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Anomalous Western Pacific Subtropical High during Late Summer in Weak La Niña Years: Contrast between 1981 and 2013

Feng XUE* and Fangxing FAN

International Center for Climate and Environment Sciences, Institute of Atmospheric Physics,
Chinese Academy of Sciences, Beijing 100029

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ABSTRACT

Both 1981 and 2013 were weak La Niña years with a similar sea surface temperature (SST) anomaly in the tropical Pacific, yet the western Pacific subtropical high (WPSH) during August exhibited an opposite anomaly in the two years. A comparison indicates that, in the absence of a strong SST anomaly in the tropics, the cold advection from Eurasian high latitudes and the convection of the western Pacific warm pool play important roles in influencing the strength and position of the WPSH in August. In August 1981, the spatial pattern of 500 hPa geopotential height was characterized by a meridional circulation with a strong ridge in the Ural Mountains and a deep trough in Siberia, which provided favorable conditions for cold air invading into the lower latitudes. Accordingly, the geopotential height to the north of the WPSH was reduced by the cold advection anomaly from high latitudes, resulting in an eastward retreat of the WPSH. Moreover, an anomalous cyclonic circulation in the subtropical western Pacific, excited by enhanced warm pool convection, also contributed to the eastward retreat of the WPSH. By contrast, the influence from high latitudes was relatively weak in August 2013 due to a zonal circulation pattern over Eurasia, and the anomalous anticyclonic circulation induced by suppressed warm pool convection also facilitated the westward extension of the WPSH. Therefore, the combined effects of the high latitude and tropical circulations may contribute a persistent anomaly of the WPSH in late summer, despite the tropical SST anomaly being weak.

Key words: western Pacific subtropical high, late summer, tropical circulation, high latitude circulation, warm pool convection

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1. Introduction

As a major circulation system of the East Asian summer monsoon (EASM), the western Pacific subtropical high (WPSH) exhibits distinct intraseasonal variation during boreal summer. Usually, it migrates northward in a stepwise manner, with two distinct northward jumps, occurring in the middle of June and late July, respectively. After the second jump, the EASM region enters into the late summer period, characterized by high temperature and high humidity. Compared with the early summer period, the WPSH weakens sharply. In the meantime, it moves to its most northern position and retreats eastward to the south of Japan. Consequently, the EASM circulation patterns exhibit contrasting characteristics between early and late summer (Su and Xue, 2010; Xue et al., 2015). If the WPSH extends westward with strong intensity in late summer, persistent high temperatures and severe drought occur in southern China, as in the case of August 2013 examined in this study.

Besides intraseasonal variability, the WPSH also shows significant interannual variability. It is generally recognized that tropical circulation largely regulated by El Niño and Southern Oscillation (ENSO) plays an important role in the interannual variability of the WPSH. In particular, the WPSH tends to extend southwestward with stronger intensity during El Niño decaying summers (Fu and Teng, 1988). Nitta (1987) found that an anomalous WPSH is more directly related to warm pool convection in the western Pacific. A Rossby wave train is generated by anomalous convection and propagates to the extratropics, thus influencing the northward movement of the WPSH. In addition, Lu (2001a) indicated that the zonal displacement of the WPSH is also affected by warm pool convection. A low-level cyclonic (anticyclonic) anomaly in the subtropical western Pacific induced by enhanced (suppressed) convection leads to eastward (westward) movement of the WPSH.

The high latitude circulation system over the Eurasian continent is considered as another important factor for WPSH variation, especially in late summer when the WPSH arrives at its most northern position. It has been demonstrated that the high pressure ridge of the WPSH in August near Japan is

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* Corresponding author: Feng XUE
Email: fxue@lasg.iap.ac.cn

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generated by a stationary Rossby wave propagating to Japan, and its intensity is regulated by the Asian jet (Enomoto et al., 2003; Enomoto, 2004). Tao and Wei (2006) found that the stationary Rossby wave in the Eurasian continent propagates eastward along the subtropical jet and excites a longwave ridge along the eastern coast of China. The development of the longwave ridge results in the westward extension of the WPSH. Even in strong La Niña years, there can be a great difference in the WPSH (e.g., between 1989 and 1999), especially in August, due to the different circulation at high latitudes (Xue, 2008).

It is worth noting that the intraseasonal variation—especially the difference between early and late summer—can further affect the interannual variation. Kawatani et al. (2008) compared WPSH variation in June, July and August and found that the interannual and submonthly variability are smallest in June and largest in August. Xue and Liu (2008) also showed that the influence of El Niño on the WPSH is weakest in June and strongest in August, suggesting that the influence of El Niño on the WPSH is more significant in late summer.

Despite the essential roles of many factors in WPSH variation, most previous studies have focused on the influence of one factor, such as El Niño, on the WPSH, with the combined influences of all possible factors having rarely been examined. For the purpose of predicting the position and strength of the WPSH more precisely, all possible factors should be taken into consideration. Besides, the role of ENSO should not be overemphasized, although it is the strongest interannual signal. In fact, the WPSH may also exhibit a persistent and significant anomaly, especially in August, under the condition of a weak tropical SST anomaly. Because it is difficult to perform conventional numerical simulations using a general circulation model without strong SST forcing, this issue concerning the WPSH anomaly associated with weak SST anomalies is not yet well understood.

The objective of this study is to explore the primary factors responsible for a persistent WPSH anomaly under a weak tropical SST anomaly condition. We pursue this investigation by comparing the anomalous WPSH patterns in two particular years (1981 and 2013). Despite the fact that both 1981 and 2013 were weak La Niña years, and the WPSH in June and July was close to normal, the WPSH anomalies in August were opposite, with a weakening in 1981 and a strengthening in 2013. During late summer 2013, the unusual westward extension of the WPSH brought about a prolonged heat

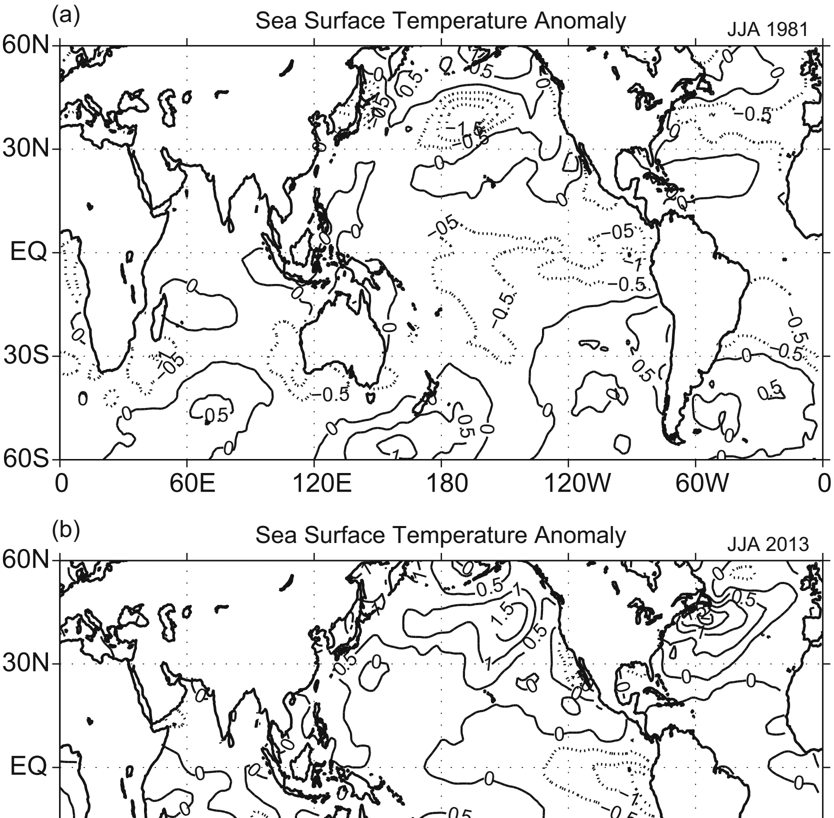

Fig. 1. SST anomaly during summer (a) 1981 and (b) 2013 (units: °C).

wave and severe drought in southern China (Sun, 2014; Peng, 2014). By comparing the WPSH in these two years, we intend to reveal the major impacting factors and their combined effects on the WPSH anomaly in late summer with a weak tropical SST anomaly, and provide new clues for WPSH prediction.

2. Data description and WPSH in 1981 and 2013

The daily data of wind and geopotential height were obtained from NCEP–DOE Reanalysis-2 on a $2.5^\circ \times 2.5^\circ$ grid from 1979 to 2013 (Kanamitsu et al., 2002). Outgoing longwave radiation (OLR) with the same resolution, used to represent the convection intensity in the tropics, was derived from NOAA satellite observations (Liebmann and Smith, 1996). The monthly mean SST data were obtained from NOAA on a $2^\circ \times 2^\circ$ grid (Smith et al., 2008). The daily data were further processed into pentad means to facilitate analysis.

The WPSH is represented by the 5880 gpm contour at 500 hPa over East Asia and the western Pacific. The west point, which is defined as the westernmost point of the 5880 gpm contour, is used to describe the zonal position of the WPSH (Zhao, 1999). For simplicity, we also take August as the late summer period, which usually begins from late July (Su and Xue, 2010).

The WPSH in 1981 was selected for comparison with that in 2013 because both 1981 and 2013 were weak La Niña years with a similar tropical SST anomaly. As shown in Fig. 1, the SST anomaly during summer (June–July–August mean) in the tropical Pacific had a typical La Niña pattern, i.e., negative anomalies in the central and eastern Pacific and positive anomalies in the western Pacific. The SST anomaly in 2013 was slightly stronger than that in 1981, with a maximum negative anomaly of -1°C off the Peru coast and a max-

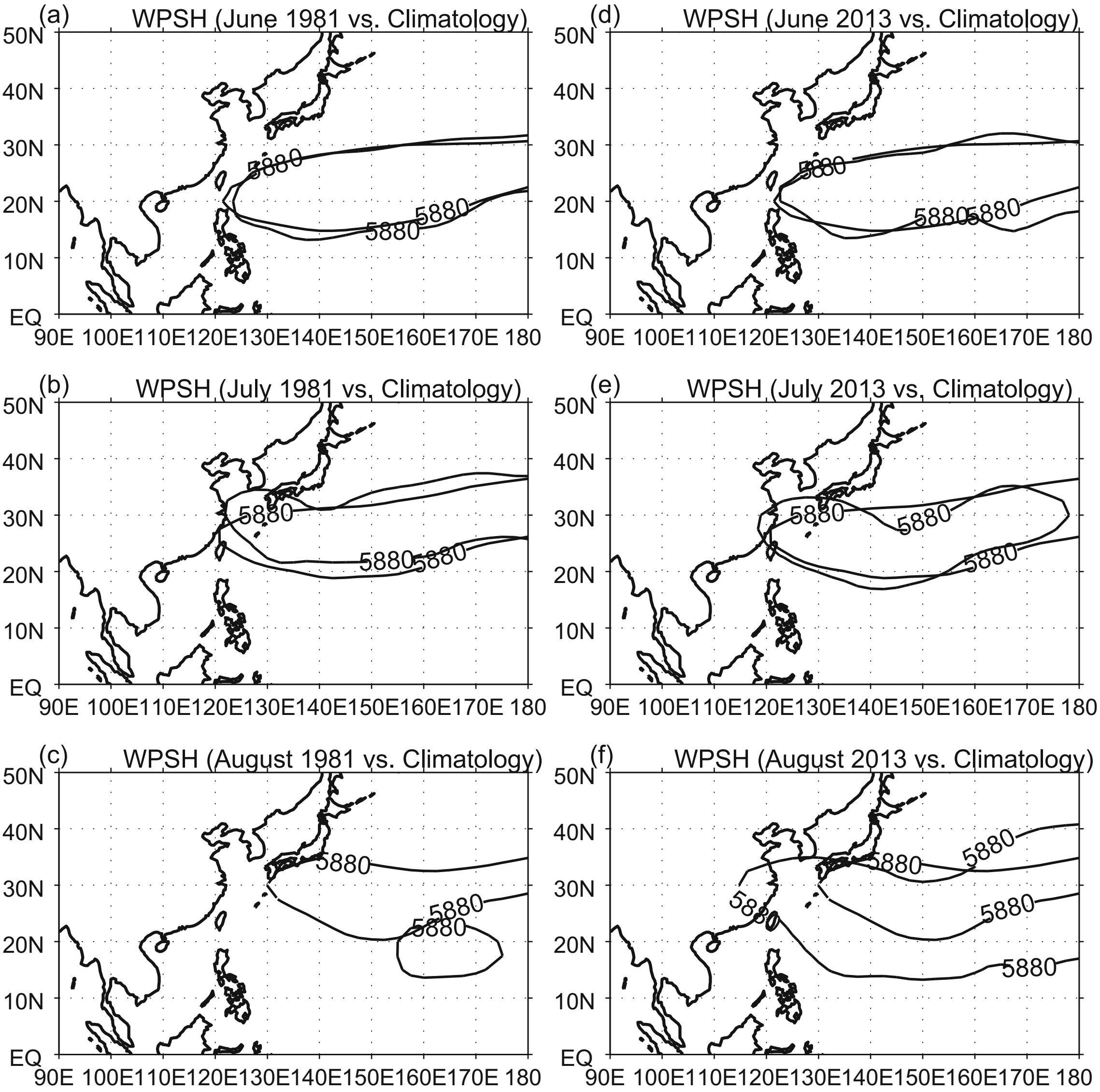

Fig. 2. The WPSH represented by the 5880 gpm contour in June, July and August (a–c) 1981 and (b–f) 2013. The climatological mean is represented by the dashed contour for comparison (units: gpm).

imum positive anomaly of 0.5°C in the warm pool region of the western Pacific.

Figure 2 illustrates the monthly mean WPSH represented by the 5880 gpm contour in June, July and August, together with the climatological mean for comparison. While the WPSH was close to the climatology in June and July, there was a significant discrepancy in August. In August 1981 (Fig. 2c), the WPSH was located more southeastward, with the west point at 155°E and the ridge line at about 17.5°N. Meanwhile, the WPSH became very weak. In sharp contrast, the WPSH in August 2013 extended westward to 115°E with much stronger intensity (Fig. 2f). Different from the pattern in a typical La Niña year, the anomalous pattern of the WPSH in 2013 was similar to that in a strong El Niño year (Xue and Liu, 2008).

3. The influence of circulation in high-latitude Eurasia

Since the response of the WPSH to a La Niña signal is generally weak and the intensity of La Niña in the two years was also weak (Xue, 2008), the large discrepancy of the WPSH in August between the two years cannot be attributed to the tropical SST forcing. In addition, there were strong SST anomalies in the North Pacific and North Atlantic in 2013 (Fig. 1b), but the anomaly in the midlatitude oceans is driven by the atmospheric circulation and the response of the atmosphere to the SST anomaly is generally believed to be weak (Frankignoul, 1985; Park and Schubert, 1997). Therefore, the SST anomaly in the midlatitude oceans is not a major factor.

In contrast to the similar SST anomaly in the tropics, there was a large discrepancy of 500 hPa geopotential height in high-latitude Eurasia during August in the two years (Fig. 3). In August 1981, the circulation pattern was characterized by two ridges and two troughs over Eurasia. With a strong ridge in the Ural Mountains and a deep trough in Siberia, this pattern was favorable for the southward invasion of cold air from high latitudes, thereby influencing the WPSH. By comparison, the circulation in August 2013 was a zonal pattern superimposed with small ridges and troughs.

The anomalous geopotential height in Fig. 4 is consistent with that in Fig. 3, with a positive anomaly in the ridge

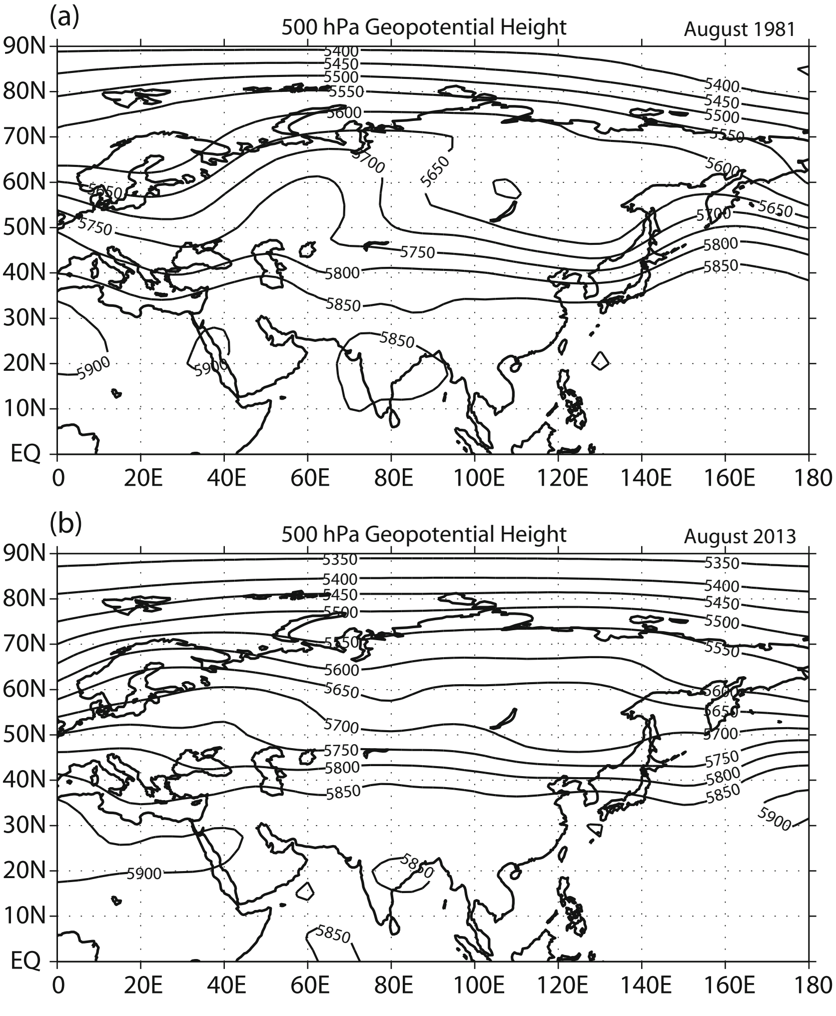

Fig. 3. The 500 hPa geopotential height in August (a) 1981 and (b) 2013 (units: gpm).

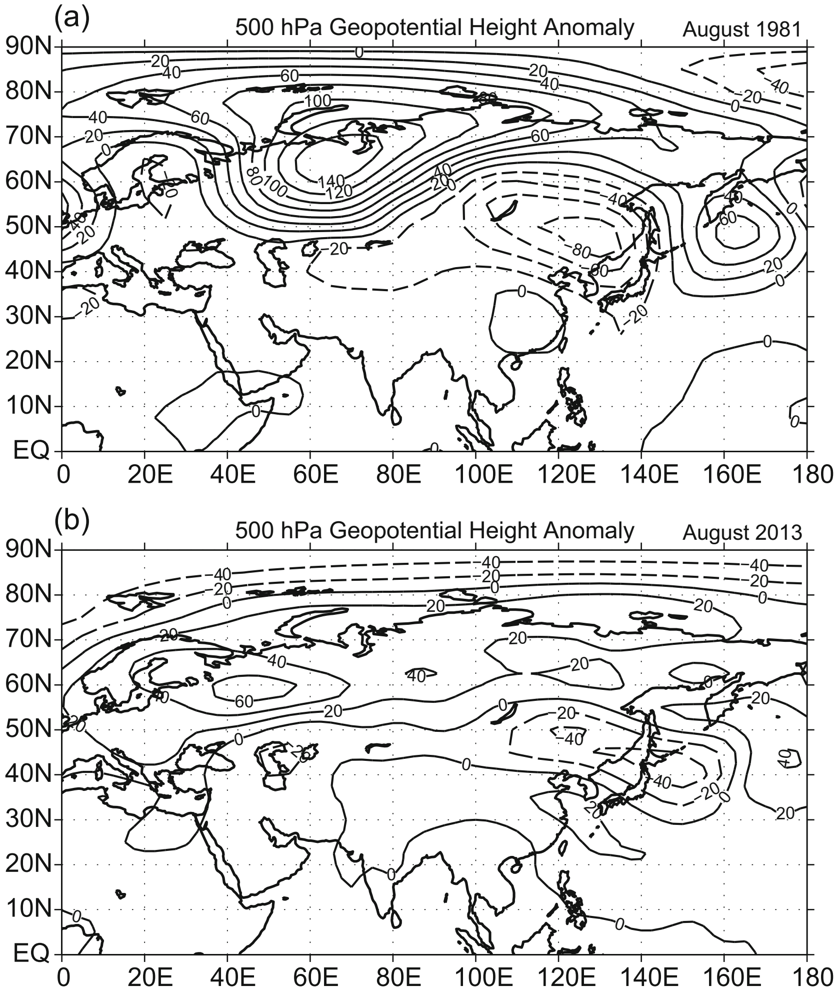

Fig. 4. The 500 hPa geopotential height anomaly in August (a) 1981 and (b) 2013 (units: gpm).

region and a negative anomaly in the trough region. Over the Northeast Asian region, there was a negative anomaly in both years, but the intensity in 2013 was only half of that in 1981. In addition, the negative anomaly in 1981 extended southward into the deep tropics, indicating that the circulation at high latitudes played an important role in weakening the WPSH in August 1981.

To further reveal the influence of high-latitude circulation on the WPSH, Figs. 5 and 6 show the longitude–pentad cross section of the 850 hPa meridional wind anomaly along 40°N (north of the WPSH) and the 500 hPa geopotential height anomaly along 30°N (the WPSH area). In 1981 (Fig. 5a), a northerly anomaly appeared to the northwest of the WPSH (near 120°E) from Julian pentad 42 (hereafter P42; 25–29 July) and reached its maximum during P44–P45 (4–18 August). Corresponding to the northerly anomaly, there was a negative geopotential height anomaly east of 130°E, with a maximum over −40 gpm in late summer (Fig. 5b). It is also noted that the maximum geopotential height anomaly was preceded by the maximum northerly anomaly about one pentad, indicating that the northerly anomaly at high latitudes plays a leading role in the anomalous WPSH. In contrast with 1981, a southerly anomaly in late summer 2013 was associated with a positive geopotential height anomaly (Figs. 6a and b). Both the maximum southerly anomaly and geopotential height anomaly emerged simultaneously in P43 (30 July to 3 August). Therefore, the northerly anomaly from the high latitudes plays a more active role in reducing geopotential height, whereas the southerly anomaly helps sustain the positive anomaly in the WPSH area to a certain degree.

As an example, the eastward retreat at the beginning of August 1981 is used to explain how the circulation at high latitudes affects the WPSH (Fig. 7). In P43 (30 July to 3 August), the WPSH extended more northwestward with the west point at 95°E. In P44 (4–8 August), however, the WPSH retreated rapidly to the east of 140°E with sharply weakened intensity.

The eastward retreat between P43 and P44 was related to the circulation at high latitudes. Corresponding to the strong ridge in the Ural Mountains (Fig. 3a), there was an anomalous anticyclone in high-latitude Eurasia (Fig. 8a). In East Siberia, there was a strong northerly anomaly just to the north of the WPSH. Due to the cold advection anomaly, the geopotential height in Northeast Asia was largely reduced, with a

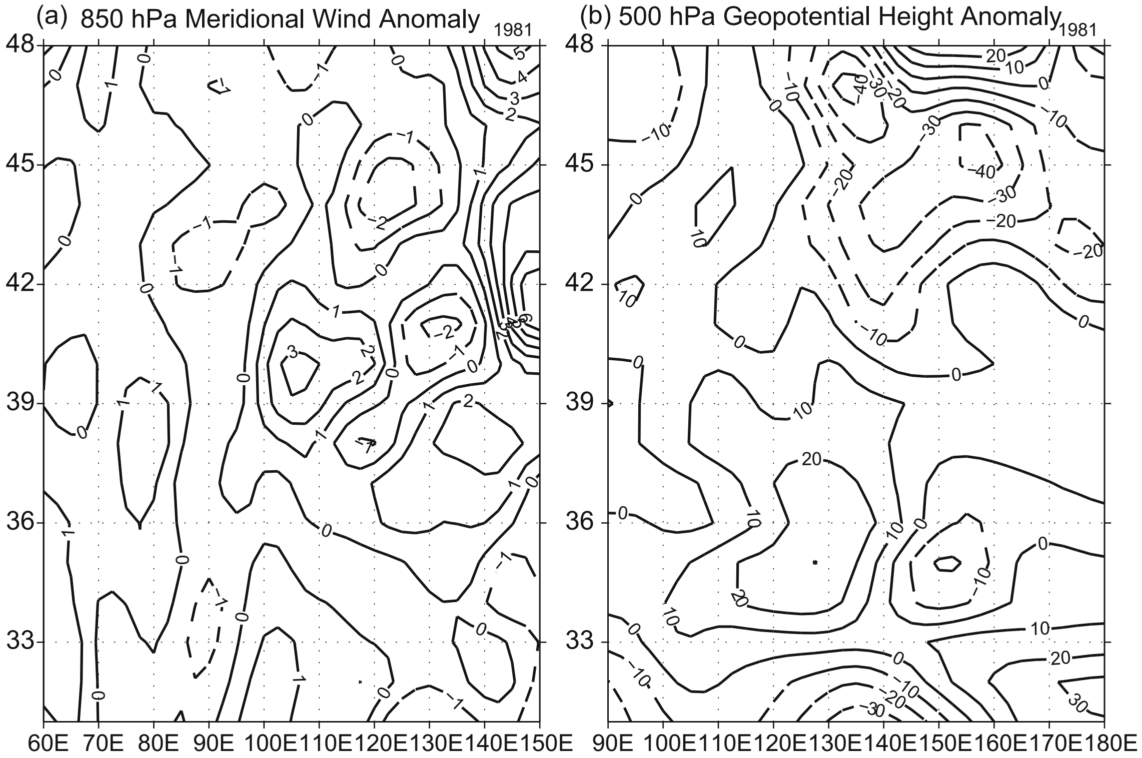

Fig. 5. Longitude–pentad cross section of the (a) 850 hPa meridional wind anomaly along 40°N (units: m s^{-1}) and (b) 500 hPa geopotential height anomaly along 30°N (units: gpm) during summer 1981. The numbers on the ordinate represent the Julian pentad.

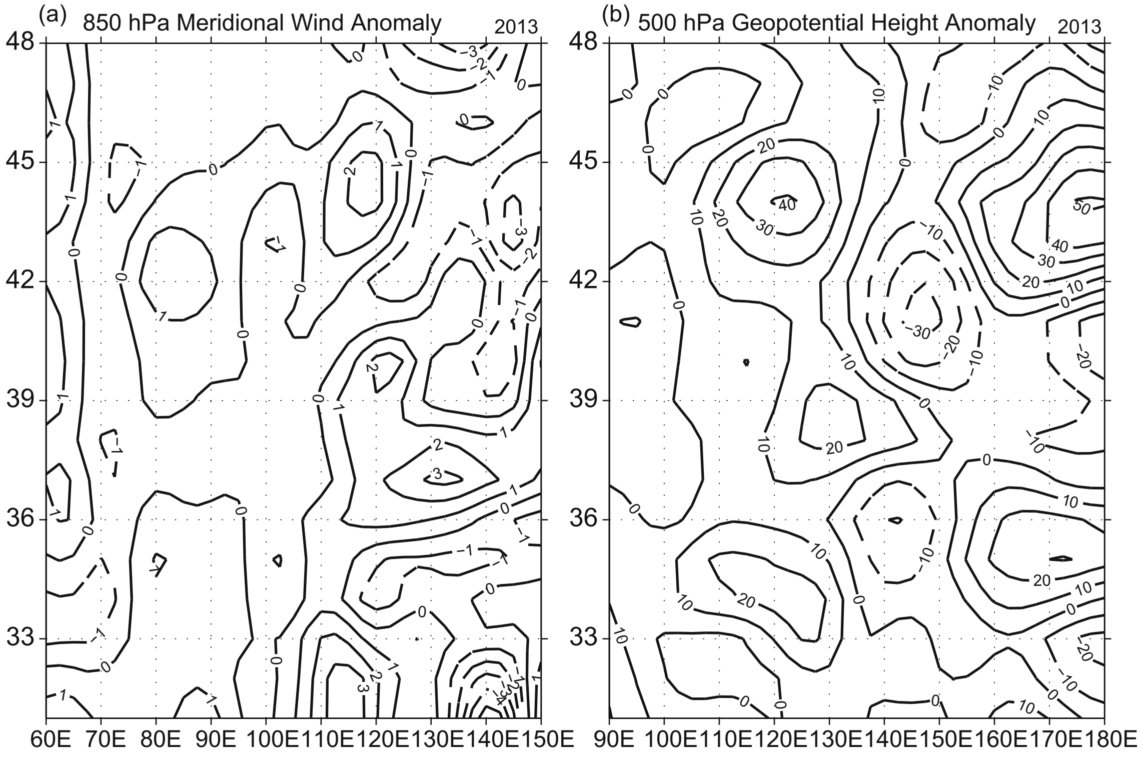

Fig. 6. As in Fig. 5, except for 2013.

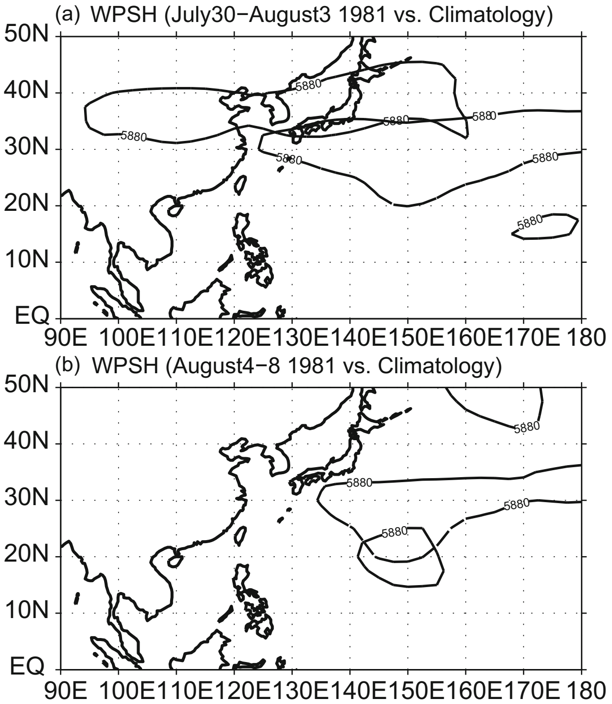

Fig. 7. The WPSH in (a) P43 (30 July to 3 August) and (b) P44 (4–8 August) 1981. The climatological mean is represented by the solid and dashed contours, respectively (units: gpm).

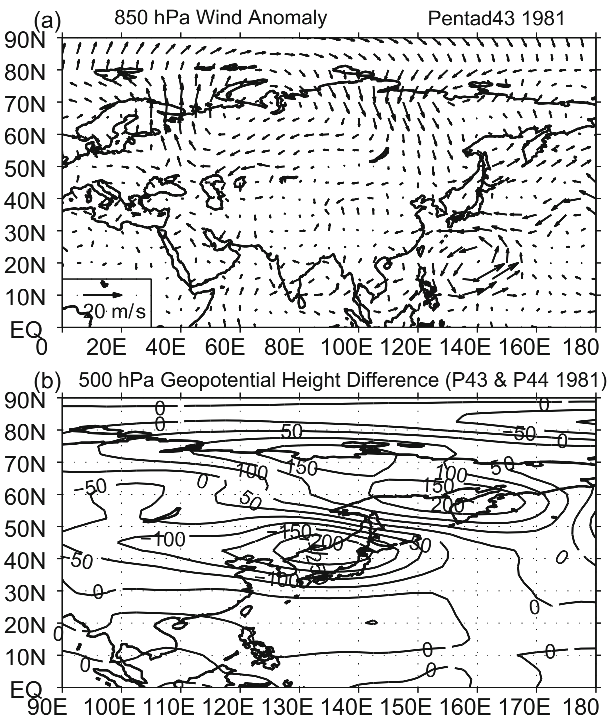

Fig. 8. The (a) 850 hPa wind anomaly in P43 in 1981 (units: m s^{-1}) and (b) the difference in 500 hPa geopotential height between P43 and P44 in 1981 (units: gpm).

maximum over 200 gpm near the Sea of Japan (Fig. 8b). As a result, the WPSH split into two parts, and the main body retreated rapidly to the east of 140°E in P44 (Fig. 7b).

Since the WPSH in August is located at a higher latitude, it is easily influenced by the circulation at high latitudes. The above example is not unique and can frequently be seen in other years, such as August 1989 (Xue, 2008). By contrast, the zonal circulation pattern in August 2013 could not result in a similar retreat of the WPSH as in 1981 (Fig. 3b). Instead, the WPSH tended to be located more westward (Fig. 2f).

4. The influence of tropical circulation

Besides the circulation at high latitudes, the WPSH is also influenced by tropical circulation. In particular, enhanced (suppressed) warm pool convection can excite an anomalous cyclone (anticyclone) over the subtropical western Pacific in the lower troposphere, inducing eastward (westward) movement of the WPSH (Lu, 2001a). The warm pool convection is related to the SST anomaly as well as atmospheric perturbations, especially cross-equatorial flow (Lu, 2001b; Su and Xue, 2010).

Figure 9 shows the longitude–pentad cross section of the cross-equatorial flow anomaly and OLR anomaly at 15°N in 1981. Note that the latter is used as a surrogate for the warm pool convection anomaly, with a negative (positive) anomaly corresponding to enhanced (suppressed) convection. The cross-equatorial flow near 145°E during July–August was apparently intensified, and the anomaly exceeded 2 m s^{-1} from P40 (15–19 July). Afterwards, the warm pool convection began to enhance gradually, with OLR anomalies lower than −40 W m^{-2} between P43 and P45 (9–13 August). The negative OLR anomaly lasted for one month. It is also noted that the cross-equatorial flow near 130°E was largely reduced, as indicated by a negative anomaly, and it was less related with the warm pool convection.

In contrast, the cross-equatorial flow in 2013 was generally weak (Fig. 10a). After P39 (10–14 July), it changed to a negative anomaly. Correspondingly, there were positive OLR anomalies (suppressed convection) during late summer (Fig. 10b). The OLR anomaly reached maximum intensity in P42 (25–29 July) and weakened slightly in P44 (4–8 August), before beginning to intensify again up until the end of August. The positive OLR anomaly lasted as long as one and a half months.

It is evident that the warm pool convection anomaly is related to the seasonal march of atmospheric circulation in the western Pacific during summer. Compared with early summer, the anomaly of warm pool convection in late summer is much more significant and lasts for a relatively long time. As noted previously (Ueda et al., 1995; Xiang et al., 2013), warm pool convection tends to be enhanced during the seasonal march from July to August, corresponding to the onset of the western Pacific summer monsoon. As a result, warm pool convection is much more sensitive to cross-equatorial flow.

An anomalous cyclonic circulation in August 1981 appeared in the subtropical western Pacific due to enhanced

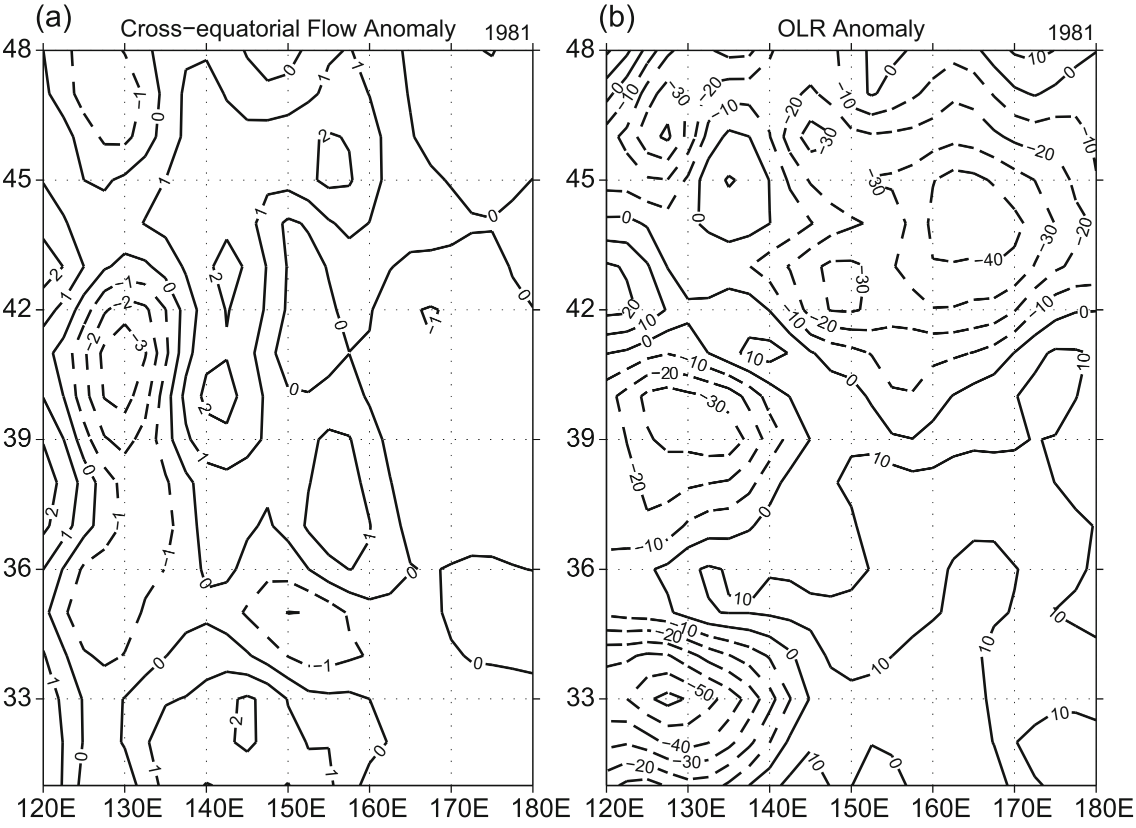

Fig. 9. Longitude–pentad cross section of the 850 hPa (a) cross-equatorial flow anomaly (units: m s^{-1}) and (b) OLR anomaly along 15°N (units: W m^{-2}) during summer 1981. The numbers on the ordinate represent the Julian pentad.

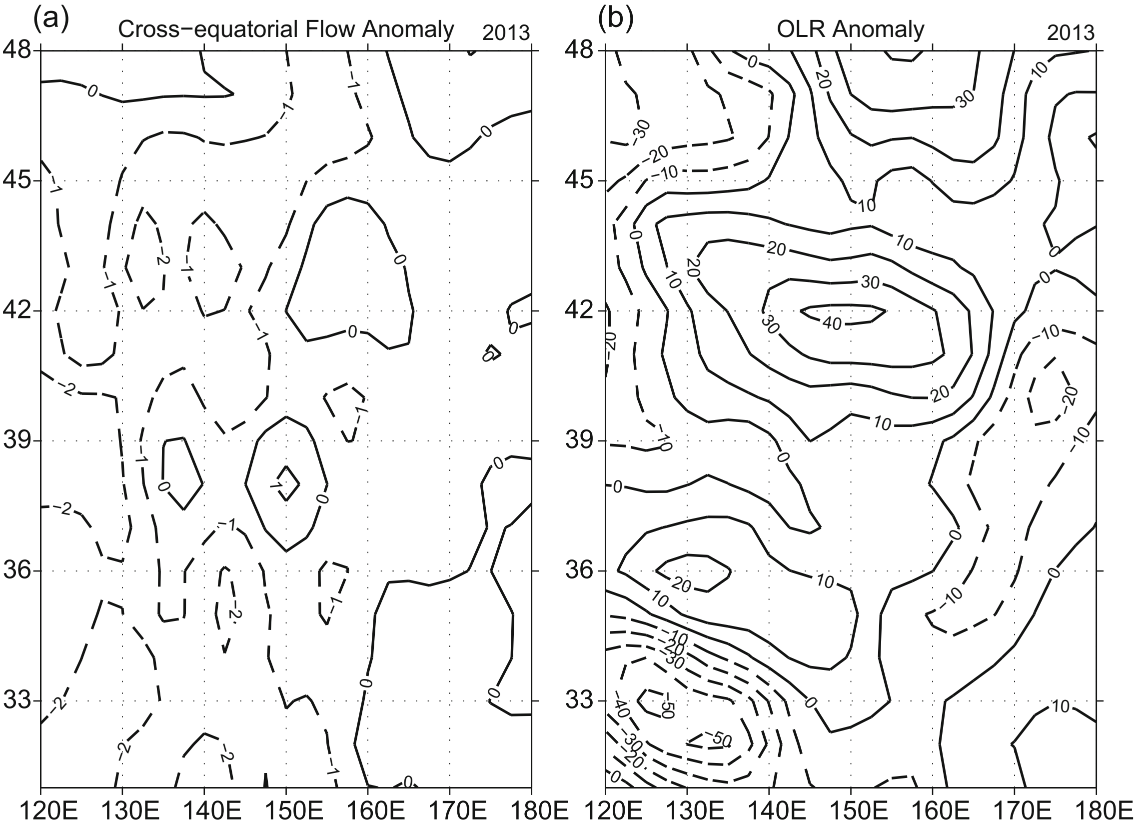

Fig. 10. As in Fig. 9, except for 2013.

warm pool convection (Fig. 11a), further inducing lower geopotential height and an eastward retreat of the WPSH (Fig. 4a). By contrast, there was an anomalous anticyclonic circulation due to suppressed convection in August 2013 (Fig. 11b). With higher geopotential height in the subtropics (Fig. 4b), the WPSH tended to extend westward with stronger intensity (Fig. 2f). This anomalous pattern persisted throughout late summer due to the lack of the influence of cold advection from high latitudes as in August 1981. It is also important to note that the anomalous cyclonic circulation (Fig. 11a) was located more northeastward than the anomalous anticyclonic circulation (Fig. 11b), because the subtropical circulation in August 1981 was also affected by the circulation at high latitudes.

It should be emphasized that the warm pool SST was higher during summer in both years, and was even higher in 2013 than in 1981 (Fig. 1). Hence, the contrast in warm pool convection between the two years did not mainly result from the SST difference in the tropics. Instead, the cross-equatorial flow played a more important role in the warm pool convection.

5. Summary and discussion

Although both 1981 and 2013 were weak La Niña years with a typical La Niña pattern (i.e., negative SST anomalies in the central and eastern Pacific and positive SST anomalies in the western Pacific), the WPSH exhibited an opposite anomaly in August in the two years. While the WPSH in August 1981 retreated eastward with weak intensity, the WPSH in August 2013 extended westward with strong intensity, despite the normal conditions in June and July.

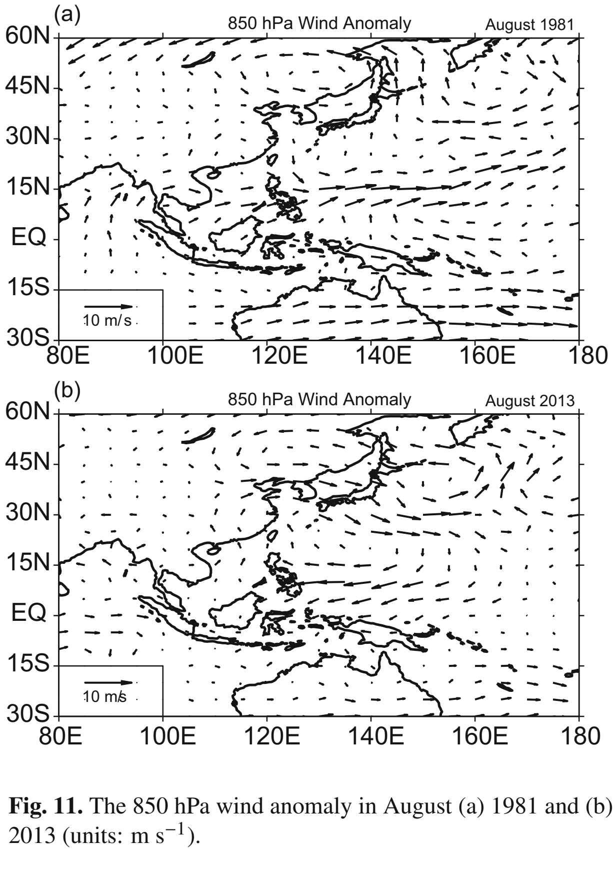

Fig. 11. The 850 hPa wind anomaly in August (a) 1981 and (b) 2013 (units: m s^{-1}).

The contrast between the two years indicates that there was a significant discrepancy in the high latitude circulation over the Eurasian continent during August. In August 1981, there was a meridional circulation pattern in Eurasia, with a strong ridge in the Ural Mountains and a deep trough in Siberia. In particular, the anomalous northerly ahead of the trough induced a lower geopotential height in Northeast Asia through a cold advection anomaly. As a result, the WPSH tended to retreat eastward. In August 2013, however, there was a zonal circulation system in Eurasia, with weak ridges and shallow troughs. Accordingly, the WPSH was less affected by the circulation at high latitudes.

Besides the circulation at high latitudes, there was a large difference in tropical circulation between the two years. In late summer 1981, an anomalous cyclonic circulation appeared in the subtropical western Pacific, excited by the enhanced warm pool convection due to the perturbation from a strong cross-equatorial flow, thereby leading to the weakening of the WPSH. By contrast, there was an anomalous anticyclonic circulation in late summer 2013, corresponding to suppressed convection over the warm pool associated with a weak cross-equatorial flow, resulting in the westward extension of the WPSH. In the meantime, the weak influence of cold advection from high latitudes helped sustain the strong intensity of the WPSH.

Even with a weak tropical SST anomaly, the WPSH may also exhibit a persistent anomaly in late summer owing to the combined effects of the difference in tropical circulation and the circulation at high latitudes. When predicting the WPSH, we must pay special attention to the in-phase condition of these two factors. In late summer 2013, for instance, both the zonal circulation at high latitudes and suppressed warm pool convection contributed to the westward extension and prolonged maintenance of the WPSH, resulting in a heat wave and drought in southern China. If there had been a meridional circulation system at high latitudes in August 2013 as in August 1981, the anomalous WPSH could not have persisted for a long time. Instead, the WPSH would have retreated eastward due to the influence of the high-latitude circulation.

Our findings concerning the roles of tropical and high-latitude circulation in the development and persistence of an anomalous WPSH during late summer are similar to those presented in some previous studies. Ogasawara and Kawamura (2007) found that anomalous summer weather in Japan is affected by two teleconnection patterns: the West Asia–Japan and Pacific–Japan patterns. The combination of these two patterns is favorable for the establishment of a zonally elongated anticyclonic anomaly in Japan, resulting in hot weather there. In agreement with our results, they noted that the combined effect of the two patterns on anomalous weather in Japan is much more significant than those of each single pattern.

The contrast between 1981 and 2013 also indicates that the WPSH in late summer is very different from that in early summer. Even though the WPSH is close to the climatology in June and July, it may exhibit a significant anomaly in August with the seasonal march of the circulation in East Asia and the western Pacific. In the seasonal march from July to August, enhanced warm pool convection makes the tropical circulation more sensitive to perturbations like cross-equatorial flow, thereby influencing the WPSH anomaly. In addition, due to the fact that the WPSH is located at a higher latitude in late summer, it is easily affected by the circulation at high latitudes. Therefore, for WPSH prediction in late summer, a combination of these two factors must be considered comprehensively, especially when the tropical SST anomaly is weak.

It is also important to note that the WPSH exhibits a consistent westward extension throughout the whole summer in strong El Niño years (Xue, 2008). However, when the tropical SST anomaly is weak, as in 1981 and 2013, the WPSH anomaly cannot persist throughout the whole summer. In this case, the seasonal forecast is largely limited due to the lack of strong tropical forcing. Instead of relying merely on long-range forecasting, we should place emphasis on monthly forecasting in order to further improve the forecast skill.

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