Features and Sources of the Anomalous Moisture Transport for the Severe Summer Rainfall over the Upper Reaches of the Yangtze River*

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ABSTRACT

Using the daily NCEP/NCAR reanalysis dataset and the observation rainfall data in China for the 1980-1997 period, features of severe summer rainfall over the upper reaches of the Yangtze River are investigated and then sources of moisture contributing to severe rainfall over eastern and western Sichuan Province (ES and WS for short) are examined with particular reference. It turns out that the severe rainfall occurring locally dominates summer rainfall over the upper reaches of the Yangtze River. Climatological rainfall and anomalous one constitute severe rainfall, but the latter accounts much for severe rainfall. The meridional moisture transport dominates the composite moisture transport on the occurrence day for ES region, while the zonal is equivalent to the meridional for WS region. Correlation between the moisture transport fluxes over the two regions of severe rainfall and other regions, the anomaly and variation of the moisture transport day by day during the period of severe rainfall lend a support for the conclusion that the meeting of the moisture from the West Pacific through the South China Sea (SCS) and the one from northwestern China exerts a vital effect on the occurrence of severe rainfall, which can not be neglected.

Key words: the upper reaches of the Yangtze River, severe summer rainfall, source of moisture transport

1. Introduction

As one of the important processes in the global climate system, the water cycle and moisture transport have long been an important research subject either domestically or internationally. In East Asian monsoon region, summer monsoon circulation as carriers of moisture transport exerts extraordinarily important impacts on rainfall, especially severe summer rainfall in China (Zhu, 1934; Xie and Dai, 1959). Studies on sources and transport of moisture leading to severe rainfall are of fundamental importance not only to the forrnative mechanism and prediction of severe rainfall but also to the alleviations of flood loss in China.

The present research concerning the moisture sources of the rainfall in China mostly focuses on East China. Tao and Chen (1987) explored moisture sources of summer rainfall east of 100°E in China and put forward that there may be mainly three moisture sources entering the mainland of China. Briefly speaking, they are the moisture transport channels from the cross-equatorial flow over Asian-Australian monsoon region, from the Bay of Bengal (BOB) and from the subtropical monsoon flow over the south and west of the West Pacific subtropical high. Some scholars (Ion et al., 1999; Ninomiya, 1999) pointed out that the summer rainfall over eastern China is mainly influenced by the moisture transport from the BOB and the summer monsoon over the South China Sea (SCS). Xu et al. (2002) put forward that a triangular model consisting of the Tibetan Plateau, Indian monsoon, and SCS monsoon is closely connected with the drought and flood abnormality of China. Studies (Ding and Sun, 2001; Ding and Hu, 2003; Xie et al., 2002)...

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emphasized that the moisture from the BOB, which transports northward after accumulating over the SCS, plays the most important role in the severe summer rainfall of China. At present there are some studies (Guo and Wang, 1988; Chen et al., 1991; Zhang, 2001; Tian et al., 2002; Li, 2004) indicating that rainfall over eastern China is in little connection with moisture transport from the BOB but in close association with that from the West Pacific. Therefore, it is still an open question that whether the moisture transport from the BOB or from the West Pacific and the SCS is primarily vital to the occurrence of severe rainfall over China.

The upper reaches of the Yangtze River are also one of the regions where torrential rain occurs frequently. It is well known that during the summer of 1998, serious flood took place over the upper reaches of the Yangtze River, which exerted a profound influence on the occurrence of the flood over the middle and lower reaches of the Yangtze River (National Climate Center, 1998). The studies of Tan and Ma (1997), Xiao and Yu (2003) suggested that the circulation of the West Pacific subtropical high is one of the important factors affecting the rainy season in Sichuan Province of China. Consequently, in conflict with the long-standing viewpoint (Shen et al., 1982), the moisture affecting the occurrence of the severe rainfall over the upper Yangtze River maybe do not solely come from the region from the Arabian Sea to the BOB; there may be the moisture transport from the Pacific subtropical high according to the above studies.

In our viewpoint, moisture sources of rainfall consist of two components. One component mainly results in climatologically average rainfall, which contributes little to rainstorm. And the other component brings about severe rain, which can be quite different from the former. Therefore the anomalous moisture transport for severe rain should be distinguished from that for climatological rain. It is necessary to further investigate and discuss the issue on the transport of water vapor for rainstorms over the upper reaches of the Yangtze River on the ground that the moisture transport has not been computed in detail. Characteristics of rainfall over the upper reaches of the Yangtze River are studied in this paper firstly. Then, the moisture transport and its sources are discussed in detail using synthetic method and correlation analysis.

2. Data and computational method

Dataset used in this paper includes: (1) the daily NCEP/NCAR reanalysis data, they are: horizontal wind components $u, v$ and specific humidity at 8 standard pressure levels (1000, 925, 850, 700, 600, 500, 400, and 300 hPa) for the 1980-1997 period; and (2) the daily rainfall data of 44 weather stations over the region of $28^\circ-32^\circ$N, $100^\circ-110^\circ$E, including 22 for the east and west parts of the region, respectively.

The vertically integrated moisture flux vectors can be conventionally expressed as

$$ Q = Q_\lambda \hat{i} + Q_\varphi \hat{j}, $$

$$ Q_\lambda = \frac{1}{g} \int_{300}^{P_s} q u d\varphi, $$

$$ Q_\varphi = \frac{1}{g} \int_{300}^{P_s} q v d\varphi, $$

where $\lambda$ is longitude and $\varphi$ latitude, $P_s$ the surface pressure, $q$ specific humidity, and $u, v$ the zonal and meridional components of the horizontal wind vector $V$.

Sichuan Province lies on the majority of the upper reaches of the Yangtze River. Briefly, we choose a region of $28^\circ-32^\circ$N, $100^\circ-110^\circ$E as the main region of the upper reaches of the Yangtze River. Divided by $105^\circ$E, there are two parts of the region, i.e., $28^\circ-32^\circ$N, $105^\circ-110^\circ$E (including eastern Sichuan Province and some areas over southern Shaanxi Province) and $28^\circ-32^\circ$N, $100^\circ-105^\circ$E (including western Sichuan Province), respectively. In this paper, we stipulate that two cases of severe rainfall day should be separated at intervals of four days at least. According to this regulation, the occurrence day of severe rainfall is defined as day 0 and the criterion of severe rainfall is set to be the daily rainfall amount greater than 50 mm occurring over more than five stations for the east region ($28^\circ-32^\circ$N, $105^\circ-110^\circ$E) and four stations for the west ($28^\circ-32^\circ$N, $100^\circ-105^\circ$E). And the four days before the occurrence day are defined as days -4, -3, -2, and -1. To be
compared with the normal moisture transport, the departures of moisture transport on each day (days 0, -1, -2, and -3) from the corresponding pentad-mean from 1980 to 1997 are calculated as the anomalous moisture flux. Here, we call the region of 28°-32°N, 105°-110°E as ES (eastern Sichuan Province) and the region of 28°-32°N, 105°-110°E as WS (western Sichuan Province) for simplicity. According to the regulation of severe rainfall mentioned above, the 20 cases of severe rainfall in ES region and 32 cases in WS region can be found during summers of 1980-1997.

3. Features of the severe rainfall over ES and WS

The climatological mean summer rainfall amount and percentage of the total severe rainfall amount are calculated according to the observed rainfall data and shown as Figs.1a and 1b, respectively. With reference to Fig.1a, three rainfall centers are located over the region of 28°-32°N, 100°-110°E during the summer time, i.e., 1) around 31.5°N, 108°E with rainfall amount more than 7 mm d⁻¹; 2) near 30.5°N, 110°E with rainfall amount above 9 mm d⁻¹; 3) over the region of 29°-30°N, 103°-104°E with rainfall amount greater than 10 mm d⁻¹. Both the centers 1 and 2 lie on the east part of Sichuan Province. The total rainfall amount during whole summer (from June to August) over each rainfall center reaches 644, 828, and 920 mm, respectively. Correspondingly, there are also three centers in Fig.1b with percentage coming to 50% and locations in good agreement with the above three centers in Fig.1a. For the main part of the region in

Fig.1. Characteristics of climatological rainfall over the upper reaches of the Yangtze River. (a) Climatological summer rainfall (averaged from June to August 1980-1997), (b) percentage (%) of the severe rainfall amount (total severe rainfall amount divided by that of the whole summer for the period of 1980-1997), (c) distribution of 20-case daily mean rainfall over ES region for the period of 1980-1997, (d) same as (c), but for 32 cases over WS region. The unit of rainfall in (a), (c), and (d) is mm d⁻¹.
our study, percentage of the severe rainfall amount to that of the whole summer is more than 30%. Thus, the severe rainfall can be regarded as one of major parts of rainfall during the whole summer. And it is of much significance to investigate moisture sources of the severe rain consequently.

Figures 1c and 1d present the daily mean rainfall of 20 cases over ES region and 32 cases over WS region, respectively. For ES region (Fig.1c), the strong rainfall center with magnitude about 70 mm is around 31.7°N, 107.2°E. And the region with rainfall above 50 mm is located in 30°-32°N, 105.5-108.5°E, which is consistent with the center over the northeast ES in Fig.1a. But the magnitude of the center in Fig.1c is 10 times as large as that in Fig.1a. For WS region (Fig.1d), an extensive rainfall area with its center reaching 70 mm occurs at the region of 29.5°N, 103.5°E (E’mei Mountain of Sichuan Province), and the region with rainfall more than 50 mm covers a region of 28.5°-31°N, 103°-105°E (along Chengdu-Ya’an-Luzhou in WS region). The center in Fig.1d is in the vicinity of that over WS region in Fig.1a, while the magnitude of the former is 7 times more than the latter. It can be inferred that the severe rainfall case happens locally to a large extent either for ES or for WS region. Severe rainfall amount can be as much as 7-10 times the climatological rainfall amount, which means that rainfall anomaly as much as 6-9 times the climatological rainfall deserves to be studied and anomalous moisture transport should be further explained. Whether the moisture transport of anomalous rainfall originates from the same places as those of climatological rainfall or not will be researched and discussed in the following.

4. Features of the composite moisture transport for the severe summer rainfall over the upper reaches of the Yangtze River and its daily variation

4.1 Features of the composite moisture transport for the severe summer rainfall over ES

Figure 2a illustrates the composite moisture flux of the whole air column on the occurrence day of severe rainfall for 20 cases over ES region. For the moisture transport over ES region, it can be easily seen that the moisture injected through the south boundary is the predominant source of the moisture responsible for severe rainfall. And there is also the moisture from the west boundary of the region, which makes contributions to severe rainfall to some extent. Two noticeable branches of moisture transport enter into ES region through the south boundary. One comes from the region of the Arabian Sea-the BOB, which incorporates with the eastward moisture from the Tibetan Plateau and then enters into ES region across the south boundary. And the other also originates from the BOB, which rapidly weakens as soon as it arrives at the west coast of Peninsula. Some moisture of the second branch enters into the mainland via Indo-China Peninsula and then reaches ES through Guangxi Region and Guizhou Province. The third branch from the West Pacific can also be detected because the second branch bends westward when it lands on the mainland of China through the South China. It may be affected by the West Pacific subtropical high. So the third branch may derive from the West Pacific. But it is not easy to distinguish the third branch from the first and second one and we will try to separate it from the others in the next context. As supplement, the cross-equatorial moisture transport shifts northward after combining with the moisture from the BOB over the southeastern coast of Indo-China Peninsula. But it is hard to decide whether it enters into the mainland of China or not. As regard to the west boundary, the northward moisture directly from the BOB diminishes much before entering into ES region via Yunnan Province, i.e., little moisture directly from the BOB reaches ES region through west boundary. It should be noted that a trough of moisture transport flux (i.e., the moisture transport flux with cyclonic circulation, the same hereinafter) appears over the northwestern side of ES region, which means that moisture transport from the westerlies can also affect the formation of severe rainfall over ES. In addition, we compute the composite moisture transport flux of 20 cases on four boundaries of ES region on the occurrence day of
severe rainfall. Thereinto, the proportion of the moisture transport flux on the south boundary to that on the west is $1052/59$ (Units of flux are $10^5$ kg s$^{-1}$) respectively. Put it in another way, the meridional moisture transport from the south boundary dominates on the occurrence day of severe rainfall.

4.2 Features in the daily evolution of moisture transport during the period of severe rainfall over ES region

Differences of moisture flux between consecutive two days during the severe rainfall period over ES and WS regions are calculated in order to examine the daily evolution of moisture transport. Here we delineate the difference chart of ES region (Fig.2b) so as to investigate the variation of moisture transport from day -1 to the occurrence day (day 0) over the region.

From day -1 to 0, the strongest difference entering into ES region is the one on the southward side of the anticyclone, (which means that the difference of moisture transport is carried out by anticyclonic circulation, similar hereinafter,) centered on the Yellow Sea, i.e., the eastward one stemming from the West Pacific along the eastern China. And the stronger difference is the westward one from the moisture transport trough over the northwestern China. Besides, the difference from the cross-equatorial flow over the SCS swerves northwestward to ES region after reaching the coast of South China. It is difficult to notice moisture transport difference deriving from India or the BOB entering into ES region from Fig.2b.

**Fig.2.** Streamlines of 20-case composite moisture flux on the occurrence day of severe rainfall (a) and 20-case composite difference of the moisture flux between severe rainfall day and day -1 (b) over ES region. Streamlines of 32-case composite moisture flux on the occurrence day of severe rainfall (c) and 32-case composite difference of the moisture flux between severe rainfall day and day -1 (d) over WS region. The unit of moisture flux is $10^{-5}$ kg m$^{-1}$ s; shading areas denote value of moisture flux.
4.3 Features of the composite moisture transport for the severe summer rainfall over WS region

For the composite moisture transport on the occurrence day of severe rainfall over WS region, the result of calculation represents that the proportion of the moisture transport flux on the west boundary of WS region to that on the south boundary is $233 \times 10^5$ kg s$^{-1}$ to $280 \times 10^5$ kg s$^{-1}$. That is to say, the zonal moisture transport on the west boundary is equivalent to the meridional one on the south boundary over WS region on the occurrence day. In light of Fig.2c, the main part of the moisture transport entering into the west boundary originates from the Tibetan Plateau and some from the BOB, while that on the south boundary is mainly concentrated on the eastern WS region. The moisture transport over the eastern WS region is more than that over other parts of WS region, which may be in that the moisture from the south wind veering from the west side of the West Pacific subtropical high merges with the moisture from the BOB and then transfers northward into WS region.

4.4 Characteristics of the daily evolvement for moisture transport over WS region during the period of severe rainfall

Now comes to the analysis of daily variation during the period of severe rainfall over WS region. Same as the analysis of that over ES region, we depict the variation between day -1 and the occurrence day as shown in Fig.2d. From day -4 to day -2 (figures not shown for space limitation). On the one hand, the westward moisture transport from the West Pacific and the SCS moves northward into WS region after reaching the Indo-China Peninsula; and on the other hand, cyclonic difference of moisture transport occurs over the BOB, signifying that the really eastward moisture transport from the BOB decreases day by day during this period. From day -2 to day -1, there appears a trough of moisture transport difference over the northwest side of WS region, which means that the really eastward moisture transport from the northwest increases. Finally, from day -1 to the occurrence day (Fig.2d), the trough moves slightly to the southeast and WS region lies on the bottom and the front of the trough. The trough contributes to the formation of severe rainfall by carrying more moisture from the north to WS region. It can be speculated from Fig.2d that the moisture transport difference from the BOB has no effect on WS region although the moisture transport difference is eastward. In short, as far as the daily variation of moisture transport concerned, it is the difference moisture from the West Pacific and the SCS that mainly influences WS region before day -1; while that from the northwest mainly affects the region after day -1. And there is no evidence indicating that the moisture transport difference from the BOB makes pronounced contribution to the moisture transport difference responsible for severe rainfall over WS region.

Comparing the daily variation of moisture transport for WS region with that for ES region, we find something in common between them: the westward moisture transport from the West Pacific entering into rainfall regions augments before the severe rainfall day, and the eastward moisture transport from the Tibetan Plateau entering into rainfall regions enlarges on the occurrence day of severe rainfall. However, there are differences between the two variation processes. For ES region, the above moisture transport from the West Pacific increases from day -2 until the severe rainfall day, and the difference moisture transport from the Tibetan Plateau affects ES region from day -1 to the severe rainfall day. For WS region, the moisture from the West Pacific and the SCS increases from day -4 to day -2, and hereafter, the moisture transport from the Tibetan Plateau enhances from day -1 to the occurrence day of severe rainfall.

5. Sources of moisture transport causing the severe summer rainfall over ES region

5.1 Analysis of the correlation between meridional or zonal moisture transport over ES region and those over Asian area

In order to examine the possible sources of moisture transport causing the severe rainfall in ES region, we compute the correlation between the regional mean zonal or meridional moisture transport (called as $UQ$ or $VQ$ for short) over ES region on day 0 and grid
zonal or meridional moisture transport (\(uq\) or \(vq\) for short) in Asia on days 0, -1, -2, and -3, respectively.

By reason that the moisture transport is mainly meridional for ES region, here we only present the distribution of correlation between \(VQ\) and \(uq\) or \(vq\) as shown in Fig.3. We firstly investigate the correlation between \(VQ\) and \(uq\) (shading areas in Fig.3). On day -3 (Fig.3a), two negative correlation belts between \(VQ\) and \(uq\) with the significance level up to 99% can be observed over the West Pacific and the west of Indonesia in the Southern Hemisphere. There is also a correlation belt over Bashi Channel north of Philippine with 95% confidence level, but it is very small compared with the above two belts. The belt over the Southern Hemisphere exerts no influence on rainfall of ES region in virtue of the northward \(VQ\). Moreover, the belt over the Southern Hemisphere mentioned above disappears after day -1. Thus on day -3 only the moisture transport from the West Pacific has impact on heavy rain of ES region. On day -2 (Fig. 4b), the belt over the West Pacific moves westward and then incorporates with the one over Bashi Channel and continuously moves westward from day -2 to day 0. The westward correlation belt has expanded to Hainan Island on day -1 (Fig.3c). As indicated in Fig.3d, the negative correlation belt extends westward to Indo-China Peninsula through the SCS from the West Pacific on the occurrence day, meaning that the main part of the westward moisture transport from the West Pacific has entered into the SCS since day -3. Besides, the positive correlation center on the northwest side of ES region on day -1 moves eastward and reaches ES region on the occurrence day of severe rainfall. That is to say, the eastward moisture transport from the northwestern side of ES region also plays a role in the occurrence of severe rainfall.

![Fig.3](image_url)

**Fig.3.** Distribution of correlation (%) between \(VQ\) over ES region and \((uq, vq)\) over Asian areas. (a) \(VQ-(uq, vq)\) on day -3; (b) \(VQ-(uq, vq)\) on day -2; (c) \(VQ-(uq, vq)\) on day -1; (d) \(VQ-(uq, vq)\) on day 0. (Shading areas denote \(VQ-uq\) and contours \(VQ-vq\). Solid line denotes positive correlation and dash line the negative. 44 (-44) represent the least correlation coefficient (0.44) exceeding the significance level of 95% while 56 (-56) the least correlation coefficient (0.56) exceeding the significance level of 99%).
To cause severe rainfall, there must be northward moisture transport entering ES other than the westward one from the West Pacific and the SCS. Hence, the correlation between $VQ$ of ES region and $vq$ over Asian area is calculated (see contours in Fig.3). A positive correlation belt signifying northward moisture transport extends to eastern China from the East China Sea on day -2 (Fig.3b). The belt shifts westward since day -2. And the belt covers the region from Guangxi Region and the west coast of Guangdong Province to the whole ES region on the occurrence day (Fig.3d), which indicates that the westward moisture transport from the West Pacific and the SCS swerves northward to ES region and then contributes to the severe rainfall of the region.

The correlation between $UQ$ of the region and $uq$ or $vq$ over Asian area is also calculated (figure omitted). By combining the correlation between $UQ$ and $uq$ with that between $UQ$ and $vq$, only the westward $uq$ from the West Pacific via the SCS connects with the northward $vq$ and turns to east, while there is no distinct correlation belt over other Asian area.

To sum up, no correlation belt with significance level above 95% is found over India, the BOB and the region across the equator either for the correlation between $UQ$ and $uq$ or $vq$ or for that between $VQ$ and $uq$, $vq$. According to the result of correlative analysis, on the one hand the moisture transports tracing from India, the BOB and the region across the equator bear no notable correlation passing confidence test to that of ES region either before or on the occurrence day of severe rainfall, and on the other hand, the latter more obviously associates with the moisture transport form the West Pacific, the SCS and northwestern China.

Fig.4. Composite anomalous moisture flux over the ES region (20 case-mean for the period of 1980-1997) on (a) day -3, (b) day -2, (c) day -1, and (d) day 0. The unit of moisture flux is $10^{-5}$ kg m$^{-1}$ s, shaded areas denote the value of moisture flux.
5.2 Characteristics of the anomalous moisture transport causing severe summer rainfall over WS region

Based on Section 3, the anomalous rainfall constitutes the main part of severe rainfall, which is much more than the climatological rainfall. In order to acquire sources of the anomalous moisture resulting in severe rainfall over ES region, we calculate the departures of moisture transport on each day (days 0, -1, -2, and -3) from the corresponding pentad-mean during 1980 to 1997 as the anomalous moisture transport shown in Fig.4.

As indicated in Fig.4d, on day 0 two anticyclonic anomalous moisture transports (anomalous moisture transport with anticyclonic circulation, similar hereinafter) have effect on ES region, i.e., one centered on the northern Philippines and the other centered on the region between the Yangtze River and Huaihe River Basins. For the former anticyclone, the anomalous moisture from the West Pacific is carried to the SCS and then moves westward combining with the anomalous moisture of the SCS after landing on the coast of South China and enters into ES region finally. As to the latter, the moisture from the Yellow Sea is injected into ES region via southeastern China. Moreover, ES region is in the front of the trough of anomalous moisture transport (anomalous moisture transport with cyclonic circulation, similar hereinafter) coming from the Tibetan Plateau, and moisture of the trough enters into the region across the south and west boundaries. Consistent with the results of correlative analysis, the anomalous moisture from the northwest encounters the one from the south over ES region and then results in severe rainfall. On the occurrence day, adverse to the corresponding eastward climatological moisture transport, the anomalous moisture transport from the Yellow Sea is westward, which may make more moisture from the West Pacific and the SCS accumulate in ES region so as to cause severe rainfall by decreasing the eastward moisture transport out of the region. Attention should also be paid to the anomalous moisture transport deviating to the west region from the central BOB to Indo-China Peninsula south of 20°N on the occurrence day, which denotes the eastward anomalous moisture transport from the BOB is abnormally weak on that day. The anomalous moisture from the BOB exerts influence mainly on Indian Peninsula for a strong cyclonic anomalous moisture transport occurs over the west coast of Indian Peninsula. According to Fig.4d, the anomalous moisture from the BOB is not the main part of the one for the formation of severe rainfall although some anomalous moisture of the BOB is carried to ES region by the anticyclone over the northeastern BOB. We can also see that the anomalous moisture transport from the cross-equatorial flow over the SCS has little impact on the occurrence of severe rainfall because the moisture transport veers southwestward before arriving at 10°N.

As regard to the anomalous moisture transport during three days prior to severe rainfall (see Fig.4), it is most obvious that the anomalous moisture transport deviating to the west appears over the region from the central BOB to Indo-China Peninsula and the SCS, i.e., south of 25°N. It can be inferred that the eastward moisture transport from the BOB reaching the mainland of China is extraordinarily anomalous weak. For the anomalous moisture transport from the cross-equatorial flow, case is the same as that from the BOB since southward anomalous moisture transport occurs over the cross-equatorial region of 110°-120°E. During these days, an anticyclonic anomalous moisture transport always lies over the region from the SCS to the coast of South China and it has affected ES region since day -1.

The anomalous moisture transports through the four boundaries of ES region on the occurrence day of severe rainfall are also calculated. As to the south boundary, the anomalous moisture transport is \(465 \times 10^5\ \text{kg s}^{-1}\), nearly accounting for half of the real moisture transport (\(1052 \times 10^5\ \text{kg s}^{-1}\)) through the south boundary on the same day. It turns out that the anomalous moisture transport is important to severe rainfall over ES region.

6. Sources of the anomalous moisture transport leading to the severe summer rainfall over WS region

As having done for ES region, we find 32 cases of
severe rainfall that occurred over WS region from 1980 to 1997. And then we perform correlation analysis and discuss the features of the anomalous moisture transport and the transformation of the moisture transport during the period of severe rainfall in the following context.

6.1 Analysis of the correlation between meridional or zonal moisture transport over WS region and those over Asian area

As suggested in Section 4 (Fig.2c), the moisture transport of WS region on the severe rainfall day includes the meridional moisture transport through the south boundary as well as the zonal one across the west boundary. Thus, we calculate not only the correlation between the regional mean zonal moisture transport over WS region ($U_Q$) and grid moisture transport ($u_q$ or $v_q$) over Asian area (shown as Fig.5) but also that between the regional mean meridional moisture transport over WS region ($V_Q$) and $u_q$ or $v_q$ (figure omitted) in the same way as the correlation analysis for ES region.

For the correlation of $U_Q$-$u_q$ (shading areas in Fig.5), on day -3, the negative correlation belt (centered on $15^\circ$-$20^\circ$N, $130^\circ$-$135^\circ$E) over the West Pacific with confidence level up to 99% denotes the westward moisture transport from the West Pacific. From day -3 on, the negative correlation belt shifts from the West Pacific westward to the SCS day by day. And on day 0, the belt has extended into the western SCS. Correspondingly, for the correlation between $U_Q$ and $v_q$ (contours in Fig.5), on day -3, the positive correlation belt (i.e., northward moisture transport) over East China connects with the positive one of $U_Q$-$u_q$ (i.e., eastward moisture transport) on the north side, thus forms moisture transport with anticyclonic circulation. The anticyclonic situation moves westward and arrives at the east boundary of WS region on day

![Fig.5](image-url). As in Fig.4, but for the correlation between $U_Q$ and ($u_q$, $v_q$) for 32 cases over WS region. (34.9 represent the least correlation coefficient (0.349) exceeding the significance level of 95% while 44.9 (-44.9) represent the least correlation coefficient (0.449) exceeding the significance level of 99%).
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-2 (Fig.5c). On the severe rainfall day (Fig.5d), the westward moisture transport from the West Pacific to the SCS enters into WS region by jointing to the northward moisture over the mainland of China, and then moves eastward from WS region. Obviously, the situation of the severe rainfall day is also anticyclonic. In other words, the anticyclonic circulation of moisture transport marches westward from day -3 on, and severe rainfall occurs when the circulation affects WS region. In addition, the eastward moisture transport from the west side of WS region enters into WS region from day -1 on. Therefore, according to the statistic correlation, the moisture resulting in severe rainfall over WS region mainly consists of the northward one that enters into the mainland of China from the West Pacific via the SCS and the eastward one from the Tibetan Plateau.

Here we also analyze the correlation of $VQ$ of WS region and $uq$ or $vq$ over Asian area. For the correlation between $VQ$ and $uq$, a negative correlation belt appearing over the West Pacific on day -3 shifts westward and then reaches the east coast of Indo-China Peninsula on the occurrence day of severe rainfall. Furthermore, a positive correlation belt occurring over the west side of WS region on day -1 transfers eastward to the region on day 0. State in another way, the eastward moisture transport from the plateau also contributes to the severe rainfall. As to the correlation between $VQ$ and $vq$, the northward moisture transport from the east coast of Indo-China Peninsula arrives at WS region. In short, same as the process of evolvement in Fig.5, to a large extent, the westward and then northward moisture transport from the West Pacific through the SCS and the eastward one from the west side of WS region jointly result in the severe rainfall over WS region. And on the other hand, the impact of moisture transport from the BOB on the severe rainfall is not so distinct that the correlation belt cannot pass through level confidence more than 95% over the BOB.

No correlation belt with significance level over 95% over the region of BOB for both $UQ$-($uq, vq$) and $VQ$-($uq, vq$) suggests that the influence of moisture transport from the BOB on the severe rainfall over WS region is not so much as those from the West Pacific via the SCS and the Tibetan Plateau. Therefore, the moisture responsible for the occurrence of severe rainfall over WS region maybe mainly comes from the West Pacific through the SCS to the mainland of China and that from the plateau trough.

6.2 Features of the anomalous moisture transport causing the severe summer rainfall over WS region

Figures 6 shows the anomalous moisture transport during the severe rainfall over WS region. We can see that the westward anomalous moisture transport always appears in south of 20°N along the region from the Arabian Sea and the BOB to Indo-China Peninsula from day -2 to day 0, which means that the eastward moisture transport from the BOB has weakened since day -2. And the cyclonic moisture transport anomalies near the BOB lead to the diminishing of the northward moisture transport from the BOB that directly enters WS region on days -3 and -2. On day -2, the anomalous moisture transport with anticyclonic circulation centered around the east side of Philippines and the one occurring over the SCS means that the moisture from the West Pacific combines with the moisture from the SCS and then transports the above moisture into WS region via the coast of Guangxi Region. On day -1, the two anticyclones remain over the West Pacific to the east of Philippines and South China although the anticyclone weakens to some extent. That is to say, the moisture transport from the West Pacific and the SCS increases on the day before severe rainfall. In addition, anomalous trough of moisture transport occurs over the western Tibetan Plateau since day -2. The trough gradually moves eastward and reaches WS region on the severe rainfall day. On day 0, WS region lies on the bottom and the front of the trough. Severe rainfall breaks out over WS region as soon as the anomalous moisture transported by the trough arrives and encounters the anomalous moisture from the south accumulated over WS region a few days prior to severe rainfall. On the basis of above analysis, for the anomalous moisture transport, the anomalous moisture from the BOB affects little on the occurrence of
severe rainfall. The anomalous moisture transports on each boundary of WS region on the occurrence day of severe rainfall are also calculated. As regard to the south boundary, the anomalous moisture transport is \(4.88 \times 10^5\) kg s\(^{-1}\), nearly half of the real moisture transport \((1.034 \times 10^6\) kg s\(^{-1}\)) through the south boundary on the same day. Obviously, the anomalous moisture transport is of great importance to the severe rainfall over WS region, and naturally the anomalous moisture from the West Pacific via the SCS and the one from the north exert comparatively significant influences on the severe rainfall.

7. Concluding remarks

The features of severe summer rainfall over the upper reaches of the Yangtze River (mainly Sichuan Province) are firstly analyzed using the daily rainfall data covering 44 weather stations over that region for an 18-year period from 1980 to 1997 in this paper. Then according to our definitions 20 cases of severe rainfall over ES region and 32 cases over WS region in summer are chosen during the same period. For ES and WS regions, respectively, during the period of severe rainfall, the composite vertically integrated moisture flux is calculated and the correlation between the moisture transport of ES or WS region and those at every grid point in Asia is analyzed. The characteristics of the anomalous moisture transport and the daily evolution of the moisture transport during the period of severe rainfall are also explored over the two regions. The main conclusions may be drawn as follows:

(1) Severe summer rainfall is the major part of the total rainfall over the upper reaches of the Yangtze River. And heavy rain occurs locally over either ES region or WS region. Severe rainfall can be composed of climatological rainfall and anomalous one, and the latter accounts much for severe rainfall.

(2) The meridional moisture transport dominates the composite moisture transport on the occurrence...
Fig.7. Sketch map for the possible course of moisture transport from the West Pacific via the SCS before the severe rainfall over the upper reaches of the Yangtze River. (Solid contours and dashed ones denote real and conjectural moisture transport respectively; 0, -1, -2, and -3 are the occurrence day of severe rainfall and the first, second, third day prior to severe rainfall, respectively.) (a) For ES region; (b) for WS region.

day for ES region, while the meridional is equivalent to the zonal for WS region. According to the daily evolution of moisture transport for both ES and WS, the westward moisture transport from the West Pacific that enters into rainfall region strengthens before severe rainfall, and severe rainfall happens when the eastward moisture transport from the Tibetan Plateau reaches rainfall region. The correlation belts with confidence level above 95% between $UQ$, $VQ$ over either ES region or WS region and $uq$, $vq$ over Asian area indicate that the association of severe rainfall over the upper reaches of the Yangtze River with moisture transport from the BOB is not so notable as that with moisture transport from the West Pacific via the SCS and from the Tibetan Plateau. The anomalous moisture transport during the period of severe rainfall illuminates that the anomalous moisture over both ES and WS regions leading to severe rainfall largely derives from the northward moisture transport from the West Pacific via the SCS and the moisture from the northwest while the anomalous moisture transport from the BOB contributes little to the whole anomalous moisture causative of severe rainfall. Consequently, apart from the moisture transport from the BOB, there is also the one from the West Pacific via the SCS that enters severe rainfall region. Here we put forward a possible course of moisture transport from the West Pacific via the SCS as shown in Fig.7. (the course from the BOB is not included here since many have been discussed about it.)

(3) All of the above are results based on statistic analysis. Statistically, correlation coefficient between elements A and B largely signifies that the possibility of concurrence for A and B is considerably more distinct than that for B and other elements (C for example). But it does not mean that C cannot coexist with B. Based on the analytic results in this paper, the moisture transport from the BOB does make some contributions to the severe rainfall over the upper reaches of the Yangtze River, but the influences of the moisture transport from the West Pacific via the SCS on the severe rainfall cannot be neglected either. To some extent, the letter may be more important to the severe rainfall over ES and WS than the former according to the statistic analysis.

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