Breakdown of the Summertime Meridional Teleconnection Pattern over the Western North Pacific and East Asia since the Early 2000s

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ABSTRACT

The meridional teleconnection over the western North Pacific and East Asia (WNP–EA) plays a predominant role in affecting the interannual variability of East Asian climate in summer. This study identified a breakdown of the meridional teleconnection since the early 2000s. Before the early 2000s, there are close tropical–extratropical relationships in light of both circulation and rainfall anomalies. For instance, the westward extension of the western North Pacific subtropical high (WNPSH) is closely associated with the southward shift of the East Asian westerly jet (EAJ), and more rainfall in the tropical WNP closely corresponds to less rainfall in the subtropical WNP–EA. However, after the early 2000s, the tropical–extratropical relationships are absent. Particularly, the tropical WNP precipitation anomalies can induce WNPSH anomalies, but the WNPSH anomalies cannot induce subtropical precipitation in the latter period, due to the absence of EAJ-related extratropical circulation anomalies. Further results indicate that in the latter period, the westward extension of the WNPSH is associated with the decay of central Pacific-like El Niño, and simultaneous summer sea surface temperature (SST) anomalies in the central eastern Pacific favor the northward shift of the EAJ, resulting in the disruption of the WNPSH–EAJ relationship. This evolution of tropical SSTs is sharply different from the decay of canonical El Niño and simultaneous summer tropical Indian Ocean warming, which favor the WNPSH–EAJ correspondence in the former period.

1. Introduction

It has been well known that there is a meridional teleconnection over the western North Pacific and East Asia (WNP–EA) during summer (e.g., Nitta 1987; Wang et al. 2001; Lu 2004; Kosaka and Nakamura 2006, 2010; Huang et al. 2012; Gong et al. 2018; X. Li et al. 2019; Sun et al. 2019). This teleconnection is referred to as the Pacific–Japan pattern (Nitta 1987) or East Asia–Pacific pattern (Huang and Sun 1992). It is characterized by the zonally elongated anomalies that appear alternately in the meridional direction over the WNP–EA. These anomalies appear over both the tropical and extratropical regions, with the longitude mainly ranging from 110° to 160°E. Therefore, this meridional teleconnection plays a predominant role in linking the tropical forcings,

such as ENSO, and extratropical East Asian climate (Huang and Wu 1989; Lee et al. 2006; Yang et al. 2007; Kim et al. 2009; Sun et al. 2010; Xie et al. 2016; Li et al. 2017).

The establishment of the meridional teleconnection manifests as strong tropical–extratropical connections over the WNP–EA. It is well known that the meridional teleconnection is closely associated with the precipitation or convection anomalies over the tropical WNP (e.g., Nitta 1987; Lau et al. 2000; Wang et al. 2001; Lu and Lin 2009; Li and Lu 2017; H. Li et al. 2019). Suppressed (enhanced) precipitation over the tropical WNP induces a lower-tropospheric anticyclonic (cyclonic) anomaly in the subtropical WNP, which corresponds to the westward extension (eastward retreat) of the WNP subtropical high (WNPSH) in the lower troposphere and the southward (northward) displacement of the East Asian westerly jet (EAJ) in the upper

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troposphere. The anticyclonic (cyclonic) anomaly favors enhanced (suppressed) rainfall over the subtropical East Asian rainband through modifying water vapor transport (Huang and Sun 1992; Wang et al. 2001; Zhou and Yu 2005; Li and Lu 2017, 2018), and the southward (northward) shift of the EAJ is also favorable for enhanced (reduced) subtropical rainfall (Liang and Wang 1998; Lu 2004; Xuan et al. 2011; Li and Zhang 2014; Du et al. 2016; Wang et al. 2018, 2019; Yan et al. 2019). The subtropical rainfall anomalies, as a heat source, can in turn enhance the meridional teleconnection (Lu and Lin 2009; Sun et al. 2010). Therefore, with regard to circulation anomalies, the meridional teleconnection can be illustrated by the correspondence of the westward extension (eastward retreat) of the WNPSH and the southward (northward) shift of the EAJ (Wang et al. 2001; Lu 2004; Lu and Lin 2009; Lin et al. 2010); and with regard to precipitation anomalies, it can be described by a seesaw pattern between the tropical and subtropical WNP–EA precipitation (Lau et al. 2000; Lu 2004; Kwon et al. 2005; Yim et al. 2008a; Kosaka et al. 2011; Li and Lu 2017). The absence of these tropical–extratropical connections suggests the breakdown of the meridional teleconnection, which is the main concern in this study.

The sea surface temperature (SST) anomalies over the tropical central eastern Pacific significantly affect the components of the meridional teleconnection. Particularly, as a strong tropical interannual variability, ENSO plays an important role. During the El Niño peaking winter, an anticyclonic anomaly appears over the subtropical WNP and maintains into the following summer, corresponding to the westward extension of the WNPSH (e.g., Wang et al. 2000; Yang et al. 2007; Xie et al. 2009; Wang et al. 2013; Xie et al. 2016; Jiang et al. 2019). Associated with the decay of El Niño, significant positive SST anomalies appear over the tropical Indian Ocean in the following summer, and play an important role in reinforcing the anticyclonic anomaly (Yang et al. 2007; Xie et al. 2009; Huang et al. 2010; Yun et al. 2013; Xie et al. 2016; Huang et al. 2016; Li et al. 2017). On the other hand, ENSO may exert an influence on the meridional displacement of the EAJ through the meridional teleconnection, or through the SST anomalies over the tropical central eastern Pacific in simultaneous summer (Lin and Lu 2009; Lin 2010; Qu and Huang 2011).

However, the meridional teleconnection, including the associated seesaw pattern in precipitation between the tropical and subtropical WNP, tends to show decadal or interdecadal changes (Wu and Wang 2002; Kwon et al. 2005; Yim et al. 2008a,b; Lin et al. 2010; Kubota et al. 2016; Huang et al. 2018; Xu et al. 2019). In the previous studies, there is a clear diversity in the turning points of decadal changes, such as in the 1970s (Wu and

Wang 2002; Lin et al. 2010) and in the 1990s (Kwon et al. 2005; Yim et al. 2008b; Huang et al. 2018; Xu et al. 2019), mainly due to their different focuses. Furthermore, different possible reasons for the decadal changes are proposed. For example, Wu and Wang (2002) attributed the enhanced tropical–subtropical seesaw pattern in the late 1970s to the change of the location of the tropical WNP convection and Lin et al. (2010) highlighted the role of the easterly shear over the tropical WNP in weakening June meridional teleconnection in the late 1970s. Xu et al. (2019) also suggested that the convection location and easterly shear over the tropical WNP result in the weakened and eastward shifted teleconnection after the late 1990s. Furthermore, some studies discussed the role of ENSO evolution in affecting the components of the teleconnection (Yim et al. 2008b; He and Wu 2018; Huang et al. 2018; Wu and Wang 2019; Huang et al. 2020), but these studies mainly focused on the tropical anomalies rather than the tropical–extratropical couplings. In this study, we would show a comprehensive breakdown of the meridional teleconnection in the early 2000s, focusing on the tropical–extratropical connections, and explore the possible role of tropical SSTs in inducing the breakdown of teleconnection.

The rest of this article is arranged as follows: In section 2, we describe the data and indexes. In section 3, the meridional teleconnection and its decadal change are diagnosed by using the reanalysis data. In this section, we show a breakdown of the WNPSH–EAJ relationship in the early 2000s, and the vague WNPSH–EAJ relationship results in the weakened impact of the WNPSH on subtropical rainfall after the early 2000s, inducing the breakdown of the seesaw pattern in tropical–subtropical rainfall anomalies. Section 4 discusses the role of the tropical SST evolution in the decadal change of the meridional teleconnection. Section 5 provides a summary and discussion.

2. Data and indexes

The data used in the present study include the monthly European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERA-Interim; Dee et al. 2011) and the NOAA extended reconstructed SST version 4 (ERSST.v4) data. The horizontal resolution of the ERA-Interim reanalysis data is $1.5^{\circ} \times 1.5^{\circ}$, and that of the SST data is $2.0^{\circ} \times 2.0^{\circ}$. Also used are the precipitation data derived by the Global Precipitation Climatology Project (GPCP; Huffman et al. 1997; Adler et al. 2003). All data are extracted during 1979–2017 and the months of June, July, and August (JJA) are used to represent summer.

In this study, we mainly use the WNPSH–EAJ correspondence and the tropical–subtropical seesaw pattern in precipitation to describe the meridional teleconnection. To

FIG. 1. Regression of (a) 850-hPa horizontal winds (vectors; m s^{-1}) and (b) 200-hPa zonal winds with respect to the normalized WNPSHI during 1979–2017. The bold black line in (b) represents the climatological jet axis during summer and the contour interval is 0.5 m s^{-1} . Zero contours are omitted. Shading in (a) indicates that either zonal or meridional wind anomalies are significant at the 95% confidence level based on Student's t test and in (b) refers to the significant zonal wind anomalies.

facilitate the discussion on the relationship between the interannual variability of the WNPSH and the meridional displacement of the EAJ, the WNPSH index (WNPSHI) defined by Wang et al. (2001) and the EAJ index (EAJI) defined by Lu (2004) are adopted. The WNPSHI is defined as the difference of averaged zonal winds at 850 hPa between 20° – 30°N , 110° – 140°E and 5° – 15°N , 100° – 130°E . This definition is the same as Wang et al. (2001), but with opposite sign. Therefore, a positive (negative) WNPSHI indicates an anticyclonic (cyclonic) anomaly over the subtropical WNP, and the WNPSH extends westward (retreats eastward). The EAJI is measured by the difference between the 200-hPa zonal winds averaged over 30° – 40°N , 120° – 150°E and 40° – 50°N , 120° – 150°E (Lu 2004). A positive EAJI indicates that the EAJ shifts southward, and vice versa. We also define the tropical WNP precipitation index (WNPPi) and the subtropical precipitation index (STPI) to facilitate the seesaw pattern in precipitation between the tropical WNP and the subtropical WNP–EA: the former is defined as the precipitation anomalies averaged over 10° – 20°N , 110° – 160°E (Lu 2001, 2004; Wu and Wang 2001; Lu and Lu 2015; Li and Lu 2017) and the latter is defined as those averaged over 30° – 40°N , 135° – 155°E (Lu and Lin 2009). In addition, the Niño-3 index is defined as SST anomalies averaged over 5°S – 5°N , 150° – 90°W .

3. Decadal change of the tropical–extratropical connections

a. The WNPSH–EAJ relationship during 1979–2017

Figure 1 shows the 850-hPa horizontal wind anomalies and 200-hPa zonal wind anomalies regressed onto the normalized WNPSHI during 1979–2017. Here, the jet

axis is determined as the first derivative of 200-hPa zonal winds being zero. At 850 hPa (Fig. 1a), the westward extension of the WNPSH corresponds to a zonally elongated anticyclonic anomaly over the subtropical WNP. In addition, there is a cyclonic anomaly over the Korean Peninsula and southern Japan and another anticyclonic anomaly over northeastern Asia. These anomalies are the manifestation of the meridional teleconnection pattern over the WNP–EA, consistent with the previous studies (e.g., Wang et al. 2001; Lu and Lin 2009). The meridional teleconnection also appears at 200 hPa (Fig. 1b), with alternately westerly and easterly anomalies over the WNP–EA. Especially, there are westerly anomalies to the south of the EAJ axis and easterly anomalies to the north, indicating that the westerly jet shifts southward.

The meridional displacement of the EAJ also corresponds to remarkable circulation anomalies in both the lower and upper troposphere (Fig. 2), and these anomalies also manifest as the meridional teleconnection over the WNP–EA. In the lower troposphere (Fig. 2a), there is a significant anticyclonic anomaly over the subtropical WNP, albeit weaker than that associated with the WNPSHI (Fig. 1a), confirming that the southward shift of the EAJ is connected to the westward extension of the WNPSH. Compared to that associated with the WNPSHI, the cyclonic anomaly associated with the EAJI over the Korean Peninsula and Japan is stronger and more significant (Fig. 2a), which is associated with the stronger anomalies to the south and north of the jet axis in the upper troposphere (Fig. 2b). Overall, these results confirm that the meridional displacement of the EAJ is closely associated with the zonal shift of the WNPSH during 1979–2017, and this correspondence

FIG. 2. As in Fig. 1, but for EAJI.

manifests as the meridional teleconnection over the WNP-EA.

Figure 3a shows the time series of the standardized WNPSHI and EAJI. Both indexes show clear interannual variations, but no distinct decadal variations. The correlation coefficient between the WNPSHI and EAJI

FIG. 3. (a) Time series of the standardized WNPSHI (black bar; m s^{-1}) and EAJI (line; m s^{-1}) and (b) the 15-yr running correlation coefficient between WNPSHI and EAJI. The vertical dashed lines indicate the year of 2002. The horizontal dashed line in (b) represents the significance of the correlation coefficient at 95% confidence level according to Student's t test.

is 0.41 during 1979–2017, significant at the 95% confidence level. However, a 15-yr running correlation indicates that the relationship between the WNPSHI and EAJI experiences a significant decadal change at around 2002/03 (Fig. 3b). That is, the relationship is strong and significant during 1979–2002, but sharply weakened during 2003–17. The correlation coefficient between these two indexes is 0.50 in the former period, significant at 95% confidence level, but only 0.15 in the latter period. We examined the regime shift of the WNPSHI–EAJI relationship based on Rodionov (2004, 2006), where the cutoff length is set to be 15, the probability level is 0.05, and Huber's weight parameter is 1.0, and found that the shift occurs at 2002/03. In the following, the whole period is divided into two stages, 1979–2002 and 2003–17, to discuss the decadal change in the tropical–extratropical relationships.

b. Decadal change of the WNPSH–EAJ relationship

Figure 4 shows the 850-hPa horizontal wind anomalies and 200-hPa zonal wind anomalies regressed onto the normalized WNPSHI during 1979–2002 and 2003–17, respectively. For the former period, the circulation anomalies for both the lower and upper troposphere resemble those during 1979–2017 (Figs. 4a,c vs Fig. 1), and are exhibited as the meridional teleconnection over the WNP-EA. The 850-hPa wind anomalies are characterized by the anticyclonic–cyclonic–anticyclonic anomalies from the tropical to extratropical WNP-EA (Fig. 4a) and the 200-hPa zonal wind anomalies feature alternately positive and negative anomalies (Fig. 4c). The westerly anomalies to the south of the jet axis and the easterly anomalies to the north are both stronger and more significant than those during 1979–2017 (Figs. 1b and 4c), confirming a stronger WNPSH–EAJ relationship.

However, during the latter period, the circulation anomalies show distinctly different features for both the

FIG. 4. Regression of (a),(b) 850-hPa horizontal winds (vectors; m s^{-1}) and (c),(d) 200-hPa zonal winds with respect to the normalized WNPSHI during (left) 1979–2002 and (right) 2003–17. The bold black lines in (c) and (d) represent the correspondingly climatological jet axis for 1979–2002 and 2003–17, respectively. The contour interval is 0.5 m s^{-1} , and zero contours are omitted. Shading in (a) and (b) indicates that either zonal or meridional wind anomalies are significant at the 95% confidence level based on Student's t test, and shading in (c) and (d) refers to the significant zonal wind anomalies.

lower and upper troposphere. In the lower troposphere (Fig. 4b), there is only a significant anticyclonic anomaly over the subtropical WNP, but the midlatitude cyclonic anomaly is absent. Without the midlatitude cyclonic anomaly, the north flank of the anticyclonic anomaly shifts from westerly to northwesterly anomalies, which would result in the absence of the subtropical WNP–EA precipitation anomalies, as discussed in latter analyses. In addition, a cyclonic anomaly appears over southeast Japan and an anticyclonic anomaly east of this cyclonic anomaly, but with marginal significance. On the other hand, in the upper troposphere (Fig. 4d), significant anomalies only appear over the tropical WNP–EA, but not to the south and north of the EAJ axis, consistent with the weak relationship between the WNPSH and EAJ. In addition, there are significant negative and positive anomalies over the extratropical WNP. These results confirm that the WNPSH–EAJ relationship becomes obscure and the meridional teleconnection pattern cannot be established during the latter period.

Figure 5 shows the 850-hPa horizontal wind anomalies and 200-hPa zonal wind anomalies regressed onto the normalized EAJI during 1979–2002 and 2003–17, respectively. For both periods, the 200-hPa zonal wind anomalies show significant westerly anomalies to the south of the jet axis and easterly anomalies to the north (Figs. 5c,d). However, the circulation anomalies in the lower troposphere are distinctly different between these two periods. In the former period (Fig. 5a), the wind anomalies resemble those for 1979–2017 (Fig. 2a) and there is a significant anticyclonic anomaly over the subtropical WNP, corresponding to the westward extension of the WNPSH. While in the latter period (Fig. 5b), the anticyclonic anomaly disappears and the wind anomalies are only characterized by a significant cyclonic anomaly over the midlatitudes. Using the NCEP2 reanalysis dataset, Huang et al. (2018) reported similar changes in circulation anomalies associated with the leading mode of the 200-hPa zonal winds over East Asia, which exhibits as the meridional displacement of the EAJ, in

FIG. 5. As in Fig. 4, but for EAJI.

the late 1990s. Therefore, the present results are not sensitive to the choice of EAJ index.

c. Decadal change of the seesaw pattern between tropical and subtropical WNP–EA precipitation

The previous subsection indicates that the meridional teleconnection, illustrated by the WNPSH–EAJ relationship, is absent during 2003–17. Associated with the breakdown of the circulation teleconnection, precipitation anomalies over the WNP–EA also experience a significant decadal change (Fig. 6). During the former period, precipitation anomalies associated with the WNPSHI and EAJI both exhibit as significant triple pattern over the WNP–EA (Figs. 6a,c). There are negative anomalies over the tropical WNP, positive anomalies along the East Asian rainband, and negative ones over northeastern Asia. However, during the latter period, these well-organized anomalies are disrupted. For the WNPSHI-related anomalies (Fig. 6b), the most striking feature is the weak rainfall anomalies over the subtropical region. The rainfall anomalies associated with the WNPSHI averaged over 30° – 40° N, 135° – 155° E, which is used to represent the subtropical WNP–EA precipitation in a previous study (Lu and Lin 2009), is 0.66 mm day^{-1} during the former period but only 0.07 mm day^{-1} during the latter period. Instead, positive

anomalies appear over the midlatitude WNP, corresponding to the anomalous lower-tropospheric cyclone there (Fig. 4b).

For the EAJI-related anomalies (Fig. 6d), on the other hand, enhanced rainfall also appears along the East Asian rainband, becoming weaker and less significant than the former period. The most impressive feature for this case is that the rainfall anomalies over the tropical WNP are sharply reduced: the anomalies averaged over 10° – 20° N, 110° – 160° E are -0.67 and $-0.14 \text{ mm day}^{-1}$ for the former and latter periods, respectively. Besides, the correlation coefficient between the WNPPi and STPI is -0.57 in the former period but only -0.08 in the latter period. These results are partially consistent with previous studies (Huang et al. 2018; Xu et al. 2019). Huang et al. (2018) reported that after the late 1990s, both the WNPSH–East Asian rainfall relationship and the EAJ–tropical WNP convection relationship are weakened. Xu et al. (2019) also showed that the extratropical anomalies associated with the meridional teleconnection have been weakened after the late 1990s.

Table 1 lists the correlation coefficients between the indexes that feature the meridional teleconnection during the former and latter periods. It is found that the relationship between the WNPPi and the WNPSHI survives during the latter period; that is, suppressed

FIG. 6. Regression of precipitation with respect to the normalized (a),(b) WNPSHI and (c),(d) EAJI during (left) 1979–2002 and (right) 2003–17. The marked regions in (a) represent the areas used to define the WNPPPI and STPI, respectively. The contour interval is 0.5 mm day^{-1} , and zero contours are omitted. The shading denotes the 95% confidence level based on Student's t test.

convection over the tropical WNP can induce the anticyclonic anomaly. However, the WNPSHI/WNPPPI–STPI relationship becomes obscure, suggesting that the anticyclonic anomaly cannot induce the subtropical precipitation anomalies, and thus breaks down the seesaw pattern in precipitation between the tropical and subtropical WNP–EA. This phenomenon is further explored.

It has been well known that the subtropical East Asian rainband features a strong meridional gradient of moisture in the lower troposphere (Chen and Chang 1980; Ding 1992). Therefore, the equivalent potential temperature θ_e , which combines both moisture and temperature, is widely used to describe the subtropical rainfall (Zhu et al. 2000; Park et al. 2015; Li and Lu 2017, 2018; Gao et al.

2019). A higher value of θ_e indicates more humid and warmer conditions. In climatological mean, θ_e decreases with latitude over East Asia and shows its largest gradient along the rainband, favoring enhanced precipitation by inducing the generation of convective instability (Ninomiya 1984; Ninomiya and Shibagaki 2007).

Figure 7 shows the θ_e anomalies at 850 hPa regressed onto the normalized WNPSHI during 1979–2002 and 2003–17, respectively. The significant precipitation anomalies and 850-hPa wind anomalies are also shown to facilitate comparison. The corresponding meridional gradient anomalies of θ_e averaged over 135° – 155° E are shown in the right-hand panels. Here, a positive value indicates the decrease of θ_e in the northward direction and thus the enhancement of the θ_e gradient. During the former period (Fig. 7a), there are positive θ_e anomalies to the south of 35° N and negative θ_e anomalies to the north of this latitude, which enhance the meridional gradient of climatological θ_e over the subtropical WNP–EA. The difference in θ_e anomalies between the southern edge (averaged along 30° N, 135° – 155° E) and the northern edge (averaged along 40° N, 135° – 155° E) of the subtropical WNP–EA is 0.89 K, and this increase is about 7.5% of the climatological difference between the southern and

TABLE 1. The correlation coefficients between the indexes that feature the meridional teleconnection during 1979–2002 and 2003–17, respectively. Boldface numbers are significant at the 95% confidence level based on Student's t test.

	EAJI	WNPPPI	STPI
WNPSHI	0.50 /0.15	−0.92 /−0.92	0.59 /0.04
EAJI		−0.52 /−0.18	0.79 /0.40
WNPPPI			−0.57 /−0.08

FIG. 7. Regression of 850-hPa equivalent potential temperature θ_e anomalies with respect to the normalized WNPSHI during (a) 1979–2002 and (b) 2003–17. The contour interval is 0.2 K, and zero contours are omitted. Shading denotes the 95% confidence level based on Student's t test. The scopes (red lines) of the significant positive precipitation anomalies and the significant horizontal wind anomalies (vectors) at 850 hPa are also given for comparison. Precipitation anomalies are based on the GPCP grid data. The curves in the right-hand panels show the corresponding meridional gradient anomalies ($10^{-6} \text{ K km}^{-1}$) of θ_e , which are averaged over 135° – 155°E .

northern edges during this period (11.80 K). The enhanced θ_e gradient anomalies correspond well to the enhanced precipitation anomalies. This is expected, as the enhanced meridional gradient of θ_e favors the generation of convective instability, and thus results in large amounts of precipitation (Ninomiya and Shibagaki 2007). In addition, the positive and negative θ_e anomalies correspond well to the westerly and easterly anomalies, respectively, suggesting that the WNPSHI-related circulation anomalies play an important role in the formation of θ_e anomalies. During the latter period (Fig. 7b), however, the distribution of θ_e anomalies becomes quite different. There are no clear θ_e and its meridional gradient anomalies over the subtropical WNP–EA and thus no significant rainfall anomalies (Fig. 7b). The reason for the absence of the θ_e anomalies in the latter period will be discussed in the following.

Figure 8 shows the climatological mean of θ_e and the significant horizontal wind anomalies associated with the normalized WNPSHI at 850 hPa during the former and latter periods, respectively. At both periods, high θ_e values, which represent the warm and moist air, appear over South China and Indochina. The θ_e values decrease with both latitude and longitude, particularly with latitude over central China, which is a typical feature of mei-yu. Although the patterns of mean θ_e are similar between the former and latter periods, the match between the wind anomalies and mean θ_e is quite different. In the former period (Fig. 8a), the westerly anomalies associated with the WNP anticyclonic anomaly travel from high to low θ_e regions over the subtropical WNP, suggesting that there is positive horizontal advection of θ_e . In addition, the easterly and northeasterly anomalies associated with the midlatitude cyclonic anomaly travel

FIG. 8. Climatological mean of equivalent potential temperature θ_e (shading and contours) and the 850-hPa horizontal winds (vectors; m s^{-1}) with respect to the normalized WNPSHI during (a) 1979–2002 and (b) 2003–17. The contour interval is 3.0 K, and only vectors significant at 95% confidence level based on Student's t test are shown.

from low to high θ_e regions over East Asia, suggesting that there is negative horizontal advection of θ_e . As a result, positive and negative θ_e anomalies appear over the south and north of the subtropical WNP–EA, respectively, and the θ_e meridional gradient is enhanced (Fig. 7a).

In contrast, in the latter period (Fig. 8b), the north flank of the anticyclonic anomaly shifts from westerly to northwesterly anomalies, in association with the absence of the midlatitude cyclonic anomaly. These wind anomalies are nearly parallel to the climatological θ_e contours, and thus there is no horizontal advection of θ_e over the subtropical WNP–EA. As a result, the WNPSHI-related circulation anomalies cannot induce θ_e meridional gradient anomalies and the associated precipitation there (Fig. 7b). In addition, there are also no clear θ_e anomalies in the north of the subtropical WNP–EA, as a result of the absence of the midlatitude cyclonic anomaly (Figs. 7b and 8b).

Previous studies documented that the subtropical WNP–EA precipitation anomalies, as the latent heat source, can in turn induce a zonally elongated cyclonic anomaly in the midlatitude WNP–EA, which appears in both the lower and upper troposphere, and thus enhance the meridional teleconnection (Lu and Lin 2009). The present results indicate that the subtropical WNP anticyclonic anomaly cannot induce the subtropical rainfall anomalies in the latter period. This is because the north flank of the anticyclonic anomaly shifts from westerly to northwesterly anomalies and there is no transportation of equivalent potential temperatures. Therefore, the feedback role of the subtropical precipitation anomalies in enhancing the meridional teleconnection becomes obscure, further favoring the breakdown of the teleconnection.

Overall, the present results demonstrated that the meridional teleconnection, which can be illustrated by the WNPSH–EAJ relationship or the seesaw pattern in precipitation between the tropical WNP and subtropical WNP–EA, is well established during 1979–2002. However, the tropical–extratropical connections are sharply weakened during 2003–17. The reason for the breakdown of the meridional teleconnection is to be discussed in the next section.

4. Possible mechanism

In the previous section, it was shown that the WNPSH–EAJ relationship is well established during 1979–2002, but becomes absent during 2003–17. In this section, we would further explore the possible mechanism responsible for this change.

It is notable that the decadal change in the WNPSHI–EAJI relationship could just be a result of the weakened

interannual variability of the WNPSHI or the EAJI. In fact, the standard deviations of both indexes indeed decrease since 2003: the standard deviation of the WNPSHI (EAJI) is 2.63 m s^{-1} (4.84 m s^{-1}) during 1979–2002, but reduced to 2.04 m s^{-1} (3.60 m s^{-1}) during 2003–17. To test the effect of the change in the variability of the WNPSHI, we exclude the four years that contribute most to the standard deviation of the WNPSHI in the former period (1980, 1983, 1985, and 1998) and make the standard deviation comparable to that in the latter period (2.07 vs 2.04 m s^{-1}). The correlation coefficient between the WNPSHI and the EAJI in the former period becomes 0.34, still larger than that in the latter period (0.15). These results indicate that the decrease of the interannual variability of WNPSHI is not the only reason that induces the change in the WNPSHI–EAJI relationship. Similarly, we exclude the years which contribute most to the standard deviation of the EAJI in the former period (1982, 1984, 1990, and 1994), and make its standard deviation comparable to that in the latter period (3.55 vs 3.60 m s^{-1}). The correlation coefficient between these two indexes in the former period becomes 0.56, even larger than that before excluding these years (0.50). These results indicate that the decadal change in the WNPSHI–EAJI relationship should not be attributed to the change in the interannual variability of the EAJI, and the other possible mechanisms should be explored.

Therefore, we hypothesize that large-scale environmental conditions, in particular SSTs in the tropics, may experience a certain change, and induce the decadal change in the WNPSH–EAJ relationship. Figure 9 shows the evolution of SST anomalies from the preceding winter [December–February (DJF)] to summer associated with the normalized WNPSHI and EAJI during 1979–2002. The SST anomalies associated with the WNPSHI exhibit as the decay of canonical El Niño (left panels of Fig. 9). There are significant positive SST anomalies over the tropical eastern Pacific and negative ones over the western Pacific in preceding winter (Fig. 9a), which induce an anticyclonic anomaly over the subtropical WNP (Wang et al. 2000). It is well known that this anticyclonic anomaly is maintained from winter to the following summer, through a positive feedback role of atmosphere–ocean interaction in the WNP (Wang et al. 2000) or the Indian Ocean capacitor effect (Terao and Kubota 2005; Yang et al. 2007; Li et al. 2008; Xie et al. 2009, 2016). Indeed, the positive SST anomalies over the tropical eastern Pacific gradually decay and become weak and insignificant in the following summer (Fig. 9e). Instead, SST anomalies over the tropical Indian Ocean and South China Sea become strong and significant, consistent with these previous theories.

1979–2002

FIG. 9. Evolution of sea surface temperature (SST) anomalies ($^{\circ}\text{C}$) from the preceding winter [$D(-1)\text{JF}(0)$] to the subsequent summer [$\text{JJA}(0)$] with respect to the normalized (left) WNPSHI and (right) EAJI during 1979–2002. Zero contours are omitted. Hatching indicates that the SST anomalies are significant at the 95% confidence level based on Student's t test. The marked region is used to define the winter Niño-3 index (see text for definitions), which is used for latter analysis.

The evolution of SST anomalies associated with the EAJI resembles that with the WNPSHI (right panels of Fig. 9). It is characterized by canonical El Niño decay from the preceding winter to summer over the tropical eastern Pacific, and positive SST anomalies appear over the tropical Indian Ocean in simultaneous summer (Fig. 9f), although these anomalies are weaker and less significant than those associated with the WNPSHI. The link between ENSO and the meridional displacement of the EAJ has also been extensively studied (e.g., Shaman and Tziperman 2007; Lin and Lu 2009; Qu and Huang 2011; Hong and Lu 2016). The decay of canonical El Niño and the associated positive SST anomalies in tropical Indian Ocean in simultaneous summer induce tropospheric warming in the tropics, and the associated thermal wind result in the southward shift of the mid-latitude jet (Held and Hou 1980; Bretherton and Sobel 2003; Seager et al. 2003; Chen et al. 2008; Lu et al. 2008; Gong et al. 2010; Sun et al. 2013). Overall, these results indicate that the correspondence between the zonal shift of the WNPSH and the meridional displacement of the EAJ is modulated by canonical ENSO in the former period.

Figure 10 shows the evolution of SST anomalies from the preceding winter to summer associated with the normalized WNPSHI and EAJI during 2003–17. The evolution of SST anomalies is quite different from that

in the former period, for both WNPSHI and EAJI. The anomalies associated with the westward extension of the WNPSH look like the decay of central Pacific (CP) El Niño (left panels of Fig. 10; Ashok et al. 2007; Kao and Yu 2009), although with marginal significance. The correlation coefficient between the CP El Niño index defined by Ashok et al. (2007) and WNPSHI in the latter period is 0.33, larger than that between the preceding winter Niño-3 index and the WNPSHI (0.20). There are positive SST anomalies over the tropical central Pacific during previous winter (Fig. 10a). These positive anomalies decay rapidly and negative SST anomalies appear over the tropical central and eastern Pacific during summer (Figs. 10c,e). It has been reported that cooler (warmer) SST in the tropical central and eastern Pacific can favor less (more) rainfall over the tropical WNP and thus an anticyclonic (cyclonic) anomaly to the northwest (Lau and Nath 2006; Wang et al. 2013). These results are also consistent with some recent studies (He and Wu 2018; Wu and Wang 2019), who reported that the tropical WNP precipitation or anticyclonic anomaly is more associated with the simultaneous SST anomalies in the tropical central and eastern Pacific in the recent decade.

By contrast, the SST anomalies associated with the EAJI are basically opposite signed with those associated

2003–2017

FIG. 10. As in Fig. 9, but for 2003–17. Marked regions are used to define the CP_SST index and summer Niño-3 index (see text for definitions), which are used for latter analyses.

with the WNPSHI over the tropical central eastern Pacific, resembling the CP La Niña decay (right panels of Fig. 10). Negative SST anomalies appear over the tropical central Pacific in the preceding winter (Fig. 10b). These negative anomalies become much weaker in the following spring (Fig. 10d). In summer, the SST anomalies are characterized by significant positive anomalies over the tropical central and eastern Pacific (Fig. 10f). These positive SST anomalies can induce warming in the tropical troposphere and the southward shift of the midlatitude westerly jet, as mentioned previously.

The present results indicate that during the former period, the WNPSH and the EAJ are both associated with the decay of canonical El Niño and the subsequently positive SST anomalies over the tropical Indian Ocean in summer. However, during the latter period, the decay of CP-like El Niño and the associated negative SST anomalies over the tropical central and eastern Pacific in summer favor a nearly conversed WNP–EAJ correspondence (i.e., an anticyclonic anomaly over the subtropical WNP but a northward displaced EAJ). The transfer of dominant role from canonical El Niño in the former period to CP-like El Niño in the latter period is consistent with previous studies, which have reported that CP El Niño has occurred more frequently and exhibits as the leading mode of Pacific SST anomalies in the recent two decades (e.g., Yeh et al. 2009; McPhaden

2012; Hu et al. 2013; Xiang et al. 2013; Wen et al. 2014; Yu et al. 2015).

Figure 11 shows the 850-hPa horizontal wind anomalies and 200-hPa zonal wind anomalies regressed onto the normalized previous winter Niño-3 index during 1979–2002 and 2003–17, respectively. During the former period (Figs. 11a,c), the circulation anomalies in the lower and upper troposphere are both characterized by the meridional teleconnection. Especially, in the lower troposphere (Fig. 11a), there is an anticyclonic anomaly over the subtropical WNP, corresponding to the westward extension of the WNPSH; and in the upper troposphere (Fig. 11c), there are significant positive zonal wind anomalies to the south of the westerly jet and negative anomalies to the north, corresponding to the southward displacement of the EAJ.

However, during the latter period, circulation anomalies in the lower and upper troposphere both become weak and insignificant, and the meridional teleconnection is absent (Figs. 11b,d). The correlation coefficient between the previous winter Niño-3 index and the WNPSHI is 0.68 during 1979–2002, significant at 99% confidence level, but it sharply reduces to 0.18 during 2003–17; and that with the EAJI is 0.33 during the former period, but -0.16 during the latter period (Table 2). These results indicate that the zonal shift of the WNPSH and the meridional displacement of the EAJ are less affected by canonical El Niño in the latter period.

FIG. 11. Regression of (a),(b) 850-hPa horizontal winds (vectors; m s^{-1}) and (c),(d) 200-hPa zonal winds with respect to the normalized previous winter Niño-3 index during (left) 1979–2002 and (right) 2003–17. The bold black lines in (c) and (d) represent the correspondingly climatological jet axis for 1979–2002 and 2003–17, respectively. The contour interval is 0.5 m s^{-1} , and zero contours are omitted. Shadings in (a) and (b) indicate that either zonal or meridional wind anomalies are significant at the 95% confidence level based on Student's t test and in (c) and (d) refer to the significant zonal wind anomalies.

To illustrate the reason for the weakened impact of canonical El Niño on the meridional teleconnection in the latter period, Fig. 12 shows the evolution of SST anomalies from the preceding winter to summer associated with the normalized previous winter Niño-3 index during 1979–2002 and 2003–17, respectively. During the former period, the evolution of SST anomalies resembles that associated with the WNPSHI (left panels of Fig. 9 vs left panels of Fig. 12), exhibiting as the decay of canonical El Niño in tropical eastern Pacific. Significant positive anomalies appear over the tropical Indian Ocean in summer (Fig. 12e), maintaining the subtropical anticyclonic anomaly by the Indian Ocean capacitor effect. During the latter period, SST evolution also exhibits as the decay of El Niño, but shows some appreciable differences. First, the positive centers of the SST anomalies over the tropical Pacific locate more westward in previous winter and spring—that is, around 150°W in the latter period (Figs. 12b,d) but 125°W in the former period (Figs. 12a,c). Therefore, the evolution of SST anomalies during the latter period looks more like the decay of CP El Niño, consistent with the enhanced frequency of CP El Niño in

the latter period (McPhaden 2012; Hu et al. 2013; Xiang et al. 2013; Yu et al. 2015). Second, for the latter period, positive anomalies over the Indian Ocean are very weak during summer, suggesting that the bridge role of the Indian Ocean is weakened (Fig. 12f). Therefore, the WNPSH is less affected by SST anomalies in the tropical eastern Pacific during previous winter in the latter period. On the other hand, as the positive SST anomalies over the tropical Indian Ocean and central eastern Pacific in simultaneous summer are much weaker during the latter period (Figs. 12e,f), the ENSO-related warming in the

TABLE 2. The correlation coefficients between the Niño-3 index, for the previous winter and simultaneous summer, and the WNPSHI and EAJI during 1979–2002 and 2003–17, respectively. Boldface numbers are significant at the 95% confidence level based on Student's t test.

	Previous winter Niño-3 index	Simultaneous summer Niño-3 index
WNPSHI	0.68 /0.18	−0.02/−0.40
EAJI	0.33/−0.16	0.14/ 0.57

FIG. 12. Evolution of sea surface temperature (SST) anomalies ($^{\circ}\text{C}$) from the preceding winter [$D(-1)\text{JF}(0)$] to the subsequent summer [$\text{JJA}(0)$] with respect to the normalized previous winter Niño-3 index during (left) 1979–2002 and (right) 2003–17. Zero contours are omitted. Hatching indicates that the SST anomalies are significant at the 95% confidence level based on Student's t test.

tropical troposphere is also weakened (not shown). As a result, the impact of ENSO on the meridional displacement of the EAJ is also weakened.

The present results indicate a breakdown of the relationship between the meridional teleconnection and canonical ENSO in the latter period. In this period, the SST anomalies over the tropical central and eastern Pacific in simultaneous summer seem to become important. It has been reported that warm SST anomalies over the tropical central and eastern Pacific in simultaneous summer are favorable for the eastward retreat of the WNPSH (Wang et al. 2013) and the southward shift of the EAJ (Lu 2005; Lin 2010). The correlation coefficient between the summer Niño-3 index and the EAJI during 2003–17 is 0.57, significant at 95% confidence level; and that between the summer Niño-3 index and the WNPSHI is -0.40 (Table 2). These results confirm that the SST anomalies over the tropical central and eastern Pacific in simultaneous summer tend to result in a nearly inversed WNPSH–EAJ correspondence during the latter period.

On the other hand, the SST anomalies over the tropical central Pacific in previous winter is opposite signed with those over the tropical central eastern Pacific in the following summer during the latter period (Fig. 10). This is similar to the CP-like El Niño (La Niña) decay and to some extent consistent with previous studies (Feng et al.

2011; Li et al. 2015), which reported that the SST anomalies associated with the CP El Niño decay rapidly, and that the end of CP El Niño (La Niña) tend to be accompanied by the onset of canonical La Niña (El Niño). To test whether the out-of-phase configuration of the SST anomalies occurs more frequently in the latter period, we define the central Pacific SST anomalies index (CP_SST) as the SST anomalies averaged over 10°S – 10°N , 170°E – 130°W , which is marked in Fig. 10. Figure 13 shows the scatter diagram of standardized CP_SST in previous winter and the simultaneous summer Niño-3 index during 1979–2002 and 2003–17. Before 2003, 17 of 24 cases exhibit as in-phase configuration of these two indexes, consistent with the positive SST anomalies over the tropical central eastern Pacific in both previous winter and the following summer associated with the WNPSHI or EAJI (e.g., Figs. 9a,e). However, during the latter period, 10 out of 15 cases exhibit as out-of-phase configuration of these two indexes. These results confirm that the change in the features of SST anomalies over tropical central eastern Pacific may act as the background that favors the weakened WNPSH–EAJ relationship.

The analyses in this section indicate that the establishment of the WNPSH–EAJ relationship is associated with the decay of the canonical El Niño and the warm SST anomalies over the tropical Indian Ocean in

FIG. 13. Scatter diagrams of the standardized CP_SST index (see text for definition) in previous winter and the simultaneous summer Niño-3 index during 1979–2002 (hollow dots) and 2003–17 (solid dots), respectively.

simultaneous summer in the former period, consistent with previous studies. However, this widely believed association no longer exists during the latter period. Instead, the negative SST anomalies over the tropical central eastern Pacific in summer, in association with the decay of CP-like El Niño, begin to play a role. These SST anomalies tend to favor the westward extension of the WNPSH and the northward shift of the EAJ, leading to a weakened WNPSH–EAJ relationship. In addition to the decadal change in tropical SST anomalies associated with the WNPSH and EAJ, we have also carefully examined the decadal changes in circulations in both lower and upper troposphere over the WNP–EA, including the intensity and meridional position of the EAJ, but failed in finding significant change in the circulation background (not shown).

5. Conclusions and discussion

There is a well-known meridional teleconnection pattern over the WNP–EA during summer, which is characterized by the zonally elongated circulation and precipitation anomalies with alternate signs in the meridional direction. Spanning the tropical and extratropical WNP–EA, this meridional teleconnection acts as a link between tropical forcings, such as ENSO, and climate anomalies over extratropical East Asia.

This study, however, found a breakdown of the meridional teleconnection since the early 2000s; more

exactly, the tropical–extratropical connections associated with the meridional teleconnection pattern become absent after the early 2000s. For instance, as two components of the teleconnection, the westward extension (eastward retreat) of the WNP subtropical high (WNPSH) is closely related to the southward (northward) displacement of the East Asian westerly jet (EAJ) during 1979–2002, but this relationship is obscure during 2003–17. In addition, the well-known seesaw pattern in precipitation between the tropical WNP and subtropical WNP–EA, which is clear in the former period, is also absent in the latter period. Although the precipitation anomalies in the tropical WNP can induce significant WNPSH anomalies in both periods, the WNPSH anomalies can affect precipitation in the subtropical WNP–EA only in the former period, not in the latter period.

Further results indicate that the evolution of tropical SST anomalies associated with the components of the meridional teleconnection experiences a considerable decadal change. In the former period, the SST anomalies associated with the westward extension of the WNPSH and the southward displacement of the EAJ both exhibit as the decay of canonical El Niño, and there are significant positive anomalies over the tropical Indian Ocean in simultaneous summer, as previously well documented. However, in the latter period, the SST anomalies associated with the westward extension of the WNPSH exhibit as the decay of CP-like El Niño, rather than canonical El Niño, and correspondingly, SST anomalies in the following summer become significantly negative in the tropical central and eastern Pacific but very weak in the Indian Ocean. The negative SST anomalies in the tropical central and eastern Pacific in summer favor the northward displacement of the EAJ, and thus hinder the correspondence between the westward extension (eastward retreat) of the WNPSH and the northward (southward) displacement of the EAJ in the latter period.

The interaction between circulation and precipitation anomalies over the WNP–EA also plays a role in changing the WNPSH–EAJ relationship. In the former period, both the WNPSH and EAJ anomalies are significantly related to the precipitation anomalies along the East Asian summer rainband (i.e., in the subtropical WNP–EA), due to the impacts of circulations on subtropical precipitation and the positive feedback of the subtropical precipitation on circulations (e.g., Lu and Lin 2009). In the latter period, however, associated with the breakdown of the WNPSH–EAJ relationship, the WNPSH anomalies do not relate to the cyclonic or anticyclonic anomalies in the lower troposphere over the midlatitude WNP–EA, which are the lower-tropospheric representation of the meridional displacement of the EAJ. The present results indicate

FIG. 14. Schematic diagram describing (a) the establishment of the teleconnection in the former period and (b) its breakdown in the latter period. In the former period shown in (a), the decay of canonical El Niño (red thin circle with “Previous DJF warming”) and simultaneous summer tropical Indian Ocean warming (red thick circle with “① JJA warming”) favor the westward extension of the WNPSH (black solid curve with “② WNPSH”) and the southward shift of the EAJ (red arrows with “② EAJ”). The lower-tropospheric cyclonic anomaly in midlatitude East Asia (solid curve with black arrows under the red ones), associated with the southward shift of EAJ, results in westerly and southwesterly anomalies in the north flank of the WNPSH. These anomalies travel from high (θ_e) to low θ_e regions (orange arrow with “③ θ_e advection”) and favor enhanced subtropical rainfall (green oval with “④ Rainfall”). In the latter period shown in (b), the cooler SSTs in tropical central eastern Pacific in summer (blue thick circle with “① JJA cooling”), in association with the decay of CP-like El Niño (red thin circle with “Previous DJF warming”), tends to result in the northward shift of EAJ (blue dashed arrows with “② EAJ”), which offsets the southward shift effect induced by the tropical WNP convection. As a result, the WNPSH–EAJ relationship is absent. The vague WNPSH–EAJ relationship leaves WNPSH as its own shape (black circle with “② WNPSH”), i.e., a typical anticyclonic anomaly over the WNP with northwesterly anomalies in its north flank (black arrow). The northwesterly anomalies in the north flank of the WNPSH cannot induce advection of climatological θ_e (orange arrow with “③ No θ_e advection”) and thus cannot induce the subtropical precipitation (green dashed circle with “④ Rainfall”), resulting in the breakdown of the tropical–subtropical seesaw pattern. In (b), dashed marks represent the absence of corresponding anomalies.

that without the midlatitude cyclonic or anticyclonic anomalies, the WNPSH anomalies exhibit as a typical anticyclonic anomaly over the WNP with northwesterly anomalies in its north flank. These northwesterly anomalies cannot induce subtropical WNP–EA rainfall, due to the lack of transportation of equivalent potential

temperatures, and the tropical–subtropical seesaw pattern in precipitation is absent. Therefore, the impact of anomalous WNPSH on the subtropical WNP–EA precipitation, which has been widely believed previously, is not guaranteed and may be sensitive to extratropical circulation anomalies.

Based on the present and previous results, we propose the following physical processes responsible for the decadal change of the meridional teleconnection in the early 2000s, as summarized schematically in Fig. 14. In the former period (Fig. 14a), the decay of canonical El Niño and tropical Indian Ocean warming in simultaneous summer favor the westward extension of the WNPSH and the southward shift of the EAJ; and these circulation anomalies are significantly related to the subtropical rainband, favoring the tropical–subtropical seesaw pattern in precipitation. By contrast, the latter period is featured with distinctly different processes (Fig. 14b). First, the negative SST anomalies in tropical central eastern Pacific in summer, in association with the decay of CP-like El Niño, results in the absence of the WNPSH–EAJ relationship. Second, the vague WNPSH–EAJ relationship leaves WNPSH as its own shape (i.e., a typical anticyclonic anomaly over the WNP with northwesterly anomalies in its north flank). Third, the northwesterly anomalies cannot induce advection of climatological equivalent potential temperature and thus cannot induce the subtropical precipitation, resulting in the breakdown of the tropical–subtropical seesaw pattern.

The breakdown of the meridional teleconnection suggests a great challenge for seasonal forecast of East Asian climate in summer, which essentially depends on the tropical–extratropical coupling (Li et al. 2012; Lu et al. 2012; Yim et al. 2016; Xing et al. 2017; Bett et al. 2018; Martin et al. 2020). Currently, climate models show a considerable capability in the seasonal forecast of the WNPSH (Li et al. 2012, 2014; Kosaka et al. 2013; Shin et al. 2019), but a weak predictability of the EAJ (Li and Lin 2015). It can be inferred that without the tropical–extratropical coupling over the WNP–EA, the extratropical circulation will be harder to be predicted, and thus further hinder the seasonal predictability of East Asian summer rainfall (Li et al. 2016; Lin et al. 2018). On the other hand, it would be interesting to further investigate the decadal changes in the relationship between the meridional teleconnection and tropical SSTs by analyzing the simulations of climate models, in order to better understand the potential diversity of such a relationship.

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