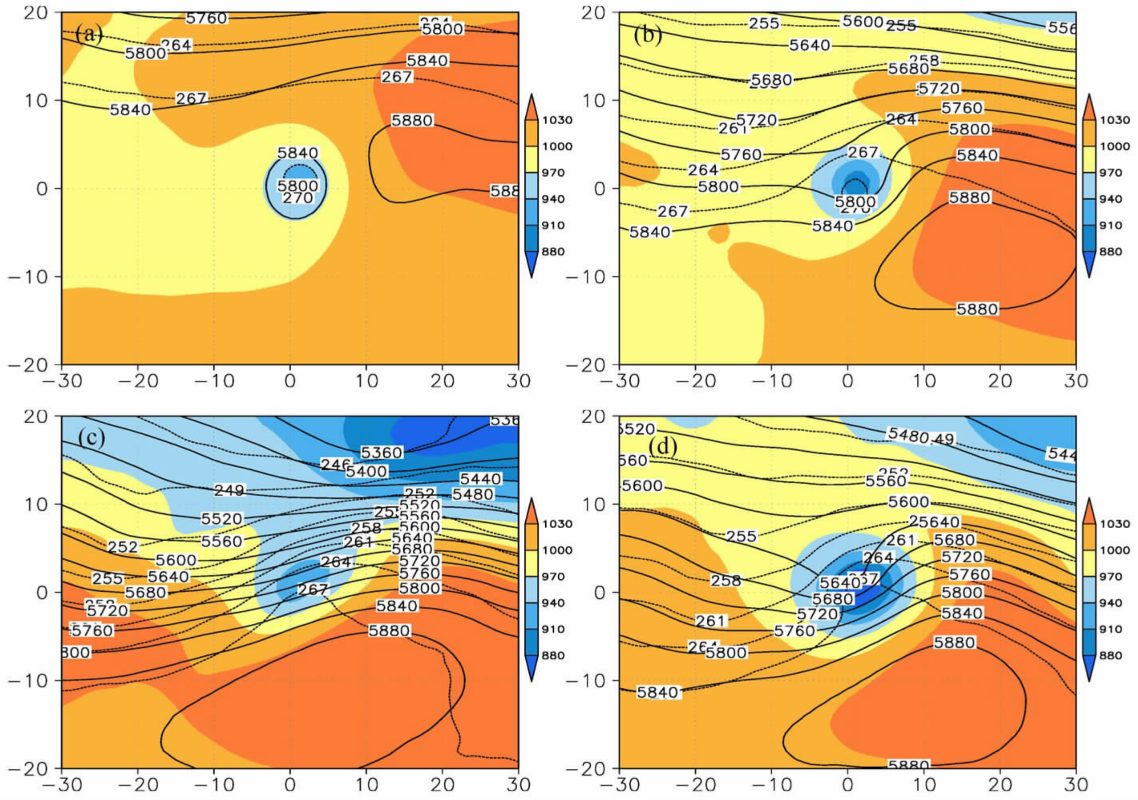

Figure 5. Composite fields of each cluster. Geopotential height on 900 hPa (colorful shaded, in gpm), geopotential height (solid line, in gpm) and temperature (dashed line, in K) on 500 hPa. a. Cluster 2; b. Cluster 4; c. Cluster 6; d. Cluster 7. Vertical (horizontal) coordinate represents latitude (longitude) distance in °. The origin of coordinates (0, 0) is the center of composite cyclone.

of cyclone in the two clusters remains unchanged. The difference between cluster 5 and 6 is as follows: the north area of the cyclone for the former is a broad low pressure area, but for the latter the low pressure in the northeast of the cyclone turns to be the main low pressure system in the mid-latitude, similar to the northwest pattern proposed by Harr and Elsberry[2, 10]. This indicates that the transformed cyclone cannot strengthen, corresponding with the cyclone path in Fig. 3. Cluster 7 is converted from cluster 4, 5 and 6, i.e. cluster 7 is the result of ET or post-ET. In its composite image (Fig. 5d), the upper-level environment is similar with those of cluster 5 and 6, but the geopotential height at the low-level cyclone center is lower, and the angel between the cold front and the warm front is smaller. This means cluster 7 represents transforming cyclone or strengthening extratropical cyclone. The common cyclone structure of cluster 7 has such features as cold core in the upper layer and warm core in lower level, as shown in Table 1. Except from TC experiencing ET (cluster 4 to cluster 7), this cluster mainly converts from the extratropical cyclone having finished ET process (cluster 5 and 6 to cluster 7). The result shows that, if the extratropical cyclone can sustain for a certain period, it will keep transforming, the lower level cold core structure will transform to warm core. It can be inferred that the diabatic effect assists the transforming or transformed cyclone keep or generate warm core in the lower layer since the cyclone is primarily located on the ocean with rich moisture (refer to Fig.1). Thereby a mixed cyclone structure is formed.

4.2 *Physical characteristics during cluster conversion*

According to the cluster analysis and cyclone structure path in CPS, we can propose two important questions about ET: under what condition does the ET happen? Under what condition does the ET complete? The comparison analysis on Cluster 3 to Cluster 2 and Cluster 3 to Cluster 4 can explain the first question. The former one represents the depression of TC. The later one indicates that the TC undergoes ET. As for the second question, the transformation from Cluster 4 to Cluster 1 and Cluster 4 to Cluster 5 can be used as combined analysis. The former one represents the TC undergo ET but it weakens and does not complete ET. The later one shows the cyclone completes ET and transforms into an extratropical cyclone. The composite analysis is as follows.

4.2.1 CONDITIONS FOR START OF ET

From Fig.6a and 6b, we can find that the environment fields for determining whether ET of TC will commence are very different. In the west north area of TC which will undergo ET, PV has evident gradient, and extends along the lower latitude area in the west. However, the north area of TC which will prefer to

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weaken rather than undergo ET only has PV gradients along the latitude, that is, there is no obvious PV anomaly to the west. In the lower troposphere, to the northwest, especially to the north, of TC that is going to undergo ET, there are dense isothermal lines. However the environment isothermal lines of TC that is going to weaken are very sparse, implying there is no evident baroclinic zone. Correspondently, the divergence around the cyclone has obvious difference between the two situations. In the lower level of the troposphere, there only is isolated convergence zone around the TC going to weaken. As for the TC going to undergo ET the convergence in cyclone area increases due to superposing the convergence in the baroclinic zone. The tropical wind shear over the tropical cyclone going to weaken is about 10–20 m/s, as shown in Fig.6c. At the time, although the cyclone is still on the sea above 300 K, the overlarge wind shear will destroy tropical cyclone structure, resulting in the reduction of cyclone intensity. The vertical wind shear over the TC going to undergo ET is much larger, which can reach 20 m/s. The maximum of vertical wind shear to the north is corresponding to the upper-level jet, which is related to a baroclinic frontal zone. At this point, the cyclone has moved to colder ocean, and the surface temperature has obvious gradients. This indicates that although the tropical cyclone going to undergo ET encounters colder ocean and much larger vertical wind shear, it survives till the ET, for the interaction with baroclinic zone, which means the energy supply in transforming, is changed (Chen and Ding[6]; Zhu et al.[28]).

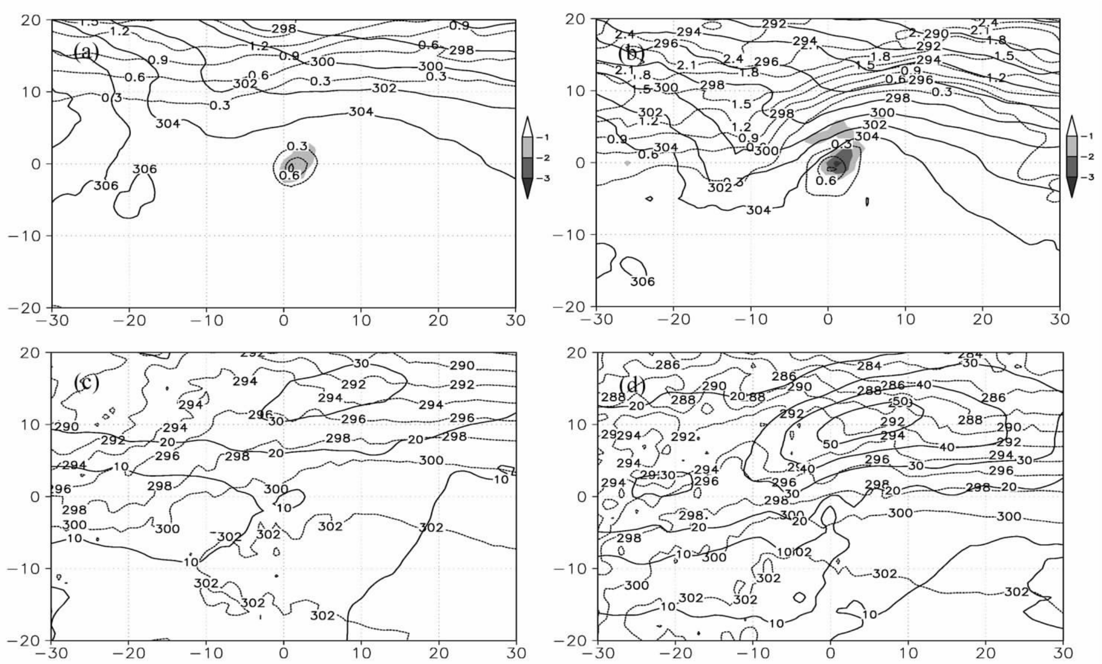

Figure 6. Environment field comparison of whether TC undergoes ET. a to b are PV distribution on 345 K potential temperature surface (dashed line, interval 0.3 PVU) , potential temperature (solid line, interval 2 K) and divergence (shaded, in 10^{-5} s^{-1}, show only less than -1.0) on 850 hPa; c to d are surface temperature (dashed line, in K) and the vertical shear of horizontal wind ($\Delta V_{200hPa-850hPa}$, solid line, in m/s). a and c are cluster 3 observations that convert into cluster 2; b and d are cluster 3 observations that convert into cluster 4. Coordinate description as in Fig.5.

4.2.2 COMPARATIVE ANALYSIS FOR COMPLETION OF ET

Although the transforming TCs are already in average westerly wind belt (Fig.7a and 7b), the environments for not completing or completing ET are significantly different. The former is basically zonal and the west of cyclone does not show distinct PV gradient, which is against the development of cyclone. The latter is obviously longitudinal and the west of cyclone shows distinct PV gradients. The lower tropospheric layer for the former is cooler in the west-north area, warmer in east-south area, but the potential temperature gradient is very small, there just exists a weak warm front in the north-east of the cyclone, corresponding to a north-extending weak convergence zone. As for the latter, an obvious baroclinic zone moves to the central area of cyclone, interacting with higher-level positive potential vorticity anomaly, which is conducive to the further development of lower-layer baroclinic cyclone. The convergence zone of front and cyclone emerge into an obvious convergence center. The diabatic heating from water vapor to cyclone is conducive to the maintenance and development of the cyclone. The transforming cyclone not completing ET is isolated from the water vapor channel nearby (Fig.7c). While for the transforming cyclone completing the ET there maintains a water vapor transport channel from the easterly wind zone southeast of the subtropical high (Fig.7d).

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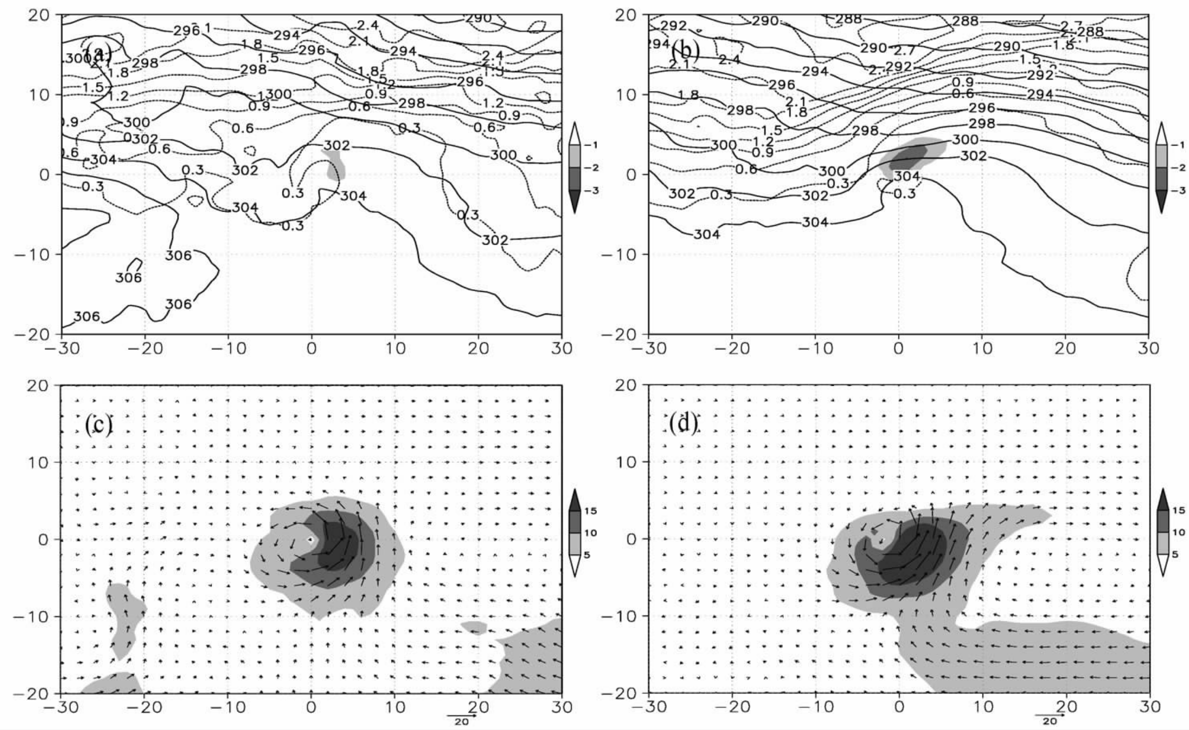

Figure 7. Environment field comparison of whether transforming TC can complete ET. a to b are PV distribution on 345 K potential temperature surface (dashed line, interval 0.3 PVU), potential temperature (solid line, interval 2 K) and divergence (shaded, in 10^{-5} s^{-1} , show only less than -1.0) on 850 hPa; c to d are the value (shaded) and vector of water vapor flux (in g/(cm·hPa·s)) on 850 hPa. a and c are cluster 4 observations that convert into cluster 1; b and d are cluster 4 observations that convert into cluster 5. Coordinate description as in Fig.5.

5 CONCLUSIONS AND DISCUSSION

2,021 CPS parameter observations (at 6-hour intervals) of 58 extratropical transition (ET) cases over the western North Pacific are analyzed using cluster analysis method. They are divided into seven clusters, each representing different transforming stage of the TCs. Based on the cyclone structure, the seven clusters are divided into three categories: (1) tropical cyclone, with symmetrical thermal structure and warm core in both upper and lower layers; (2) extratropical cyclone, with asymmetric thermal structure and cold core in both upper and lower layer; (3) transforming cyclone, with asymmetric thermal structure, cold core in upper layer and warm core in lower layer. ET lasts an average duration of about 28 hours. During this time the transforming cyclone is often operationally declared as TC or extratropical cyclone.

Strong TC is more likely to undergo ET. ET often begins with cyclone thermal asymmetry increase, then continues with the emergence and strengthening of cold core structure of upper layer, completes with emergence of cold core structure of lower layer. The detail analysis of cases shows that the development of thermal asymmetric structure and the emergence of lower level cold core structure are helpful on judging the start and end of ET respectively. Based on this method, adding ‘transforming stage’ to the life cycle of TC may be more in line with the facts.

Although the evolution of ET is a continuing process, cluster analysis can identify the staged change of cyclone structure. Transformation from one cluster to another means major changes in the thermal symmetry and thermal wind structure of TC. These changes are associated with the environment fields around the TC. TC is independent of westerly wind belt system at the start and then it gradually embeds in when moving northward. Under the influence of mid-latitude baroclinic system, TC transforms into extratropical cyclone finally. As for the TC that undergoes and completes ET, there are obvious potential vorticity gradient on its north-west side, and obvious water vapor transport channel in its surrounding environment.

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Citation: WEI Guo-fei, ZHU Pei-jun, JIANG Jia et al. Analysis of structure evolution and environmental conditions of tropical cyclones over the western North Pacific during extratropical transition [J]. J Trop Meteorol, 2017, 23(1): 15-24.

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