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Conversion of Kinetic Energy from Synoptic Scale Disturbance to Low-Frequency Fluctuation over the Yangtze River Valley in the Summers of 1997 and 1999

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ABSTRACT

In order to investigate the conversion of kinetic energy from a synoptic scale disturbance (SSD; period⩽seven days) to a low-frequency fluctuation (LFF; period>seven days), the budget equation of the LFF kinetic energy is derived. The energy conversion is then calculated and analyzed for the summers of 1997 and 1999. The results show that the energy conversion from the SSD to the LFF is obviously enhanced in the middle and lower troposphere during the heavy rainfall, suggesting this to be one of mechanisms inducing the heavy rainfall, although the local LFF kinetic energy may not be enhanced.

Key words: kinetic energy conversion, synoptic scale disturbance, low-frequency fluctuation, heavy rainfall, Yangtze River valley

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1. Introduction

To improve the prediction of summer short-term climate, it is necessary not only to analyze the observed weather and climate systems, but also to understand the various physical processes and their interactions. One way of enhancing this understanding is through detailed diagnostic energy analyses (Vincent and Chang, 1975). Furthermore, this type of study also provides a valuable insight into the mechanisms responsible for monsoon heavy rainfalls.

In the past, investigations have mainly been carried out at spatial scales, including different kinetic energy exchange and interplay processes etc. For example, Xue and Ding (1993) studied the budget equations of the large-scale mean and its disturbance kinetic energy, as well as the typhoon-scale mean and its disturbance kinetic energy, and then found that kinetic energy generation and residual terms play an important part in balancing kinetic energy equations. They also verified that short waves are kinetic energy sources for typhoon and large scales. Carney and Vincent (1986) described the development and application of a set of kinetic energy budget equations that explicitly account for meso-synoptic scale interactions. Lin et al. (1993) found, using Dual-Doppler data, that computed tendencies decrease the mean kinetic energy at low levels and increase at middle levels, which are attributable to the generation and redistribution of kinetic energy and latent heat releases by organized convection associated with the rainband. However, frictional dissipation occurs as an end result of a turbulent energy cascade from the convective scales to a smaller scale in moist convection (Pauluis et al., 2000).

Holopainen (1984) used time-filtered grid-point data for the northern extratropics in winter to study energy conversion from the time-mean flow to synoptic-scale eddies, or vice-versa. Chen and Xie (1981) investigated two storm rainfall processes and showed that sub-synoptic scale systems are kinetic energy sources for synoptic-scale systems. Lau and Lau (1984) indicated by using time-filtering techniques that fluctuations with short time scales are elongated in the meridional direction, whereas those with long time scales are elongated in the zonal direction.

Kanamitsu et al. (1972) presented results of computations of energy exchanges between waves and waves, and between waves and zonal flows. They pointed out that zonal wave number one appears to be a major energy source for the tropics. Kung (1966)

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studied kinetic energy generation and dissipation in large-scale atmospheric circulation, and investigated diurnal and long-term variations of the kinetic energy generation and dissipation for a five-year period (Kung, 1967). Kung also studied the latitude-height distributions of kinetic energy generation and dissipation over North America (Kung, 1970), and then further found (Kung and Smith, 1974), for the total system, that generation of new kinetic energy by cross-isobaric flow is the principle energy source, but that transport of kinetic energy appears as an important secondary source. However, despite the intense energy generation in the system, the inflow of kinetic energy in the area indicates that, on average, more kinetic energy could be dissipated than generated, even during intense thunderstorm activity. Thus, despite their energy-generating mechanism, the net effect of a severe sub-synoptic scale disturbance seems to be energy cascading rather than generating. The flux convergence of potential energy from the source in lower latitudes is identified as the single major source of kinetic energy in higher latitudes. The contribution of baroclinic conversion is minor (Kung et al., 1983). The budgets of divergent and rotational kinetic energy have been studied by many scientists (e.g., Buechler and Fuelberg, 1986; Ding and Liu, 1986a,b; Krishnamurti et al., 1998; Chen and Chen, 2002). We have taken a lot from previous studies, and have been motivated to investigate the relationship between local heavy rainfalls and energy conversion from the synoptic scale disturbance (SSD) to low-frequency fluctuation (LFF). The relationship has received little attention up until now.

Generally, monsoon rainfall is located over the Yangtze-Huaihe River valley, in conjunction with El Niño. It normally falls the Yellow River and its northern area in the La-Niña condition (National Climate Center, 1998; Li, 2002). However, the pattern of rainfall is very similar in the summers of 1997 (south of the Yangtze River valley) and 1999 (in the valley, and to the south of it) over eastern China (not shown) under the striking contrast of SSTs. An El-Niño event occurred in 1997, reaching its most intense levels for the last 50 years, and the La-Niña phenomenon was evident in 1999. It is the notable differences in SSTs that makes it difficult to understand and predict similar patterns of rainfall over eastern China for the two flood seasons. We also know that flooding is one of the major meteorological disasters that takes place in China, and often occurs in the Yangtze River valley. All of the above motivates us to investigate carefully the mechanisms of heavy rainfall.

In this paper, the budget equation of the LFF kinetic energy is derived (section 2). The conversion of kinetic energy from the SSD (period⩽seven days) to the LFF (period>seven days) is then investigated using the residual method (section 3). We also analyze the relationship between monsoon rainfall and energy conversion over the Yangtze River valley (27°–32°N, 105°–120°E). Namely, the contribution of the SSD is studied within the troposphere in three rainfall periods: before the heavy rainfall (14–30 June 1997; 1–15 June 1999); during the heavy rainfall (1–21 July 1997; 16 June to 1 July 1999), and after the heavy rainfall (22–31 July 1997; 2–15 July 1999) (Fig. 1). Finally, a discussion and conclusions are presented in section 4.

2. Scheme of study and data

A Gausi low-pass filter is used to decompose the transient energy into a low-pass or LFF (period>seven days) and a high-pass or SSD (period⩽seven days) [see Holopainen (1984) time scale division]. The response function of frequency is $H(f)=\exp(-2\pi^2\sigma^2 f^2)$, in which $\sigma=7/6$. The two energy scales are included in every term of the transient kinetic energy equation, and in order to study the conversion between the two scales, the following method is used to obtain the LFF equation from the total transient equation.

The equation of instantaneous motion is written in pressure as the vertical coordinate:

$$\frac{\partial \boldsymbol{V}}{\partial t}=-\nabla\phi-(\boldsymbol{V}\cdot\nabla)\boldsymbol{V}-\omega\frac{\partial \boldsymbol{V}}{\partial p}-f\boldsymbol{k}\times\boldsymbol{V}+\boldsymbol{F}\ , \quad (1)$$

where $\boldsymbol{V}$ denotes a horizontal vector wind field, ϕ is geopotential height, ω is the vertical velocity in the p-coordinate system, f is the Coriolis parameter, and $\boldsymbol{F}$ is friction. We perform the time-average for the equation of instantaneous motion and $\overline{q_1q_2}=\bar{q}_1\bar{q}_2+\overline{q_1'q_2'}$, then:

$$\frac{\partial \overline{\boldsymbol{V}}}{\partial t}=-\nabla\bar{\phi}-(\overline{\boldsymbol{V}}\cdot\nabla)\overline{\boldsymbol{V}}-\omega\frac{\partial \overline{\boldsymbol{V}}}{\partial p}-$$

$$f\boldsymbol{k}\times\overline{\boldsymbol{V}}+\overline{\boldsymbol{F}}-\overline{(\boldsymbol{V}'\cdot\nabla)\boldsymbol{V}'}-\overline{\omega'\frac{\partial \boldsymbol{V}'}{\partial p}}\ . \quad (2)$$

In addition, any meteorological variable X can be partitioned into the two components of time-mean $\overline{X}$ and its derivation X'. Namely, $X=\overline{X}+X'$. The equation of instantaneous motion (namely X) in isobaric coordinates can also be written:

$$\frac{\partial(\overline{\boldsymbol{V}}+\boldsymbol{V}')}{\partial t}=-\nabla(\overline{\phi}+\phi')-[(\overline{\boldsymbol{V}}+\boldsymbol{V}')\cdot\nabla](\overline{\boldsymbol{V}}+\boldsymbol{V}')-$$

$$(\overline{\varpi}+\omega')\frac{\partial(\overline{\boldsymbol{V}}+\boldsymbol{V}')}{\partial p}-$$

$$f\boldsymbol{k}\times(\overline{\boldsymbol{V}}+\boldsymbol{V}')+\overline{\boldsymbol{F}}+F'\ . \quad (3)$$

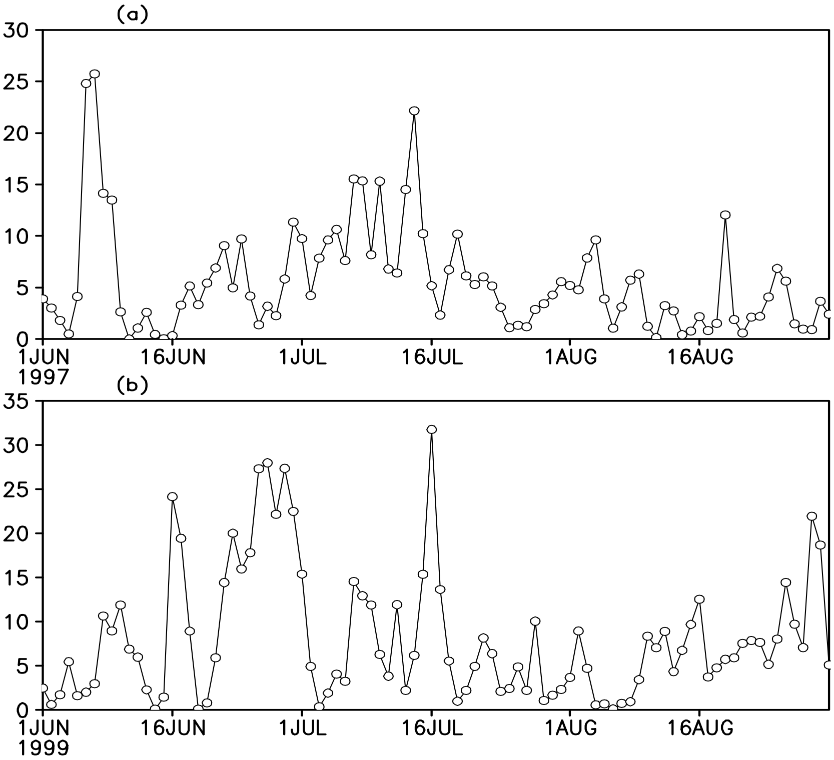

Fig. 1. Diurnal variation of rainfall over the Yangtze River valley (27°–32°N, 105°–120°E) during the summers of (a) 1997 and (b) 1999, obtained from the observed daily rainfall in China (mm d^{-1}).

The equation of transient motion (namely X') can be obtained by subtracting the time-mean equation from the equation of instantaneous motion. Equation (3)–Eq. (2) yields:

$$\frac{\partial \boldsymbol{V}'}{\partial t} = -\nabla\phi' - (\overline{\boldsymbol{V}}\cdot\nabla)\boldsymbol{V}' - (\boldsymbol{V}'\cdot\nabla)\overline{\boldsymbol{V}} - (\boldsymbol{V}'\cdot\nabla)\boldsymbol{V}' - \overline{\omega}\frac{\partial \boldsymbol{V}'}{\partial p} - \omega'\frac{\partial \overline{\boldsymbol{V}}}{\partial p} - \omega'\frac{\partial \boldsymbol{V}'}{\partial p} - f\boldsymbol{k}\times\boldsymbol{V}' + \boldsymbol{F}' + \overline{(\boldsymbol{V}'\cdot\nabla)\boldsymbol{V}'} + \overline{\omega'\frac{\partial \boldsymbol{V}'}{\partial p}}\,. \quad (4)$$

Multiplying Eq. (4) by $\boldsymbol{V}'$, because $(\boldsymbol{B}\times\boldsymbol{A})\cdot\boldsymbol{A}=0$, means Eq. (4) becomes:

$$\boldsymbol{V}'\cdot\frac{\partial \boldsymbol{V}'}{\partial t} = -\boldsymbol{V}'\cdot\nabla\phi' - \boldsymbol{V}'\cdot(\overline{\boldsymbol{V}'}\cdot\nabla)\boldsymbol{V}' - \boldsymbol{V}'\cdot(\boldsymbol{V}'\cdot\nabla)\overline{\boldsymbol{V}'} - \boldsymbol{V}'\cdot(\boldsymbol{V}'\cdot\nabla)\boldsymbol{V}' - \boldsymbol{V}'\cdot\overline{\omega}\frac{\partial \boldsymbol{V}'}{\partial p} - \boldsymbol{V}'\cdot\omega'\frac{\partial \overline{\boldsymbol{V}'}}{\partial p} - \boldsymbol{V}'\cdot\omega'\frac{\partial \boldsymbol{V}'}{\partial p} + \boldsymbol{V}'\cdot\boldsymbol{F}' + \boldsymbol{V}'\cdot\overline{(\boldsymbol{V}'\cdot\nabla)\boldsymbol{V}'} + \boldsymbol{V}'\cdot\overline{\omega'\frac{\partial \boldsymbol{V}'}{\partial p}}\,. \quad (5)$$

Equation (5) can be expressed as:

$$\frac{\partial K'}{\partial t} = M + N + I + P + B + F \quad (6)$$

where

$$K' = \frac{1}{2}(u'^2 + v'^2)\,,$$

$$M = -\left(\boldsymbol{V}'\cdot(\overline{\boldsymbol{V}'}\cdot\nabla)\boldsymbol{V}' + \boldsymbol{V}'\cdot\overline{\omega'}\frac{\partial \boldsymbol{V}'}{\partial p}\right) = -\left(\overline{u}\frac{\partial K'}{\partial x} + \overline{v}\frac{\partial K'}{\partial y} + \overline{\omega}\frac{\partial K'}{\partial p}\right)\,,$$

$$N = -\left(\boldsymbol{V}'\cdot(\boldsymbol{V}'\cdot\nabla)\boldsymbol{V}' + \boldsymbol{V}'\cdot\omega'\frac{\partial \boldsymbol{V}'}{\partial p}\right) = -\left(u'\frac{\partial K'}{\partial x} + v'\frac{\partial K'}{\partial y} + \omega'\frac{\partial K'}{\partial p}\right)\,,$$

$$I = -\left(\boldsymbol{V}'\cdot(\overline{\boldsymbol{V}'}\cdot\nabla)\overline{\boldsymbol{V}} + \boldsymbol{V}'\cdot\omega'\frac{\partial \overline{\boldsymbol{V}}}{\partial p}\right) = -\left(u'u'\frac{\partial \overline{u}}{\partial x} + u'v'\frac{\partial \overline{u}}{\partial y} + u'\omega'\frac{\partial \overline{u}}{\partial p} + \right.$$

$$u'v'\frac{\partial\overline{v}}{\partial x}+v'v'\frac{\partial\overline{v}}{\partial y}+\omega'v'\frac{\partial\overline{v}}{\partial p}\Bigg)\ ,$$

$$P=-\boldsymbol{V}'\cdot\nabla\phi'=-\left(u'\frac{\partial\phi'}{\partial x}+v'\frac{\partial\phi'}{\partial y}\right)\ ,$$

$$B=\boldsymbol{V}'\cdot\overline{(\boldsymbol{V}'\cdot\nabla)\boldsymbol{V}'}+\boldsymbol{V}'\cdot\overline{\omega'\frac{\partial\boldsymbol{V}'}{\partial p}}$$

$$=u'\overline{u'\frac{\partial u'}{\partial x}}+u'\overline{v'\frac{\partial u'}{\partial y}}+u'\overline{\omega'\frac{\partial u'}{\partial p}}+$$

$$v'\overline{u'\frac{\partial v'}{\partial x}}+v'\overline{v'\frac{\partial v'}{\partial y}}+v'\overline{\omega'\frac{\partial v'}{\partial p}}\ ,$$

$$F=\boldsymbol{V}'\cdot\boldsymbol{F}=u'F'_x+v'F'_y\ .$$

M and N in Eq. (6) represent the horizontal and vertical advection of transient kinetic energy transports produced by time-mean and transient eddy wind, respectively. I is the energy transformation between time-mean and transient winds. P describes the generation (destruction) of transient kinetic energy by cross-contour transient flow from higher to lower (lower to higher) values of geopotential. The term also reveals the work achieved by pressure forces. B is the interaction contribution by different direction transient winds to the variation of local transient kinetic energy. Because F is calculated as a residual to balance Eq. (6), it contains kinetic energy losses due to viscous dissipation, energy transfers between resolvable scales of motion (within the observation network), and unresolvable scales of motion (the sub-grid scale, that is), as well as errors that occur in other terms (Carney and Vincent, 1986).

Every term is calculated by time-filtered grid point daily data of Natioanal Centers for Environmental Predition-National Center for Atmospheric Research (NCEP-NCAR) (Kalnay et al., 1996). The LFF is expressed by the subscript l. Subscript h denotes the SSD. There is $X'=X_{\rm l}+X_{\rm h}$ for any transient variable, substituting the formula into above every term (except F), and the kinetic energy equation of the LFF still uses the format of Eq. (6). Then,

$$\frac{\partial K'}{\partial t}=\frac{\partial K_{\rm l}}{\partial t}+A$$

$$A=\frac{\partial(K_{\rm h}+u_{\rm l}u_{\rm h}+v_{\rm l}v_{\rm h})}{\partial t}$$

$$M=-\left(\overline{u}\frac{\partial K_{\rm l}}{\partial x}+\overline{v}\frac{\partial K_{\rm l}}{\partial y}+\overline{\omega}\frac{\partial K_{\rm l}}{\partial p}\right)+B=M_{\rm l}+B$$

$$B=-\Bigg[\overline{u}\frac{\partial(K_{\rm h}+u_{\rm l}u_{\rm h}+v_{\rm l}v_{\rm h})}{\partial x}+$$

$$\overline{v}\frac{\partial(K_{\rm h}+u_{\rm l}u_{\rm h}+v_{\rm l}v_{\rm h})}{\partial y}+$$

$$\overline{\omega}\frac{\partial(K_{\rm h}+u_{\rm l}u_{\rm h}+v_{\rm l}v_{\rm h})}{\partial p}\Bigg]\ ,$$

$$N=-\left(u_{\rm l}\frac{\partial K_{\rm l}}{\partial x}+v_{\rm l}\frac{\partial K_{\rm l}}{\partial y}+\omega_{\rm l}\frac{\partial K_{\rm l}}{\partial p}\right)+C=N_{\rm l}+C\ ,$$

$$C=-\Bigg[u_{\rm l}\frac{\partial(K_{\rm h}+u_{\rm l}u_{\rm h}+v_{\rm l}v_{\rm h})}{\partial x}+$$

$$v_{\rm l}\frac{\partial(K_{\rm h}+u_{\rm l}u_{\rm h}+v_{\rm l}v_{\rm h})}{\partial y}+$$

$$\omega_{\rm l}\frac{\partial(K_{\rm h}+u_{\rm l}u_{\rm h}+v_{\rm l}v_{\rm h})}{\partial p}+$$

$$u_{\rm h}\frac{\partial K'}{\partial x}+v_{\rm h}\frac{\partial K'}{\partial y}+\omega_{\rm h}\frac{\partial K'}{\partial p}\Bigg]\ ,$$

$$I=-\Bigg(u_{\rm l}u_{\rm l}\frac{\partial\overline{u}}{\partial x}+u_{\rm l}v_{\rm l}\frac{\partial\overline{u}}{\partial y}+u_{\rm l}\omega_{\rm l}\frac{\partial\overline{u}}{\partial p}+u_{\rm l}v_{\rm l}\frac{\partial\overline{v}}{\partial x}+$$

$$v_{\rm l}v_{\rm l}\frac{\partial\overline{v}}{\partial y}+v_{\rm l}\omega_{\rm l}\frac{\partial\overline{v}}{\partial p}\Bigg)+D=I_{\rm l}+D\ ,$$

$$D=-\Bigg[(u_{\rm l}u_{\rm h}+u_{\rm h}u')\frac{\partial\overline{u}}{\partial x}+(u_{\rm l}v_{\rm h}+u_{\rm h}v')\frac{\partial\overline{u}}{\partial y}+$$

$$(u_{\rm l}\omega_{\rm h}+u_{\rm h}\omega')\frac{\partial\overline{u}}{\partial p}+(u_{\rm l}v_{\rm h}+u_{\rm h}v')\frac{\partial\overline{v}}{\partial x}+$$

$$(v_{\rm l}v_{\rm h}+v_{\rm h}v')\frac{\partial\overline{v}}{\partial y}+(\omega_{\rm l}v_{\rm h}+\omega_{\rm h}v')\frac{\partial\overline{v}}{\partial p}\Bigg]\ ,$$

$$P=-\left(u_{\rm l}\frac{\partial\phi_{\rm l}}{\partial x}+v_{\rm l}\frac{\partial\phi_{\rm l}}{\partial y}\right)+E=P_{\rm l}+E\ ,$$

$$E=-\left(u_{\rm l}\frac{\partial\phi_{\rm h}}{\partial x}+u_{\rm h}\frac{\partial\phi'}{\partial x}+v_{\rm l}\frac{\partial\phi_{\rm h}}{\partial y}+v_{\rm h}\frac{\partial\phi'}{\partial y}\right)\ ,$$

$$B=u_{\rm l}\overline{u_{\rm l}\frac{\partial u_{\rm l}}{\partial x}}+u_{\rm l}\overline{v_{\rm l}\frac{\partial u_{\rm l}}{\partial y}}+u_{\rm l}\overline{\omega_{\rm l}\frac{\partial u_{\rm l}}{\partial p}}+v_{\rm l}\overline{u_{\rm l}\frac{\partial v_{\rm l}}{\partial x}}+$$

$$v_{\rm l}\overline{v_{\rm l}\frac{\partial v_{\rm l}}{\partial y}}+v_{\rm l}\overline{\omega_{\rm l}\frac{\partial v_{\rm l}}{\partial p}}+F=B_{\rm l}+F\ ,$$

$$F=u_{\rm l}\overline{\left(u_{\rm l}\frac{\partial u_{\rm h}}{\partial x}+u_{\rm h}\frac{\partial u'}{\partial x}\right)}+u_{\rm l}\overline{\left(v_{\rm l}\frac{\partial u_{\rm h}}{\partial y}+v_{\rm h}\frac{\partial u'}{\partial y}\right)}+$$

$$u_{\rm l}\overline{\left(\omega_{\rm l}\frac{\partial u_{\rm h}}{\partial p}+\omega_{\rm h}\frac{\partial u'}{\partial p}\right)}+v_{\rm l}\overline{\left(u_{\rm l}\frac{\partial v_{\rm h}}{\partial x}+u_{\rm h}\frac{\partial v'}{\partial x}\right)}+$$

$$v_{\rm l}\overline{\left(v_{\rm l}\frac{\partial v_{\rm h}}{\partial y}+v_{\rm h}\frac{\partial v'}{\partial y}\right)}+v_{\rm l}\overline{\left(\omega_{\rm l}\frac{\partial v_{\rm h}}{\partial p}+\omega_{\rm h}\frac{\partial v'}{\partial p}\right)}\ .$$

$$+ u_{\mathrm{h}}\overline{u'\frac{\partial u'}{\partial x}} + u_{\mathrm{h}}\overline{v'\frac{\partial u'}{\partial y}} + u_{\mathrm{h}}\overline{\omega'\frac{\partial u'}{\partial p}} +$$

$$+ v_{\mathrm{h}}\overline{u'\frac{\partial v'}{\partial x}} + v_{\mathrm{h}}\overline{v'\frac{\partial v'}{\partial y}} + v_{\mathrm{h}}\overline{\omega'\frac{\partial v'}{\partial p}} \,.$$

All of the SSD contribution to the variation of the LFF kinetic energy is put into T. Then: $T = B + C + D + E + F - A$, and thus the budget equation of the LFF kinetic energy can be written as:

$$\frac{\partial K_l}{\partial t} = M_l + N_l + I_l + P_l + B_l + (F + T)\,. \qquad (7)$$

This investigation is based on the daily 2.5° × 2.5° NCEP data. Thus, the sub-grid scale, which mostly belongs to the synoptic scale (Chen and Xie, 1981), and less than one day period wave, will naturally be put into the residual $F + T$. This is just consistent enough for the purposes of this study.

Generally, the direction of motion and the direction of frictional force are opposite to each other. Likewise, we can consider the direction of disturbance frictional force induced by a transient eddy as opposite to that of transient eddy motion. Thus, the transient frictional force often makes a negative contribution to the variations of kinetic energy of a local transient eddy. In other words, the kinetic energy is almost always dissipated by the friction force. Therefore, it is evident that the SSD transfers its kinetic energy to the LFF while the sign of $F+T$ is positive, which is obtained after overcoming the negative magnitude offered by frictional forces. This explanation is similar to that given by Vincent and Chang (1975). The physical meanings of other terms in Eq. (7) correspond with the terms in Eq. (6), but for the composition of the LFF.

The daily precipitation data are the observations of 743 stations in China in the summers of 1997 and 1999, provided by the National Meteorological Information Center in China.

3. Results

Every term of Eq. (7) is calculated in order to obtain the residual $F+T$. According to the above explanation, we know $F+T$ can represent the conversion of kinetic energy from the SSD to the LFF when it is equal to a positive number. Thus, we explore this further. $\partial K_{\mathrm{l}}/\partial t$ will also be investigated in an attempt to uncover the effect of the conversion.

The conversion of kinetic energy is revealed by the latitude-height cross section of $F + T$ at 105°–120°E (Fig. 2). Comparing 1997 (left-hand panels: a1, b1, and c1) with 1999 (right-hand panels: a2, b2, and c2), similar conditions are noted in the middle and lower troposphere during the three periods. Before the heavy rainfall (Figs. 2a1 and 2a2), the LFF gained slightly kinetic energy from the SSD in the middle and lower troposphere over South China and the Yangtze River valley. There was a center in the lower troposphere in 1997 and 1999. Meanwhile, a certain difference of latitudinal distribution is shown in the upper troposphere between 1997 and 1999. During the heavy rainfall (Figs. 2b1 and 2b2), $F+T$ dissipates the LFF kinetic energy at around 400–500 hPa for 1997, and above 400 hPa for 1999 over the Yangtze River valley (at least, the SSD does not overcome the frictional force to make a positive contribution to the variation of the LFF kinetic energy). However, the SSD releases more energy to the LFF than that of the previous stage in the lower and middle troposphere (from 1000 hPa to 500 hPa), in both 1997 and 1999. In other words, this is a common characteristic that existed during the heavy rainfall in both 1997 and 1999. After the heavy rainfall (Figs. 2c1 and 2c2), the SSD contributes its kinetic energy to the LFF in the upper and lower troposphere. The intensity of the contribution returns to a small magnitude in the lower troposphere, as it was before the heavy rainfall. $\partial K_{\mathrm{l}}/\partial t$ represents the local variation of the LFF kinetic energy per unit mass. The variation of kinetic energy exhibits distinct differences not only on regional levels (not shown), but also on vertical levels. The variations of the LFF kinetic energy, along with altitude over the Yangtze River valley, are shown in Fig. 3. The variations are almost opposite in 1997 (Fig. 3a) and 1999 (Fig. 3b) for their three periods. Before the heavy rainfall of 1999, the local kinetic energy of the LFF was slightly enhanced, moderately reduced, and notably enhanced in the lower, middle and upper troposphere, respectively. The most noteworthy enhancement of energy was at 200–150 hPa. It seems the LFF energy was rapidly saved at this level. However, during the heavy rainfall of 1999, the LFF kinetic energy was released in the upper troposphere, and the most notable release also occurred at 200–150 hPa. It seems the LFF supplied its kinetic energy to the local heavy rainfall. A similar phenomenon does not happen in the middle and lower troposphere. After the heavy rainfall of 1999, the LFF kinetic energy begins to increase again in the upper troposphere, but the variations are not obvious at other levels. However, it is regrettable that similar conditions cannot be found in the three corresponding periods of 1997.

Comparing $F + T$ (Fig. 2) and $\partial K_{\mathrm{l}}/\partial t$ (Fig. 3), before the heavy rainfall, the same sign exists between $F+T$ and $\partial K_{\mathrm{l}}/\partial t$ in the lower and upper troposphere over the Yangtze River valley for the two years. How-

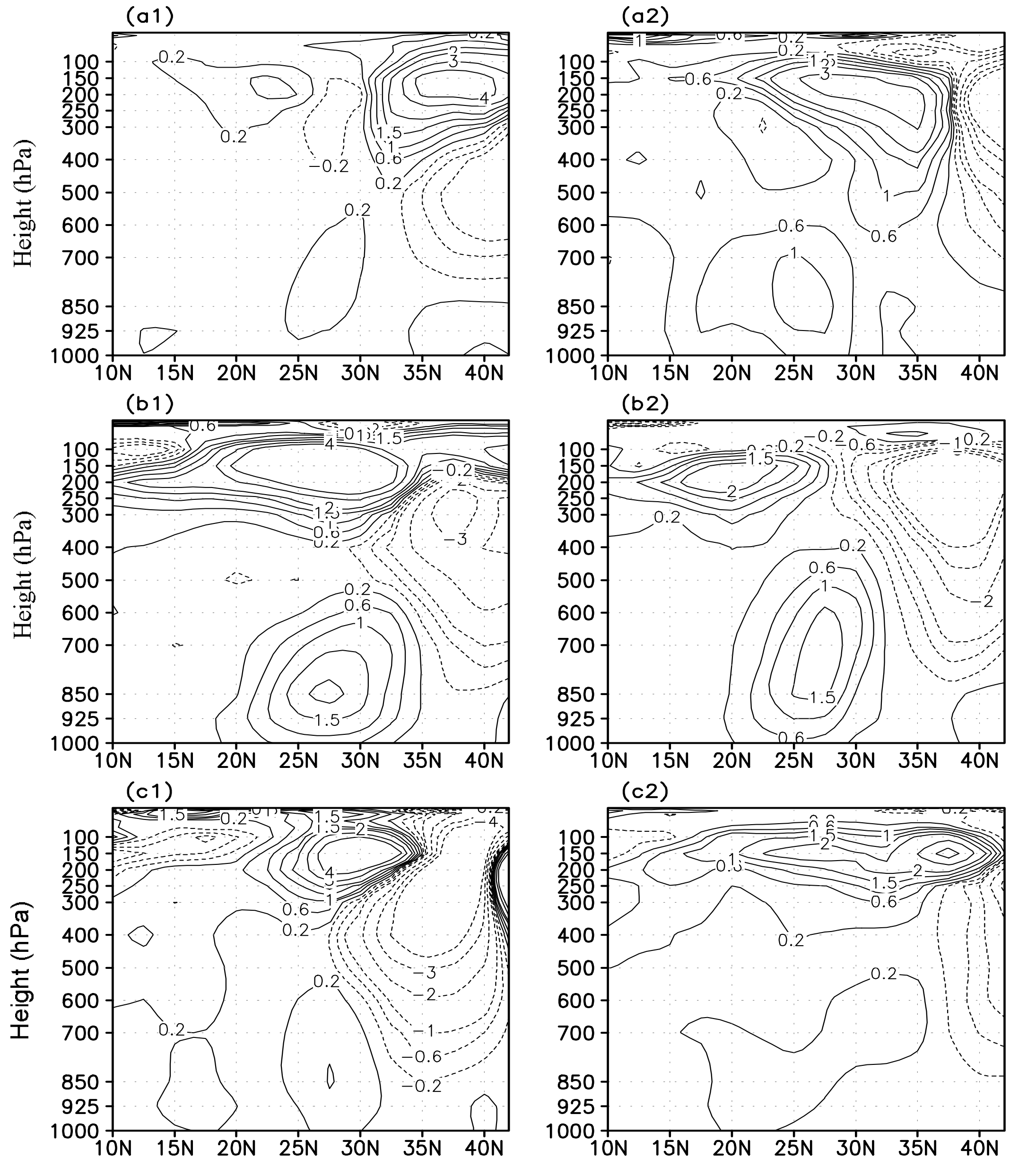

Fig. 2. Latitude-height cross sections of F_k+T_k averaged at 105°–120°E. Before the heavy rainfall: (a1) 14–30 June 1997; (a2) 1–15 June 1999. During the heavy rainfall: (b1) 1–21 July 1997; (b2) 16 June to 1 July 1999. After the heavy rainfall: (c1) 22–31 July 1997; (c2) 2–15 July 1999. The zero lines are not drawn to improve clarity. (10^{-3} m^2 s^{-3}).

ever, in the middle troposphere, the negative magnitude of other-term-mean and frictional dissipation in Eq. (7) is larger than the positive of SSD for 1999. During the heavy rainfall, the enhancement (1997) and reduction (1999) of $\partial K_1/\partial t$ are partly due to $F+T$. In other words, $F+T$ and $\partial K_1/\partial t$ have the same sign in the upper troposphere. From the lower to middle troposphere, the positive contribution of SSD almost balances the negative contribution of other-term-mean and frictional dissipation for the two years. Namely, $\partial K_1/\partial t$ is nearly equal to zero in both 1997 and 1999. After the heavy rainfall, the positive contribution of $F+T$ is almost equal to the negative number of other-term-mean in the middle and lower troposphere in 1999. $F+T$ and $\partial K_1/\partial t$ have the same sign in the upper troposphere. However, for 1997, the absolute value of negative other-term-mean is larger than the positive contribution of $F+T$ in the upper and lower troposphere. From the above comparison and contrast, we can deduce that the sign is uncertain between $F+T$

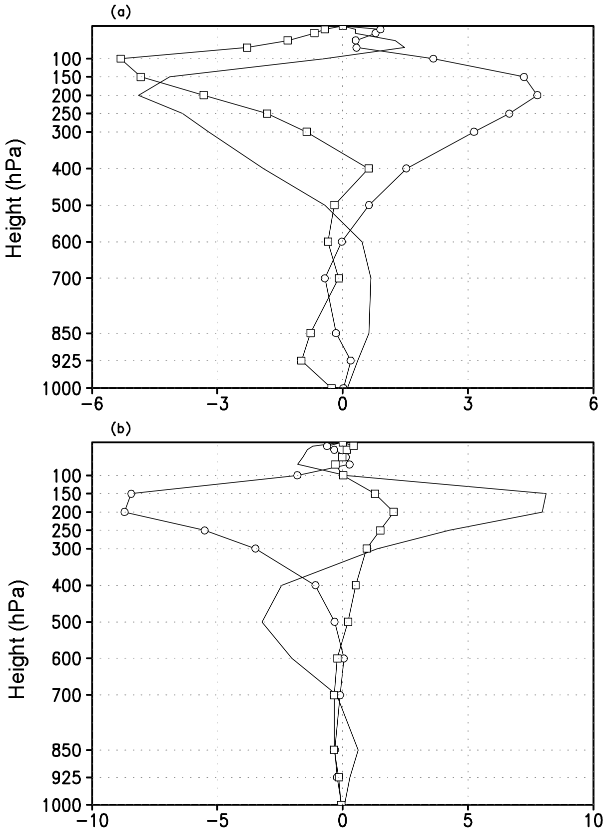

Fig. 3. Vertical profile of $\partial K_1/\partial t$ over the Yangtze River valley (27°–32°N, 105°–120°E). (a) 1997: before the heavy rainfall (14–30 June—solid line), during the heavy rainfall (1–21 July—open circle), after the heavy rainfall (22–31 July—open square); (b) 1999: before the heavy rainfall (1–15 June—solid line), during the heavy rainfall (16 June to 1 July—open circle), after the heavy rainfall (2–15 July—open square) (10^{-5} m^2 s^{-3}).

and $\partial K_1/\partial t$.

4. Discussion and conclusions

To investigate the conversion of kinetic energy, the budget equation of the LFF kinetic energy was derived. The energy conversion between the SSD and the LFF was then calculated and analyzed using the residual method. The analyses have shown that $\partial K_1/\partial t$ may be enhanced or reduced in the troposphere before, during, or after the heavy rainfall. During the heavy rainfall, however, $F+T$ increased obviously in the middle and lower troposphere both in 1997 and in 1999. In other words, the SSD clearly released its energy to the LFF during the heavy rainfall. At the same time, $F+T$ bore more notable local features than that of the former and latter periods. However, a certain relationship did not exist between $F+T$ and $\partial K_1/\partial t$. Certainly, on the evidence of this study, a universal conclusion regarding the relationship between the conversion of kinetic energy and the heavy rainfall cannot be given. Further detailed investigations need to be made.

After studying two-dimensional turbulence, Leith (1968a,b) suggested that more of the energy is transferred up scale, and only very little cascading actually takes place. In the present study, a similar phenomenon was found (in three-dimensional space) over the Yangtze River valley, particularly in the lower and middle troposphere, during the heavy rainfall. Furthermore, it can be speculated that some forcing produces the SSD, and then the SSD kinetic energy is transferred upscale to the LFF. When the energy conversion reaches a certain intensity, it becomes one of the mechanisms resulting in the local heavy rainfall. Moreover, previous theoretical analyses have shown that if eddy kinetic energy is generated by baroclinic processes on a certain scale, then energy is transferred barotropically both up-and downscale (Kanamitsu et al., 1972). Furthermore, for pure barotropic flows, there can be no systematic cascade of energy in either end of the spectrum (namely, long or short waves). Therefore, what relationships exist between the direction of energy conversion in time domain and the local baroclinic/barotropic process also leads us to suggest further investigation is necessary.

The SSD does not follow a simple regularity. Also, it is very difficult to gain a sound grip on its interaction with short-term climate. Moreover, the mechanisms inducing flood are multiple, complicated, and annually variable, even for the same region. Thus, we must overcome many contradictions and puzzles in exploring the mechanisms. This paper is only an attempt to investigate the mechanisms from the conversion of kinetic energy.

The calculated accuracy is affected by error accumulation in the data of wind. To calculate each term in Eq. (7), the LFF wind speed, the square of the LFF wind, or the cube of the LFF wind, is used. Thus, $F+T$ includes the overall errors of other terms due to using the residual method. In addition, the error influence normally increases with altitude in the troposphere (Vincent and Chang, 1975). However, if errors are the same for the three periods averaged in the local region, we can consider the differences of $F+T$ among the three periods as primarily caused by the variation of kinetic energy conversion.

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