The Impact of the Eastward Propagation of Convective Systems over the Tibetan Plateau on the Southwest Vortex Formation in Summer

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Abstract Based on the temperature of the black body (TBB), station observed and NCEP reanalysis data, the impacts of the eastward propagation of convective cloud systems over the Tibetan Plateau on the southwest vortex (SWV) formation that occurred at 1800 UTC on 29 June 2003 are analyzed by using the Zwack-Okossi (Z-O) equation to diagnose the thermal and dynamic processes. It is found that, in summer, severe convective activities often occur over the Tibetan Plateau due to the abundant supply of moisture. The convective cloud near the east edge of the plateau could move eastward with a short-wave trough in the westerly. The divergent center that is induced by latent heat release, which is associated with severe convective activities, moves out with the convective cloud and contributes to the low level decompression which is favorable for the formation of plateau edge cyclogenesis (PEC). The Z-O equation indicates that, in this case, the latent heat release and convergence are the two most important factors for SWV formation, which amounts to about 42% and 15% of the term TOTAL, respectively. It is implied that the thermal process effect was more important than the dynamic process during SWV formation.

Keywords: Tibetan Plateau, southwest vortex, convective system, temperature of the black body, latent heat release, plateau edge cyclogenesis

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1 Introduction

The Tibetan Plateau (Fig. 1) is the highest plateau on Earth (above 4000 m) and has prominent influences on both the weather and climate of East Asia or even the whole world. First, the Tibetan Plateau has distinguished dynamic influences that cause troughs in the southern part and ridges in the northern part (Ye and Gao, 1979; Yang and Yang, 1987; Zhang et al., 1988). Second, the Tibetan Plateau has remarkable thermal influences: It is a cold source in winter, while it is a heat source in summer. Furthermore, with the summer monsoon breakout, severe convective systems often occur over the Tibetan Plateau (Kato et al., 1995; Li and Chen, 2001; Lu et al., 2002; Jiang and Fan, 2002; Zhang et al., 2002; Zhuo et al., 2002; Yasunari and Miwa, 2006), and under some favorable circulations these convective systems (convective clouds near the east edge of the plateau are easier to move out) can move out of the plateau (Fig. 2) and intensify rainfall downstream. Sometimes, the convective systems can cause the formation of plateau edge cyclogenesis (Yasunari and Miwa, 2006), which will trigger the southwest vortex (SWV). The SWV is an important disastrous weather system (Anthes and Heagenson, 1983; Lu, 1986; Yang and Yang, 1987; Gao, 1987; Chen et al., 2003; Zhao and Fu, 2007) that usually appears to the east of the Tibetan Plateau (southwest China) with a horizontal scale of 200–500 km (Zhao, 1977; Lu, 1986). In most cases, the SWVs not only influence their initiation places but some can also move eastwards to impact the middle and lower reaches of the Yangtze River (Lu, 1986; Chen and Min, 2000). In addition, a few SWVs can move to the southeast and cause heavy rainfall in South China (Chen and Min, 2000). The contributions of the dynamic and thermal processes to the formation period of the SWV are complicated, and in different cases the extent of their influence can be different. Previous studies have not given a quantitative diagnosis of the contribution of the dynamic and thermal processes to the formation of SWVs. A SWV with heavy rainfall, which is associated with eastward moving convective systems, is investigated to study the quantitative effect of dynamic and thermal processes in this paper. In this case, the severe convective system formed at the east edge of the Tibetan Plateau at 1200 UTC 29 June 2003 and moved out at 1800 UTC 29 June to trigger a SWV in Sichuan. The maximum six-hour precipitation during the heavy rainfall was about 56 mm, which caused severe floods in Sichuan and Chongqing.

2 Data and methods

The temperature of the black body (TBB) represents the temperature of the cloud top and is a criterion for convective action. The hourly satellite data from the Geostationary Operational Environmental Satellite-9 (GOES-9) with a resolution of 0.05°×0.05° is used to investigate the evolution of convective systems. Reanalysis data with a resolution of 1°×1° from the National Centers for Environmental Prediction (NCEP) is used to study the synoptic

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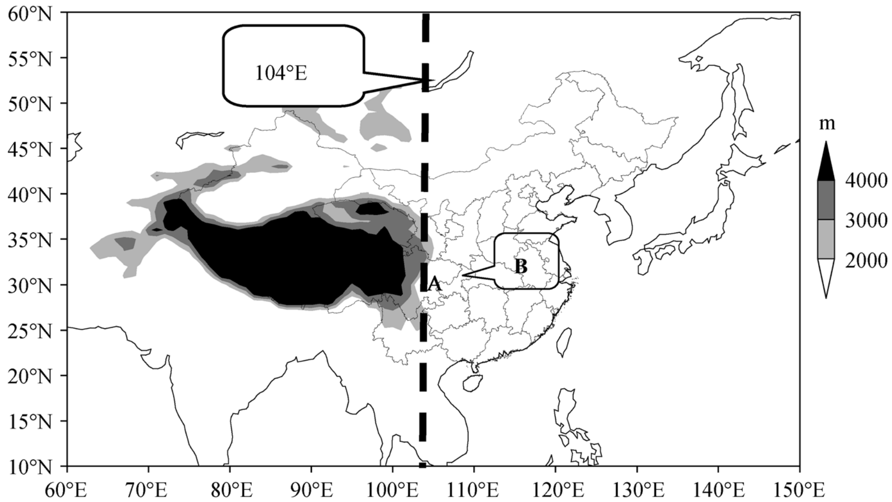

Figure 1 The orography of the Tibetan Plateau; the bold solid line is the east boundary line (104°E) of the Tibetan Plateau, where A stands for Sichuan and B represents Chongqing.

circulation and to calculate some diagnostic variables. In addition, conventional surface observation data are also used to analyze the evolution of convective systems and heavy rainfall.

The diagnostic tool that is used in this study is the Zwack-Okossi (Z-O) equation, which was originally derived by Zwack and Okossi (1986) and then redeveloped by Lupo et al. (1992). The generalized Z-O equation (Lupo et al., 1992) is given as Eq. (1):

$$\frac{\partial \zeta_{gl}}{\partial t} = PD\int_{pt}^{pl}(-\boldsymbol{V}\cdot\nabla\zeta_{\mathrm{a}})\mathrm{d}p - PD\int_{pt}^{pl}\left[\frac{R}{f}\int_{p}^{pl}\nabla^2\left(-\boldsymbol{V}\cdot\nabla T+\frac{\dot{Q}}{c_p}+S\omega\right)\frac{\mathrm{d}p}{p}\right]\mathrm{d}p + PD\int_{pt}^{pl}\boldsymbol{k}\cdot\nabla\times\boldsymbol{F}\mathrm{d}p + PD\int_{pt}^{pl}-\frac{\partial\zeta_{\mathrm{ag}}}{\partial t}\mathrm{d}p + PD\int_{pt}^{pl}-\omega\frac{\partial\zeta_{\mathrm{a}}}{\partial p}\mathrm{d}p + PD\int_{pt}^{pl}\left(-\frac{\partial\omega}{\partial x}\frac{\partial v}{\partial p}+\frac{\partial\omega}{\partial y}\frac{\partial u}{\partial p}\right)\mathrm{d}p + PD\int_{pt}^{pl}\zeta_{\mathrm{a}}\frac{\partial\omega}{\partial p}\mathrm{d}p, \quad (1)$$

where pl is the near-surface pressure level, T is the temperature, $\boldsymbol{k}$ is unit vector along Z direction, ζ_{ag} is the geostrophic absolute vorticity, pt is the upper pressure level, ζ_{gl} is the near-surface geostrophic vorticity, ζ_{a} is the absolute vorticity, f is the Coriolis parameter, R is the dry-air gas constant, $\boldsymbol{V}$ is the horizontal wind vector, $\dot{Q}$ is the diabatic heating/cooling rate per unit mass, c_p is the specific heat at constant pressure, S is the static stability parameter, ω is the vertical motion in isobaric coordinates, $\boldsymbol{F}$ is the frictional force, p is the pressure, and $PD=(pl-pt)^{-1}$. Lupo et al. (1992) suggest that Eq. (1) can be simplified as follows:

$$\frac{\partial \zeta_{gl}}{\partial t} = PD\int_{pt}^{pl}(-\boldsymbol{V}\cdot\nabla\zeta_{\mathrm{a}})\mathrm{d}p - PD\int_{pt}^{pl}\left[\frac{R}{f}\int_{p}^{pl}\nabla^2\left(-\boldsymbol{V}\cdot\nabla T+\frac{\dot{Q}}{c_p}+S\omega\right)\frac{\mathrm{d}p}{p}\right]\mathrm{d}p, \quad (2)$$

$$\mathrm{VORA} = PD\int_{pt}^{pl}(-\boldsymbol{V}\cdot\nabla\zeta_{\mathrm{a}})\mathrm{d}p,$$

$$\mathrm{TEMP} = -PD\int_{pt}^{pl}\left[\frac{R}{f}\int_{p}^{pl}\nabla^2\left(-\boldsymbol{V}\cdot\nabla T\right)\frac{\mathrm{d}p}{p}\right]\mathrm{d}p,$$

$$\mathrm{DIA} = -PD\int_{pt}^{pl}\left[\frac{R}{f}\int_{p}^{pl}\nabla^2\left(\frac{\dot{Q}}{c_p}\right)\frac{\mathrm{d}p}{p}\right]\mathrm{d}p,$$

$$\mathrm{ADI} = -PD\int_{pt}^{pl}\left[\frac{R}{f}\int_{p}^{pl}\nabla^2\left(S\omega\right)\frac{\mathrm{d}p}{p}\right]\mathrm{d}p,$$

where VORA and TEMP represent the effect of the absolute vorticity advection and the temperature advection, respectively. DIA is the diabatic heating/cooling and ADI is the adiabatic heating or cooling. Sensible heat, radiation heating, and latent heat release were all calculated in this case; the results show that the latent heat release was much larger than the other two terms (not shown). As a result, only the latent heat release is retained in the DIA term and all other diabatic heating effects are ignored. Kuo (1974) modified his cumulus parameter scheme (Kuo, 1965), which has been further developed by Edmon and Vincent (1976). The modified Kuo scheme is used to calculate the latent heat release; the precipitation that is calculated by this scheme approximately coincides with the observed rainfall (Fig. 2). Many previous studies show (Lu, 1986; Chen et al., 2003; Zhao and Fu, 2007; Fu, 2009) that the convergence term in the vorticity equation, which may be due to friction in the boundary layer, is very important to vorticity development in the SWV; as a result, we add the convergence effect to Eq. (2):

$$\frac{\partial \zeta_{gl}}{\partial t} = PD\int_{pt}^{pl}(-\boldsymbol{V}\cdot\nabla\zeta_{\mathrm{a}})\mathrm{d}p - PD\int_{pt}^{pl}\left[\frac{R}{f}\int_{p}^{pl}\nabla^2\left(-\boldsymbol{V}\cdot\nabla T+\frac{\dot{Q}}{c_p}+S\omega\right)\frac{\mathrm{d}p}{p}\right]\mathrm{d}p + PD\int_{pt}^{pl}\zeta_{\mathrm{a}}\frac{\partial\omega}{\partial p}\mathrm{d}p, \quad (3)$$

$$\mathrm{CON}=PD\int_{pt}^{pl}\zeta_{\mathrm{a}}\frac{\partial\omega}{\partial p}\mathrm{d}p\,,$$

where CON is the convergence effect, which can be written in the form of convergence by using the continuity equation. It is to be noted that, since CON is calculated by integrating from low levels to high levels and since the sign of low level convergence and high level divergence is opposite, the total effect may be smaller than that of low level convergence or high level divergence. In this paper, we set *pl* at 850 hPa, which is near the low level for the SWV, while *pt* is set to 650 hPa, which is the top level of the SWV.

3 Results

A severe convective cloud C (TBB < 210 K) occurred in the southeast part of the Tibetan Plateau at 1200 UTC 29 June near the moisture convergence center at 500 hPa (Figs. 3a and 3b). The convective cloud C moved slowly eastward and contributed to the formation of a SWV (plateau edge cyclogenesis (PEC)) at 1800 UTC 29 June, which stayed quasi-stationary and dissipated at 0000 UTC 31 June with a lifetime of about 30 hours. During the lifetime of the SWV, heavy rainfall occurred in the eastern part of Sichuan and Chongqing; the maximum six-hour precipitation of 56 mm occurred in the southwestern part of Chongqing. It can be found that (from Figs. 3a and 3b) the convective cloud C formed and maintained association with a short-wave trough in the westerly at 500 hPa. The convective system formed due to the upward motion zone near the trough-line of the short-wave trough; the upward motion maintained the convective system. As Figs. 3a and 3b shows, the west wind ahead of the trough was favorable for eastward movement of the convective systems; they moved eastward with the trough and almost in the same direction as the 200–500 hPa averaged wind (this layer corresponds approximately to the layer between the top and bottom of the convective systems, it is not shown).

The divergent center ($2\times10^{-5}\,\mathrm{s}^{-1}$) "E" at about 200 hPa moved eastward with the convective cloud C and became more intensive from 0000 UTC to 0600 UTC 30 June, when the heavy rainfall that was associated with the SWV enhanced (Figs. 3c–j and Fig. 2). The divergent center "E" may appear from the heavy latent heat release that is associated with the convective cloud C and is favorable for decompression at low levels*, which finally contributed to the formation of the SWV (PEC). It should be noted that, in most cases, if the convective cloud triggers new convections, the divergent center will last much longer; if not, it will disappear soon. A positive vorticity center in the Sichuan Basin is coherent with the horizontal wind shear (Figs. 3c–j). Six hours before the formation of the SWV, a weak positive vorticity zone that was associ-

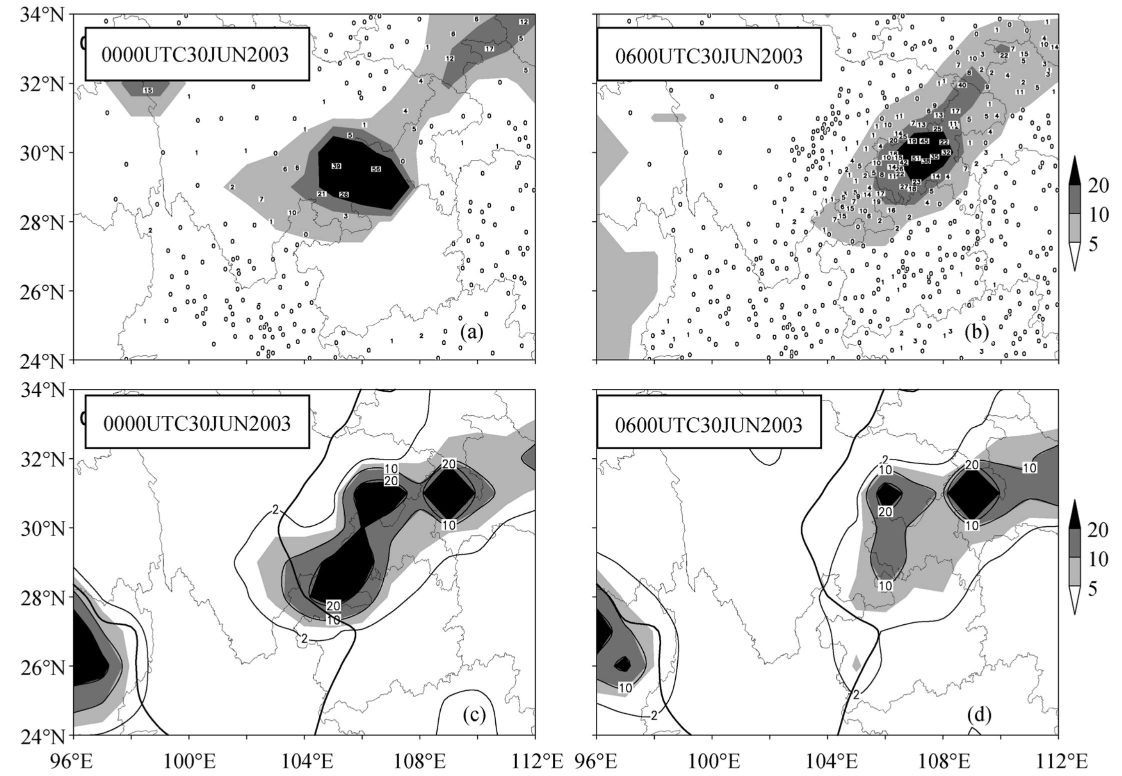

Figure 2 (a) and (b): Observed rainfall; (c) and (d): the rainfall calculated from the Kuo scheme 1974 (Units: mm).

* The latent heat release that is associated with convective activities enhanced the divergence at higher levels, which was favorable for decompression at lower levels; this resulted in the compensation current into the low levels beneath the convection center, which enhanced the convergence there. From the vorticity budget equation, it is obvious that convergence is very favorable for a positive vorticity increase; as a result, this would be favorable for SWV formation.

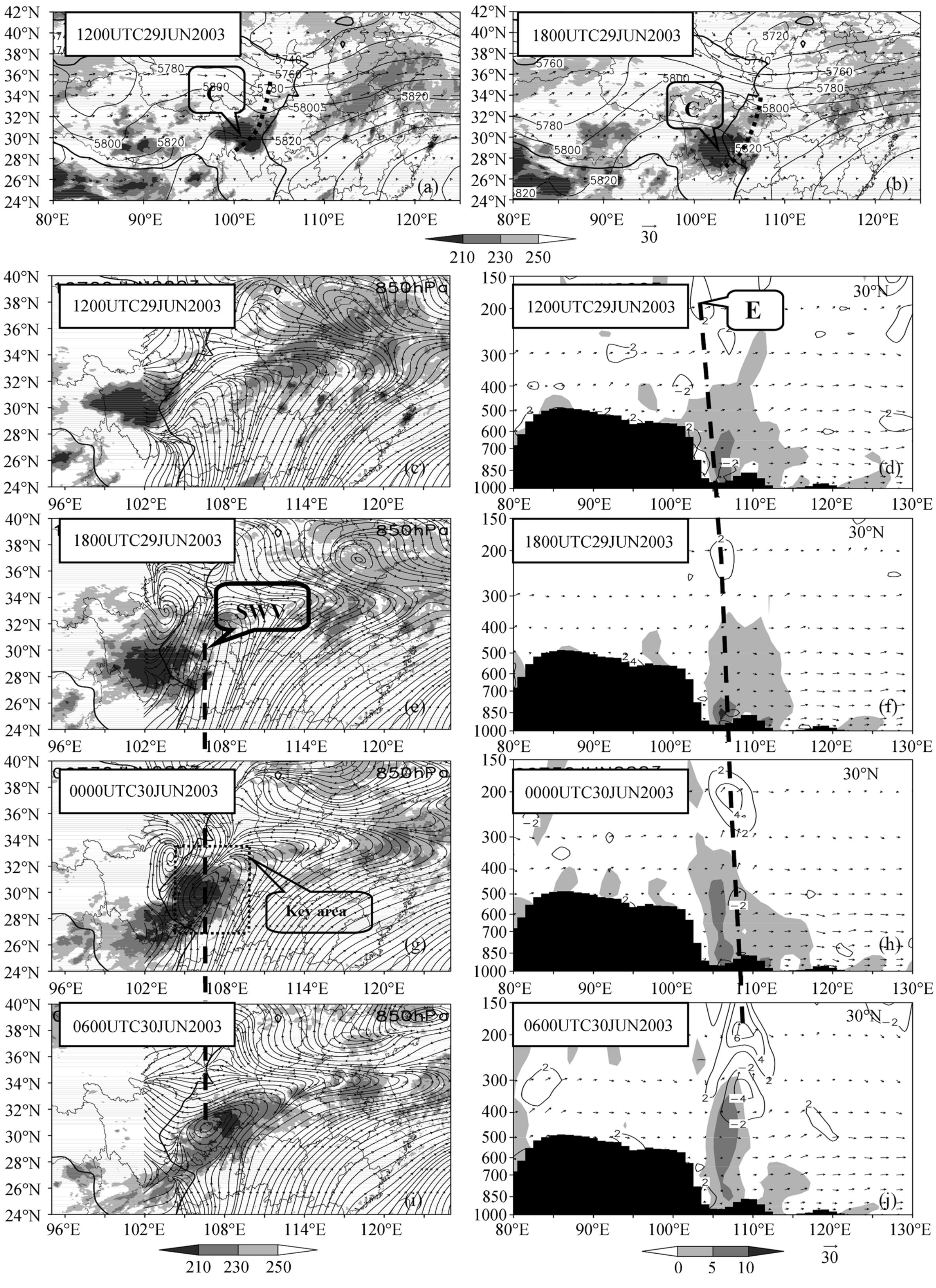

Figure 3 The synoptic weather pattern of the convective system's eastward propagation from the Tibetan Plateau. (a) and (b): The synoptic circulation at 500 hPa, where the solid lines are the geopotential height in gpm, the shaded areas are the TBB (K) and the vector is the wind field averaged between 200 hPa and 500 hPa (Units: m s^{-1}). (c)–(j): The streamline at 850 hPa and the zonal (30°N) sections of the vorticity. In the left column, the shaded areas are the TBB (Units: K), the thick black dashed line stands for propagation of the southwest vortex, the dashed rectangles are the key area of the SWV and the solid black line indicates the topographic contour for 1500 m. In the right column, the shaded areas are the vorticty (Units: 10^{-5} s^{-1}), the solid line is the convergence (Units: 10^{-5} s^{-1}), the arrows are the zonal wind and the vertical velocity×200 (Units: m s^{-1}). "E" represents the divergence center that is associated with the latent heat release.

ated with the short-wave trough moved eastward from the east edge of the Tibetan Plateau. The vertical motion intensified and extended from the low level to the middle level, while the SWV also intensified at the same time. The SWV strengthened six hours after its formation, associated with the heavy rainfall period (Fig. 2).

From the analysis above, we can conclude that the formation of the SWV is a very complex process since it is associated with thermal and dynamic processes. From the Z-O equation, the thermal process and the dynamic process can be separated for a quantitative analysis. From Fig. 2, it is clear that the distribution and intensity of the calculated rainfall by the Kuo scheme is approximately consistent with the observation, although the maximum rainfall is slightly different. As a result, the heat calculation by modified Kuo scheme can be used to do further studies.

Since the SWV remained stationary, we define the key area to be 27–34°N, 104–110°E, which includes the central part of the SWV (rectangles in Fig. 3 and Fig. 4). From Figs. 4a and 4b, it is found that at 1200 UTC 29 June, six hours before the SWV formation, there was a positive vorticity center (above 10^{-4} s^{-1}) in the Sichuan Basin that was associated with the latent heat release (DIA) center; this indicates that latent heat release will enhance the positive vorticity, which is favorable for the SWV formation (the SWV formed six hours later). At 1800 UTC 29 June, both DIA center and the positive vorticity center increased rapidly as a result of the severe heavy rainfall, which is favorable for the maintenance and development of the SWV.

Term TOTAL is defined as the total effects of terms on the right side of Eq. (3), namely, TOTAL=VORA+TEMP+DIA+ADI+CON. At 1800 UTC 29 June (Fig. 4c), six hours before the SWV formed, DIA, which amounted to about 42% of the TOTAL, is the most important positive effect; the term CON, which amounts to about 15% of the term TOTAL, is the most important positive dy-

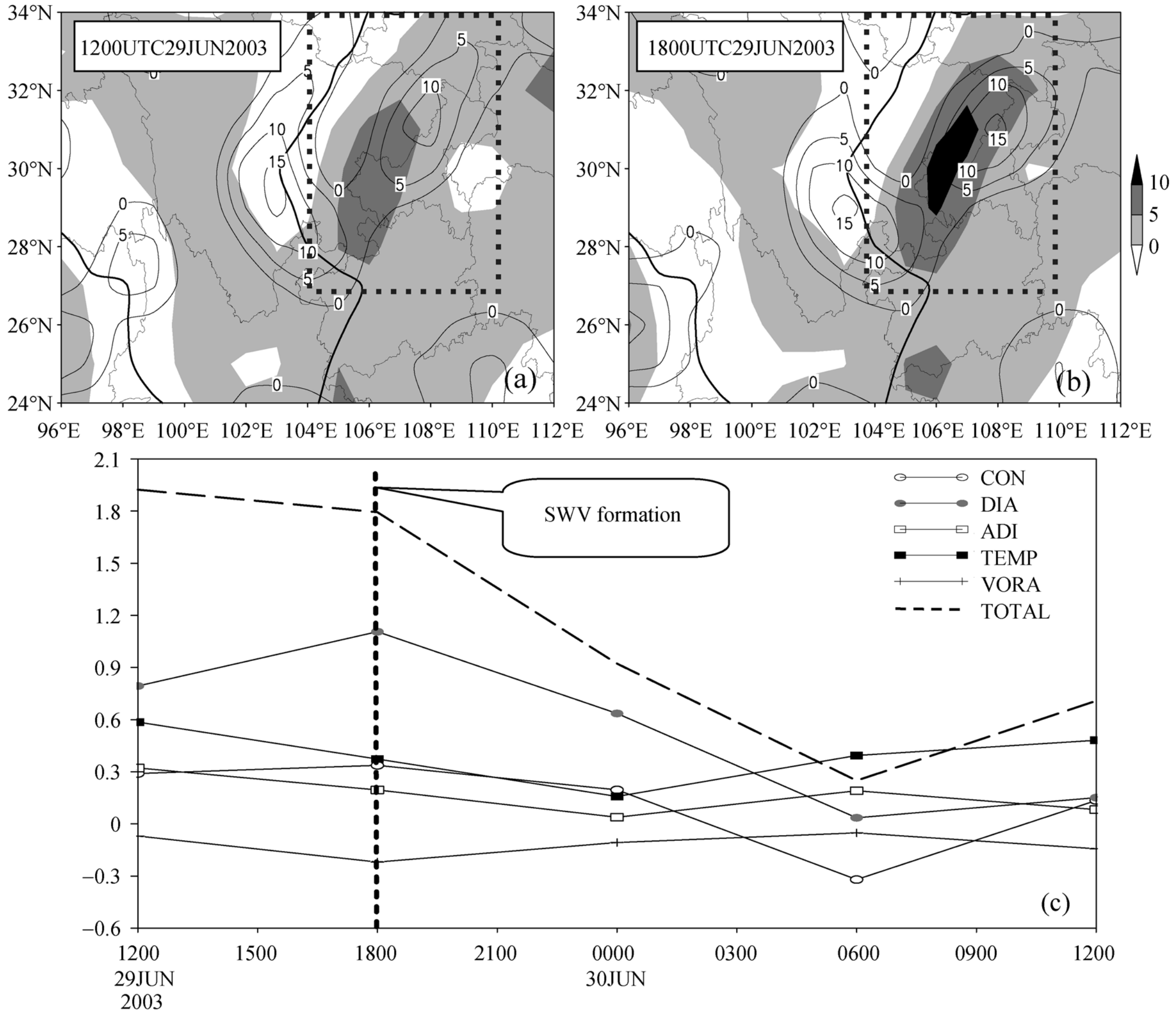

Figure 4 The calculation of the terms from the Z-O equation. (a) and (b): The diabatic heating term (solid lines, units: 10^{-9} s^{-2}) and the vorticity (shaded, units: 10^{-5} s^{-1}) at 850 hPa, where the dashed rectangles represent the key areas of the SWV (27–34°N, 104–110°E) and the thickest solid line is the topographic contour for 1500 m. (c) The Z-O equation terms for the averaged key area (27–34°N, 104–110°E), where CON stands for the convergent term, DIA is the diabatic heating term, ADI is the adiabatic term, TEMP is the temperature advection term, VORA is the absolute vorticity advection term, and the TOTAL is the total effect of all the terms above. The units of all the above terms are 10^{-9} s^{-2} and the dotted lines stand for the SWV formation time.

namic process, while the absolute vorticity advection effect was negative. The SWV formed at 1800 UTC 29 June when the term DIA reached its maximum, which amounted to about 63% of the TOTAL; these conditions were very favorable for maintaining and developing the SWV. At the same time, the term CON also slightly increased, which corresponds to the convergence increasing (not shown). From 0000 UTC 30 June to 0600 UTC 30 June, the term DIA decreased, while the rainfall enhanced (Fig. 2). It can be found that, according to Eq. (3), the term DIA is defined not only by the amount of latent heat release but also by the distribution of it; thus, as the vertical gradient of the latent heat release increases, the term DIA increases. Based on the above-mentioned analyses, during the formation period of the SWV, the thermal process (Term DIA) is more important than the dynamic processes (Term VORA and Term CON). Generally speaking，during the formation of the SWV, the relative importance of the thermal and dynamic processes are different; in some cases, the dynamic processes play the leading role (there was little convective activities before the SWV formation), while in other cases, the thermal processes take charge (like the case in the paper). For different kinds of vortexes, the relative importance of the thermal and dynamic processes are also different; for instance, Lupo et al. (1992) investigated two extratropical cyclones (one land cyclone and one marine cyclone) and indicated that the dynamic process were more important for the marine cyclone, while the thermal processes that are related to latent heat release were more important for the land cyclone. As for tropical cyclones, such as typhoons, the dynamic processes (such as convergence) are very important during the formation stage, while the thermal processes (CISK) make the typhoon develop quickly after formation.

4 Conclusions

In this paper, a SWV (PEC) process (29–30 June 2003), which caused heavy rainfall in Sichuan and Chongqing, was investigated by using the Z-O equation to diagnose the thermal and dynamic processes. The results are as follows.

(1) In summer, favorable moisture conditions and severe convective activities (TBB<210 K) often occur over the Tibetan Plateau. When a short-wave trough in the westerly propagates from the Tibetan Plateau to the eastern part of the Tibetan Plateau, the convective cloud system near the east edge of the plateau is easy to move eastward out of the plateau.

(2) The divergent center, which is associated with latent heat release by severe convective activities, moves out with the convective cloud, and it contributes to low level decompression that can induce the formation of the SWV (PEC). In most cases, the divergent center will last longer if the convective cloud triggers new convections; otherwise, it will dissipate soon.

(3) The Z-O equation analysis indicates that, in this case, during the SWV formation period, the thermal process effect was much more important than the dynamic process. The latent heat release was the most important factor (about 42% of TOTAL), which contributed to the SWV formation. The convergence term (about 15% of TOTAL) that is associated with terrain characteristics is the second important factor for the formation of the SWV.

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