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An Analysis of the Eddy Kinetic Energy Budget of a Southwest Vortex during Heavy Rainfall over South China

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Abstract Based on the 6-hour-interval reanalysis data with $1^{\circ}\times 1^{\circ}$ resolution from the National Center for Environmental Prediction/the National Center for Atmospheric Research (NCEP/NCAR), the eddy kinetic energy (EKE) budget of a southwest vortex (SWV) that caused heavy rainfall in Guangxi over South China (from 1200 UTC 11 to 0000 UTC 13 June) is calculated. The results are as follows: (a) The SWV is a kind of subtropical vortex, with characteristics of both an extratropical vortex and a tropical vortex. (b) In the case examined, large-scale circulation and other perturbation fields contributed to the formation and development of the SWV. (c) When the SWV moved from weak large-scale circulation EKE areas to strong ones, the EKE of the SWV increased, and vice versa**.** (d) Sub-grid processes and frictional dissipation were the main sinks of the SWV EKE, which contributed to the decay of the SWV. (e) The residual term (RES) and the Total (composite effect of all right hand side (rhs) terms except the RES in the EKE equation) varied almost in the same tendency, which kept the EKE varying in a moderate way. (f) The EKE between 550 hPa and 850 hPa increased most intensively, corresponding to the vertical stretching of the SWV.

Keywords: SWV, EKE, barotropical transition, baroclinic transition

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1 Introduction

The southwest vortices (SWVs) that are generated in southwest China are of a kind of meso-scale vortex with a horizontal scale of ~200–500 km. Generally, the cyclonic circulation mainly appears in the low-level troposphere (below 700 hPa). The special topography of the Tibetan Plateau and Sichuan Basin and a favorable synoptic circulation are two important factors that contribute to the formation of these SWVs. As important heavy rainfall producing systems, SWVs occur with a high frequency, especially in the summer and autumn (Lu, 1986). Many previous studies have examined the structure of SWVs (Zhao, 1977; Lu, 1986), their formation and developmental mechanisms (Gao, 1987; Wu and Liu, 1999; Zhao and Fu, 2007), their statistical features (Chen and Min, 2000), numerical simulations of them (Anthes and Heagenson, 1984; Chen and Lorenzo, 1984; Kuo et al., 1988; Wang and Gao, 2003) and the relationship between heavy rainfall and SWVs (Chen et al., 2003; Zhao and Fu, 2007).

Eddy kinetic energy (EKE) is an important energy (it can reveal synoptic perturbation), and has been examined in order to reveal the developmental mechanisms of cyclones. Ding and Liu (1985) have analyzed the eddy kinetic energy budget of a typhoon, and their results show that the EKE remained convergent during the period prior to the typhoon and changed to divergent during the mature period of the typhoon. Orlanski and Katzfey (1991) have calculated the eddy energy budget of a cyclone wave in the Southern Hemisphere and found that while the wave grew initially by the poleward advection of heat, the system evolved only up to the point where this source of eddy energy and the conversion of eddy potential energy to eddy kinetic energy was compensated for by an energy flux divergence. Liu and Liang (1993) have calculated the eddy kinetic energy budget of monsoon depressions over the South China Sea and found that convergence is very important to the development of EKE. Zhu and Sun (2001) have examined EKE to analyze the maintenance of storm tracks. However, until now, there has not been an analysis of the eddy kinetic energy budget during the formation and developmental process of an SWV. In the present paper, a southward propagating SWV that produced heavy rainfall in southern China has been selected to study the eddy kinetic energy budget of an SWV. Based on previous work, the eddy kinetic energy budget of this SWV is calculated in this paper.

2 Data and methods

The eddy kinetic energy budget is calculated based on the 6-hour-interval reanalysis data with $1^{\circ}\times 1^{\circ}$ resolution from the National Center for Environmental Prediction/the National Center for Atmospheric Research (NCEP/NCAR). The budget equation of the EKE is as follows (Ding and Liu, 1985):

$$\frac{\delta K_{\mathrm{E}}}{\delta t} = \underbrace{I(K_{\mathrm{Z}}, K_{\mathrm{E}})}_{\text{Term1}} + \underbrace{I(P_{\mathrm{E}}, K_{\mathrm{E}})}_{\text{Term2}} + \underbrace{F_{\mathrm{H}}(K_{\mathrm{E}})}_{\text{Term3}} + \underbrace{F_{\mathrm{V}}(K_{\mathrm{E}})}_{\text{Term4}} + \underbrace{F_{C}(K_{\mathrm{E}})}_{\text{Term5}} + \underbrace{F_{\mathrm{H}}(P_{\mathrm{E}})}_{\text{Term6}} + \underbrace{F_{\mathrm{V}}(P_{\mathrm{E}})}_{\text{Term7}} + \underbrace{D(K_{\mathrm{E}})}_{\text{RES}}. \quad (1)$$

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The left hand side (lhs) of Eq. (1) gives the Lagrangian coordinates following the SWV, and the right hand side (rhs) terms of the equation are defined as Term1−Term7 and RES. The explanations of Term1−Term7 and RES are as follows:

$$I(K_Z, K_E) = -\overline{[u'v']\frac{\cos\varphi}{a}\frac{\partial}{\partial\varphi}\frac{[u]}{\cos\varphi}} - \overline{[v'v']\frac{1}{a}\frac{\partial[v]}{\partial\varphi}} - \overline{[u'\omega']\frac{\partial[u]}{\partial p}} - \overline{[v'\omega']\frac{\partial[v]}{\partial p}} + \overline{[u'u'][v]\frac{\tan\varphi}{a}},$$

where [ ] stands for the zonal mean, thus, variables can be written as $p=[p]+p'$, where p' represents eddy and $\overline{[p]}$ stands for the area-averaged variable. $K_E=(u'^2+v'^2)/2$ is the eddy kinetic energy per unit mass, and $K_Z=\overline{([u]^2+[v]^2)/2}$ is the area-averaged zonal mean kinetic energy. φ is latitude, a is radius of the earth, u is zonal wind, v is meridional wind, and p is pressure. $I(K_Z, K_E)$ is defined as Term1, which represents the transition between zonal mean kinetic energy and EKE, namely, it is the barotropical energy transition.

$$I(P_E, K_E) = -\frac{R}{p}\overline{[\omega' T']},$$

where R is gas constant. $I(P_E, K_E)$ is defined as Term2, which stands for the transition between available potential energy and EKE, namely, the baroclinic energy transition.

$$F_H(K_E) = -\overline{\left[\frac{1}{a\cos\varphi}\frac{\partial(uK_E)}{\partial\lambda}\right]} - \overline{\left[\frac{1}{a\cos\varphi}\frac{\partial(vK_E\cos\varphi)}{\partial\varphi}\right]},$$

where λ is lontitude. $F_H(K_E)$ is defined as Term3, which stands for the horizontal flux divergence of EKE, namely, the horizontal transportation of EKE by large scale circulation.

$$F_V(K_E) = -\overline{\left[\frac{\partial(\omega K_E)}{\partial p}\right]},$$

where ω is vertical velocity (Pa s^{-1}). $F_V(K_E)$ is defined as Term4, which represents the vertical flux divergence of EKE, namely, the vertical transportation of EKE by large-scale circulation.

$$F_C(K_E) = \overline{\left[\frac{c_\lambda}{a\cos\varphi}\frac{\partial K_E}{\partial\lambda}\right]} + \overline{\left[\frac{c_\varphi}{a\cos\varphi}\frac{\partial(K_E\cos\varphi)}{\partial\varphi}\right]}.$$

$F_C(K_E)$ is defined as Term5, which represents the horizontal divergence of EKE caused by the system movement ($\boldsymbol{c}=c_\lambda \boldsymbol{i}+c_\varphi \boldsymbol{j}$ stands for the propagation velocity of the system).

$$F_H(P_E) = -\overline{\left[\frac{1}{a\cos\varphi}\frac{\partial(u'\phi')}{\partial\lambda}\right]} - \overline{\left[\frac{1}{a\cos\varphi}\frac{\partial(v'\phi'\cos\varphi)}{\partial\varphi}\right]},$$

where ϕ' is geopotential perturbation. $F_H(P_E)$ is defined as Term6, which represents the horizontal flux divergence of eddy potential energy, namely, the horizontal transportation of eddy potential energy by perturbations.

$$F_V(P_E) = -\overline{\left[\frac{\partial(\omega'\phi')}{\partial p}\right]}.$$

$F_V(P_E)$ is defined as Term7, which represents the vertical flux divergence of eddy potential energy, namely, the vertical transportation of eddy potential energy by perturbations.

$D(K_E)$ is defined as RES, which stands for the dissipation of EKE by friction and sub-grid processes, and this term can be calculated from the residual term.

Total is defined as Total=Term1+Term2+Term3 +Term4+Term5+Term6+Term7, which represents the composite effect of Term1−Term7 (and does not include RES).

3 Results

During the period of 11–13 June 2008, an SWV formed in southern Sichuan and moved southeastward firstly, and then turned northeastward (Fig. 1), producing heavy rainfall in the Guangxi Province. According to the lifetime of the SWV, the development of the SWV can be divided into four stages: (a) 1800 UTC 10–0000 UTC 11 June, which is the formation period; (b) 0600 UTC–1800 UTC 11 June, which is the maintenance period of the SWV; (c) 0000 UTC–1200 UTC 12 June, which is the mature period of the SWV; and (d) 1800 UTC 12–0000 UTC 13 June, which is the decay period of the SWV and the formation period of vortex B (Fig. 1). According to the vorticity and streamlines, the key areas (relying on) of the SWV are identified in Fig. 1, and the key areas of the SWV during the different stages are listed in Table 1.

The budget of the EKE in the key areas of the SWV at 700 hPa is shown in Fig. 2. It is revealed that Term1 is always positive during the formation and maintenance period of the SWV (1800 UTC 10–1800 UTC 11 June). Subsequently, there was less than a 1.5 J kg^{-1} s^{-1} barotropical energy transition, and after that, a stronger energy transition occurred from 0000 UTC to 1200 UTC 12 June during the mature period of the SWV. Therefore, the barotropical energy transition was favorable for the increase of EKE, which contributed to the formation and maintenance of the SWV.

The baroclinic energy transition (Term2) was unfavorable for the formation of the SWV before 0000 UTC 11 June. Then, it contributed to the development of the SWV in the period of 0000 UTC–1800 UTC 11 June (Term2 was positive during this period, which means the available potential energy was converted to EKE), and finally, the decay of the SWV was accelerated (Term2, Term3, Term5, and RES are the main terms that contributed to the decay of the SWV). Comparing Term1 and Term2, it is clear that the intensity of the baroclinic energy transition is significantly stronger than barotropical energy transition, thus, the SWV is a kind of subtropical perturbation.

Except for during the decay period of the SWV, the horizontal flux divergence of the EKE (Term3) in key areas was always convergent (Fig. 2). The horizontal EKE was transported into key areas of the SWV by the large-scale circulation, and this was favorable for the formation and maintenance of the SWV. During the decay period of the SWV, Term3 changed to being divergent,

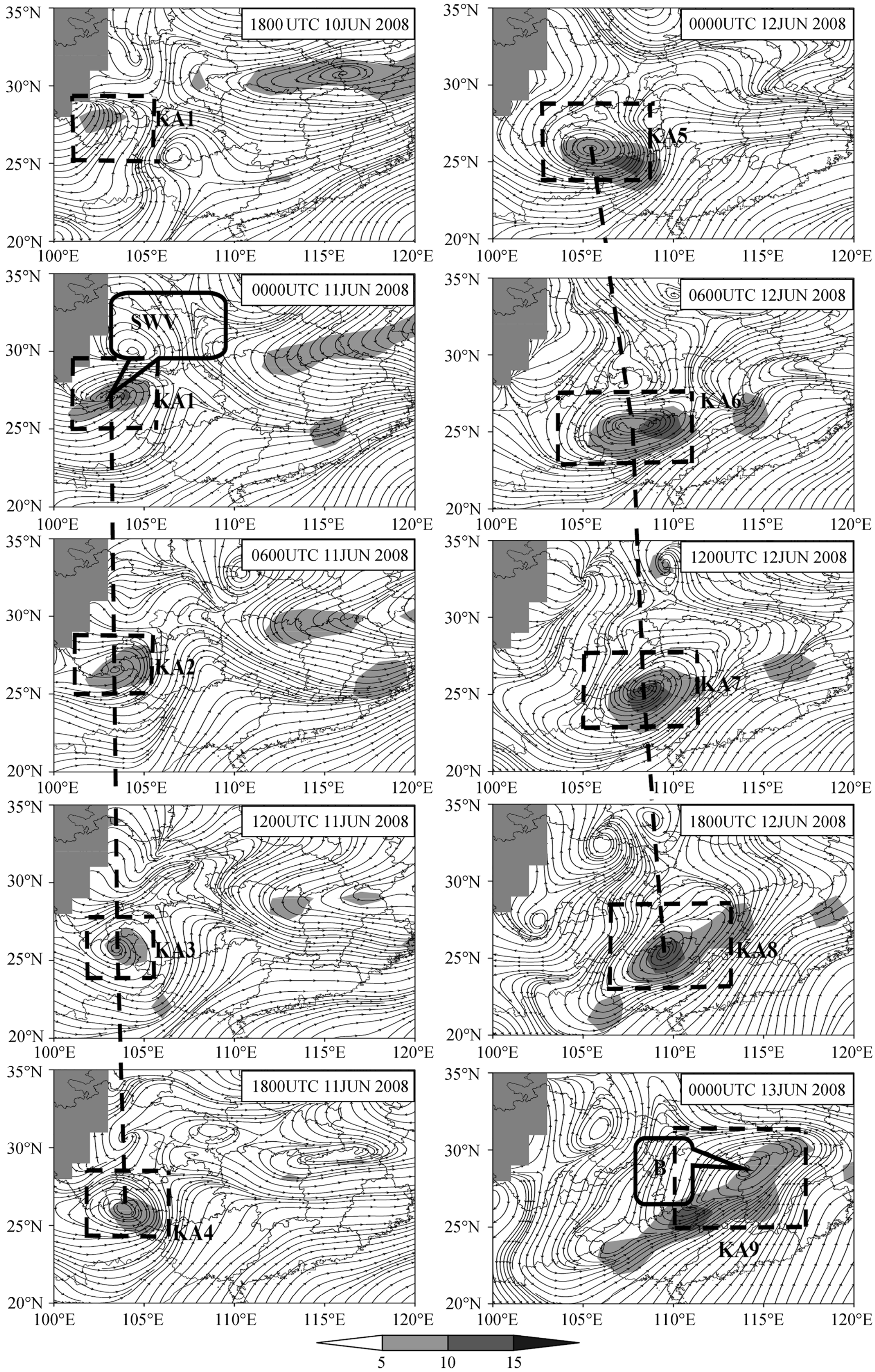

Figure 1 Stream field at 700 hPa. Shaded areas show the vorticity (units: s^{-1}); solid lines are the streamlines; terrain above 3000 m is colored (on the top left side): dashed lines stand for how the system moved; and dashed rectangles stand for KA of the SWV.

Table 1 Key areas of the SWV during its evolution.

Period of SWV	Time	Key areas (KA) of the SWV
Formation stage	1800 UTC 10–0000 UTC 11 June	KA 1: 25–29°N, 101–106°E
Maintenance stage	0600 UTC 11 June	KA 2: 25–28.5°N, 101–105.5°E
	1200 UTC 11 June	KA 3: 24–28°N, 101.5–105.5°E
	1800 UTC 11 June	KA 4: 24–28°N, 102–106.5°E
Mature stage	0000 UTC 12 June	KA 5: 23.5–28°N, 102.5–109°E
	0600 UTC 12 June	KA 6: 22.5–27.5°N, 103.5–111°E
	1200 UTC 12 June	KA 7: 23–28°N, 105–111.5°E
Decay stage of SWV	1800 UTC 12 June	KA 8: 23–29°N, 106–113°E
Formation of vortex B	0000 UTC 13 June	KA 9: 25–31°N, 110–117°E

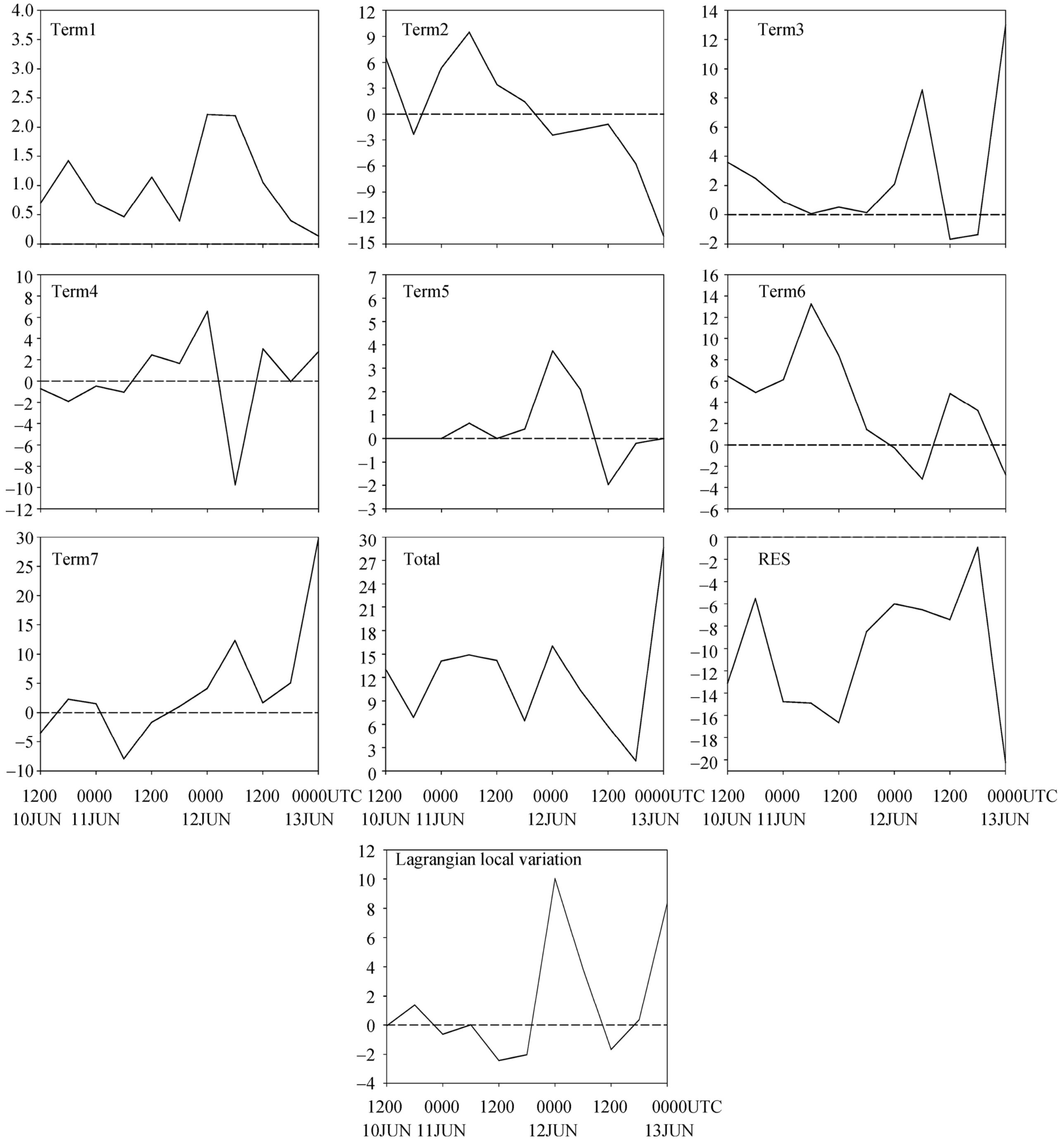

Figure 2 The budget of eddy kinetic energy in key areas of the SWV at 700 hPa (units: 10^{-4} J kg^{-1} s^{-1}).

which contributed to the decay of the SWV. The vertical flux divergence of the EKE (Term4) was divergent (Fig. 2) before 0000 UTC 12 June (during the formation and maintenance periods), which was unfavorable for the formation and maintenance of the SWV. During the mature and decay periods of the SWV, Term4 was mainly convergent (except for the period of 0600 UTC 12, when there was a maximum in Term3 at the same time). The intense horizontal convergence may have caused the intense vertical divergence, contributing to the development of the SWV. The composite effect of the horizontal and vertical flux divergences of the EKE were mainly convergent in the key areas of the SWV; therefore, the large-scale circulation is favorable for the formation and development of an SWV.

From Figs. 1 and 2, it can be seen that Term5 was positive when the SWV propagated southeastward, which was favorable for the development of the SWV. On the contrary, Term5 was negative when the SWV moved northeastward, which was unfavorable for the maintenance of the SWV. As the equation of Term5 shows, the sign of Term5 is determined by the direction of the movement of the SWV. Figure 3 shows that the EKE increased when the SWV moved from areas of weak EKE to areas of strong EKE, which was favorable for the maintenance of the SWV. On the other hand, the EKE decreased when the SWV moved from areas of strong EKE to areas of weak EKE, which was unfavorable for the maintenance of the SWV.

Term6 remains convergent with a maximum of 14×10^{-4} J kg^{-1} s^{-1} (Fig. 2) before 0000 UTC 12 June (during the formation and maintenance stages of the SWV), which is favorable for the formation and maintenance of the SWV. In the latter period of the SWV, Term6 became weakly convergent and divergent, which slowed down the development of the SWV and induced its decay.

Before 0000 UTC 12 June (the formation and maintenance stages of the SWV), Term7 was weakly convergent and divergent (Fig. 2), which was not favorable for the development of the SWV. After that, in the mature period of the SWV, Term7 remained relatively strongly conver gent, which was favorable for the development of the SWV. The composite effect of Term6 and Term7 indicates that the transportation of the perturbation field was mainly convergent in the key areas of the SWV; this means that the horizontal and vertical flux divergences were favorable for the formation and maintenance of the SWV.

The Total term was always positive (Fig. 2) for the entire lifetime of the SWV, but it was stronger during the formation and maintenance stages of the SWV (before 0000 UTC 12) than during the mature and decaying stages. The decrease of the Total term may have induced the decay of the SWV. The RES term was always negative (Fig. 2), which means that the composite effect of the friction, dissipation and sub-grid processes always weakened the EKE of the SWV and that the RES is stronger in the maintenance stage of the SWV than in the mature stage. Comparing the RES and Total, these two terms almost always varied in the same manner, that is, when the EKE production was strong, the EKE dissipation was also strong (which made the EKE vary in a moderate way).

From the Lagrangian local variation of the SWV (Fig. 2), it can be seen that, before 0000 UTC 12 June, the EKE varied between -2×10^{-4} J kg^{-1} s^{-1} and 2×10^{-4} J kg^{-1} s^{-1}. This shows that the EKE did not increase during the formation and maintenance stages. However, during the mature stage, the EKE increased remarkably from 2×10^{-4} J kg^{-1} s^{-1} to 10×10^{-4} J kg^{-1} s^{-1}, which was favorable for the development of the SWV. During the decay period, the EKE decreased significantly. However, the EKE increased intensively while vortex B formed at 0000 UTC 13 June.

Since the SWV stretched vertically from 900 hPa to 550 hPa, the vertical distribution of the EKE below 450 hPa is shown in Fig. 4. The figure shows that the barotropical energy transition (Term1) is the most significant between 850 hPa and 700 hPa, corresponding to the strongest cyclonic circulation of the SWV being located

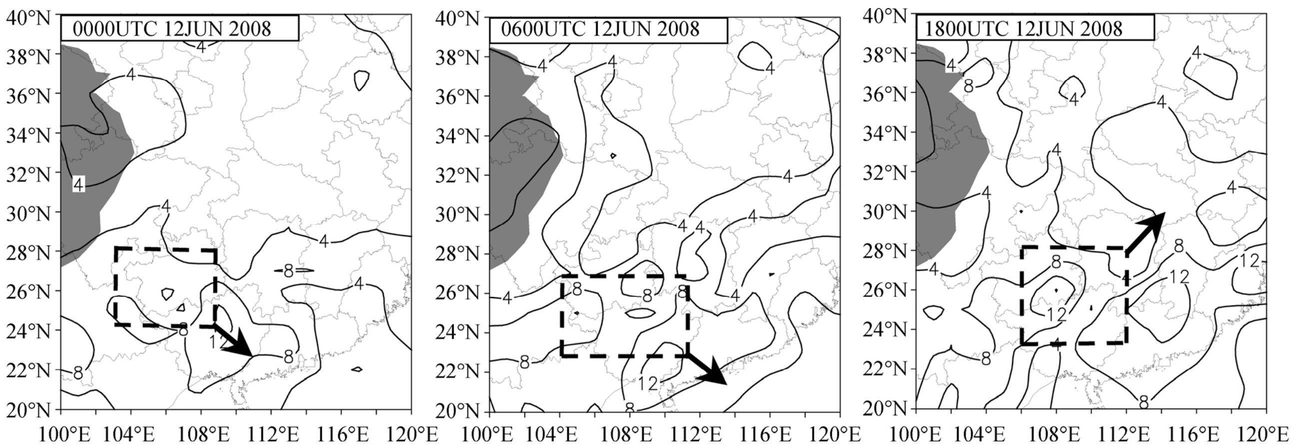

Figure 3 The distribution of eddy kinetic energy and the movement of the SWV. The solid line is the eddy kinetic energy (units: J kg^{-1}); the dashed rectangles are the key areas of the SWV; the arrows stand for the direction of the movement of the SWV, and the terrain above 3000 m is colored in grey.

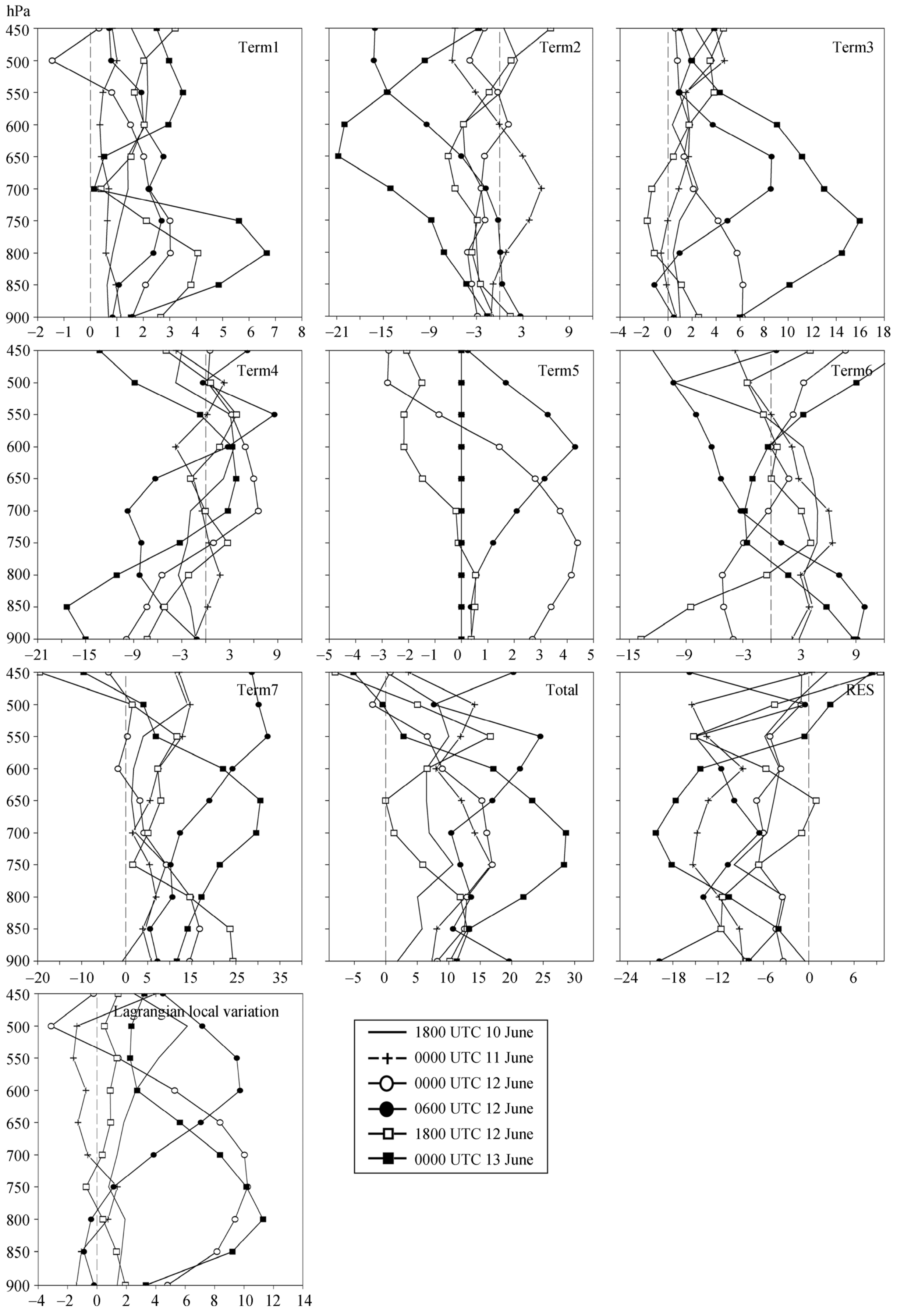

Figure 4 Cross sections of area-averaged terms of the eddy kinetic-energy budget in key areas of the SWV (10^{-4} J kg^{-1} s^{-1}).

in the lower troposphere. During the formation and mature stages, the barotropical energy transition at 700 hPa was stronger than that at 850 hPa, and vice versa during the decay stage. The baroclinic energy transitions (Term2) at higher levels were stronger than those at lower levels were, and after 0000 UTC 11 June, the baroclinic energy transition remained negative, which contributed to the decay of the SWV. The horizontal flux divergence (Term3) was mainly convergent at 550–900 hPa with its maximum at 700 hPa. The vertical flux divergence (Term4) was convergent at higher levels and divergent at lower levels. The movement of the SWV (Term5) influenced the EKE more remarkably during the mature stage than during the decay period. Term6 was the largest at 850 hPa, and varied slightly between 600–750 hPa. Term7 remained convergent (across 550–900 hPa), which was very favorable for the formation and development of the SWV. The Total was positive across 550–900 hPa, with its maximum at 700 hPa, while the RES was negative with its minimum at 700 hPa. From the Lagrangian local variation of the SWV, it is evident that the EKE at 550–850 hPa increased most intensively, corresponding to the approximately vertical stretching of the SWV.

4 Conclusions

In this paper, EKE budget of an SWV that caused heavy rainfall in Guangxi over South China (from 1200 UTC 11 to 0000 UTC 13 June) was calculated, and the main results are as follows: the process of the baroclinic energy transition was more obvious than the barotropical energy transition, which means it was of the mixed transition type; and the baroclinic characteristics of the SWV are stronger than the barotropical ones. Consequently, the SWV is a kind of subtropical vortex, with characteristics of both an extratropic vortex and a tropical vortex. In this case, the large-scale circulation and perturbation fields maintained the convergence of the EKE transition in key areas of the SWV that were responsible for the formation and development of the SWV. When the SWV moved from areas of weak EKE to areas of strong EKE, it was favorable for the maintenance of the SWV. In contrast, when the SWV moved from areas of strong EKE to areas of weak EKE, the EKE decreased, which did not favor the maintenance of the SWV. Sub-grid processes and frictional dissipation were the main sinks of the EKE, which mainly induced the decay of the SWV. The RES and Total terms varied almost in the same manner, thus, the more EKE was produced the more EKE was dissipated, which kept the EKE varying in a moderate way. The EKE between 550 hPa and 850 hPa increased most intensively, corresponding to the vertical stretching of the SWV.

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