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Shifts in Multi-decadal Sea Level Trends in the East/Japan Sea over the Past 60 Years

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Abstract – Data derived from altimetry shows that since 1993 the mean sea level over the East /Japan (EJS) Sea is increasing at a rate of ~3 mm/year, but tide gauge records indicate that a multi-decadal reversal trend occurred prior to the early 1980s. We here characterize and quantify the multi-decadal trend of mean sea level in the EJS from the reconstructed sea levels and the in-situ ocean profiles over the past 60 years. Our analysis shows that sea level trends have undergone a shift, revealing a declining trend before the early 1980s, followed by a rising trend from the early 1980s onward with a near basin-wide sea level fluctuation. The trend reversal strongly corresponds to changes in the upper-ocean heat content over the EJS, revealing a negative correlation with the Pacific Decadal Oscillation (PDO) index that correlates negatively with wind stress curl (WSC) in the subtropical North Pacific. The PDO-related WSC, which changes the transport of the western boundary current in the subtropical gyre, may account for the observed trend reversal in the EJS sea level on a multi-decadal time scale.

Key words – sea level trend, multidecadal shift, ocean heat content, Pacific Decadal Oscillation, East/Japan Sea

1. Introduction

The 20-year sea level data from satellite altimeters has significantly advanced our understanding of global mean sea level (GMSL), which has been rising throughout the 20th century at a rate of ~3 mm/year over the past two decades (Alain et al. 2009; Cazenave and Llovel 2010). The satellites provide an almost complete global sampling of sea levels and show that the sea level rise (SLR) is not geographically uniform and that time scales range from the intra-seasonal to the decadal. The regional differences in sea level are closely related to the dynamical upper-ocean responses to surface wind forcing (Merrifield 2011; Bromirski et al. 2011; Qiu and Chen 2012). However, the relation between large-scale ocean circulations and regional sea level variability, particularly in marginal seas in the Pacific, is not still completely understood.

The East/Japan Sea (the EJS hereafter) is a semi-enclosed marginal sea of the North Pacific, surrounded by the Asian continent and the Islands of Japan. The time-mean circulation of the EJS is characterized by warm and saline water entering the EJS through the Korea Strait and leaving the basin mostly through the Tsugaru and Soya Straits (Hirose and Ostrovskii 2000; Chang et al. 2004; Kim and Fukumori 2008). With respect to the sea level variability, using sea level records from the satellite altimeter (TOPEX/Poseidon, T/P) Choi et al. (2004) showed that about 60% of the sea level variability is due to a non-seasonal component which has a spatially uniform pattern within the EJS. The near-uniform basin-wide sea level fluctuation is also found with the periods ranging from 20 days to a year, suggesting that the surface wind forcing near the straits of the EJS plays an important role in the fluctuation (Kim and Fukumori 2008). On inter-annual and decadal time scales, a connection between the EJS sea level and the North Pacific has been noted by Gordon and Giulivi (2004) who focused on the low-frequency variability associated with the Pacific Decadal Oscillation (PDO), using a 9-year record from the T/P satellite altimeter, tide gauges, and hydrographic data from 1927 to 1999 in the southern EJS. They suggested that the sea level variability in the EJS is correlated with the PDO; a higher sea level occurs during the negative phase of the PDO, with the opposite trend occurring during the positive PDO phase.

Understanding about inter-annual and decadal sea level changes has been improved by satellite altimeters since the

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*Corresponding author. E-mail: jhmoon@jejunu.ac.kr early 1990s (e.g. Lee and McPhaden 2008), but the relatively short period of altimeter data records do not allow for the evaluation of either the ocean state prior to 1993 or the multi-decadal low-frequency signals in the ocean. Sea level variations on longer time scales are known to contribute to the estimation of sea level trends (e.g. Woodworth et al. 2011; Chamber et al. 2012; Hamlington et al. 2013). On multi-decadal and longer time scales, most of the studies have relied on sparsely distributed tide gauge data (e.g. Feng et al. 2004, 2010; Merrifield 2011) because prior to the early 1990s, the only way of measuring sea level was through tide gauges distributed along the coastlines around the world. While tide gauges provide longer records, the data are limited in terms of spatial extent due to a lack of gauges in the middle of ocean basins and geographical clustering (Hamlington et al. 2011) so that the data are not sufficient to fully understand large-scale spatial patterns of ocean variability. Accordingly, less attention has been paid to the spatial variability of multi-decadal sea level trends, particularly from a regional perspective. Recently, sea level reconstructions which combined these two data sets, i.e., altimeters and tide gauges records, provide a data set with the high spatial resolution of altimetry and the longer record length of tide gauges. The long-term reconstructed sea level data with near-global coverage can be a valuable resource for studying regional sea level variability prior to the altimetry era, allowing us to gain insight into longer-time scale climate signals, e.g., multi-decadal low-frequency signals.

In this paper, we characterize and quantify multi-decadal regional sea level changes in the EJS and their relationship with large-scale North Pacific circulations, using different observational datasets: the tide-gauge sea surface height (SSH), altimetry-based SSH, 2-D past sea level reconstructions, and in situ-derived steric sea level (SSL) and ocean heat content (OHC). Considering these sea level datasets together, in terms of multi-decadal sea level trends, is essential for corroborating the accuracy and reliability of the observed sea level fluctuations and the reconstructions.

2. Datasets

We used multiple datasets for sea level and wind field for the period 1950–2009: the altimetry SSH since 1993, tide gauge SSH, recent sea level reconstructions of Hamlington et al. (2011) and Meyssignac et al. (2012) (hereafter H2011 and M2012, respectively), upper-ocean measurements from Ishii and Kimoto (2009), and surface wind from the National Center for Environmental Prediction (NCEP) reanalysis data (Kalnay et al. 1996).

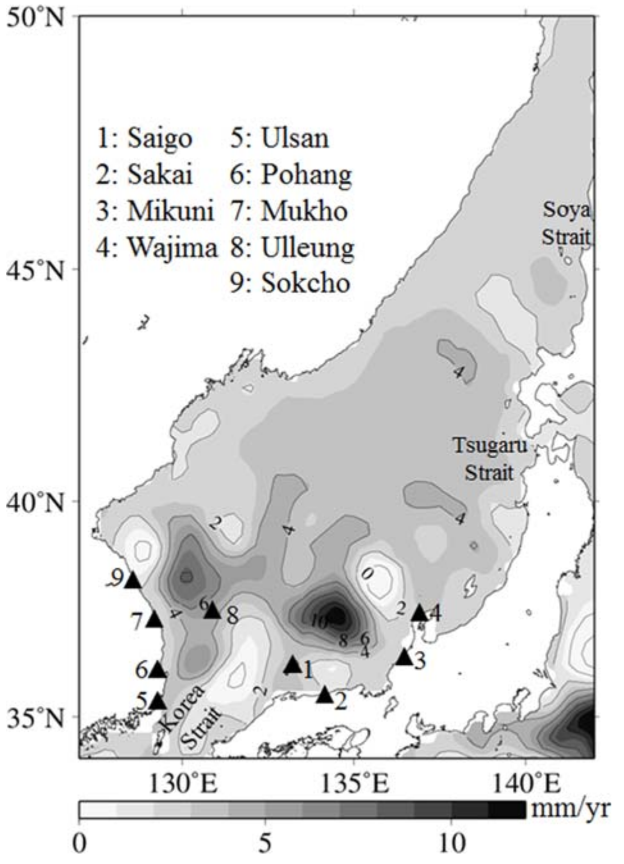

Fig. 1. Sea level trend over the East/Japan Sea (EJS) derived from altimetry from 1993 to 2010. Tide gauge stations used in this analysis are indicated (marked by Symbol ▲)

Altimetry-based sea level observations over 1993–2010 are used to estimate the recent SLR trends in the EJS. The altimetry-based sea level is a merged product of several altimeter missions (TOPEX/Poseidon, Jason-1, ERS-1, ENVISAT). The sea level data were produced and distributed by AVISO (http://www.aviso.oceanobs.com/) as part of the Ssalto ground processing segment. Tide gauge records along the east coast of Korea and west coast of Japan, with 30–60 years of data available at most stations, were also examined to compare the multi-decadal sea level trends from the reconstructed sea levels (Fig. 1).

H2011 presented a new method for reconstructing sea level involving cyclo-stationary empirical orthogonal functions (CSEOF), using both the tide gauge records for the period 1950 through 2009 and the satellite altimetry records during 1992–2009. H2011 produced a sea level reconstruction on a 0.5° × 0.5° grid with global coverage over the period of June

1950–June 2009, and demonstrated the reliability of the CSEOF-based reconstruction for climate monitoring when focusing on climate signals like ENSO. The detailed descriptions of the reconstruction technique and the computation of the CSEOF are found in H2011 and Kim at al. (1996). The other sea level reconstruction used here is from M2012, which is based on the technique developed by Llovel et al. (2009). This consists of first performing an EOF decomposition of 2-D sea level fields on a 1° × 1° grid, based on the altimeters and output from OGCMs: DRAKKAR/NEMO and SODA (Penduff et al. 2010; Carton and Giese 2008), and then computing new principal components over a longer period covered by tide gauge records and constraining them with a least squares optimal interpolation.

In addition to the sea level reconstructions, we also examined SSL derived from in situ upper-ocean (0–700 m) profiles. The monthly objectively analyzed subsurface temperature and salinity for the period 1945–2010 is the newest available dataset produced by Ishii and Kimoto (2009, hereafter IK2009). The SSL has been computed at each 1° grid point of temperature and salinity by integrating down to 700 m.

$$\mathrm{SSL} = \int_{-H}^{0} \frac{\rho_0(x,y,z) - \rho(x,y,z,t)}{\rho_0(x,y,z)} dz \qquad (1)$$

where $\rho_0(x, y, z)$ is the reference density; a function of temperature and salinity in climatology and depth, z. $\rho(x, y, z, t)$ is a nonlinear function of temperature and salinity. Note that because of the coarse resolution, i.e., 1° × 1°, we only use the EJS basin mean of the SSL data to infer the ocean thermal expansion.

3. A Multi-decadal Sea Level Shift in the Early 1980s

During the altimetry period, the most dominant feature in the EJS is a near basin-wide positive SLR trend (Fig. 1) with a mean rate of ~3 mm/year, except for the strongest rise around the north of Ulleung Island (131°E, 39°N) and southern Yamato Basin (135°E, 38°N). The East Korea Warm Current (EKWC) flows northward along the east coast of Korea. It separates from the coast at around 38°N and then meanders to the east, accompanying the mesoscale eddies (Kim et al. 2002; Chang et al. 2004; Kang et al. 2005). The mesoscale activity associated with the meandering of EKWC and migration of eddies can produce the strongest SLR trend near the Ulleung Island and Yamato Basin.

The coastal sea level measurements from 9 tide-gauge

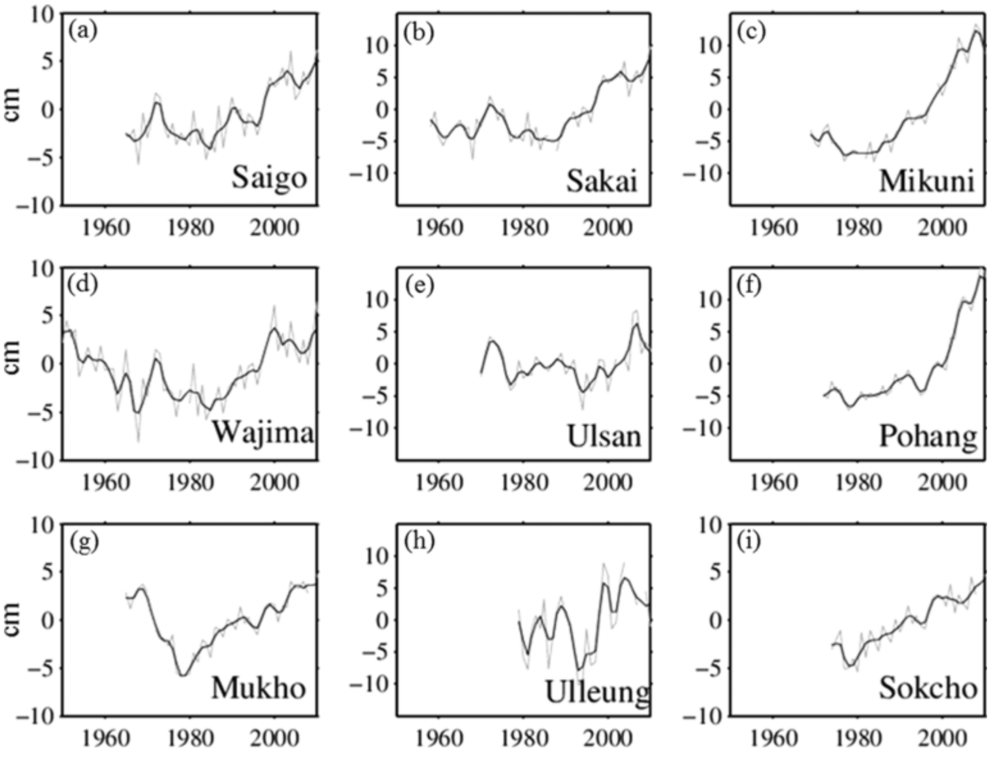

Fig. 2. Time series of annual sea level from tide gauge stations along the east coast of Korea and west coast of Japan marked in Fig. 1. The gray lines indicate 8-year running mean of the coastal sea levels

stations along the Korean and Japanese coasts are used to examine how the sea levels have changed over the past few decades (Fig. 2). Even though the sea levels for all stations show an increasing trend over the last 30–60 years, a long-term SLR shift occurred around the early 1980s in most stations. There are decreasing or near-stationary trends of sea level prior to the early 1980s, but upward trends after that period. For instance, a decreasing trend of sea level at Wajima, which has a tide gauge record that stretches over 60 years, was fully reversed after the early 1980s (Fig. 2d). It should be noted that the term "trend" used here refers to a part of the multi-decadal fluctuations.

While the satellite altimetry-based record alone is too short, it is possible to assess the decadal and multi-decadal signals using the sea level reconstructions. With the sea level reconstructions, we can investigate the basin-mean sea level trends for longer time periods. The time series of annual mean sea level and their long-term trend changes over 1950–2008 are presented in Fig. 3, which shows the sea level reconstructions of H2011 (thick lines) and M2012 (dashed lines) with the altimeter (gray) since 1993. The GMSL trend in each data set was removed to highlight the regional variability. Since we are interested in the regional multi-decadal trends and their temporal changes associated with climate variability, the GMSL trend appears as a mean in our result and can thus be removed without significantly impacting the analysis. The two sea level reconstructions agree well over the 60 year time frame, with high correlations of above 0.7 (statistically significant above the 95% level). The reconstructions also match the altimetry-based sea level variation since 1993, confirming the reliability of reconstructed sea level fluctuations. The mean sea level over the EJS reveals a steadily declining trend from 1950s to the early 1980s, followed by a full rebound after the early 1980s (Fig. 3b). This is consistent with the sea level fluctuations observed from the tide gauges. A quantitative comparison of the SLR trends among the sea level products is shown in Table 1. The multi-decadal trend reversal of sea level is more clearly visible in Fig. 4, which shows the spatial patterns of SLR trends over the following two multi-decadal periods: period I (1950–1983) and period II (1984–2008). The spatial pattern of SLR trend over period II is quite similar to those revealed by altimeters, but the pattern in period I is opposite to the altimeter data. This indicates that the SLR pattern has been persistent since the early 1980s, representing a near basin-wide multi-decadal SLR shift beginning in the early 1980s. Similar fluctuations in sea surface temperature (SST) have been reported by Yeh et al. (2010) and Na et al. (2012), who have shown that the EJS has undergone a significant warming trend from the mid-1980s to the present, based on the long-term SST datasets. The long-term tide gauges and two reconstruction data sets indicate that the sea levels have fluctuated on a multi-decadal time scale during at least 60 years, although the amplitude of their variability is much smaller than the inter-annual signals.

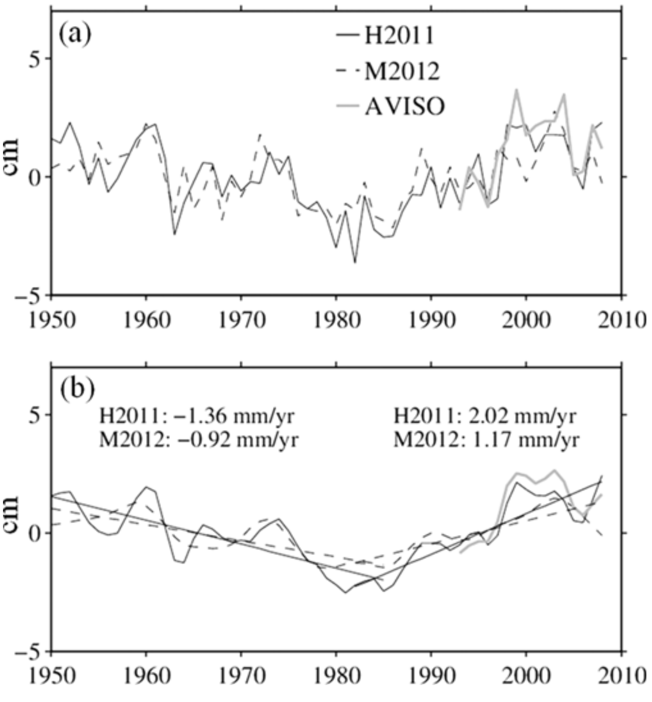

Fig. 3. Time series of (a) annual mean sea level over the East/Japan Sea (EJS) from the two sea level reconstructions (H2011 and M2012, black thick and dashed, respectively) and altimeter (gray lines), and (b) their linear trends over the following multi-decadal periods: 1950–1983 and 1984–2008

Table 1. Linear (mm/yr) trends of two reconstructions (H2011 and M2012) and steric sea level (SSL) derived from IK2009 in the EJS during the two multi-decadal period: I) 1950–1983, and II) 1983–2008. The global mean sea level trend in each dataset was removed

	Period I (1950–1983)	Period II (1984–2008)
H2011	-1.36 mm/yr	2.02 mm/yr
M2012	-0.92 mm/yr	1.17 mm/yr
IK2009 (SSL)	-1.4 mm/yr	1.11 mm/yr

Because steric expansion associated with change in temperature structure is the most important cause for sea level variations and their regional differences (e.g. Antonov et al. 2005; Levitus et al. 2009), we also examined SSL and OHC derived from in situ upper-ocean (0–700 m) profiles of IK2009 (Fig. 5).

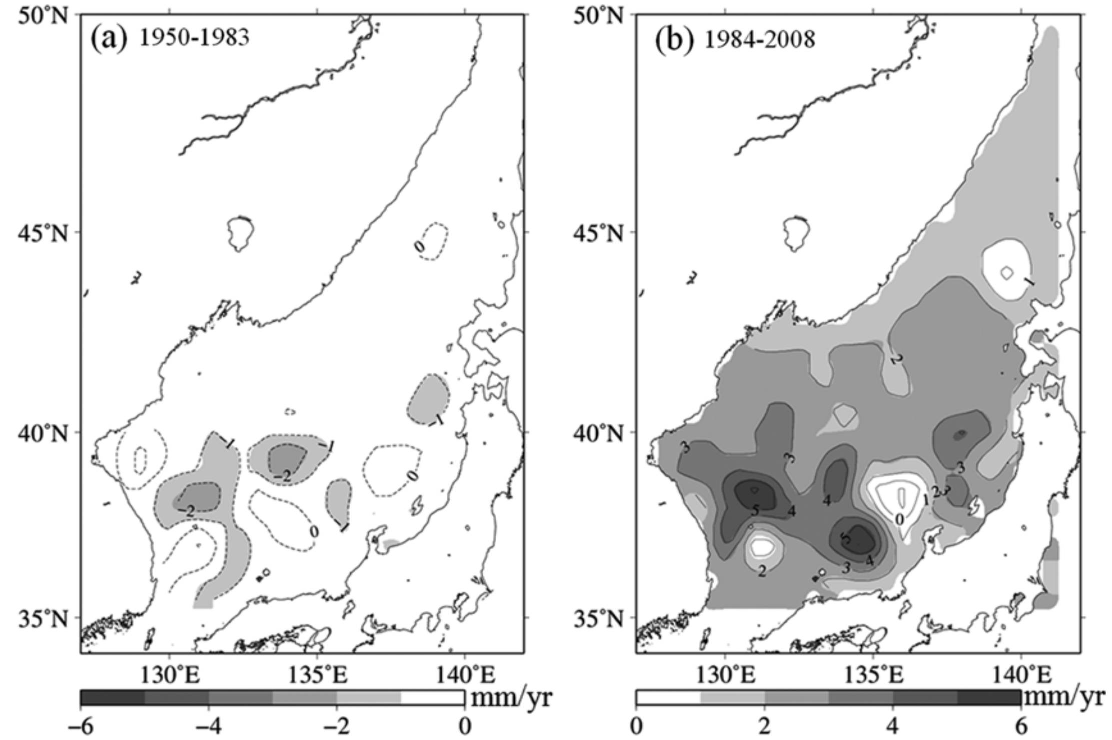

Fig. 4. Sea level trends over the East/Japan Sea (EJS) derived from the sea level reconstruction of H2011 over two multi-decadal periods: (a) 1950–1983 and (b) 1985–2008. The global mean sea level trend in dataset was removed

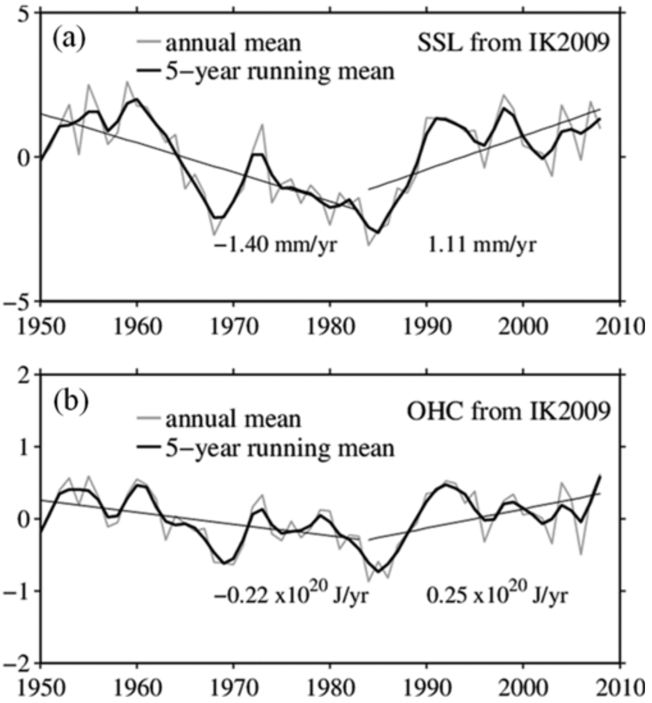

Fig. 5. Time series of (a) in-situ upper 700 m steric sea level (SSL) and (b) ocean heat content (OHC) in the East/Japan Sea (EJS) derived from Ishii and Kimto, (2009, IK2009) over 1950–2008. The multi-decadal linear trends are also presented

There is a strong correspondence between the basin-mean sea level and upper-ocean SSL trends; i.e., multi-decadal declining trend of SSL is reversed after the early 1980s, with rates of -1.4 mm/year and 1.1 mm/year before and after the early 1980s, respectively (Fig. 5a). It is shown that the sea level trend in the EJS can be explained by the steric effect due to density changes, including surface heat and heat redistribution by ocean circulations. The SSL includes both thermosteric and halosteric changes, but is mainly dominated by the thermosteric, i.e., thermal expansion changes (Domingues et al. 2008; Moon and Song 2013; Moon et al. 2013). The effect of thermal expansion on the multi-decadal SLR trends is evident in time series of regionally averaged OHC in the EJS (Fig. 5b), which is given by

$$\text{OHC} = \rho C_p \iiint_V \theta \, dx\,dy\,dz \tag{2}$$

where C_p is the specific heat capacity of seawater, ρ is the water density, and θ is potential temperature. The change of OHC is consistent with the reversal trends of sea level and SSL, confirming a close correspondence between the sea level and thermal change.

4. Sea Level Shift Associated with the PDO

We also performed an Empirical Orthogonal Function (EOF) analysis on the long-term sea level reconstruction of H2011 to examine statistically the spatial and temporal variability of the low-frequency sea level. The EOFs are evaluated using singular value decomposition that separates the sea levels into orthogonal spatial modes and associated amplitude time series. The data was smoothed with an 8-year low-pass filter prior to the EOF analysis to focus on the low-frequency sea level fluctuations. Fig. 6 shows the spatial pattern (eigen vector) of the EOF mode 1 and associated time series (principal component), which is normalized by its standard deviation. The first mode of sea level variation accounts for about 78% of the total variance in the EJS. Because the spatial values of EOF 1 are positive over the entire basin, the first mode shows simultaneous basin-wide low-frequency sea level variation which is similar to the multi-decadal SLR trends (see Fig. 4). The time series is characterized by multi-decadal trends with a shift during the early 1980s from a decreasing to an increasing trend, emphasizing that the trend reversal is the dominant mode of sea level variation over the past 60 years.

To identify the relationship between the SLR and the Pacific climate variability on multi-decadal time scales, the temporal variation of mode 1 is compared with the low-pass filtered PDO and the Southern Oscillation Index (SOI) (Fig. 6c). The PDO and SOI indices were obtained from the Joint Institute for the Study of the Atmosphere and Ocean (JISAO; http://jisao.washington.edu/) and the Australian Bureau of Meteorology, National Climate Centre, respectively. The PDO index exhibits a trend change in the mid-1980s that is closely correlated with the temporal change of the first EOF mode. The sea level shows a declining trend prior to the early 1980s when the PDO index is in a rising trend; on the other hand, it rises during the most recent 30 years when the index is in a declining trend, indicating a significant negative correlation between the EJS sea level and the PDO index. The strong relationship is demonstrated by a correlation of -0.62 (statistically significant above the 95% level) between the 8-year filtered sea level in the EJS and the PDO index over the 1950–2008 period. The near basin-scale relationship between the EJS sea level and the Pacific climate variability is illustrated by the spatial correlation map of Fig. 7, which represents a negative correlation between the PDO and the sea level in the entire EJS. Relatively weak negative correlations may be associated with mesosclae activity such as the meandering of the EKWC and migration of eddies (Choi et al. 2004). The negative correlation with the PDO was reported by Gordon and Giulivi (2004) who examined the

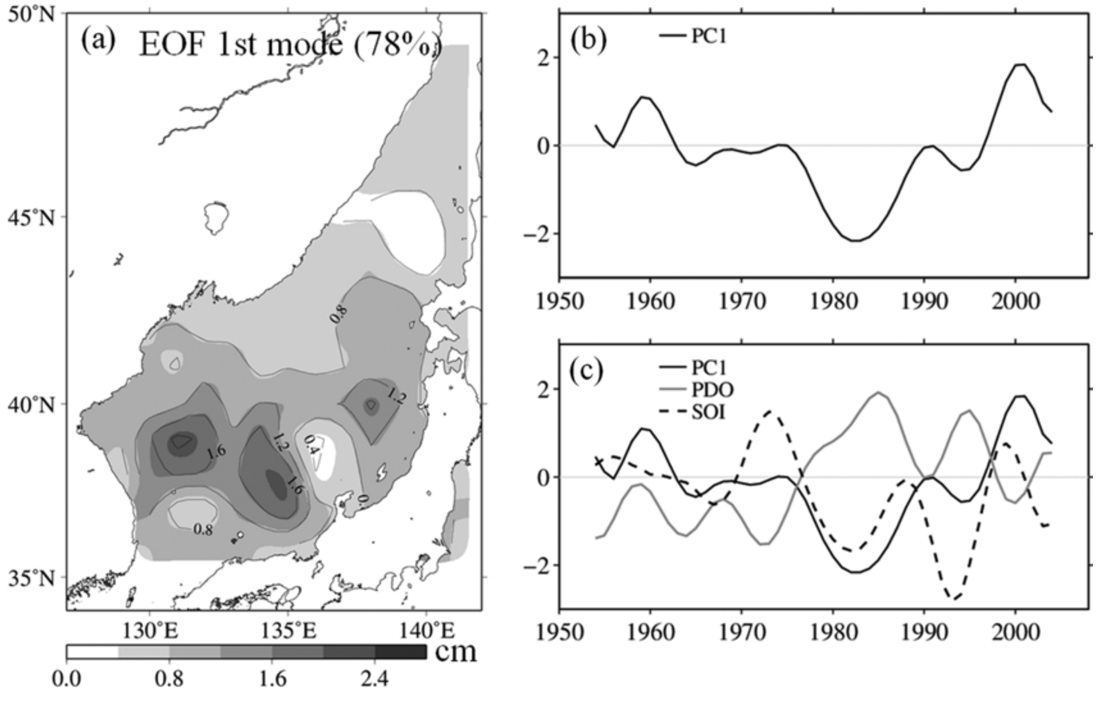

Fig. 6. First EOF mode of 8-year low-pass filtered sea level over the East/Japan Sea: (a) spatial structure of first EOF, (b) temporal variation of first EOF, and (c) time series of low-pass filtered PDO (gray) and SOI (dashed) indices with the temporal variation of first EOF (thick lines). The time series have been normalized by their standard deviations

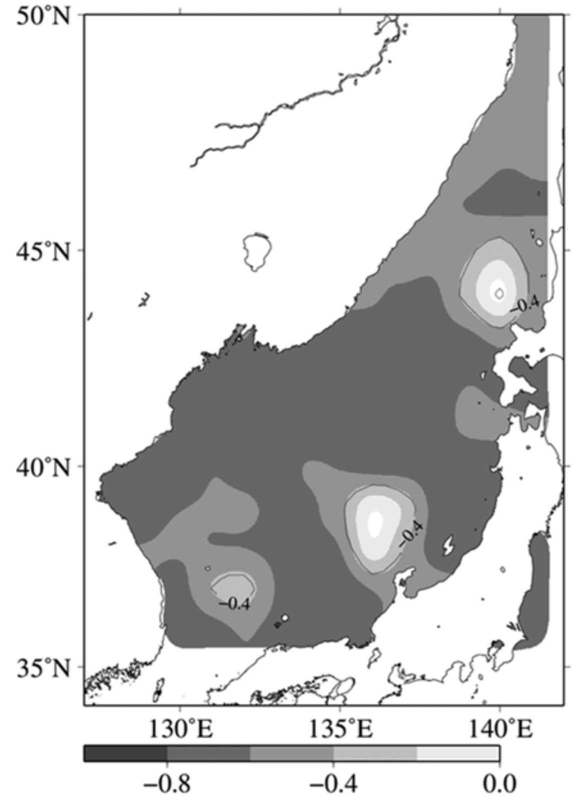

Fig. 7. Correlation map of 8-year running mean PDO index with sea level reconstruction of H2011 over 1950–2008

sea level variability associated with the PDO on inter-annual and decadal time scales. This result identifies an association between the EJS sea level and the climate-forced large-scale patterns of the North Pacific.

Meanwhile, the EJS sea level reveals a relatively weak correlation with the low-frequency ENSO variations captured by the SOI, showing a positive correlation less than 0.4. The connection between the EJS and the ENSO event was discussed by Park and Oh (2000) and Hong et al. (2001). They showed that the SST in the EJS is closely related to the ENSO on an inter-annual time scale. It has also been suggested that PDO may contribute to decadal changes in ENSO activity (Yu et al. 2000). Recently, a decadal fluctuation associated with the Central Pacific (CP) El Niño has been reported by Behera and Yamagata (2010). They argued that frequent occurrences of CP El Niño events have influenced the decadal sea level variability in the tropical Pacific during the most recent decade. However, little is known regarding the connection of low-frequency ENSO signals with the SST and sea level in the EJS. Our analysis shows a weak connection between the ENSO and sea level on inter-annual to multi-decadal time scales. In particular, on a multi-decadal time scale, the EJS sea level has a downward trend from the 1950s to the early 1980s, followed by a full reversal after the early 1980s (black line), while the SOI appears to be experiencing a reversal shift since the early 1990s (dashed line in Fig. 6c). The multi-decadal trend change in SOI has been noted by Feng et al. (2011) who focused on a close connection between the sea level at Fremantle, Western Australia and the equatorial Pacific trades. Recently, Merrifield et al. (2012) also suggested that a significant SLR trend in the western tropical Pacific after the early 1990s is consistent with the fluctuation observed at Fremantle, showing a relationship with the low-frequency ENSO-related index.

5. Sea Level Shift and PDO-related Wind Stress Curl

Surface wind forcing can be one of the important contributors for regional sea level variability and long-term trend changes that dynamically drives the upper-ocean circulation (e.g. Timmermann et al. 2010; Merrifield et al. 2012). Considering that the sea level in the EJS is well correlated with the PDO, we expect the EJS sea level variations to be the result of PDO-related wind forcing in the North Pacific. To assess the surface wind pattern associated with the Pacific climate variability, we regressed the NCEP reanalysis wind stress (Kalnay et al. 1996) onto the PDO index (Fig. 8a). The PDO corresponds to wind patterns at high-latitudes (i.e. the Aleutian

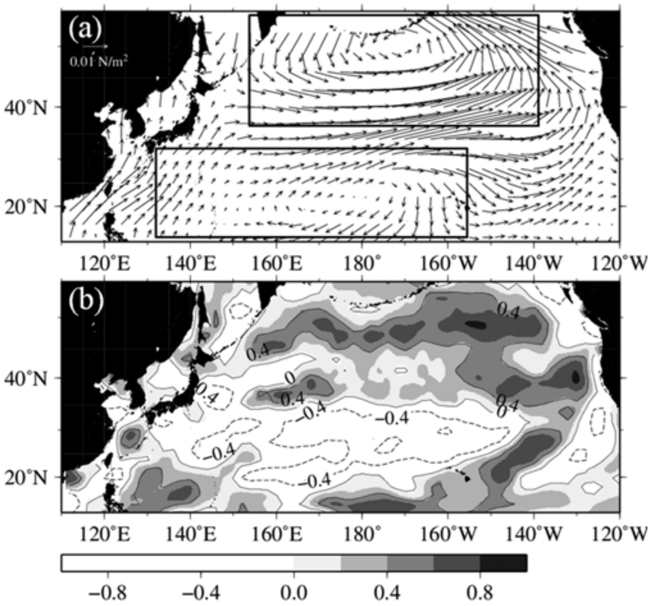

Fig. 8. (a) NCEP wind stress regressed onto the PDO index anomalies over 1958–2008. (b) Correlations of wind stress curl with PDO index. The boxes indicate the regions for averaging wind stress curl in Fig. 9

low region) and mid-latitudes in the western/central North Pacific, describing counter-rotating winds at mid- and high-latitudes (Merrifield et al. 2012; Moon et al. 2013). These patterns are also pointed out by Fig. 8b which show the correlation map of wind stress curl (WSC = $\nabla \times \vec{\tau}$) with PDO index. The WSC at mid-latitudes negatively correlates with that at high-latitudes, indicating an imprint of PDO on the surface wind pattern in the subtropical region of the North Pacific.

The wind patterns in the North Pacific are evident in time series of regionally averaged WSC at high (150°E–140°W, 35°N–55°N, Fig. 9a) and mid-latitudes (125°E–160°W, 10°N–30°N, Fig. 9b) in the western/central North Pacific. The multi-decadal weakening trend of the negative WSC at high latitude was reversed after the early 1980s in line with the PDO index. On the other hand, the trend at mid-latitude shows an opposite trend of the WSC at high latitude, i.e., a weakening trend of positive WSC before the early 1980s, followed by a strengthening trend of positive WSC from the early 1980s to the present. The significant negative correlation (-0.71, statistically significant above the 95% level) between the two WSC anomalies is consistent with the previous study by Andres et al. (2009) who have shown that the PDO index is negatively correlated with WSC over the central North Pacific at mid-latitudes.

Using observational data with Sverdrup transport calculations, Andres et al. (2009) suggested that when the PDO index is negative, positive WSC anomalies prevail over the western/central North Pacific at mid-latitudes that forces weaker Sverdrup flow in the subtropical gyre. This is compensated for by a weaker return Kuroshio flow in the East China Sea (ECS), i.e., the Western Boundary Current (WBC), which corresponds with topographically controlled Kuroshio jet resulting in warmer subtropical water entering the EJS through the Korea Strait and therefore higher sea level in the EJS. On the other hand, when the PDO index is positive, the Kuroshio transport becomes stronger due to negative WSC anomalies at mid-latitudes that results in a low EJS sea level because the Kuroshio jet is intertially controlled to continue in a straight path through the Tokara Strait. Our result shows that multi-decadally modulating surface WSC matches well with the sea level changes in the EJS. During the period prior to the early 1980s, the weakened positive WSC at mid-latitudes (-1.1×10^{-8} N/m^3/year) contributed to a low sea level in the EJS due to the connection between the ECS-Kuroshio transport and the PDO index (Gordon and Giulivi 2004; Andres et al. 2009). Since the early 1980s, the EJS sea level trend has revealed an increasing trend, corresponding to the strengthening trend of positive WSC in the western/central North Pacific at mid-latitude at a rate of 1.8×10^{-8} N/m^3/year. Nonetheless, this interpretation has a limitation since the data analysis only may have been insufficient to clearly delineate the underlying physics clearly. Therefore, further studies based on experiments from ocean circulation models are needed to clarify the relationship between the EJS sea levels and the Kuroshio transport.

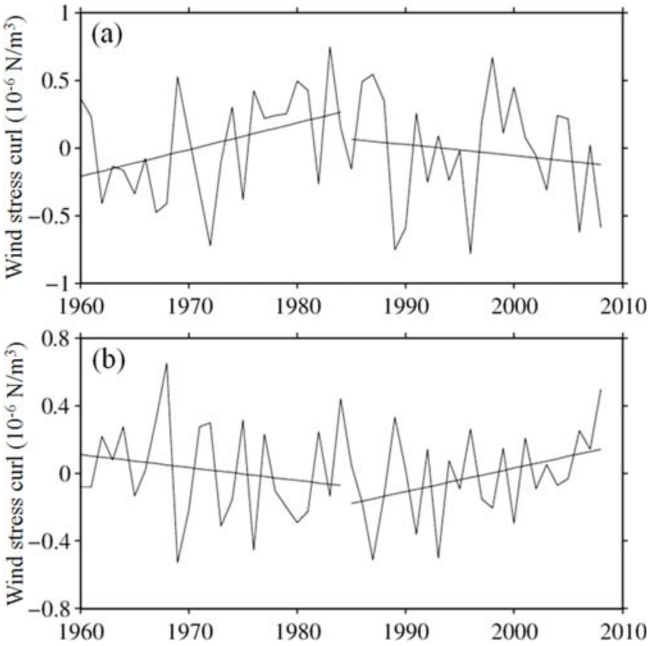

Fig. 9. Time series of (a) mean wind stress curl over the North Pacific at high-latitudes and (b) mid-latitudes (boxed regions in Fig. 8a). The multi-decadal linear trends are also presented

6. Concluding Discussions

Previous studies based on the altimetry-based data have looked at the sea level variations in the EJS on intra-seasonal to decadal time scales (e.g. Gordon and Giulivi 2004; Choi and Haidvogel 2004; Kang et al. 2005; Kim and Fukumori 2008), but this paper has attempted to quantify the EJS sea level changes and their connection with large-scale North Pacific circulations on a multi-decadal time scale, which is known to contribute to the SLR trends. The use of satellite altimeter measurements, tide gauge records, and reconstructed sea levels has allowed us to identify that there has been a shift in the multi-decadal SLR trend in the EJS over the past 60 years. The EJS mean sea levels from the reconstructions reveal a steadily declining trend prior to the early 1980s, followed by a full reversal from the early 1980s onward. This is consistent with the multi-decadal SLR trend observed from the tide gauges along the coasts of Korea and Japan. The spatial pattern of the SLR trend since the early 1980s is quite similar to the altimetry-based trend, which shows a linear trend over the altimetry period. This result indicates that the recent rising trend of the EJS sea level has been persistent since the early 1980s, representing a near basin-wide multi-decadal SLR shift.

Because thermal steric expansion associated with changes in temperature is the most important cause for sea level changes, we also used the SSL and OHC derived from in- situ upper-ocean (above 700 m) profiles. It is shown that the upper-ocean heat change significantly contributes to the multi-decadal SLR shift in the EJS, correlating negatively with Pacific climate variability, i.e., the PDO index. Analyzing the wind patterns in the North Pacific reveals a negative correlation between the WSC at mid-latitudes and the PDO index that may result in changes in the WBC transport in the subtropical North Pacific gyre. This is consistent with the connection between the Kuroshio transport in the ECS and the PDO index reported by Andres et al. (2009). The WBC's response to the PDO-related WSC may result in more warmer subtropical water entering (blocking) into the EJS due to the topographically (inertially) controlled Kuroshio jet which exits the ECS through the Tokara Strait.

These results indicate the important role played by the ocean's response to winds in redistributing heat on multi-decadal time scales. Although not focused on in this study, the decadal variability of the EJS sea level would be an interesting subject for future study. According to our analysis (see Fig. 6c), on a decadal time scale the EJS sea level has been negatively correlated with the PDO index since 1970s, but not significantly correlated with the index from 1950s to 1970s. This may be associated with a sharp climatic regime shift in the mid-1970s, followed by more frequent El Niño conditions and a positive phase of the PDO (e.g. Trenberth 1990; Graham 1995). The PDO may be one of the dominant factors that contributes to sea level fluctuations, but is not the sole factor for sea level changes in the EJS. Therefore, more studies are clearly needed to gain a better understanding of the ocean processes that cause sea level changes in the EJS.

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