Pacific Decadal Oscillation and Sea Level Variability in the Bohai, Yellow, and East China Seas

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(Manuscript received 24 July 2007, in final form 1 May 2008)

ABSTRACT

Sea level variability off East China has been investigated based primarily on 10 years of Ocean Topography Experiment (TOPEX)/Poseidon altimetry data. The altimetric annual harmonic has a magnitude of 10 to 30 cm in amplitude and is highest in summer, agreeing well with independent tide-gauge data. After the inverse barometer effect is removed, the annual sea level cycle can be approximately accounted for by the steric height variation. Significant interannual sea level change was also observed from altimetry and tide-gauge data, with a range of ~10 cm. The interannual and longer-term sea level variability in the altimetric data are negatively correlated (significant at the 95% confidence level) with the Pacific decadal oscillation (PDO), attributed in part to steric height change. The altimetric sea level rise rate is 0.64 cm yr\(^{-1}\) for the period from 1992 to 2002, consistent with the tide-gauge rate of 0.6 cm yr\(^{-1}\). These values are much larger than the rate of 0.24 cm yr\(^{-1}\) observed at the same tide gauges but for the period from 1980 to 2002, implying the sensitivity to the length of data as a result of the decadal variability. The potential role of the PDO in the interannual and longer-term sea level variability is discussed in terms of regional manifestations such as the ocean temperature and salinity and the Kuroshio transport.

1. Introduction

The Bohai, Yellow, and East China Seas (Fig. 1) are shallow marginal seas enclosed by East China, the Korean Peninsula, and Japan with open connections to the northwest Pacific, the South China Sea, and the Sea of Japan (Su 1998). In addition to local atmospheric forcing and freshwater runoff, the large-scale atmospheric and oceanic variability, such as the Pacific decadal oscillation (PDO) may impact the seasonal and longer-term hydrography and circulation variability in this region (http://www.pices.int/publications/special_publications/NPESR/2005/File_3_pp_59_78.pdf). The PDO index (http://jisao.washington.edu/pdo/PDO.latest) is defined as the leading principal component of North Pacific (poleward of 20°N) monthly sea surface temperature (SST) variability (Mantua et al. 1997). The positive PDO is associated with the intensified Aleutian low and strong westerlies. The SST in the midlatitude North Pacific is usually cool in the positive phase (Gordon and Giulivi 2004).

Based primarily on tide gauge observations, the global mean sea level rose at a rate of 1–2 mm yr\(^{-1}\) during the last century (Church et al. 2001). The geocentric rate of the sea level rise for the period from 1993 to 2003 was estimated to be 2.8 ± 0.4 mm yr\(^{-1}\) (Cazenave and Nerem 2004). Studies using tide gauge data and satellite altimetry indicated significant regional differences, with some areas 10 times as high as the global average (Cazenave and Nerem 2004) and others essentially unchanged (Han 2002, 2004). In the Bohai, Yellow, and East China Seas, coastal tide-gauge data have indicated significant sea level variability on seasonal and interannual scales and evident sea level rise since the 1950s (Yanagi and Akaki 1994). As we know, sea level is an integrated manifestation of the ocean’s response to all dynamic and thermodynamic processes of oceanic, atmospheric, cryospheric, and terrestrial origin. Therefore, the seasonal and interannual sea level
variability off East China could have important large-scale climatic implications.

Applications of satellite altimetry to low-frequency sea level variability are limited in the Bohai, Yellow, and East China Seas. In addition to lower data availability in the coastal seas, tidal correction errors have been an obstacle. Nevertheless, applications of altimetry data to these shallow seas with substantial tidal correction errors are surely feasible with appropriate methods for certain issues (Han et al. 2002). In fact, application of satellite altimetry in coastal regions has become a heated subject in recent years and an important direction of the Ocean Surface Topography Sciences Team (http://www.aviso.oceanobs.com/en/courses/ostst/index.html).

In this study we investigate annual, interannual, and long-term sea level changes from Ocean Topography Experiment (TOPEX)/Poseidon (T/P) altimetric measurements, tide gauge observations, and hydrographic data and explore potential mechanisms underlying these changes along the Chinese coast and over the adjacent shelf seas. Annual harmonics of sea level variation and residual tides are extracted from altimetric sea surface heights using a modified response analysis method. The residual sea levels are averaged by season and year for interannual variability and trend detection. We used the modified response analysis method to remove the variability at the aliasing frequencies for the major semidiurnal and diurnal constituents. Tidal waves have distinct physical periods that are aliased into periods much longer in the altimetric data. For eight major semidiurnal \( (M_2, S_2, N_2, K_2) \) and diurnal \( (K_1, O_1, P_1, \text{and } Q_1) \) constituents, their aliased periods are all shorter than half a year. Therefore they can be well separated from the annual cycle given 10 years of T/P data. Their effects on the interannual variability and longer-term trend should not be a concern. Therefore, the present tidal removal method is a valid alternative for not using the most recent local tidal model in the tidal correction.

The paper has six sections. Section 2 describes the methodology of processing satellite altimetry measurements, tide gauge data, and temperature and salinity data. Section 3 presents and interprets the annual sea level cycle. In section 4 the interannual and longer-term sea level variability is presented and possible mechanisms underlying the variability are discussed. Section 5 concludes the paper.

2. Methodology

a. Altimeter data processing and analysis techniques

We have used 1-s corrected collinear TOPEX/Poseidon sea surface height anomalies with an along-track resolution of \(-6 \text{ km}\) produced by the NASA Ocean Pathfinder Project (version 9.1; information on a slightly newer version 9.2 is available at http://podaac.jpl.nasa.gov/PRODUCTS/p202.html). All standard corrections for atmospheric (wet troposphere, dry troposphere, and ionosphere delays) and oceanographic (electromagnetic bias; ocean, load, solid earth, and pole tides) effects were made according to principles described by Benada (1997), except for the inverse barometric response. The data on six ascending and four descending tracks (see Fig. 1) from October 1992 to July 2002 are chosen for further processing. The T/P satellite repeats its ground track every 9.9156 days. Ideally, there are 360 cycles of data for a given track location, but the number of available data records may be lower, depending on location. A location is included.
for analysis only if there are more than 220 cycles of observations available.

The sea surface height anomalies are then subject to a modified response analysis (e.g., Cartwright and Ray 1990; Han et al. 2002) to separate the annual cycle from variations at alias frequencies of oceanic tides. In the modified response analysis, the sea level anomalies are expressed as

$$\zeta(\phi, \lambda, t) = \sum_{m=1}^{2} \sum_{k=0}^{2K} \left[ \mathcal{U}_k^m(\phi, \lambda)P_k^m(t) + \mathcal{V}_k^m(\phi, \lambda)Q_k^m(t) \right] + C \cos \omega t + S \sin \omega t + r,$$

where $\zeta$ is the sea level anomalies, $\phi$ and $\lambda$ are longitude and latitude, $t$ is the time, $m$ denotes the tidal species (1 for the diurnal and 2 for the semidiurnal), and $k$ is time lag in days ($K = 1$ is adequate); $\mathcal{U}_k^m$ and $\mathcal{V}_k^m$ are unknowns to be determined, from which amplitudes and phases for the diurnal and semidiurnal can be obtained; $P_k^m$ and $Q_k^m$ are nearly orthogonal in time, associated with the real and imaginary parts of the time-varying portion of the tide-generating potential; $C$ and $S$ are cosine and sine coefficients for the annual cycle that are to be determined; $\omega$ is the annual frequency; and $r$ is the residual sea level anomalies. A least squares technique is used to solve Eq. (1). The residual sea level anomalies are used to examine the interannual variability and the sea level rise.

We apply the modified response method to the initially corrected T/P sea surface height anomalies to extract the annual and semiannual cycles and to remove the remaining variability of major semidiurnal ($M_2$, $S_2$, $N_2$, $K_2$) and diurnal ($K_1$, $O_1$, $P_1$, and $Q_1$) tides. With the repeat cycle of approximately 10 days for the T/P altimeter, semidiurnal and diurnal tides in the T/P data have much longer alias periods (Han et al. 1996), for example, 62 days for $M_2$. Therefore, the response analysis may reduce both residual tidal variability and nontidal oceanic features at the alias periods. The ocean tide in the Pathfinder T/P data was corrected by the GOT00 global tide model (an updated version of Ray 1999). The model $M_2$ amplitudes are of order of 100 cm (Naimie et al. 2001). The present response analysis indicates that at the alias period of $M_2$, the amplitude of the residual fluctuation increases from 5 cm in the central East China and Yellow Seas toward the Chinese coast where the magnitude can exceed 15 cm (Fig. 2), consistent with the tidal errors of Lefevre et al.’s (2000) and Teague et al.’s (2000) models. The significant residual tide suggests that an alternative local model with higher accuracy should be considered in detiding altimetric data off East China. A recent study (Fang et al. 2004) indicated that the accuracy of the T/P-derived tides for the region could reach 2–4 cm in amplitude and 5° in phase for major semidiurnal and diurnal constituents. Nevertheless, because the alias periods of the major semidiurnal and diurnal tidal constituents are shorter than half a year, the tidal errors are not a concern to the present investigation of the annual and interannual variability, but can be a problem for a study of dynamical processes at intraseasonal scales.

The cosine and sine coefficients of the annual cycle on the track locations are spatially mapped onto a regular grid of 0.25° in latitude by 0.25° in longitude, by an objective analysis method. The decorrelation scale used is 2° in latitude by 3° in longitude, in consideration of the cross-track spacing. We then construct amplitude and phase fields of the annual cycle from the interpolated cosine and sine coefficients. The same procedure is used to generate altimetric height estimates at coastal tide-gauge locations for comparison with in situ observations. Note that no altimetric data are available within a couple of tens of kilometers from the coast.
Table 1. Comparison of the T/P (braced values) and steric sea level annual cycle at the selected locations, representing the southern East China Sea (SECS), central East China Sea (CECS), Yellow Sea (YS), and Bohai Sea (BS). The yearday indicates the time when the annual sea level is highest. The steric height is calculated using Ishii et al.’s (2006) temperature and salinity climatology, relative to 100 db. The last column is the annual temperature range averaged over the upper 50 m.

<table>
<thead>
<tr>
<th>Location</th>
<th>Amplitude (cm)</th>
<th>Yearday</th>
<th>Temperature range (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>26.5°N, 124.5°E (SECS)</td>
<td>8.0 (6.7)</td>
<td>241 (227)</td>
<td>6.3</td>
</tr>
<tr>
<td>29.5°N, 124.5°E (CECS)</td>
<td>10.7 (8.7)</td>
<td>247 (248)</td>
<td>12.2</td>
</tr>
<tr>
<td>35.5°N, 123.5°E (YS)</td>
<td>7.3 (6.5)</td>
<td>258 (249)</td>
<td>12.7</td>
</tr>
<tr>
<td>38.5°N, 122.5°E (BS)</td>
<td>7.6 (11.3)</td>
<td>255 (233)</td>
<td>12.3</td>
</tr>
</tbody>
</table>

b. Tide gauge data

We obtained monthly mean sea level data at eight tide gauge stations (see Fig. 1 for locations) along the Chinese coast and at Ishigaki II from the Permanent Service for Mean Sea Level (PSMSL) (http://www.pol.ac.uk/psmsl). The data duration at the nine stations varies significantly from station to station and is usually more than 10 yr, starting as early as the 1950s and ending as late as 2002. For the eight Chinese coastal stations we used all available data to derive the annual cycle. For longer-term sea level variability and rise, we used monthly sea level data at Kanmen, Lusi, and Dalian from 1970 to 2002. Data from 1993 to 2002 are used at Ishigaki II.

Monthly mean sea level anomalies are computed by removing the means from the sea level data for each station. A least squares analysis is performed to extract annual and semiannual cycles from the monthly anomalies. At Kanmen, Lusi, Dalian, and Ishigaki II, the residual monthly data with the annual and semiannual cycles removed are then used to generate seasonal-mean (January–March for winter, April–June for spring, July–September for summer, and October–December for fall) sea level anomalies. A least squares regression was used to extract the linear trend.

The analysis of the tide gauge data indicates that the semiannual cycle is 1–2 cm in amplitude, much less than the annual cycle. Therefore, we will only discuss the annual cycle hereafter.

c. Temperature and salinity data

We have used the Ishii et al. (2006) monthly mean temperature and salinity datasets to calculate the steric height at four selected locations relative to 100 db (see Table for their longitudes and latitudes) in the study region. The Ishii et al. (2006) temperature and salinity fields were objectively analyzed on a 1° by 1° grid at the upper 16 standard levels (the deepest level is 700 m) for 1945–2003. They used various historical hydrographic datasets, which include the latest version of the observational data, climatology and standard deviations compiled by the National Oceanic and Atmospheric Administration/National Oceanographic Data Center (NODC). In addition, the Ishii et al. (2006) climatology used a tropical and subtropical Pacific Ocean sea surface salinity dataset for 1970–2001 and a global database archived by the NODC Global Temperature–Salinity Profile Program from 1990 to 2003.

3. Annual sea level variability

a. Results

The response analysis extracted the annual cycle of sea level while simultaneously removing sea level variability at the tidal alias frequencies (discussed in the preceding section) in the T/P sea level time series from 1992 to 2002. In this section, we examine amplitude and phase of the annual cycle of altimetric sea levels and compare the altimetric results with coastal tide-gauge measurements.

The magnitude of the annual cycle varies from 10 to 30 cm, smaller in the East China Sea and largest in the Bohai Sea (Fig. 3a). The phase (indicating the time of annual maximum sea level) pattern shows substantial changes with a general lag (about 2 months) from north to south. Overall, the sea level associated with the annual harmonic was highest in July–August and lowest in January–February.

The error associated with the T/P annual cycle was estimated using the Han et al. (2002) crossover method, which defines the error as the root sum square of the cosine and sine term differences at each crossover. The error in the study region is about 2 cm on average, much smaller than the annual amplitude. Comparisons of the T/P annual cycle with tide gauge measurements indicate overall good agreement (Fig. 4), with the correlation coefficients of 0.98 and 0.99 for the amplitude and phase, respectively. The root-mean-square amplitude and phase differences are 1.7 cm and 6 days. Assuming that the errors in the T/P and tide gauge measurements are uncorrelated, we can estimate the amplitude and phase errors by dividing the rms differences by the square root of 2, that is, 1.2 cm and 4 days. The good agreement demonstrates the ability of the T/P altimetry observing annual sea level variability off the Chinese coast.
b. Discussion

The annual sea level variability can be caused by atmospheric pressure variability, ocean density evolution, and surface wind shifts. We examined the annual cycle (Fig. 3b) derived from the altimetric sea surface height data with the inverse barometric effect corrected, which were also obtained from the NASA Ocean Pathfinder Project. As has been shown, the atmospheric pressure effects account for a significant amount of the annual sea level variability in magnitude and cause the sea level to peak up to a month in advance. Although the inverse barometric response of the sea level may not be perfect, on seasonal and longer time scales the assumption is reasonably good and robust (Han et al. 1993). Hereafter, we will focus on the dynamical sea level variability with the inverse barometric effect removed and attempt to give a qualitative interpretation of the underlying forcing mechanisms.

The amplitude of the annual cycle varies from 12 (in the south) to 16 (in the north) cm in the Bohai Sea (Fig. 3b) where the sea level was highest in August and lowest in February. In addition to the steric effect (Table 1) due mainly to thermal expansion in response to the seasonal solar heating, a sea level setdown along the northern coast due to the strong northerly wind in winter months plays an important role (Naimie et al. 2001). The steric height in Table 1 was calculated relative to 100 db based on the Ishii et al. (2006) temperature and salinity data.

In the Yellow Sea, there is increased sea level variability toward the Chinese coast (Fig. 3b). The amplitude is 8 cm in the central Yellow Sea and 10 cm over the inner shelf. When combined with the phase information, it can be shown that sea level increases onshore in summer. The sea level variability can be mostly accounted for by the steric effect (Table 1). The onshore sea level increase in summer is qualitatively consistent with a cyclonic eddy over the Yellow Sea “Cold Water”
as shown by Naimie et al. (2001). The phase pattern in the Yellow and East China Seas indicates sea level peaks in September. The southward time delay in the sea level peak is a result of the increased water depth from the Bohai Sea to the East China Sea. There is good agreement between the T/P and steric sea level in the central East China Sea (Table 1). The amplitude of the annual cycle (Fig. 3b, Table 1) also indicates that the sea level variability decreases southward in the East China Sea. The decreased annual range may be in part related to a reduced thermosteric effect. In the southern East China Sea, but north of the Kuroshio, the oceanographic conditions can be affected by the flow from the South China Sea through Taiwan Strait and by the Kuroshio (Su 1998). The Ishii et al. (2006) hydrographic data indicate that the ocean water in the southern East China Sea is warmer and saltier in general but with a smaller annual range in temperature (Table 1). Therefore, thermosteric height variation is smaller annually.

4. Interannual and longer-term sea level variability

a. Results

Interannual and longer-term sea level variability is investigated by examining seasonal-mean sea level anomalies, after the annual cycle and tidal residuals (including the semiannual cycle; see section 3) are removed from altimetric data. The seasonal-mean sea level anomalies are calculated and detrended by a least squares analysis.

The altimetric sea level was lower in late 1995 and early 1996 and higher in late 1999 and early 2000 (Fig. 5a). The high–low range amounted to 10 cm. Tide gauge data (Fig. 5b) exhibited a similar evolution in terms of the magnitude and sequence but were more variable at shorter time scales. The correlation coefficient between the altimetric and tide-gauge sea level anomalies is 0.54, significantly different from zero at the 95% confidence level. Their rms difference is 2.7 cm. By assuming that the errors in the T/P and tide-gauge measurements are uncorrelated, we obtain an estimated rms error of 1.9 cm. In addition to data errors associated with the altimetric and tide gauge data, the difference may be related to data availability and geographic locations: tide gauge results are obtained from three coastal stations only; whereas the T/P results are generated from many more offshore locations in the Yellow, Bohai, and East China Seas.

There are evident sea level rises in both T/P and tide gauge observations. Note that an altimeter measures the geocentric sea level (related to the earth’s center), while a tide gauge measures the sea level relative to the local land. From the T/P data, the mean geocentric rate of the sea level rise is 0.64 cm yr$^{-1}$. The average sea level trend observed by the tide gauges is estimated to be a rise of 0.66 cm yr$^{-1}$ at Dalian, Lusi, and Kanmen for the T/P period. One could argue that the coastal
land is subject to vertical movement (subsidence). Based on a global glacial isostatic adjustment model (Peltier 2004), the subsidence rate is about 0.06 cm yr\(^{-1}\) at the three locations. As a result, with the model land subsidence accounted for, the corresponding rate of the sea level rise is 0.60 cm yr\(^{-1}\), in good agreement with the T/P geocentric rate. In contrast, the average rate based on the 1980–2002 tide gauge data for Dalian, Kanmen, and Lusi (Fig. 6) is 0.24 cm yr\(^{-1}\), after the model land subsidence rate being accounted for, indicating the degree of sensitivity of the calculated rate to the record length as a result of the decadal sea level variability. The average subsidence-corrected rate at the three tide gauges was 0.27 cm yr\(^{-1}\) for the period from 1970 to 2002.

The local T/P period sea level rise rate is notably larger than the global-mean rate of 0.28 cm yr\(^{-1}\) based on the T/P data (Cazenave and Nerem 2004). The difference indicates the regional inhomogeneity of the sea level rise. An earlier study of Han (2002) found the geocentric rate of T/P sea level rise is essentially zero at Halifax, Nova Scotia, off Atlantic Canada during 1992–2000.

b. Discussion

The interannual and longer-term sea level variability off East China can be caused by a number of factors of oceanographic, atmospheric, and terrestrial origin. The East China Sea receives inflows through Taiwan Strait and interacts and exchanges with the Kuroshio. The region also receives a large amount of freshwater runoff, such as from the Yangtze River. Air temperature, wind, and precipitation are factors impacting heat and water fluxes across the sea surface over these seas. They affect water properties and steric and dynamic sea level variations.

1) STERIC EFFECT

The seasonal-mean steric heights averaged for the four selected sites (see Table 1 for locations) exhibited similar interannual fluctuations to the altimeter and tide gauge data during the T/P period but with much smaller magnitude (Fig. 7). This implies that the steric effect can account only for a portion of the interannual sea level variability as seen in the T/P and tide gauge data. The sea level rise rate of 0.23 cm yr\(^{-1}\) in the steric height is only 40% of that revealed by the altimeter and tide gauge data.

Substantial interannual and decadal variability can also be seen in the steric height data for the period from 1980 to 2002 (Fig. 7). The correlation of the steric height with PDO is calculated to be 0.4 and 0.33 before and after detrending, respectively (both are significantly different from zero at the 95% confidence level). The rate of steric height rise (Fig. 7) is estimated to be 0.88 mm yr\(^{-1}\) for 1980–2002, lower than that of the tide-gage sea level rise discussed in section 4a. The rates for 1980–2002 are significantly lower than those for the T/P period, implying the great sensitivity to the record of length and decadal variability.

2) ROLE OF PDO

Casey and Adamec (2002, their Fig. 1), from the 1993–99 satellite data, clearly showed that the northwest Pacific was cooler and the sea level was lower in 1997 when the PDO was highly positive. A comparison of the PDO index with the Kuroshio geostrophic transport from the 1950s to 1990s (Gordon and Giulivi 2004) suggested that the Kuroshio transport is positively correlated with the PDO. Gordon and Giulivi also found the T/P sea level, steric height, and SST in the Japan/
East Sea to be negatively correlated with PDO. The correlation coefficient is $-0.4$, significant at the 95% confidence level. They proposed two mechanisms: 1) During a positive PDO phase the buoyant North Pacific subtropical water into the Japan/East Sea decreased as a consequence of the inverse relationship between the Kuroshio transport and the Tsushima Current and 2) the decrease of the Yangtze River runoff.

![Fig. 6](image1.png)

**Fig. 6.** Seasonal-mean tide-gauge data averaged for Dalian, Lusi, and Kanmen from 1980 to 2002. The sea level anomalies (blue) are shown without (solid) and with (dashed) detrending. Seasonal-mean PDO anomalies (green) are also depicted without (solid) and with (dashed) detrending.

![Fig. 7](image2.png)

**Fig. 7.** Seasonal-mean steric height averaged for the four selected locations (see Table 1) from 1980 to 2002. The sea level anomalies (blue) are shown without (solid) and with (dashed) detrending. Seasonal-mean PDO anomalies (green) are also depicted without (solid) and with (dashed) detrending.
may reduce the freshwater inflow from the East China Sea. The inverse Kuroshio–Tsushima relationship may be accounted for by a concept that a weaker Kuroshio could force an expansion of the surface layer of the subtropical gyre in the northwest Pacific, which would feed more subtropical water into the Tsushima Current (Gordon and Giulivi 2004).

Here we explore the role of the ocean temperature, salinity, Kuroshio transport, the Yangtze River runoff, and the PDO in the regional interannual and longer-term sea level variability of the Bohai, Yellow, and East China Seas. There was significant interannual and decadal variability in temperature (Fig. 8) and salinity (Fig. 9) for the period from 1980 to 2003. The correlation coefficients of the temperature and salinity with the PDO were calculated to be $-0.32$ (significant at the 95% confidence level) and 0.12, respectively. The temperature increased at a rate of 0.047 °C yr$^{-1}$. The salinity decreased at a rate of 0.0017 psu yr$^{-1}$. The increase of temperature and decrease of salinity lead to the rise of the steric height. For the T/P period, the correlation coefficients with the PDO were $-0.26$ (significant at the 90% confidence level) for temperature and 0.37 (significant at the 95% confidence level) for salinity. The temperature increase rate was 0.064 °C yr$^{-1}$ and the salinity decrease rate was 0.0172 psu yr$^{-1}$. While the overall contribution to the steric sea level change was dominated by the temperature variation, the salinity decrease plays a more significant role in the sea level rise during the T/P period than before.

One of the factors that can affect salinity is the freshwater runoff. The Yangtze River provides dominant freshwater runoff to this region. The runoff can significantly impact the salinity distribution in the East China Sea and Yellow Sea. In general, high runoff reduces salinity and hence is expected to increase steric height. Nevertheless, the Yangtze River runoff had low negative correlation with both the ocean salinity and with the PDO for the period from 1980 to 2002 (Fig. 10). The yearly mean runoff data at Datong Hydrographic Station (the tidal limit of the Yangtze River mouth; located at 30°46′N, 117°37′E) were obtained from Yang et al. (2005, their Fig. 6). It is suspected that on the interannual scale the Yangtze River runoff may also be affected by the El Nino–Southern Oscillation and Asian monsoon variations. While the negative correlation between the Yangtze River runoff and the PDO was weak from 1980 to 2002, it is consistent with the Gordon and Giulivi (2004) analysis for the period from 1900 to 1980.

![Figure 8](image1.png)  
**Fig. 8.** Seasonal-mean upper-layer (50 m) temperature anomalies (solid curve) averaged for the four selected locations (see Table 1) from 1980 to 2002. Seasonal-mean PDO anomalies (dashed curve) are also depicted.

![Figure 9](image2.png)  
**Fig. 9.** As in Fig. 8, but for salinity.

![Figure 10](image3.png)  
**Fig. 10.** Yearly mean Yangtze River runoff (dashed curve) at Datong Station. Yearly mean upper-layer (50 m) salinity (solid curve) averaged for the four selected locations (see Table 1) from 1980 to 2002 is also shown.
These results support the negative correlation between the sea level in the study region and PDO on the decadal scale.

Given that the steric height effect can account for only half of the interannual sea level variability and the sea level rise in the 1990s, and even to a lesser degree for 1980–2003, we now discuss potential impact of the Kuroshio variability in consideration of its proximity to the study region. Under the geostrophic assumption, variations in the Kuroshio geostrophic transport are associated with those of the sea level difference across the Kuroshio between the northwest Pacific and the three seas of interest; that is, the stronger the Kuroshio, the larger the sea level difference.

Gordon and Giulivi (2004) hypothesized that the Kuroshio geostrophic transport was positively correlated with the PDO from the 1950s to the 1990s. We calculated the difference of the seasonal-mean sea level anomalies across the Kuroshio from T/P data for Track 120 during the study period and from data at the Ishikagi II and Kanmen tidal stations (Fig. 11). The sea level differences can be used as a proxy indicator of the geostrophic transport of the Kuroshio. The T/P values are calculated as the averages for the segments south (23°–24.5°N) and north (26°–27.5°N) of the Kuroshio near Taiwan (see Fig. 1). There is positive correlation (0.32 for T/P, different from zero at the 95% confidence level; but 0.13 only for the tide gauge data) between the PDO and the sea level differences (and therefore the Kuroshio geostrophic transport) for the T/P period. It is understood that the change of the sea level differences may be associated with sea level change on either side of the Kuroshio. Combining the PDO relationship with the northwest Pacific sea level (negative correlation, Casey and Adamec 2002) and with the Kuroshio (positive correlation, this study), it is plausible to conclude that the sea level in the three seas would be lower with an intensified PDO. The relationship between the PDO and the regional sea level is summarized schematically in Fig. 12.

The correlation coefficient between the altimetric sea level (spatially averaged in the study region) and PDO for 1992–2002 is −0.66 and −0.47 before and after detrending (Fig. 5a), both significantly different from zero at the 95% confidence level. The difference of the correlation coefficient results from the increasing sea level and decreasing PDO during the period. Between the tide-gauge sea level and PDO, the correlation coeffi-

\[
\eta_{\text{BYE}} = \eta_{\text{NWP}} - \delta \eta
\]

\[
\eta_{\text{NWP}}
\]

Positive PDO, low \( \eta_{\text{NWP}} \) (Casey and Adamec, 2002)
Positive PDO, stronger Kuroshio, large \( \delta \eta \)
Positive PDO, therefore, low \( \eta_{\text{BYE}} \)

Fig. 12. Schematic illustration of the relationship between the PDO and the sea level in the Bohai, Yellow, and East China Seas in which \( \eta \) represents sea level, \( \delta \eta \) the sea level difference across the Kuroshio flowing into the page, NWP the northwest Pacific, and BYE the Bohai, Yellow, and East China Seas (adapted from Gordon and Giulivi 2004, their Fig. 7).
coefficients for 1992–2002 are −0.38 and −0.11 before and after detrending (Fig. 5b), with the former significantly different from zero at the 95% confidence level. These values for 1980–2002 are −0.30 (significantly different from zero) and −0.08 before and after detrending (Fig 6).

The present analysis indicates some role of PDO in the regional sea level variability on the interannual and longer time scales, but the exact extent and mechanisms remain unknown. The low correlation coefficients suggest that other factors such as the Asian monsoon may play a role, too. A similar analysis indicates that the correlation between the yearly mean T/P or tide-gauge sea level and the Asian summer monsoon index is positive but statistically insignificant at the 95% confidence level. The summer (June, July, and August) monsoon index was taken from Wang et al. (2001). In terms of overall statistical insignificance, it will not be discussed further.

5. Conclusions

We have investigated annual, interannual, and long-term sea level variations in the Bohai, Yellow, and East China Seas, using the T/P altimeter observations (http://podaac.jpl.nasa.gov/PRODUCTS/p202.html) for the period from 1992 to 2002 in conjunction with PSMSL coastal tide-gauge data (http://www.pol.ac.uk/psmsl) and temperature and salinity climatology (Ishii et al. 2006). Potential underlying mechanisms were discussed.

The present analysis reveals a substantially variable spatial distribution of the annual sea level cycle, with the amplitude including the inverse barometric effect changing from ~10 cm in the East China Sea to ~30 cm in the northern Bohai Sea. The sea level was highest in the Bohai Sea in late July, in the Yellow Sea in August, and near Kanmen in September. The inverse barometric effect is an important contributor to the annual cycle. The remaining annual cycle can be approximately accounted for by the steric height variation, except for the Bohai Sea where the shift of the wind forcing from the strong northwesterlies in winter to the weak southeasterlies in summer may also be important. The T/P altimetric results agree well with tide gauge observations for the annual cycle, demonstrating the T/P ability in observing seasonal sea level variations in the region.

Interannual/decadal variability off East China for the study period features the sea level low in 1995–96 and high in 1998–99 according to T/P observations. The range of the sea level change is 10 cm. The altimetric results are generally consistent with tide gauge observations. Their correlation coefficient is 0.54 (significantly different from zero at the 95% confidence level) and the rms difference is 2.8 cm. The steric height can only account for half of the magnitude in the interannual variability.

The analysis of T/P data showed a rate of sea level rise at 0.64 cm yr\(^{-1}\) for the period from 1992 to 2002. The altimetric result is consistent with tide gauge result (0.60 cm yr\(^{-1}\)) corrected for the subsidence based on the glacial isostatic adjustment model (Peltier 2004). The steric height change (as a result of the temperature increase and salinity decrease) can explain about half of the sea level rise. The present T/P and tide gauge values are much larger than both the global-mean sea level rise rate of 0.28 cm yr\(^{-1}\) based on the T/P data (Cazenave and Nerem 2004) and the long-term regional rate of 0.2–0.3 cm yr\(^{-1}\) based on the longer-term tide gauge data. The differences may represent the regional inhomogeneity of the sea level rise or the sensitivity of the calculated rate to the record length as a result of the decadal variability (e.g., an accelerated rise of steric sea level in the 1990s).

The present analyses also reveal negative correlation between sea level and the PDO on the interannual and longer time scales. The relationship represents various regional connections and manifestations, such as ocean temperature and salinity change, and possibly the Kuroshio transport variability.

Acknowledgments. The T/P data were obtained from the NASA Ocean Pathfinder Project. We thank M. Ishii for providing the temperature and salinity climatology. Constructive comments and suggestions were received from Dr. Lynne Talley and two anonymous reviewers. The research was conducted under a Fisheries and Ocean Canada and State Oceanic Administration of China collaborative project in which GH is the Canadian leading scientist, and partially supported by the scientific research funds of the Second Institute of Oceanography, State Oceanic Administration of China.

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