Comparison of the two modes of the Western Pacific subtropical high between early and late summer

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Abstract

In this work, the first two leading modes of the western Pacific subtropical high (WPSH) between early and late summer are compared. Results show that the first mode of both June and August is featured by an anomalous anticyclonic circulation in the western North Pacific region. The second mode of June (August) is featured by an east–west (south–north) dipole over the North Pacific. Then, the association between the WPSH leading modes and El Niño-Southern Oscillation (ENSO) is examined. Results show that all PCs are connected with ENSO developing phase. The connection between June–July–August (JJA) PC2 and ENSO decaying can only be seen in July. In June and August, the connection with ENSO is relatively weak. Finally, the PCs-related precipitation anomaly is explored. The regressed precipitation anomaly patterns have close connection with the 850-hPa wind field anomaly. The PC1-related precipitation shows negative anomaly in the western equatorial Pacific and positive anomaly in the maritime continent. In June a PC1-related positive rain band is located south to Japan along 30°N, which is absent in August. The PC2-related positive anomaly in equatorial central Pacific in JJA is mainly attributed to August, while the positive anomaly along the east coast of East Asia is in June and July rather than August. The reasons for the differences between early and late summer are also discussed.

Keywords: western Pacific subtropical high; leading modes; early summer; late summer; sub-seasonal variation

1. Introduction

The Western Pacific Subtropical High (WPSH), which is also known as the North Pacific subtropical high, the western North Pacific subtropical high or the western North Pacific anticyclone, is an essential component of the East Asian and western North Pacific summer monsoons. It largely determines the amount of rainfall in the rainy season in the region, which contains large populations. Thus, it is of great value to understand the variability of the WPSH on multiple timescales and the associated mechanisms (Tao and Chen, 1987).

On the interannual timescale, the variability of the WPSH is closely related to the tropical sea surface temperature (SST) anomaly. Wang et al. (2000) claimed that due to the local air–sea interaction over the western North Pacific, the anomalous WPSH can be sustained from winter to summer. Xie et al. (2009) argued that the Indian Ocean SST anomaly can also play an important role in sustaining the anomalous WPSH through Kelvin-wave stimulation and the associated Ekman divergence mechanism. Recently, a new perspective has been proposed in which anomalous Northwest Pacific anticyclone variability can be explained by the nonlinear interaction between the El Niño-Southern Oscillation (ENSO) and the annual cycle of warm pool SSTs (Stuecker et al., 2015). Besides, the maritime continent SST (through a local Hadley circulation) and the tropical Atlantic SST (remote influence through atmospheric teleconnection) can both affect the variability of the WPSH. A detailed description of the interannual variability of the WPSH and its mechanisms can be found in a recent review by He et al. (2015).

Two interannual modes of the WPSH have been identified (e.g. Park et al., 2010; He et al., 2013; Wang et al., 2013). The first mode is associated with a switch from an El Niño SST anomaly to a La Niña SST anomaly between winter and the following summer, and the second mode is related to the persistent warming in the tropical central and eastern Pacific (Park et al., 2010; He et al., 2013). Park et al. (2010) identified decadal shifts in the two modes of the WPSH after the mid-1990s. The performances of the Coupled Model Inter-comparison Project (CMIP) models on reproducing these two modes have also been evaluated, and results have shown that the two modes can be reasonably captured (He and Zhou, 2014, 2015a).

Most previous research has focused on the summer mean WPSH variability. However, in addition to the summer mean results, the WPSH exhibits differences between early and late summer (Lu, 2001; Kawatani et al., 2008; Wu et al., 2010; Dong, 2016). In this study, using reanalysis data, the two modes of the WPSH are examined in early and late summer. The connection with ENSO and associated precipitation anomaly are also examined.
2. Data and method

In this study, the zonal and meridional wind fields at 850 hPa from the NCEP-DOE Reanalysis 2 (NCEP2) dataset (Kanamitsu et al., 2002) are adopted to calculate the two leading modes of the WPSH in early and late summer. Moreover, ERA-Interim reanalysis dataset (Dee et al., 2011) is also used to compare with the NCEP2 results and validate the robustness of our conclusions. Actually, from our analysis the first two modes of the WPSH are independent of the datasets used. To examine the PC-related SST and anomalous precipitation fields, the NOAA Extended Reconstructed Sea Surface Temperature (ERSST) dataset (V3b) (Smith et al., 2008) and Global Precipitation Climatology Project (GPCP) monthly precipitation dataset (Adler et al., 2003) are used. The ERSST dataset is a global monthly SST analysis from 1854 to the present derived from ICOADS data with missing data filled in by statistical methods (Smith et al., 2008). The horizontal resolution for ERSST is 2.0°×2.0°. The GPCP dataset spans from 1979 to present and combines observations and satellite precipitation data; it has a horizontal resolution of...
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3. Results

3.1. Two leading modes of the WPSH

The first two leading modes of the WPSH in JJA, June, July and August are shown in Figure 1. In June, the first (second) mode explains 28.3% (15.9%) of the total variance. As in He et al. (2013), the first mode can be considered the Equatorial Easterly Mode (EEM), which is associated with an easterly anomaly in the equatorial Pacific. The second mode is termed the Equatorial Westerly Mode (EWM). Similar to the summer mean results (Figure 1(a)), the first mode exhibits an anomalous anticyclonic circulation in the western North Pacific. Moreover, a cyclonic anomaly is located east of Japan, which is also observed in the summer mean results. However, with respect to the second mode, the early summer results differ from the summer mean (an anticyclonic anomaly in the western North Pacific). In June, the second mode (EWM) exhibits a cyclonic (anticyclonic) circulation west (east) of 140°E at approximately 30°N, i.e. forming an east-west dipole mode.

In late summer (August), the first two modes of the WPSH are slightly different from that in early summer. The first (second) mode of the WPSH in late summer explains 36.7% (17.0%) of the total variance. In EOF1, the center of the anticyclonic anomaly over the western North Pacific shifts slightly eastward, whereas its influence extends northward compared to that in early summer (June), which is associated with the northward shift in the monsoon system from early to late summer.

In late summer (August), the second mode (EWM) is very different from that in early summer (June). EOF2 exhibits an anticyclonic circulation anomaly west of 150°E at 30°N, and a cyclonic anomaly is located south of the anticyclonic anomaly, i.e. forming a south–north dipole mode.

From the above analysis, the common feature of the first mode between June, July, August and JJA is in the tropical region, in which an easterly anomaly exists in the equatorial Pacific, while the second mode is associated with a westerly anomaly especially in the central and eastern equatorial Pacific. However, the spatial patterns of these two leading modes in subtropical and mid-latitude are slightly different among June, July, August and JJA, which may be due to the following reasons. First, the sub-seasonal variation of the general circulation may contribute to this difference. That is, the mean states of the monsoon circulation changes from early to late summer, which can modulates the leading modes of WPSH (Wang et al., 2009). Besides, the WPSH-SST interaction in the western North Pacific on sub-seasonal time scale may also be a contributing factor (Ren et al., 2013). Second, the East Asian summer monsoon system is mainly influenced by two teleconnection patterns, one is the Silk Road teleconnection at zonal direction and the other is the Pacific-Japan teleconnection at meridional direction (Nitta, 1987; Enomoto et al., 2003). It is interesting that the second mode in June seems a zonal mode while in August it seems a meridional mode. Thus, the relative strengths of these two teleconnections

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may also contribute to the sub-seasonal differences in the leading modes of WPSH between early and late summer. Figure 2 shows the time series of the first two PCs, which exhibit notable interannual variability. The correlation coefficient (CC) of PC1 (PC2) between June/July/August and JJA is 0.76/0.76/0.88 (0.58/0.76/0.64), respectively. The relationship among the PCs has notable decadal modulation. For example, with respect to PC2, before 1995 there is large spreads among the four PCs while after 1995 the PCs are well consistent with each other. He and Zhou (2015b) have investigated the decadal modulation of the connection between WPSH and tropical SST in the early 1990s and stated that after this decadal change, the interannual variability of the WPSH is more strongly regulated by the SST anomaly over the equatorial central Pacific and the maritime continent. Whether this decadal modulation contributed to the decadal change in the relationship of the WPSH PCs deserves future study.

3.2. Association with ENSO

ENSO is the most important signal at the interannual timescale and to examine the relationship between the WPSH PCs and ENSO, Table 1 provides the CCs between the Niño3.4 index and the WPSH PCs. It is interesting that there is a significant connection between all PC1s and the Niño3.4 index in the following winter. With respect to PC2, only in JJA and July, the relationship between PC2 and Niño3.4 index in the preceding winter is significant. That is, PC1 is mainly associated with the ENSO developing phase, while PC2 is related to the ENSO decaying phase. This can be more clearly shown in Figure 3, the longitude-time plot of the correlation coefficients between equatorial Indian-Pacific (40°E–90°W) SST anomalies (averaged between 10°S and 10°N) and the PCs of WPSH. Values that higher than 0.35 (or lower than −0.35) are shown in dark colors, indicating statistically significant at 95% level.

Figure 3. The longitude-time plot of the correlation coefficients between equatorial Indian-Pacific (40°E–90°W) SST anomalies (averaged between 10°S and 10°N) and the PCs of WPSH. Values that higher than 0.35 (or lower than −0.35) are shown in dark colors, indicating statistically significant at 95% level.
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Figure 4. The spatial pattern of sea surface temperature (SST) anomaly regressed on the PC1s of the WPSH in JJA, June, July and August. The cross region denotes values that exceed the significance test at 95% level. (Units: °C)

Figure 5. The same as Figure 4, except for the PC2.
precipitation anomaly patterns have close connection with the 850-hPa wind field anomaly (Figure 1). According to the summer mean results described in Park et al. (2010), the PC1-related precipitation pattern exhibits positive (negative) anomalies over the maritime continent (equatorial western Pacific and the western North Pacific) (their Figures 4(a) and 5(a)). Figure 6 shows that the negative precipitation anomalies in the western North Pacific and equatorial western Pacific can be identified in PC1-related anomalous precipitation fields in JJA, June, July and August. Moreover, the positive precipitation anomalies over the maritime continent are also found in four PC1s, with larger values in July and August than June. The difference in the PC1-related precipitation anomalies is that the positive precipitation band along 30°N (i.e. south of Japan) occurs primarily in June; in July and August, this precipitation feature is not significant. Thus, the meridional teleconnection pattern over East Asia and the western North Pacific identified in Park et al. (2010) is more pronounced in June. However, in August, significant positive anomalies can be seen over continental East Asia along 30°N, which is absent in June. Furthermore, in July and August, significant negative precipitation anomalies are located along the equatorial central and eastern Pacific, which are absent in June. In Figure 6(a), significant positive precipitation anomalies were identified north of the equatorial eastern Pacific (100°W), which may be mainly attributed to the signal in August (Figures 6(a) and (g)).

Figure 6. The spatial pattern of precipitation anomaly regressed on the PCs of the WPSH in JJA, June, July and August. The cross region denotes values that exceed the significance test at 95% level. (Units: mm day\(^{-1}\))
Table 2. Correlation coefficients between the principal components (PCs) of WPSH and the corresponding precipitation PCs.a

|                 | Pre JJA PC1 | Pre JJA PC2 | Pre JJA PC3 |
|-----------------|-------------|-------------|-------------|
| WPSH JJA PC1    | 0.30        | 0.12        | −0.14       |
| WPSH JJA PC2    | 0.26        | −0.01       | 0.49        |

|                 | Pre June PC1 | Pre June PC2 | Pre June PC3 |
|-----------------|--------------|--------------|--------------|
| WPSH June PC1   | 0.28         | 0.06         | 0.33         |
| WPSH June PC2   | 0.15         | 0.60         | 0.02         |

|                 | Pre July PC1 | Pre July PC2 | Pre July PC3 |
|-----------------|--------------|--------------|--------------|
| WPSH July PC1   | 0.43         | 0.42         | 0.05         |
| WPSH July PC2   | 0.38         | 0.27         | 0.18         |

|                 | Pre August PC1 | Pre August PC2 | Pre August PC3 |
|-----------------|----------------|---------------|---------------|
| WPSH August PC1 | 0.13           | 0.36          | 0.24          |
| WPSH August PC2 | 0.29           | 0.03          | 0.09          |

aThe bold type denotes that the correlation coefficients exceed the significance test at 95% level.

With respect to PC2, the associated precipitation anomaly in July and August is more similar to the summer mean results. The PC2-associated east–west precipitation contrast between the maritime continent and the equatorial western Pacific in July and August is opposite to that of PC1 (Park et al., 2010). In June, a PC2-related positive precipitation anomaly is located on the eastern coast of East Asia (Figure 6(d)). From June to August, this positive anomalous precipitation band moves northward, associated with the seasonal march of the East Asian monsoon system.

In a previous work, Wang et al. (2009) identified three distinct rainfall modes over East Asia in early and late summer. To examine the relationship between the WPSH modes and the three rainfall modes, we also calculated the correlation coefficients between WPSH PCs and rainfall PCs (Table 2). The rainfall modes are calculated as in Wang et al. (2009), except that we used monthly mean rainfall in June, July and August, rather than bimonthly rainfall in Wang et al. (2009). Results show that the WPSH modes can explain the distinct rainfall modes to some extent. For example, the precipitation PC2 in June is significantly correlated with the WPSH PC2 in June (CC = 0.60). With respect to the JJA mean, WPSH PC2 is significantly correlated with precipitation PC3 (CC = 0.49). However, not each WPSH PC is significant correlated with the corresponding precipitation PC, indicating that besides the WPSH, precipitation can be influenced by other factors.

4. Summary

In this work, a comparison of the first two leading modes of the WPSH between early and late summer has been conducted. Results demonstrate that the first mode in June is indicative of an anomalous anticyclonic circulation in the western North Pacific, while the second modes featured by a cyclonic (anticyclonic) circulation west (east) of 140°E and along 30°N (east–west dipole). In August EOF1 the center of the anticyclonic anomaly in the western North Pacific shifts slightly eastward, and its influence extends more northward compared to June. Moreover, the August EOF2 exhibits an anticyclonic circulation anomaly west of 150°E and along 30°N, and a cyclonic anomaly is located south of the anticyclonic anomaly, which forms a south–north dipole mode. Possible causes of the differences of WPSH modes between early and late summer are also discussed. Then, the association between the WPSH leading modes and ENSO is examined. Results show that there is significant connection between all PC1s and the Niño3.4 index in the following winter. With respect to PC2, only in JJA and July the relationship between PC2 and Niño3.4 index in the preceding winter is significant. In June and August, the correlation is rather weak. Finally, the PCs-related precipitation anomalies are explored.

Acknowledgements

This research is jointly supported by the Natural Science Foundation of China (Grant No. 41475052) and the China Postdoctoral Science Foundation (Grant No. 2015M571095). F. F. acknowledged the support from the Natural Science Foundation of China (Grant No. 41405058).

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