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COMPARISON OF THE STRUCTURAL CHARACTERISTICS OF DEVELOPED VERSUS UNDEVELOPED MID-LEVEL VORTEXES

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Abstract: Using the NCEP 1 °×1 ° reanalysis data, several obvious differences of the structural characteristics of developed versus undeveloped mid-level vortexes are studied. First, the central vorticity of the developed mid-level vortex increases towards higher levels while the undeveloped one decreases. The low-level convergence structure maintains well in the developed mid-level vortex whereas the undeveloped one does badly. Second, on the one hand, according to the symmetric analysis, the horizontal wind field and wind vertical section of the developed mid-level vortex are well symmetric while those of the undeveloped one are less symmetric. Meanwhile, weak wind vertical shear help the developed mid-level vortex to establish a warm core in upper- and mid-levels of the troposphere. On the other hand, according to the balance analysis, better balance between wind and pressure is shown in the mid- and lower-levels of the troposphere of the developed mid-level vortex than in those of the undeveloped vortex. Third, positive anomaly of potential vorticity is enhanced and developed in the vertical direction of the developed vortex. However, the undeveloped vortex weakens with a weak positive anomaly.

Key words: South China Sea area; tropical cyclone; genesis and development; mid-level vortex; structural characteristics

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1 INTRODUCTION

The genesis and development of tropical cyclones (TCs) are one of the most complicated issues in TC research[1, 2]. As shown in San and Costa[3], initial disturbances usually evolve into the TC through two ways, either "bottom-up" or "top-down". The "bottom up" pattern occurs with the TC, whose initial disturbance shows maximum amplitude of vorticity on the surface, develops upward and possesses a warm core through the mechanisms of Ekman-pumping or Wind-Induced Surface Heat Exchange (WISHE)[4]. The "top-down" pattern is typical of TC genesis in which a vortex develops downward after forming at the mid- and higher-troposphere[5, 6].

Mid-level vortexes are formed in a number of ways, the most common of which is the one resulting from the interactions between mesoscale convective systems from local stratiform[5, 7, 8]. Besides, convective condensation can also trigger mid-level cyclonic vortexes[9]. As shown in a recent study[10], significant differences exist between the TCs forming in the western North Pacific and those in the South China Sea (SCS) and their ambient surroundings. The initial disturbance and structure of the SCS TCs are also different from those of the western North Pacific, particularly in that low-latitude cold vortexes, baroclinic disturbances and Southwest Monsoon disturbances take up more than 1/3 of all disturbances, which is much higher than that of the western North Pacific, in addition to the fact that they generally originate from the SCS and the land bordering on it[11, 12]. As shown in observational facts, the SCS monsoon depression is structured like a mid-level vortex with the maximum cyclonic vorticity near 700 hPa and a cold core below 850 hPa[13]. Besides, such a cold core is usually typical of the initial vortex, which precedes the TC triggered in low-latitudes by upper-level cold

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vortexes or troughs that have been truncated from the westerly trough there[11]. Generally speaking, the TC generated through the triggering mechanism of a low-latitude mid-level vortex takes up considerable ratio in the SCS region.

Using composite sounding data, Mcbride et al.[14] studied the structural characteristics of developed and undeveloped TCs over the northwestern Pacific and Atlantic. As for their counterparts in the SCS, studies and discussions were conducted previously from different points of view. Liang et al.[15] used composite data to study, both dynamically and thermodynamically, the developed and undeveloped depressions in the SCS. Li et al.[16] simulated developed and undeveloped cases using numerical models and gridpoint data from the European Center for Medium-Range Weather Forecast. Focusing on energy budgets, Zhang et al.[17] examined how energy is converted in both developed and undeveloped cases of SCS depressions.

Triggering mid-level low-latitude vortexes to form TCs in the SCS, the initial disturbance generally comes from the SCS and its adjacent land and usually covers a small area. In forecasting practice, it is difficult to decide whether it will further develop into a TC. Based on the previous work on determination of mid-level vortexes in the SCS region, this work selects a number of typical, representative cases to compare the structural characteristics of developed and undeveloped mid-level vortexes, such as the wind, vorticity, divergence fields, the symmetry and equilibrium, and the evolution of potential vorticity. In a word, this work tries to deepen the understanding of the structure of mid-level vortexes that generate and develop in the SCS.

2 DATA AND CASES

2.1 *Data*

The data used in this work are the 1 °×1 ° reanalysis at intervals of six hours from the National Centers for Environmental Prediction (NCEP, USA), which covers a horizontal area of the SCS and the adjacent area (95-140°E, 5°S-30°N). For the TCs, their data are primarily from the TC best tracks compiled by China Meteorological Administration, which are supplemented for undeveloped tropical depressions by two other datasets from the Joint Typhoon Warning Center at Guam and Regional Specialized Meteorological Center Tokyo - Typhoon Center.

2.2 *Cases compared*

To study the structures of the developed and undeveloped mid-level vortexes, this work selects eight cases, four for either type. By definition, the undeveloped vortex is the one that does not develop into a TC at all. To shed light on the differences between the two types of vortex, this work selects some specific time points on top of 17 moments of the NCEP data around the genesis of tropical storms following the principles presented below. For the developed mid-level vortex, the temporal point for study was set at the hour right before the maximum central wind speed strengthened to a tropical storm; for the undeveloped vortex, it was set at the hour at which the maximum central wind speed began to decrease. For details of the vortexes and temporal points selected, see Table 1. The time in this study observes the Coordinated Universal Time (UTC).

Table 1. Comparisons of developed with undeveloped cases of mid-level vortexes.

Developed vortexes		
Cyclone code	Duration studied	Time focused
0103	01062700—01070100	01063000
0220	02092100—02092500	02092418
0508	05072512—05072912	05072906
0601	06062312—06062712	06062618
Non-developed vortexes		
Cyclone code	Duration studied	Time focused
9938	99121212—99121612	99121518
0431	04051312—04051712	04051612
0632	06082112—06082512	06082418
0732	07080100—07080500	07080406

Notes: The codes for the undeveloped 9938, 0431, 0632 and 0732 are assigned by the authors.

It is shown in the 850-hPa moving tracks of the compared vortex centers at the time of study (Figure 1) that the eight vortexes are representative to some extent since they all generate and develop over the northern, central and southern parts of the SCS. Next, these developed and undeveloped cases will be based to perform composite analysis and compare typical cases. It should be noted here that (1) the SST for the ambient waters of the eight vortexes studied is all at or above 28°C, as shown in the study of the NCEP reanalysis for the marine areas over which the two groups of vortex travel, (2) the lower levels (below 700 hPa) are unstable stratification during the genesis and development stages of the two groups of vortex, as shown in the study of the stability (θ_{se}) at the vortex centers (in area mean within a range of ± 4 °), and (3) the lower levels of vortex centers have the right conditions of humidity (with relative humidity larger than 80%, figure omitted). All of these analyses show that warm ocean surface, unstable stratification at lower levels and appropriate moisture conditions are conducive for the genesis and development of mid-level vortexes in the SCS.

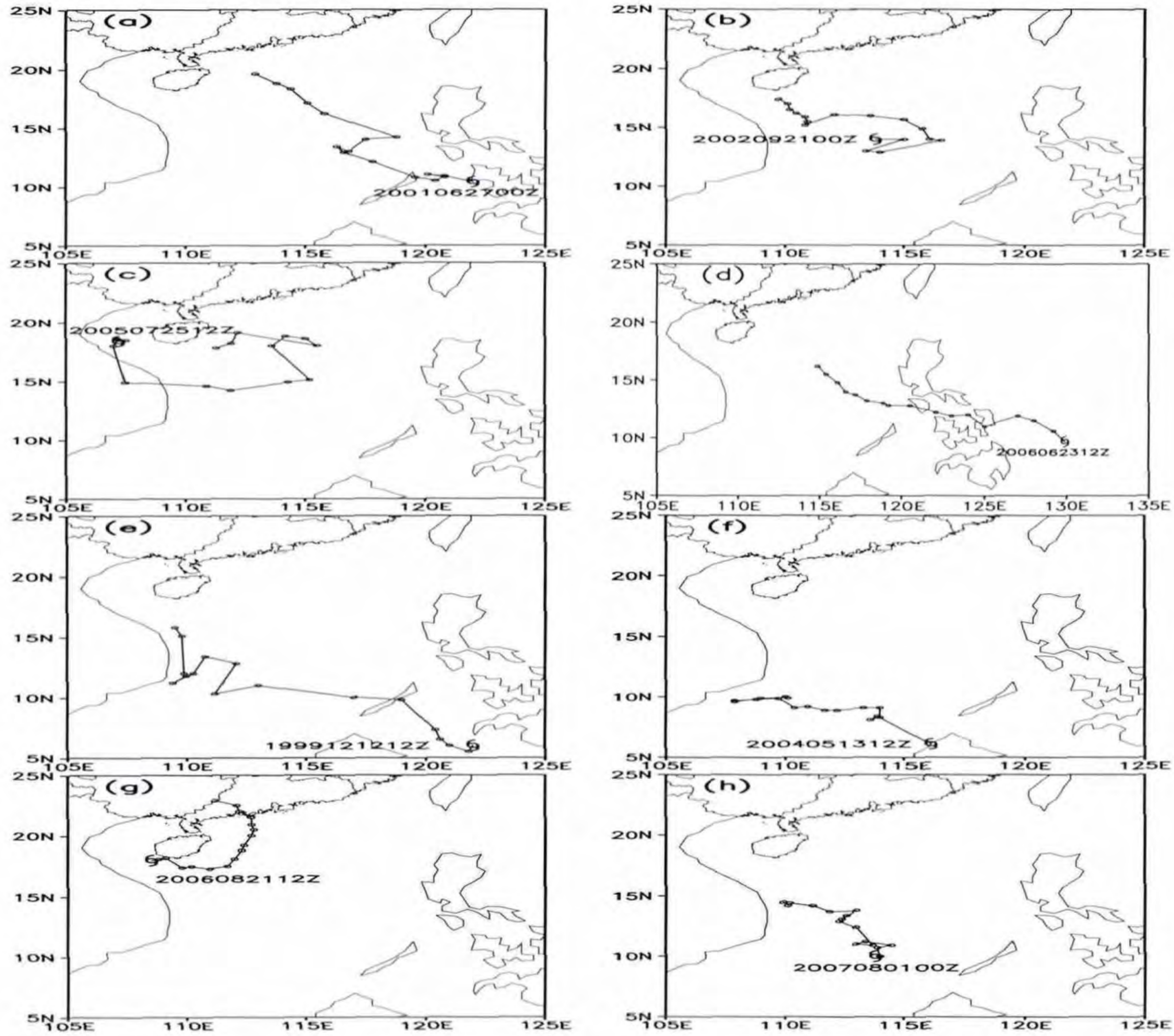


Figure 1. Tracks of movement for the centers of eight vortexes at the level of 850 hPa. (a) to (d): developed vortexes: (e) to (h): undeveloped vortexes. The TC symbol and time are for the initial location and time of the TC.

3 STRUCTURES OF THE DEVELOPED AND UNDEVELOPED VORTEXES

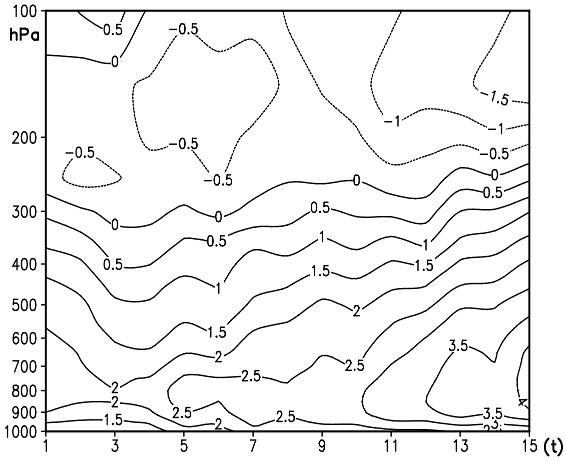
3.1 *Vorticity and divergence field of the center of the mid-level vortexes*

During the formation of the TC being triggered by mid-level vortexes over the SCS, the cyclonic vorticity at the center should be growing constantly. Meanwhile, the basic ambient flow field around the center should also be conducive to the development of cyclonic vorticity. Generally, such vorticity should develop both upwards and downwards while intensifying, during which a large amount of moist airflow flows in from low-level vortex centers. As the airflow converges and ascends, heat is being transported from above the sea surface to the atmosphere. Correspondingly, upper levels should have an anti-cyclonic field to allocate both the upper- and lower-flow fields to keep sending to the upper levels energy (i.e., water vapor and heat) obtained from the sea surface and lower levels[18]. To learn about the temporal variation of the central vorticity and divergence of the mid-level vortex, Figs. 2 and 3 give the composite vertical distribution (averages within a range of ± 4 °) of the above characteristics in the developed and undeveloped vortexes (t=13 is a specified point of time). At the last few points of time in the time series of vorticity (Figure 2), the central vorticity in the developed case increases gradually and develops towards both the upper and lower levels simultaneously, but it decreases in the undeveloped case and does not develop upwards. Similarly, at the last few points of time of divergence (Figure 3), low-level convergence in the developed case intensifies gradually with expanding areas of convergence and ascending motion, but it decreases in the undeveloped case with shrinking areas of convergence and ascending motion, suggesting the filling-up of its mid-level and the reduction of convergence and ascending motion at the lower level, thus unfavorable for sustained development of the vortex.

3.2 *Symmetry and equilibrium*

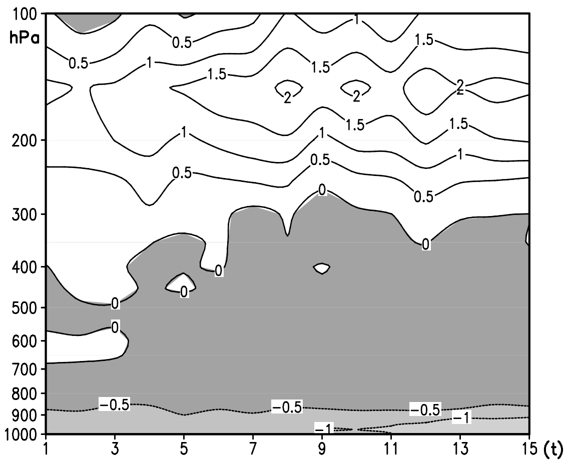
3.2.1 SYMMETRY

Being symmetric and equilibratory is not only typical of TC's structure but also two prerequisites for its strengthening. If the symmetry and equilibrium are compromised, the TC will weaken and dissipate[19, 20]. Fig. 4 gives the 850-hPa horizontal wind field for specific points of time of the two types of vortex. It shows that the wind field of a developed vortex is usually symmetrically cyclonic (Fig. 4a to 4d) while that of an undeveloped one varies (Fig. 4e to 4h): Vortexes 9938, 0431 and 0632 are well asymmetric, while Vortex 0732 is symmetric, in the horizontal structure. It suggests that it is not sufficient to analyze the structure of the low-level horizontal wind field alone for determination whether or not a vortex is likely to generate and develop.



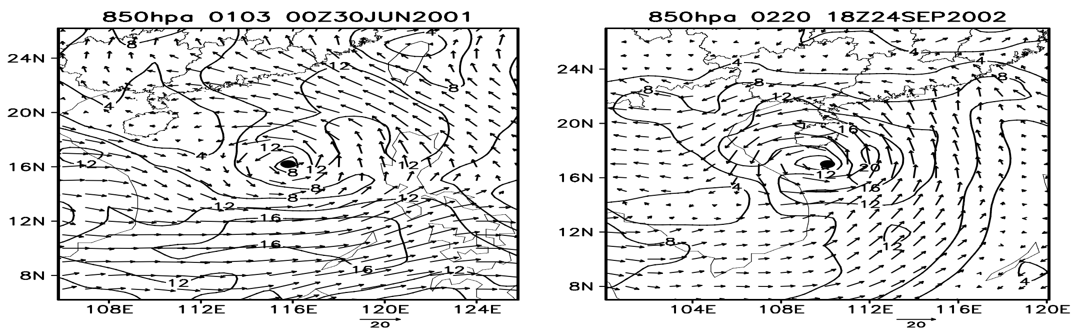
(a) Developed vortex (b) Undeveloped vortex

Figure 2. Composite evolution of the vorticity. The vortex center is within a range of ±4 °. Units: 10^{-5} s^{-1}.



(a) Developed vortex (b) Undeveloped vortex

Figure 3. Composite evolution of the divergence. The vortex center is within a range of ±4 °. Units: 10^{-5} s^{-1}. Positive values are for the divergence and negative values the convergence with the shades standing for the area of convergence.



(a) 0103 (b) 0220

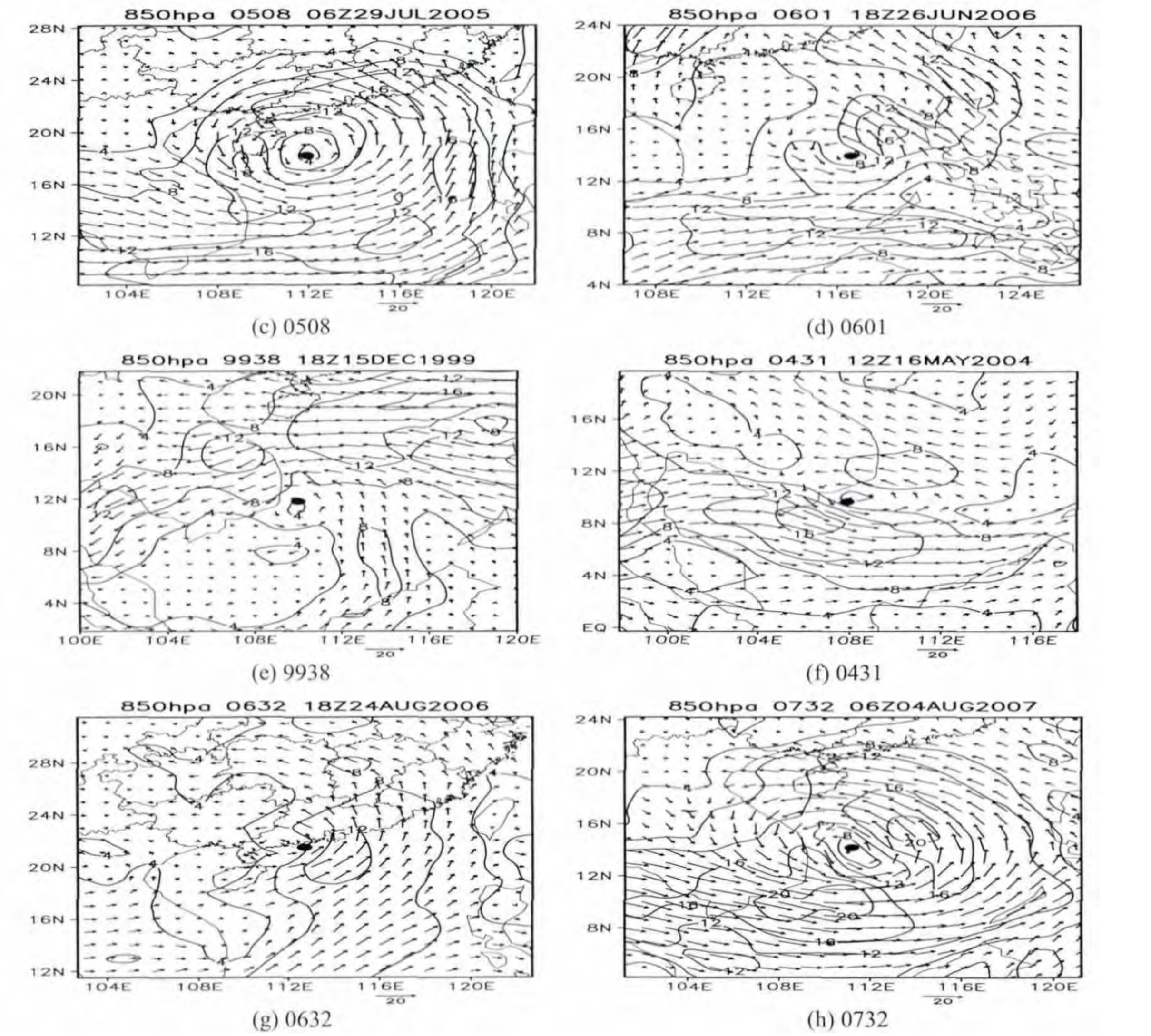


Figure 4. Horizontal wind field at 850 hPa. Contours are the wind speed and the vortex center (the solid dot) is within a range of ±10 °; Units: m/s.

Latitudinal or longitudinal cross sections of the *u* and *v* components of wind speed can help study the structure of the vertical wind field of a mid-level vortex (within a range of ±8 °). Fig. 5 compares the latitudinal cross section of the *v* component between Case 0508 and Case 0632. At the middle and lower levels (below 500 hPa), the vertical wind field is basically symmetric in the former case, favorable for the sustained development of the vortex, while being much asymmetric in the latter case, unfavorable for the sustained development of the vortex. Besides, vortexes with symmetric horizontal wind fields are also relatively symmetric in the vertical wind field, as shown in the comparison of the eight cases (figure omitted).

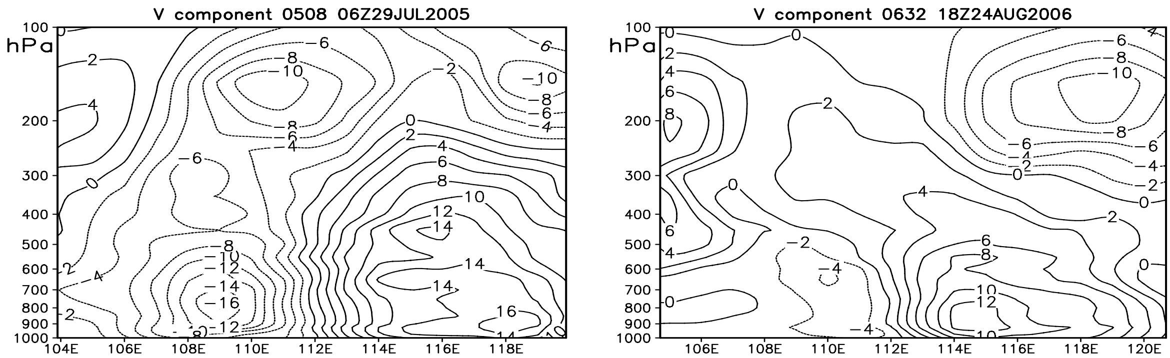


Figure 5. Comparisons of the *v* component of wind speed between Case 0508 and Case 0632. The vortex center (solid dot) is within a range of ±8 °; Units: m/s.

The fields of vertical shear of the *u* and *v* components of wind speed are also commonly used methods in determining whether a cyclone will generate and develop[14, 15]. Weak vertical shear of wind speed is a necessary condition for the eye to form. For definition of wind shear, we have

$$V\,\text{shear}=\sqrt{(U_{200}-U_{850})^2+(V_{200}-V_{850})^2} \quad (1)$$

With Eq. (1), the temporal evolution of wind shear ±5 ° around the vortex center is determined (Fig. 6, *t*=13 is a specific point of time). It is found that the wind shear is always smaller with the center of a developed vortex than with an undeveloped one, especially at a few points of time prior to the specific point of time.

By examining both the developed and undeveloped vortex for specific points of time (Fig. 7), this study discovers that the vertical wind shear of the developed vortex is smaller than that of the undeveloped one. Gray[21] pointed out that the vertical shear of tropospheric wind speed represents the conditions of ventilation around the disturbance and weak vertical shear concentrates the heat in the middle- and upper-troposphere created by cumulus so that a well-defined warm core is formed at these levels, conducive to the genesis and development of the cyclone. It is shown in Fig. 8. The figure gives the composites of anomalous temperature evolution of the enter of a developed vortex. In contrast, the warm core of the undeveloped vortex is in the middle- and lower-troposphere and keeps decreasing.

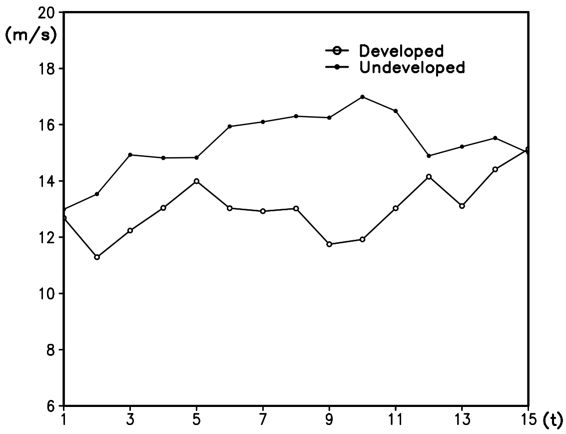
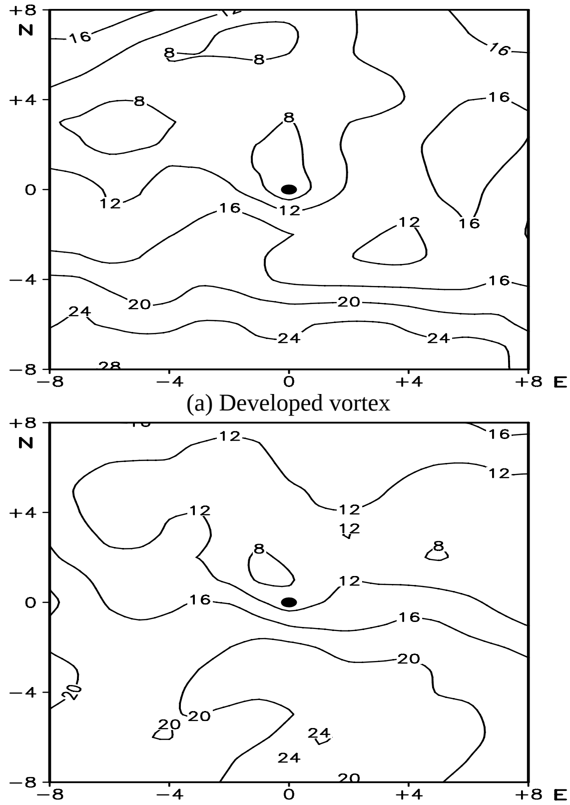


Figure 6. Comparisons of the evolution of vertical shear of wind speed for the developed and undeveloped vortexes. The vortex center is within a range of ±5 ° and the unit is m/s.



(a) Developed vortex

(b) Undeveloped vortex

Figure 7. Comparisons of the composites of vertical shear fields of wind speed at specific points of time. The vortex center is within a range of ±8 ° and the unit is m/s.

3.2.2 Equilibrium

The following equation is used to analyze the equilibrium of TCs at low latitudes

$$\begin{cases} u\dfrac{\partial u}{\partial x}+v\dfrac{\partial u}{\partial y}+\omega\dfrac{\partial u}{\partial p}-fv=-\dfrac{\partial \phi}{\partial x} \\ u\dfrac{\partial v}{\partial x}+v\dfrac{\partial v}{\partial y}+\omega\dfrac{\partial v}{\partial p}+fu=-\dfrac{\partial \phi}{\partial y} \end{cases} \quad (2)$$

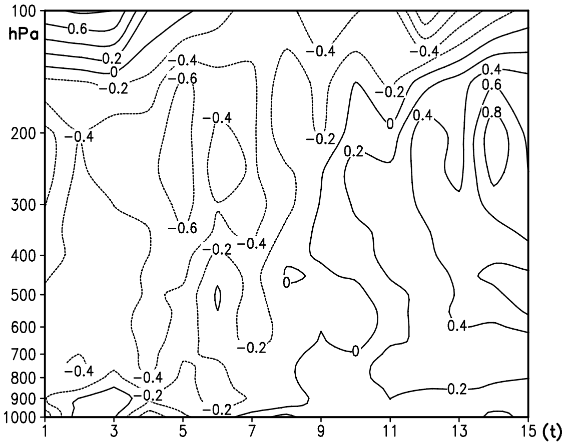
Make the left-hand side (l.h.s.) of the upper expression of Eq. (2) equal to A_1 and the right-hand side (r.h.s.) equal to B_1, and denote the l.h.s. of the lower expression of Eq. (2) as A_2 and the r.h.s. as B_2. At the same time, let

$$\delta_{i,j}=(A_1-B_1)^2+(A_2-B_2)^2 \quad (3)$$

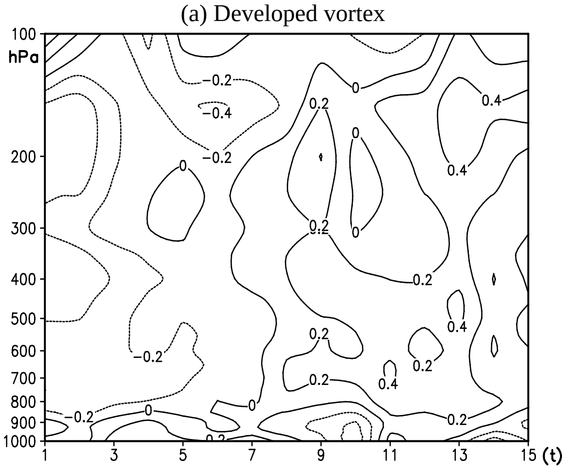
and define a standardized factor for equilibrium as in

$$C=\frac{\sum_{i,j}\delta_{i,j}}{\sum_{i,j} f\sqrt{(u^2+v^2)}} \quad (4)$$

Here, Eq. (4) is used to study the equilibrium of the mid-level vortex by taking the center of the vortex at (*i*=0, *j*=0) with (*i*, *j*=±4). From comparison and analysis of the equilibrium of composites of the developed and undeveloped vortexes (Fig. 9), it is known that the value of C is all relatively small on all levels of the mid- and lower-troposphere, suggesting good wind-pressure equilibrium in the developed vortex at these levels (In the case of an axisymmetric vortex, Eq. (2) denotes the equilibrium of the gradient wind). It implies that once the diabatic heating—associated with the vortex—occurs, the wind field will adjust itself immediately to balance the changes in the thermodynamic field so as to increase the kinetic energy, making the vortex develop rapidly. At the mid- and lower-troposphere, however, the absence of appropriate dynamic constrains for equilibrium and relatively inefficient wind-field response to diabatic heating prevent the undeveloped vortex from evolving into a TC.



(a) Developed vortex



(b) Undeveloped vortex

Figure 8. Composites of anomalous evolution of temperature of vortex centers. The vortex center is within a range of ±4 ° and the unit is K.

3.3 *Evolution of potential vorticity*

Potential vorticity is a physical quantity that combines thermodynamic and dynamic action, often used to diagnose the genesis and development of cyclones[22-24]. Though inappropriate in studying the fine structure of a vortex within the eyewall, the NCEP 1°×1° reanalysis data are sufficient for examining its anomalous distribution against the background. When a TC is developed on an isotopic plane, a positive anomalous vortex appears over the eye in the large-scale vertical background field. While enhancing constantly, the vortex is developed towards upper levels and shrinking horizontally at the same time[25, 26].

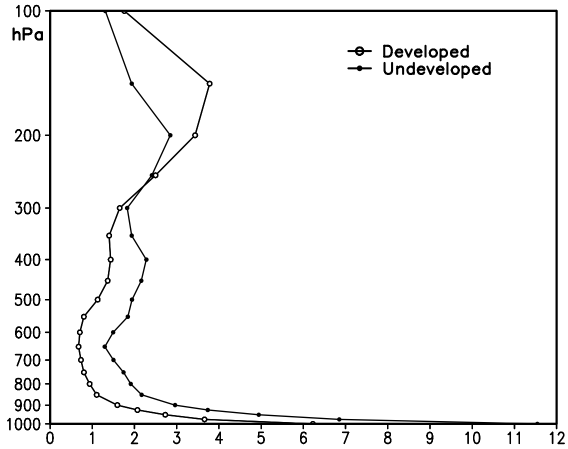


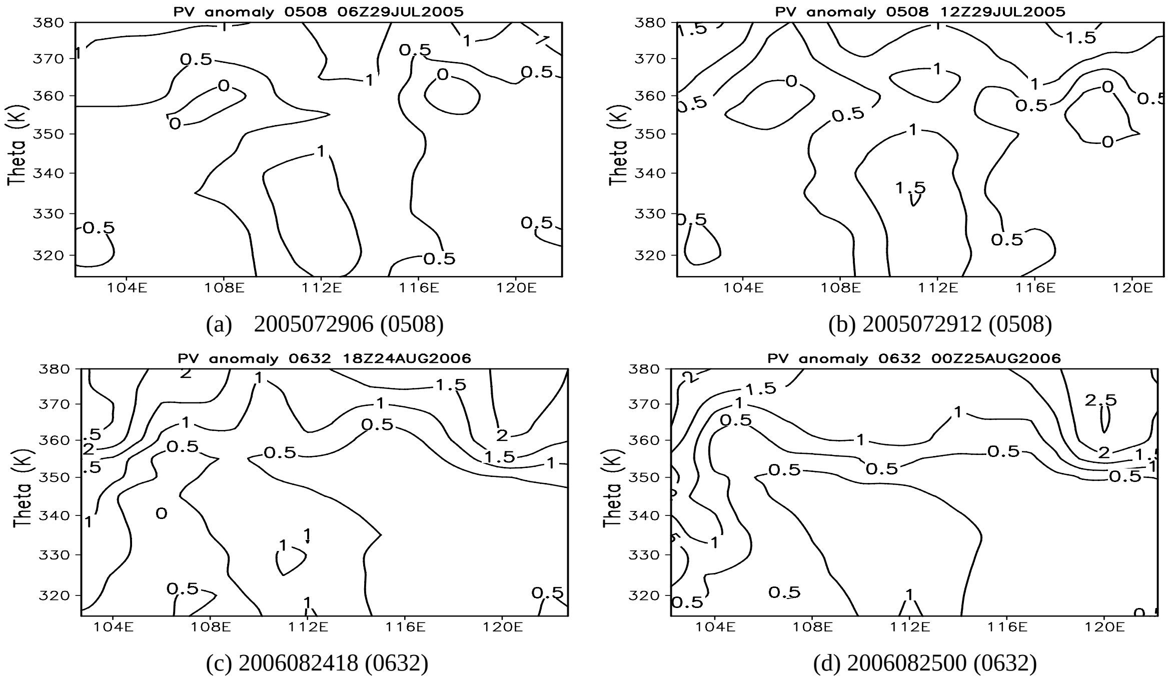
Figure 9. Comparisons of equilibrium between the developed and undeveloped vortexes. The abscissa is for the value of C multiplied by 10^{-4}.

Under the *p*-coordinates, an expression for dry potential vorticity is presented below that has ignored the horizontal variation of ω (vertical velocity),

$$PV \approx -g(\xi + f)\frac{\partial \theta}{\partial p} + g(\frac{\partial v}{\partial p}\frac{\partial \theta}{\partial x} - \frac{\partial u}{\partial p}\frac{\partial \theta}{\partial y}) \quad (5)$$

where g is the gravitational acceleration, ζ the vorticity, f the geostrophic vorticity, θ the potential temperature and p the pressure.

Figure 10 gives the comparison and analysis of anomalous evolution of potential vorticity on the zonal cross section through the centers (with accuracy of location at ±10 °) of two cases (0508 and 0632) for a specified point of time and the one right after it. From the comparison of Fig. 10a and 10b, which shows the evolution of positive potential vorticity at the middle and lower levels of the troposphere for the two points of time, we noted substantial upward development of the developed vortex 0508 while enhancing, a sign that it is growing persistently. In contrast, the positive vorticity anomalies in the undeveloped vortex 0632 are weakening while remaining where they have been and even breaking up, suggesting that it has reduced gradually and tends to dissipate (Fig. 10c and 10d).



(a) 2005072906 (0508) (b) 2005072912 (0508)

(c) 2006082418 (0632) (d) 2006082500 (0632)

Figure 10. Comparisons of anomalous evolution of potential vorticity through the zonal cross sections of vortexes 0508 (a, b) and 0632 (c, d). The centers of the vortexes are ±10° in accuracy. Units: PVU, where 1 PVU=10^{-6} m^2·K/(s·kg).

4 CONCLUSIONS AND DISCUSSION

(1) For a developed mid-level vortex, the central vorticity is increasing gradually while developing towards both the upper level and lower level; for an undeveloped mid-level vortex, the central vorticity is decreasing gradually and does not develop to upper levels. Likewise, the lower-level convergence, which maintains and keeps developing to upper levels, allocates well with the upper-level divergence. In contrast, undeveloped vortexes tend to weaken at the lower level and a convergence center appears at the middle and lower level, making it unlikely for the vortex to develop.

(2) As shown in our study on symmetry, the horizontal wind field and the vertical cross section of the wind speed are well symmetric in the developed mid-level vortex while showing poor symmetry in most of the undeveloped vortexes. As shown in the shear analysis, the wind shear is always smaller at the center of the developed vortex than that of the undeveloped one, especially so for the few points of time around a specific point of time. Weak wind vertical shear helps a warm core to establish and intensify gradually at the middle and upper level of the developed vortex while the warm core of an undeveloped vortex is located at the middle and lower level of the troposphere and weakens gradually. As shown in our analysis of equilibrium, the developed vortex maintains good equilibrium and wind-pressure relation at the middle and lower troposphere, favorable for the development of the vortex. In contrast, equilibrium is weak at the middle and lower troposphere in the case of the undeveloped vortex.

(3) As shown in the analysis of the anomalous evolution of potential vorticity across the zonal cross section, the positive anomalous potential vorticity is increasing while developing upwards in the case of the developed vortex, suggesting that it is persistently developing. It is just the opposite in the case of undeveloped vortex. Positive potential anomalies are weakening while staying where they have been, suggesting that it has gradually reduced and is on its way towards dissipation.

It is shown in our study that the structure is basically the same among developed mid-level vortexes but differs among undeveloped ones; some are asymmetric and the others are in poor equilibrium. In view of it, the operational forecaster needs to analyze multiple factors, such as symmetry, equilibrium and the anomalous evolution of potential vortcity, to determine whether the vortex will generate and develop, rather than on the structure alone. Only on the basis of it can an objective judgment be made to decide whether the mid-level vortex will keep on developing.

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