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Synoptic Characteristics of Heavy Rainfall Events in Pre-monsoon Season in South China

WU Liji*[1] (吴丽姬), HUANG Ronghui[2] (黄荣辉), HE Haiyan[1] (贺海晏),
SHAO Yaping[3] (邵亚平), and WEN Zhiping[1] (温之平)

[1] *Center for Monsoon and Environment Research/Department of Atmospheric Sciences, Sun Yat-sen University, Guangzhou* 510275

[2] *Center for Monsoon System Research, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing* 100029

[3] *Institute for Geophysics and Meteorology, University of Cologne, Cologne* 50937, *Germany*

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ABSTRACT

Persistent heavy rainfall events in South China can be divided into pre- and post-monsoon-onset events according to the onset of the South China Sea Summer Monsoon. In this study, daily rainfall data from 174 stations in South China and daily NCEP/NCAR reanalysis data are used to investigate pre-monsoon-onset events. The synoptic characteristics of pre-monsoon-onset heavy rainfall events are examined in detail. It is found that 21 heavy rainfall cases happened in the pre-monsoon period between 1961 and 2005. Among them, more than 60% of the events happened under a saddle pattern circulation. Using a case study, the role of the saddle field is investigated and slantwise vorticity development (SVD) theory is applied to diagnose the mechanisms for heavy rainfall development. It is found that a low-level saddle field and low-level jets result in the accumulation of warm moist air in the lower troposphere over South China and provide the necessary unstable conditions for heavy rainfall development. The existence of a saddle field plays an important role in maintaining these unstable conditions. The slantwise movement of the isentropic surface over South China can increase local vorticity and lead to strong vertical motion, which then triggers heavy rainfall.

Key words: heavy rainfall, South China, pre-monsoon, moist potential vorticity

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1. Introduction

Floods are major meteorological disasters in China. Heavy rainfall events are responsible for most prolonged flooding in China and have received much attention in the literature (Zhang et al., 2002; Xiong et al., 2003; Tang et al., 2006). South China is one of the heaviest flooding areas in the country. Traditionally, the rainy season in South China lasts from April to September, with two rainfall peaks occurring: one in June and the other in August. It is conventional to divide the rainy season into the first rainy season (April to June) and the second rainy season (July to September), owing to two distinct rainfall peaks at these times (Li et al., 2002). Rainfall in the first rainy season is related to the activities of cold air from the north and the fluctuation of the South China Sea Summer Monsoon (SCSSM). It accounts for more than 40% of the annual rainfall. Rainfall in the second rainy season is mainly related to the activities of tropical systems, such as tropical cyclones (Li and Liang, 1981).

The SCSSM is a major system which causes heavy rainfall in South China in the first rainy season. On average, the onset of the SCSSM in South China occurs in the middle of May. During the monsoon period, convective areas over southern China form a monsoon

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*Corresponding author: WU Liji, wuliji_wlj@hotmail.com

rain band and contribute significantly to precipitation (Tao and Chen, 1987). The monsoon flow moves together with the monsoon rain band, then extends from South China to the Yangtze River valley, and later further into northern parts of China. Rainfall during this period is called "mei-yu" in the Yangtze River valley and "Baiu" in Japan (Ninomiya and Akiama, 1974; Chen and Chang, 1980; Chen and Yu, 1988). The relationship between the SCSSM and heavy rainfall in South China has been an active research topic (e.g. Samel et al., 1999; Wang and Lin, 2002) since the last century. It has been found that, after onset of the monsoon, South China is usually under the influence of a southwesterly low-level jet (LLJ), which brings humid and warm air to the region. The close relationship between extremely heavy rainfall events and the LLJ in the 850–700 hPa layer during the monsoon season has been confirmed both in observational studies (Akiyama, 1973a, b; Ninomiya and Akiama, 1974) and numerical simulations (Ninomiya, 1980; Kuo and Anthes, 1982).

In previous studies of heavy rainfall in South China, April to June is considered as one period, known as the first rainy season (Guo and Sha, 1998; Wu and Liang, 1992). On average, the SCSSM generally breaks out in the middle of May (Wang et al., 2004), and after that precipitation in South China increases greatly. Many heavy rainfall events, especially persistent heavy rainfall events, occur in this period. For this reason, monsoon rainfall has received much attention over the past century. In contrast, much less attention has been paid to the heavy rainfall events which occur before the onset of the SCSSM. It has been suggested in previous studies that rainfall events in this period are on a large scale, of long duration, and weak intensity. It has been pointed out recently that it is important to distinguish between heavy rainfall before and after the onset of the SCSSM, and some studies have been carried out from the point of view of large-scale circulation patterns (Liu and Zhang, 1996; Chi and He, 2005; Zheng et al., 2006a, b). However, the different mechanisms of heavy rainfall in these two different periods have not yet been studied in detail. The mechanism of heavy rainfall in the pre-monsoon-onset period requires particular attention.

The objectives of the current study are to better characterize the synoptic features of heavy rainfall events in South China in the pre-monsoon-onset period and to better understand the mechanisms which generate such events. To this end, the authors have identified all heavy rainfall cases which occurred in the first rainy season over the 45 year period between 1961 and 2005, and classified them into pre- and post-monsoon-onset cases according to the SCSSM onset index. In this paper, we will concentrate on the pre-monsoon-onset category and on the synoptic patterns associated with the heavy rainfall cases. A detailed analysis of the mechanisms of heavy rainfall in the pre-monsoon season is carried out through case studies. The paper is organized as follows:

In section 2, the data and method used for identifying the heavy rainfall cases are described. In section 3, the characteristics of these cases are examined. Section 4 describes the case studies. In section 5, the Moist Potential Vorticity (MPV) and Slantwise Vorticity Development (SVD) theories (Wu and Liu, 1999, Wu, 2001) are used to analyze the mechanisms behind the heavy rainfall events. Finally, in section 6 a conceptual model and concluding remarks are presented.

2. Data and method

There are 184 stations in the Guangdong and Guangxi provinces of South China. The record lengths of the data differ somewhat from station to station. So, to ensure data regularity, the authors selected data from 174 stations for the period 1961–2005. Among them, 88 stations are located in Guangdong Province and 86 in Guangxi Province, and daily rainfall data from these stations were used to characterize the heavy rainfall events. Also included in the study are the daily NCEP/NCAR reanalysis datasets of basic physical variables in standard pressure levels, such as wind, temperature etc.

The criterion for heavy rainfall for a given station was that daily precipitation was no less than 50 mm d^{-1}. South China (20°–28°N, 105°–118°E) was divided into cells of 0.5°×0.5° and a frame of 30 cells defined, with flexible grid numbers in the x and y directions (e.g. 10×3, 5×6 etc.) (Fig. 1). For each day, this frame was used to scan through the study area. The number of stations inside the frame with heavy

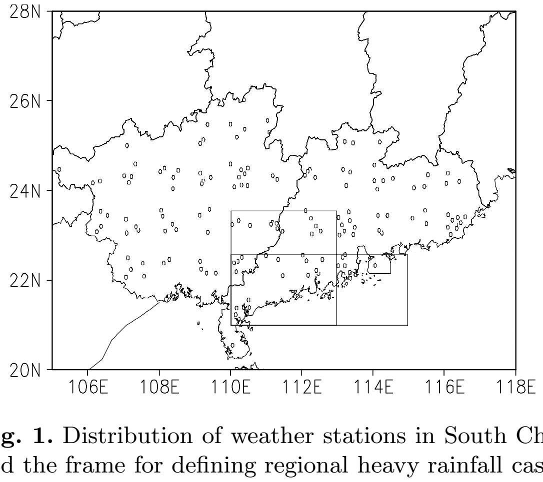

Fig. 1. Distribution of weather stations in South China and the frame for defining regional heavy rainfall cases.

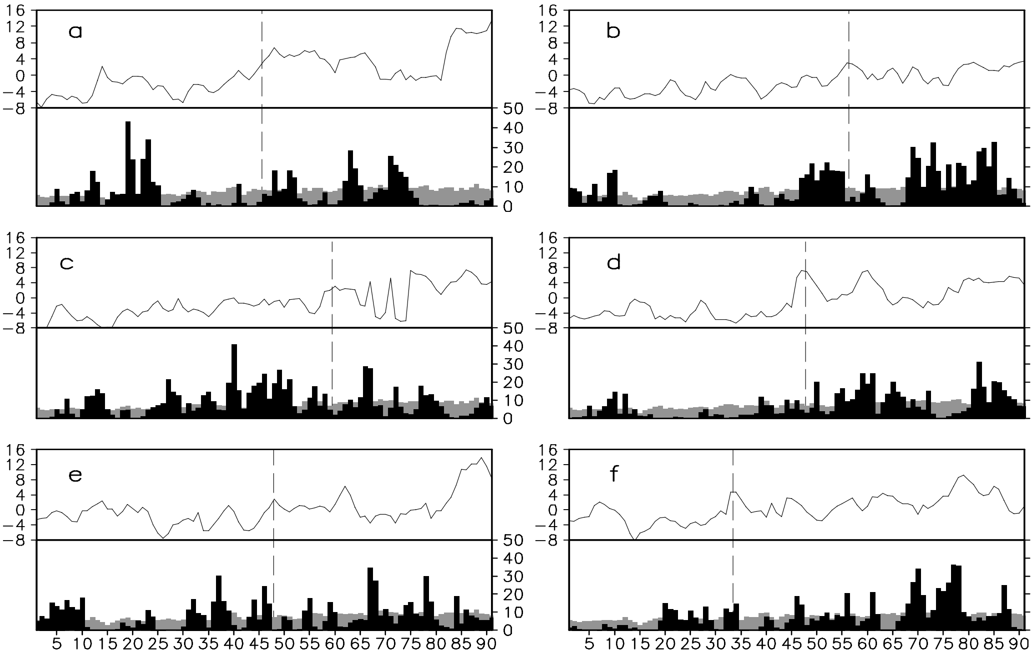

Fig. 2. Daily precipitation in South China (20°–28°N, 105°–118°E) from April to June: (a) 1961, (b) 1965, (c) 1975, (d) 1977, (e) 1992, and (f) 1994. Dark histogram is daily precipitation, units: mm; light color histogram is the climatology daily rainfall, units: mm; solid line is the daily SCSSM index; dashed line indicates the onset day of the SCSSM; and x-axis is daily variation from 1 April to 30 June.

rainfall ($\geqslant$50 mm d^{-1}) was calculated for each day, and if this number was no less than 10 then that particular day was considered to be a heavy rainfall day. If heavy rainfall lasted no less than three days, then it was defined as being a heavy rainfall event. The use of the number of heavy rainfall stations (i.e. 10 mm d^{-1}) is somewhat arbitrary, but has been shown empirically to be quite reasonable. We applied this method to identify all heavy rainfall events which occurred in the period of April to June each year. Then, according to the definition for the onset of the SCSSM (Wen et al., 2006), we divided the cases into pre- and post-monsoon-onset events.

Rainfall in South China increases greatly after the break out of the SCSSM (Figs. 2b, d, f). However, as seen in Figs. 2a, c and e, rainfall events in the pre-monsoon-onset period can produce strong precipitation, which are in some cases even stronger than those in the post-monsoon-onset period. Using the definition given above, we identified altogether 21 persistent heavy rainfall events in South China for the pre-monsoon-onset period during the years 1961 to 2005 (Table 1). Some of these events lasted for more than five days and some produced a total rainfall exceeding 1000 mm. This shows that even before the onset of the SCSSM, heavy rainfall events can occur in South China with intensities comparable to those in the post-monsoon-onset period. Heavy rainfall in the pre-monsoon period can also cause serious flooding, which should also be given due consideration.

3. Overall features of heavy rainfall events

Heavy rainfall develops only under certain synoptic conditions. Synoptic saddle fields are often found to be associated with precipitation, and Gao et al. (2008) pointed out that rainfall events during the mei-yu season are related to saddle field circulations over the Yangtze River region. An examination of the 21 heavy rainfall cases in South China indicates that a saddle field in the lower troposphere is an important synoptic pattern related to the pre-monsoon heavy rainfall cases. More than 60% of the heavy rainfall events in the pre-monsoon period occur under a saddle field circulation.

Figure 3 shows several examples. In all these cases, a saddle field can be clearly seen in the 850 hPa stream field. The occurrence of the saddle field is due to the presence of four clearly identifiable systems, namely, an anticyclone over North China (H_N), a subtropical high over the South China Sea (H_S), a trough to the Northeast of China (L_NE), and a trough to the Southwest of China (L_SW). Such a saddle field provides particularly favorable conditions for the development of heavy rainfall in South China in the pre-monsoon-onset period. During this period, cold air carried by

Table 1. A list of heavy rainfall cases before the onset of the South China Sea Summer Monsoon.

Case	Year	Month	Start day	End day	Duration (day)	Accumulative precipitation (mm)
1	1961	4	22	24	3	303.1
2	1970	5	11	13	3	502.6
3	1973	5	7	9	3	403.5
4	1973	6	1	4	4	243
5	1975	4	27	29	3	174
6	1975	5	9	11	3	337.4
7	1975	5	14	16	3	353.3
8	1980	4	21	24	4	407.2
9	1980	5	2	4	3	250.9
10	1982	5	9	13	5	829.6
11	1982	5	27	31	5	223.7
12	1984	4	25	27	3	383.3
13	1984	5	15	17	3	1024.1
14	1987	5	19	21	3	136.8
15	1987	5	31	4	5	231.2
16	1992	5	1	3	3	264.9
17	1992	5	6	8	3	219.3
18	1993	4	30	2	3	259.9
19	1993	5	22	24	3	191.8
20	2000	4	1	3	3	465.6
21	2001	4	20	22	3	490.1

the cold high (H_N) is still quite active in South China and can frequently affect the region. At the same time, the subtropical high is strengthening over the South China Sea and a trough exists to the southwest of China. Under such circumstances, a saddle field forms over South China, which is usually accompanied by a southerly LLJ located to the west of the subtropical high (not shown). The LLJ brings warm and humid air to South China, which interacts with the cold and dry air from the north. It is on the southern side of the saddle field where heavy rainfall occurs.

According to the analyses of all the heavy rainfall cases which occurred in a saddle field circulation, several common characteristics of heavy rainfall in the pre-monsoon period are found: (1) the saddle field is a shallow system, which can be clearly seen on the levels below 850 hPa, and heavy rainfall occurs mostly in the southwestern part of the saddle field, where warm and moist flow from the south prevails; (2) instead of a southwesterly LLJ, a southerly LLJ often occurs on the southern side of the saddle field and the formation of the southerly jet is closely related to the cyclone and anticyclone which occur on the south side of the saddle field; and (3) the southerly jet plays an important role in both the water vapor transportation and the formation of the unstable conditions for heavy rainfall. In the next section, we will examine a typical heavy rainfall case to add further detail to the above observations.

4. Case studies

A heavy rainfall case took place on 22–24 April 1961. Figure 4 shows the daily rainfall distribution from 21–26 April 1961. Rainfall began on 21 April in the northwest of Guangxi Province. Apart from the northwestern part of Guangxi, where daily rainfall reached 50 mm, it did not meet the heavy rainfall criterion at most of the weather stations. On 22 April, rainfall intensified in both Guangdong and Guangxi Provinces. Heavy rainfall centers were located in northwestern Guangxi and central Guangdong, where the maximum amount of daily rainfall exceeded 100 mm. Heavy rainfall persisted on 23 and 24 April, weakened on 25 April, and ceased on 26 April. The event lasted for three days, and the maximum daily rainfall was 193.2 mm (at Deqing, Guangdong Province). The maximum event-total rainfall reached 303 mm (at Changwu, Guangxi Province).

At 850 hPa (Fig. 5), a saddle field with its center at around 30°N came into existence on 21 April, accompanied by a weak LLJ along the southern coast of China. On 22 April, the saddle field was moving southward and the southerly LLJ was strengthening over South China. The strong southerly flow and the saddle field pattern lasted throughout 23 and 24 April (not shown). The appearance of a saddle field implies the existence of conditions favoring the interaction between warm and cold air. As we can see from Fig. 6, to the south of 20°N, at the low levels of the tropo-

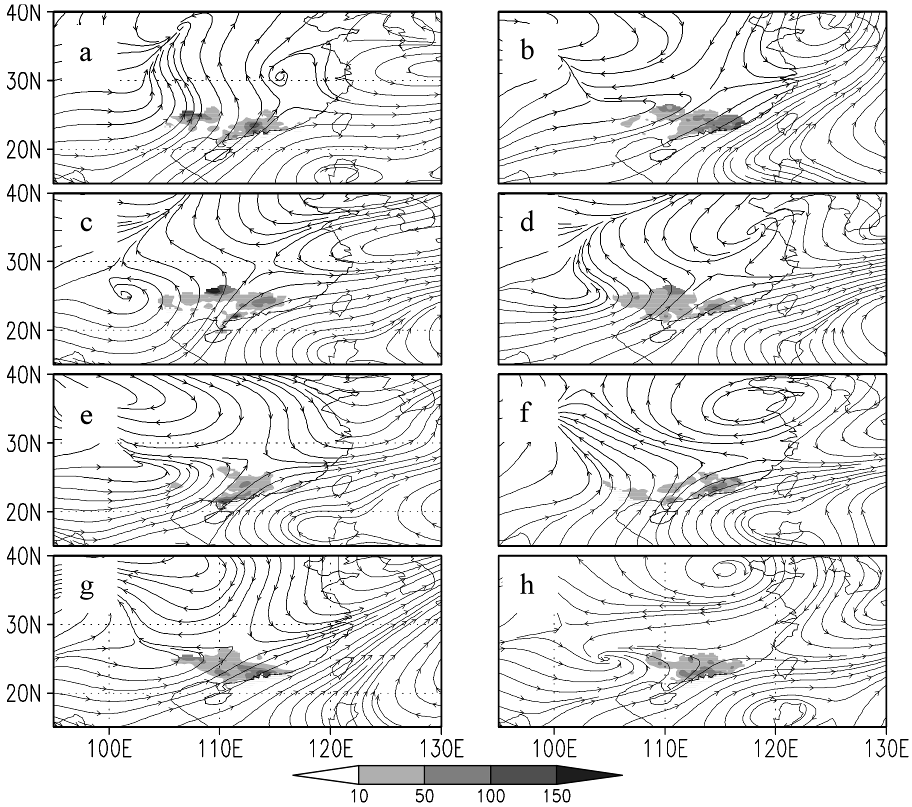

Fig. 3. Streamlines at 850 hPa and daily precipitation (shaded, in mm) at 850 hPa for: (a) 22 April 1961, (b) 7 May 1973, (c) 16 May 1975, (d) 16 May 1984, (e) 7 May 1992, (f) 21 April 2001, (g) 7 May 1992 and (h) 21 April 2001.

sphere (850 hPa and 925 hPa), air temperature began to increase on the south side of the saddle field before heavy rainfall started. At the same time, colder air occurred to the north of 30°N and a strong temperature gradient occurred. The confronting of warm and cold air is reflected by the maintenance of the saddle field in the lower layers over South China. When the anticyclone on the north side of the saddle field moved southward, the colder air controlled South China and heavy rainfall stopped. Although only one typical case is shown here, the same characteristics can be found in all heavy rainfall cases occurring under a saddle field pattern in the pre-monsoon period from 1961 to 2005.

Tao and Chen (1987) found that heavy rainfall in South China is well correlated with the low level convergence and the associated strong vertical motion and is accompanied by a rapid increase in vertical vorticity. Therefore, the diagnosis of the increase of vertical vorticity is important in analyzing heavy rainfall process.

In a pressure coordinate system, the local variation of relative vorticity can be expressed as follows:

$$\frac{\partial\zeta}{\partial t}=-\left(u\frac{\partial\zeta}{\partial x}+v\frac{\partial\zeta}{\partial y}\right)-\left(u\frac{\partial f}{\partial x}+v\frac{\partial f}{\partial y}\right)-$$

$$\omega\frac{\partial\zeta}{\partial p}+\left(\frac{\partial\omega}{\partial y}\frac{\partial u}{\partial p}-\frac{\partial\omega}{\partial x}\frac{\partial v}{\partial p}\right)-(f+\zeta)\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)\ . \quad (1)$$

Here, u, v, ω is the zonal, meridional, and vertical components of motion respectively,

$$\zeta=\frac{\partial v}{\partial x}-\frac{\partial u}{\partial y}$$

is the vertical component of relative vorticity (simply relative vorticity hereafter); f is the Coriolis parameter and p means it is in pressure coordinate. The five terms on the right side of the equation are, respectively: the advection of the relative vorticity; advection of planetary vorticity; vertical advection of relative vorticity; the twisting term; and the divergence term. We have calculated each of these five terms to estimate their contributions to the rate of change of the relative vorticity.

Figure 7 shows a cross section of ζ and the five terms along 110°E for 21 April. Before the start of the heavy rainfall, ζ increased below 850 hPa (Fig. 7a) and the major contributor to this increase is the divergence term (Fig. 7b), with the contributions from the other terms being either small or negative (Figs. 7c–f). This means that before the start of the rainfall,

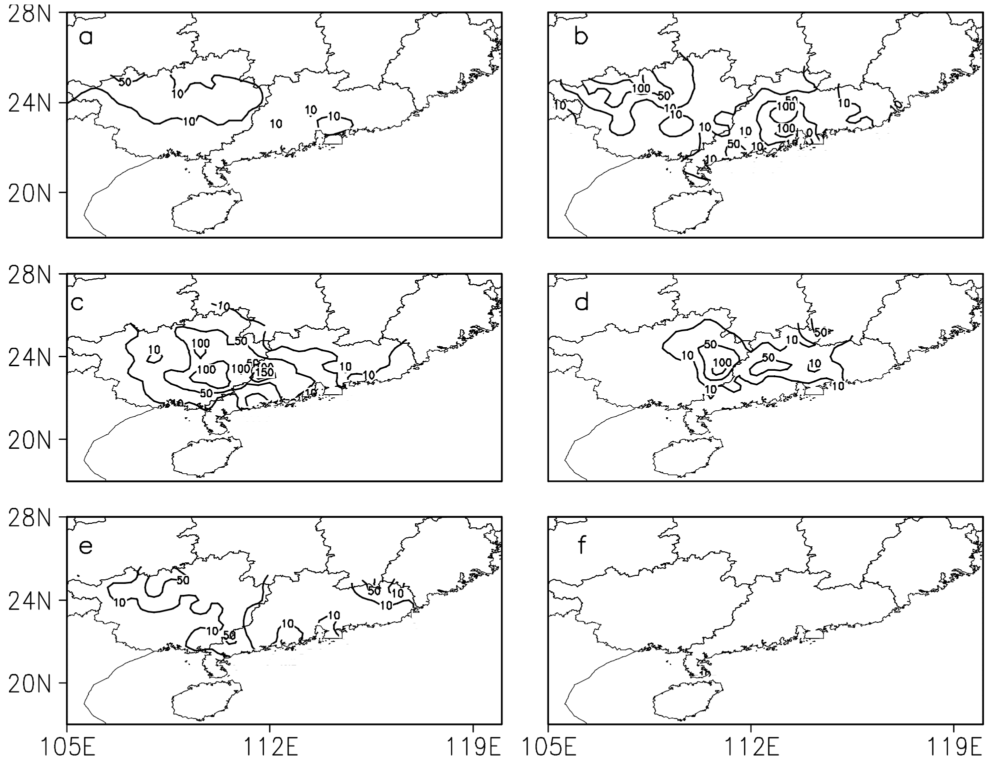

Fig. 4. Daily precipitation from (a) 21 to (f) 26 April 1961 (units: mm).

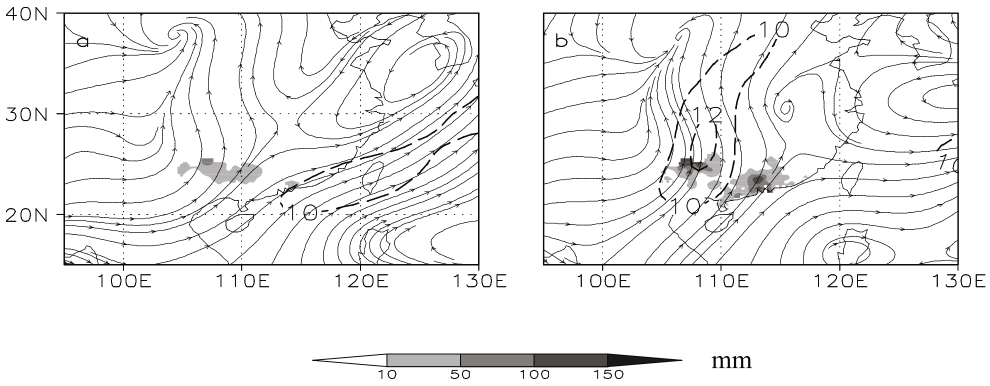

Fig. 5. Streamlines at 850 hPa and daily precipitation for (a) 21 April and (b) 22 April. Shaded areas indicate precipitation and dashed lines are contours of wind speed exceeding 10 m s^{-1}.

a moisture convergence exists in the lower layers of the atmosphere. On the next day, ζ increased dramatically over South China (Fig. 8a) and two positive ζ centers can be clearly seen, one at 1000–925 hPa and the other at 850–700 hPa. The dramatic increase in ζ is accompanied by strong vertical motion (shaded area) and heavy rainfall. Among the five terms on the right hand side of Eq. (1), the divergence term remains to be the dominant term contributing positively to the increase of ζ in the atmosphere below 850 hPa. On 22 April, the increase of ζ in the layer between 700 hPa and 850 hPa was mainly due to the advection term. The vertical advection term and the twisting term were small and the planetary vorticity advection term was negative.

The above analysis suggests that two phenomena deserve particular attention:

(1) The confrontation of cold and warm air is an important characteristic of pre-monsoon heavy rainfall in South China. On the south side of the saddle field, the southerly LLJ can bring warm and moist air to South China, while on the north side of the saddle field it is dominated by cold air.

(2) Analysis of the vorticity equation shows that

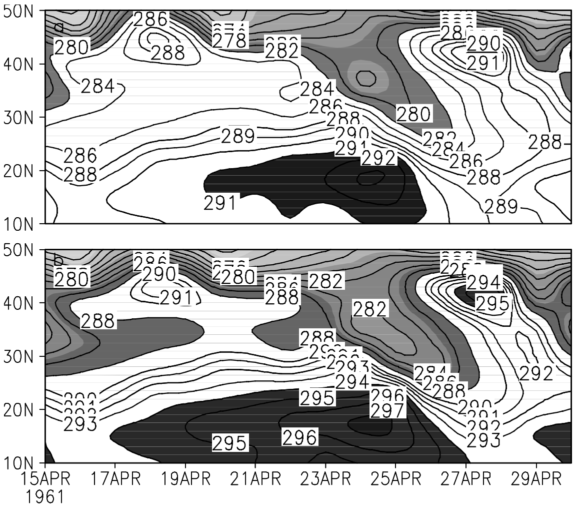

Fig. 6. Latitude–time cross section of temperature at (a) 850 hPa and (b) 925 hPa averaged from 105°–120°E during 15–30 April 1961.

before the rainfall starts, convergence of moisture has a positive contribution to the increase of ζ in the lower layers. When rainfall begins, the advection term becomes more important for the increase of vorticity in the 850–700 hPa layer. The center of the vorticity increase is consistent with the center of the vertical velocity increase.

In the next section, we will use MPV theory to explain the formation of the vorticity center which is related to the strong vertical motion over South China. The role of the saddle field will also be discussed.

5. MPV theory and mechanisms for heavy rainfall development

5.1 *MPV theory*

MPV, an extension of Potential Vorticity (PV), is a useful quantity for the diagnosis of atmospheric thermodynamic processes. The development of PV theory can be traced back to Rossby (1940) who found that ζ_{a}/H, called potential vorticity, is conserved during the movement of an air column, where ζ_{a} and H are respectively the absolute vorticity and the depth of the air column. Ertel (1942) found that PV is conserved in a frictionless and dry adiabatic atmosphere. PV can be used as an air mass tracer in synoptic analysis (Kleinschmidt, 1950; Reed and Sanders, 1953). A review of the development of PV theory and its applications has been carried out by Hoskins et al. (1985).

PV theory is most useful for analyzing the development of weather systems at middle and high latitudes. At low latitudes, however, PV is rather small and difficult to use. Further, PV theory does not include the effects of distribution of moisture, which is obviously important to the development of heavy rainfall. MPV theory has been developed to overcome these deficiencies of PV theory.

Equivalent potential temperature is used to deduce the MPV equation. Following Wu et al. (1995), the MPV equation can be written as:

$$\frac{d(\mathrm{MPV})}{dt}=\alpha(\nabla P\wedge\nabla\alpha)\cdot\nabla\theta_{\mathrm{e}}+\alpha\nabla\theta_{\mathrm{e}}\cdot\boldsymbol{F}+\alpha\boldsymbol{\zeta}_{\mathrm{a}}\cdot\nabla Q\,, \quad (2)$$

where $\mathrm{MPV}=\alpha\boldsymbol{\zeta}_{\mathrm{a}}\cdot\nabla\theta_{\mathrm{e}}$ is moist potential vorticity, $\boldsymbol{\zeta}_{\mathrm{a}}$ is absolute vorticity, α is specific volume, θ_{e} is equivalent potential temperature, $\boldsymbol{F}$ is friction, and

$$Q=\frac{\theta_{\mathrm{e}}}{c_pT}Q_{\mathrm{d}}$$

and Q_{d} are diabatic heating, c_p is specific heat at constant pressure. In a saturated, frictionless and adiabatic atmosphere, the three terms on the right side of Eq. (2) are equal to zero. MPV is conserved and can be used to analyze heavy rainfall processes.

5.2 *MPV components and the role of the saddle field*

Assuming that the horizontal change in vertical velocity is much smaller than the vertical change in horizontal wind speed, MPV in a P-coordinate can be written as:

$$\mathrm{MPV}=-g(\zeta+f)\frac{\partial\theta_{\mathrm{e}}}{\partial p}+g\frac{\partial v}{\partial p}\frac{\partial\theta_{\mathrm{e}}}{\partial x}-g\frac{\partial u}{\partial p}\frac{\partial\theta_{\mathrm{e}}}{\partial y}\,. \quad (3)$$

In dry air conditions, $q=0$, then MPV is identical to PV. We can separate MPV into two terms, namely:

$$\mathrm{MPV1}=-g\zeta\frac{\partial\theta_{\mathrm{e}}}{\partial p} \quad (4)$$

and

$$\mathrm{MPV2}=g\frac{\partial v}{\partial p}\frac{\partial\theta_{\mathrm{e}}}{\partial x}-g\frac{\partial u}{\partial p}\frac{\partial\theta_{\mathrm{e}}}{\partial y}\,. \quad (5)$$

MPV1 is the vertical component of MPV, which is related to the vertical absolute vorticity and the vertical gradient of equivalent potential temperature (representing convective instability); and MPV2 is the horizontal component of MPV, which is related to the wind shear and moist baroclinity. It has been shown in many previous studies (e.g. Yuan and Shou, 2001; Liu and Ding, 2005) that MPV1 and MPV2 are useful variables for describing the instability of the atmosphere during heavy rainfall. Therefore, we use MPV1 and MPV2 to explain the roles of the saddle field and the LLJ in the development of heavy rainfall in South China.

Figure 9 shows the distribution of MPV1 at the 850 hPa level from 21–26 April 1961. MPV1 was negative over South China before the rainfall started, which

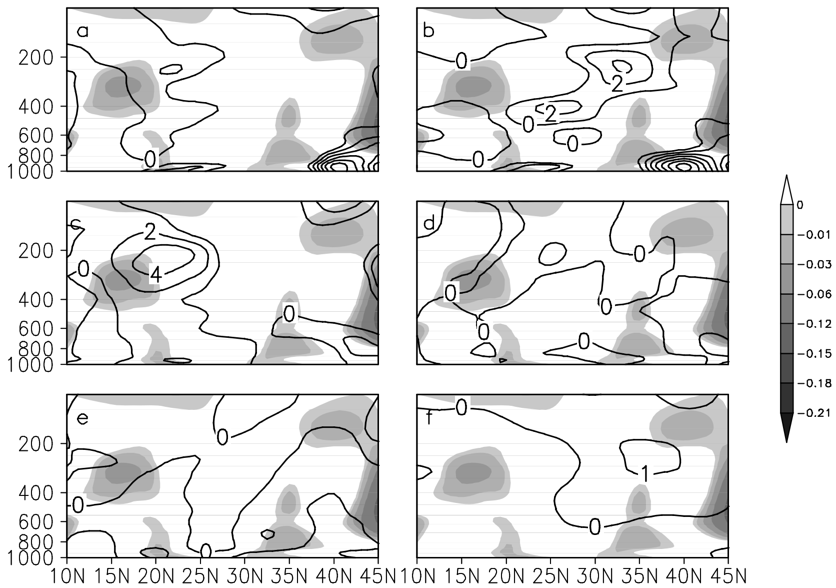

Fig. 7. Cross section map along 110°E for 21 April: (a) local changing of vertical; (b) divergence term; (c) advection of vorticity term; (d) vertical transport term; (e) twisting term; and (f) advection of geostropic vorticity term (units: m s^{-2}). Shading indicates increment of vertical velocity (units: Pa s^{-1}).

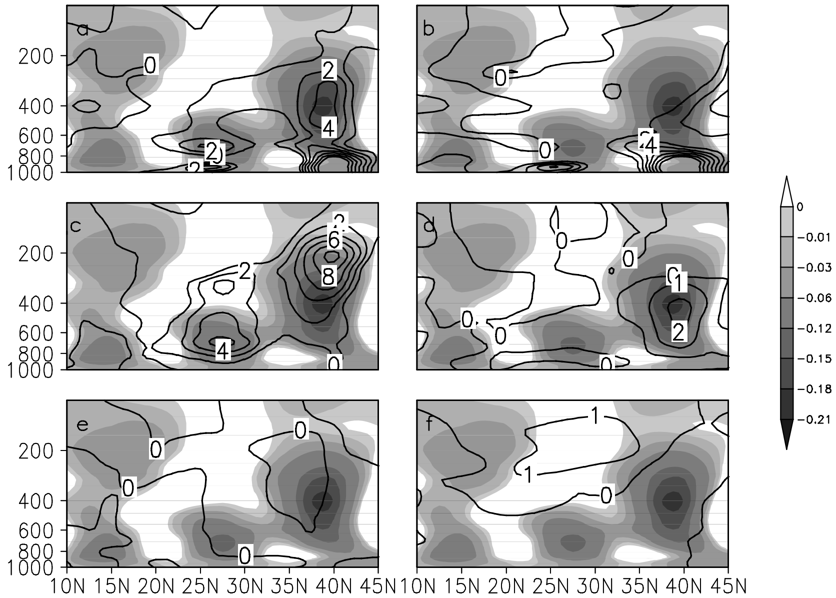

Fig. 8. Same as Fig. 7 but for 22 April 1961.

means that the atmosphere was convectively unstable. Over the northeastern part of China and South Korea, there was an area of positive MPV1 representing the colder and more stable air to the north side of the saddle field. During the heavy rainfall (Figs. 9b–d), the saddle field maintained above South China and the atmosphere remained convectively unstable (stable) to the south (north) side of the saddle field. Heavy rainfall occurred to the east side of the negative center. From 25–26 April, the saddle field began to move southward, South China was dominated by colder air coming with the anticyclone to the north of the saddle field (Figs. 9e and f), and the atmosphere became stable. The distribution of MPV1 at 850 hPa demonstrates that maintenance of a saddle field over South China is a benefit for heavy rainfall. Once the saddle field moved southward, the colder and stable air from the north arrived and dominated South China, and the

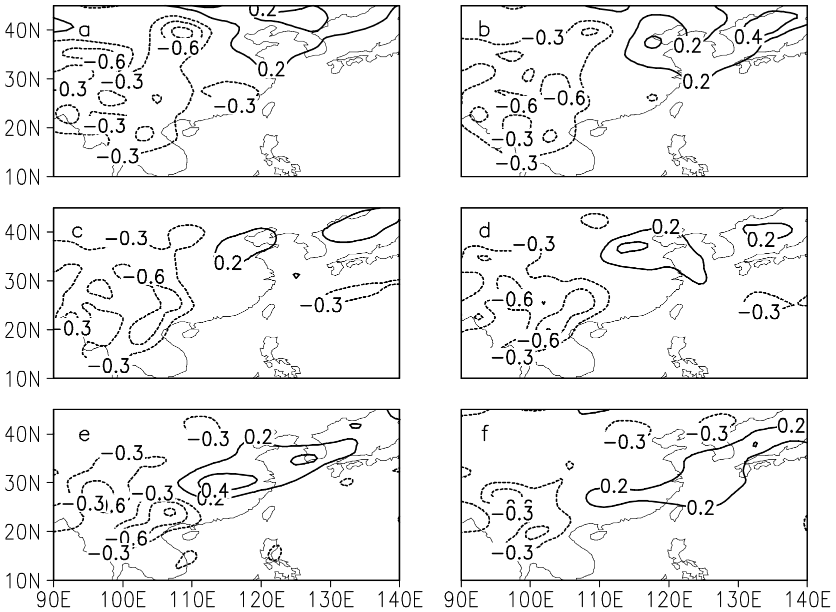

Fig. 9. Distribution of MPV1 at 850 hPa for case 1 for: (a) 21 to (f) 26 April 1961 (in PVU, 1 PVU = 10^{-6} m^2 K s^{-1} kg^{-1}).

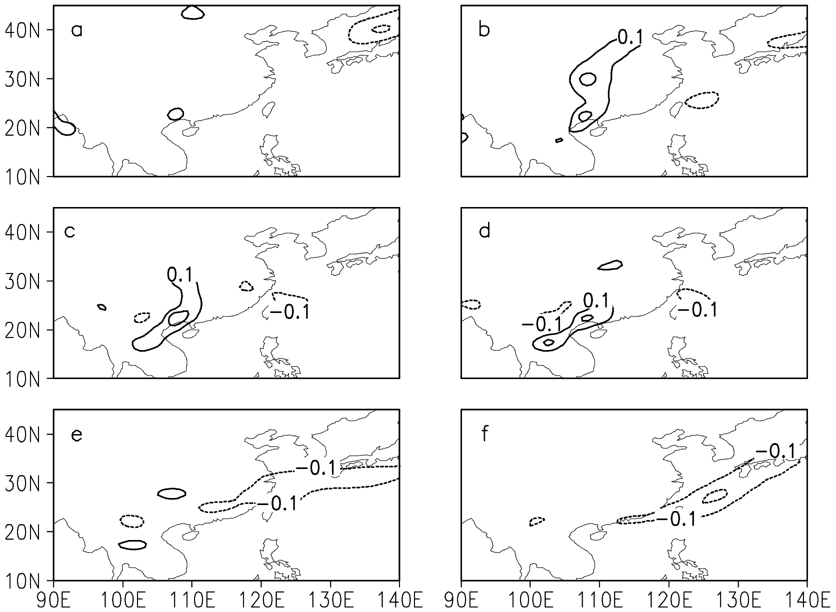

Fig. 10. Distribution of MPV2 at 925 hPa for: (a) 21 to (f) 26 April 1961 (units: PVU).

interaction of warm and cold air disappeared over the region. It is obvious that only suitable strength of the warm and cold air confrontation can form the saddle field pattern, and the maintenance of the saddle field pattern is valid for the maintenance of heavy rainfall.

The movement of a positive MPV2 center can be used as a tracer for the movement of warm and moisture air. A southerly LLJ occurred during the heavy rainfall of 22–24 April. As can be seen in Fig. 10, a positive center of MPV2 formed over South China during heavy rainfall (Figs. 10b–d), and the positive MPV2 center weakened on 25–26 April (Figs. 10e–f). The position of the positive MPV2 center is the same as that of the LLJ. MPV2 is a good variable for tracing the movement of the LLJ and warm and moisture air in the lower layers. When the LLJ occurred, convergence of warm and wet air over South China increased the local vorticity, which is shown in the analysis of the vorticity equation.

An examination of MPV1 reveals the role of the saddle field in the pre-monsoon heavy rainfall process, and MPV2 is a good variable for tracing the movement of warm and moisture air. Both the saddle field and the LLJ offer a good environment for the formation of heavy rainfall. As seen in this last section, the increasing vertical velocity is related to the two increasing vertical vorticity centers between 1000 and 700 hPa. Occurrence of the LLJ can explain the increase of vertical vorticity below 850 hPa. The advection term, which contributes to the increase of vertical vorticity above 850 hPa, can be explained through SVD theory in the next section.

5.3 *Distribution of vertical vorticity*

After deducing the moist potential vorticity equation, Wu (2001) also introduced a SVD theory to diagnose the changing of the vertical vorticity component. In a z-coordinate system, MPV can be written as:

$$\mathrm{MPV}=\zeta_{\mathrm{n}}\theta_{\mathrm{en}}=\zeta_{\mathrm{s}}\theta_{\mathrm{es}}+\zeta_z\theta_{\mathrm{e}z}=\mathrm{const}\ , \qquad (6)$$

$$\zeta_z=(\zeta_n\theta_{\mathrm{en}}-\zeta_{\mathrm{s}}\theta_{\mathrm{es}})/\theta_{\mathrm{e}z}\ . \qquad (7)$$

Here ζ_{s}, ζ_z and θ_{s}, θ_z represent the horizontal and vertical component of vorticity (ζ_{n}) and equivalent potential temperature (θ_{en}) respectively. Equations (6) and (7) show that, when MPV is conserved, if $\zeta_{\mathrm{s}}\theta_{\mathrm{es}}/\theta_{\mathrm{e}z}<0$ ($\mathrm{MPV2}/\theta_{\mathrm{e}z}<0$), rapid increase of vertical vorticity (ζ_z) will happen. In addition, the change of vertical vorticity (ζ_z) is according to the slant of the isentropic surface, and it is related to the convective instability ($\theta_{\mathrm{e}z}$), the vertical wind shear ($\zeta_{\mathrm{s}}\propto\partial V_{\mathrm{s}}/\partial z$) and the horizontal distribution of θ_{es}. These three factors can lead to the slant of the isentropic surface and lead to the increasing of vertical vorticity (Wu et al., 1995). In the last section, it was found that during the heavy rainfall, in the lower layers over South China, the atmosphere is convectively unstable ($\theta_{\mathrm{e}z}<0$), while the southerly LLJ occurred, MPV2>0. When $\mathrm{MPV2}/\theta_{\mathrm{e}z}<0$, the slant of the isentropic surface will occur. As we can see in Fig. 11, on 21 April (Fig. 11a), the isentropic surface (340 K) remained flat, it became steeper on 22 April (Fig. 11b), and the air column above South China is elongated. According to SVD theory, this slantwise motion will lead to the rapid increase of vorticity in the lower layers (850–700 hPa). The slantwise motion of the isentropic surface can explain the second vertical vorticity center that was found according to the diagnosis of the vorticity equation in section 4. When strong vorticity occurred above South China, it induced stronger upward motion. As a consequence, the warm and humid air which is accumulated over South China will be lifted and the unstable energy will be released over an extensive area. Since the saddle field pattern maintained in the lower layers during the heavy rainfall process, more and more warm and moist water vapor are transported to South China to maintain the unstable air conditions, and the heavy rainfall persists. The rainfall came to an end on 26 April (Fig. 11c). The center of positive MPV moved eastward and the isentropic surface above South China became flat.

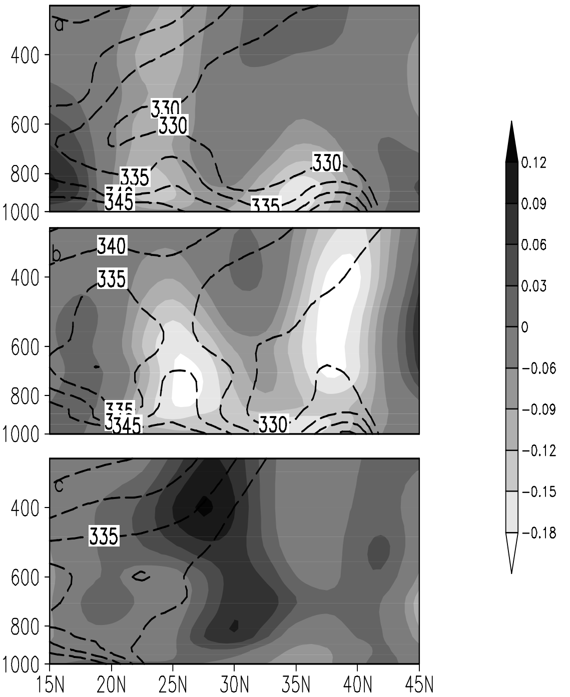

Fig. 11. Cross section of vertical motion (shaded, units: Pa m^{-1}) and θ_{e} (black lines, units: K) along 110°E for (a) 21, (b) 22 and (c) 26 April 1961.

Analysis of the vorticity equation showed that the increase of vorticity is mainly caused by the divergence term below 850 hPa and the advection of vorticity term above 850 hPa. The increase of the vorticity center above 850 hPa is closely related to the occurrence of heavy rainfall. The local vorticity increase around 850–700 hPa, which is related to the strong vertical motion, is caused by the slantwise motion of the isentropic surface. The slantwise motion occurring during the heavy rainfall can lead to the rapid increase of vorticity around 850 hPa, and is the mechanism of the occurrence of heavy rainfall.

6. Summary

In this study, the authors identified all heavy rainfall cases in South China from 1961–2005 and separated them into pre- and post-monsoon-onset categories according to the onset of the SCSSM. The mechanisms for the pre-monsoon-onset heavy rainfall cases have been analyzed. The conclusions are as follows:

During 1961–2005, 21 heavy rainfall events occurr-

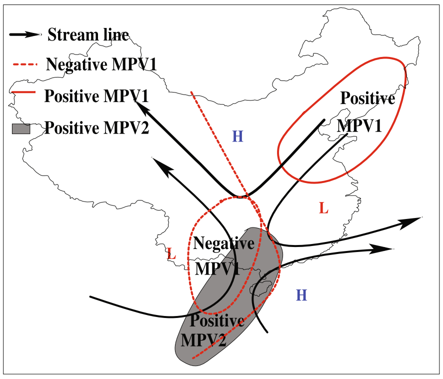

Fig. 12. A conceptual model for a heavy rainfall event in South China: 850 hPa level.

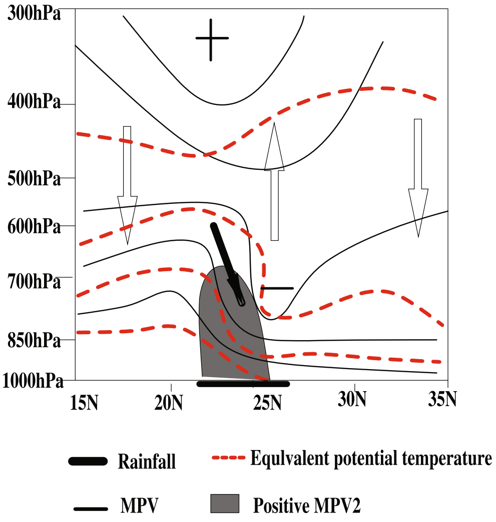

Fig. 13. A conceptual model for a heavy rainfall event in South China: vertical cross section (black and white arrows represent the movement of air flow).

ed in the pre-monsoon-onset period. The amount of precipitation in the pre-monsoon period can be as large as that in the monsoon period. Among these 21 cases, approximately 60% were associated with a low-level synoptic saddle field. One such case was selected as an example to study the mechanisms of pre-monsoon heavy rainfall.

It was found that the rapid increase of the vertical component of vorticity can be explained using the slantwise theory of the isentropic surfaces, which in turn resulted in the increase of vertical motion over South China. Other heavy rainfall cases have also been examined (not shown) and it has been found that the slantwise motion on isentropic surfaces is a common feature of all cases happening under a saddle field circulation pattern.

The mechanisms for the development of heavy rainfall events are shown in Figs. 12 and 13, which were constructed from all heavy rainfall cases associated with a saddle field. Figure 12 shows that the existence of a saddle field provides favorable conditions for heavy rainfall, as it enables the accumulation of cold air to its north side and the accumulation of warm and wet air to its south side. The atmosphere is convectively unstable on the southwestern side of the saddle field where warm and moist air and unstable energy are accumulated. The slow movement of the saddle field is important for maintaining these kinds of unstable conditions. When the saddle field moves southward, cold air starts to dominate over South China and the rainfall stops. The existence of the saddle field and the southerly LLJ are important for the accumulation of warm moist air over south China and the formation of favorable conditions for slantwise motion.

A trigger mechanism is required for the release of the unstable energy accumulated in the lower troposphere over South China. As shown in Fig. 13, the atmosphere over South China is convectively unstable, with $\theta_{ez} < 0$ and MPV2>0 (strong vertical wind shear and moist baroclinity). The criterion for slantwise motion of the isentropic surface is satisfied ($\mathrm{MPV2}/\theta_{ez} < 0$). Slantwise motion will lead to the rapid increase of vorticity at 850 hPa, resulting in a dramatic increase of upward motion in South China and the release of the unstable energy.

MPV has been found to be a more useful quantity than PV in studying the heavy rainfall processes at low latitudes. We compared the distributions of PV, MPV, potential temperature and pseudo virtual potential temperature, and found that instability is confined to the lower troposphere. This instability can be clearly seen from the vertical distribution of pseudo virtual potential temperature but not from that of potential temperature. This reveals that warm and moist air is important to the precipitation in the low-latitude regions.

More than 60% of the pre-monsoon-onset heavy rainfall cases are associated with saddle fields. The remaining cases are related to other types of synoptic systems. Detailed analyses of the latter are yet to have been carried out. Furthermore, most pre-monsoon-onset heavy rainfall cases are associated with a southerly LLJ. The formation of the southerly LLJ can be attributed to the strong pressure gradient between the cyclone and anticyclone on the south side of the saddle field. The formation of the southerly LLJ also deserves further research.

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