Changes in the Relationship between ENSO and Asia–Pacific Midlatitude Winter Atmospheric Circulation

SHENGPING HE

Nansen-Zhu International Research Centre, Institute of Atmospheric Physics, and Climate Change Research Center, Chinese Academy of Sciences and University of Chinese Academy of Sciences, Beijing, China

HUIJUN WANG

Nansen-Zhu International Research Centre, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

JIPING LIU

State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

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ABSTRACT

Interdecadal changes in the relationship between El Niño–Southern Oscillation (ENSO) and midlatitude atmospheric circulation are investigated in this study. Comparison of associations between ENSO and midlatitude atmospheric circulation anomalies between 1958–76 and 1977–2010 suggest that during 1958–76, ENSO exerted a strong impact on the East Asian winter monsoon (EAWM) and the associated atmospheric circulation pattern was similar to the positive North Pacific Oscillation (NPO). In contrast, during 1977–2010, the NPO-like atmospheric pattern disappeared. Instead, ENSO exerted a strong impact on the eastern North Pacific Ocean (NP) and North America, and the associated atmospheric circulation pattern resembled the Pacific–North America (PNA) teleconnection. Also, significant correlations between ENSO and sea surface temperature anomalies (SSTAs) over the western subtropical NP during 1958–76 became insignificant during 1977–2010, whereas negative correlations between ENSO and SSTAs in the central and northeastern subtropical NP became more significant since the mid-1970s. Further analyses suggest that the interdecadal shift of the Aleutian low, which occurred around the mid-1970s, might be responsible for the identified changes. Before the mid-1970s, warm ENSO events generated an anomalous anticyclone over the western NP, which is a key system bridging ENSO and EAWM-related atmospheric circulation. After the mid-1970s, the Aleutian low intensified and shifted eastward, leading to the impact of ENSO prevailing over the eastern NP. In addition, the weakened (strengthened) ENSO–NPO/EAWM (ENSO–PNA) relationship likely contributed to the weakened (strengthened) relationship between ENSO and SSTAs over the western (central and eastern) subtropical NP.

1. Introduction

As one of the dominant climate features over East Asia in boreal winter, the variability of the East Asian winter monsoon (EAWM) has substantial impacts on both adjacent and far away regions (Lau and Li 1984; Huang et al. 2007; Sun et al. 2010; Wang et al. 2011; Li and Wang 2012; Liu et al. 2012). The EAWM-related atmospheric circulation and associated mechanisms have been extensively studied (Chen et al. 2005; Liu et al. 2010), and the pioneering study dates from the 1950s (Tao 1957). Because the variations of sea surface temperature (SST) associated with El Niño–Southern Oscillation (ENSO) events are considered to be an important driving factor for the variations of atmospheric circulation over the tropics and midlatitudes (Namias 1973; Cayan 1980; Frankignoul 1985), ENSO and its connection with the EAWM has also drawn much attention. Li (1988, 1990) found that the anomalous atmospheric

Corresponding author address: Shengping He, Nansen-Zhu International Research Centre, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China.
E-mail: hshp@mail.iap.ac.cn

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circulation in winter induced by an El Niño event could lead to a weaker winter monsoon, and the anomalously stronger EAWM could in turn result in an El Niño event. Tornita and Yasunari (1996) suggested that the northeast winter monsoon might influence the biennial oscillation of the ENSO/monsoon system. Zhang et al. (1996) revealed that a southerly wind anomaly appeared in the lower troposphere along the coast of East Asia during the mature phase of El Niño events. Based on a new EAWM index defined by averaging the low-level meridional wind, Chen et al. (2000) indicated that in boreal winter the interannual variations of midlatitude atmospheric circulation and surface air temperature over the East Asian continent and North Pacific Ocean are closely connected with SST anomalies (SSTAs) both in the western and eastern tropical Pacific. Similar conclusions were drawn by Wang et al. (2000). They further pointed out that the anomalous lower-tropospheric anticyclone (cyclone) located in the western North Pacific was a key system to bridge the El Niño (La Niña) event and the weak (strong) EAWM.

Meanwhile, the connection of ENSO with the atmospheric circulation over the eastern North Pacific and North America has also been extensively examined. As first noted by Bjerknes (1966, 1969), the Aleutian low tends to intensify and shift southeastward during El Niño events. Latif and Barnett (1994) found that the atmospheric response to El Niño events is highly significant with an anomalous cyclonic anomaly appearing over the North Pacific, which indicates a close connection between ENSO and the Aleutian low. Horel and Wallace (1981) pointed out that the atmospheric teleconnection [i.e., the Pacific–North America (PNA) pattern] significantly correlates with ENSO events. Namias et al. (1988) and Nitta and Yamada (1989) revealed that the atmospheric anomalies related to the PNA may be associated with the changes of tropical SST.

However, these linkages are not stationary, especially when a climate shift occurs. In fact, a number of evidences have indicated an interdecadal change in the North Pacific atmosphere and ocean in the mid-1970s. The oceanic change is characterized as a cooling SSTA in the central and western North Pacific and a warming SSTA in the eastern tropical Pacific since 1976 (Trenberth 1990; Deser et al. 1996; Guilderson and Schrag 1998). The atmospheric change includes an intensification and eastward shift of the Aleutian low (Trenberth 1990; Graham 1994; Trenberth and Hurrell 1994) and a significant lowering of 500-hPa geopotential height in the North Pacific related to the PNA teleconnection (Nitta and Yamada 1989). The atmospheric change was often accompanied by changes in winds, upper-ocean heat content, and moisture (Rogers and Raphael 1992; Latif and Barnett 1994; Wang 2001; Sun et al. 2008). This climate shift would in turn have a significant impact on ENSO mode and frequency (Wang 1995; An and Wang 2000). Such interdecadal changes of the ocean–atmosphere system could strongly affect and modulate the interannual relationship between the tropical SSTAs and atmospheric circulation (Ding et al. 2010). As suggested by Yamagata and Masumoto (1992), the decadal variability of the SSTAs in the tropical North Pacific may involve changes of the Aleutian low and the Asian winter monsoon system. In recent years, many studies have focused on the instability of the relationship between the tropical SSTAs and the summer monsoon. Kumar et al. (1999) found that the inverse relationship between ENSO and the Indian summer monsoon has broken down in recent decades. Wang (2002) has demonstrated that there exists instability in the relationship between the East Asian summer monsoon (EASM) and ENSO. Wu and Wang (2002) illustrated that the ENSO-related EASM circulation anomaly has experienced a remarkable change after the late 1970s, which is attributed to the western North Pacific convection anomaly being enhanced and shifting to higher latitudes.

Recently, Wang and He (2012) suggested that the correlation between ENSO and EAWM shows an obvious weakening since the mid-1970s. However, the mechanisms responsible for the change in the ENSO–EAWM relationship, and the question of whether there exists interdecadal change in the relationship between ENSO and midlatitude atmospheric teleconnection [i.e., the North Pacific Oscillation (NPO) and PNA] are still not well studied. Therefore, the purpose of this paper is to investigate how the connection between ENSO and midlatitude atmospheric circulation changes in the context of the interdecadal climate shift in the mid-1970s, hoping to provide some new and useful information for the climate prediction. First, we will document the interdecadal shift of the relationship between ENSO and midlatitude atmospheric circulation and extratropical SSTAs during 1958–2010. Second, we will explore the possible mechanisms responsible for the changes in the relationship. This paper is arranged as follows. Section 2 describes the data and methods used in this study. Section 3 examines the distinctive ENSO-related atmospheric circulation anomalies between 1958–76 and 1977–2010. Section 4 displays the different SSTA patterns in the North Pacific between the two periods and their relationships with midlatitude atmospheric circulation. The possible mechanism for the change in the relationship is further explored in section 5. The last section presents the summary and discussion.

2. Data and methods

The datasets used in this study include 1) monthly-mean sea level pressure (SLP), winds at 850 and 300 hPa, surface air temperature, and geopotential height at 500 hPa obtained from the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis (Kalnay et al. 1996) and 2) monthly-mean SST obtained from the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed SST analysis, version 3 (Smith et al. 2008). The 500-hPa geopotential height from the 40-yr European Center for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40; Uppala et al. 2005) is also used.

Several climate indices are used to facilitate the analysis, including 1) the East Asian trough index, which is defined as the negative area-averaged winter 500-hPa geopotential height within the domain of 25°–45°N, 110°–145°E. A positive (negative) phase of the East Asian trough index means a strong (weak) EAWM (Sun and Li 1997; Wang et al. 2009). Also used were 2) the Aleutian low index, which is defined as the winter SLP averaged within 30°–70°N and 155°E–130°W (He and Wang 2012); 3) the North Pacific Oscillation index (Linkin and Nigam 2008), which is defined as the principal component of the leading mode of the empirical orthogonal function (EOF) analysis for the winter SLP over the North Pacific (20°–80°N, 120°E–120°W) and is therefore independent from the PNA; 4) the Niño-3.4 index (INiño34), which is defined as the area-averaged SSTAs in the Niño-3.4 region (5°S–5°N, 120°–170°W); and 5) the PNA index, which is obtained from the National Weather Service Climate Prediction Center (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/pna.shtml).

In this study, we generate winter [December–February (DJF)] averages for the aforementioned data from 1958 to 2010. Here, the winter of 1958 refers to the 1958/59 winter. To document the interdecadal change in the relationship between ENSO and midlatitude atmospheric circulation and extratropical SSTAs, we divide the entire period (1958–2010) into two subperiods: 1958–76 and 1977–2010. The selection of the two periods is based on the 23-yr sliding correlation of the Niño-3.4 index with the East Asian trough index and the Aleutian low index (Wang and He 2012). To emphasize the interannual variability, we remove the linear trend for the aforementioned data.

3. Change in the relationships between ENSO and midlatitude atmospheric circulation

In boreal winter, there is a broad East Asian trough anchored off the east coast of East Asia (Jhun and Lee 2004), the strength of which can reflect the variability of the EAWM (Sun and Li 1997; Wang et al. 2009). In addition, there is a warm Aleutian low located over the northern Pacific, and its strength is a primary indicator of the winter North Pacific climate system and depicts the variability of the PNA teleconnection (Trenberth and Hurrell 1994; Overland et al. 1999). Both systems are located in midlatitudes. To depict the climate over the North Pacific, we display the interannual variation of the East Asian trough index, Aleutian low index, and Niño-3.4 index in Fig. 1. Clearly, there is a transition for the East Asian trough index starting around the mid-1980s after which the EAWM became weaker, as suggested by Chang et al. (2006). We can notice such a change in SLP field over the North Pacific, which is characterized by a strengthening of Aleutian low since the mid-1970s, which has been highlighted by Overland et al. (1999). Such change is also evident in the SST in the Niño-3.4 region, indicating that the warm ENSO episode becomes more frequent since the mid-1970s (Lau and Nath 1996). This is consistent with the Southern Oscillation index trends, which show negative values since the late 1970s (Namias et al. 1988; Nitta and Yamada 1989). Associated with these interdecadal climate changes, the relationship between ENSO and atmospheric circulation, we suppose, might undergo remarkable change. As shown in Fig. 2, ENSO and the Aleutian low show a significant out-of-phase relationship since the late 1970s, which is consistent with the results of Wang and He (2012). They suggested that the ENSO–EAWM relationship has weakened since the mid-1970s, whereas the ENSO–Aleutian low relationship has strengthened.

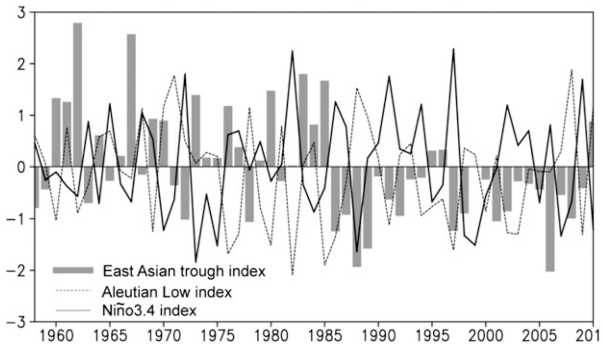

FIG. 1. The standardized interannual variation of the East Asian trough index (bar), Aleutian low index (dotted line), and Niño-3.4 index (solid line) during 1958–2010 winters.

To further identify where the ENSO–atmospheric circulation relationship experiences the most noticeable change before and after the mid-1970s, we compare the correlation between the Niño-3.4 index and 500-hPa

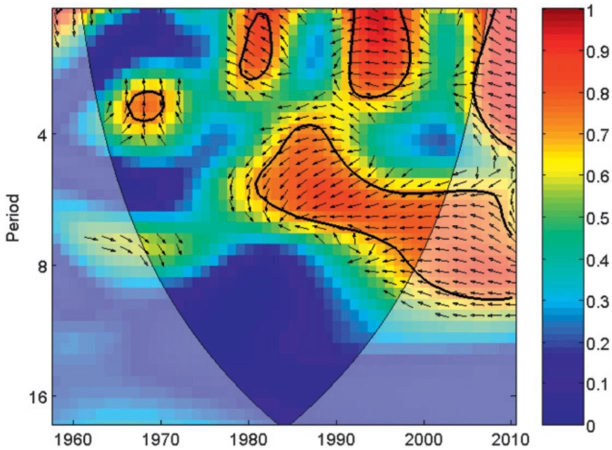

FIG. 2. Wavelet coherence between the standardized Niño-3.4 index and Aleutian low index time series for 1958–2010. The values exceeding the 95% significance level are shown within the thick contour. The relative phase relationship is shown as arrows (with in-phase pointing right and antiphase pointing left). The software is provided online (http://noc.ac.uk/using-science/crosswavelet-wavelet-coherence).

geopotential height anomalies for 1958–76 and 1977–2010. As shown in Fig. 3, dramatic differences are observed in the middle and high latitudes between the two periods, although the correlation pattern is similar in the tropical regions. That is, during 1958–76 (Fig. 3a) significant negative correlations are located in the Sea of Okhotsk and northwestern North Pacific, as well as in the eastern Pacific off the coast of the United States, which are accompanied by significant positive correlations over eastern and southern China and southern Japan where the East Asian trough is located. The correlation pattern over East Asia and North Pacific is similar to the NPO pattern (Walker and Bliss 1932; Linkin and Nigam 2008), implying that ENSO has a close relationship with the EAWM-related atmospheric circulation during 1958–76. In contrast, during 1977–2010 the NPO-like correlation pattern disappears, indicating that the connection between ENSO and atmospheric circulation over East Asia and western North Pacific becomes weaker. Instead, significant negative correlations appear in the northeastern North Pacific and the Gulf of Mexico, which are accompanied by significant positive correlations in much of North America (Fig. 3b). This pattern is similar to the PNA teleconnection (Wallace and Gutzler 1981), suggesting that ENSO has a close connection with atmospheric circulation over the eastern North Pacific and North America during 1977–2010. Apparently, the ENSO-related atmospheric circulation over East Asia and the western North Pacific undergoes an interdecadal weakening from 1958–76 to 1977–2010, whereas ENSO-related atmospheric circulation over the eastern North Pacific–North America undergoes an interdecadal strengthening. This implies that the influence of ENSO on midlatitude atmospheric circulation shifts eastward after the mid-1970s.

To confirm the robustness of the interdecadal changes of ENSO-related atmospheric circulation identified using the NCEP–NCAR reanalysis, we repeat these analyses using the ERA-40. The correlation patterns of 500-hPa geopotential height of the ERA-40 data closely resemble those of the NCEP–NCAR data (cf. Figs. 3c and 3a, and Figs. 3d and 3b).

To validate the change of the relationship between the EAWM and ENSO, an EAWM index—which is defined by Shi (1996); its interannual correlation with the East Asian trough index is about 0.81—is used to calculate the sliding correlation with the Niño-3.4 index. It is found that the EAWM and ENSO exhibit a significant relationship during 1958–76 but an insignificant one during 1977–2010 (Fig. 4). The results are consistent with those shown in Fig. 3, confirming that the impact of ENSO on the EAWM is very different before and after the mid-1970s.

However, there is still another issue which might be questioned: Why is the change in the ENSO–NPO relationship different from that in the ENSO–PNA relationship? Some previous studies (Wallace and Gutzler 1981; Trenberth 1990; Rogers et al. 2001) have pointed out that the NPO is closely tied with the PNA teleconnection. To answer this question and to support our aforementioned assumption, we show the 23-yr sliding correlations of the Niño-3.4 index with the PNA index and NPO index in Fig. 5, which validates the evolution of the relationship between ENSO and the NPO and PNA. The correlation coefficient between the NPO and PNA indices is -0.08, accounting for little shared variance, which means that such an NPO is in quadrature and uncorrelated with the PNA. Consistent with Fig. 3, it turns out that ENSO and NPO (PNA) show a significant (insignificant) correlation before the mid-1970s, followed by an obvious weakening (strengthening) of correlation in the late 1970s.

Figure 6 shows the regression maps of winter SLP, 850-hPa winds, and 300-hPa zonal wind anomalies with respect to the Niño-3.4 index for 1958–76 and 1977–2010, respectively. During 1958–76, the regression map of SLP exhibits a dipole pattern over the North Pacific (Fig. 6a), which looks like the NPO pattern. The negative anomalies over Siberia and the northern North Pacific result in a weakening of the Siberian high and a strengthening of the Aleutian low. Consistent with the SLP anomalies, there are two anomalous cyclones over Siberia and the northern North Pacific at 850 hPa (Fig. 6c). Also, an anomalous anticyclone is observed in

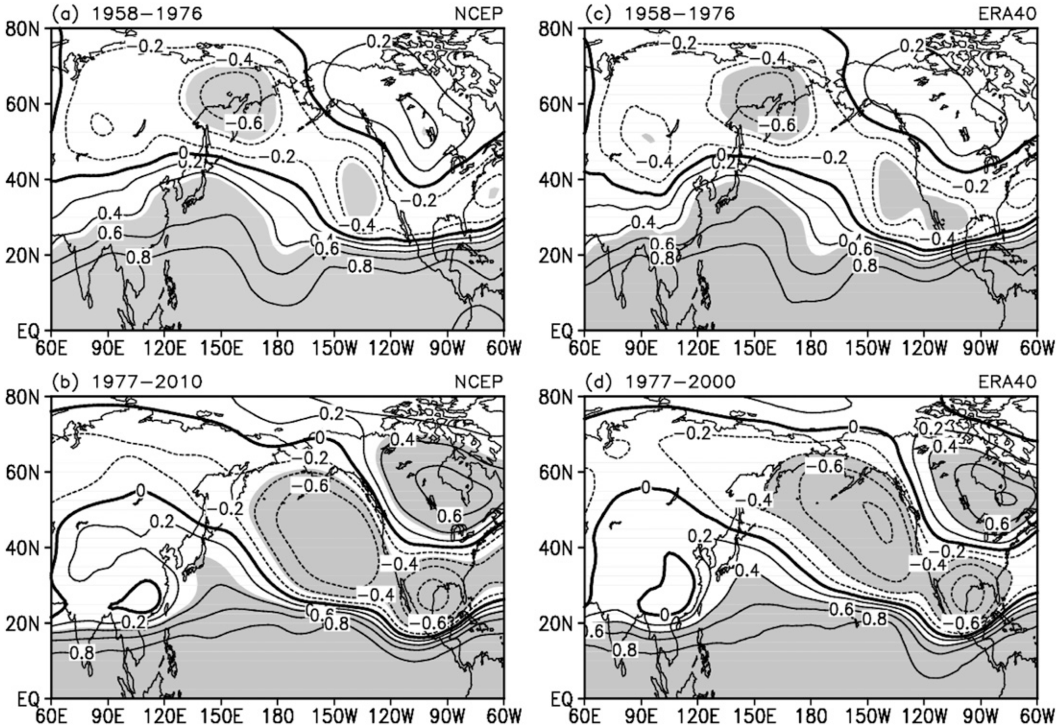

FIG. 3. Correlation coefficients between the 500-hPa geopotential height anomalies derived from the NCEP–NCAR reanalysis dataset and the Niño-3.4 index in (a) 1958–76 and (b) 1977–2010, respectively. (c),(d) As in (a),(b), but for the 500-hPa geopotential height anomalies from the ERA-40 dataset. Shaded values are significant at the 95% level from a two-tailed Student's t test.

the western North Pacific, which results in anomalous southerly wind in eastern China and a weakening of EAWM (Wang et al. 2000). In addition, the 300-hPa zonal wind shows zonal elongated positive anomalies extending from northern Japan to the Gulf of Mexico, and negative anomalies to the north extending from eastern Siberia to the northern United States and to the south including southern Japan and the central and eastern tropical Pacific (Fig. 6e). The negative anomalies of the East Asian jet stream are concurrent with the weak EAWM (Jhun and Lee 2004; Li and Yang 2010).

In contrast, during 1977–2010, the NPO-like SLP regression pattern disappears, suggesting a weakening of the ENSO–NPO relationship. Compared with Fig. 6a, positive anomalies appear in central and eastern North America. Significant negative anomalies are located more eastward over the eastern North Pacific and the magnitude of the correlations is much larger (Fig. 6b), which represents a deepening and eastward shift of the Aleutian low. Moreover, the regions with significant negative anomalies in the eastern North Pacific extend southeastward to South America. At 850 hPa, cyclonic anomalies located in the northwestern North Pacific during 1958–76 (Fig. 6c) shift eastward to the northeastern North Pacific and become much stronger during 1977–2010 (Fig. 6d). Meanwhile, obvious anticyclonic anomalies appear in North America. Furthermore, the anticyclone over the western North Pacific, which is a key system to bridge ENSO events and EAWM (Wang et al. 2000), becomes much weaker from 1958–76 to 1977–2010. This change further demonstrates that the relationship between ENSO and EAWM has weakened for the past three decades. In addition, the striking changes in the eastern North Pacific and North America imply the strengthening of the relationship between ENSO and the PNA teleconnection. The 300-hPa zonal wind anomalies also show distinct differences between the two periods (cf. Figs. 6e and 6f). An enlarged area with larger values of negative anomalies appears in central and eastern China and southern Japan during 1977–2010 (relative to the values during 1958–76), while significant positive anomalies located over the northern Japan become smaller. Another evident difference is the negative–positive–negative anomaly pattern over the eastern North Pacific, which mimics the ENSO-related atmospheric feature and influences the earth's climate extensively, with the strongest impact on

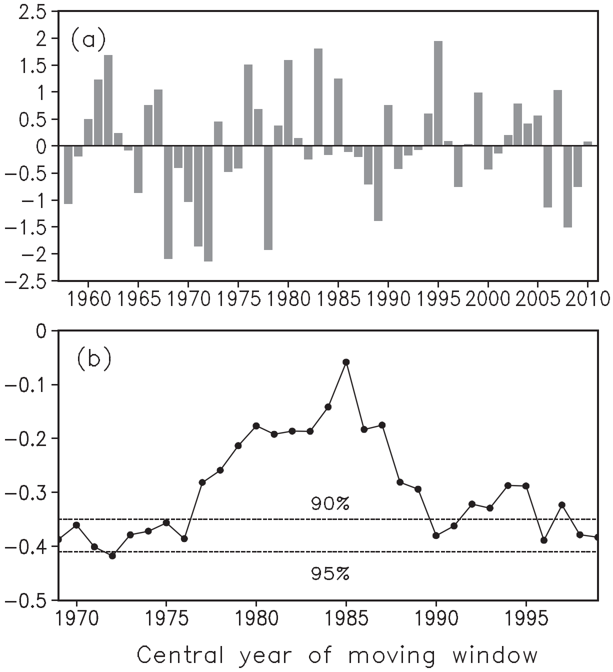

FIG. 4. (a) The standardized interannual variation of the East Asian winter monsoon index defined by Shi (1996). (b) The 23-yr sliding correlation of the Niño-3.4 index with the East Asian winter monsoon index. The dashed horizontal lines denote the values significant at the 90% and 95% levels from a two-tailed Student's t test.

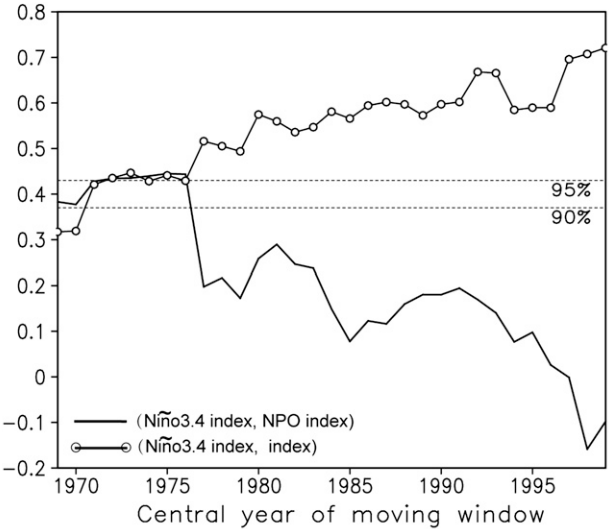

FIG. 5. The 23-yr sliding correlation of the Niño-3.4 index with the NPO index (solid line) and PNA index (solid line with unfilled circles). The dashed horizontal lines denote the values significant at the 90% and 95% levels from a two-tailed Student's t test.

climate over the central and eastern Pacific (Yang et al. 2002).

4. Different patterns of the North Pacific SSTA and their relationships with the extratropical circulation

Many studies suggest that the tropical SSTAs can induce large-scale atmospheric circulation anomalies (Wu et al. 2000; Yuan et al. 2008).The midlatitude atmospheric circulation anomalies can in turn drive the variations of extratropical SSTAs (Davis 1976; Miller et al. 1994). Also, the "atmospheric bridge" serves as a crucial link between SST fluctuations in the tropical Pacific and those in the midlatitude (Lau and Nath 1996; Lau 1997; Alexander et al. 2002). Because of the aforementioned interdecadal change of the relationship between the eastern tropical Pacific SSTAs and midlatitude atmospheric circulation, the SSTA pattern in the North Pacific might also show some differences between 1958–76 and 1977–2010.

Figure 7 shows the correlation pattern between winter SSTAs and the Niño-3.4 index for 1958–76 and 1977–2010, respectively. For both periods, the spatial pattern shows a similar elliptical shape in the central and eastern tropical North Pacific, which is the typical ENSO pattern (Nitta and Yamada 1989; Yeh and Kirtman 2004). However, distinct differences are observed in the extratropical North Pacific. During 1958–76 (Fig. 7a), a region with significant positive correlations appears off the coast of Japan, accompanied by two regions with negative correlations located toward its south and northeast, respectively. However, the significant positive correlation region in the midlatitudes tends to disappear during 1977–2010 (Fig. 7b). Meanwhile, a belt with significant negative correlation shows up, extending from the western tropical North Pacific to the eastern subtropical regions. Analogous changes also happen to the correlation pattern between the winter Niño-3.4 index and other seasons' SSTAs between the two periods (not shown).

To further investigate these identified changes of SSTA spatial pattern, we also perform the EOF analysis on the winter surface air temperature (SAT) anomaly for 1958–76 and 1977–2010, respectively. The EOF modes shown in Fig. 8 are statistically significant and distinct from the other EOF modes based on the method proposed by North et al. (1982). It appears that the first EOF mode of the winter SAT anomaly during 1958–76 (Fig. 8a), which explains 36.7% of the total variance, shows a spatial pattern similar to that in Fig. 7a. Similarly, the first leading EOF mode of the winter SAT anomaly during 1977–2010 (Fig. 8b), which explains 31.5% of the total variance, is in good agreement with Fig. 7b. It is also found that distinct features are mainly located in the extratropical North Pacific. During

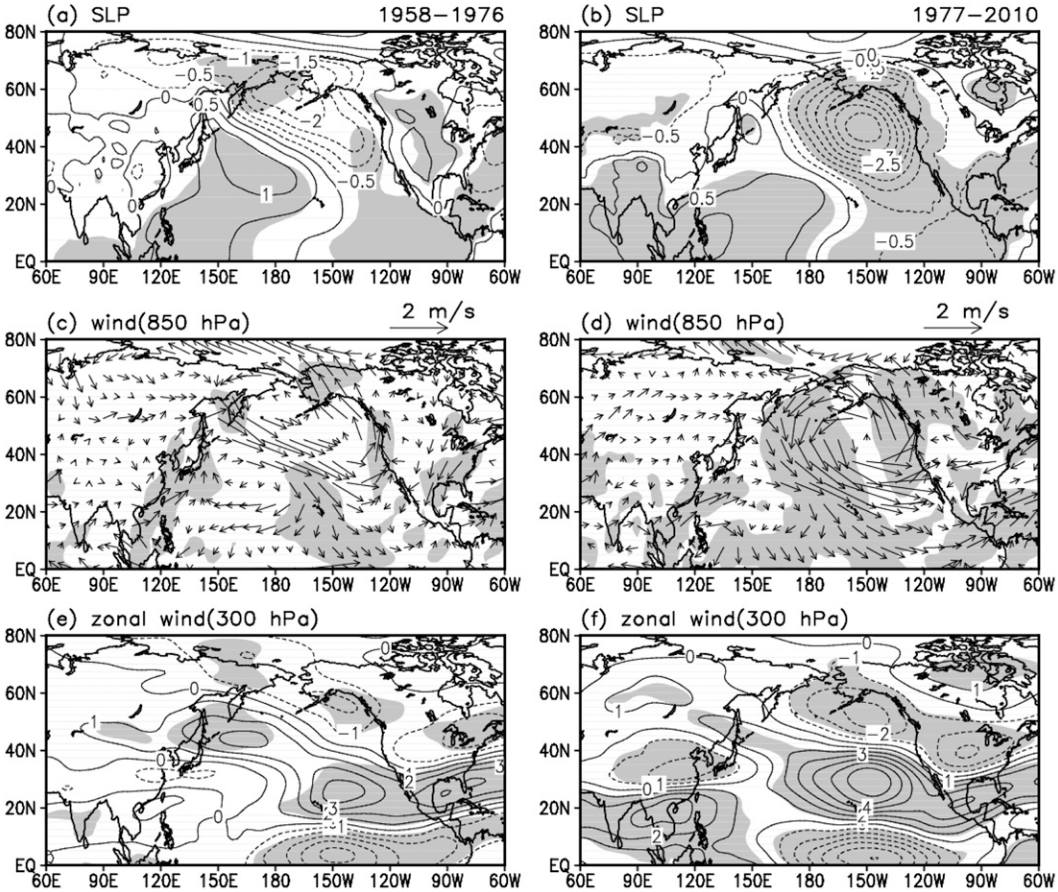

FIG. 6. The regression pattern of winter circulation anomalies with regard to the Niño-3.4 index for the periods (a),(c),(e) 1958–76 and (b),(d),(f) 1977–2010. From top to bottom are SLP, 850-hPa wind, and 300-hPa zonal wind. Shaded values are significant at the 95% level from a two-tailed Student's *t* test.

1958–76 (Fig. 8a), it is dominated by a large-amplitude negative SAT anomaly centered about 40°N and 160°W, accompanied by anomalies of the opposite sign along the eastern coast of East Asia and the western coast of North America (Fig. 8a). During 1977–2010 (Fig. 8b), the negative anomalies in the North Pacific are quantitatively larger and spatially broader, extending southwestward to the western tropical North Pacific. In addition, the positive anomalies along the eastern coast of East Asia are quantitatively smaller and spatially narrower. This means that the impact of ENSO on the temperature over East Asia and the western North Pacific has shifted eastward from 1958–76 to 1977–2010.

Because of the interdecadal changes in ENSO-related pattern, the North Pacific SSTAs show strikingly different correlations with the midlatitude atmospheric circulation between 1958–76 and 1977–2010. As shown in Fig. 9, during 1958–76, the East Asian trough index has significant negative correlations with the SSTAs extending from the western North Pacific east of Japan through the East China Sea, to the South China Sea, and in the central and eastern tropical Pacific. Significant positive correlations with the SSTAs occur in the western warm pool (Fig. 9a). During 1977–2010, the magnitude of the correlations in these regions has reduced substantially (Fig. 9b). The correlation pattern between the winter SSTAs and the Aleutian low index also shows remarkable differences in the North Pacific between the two periods (Figs. 9c,d). In contrast to the weak correlations occupying the entire central and eastern tropical Pacific during 1958–76 (Fig. 9c), significant negative correlations appear in the entire eastern tropical Pacific during 1977–2010 (Fig. 9d). Also, positive correlations appear in the western tropical Pacific and eastern South Pacific. The correlation pattern between the midlatitude atmospheric circulation (EAWM and Aleutian low) and the North Pacific SSTAs is much more similar to the conventional ENSO pattern (Figs. 9a,d), although the SSTA pattern more resembles ENSO Modoki in recent decades (Ashok et al. 2007).

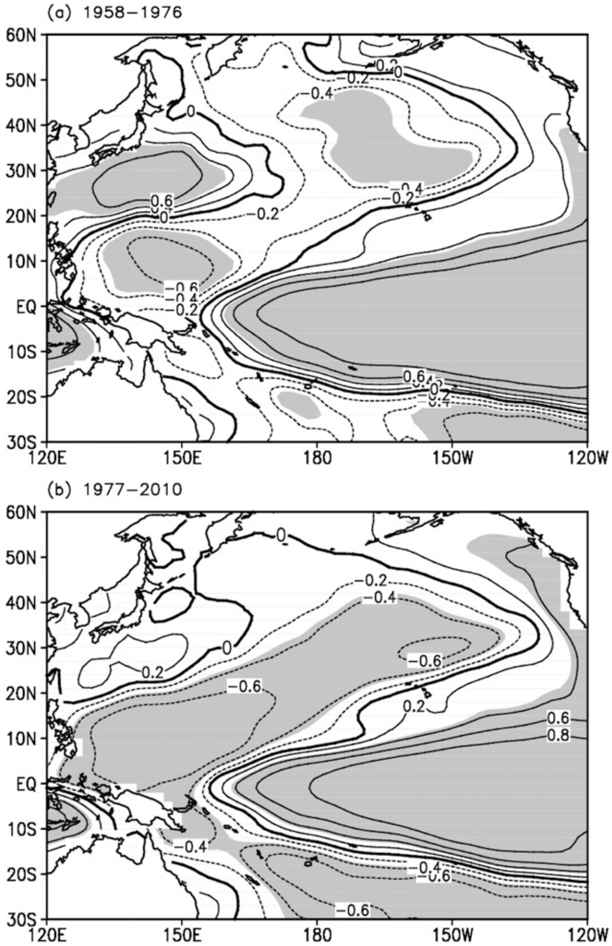

FIG. 7. Correlations coefficients of the winter (DJF) INiño34 with the SSTAs of the same time in (a) 1958–76 and (b) 1977–2010. Shaded values are significant at the 95% level from a two-tailed Student's *t* test.

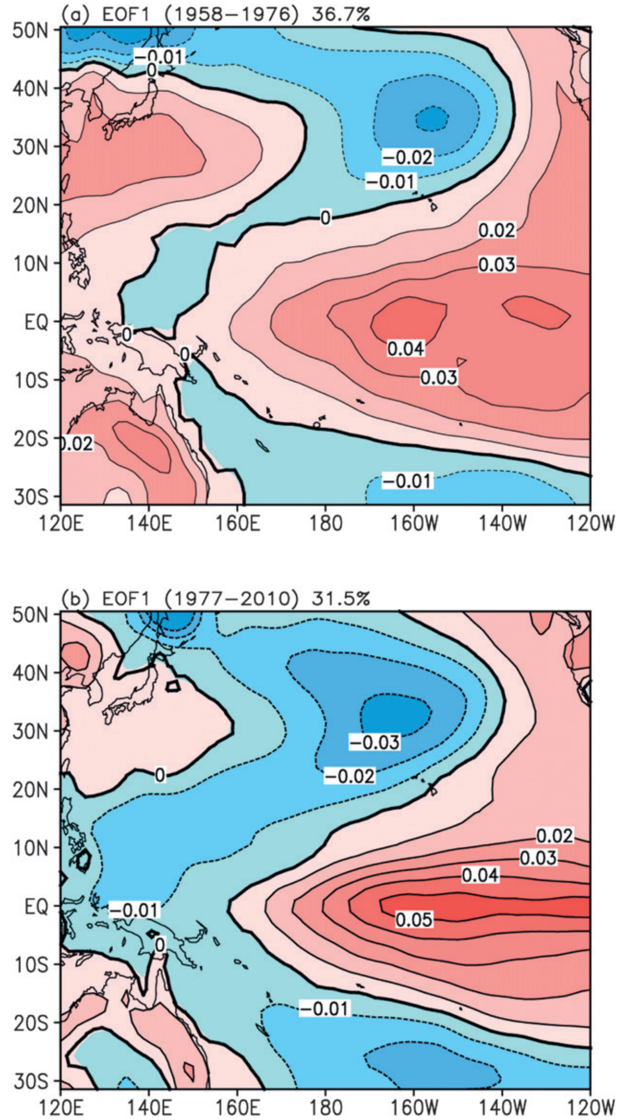

FIG. 8. The first leading mode of the EOF for the winter surface air temperature (2 m) anomaly in (a) 1958–76 and (b) 1977–2010.

5. Further analysis on the interdecadal change in the relationship

As is pointed out by the aforementioned analysis, both the ENSO-related atmospheric circulation in the midlatitudes and the SSTA pattern in the North Pacific midlatitudes show interdecadal changes during 1958–2010. To investigate the changes in the covariability between the atmospheric circulation and North Pacific SSTAs, a singular value decomposition (SVD) analysis is applied to the normalized 500-hPa geopotential height anomalies and normalized SSTAs within the domain of 0°–80°N and 60°E–60°W. Figure 10 is the heterogeneous correlation map for the first SVD mode in the two periods, which also shows great distinction between 1958–76 and 1977–2010; that is, the distribution in the central and eastern tropical North Pacific is almost the same in the two periods, whereas distinct differences appear in the extratropical North Pacific (Figs. 10b,d). Accompanying the different pattern of the SSTA, the distribution of the heterogeneous correlation pattern of 500-hPa geopotential height anomalies during 1958–76 (Fig. 10a) is different from that during 1977–2010 (Fig. 10c).

During 1958–76, significant positive SSTAs lie in the central and eastern tropical North Pacific and off the coast of southern China and southern Japan (Fig. 10b). In addition, there are two significant negative centers located in the northern North Pacific and to the east of the Philippines, respectively. The correlation between the time coefficients of the two fields is 0.925. This suggests that the 500-hPa geopotential height shows positive anomalies in East Asia, the tropical North Pacific,

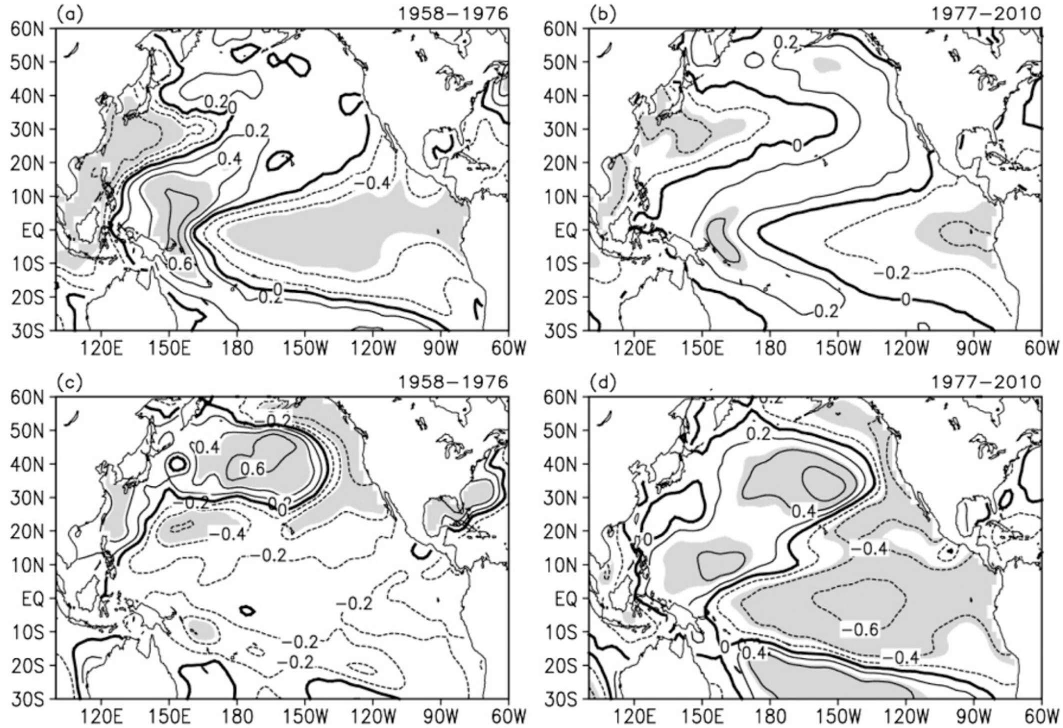

FIG. 9. The correlation coefficients of the winter SSTAs (DJF) with the EAMW index in (a) 1958–76 and (b) 1977–2010; (c),(d) as in (a),(b), but for the DJF SSTAs with the Aleutian low index. The values in the shaded area are significant at the 95% level.

and North America and negative anomalies in Siberia and the northern and eastern North Pacific associated with warm ENSO events (Fig. 10a). During 1977–2010, except for some regions off the coast of East Asia, the northwestern North Pacific shows significant negative SSTAs (Fig. 10d). The most striking distinction is that the values located in the regions around 25°N and 180° change from positive during 1958–76 to negative during 1977–2010. Meanwhile, the negative and positive 500-hPa geopotential height anomalies located in the Sea of Okhotsk and East Asia become smaller (Fig. 10c). In contrast, the positive and negative values over North America and the eastern North Pacific become larger. The correlation between the time coefficients of the two fields in 1977–2010 is 0.947, indicating a strong relationship between the PNA-related atmospheric circulation and the North Pacific SSTAs during this period. The heterogeneous correlation patterns of 500-hPa geopotential heights (SSTAs) during 1958–76 [see Fig. 10a (Fig. 10b)] and 1977–2010 [Fig. 10c (Fig. 10d)] are quite similar to Figs. 3a and 3b (Figs. 7a and 7b), respectively. Thus, the interdecadal changes in the atmospheric circulation patterns might be one of the primary causes for the interdecadal change in the relationship of ENSO with the midlatitude circulation and extratropical SSTAs.

As revealed by many previous studies, the most striking abrupt change in the large-scale boreal winter atmospheric circulation over the North Pacific is the southeastward shift (Graham 1994) and intensification of the Aleutian low since the 1970s (Trenberth 1990; Trenberth and Hurrell 1994). Considering its important role in connecting tropical Pacific SSTAs with extratropical SSTAs (Latif and Barnett 1994; Miller et al. 1994) and midlatitude atmospheric circulation (Graham 1994), we attempt to understand to what extent the Aleutian low can influence the interdecadal change in the relationship between ENSO and midlatitude atmospheric circulation and extratropical SSTAs. To remove the possible linear influences of the winter Aleutian low, we compute partial correlations of the Niño-3.4 index with the 500-hPa geopotential height anomalies during 1958–76 and 1977–2010, respectively. The results during 1958–76 (Fig. 11a) are similar to those in Fig. 3a. However, Fig. 11b demonstrates that the significant impact of the Aleutian low on the relationship between ENSO and midlatitude atmospheric circulation does occur during 1977–2010. Specifically, after removing the linear influence of the Aleutian low, ENSO shows a significant positive correlation with the East Asian trough, and the PNA-like correlation pattern disappears during 1977–2010.

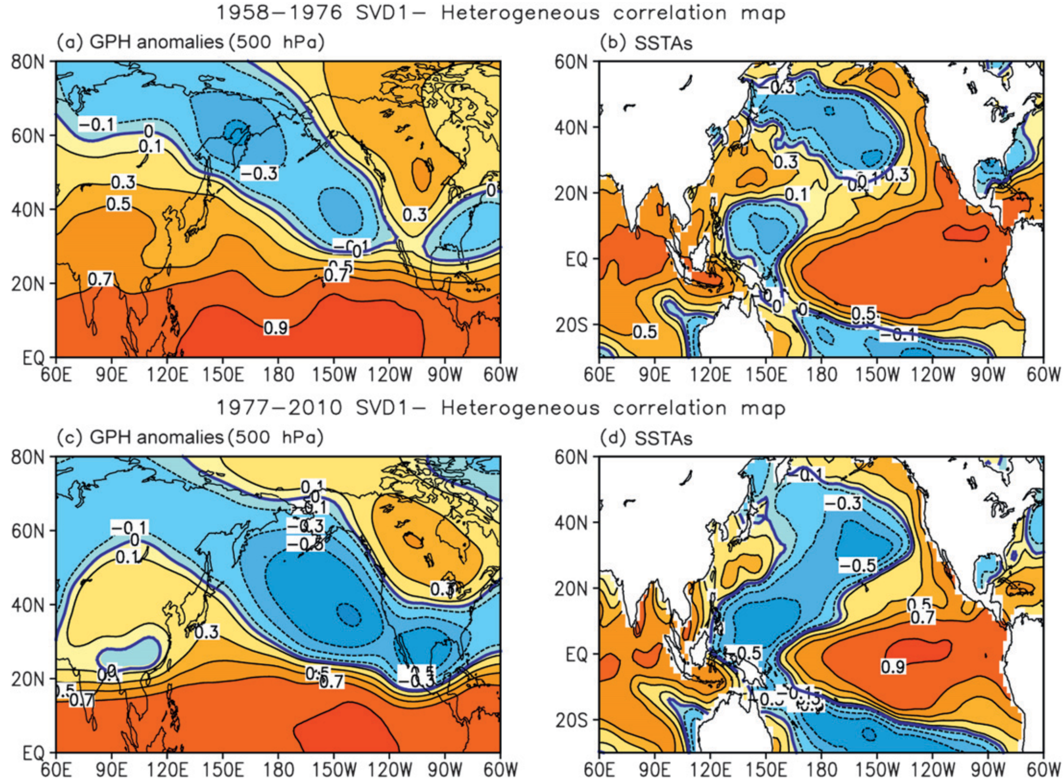

FIG. 10. The heterogeneous correlation map of the first mode of SVD for (left) 500-hPa geopotential height anomalies and (right) SSTAs for (a),(b) 1958–76 and (c),(d) 1977–2010.

Further evidence in support of this analysis comes from the regression patterns of winter SLP and 850-hPa wind anomalies with regard to the Niño-3.4 index, given that the linear influence of the Aleutian low is removed (Fig. 12). The regression patterns of atmospheric circulation during 1958–76 (Figs. 12a,c) exhibit similar distributions to those in Figs. 6a and 6c. However, there is distinct difference between the regression patterns of atmospheric circulation with (Figs. 6b,d) and without (Figs. 12b,d) the Aleutian low in the latter period.

During 1977–2010, after the linear influence of the Aleutian low is removed, the relationship between ENSO and atmospheric circulation over the western subtropical North Pacific strengthens. In contrast, the ENSO–PNA relationship weakens (Fig. 12b). For the regression pattern of 850-hPa wind anomalies without the Aleutian low (Fig. 12d), an obvious anomalous anticyclone is found in the western North Pacific, which leads to a significant positive correlation of the warm ENSO event with the anomalous southerly winds along the east coast of East Asia. In addition, the anomalous cyclone over the eastern North Pacific and anomalous anticyclone over North America are weakened. This analysis implies that ENSO would have a strong (weak) relationship with the midlatitude circulation over the western (eastern) North Pacific during 1977–2010 if there were no deepening and eastward shift of the Aleutian low in the mid-1970s.

These analyses show that the interdecadal change of the Aleutian low that occurred around the mid-1970s does contribute to the interdecadal change of the relationship between ENSO and the midlatitude atmospheric circulation. We further detect the interdecadal change of the relationship among various climate indices. As shown in Fig. 13, there is a persistent strong relationship between the intensity of the anomalous anticyclone located in the western North Pacific and East Asian trough index (solid line). However, the correlation between the anomalous anticyclone index and the Niño-3.4 index shows an obvious weakening since the mid-1970s (solid line with unfilled circles). This may explain why the relationship between ENSO and EAWM has weakened in recent decades. When the linear impact of the Aleutian low is removed, there is no significant weakening in the relationship between the Niño-3.4 index and the anomalous anticyclone index (solid line with filled circles). This further confirms the speculation that the deepening and eastward shift of the Aleutian

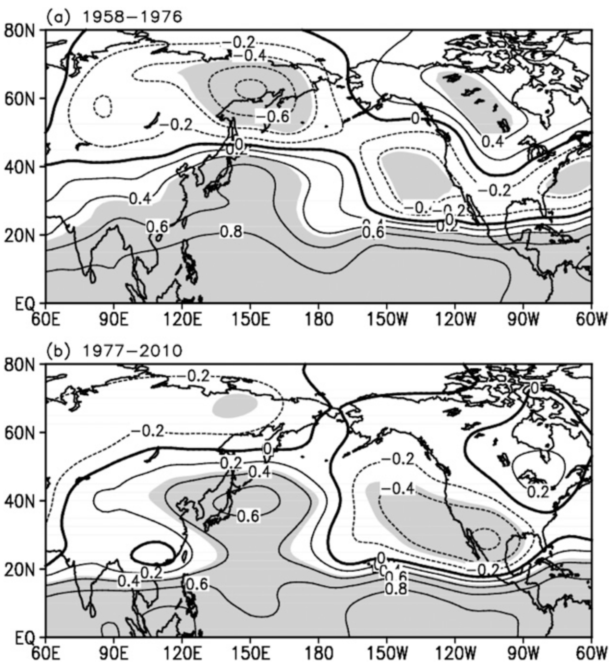

FIG. 11. After removing the linear influence of the Aleutian low, the winter (DJF) partial correlation between the Niño-3.4 index and 500-hPa geopotential height anomalies in (a) 1958–76 and (b) 1977–2010. Shaded values are significant at the 95% level from a two-tailed Student's t test.

low since the mid-1970s suppresses the influence of ENSO on the anomalous anticyclone over the western North Pacific.

Furthermore, as shown in Fig. 14, the correlation between the NPO index and the negative anomalous anticyclone index maintains high correlation from 1958 to 2010 (solid line with plus signs). The weakening of relationship between ENSO and the anomalous anticyclone over the western North Pacific may lead to the weakening of relationship between ENSO and the NPO (solid line with filled circles). At the same time, the NPO index and the East Asian trough index are strongly correlated with each other from 1958 to 2010 (solid line with times signs). Thus, the weakening of the relationship between ENSO and the NPO may be another cause for the weakening of the ENSO–EAWM relationship.

Consistent with Fig. 3, the Niño-3.4 index and the PNA index show a very weak correlation before the mid-1970s, followed by a strong correlation after the late 1970s (Fig. 15, solid line with unfilled circles). This temporal evolution of the correlation confirms that the impact of ENSO on the midlatitude atmospheric circulation shifts eastward and the relationship between ENSO and the PNA has therefore strengthened since the mid-1970s. When the linear influence of the Aleutian low is removed, there is no significant correlation between ENSO and the PNA (Fig. 15, solid line with filled circles). This implies that the deepening and eastward shift of the Aleutian low since the mid-1970s may promote the connection between ENSO and the atmospheric circulation over the eastern North Pacific and North America.

Based on this analysis, four key regions are selected in the extratropical North Pacific: north (40°–50°N, 160°E–160°W), west (24°–30°N, 125°–145°E), middle (15°–30°N, 160°E–180°), and east (25°–30°N, 160°–140°W). Four SSTA indices are defined as the area-averaged SSTAs in the four regions, referred as NPI, WPI, MPI, and EPI, respectively.

To examine the evolution of the relationship between ENSO and the extratropical SSTAs, we calculate the 21-yr sliding correlation between the Niño-3.4 index and the four indices (Fig. 16). Consistent with Figs. 7a and 7b, all the sliding correlations show obvious interdecadal shift. The winter Niño-3.4 index and NPI show significant and high negative correlations before the late 1970s, followed by an obvious weakening of the correlation (Fig. 16a). The relationship between the Niño-3.4 index and WPI also weakens since the mid-1980s (Fig. 16b). The weakening of the relationship between ENSO and the northwestern North Pacific SSTAs may be attributed to the interdecadal change of the extratropical atmospheric circulation. As mentioned earlier, ENSO-related atmospheric circulation anomalies in the North Pacific are similar to the NPO pattern during 1958–76 (Fig. 6a). An anomalous cyclone is found over the northern North Pacific and an anomalous anticyclone is observed in the western North Pacific, resulting in northwesterly wind anomalies in the northern subtropical North Pacific and southerly wind anomalies along the east coast of East Asia (Fig. 6c). Anomalous northwesterly winds in the northern subtropical North Pacific are expected to bring cold air to the northern subtropical North Pacific and favor negative SSTAs in this area. This is why ENSO and northern subtropical North Pacific SSTAs show significant negative correlations during 1958–76 (Fig. 7a). However, the connection between ENSO and the extratropical Asian–Pacific atmospheric circulation is disrupted by the climate shift in the mid-1970s. The weakening of the relationship between ENSO and the midlatitude East Asian–Pacific atmospheric circulation therefore weakens the linkage between the northern subtropical North Pacific SSTAs and ENSO in recent decades (Figs. 7b and 16a). Anomalous southerly winds along the coast of East Asia are helpful for a weak EAWM, which tends to prevent cold air from getting to the western subtropical North Pacific and results in positive SSTAs in this region. This can, to some extent, explain the significant positive

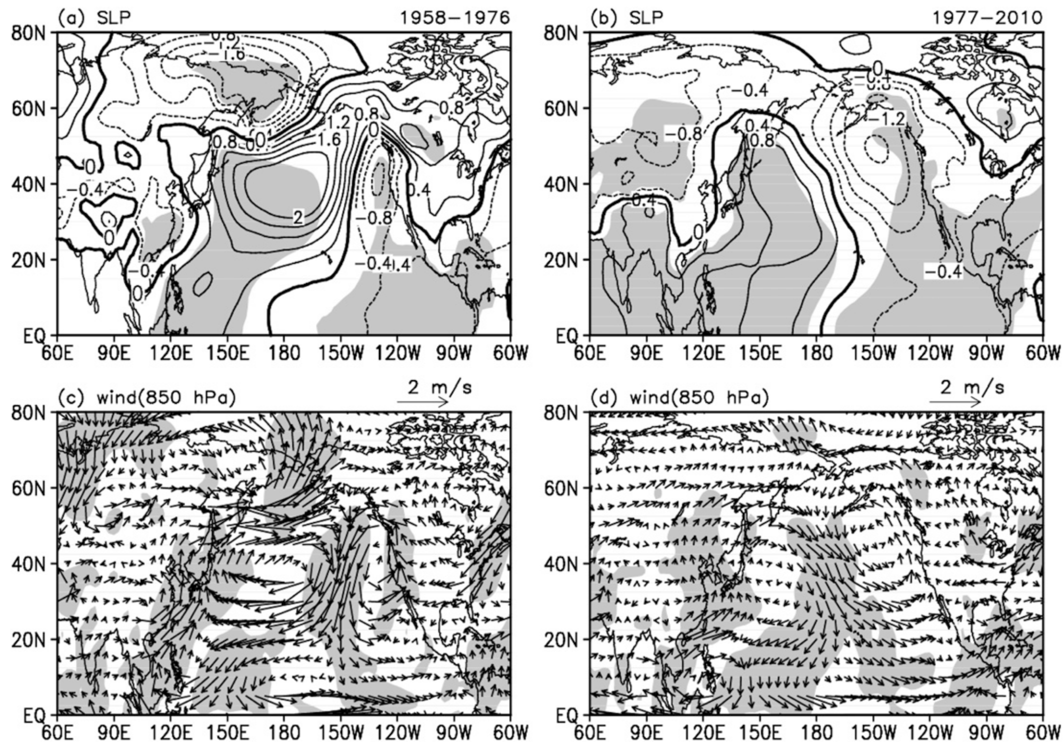

FIG. 12. After removing the linear influence of the Aleutian low, the regression pattern of winter circulation anomalies with regard to the Niño-3.4 index for (top) SLP and (bottom) 850-hPa wind for (a),(c) 1958–76 and (b),(d) 1977–2010. Shaded values are significant at the 95% level from a two-tailed Student's *t* test.

correlations between ENSO and the western subtropical North Pacific SSTAs during 1958–76 (Figs. 7a and 16b). As the Aleutian low shifted eastward in the mid-1970s, the significant correlation between ENSO and the anomalous anticyclone over the western North Pacific became weak during 1977–2010. Therefore, ENSO-related anomalous southerly winds along the coast of East Asia have weakened significantly (Fig. 6d). This suggests that the linkage between ENSO and the western subtropical North Pacific SSTAs is suppressed, which may account for the weakening of the relationship between ENSO and the western subtropical North Pacific SSTAs.

On the contrary, the relationship between ENSO and SSTAs in the central and eastern subtropical North Pacific has strengthened in recent decades (Figs. 7b and 16c,d). Before the mid-1970s, the correlation between the Niño-3.4 index and the MPI is weak and cannot exceed 95% significant level. However, the INiño34–MPI relationship has strengthened around the mid-1970s and has maintained a significant and stable level since the late 1970s (Fig. 16c). The correlation between the Niño-3.4 index and EPI shows an obvious strengthening of the relationship around the early 1970s (Fig. 16d). These facts raise a hypothesis: the change of the SSTAs in the subtropical North Pacific in response to ENSO may be also related to the deepening and eastward shift of the Aleutian low in the mid-1970s. As revealed by the 850-hPa wind pattern in Fig. 6d, the anomalous northerly winds over the central subtropical North Pacific are much stronger and can reach lower latitudes during 1977–2010 than that during 1958–76, which can advect cold air to the central and eastern subtropical North Pacific. As a consequence, SST in the central and eastern subtropical North Pacific decreases with El Niño events.

The idea of this mechanism can be summarized as follows. Associated with the anomalous anticyclone located in the western North Pacific, ENSO can connect with the EAWM-/NPO-related atmospheric circulation, which in turn can transport the ENSO signal to the SST in the western and northern subtropical North Pacific. On the other hand, the Aleutian low acts as a key system connecting ENSO with the PNA-related atmospheric circulation and the SSTAs in the central and eastern subtropical North Pacific. After the mid-1970s, the Aleutian low shifted eastward, which likely weakened (strengthened) the influence of ENSO on the western North Pacific anticyclone (Aleutian low). Therefore, the correlation between ENSO and the EAWM-/NPO-related (PNA-related) circulation is weakened (strengthened), likely contributing to the weakened (strengthened)

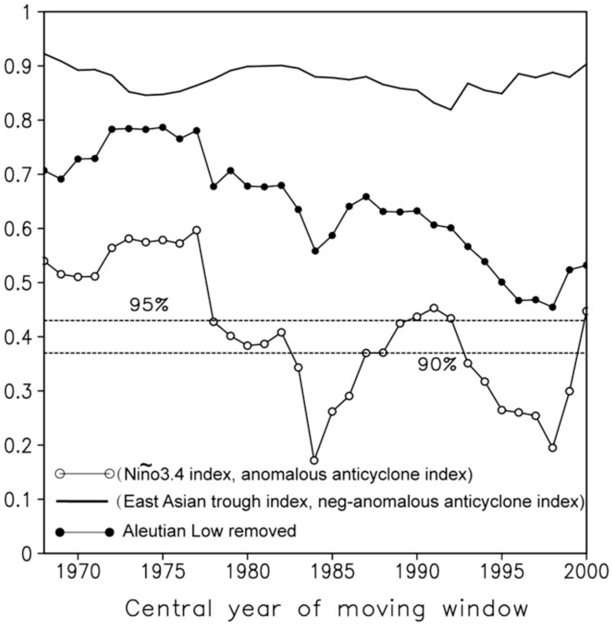

FIG. 13. The 21-yr sliding correlation of the Niño-3.4 index with the anomalous anticyclone index, which is defined as the area-averaged SLP over the western subtropical North Pacific (20°–40°N, 130°E–180°) (solid line with unfilled circles), and that when the signals of the Aleutian low are removed (solid line with filled circles). The 21-yr sliding correlation between the East Asian trough index and the negative anomalous anticyclone index is also shown (solid line). The horizontal dashed lines indicate the values significant at the 90% and 95% levels from a two-tailed Student's t test.

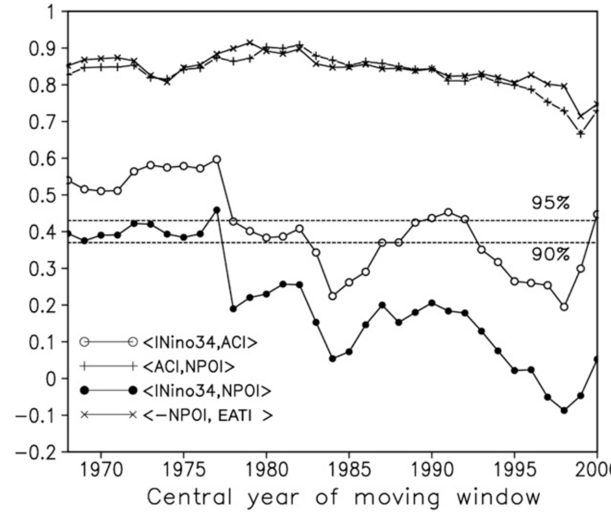

FIG. 14. The 21-yr sliding correlation of the Niño-3.4 index (INiño34) with the anomalous anticyclone index (ACI; solid line with unfilled circles) and NPO index (NPOI; solid line with filled circles). The 21-yr sliding correlation between the NPO index and anomalous anticyclone index and that between the East Asian trough index (EATI; solid line with times signs) and the negative NPO index (solid line with plus signs) are also shown. The dashed horizontal lines denote the values significant at the 90% and 95% levels from a two-tailed Student's t test.

relationship between ENSO and SSTAs in the northwestern (central and eastern) subtropical North Pacific.

6. Summary and concluding remarks

This study compares the correlation between ENSO and midlatitude atmospheric circulation in boreal winters between 1958–76 and 1977–2010. A pronounced different correlation pattern is found in the midlatitudes. During 1958–76, the NPO-like atmospheric circulation anomaly pattern shows a significant correlation with ENSO, suggesting a close connection between ENSO and EAWM-related atmospheric circulation. But during 1977–2010, the NPO-like correlation pattern disappears. Instead, significant negative and positive correlations appear in the eastern North Pacific and North America, respectively, similar to the PNA teleconnection. These changes can also be depicted clearly by the weakening (strengthening) of correlations between the Niño-3.4 index and the NPO index (PNA index) in the mid-1970s, which indicates that the impact of ENSO on the midlatitude atmospheric circulation has shifted eastward in recent decades. In addition, great changes have taken place in the correlations between ENSO and extratropical North Pacific SSTAs. During 1958–76, significant negative and positive correlations are found in the northern and western subtropical North Pacific, respectively. However, the positive correlations

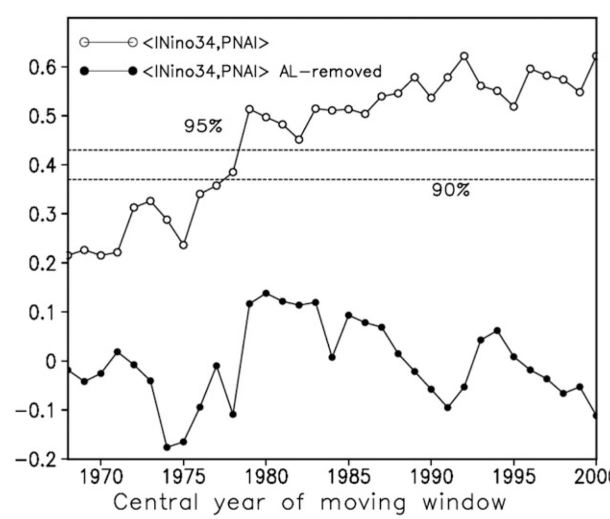

FIG. 15. The 21-yr sliding correlation of the Niño-3.4 index with the PNA index (solid line with unfilled circles) and when the Aleutian low effect is removed (solid line with filled circles). The horizontal dashed line indicates the values significant at the 90% and 95% levels from a two-tailed Student's t test.

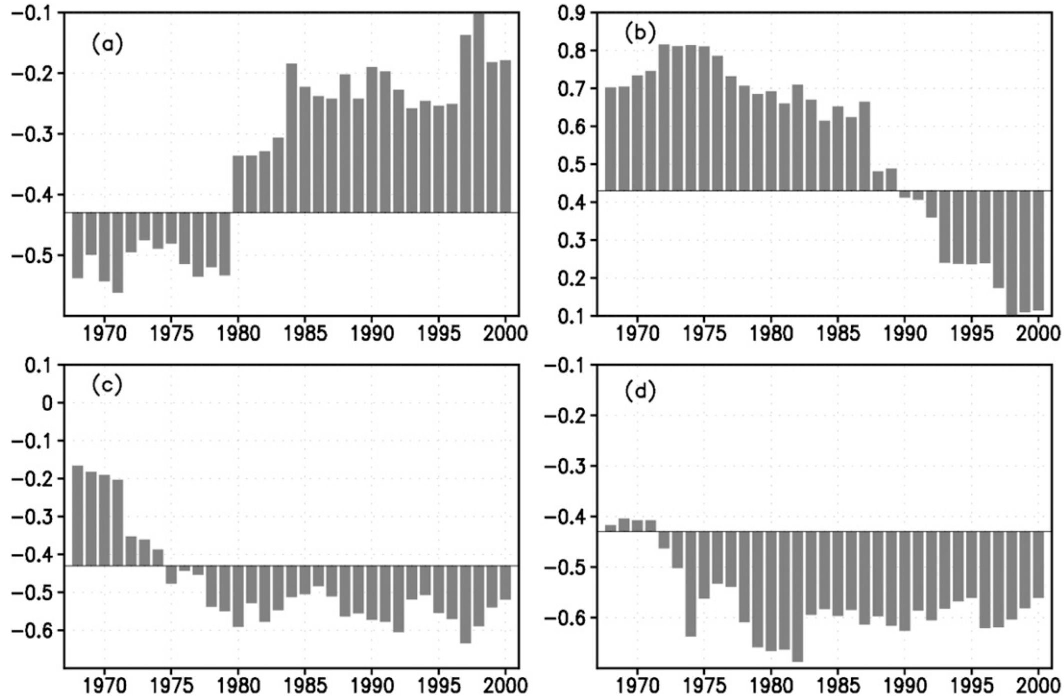

FIG. 16. The 21-yr sliding correlation between the Niño-3.4 index and North Pacific area-averaged SSTAs in (a) north (40°–50°N, 160°E–160°W; NPI), (b) west (24°–30°N, 125°–145°E; WPI), (c) middle (15°–30°N, 160°E–180°; MPI), and (d) east (25°–30°N, 160°–140°W; EPI) during 1958–2010 winters. The base of bar is −0.43 (or 0.43), which indicates the standard significant at the 95% level from a two-tailed Student's t test.

located in the western subtropical North Pacific become insignificant during 1977–2010. Also, the negative correlation pattern located in the northern subtropical North Pacific during 1958–76 shifts eastward and extends southwestward in the latter period, implying that there is a strengthened relationship between ENSO and SSTAs in the central and northeastern subtropical North Pacific since the mid-1970s.

One way by which ENSO influences the EAWM-related atmospheric circulation is through the anomalous anticyclone located in the western North Pacific (Wang et al. 2000). It is indicated that the winter El Niño events in 1958–76 can cause an anomalous anticyclone over the western North Pacific, the intensity of which shows a close relationship with the EAWM-/NPO-related atmospheric circulation. However, the connection between ENSO and the western North Pacific anticyclone is disrupted in the mid-1970s. Instead, the winter El Niño events during 1977–2010 are associated with significant lowering of SLP and an anomalous cyclone over the eastern North Pacific, which are related to the PNA teleconnection (Nitta and Yamada 1989).

Further analyses indicate that the interdecadal shift of the Aleutian low, which occurred around the mid-1970s, might be responsible for these identified changes. When the linear influence of the Aleutian low is removed, significant intensification of SLP and an obvious anticyclone over the western North Pacific are observed when the winter El Niño events occur during 1977–2010, which is analogous to the situation during 1958–76. In contrast, no obvious changes in the eastern North Pacific atmospheric circulation are observed. Also, there is no obvious weakening (strengthening) of correlations between the Niño-3.4 index and the anomalous anticyclone index (PNA index). This analysis suggests that the deepening and eastward shift of the Aleutian low might promote the impact of ENSO prevailing over the eastern North Pacific during 1977–2010, leading to the weakening (strengthening) of the correlation between ENSO and EAWM-/NPO-related (PNA-related) atmospheric circulation in the mid-1970s.

Based on the atmospheric bridge theory (Lau and Nath 1996; Lau 1997; Alexander et al. 2002), this study suggests that changes in the connection between ENSO and midlatitude atmospheric circulation are likely to contribute to the different correlations of ENSO with extratropical SSTAs between 1958–76 and 1977–2010. During 1958–76, the El Niño events are associated with an anomalous cyclone over the northern North Pacific and an anomalous anticyclone over the western North

Pacific, causing northwesterly wind anomalies to occur in the northern subtropical North Pacific and southerly wind anomalies to occur along the coast of East Asia. Anomalous northwesterly winds are expected to bring cold air to the northern subtropical North Pacific and favor negative SSTAs in this area. Meanwhile, the anomalous southerly winds are favorable for a weak EAWM, which prevents cold air reaching the ocean along East Asia and causes positive SSTAs in this region. As the relationship between ENSO and the anomalous anticyclone over the western North Pacific has weakened since the mid-1970s, the impact of ENSO on SSTAs in the western subtropical North Pacific is therefore suppressed during 1977–2010. Whereas the anomalous cyclone is located more eastward during 1977–2010 and is supposed to advect more cold air to the central and eastern subtropical North Pacific. As a result, negative SSTAs occupy the central and eastern subtropical North Pacific when the El Niño events occur in the latter period.

The mechanism for changes in the relationship between ENSO and midlatitude atmospheric circulation is rather complex. As suggested by Wang et al. (2008), the interannual relationship between ENSO and the EAWM is weak and insignificant when the Pacific decadal oscillation (PDO) is in its high phase. When the PDO is in its low phase, ENSO exerts a strong impact on the EAWM. Actually, the low phase of the PDO prevailed from 1947 to 1976, whereas the high phase of the PDO dominated from 1977 to the mid-1990s (Hare and Francis 1995; Zhang et al. 1997; Mantua and Hare 2002; Dai 2012). Thus, the weakening of the relationship between ENSO and the EAWM discussed here may also result from the high phase of the PDO since the mid-1970s. The influence of the PDO on the nonstationary EAWM–ENSO relationship is also documented by Zhou et al. (2007). However, considering the significant correlation coefficient between the intensity of the PDO and the Aleutian low (Sun and Wang 2006), the interdecadal shift of the PDO and the Aleutian low might be two aspects of the same thing. What is more, other external factors (e.g., snow cover or sunspots) may exert impacts on the EAWM variability through feedback processes with ENSO (Zhou et al. 2007). More work and modeling studies are needed to better understand the physical processes of the weakening (strengthening) of the relationship between ENSO and the East Asian–western North Pacific (eastern North Pacific–North America) atmospheric circulation.

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