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PRELIMINARY ANALYSIS ON THE INTENSITY AND STRUCTURE OF TYPHOON MORAKOT (2009) DURING ITS LANDING PROCESS

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Abstract: NCEP GFS (Global Forecast System) analytical data (available 4 times per day), satellite cloud image data and real-time observations of path and intensity of Typhoon Morakot are employed to investigate the variation of synoptic dynamics in its intensity and structure before and after the landing. This study intends to offer some hints for the forecast of intensity and structure of typhoons. Results show that in the tangential direction, the averaged asymmetry amplitude of wind on the radius of a large-value center of the low-level wind can be used as an important parameter for diagnosing the intensity of typhoons. Besides, the maximum of the upper dry potential vorticity in Morakot's center tends to extend downward along the intensive gradient of tangential wind situated on the inner side of a large-value center of the low-level tangential wind. Additionally, the radial advection of the tangential wind determines the variation of tangential wind in conjunction with the vertical transmission of the tangential wind, the inertial centrifugal force and the Coriolis force. These four items are dominant in the motion equation of tangential wind based on a cylindrical coordinate without the effects of friction and turbulence. Moreover, the low-level convergence center of the typhoon has a tendency of shifting and developing along the intensive gradient of the tangential wind in the tangential direction.

Key words: diagnostic analysis; typhoon; tangential wind; dry potential vorticity

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1 INTRODUCTION

In the study of the mechanism for the movement, structure and intensity changes in tropical cyclones (TCs), the physical variation of potential vorticity (PV) has been widely used in TC dynamical diagnostic analysis because of its principle of conservation and invertibility[1]. Moller and Shapiro[2] used PV inversion technique to analyze the intensity evolution of the 1995 Hurricane Opal for evaluating the effects of heating, friction and other aspects on the asymmetrical balance. Chen and Yau[3] pointed out that around a typhoon landing the TC asymmetric structure, including the friction and convection on the boundary layer, could lead to the positive PV in front of the TC center, and the interaction between the PV anomaly and the PV ring around the eyewall could change transient weakening or strengthening of its intensity.

For the role of TC tangential wind in TC structure evolution, Mallen and Montgomery[4] studied the 1997-2001 Western Pacific and East Pacific TCs to demonstrate that the TC structure near its central area can be described by relatively slowly weakened tangential wind, and it is related to the distribution of the cyclonic relative vorticity with negative radial gradient. Stern and Nolan[5] re-examined the vertical structure of TC tangential wind via the observational and theoretic analysis. They believed that the RWM (radius of maximum winds) axis tilting with height is related with the angular momentum surface and the TC scale, but is not necessarily associated with the TC intensity. In their investigation of TC spiral rainband impact on the scale of TC core, Xu and Wang[6]

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claimed that under the influence of an inner flow within the boundary layer outside the eye wall, the TC spiral rainband and associated diabatic heating accelerates the tangential wind outside the eyewall, and the tangential wind expands in the radial direction, impacting the scale of TC inner core. Wang[7] discussed the way in which the outer spiral rainband affects the TC structure and intensity, pointed out that the diabatic heating caused by the outer spiral rainband reduces the gradient of sea level pressure on the inner side of the rainband with relatively high inertial stability according to the static equilibrium adjustment, exerting a significant impact on the changes in the radial direction of maximum tangential wind at the low level and the TC inner core. While studying the influence of environmental field on the asymmetric intensity of TC, Wu and Braun[8] pointed out that the environmental field closely related with the eddy flux has a great impact on the tangential wind and the speed of radial wind. Xu and Wu[9] examined the asymmetric distribution of hurricane intensity caused by the environmental field using a numerical model, and found that the eddy flux is a mutual conversion of momentum between asymmetric flow and symmetric flow. Han and Wu[10], by studying the distribution of horizontal vortex tube of a TC at different stages of development, argued that when large differences exist between the upper and lower tangential wind, the horizontal vortex vector and the structure of spiral cloud bands are parallel to the direction of TC radial wind. Yu[11] studied the nonlinear effect on the change in tangential wind speed of the TC basic flow, and pointed out that under the condition of double vortex distribution, the vortex outside the typhoon circulation weakens the influence of a convection vortex inside or near the eyewall on the tangential wind speed of TC. Li[12] carried out a numerical simulation with a spatial resolution of 6 km to study TC Vongfong (2002) that occurred over the South China Sea, and the result showed that the maximum wind radius of the axisymmetric structure in Vongfong decreases with height, which is opposite to the counterpart of the Atlantic hurricane and the Western Pacific typhoon. Shen[13] used the equations of the barotropic shallow water and the baroclinic disturbance based on cylindrical coordinates to treat the axisymmetric tangential velocity item as a basic flow, and he defined the two types of Rossby vortex waves in a typhoon vortex system.

Taking Typhoon Morakot (0908) in 2009 as example, this paper employs the NCEP global forecast field analytical data (4 times per day) with a horizontal resolution of 0.5°×0.5° and the Japanese MTSAT satellite cloud image data. The objective is to explain several questions, including (1) what dominates the position of large-value center of the tangential wind in the tangential wind motion equations based on cylindrical coordinates, and (2) how the tangential wind affects the evolution of the potential vorticity in the vertical direction, as well as the evolution of the low-level convergence center in the tangential direction. It also provides some guidance for the forecasting and diagnostic analysis of the TC intensity and structure. In this paper, the concentrated period is mainly from the 00:00 6 August to 00:00 9 August, 2009. Unless otherwise specified, the time involved in the analysis is the coordinated universal time.

The observed path and strength of Typhoon Morakot (2009) before and after its landing are briefly introduced in section 2. Section 3 reveals the evolution of the characteristics of the tangential wind. The major items of the tangential momentum equation are discussed in section 4. Besides, we analyzed the effect of tangential wind on the distribution of potential vorticity. Section 5 describes a possible mechanism of tangential evolution for the convergent center at low altitudes. The main conclusions are given at the end of the paper.

2 OVERVIEW OF TYPHOON TRACK AND INTENSITY

Morakot was generated on 3 August 2009 as a tropical depression, and then developed into a typhoon on 5 August. It landed on Hualian, Taiwan Island, around 23:45 on 7 August, followed by landing on Xiapu, Fujian province at 16:20 on 9 August, before weakening to a strong tropical storm during the night. The TC was severe, rarely seen in history. It existed for a long time with unstable moving speed, a complex and changeable track and an asymmetrical structure. Its influence was extensive to cause serious casualties and property losses in many provinces and cities in China, especially the Taiwan Island. (Note: the time in this section is Beijing time.)

Figures 1 and 2 give the TC track, sea level pressure and maximum wind speed near the center with an interval of 6h, respectively. Both of them are drawn based on the TC intensity and track provided by Japan Meteorological Agency, and the TC best track offered by Shanghai Typhoon Institute of China Meteorological Administration. Before landing on the Taiwan Island, the averaged moving speed of Morakot is about 10 to 15 m/s over the ocean. Then it moves more slowly after landing on the island at 18:00, on 7 August. From 00:00 6 August to 18:00 7 August, minimum sea level pressure is well corresponding to the maximum wind speed near the center. It is at this very moment that Morakot is most powerful during the development stage (Fig. 2).

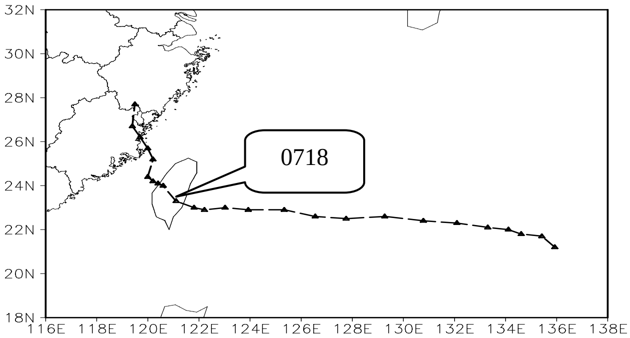
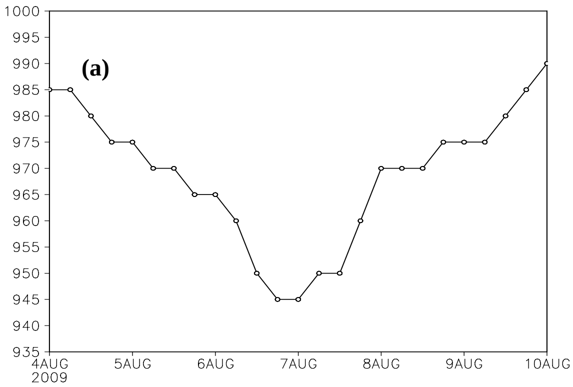


Figure 1. Track of typhoon Morakot from 00:00 4 August to 00:00 10 August with an interval of 6 hours (0718 represents 18:00 7 August, the time at which Morakot made landfall in Taiwan Island).



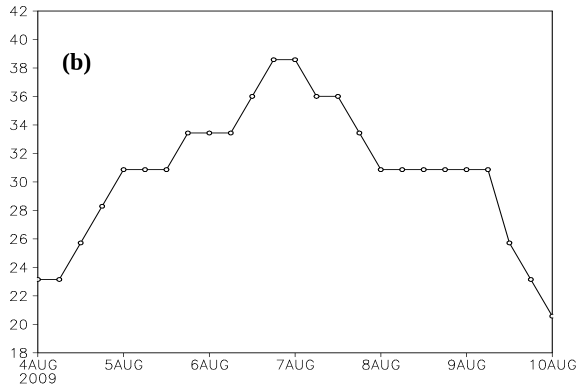


Figure 2. Time series of the sea level pressure (a, units: hPa) and the maximum wind speed (b, unit: m/s) near the center from 00:00 4 August to 00:00 10 August.

Figure 3 is derived from the Japanese MTSAT satellite IR images. At 08:00 5 August, the TC periphery clouds are generally located in the center of the southeast quadrant. The west side of the cloud in the center continues to gather as the TC is strengthening. From 08:00 6 August to 08:00 7 August, the TC structure is symmetrical, showing round-shaped clouds. After landing at 08:00 8 August, the west side of the TC cloud splits and then changes from an oval shape to a belt shape in the meridional direction.

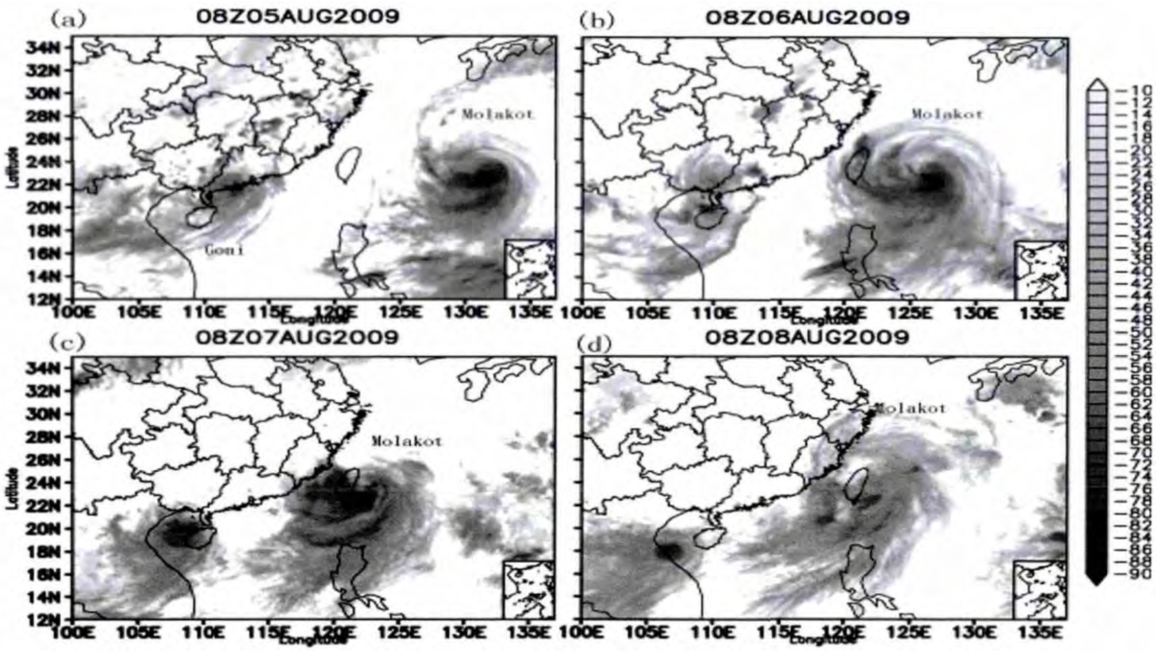


Figure 3. Evolution of clouds according to the Japanese MTSAT geostationary satellite infrared data. (a): 08:00 5 August; (b): 08:00 6 August; (c): 08:00 7 August; (d): 08:00 8 August.

3 DYNAMICAL CHARACTERISTICS OF THE AMBIENT FIELD

3.1 *Characteristics of the low-level horizontal wind field and vorticity field*

It is well-known that the distribution and intensity of a low-level positive vorticity ring around the center is correlated with the typhoon intensity. Fig. 4 shows the characteristics of low-level wind field and the vorticity field near the TC center in an 11°×11° area at each time. At 18:00 6 August, the TC vortex ring covers a large area and its radius increases to a distance about 5 times the longitude difference in the meridional direction. At 06:00 7 August the radius of the vortex ring begins to shrink, accompanied by enhanced positive vorticity of the southwest quadrant. Influenced by the vorticity advection of the counterclockwise rotating wind field and the low-level horizontal convergence, the vorticity of TC southeast quadrant further increases at 18:00 7 August. After Morakot's landfall in Taiwan Island, the inward transport of the heat flux and the water vapor energy are weakened because the terrain blocks the inward flow of the radial flow. Then, the convection in the west of the TC is suppressed[14]. In addition to the blocking effect of terrain on the energy channels, the friction also weakens TC circulation energy, especially on the western side of the vortex ring. The entire vortex ring shows an asymmetric pattern of distribution in which the east is strong while the west is weak (Fig. 4d).

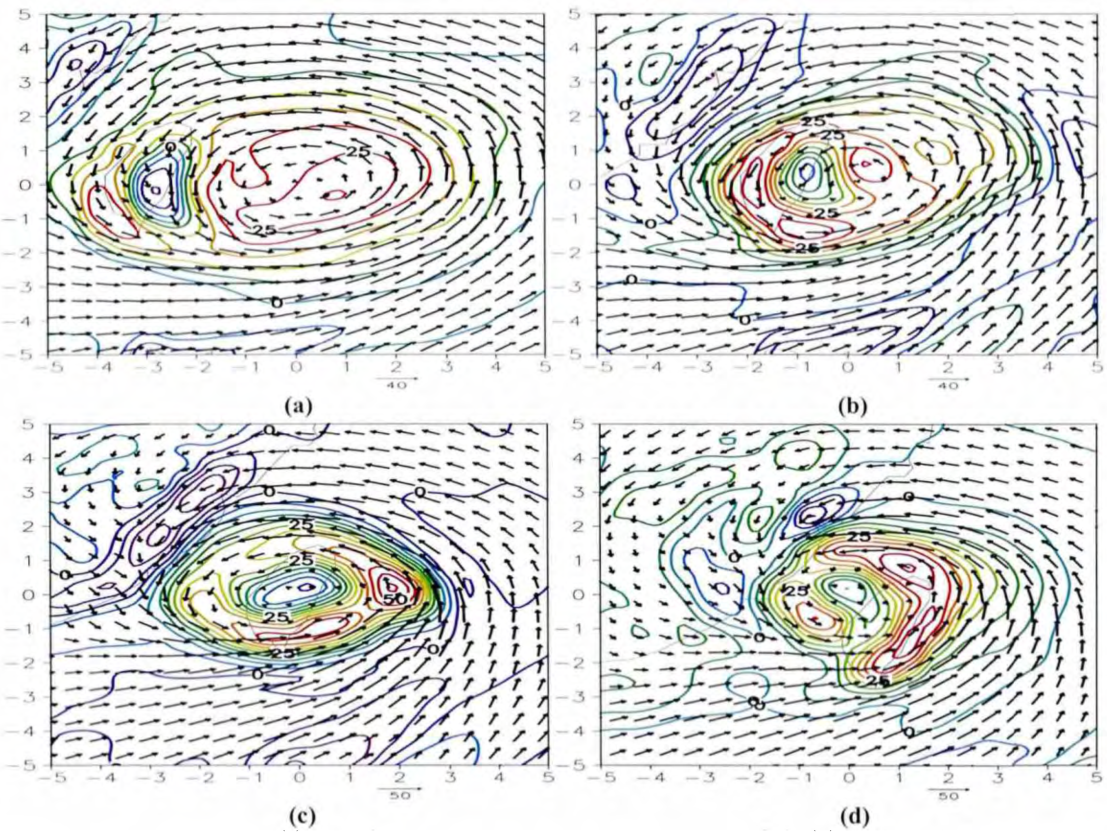


Figure 4. Horizontal wind field (vectors, m s^{-1}) and the vorticity (isoline, units: 10^{-5}s^{-1}) at 800 hPa (coordinates are latitude and longitude grid spacing (unit: 1°), respectively). (0, 0) is for the TC center) at (a) 18:00 6 August; (b) 06:00 7 August; (c) 18:00 7 August; (d) 12:00 8 August.

The maximum vorticity around the TC center are generally not located in the center of the storm but 1 to 2 latitudes away from it. On one hand, it may be associated with the data resolution. On the other hand, it may be related with the distribution of strong horizontal gradient of tangential wind.

3.2 *Evolution of tangential wind distribution*

Mallen et al.[4], in the study of TC radial structure near the center, employed the tangential mean tangential wind and its deviation to assess the asymmetry degree of the tangential wind in the tangential direction. Thus the evolution of the axisymmetric structure of the TC is examined.

The asymmetry amplitude of the tangential wind at each point of a certain radius in the tangential direction can be defined as:

$$v'_{\lambda i} = \sqrt{\frac{(v_{\lambda i} - \overline{v_{\lambda}})^2}{\overline{v_{\lambda}}^2}}$$

Then the expression of the tangential-mean asymmetry amplitude of the tangential wind along a certain radius is:

$$v'_{\lambda ave} = \frac{1}{N}\sum_{i}^{N} \sqrt{\frac{(v_{\lambda i} - \overline{v_{\lambda}})^2}{\overline{v_{\lambda}}^2}}$$

In the expression, $\overline{v_{\lambda}}$ is the tangential wind of the tangential mean of the radius, while $v_{\lambda i}$ is the tangential wind at each point of a certain radius in the tangential direction. And *N* and *i* are the number of grid points taken in the tangential direction and the label for each point, respectively.

Before and after Morakot's landfall in the island from 12:00 6 August to 12:00 8 August, there is a large-value center at 800 hPa, which is 150 to 350 km away from the TC center. Note that a horizontal resolution of 0.5°×0.5° is too coarse to reveal the small-scale features in the inner core of TC perfectly. Therefore, the large-value center radius of the low-level tangential wind obtained here can only represent the region with maximum wind of the typhoon outer ring.

Here we study the tangential asymmetric structure of the 800 hPa tangential wind 250 km away from the Typhoon center. It is seen from Fig. 5, from 12:00 to 18:00 6 August, a large asymmetric deviation of tangential wind is situated in the west-southwest of the TC center. At 12:00 6 August, the asymmetry amplitude of the tangential wind reaches its maximum value (65%). As showed in Fig. 2, from 00:00 to 06:00 7 August, the sea level pressure near the center is low, and the maximum wind speed is strong, causing small asymmetric deviation at each of the points in the tangential direction during this period when all the asymmetry amplitudes are less than 25%. After 12:00 7 August, a large asymmetric deviation of the tangential wind appears on the east side of the TC center, where the tangential wind is constantly increasing. After the landing at 18:00 7 August, the west side of the clouds diminishes to weaken the tangential wind in this direction. Therefore, there is always large asymmetric amplitude of the tangential wind in the west of the TC.

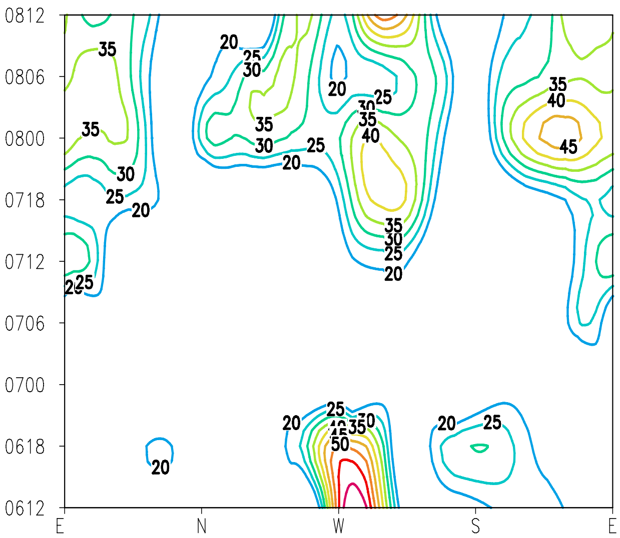


Figure 5. Evolution in the tangential direction of the asymmetric amplitude (greater than 20%) of the tangential wind at 800 hPa 250 km away from the TC center (the abscissa represents directions (E: East; N: North; W: West; S: South); the ordinate represents the date (first two digits) and time (latter two digits).

Figure 6 indicates that the time series of the tangential-mean asymmetric amplitude of the tangential wind is similar to that of the sea level pressure near the TC center, as well as the evolution of the maximum wind speed as shown in Fig. 2. The tangential-mean asymmetric amplitude of the tangential wind along the large-value center of the lower tangential wind reflects the deviation at all points in the tangential direction from the tangential mean value. As the typhoon has a higher symmetry in its strong stage, the tangential-mean asymmetric amplitude of the tangential wind on the radius of the strong wind circle near the typhoon center is relatively small. After landing, because of the diminished tangential wind in the west and the strengthened tangential wind in the east of the TC center, such asymmetric amplitude increases rapidly, corresponding to the evolution of wind field and vorticity field (Fig. 4c to 4d). It provides a possible method to analyze the trends of TC intensity. However, more different types of TC cases are required to verify the applicability.

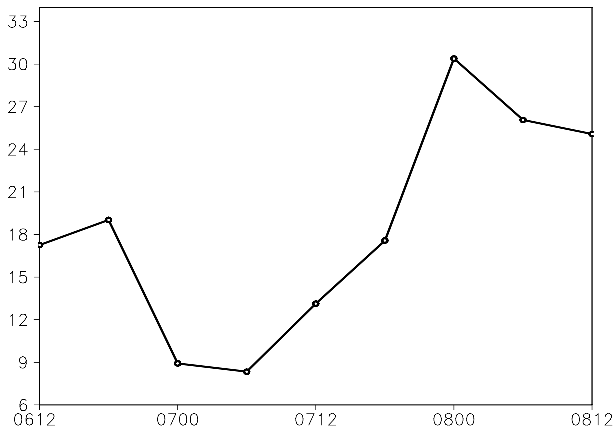


Figure 6. Time series of the tangential mean (%) of the asymmetry amplitude of the tangential wind at 800 hPa 250 km away from the TC center (the abscissa represents the date (first two digits) and time (latter two digits); the ordinate represents the asymmetric amplitude of the tangential wind).

4 VERTICAL PROFILE OF RELATED PHYSICAL QUANTITIES

4.1 *Vertical distribution of the tangential wind and dry potential vorticity*

The method applied here is from the Xu and Wu[9] and Liu et al.[15]. First, the local Cartesian coordinates (x, y, p) of a physical quantity is converted to the cylindrical coordinates (r, λ, p) with the TC center at the origin. Then the column coordinates of the physical quantity A is divided into the axisymmetric part $\overline{A}$, which is the tangential mean along azimuth, and the non-axisymmetric perturbation part A', i.e. $A = \overline{A} + A'$.

Before 00:00 6 August, the large-value center of the tangential wind is about 400 to 450 km away from the typhoon center. At 00:00 6 August, the radius of the tangential wind center is getting smaller, and the TC is gathering strength. From 00:00 6 August to

12:00 8 August, the radius of the large-value center of the tangential wind is located at 900 to 700 hPa height in the lower troposphere, and is 200 to 300 km away from the TC center. At 00:00 7 August, the large-value center of the tangential wind is located about 280 km away from the TC center at 800 hPa (Fig. 7a), and between them the radial gradient of the tangential wind is intensive. The tangential wind exhibits a strong horizontal shear in the radial direction, which is conducive to developing the local potential vorticity (PV). The strong horizontal gradient of the tangential wind is accompanied by the large value of the positive PV (Fig. 7). At 12:00 7 August, the center radius of the typhoon peripheral gale area shrinks and is 250 km away from the TC center (Fig. 7b). At this moment, the tangential wind at 900 to 600 hPa has also been enhanced, with the value of the gale area center at 800 to 700 hPa increasing to 35 m/s. The intensity of the PV vortex center located at 300 to 250 hPa around the TC center has exceeded 4 PVU. The maximum of the high-level positive PV is extending from the high level of the TC center to the low-level TC periphery along the direction as shown by the arrow with solid black line in Fig. 7b to 7c (the intensive horizontal gradient of tangential wind). At 00:00 8 August, the large-value center of the tangential wind located at 800 hPa is 200 to 250 km away from the TC center. Further shrinking of the radius of the maximum tangential wind speed in the lower troposphere is related to the enhanced lower radial flow (not shown). At 18:00 7 August, the lower radial inflow is located below 700 hPa with its center about 300 km away from the TC center, while the radial outflow is mainly above 700 hPa (not shown). This vertical distribution of radial flow leads to the positive dry PV at 00:00 8 August, which is situated over the large-value center of the 600 hPa tangential wind and tilts outward with height (along the direction shown by the arrow of the dotted line in Fig. 7c). At 00:00 9 August, the TC is weakening, and the large-value center of the tangential wind shifts outward in the radial direction to be located at 900 to 700 hPa, about 350 km away from the TC center. Besides, its strength is weakened to 24 m/s (Fig. 7d). The dry PV center stays at 800 to 700 hPa near the TC center, tilting outward with height gradually.

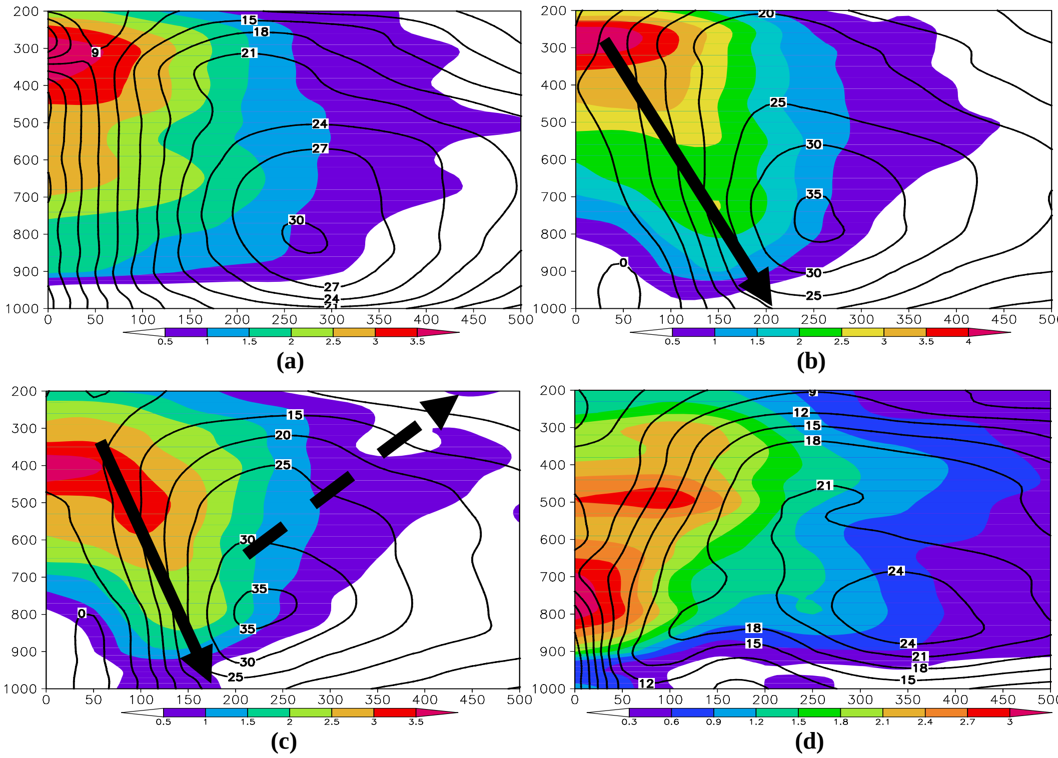


Figure 7. Radial-pressure cross sections of tangentially averaged tangential wind (contours, unit: m/s) and the dry potential vorticity (shaded, unit: PVU = $10^{-6}m^2$ K s^{-1} kg^{-1}). The abscissa and the ordinate represent the radial distance (unit: km) and the mandatory pressure (unit: hPa), respectively. (a): 00:00 7 August; (b): 12:00 7 August; (c): 00:00 8 August; (d): 00:00 9 August.

From 00:00 5 August to 00:00 9 August, the distribution and the order of dry PV magnitude near the TC center is dominated by the barotropic item. The barotropic item $PV_1 = -g(\zeta_p + f)\frac{\partial \theta}{\partial p}$ is about 1 to 2 orders of magnitude larger than that of baroclinic item $PV_2 = -g\frac{\partial u}{\partial p}\frac{\partial \theta}{\partial y} + g\frac{\partial v}{\partial p}\frac{\partial \theta}{\partial x}$ (related physical quantities in the expression are defined in the conventional sense). The presence of a high-level warm center in the TC center increases the vertical gradient of potential temperature there, favoring the PV development in the upper troposphere. Meanwhile, a strong horizontal wind shear appears in the area with intensive horizontal gradient of the tangential wind inside the large-value center of the tangential wind, extending the high-level PV downward along the strong gradient of tangential wind[6, 7] (Fig. 7).

As analyzed above, Fig. 7 indicates that in the mid-lower troposphere, the evolution of the large-value center of the tangential wind will have impact on the vertical distribution of PV, in conjunction with the intensive gradient of the horizontal wind shear inside the tangential wind. Then how does the maximum of the tangential wind evolve? This question will be investigated in the follow section by dynamically diagnosing the motion equation of the tangential wind.

4.2 *Diagnostic analysis of the maximum of the low-level tangential wind*

Based on a cylindrical coordinate and with the typhoon center at the origin (without the role of friction and turbulent mixing), the tangential momentum equation is expressed as follows:

$$\frac{\partial v_\lambda}{\partial t} = -v_r\frac{\partial v_\lambda}{\partial r} - \frac{v_\lambda \partial v_\lambda}{r\partial\lambda} - \omega\frac{\partial v_\lambda}{\partial p} - \frac{v_r v_\lambda}{r} - fv_r - \frac{1}{r}\frac{\partial\phi}{\partial\lambda} \quad (1)$$

in which v_λ and v_r is the tangential and the radial wind, respectively, while ϕ and λ are the geopotential height and the tangential azimuth respectively.

The calculation shows that the trend of the tangential wind is controlled by the first term (the radial advection of the tangential wind), the third item (the vertical transmission of the tangential wind), the fourth item (the inertia centrifugal force), and the fifth item (the Coriolis force) on the right hand side (r.h.s.) of Eq. (1).

At 12:00 7 August, the strongest radial advection component of the tangential wind at 1000 to 900 hPa is 200 to 250 km away from the TC center, with the contour of zero located near 225 km (Fig. 8a). Moreover, at this time the lower radial inflow is 150 to 500 km away from the TC center (not shown). The distribution of both the radial advection component of tangential wind and the radial wind in the lower troposphere indicate that within the range of 200 to 250 km from the TC center, the maximum of the tangential wind is likely to emerge in the lower troposphere, corresponding to the strongest 800 hPa tangential wind whose speed reaches 35 m/s after 12 hours at 08:00 (Fig. 7c).

At 12:00 7 August, the zero contour of the vertical transmission component of tangential wind exists 200 to 250 km away from the TC center at 800 to 750 hPa (Fig. 8b), accompanied by strong local ascending motion (not shown). The vertical transmission term is negative below 800 hPa but is positive above the height of the zero contour, indicating the appearance of maximum center of tangential wind 200 to 250 km away from the center near 800 hPa. Fig. 8b shows that, from the zero contour to 400 hPa, the positive vertical transmission belt tilts outward with height, while the tangential wind outside its large-value center tilts outward with height at 00:00 8 August at 800 hPa (Fig. 7c).

At 12:00 7 August, the positive inertial centrifugal force, which is 150 to 350 km away from the TC center, is evidently below 750 hPa, but the component is negative above 750 hPa and tilts outward with height. This implies that in the high-speed counterclockwise rotating TC circulation system in the lower troposphere, the radial wind above 750 hPa outflows to develop the radial secondary circulation. Located inside the maximal ascending region near the typhoon center, a sinking branch of the secondary circulation is conducive to the downward transmission of the high-level PV.

At 12:00 7 August, the region 150 km away from the TC center is controlled by the larger Coriolis force in the lower troposphere, but the smaller one is within the range of 150 km away from the TC center, associated with the distribution of the radial flow in the radial direction.

As mentioned above, the magnitude orders of the first, third, fourth, and fifth terms of the motion equation of tangential wind are equivalent to each other so that they can all influence the strength of the tangential wind. The changes in the maximum position of the mid- and lower-level tangential wind are related to the distribution of mid- and lower-level zero contours of the major components in the motion equation of tangential wind. The cooperation of the intensive gradient (area “A”) near the mid- and lower-level zero contours of the main components (Fig. 8e) and the maximum position of the mid- and lower-level tangential wind can qualitatively determine the evolution of the tangential wind as a whole.

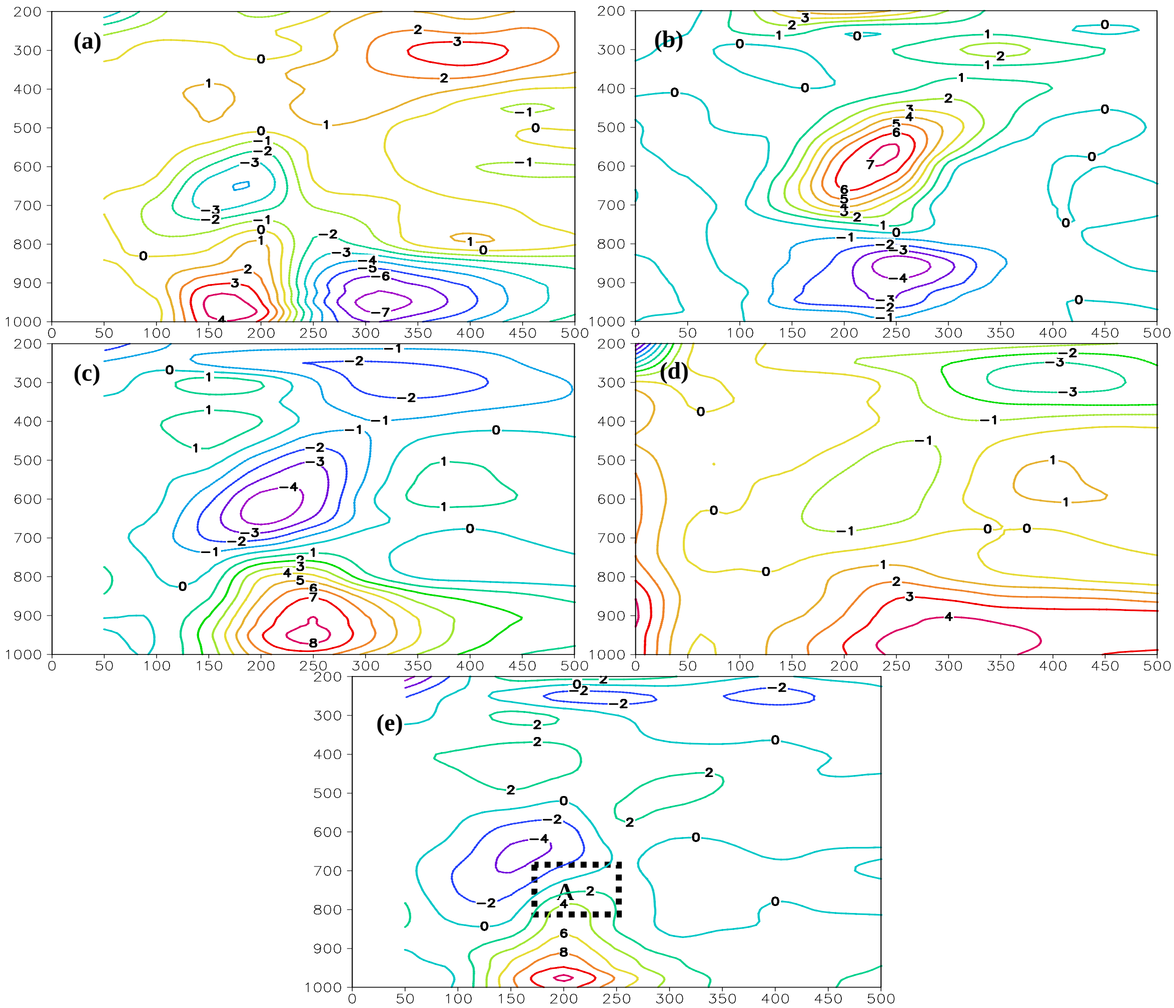


Figure 8. Radial-pressure cross sections of the main terms in the motion equation of tangential wind along the azimuth at 12:00 7 August (coordinates are the same as in Fig. 7). (a) First term (radial advection of the tangential wind); (b) third term (vertical transmission of the tangential wind); (c) fourth term (inertia centrifugal force); (d) fifth term (the Coriolis force); (e) composition term.

5 CHARACTERISTICS OF THE ELEMENTS IN TANGENTIAL DIRECTION

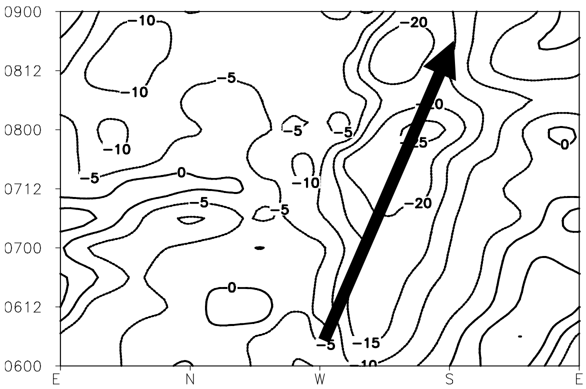
According to the constraints of the gradient wind balance near the center, the inflow radial wind of the TC inner ring is weak. Before and after Morakot's landing in Taiwan Island, its inflow radial wind is 200 to 500 km away from the center and generally situated in the lower troposphere (not shown in figures) at less than 900 hPa. Here the horizontal vortex tube is very strong, but it is not located at the height of the vertical rising speed center. Thus there is not evident conversion from the horizontal vortex tube to vertical vorticity caused by the ascending. For studying the evolution of radial wind and the tangential wind in the tangential direction, which is related to the development of low-level vertical vorticity and the convergence center, we will examine the radial mean radial wind and the tangential wind at 900 hPa within a radius of 200 to 500 km.

Figure 9a shows that at 00:00 6 August the radial inflow is mainly concentrated in the southwestern quadrant of the TC center, exhibiting an asymmetric structure. Then the large-value band of this inflow rotates counterclockwise around the center. That is, it spreads in the tangential direction along the direction denoted by the black arrow in Fig. 9a. At 00:00 8 August, the radial wind center of the influx located in the south-southwest direction is up to –25 m/s. The large-value area of the radial inflow gradually moves from the west to the south side of the TC, indicating the blocking effect of terrain on the west side of the radial inflow channel after the landfall.

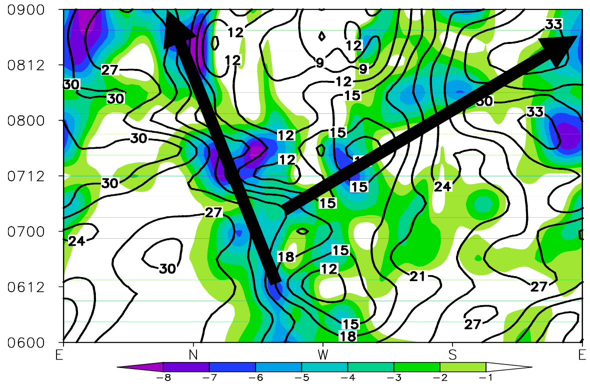
Shen[13] argued that the changes in ether the vertical vorticity of basic flow in the radial direction or the secondary shear of tangential velocity of basic flow in the radial direction can result in the vibrating of air particles of the Barotropic Vortex Rossby waves in the radial direction and then generates the wave propagating counterclockwise or clockwise along the tangential direction. It is seen from Fig. 9b that before 12:00 7 August the low-level positive convergence at 900 hPa is mainly located in the west-northwestern quadrant of the TC center. After 12:00, the positive convergence along the area with intensive gradient of the tangential wind (in the direction marked by the black arrow in Fig. 9b) expands clockwise to the directions of the north side, and counterclockwise to the south side of the TC center. The expression of horizontal disturbance divergence based on cylindrical coordinates is as follows:

$$D=\frac{1}{r}\frac{\partial}{\partial r}(rv_r)+\frac{\partial v_\lambda}{r\partial\lambda} \qquad (2)$$

in which the elements of the equation are the same as that in Eq. 1. It shows that the position of disturbance convergence center is associated with the tangential gradient of tangential wind. As a result, the convergence center in Fig. 9b will develop along the intensive gradient of tangential wind. The convergence is expanding in the tangential direction of the entire vortex ring. The convergence center developing toward the north of typhoon center is stronger than that moving southward with the cyclonic flow field. At 18:00 7 August the convergence center located in the northwestern quadrant is over $-8\times10^{-5}\text{s}^{-1}$. After turning continuously for 24 hours, the convergence center is enhanced and located in the north of the TC center at 18:00 8 August. The typhoon center moves slowly in the tangential direction with a speed of approximately 3 to 5 m/s. A possible reason is that the center develops in an opposite direction to the tangential basic flow. Another convergence region moves fast southward with the cyclonic flow field. At 12:00 7 August, the maximum of the convergence center on the west side of the TC is $-6\times10^{-5}\text{s}^{-1}$. After 30 hours, i.e. 18:00 8 August, it has shifted to the east-northeast of the TC center with a speed of about 6 to 14 m/s. The fast movement and development of the convergence zone in the tangential direction may be attributed to the enhancement of the radial inflow (in the direction marked by the black arrow in Fig. 9a).



(a)



(b)

Figure 9. Temporal evolution of radial mean wind at 900 hPa within the radius of 200 to 500 km from the typhoon center (a, unit: m/s), the tangential wind (b, isoline, unit: m/s) and the convergence (b, shading, units: 10^{-5}s^{-1}). The coordinates are the same as in Fig. 5.

Figure 9b also demonstrates that the low-level convergence center develops from the west side of the TC to the north and the south side along the dense gradient of tangential wind (indicated by the black arrow in Fig. 9b), consistent with the stretch and clouds development in the meridional direction shown in Fig. 3d. After 00:00 8 August, the convergence center disappears gradually at the west side of the TC, and the positive vorticity is enhanced in the east side of the TC in the meantime (Fig. 4d).

6 CONCLUSIONS

The GFS analytical data, satellite cloud image data, and real-time observation data are used to conduct a synoptic dynamics analysis on the mechanism for the tangential wind near the TC center. The results reveal the relationship between the tangential wind and the strength and structure of Typhoon Morakot. The major points are concluded as follows.

(1) The asymmetry amplitude of tangential wind located on the radius of the large-value center of low-level tangential wind can be employed to investigate the temporal evolution of asymmetry deviation of tangential wind in the tangential direction, and further to determine the asymmetric degree in different orientation qualitatively. The smaller the tangential-mean asymmetry amplitude of tangential wind, the higher symmetric degree of the TC structure it represents. This corresponds to the evolution of TC intensity.

(2) An intensive horizontal gradient of tangential wind is located on the inner side of the maximum tangential wind in the lower troposphere near the center. The horizontal wind shear is large enough to develop the potential vorticity. At the same time, based on the gradient wind balance, the ascending appears on the radius of the maximum tangential wind,

which results in the upper subsiding over the inner side of the low-level tangential wind center. It also facilitates the large potential vorticity in the upper troposphere near the center to extend downward along the intensive gradient of tangential wind in the middle and low troposphere.

(3) Scale analysis shows that the radial advection of tangential wind, the vertical transmission of tangential wind, the inertial centrifugal force and the Coriolis force are the dominant terms in the tangential wind equations. It is pointed out that near the low-level zero contours of these terms, their intensive gradient can qualitatively determine the evolution and distribution of tangential wind.

(4) Within the radius of strong radial inflow on the low level, the convergence center tends to shift and develop in the tangential direction along the intensive gradient of tangential wind. Its speed and development may be associated with the direction and strength of the tangential basic flow, as well as the evolution of intensity radial inflow intensity in the tangential direction.

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