Continental Shelf Research 30 (2010) 1428–1434

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Recent warming in the Yellow/East China Sea during winter and the associated atmospheric circulation

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ARTICLE INFO

Article history:
Received 4 July 2009
Received in revised form
24 April 2010
Accepted 10 May 2010
Available online 31 May 2010

Keywords:
Yellow/East China Sea
A warming trend
NPO-like sea level pressure

ABSTRACT

We examine characteristics in the variability of sea surface temperature (SST) in the Yellow/East China Sea during the boreal winter (December–January–February) for the period 1950–2008 in observations. It is found that the mean SST in the Yellow Sea/East China Sea gradually increases during recent decades. A warming trend of a basin scale SST is significant in most of the regions in the Yellow/East Sea, which is well explained by the variability of the first empirical orthogonal function SST mode. We suggest one candidate mechanism that the North Pacific oscillation (NPO)-like sea level pressure play an important role to warm the Yellow/East China Sea. Anomalous anticyclonic circulation, which is the southern lobe of NPO-like sea level pressure over the North Pacific, causes a weakening of northerly mean winds over the Yellow/East China Sea during winter. This contributes to increase in the SST in the Yellow/East China Sea through the changes in the latent heat and sensible heat fluxes.

1. Introduction

The Yellow Sea/East China Sea (hereafter YES) is a part of the East Asian Marginal Seas, which is bounded on by Korea and Japan (North), China (West), Taiwan (South) and the Ryukyu islands (East) (Chu et al., 2005, Fig. 1a). The YES is a northern branch of the China Sea at the western edge of the Pacific Ocean, which is connected with the South China Sea by the Taiwan Strait and the East/Japan Sea through the Korea/Tsushima Strait (Fig. 1a).

The physical properties of YES are relatively well known in terms of its hydrography and water mass features based on the observations and high-resolution numerical modeling (Lie et al., 1998, 2001; Tseng et al., 2000; Lie and Cho, 2002; Ichikawa and Beardsley, 2002; Chu et al., 2005). In spite of debating details of the current system in the YES, it is mainly characterized by the bifurcation of the Kuroshio currents (Lie and Cho, 2002; Ichikawa and Beardsley, 2002), which carry a large amount of heat from the tropics and ocean materials from the open ocean. As shown in Fig. 1a, in addition, the YES is a well-developed continental shelf to the north-west and its depth is shallower than 200 m, more than 70% of the entire basin. Because of such geographical characteristics, the YES acts as a large reservoir and sink/source of heat energy from the ocean to the atmosphere and vice versa (Lie and Cho, 2002). In particular, the YES is located in the upstream of the Korean peninsular and Japan, the year-to-year variations of sea surface temperature (SST) in the YES may significantly affect the Korean and Japanese climate. Therefore, it is important to examine the characteristic variability of SST in the YES, which may help to assess its influence to the climate variability over the adjacent countries. In spite of the wealth of understanding the physical hydrography in the YES, a long time series of the SST variability in the YES has received little research attention so far.

Fig. 1b shows the time series of SST averaged over the YES (25°N–40°N, 118°E–127°E) during winter for the period 1950–2008. Note that red line in Fig. 1b indicates the 9-year running mean time series and the winter is defined as the three months from December to February in the following year; for example, the 2008 winter indicates December (2008), and January and February (2009). The most striking feature is that the mean state of the YES SST warms during recent decades. The 9-year running mean time series indicates that the mean SST in the YES gradually increases since the mid-1980s. In this study, we examine the characteristics of SST variability in the YES during winter for the period 1950–2008; furthermore, we suggest a possible mechanism in relation to recent warming in the YES.

2. Data

The long-term SST analyzed in this study is taken from the Hadley Center SST dataset (HadISST, Rayner et al., 2003) for the period 1950–2009. The starting year of the HadISST data set is 1870; however, our analyzed period is limited from 1950 to the present because of lack of quality and reliability of the data set

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doi:10.1016/j.csr.2010.05.002

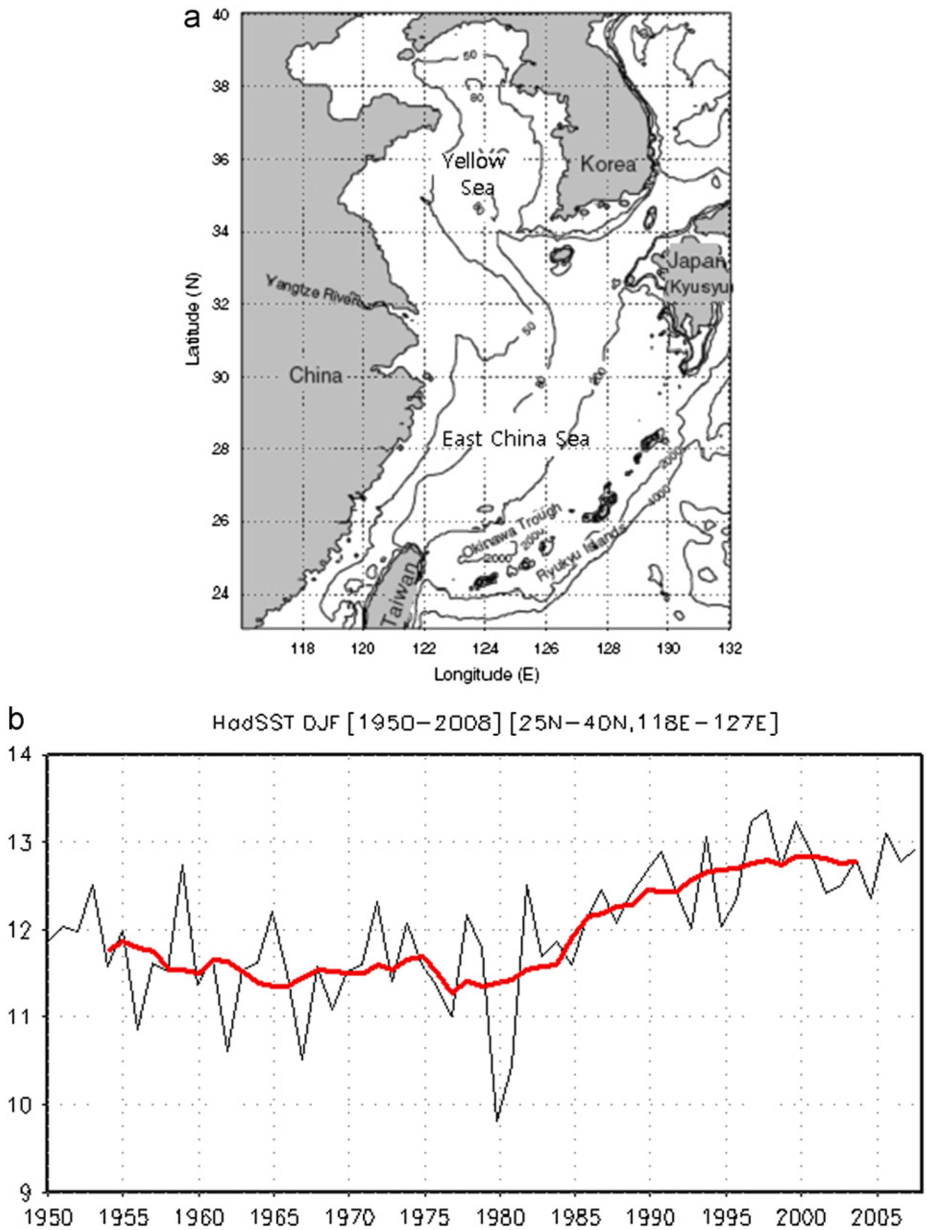

Fig. 1. (a) Topography of the Yellow/East China Sea and (b) the time series of SST averaged over the region 25°N–40°N,118°E–127°E during winter for the period 1950–2008. Red line indicates the 9-year running mean time series and the unit is °C. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

before 1950. The HadISST is based on data contained within the recently created Comprehensive Ocean and Atmosphere Data Set (Woodruff et al., 1998), with a relatively high spatial resolution of $1^\circ \times 1^\circ$, and so is superior in geographical coverage to previous data sets and has smaller uncertainties (Rayner et al., 2003). In order to analyze atmospheric variables the reanalysis products of the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) (Kalnay et al., 1996) are utilized in some cases as explained in the text.

3. Warming in the YES

We first begin to show the first empirical orthogonal function (EOF) SST in the YES during winter for the period 1950–2008 (Fig. 2a). The first EOF (EOF1) explains significantly high 69.1% of the total variance and it is clearly separated from the rest according to the criterion of North et al. (1982). Note that winter SST anomaly (SSTA) is defined as seasonal deviation from a climatological (1950–2008) winter mean.

The EOF1 represents a robust feature of SST variability during winter, which is characterized by a basin scale structure in the YES. The strongest SST variance is oriented northeastward from the Taiwan Strait to the East China Sea where the Taiwan warm current originates from the Kuroshio current (Chen and Sheu, 2006) and the second maximum variance is observed in the Yellow sea. In addition, one can find a strong gradient of SST variance to the northwest–southeast direction where the continental shelf breaks (see Fig. 1a) and it represents the Kuroshio current system bounded by the 200 and 4000 m contours (Chu et al., 2005).

Fig. 2b indicates the time series of the EOF1 principal components (PCs) for the period 1950–2008. The most striking feature is that the EOF1 SST of variability is dominated by a

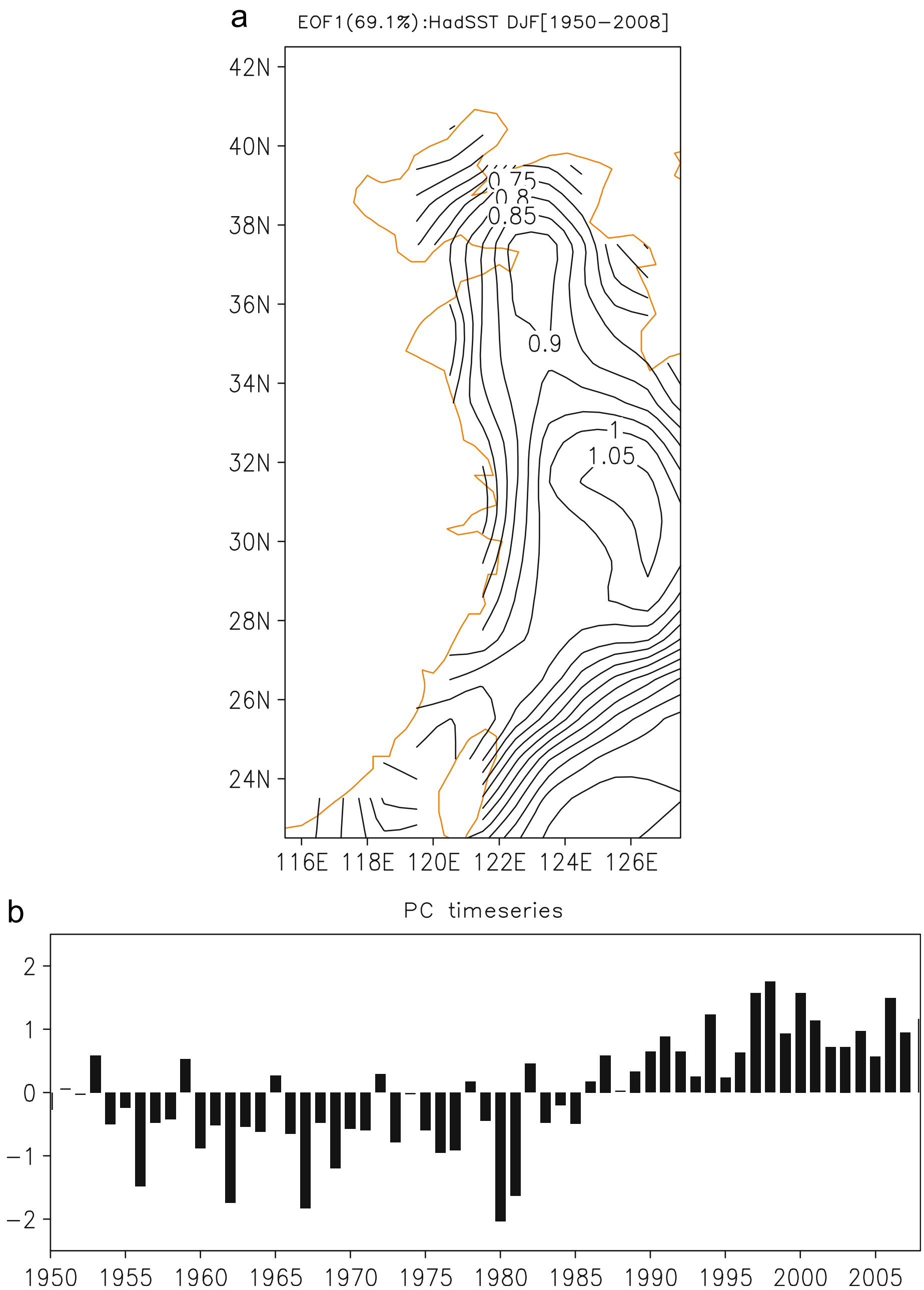

Fig. 2. (a) The first EOF SST in the Yellow/East China Sea during winter for the period 1950–2008. Contour interval is 0.05 and unit is nondimensional. (b) The time series of the first EOF principal component for the period 1950–2008. Unit is °C.

significant warming which occurred around the mid-1980s. A dominant sign of the EOF1 PC time series changes from a negative to a positive before and after the mid-1980s, respectively. We calculate a simultaneous correlation coefficient between the EOF1 PC time series (Fig. 2b) and the time series of SST averaged in the YES during winter (Fig. 1b), which is statistically significant at 99% confidence level (r=0.98, here r denotes a simultaneous correlation coefficient).

In order to show details of warming in the YES, we display a linear trend of SST during winter for the entire analyzed period in the YES (Fig. 3). Note that shading in Fig. 3 indicates a statistical significance at 95% confidence level based on a t-test. As expected, a significant warming trend is everywhere in the YES except for the region around the east coast of China in the Yellow Sea. It is interesting to note that the spatial pattern of a linear trend (Fig. 3) is quite similar to that of the EOF1 (Fig. 2a). The maximum warming trend is around 0.04 °C/year, which is observed in the inner region along the continental shelf to the northeast–southwest orientation in the YES where the maximum SST variance is observed (see Fig. 2a). Therefore, it is reasonable to examine the EOF1 SST of variability to understand a recent warming in the YES.

4. Mechanism

In order to examine a possible mechanism to warm the YES we first display the regressed sea level pressure (SLP) and the winds at

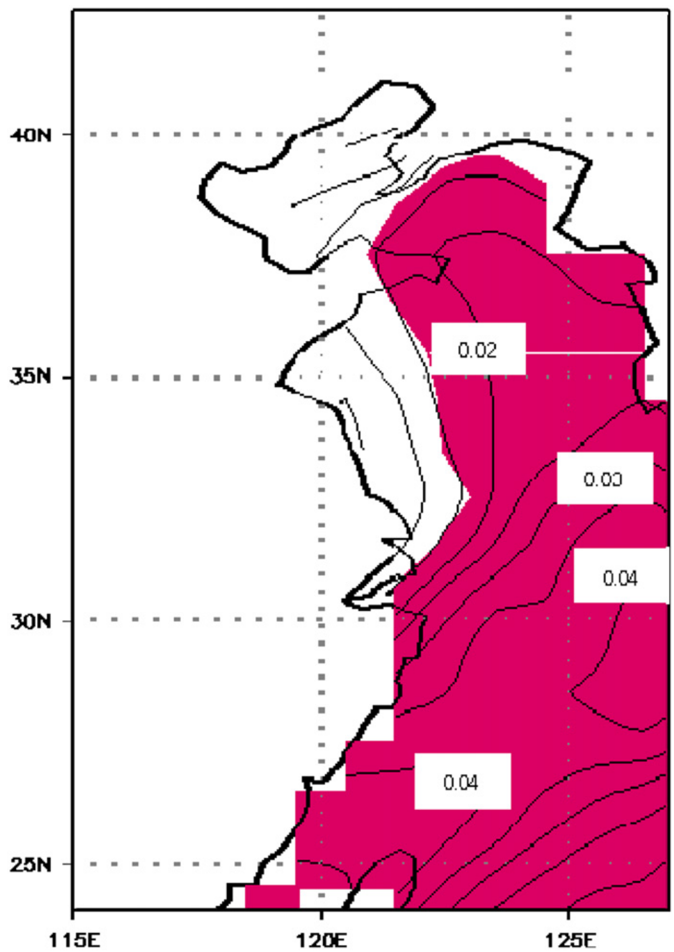

Fig. 3. A linear trend of SST in the Yellow/East China Sea for the period 1950–2008 during winter. Contour interval is 0.005 °C/year and shading denotes a region which is statistically significant at 95% confidence level.

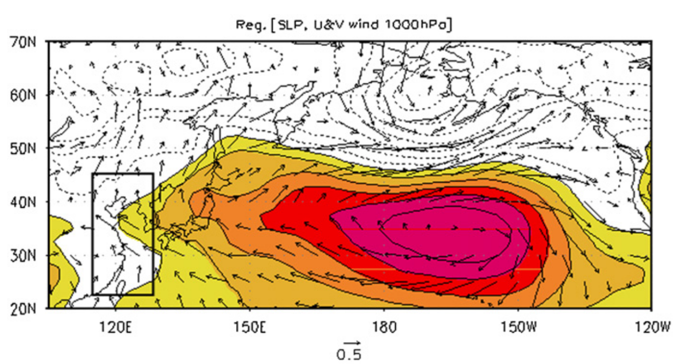

Fig. 4. The regressed sea level pressure and the low-level winds at 1000 hPa against the first EOF principal component for the period 1950–2008. Contour interval is 0.3 hPa/°C. The arrow scale is shown below and the unit is m/s.

1000 hPa during winter against the EOF1 PC time series (Fig. 4)[1]. It is remarkable that a dipole-like structure of regressed SLP is dominant in the meridional direction over the North Pacific Ocean.

[1] In order to obtain the regressed coefficients in Fig. 4, we first multiply the EOF1 PC time series shown in Fig. 2b by sea level pressure and low-level winds during winter for the period 1950–2008. And then, those values are divided by a square of the EOF1 PC time series. A physical meaning of the regression coefficients in Fig. 4 is how the sea level pressure and low-level winds change when the EOF1 PC time series varies.

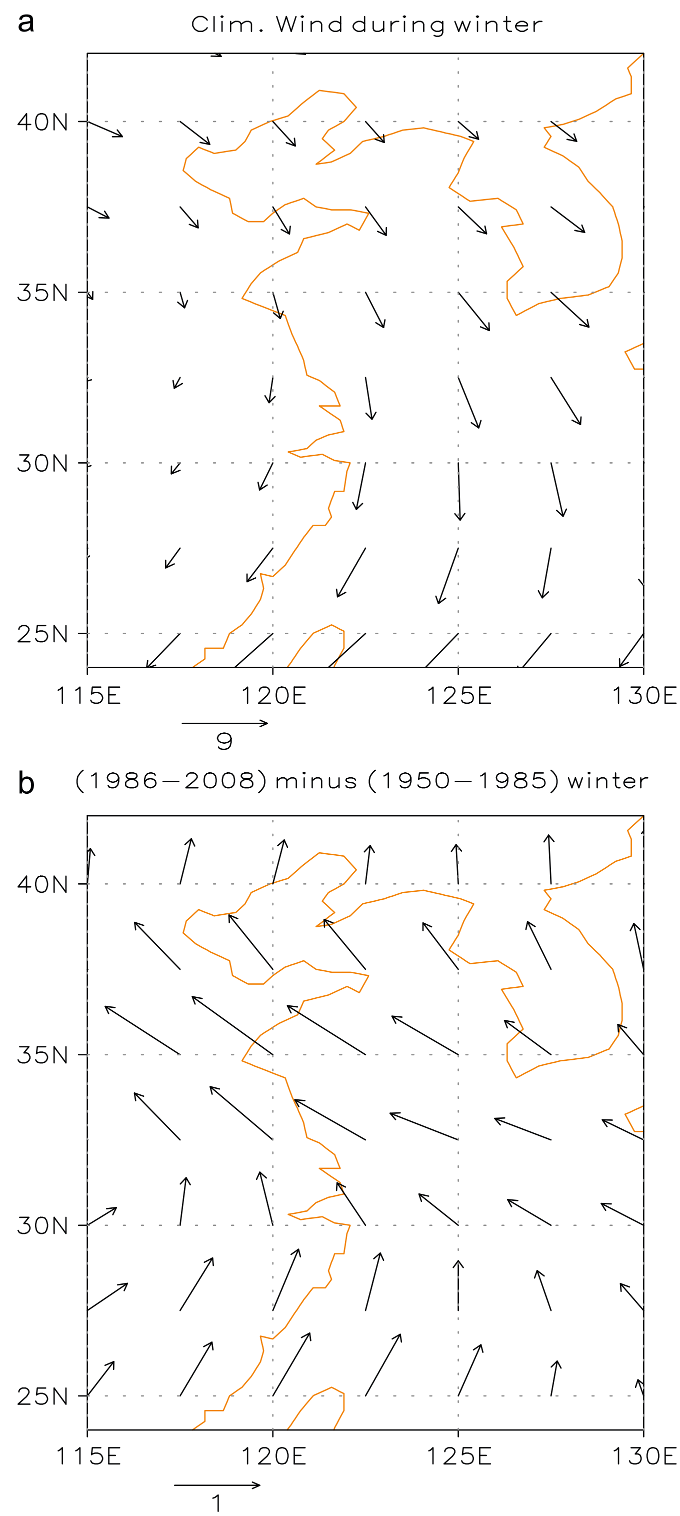

Fig. 5. (a) The mean wind structure at low level (here,1000 hPa) over the YES during winter for the period 1950–2008. (b) The difference of mean wind at 1000 hPa over the YES during winter before and after the mid-1980 s, i.e., 1986–2008 minus 1950–1985. The arrow scale is shown below and the unit is m/s.

A negative center of regressed SLP is observed at 60°N,170°W over the Bering Sea. On the other hand, a positive center is located at the southern part over the North Pacific at approximately 35°N,165°W. Such a dipole-like pattern of regressed SLP has remarkable resemblance to the north pacific oscillation (NPO), which constitutes a prominent mode of midlatitude wintertime atmospheric SLP variability (Walker and Bliss, 1932). This will be shown later. In association with a dipole-like SLP structure, anomalous westerlies are dominated over the central part of the North Pacific Ocean between 40°N and 55°N. In contrast, anomalous easterlies are dominated over the subtropical North Pacific Ocean between 20°N and 35°N, which is due to anomalous anticyclonic circulation in the southern lobe of the NPO-like SLP. In addition, such an anticyclonic circulation also causes anomalous southerly winds over the western part of the North Pacific including East Asian Marginal seas. One can find that the regressed southerly winds prevail over the YES (box in Fig. 4), which may cause an advection of warm air from the subtropics over the YES. Such a warm advection may play a role to increase the SST in the YES through anomalous heat fluxes into the ocean.

To show details of wind changes in association with a warming in the YES, we first show a mean wind structure at low level (here 1000 hPa) over the YES during winter for the period 1950–2008 (Fig. 5a). It is evident that the northerly wind prevails over the YES during winter. This is because the surface circulation over east Asia during winter monsoon is dominated by the Siberian High pressure system located over the East Asian continent (Chang, 2004) and such atmospheric circulation could bring cold northerly winds over the YES. Fig. 5b displays the difference of mean wind before and after the mid-1980s, i.e., 1986–2008 minus 1950–1985. As we showed earlier, the mean state of SST in the YES experiences a significant warming after the mid-1980s (Fig. 1b and Fig. 2b), therefore results in Fig. 5b are indicative of the changes in the mean wind associated with a SST warming in the YES. Anomalous southerly winds are dominated over the YES, indicating that the climatological northerly winds over the YES weakened after the mid-1980s, which might be associated with the NPO-like atmospheric pattern shown in Fig. 4.

The above result has an important implication that recent warming in the YES is associated with a large scale atmospheric variability, which can be seen in the analysis of atmospheric SLP variability over the North Pacific basin. To show this we display the second EOF SLP of variability during winter for the period 1950–2008 and its associated PC time series. Note that the first EOF SLP (not shown) represents the Aleutian low whose center of action is located in the northern part of the North Pacific at approximately 50°N,170°W. The spatial pattern of the second EOF SLP (Fig. 6a) is characterized by a dipole-like structure in the meridional direction in the North Pacific basin, which describes the NPO as suggested by many previous studies (Rogers, 1981, Wallace and Gutzler, 1981). Interestingly, this spatial pattern is quite similar to the regressed SLP against the PC time series of the EOF1 SST in the YES as in Fig. 4.

Fig. 6b shows the time series of the second EOF SLP (i.e., NPO) for the entire analyzed period. The NPO exhibits considerable interannual variability, in addition, it has some feature of decadal variability. A striking feature of the NPO is the occurrence of extended periods with a predominant positive sign since the mid-1980s. This result is indicative of a phase transition of the NPO on

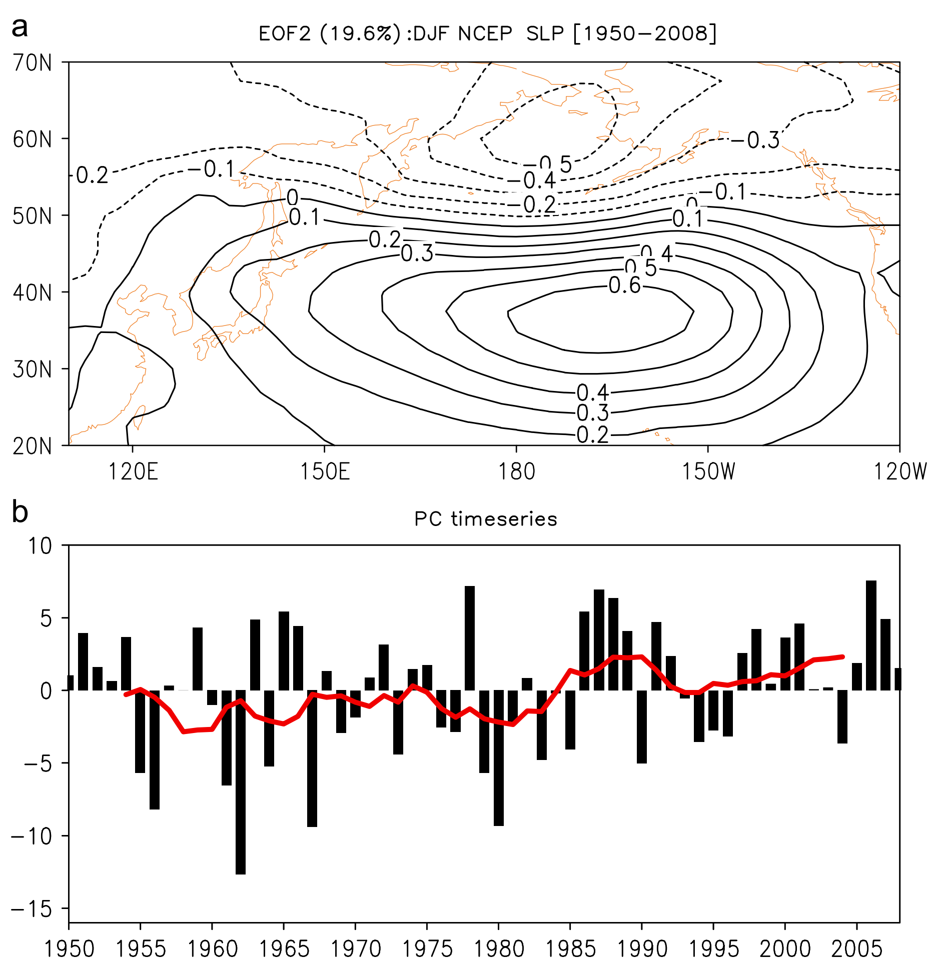

Fig. 6. (a) The second EOF sea level pressure over the North Pacific Ocean during winter for the period 1950–2008. Contour interval is 0.1 and broken lines indicate negative values. Unit is nondimensional. (b) The time series of the second EOF principal component for the period 1950–2008 and red line denotes a 9-year running mean. Unit is hPa. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

interdecadal fluctuations around the mid-1980s. The 9-year running mean of the PC time series (red line in Fig. 6b) shows that a phase of NPO PC time series changes before and after the mid-1980s, which supports the above argument. Interestingly, the 9-year running mean of NPO PC time series is well correlated with the 9-year running mean time series of SST averaged over the YES as shown in Fig. 1b (red line). A simultaneous correlation coefficient between the two time series on the low-frequency timescales (i.e., 9-year) is 0.79, which is statistically significant at 95% confidence level based on a *t*-test.

These results indicate that the dominant SST variability in the YES during winter (i.e., EOF1 in Fig. 2) is largely associated with the NPO-like SLP of variability. Furthermore, the circulation anomalies associated with the NPO-like SLP of variability are associated with a weakening of northerly winds in relation to a warming in the YES during recent decades.

One may argue that decrease in northerly winds could cause increase in SST due to decrease in the latent heat flux. To examine a role of atmospheric circulation in relation to the SST warming in the YES, we show the time series of wind speed anomaly averaged over the YES during winter for the period 1950–2008 (Fig. 7a). As expected, the wind speed anomaly over the YES decreases during recent decades, which is largely consistent with a regressed sea level pressure in relation to a SST warming in the YES (Fig. 4) and a spatial pattern of NPO after a phase transition around the mid-1980s (Fig. 6a). In other words, the NPO-like atmospheric circulation seen in Fig. 4 acts to reduce the northerly mean winds during winter, resulting in a reduced wind speed anomaly over the YES.

Fig. 7b displays the regressed latent heat flux against the time series of wind speed anomaly over the YES shown in Fig. 7a. Note that a negative sign is indicative of anomalous heat flux from the atmosphere into the ocean. That is, a reduced wind speed induces the reduced latent heat flux into the atmosphere, which contributes to increase the SST in the YES during the recent decades. On the other hand, the anomalous southerly winds over the YES after the mid-1980s may induce a warm thermal advection into the YES, which is associated with changes in the sensible heat flux between the ocean and the atmosphere. In order to show sensible heat flux exchange over the YES, we display the regressed net sensible heat flux against the PC time series of the EOF1 SST in the YES, as shown in Fig. 2b. It is evident that a negative sign is dominant in the YES except for a limited region (Fig. 7c), indicating that the decrease in the northerly wind would decrease the advection of cool temperature along with the wind, resulting in decrease in sensible heat flux.

These results suggest that after the mid-1980s the southern lobe of NPO-like SLP is characterized by anomalous anticyclonic circulation over the North Pacific basin, and such circulation anomalies contribute to increase the SST in the YES through latent heat and sensible heat fluxes.

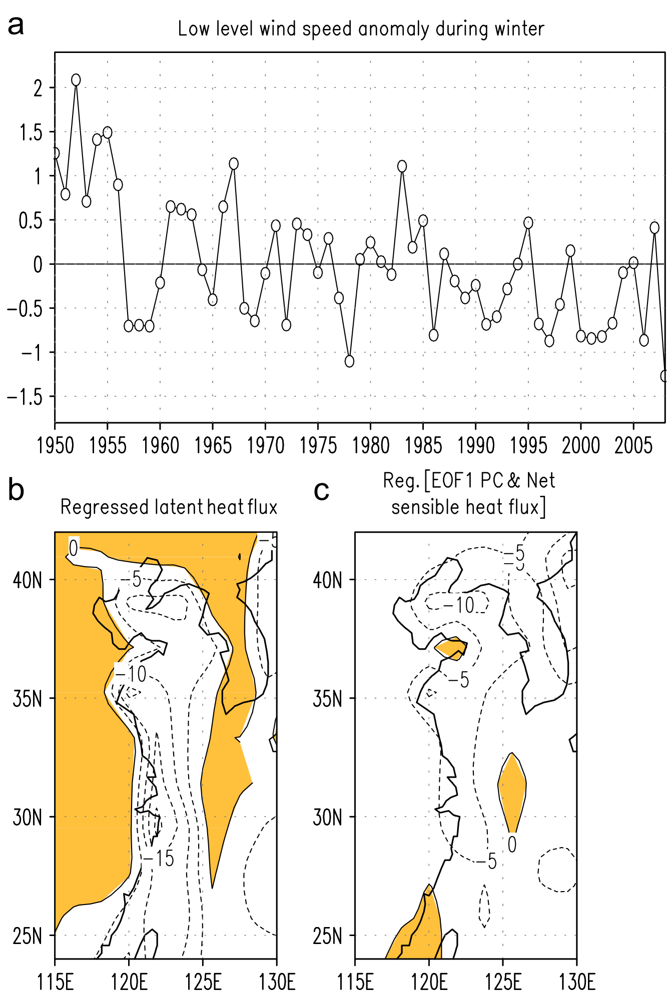

Fig. 7. (a) The time series of wind speed anomaly averaged over the YES (25°N–40°N,118°E–127°E) during winter for the period 1950–2008. Unit is m/s. (b) The regressed latent heat flux against the wind speed anomaly shown in Fig. 7a. Contour interval is 5 w sec/m^3. (c) The regressed sensible heat flux against the first EOF SST PC in the YES for the period 1950–2008. Contour interval is 5 w/m^2 °C. Dashed lines in (b) and (c) indicate negative value and shading denotes above zero.

5. Concluding remarks

In this study, we examined a long time series of the variability of SST in the YES during winter for the period 1950–2008 in observations. It is remarkable that the mean state of the YES SST warms during recent decades. The leading EOF SST in the YES is characterized by a basin scale structure. In addition, its PC time series indicates that a basin scale SST variability in the YES experienced a significant warming around the mid-1980s. Further analysis indicates that the leading EOF SST in the YES well represents a linear trend of SST in the YES, suggesting that a linear trend explains much part of SST variability in the YES. The intergovernmental panel on Climate Change Forth Assessment Report also reported an unambiguous increase of the North Pacific mean SST over the last decades (Meehl et al., 2007). Therefore, one may conclude that recent warming in the YES is associated with global warming due to an increase of greenhouse gas concentration. In other words, a warming in the YES during recent decades could be a manifestation of the recent global warming of the world ocean (Levitus et al., 2000, 2005) although we did not examine details of global warming issue in this study.

In order to examine one candidate mechanism in relation to recent warming in the YES, we calculated the regressed SLP and the low-level winds against the PC time series of the EOF1 SST in the YES. It is found that the NPO-like SLP over the North Pacific basin is closely associated with the EOF1 SST of variability in the YES. In addition, the low frequency of NPO is well correlated with the low frequency time series of a basin SST averaged in the YES. We argued that anomalous anticyclonic circulation in the southern lobe of NPO-like SLP is associated with a weakening of the northerly mean wind over the YES during winter, which contributes to increase the SST in the YES through the latent heat and sensible heat fluxes. Our result suggests that recent warming in the YES is associated with a large scale atmospheric circulation over the North Pacific basin such as the NPO.

Acknowledgements

SWY was supported by the National Research Foundation of Korea Grant funded by the Korean Government (MEST) (NRF-2009-C1AAA001-2009-0093042). C.-H. Kim is supported by the research programs MLTM (PM55670) and KORDI (PE98445).

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