The North Pacific Climate Transitions of the Winters of 1976/77 and 1988/89

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ABSTRACT

This paper examines characteristic changes in North Pacific sea surface temperature (SST) variability during the boreal winter (December–February) for two subperiods (1956–88 and 1977–2009) during which the 1976/77 and the 1988/89 climate transitions occurred. It is found that the Pacific decadal oscillation (PDO)-like SST variability plays a dominant role in the 1976/77 climate transition, while both the North Pacific Gyre Oscillation (NPGO)-like and PDO-like SST variability contribute to the 1988/89 climate transition. Furthermore, the leading mode changes from PDO-like SST variability during the period 1956–88 to NPGO-like SST variability during the period 1977–2009, indicative of an enhancement of NPGO-like SST variability since 1988. Changes in sea level pressure across the 1976/77 climate transition project strongly onto the Aleutian low pressure system. But sea level pressure changes across the 1988/89 climate transition project primarily onto the North Pacific Oscillation, which is associated with remote changes in the Arctic Oscillation over the polar region as well. This contributes to enhancing the NPGO-like SST variability after 1988. The authors also analyze the output from an ensemble of Tropical Ocean and Global Atmosphere (TOGA) experiments in which the observed SSTs are inserted only at grid points in the tropics between 20°S and 20°N. The results indicate that the changes in the North Pacific atmosphere in the 1976/77 climate transition are mostly due to the tropics, whereas those in the 1988/89 climate transition are not.

1. Introduction

A considerable body of literature is devoted to the discussion of persistent widespread changes in the North Pacific basin climate (Trenberth 1990 and references therein). The wealth of studies of North Pacific climate indicates that North Pacific sea surface temperature (SST) variability is dominated by decadal-to-multidecadal time scales, although the underlying climate dynamics still remain unclear (Nitta and Yamada 1989; Trenberth and Hurrell 1994; Miller et al. 1994b; Latif and Barnett 1994; Lau and Nath 1994; Mantua et al. 1997; Nakamura et al. 1997; Minobe 1997; Jin 1997; Giese and Carton 1999; Garreaud and Battisti 1999; D'Arrigo et al. 1999; Miller and Schneider 2000; Mantua and Hare 2002; Yeh and Kirtman 2004; Deser et al. 2004; Wu et al. 2005; Mestas-Nunez and Miller 2006). Decadal climate variations in the North Pacific are characterized by changes in the intensity of the large-scale atmospheric circulation accompanied by changes in oceanic properties, such as SST, sea surface salinity, and mixed layer depth in the North Pacific (Alexander et al. 2002; Deser et al. 2004). Among these variations, it is well known that the North Pacific climate experienced a significant change in the winter of 1976/77. Because of the rapid onset and large amplitude, this variation has been termed the ''climate

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transition'' or ''climatic regime shift''[1] of the winter of 1976/77 (Trenberth 1990; Miller et al. 1994b; Graham et al. 1994; Deser and Phillips 2006).

During the winter of 1976/77, the atmosphere–ocean climate system over the North Pacific was observed to shift its basic state abruptly (Graham 1994; Miller et al. 1994a). Time series of mean sea level pressure over the entire North Pacific showed that the Aleutian low pressure significantly deepened during the winter of 1976/77. Concomitantly, the Pacific–North America (PNA) teleconnection pattern changed. In addition, the difference of observed winter SST before and after 1976/77 is characterized by a large cooling over an elliptical area in the western and central North Pacific along with a warming of the coastal northeastern Pacific Ocean (Trenberth 1990; Deser and Phillips 2006). Regarding the origin of the North Pacific 1976/77 climate transition, most previous studies argued that it was mainly due to changes in the tropical Pacific SST, whose effect is transmitted through atmospheric teleconnections to the midlatitudes (Trenberth and Hurrell 1994; Graham 1994; Zhang et al. 1997; Deser et al. 2004; Deser and Phillips 2006). Meanwhile, there exists another point of view that it could be affected by atmosphere–ocean coupled interactions in the midlatitudes (Latif and Barnett 1994, 1996; Schneider et al. 2002; Qiu 2003; Kwon and Deser 2007).

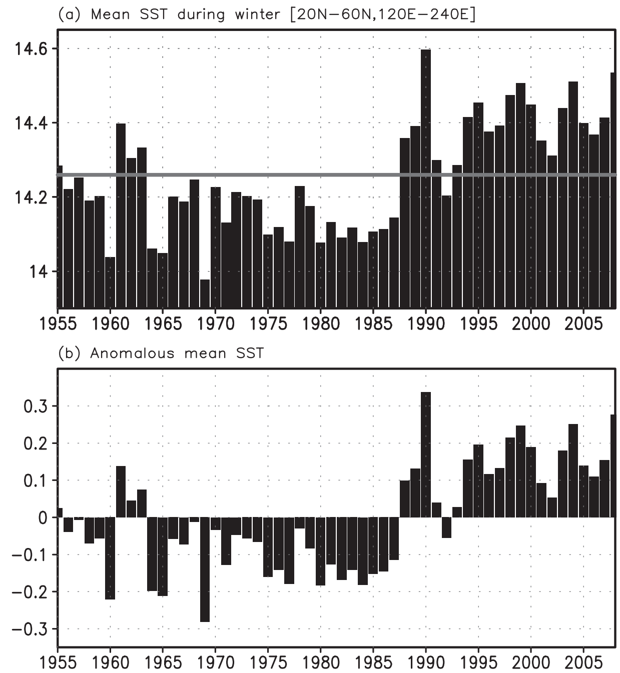

FIG. 1. Time series of mean SST (°C) in the North Pacific basin (20°–60°N, 120°E–120°W) during winter for the period 1955–2009. Gray bar indicates a climatological mean. (b) As in (a), but subtracting the climatological mean.

Figure 1a shows the time series of the mean SST in the North Pacific basin (20°–60°N, 120°E–120°W) during winter (December–February) for the period 1956–2009. Figure 1b is as in Fig. 1a but subtracting the climatological mean (gray line in Fig. 1a). Figure 1b shows that a pronounced change of North Pacific basin SST, with higher temperatures during winter, occurred in the late 1980s. Not surprisingly, recent studies have provided evidence of other shifts, with particular attention focused on the shift that occurred in winter 1988/89 in the North Pacific basin climate (Hare and Mantua 2000; Hollowed et al. 2001; Yasunaka and Hanawa 2003). Hare and Mantua (2000) documented many coherent changes in biological variables during the 1988–89 climate regime shift. They further argued that the 1988/89 changes were neither as prominent as in 1976/77 nor did they signal a simple return to pre-1976/77 conditions throughout the North Pacific climate and marine ecosystem. They found that a notable feature of the 1988/89 regime shift is its clarity in biological records in contrast to the lack of clear changes expressed in indices of Pacific climate. Overland et al. (1999) argued that the signature of the shift in the winter of 1988/89 was a persistent change in the Arctic Oscillation rather than in the Aleutian low, indicative of a short-lived PNA teleconnection change. In addition, several studies pointed out the different large-scale structure of decadal changes across the winter of 1988/89 might have characteristics different from that for the winter of 1976/77 (Walsh et al. 1996; Tanaka et al. 1996; Watanabe and Nitta 1999). The result in Fig. 1 also indicates that there is no significant change in the North Pacific basin SST during winter before and after the mid-1970s, which is a contrast to that around the late 1980s. This is because of the different spatial patterns of SST changes for the two climate transitions, which will be discussed later. These results indicate that the shift in the winter of 1988/89 in the North Pacific climate differs from the shift in 1976/77 in terms of atmospheric circulation and associated surface climate variations. Therefore, we retrospectively reexamine the 1988/89 climate transition compared with 1976/77. A better knowledge of the differences between the two climate transitions may be helpful in understanding the origins of North Pacific decadal SST variability.

Presently, there is little systematic analysis highlighting the differences between the 1976/77 and the 1988/89 climate transitions in terms of characteristic changes in

[1] A ''regime shift'' is characterized by an abrupt transition from one quasi-steady climate state to another, and its transition period is much shorter than the length of the individual epochs of each climatic state.

SST variability of the North Pacific. In this paper, we mostly rely on an empirical orthogonal function (EOF) analysis to extract the dominant SST variability in the two climate transition periods. By comparing the first two EOFs of North Pacific SST anomalies (SSTAs) in each case, we identify characteristic changes in the North Pacific SST variability associated with the two climate transitions.

2. Data and methodology

We use multiple observational datasets for the period from December 1955 through February 2009. Monthly SST is taken from the monthly-mean $2^\circ \times 2^\circ$ gridded Extended Reconstruction SST (ERSST), version 3 (ERSST.v3; Smith et al. 2008; available online at http://www.esrl.noaa.gov/psd/data/gridded/), which is the most recent version of the ERSST analysis. The analysis is based on the International Comprehensive Ocean–Atmosphere Data set release 2.4. At the end of every month, the ERSST analysis is updated with the available Global Telecommunications System (GTS) ship and buoy data for that month. The monthly-mean atmospheric fields include mean sea level pressure (SLP) and zonal wind at low level from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) Global Reanalysis 1 (Kalnay et al. 1996) for 1958–2008 (available online at http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html).

To reveal climate transitions in the North Pacific, we relate our results to climate indices such as Pacific decadal oscillation (PDO), which is the dominant SST mode of the midlatitude North Pacific. We use the PDO index by Mantua et al. (1997) (available online at http://jisao.washington.edu/pdo/PDO.latest) to compare with the analyzed results in this paper. Recent studies argued that a single indicator of North Pacific decadal variability such as PDO is incomplete in characterizing North Pacific climate (Bond et al. 2003; Di Lorenzo et al. 2008). Therefore, we examine the first two EOFs to describe regime shifts and decadal-scale variability in the North Pacific climate. According to Bond et al. (2003), the amplitude of the second mode of North Pacific SST variability becomes substantial after the mid-1980s and its spatial pattern, which is characterized by a dipole-like structure in the meridional direction, is similar to the SSTA field for recent years.

We focus on the winter season in this study. This is because the atmospheric circulation over the North Pacific during winter has undergone a substantial long-term intensification, which is responsible for physical changes within the North Pacific Ocean (Miller et al. 1994b; Mantua et al. 1997; Deser and Phillips 2006). In addition, the midlatitude atmospheric response to the tropical SST forcing is the strongest in the winter season (Chen 1982); therefore, it is reasonable to analyze the North Pacific SST variability during winter to examine whether it is associated with the tropical SST forcing (Lau and Nath 1996). We defined winter as the three months from December to February for the SST data and atmospheric variables; therefore, 1956 winter indicates December 1955, January 1956, and February 1956. Unless stated otherwise in the text, the results are for the winter season only. Note that seasonal means are calculated from the monthly data during winter and seasonal anomalies are obtained by subtracting seasonal means from the total winter-mean field.

The EOF analysis is performed on the covariance matrix after removing a linear trend to suppress any long-term/secular global warming signals. The gridded data are scaled by the square root of the cosine of latitude to account for the varying gridbox sizes. The statistical significance test used in this study is basically based on a Student's t test, because we compared the mean state changes between the two periods. The effective degrees of freedom to calculate the statistical significance is obtained by the methodology in Livezey and Chen (1983). In addition, we defined the amplitude of the EOF principal component (PC) as $\sqrt{(\text{EOF PC}) \times (\text{EOF PC})}$. Furthermore, we are able to reconstruct the time series by projecting the regressed field against the EOF PC time series onto the target variable to obtain its temporal variability in relation to the EOF pattern.

3. Analysis

a. Changes in mean SST

We first calculate the change in mean SST of 1956–88 and 1977–2009, when the 1976/77 and 1988/89 climate transitions occurred, respectively, in the Pacific Ocean. The changes in the North Pacific mean SST across 1976/77 and 1988/89 are shown in Figs. 2a,b, respectively. Between 1956–76 and 1977–88, the North Pacific mean SST decreased significantly by approximately -0.9° to -1.1°C in the western and central North Pacific with an elliptical shape and increased around 0.6°–1.5°C in the northern part of the North Pacific (Fig. 1a), which is consistent with previous results (Deser and Phillips 2006). It is not surprising to find no significant change in the basinwide North Pacific mean SST before and after the mid-1970s (see Fig. 1), because the SST changes are characterized by a dipole-like structure in the meridional direction. Between 1977–88 and 1989–2009, in contrast, the North Pacific mean SST increased by approximately 0.6°–0.8°C in the western and central North Pacific with

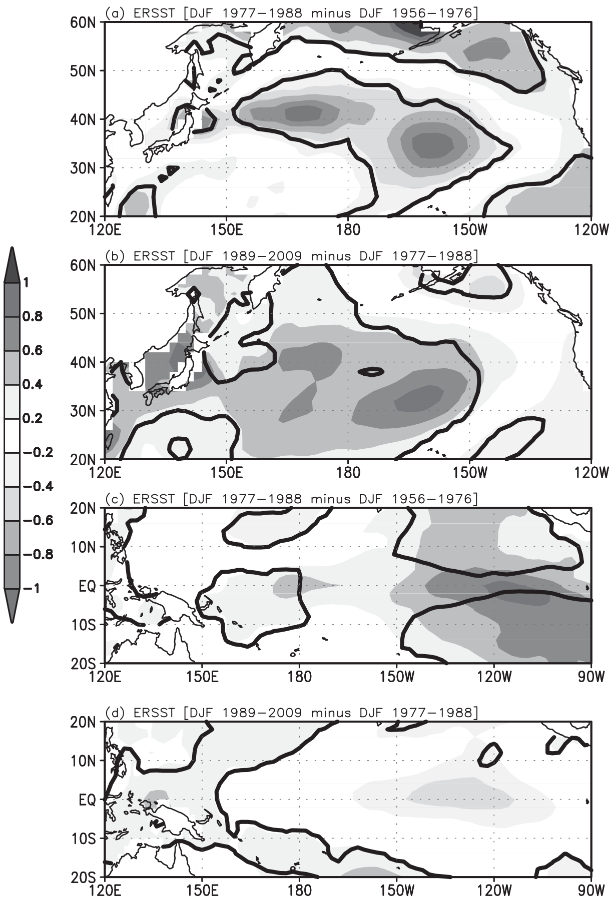

FIG. 2. Difference in North Pacific (20°–60°N, 120°E–120°W) winter-mean SST (°C) (a) between 1977–88 and 1956–76 and (b) between 1989–2009 and 1977–88. Thick contours denote the region where the statistical significance is above the 95% confidence level based on a Student's *t* test. (c),(d) As in (a),(b), but for equatorial tropical Pacific (20°–20°S, 120°E–90°W).

a significant increase in East Asian marginal seas (Fig. 2b). Unlike the SST differences across 1976/77, significant cooling of SST is limited to small regions of the northern and eastern parts of the North Pacific. Therefore, one can argue that the SST changes across the 1988/89 climate transition are characterized by a basin-scale warming, which can be seen in Fig. 1.

Figures 2c,d are as in Figs. 2a,b but for the tropical Pacific. As previous studies pointed out, the North Pacific 1976/77 climate transition is concurrent with significant changes in tropical Pacific SSTs (Fig. 2c). The maximum SST changes are observed in the eastern equatorial Pacific, where an approximately 0.6°C high occurred across 1976/77. This result supports the hypothesis that tropical SST forcing is responsible for the 1976/77 climate transition in the North Pacific, as previous studies suggested (Minobe 1997; Graham et al. 1994; Zhang et al. 1997; Deser et al. 2004; Mestas-Nunez

TABLE 1. Occurrence number of El Niño and La Niña events for the periods 1956–76, 1977–88, and 1989–2009.

	1956–76	1977–88	1989–2009
El Niño occurrence (occurrence ratio)	6 (0.28 yr^{-1})	4 (0.33 yr^{-1})	6 (0.28 yr^{-1})
La Niña occurrence (occurrence ratio)	9 (0.42 yr^{-1})	2 (0.16 yr^{-1})	7 (0.31 yr^{-1})

and Miller 2006). Since El Niño–Southern Oscillation (ENSO) variability strongly controls changes in the tropical-Pacific-mean SST, we compared the occurrence number of El Niño and La Niña events between the two periods: 1956–76 and 1977–88 (Table 1). Note that El Niño and La Niña events are defined when the Niño-3 SST index during winter is above 0.5°C and below −0.5°C, respectively. El Niño events occurred more frequently than La Niña events during 1977–88 than during 1956–76. During the 1977–88 period, the occurrence ratio of El Niño to La Niña event is larger than 2:1. Furthermore, the 1977–88 period contains the strong 1982/83 El Niño event. The difference of occurrence frequency of El Niño versus La Niña event between the two periods could change the tropical-Pacific-mean SST, resulting in altered North Pacific–mean SST by atmospheric teleconnections (e.g., Graham et al. 1994).

In contrast, there are no significant changes in mean SST in the equatorial Pacific across 1988/89, although low SST is observed in the eastern equatorial Pacific (Fig. 2d). Note that the occurrence ratio of El Niño to La Niña event during 1989–2009 is close to 1:1 (Table 1). These results suggest that the North Pacific 1988/89 climate transition is not simply related to changes in the tropical-Pacific-mean SSTs, unlike the 1976/77 climate transition. So without significant changes in the tropical Pacific SSTs, the North Pacific Ocean SSTs experienced a basin-scale warming between 1977–88 and 1989–2009 (Fig. 2b). This suggests that the dominant driving mechanism of North Pacific climate transitions differs between the two cases of 1976/77 and 1988/89.

b. Two EOFs in the entire period

We first examine the characteristics of SST variability during the entire period of 1956–2009. Figure 3 displays the first two EOFs (EOF1 and EOF2) of North Pacific SSTAs (Figs. 3a,b) and their PC time series for the period 1956–2009 (Figs. 3c,d). The percent variance explained by EOF1 and EOF2 is 30.6% and 18.7%, respectively, so there is clear separation between EOF1 and EOF2 according to the criterion of North et al. (1982). The domain is limited to the region of 20°N only because ENSO has the potential to contaminate SST variability in the North Pacific. The case with an extended

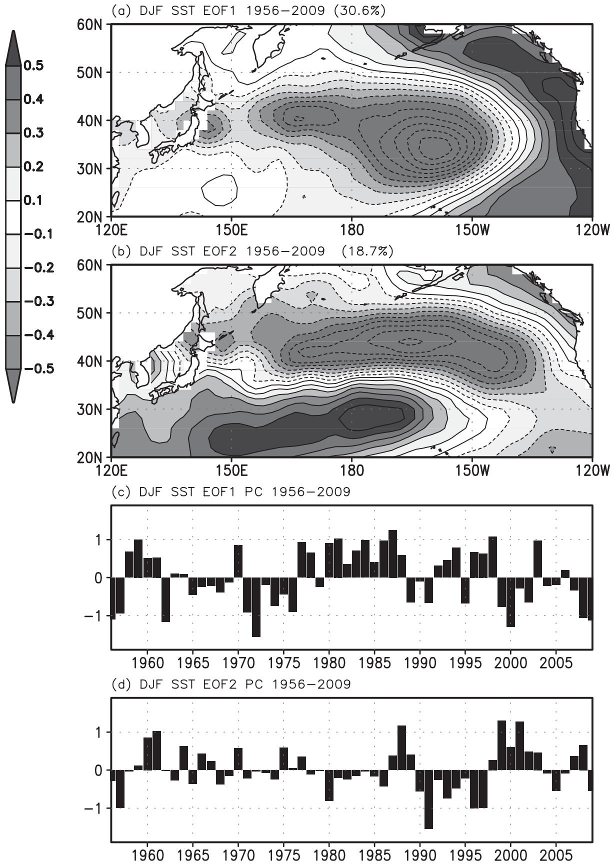

FIG. 3. (a) First and (b) second EOFs of North Pacific SSTAs (nondimensional) for the period 1956–2009 during winter. (c),(d) PC time series (°C) of the first and second EOFs for the period 1956–2009, respectively.

Pacific domain (60°N–20°S, 120°E–90°E), however, reveals that the first two EOFs and their corresponding PCs (not shown here) are not much different[2] in comparison with the results in Fig. 3.

The spatial manifestation of EOF1 (Fig. 3a) for the entire period is characterized by anomalously low SST over an elliptical shape in the western and central North Pacific that is accompanied by anomalies of the opposite sign to the east, north, and south, which is quite similar to the structure of the PDO (Mantua et al. 1997). To confirm this, we calculate a simultaneous correlation coefficient between the EOF1 PC and the Mantua's PDO index during winter. Mantua's PDO index during winter is obtained by the PDO index averaged for wintertime (i.e., December–February). A correlation coefficient between the EOF1 PC (Fig. 3c) and Mantua's PDO index is 0.88, which is significantly high, whereas between the EOF2 PC (Fig. 3b) and Mantua's PDO index it is low, 0.22.

Conversely, the spatial manifestation of EOF2 (Fig. 3b) is characterized by a dipole-like structure in the meridional direction with a nodal line approximately along 40°N. Anomalous high SST south of 40°N extends from the East Asian marginal seas to the central North Pacific, while anomalously low SST north of 40°N reaches from the west to the east with its maximum variance located in the central and eastern North Pacific. Note that EOF2 is quite similar to EOF2 of Bond et al. (2003) (their Fig. 5b), which became colloquially known as the ''Victoria mode.'' Di Lorenzo et al. (2008, 2009) subsequently showed that this EOF of SST is a component of a large-scale dynamic oceanic mode of the North Pacific that includes sea level height, currents, and salinity. Because the oceanic response reflects adjustments of the gyre circulation, it was termed the North Pacific Gyre Oscillation (NPGO) (Di Lorenzo et al. 2008). Chhak et al. (2009) revealed that the dominant driving mechanism for the NPGO is the North Pacific Oscillation (NPO) of atmospheric SLP (Walker and Bliss 1932; Rogers 1981).

Both EOF1 PC and EOF2 PC are characterized by significant variations on interannual-to-decadal time scales. While EOF PC1 exhibits a pronounced shift in 1976/77 (Fig. 3c), the shift in 1976/77 is not apparent in EOF2 PC (Fig. 3d). Conversely, EOF1 PC shows a shift in 1988/89 (Fig. 3c) that appears to be accentuated by sharp changes in EOF2 PC in the late 1980s (Fig. 3d). Thus, EOF1 and EOF2 contribute different structures to the two climate transitions in the North Pacific, resulting in different of changes in SST across the 1976/77 and 1988/89 winters.

c. *Changes in SST variability in the two subperiods*

To examine details of the changes of SST variability in relation to the two climate transitions, we perform an EOF analysis during the two subperiods of 1956–88 [period 1 (P1)] and 1977–2009 [period 2 (P2)]. Figure 4 displays EOF1 and EOF2 of North Pacific SSTAs (Figs. 4a and b) and their PC time series (Figs. 4c and d) for the P1 period, which includes the 1976–77 climate transition. (notice we define the SSTAs relative to the 1956–88 mean SST.). By directly comparing the EOF1 (i.e., PDO) and the EOF2 (i.e., NPGO) with the entire period (Figs. 3a,b), we find that EOF1 for P1 (Fig. 4a) represents PDO-like SST variability. Likewise, EOF2 (Fig. 4b) represents NPGO-like SST variability, although

[2] EOF1 for the Pacific domain has some differences and similarities with EOF1 (Fig. 3a) in the North Pacific only. For example, EOF1 in the Pacific domain has a weak anomaly in the western North Pacific, which differs from that in the North Pacific only. Despite this, the correlation coefficients between the first two EOFs PC in Figs. 3c,d and those in the Pacific domain are 0.62 and 0.75, respectively, which are significantly high.

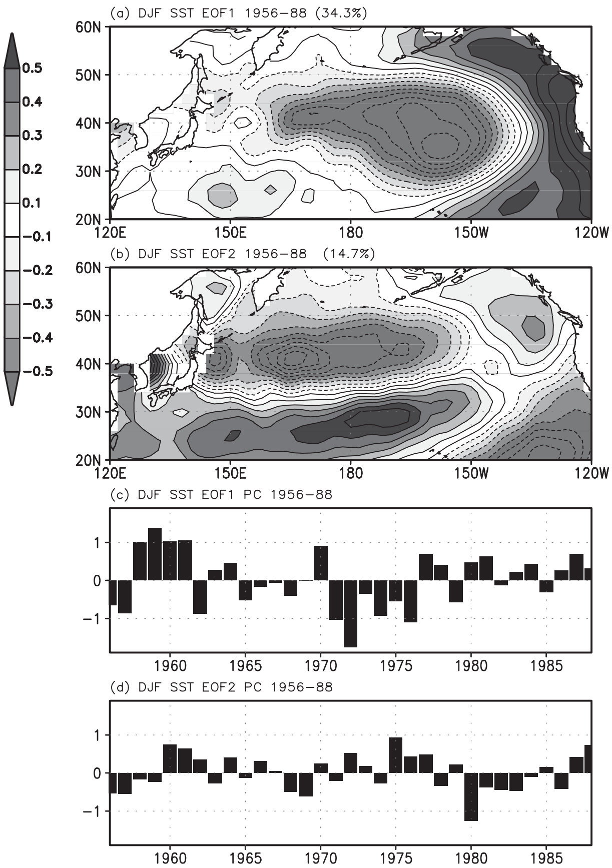

FIG. 4. As in Figs. 3a–d, but for the period 1956–88.

there are subtle differences with the NPGO mode for the entire period, including large variance of SST located in the western North Pacific and a strong SST gradient below 40°N. Table 2 summarizes the correlation coefficients between the EOF PCs in the entire period (1956–2009) versus the two subperiods, supporting the notion that EOF1 and EOF2 for P1 represent PDO-like and NPGO-like SST variability, respectively.

The spatial structure of EOF1 (Fig. 4a) is similar to that of the SST change of the 1976/77 climate transition (see Fig. 2a). The spatial pattern correlation between EOF1 (Fig. 4a) and the mean SST difference across 1976/77 (Fig. 2a) is 0.76, which is significantly high. In contrast, the correlation between EOF2 (Fig. 4b) and the mean SST difference across 1976/77 is 0.12, indicating that the NPGO-like EOF2 does not capture the North Pacific mean SST changes in the 1976/77 climate transition. Notice that the spatial pattern correlation coefficient is defined as the correlation coefficient for all overlapping grid points between the two spatial patterns. This shows that the 1976/77 climate transition strongly projects onto the PDO-like EOF1 of P1. Furthermore, this can also be seen in the time series of the EOF1 PC (Fig. 4c), which exhibits a pronounced shift in 1976/77. However, there is no significant shift in the PC time series of EOF2 (Fig. 4d). We conclude that the climate transition in 1976/77 is mainly explained by the PDO-like EOF1 of SST variability.

We next examine characteristics of North Pacific SST variability for P2, during which the 1988/89 climate transition occurred. Figures 5a–d are as in Figs. 3a–d but for P2 (notice that we define the SSTAs relative to the 1977–2009 mean SST). There is a striking difference in the characteristics of the dominant SST variability modes of the North Pacific for P2 compared to the entire period (1956–2009). First, EOF2 for P2 (Fig. 5b) shares some degree of similarity in terms of its spatial pattern with EOF1 (i.e., PDO) for the period 1956–2009 (see Fig. 3a). The patterns are characterized by anomalously low temperatures in the western and central North Pacific with an elliptical shape, which are accompanied by anomalies of the opposite sign to the east, north, and south. The spatial pattern correlation between EOF2 for P2 (Fig. 5b) and EOF1 for the period 1956–2009 (Fig. 3a) is 0.79, which is significantly high. In addition, the correlation coefficient of the two PC time series for EOF2 for P2 (Fig. 5d) and EOF1 for the period 1956–2009 (Fig. 2c) during the overlapping period is 0.61, which is statistically significant at the 99% confidence level (Table 2). We also calculate the correlation coefficient between the EOF2 PC and Mantua's PDO index during winter for P2 to be 0.86, which is also statistically significant at the 99% confidence level. These results indicate that the PDO-like EOF structure has been subsumed into EOF2 for P2.

TABLE 2. Summary of the correlation coefficients between the EOF PCs in the entire period (1956–2009) vs P1 and P2. An asterisk denotes statistical significance at the 99% confidence level.

	Subperiod			
	P1		P2	
Entire period	EOF1 PC (PDO like)	EOF2 PC (NPGO like)	EOF1 PC (NPGO like)	EOF2 PC (PDO like)
EOF1 PC (PDO like)	0.89*	−0.08	−0.54*	0.61*
EOF2 PC (NPGO like)	−0.39	0.82*	0.80*	0.55

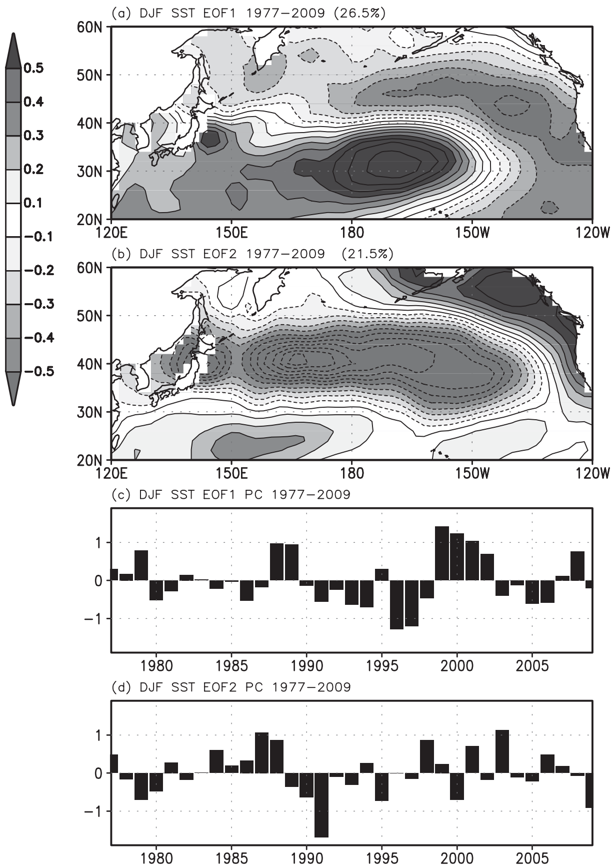

FIG. 5. As in Figs. 4a–d, but for the period 1977–2009.

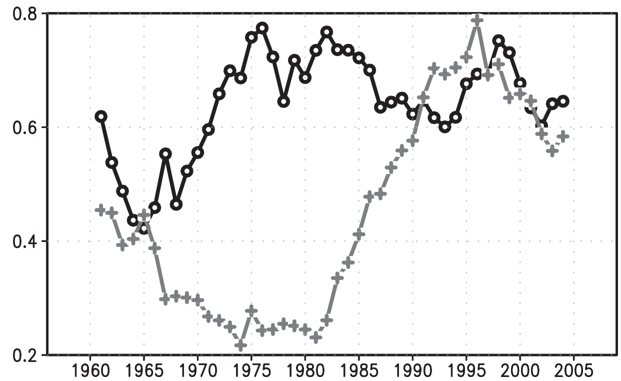

FIG. 6. Time series of 7-yr running mean EOF1 (circle) and EOF2 PC (cross) amplitude (°C) for the period 1956–2009. See text for definition of EOF PC amplitude.

On the other hand, EOF1 for P2 (Fig. 5a) is similar to the EOF2 (i.e., NPGO) for the period 1956–2009 (see Fig. 3b), although there exist some differences. As previously discussed, NPGO-like SST variability is characterized by a dipole-like pattern in the meridional direction with a nodal line at approximately 40°N, which is evident in Fig. 5a. The spatial pattern correlation between EOF1 for P2 (Fig. 5a) and EOF2 for the period 1956–2009 (Fig. 2b) is 0.75, which is significant. The correlation coefficient of the two PC time series for EOF1 for P2 (Fig. 5c) and EOF2 for the period 1956–2009 (Fig. 2d) during the overlapping period is 0.80, which is significant at the 99% confidence level (Table 2). We also calculate the correlation coefficient between the EOF1 PC and Mantua's PDO index during winter for P2 to be −0.33, which does not pass the significance test. Table 2 also indicates that the two PC time series for EOF1 for P2 (Fig. 5d) and EOF1 for the period 1956–2009 (Fig. 2c) during the overlapping period is negatively correlated. This indicates that the NPGO-like SST variability has risen into EOF1 during P2.

The above-mentioned results indicate that after 1988/89, NPGO-like SST variability is of primary importance and PDO-like SST variability is of secondary importance. This implies that the strengthening of NPGO-like SST variability contributes to the changes in the dominant SST variability of the North Pacific after 1988. In other words, the change in the SST variability in the North Pacific exists around 1988. To examine this issue, we display the time series of an 11-yr running mean of the EOF1 and EOF2 PC amplitude, which represents the magnitude of SST variability explained by the EOF1 and EOF2, for the period 1956–2009 (Fig. 6). It is evident that the strength of EOF1 SST variability (i.e., PDO) fluctuates on decadal time scales; however, the strength of EOF2 SST variability (i.e., NPGO) is significantly enhanced after the late 1980s, which is consistent with the above-mentioned results. We apply the same methodology to the EOF1 PC and EOF2 PC for P2 (not shown) and found that the strength of NPGO-like SST variability is larger than that of PDO-like SST variability after the late 1980s, which is consistent with previous studies that have argued that the NPGO pattern explains more wintertime North Pacific SSTA variance than the PDO pattern during the period 1990–2002 (Bond et al. 2003; Di Lorenzo et al. 2008).

The two EOF PC time series provide further details of the change in mean SSTs associated with the 1988/89 climate transition. The EOF1 PC time series (Fig. 5c) has weakly negative values in the period 1977–87 followed by a sign change in 1988 and 1989. This implies that the NPGO-like SST variability contributes to increasing (decreasing) SST in the southern (northern) part of the North Pacific, earlier than the 1988/89 climate transition. However, the sign of the EOF1 PC time series reverses after 1990, contributing to decreased (increased) SST in the southern (northern) part of the North Pacific until the late 1990s. Conversely, Fig. 5d indicates that the PDO-like EOF2 of SST variability also plays a role to the North Pacific 1988/89 climate transition. Before 1989, the EOF2 PC time series is positive in the period 1977–88, after which its sign suddenly changes. This indicated that the PDO-like SST variability also contributes to increasing SST in the western and central North Pacific after 1988/89. This can be seen more clearly in the time series in Fig. 6, which shows that the amplitude of both the PDO and NPGO SST variability is comparable around 1988/89. While the 1976/77 climate transition can be largely explained by the PDO-like SST variability, the above-mentioned results suggest that both the NPGO-like SST and PDO-like SST variability contribute to the 1988/89 climate transition in the North Pacific basin.

PDO-like SST variability was of primary importance during P1 and played the major role in the 1976/77 climate transition in the North Pacific. When focusing on more recent decades, in contrast, NPGO-like SST variability was of primary importance with PDO-like SST variability playing a much reduced role for P2. NPGO-like SST variability becomes much stronger that PDO-like SST variability after the late 1980s. Despite the reduced importance of PDO-like SST variability, however, both NPGO-like and PDO-like SST variability contributed to the 1988/89 climate transition in the North Pacific.

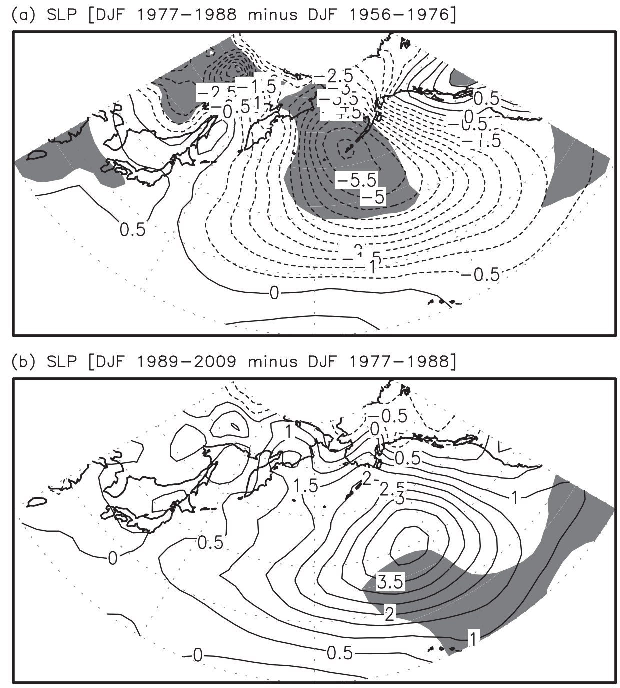

FIG. 7. Changes in winter mean SLP (a) between 1977–88 and 1956–76 and (b) between 1988–2009 and 1977–88. Contour interval is 0.5 hPa, and shading denotes the region where the statistical significance exceeds the 95% confidence level.

d. Changes in associated sea level pressure pattern in the two subperiods

As shown previously, changes in tropical-Pacific-mean SST were significant during the 1976/77 climate transition but not during the 1988/89 period (see Figs. 1c,d). Significant differences in the changes in mean SLP over the North Pacific also occurred for the two climate transitions. Figures 7a,b display the changes in winter-mean SLP between 1956–76 and 1977–88 and between 1977–88 and 1989–2009, respectively, over the North Pacific basin. The difference in mean SLP across 1988/89 (Fig. 7b) is not simply a mirror image of the transition of mean SLP across 1976/77 (Fig. 7a). Across the 1976/77 shift (Fig. 7a), a significant deepening of Aleutian low over the North Pacific basin occurs. Previous studies have argued that such a deepening of the Aleutian low across 1976/77 is associated with tropical SST forcing, as shown in Fig. 1c. By conducting numerical experiments, for instance, Graham et al. (1994) demonstrated that a deepening of the Aleutian low over the North Pacific is primarily a response to changes in tropical SSTs.

Across the 1988/89 shift (Fig. 7b), however, no significant change of the strength of the Aleutian low occurs, although the sign of the change (higher pressure) is consistent with the reversed sign of the SST changes in the tropical Pacific (Figs. 2c,d). The lack of significant tropical SST forcing (Fig. 1b) may explain this weaker-mean SLP response. The strength of the Aleutian low, which is defined as the SLP anomalies averaged over 40°–60°N, 160°E–160°W (Overland et al. 1999), seems to be weaker after the 1988/89 shift, and the higher pressure that forms in the central North Pacific is strong and significant (Fig. 7b). Conversely, this result may indicate that the Aleutian low is displaced southeastward after 1988/89, whereas a latitudinal change in the Aleutian low implies that the anomalous SLP projects onto the NPO of atmospheric SLP, whose dipole center is located near the central North Pacific. We found (not shown) that the variation in the latitudinal position of the Aleutian low is closely associated with the variation of the NPO-like SLP pattern over the North Pacific during winter. Not surprisingly, the deviation of North Pacific SLP after the 1988/89 from the climatological (1956–2009) mean is characterized by a dipole-like structure in the meridional direction with an enhancement of mean SLP in the southeastern North Pacific (Fig. 8). This is consistent with the idea that an NPO-like SLP pattern, whose dipole center is located near the central North Pacific (Rogers 1981; Wallace and Gutzler 1981; Linkin and Nigam 2008; Chhak et al. 2009), was enhanced after 1988/89.

Next we quantify the relations between the SST EOF variations and the atmospheric pressure patterns using regression analysis. Figure 9a shows the mean SLP regressed

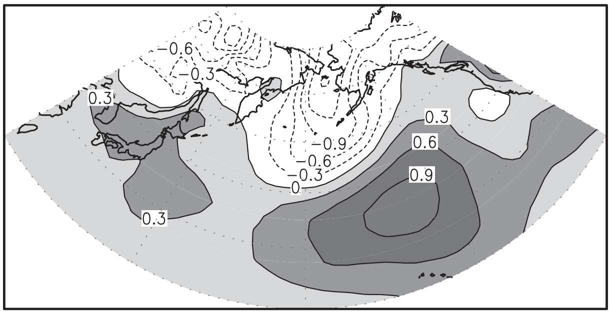

FIG. 8. Deviation of North Pacific SLP after the 1988/89 transition from the climatological (1956–2009) mean. Shading (dashed line) denotes positive (negative) values. Contour interval is 0.3 hPa.

with NPGO-like SST EOF1 PC for P2, including the 1988/89 shift. The structure is similar to that found for the change in the mean SLP across the 1988/89 shift (Fig. 7b). This pattern of mean SLP is characterized by a dipole-like pattern in the meridional direction over the North Pacific, which is reminiscent of the NPO-like SLP pattern. In contrast, when mean SLP is regressed against the SST EOF2 PC time series for P2 (Fig. 9b), the pattern clearly corresponds to the Aleutian low, which is associated with a PDO-like SST response. These results indicate that the changes in mean SLP across the 1988/89 climate transition project onto the NPO-like SLP variability, resulting in an enhancement of the NPGO-like SST variability after 1988/89 (Chhak et al. 2009), which is consistent with the low-frequency time series of the amplitude of NPGO SST variability, as shown in Fig. 6, and the climatological deviation of mean SLP after 1988/89, as shown in Fig. 8. In addition, we compute a reconstructed time series by projecting the regressed NPO-like SLP pattern (Fig. 9a) onto the SLP anomalies during winter for the period 1977–2009. The correlation coefficient between the reconstructed time series and the NPGO-like SST EOF1 PC (Fig. 5c) is 0.56, which is statistically significant at the 95% confidence level, supporting the above-mentioned argument.

For comparison, we also regressed-mean SLP against the EOF1 and EOF2 PC time series for the period including the 1976/77 shift in Figs. 9c,d, respectively. The Aleutian low and NPO patterns are again recovered, albeit for regressions of mean SLP with EOF1 PC (Fig. 9c) and EOF2 PC (Fig. 9d) time series, respectively. Furthermore, the spatial pattern of mean SLP regressed with the EOF1 PC is quite similar to that of the difference of mean SLP across the 1976/77 shift (see Fig. 7a), supporting the notion that PDO-like SST variability plays the leading role in the North Pacific 1976/77 climate transition response to changes in the Aleutian low.

Then we consider the relationship between the NPGO-like SST variability in the North Pacific and

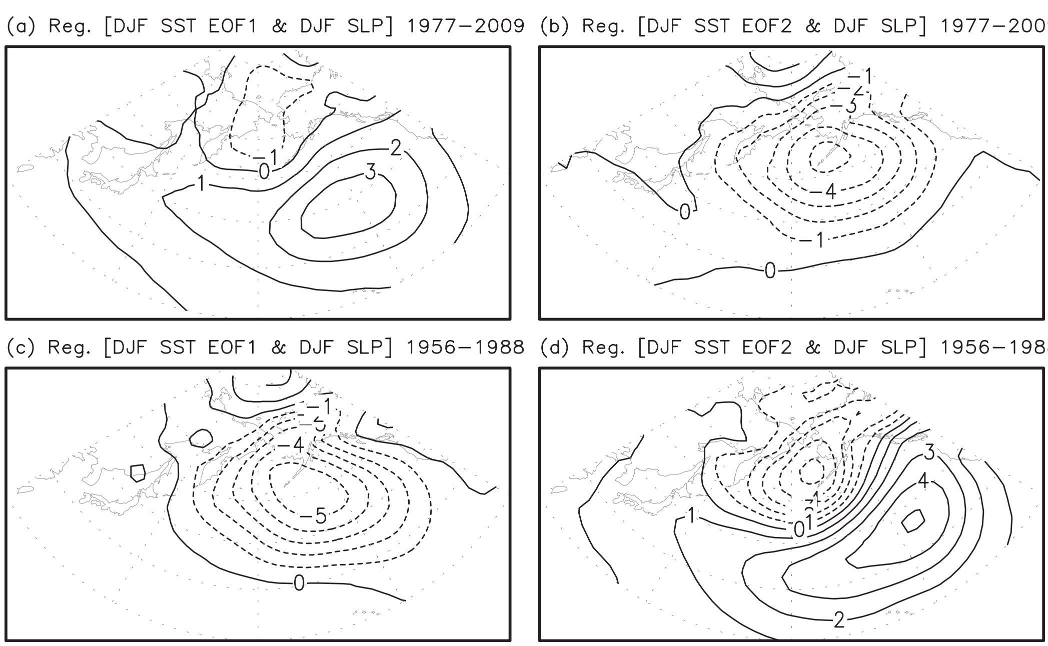

FIG. 9. (a) Mean SLP regressed with NPGO-like SST EOF1 PC time series for P1 (i.e., Fig. 5c), and (b) as in (a), but for PDO-like SST EOF2 PC time series (i.e., Fig. 5d). (c) Mean SLP regressed with PDO-like SST EOF1 PC time series for P1 (i.e., Fig. 4c), and (d) as in (c), but for NPGO-like SST EOF2 PC time series (i.e., Fig. 4d). Contour interval is 1 hPa C^{-1}, and dashed line denotes negative.

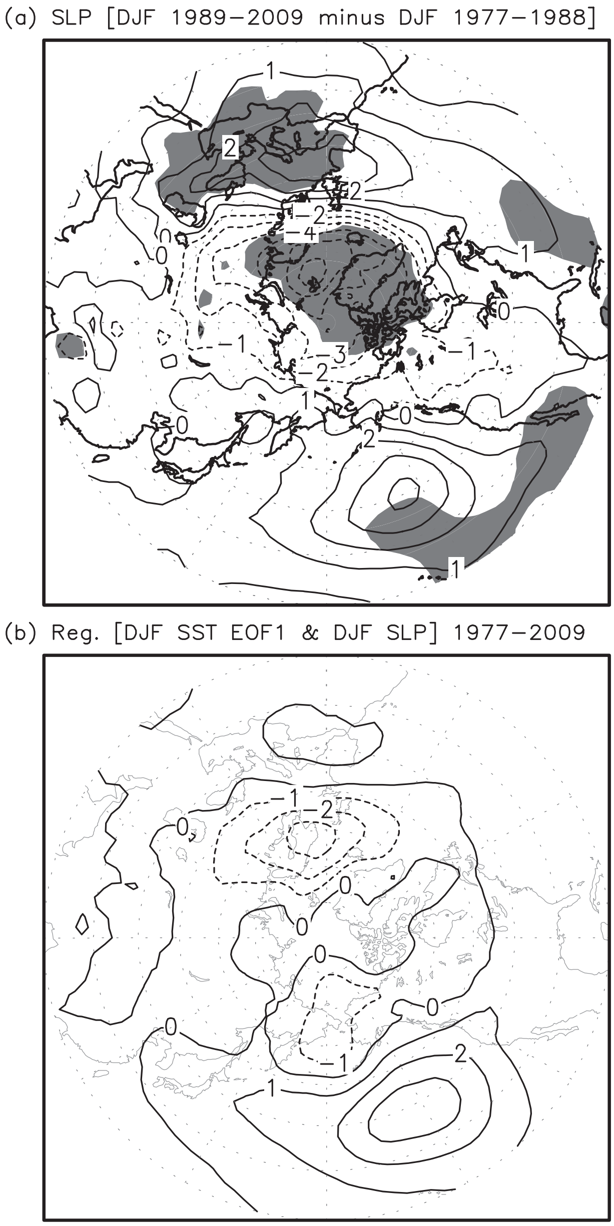

FIG. 10. (a) As in Fig. 7b, but for the entire Northern Hemisphere. (b) As in Fig. 9a, but for the entire Northern Hemisphere.

remote-atmospheric-mean SLP by extending the analysis domains of Figs. 7b and 9a to the entire Northern Hemisphere for the period including the 1988/89 shift. Figure 10a (cf. Fig. 7b) and Fig. 10b (cf. Fig. 9a) show that both SLP patterns have centers of action of anomalously high pressure over the central North Pacific and Europe and a center of the negative one over the Arctic. The shift in mean SLP of the Arctic Oscillation across the 1988/89 climate transition, which was pointed out as a persistent controlling influence on the shift in previous studies (Overland et al. 1999; Watanabe and Nitta 1999), can be seen in Fig. 10a. In addition, the signature of the Arctic Oscillation can also be found in the regressed-mean SLP pattern associated with NPGO-like SST variability over the period 1977–2004 (Fig. 10b). Figure 10 indicates that the changes in the mean SLP associated with the 1988/89 climate transition extend across the North Pacific onto the polar region, so that the Arctic Oscillation is associated with NPO-like SLP variations over the North Pacific, contributing to enhanced NPGO-like SST variability after 1988.

It is important to identify why changes in mean SLP associated with the 1988/89 climate transition are linked to the Arctic Oscillation, but this is not the focus of this study. Previous studies suggested several possibilities. For example, Walsh et al. (1996) and Tanaka et al. (1996) reported that the northern polar vortex was persistently intensified after the 1988 winter. Alternatively, natural variability or an interdecadal cycle within the Arctic climate system and changes in the Arctic ice cover may have been involved (Mysak et al. 1990; Mysak and Power 1992; Maslanik et al. 1996; Tachibana et al. 1996).

4. Model analysis

To examine the changes in the North Pacific atmosphere and the tropical Pacific SSTs, we analyze the Tropical Ocean and Global Atmosphere (TOGA) experiment (a detailed description is available online at http://www.ccsm.ucar.edu/working_groups/Variability/experiments.html) in the Community Atmosphere Model version 3 (CAM3), in which the observed month-to-month SSTs are inserted only at grid points in the tropics between 20°S and 20°N and a climatological seasonal cycle of SSTs is used poleward of 30° with linear interpolation between 20° and 30°. We analyze the ensemble-mean results from a five-member ensemble of TOGA experiments for the period 1950–2000. The purpose of this analysis is to identify whether the changes in the North Pacific atmosphere across 1976/77 and 1988/89 are driven by changes in tropical Pacific SSTs.

The changes in the tropical-Pacific-mean SST across 1976/77 and 1988/89 are shown in Figs. 11a,b, respectively. Between 1956–76 and 1977–88, the maximum SST changes are observed in the eastern equatorial Pacific, where an approximately 1.0°C high occurred across 1976/77. In contrast, changes in mean SST in the equatorial Pacific across 1988/89 (1989/99 minus 1977/88) are weak (Fig. 11b). Low SST is observed in the eastern equatorial Pacific, but it is not a significant change. There are some differences in comparison with the results in Figs. 2c,d, which might be due to a different SST dataset and the analyzed period (Figs. 2d, 11b).

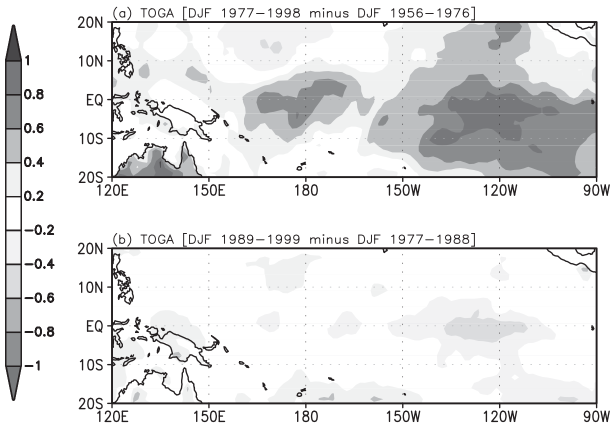

FIG. 11. Difference in equatorial tropical Pacific (20°–20°N, 120°E–90°W) winter-mean SST (°C) (a) between 1977–88 and 1956–76 in the ensemble-mean TOGA experiments and (b) between 1989–99 and 1977–88.

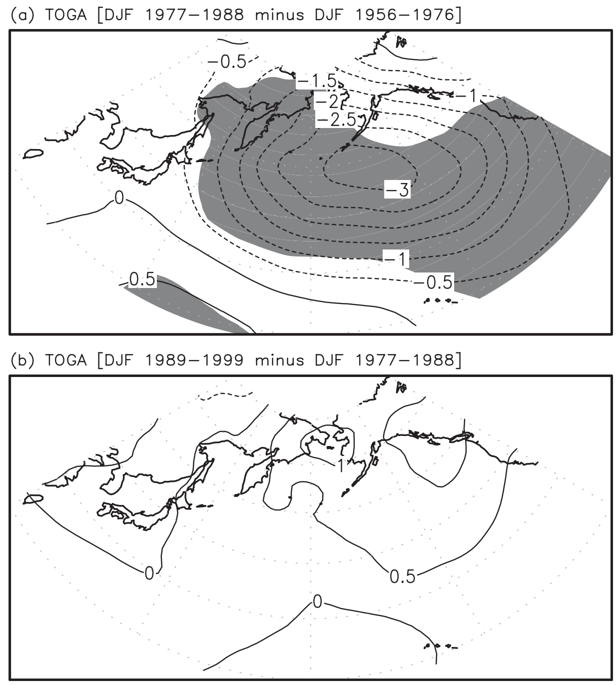

FIG. 12. Changes in winter mean SLP (a) between 1977–88 and 1956–76 in the ensemble-mean TOGA experiments and (b) between 1988–99 and 1977–88. Contour interval is 0.5 hPa, and shading denotes the region where the statistical significance exceeds the 90% confidence level.

Figure 12a displays the changes in winter-mean SLP between 1956–76 and 1977–88 over the North Pacific basin, which is as in Fig. 7a but for the ensemble-mean TOGA experiment in CAM3. The difference of mean SLP associated with the 1976/77 shift in the tropical Pacific is characterized by a significant deepening of the Aleutian low over the North Pacific basin, which is quite similar to Fig. 7a. This result supports the notion that the origin of the North Pacific 1976/77 climate transition is mainly due to changes in the tropical Pacific SST, consistent with the modeling results of Graham (1994) and Graham et al. (1994). Conversely, Fig. 12b is the same as in Fig. 12a but for the difference of mean SLP between 1989 and 1999 and 1977 and 1988. Although the period is necessarily different compared to Fig. 7b,[3] the result in Fig. 12b shows the changes in the North Pacific atmosphere across 1988/89, which are due to tropical Pacific SSTs. In contrast to Fig. 12a, there is no region where the difference of mean SLP is statistically significant. This result indicates that changes in tropical Pacific SSTs across 1988/89 are not sufficient to change the North Pacific atmosphere. Furthermore, the TOGA experiment fails to reproduce the enhanced Aleutian low pressure over the central North Pacific shown in Fig. 7b. This indicates that a latitudinal change in the Aleutian low across 1988/89, which implies a strong projection onto the NPO of atmospheric SLP, is not due to changes in tropical Pacific SSTs. In the previous section, we argued that the NPO over the North Pacific is closely associated with the NPGO. We therefore suggest that the enhancement of NPGO-like SST variability across the 1988/89 climate transition is not remotely forced by the tropical Pacific SSTs.

5. Summary and conclusions

North Pacific SST exhibits long-term variations on decadal time scales, including signatures of climate regime shifts. We examined the differences between the two well-known climate transitions, which occurred during the winters of 1976/77 and 1988/89, by highlighting characteristic changes in the SST variability for the periods surrounding those shifts. We analyzed the first two leading EOF SST modes of variability in the entire period (1956–2009) with the two partially overlapping periods, P1 (1956–88) and P2 (1977–2009). The analysis yielded the following conclusions.

- While the SST changes in the 1988/89 climate transition are characterized by a basin-scale warming, those in the 1976/77 climate transition are characterized by a dipole-like structure in the meridional direction.
- The SST change in the North Pacific occurs concurrently with a SST change in the tropical Pacific during the 1976/77 climate transition period, but it is limited to the North Pacific during the 1988/89 climate transition.

[3] Because of the limited period of the TOGA experiment (1950–2000), we are not able to obtain the difference of MSLP between 1989 and 2009 and 1977 and 1988 as in Fig. 7b.

TABLE 3. Correlation coefficients between Niño indices and the first two EOF PCs during P1 and P2. An asterisk denotes statistical significance at the 90% level, and two asterisks denote significance at the 95% confidence level.

	P1		P2	
	EOF1 PC (PDO like)	EOF2 PC (NPGO like)	EOF1 PC (NPGO like)	EOF2 PC (PDO like)
NIÑO-3 SST index	0.50**	0.02	−0.21	0.27
NIÑO-4 SST index	0.52**	−0.04	−0.43*	0.05

- The North Pacific SST variability during the entire period, 1956–2009, is well represented by the first two leading EOF modes of SST variability, which are clearly identified as PDO and NPGO variability. The strength of the PDO SST variability fluctuates on decadal time scales; however, the strength of the NPGO SST variability is significantly enhanced after the late 1980s.
- The PDO-like SST variability is of primary importance in P1, and it plays a major role in the 1976/77 climate transition in the North Pacific. In contrast, the NPGO-like SST variability is of primary importance in P2, with enhanced variability after the late 1980s. It contributes strongly to the 1988/89 SST climate transition, with PDO-like SST variability also contributing to that shift.
- While PDO-like SST variability is associated with Aleutian low pressure variations, the NPGO-like SST variability is associated with the NPO. These two types of SST variability yield different effects on the two climate transitions, indicative of the differences in changes of mean SLP across the two climate transitions. While the Aleutian low is significantly strengthened after the 1976/77 climate transition, there is little change in its intensity across the 1988/89 climate transition. Instead, the NPO-like SLP pattern, whose dipole center is located in the central North Pacific, is enhanced after 1988.

We also discussed a possible mechanism for the enhancement of the NPGO-like SST variability after 1988. The shift in mean SLP across the 1988/89 climate transition is evident in the Arctic Oscillation, unlike the 1976/77 transition. Since the Arctic Oscillation projects onto the NPO, which drives the NPGO-like SST variability, the enhanced persistence of the Arctic Oscillation after 1988/89 may play a role in enhancing the NPGO-like SST variability.

While the PDO and its transition in 1976/77 are associated with changes in the tropical Pacific, it may involve extratropical–tropical interactions at lower frequencies (Clarke and Lebedev 1999; Cessi and Otheguy 2003; Wu et al. 2007). In addition, there may exist multiple processes that contribute to PDO and NPGO SST variability (Schneider and Cornuelle 2005; Newman 2007; Chhak et al. 2009; Ceballos et al. 2009). For instance, Schneider and Cornuelle (2005) argued that PDO can be forced by the variability of the Aleutian low, ENSO, and oceanic zonal advection anomalies in the Kuroshio–Oyashio Extension. Climate transitions in the North Pacific may therefore result from changes in the alignment of these multiple forcings. We indeed found changes in the relationship with ENSO in the PDO-like and NPGO-like SST variability during P1 and P2, respectively (Table 3). That is, the PDO-like SST variability was highly associated with the tropical Pacific SST variability during P1; however, that relationship was significantly weakened during P2. In contrast, NPGO-like SST variability has little connection with the tropical Pacific SST variability during P1, but it has a close relationship with the SST variability in the central tropical Pacific (i.e., Niño-4 region, 5°N–5°S, 160°E–150°W) during P2.

To examine whether the changes in the North Pacific atmosphere across 1976/77 and 1988/89 are driven by changes in tropical Pacific SSTs, we analyzed an ensemble of TOGA experiments using the CAM3. It is found that a significant deepening of the Aleutian low over the North Pacific basin across the 1976/77 shift is mainly due to changes in the tropical Pacific SSTs. However, the TOGA experiment fails to reproduce the projection onto the NPO of atmospheric SLP over the North Pacific across the 1988/89 climate transition. Therefore, the enhancement of the NPGO-like SST variability after 1988, which is associated with the NPO over the North Pacific, is not simply due to the tropical Pacific SSTs.

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