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STUDY OF DOUBLE RAIN BANDS IN A PERSISTENT RAINSTORM OVER SOUTH CHINA

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Abstract: Using the U.S. National Centers for Environmental Prediction/National Center for Atmospheric Research reanalysis data at 1°×1° resolution, analysis is performed on a persistent heavy rainfall event with two rain bands to the south of the Yangtze River during 17–22 June 2005. The northern rain band was related to the atmospheric mass adjustment of cold front precipitation and the associated ageostrophic feature to the rear right of subtropical westerly jets, while the southern counterpart formed under the joint influence of easterly/westerly jets and the South Asian high (SAH). The ageostrophic wind field to the rear right of the easterly jet center gives rise to an anti-circulation that favors the genesis of the southern belt. The feature of du/dt <0 around the SAH ridge line and to the rear right of the easterly jet streak results in a strong $v - v_g$<0 field in the vicinity of the rain region as well as to its south. When westerly jets move southward, an intense $v - v_g$>0 feature appears to the north of the rain region, i.e., behind the center of the westerly jets. The associated mass adjustment leads to vigorous divergence over the rain region, which is responsible for the strong precipitation from the warm sector of the front. Also, a θe front at the middle level of the southern rain band and the cold front favor the release of instable energy to enhance the rainstorm. The southern and northern fronts approach each other and the two rain belts merge into one.

Key words: easterly/westerly upper-air jets; warm-region rainstorm; middle-level θ front; mass adjustment

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1 INTRODUCTION

Uccellini and Johnson[1] indicated that atmospheric mass adjustment, caused by ageostrophic wind around an upper-level westerly jet, can produce a secondary circulation that leads to precipitation development. Ninomiya[2] and Sotais et al.[3] noted that convection-caused vertical transport of momentum can bring about the development of low-level jet flows at the exit region of upper-level westerly jets. Many scientists have investigated the relationship between the mass adjustment caused by high-level westerly jets with the coupling of jets at high and low levels, strong rainfall and cyclonic explosive intensification (Uccellini et al.[4]; Ding et al.[5]; Wang et al.[6] 2006). Chen[7], for example, showed that a Meiyu rainstorm in China was related to a region of entranced easterly jets. He also found a spatial linkage of a rainstorm zone to high- and low-level westerly jets and South-Asian easterly jets in his numerical experiments for the early and middle summer of China, and the coupling of the high and lower troposphere air mainly occurs between low-level jets and southern Asian easterly jets, which is characterized mainly by rising (sinking) in the north (south) as an anti-circulation. Lu et al.[8] as well as Zhe and Gao[9] discovered that during a Meiyu rainstorm, there occurred a northerly gale axis in the upper troposphere to the east of the Tibetan high that spreads eastward, thus resulting in a high-level divergence zone moving eastward with the high. The axis is often ahead of and above low-level jets, causing the coupling between upper-level northeast and low-level southwest winds.

Many studies have been conducted on

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easterly/westerly jets associated with mesoscale systems. Liu and Chen[10] examined cloud-derived winds in the upper troposphere and found two passages for the outflow of a mesoscale convective system (MCS) inside the East-Asian Meiyu front clouds. One is that the MCS manifests itself as a mesoscale high, with the upper-level mesoscale jets east of the MCS flowing out eastward and then turning southward into the South Asian easterly jets around 20°N, which serves as the principal MCS outflow channel in the upper troposphere. Through a numerical study of a Meiyu-front rainstorm, Long and Cheng[11] claimed that in the development of a mesoscale- α shear-line vortex, low-level strong southwesterly and northeasterly jets intensify convergence, while the high-level westerly and easterly jets enhance divergence therein. The distribution of circulations from upper to lower levels promotes the steady intensification of the mesoscale- α vortex. Thus it is evident that previous studies focus on the contribution of tropical easterly and subtropical westerly jets, coupled with low-level southwest wind, to the development of Meiyu-front torrential rains.

Yu and Lu[12] are the first to reveal a double-rainbelt pattern in the Meiyu rainstorm in their mesoscale experiment. Zheng et al.[13] revealed the existence of a mesoscale- α double-band pattern in the Meiyu-front rainstorms in 1981 and the structure of associated physical fields[14]. In their investigation of the structure of Meiyu fronts in 1998 and 1999, Gao and Zhou[15] indicated that the southern front at 850–500 hPa is a dew-point front that favors the development of precipitation except that the rainfall is mostly of single belt nature. In their study of an event of South-China persistent precipitation during June 18–24, 2005, Zhao and Li[16] found that between Meiyu frontal rainfall and pre-front warm-sector rainfall there are vast differences in mesoscale rain cluster activity, dynamics, atmospheric instability mechanism and heating structure as well as some discrepancy in vapor transport, mesoscale environment and rainstorm-related vertical circulation. All of these may be the main reasons for the difficulty in simulating and predicting heavy rains from the pre-front warm sector. Whether there is a double-rain-band structure associated with the two fronts in South China, what their genesis mechanism is and what the relationship is of such rainstorms with upper-level easterly/westerly jets and a South Asian high (SAH) will be investigated in this paper.

A pattern of two rain bands is often shown in June in the process of persistent torrential rain from the area south of the Yangtze River to South China, with one band between the River and the Nanling Mountains (referred to as the northern rain band [NRB] hereafter) and the other south of the Mountains (the southern rain band [SRB]). As shown by Ding et al.[17], for the situation of lasting rainstorms of June, the probability exceeds 40% for the SRB to appear in company with the NRB. A pattern of such double bands was observed in 1994, 1998 and 2005. The SRB denotes the precipitation mainly from the frontal warm sector in the vicinity of the ridge line of the SAH while the NRB rainfall is dominantly associated with fronts and cold air activities. Zhou et al.[18] showed that climatically South China remains to the north of the main body of the subtropical high during April–June, with rainfall in close association with westerly systems, but rainstorms do not take place in front of or behind it. In particular, strong rainfall tends to occur on the side of warm air ahead of the front so that rainstorms from the warm sector are the most prominent feature of rainfall in South China. The warm-sector rainstorm is marked by appreciable mesoscale characteristics. Most of the ongoing research is devoted to their structures by means of numerical study, synoptic analysis and radar measurements (Sun and Zhao[19]). There are more studies on rainstorm-related subtropical westerly and easterly jet currents in the investigation of Meiyu precipitation (e.g., Zhe 1998[20]; Zhu et al.[21]). This study examines the rainfall event and the associated systems related to the two rain bands, with a focus on the SRB-associated upper-air easterly/westerly jets, as well as to the SAH.

2 ACTIVITIES OF UPPER-AIR EASTERLY/WESTERLY JETS IN RELATION TO PRECIPITATION

Data used in this study consist of the U.S. National Centers for Environmental Prediction (NCEP) reanalysis data at 1°×1° resolution, with 21 layers in the vertical at 6-h intervals and hourly rainfall measurements from about 1700 automatic weather stations provided by the "973" Project team.

Figure 1a shows two distinct rain bands south of 30°N, separated around 24°N and 27°N. Each rain band is associated with a rainfall maximum above 500 mm during the period. The SRB precipitation is mainly between 108°–118°E, with the strongest core at 24°N, 114°E and the NRB rainfall occurs in 113°–121°E, with a maximum at 27°N, 118°E. Figure 1a shows that the precipitation associated with the NRB is concentrated, with a large area of strong rainfall. Three rainfall centers are associated with the SRB with a small zone of hard rainfall. As indicated in the analysis of daily precipitation (not shown), strong SRB rainfall occurred from 0000 UTC June 19 to 0000 UTC June 22, with varying precipitation centers. The most vigorous rainfall happened during the 24-h period starting from 0000 UTC on June 21. On the other hand, the daily NRB precipitation exceeded 100 mm from 0000 UTC June 18 to 0000 UTC June 22 and the rainfall position was relatively fixed. As shown in the distribution of 6-hourly precipitation along 114°E (Fig. 1b), there are two rain belts during the persistent precipitation, with the NRB between 26°–29°N and to the SRB between 22°–25°N.

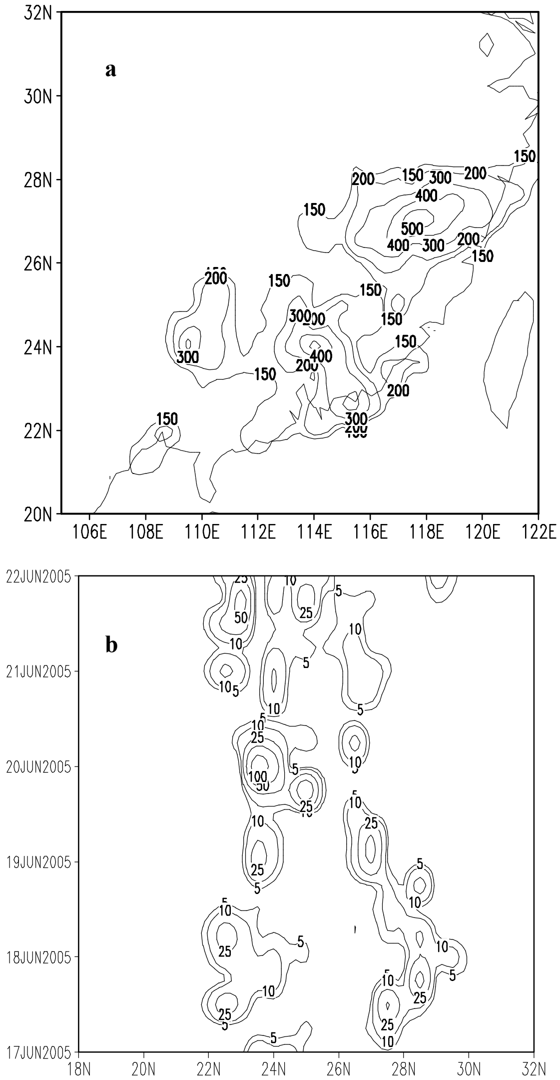

Fig. 1. Total rainfall (mm) from 0000 UTC June 17 to 0000 UTC June 23, 2005 in a) and 6-hour rainfall (mm) along 114°E from 0000 UTC, June 17 to 0000 UTC, June 22, 2005 in b)

Figures 2a and 2b are the plots of mean wind velocities at 200 hPa and 150 hPa, respectively, for June 17–21. At the 200 hPa level (Fig. 2a), the axis of subtropical westerly jets is positioned around 35°N and strong westerlies are over the rain zones from the area south of the Yangtze River to the Nanling Mountains. The two belts are to the rear right of the center of subtropical westerly jets, with South China located in the vicinity of a low-value wind core close to the SAH ridge line. To the south of the SRB, there is an easterly jet streak of 22 m/s centered on about 14°N, 113°E with the central axis line between 10°–15°N. Its intensity falls short of that of a high-level jet stream. As shown in Fig. 2b, the center of westerly jets at 150 hPa corresponds to that at 200 hPa except for its lower winds, being in sharp contrast to the case of easterly jets. The center is at 12°N and west of 90°E and the warm-sector rainstorm comes from the entrance region of easterly/westerly jets, with winds higher than 25 m/s.

The strongest phase of the torrential rain occurred during the 24 hours beginning from 0000 UTC, June 21. The 150-hPa mean wind speeds of easterly jets were enhanced greatly (Fig. 2d). The easterly winds of >30 m/s concentrate to the west of 105°E with the central axis at about 12°N. An isotach of 20 m/s easterly is around 17°N. The SRB is to the rear right of easterly jets around the SAH ridge line. On the other hand, the central intensity of westerly jets exceeds 45 m/s, with the axis line at about 35°N. Strong westerly winds occurred over the NRB. The central vigor of westerly jets is >50 m/s at 200 hPa (Fig. 2c), with easterly flows much weaker at 200 hPa than at 150 hPa.

Note that the axis of westerly jets extends appreciably more southward at 150 hPa (Fig. 2d) than at 200 hPa (Fig. 2c), thereby leading to stronger westerlies above the warm-sector rainfall zone at 150 hPa than at 200 hPa. The SAH ridge in the vicinity of the rain band slightly tilts northward (Figs. 2d vs 2c), as displayed in the distribution of the 6-hourly precipitation pattern.

Figure 2 depicts weak easterly jets and strong westerly jets at 200 hPa. The easterly jets are much stronger at 150 hPa than at 200 hPa, suggesting a greater effect on the SRB than on the NRB. The westerly jets are weaker at 150 hPa than at 200 hPa. We can see in the figure that the NRB is to the rear right of the westerly jet center, while the SRB is positioned around the SAH ridge line and to the rear right of the entrance regions of easterly/westerly jets. Therefore, the SRB formation may be due to the joint action of the SAH and easterly/westerly jets.

The center of easterly flows is at 150 hPa (cf. Fig. 3c). The SAH has its ridge line tilting northward in the rain zone so that the SRB is closer to the SAH ridge at 150 hPa than at 200 hPa. The SRB is to the rear right of the center of 150 hPa easterly jets. In general, the enhancement of the easterly jets is accompanied with the rainstorm in southern China. As a result, the contribution of the 150 hPa easterly flows to the torrential rains is by no means negligible. In the strongest phase of the rainstorm, the westerly jets are quite strong at 150 hPa around the SHB. The causes of the intensification, together with its effect on the rainstorm, deserve further study. In the previous studies on torrential rains, their focus tends to be on the role of the 200 hPa jets. Doubtlessly, the 200 hPa jet core remains intense as found in the present study. But in this study, the 150 hPa easterly/westerly jets seem to have greater impacts on the SRB, so that attention should be given to the activity of the 150 hPa jet currents in the research on the southern China SRB rainstorms.

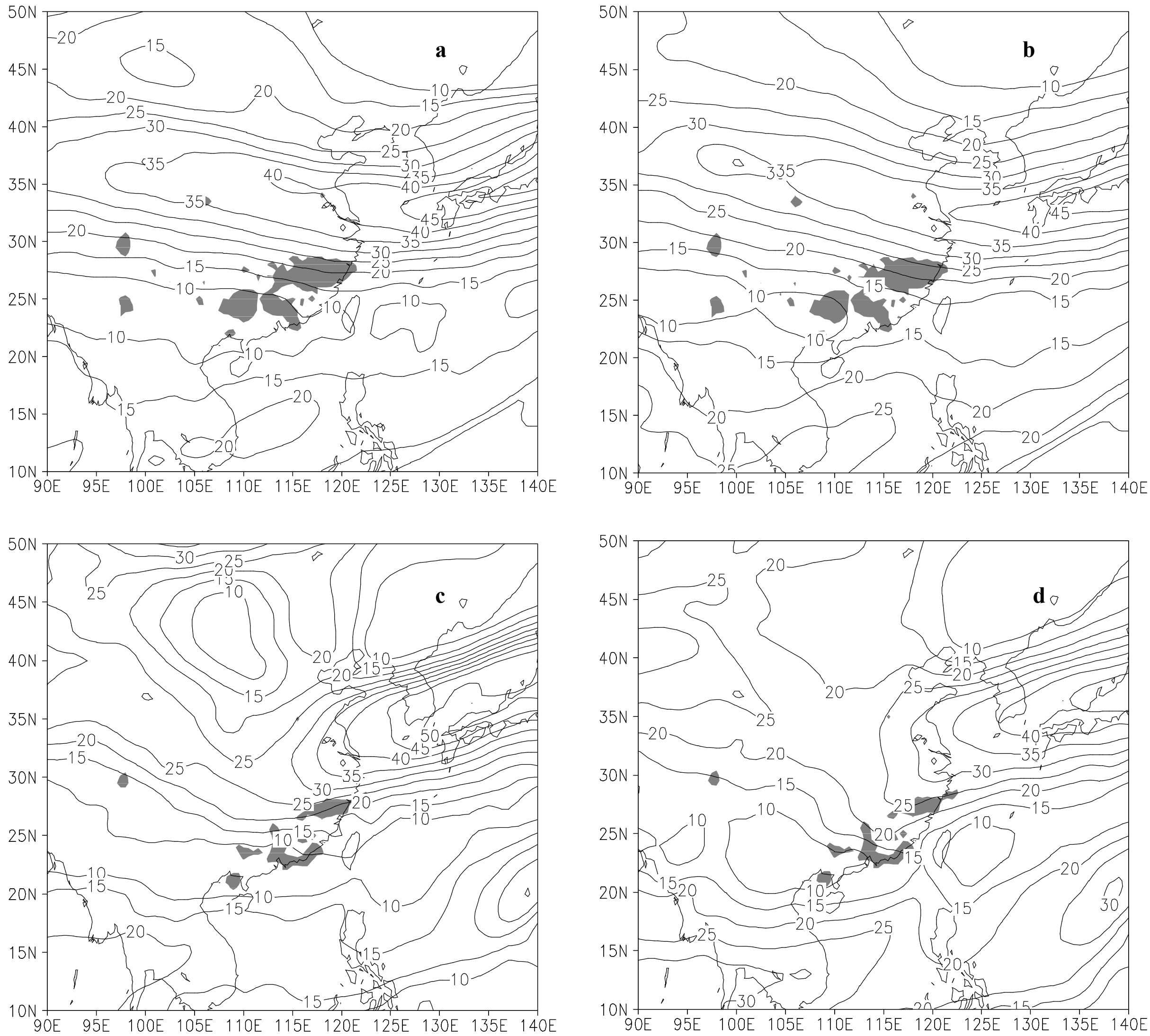

Fig. 2. Mean winds for 0000 UTC, June 17 to the same hour, June 21 at 200 hPa in a) and at 150 hPa in b), and mean winds for 0000 UTC, June 21 to the same hour, June 22 at 200 hPa in c) and at 150 hPa in d), with the shading for the positions of the two rain belts and the dashed line denoting the SAH ridge

3 ACTIVITIES OF UPPER-LEVEL EASTERLY/WESTERLY JETS ASSOCIATED WITH THE DISTRIBUTION OF DIVERGENCE

Analysis of the mean divergence fields at 200 hPa and 150 hPa (see Figs. 3a and 3b, respectively) shows that the 200 hPa divergence centers are mainly north of 25°N and the strongest core is corresponding well to the NRB. While the centers at 150 hPa are dominantly southward of 25°N, the strongest core on the SAH ridge line is related to the warm-zone rain band. It is clear that westerly jets have a considerably greater effect on the NRB than on the SRB. Particularly, the SAH ridge position and easterly jets exert even greater impacts upon the SRB. On the whole, the divergence field to the rear right of the entrance regions of high-level easterly/westerly jets is the principal cause of generating two rain bands. Like the subtropical westerly jet, the zone of strong easterly jets has great impacts on precipitation.

The 114°E diagram of mean wind velocity for 0000 UTC June 17 to 0000 UTC June 22 (Fig. 3c) delineates that one center is at 35°N and the other at

14°N, with the core of westerly (easterly) jets at 200 (150) hPa. The SRB is between the centers at 35°N and 14°N, with the low-level jet core being at 24°N between 700 hPa and 800 hPa, and 24°N being the central location of the SRB. Analysis of the mean *v* component field shows that the lower-level convergence and upper-level divergence depend strongly on the *v* component for the SRB. From the difference in the altitude of high-level divergence centers and the associated jet centers between the two rain belts, we come to the conclusion that the divergence-producing SRB (NRB) is related to 150 (200) hPa easterly (westerly) jets.

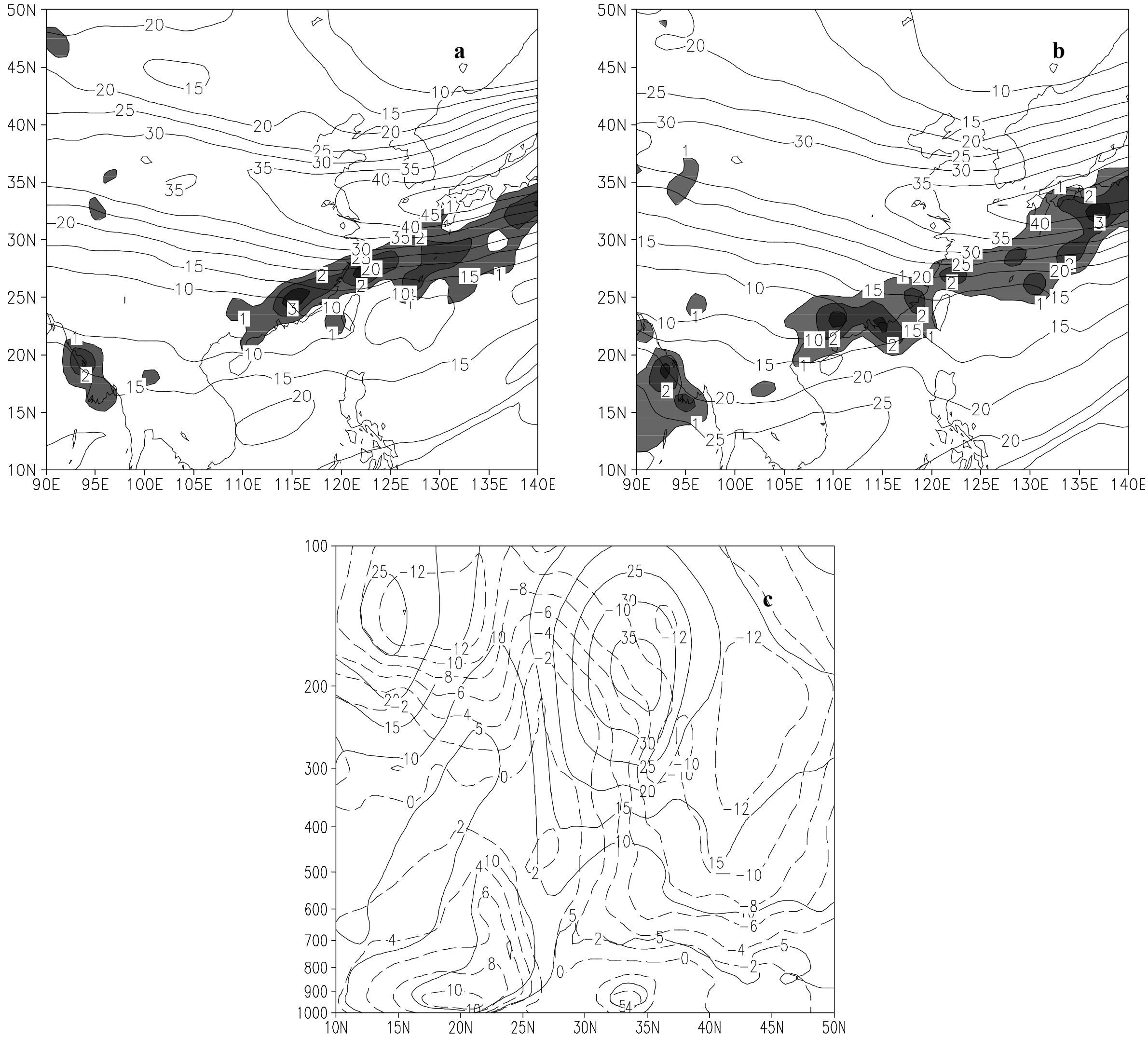

Fig. 3. Mean wind velocity and divergence at 200 hPa in a) and at 150 hPa in b) where the divergence zone is shaded, with units of hPa given on the ordinate. Solid line: 114°E cross-section of mean winds; dashed line: *v* component; blackened triangle below the abscissa: the position of the rain band in c), from 0000 June 17 to 0000 UTC June 22.

4 RELATIONSHIP OF UPPER-AIR EASTERLY/WESTERLY JETS AND SAH TO THE RAINSTORM GENESIS

Why is the double-belt precipitation associated with the locations of easterly/westerly jets and the SAH ridge line? Neglecting fictional force, we have the equations of momentum in the form

$$\frac{du}{dt} = f(v - v_g), \qquad (1)$$

$$\frac{dv}{dt} = -f(u - u_g). \qquad (2)$$

In the presence of westerly jets (Ding[22]), divergence (convergence) occurs, owing to ageostrophic mass adjustment, to the right (left) of the entrance region, leading to the mass adjustment at lower levels and resulting in a positive circulation with sinking (rising) to the left (right). For westerly jets, therefore, $v - v_g > 0$ prevails on the right side of the entrance region. In the entrance region of easterly jets, atmospheric mass adjustment is responsible for an anti-circulation with sinking to the left and rising to the right. Hence, for easterly jets, $v-v_g$ < 0 is dominant in the entrance region.

It is clear from Eq. (2) that $u - u_g > 0$ when north (south) winds increase (decrease) and $u - u_g < 0$ when north (south) winds decrease (increase). Analysis shows that $u - u_g > 0$ is always existent in the vicinity of a rainstorm zone, indicative of increased north winds. On the whole, this term has smaller effects on precipitation (not shown), and will not be addressed below.

Figure 4a depicts that in the averaged $v-v_g$ field at 150 hPa on June 17–22, the zone of $v-v_g$ > 0 is north of 24°N, with the maximum being <2 m/s south of 30°N, suggestive of the impact of westerly jets. The NRB is in the zone of $v-v_g$ > 0 and a strong $v-v_g$ < 0 feature is around the SRB and to the north of the easterly jet axis, indicating the effect of the stream field around the SAH ridge line and easterly jets. To the north (south) of the SAH ridge line are west (east) winds, showing that airflows move in a clockwise sense, i.e., they decelerate leading to du/dt<0 around the SAH ridge line to produce $v-v_g$ <0 thereabout. As the gradient of east wind speeds increases on the south side (i.e. the intensification of easterly jets), $v-v_g$< 0 is strengthened. Due to the fact that the westerly jet-caused $v-v_g$> 0 zones are dominantly on the north side of the SAH, intense upper-air divergence takes place for increased precipitation when the two fields of opposite-sign $v-v_g$ are combined. This may be the principal cause of the SRB situated around the SAH ridge. In the strongest phase of rainstorm (June 21–22, Fig. 4b), the NRB remains in the region of stronger $v-v_g$> 0. With increasing $v-v_g$, there occurs distinct divergence due to $v-v_g$> 0. In the neighborhood of the SRB center (23.5°N, 114.5°E) the gradient of $v-v_g$ is the largest and strong $v-v_g$> 0 (with a positive center of 9 m/s) emerges to the north and a zone of strong $v-v_g$< 0 is around the SAH ridge line and to its south, so that vigorous ageostrophic wind divergence happens above the center of the SRB. Evidently, the genesis of $v-v_g$< 0 bears a close relation to enhanced easterly jets for the SRB rainstorm occurs to the rear right of easterly jets. The pattern of $v-v_g$ at 200 hPa resembles that at 150 hPa except that its negative (positive) values are lower (higher) compared to those at 150 hPa. The position of the hyetal zone shows that effects of westerly jets on the NRB are greater at 200 hPa than 150 hPa, and easterly jets have a larger effect on the SRB at 150 hPa than at 200 hPa, thereby substantiating the close relationship between easterly jets and the SRB as well as the bigger contribution of westerly jets to the NRB, as discussed in the previous section.

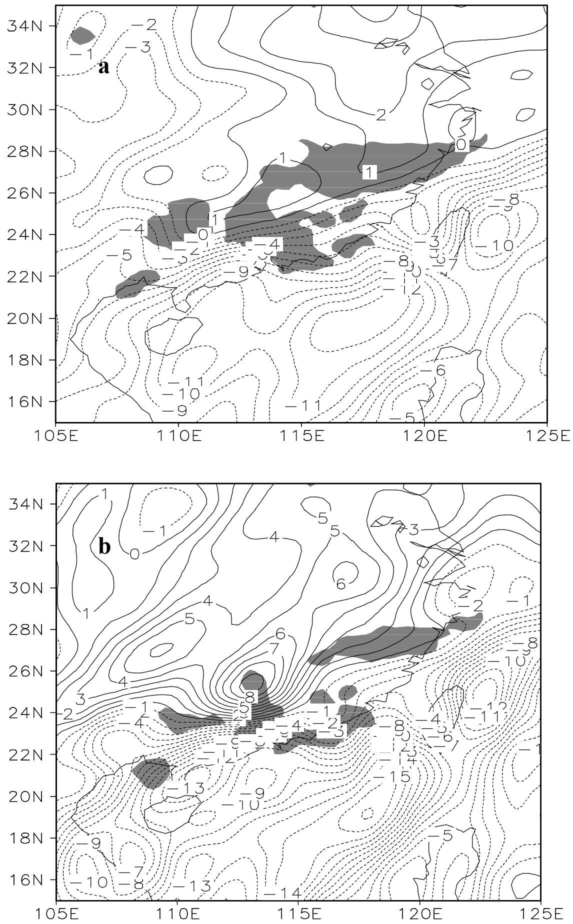

Fig. 4. Mean $v-v_g$ field from 0000 UTC June 17 to 0000 UTC June 21 at 150 hPa in a), the mean $v-v_g$ across 21–22 June at 200 hPa in b), with the shading denoting the two rain bands

Analysis of the intense $v - v_g > 0$ ($v - v_g < 0$) feature above the north (south) side of the rainstorm center shows that the warm-sector rainfall should be related to the joint action of easterly/westerly jets and the SAH. The SRB is farther away from the center of westerly jets. Why the genesis of the northern strong $v - v_g > 0$ center depends on the westerly jet needs to be explored further. As shown in Fig. 5a, there is a strong jet center of 20 m/s ahead of the vigorous rainfall core around 24°N, 114°E at 150 hPa at 0600 UTC, June 21, 2005. Behind the jet center is a strong core of $v - v_g > 0$, with its central value reaching 12 m/s (cf. Fig. 5b), suggestive of the ageostrophic field produced by acceleration behind the center of westerly jets. Examining 200 hPa, we see no distinct westerly jet core ahead of the SRB center, with the central value of $v - v_g > 0$ arriving only at 6 m/s (not shown). Consequently, the production of the SRB rainfall is associated with the southward intensification of 150 hPa westerly jets.

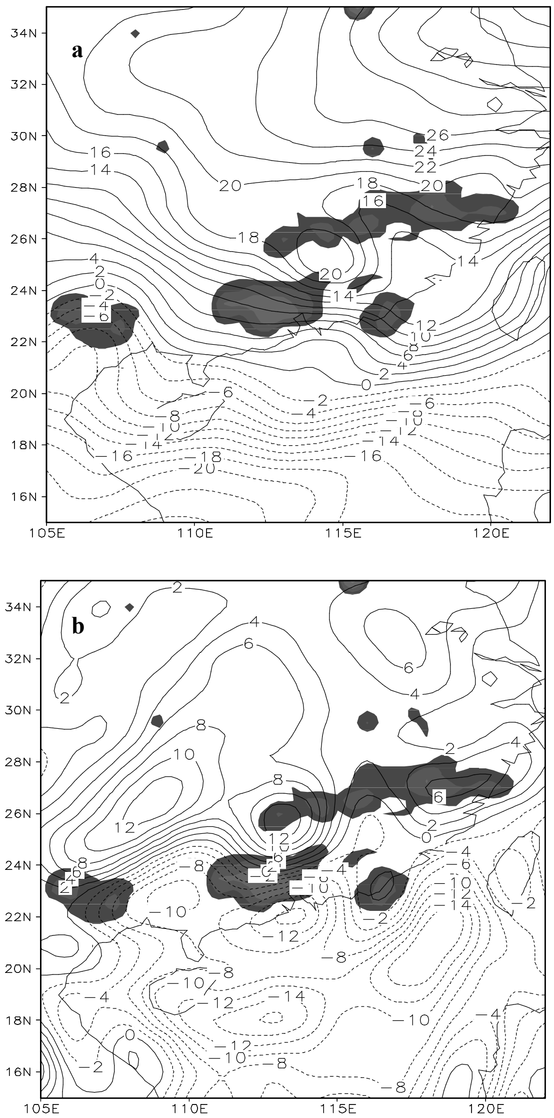

Fig. 5. The u field and $v - v_g$ field at 0600 UTC June 21 in a) and b), respectively, with the rain bands shaded

The formation of $v - v_g < 0$ around the rainstorm core is associated with a quick decrease in the westerly component in the vicinity of the SAH ridge, but there is no intense center of $v - v_g < 0$ both around the SAH ridge and to the rear right of easterly jets. From the wind field we notice that the $v - v_g < 0$ centers emerge mostly in areas of large wind gradient in the y direction, exemplified by the cores southward of 22°N in Fig. 5b, which correspond to zones of maximal wind gradient in Fig. 5a. This is likely to be related to frequent northerlies around the SAH ridge and to its south, which may cause du/dt to reduce rapidly in their southward movement. Their movement across the zone of high-value gradient leads to the core of $v - v_g < 0$. In the neighborhood of the rain region, the genesis of $v - v_g < 0$ center in the vicinity of the SAH ridge line follows the same principle.

The mean circulation pattern from 0000 UTC June 17 to 0000 UTC June 22 along 114°E (Fig. 6) shows that the SRB is under the control of a distinct, closed anti-circulation compared to the positive circulation over the NRB. Although the positive circulation is not closed, there is subsidence (rising) to the left (right) of upper-air jets, suggestive of greater contribution of the mass adjustment behind the easterly jet center to the anti-circulation that is responsible for the genesis of the SRB. Maximal low-level winds were observed in the neighborhood of the SRB. Note that strong precipitation from the SRB happened mostly in the vicinity of the low-level jet center or to its south. This may be associated with the anti-circulation cell (due to air mass adjustment behind the center of upper-air easterly jets) that is potentially converted into kinetic energy in its northward branch of sinking air. In addition, the high-level divergence over the rain region is so sufficient that the low-level pressure reduces substantially fast to augment the pressure gradient around the rain region, producing a strong jet at lower levels, which supplies plenty of water vapor and momentum for increased precipitation.

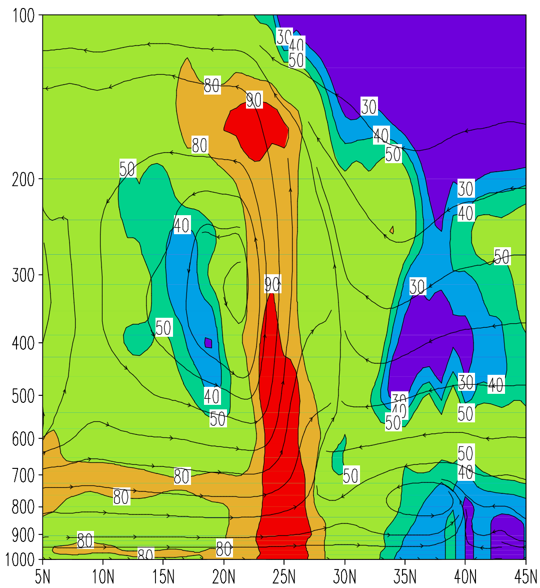

Fig. 6. Pattern of mean circulations from 0000 UTC June 17 to 0000 UTC June 22 along 114°E, with the ordinate denoting units of hPa and blackened triangles giving the centers of rainstorm and shading for relative humidity

From the above discussion, we conclude that the

NRB is located in the divergence field of $v - v_g > 0$ to the rear right of westerly jets, while the SRB is positioned in the $v - v_g < 0$ divergence field produced by du/dt <0 around the SAH ridge and northward of the easterly jet axis. The SRB is under the joint effect of easterly/westerly jets and SAH in the strongest rainfall period; $v - v_g < 0$ in the SAH center and to the rear right of easterly jets produces intense southward geostrophic deviation and the westerly jet center splits and goes south whereas strong $v - v_g > 0$ to the rear of the jet center generates vigorous northward geostrophic departure to cause intense mass adjustment in the hyetal zone (i.e., strong divergence), responsible for increased rainfall, especially at 150 hPa. The mass adjustment to the rear right of upper-air easterly jets produces an anti-circulation cell matching the SRB and the cell intensifies low-level jets. Also, the rising (sinking) occurs to the rear right of westerly jets but on the left (right) side for the NRB, respectively.

5 ANALYSIS OF CAUSES OF THE MID-LEVEL FRONTOGENESIS OVER THE SRB

5.1 *SRB and mid-level front*

Figure 7a presents the mean θ_e field along 114°E from 17 to 22 June, with a zone of iso-θ_e lines both above the NRB and SRB. For the NRB, a band of strong iso-θ_e lines extends from 900 hPa to below 200 hPa [J_w (J_e) stands for the position of the westerly (easterly) jet] and connects with the tropopause, whereas for the SRB, the intense θ_e band is only at 700–400 hPa. Such a mid-level intense θ_e band can be observed on 17–22 June (figures not shown). Prior to 21 June the NRB and SRB were far apart from each other and respective strong rain bands were maintained at the leading edge of the zones of strong iso-θ_e lines. After 21 June the northern θ_e band moved considerably towards the south. The two bands merged into one at 0800 UTC, 22 June, showing the two rain belts approaching toward each other. It shows that the mergence of the fronts is the main cause. More attention is deserved as to how the mid-level front is generated above the SRB.

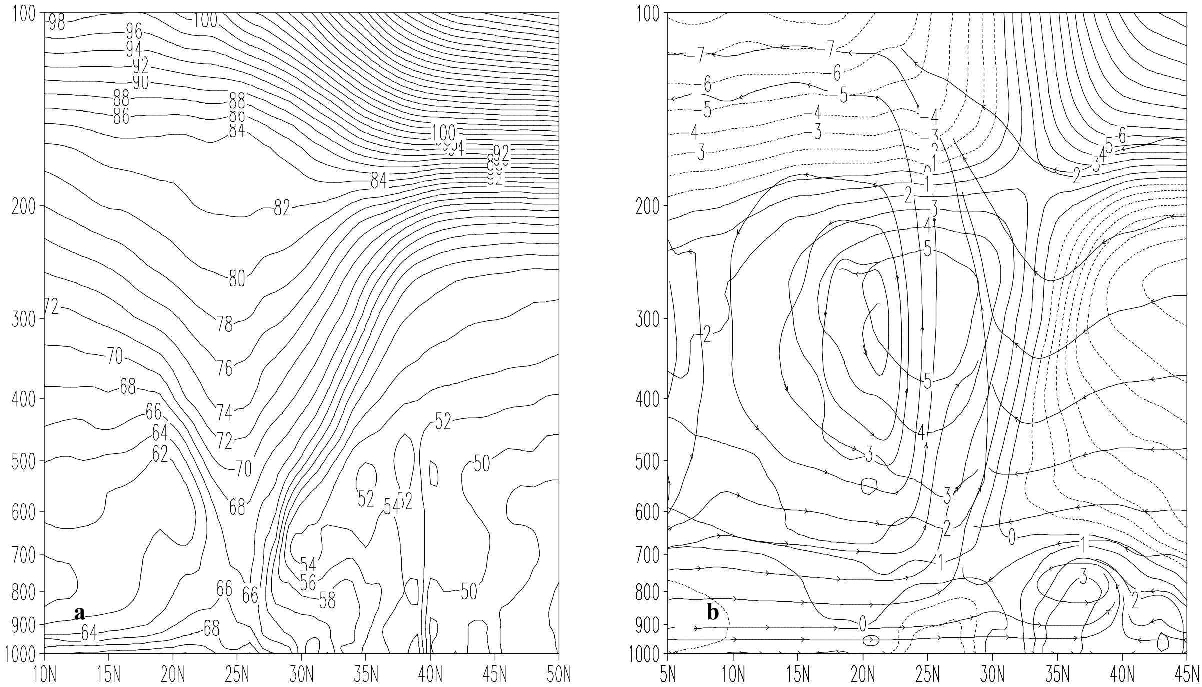

Fig. 7. The 114°E cross section of mean iso-θ_e lines in a) and the mean circulation and perturbed temperature field in b) from 0000 UTC June 17 to 0000 UTC June 22, with the ordinate giving units of hPa and blackened triangles denoting the positions of the rain belts

5.2 *Distribution of relative humidity and dry kernels*

Figure 6 is the distribution of relative humidity, indicating that below 500 hPa a zone of strong relative humidity emerges on the SRB's south side, with the value exceeding 80% at 700–1000 hPa compared to that of <70% throughout the whole air column in the northern part of the NRB. Inspection of the distribution of the airflow and related humidity fields (Fig. 6) and trajectories of particles (not shown) shows that the vapor into the two rain belts comes mainly from the south below 700 hPa. At 500–250 hPa inside the sinking branch of air immediately next to the SRB there is a dry zone of >40% relative humidity, a zone still drier and of even bigger gradient compared to that on the NRB's north side; this branch of dry downdraft tilts northward till below 500 hPa to extend to the neighborhood of the hyetal zone. The dry air to the north of the NRB approaches the rain band from below 500 hPa, too. Compared to the south side the dry zone drops to a lower height. The SRB mid-level frontogenesis is related to the existence of a southern dry kernel at mid levels. Relative humidity in the south of the SRB, increasing to >70% upward from 200 hPa, may be associated with north wind carrying vapor southward above the rain band. Two dry zones extend downward in subsiding air.

Analysis shows that there is a moist zone both near the NRB and SRB, with a zone of >80% relative humidity extending up above 150 hPa and covering 5 latitudes. The >80% moist band is narrowed when the SRB and NRB merge into one, with the two dry regions becoming closer to each other over the two rain bands below 200 hPa (figures not shown).

5.3 *Distribution of meridional perturbed temperatures*

The dry, cold air over the NRB bears relation to the cold front. What is the cause of such air over the SRB? We plotted a cross section along 114°E of averaged meridional perturbed temperature T from 0000 UTC June 17 to 0000 UTC June 22 for all levels at 5–45°N (Fig. 7). We see that a warm center is kept around 300 hPa above the SRB and the latent heat release via condensation in rainfall serves as one of the causes of forming the warm center. A relatively cold region emerges below 200 hPa to the north of the NRB, with a relatively warm zone above 200 hPa to the south of the SRB. The gradient of horizontal mean perturbed temperature below 200 hPa is bigger in the SRB than in the NRB, suggesting that the latter is produced largely by the cold front. The SRB also shows a southward perturbed temperature gradient, particularly at 200–600 hPa, which acts as the principal source of cold air on the south side. Because the region of lower relative humidity is situated inside the downdraft, which carries downward relatively dry, cold air from high levels, sinking-caused warming also decreases relative humidity. This is the likely cause of dry, cold air appearing on the SRB's south side.

Evidently, the existence of a mid-level dry region in the SRB as well as the temperature gradient extending outward from the warm center are responsible for the zone of dense lines of equivalent potential temperature (iso- θ_e lines) at middle levels, leading to the genesis of the front there. During 19–22 June, when mid-level iso- θ_e lines were close together, the SRB produced heavy rainfall, indicating that the intensified mid-level front favors the enhancement of precipitation from the warm sector.

6 CONCLUDING REMARKS

Based on the analysis and diagnosis of high-level jets, SAH and a mid-level front in association with the double rain band pattern occurring in the persistent rainstorm on 17–22 June 2005, we have the following conclusions:

(1) The NRB is mainly in the zone of $v - v_g > 0$, causing divergence to the rear right of westerly jets, whereas the SRB is dominantly in the strong $v - v_g < 0$ divergent field due to $du/dt < 0$ around the SAH ridge and on the north side of an easterly jet axis. In the strongest stage of precipitation, the SRB is under the joint action of easterly/westerly jets and the SAH. The feature of $v - v_g < 0$ in the vicinity of the SAH center and to the rear right of easterly jets produces intense southward geostrophic deviation, leading to the splitting of the westerly jet center. The intense $v - v_g > 0$ generated in the rear suggests strong northward geostrophic departure, which gives rise to strong divergence (mass adjustment) in the rainfall region and thus intensifies torrential rains, particularly at 150 hPa. The mass adjustment to the rear right of an upper-air easterly jet is responsible for an anti-circulation matching the SRB, enhancing jets at lower levels. Above the NRB there appears sinking (rising) on the left (right) side of the rear right portion of westerly jets, which is indicative of the joint effect of easterly/westerly jets and SAH when the vigorous warm-sector rainstorm occurs.

(2) In the case of double rain belts, on the south side of the SRB there is a dry region between 700–200 hPa, with the center mostly below 300 hPa; the dry domains are smaller, mostly in the sinking branch of the anti-circulation, accompanied by zones of low-humidity potential temperature. This situation leads to a zone of densely distributed θ_e isolines (i.e., the mid-level front) at 400–700 hPa over the SRB. The front favors the release of instable energy to enhance precipitation. When the mid-level front is combined with the NRB front, the two rain bands merge into a single belt.

(3) It is found that divergence and easterly jets are strongest, and over the SRB, the SAH ridge line is closer to the hyetal zone at 150 hPa than at 200 hPa. These are closely related to the genesis of the rainstorm and the maintenance of rainstorm-associated circulations and systems. In consequence, the 150-hPa systems can by no means be neglected in the study of torrential rains in the south of China.

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