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- Relationship of SST variability between tropical Pacific and North Pacific changed across 1998/1999
- Westward shift of the tropical Pacific convection enhanced the teleconnection to the North Pacific
- The seasonal predictability of the North Pacific SST has increased since 1998/1999

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Changes in the relationship in the SST variability between the tropical Pacific and the North Pacific across the 1998/1999 regime shift

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Abstract This study shows that sea surface temperature (SST) variability in the central to eastern tropical Pacific has a strong negative correlation with that of the central to eastern North Pacific in the boreal winter after the 1998/1999 regime shift. This phenomenon is in contrast to before the 1998/1999 regime shift. The anomalous Aleutian low pressure associated with the tropical SST forcing became stronger, and its center shifted to the south and to the west after 1998/1999. Such a modulation caused the change in the North Pacific SST response. This also resulted in a close relationship between the tropical Pacific and North Pacific SST variability. The modulation of the Aleutian low pressure is primarily due to the westward shift in the location of the tropical convective heating around the dateline, which occurred during 1998/1999. The results of simple atmospheric model experiments support this hypothesis that the shift in the tropical convective heating to the west is responsible for the modulation of the Aleutian low pressure and the associated change in the relationship of the SST variability between the tropical Pacific and North Pacific. These results imply that the seasonal predictability of the North Pacific SST has increased since 1998/1999 due to its increased correlation with the tropical Pacific SST variability.

1. Introduction

It is important to understand sea surface temperature (SST) variability in the North Pacific on decadal to multidecadal time scales because it is significantly linked to the global weather and climate variability [*Trenberth and Hurrell*, 1994; *Hare and Mantua*, 2000; *Miller et al.*, 2004; *Yeh and Kirtman*, 2004; *Di Lorenzo et al.*, 2009; *Yoon and Yeh*, 2012; *Jo et al.*, 2014]. At this time, a wealth of studies exists that have examined the origin of the North Pacific SST variability including its regime shifts [*Deser and Phillips*, 2006; *Yeh et al.*, 2011; *Miyasaka et al.*, 2014]. One line of thought is that the North Pacific SST variability is primarily influenced by the tropical SST forcing [*Deser and Phillips*, 2006; *Lyon et al.*, 2013]. In other words, tropical SST variability, including El Niño–Southern Oscillation (ENSO) events, serves as a strong tropical heating source, causing the anomalous atmospheric circulation over the North Pacific via atmospheric teleconnections from the tropics to the extratropics. Such an anomalous atmospheric circulation, which is associated with the modulation of the Aleutian low pressure, subsequently acts to produce SST changes over the North Pacific through air-sea interactions [*Lau and Nath*, 1996; *Alexander et al.*, 2002]. Therefore, the tropical Pacific and the North Pacific SST variability are closely linked to each other via the atmospheric teleconnections, through the intensity and the position of the Aleutian low pressure in particular.

Recent studies have reported a North Pacific regime shift in the winter of 1998/1999, which is characterized by a dipole-like SST structure along 40°N where significant warming is prominent in the western and central North Pacific, in association with the changes in the atmospheric and oceanic circulation over the equatorial Pacific [*Minobe*, 2002; *Hong et al.*, 2013; *Jo et al.*, 2013; *Lyon et al.*, 2013]. In addition, it has been recognized that the relationship between the tropical Pacific and the North Pacific SST variability significantly changed in the late 1990s [*Yeo et al.*, 2012]. However, the cause of the decadal change in the relationship between the tropical Pacific and the North Pacific still remains unclear. In this study, we examine the changes in the relationship in the SST variability between the tropical Pacific and the North Pacific during the 1998/1999 regime shift.

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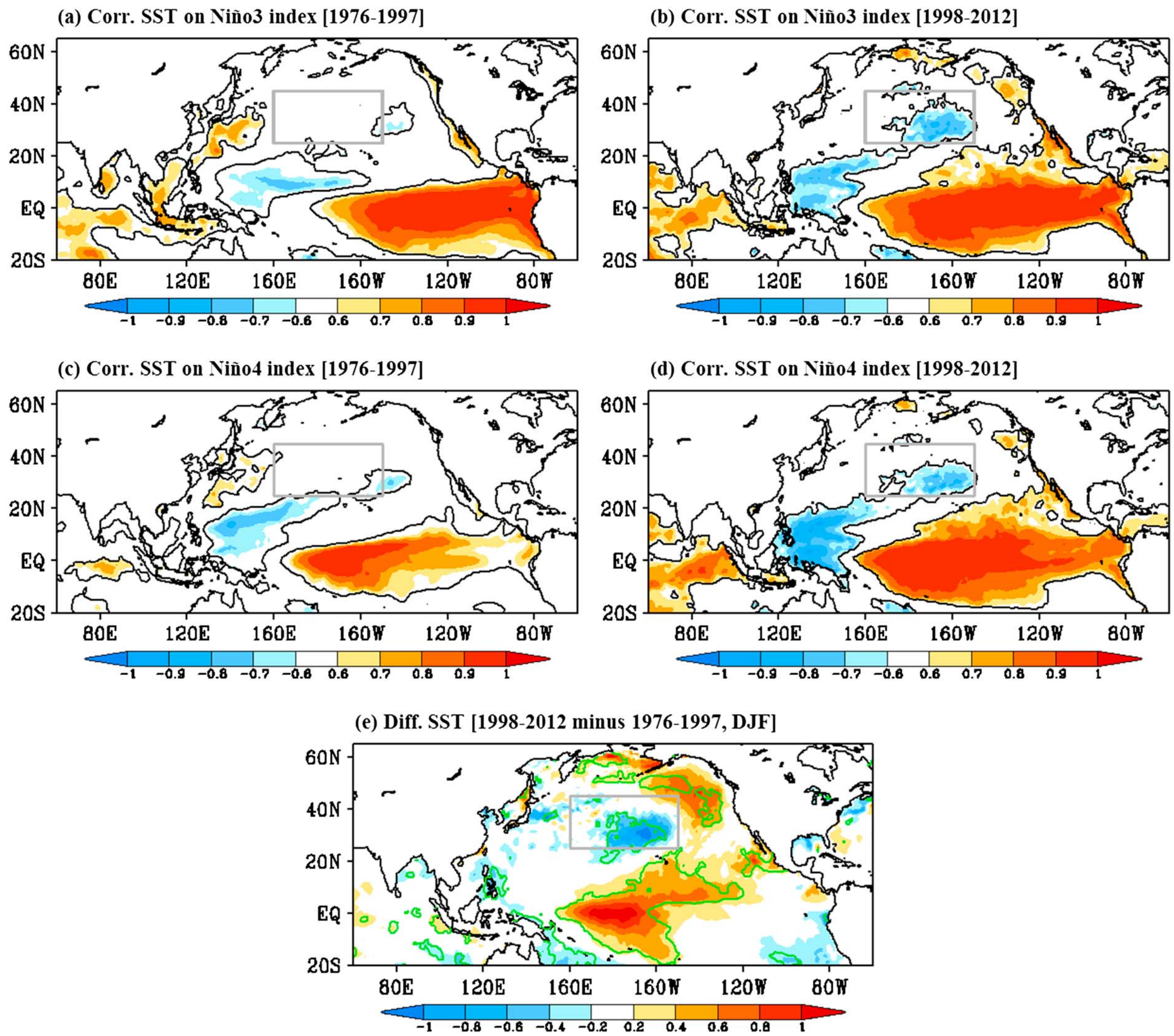

Figure 1. A correlation map of the SST for the boreal winter (December–February) with the Niño3 SST index for (a) 1976–1997 and for (b) 1998–2012. (c and d) Same as in Figures 1a and 1b except for the Niño4 SST index. (e) The difference of mean SST during El Niño occurrence before and after 1998/1999. The *thick lines* denote the 95% confidence level, and the box in Figure 1 indicates the central to eastern North Pacific. See the text for the El Niño definition.

2. Data and Models

2.1. Data

We use multiple observational data sets for the period from December 1976 through February 2012. The monthly mean SST data on a 1° longitude by 1° latitude grid were obtained from the objectively analyzed air-sea fluxes (OAflux) [*Yu et al.*, 2008]. The monthly mean outgoing long-wave radiation (OLR) data on a 2.5° longitude by 2.5° latitude were obtained from the NOAA [*Liebmann and Smith*, 1996]. The atmospheric variables are obtained from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) Reanalysis [*Kalnay et al.*, 1996]. In this study, we used the seasonal mean data during the boreal winter (December–February). The seasonal means were calculated from the monthly data during the winter, and the seasonal anomalies were obtained by subtracting the seasonal means from the total winter-mean fields. The analysis was performed after removing a linear trend in order to suppress any long-term global warming signals. The statistical significance test used in this study is basically based on a Student's *t test*. The effective degrees of the freedom to calculate the statistical significance were obtained from *Livezey and Chen* [1983].

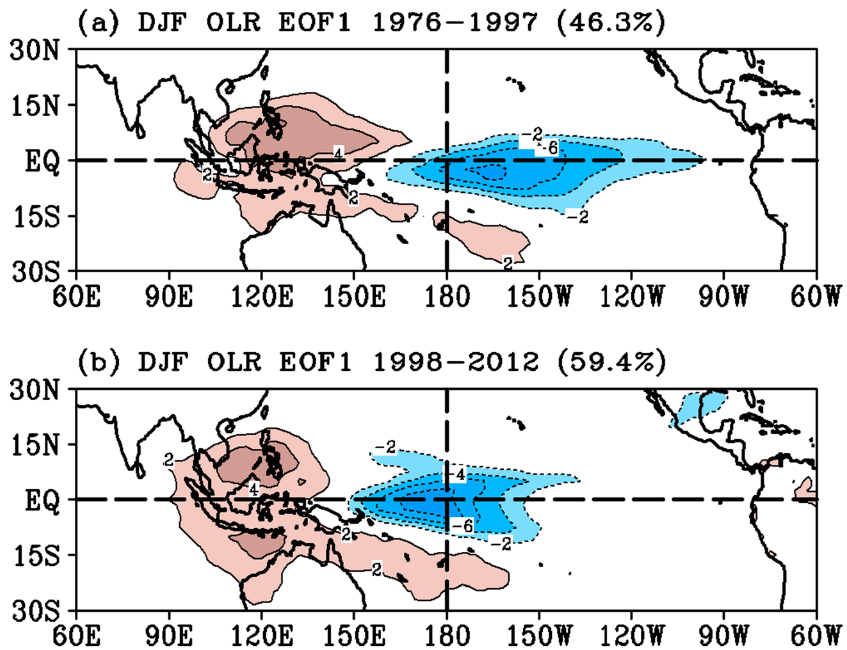

Figure 2. (a) The first EOF of tropical Pacific OLR anomalies for 1976–1997 during the boreal winter. (b) As in Figure 2a but for 1998–2012. Units are non-dimensional.

2.2. Simple Atmospheric Model

In order to gain insight into the local and remote responses to tropical heating anomalies, we used a simple atmospheric model developed by *Lee et al.* [2009]. It is a steady state two-level (at 250 hPa abd 750 hPa) spherical-coordinate primitive equation model, linearized around a specified background flow. The model uses 18 triangular truncations for the horizontal grid. There are fundamental dynamic processes that the simple model simulates to capture heat-induced baroclinic and barotropic modes and the atmospheric teleconnections to high latitudes, as in the barotropic stationary wave model of *Branstator* (1983). Some studies that use the simple model demonstrated the local and remote responses of the atmosphere to the tropical heating anomalies over the equatorial Pacific [*Lee et al.*, 2009; *Wang et al.*, 2010; *Zheng et al.*, 2013]. The detailed description of the simple model is given by *Lee et al.* [2009].

3. Results

3.1. Observational Analysis

Figures 1a and 1b depict the correlation maps between the Pacific SST variability and the Niño3 (5°S–5°N, 150°W–90°W) SST index before and after 1998/1999, respectively, during the boreal winter (December–February). Figures 1c and 1d are as in Figures 1a and 1b but for the Niño4 (5°S–5°N, 160°E–150°W) SST index. The spatial pattern of the correlation coefficients reveals remarkable differences between the two periods (i.e., before and after 1998/1999) in the North Pacific as well as the tropical Pacific. While the SST variability in the central to eastern tropical Pacific (Niño3 and Niño4 regions) has a strong negative correlation with that of the central to eastern North Pacific after the 1998/1999 regime shift, such a correlation is very weak and negligible before the 1998/1999 shift. This result indicates that the predictability of the North Pacific SST after the 1998/1999 regime shift has enhanced due to the high correlation with the tropical Pacific SST variability, which is in contrast to that before the 1998/1999 shift. The structure of the eastern tropical Pacific SST anomalies is different between the two periods with a center of the SST anomalies shifted to the west after 1998/1999 (Figures 1b and 1d). Those SST anomalies after 1998/1999 resemble more of the central Pacific El Niño-type structure (or some hybrid) than the canonical ENSO signature seen in the earlier period [*Yeo et al.*, 2012]. This becomes in the differences of composited SST in El Niño events which occurred before and after 1998/1999 (Figure 1e). The most notable difference in the tropical Pacific SST anomalies is the warming in the central Pacific after

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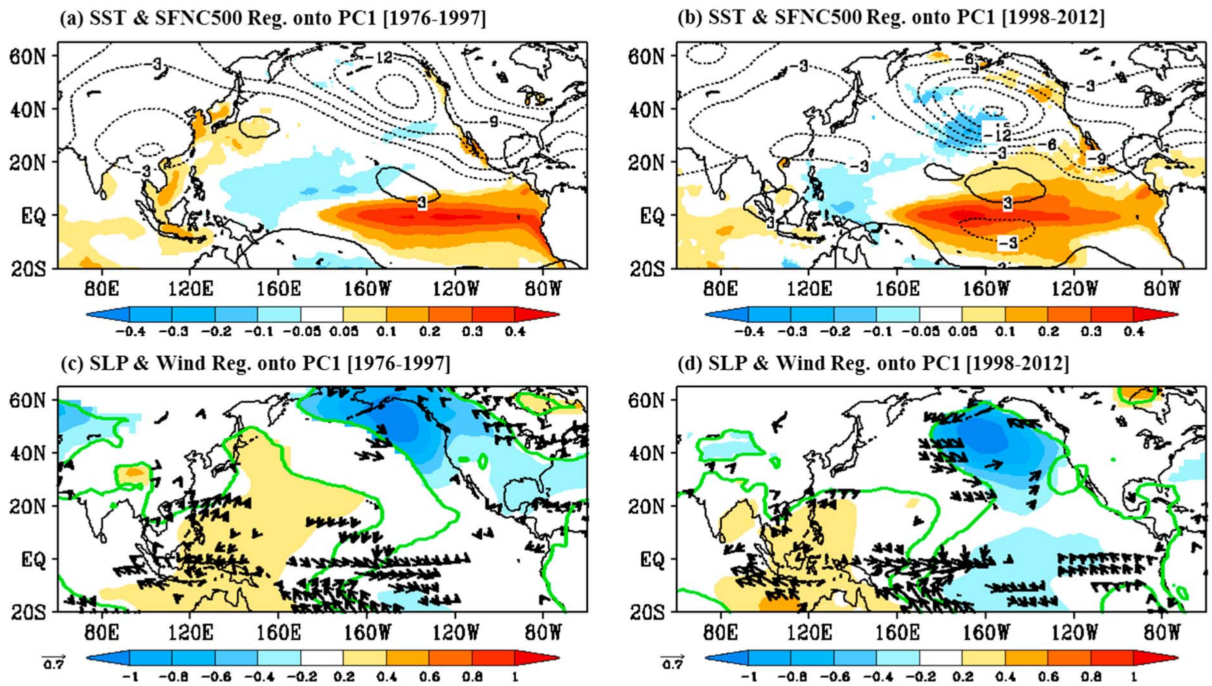

Figure 3. (a) Regression of SST (*shading*; C) and 500 hPa streamfunction (*contours*; m^2 s^{-1}) anomalies onto the leading PC time series of 1976–1997 December–February (DJF) OLR. (b) Regression of SLP (*shading*; hPa) and near-surface wind (*vector*; m s^{-1}) anomalies onto the leading PC time series of 1976–1997 DJF OLR. (c) As in Figure 3a but for the leading PC time series of 1998–2012 DJF OLR. (d) As in Figure 3b but for the leading PC time series of 1998–2012 DJF OLR. The *green contours* denote the 95% confidence level for the SFNC500 and SLP, respectively. For the *vector and shading*, only those exceeding the 90% confidence level are plotted.

1998/1999. Note that El Niño events are defined when the Niño-3.4 SST index during winter is above 0.5°C (1976/1977, 1977/1978, 1979/80, 1982/83, 1986/1987, 1991/1992, 1994/1995, 1997/1998, 2002/2003, 2004/2005, 2006/2007, and 2009/2010).

In order to understand the physical mechanism, we first examine the characteristics of OLR, which represents the structure of deep convective forcing over the tropical Pacific, before and after the 1998/1999. Figures 2a and 2b display the first empirical orthogonal function (EOF1) of OLR anomalies before and after the 1998/1999. The spatial pattern of EOF1 for the two periods is characterized by enhanced (suppressed) convective forcings over the central to eastern tropical Pacific (western tropical Pacific). However, some differences exist in the EOF1 in terms of their spatial structure before and after the 1998/1999 regime shift. The center of the convective forcing is shifted westward to the dateline, which may significantly modulate the atmospheric teleconnections from the tropics to the midlatitude [*Barsugli and Sardeshmukh*, 2002]. In addition, the suppressed OLR center also shifted westward to the Indo-Western tropical Pacific during the 1998/1999 regime shift. These results suggest that the changes in the location of the convective forcings in the tropical Pacific are evident, which are also observed in the difference of composited OLR in El Niño events (not shown). Note that the spatial pattern of the EOF1 before and after the 1998/1999 regime shift is similar to that of EOF1 and EOF2 of the entire period (1976–2012) except for a location of its center (Figure S1 in the supporting information). Therefore, it is evident that there is low-frequency variability in both the EOF1 and EOF2 PC time series, indicating that the EOF1 before and after 1998/1999 contributes to the first two EOFs for the entire period on the low-frequency time scales.

We further calculate the regression maps of several oceanic and atmospheric variables against the EOF1 principal component time series (Figure 3). Before the 1998/1999 regime shift, the pattern of the regressed SST anomalies is characterized by the so-called "Pacific-East Asian teleconnection" pattern [*Wang et al.*, 2000], which is closely associated with the canonical El Nino (Figure 3a). In other words, the central to eastern tropical Pacific SST anomalies are more correlated with those in the western North Pacific before the 1998/1999 shift. On the other hand, the atmospheric teleconnections from the tropics to the midlatitudes before the 1998/1999 shift are characterized by the so-called Tropical-Northern Hemisphere

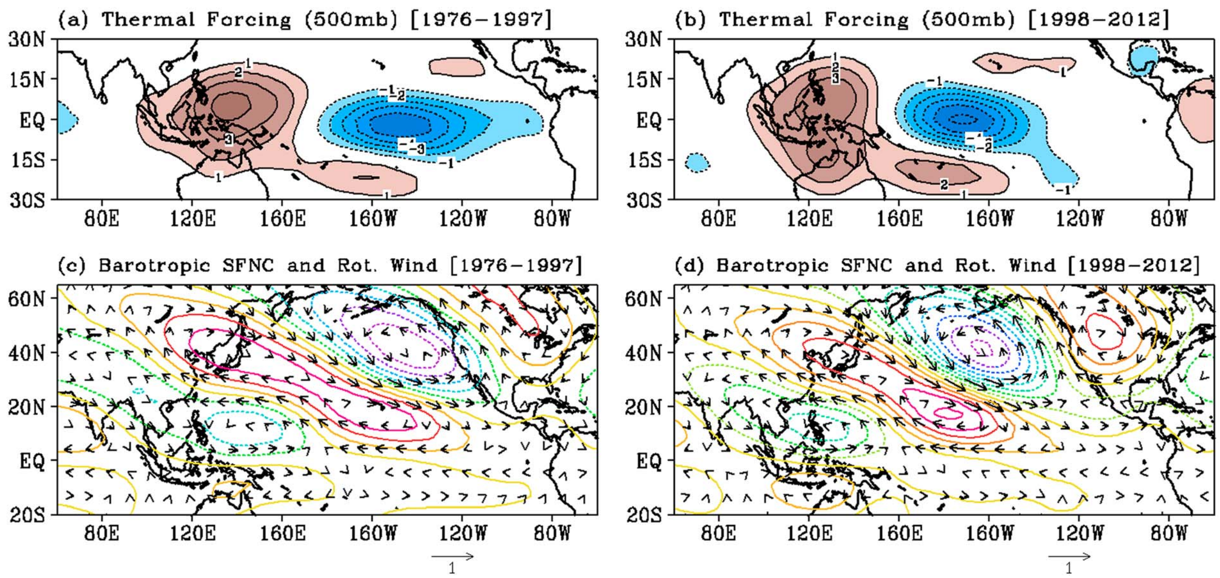

Figure 4. (a) Thermal forcing at 500 hPa based on EOF1 OLR field in boreal winter (DJF) for 1976–1997 from the simple model experiment. (c) Barotropic stream function and rotating wind (*vector plot*) of Figure 4a. (b and d) As in Figures 4a and 4c but based on EOF1 OLR field for 1998–2012. The thick and dashed lines are for the positive and negative values. The contour interval is 10^5 m^2s^{-1}.

teleconnection mode over the Pacific-North American (PNA) region [*Wallace and Gutzler*, 1981; *Barnston and Livezey*, 1987], which is evidenced by the regressed stream function anomalies at 500 hPa (i.e., barotropic stream function) (Figure 3a) and 250 hPa minus 700 hPa stream function anomalies (i.e., baroclinic stream function) (see Figure S2a in the supporting information). At the surface level (Figure 3c), it is evident that the anomalous Aleutian low-pressure center shifted toward the U.S. west coast from the climatological position (150°W, 47°N), leading to the barotropic atmospheric circulation from the surface level to the upper level. However, the strength of the anomalous Aleutian low pressure is not quite as strong as that after the 1998/1999 regime shift (Figure 3c), which results in surface winds that are not statistically significant in the North Pacific. Therefore, we speculate that the SST variability induced by the surface wind through the air-sea interactions [*Cayan*, 1992] is also weak in the North Pacific.

In contrast, the regressed cool SST anomalies are prominent in the central to eastern North Pacific after the 1998/1999 regime shift. In particular, the regressed stream function anomalies at 500 hPa (i.e., barotropic stream function) (Figure 3b) and 250 hPa minus 700 hPa stream function anomalies (i.e., baroclinic stream function) (see Figure S2b in the supporting information), which is associated with the PNA-like atmospheric circulation, become much stronger over the North Pacific after the 1998/1999 shift than they are before the shift. In more detail, the Aleutian low pressure become stronger, and its center shifted to the south and to the west from the climatological position along with the statistically significant surface wind (Figure 3d). Consequently, significant cyclonic surface wind anomalies cause cooling in the North Pacific through the wind-evporation-SST interactions. This results in the strengthening of the relationship between the tropical Pacific and the North Pacific SST variability after the 1998/1999 regime shift. These results suggest that the changes in the location of the convective forcings in the tropical Pacific (Figure 2) may lead to the changes in the PNA-like atmospheric teleconnection pattern including the Aleutian low pressure after the 1998/1999 regime shift.

3.2. Simple Atmospheric Model Experiments

The location of the tropical forcing is important for inducing different upper tropospheric divergences and Rossby wave propagations in the tropics, leading to the sensitivity of the midlatitude response to the tropical forcing according to the results of previous studies [*Trenberth et al.*, 1998; *Cherchi et al.*, 2012; *Ji et al.*, 2014]. In this subsection, we conduct two idealized experiments using a simple atmospheric model [*Lee et al.*, 2009] to examine the role of the tropical convective forcing before and after the 1998/1999. One experiment includes the thermal forcing (Figure 4a), which is obtained from the EOF1 OLR field for

1976/1977–1997/1998 (hereafter, referred to as Exp 76–97). The other experiment is the same as in Exp 76–97 except that the thermal forcing (Figure 4b) is obtained from the EOF1 OLR field for 1998/1999–2012/2013 (referred to as Exp 98–12). It should be noted that the basic mean states are obtained from the zonally averaged stream functions between 120°E and 120°W, and the velocity potential at 250 and 750 hPa for each period (i.e., 1976–1997 and 1998–2012) in Exp 76–97 and Exp 98–12. All of the data sets are from the NCEP-NCAR Reanalysis [*Kalnay et al.*, 1996]. Since the simple model consists of two levels, the variables could be separated into the barotropic ($\overline{\psi}$) and baroclinic ($\hat{\psi}$); the baroclinic and barotropic stream functions are calculated as $\overline{\psi} = 0.5(\psi_{750\text{mb}} + \psi_{250\text{mb}})$ and $\hat{\psi} = 0.5(\psi_{750\text{mb}} - \psi_{250\text{mb}})$, respectively, where ψ stands for any variable with subscripts 1 and 2 denoting the values at the upper (250 hPa) and lower (750 hPa) levels, respectively.

Figures 4c and 4d show the barotropic stream function and baroclinic stream function (see Figures S2c and S2d in the supporting information) simulated in Exp 76–97 and Exp 98–12, respectively. In both of the experiments, the PNA-like atmospheric teleconnection patterns are reasonably simulated. In addition, the center of the stream function over the central to eastern North Pacific, which is associated with the anomalous Aleutian low pressure, is shifted to the south and to the west along with its enhancement in Exp 98–12 (Figure 4d) compared to that in Exp 76–97 (Figure 4c). This result is consistent with the results in Figures 2 and 3. Therefore, the results of the model experiment support our conclusion that the westward shift of the tropical convective forcing during the 1998/1999 regime shift is responsible for the strengthening of the relationship of the SST variability between the tropical Pacific and North Pacific.

4. Summary and Discussion

Based on the correlation and regression analysis, we showed that the SST variability in the central to eastern tropical Pacific had a strong negative correlation with that in the central to eastern North Pacific after the 1998/1999 regime shift. Such a correlation was very weak and negligible before the 1998/1999 shift largely because the PNA-like atmospheric teleconnections associated with the tropical SST forcing became stronger, after the 1998/1999 regime shift. As a result, the Aleutian low pressure became stronger, and its center shifted to the south and to the west accompanied by statistically significant surface wind anomalies after the 1998/1999 regime shift. This was primarily due to fact that the center of the tropical Pacific convective forcing shifted westward to the dateline after the 1998/1999 regime shift. Previous studies have argued that there are different sensitivities of the midlatitude response to the location of the tropical forcing [*Trenberth et al.*, 1998; *Cherchi et al.*, 2012; *Ji et al.*, 2014]. In particular, the PNA-like atmospheric teleconnection is quite sensitive to the convective forcing in the central tropical Pacific [*Barsugli and Sardeshmukh*, 2002], which is largely consistent with the results in the present study. Furthermore, *Anderson et al.* [2013] also argued that the midlatitude atmospheric circulation is also affected by ENSO asymmetry such that longitudinal position of resultant ENSO-related SST with warm (cold) events systematically shifted to the east (west) of the typical SST anomalies.

One may argue whether such changes in the relationship of the SST variability between the North Pacific and the tropical Pacific exist before 1976. Figure 5 displays the 11 year running mean correlation coefficient between the North Pacific SST index and the Niño4 SST index along with the 11 year running mean of the anomalous SST in the Niño4 region. Here the North Pacific SST index is defined as the anomalous SST averaged in 25°N–45°N, 160°E–150°W. It is evident that the relationship of the North Pacific SST index-Niño4 SST index changes on the low-frequency time scales has a strong negative correlation during some periods (for the late 1960s to the late 1970s and after the late 1990s) but a weaker negative correlation during other periods (before the late 1960s and for the late 1970s to the late 1990s). These results indicate that the change in the relationship in the SST variability between the tropical Pacific and the North Pacific SST across the 1998/1999 regime could be due to internal variability and not anthropogenically forced. In addition, the two time series are highly correlated. The simultaneous correlation coefficient is 0.78, which is statistically significant at a 95% confidence level. In other words, the relationship between the North Pacific SST index and Niño4 SST index is weak when the central tropical Pacific is warm. In contrast, the relationship between the North Pacific SST index and Niño4 SST index is strong when the central tropical Pacific is cool. This result indicates that the change in the central tropical Pacific mean SST is highly

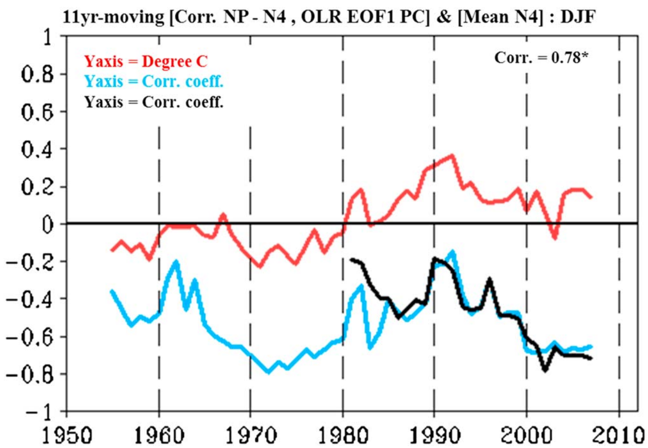

Figure 5. The 11 year running correlation coefficient between the North Pacific SST index and the Niño4 index for 1950–2012 in winter (blue line) and the OLR EOF1 PC time series for 1976–2012 (black line). The red line indicates the 11 year running mean of the anomalous mean SST in the central tropical Pacific (i.e., Niño4 region). The correlation coefficient between blue line and red line is written at the top right corner. An asterisk denotes statistical significance at the 95% confidence level.

associated with the relationship in the SST variability between the tropical Pacific and the North Pacific on low-frequency time scales. Such a decadal change in the tropical Pacific mean state can be induced by the change in ENSO asymmetry on the low-frequency time scales [*Sun and Yu*, 2009; *Yu and Kim*, 2011]. The relationship between the North Pacific SST index and the EOF1 OLR PC time series for 1976–2012 (Figure S3) is also displayed in Figure 5. The leading PC time series of OLR is highly correlated with the 11 year running mean correlation coefficient between the North Pacific SST index and the Niño4 SST index and with the anomalous mean SST in the central tropical Pacific (i.e., Niño4 region). This indicates that the location in the convective forcings in the tropical Pacific plays a crucial role in the relationship of the SST variability between the North Pacific and the tropical Pacific.

Further analysis is required to understand how the mean SST change in the tropical Pacific is associated with the convective forcing on the low-frequency time scales. An increase or decrease in the tropical mean SST may influence the air-sea interactions, resulting in the modulation of convective forcing in terms of its intensity and spatial pattern. The model experiment using an atmospheric general circulation model may be useful to examine this issue.

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