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SPATIAL VARIATION OF WINTER SEA SURFACE TEMPERATURE IN NORTH PACIFIC AND ITS RELATION TO ATMOSPHERIC OSCILLATION MODES

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Abstract: The spatial variation of sea surface temperature anomalies (SSTA) in the North Pacific Ocean during winter is investigated using the EOF decomposition method. The first two main modes of SSTA are associated with Pacific Decadal Oscillation (PDO) mode and North Pacific Gyre Oscillation (NPGO) mode, respectively. Moreover, the first mode (PDO) is switched to the second mode (NPGO), a dominant mode after mid-1980. The mechanism of the modes' transition is analyzed. As the two oceanic modes are forced by the Aleutian Low (AL) and North Pacific Oscillation (NPO) modes, the AR-1 model is further used to examine the possible effect and mechanism of AL and NPO in generating the PDO and NPGO. The results show that compared to the NPO, the AL plays a more important role in generating the NPGO mode since the 1970s. Likewise, both the AL and NPO affect the PDO mode since the 1980s.

Key words: North Pacific; sea surface temperature; sea level pressure; climate mode; variation

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1 INTRODUCTION

With the accumulating oceanic observation datasets and numerical products, two climate modes in the North Pacific Ocean have been much studied. There are two classical decadal modes in the North Pacific, i.e., the Pacific Decadal Oscillation (PDO) mode and the North Pacific Gyre Oscillation (NPGO) mode. The PDO mode is defined as the first EOF of North Pacific monthly sea surface temperature anomalies (SSTA) poleward of 20°N (Mantua et al.[1]). A lot of research has been done to reveal its spatial and temporal structure (Zhang et al.[2]; Tourre et al.[3];Yang et al.[4]). However, recent works have shown that PDO index cannot illustrate the decadal fluctuations in salinity, nutrients, chlorophyll and fish stocks in the Northeast Pacific. Therefore, Di Lorenzo et al.[5] defined a new pattern of climate change, i.e., NPGO, and showed that its variation significantly correlated with the fluctuations of salinity, nutrients and chlorophyll. The NPGO is defined as the second EOF of Northeast Pacific (180º–110ºW, 25–62ºN) monthly sea surface height anomalies (SSHA). Both the PDO and NPGO can reflect the decadal variation of SSTA since the SSTA and SSHA are well correlated (Cummins et al.[6]).

In the long term, PDO and NPGO are two independent phenomena, and their correlation coefficient is only 0.15. However, recent studies have found that the PDO and NPGO indexes are somewhat correlated, which is particularly significant after 1990, and the coefficient is 0.4 (Ceballos et al.[7]). Furthermore, the NPGO mode strengthened from 1993, and the amplitude of NPGO is greater than that of PDO in the past 10 years (Cummins and Freeland[8]). The GFDL coupled climate model (Version 2.0) also shows an amplification of the NPGO variance by 38% and a reduction of the PDO variance by 58% between the periods 1900–2000 and 2000–2100. In addition, this recent strengthening of the NPGO mode is also revealed by the fact that the second EOF of SSTA (the "Victoria" mode) can explain more wintertime North Pacific SSTA variance than the PDO pattern for the 1990–2002 period (Bond et al.[9]). Meanwhile, the variation of spatial structure is another issue that needs to be analyzed, i.e., the changes of climate modes in the North Pacific in the 1980s are not the reversion of the PDO mode (Hare and Mantua[10]). EOF analysis of North Pacific SSTA during winter for the period 1956–1988 and 1977–2009 shows that the dominant mode in the former period is a PDO-like mode, while changing to

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a NPGO-like mode during the latter period (Yeh et al.[11]). In addition, the spatial structure of SST in the North Pacific is obviously different with the PDO mode after 1990s (Bond et al.[9]). It implies that the structure of the major climate modes in the North Pacific during winter may be changed.

Generally, the oceanic modes are mainly controlled by the atmospheric forcing field. The NPGO mode and PDO mode are associated with the North Pacific Oscillation (NPO, Walker and Bliss[12]; Ceballos et al.[7]) and the Aleutian Low (AL, Trenberth and Hurrel[13]; Chhak et al.[14]). The results could be obtained from both the satellite observations (Qiu and Chen[15]) and the hindcast results of oceanic models (Chhak et al.[14]), which were also verified with the IPCC AR4 Ocean-Atmospheric Coupled Model (Furtado et al.[16]).

To reveal the variability of the spatial structure and its mechanism in the North Pacific during winter, the EOF method is used to analyze the spatial structure of major SSTA modes and major sea level pressure anomaly (SLPA) modes in the North Pacific (24–62ºN, 110ºE–110ºW), which aims to answer the following two questions: (1) Has the spatial structure transition of the first two major modes in the North Pacific occurred? If the answer is "yes", then when did they occur? (2) What is the mechanism of the oceanic modes transition in the North Pacific?

2 DATA

Monthly SST field data is obtained from the monthly-averaged 2°×2° gridded Extended Reconstruction SST, version 3 (ERSST.v3; Smith and Reynolds[17]), which is provided by the National Climate Data Center (USA). Compared with the previously released ERSST.v2, most of the improvements are justified by testing with simulated data, reducing the SST anomaly damping before 1930 using the optimized parameters. In addition, since 1985, ERSST.v3 has also been improved by explicitly including bias-adjusted satellite infrared data from AVHRR. The monthly-averaged SLP data is taken from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR, USA) Reanalysis project (Kalnay et al.[18]), whose horizontal resolution is 2.5°×2.5°. The linear trend of SST and SLP is used to remove the effects of global warming. To reveal the transition of the oceanic modes in the North Pacific, the domain is taken as (24–62ºN, 110ºE–110ºW). The SST and SLP datasets are used in the period from January 1950 to December 2008, or 708 months.

The climate indices such as PDO and NPGO are also used. The PDO is the first EOF of North Pacific monthly SSTA poleward of 20°N and its index (http://jisao.washington.edu/pdo/pdo.latest) is defined as the time series of the first principal component (PC) (Mantua et al.[1]). The NPGO is the second EOF of Northeast Pacific (25–62ºN,180º–110ºW) monthly SSHA and its index (http://www.ocean3d.org/npgo) is defined as the time series of the second principal component (PC) (Di Lorenzo et al.[5]).

This paper focuses on the winter season, which is defined as the three months from January to March for the SST data. The 1951 winter thus indicates January-February-March. For the SLP data, however, winter is defined as the three partially overlapped months from December to February so that the 1951 winter includes December (1950), January (1951) and February (1951).Unless otherwise stated in the text, the results are for the winter season only.

3 CHARACTERISTICS OF SSTA MODES IN THE NORTH PACIFIC

3.1 *Spatial structure*

Generally speaking, the NPGO can be described as the second EOF of Northeast Pacific SSTA (also known as the "Victoria" mode, Bond et al.[9]). To reveal the spatial structures of PDO mode and NPGO mode, the regression maps of PDO and NPGO indices with the SSTA are shown in Figures 1a to 1b for the period 1950–2008 during winter. The PDO mode is characterized by anomalously warm temperatures over an elliptical shape in the western and central North Pacific and is accompanied by anomalies of the opposite sign along the western North American coast (Figure 1a), which is in the negative phase. The NPGO mode is characterized by a dipole-like structure in the meridional direction with the zero line nearly along 40°N. The negative SSTA south of 40°N extends from the East Asia marginal seas to the central North Pacific, while positive SSTA north of 40°N spans from the east to the west with its center located in the central North Pacific.

Then the inter-relationship between the two major SSTA modes in the North Pacific is examined with EOF analysis. Figures 1c and 1d show the first two EOFs (hereafter, EOF1 and EOF2) of SSTA in the North Pacific. The percentage variances explained by EOF1 and EOF2 are 32.11% and 19.27%, respectively. Therefore, there is clear separation between EOF1 and EOF2 according to the criterion of North et al.[19]. The spatial structure of EOF1 for this period is characterized by negative SSTA in the western and central North Pacific and positive SSTA along western North American coast (Figure 1c), which is quite similar to the structure of the PDO mode. EOF2 of North Pacific SSTA (Figure 1d) is characterized by a dipole-like structure in the meridional direction, which is quite akin to the NPGO mode's spatial structure.

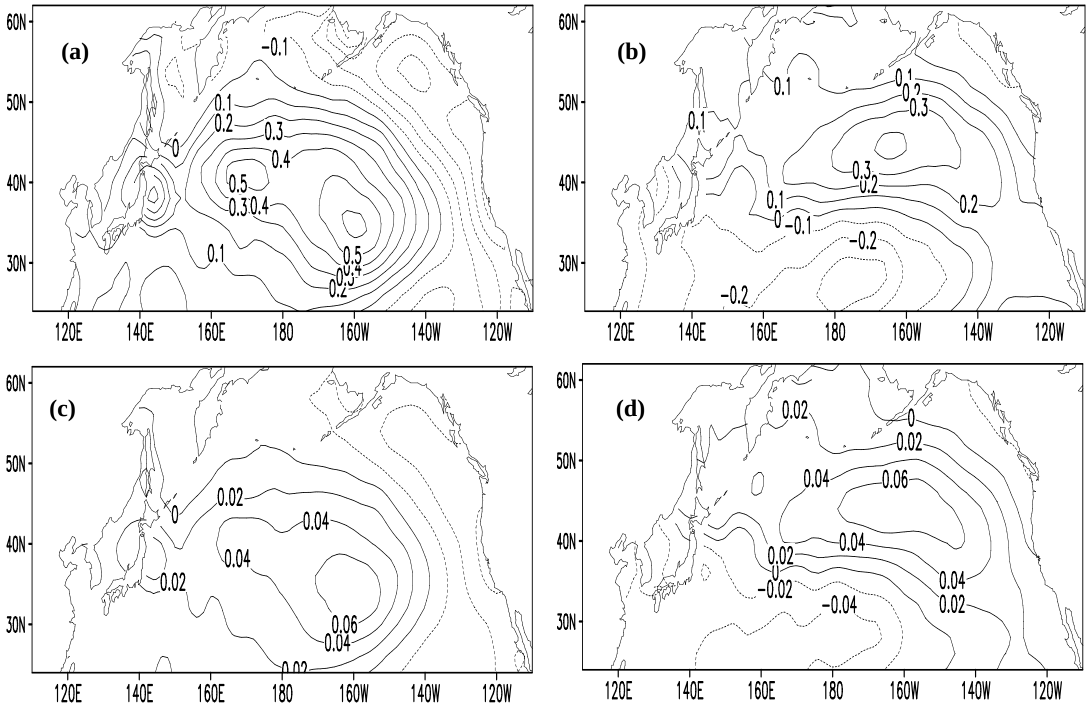

Figure 1. Regression maps of PDO (a) and NPGO index (b) with the SSTA in the North Pacific for the period of 1950–2008 during winter; The first (c) and second (d) EOF of SSTA are for the same period. The dashed line denotes negative values. The unit is nondimensional.

The correlation coefficient of the spatial structure between the EOF1 and the PDO mode is 0.9763, while the one between the EOF2 and NPGO mode is 0.9419. In addition, the correlation between the time series of EOF1of SSTA (hereafter, PC1) and PDO index is 0.8627, and the one for the time series of EOF2 of SSTA (hereafter, PC2) and NPGO index is 0.7187. The above results show that the EOF1 and EOF2 of SSTA in the North Pacific are quite similar to the spatial structure of classic PDO mode and NPGO mode, respectively. Similarly, the PC1 and PC2 of SSTA closely follow the PDO index and NPGO index, respectively. Therefore, we define the EOF1 of SSTA as a PDO-like mode and EOF2 of SSTA as an NPGO-like mode in the following study.

3.2 *Changes of the modes' spatial structures*

To reveal the temporal variations of major SSTA modes in the North Pacific, EOF analysis is used for different periods of SSTA during 1950–2008 using a time-slippage method. Because the periods of 30 years can well be used to depict the climatological characteristics, the time domains of 1950–1979, 1951–1980, …, 1989–2008, totally 40 different periods, are obtained. Note that the last 10 time domains (from 1980 to 2008 and from 1989 to 2008) are shorter than 30 years as a result of the limitation of datasets. Conveniently, each time domain will be represented by the first year of this period, for example, 1950 indicates the period 1950–1979.

The spatial structure of the EOF1 and EOF2 of SSTA in the North Pacific during the time domains (1968–1997, 1976–2005 and 1988–2008) are shown in Figures 2 and 3, respectively. Analysis of the temporal variability of EOF1 in the North Pacific indicates that the spatial structure is characterized by centers in the western and central North Pacific and along the western coast North America before 1971, which shows the PDO spatial structure in Figure 1c. Note that, the center in the central North Pacific moves southeastward after 1971, and exhibits a dipole structure around 1984, which is quite similar to the structure of the NPGO mode in Figure 1d. The temporal variation of EOF2 in North Pacific shows that the EOF2 is characterized by a dipole structure with two opposite SSTA centers located at the south and north of mid-latitude North Pacific, respectively. The distribution feature is more obvious for the period between 1968 and 1971.The north center of EOF2 moves to the central North Pacific and becomes abnormally large from 1971, while the south center diminishes after 1973 and finally disappears around 1984. That is, only an anomalous temperature center exists in the mid-latitude North Pacific after 1984, which is quite similar to the structure of the PDO-like mode in Figure 1c.

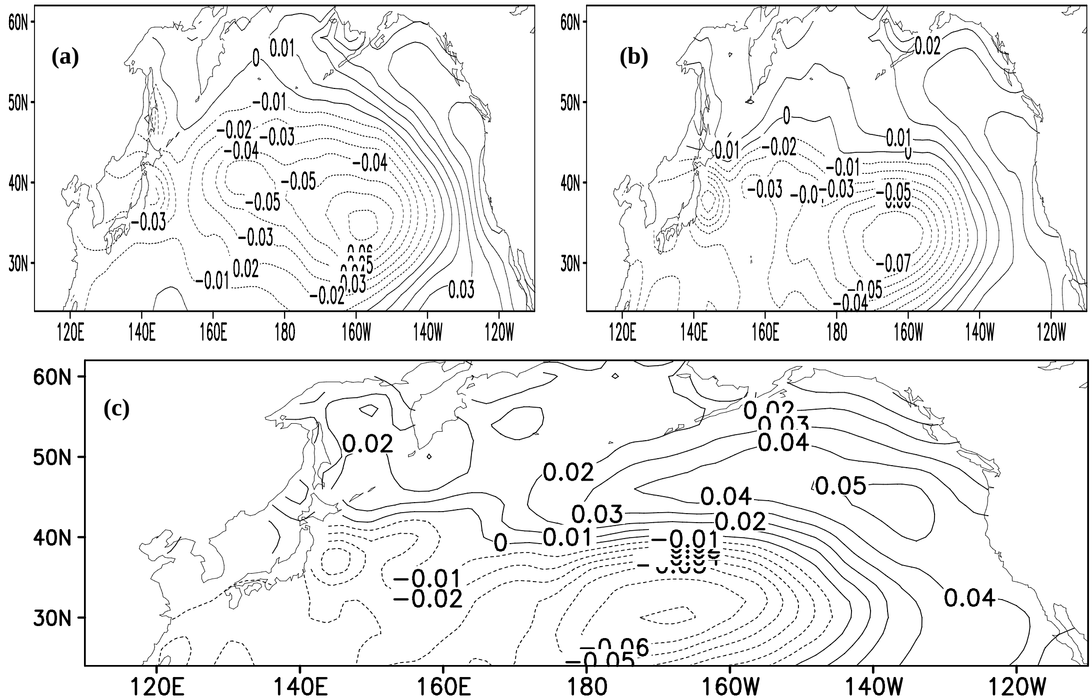

Figure 2. The first EOF of SSTA is for the period of (a) 1968–1997, (b) 1976–2005 and (c) 1988–2008, respectively. The dashed line denotes negative values. The unit is nondimensional.

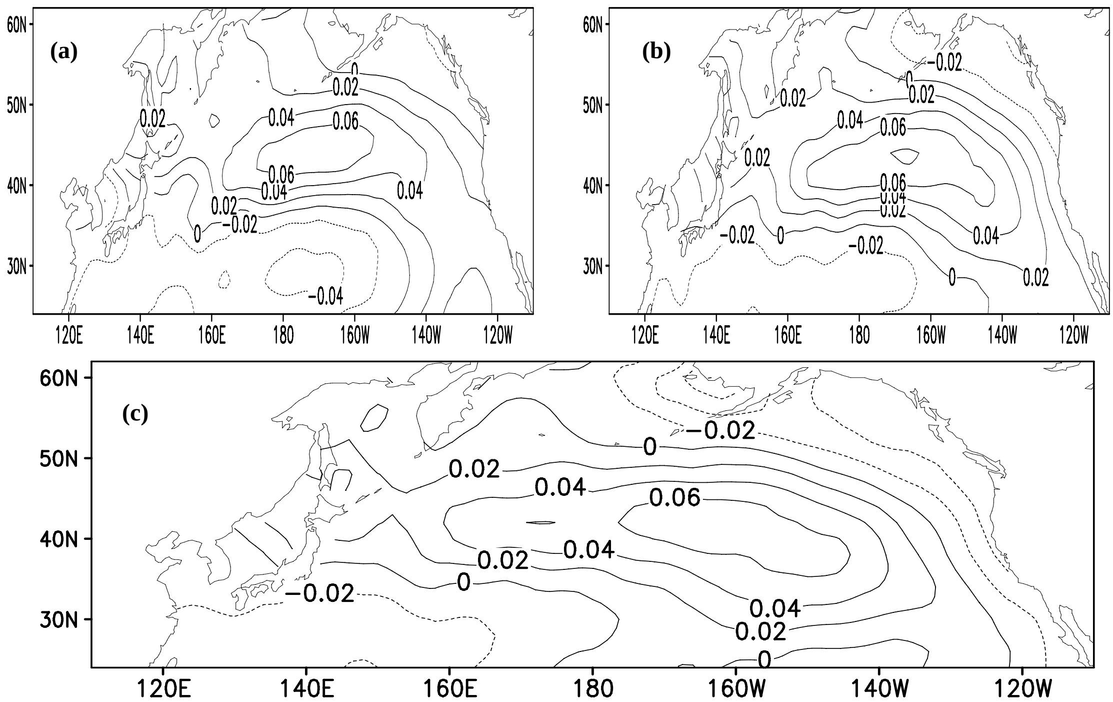

Figure 3. The second EOF of SSTA is for the period of (a) 1968–1997, (b) 1976–2005 and (c) 1988–2008. The dashed line denotes negative values. The unit is nondimensional.

The temporal variations of the two major SSTA modes in the North Pacific indicate that obvious transition of oceanic modes occurs around the 1980s. The structure of the EOF1 changes from the PDO to NPGO mode, and the structure of the EOF2 changes from NPGO to PDO mode.

To analyze the temporal variations of the major SSTA modes in the North Pacific further, spatial pattern correlation analysis is used for the EOF1 and EOF2 of SSTA in the North Pacific between the period 1950–2008 and the 40 different periods (denoted by SSTA-V2 and SSTA-V2, figures omitted). Here, R_{P-1} is the spatial pattern correlation between the PDO-like mode and SSTA-V1, R_{P-2} the spatial pattern correlation between the PDO-like mode and SSTA-V2, R_{N-1} the spatial pattern correlation between the NPGO-like mode and SSTA-V1, and R_{N-2} the spatial pattern correlation between the NPGO-like mode and SSTA-V2. The time variations of R_{P-1}, R_{P-2}, R_{N-1} and R_{N-2} are shown in Figure 4. It shows that R_{P-1} and R_{N-2} decrease with time, while R_{P-2} and R_{N-1} increase, which are more obvious after 1969. Furthermore, R_{N-1} and R_{P-2} exceeds R_{P-1} and R_{N-2} around 1984, respectively. The phenomenon indicates that the structure of EOF1 of SSTA in the North Pacific is consistent to the PDO mode before 1969, while the EOF2 agrees with the NPGO mode. However, the structure of EOF1 and EOF2 begins transition after 1969. Around 1984, the structure of the EOF1 changes to that of the NPGO-like mode, while structure of EOF2 changes to that of the PDO-like mode. The above analysis supports the results of qualitative analysis further, i.e., obvious transition of major SSTA modes occurs in the North Pacific around the 1980s. The NPGO mode becomes the major mode in the North Pacific in 1984–2008.

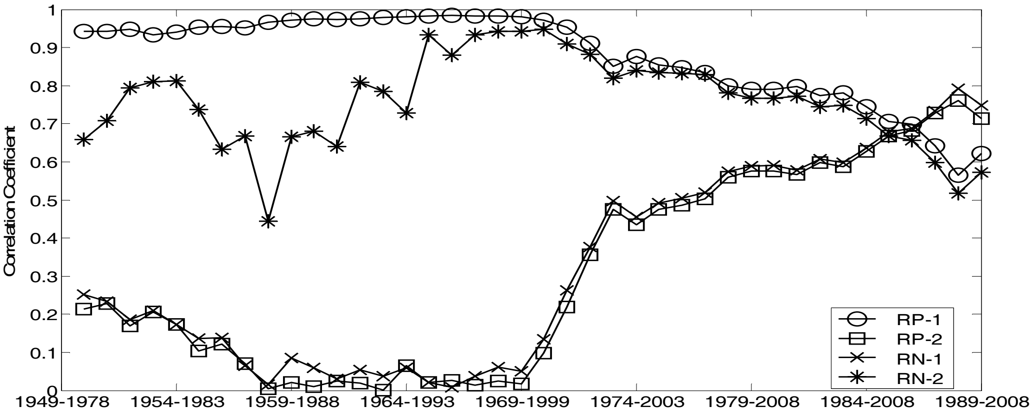

Figure 4. Time variations of absolute value of spatial pattern correlation coefficient for different time domains.

3.3 *Temporal variation of SSTA modes*

To filter out the influence of El Niño/La Niña-Southern Oscillation, 5-year moving average is done on the time series of EOF1 and EOF2 of SSTA for the period 1950–2008 in the North Pacific during winter (hereafter, PC1 and PC2). The temporal variability of PC1 and PC2 are shown in Figure 5. It shows that the amplitude of PC1 decreases after the 1980s and the frequency becomes lower, which exhibits variations opposite to that of PC2. The temporal evolution indicates that the EOF1 (EOF2) is converted to high (low) frequency. Moreover, Figure 5 shows that the sign of PC1 changes from positive to negative and the amplitude increases around 1976; afterwards, the phase converts to positive around 1988 and then becomes negative in 1990. The characteristic of PC2 in 1976 is analogous to that of PC1, while the phase converts to positive in 1990 and the amplitude increases. Comparisons of Figure 5a with Figure 5b clearly shows that the PC1 phase change in 1976/1977 is more notable than that of PC2, while the opposite is true for 1988/1989. The climate modes in the North Pacific play different roles in the two climate regime shift, and the second mode becomes more important (Yeh et al.[11]).

3.4 *Average SSTA in the North Pacific during winter*

The variation of climate modes in the moving time domains is analyzed, and the average SSTA in the typical periods of 1950–1976, 1977–1988, 1989–1999 and 2000–2008 are shown in turn to exhibit the spatial structures of the entire SSTA. In Figures 6a and 6b, the spatial structures of average SSTA of 1950–1976 and 1977–1988 show analogous patterns with opposite phases, with the center located in the central North Pacific, which are similar to that of the PDO mode. The spatial structures of average SSTA of 1989–1999 (Figure 6c) and 2000–2008 (Figure 6d) also exhibit similar structures with opposite phases, which characterizes a dipole-like structure and resembles to that the NPGO mode. Note that the spatial structures of average SSTA are distinct among 1950–1976, 1977–1988 and 1989–1999, 2000–2008, with the patterns transform from the PDO to NPGO mode. This result implies that the phase transition of SSTA in the North Pacific occurs around 1976/1977 and 1999/2000, however, the spatial structure of SSTA changes after the climate transition in 1988/1989.

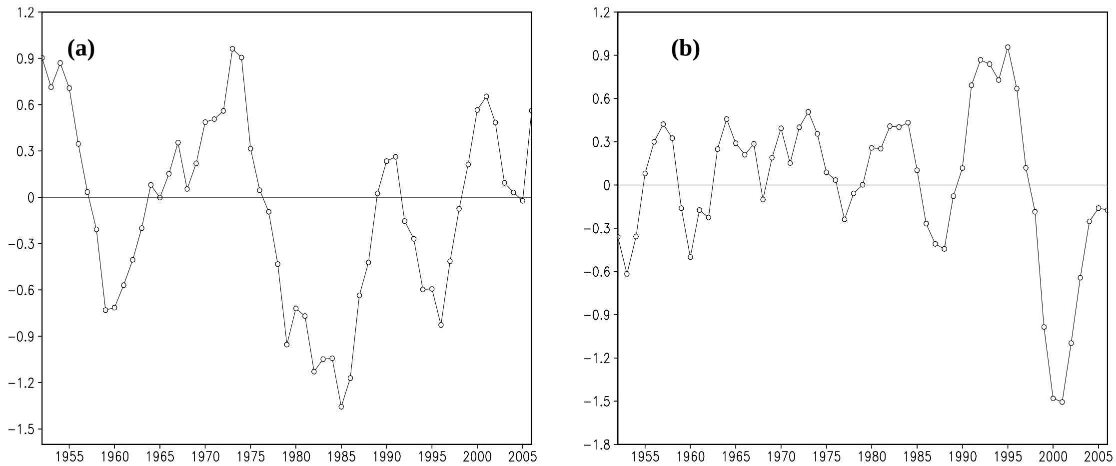

Figure 5. Time series of the first mode (a) and second mode (b) of SSTA for the period of 1950–2008.

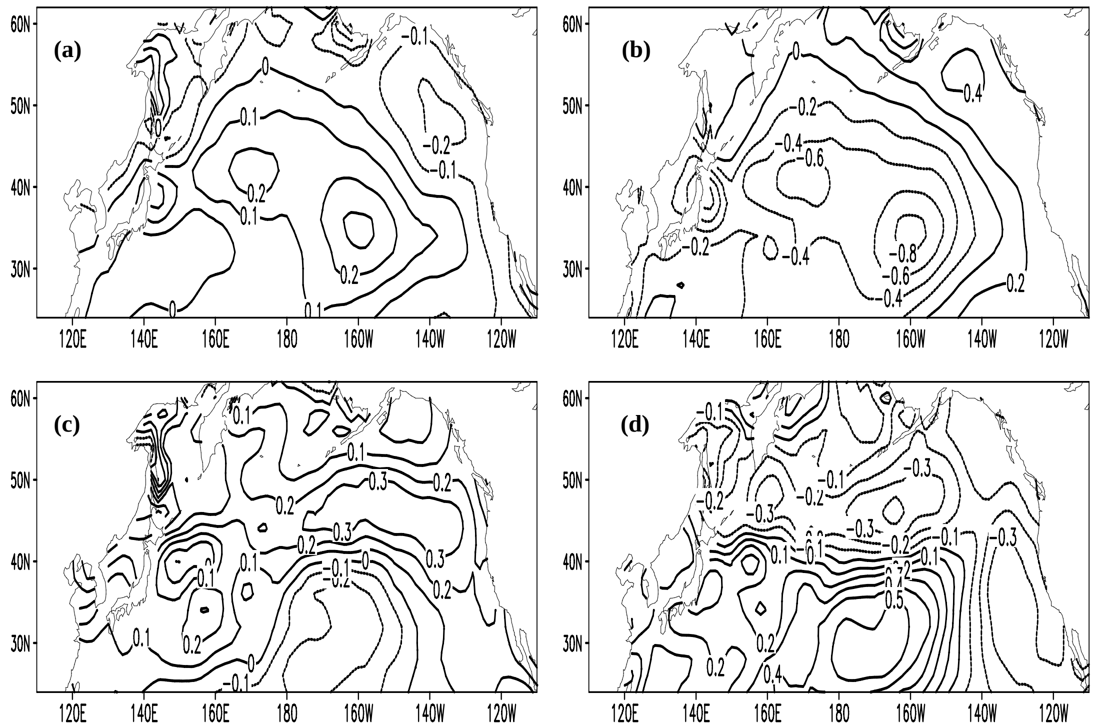

Figure 6. The average SSTA in the North Pacific for the period of 1950–1976 (a), 1977–1988 (b), 1989–1999 (c) and 2000–2008 (d) during winter. The dashed line denotes negative values. The unit is nondimensional.

4 RELATIONSHIP BETWEEN THE OCEANIC MODES TRANSITION AND THE ATMOSPHERIC MODES

Observation and numerical simulation show that the PDO and NPGO modes are the oceanic expressions of the AL and NPO, respectively. The AL is defined as the first EOF of North Pacific monthly SLPA (Trenberth and Hurrel[13]). The NPO is defined as the second EOF of North Pacific monthly SLPA (Walker and Bliss[12]). Therefore, we will focus on the temporal variation of spatial structure of SLPA and its forcing effect on oceanic modes to explain the transition of main SSTA modes in the North Pacific around the 1980s.

4.1 *Spatial structures of SLPA modes in the North Pacific*

To reveal the spatial structures of AL mode and NPO mode, EOF analysis is used for SLPA in the North Pacific for the period 1950–2008 during winter. The EOF1 of SLPA for this period shows an anomalous elliptical distribution in the North Pacific (Figure 7a), which is quite similar to the structure of the classical AL mode. EOF2 of North Pacific SLPA is characterized by a dipole-like structure (Figure 7b) in which the north center of maximum variance is within (55–62ºN, 175ºE–155ºW), and the south center (28–40ºN, 175ºE–150ºW), which is consistent to the structure of the classical NPO mode. The variances explained by EOF1 and EOF2 are 44.23% and

19.31%, respectively. Furthermore, the relationship between the two SLPA modes in the North Pacific and two oceanic climate modes are examined by the regression analysis method. The regression maps of PDO and NPGO indices to the SLPA are shown in Figures 7c and 7d in the period 1950–2008, respectively. The regression map of the PDO index with SLPA (Figure 7c) is characterized by a single anomalous SLP center with an elliptical shape in the North Pacific, which is quite similar to the structure of the AL mode in Figure 7a. The regression map of NPGO index with SLPA (Figure 7d) represents a dipole-like distribution, consistent to the structure of the NPO mode in Figure 7b. In addition, the spatial pattern correlation between the AL mode and the regression coefficient field of PDO index with SLPA is 0.96, and the correlation between the NPO mode and the regression coefficient field of the NPGO index with SLPA is 0.91. The results indicate that the AL mode and the NPO mode are the atmospheric forcing fields of the oceanic PDO mode and the NPGO mode respectively, which agrees with previous observations and numerical results. To reveal the mechanism of the transition of major SSTA modes in the North Pacific, EOF analysis is used for the 40 periods of SLPA during 1950–2008 as mentioned in section 3.2. The temporal variations of the first two major SLPA modes show that the EOF1 of SLPA is characterized by a single anomalous center in the North Pacific, and the EOF2 of SLPA represents the dipole-like distribution all the time. However, the abnormal center locations and scopes experience several changes. The center of the first mode moves southeastward. The north center of the second mode diminishes after 1958 and returns around 1967, meanwhile the south center becomes abnormally large after 1967, e.g. the anomalous scope of maximum variance is located near (26–42ºN,150ºE–140ºW) in 1972.

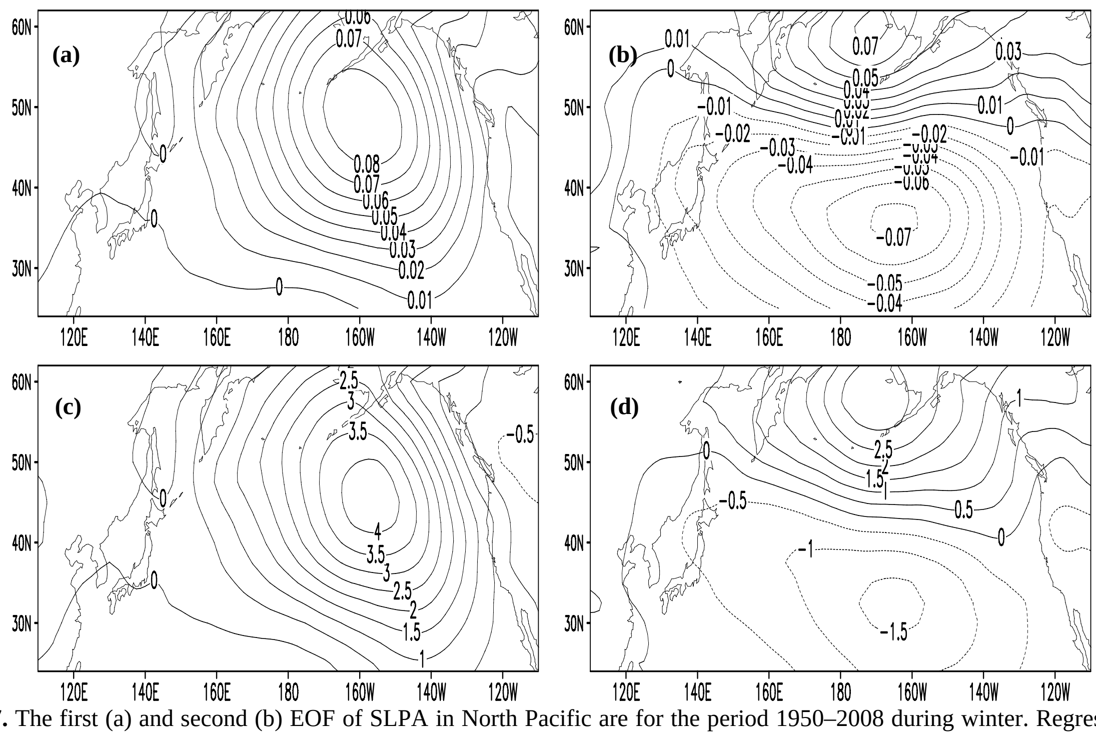

Figure 7. The first (a) and second (b) EOF of SLPA in North Pacific are for the period 1950–2008 during winter. Regression maps of PDO (c) and NPGO index (d) with SLPA are for the same period. The dashed line denotes negative values. The unit is nondimensional.

It implies that although the spatial structure of EOF1 and EOF2 of SLPA in the North Pacific changes slightly, the location of abnormal SLP is displaced significantly. Especially the south center of the second mode represents elliptical distribution and its coverage becomes abnormally large from 1969, showing consistency to the structure of the AL mode.

4.2 *Forcing of atmospheric field on SSTA modes in the North Pacific*

Through the above analysis, it is found that there has not been any transition of major SLPA modes in the North Pacific. The structure of EOF1 of SLPA still represents the AL mode, and the EOF2 is the NPO mode. However, the spatial distributions of EOF1 and EOF2 of SLPA have changed since early 1970s. It is naturally asked: Have the variations of spatial distributions relating to the oceanic modes experienced any transition? To seek an assured answer to this question, spatial pattern correlation analysis is used between regression patterns of the above mentioned 40 periods (denoted by b1 and b2) and spatial pattern of the first two EOFs of SLPA in the North Pacific for 1950–2008 (denoted by SLPAV1 and SLPAV2). The regression pattern b1 is obtained by calculating regression coefficient of PC1 of SSTA with SLPA at each period, and b2 is regression coefficient of PC2 of SSTA with SLPA (Figure 8). In Figure 8, $R_{b1\text{-}SLPAV1}$ is the spatial pattern correlation between b1 and SLPAV1, $R_{b1\text{-}SLPAV2}$ between b1 and SLPAV2, $R_{b2\text{-}SLPAV1}$ between b2 and SLPAV1, and $R_{b2\text{-}SLPAV2}$ between b2 and SLPAV2.

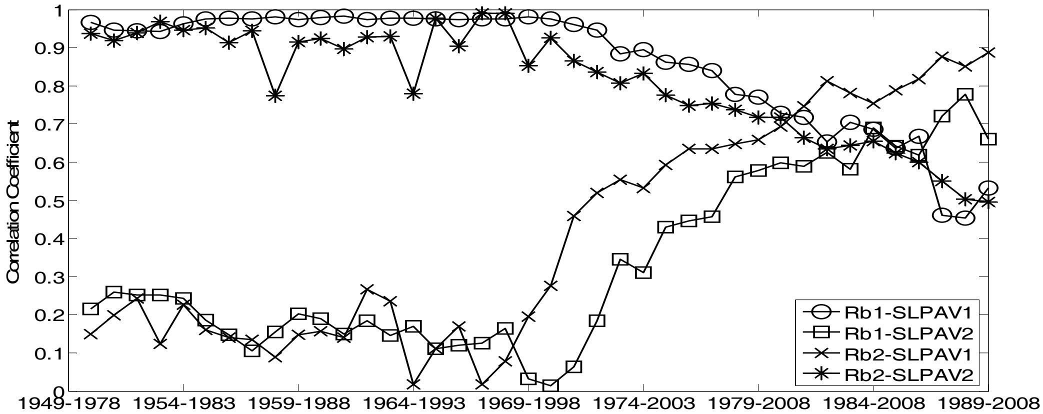

Figure 8. Time variation of absolute values of field correlation coefficient for different time domains.

Figure 8 shows that $R_{b1\text{-}SLPAV1}$ declines after 1969, while $R_{b2\text{-}SLPAV1}$ ascends quickly after 1967, and $R_{b2\text{-}SLPAV1}$ exceeds $R_{b1\text{-}SLPAV1}$ around 1981. $R_{b2\text{-}SLPAV2}$ fluctuates before 1974 and then declines, while $R_{b1\text{-}SLPVA2}$ ascends after 1970, and $R_{b1\text{-}SLPVA2}$ also exceeds $R_{b2\text{-}SLPVA2}$ around 1984. The temporal variations of spatial pattern correlations indicate that the first SSTA mode in the North Pacific begins to change after 1967, and becomes NPGO-like mode around 1981. At the same time, the second major SSTA mode changes to the PDO-like mode. Note that $R_{b1\text{-}SLPAV1}$ is comparatively high (greater than 0.45) all the time. Furthermore, the difference between $R_{b1\text{-}SLPAV1}$ and $R_{b1\text{-}SLPAV2}$ diminishes obviously with time, as well as the difference between $R_{b2\text{-}SLPAV2}$ and $R_{b2\text{-}SLPAV1}$. The phenomenon shows that the forcing effect of the atmospheric AL mode on the NPGO-like mode is enhancing, and both the AL and NPO mode play important roles in forcing the NPGO mode after 1970s.

To analyze the forcing effect of different atmospheric modes on oceanic modes, an autoregressive (AR)-1 model forced by a prescribed forcing index is used (Chhak et al.,[14]), and can be written as

$$I_{\text{rec}}(t)=\alpha \cdot I(t\text{-}1)+\beta \cdot F(t) \tag{1}$$

where $I_{\text{rec}}(t)$ stands for the reconstructed oceanic mode index at the moment of t, $I(t\text{-}1)$ represents the oceanic mode index at t-1, $F(t)$ is the atmospheric forcing mode index at t. The coefficients α and β are obtained by a least squares estimation according to the actual data

To reconstruct the oceanic mode index, $F(t)$ is defined as the PC1(AL index) and PC2 (NPO index) of SLPA in the North Pacific, and $I(t\text{-}1)$ is the same as the PC1 and PC2 of SSTA between the interval [2, n] in the North Pacific, respectively. Substituting the AL index and PC1 into Eq. (1), and the reconstructed oceanic mode index $I_{1\text{-}AL}$ is obtained.

The experiments are designed in Table 1. in which $R_{1\text{-}AL}$, $R_{1\text{-}NPO}$, $R_{2\text{-}NPO}$, and $R_{2\text{-}AL}$ are the correlation coefficients between $I_{1\text{-}AL}$ and PC1 of SSTA in [1, n-1], $I_{1\text{-}NPO}$ and PC1 of SSTA in [1, n-1], $I_{2\text{-}NPO}$ and PC2 of SSTA in [1, n-1], $I_{2\text{-}AL}$ and PC2 of SSTA in [1, n-1], respectively. Note that the four experiments are conducted at each period of the 40 periods obtained in Section 3.2. The temporal variations of the absolute value of $R_{1\text{-}AL}$, $R_{1\text{-}NPO}$, $R_{2\text{-}NPO}$ and $R_{2\text{-}AL}$ are shown in Figure 9. Generally, $R_{1\text{-}AL}$ changes slightly, while declining after 1970. $R_{2\text{-}NPO}$ fluctuates before 1975 and then declines. In addition, $R_{1\text{-}NPO}$ and $R_{2\text{-}AL}$ increase after 1970. Furthermore, the contrast between $R_{1\text{-}AL}$ and $R_{2\text{-}AL}$ shows that the minimum value of $R_{1\text{-}AL}$ is 0.6, and it is greater than $R_{2\text{-}AL}$ before 1977. The tendency variations of correlation coefficients show that the forcing effects of atmospheric modes are changing with the oceanic mode transition. For the first major SSTA mode in the North Pacific, the forcing effect of the AL mode is less than the NPO mode after the 1980s, indicating an enhancement of the AL mode to NPGO mode. The second major SSTA mode is the same as the first major SSTA mode except that the tipping time is around 1977.

The above outcome demonstrates that the transition of major SSTA modes in the North Pacific is the result of the atmospheric forcing. Furthermore, the change of atmospheric forcing (Figure 8) occurred in the mid-1970s, and the transition of oceanic modes appeared in the late 1970s and early 1980s.

Table 1. Experiment Design.

	$I(t\text{-}1)$	$F(t)$	$I_{rec}(t)$	R
Exp. 1	PC1 of SSTA (PC1)	AL index	Reconstructed index ($I_{1\text{-}AL}$)	$R_{1\text{-}AL}$
Exp. 2	PC1 of SSTA (PC1)	NPO index	Reconstructed index($I_{1\text{-}NPO}$)	$R_{1\text{-}NPO}$
Exp. 3	PC2 of SSTA (PC2)	NPO index	Reconstructed index($I_{2\text{-}NPO}$)	$R_{2\text{-}NPO}$
Exp. 4	PC2 of SSTA (PC2)	AL index	Reconstructed index($I_{2\text{-}AL}$)	$R_{2\text{-}AL}$

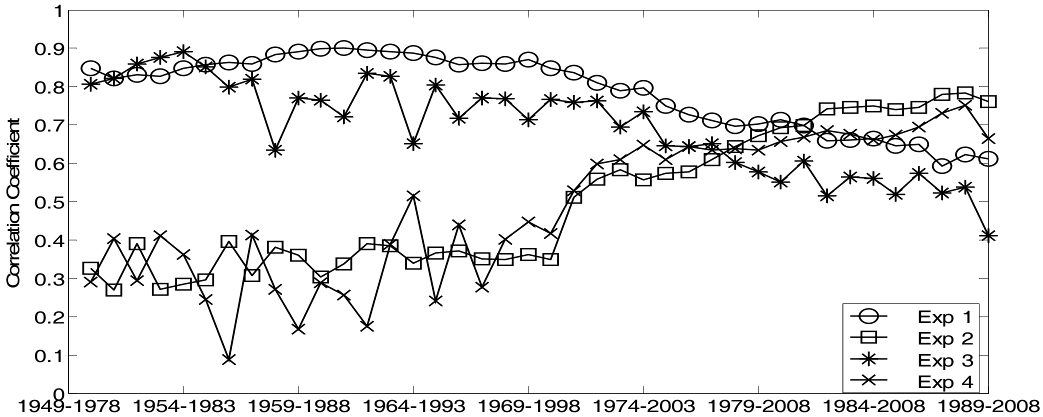

Figure 9. Time variation of absolute values of correlation coefficient for different time domains.

5 CONCLUSIONS

In this paper, the variability of main SSTA climate modes in the North Pacific for the period 1950–2008 during winter is analyzed using the EOF method. In addition, the AR-1 model is used to demonstrate the relationship between the transition of the oceanic modes and the atmospheric forcing modes. The main conclusions are summarized as follows:

(1) The EOF decomposition of SSTA in different time domains show that the transition of oceanic climate modes in the North Pacific occurred in the mid-1980s, i.e., the EOF1 of SSTA changed from the PDO into NPGO mode, and the EOF2 of SSTA changed from the NPGO into PDO mode. The time series of EOF1 and EOF2 of SSTA for the period 1950–2008 in the North Pacific during winter indicate that the EOF1 of SSTA experienced variation in high frequency, and the same happened to the EOF2, which means that the variation feature of the climate mode of SSTA in the North Pacific changed around the 1980s.

(2) Analysis of average SSTA for the periods 1950–1976, 1977–1988, 1989–1999 and 2000–2008 show that the spatial structures of average SSTA were much different between the four time domains, which changed from the PDO to NPGO mode. The spatial structure of SSTA in the North Pacific during winter changed after 1988/1989.

(3) Regression analysis and correlation analysis show that the atmospheric forcing modes of oceanic modes are the AL and NPO mode. Although the main atmospheric modes in the North Pacific exhibit no difference with time, the abnormal locations changed significantly. While the center of the AL mode moved southeastward, the centers of the NPO mode changed asymmetrically. Meanwhile, the northern center diminished and moved eastward, and the southern center became abnormally large.

(4) The forcing effects of the atmospheric modes on the oceanic modes have changed since the mid-1970s. The AL mode is playing a more important role in forcing the NPGO-like mode as well as the NPO mode. It indicates that the transition of major SSTA modes that occurred in the North Pacific was induced by the forcing from the AL and NPO modes.

For the future study, a number of important questions are deserved to be explored and answered. For example, what is the relationship between the atmospheric modes and oceanic modes? Does the transition of the oceanic modes influence the atmospheric modes? These questions will be considered in a subsequent work.

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