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APPLICATION OF ADVECTIVE VORTICITY EQUATION TO TYPHOON FUNG-WONG

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Abstract: The momentum advection vorticity equation in the form of cross multiplication is introduced, in which the divergence term in the classic vorticity equation does not appear explicitly. This equation includes the rotation effect of the horizontal wind advection, which are not explicitly included in the classic vorticity equation. The vorticity and its tendency of Typhoon Fung-Wong (0808) that occurred in July 2008 are analyzed. The computed results show that the rotation effect of the advection of the horizontal wind is a leading factor in determining the change of vertical vorticity for Fung-Wong during its life cycle, especially in the period leading up to landfall. The advection term represents the tendency variation of the vertical vorticity, and the positive-value region of the vertical vorticity tendency is almost in accord with the track of Fung-Wong, which may be taken as a factor to locate the key observational region of Fung-Wong. The equation provides a supplementary diagnostic tool for the systems related with strong advection of horizontal wind.

Key words: advection; vorticity equation; synoptic analysis

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1 INTRODUCTION

Vorticity is one of the important dynamic parameters[1] associated with the speed and direction of the fluid parcel rotation. Defined as $\vec{\zeta} = \nabla \times \vec{v}$, where $\vec{v}$ represents three-dimensional velocity, this expression means that the vorticity is the curl of the parcel velocity. From planetary-scale waves to synoptic-scale cyclones, the vertical component of the vorticity is much more important than the horizontal component, such as the negative vorticity in the regions of the blocking high and subtropical high and the positive vorticity in cyclones, shear line, and polar low, etc. Due to the quasi-horizontal motion of the atmosphere, only the vertical component of the vorticity (i.e., $\xi = \dfrac{\partial v}{\partial x} - \dfrac{\partial u}{\partial y}$) is focused in operational analyses.

When vorticity is combined with other physical variables, it can yield some new physical quantities, such as potential vorticity, moist potential vorticity, convective vorticity vector as well as dynamical vorticity vector, which have unique capabilities in the structural analysis of synoptic systems and diagnosis of heavy rain[2-10]. Because the life cycle of a synoptic system can be depicted by the change in vertical vorticity, the vertical vorticity equation has been widely used in diagnosis of synoptic systems. For example, Sherman[11] applied the vorticity equation to estimate the vertical velocity and locate heavy rainfall; Sundstrom[12] discussed the stability theorems using the barotropic vorticity equation; Grotjahn[13] used the frictionless, nonlinear vorticity equation to examine the extratropical cyclone. Wu and Liu[14] discussed the vertical vorticity development as a result of down-sliding on slantwise isentropic surfaces, and Chen[15] discussed the full vorticity equation and its limitation in neutral stratification. Thus, vertical vorticity equation is a basic equation and associated

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research is one of the hottest issues for atmospheric science and fluid dynamics.

In p-coordinate, the classic vertical vorticity equation[1] in the frictionless atmosphere can be expressed by

$$\frac{\partial \xi}{\partial t}=\vec{v}.\nabla(\xi+f)-(f+\xi)(\nabla_h.\vec{v})-\omega\frac{\partial \xi}{\partial p}+\vec{k}\cdot(\frac{\partial \vec{v}}{\partial p}\times\nabla\omega)+\beta\vec{v}$$

where $\vec{v}.\nabla(\xi+f)$ is the vorticity advection, $(f+\xi)(\nabla_h.\vec{v})$ is the concentration or dilution of vertical vorticity due to the convergence or divergence of the horizontal wind, $\omega\frac{\partial \xi}{\partial p}$ is the vertical advection term of vertical vorticity, $\vec{k}\cdot(\frac{\partial \vec{v}}{\partial p}\times\nabla\omega)$ is the torsion effect of the horizontal vorticity on the vertical direction (tilting term), $\beta\vec{v}$ represents the β effect. The classic vorticity equation is mainly used to analyze the change of vertical vorticity for various synoptic systems, but the divergence term in this equation, which is a main factor in the change of vertical vorticity, cannot be calculated accurately. Recently, Kirk[16] derived a vertical vorticity equation with the form of cross multiplication of momentum advection, which can be expressed by

$$(\frac{\partial \xi}{\partial t})_e=-\vec{k}\cdot\nabla\times[(\vec{v}_e\cdot\nabla)\vec{v}_e]-\vec{k}\cdot\nabla\times(\omega_e\frac{\partial \vec{v}_e}{\partial p}) .$$

In this new vertical equation, the divergence term does not appear explicitly, and it was used to analyze the development of meso-scale system successfully, which is an improvement over the classic vertical equation. This vorticty equation with the form of cross multiplication has been successfully applied to diagnose the change in vorticity. However, this equation is derived in an inertial framework, whose origin point is the spherical center of the Earth, and the subscript e means that the variable is relative to the inertial system. Thus, the point on the rotational spherical surface is not fixed on the spherical center, which cannot be calculated in a simple and convenient way, and is not suitable for the p-coordinate system. Then, can a similar vorticity equation with momentum advection formed in the p-coordinate be derived? Can it be easily and accurately applied to synoptic system analysis? In order to resolve these two questions, a new advective vorticity equation in the p-coordinate is derived [17], and applied here in this paper to diagnose the change in vertical vorticity with typhoon Fung-Wong. In section 2, a simple introduction was given.

2 A BRIEF INTRODUCTION TO ADVECTIVE VORTICITY EQUATION IN P-COORDINATE

In the p-coordinate, the horizontal wind vector is $\vec{V}=u\vec{i}+v\vec{j}$, where u and v are zonal and meridional wind components. ω is the vertical velocity, ϕ, ρ, T, and θ are the geopotential height, air density, temperature and potential temperature, respectively. There are also $u=u(x,y,p,t)$, $v=v(x,y,p,t)$, $\zeta=\zeta(x,y,p,t)$, $\omega=\omega(x,y,p,t)$, $\phi=\phi(x,y,p,t)$, and $\rho=\rho(x,y,p,t)$. The governing equations can be written as

$$\frac{\partial u}{\partial t}+\vec{V}.\nabla u+\omega\frac{\partial u}{\partial p}+(f+\beta y)v=-\frac{\partial \phi}{\partial x}, \tag{1a}$$

$$\frac{\partial v}{\partial t}+\vec{V}.\nabla v+\omega\frac{\partial v}{\partial p}-(f+\beta y)u=-\frac{\partial \phi}{\partial y}, \tag{1b}$$

$$\frac{\partial \phi}{\partial p}=-\frac{1}{\rho}, \tag{1c}$$

$$\nabla\cdot\vec{V}+\omega\frac{\partial \omega}{\partial p}=0 . \tag{1d}$$

Taking $\frac{\partial}{\partial x}$(1b) $-\frac{\partial}{\partial y}$(1a), we get

$$\begin{aligned}&\frac{\partial^2 v}{\partial x\partial t}+\frac{\partial u}{\partial x}\frac{\partial v}{\partial x}+u\frac{\partial^2 v}{\partial x^2}+\frac{\partial v}{\partial x}\frac{\partial v}{\partial y}+v\frac{\partial^2 v}{\partial y\partial x}+\frac{\partial \omega}{\partial x}\frac{\partial v}{\partial p}+\omega\frac{\partial^2 v}{\partial x\partial p}-(f+\beta y)\frac{\partial u}{\partial x}-\\&\frac{\partial^2 u}{\partial y\partial t}-\frac{\partial u}{\partial y}\frac{\partial u}{\partial x}-u\frac{\partial^2 u}{\partial y\partial x}-\frac{\partial v}{\partial y}\frac{\partial u}{\partial y}-v\frac{\partial^2 u}{\partial y^2}-\frac{\partial \omega}{\partial y}\frac{\partial u}{\partial p}-\omega\frac{\partial^2 u}{\partial y\partial p}+\beta v-(f+\beta y)\frac{\partial v}{\partial y}=0\end{aligned} . \tag{2}$$

Taking $\frac{\partial}{\partial t}+u\frac{\partial}{\partial x}+v\frac{\partial}{\partial y}+\omega\frac{\partial}{\partial p}$ on ξ, we get

$$\frac{\partial\xi}{\partial t}+u\frac{\partial\xi}{\partial x}+v\frac{\partial\xi}{\partial y}+\omega\frac{\partial\xi}{\partial p}=\frac{\partial^2 v}{\partial x\partial t}-\frac{\partial^2 u}{\partial y\partial t}+u(\frac{\partial^2 v}{\partial x^2}-\frac{\partial^2 u}{\partial y\partial x})+v(\frac{\partial^2 v}{\partial y\partial x}-\frac{\partial^2 u}{\partial y^2})+\omega(\frac{\partial^2 v}{\partial x\partial p}-\frac{\partial^2 u}{\partial y\partial p}). \quad (3)$$

Substituting $(\frac{\partial^2 v}{\partial x\partial t}-\frac{\partial^2 u}{\partial y\partial t})$ of Eq.(2) into Eq.(3) leads to

$$\frac{\partial\xi}{\partial t}=-(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y})\xi-(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y})f-(\frac{\partial\xi}{\partial y}+\beta)v-u\frac{\partial\xi}{\partial x}-\frac{\partial\omega}{\partial x}\frac{\partial v}{\partial p}-\omega\frac{\partial\xi}{\partial p}-\beta y\frac{\partial u}{\partial x}+\frac{\partial\omega}{\partial y}\frac{\partial u}{\partial p}-\beta y\frac{\partial v}{\partial y}. \quad (4)$$

With

$$-[\nabla\cdot\vec{V}(\xi+f+\beta y)]=-u\frac{\partial\xi}{\partial x}-(\xi+f+\beta y)\frac{\partial u}{\partial x}-(\frac{\partial\xi}{\partial y}+2\beta)v-(\xi+f+\beta y)\frac{\partial v}{\partial y}, \quad (5)$$

substituting $\xi=\frac{\partial v}{\partial x}-\frac{\partial u}{\partial y}$ into Eq.(5) yields

$$-[\nabla\cdot\vec{V}(\xi+f+\beta y)]=\begin{matrix}-u\frac{\partial^2 v}{\partial x^2}+u\frac{\partial^2 u}{\partial y\partial x}-\frac{\partial u}{\partial x}\frac{\partial v}{\partial x}+\frac{\partial u}{\partial x}\frac{\partial u}{\partial y}-f\frac{\partial u}{\partial x}-\beta y\frac{\partial u}{\partial x}-\\ v\frac{\partial^2 v}{\partial y\partial x}+v\frac{\partial^2 u}{\partial y^2}-\beta v-\frac{\partial v}{\partial y}\frac{\partial v}{\partial x}+\frac{\partial v}{\partial y}\frac{\partial u}{\partial y}-f\frac{\partial v}{\partial y}-\beta y\frac{\partial v}{\partial y}\end{matrix}. \quad (6)$$

With

$$-\vec{k}\cdot[\nabla\times(\omega\frac{\partial\vec{V}}{\partial p})]=-\frac{\partial\omega}{\partial x}\frac{\partial v}{\partial p}-\omega\frac{\partial^2 v}{\partial x\partial p}+\frac{\partial\omega}{\partial y}\frac{\partial u}{\partial p}+\omega\frac{\partial^2 u}{\partial y\partial p}, \quad (7)$$

substituting Eq.(5) and Eq.(7) into Eq.(4) leads to

$$\frac{\partial\xi}{\partial t}=\left\{-[\nabla\cdot\vec{V}(\xi+f+\beta y)]\right\}-\vec{k}\cdot[\nabla\times(\omega\frac{\partial\vec{V}}{\partial p})]. \quad (8)$$

Define $\vec{F}$ and $\vec{\eta}$ as

$$\vec{F}=(u-fy-\frac{1}{2}\beta y^2)\vec{i}+v\vec{j}, \quad \vec{\eta}=\vec{V}\cdot\nabla(u-fy+\frac{1}{2}\beta y^2)\vec{i}+\vec{V}\cdot(\nabla v)\vec{j} \quad (9)$$

and $\vec{\eta}$ can be written as

$$\vec{\eta}=[u\frac{\partial u}{\partial x}+v(\frac{\partial u}{\partial y}-f-\beta y)]\vec{i}+(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y})\vec{j}. \quad (10)$$

Thus, $\vec{\eta}$ contains the advections of zonal wind and meridional wind.

The projection of a curl $\vec{\eta}$ onto the vertical direction yields

$$-\vec{k}\cdot(\nabla\times\vec{\eta})=-\frac{\partial u}{\partial x}\frac{\partial v}{\partial x}-u\frac{\partial^2 v}{\partial x^2}-\frac{\partial v}{\partial y}\frac{\partial v}{\partial x}-v\frac{\partial^2 v}{\partial y\partial x}+\frac{\partial u}{\partial x}\frac{\partial u}{\partial y}+u\frac{\partial^2 u}{\partial y\partial x}+\frac{\partial v}{\partial y}(\frac{\partial u}{\partial y}-f-\beta y)+v(\frac{\partial^2 u}{\partial y^2}-\beta). \quad (11)$$

Replacing $\vec{F}$ and $\vec{\eta}$ with the vorticity equation (8), the final vertical vorticity equation can be expressed as:

$$\frac{\partial\xi}{\partial t}=-\vec{k}\cdot(\nabla\times\vec{\eta})-\vec{k}\cdot[\nabla\times(\omega\frac{\partial\vec{F}}{\partial p})]-(f+\beta y)\frac{\partial u}{\partial x}. \quad (12)$$

Because $\vec{\eta}$ contains the advection of horizontal winds, the first term on the right-hand side of the vorticity tendency equation (12) can be called an advection term for it explicitly includes the rotation of advection of the horizontal wind. The second term is a tilting term, which is similar to that in the classic vorticity equation. The third term is related to geostrophic vorticity and horizontal divergence, which is similar to that in the classic vorticity equation. Because the advection term is included explicitly, which is not included explicitly in classic vertical vorticity equation, the new derived vorticity equation is called an advection vorticity equation in the *p*-coordinate.

3 APPLICATION OF THE ADVECTIVE VORTICITY EQUATION TO TYPHOON FUNG-WONG

In this section, the vorticity budget of the advective vorticity equation is done by analyzing Fung-Wong, the first landfall storm in China as a strong typhoon in the year and caused heavy rain over mainland China. At 1400 LST (local standard time, the same below) 25 July 2008, Fung-Wong was moving westward, after forming over the ocean east off the Philippines. Subsequently, it evolved into a severe tropical storm at 0800 July 26 and became a typhoon at 2000 July 27. After landing on Hualian of the island of Taiwan at 0630 July 26, Fung-Wong moved to the southeast coast with high winds, rain, and storm surge on the morning of July 28. At 2200 July 28, it landed at the town of Donghan in Fuqing, Fujian province, with a central pressure of 975 hPa and central maximum wind speed of nearly 33 m s^{-1}, and then moved northwestward but decreased gradually. On the night of July 29, after staying over Fujian for 23 hours, it moved into northeastern Jiangxi province. On the afternoon of July 30, it weakened into a tropical depression in Panyang, Jiangxi province. At 0200 LST July 31, it was removed from the list of coded storms. Since the landfall on Fujian, Fung-Wong had stayed inland for about 52 hours. Figure 1 shows the wind distribution of Fung-Wong at 850 hPa during 0800 July 27–0800 July 30. Winds of Fung-Wong apparently showed an asymmetric structure. Strong winds extended from the southwest side of the typhoon circulation to its south, east and north sides when it shifted its orientation of movement from northwestward to westward. Maximum wind speed at 850 hPa increased from 32 m s^{-1} on July 27 to 36 m s^{-1} on July 28 (Fig. 1a & 1b) before it landed, and then gradually weakened after the landfall. The role of advection in the vorticity equation in this typhoon case will be analyzed through a comparison of the terms on the right hand side of advective vorticity equation, namely, the three terms on the right hand side of Eq.(12) in section 2.

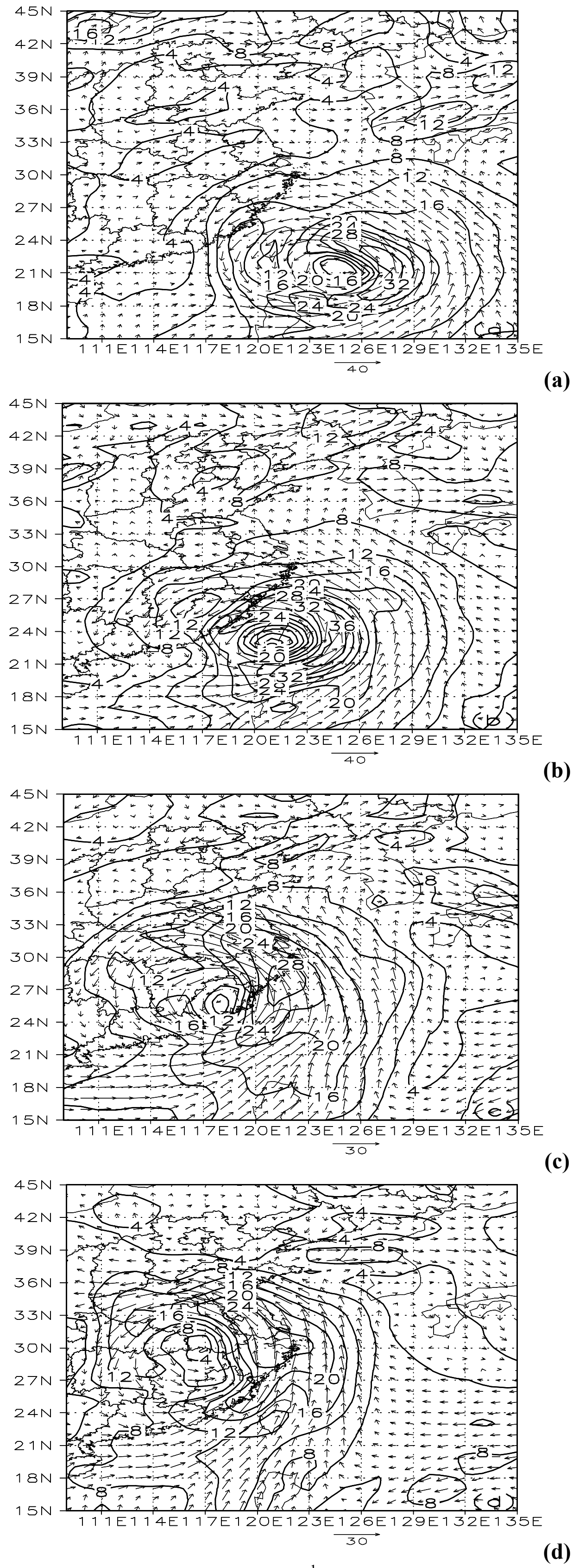

Fig.1 The horizontal wind (m s^{-1}) of Typhoon Fung-Wong at 850 hPa at (a) 0800 July 27, (b) 0800 July 28, (c) 0800 July 29, and (d) 0800 July 30.

Figure 2 shows the distributions of vorticity and vorticity tendencies as calculated from the classic vorticity equation and the advective vorticity equation, respectively, and the advection term, tilting term, and geostrophic vorticity and horizontal divergence term (the three terms to the right hand side of the advective vorticity equation) at 850 hPa on 0800 July 27. As shown in Fig. 2a, positive vorticity is located in the center and the adjacent region of Fung-Wong typhoon. The vorticity tendency calculated from the classic vorticity equation showed that positive vorticity tendency is in the western and eastern parts of Fung-Wong, and negative in the northern and southern parts (Fig. 2b). The value in the western part was larger than that in the eastern part. While the vorticity tendency from the advective vorticity equation suggested that the positive areas in western and eastern parts are linked (Fig. 2c), the positive center in the west is larger than that in the east. Although the positive center of vorticity in the west (5×10^{-5} s^{-1}) calculated from the advective vorticity tendency equation is larger than that (4×10^{-5} s^{-1}) from the classic vorticity equation, the tendencies are similar. The vorticity tendencies associated with the advective vorticity equation at both north and south of the typhoon are negative, but the negative vorticity tendency in the south is significantly larger than that in the north. Since the storm moved to the areas with maximum positive vorticity tendency, the vorticity tendency indicates that the typhoon will move northward, which is demonstrated by the fact that Fung-Wong apparently moved about 400 km northwestward from (21.5°N, 125°E) at 0800 July 27 to (23°N, 121°E) at 0800 July 28 (Fig. 1b). This shows that both vorticity equations can diagnose the movement of Fung-Wong. Further analysis of the different terms of the advective voticity equation (namely, the advective term, tilting term, and the geostrophic vorticity and horizontal divergence term) in Fig. 2c, 2d and 2e shows that the distribution of positive vorticity tendency resulting from the advection is basically consistent with the change of vorticity and the central value (5×10^{-5} s^{-1}) of tendency is greater than that of the other two terms (1×10^{-5} s^{-1} – 1.5×10^{-5} s^{-1}). Thus, the main term that affects the vorticity change of Fung-Wong is the advection term.

At 0800 July 28, the areas with positive vorticity were located at the center and the nearby region of the Fung-Wong circulation (Fig. 3a). The distribution of vorticity tendency (Fig. 3b) derived from the classic vorticity equation shows that a large area of negative vorticity tendency is located in the southeast of Taiwan Island. The positive vorticity tendency calculated from the advective vorticity equation occurs only along the southeast coastline and the Taiwan Strait while the negative vorticity tendency appears over the southeast of Taiwan Island. This indicates that the vorticity over the southeast coastline and Taiwan Strait would enhance and Fung-Wong would move toward this region. The areas where Fung-Wong made landfall at 0800 July 29 were covered by the positive tendency according to calculations from the advective vorticity equation (Fig. 1c). However, the vorticity tendency calculated from the classic vorticity equation cannot give this signal. This implies that the advective effect, which is not included in the classic vorticity equation, is important. Compared to the three terms in the advective vorticity equation (Fig. 3d, 3e and 3f), in the northwestern part of Fung-Wong, the tilting and geostrophic vorticity terms lead to negative vorticity tendency whereas the advection term causes positive vorticity tendency, but the distribution of the totally vertical vorticity tendency is similar to that of the advection term, in which they are both negative in the northeast of the typhoon and positive in the northwest (Fig. 3c & 3d). Hence, the advective term is dominant for these three terms. From its track, one can find that Fung-Wong moved to a northwestward region where the vorticity tendency was positive (Fig. 1c) and landed at 0800 July 29 just in the region where the positive vorticity tendency was on July 28. The positive-value region of the advective term is almost in accord with the track of Fung-Wong.

AT 0800 July 29, the areas of positive vorticity stretched from the southeast coastline of Fujian and Zhejiang provinces to Jiangxi and Anhui provinces (Fig. 4a). The vorticity tendencies derived from the two equations show saddle-shaped distributions. In the typhoon center, the negative vorticity tendencies are in the north and south while the positive vorticity tendencies are in the east and west (Fig. 4b & 4c). The positive vorticity tendency center calculated from the two equations in other areas is basically the same. The maximal positive vorticity area shifted more westward on July 29 than July 28. On July 28, the positive vorticity tendency region was near the southeast coastline and the Taiwan Strait but moved to Fujian and Zhejiang provinces on July 29. This indicates that the vorticity was enhanced in the region where the vorticity tendency was positive, and Fung-Wong moved northwestward to this area after it landed. In Fig. 1d, the circulation of Fung-Wong indicates that after landfall in Fujian, Fung-Wong moved northwestward into Jiangxi province. On July 29, though the vorticity tendencies from the two equations have some minor differences in magnitude and region, the main distribution patterns are similar after the advection weakens (Fig. 4b & 4c). So, both the advective vorticity equation and the classical vorticity equation could show the vorticity changes (Fig. 4 b & 4c) when horizontal advection weakens. Seen from Fig. 4d, 4e, and 4f, the advection remains the dominant term in the advective vorticity equation while the vorticity changes caused by vorticity tilting and advection have opposite signs, and geostrophic vorticity is significantly smaller than in the advective term and tilting term for Fung-Wong.

The above diagnoses of vorticity and its tendency changes during Fung-Wong's development and movement suggest that advection is a major factor that is responsible for the vertical vorticity change. Therefore, for a synoptic system with large advection, such as typhoon Fung-Wong, the advective vorticity equation is an important supplement to the classic vorticity equation. Because the typhoon moves toward regions of positive vorticity tendency in general, they may be taken as a factor to identify the key observational region of typhoons.

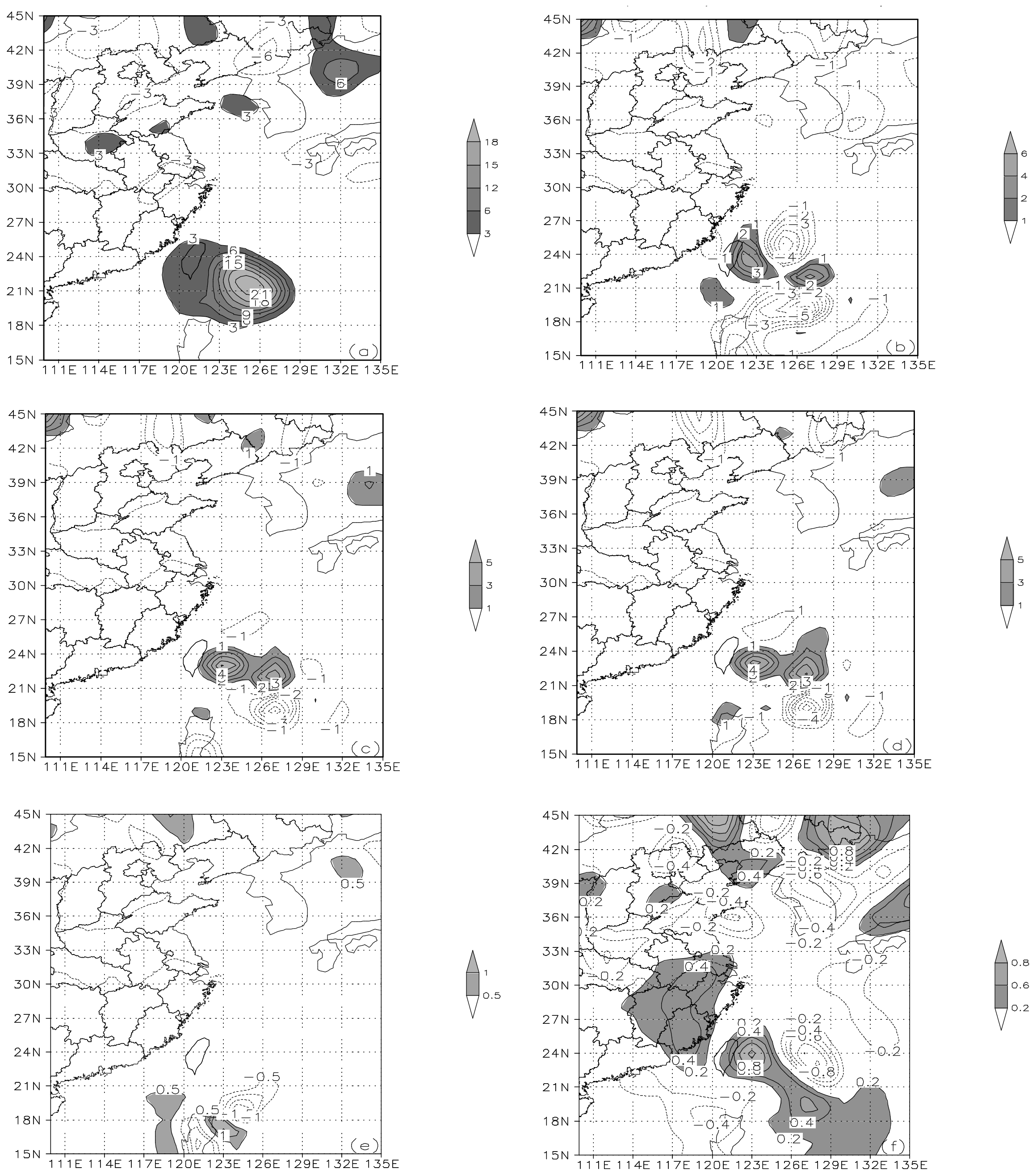

Fig.2 (a) vorticity (10^{-5} m s^{-2}), (b) vorticity tendency in the classic vorticity equation (10^{-9} s^{-1}), (c) vorticity tendency in the advective vorticity equation (10^{-9} s^{-1}), (d) the advective term of advective vorticity equation (10^{-9} s^{-1}), (e) the tilting term of advective vorticity equation (10^{-9} s^{-1}), and (f) geostrophic vorticity and horizontal divergence term (10^{-9} s^{-1}), at 850 hPa at 0800 July 27, 2008.

4 CONCLUSIONS AND DISCUSSION

The advective vorticity equation was introduced, in which the rotation of advection of horizontal wind is included explicitly. When the advection of horizontal wind is large and plays a leading role in the change of vertical vorticity tendency, the advective vorticity equation has an advantage in diagnosis of vertical vorticity tendency in various synoptic systems. The diagnosis of the vorticity and associated vorticity tendency changes in typhoon Fung-Wong shows that the advection of horizontal wind in Fung-Wong is an important factor in determining its change of vertical vorticity. The rotation effect of horizontal wind advection plays a dominative role in the typhoon and the advective term can be used to analyze its vorticity variation as a substitution of vertical vorticity tendency.

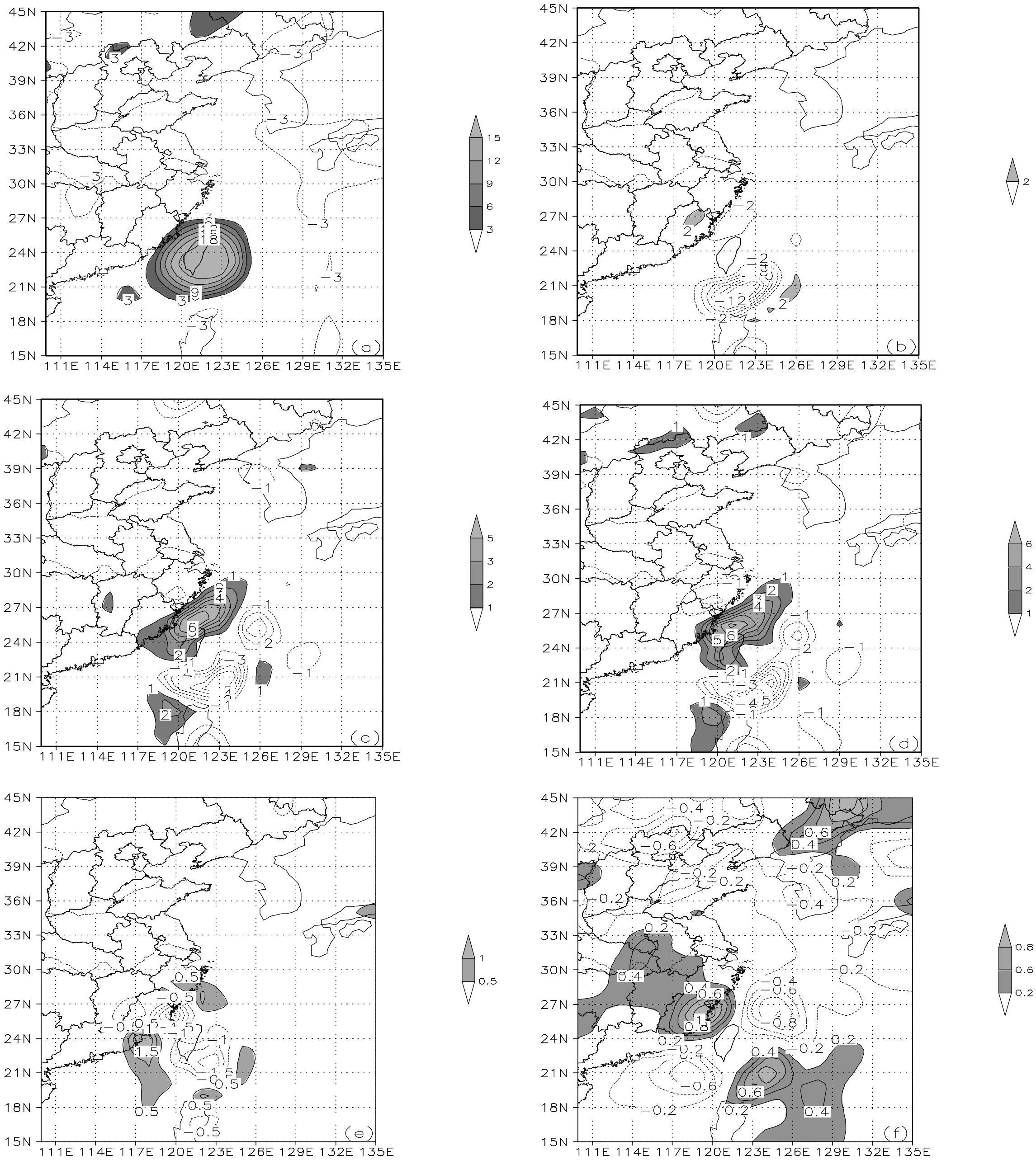

Fig.3 As in Fig.2 except for July 28.

It is necessary to point out that when the convergence or deformation of horizontal wind is important, such as the case in a Meiyu front, diagnosed results by the classic vorticity equation could be better than those by the advective vorticity equation. Nevertheless, the advective vorticity equation with an explicit advection term of horizontal wind is a supplementary diagnostic tool to the classic vorticity equation.

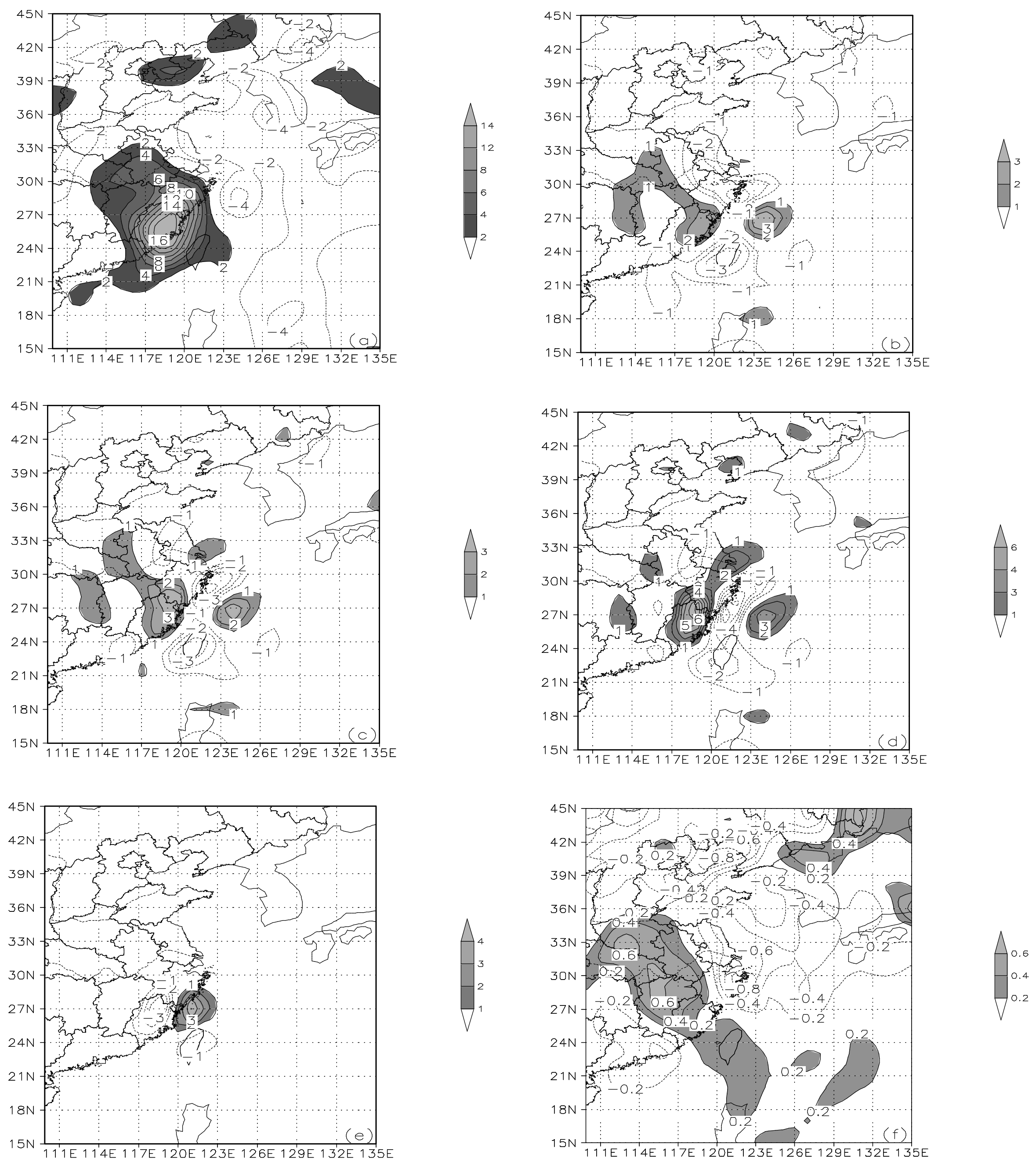

Fig.4 As in Fig.2 except for July 29.

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