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RELATIONSHIPS BETWEEN THE POSITION VARIATION OF THE WEST PACIFIC SUBTROPICAL HIGH AND THE DIABATIC HEATING DURING PERSISTENT INTENSE RAIN EVENTS IN YANGTZE-HUAIHE RIVERS BASIN

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Abstract: By using NCEP/NCAR daily reanalysis data and daily precipitation data of 740 stations in China, relationships between the position variation of the West Pacific subtropical high (WPSH) and the diabatic heating during persistent and intense rains in the Yangtze-Huaihe Rivers basin are studied. The results show that the position variation of WPSH is closely associated with the diabatic heating. There are strong apparent heating sources and moisture sinks in both the basin (to the north of WPSH) and the north of Bay of Bengal (to the west of WPSH) during persistent and intense rain events. In the basin, Q_{1z} begins to increase 3 days ahead of intense rainfall, maximizes 2 days later and then reduces gradually, but it changes little after precipitation ends, thus preventing the WPSH from moving northward. In the north of Bay of Bengal, 2 days ahead of strong rainfall over the basin, Q_{1z} starts to increase and peaks 1 day after the rain occurs, leading to the westward extension of WPSH. Afterwards, Q_{1z} begins declining and the WPSH makes its eastward retreat accordingly. Based on the complete vertical vorticity equation, in mid-troposphere, the vertical variation of heating in the basin is favorable to the increase of cyclonic vorticity north of WPSH, which counteracts the northward movement of WPSH and favors the persistence of rainbands over the basin. The vertical variation of heating in the north of Bay of Bengal is in favor of the increase of anti-cyclonic vorticity to the west of WPSH, which induces the westward extension of WPSH.

Key words: west Pacific subtropical high; complete vertical vorticity equation; persistent heavy rain events over Yangtze-Huaihe rivers basin; diabatic heating

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1 INTRODUCTION

The west Pacific subtropical high (WPSH) interacts with the rainbands in East Asia, with its changes in shape and position and seasonal advances/retreats having important impacts on regional precipitation in the summer of China. Over the past few years, destructive weather occurs frequently in the Yangtze/Huaihe Rivers basin, which is closely related with the abnormal activity of the WPSH. One of the causes for the abnormal precipitation in the middle and lower reaches of the Yangtze is the anomalously southwest extension of the WPSH[1]. As shown in some studies, the precipitation during the Mei-yu raining season of the basin corresponds well with the atmospheric heating field[2] and the activity of the WPSH is also closely linked with the diabatic heating, with its north/south and east/west shifts greatly dependent on the spatial distribution of the diabatic heating[3]. It has been confirmed that the latent heat from condensation, which is caused by monsoon precipitation in East Asia, is a key factor for the position and intensity of the WPSH in the summer of the Eastern Hemisphere[4, 5]. Through numerical simulation, the effect of vertical, inhomogeneous diabatic heating caused by precipitation is revealed on the WPSH[6].

It is obvious that it is necessary to study the

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relationships between diabatic atmospheric heating and changes in the subtropical high. While most of previous work focuses on the stationary position of the WPSH, how atmospheric thermal forcing synoptically affects its east/west and north/south advancements remains a more complicated issue[7]. As shown in Wang et al.[8], the changes in the position of the subtropical high during the Mei-yu raining season in the basin in 1998 are closely associated with the diabatic heating, though whether this conclusion, made from a particular case study, can be applied universally remains to be discussed. For this purpose, this study will run a composite analysis of all persistent intense raining processes over the basin for the past 20 years to identify the effects of the diabatic heating during the rains on the variation of the WPSH and their mechanisms and to deepen the understanding of the abnormal shifts of the WPSH position during these processes.

2 DATA AND METHODS

2.1 *Data used*

The data used in this study include daily precipitation observations from 740 weather stations across China from 1985 to 2005, which are from National Meteorological Information Center, China Meteorological Administration, and global daily reanalysis of geopotential heights, winds, temperatures and humidity from 1958 to 2005[9] (with a horizontal resolution of 2.5°×2.5°), which are provided by National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR, USA).

2.2 *Determination of atmospheric apparent heat source and apparent water vapor sink*

See Yanai and Johnson[10] for the determination of atmospheric apparent heat source Q_1 and apparent water vapor sink Q_2. From the tropopause p (100 hPa is taken for Q_1 and 300 hPa is assumed for Q_2) to the surface p_s, vertical integration is run for Q_1 and Q_2 to determine $\langle Q_1 \rangle$, the apparent heat source, and $\langle Q_2 \rangle$, the apparent water vapor sink, for the whole-column atmosphere, as in

$$\langle Q_1 \rangle = \frac{1}{g}\int_p^{p_s} Q_1 \,\mathrm{d}\, p = \langle Q_\mathrm{R} \rangle + LP + SH \quad (1)$$

$$\langle Q_2 \rangle = \frac{1}{g}\int_p^{p_s} Q_2 \,\mathrm{d}\, p = L\left(P - E\right) \quad (2)$$

where $\langle Q_\mathrm{R} \rangle$ is the whole-layer radiation, L the coefficient of latent heat from condensation, P the rain rate, SH the flux of surface sensible heat, and E the evaporation from surface.

3 SELECTION OF PERSISTENT INTENSE RAINS

For the basin of the two rivers (spanning at 110–125°E, 27.5–35°N), a persistent intense rain is defined to occur if the following conditions are met: (1) the regionally averaged diurnal rainfall is equal to or larger than 15 mm and persists for 7 days and more (being longer than the average duration of 3 to 5 days for a synoptic process); and 2) more than 20 out of the 91 observation stations in the basin record single-station diurnal rainfall that is equal to or greater than 25 mm, and more than three of them measure single-station diurnal rainfall that is equal to or greater than 50 mm.

Statistic analysis is conducted of the day-to-day rainfall for the 91 observation stations in the basin for the past 20 years (1986–2005) and six processes of persistent rain are selected. To study the common character of the rains in association with the WPSH that is abnormally positioned, composite analysis is done of the most significant 7 days within each of the intense rains (Table 1).

Table 1. Typical periods of time for persistent intense rains in the Yangtze-Huaihe Rivers basin.

year	Periods of time /date	year	Periods of time /month. day	year	Periods of time /month. day
2003	30 June–6 July	1999	25 June–1 July	1996	29 June–5 July
1995	20–26 June	1991	30 June–6 July	1987	2–8 Jul.

4 ABNORMAL POSITIONS OF THE WPSH DURING THE INTENSE RAIN

The summertime precipitation in the basin of the two rivers is closely related with the transportation of water vapor in the atmosphere and the abnormally westward extension of the WPSH is one of the factors affecting the latter and the variation of the WPSH is directly affecting the position of rainbands[1]. For the multi-year mean of 500 hPa (Figure 1a), the westernmost point of the WPSH ridge is around 125°E and the WPSH's bulk maintains over the West Pacific. From a composite analysis of the 500 hPa geopotential heights for the six persistent intense rains in the basin (Figure 1b), it is known from the contour of 588 dagpm that the WPSH is much enlarged and enhanced during the intense rains so that even the contour of 590 dagpm appears and the westernmost point of the WPSH ridge is around 110°E and the ridge at 120°E is around 21°N, which is much more westward than the multi-year mean for the same period of time. The WPSH covers so extensively that the provinces of Guangdong and Fujian are both under its control. Its persistently westward location is favorable for the water vapor in the Bay of Bengal, South China Sea and equatorial western Pacific to be transported constantly to the basin[1], supplying its persistent intense rains with sufficient amount of water vapor.

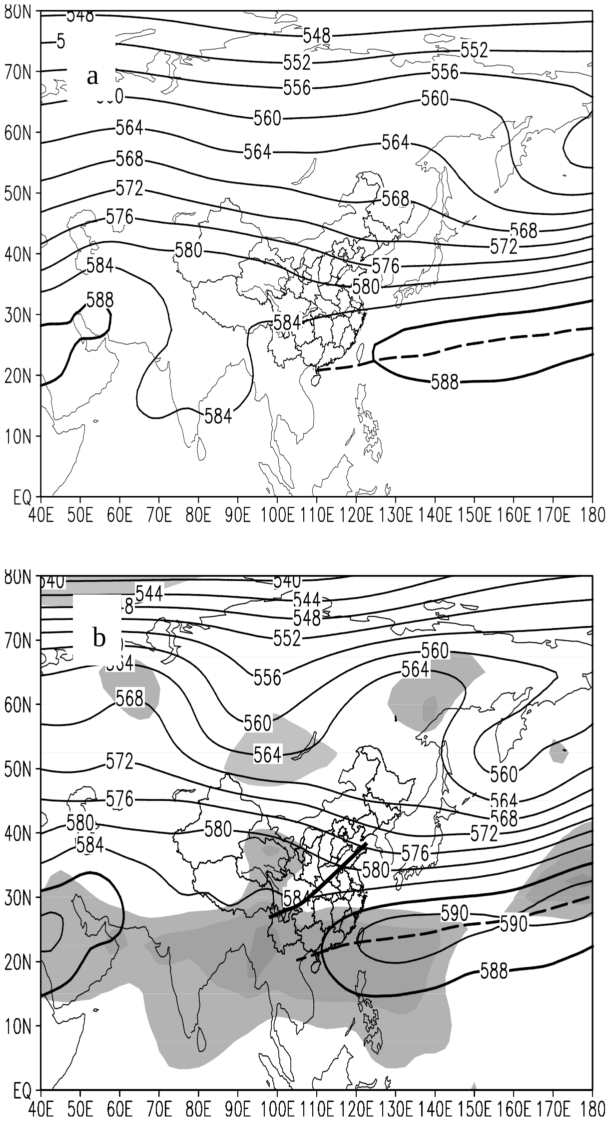


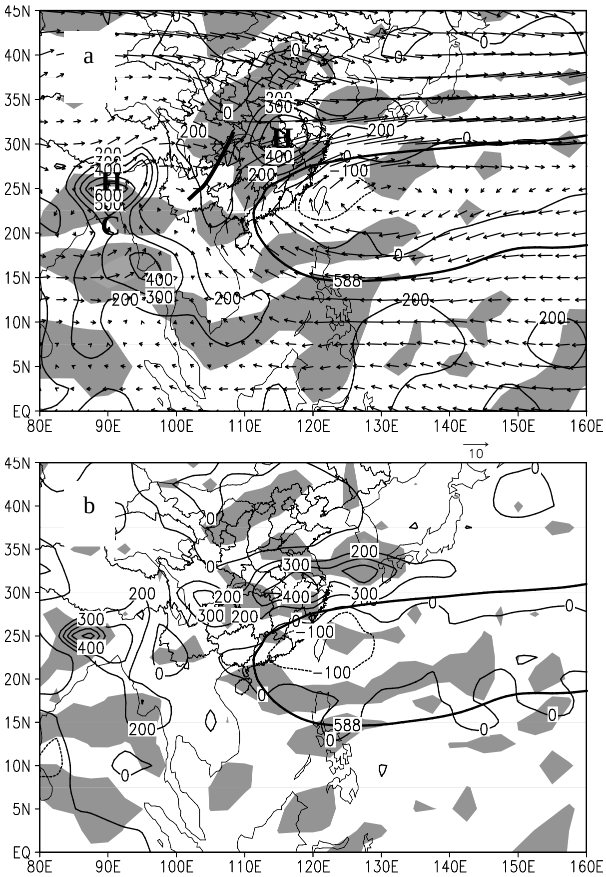
Figure 1. Composites of the 500 hPa geopotential heights for multi-year mean from June 20 to July 8 (a) and the intense rains over the basin (b). The dashed line stands for the ridgeline (i.e. u=0) of the WPSH, and the shaded areas are where the t-test surpasses the 90% confidence level.

Besides, there is an anomalously low trough in the mid-latitudes and the warm and humid airflow to the northwest of the WPSH merges over the basin with the cold air from the north, which is steered by a mid-latitude low trough. Meanwhile, the intrusion of a trough from the north is also unfavorable for the northward advancement of the WPSH, which is one of the reasons for the generation of persistent intense rains over the basin.

5 EVOLUTION OF THE DIABATIC HEATING AND WPSH POSITION DURING THE PERSISTENT INTENSE RAINS

5.1 *Distribution of apparent heat sources and apparent water vapor sinks*

The northern trough is also present in the 500 hPa wind field (Figure 2a), consistent with that in Figure 1b. The trough steers the cold air from the north to converge over the basin with the warm and humid airflow from the Bay of Bengal, SCS and equatorial western Pacific to trigger intense rainfall and release large amount of latent heat from condensation, resulting in diabatic heating in the atmosphere. Besides, there is also cyclonic circulation north of the Bay of Bengal. It causes intense convection, triggers convective, intense rainfall and releases latent heat from condensation to result in the diabatic heating, which is mainly seen in the atmosphere of the northern Bay of Bengal region.



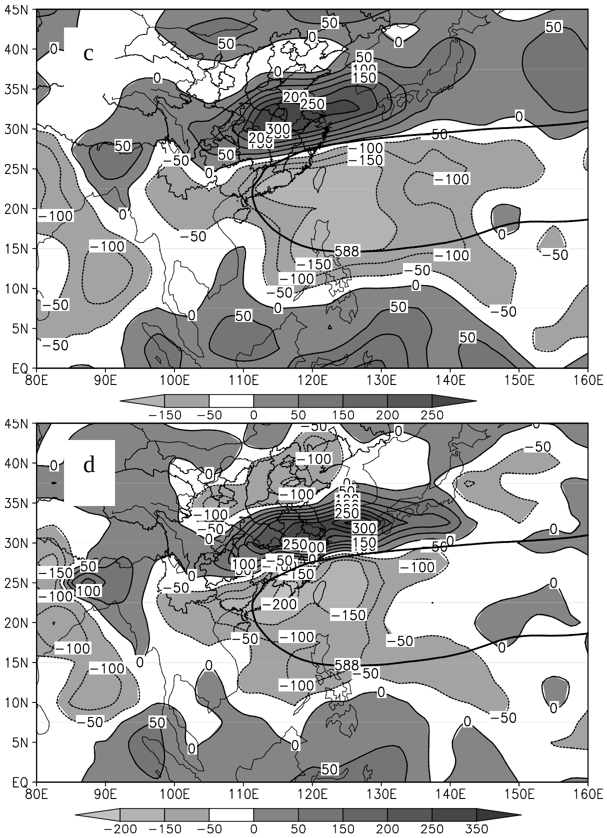


Figure 2. Composites of the apparent heat source <Q1> (a) and apparent heat sink <Q2> (b) determined with whole-column integration for the intense rains and the composite differences between the intense rains and multi-year mean <Q1> (c) and <Q2> (d) for June and July. Units: W/m^2. Solid line: contour of 588 dagpm; bold, solid line in (a): the trough; vector arrow: 500 hPa wind field; shades: areas where the *t*-test surpasses the 90% confidence level.

As shown in the apparent heat source $\langle Q_1\rangle$ (Figure 2a) and apparent water vapor sink $\langle Q_2\rangle$ (Figure 2b), which are determined from whole-column integration corresponding to the intense rains, there are two main centers of large values respectively over the basin and north of the Bay of Bengal. For the basin, the anomalously intense $\langle Q_1\rangle$ and $\langle Q_2\rangle$ are mainly to the north of the WPSH that covers most of the basin, consistent with the distribution of rainfall. Besides, as $\langle Q_1\rangle$ and $\langle Q_2\rangle$ are quite close to each other in value, a high-value center of more than 400 W/m^2 is over the middle and lower reaches of the Yangtze. According to Ding et al.[11], sensible heating and evaporation from the surface are quite small during the intense rain. If intense apparent water vapor sinks contribute to the formation of intense rain, most of the diabatic heating of the atmosphere over the basin will come from the release of latent heat from precipitation. In the northern Bay of Bengal, the central value of $\langle Q_1\rangle$ can be as large as 600 W/m^2 while the value of $\langle Q_2\rangle$ is a little smaller than that of $\langle Q_1\rangle$. In summer, this region is the center of heat sources across the globe. Liu et al.[12] discovered that the Bay of Bengal is the region of small sensible heat and negative radiative cooling during the summertime, i.e., its diabatic heating is mainly composed of the released convective latent heat from tropical summer monsoon. Inside the area enclosed by the 588 dagpm of the subtropical high, the values of both $\langle Q_1\rangle$ and $\langle Q_2\rangle$ are smaller than zero, becoming diabatic cooling, which is consistent with the cooling inside the bulk of the subtropical high[13].

Figures 2c and 2d show the composite differences between the intense rains and multi-year mean $\langle Q_1\rangle$ and $\langle Q_2\rangle$ for June and July. Positive-value areas of $\langle Q_1\rangle$ and $\langle Q_2\rangle$ are located in the basin and northern Bay of Bengal while negative-value areas are inside the subtropical high. It suggests that the time of intense rain is accompanied with anomalously growth of the heat source in the basin and northern Bay of Bengal and the rain process releases latent heat from condensation to contribute to the main part of diabatic heating in the atmosphere.

The anomalous position of the WPSH plays a role in the occurrence of persistent and intense rains over the basin. As Yao et al.[14] suggests, the generation of intense rain interacts with the variation of the WPSH mainly because the inhomogeneous distribution of diabatic heating—induced by the rain—affects the WPSH. Then, how does the diabatic heating during the intense rain in the basin affect the variation of the WPSH?

5.2 *Atmospheric diabatic heating and evolution of WPSH position during intense rains*

To study the evolution of atmospheric diabatic heating and WPSH position during the intense rain in the basin, the day on which rain commences is set at day 0 and composites are made of the apparent heat source integrated for the whole column. Figure 3 gives the time-latitude cross section of <Q1> in the basin versus the WPSH position and the time-longitude cross section of <Q2> in the northern Bay of Bengal versus the WPSH position, respectively. In the abscissa, "0" indicates the day when the rain begins, "6" the day when the rain ends, the section greater than "6" stands for the time after the rain, and negative values represents the time prior to the rain.

For the intraseasonal medium- and short-term oscillations, the WPSH usually withdraws eastward and southward, and extends westward and northward, at the same time[15]. It is shown in Figure 3a that the value of <Q1> increases with the intense rain near 30°N in the basin, becomes the largest at the mid-point of the rain and decreases rapidly after the rain. Prior to the intense rain, the shade keeps moving to the north while expanding, and correspondingly, the WPSH is moving north while strengthening, favoring the rainband to its north to relocate towards the basin of the two rivers. With the commencement of the intense rain (day 0), the shade remains stable and stays to the south of the heat source and the value of <Q1> gets smaller than that north of the heat source, unfavorable for the northward movement of the WPSH[8, 13]. At the same time, the WPSH ridge maintains around 22°N, which is favorable for the precipitation to maintain over the basin. As the intense rain ends on day 6, the <Q1> weakens where it has been over the time and the WPSH withdraws to the east and south, corresponding to a break-off of the shade.

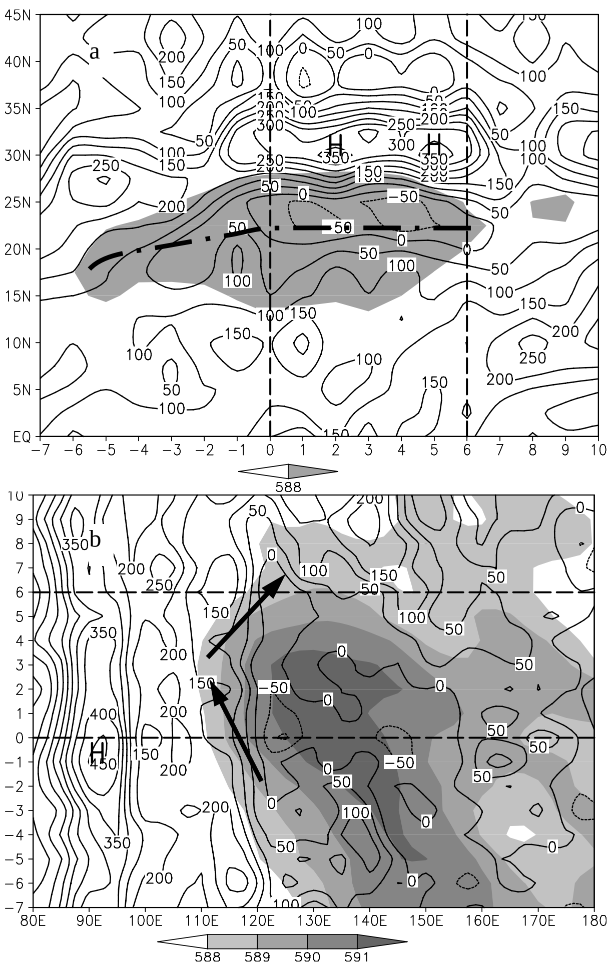


Figure 3. Time-latitude cross section (a, on 120°E) of <Q1> in the basin (110–125°E) versus the WPSH position and time-longitude cross section (b, on 22°N) of <Q2> in the northern Bay of Bengal (12.5–27.5°N) versus the WPSH position. The shades are for the region where the geopotential height of 500 hPa is larger than 588 dagpm, the dash and dot line indicates the mean position of WPSH, and the bold, solid line stands for the east-west shifts of the WPSH.

Next is an analysis of the seasonal progression of the East Asian summer monsoon and its associated rain. After the onset of convection in the region of Bay of Bengal, a stripe-shaped WPSH breaks off with its eastern part withdrawn to the east. Then, the South China Sea summer monsoon begins and the basin starts its Meiyu season[16, 17]. It is noted that intra-seasonal oscillation (ISO) also exists in the WPSH circulation and convection in the Bay of Bengal. It is shown in Figure 3b that prior to the intense rain, the WPSH keeps extending to the west with the western part of its bulk (over the northern Bay of Bengal, around 90°E) being the center of a high-value <Q1>. At the start of the rain (day 0), the WPSH is already around 112°E. Then, with the intense rain going on, the WPSH keeps extending westward and arrives at areas west of 110°E at the mid-point of the rain. At this point, the large-value <Q1> is still over the Bay of Bengal though the rain is a little weaker than at the time leading up to its onset. Afterwards, the rain weakens further while the WPSH withdraws to the east. At the end of the rain, the WPSH is already back to areas east of 120°E. Correspondingly, the <Q1> is much weakened in the northern Bay of Bengal. It can be found that the heating induced by the precipitation in the northern Bay of Bengal begins to increase significantly 3 to 5 days before the intense rain over the basin and starts to weaken before the end of the rain, which is earlier than the oscillation of the WPSH circulation.

Temporarily, the variation of the WPSH position during the intense rain of the basin corresponds well with that of the diabatic heating to its north and west (northern Bay of Bengal), something that is known from the analysis above. Then, does the diabatic heating affect the variation of the WPSH position? The following section will discuss the feedback of diabatic heating on the WPSH.

6 POSSIBLE CAUSATION FOR ANOMALOUS VARIATION OF WPSH POSITION DURING THE INTENSE RAIN

In their study on the effect of diabatic heating on the generation and variation of the WPSH using a complete form of tendency equations for vertical vorticity, Wu et al.[4] and Liu et al.[5] found that the vertical gradients of the diabatic heating and their variation are the key factors in determining the position, intensity, distribution and variation of the WPSH. For deep convection, the center of latent heating from condensation is usually located at the middle and higher levels of the troposphere, between 300 and 400 hPa. With short time scales, vertical, inhomogeneous latent heating from condensation is released to enhance the development of the cyclone beneath the center of maximum latent heating, making the vorticity field change dramatically within a day and triggering off changes in the position and intensity of WPSH[5]. In the wind field averaged over 500 hPa during the intense rain (Figure 2a), a weak westerly trough is over the basin and cyclonic circulation is present over the heating field of northern Bay of Bengal, a response of the vorticity field to the heat source.

The complete form of tendency equations for vertical vorticity, as given by Wu and Liu[18], are used and scale analysis[4] is applied to reduce the equation into

$$\frac{\partial \zeta}{\partial t}=\frac{f+\zeta}{\theta_z}\frac{\partial Q_1}{\partial z}-\beta v-\boldsymbol{V}\cdot\nabla\zeta \tag{3}$$

where $\frac{f+\zeta}{\theta_z}\frac{\partial Q_1}{\partial z}$ is the term of diabatic heating, denoted as Q_{1z}, βv the term of β–effect, and $V\cdot\nabla\zeta$ the term of vorticity advection.

The variation of the WPSH can be summarized as the generation and dissipation of negative vorticity[19]. For the case of the 500 hPa WPSH variation, the terms of Q_{1z}, βv, and $V\cdot\nabla\zeta$ are each computed for the large-value <Q1> areas at 500 hPa in the basin north of the WPSH (110–125°E, 27.5–35°N) and northern Bay of Bengal west of it (85–100°E, 12.5–27.5°N). It is shown that as compared to Q_{1z}, the values of βv and $V\cdot\nabla\zeta$ are smaller and vary less with time. Due to relatively weak southerly north of the WPSH and relatively weak vorticity advection near the western ridge, the local variation of vorticity during the intense rain is mainly subject to the vertical variation of diabatic heating. At the same time, <Q1> are comparable to <Q2> in value and atmospheric diabatic heating is mainly attributed by the release of latent heating from condensation. Eq. (3) can be reduced to

$$\frac{\partial \zeta}{\partial t}\approx\frac{f+\zeta}{\theta_z}\frac{\partial Q_1}{\partial z}=Q_{1z}\,. \tag{4}$$

Usually, if $f+\zeta\geqslant 0$ in the large-scale motion, $\theta_z=\partial\theta/\partial z$ is also always positive[20]. If $Q_{1z}>0$, then $\partial\varsigma/\partial t>0$, suggesting the growth of positive cyclonic vorticity.

For the basin, the term of diabatic heating exists both before and after the intense rain (Figure 4a), i.e. $Q_{1z}>0$, but with a smaller value than during the rain. It is mainly related to the selection of the intense rain. Around the time of the intense rain selected, it is possible that rain also occurs in the basin but it is not included as a persistent hard rain because the diurnal rainfall is less than 15 mm (moderate rain) or the duration is less than 7 days. This type of rain can induce diabatic heating, but at rates smaller than the intense rain, i.e. there is always mild growth of positive vorticity in the basin. Three days before the intense rain, however, Q_{1z} starts to increase and reaches the maximum two days after the rain onset. It then gradually decreases and tends to level off after the end of the rain. It is known from Eq. (4) that the vertical variation of the 500-hPa diabatic heating north of the WPSH results in significant growth of cyclonic vorticity in the region (Figure 5a), unfavorable for the WPSH to go northward (Figure 6). As a result, a rainband to its north produces persistent precipitation over the basin.

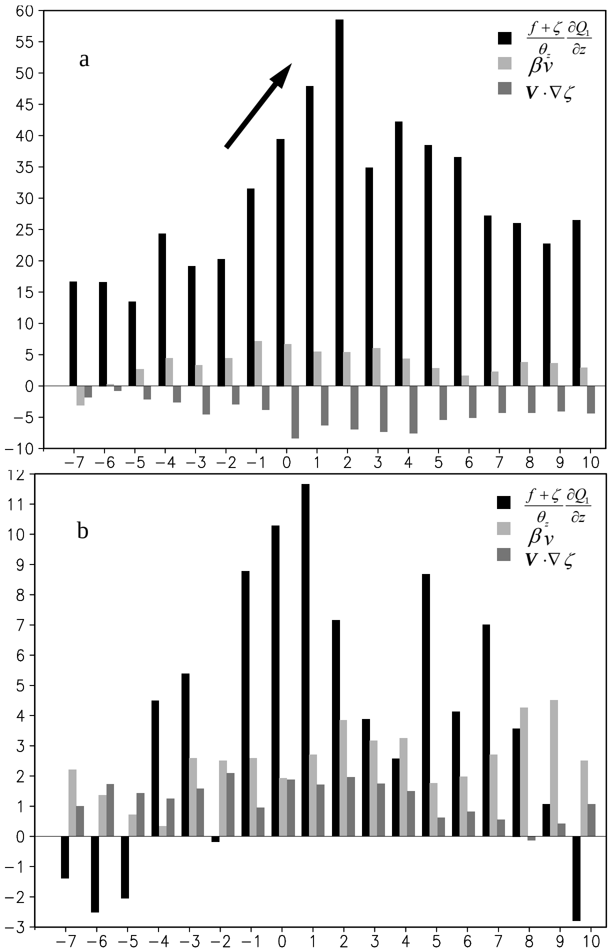


Figure 4. Temporal evolution of $\frac{f+\zeta}{\theta_z}\frac{\partial Q_1}{\partial z}$ (black), βv (grey) and $V\cdot\nabla\zeta$ (deep grey) at 500 hPa in (a) the basin (110–125°E, 27.5–35°N) and (b) northern Bay of Bengal (85–100°E, 12.5–27.5°N). Units: 10^{-11} s^{-2}. The day on which the intense rain starts is the composite for day 0.

During the intense rain, a center of intense heating is also over the northern Bay of Bengal to the west of the WPSH (Figure 2a), but the heating center is not quite close to the bulk of the WPSH. It is pointed out that a long distance between the heating field and the WPSH induces the latter to extend westward while a short distance forces it to retreat to the east (Yu and Zhao[15]). Two days before the intense rain in the basin, the Q_{1z} begins to increase in northern Bay of Bengal and reaches the maximum one day after the rain onset, inducing the WPSH to move westward (See Figure 4b). By determining the temporal evolution of vorticity for the large-value area over northern Bay of Bengal (85–100°E, 15–27.5°N, see Figure 5b), we also found that there is positive growth of cyclonic vorticity in this region, corresponding to the growth of diabatic heating. From

Eq. (4), it is known that the vertical variation of the 500-hPa diabatic heating from an intense source over the northern Bay of Bengal results in the growth of cyclonic vorticity in the region and the enhancement of the southerly east of the heat source, favorable for the anti-cyclonic vorticity to increase east of the heat source (west of the WPSH). As a result, the WPSH is induced to extend westward (Figure 6). Afterwards, the Q_{1z} decreases and correspondingly, the WPSH moves eastward to some extent. Recently, it was pointed out that the heating from the precipitation of the South Asia monsoon corresponding to the interdecadal warming over the Indian Ocean may be one of the reasons for the westward extension of the WPSH on the same scale (Zhou et al.[21]). With different time-scale from this study, it has similar dynamic mechanism. It is then clear that the basin to the north of the WPSH coacts with the northern Bay of Bengal to the west of it to contribute to a situation which is favorable for the WPSH to move north but unfavorable for it to head west.

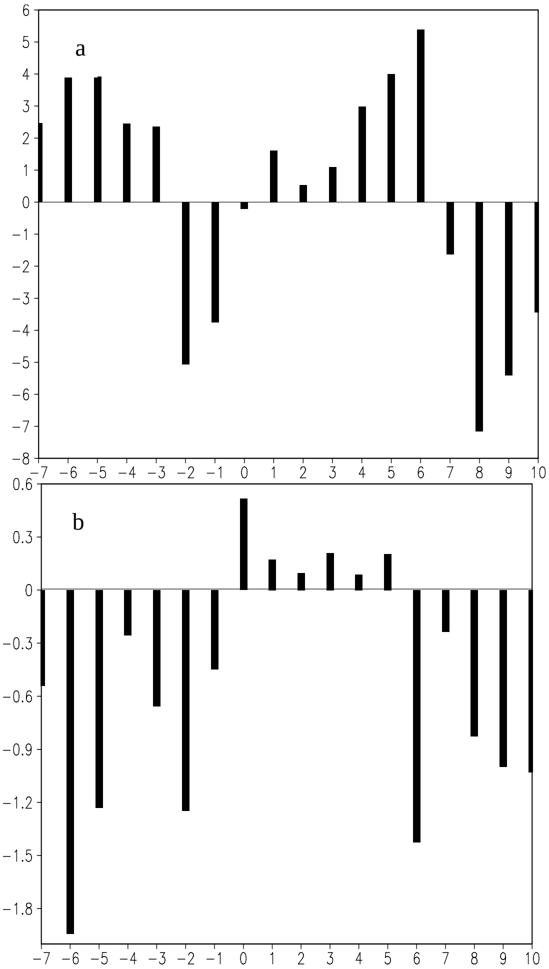


Figure 5. Temporal evolution of vorticity at 500 hPa vorticity for the large-value areas in the (a) basin (110–125°E, 27.5–35°N) and (b) northern Bay of Bengal (85–100°E, 15–27.5°N). Units: 10^{-6} s^{-2}. The day on which the intense rain starts is the composite for day 0.

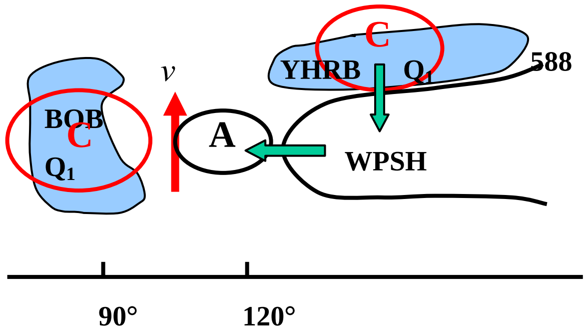
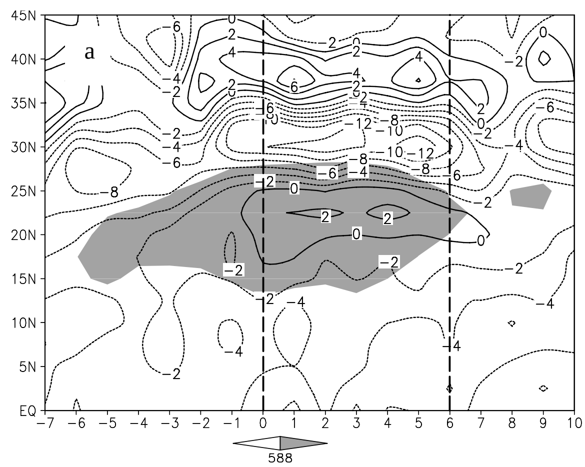


Figure 6. Schematic illustration of the heat sources in the Yangtze-Huaihe rivers basin (YHRB) and northern Bay of Bengal (BOB) and the variation of the WPSH position.

It is worth noting that the abrupt growth of Q_{1z} in Figures 4a and 4b occur 2 to 3 days before the start of the intense rain, indicating that the heating field induces the variation of the WPSH position and the precedent growth of the heating field may be related to the background of the large-scale circulation. Besides, the trend of the Q_{1z} variation corresponds well in time with the east-west and north-south shifts of the WPSH position as described previously. Therefore, the diabatic heating in the atmosphere indeed has important impacts on the variation of the WPSH position.

On the profile of the vertical velocity, it can be seen that a secondary circulation is formed due to the updraft caused by diabatic heating and downdraft within the range of WPSH (Figure 7a). Two days before the intense rain, ascending motion increases in the northern Bay of Bengal while weakening west of the WPSH and at its periphery (Figure 7b), a phenomenon consistent with the local variation of vorticity induced by the vertical variation of diabatic heating.



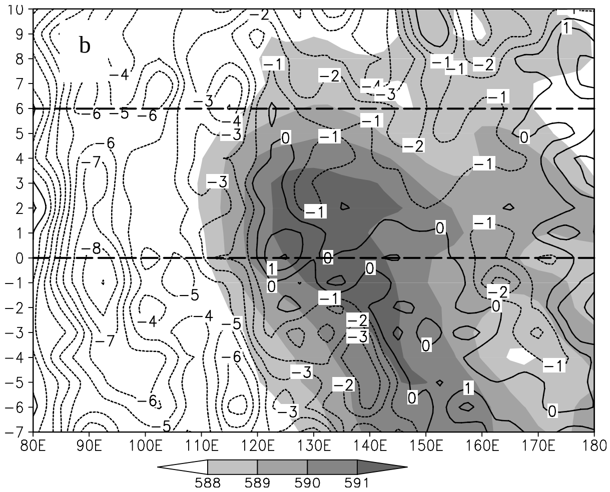


Figure 7. Composites of time-latitude cross sections of 500 hPa vertical velocity for (a) the basin (on 110–125°E) and composites of time-longitude cross sections of 500 hPa vertical velocity for (b) the northern Bay of Bengal (on 12.5–27.5°N). ω: 10^{-2} Pa/s; the shades are for the areas where the 500 hPa geopotential height is larger than 588 dagpm. a: 120°E; b: 22°N.

As shown in the variation of the flow field during the intense rain (figure omitted), the WPSH extends to the westernmost point on day 4. 500 hPa difference circulations from day 4, the mid-point of the rain, to day 0 (Figure 8a) and from day 6, the ending day of the rain, to day 4 (Figure 8b) are called the developing and decaying phase of the rain, respectively. The figure shows that there is anti-cyclonic circulation in the area of West Pacific that is formerly controlled by the WPSH, and east of the heating source (100–110°E, 20–27.5°N) in the northern Bay of Bengal (and west of the WPSH), during the developing phase (Figure 8a). It corresponds to the westward-extended WPSH induced by the heating field and is consistent with the results of Wu et al.[4]. In contrast, in the decaying phase (Figure 8b), the entire South China Sea and the area formerly controlled by the WPSH are dominated by cyclonic circulation, consistent with the observation that the WPSH retreats when Q_{1z} decreases. It further highlights the effect of diabatic heating on the WPSH position during the intense rain. More numerical simulation will be carried out in the future to verify the role of the heating field in the variation of the WPSH position.

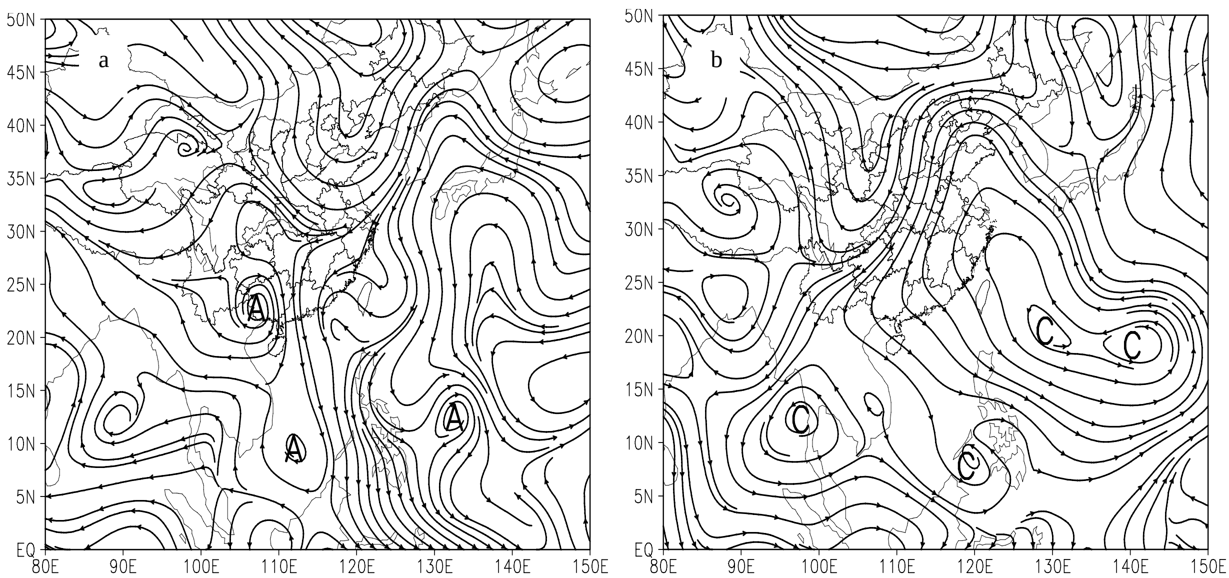


Figure 8. Composites of the 500 hPa circulation fields for the developing phase (a) and decaying phase (b) of the intense rain. Units: m/s.

7 CONCLUSIONS

(1) While the anomaly of the WPSH position affects the generation of persistent, intense rain over the Yangtze-Huaihe Rivers basin, the diabatic heating induced by the rain exerts feedback on the WPSH position. During the rain, the diabatic heating over the basin has important effects on the north-south shifts of the WPSH position. The vertical variation of the diabatic heating at the 500 hPa level of the WPSH induces the significant growth of the cyclonic vorticity in the region, which is unfavorable for the WPSH to move northward and keeps the northern rainband in the basin.

(2) The diabatic heating in the northern Bay of Bengal plays an important role in the westward extension of the WPSH. The vertical variation of the diabatic heating at 500 hPa over the strong heating source in the northern Bay of Bengal results in the growth of cyclonic vorticity in the region and the increase of the southerly east of the source, favorable for the anti-cyclonic vorticity to increase (cyclonic vorticity to decrease) to the east of the source. The WPSH is thus induced to extend westward, a situation

that maintains the intense rain over the basin.

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