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Relationship Between Persistent Heavy Rain Events in the Huaihe River Valley and the Distribution Pattern of Convective Activities in the Tropical Western Pacific Warm Pool

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ABSTRACT

Using daily outgoing long-wave radiation (OLR) data from the National Oceanic and Atmospheric Administration (NOAA) and the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data of geopotential height fields for 1979–2006, the relationship between persistent heavy rain events (PHREs) in the Huaihe River valley (HRV) and the distribution pattern of convective activity in the tropical western Pacific warm pool (WPWP) is investigated. Based on nine cases of PHREs in the HRV, common characteristics of the West Pacific subtropical high (WPSH) show that the northern edge of the WPSH continues to lie in the HRV and is associated with the persistent "north weak south strong" distribution pattern of convective activities in the WPWP. Composite analysis of OLR leading the circulation indicates that the response of the WPSH to OLR anomaly patterns lags by about 1–2 days. In order to explain the reason for the effects of the distribution pattern of convective activities in the WPWP on the persistent northern edge of the WPSH in the HRV, four typical persistent heavy and light rain events in the Yangtze River valley (YRV) are contrasted with the PHREs in the HRV. The comparison indicates that when the distribution pattern of the convective activities anomaly behaves in a weak (strong) manner across the whole WPWP, persistent heavy (light) rain tends to occur in the YRV. When the distribution pattern of the convective activities anomaly behaves according to the "north weak south strong" pattern in the WPWP, persistent heavy rain tends to occur in the HRV. The effects of the "north weak south strong" distribution pattern of convective activities on PHREs in the HRV are not obvious over the seasonal mean timescale, perhaps due to the non-extreme status of convective activities in the WPWP.

Key words: Huaihe River valley, persistent heavy rain events, convective activities in the WPWP, West Pacific subtropical high

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1. Introduction

The Huaihe River valley (HRV), situated between the middle and lower reaches of the Yangtze River and the Yellow River valleys, is located at China's transition terrain of northern climate and southern climate, and so the connecting line of the Huaihe River, the Qinling Mountains and the Bailong River has long been the geographic boundary between North and South China. The whole of the HRV features a warm climate, fertile soil and rich products. It is one of China's earlier developed areas in terms of economy and culture. In the boreal summer, the climatological mean precipitation amounts to more than 400 mm in the HRV (Bao and Huang, 2006), which is indicative of the Asian monsoon bringing a large amount of water vapor to the HRV, and subsequently these levels of rainfall can be formed.

The East Asian monsoon, as a sub-monsoon system of the Asian monsoon, has large interannual vari-

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ability. As a consequence, the mei-yu in the Yangtze River and Huaihe River valleys also manifests obvious inter-annual differences. Previous studies have usually treated the Yangtze River valley (YRV) and the HRV as a whole, viz. the Yangtze River-Huaihe River valleys to research droughts and floods caused by the anomalous monsoon in this region. The reviews by Huang et al. (2003a,b) show that the East Asia climate system has important effects on the variability of the East Asian summer monsoon (EASM) at the intraseasonal, inter-annual and inter-decadal timescales, and has a close relationship with severe climatic disasters in China, especially in the Yangtze River-Huaihe River valleys. However, sometimes floods have occurred mostly in the HRV, for instance in 1991, 2000, 2003, and 2005, which presently represents a big challenge to seasonal climatic prediction. The severe floods of 1991 and 2003 in the HRV were summarized by Ding (1993) and Zhang et al. (2004). Many studies on the floods of 1991 and 2003 have indicated the effects of atmospheric circulation characteristics and climatic factors on the maintenance of the rainband in the HRV, but the climatic backgrounds of the abnormal weather and climate in the HRV are still not clear. EOF analysis of summer rainfall in China shows that EOF1 expresses floods in the YRV and the southern parts of the HRV related to the SSTA in the tropical western Pacific Ocean; EOF2 expresses floods in the HRV and droughts to the south of the Yangtze River, but without an obvious signal in SSTA (Chen et al., 2006; Jian et al., 2006). Huang and Wu's (1989) investigation showed that the influence of ENSO events on summer climate anomalies in China depends on the different stages of the ENSO cycle. Summer monsoon rainfall may be above normal in the HRV during summers associated with the developing stage of El Niño or the decaying of La Niña. On the contrary, it may be below normal during summers associated with the decaying stage of El Niño or the developing stage of La Niña. Wang and Wang (2002) suggested that summer precipitation anomalies in the HRV are related to the preceding SSTA over the North Pacific from August to October. The decadal variation of the relationship between summer precipitation along the HRV and SST over the equatorial eastern Pacific was also studied (Gao, 2006). To sum up, the causes of the abnormal summer climate in the HRV are not understood as well as in the YRV, even though the HRV is located only 3°–4° north of the YRV.

It has been demonstrated in many studies (Nitta, 1987; Huang and Li, 1988) that thermal states in the tropical western Pacific warm pool (WPWP) and convective activities over the warm pool play important roles in the inter-annual variability of the EASM. Huang and Sun (1992) investigated the influence of thermal states in the warm pool and convective activities around the Philippines on the inter-annual anomalies of the East Asian monsoon circulation from observed data and dynamics theory. In summer, with weak convective activities in the warm pool, monsoon rainfall may be strong in the Yangtze River-Huaihe River valleys of China, in South Korea, and in Japan. On the other hand, strong convective activity in the warm pool may be associated with light rainfall in such regions. Figure 1 shows the normalized inter-annual variation of the June–July–August (JJA) mean OLR anomaly in the warm pool (10°–20°N, 110°–140°E) from 1979–2006. It can be seen that flooding (drought) in the YRV tends to occur during weak (strong) convective activities in the warm pool. It is worth noting that flooding mostly in the HRV tends to occur when convective activities are neither too strong nor too weak. Because the convective activities in the warm pool are considered as a whole in Fig. 1, the flooding in the HRV may not be related to the mean anomalous convective activities in the warm pool, but perhaps has a relationship with the distribution pattern of convective activities anomalies in the WPWP.

As early as the 1960s, Tao and Xu (1962) pointed out that persistent drought and flood in the Yangtze River and Huaihe River valleys in summer occurred under steady circulation backgrounds. Recently, the climatology of persistent heavy rainfall events in China has been emphasized (Tang et al., 2006; Bao, 2007). Bao (2007) showed that persistent heavy rain events (hereafter, PHREs) can induce the occurrence of severe floods in the HRV when the northern edge of the West Pacific subtropical high (WPSH) continues to lie in the HRV. If the northern edge of the WPSH continues to lie in the YRV, persistent heavy rain tends to occur in the YRV. The large scale EASM circulation characteristics of persistent and intense rain events over the YRV have been studied extensively (Zhang et al., 2002, 2003). Therefore, we will focus on the relationship between the persistent northern edge of the WPSH in the HRV and the distribution pattern of convective activities in the warm pool and compare it with the YRV. It may be helpful to understand the effects of convective activities on the occurrence of PHREs in the HRV.

In this paper, section 2 describes the data and cases of persistent heavy (light) rain events used in the study. The characteristics of the northern edge of the WPSH during PHREs in the HRV are examined in section 3. In section 4, we demonstrate the relationship between the location of the WPSH and the distribution pattern of convective activities in the warm pool. A comparison with persistent heavy (light) rain

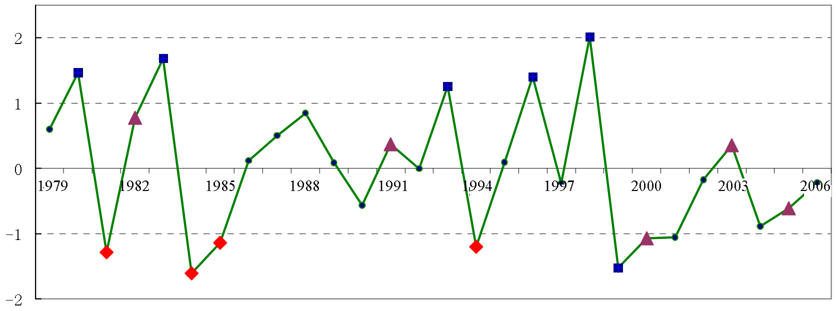

Fig. 1. Normalized inter-annual variation of JJA mean OLR anomaly in the tropical western Pacific warm pool (10°–20°N, 110°–140°E) from 1979–2006. Blue squares represent typical floods over the YRV; red diamonds represent typical droughts over the YRV; and the triangles represent typical floods over the HRV.

Table 1. Nine PHREs in the HRV and four typical persistent heavy (light) rain events in the YRV.

Events	Cases
PHREs in the HRV	(1) 16–26 June1980; (2) 13–23 July 1982; (3) 18–24 July 1983; (4) 5–12 July1989; (5) 29 June–11 July 1991; (6) 24–29 June 2000; (7) 30 June–10 July 2003; (8) 5–10 July 2005; (9) 28 June–4 July 2006
PHREs in the YRV	(1) 30 July–21 August 1980; (2) 25 June–11 July 1983; (3) 25 June–15 July 1996; (4) 6–27 June 1998
Persistent light rain events in the YRV	(1) 1–21 June 1981; (2) 1–30 August 1984; (3) 7–30 June 1985; (4) 28 June–13 August 1994

events in the YRV is given in section 5, in order to further explain the physical mechanism. A discussion and conclusions are given in section 6.

2. Data and cases

In order to study the relationship between PHREs in the HRV and the distribution pattern of convective activities in the WPWP, we used monthly, daily, and daily mean climatology outgoing long-wave radiation (OLR) data for 1979–2006 provided by the National Oceanic and Atmospheric Administration (NOAA), and the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data of geopotential height fields for 1979–2006 (Kalnay et al., 1996).

Referring to the work of Bao (2007), who researched historical typical PHREs over China in the last 50 years, we also examined the historical daily precipitation maps based on the datasets at 730 stations in the mainland of China and find nine cases for PHREs in the HRV lasting for more than five days during 1979–2006. As seen in Table 1, PHREs in the HRV generally occurred in the second half of June and in July. In order to contrast PHREs that occurred in the HRV with those in the YRV, we chose four typical cases for PHREs in the YRV and four typical cases for persistent light rain events in the YRV from 1979–2006. All cases are listed in Table 1. A typical persistent heavy rain event that occurred in the YRV in 1999 was not chosen because of local thermal forcing induced by the persistent anomalous strong air-sea interaction in the region from the South China Sea to the tropical western Pacific (Sun and Ding, 2003). This progress does not satisfy the statistical results of the relationship between summer climate in the YRV and convective activities in the WPWP in Fig. 1.

3. Characteristics of the WPSH during PHREs in the HRV

The WPSH, as an important member of the EASM system, has a distinct influence on the rainband of China (e.g. Tao and Chen, 1987). While the EASM is weak (strong) and the WPSH shifts southward (northward), the mei-yu over China usually becomes more (less) than normal in the middle and lower reaches of the YRV. Bao (2007) discussed the large-scale circulation backgrounds of PHREs in South China and in the Yangtze River-Huaihe River valleys. The results show that the northern edge of the WPSH shifts northward by 3°–4° during PHREs in the HRV compared to in the YRV.

Figure 2 shows the daily 500-hPa geopotential

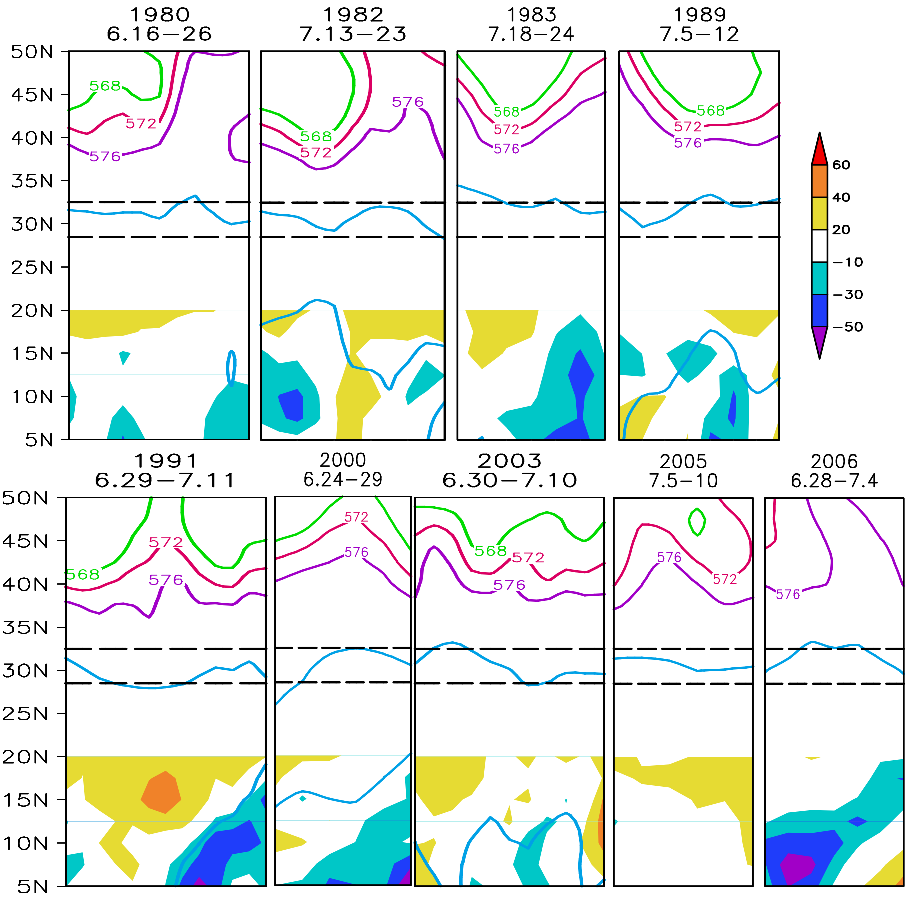

Fig. 2. Time-latitude cross section for nine cases of PHREs in the HRV. Blue lines without numerical values denote the 5860-gpm contour averaged between 110°–125°E from the 500-hPa geopotential height fields; OLR anomalies averaged between 110°–140°E are shaded from 5°–20°N (units: W m^{-2}); the 568-, 572- and 576-dagpm contours averaged between 110°–130°E from the 500-hPa geopotential height fields are indicated by solid lines; dashed lines denote the latitude at 28.5°N and 32.5°N.

heights averaged between 110°–125°E for nine cases individually. It can clearly be seen that the 5860-gpm contour for the northern edge of the WPSH in all cases is located between 28.5°–32.5°N when PHREs occur in the HRV. The composite of process averaged for nine cases indicates the 5860-gpm contour from 110° to 125°E lies in the middle and lower reaches of the Yangtze River and the 5840-gpm contour lies in the HRV (Fig. 3a). It can also be easily seen that the position of the ridge line of the WPSH is located at about 25°N and the 5860-gpm contour extends westward to about 95°E. The characteristics of the WPSH are consistent with the work of Bao (2007). The location of the WPSH during PHREs in the HRV shows that when the 5840-gpm contour for the northern edge of the WPSH lies in the HRV, the EASM brings a large amount of water vapor to the HRV, favoring the occurrence of PHREs in the HRV.

In addition, Fig. 2 shows that the 568–576-dagpm contours averaged between 110°–130°E tend to be located between 35°–45°N, which displays the weak cold air activities of middle latitudes over East Asia during PHREs in the HRV.

4. Distribution pattern of convective activities in the WPWP

Thermal forcing of the heat source in the WPWP and its mechanism with the effects on the anomalous WPSH was illustrated by Huang and Li (1988). They pointed out the influence of convective activities in the WPWP is associated with the quasi-stationary planetary wave train propagated from Southeast Asia to the western coast of North America through East Asia in summer. From the studies mentioned in section 3, it is known that the northern edge of the WPSH is steadily located between 30°–35°N during PHREs in the HRV. In this section, we will examine the distribution pat-

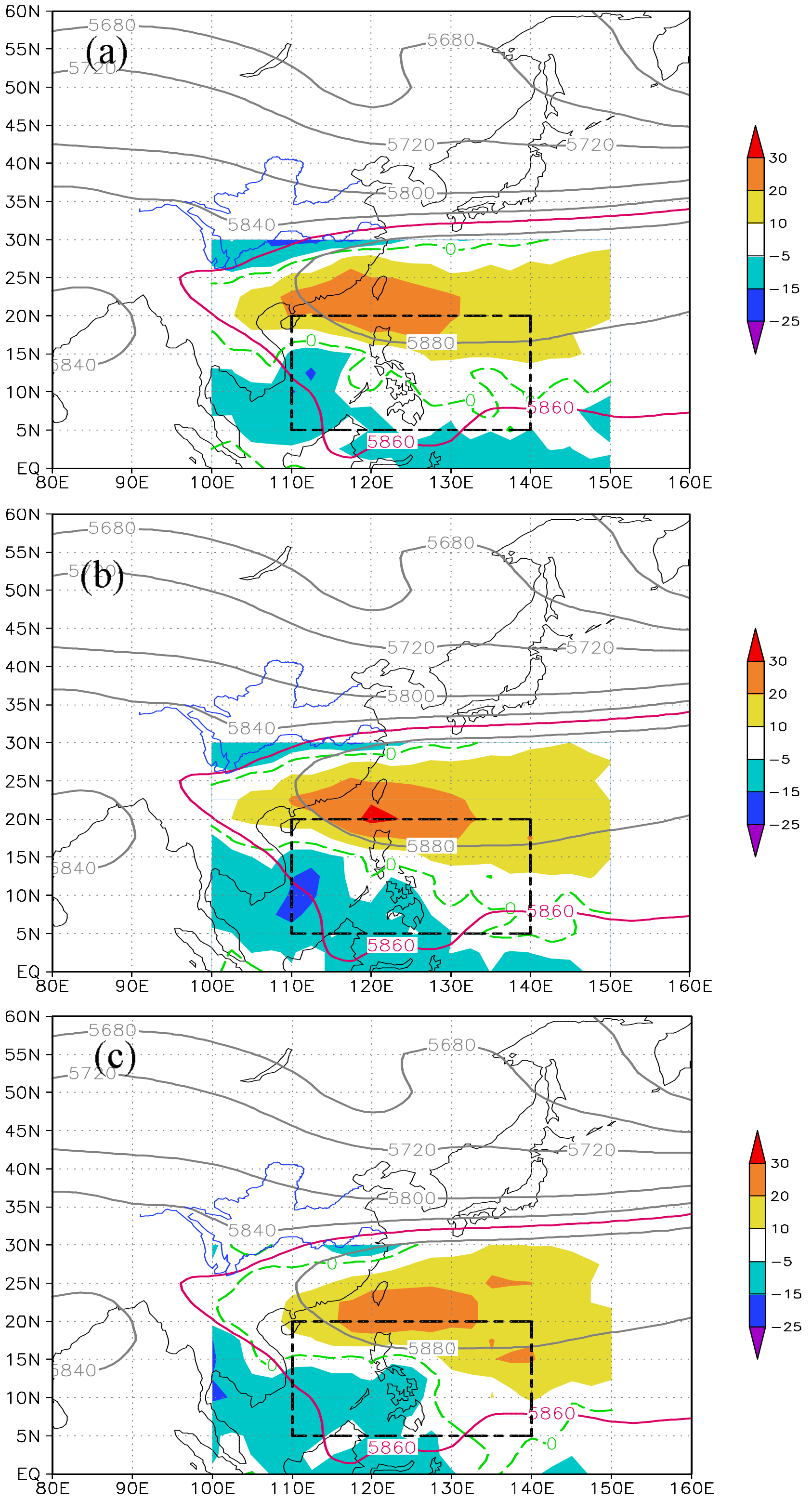

Fig. 3. Composite of nine cases for PRHEs in the HRV. (a) Simultaneous OLR anomalies; (b) leading by two days; and (c) leading by four days in the region (0°–30°N, 100°–150°E) are shaded (units: W m^{-2}). Simultaneous contours of the 500-hPa geopotential height fields are the same in (a), (b) and (c). Black outlines denote the WPWP (5°–20°N, 110°–140°E) and dashed lines represent the zero lines of the OLR anomalies.

tern of convective activities in the WPWP and its relationship with the location of the WPSH.

Figure 2 shows that OLR anomalies averaged for 110°–140°E display a "north weak south strong" distribution pattern from 5°–20°N in the WPWP. The common characteristics of the anomalous OLR pattern can be seen in nine cases, although this pattern is not very clear in each case. In order to diagnose OLR anomalies for the spatial distribution pattern in the WPWP, the composite of process averaged for nine cases of OLR anomalies in the region (0°–30°N, 100°–150°E) is given in Fig. 3a. It can be seen that there exists a dipole "north weak south strong" pattern in this area. The center of weak convective activity anomalies is located north of the Philippines and the strong convective activity anomalies south of the Philippines. The zero line of the anomalous OLR between them lies around 10°–15°N in the WPWP.

In order to explain the relationship between the location of the northern edge of the WPSH and the anomalous convective activities in the WPWP, the composites of process for the OLR anomalies leading the process for PHREs in the HRV by two days and four days are given in Fig. 3b and Fig. 3c, respectively. It can clearly be seen that the maximal anomalous OLR value appears in the composite of process for the OLR anomalies leading the process for PHREs in the HRV by two days. The composite for the OLR anomalies leading by one day (figure not given) is similar to that of two days, which also has a stronger anomalous signal than the composite for the simultaneous OLR anomalies. However, the composite process for the OLR anomalies leads the process for PHREs in the HRV by four days (Fig. 3c) and shows that the anomalous value is not as large as that for two days (Fig. 3b). The results may suggest that the response of the persistent northern edge of the WPSH located in the HRV to the persistent "north weak south strong" distribution pattern of the anomalous convective activities in the WPWP lags by around 1–2 days. The response of the WPSH to convective activities in the WPWP is consistent with the studies by Huang and Li (1988), in which pentad data were used.

5. Comparison with persistent heavy (light) rain events in the YRV

In order to further understand the effects of the distribution pattern of convective activities in the WPWP on the occurrence of persistent heavy rain events in the HRV, some typical persistent heavy (light) rain events in the YRV have been chosen to compare with PHREs in the HRV. Figure 4 shows four typical cases of PHREs in the YRV. An obvious difference between the WPSH and the convective activity anomalies exists in Fig. 2 and Fig. 4. In the cases for PHREs in the YRV, the 5860-gpm contour for the northern edge of the WPSH averaged for 110°–125°E in four cases is generally located south of 30°N, and OLR anomalies averaged for 110°–140°E display a distribution pattern of whole weak convective activities from 10°–20°N in the WPWP. The composite of the process averaged for four cases indicates the 5860-gpm contour from 110°–125°E lies south of the middle and lower reaches of the Yangtze River and the 5840-gpm contour lies in the middle and lower reaches of the Yangtze River (Fig. 5). It can also be clearly seen that the position of the ridge line of the WPSH is located at around 21°N. The location of the WPSH during PHREs in the YRV shows that when the 5840-gpm contour for the northern edge of the WPSH lies in the YRV, the EASM brings a large amount of water vapor to the YRV, which favors the occurrence of PHREs in the YRV. At the same time, weak convective activities in the whole WPWP (5°–20°N, 110°–140°E) are outstanding and the center of the weak convective activity anomalies is located near the Philippines. The zero line of the anomalous OLR south of the weak convective activities lies at around 5°N in the WPWP.

On the contrary, four typical cases of persistent light rain events in the YRV show that all the cases are associated with persistent strong convective activities in the whole WPWP from 5°–20°N (Fig. 6). The WPSH averaged for 110°–125°E displays two kinds of characteristics: one is the retreating eastward of the WPSH, such as the cases in 1981 and 1985; and the other is the shifting northward of the WPSH, such as the cases in 1984 and 1994. The former usually occurs in the early summer and the latter in the middle summer. Figure 7a is the composite of process averaged for two persistent light rain events that occurred in the early summer of 1981 and 1985. It can clearly be seen that since strong convective activity occupies the whole WPWP, the WPSH retreats eastward and cannot bring enough water vapor to eastern China, in favor of the occurrence of persistent light rain events in the YRV. Actually, the retreating eastward of the WPSH can be looked upon as the response of the WPSH to the latent heat release of the strong convective activities in the WPWP. In the other case, the composite of process averaged for two persistent light rain events in the middle of the summers of 1984 and 1994 shows that since the strong convective activities occupy the whole WPWP, the WPSH shifts northward and controls the YRV to cause persistent droughts in the YRV (Fig. 7b).

The impact of convective activities in the WPWP during summertime on the WPSH and its mechanism

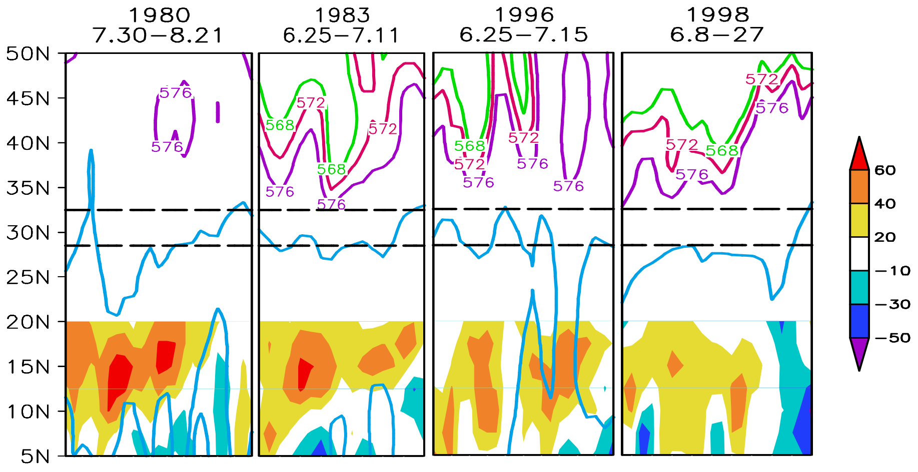

Fig. 4. As in Fig. 2 but for four cases of PHREs in the YRV.

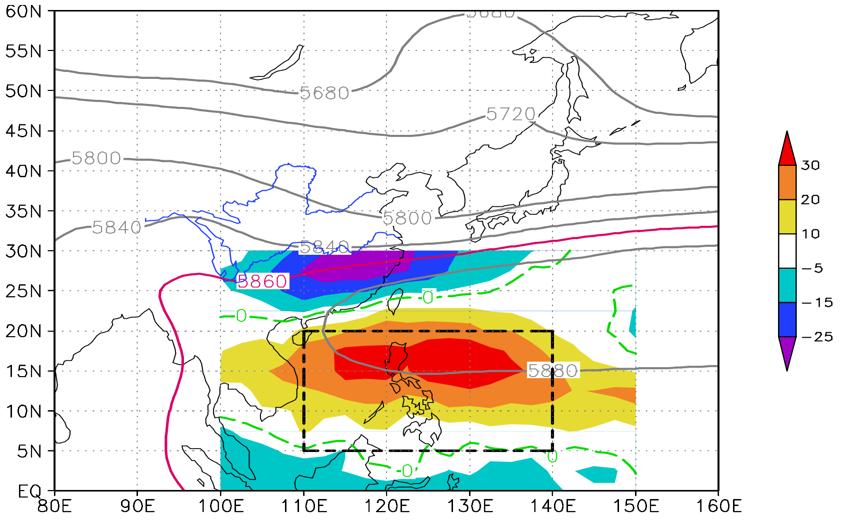

Fig. 5. As in Fig. 3a but for the composite of four typical PHREs over the YRV.

was illustrated by Huang and Li (1988) and Huang and Sun (1992) by theoretical analysis and numerical simulation. They discussed the strong and weak convective activity in the whole WPWP with two entire opposite statuses. Comparison between PRHEs in the HRV and persistent heavy (light) rain events in the YRV shows the important influence of the distribution pattern of convective activities in the WPWP. That is, when weak convective activity persists to occupy the whole WPWP, the WPSH shifts southward and the PHREs tend to occur in the YRV. When strong convective activity appears only in the southern part of the WPWP, the northern edge of the WPSH appears to lie in the HRV and PHREs tend to occur in the HRV. If strong convective activities persist to occupy the whole WPWP, the WPSH persists to shift northward or eastward and persistent light rain events tend to occur in the YRV.

Figure 4 also shows that the 576-dagpm contours averaged between 110°–130°E tend to arrive at 35°N. This phenomenon suggests that cold air activities in the middle latitudes over East Asia during PHREs in the YRV are stronger than those of PHREs in the HRV. On the contrary, cold air activity is stopped by the northward shift of the WPSH during persistent light rain events, such as in 1984 and 1994 (Fig. 6).

6. Discussion and conclusions

In this paper, the relationship between PHREs in the HRV and the distribution pattern of convective activity in the WPWP has been discussed. Nine cases of PHREs in the HRV show characteristics of the “north weak south strong” distribution pattern of convective

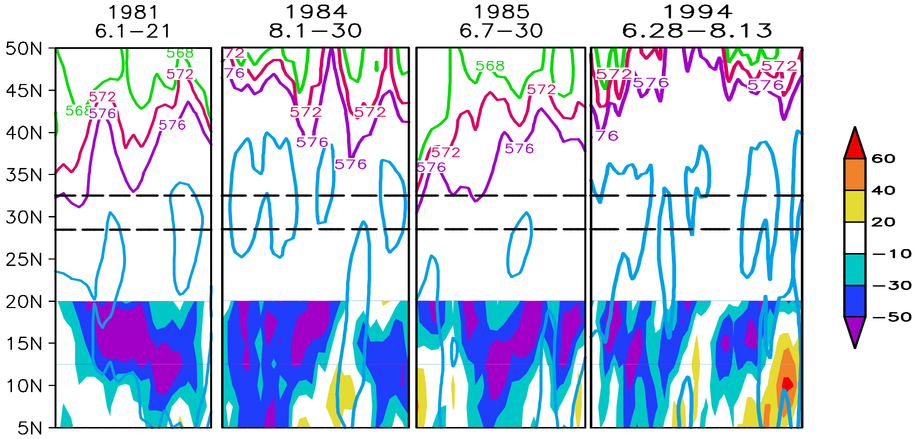

Fig. 6. As in Fig. 2 but for four cases of persistent light rain events in the YRV.

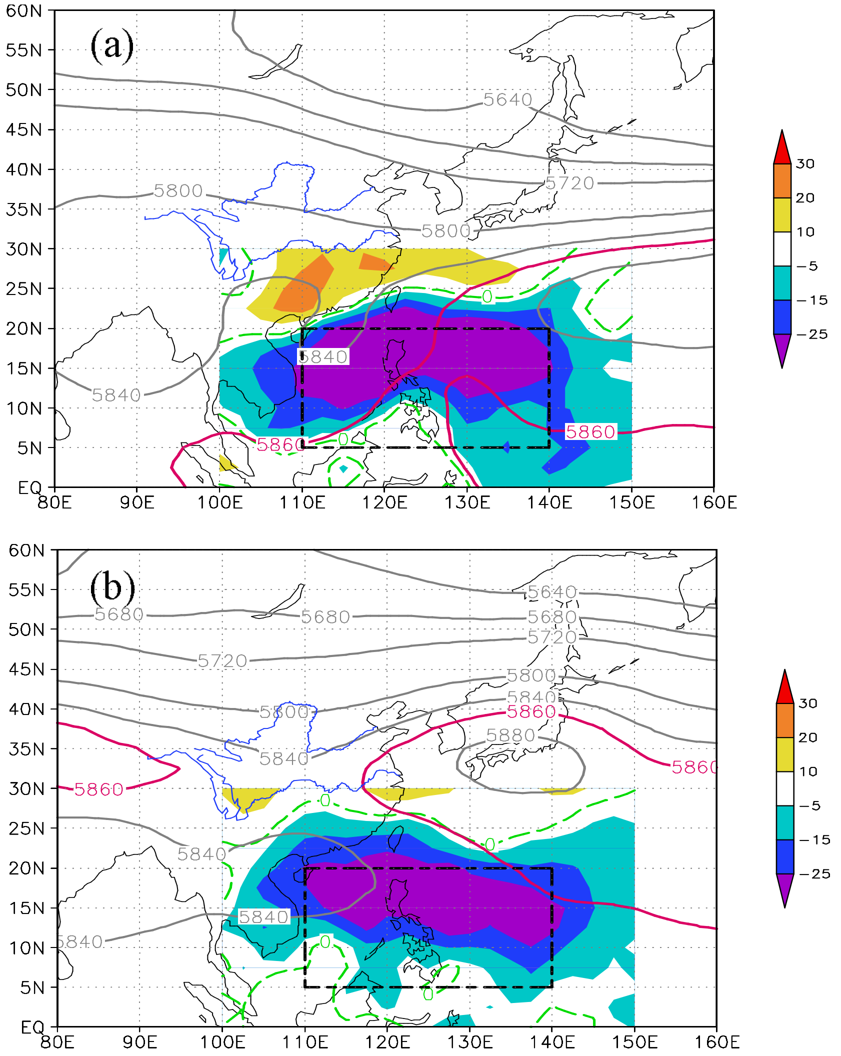

Fig. 7. As in Fig. 3a but for (a) the composite of two typical persistent light rain events over the YRV in early summer; and (b) the composite of two typical persistent light rain events over the YRV in mid summer.

activities in the WPWP. The composite analysis and contrast analysis further indicates that the occurrence of PHREs in the HRV is related to the location of the northern edge of the WPSH through the effects of the persistent "north weak south strong" distribution pattern of convective activities in the WPWP. Although the distribution pattern of convective activities in the WPWP is emphasized, the relationship only appears to be obvious during periods of PHREs. The effects of the "north weak south strong" distribution pattern of convective activities in the WPWP on PHREs in the HRV are not obvious over the seasonal mean timescale, perhaps due to the non-extreme status of convective activities in the WPWP.

Not only does the northern edge of the WPSH appear to lie in the HRV, but also the WPSH appears to extend westward when PHREs occur in the HRV. In this study, though the effects of convective activity in the WPWP on the location of the northern edge of the WPSH have been studied, the western development of the WPSH has not yet been discussed (Fig. 3). Some research work suggested that PHREs in the HRV are mostly related to the internal dynamics of atmospheric circulation (Zhang et al., 2004; Liu et al., 2006). So, the persistent "north weak south strong" distribution pattern of convective activity does not denote the occurrence of PHREs in the HRV definitively.

In this work, the relationship between PHREs in the HRV and the distribution pattern of convective activities has been analyzed by diagnostic methods. It is necessary to conduct numerical simulation experiments in the future to validate the physical effects of the distribution pattern of convective activities in the WPWP. This will help us to better understand the impact of thermal states over the WPWP on the summer climate of eastern China.

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