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Interannual Meridional Displacement of the Upper-Tropospheric Westerly Jet over Western East Asia in Summer

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ABSTRACT

The interannual meridional displacement of the upper-tropospheric westerly jet over the eastern portion of East Asia in summer has been well documented. This study, however, investigates the interannual meridional displacement of the westerly jet over the western portion of East Asia in summer, which is distinct from its eastern counterpart. The results show that the meridional displacement of the western East Asian jet shows a clear asymmetric feature; that is, there are remarkable differences between the southward and northward displacement of the jet. The southward displacement of the jet corresponds to suppressed convection in the tropical western North Pacific and Maritime Continent and enhanced convection in the equatorial Pacific, which can be explained by the warmer sea surfaces found in the northern Indian Ocean and equatorial eastern Pacific. These tropical anomalies somewhat resemble those associated with the eastern East Asian jet variability. However, the northward displacement of the western East Asian jet does not correspond to significant convection and SST anomalies in the entire tropics; instead, the northward displacement of the jet corresponds well to the positive phase of the Arctic Oscillation. Furthermore, the meridional displacement of the western jet has asymmetric impacts on rainfall and surface air temperatures in East Asia. When the western jet shifts northward, more precipitation is found over South China and Northeast China, and higher temperatures appear in northern China. By contrast, when the jet shifts southward, more precipitation appears over the East Asian rainy belt, including the Yangtze River valley, South Korea, and southern and central Japan and warmer temperatures are found South and Southeast Asia.

Key words: westerly jet, East Asia, tropical convection, Arctic Oscillation, summer

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Article Highlights:

- The southward displacement of the western East Asian upper-tropospheric jet is associated with tropical forcing, similar to its eastern counterpart.
- The northward displacement of the western East Asian jet is associated with the Arctic Oscillation but not with tropical forcing.
- The southward and northward displacements of the western East Asian jet have asymmetric impacts on the East Asian climate.

1. Introduction

The upper-tropospheric westerly jet over East Asia (EAJ) acts as a narrow and strong westerly wind belt with large horizontal and vertical wind shear and is a crucial factor within the East Asian summer monsoon system (Tao and Chen, 1987; Ding, 1992; Huang et al., 2003; Lu, 2004). The EAJ exhibits strong variability on interannual time scales, as evidenced by its change in location and intensity (Lin and Lu, 2005; Yan et al., 2014; Du et al., 2016; Hong and Lu, 2016; Zhou et al., 2022). The year-to-year variation of the EAJ exerts a strong influence on climate, particularly over East Asia (Liang and Wang, 1998; Lu, 2004; Xuan et al., 2011; Huang et al., 2014; Chen et al., 2016; Li and Lu, 2017; Wang et al., 2018b).

Most studies have mainly focused on the variation of westerly jet over the eastern portion of East Asia (EEAJ), i.

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e., 120°–150°E (Lu, 2004; Lin and Lu, 2005; Qu and Huang, 2012; Li and Lin, 2015; Zhou et al., 2020; Liang et al., 2022). For instance, Lin and Lu (2005) documented that the meridional displacement of the EEAJ is the leading mode of upper-tropospheric zonal wind variability by performing an empirical orthogonal function (EOF) analysis within the domain bounded by 27°–55°N, 120°–150°E. The meridional displacement of the EEAJ can be affected by moist convection anomalies over the tropical western North Pacific (WNP) as evidenced by the Pacific–Japan pattern or East Asia–Pacific (EAP) pattern (Kurihara and Tsuyuki, 1987; Nitta, 1987; Huang and Sun, 1992, Lau et al., 2000; Wang et al., 2001; Kosaka and Nakamura, 2006; Lin et al., 2010; Ling and Lu, 2022). Specifically, enhanced (suppressed) convection anomalies over the tropical WNP can induce an anomalous cyclone (anticyclone) to the northwest in the lower troposphere and favor a northward (southward) shift of the EEAJ.

In addition, the moist convection anomalies over the tropical WNP can act as an intermediary, linking the EEAJ variation to the tropical sea surface temperature (SST) anomalies. The positive SST anomalies in the equatorial central and eastern Pacific tend to suppress convection in the tropical WNP and induce a southward displacement of the EEAJ through the EAP pattern (Lu, 2005; Lin, 2010; Li and Lin, 2015). On the other hand, the basin-wide warming over the Indian Ocean can suppress the convection in the tropical WNP and also lead to a southward displacement of the EEAJ (Qu and Huang, 2012; Zhou et al., 2021).

In this study, we focused on the meridional displacement of the jet over the western portion of East Asia, i.e., 80°–120°E, hereafter called WEAJ for short. Our results indicate an asymmetric relationship between the WNP convection anomalies and the meridional displacement of the WEAJ. The suppressed convection in the tropical WNP corresponds well to the southward displacement of the WEAJ, but the enhanced convection does not correspond to the northward WEAJ displacement. This teleconnection with the WEAJ is quite different from the previous teleconnections found with the EEAJ. Therefore, the meridional displacement of the WEAJ and its impacts on climate are the main research theme of this paper.

The remainder of this paper is organized as follows. Section 2 describes the data and methods used in this study. Section 3 presents the relationship between the WNP convection and the upper-tropospheric zonal wind anomalies. Section 4 illustrates convection, SST, and circulation anomalies associated with WEAJ. Section 5 further investigates the effect of WEAJ on the East Asia climate. Section 6 provides a discussion and a conclusion.

2. Data and methods

This study uses the High-Resolution Infrared Radiation Sounder (HIRS) monthly outgoing longwave radiation (OLR) data as a proxy for tropical convection (Lee et al., 2007). In this way, the precipitation data from the Global Precipitation Climatology Project (GPCP) are obtained (Adler et al., 2018). The monthly zonal wind and sea level pressure (SLP) are taken from the European Center for Medium-Range Weather Forecasts (ECMWF) ERA5 reanalysis dataset (Hersbach et al., 2020). These data have a horizontal resolution of 2.5° × 2.5°. The monthly NOAA extended reconstructed SST version 5 data is used, with a horizontal resolution of 2.0° × 2.0° (Huang et al., 2017). This study also uses the monthly land precipitation and surface air temperature data based on the weather station record from the Climatic Research Unit (CRU) version 4.05 with a resolution of 0.5° × 0.5° (Harris et al., 2014). All datasets used in the present study span the period 1979–2020, focusing on summer (June–August, JJA).

To facilitate discussion on the relationship between the convection over the tropical WNP and the EAJ, the WNP convection index (WNPCI) is defined as the area mean OLR multiplied by −1 over the region (10°–25°N, 110°–160°E), which is similar to the region used in previous studies (Lu, 2001; Wu and Wang, 2001; Lu, 2004). A positive WNPCI indicates enhanced convection over the tropical WNP and vice versa. The WEAJ index (WEAJI) is measured by the difference between the 200-hPa zonal wind anomalies averaged over areas bounded by (45°–55°N, 80°–120°E) and (30°–40°N, 80°–120°E). The definition of the EEAJ index (EEAJI) is similar to that of the WEAJI but for the region (45°–55°N, 120°–150°E) and (30°–40°N, 120°–150°E). A positive (negative) WEAJI/EEAJI indicates that the westerly jet shifts northward (southward).

All the composite analyses in this study are performed when the index (WNPCI or WEAJI) exceeds 0.7 standard deviations on the positive or negative side. To reveal the asymmetric characteristics, these positive (negative) years are to be compared with all other years, i.e., years with an index between −0.7 and 0.7 standard deviations, which are used as the reference. Therefore, in this study, composite anomalies for positive (negative) years represent the differences between the positive (negative) years and reference. We have repeated the main analyses using other thresholds, including a 1.0 standard deviation, and obtained similar results.

3. Upper-tropospheric zonal wind anomalies associated with enhanced and suppressed convection in the tropical WNP

Figure 1 shows the OLR and 200-hPa zonal wind anomalies regressed onto the normalized WNPCI from 1979–2020. The most remarkable feature is the enhanced convection over the tropical WNP (Fig. 1a). There is also suppressed convection along the southwest-northeast oriented rainy belt in subtropical East Asia. These negative and positive OLR anomalies are manifestations of the meridional teleconnection pattern over the WNP and East Asia, in agreement with previous studies (Lau et al., 2000; Lu, 2004;

Kosaka et al., 2011). In addition to the north-south seesaw pattern, there is suppressed convection over the equatorial eastern-central Pacific and enhanced convection over the Maritime Continent, suggesting a weakening of the Walker circulation. The meridional teleconnection also appears in the upper troposphere, with alternate westerly and easterly anomalies over the WNP and East Asia (Fig. 1b). Specifically, positive anomalies lie to the north of about 40°N and negative ones to the south of this latitude, implying that the westerly jet shifts northward. The boundary between the positive and negative anomalies is almost along the climatological jet axis, which is determined as the first derivative of zonal winds being zero and represented by the black line. With the centers concentrated at 120°–150°E, this seesaw pattern spans over a large scope, roughly from 80° to 170°E.

Figure 2 shows the composite OLR anomalies for the positive and negative WNPCI years. The positive years include 1981, 1984, 1985, 1990, 1994, 1999, 2001, 2004, 2012, and 2018 (10 years), and the negative years include 1980, 1983, 1987, 1993, 1998, 2003, 2007, 2015, and 2020 (9 years). Positive WNPCI years correspond to enhanced convection over the tropical WNP and suppressed convection over East Asia. A similar seesaw pattern over WNP and East Asia can be found for the negative WNPCI years, but the negative convection anomalies over East Asia extend southwestward to the Yangtze River valley. On the other hand, there are negative OLR anomalies over the equatorial central Pacific and positive anomalies over Maritime Continent for the negative WNPCI years, implicating the role of El Niño.

Interestingly, the composite 200-hPa zonal wind anomalies for the positive and negative WNPCI years are quite different (Figs. 3a–b), despite the above-mentioned similarity in the seesaw pattern of convection anomalies over WNP and East Asia. Specifically, there are westerly and easterly anomalies over the eastern portion of East Asia, mainly concentrated over the longitudinal scope of 120°–150°E for the positive WNPCI years (Fig. 3a), while there are westerly anomalies over the Korean peninsula and central Japan for the negative WNPCI years (Fig. 3b); the latter roughly corresponding to the easterly anomalies for the positive years but shifted northwards. However, during the negative WNPCI years, there are no significant anomalies to the north of the jet axis over eastern East Asia. This asymmetry of zonal wind anomalies between the positive and negative years is

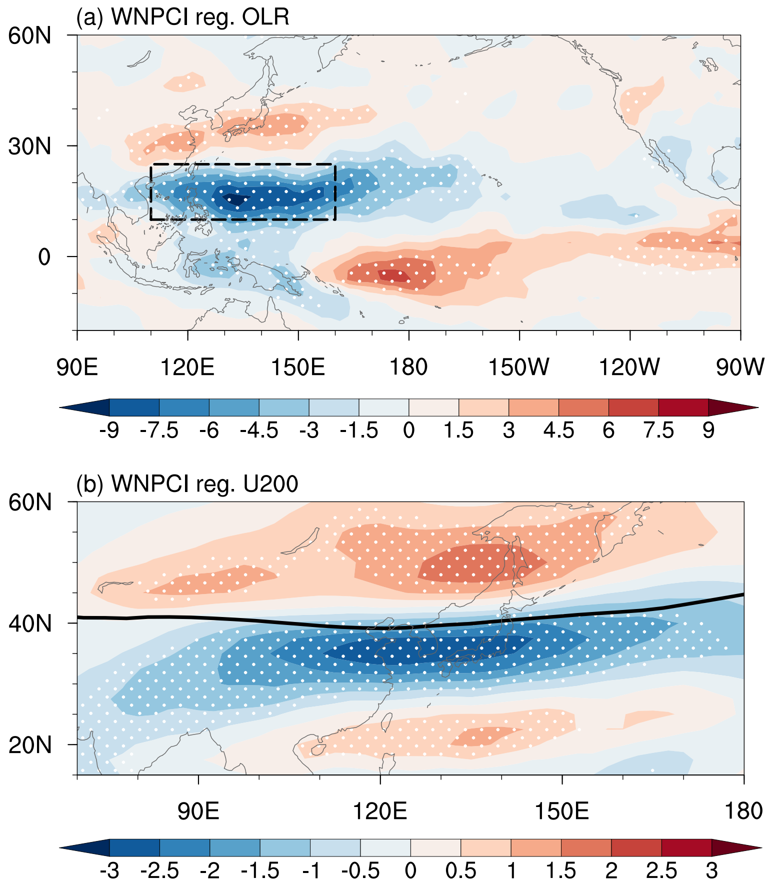

Fig. 1. Regression of (a) OLR (units: W m^{-2}) and (b) 200-hPa horizontal winds (units: m s^{-1}) with respect to the normalized WNPCI, which is defined as the OLR anomalies averaged over the rectangular region marked in (a) during 1979–2020. The thick solid line in (b) shows the axis of the climatological mean westerly jet. The dots denote regions that are significant at the 95% confidence level.

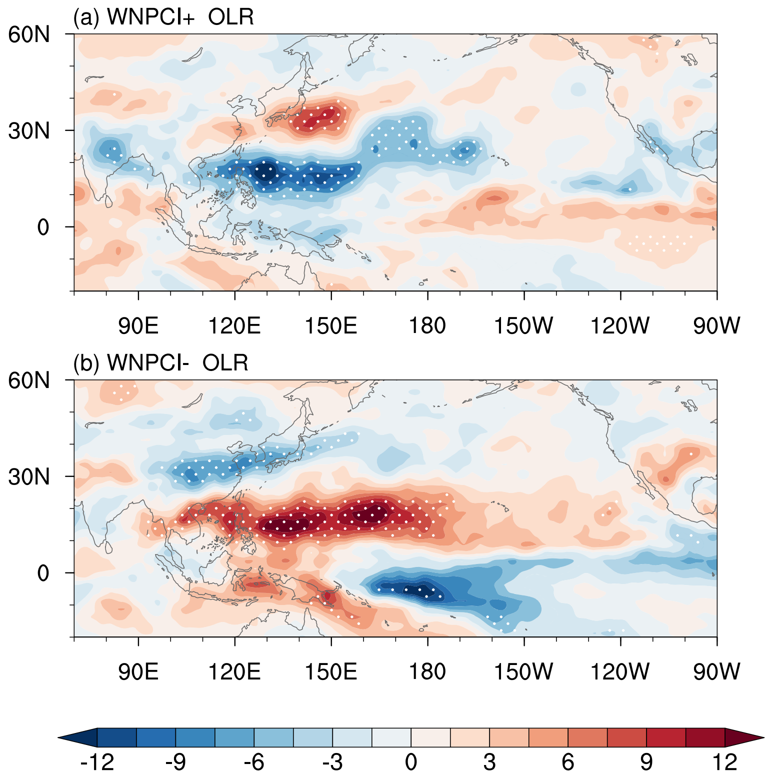

Fig. 2. Composite OLR anomalies (units: W m^{-2}) for the (a) positive and (b) negative WNPCI years. The dots denote regions that are significant at the 95% confidence level.

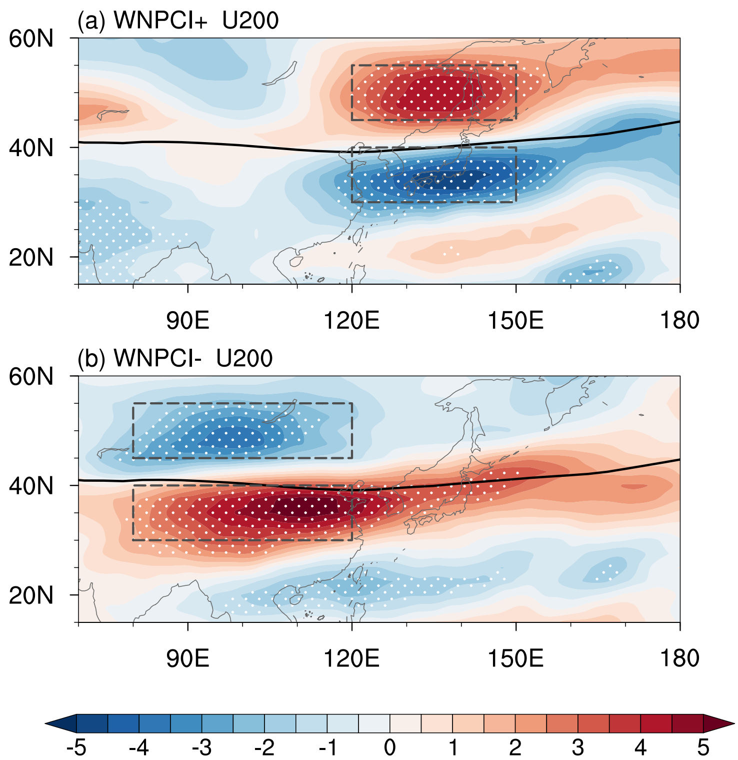

Fig. 3. Composite 200-hPa horizontal wind anomalies (units: m s^{-1}) for the (a) positive and (b) negative WNPCI years. The rectangles in (a) and (b) represent the defined region for the EEAJI (120°–150°E) and WEAJI (80°–120°E), respectively. The thick solid lines show the axis of the climatological mean westerly jet. The dots denote regions that are significant at the 95% confidence level.

partially consistent with that found by Lu et al. (2016), who suggested that enhanced precipitation over the tropical WNP corresponds to the northward displacement of the EEAJ, while suppressed precipitation does not correspond to any significant zonal wind anomalies. In other words, the asymmetry of zonal wind anomalies between the positive and negative years in the present study is relatively weaker than that suggested by Lu et al. (2016). This discrepancy is thought to mainly result from differences among the indexes depicting the tropical heating, i.e., the analog to the convection in this study is precipitation in Lu et al. (2016). The correlation coefficient between the EEAJI and WNPCI was 0.68 during 1979–2020, larger than that (0.41) between the EEAJI and the WNP precipitation index used by Lu et al. (2016). This suggests that the convection index may be a more appropriate metric to discuss the relationship between the WNP heating and jet variations.

A sharp difference in zonal wind anomalies can be found over the western portion of East Asia between the positive and negative WNPCI years. The 200-hPa zonal wind anomalies are weak and statistically insignificant over the region for the positive years (Fig. 3a). Still, there are strong and significant easterly and westerly anomalies to the north and south of jet axis (Fig. 3b), respectively, suggesting a southwardly displaced WEAJ. The averaged value of the WEAJI for the positive WNPCI years is only 0.39, which is statistically insignificant even at the 90% confidence level in relative to the reference years, i.e., the years of the WNPCI were between –0.7 and 0.7 standard deviations. By contrast, the average value of the WEAJI is –1.12 for the negative WNPCI years, which is significant at the 99% confidence level compared to the reference years.

4. Convection, SST, and circulation anomalies associated with WEAJ

Similarly, we selected the positive and negative WEAJI years, i.e., years when the index is greater (lower) than 0.7 (–0.7) standard deviations, and performed the composite analysis based on these years. The positive years include 1981, 1994, 1996, 1997,1999, 2000, 2002, 2006, 2010, 2013, 2016, and 2018 (12 years), and negative years include 1980, 1982, 1983,1987, 1993, 1998, 2003, 2009, 2014, 2015, and 2020 (11 years), as indicated by the solid circles in Fig. 4. There are only four common cases for the positive years of both the WNPCI and WEAJI, but eight common cases for the negative years, confirming the asymmetric relationship between the convection in the tropical WNP and WEAJ, as shown in Fig. 3. Furthermore, the correlation coefficient between the WNPCI and WEAJI is 0.56, significant at the 99% confidence level. This relationship between the tropical WNP convection and the WEAJ is mainly contributed by the negative WNPCI years, which can be illustrated by the weak correlation coefficient (0.18) between the WNPCI and WEAJI after removing the nine negative WNPCI years.

Figure 5 shows the composite 200-hPa zonal wind anomalies for the positive and negative WEAJI years. A north-south seesaw pattern appears clearly over the western portion of East Asia for the positive WEAJI years (Fig. 5a). By contrast, the negative WEAJI years feature an opposite seesaw pattern over western East Asia (Fig. 5b), but this pattern is not as well-organized as that for the positive years. The easterly anomalies to the north of the jet axis are much weaker. On the other hand, the zonal wind anomalies corresponding to the WEAJI tend to extend to the eastern portion of East Asia, particularly for the negative years, suggesting a relationship between the WEAJ and EEAJ. The correlation coefficient between the WEAJI and EEAJI is 0.57, significant at the 99% confidence level. Therefore, it can be concluded that the WEAJ is related to the EEAJ on an interannual timescale, but the majority of their variability is independent of each other, and thus separate research is necessary.

Figures 6 and 7 show the composite OLR and SST anomalies, respectively, for the positive and negative

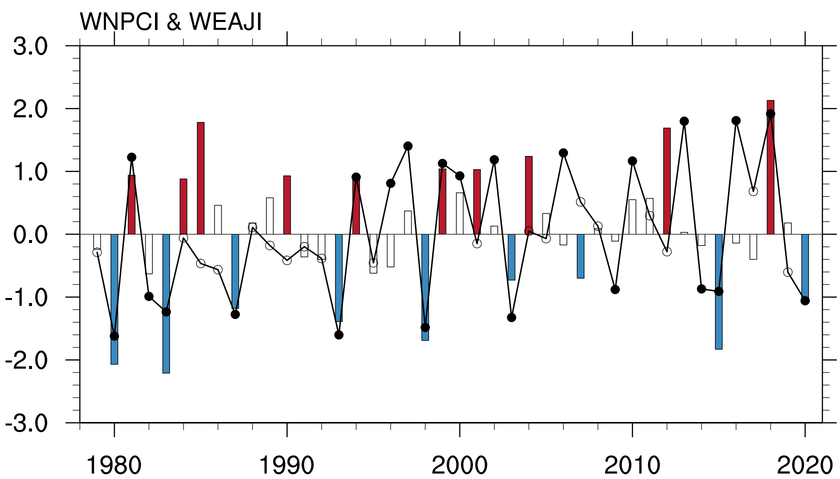

Fig. 4. Time series of the standardized WNPCI (bars) and WEAJ (line) during 1979–2020. The red (blue) bars indicate the strong (weak) convection years. The solid dots indicate the positive/negative WEAJI years, and the hollow dots indicate the reference years.

WEAJI years. There are no significant OLR anomalies in the tropics for the positive WEAJI years (Fig. 6a). Specifically, the OLR anomalies are weak and not well-organized in the tropical WNP, consistent with the weak relationship between the WEAJ and convection in the tropical WNP when the convection is enhanced (Fig. 3a). Correspondingly, there are no significant SST anomalies in the tropics for the positive WEAJI years (Fig. 7a). These results suggest that the northward displacement of WEAJ may not be affected by the tropical heat forcing, including the convection over

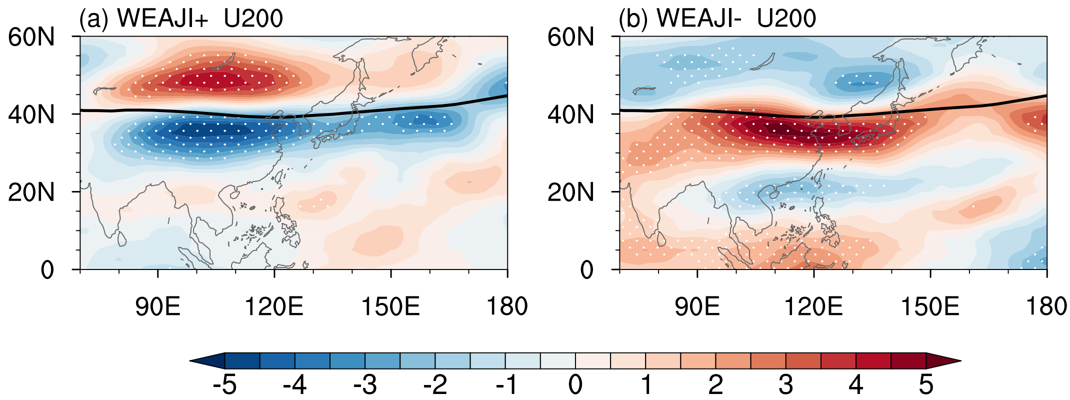

Fig. 5. As in Fig. 3, but for the WEAJI.

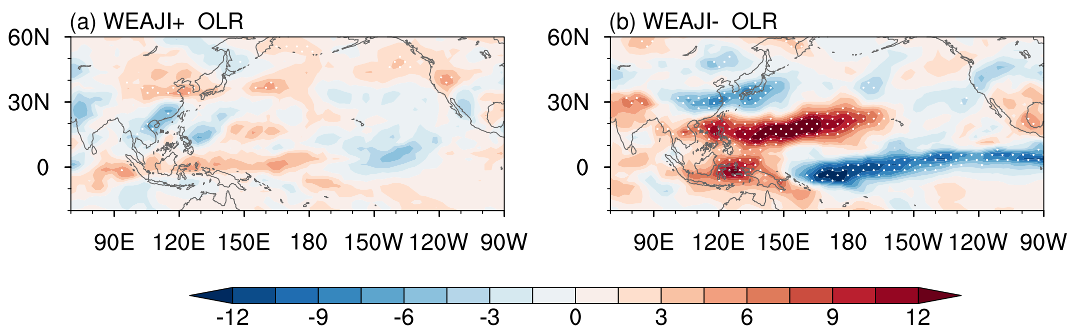

Fig. 6. As in Fig. 2, but for WEAJI.

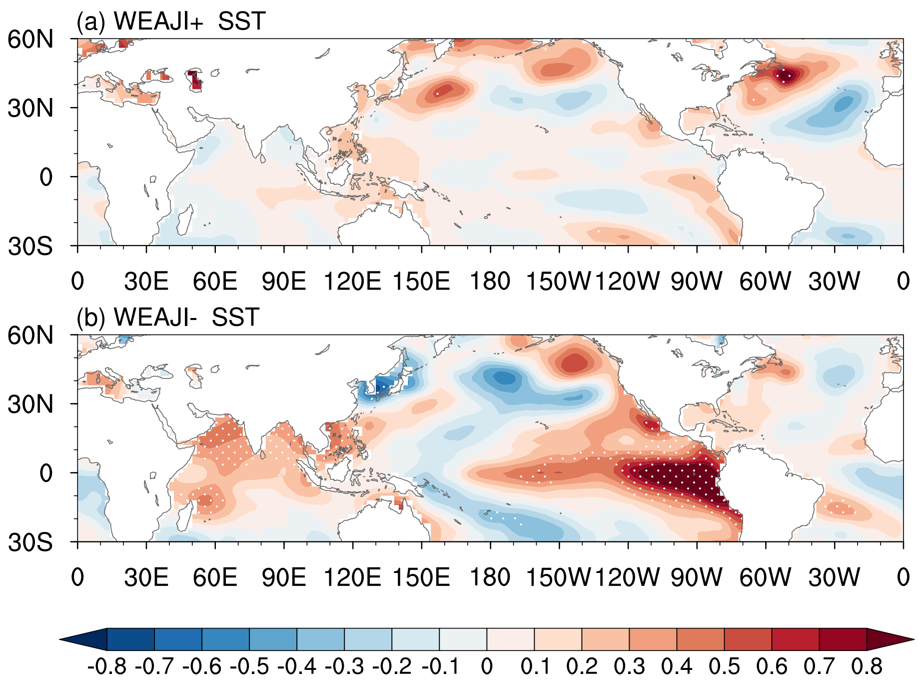

Fig. 7. Composite SST anomalies (units: ℃) for the (a) positive and (b) negative WEAJI years. The dots denote regions that are significant at the 95% confidence level.

the tropical WNP.

By contrast, there are significant OLR anomalies in the tropics for the negative WEAJI years (Fig. 6b). The convection is suppressed over the tropical WNP and enhanced convection over subtropical East Asia.In addition, the convection is enhanced over the equatorial Pacific and suppressed over the Maritime Continent. Correspondingly, there are significant positive SST anomalies in the northern Indian Ocean and equatorial eastern Pacific, which can well explain the convection anomalies in the tropics. We also examined the SST anomalies from the preceding winter to the following winter and found that positive SST anomalies in the equatorial eastern Pacific persist in all five seasons (not shown), suggesting a combination of a decaying and developing El Niño. This complex evolution of SST anomalies is different from the negative EEAJI years, which is associated with the developing El Niño (not shown).

A natural question arises: What causes the northward displacement of the WEAJ in the absence of significant tropical heat forcing? Figure 8 shows the composite SLP anomalies for the positive and negative WEAJI years. There are significant negative SLP anomalies over the Arctic and positive anomalies over midlatitudes, with centers in northern Europe and North Pacific for the positive WEAJI years (Fig. 8a). This pattern resembles the positive phase of Arctic Oscillation (AO) in summer (Ogi et al., 2016; Wang et al., 2018a), and the averaged value of the AO index (AOI) for the positive WEAJI years is 0.73, significant at the 95% confidence level in comparison with the reference summers. Here, the AOI is defined as the first principal component of the empirical orthogonal function analysis on SLP in summer for the region to the north of 20°N, following the wintertime definition (Thompson and Wallace, 1998). By contrast, the AO pattern is vague for the negative WEAJI years (Fig. 8b); in other words, there is not a seesaw pattern of SLP anomalies between the Arctic and mid-high latitudes.

The asymmetric relationship between the WEAJ and AO, i.e., the AO is clearly evident for the positive WEAJI years but vague for the negative years, can be verified by Fig. 9, which shows the composite 200-hPa zonal wind anomalies for the positive and negative AO years, respectively. Positive AO years correspond to a meridional seesaw pattern of zonal wind anomalies over the western portion of East Asia (Fig. 9a), similar to the anomalies for the positive WEAJI years (Fig. 5a), confirming the correspondence between the northward shift of WEAJ and positive AO. For the negative AO years, there are westerly (easterly) anomalies to the south (north) of the jet axis, extending from the western to eastern portions of East Asia (Fig. 9b). These zonal wind anomalies are weak and northward-shifted over western East Asia relative to those for the positive WEAJI years. These results confirm the asymmetric relationship between the AO and WEAJ, i.e., the northward displacement of the WEAJ is significantly associated with the positive phase of the AO.

5. Impacts of WEAJ meridional displacement on East Asian climate

Figure 10 shows the composite precipitation anomalies and the 850-hPa wind anomalies for the positive and negative WEAJI years. When the WEAJ shifts northward, more precipitation can be observed over South China and Northeast China, corresponding to anomalous southwesterly flow and a cyclone (Fig. 10a). For the negative WEAJI years, positive precipitation anomalies appear over the Yangtze River valley, South Korea, and southern and central Japan, which is a typical feature of intensified mei-yu (Fig. 10b). In addition, there are negative anomalies in Southeast Asia and the northern Philippines. These precipitation anomalies can be

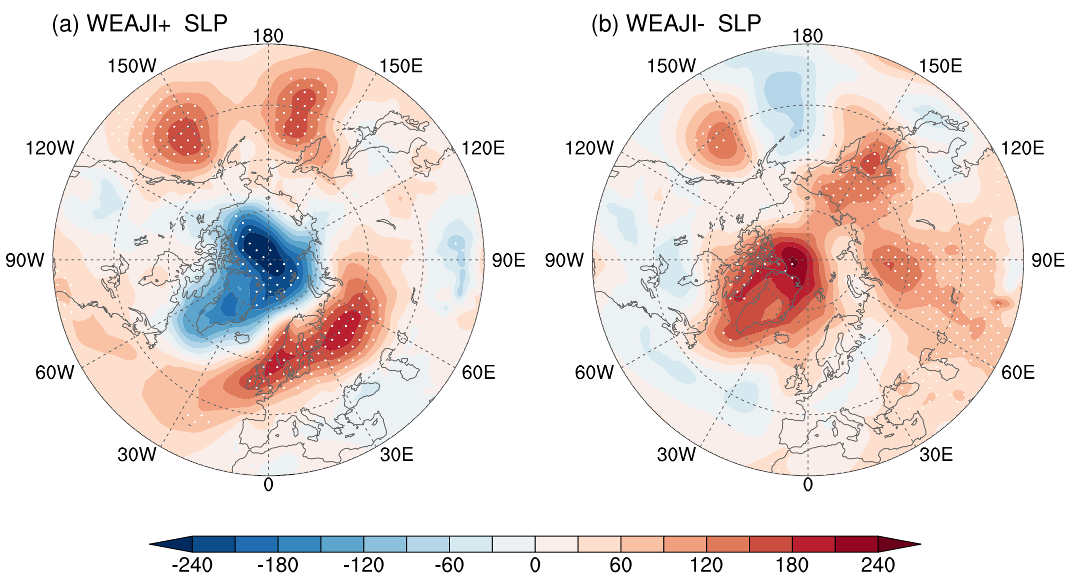

Fig. 8. Composite SLP anomalies (units: Pa) for the (a) positive and (b) negative WEAJI years. The dots denote regions that are significant at the 95% confidence level.

explained by the significant anticyclonic anomaly over the subtropical WNP, associated with the significantly suppressed convection over the tropical WNP (Fig. 6b).

We also analyzed the composite precipitation anomalies for the positive and negative EEAJI years. The result (not shown) indicates that a northward (southward) displacement of the EEAJ corresponds to less (more) rainfall over the Yangtze River valley and southern and central Japan, which has been well documented in previous studies (Kuang and Zhang, 2006; Xuan et al., 2011; Li and Lu, 2017; Wang et al., 2018b). This pattern of precipitation anomalies is similar to that for a southwardly displaced WEAJ (Fig. 10b), noting that a southward displacement of the WEAJ corresponds to stronger rainfall increases than a southward displacement of the EEAJ.

Figure 11 shows the composite surface air temperature anomalies for the positive and negative WEAJI years, respectively. When the WEAJ shifts northward, the temperatures are significantly higher over northern China, corresponding to the anticyclonic anomaly indicated by the positive anomalies of 500-hPa geopotential height (Fig. 11a). For the negative WEAJI years, the temperatures are higher in Southeast

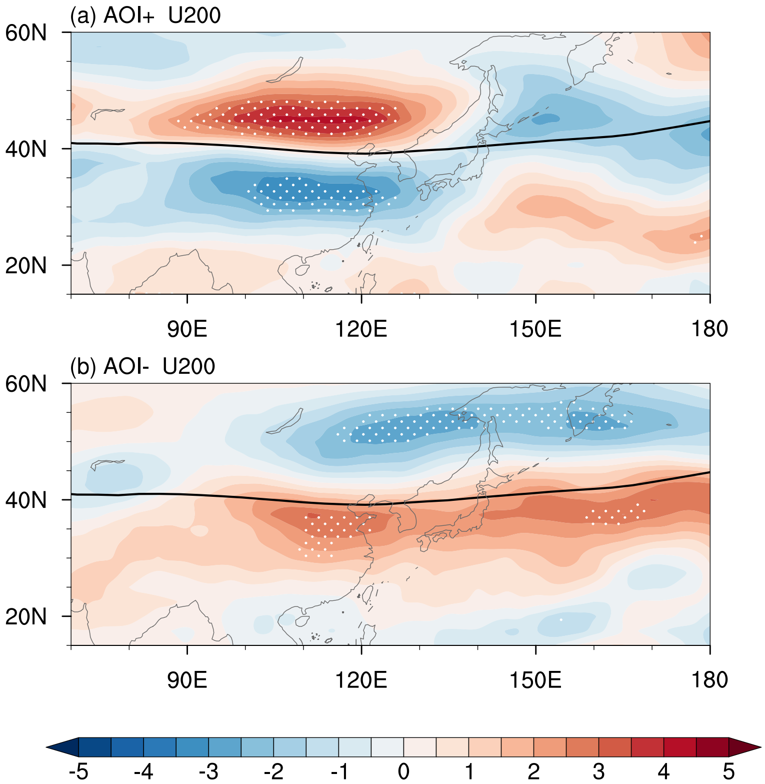

Fig. 9. As in Fig. 3, but for AOI.

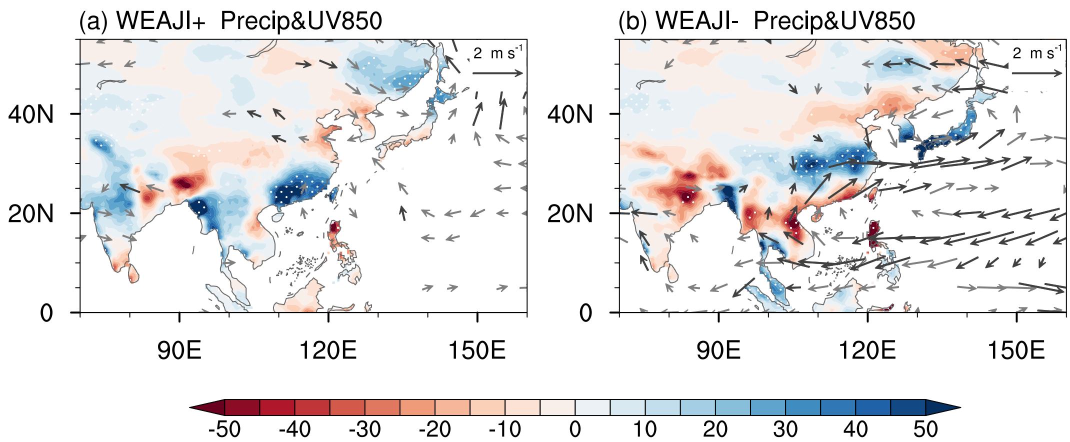

Fig. 10. Composite precipitation anomalies (units: mm month^{-1}) and 850-hPa horizontal winds (units: m s^{-1}) for the (a) positive and (b) negative WEAJI years. The dots denote regions that are significant at the 95% confidence level. The black vectors denote either zonal or meridional wind anomalies significant at the 95% confidence level. Only vectors greater than 0.4 m s^{-1} are presented.

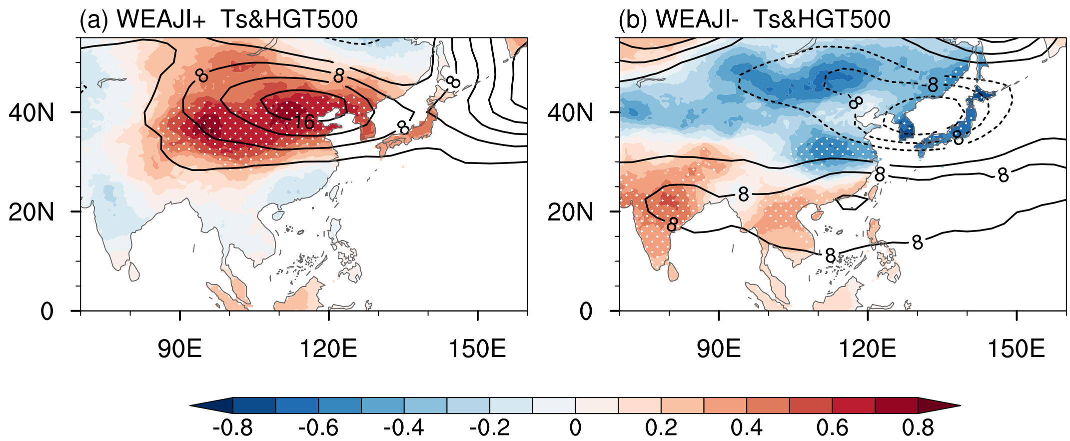

Fig. 11. Composite surface air temperature anomalies (shading; units: °C) and 500-hPa geopotential height anomalies (contours; units: m) for the (a) positive and (b) negative WEAJI years. The dots denote regions that are significant at the 95% confidence level. The contour interval is 4 m, and zero contours are omitted.

Asia and South Asia, and lower in East Asia, corresponding to the anticyclonic and cyclonic anomalies, respectively (Fig. 11b), which resembles the EAP pattern triggered by the suppressed convection over the tropical WNP.

6. Discussion and conclusions

This study investigated the meridional displacement of the upper-tropospheric westerly jet in summer over the western portion of East Asia, i.e., 80°–120°E, different from the scope of 120°–150°E widely used in the previous studies. The results indicate that the jet displacement is asymmetric on the interannual timescale. The circulation, convection, and SST anomalies associated with the northward and southward jet shift are different. In summers characterized by northward jet displacement, there is an anticyclonic anomaly over East Asia and a cyclonic anomaly over Northeast Asia, but no significant anomalies of atmospheric convection and SSTs in the tropics. The northward jet displacement is found to be related to the positive phase of the Arctic Oscillation, although the physical mechanism responsible for this relationship remains unknown. By contrast, in the summers of southward jet displacement, the atmospheric convection is significantly suppressed in the tropical western North Pacific and enhanced in East Asia. There is also enhanced convection over the equatorial Pacific and suppressed convection over the Maritime Continent. These convection anomalies can be explained by the positive SST anomalies in the northern Indian Ocean and equatorial eastern Pacific. Corresponding to the suppressed convection in the tropical western North Pacific, the circulation anomalies show the East Asia–Pacific pattern, including an anticyclonic anomaly in the subtropical western North Pacific and a cyclonic anomaly in East Asia.

Accordingly, the meridional displacement of the western East Asian jet in summer has asymmetric impacts on the climate in East Asia. Corresponding to a northwardly displaced jet, significant positive precipitation anomalies are observed over South China and Northeast China, and warmer surface air temperatures appear in northern China. On the other hand, during summers of southward jet displacement, the precipitation is enhanced in the Yangtze River valley, South Korea, and southern and central Japan, and suppressed in Southeast Asia and the northern Philippines. In addition, the surface air temperatures are lower in East Asia and higher in Southeast Asia and South Asia.

This study identifies an asymmetric relationship between the AO and the western East Asian jet. This relationship is strong when the AO is in its positive phase, i.e., the northward displacement of the western East Asian jet is closely related to the positive AO phase. This interesting result implies that the impacts of the AO on the summer climate in East Asia may be clearly dependent on the phase of the AO. The possible asymmetric impacts of the AO should be examined in the future. In addition, the physical mechanism of AO affecting the western East Asian jet should be investigated, which may help to explain the asymmetric relationship between the AO and the western East Asian jet.

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