Interdecadal Baroclinic Sea Level Changes in the North Pacific Based on Historical Ocean Hydrographic Observations

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ABSTRACT

Using historical ocean hydrographic observations, decadal to multidecadal sea level changes from 1951 to 2007 in the North Pacific were investigated focusing on vertical density structures. Hydrographically, the sea level changes could reflect the following: changes in the depth of the main pycnocline, density gradient changes across the pycnocline, and modification of the water mass density structure within the pycnocline. The first two processes are characterized as the first baroclinic mode. The changes in density stratification across the pycnocline are sufficiently small to maintain the vertical profile of the first baroclinic mode in this analysis period. Therefore, the first mode should represent mainly the dynamical response to the wind stress forcing. Meanwhile, changes in the composite of all modes of order greater than 1 (remaining baroclinic mode) can be attributed to water mass modifications above the pycnocline. The first baroclinic mode is associated with 40–60-yr fluctuations in the subtropical gyre and bidecadal fluctuations of the Kuroshio Extension (KE) in response to basin-scale wind stress changes. In addition to this, the remaining baroclinic mode exhibits strong variability around the recirculation region south of the KE and regions downstream of the KE, accompanied by 40–60-yr and bidecadal fluctuations, respectively. These fluctuations follow spinup/spindown of the subtropical gyre and meridional shifts of the KE shown in the first mode, respectively. A lag correlation analysis suggests that interdecadal sea level changes due to water mass density changes are a secondary consequence of changes in basin-scale wind stress forcing related to the ocean circulation changes associated with the first mode.

1. Introduction

Understanding the physical background of sea level variability is an important aspect of climate research because sea level reflects basin-scale changes in ocean circulation and heat and water transport due to air–sea interactions. Sea level variability corresponding to major climate variations such as El Niño–Southern Oscillation and the Pacific decadal oscillation (PDO; Mantua et al. 1997) appears in the Pacific Ocean (Lombard et al. 2005). The sea level varies in response to local changes in the vertical density structure. Suzuki and Ishii (2011a) reported that regional sea level trends of the North Pacific in recent decades are associated with dynamical responses to wind forcing and substantial water mass density changes. In particular, density changes in subtropical mode water (STMW), which is a prominent upper-ocean water mass on the southern side of the Kuroshio and the Kuroshio Extension (KE; Hanawa and Talley 2001), cause an increase in positive sea level trends. In this study, we focus on interdecadal sea level changes driven by two mechanisms: wind forcing and water mass density changes. The interdecadal variability of regional sea surface height related to the subtropical gyre in the western North Pacific was investigated in previous studies (Yasuda and Sakurai 2006; Qiu 2003). These studies suggested that the variability results from the propagation of the first baroclinic Rossby waves...
forced by changes in basin-scale wind stress. The interannual variability of water mass properties of STMW is influenced by the strength of the Kuroshio and KE (Yasuda and Kitamura 2003; Hanawa and Kamada 2001). Furthermore, Qiu and Chen (2006) also suggested that formation of the STMW is enhanced when the KE recirculation gyre strengthens. Using a 2.5-layer model, Huang and Pedlosky (1999) described the baroclinic response in the ventilated thermocline to changes in the wind stress curl and changes in the air–sea buoyancy flux, which is treated as a southward shift of the outcropping line. If the outcropping line is nonzonal, changes in wind stress curl induce the changes in upper-ocean stratification in addition to the response of the main thermocline related to the first baroclinic mode. These results suggest that the water mass density changes associated with convergence due to changes in wind stress also cause baroclinic sea level change. However, contributions of water mass density changes to the sea level fluctuations are still unclear. In addition to this, no studies compare the interdecadal baroclinic sea level fluctuations in dynamical response to wind forcing and water mass density changes.

In this study, we investigate dynamical sea level change using historical hydrographic observations. To discuss the sea level changes accompanied by ocean circulation changes, a dynamical approach based on the momentum equation is used, in which baroclinic sea level changes are defined in terms equivalent to the vertical integration of horizontal pressure gradients estimated by the density changes (Lowe and Gregory 2006). We also consider steric sea level changes, which have been used extensively to investigate regional sea level variability in previous studies (Lombard et al. 2005; Antonov et al. 2002). Steric sea level changes provide insufficient information to understand sea level changes dynamically, because of the absence of dynamic principles (Griffies and Greatbatch 2012). Local steric sea level changes are similar to baroclinic sea level changes if changes in density are restricted to the upper parts of ocean columns (Gregory 1993). In this study, we investigate baroclinic sea level changes in comparison with the thermosteric contributions. Some previous studies have examined future regional baroclinic sea level changes to understand how sea level responds to external forcing (Lowe and Gregory 2006; Suzuki and Ishii 2011b). Their results suggest that the baroclinic response clearly influences the pattern of regional sea level changes. In addition to this, Suzuki and Ishii (2011a) decomposed the baroclinic sea level change into the baroclinic modes for internal waves to understand these responses of sea surface height during recent decades. Since the trends of these responses have been previously discussed, we investigate the interdecadal fluctuations, in order to improve the understanding of the physical processes of sea level change.

2. Data and procedures

Interdecadal sea level changes are investigated using historical hydrographic observations, which are taken from a monthly objective analysis of ocean subsurface temperature and salinity of the global ocean based on those by Ishii and Kimoto (2009). Biases in temperature measurements with expendable and mechanical bathythermographs are removed in the database. The latest analysis is available from the surface to a depth of 3000 m, and the dataset includes analysis errors of temperature and salinity. The reference level depends on the bottom topography. We have used observed data in the top 3000 m and climatology below 3000 m. The variables are defined on a 1° latitude–longitude grid at 28 levels. The 5-yr-averaged baroclinic and thermosteric sea level changes are estimated for 57 yr from 1951 to 2007. To examine the regional pattern, the global means are subtracted from the gridwise sea levels uniformly.

To investigate the physical processes of the interdecadal sea level variability, we calculate the baroclinic sea level change and decompose it into the baroclinic modes. The baroclinic sea level change reflects the baroclinic pressure change at the sea surface. We decomposed the baroclinic pressure change into vertical modes of ocean stratification, following Suzuki and Ishii (2011a). Baroclinic pressure change $P'$ was computed as

$$P'(z) = \rho_0 \eta' + \int_0^z \rho' \, dz',$$  \hspace{2cm} (1)

where $\eta'$ is a baroclinic sea level change, $\rho_0$ is a reference density, and $\rho'$ is the density change. The baroclinic pressure change is decomposed as follows:

$$P'(z) = \sum_{i,m} a_{im} P_{im}(z),$$ \hspace{2cm} (2)

where $a_{im}$ represents the contribution of each mode and $P_{im}$ are vertical eigenfunctions, which are calculated from the climatological stratification averaged from 1951 to 2007 at each horizontal grid point. Additionally, we evaluate the analysis error of each baroclinic component. The analysis error of the hydrographic data at each vertical grid is projected onto the vertical eigenfunctions in a way similar to that in the estimation of the baroclinic components. The error of each baroclinic contribution is evaluated from the sum of the squared projected errors as follows:
The surface dataset analyzed by Ishii et al. (2005) to investigate the dynamical response of sea surface height to changes in the wind stress field. Moreover, an objective analysis of air–sea heat fluxes compiled by the Woods Hole Oceanographic Institution objectively analyzed air–sea fluxes (OAFlux: Yu and Weller 2007) is used to examine the contribution of sea surface heat fluxes to steric sea level changes in the upper ocean.

3. Sea level variability in the North Pacific

Figure 1 shows the time evolution of the first and remaining baroclinic modes estimated from the 5-yr-averaged baroclinic sea level anomalies relative to the average from 1951 to 2007. Sea levels of the two baroclinic modes change on interdecadal time scales. The analysis errors of the first baroclinic mode in the 1960s are quite large since hydrographic observations are very sparse below the depths of the main pycnocline, while those of the remaining baroclinic mode are fairly small during the analysis period of this study. The large number of observations available in the upper ocean is the cause of this. For the first baroclinic mode, negative sea level anomalies are observed in the early 1970s, positive anomalies are observed after the 1990s in the subtropical gyre, and organized anomalies can also be seen along the boundary between the subtropical and subarctic gyres. These fluctuations in the first baroclinic mode are reported by a model study applied with an atmospheric reanalysis (Yasuda and Sakurai 2006). Meanwhile, a PDO-like pattern is seen in the remaining mode at 1970 and 1980 for negative and positive phases of the PDO, respectively (Figs. 1 and 5c). This pattern is similar to the thermosteric sea level change in the upper 500 m, which is highly correlated with the PDO index (Lombard et al. 2005).

Figure 2 shows the lag regression of the first and remaining baroclinic modes on the 5-yr running mean of the PDO index. The hatched areas correspond to statistical significance at the 95% level (the magnitude of correlation coefficient is larger than 0.60) based on a two-tailed t test with 9 degrees of freedom, which is estimated form the number of independent 5-yr intervals (because we discussed the 5-yr-averaged anomalies) in the analysis period (1951–2007) minus 2. The basin-scale wind change related to the PDO induces changes in the wind stress forcing and changes in the air–sea buoyancy flux. Strengthening of wind stress forcing could enhance the subtropical and subarctic gyres related to the first baroclinic mode with about a 4-yr time lag (Fig. 2). Following the spinup of the subtropical gyre, the remaining baroclinic mode shows positive anomalies in the recirculation region south of the KE (Fig. 2). On the other hand, changes in buoyancy flux could induce changes in the water mass density related to the upper-ocean stratification in terms of the remaining baroclinic mode (Fig. 2). In fact, significance levels are less than 95% in the areas with

\[
\text{error}_{im} = \sum_k \left[ \int E_k(z) P_{im}(z) \, dz \right]^2, \tag{3}
\]

where \(E_k\) is a vertical pressure profile induced by a density error at level \(k\).

As a result, the magnitude of the analysis error is different for each baroclinic mode. For example, density error at the depth of the main pycnocline causes a vertical pressure change similar to the vertical eigenfunction of the first baroclinic mode. Therefore, the analysis error should be projected onto the first baroclinic mode rather than the higher baroclinic modes.

The above-mentioned eigenfunctions are purely dynamical solutions. The decomposition of the baroclinic mode in this study is conducted under the assumption that the change in the water mass density is sufficiently small to maintain the ocean main pycnocline relevant to the first mode. In this assumption, the baroclinic response is treated as a perturbation to the background stratification set up by the thermohaline circulation. The basin-averaged phase speed for the first baroclinic gravity waves, which is characterized by the main pycnocline, is acceptably persistent. It varies by only about 1% during the analysis period (not shown). Furthermore, we have confirmed that the major results are independent of the choice of climatology of the vertical eigenfunctions using climatologies made using different decades. That is to say, the assumption is reasonable in the analysis period. Therefore, changes projecting on the first baroclinic mode can be explained as the dynamical response of the main pycnocline. Meanwhile, on the interdecadal time scale, the water mass density in the upper ocean is strongly influenced by surface mixing, convection, subduction of surface masses into the ocean interior, and horizontal advections. In terms of the ventilated thermocline theory with a 2.5-layer model, the cooling and heating are not expected to affect the deep interface (Huang and Pedlosky 1999). As a result, these substantial water mass density changes should be projected onto the second and higher baroclinic modes, and moreover, further dynamical projection onto the climatological baroclinic modes might be meaningless. Therefore, we decompose the baroclinic sea level changes into the first baroclinic mode and a composite of the remaining baroclinic modes (hereafter referred to as the “remaining baroclinic mode”).

To investigate the mechanism of baroclinic sea level variability, we also use meteorological data at the sea surface. We estimated wind stress curl from an ocean surface dataset analyzed by Ishii et al. (2005) to investigate the dynamical response of sea surface height to changes in the wind stress field. Moreover, an objective analysis of air–sea heat fluxes compiled by the Woods
large analysis errors seen in Fig. 1. However, these different mechanisms are shown in the simple 2.5-layer model of Huang and Pedlosky (1999). Furthermore, the remaining baroclinic mode shows negative anomalies in the 1970s and positive anomalies after the mid-1990s in the recirculation region south of the KE, following spindown and spinup of the subtropical gyre (Fig. 1).

To examine the spatial pattern of the baroclinic sea level variability, we calculate the standard deviations of
each baroclinic mode (Fig. 3). The baroclinic mode is defined as a vertical pressure profile and it is an eigenfunction of baroclinic pressure change [Eq. (2)]. The first baroclinic mode is responsible for 78.4% of the total variance of the pressure change in the North Pacific, and that of the remaining baroclinic mode is 21.6%. In Fig. 3, we focus on the pressure change only at the sea surface, which corresponds to the baroclinic sea level change. Accordingly, the sum of variances of the first and remaining baroclinic modes at sea surface does not necessarily explain the total variance of baroclinic sea level change over the North Pacific. Figure 3b shows 49.2% of the total variance and 28.7% in Fig. 3c. These values, however, represent a substantial part of the baroclinic sea level change. Large variability of more than 2.0 cm can be seen along the boundary between the subtropical and subarctic gyres for the first baroclinic mode (green box in Fig. 3b), the variability is more than 1.0 cm in the subtropical gyre (blue box in Fig. 3b). Meanwhile, the remaining baroclinic mode shows large standard deviations south of the KE (blue box in Fig. 3c) and in the downstream region of the KE with peaks around 40°N, 175°E (green box in Fig. 3c). In the next section, we discuss the time series of the first and remaining baroclinic changes around and south of the KE in the vicinity east of Japan, in which their variability is large in amplitude.

4. Baroclinic sea level fluctuations in the subtropical gyre and along the KE

Figure 4 shows the time–latitude sections of the anomalies of the first and remaining baroclinic modes (colors) and absolute baroclinic sea levels (contours) averaged from 140° to 160°E, from 155° to 175°E, and from 170°E to 170°W. The path of the KE jet, which is located at the boundary of the subtropical and subarctic gyres, is related to a peak of the meridional gradient of absolute baroclinic sea level (from 140° to 160°E at 36°N in Fig. 4), and the KE widens around the international date line (from 170°W to 170°E in Fig. 4). Distinctive bidecadal fluctuations are seen around the climatological path of the KE jet in case of the first mode and around the downstream region of the KE in the remaining mode. Additionally, fluctuations on a 40–60-yr time scale appear in the subtropical gyre in both cases. The first baroclinic mode exhibits two distinctive features east of Japan (Figs. 1 and 4a). One is the north–south dipole pattern centered in the subarctic gyre and subtropical gyre. This pattern is related to a spinup and
spindown of the subtropical and subarctic gyres. A basinwide integrated wind stress curl along the first baroclinic Rossby wave characteristic is estimated to compare with the first baroclinic mode as follows:

\[
\text{Ek}_{\text{int}} = \int_{x_0}^{x_e} \text{curl}[\tau(x, t) \cdot (x - x_0)/c] \, dx,
\]

where \(\tau\) is a wind stress, \(x_0\) is the location of the sea level change, \(x_e\) is the eastern boundary of the basin (we set 140°W in this study), and \(c\) is the phase speed of the first baroclinic Rossby wave, which is estimated from the observed propagation speed of the signal. In response to the enhancement of local wind-induced Ekman pumping in the subtropical gyre in the 1970s, the first baroclinic sea level gradually increased south of the KE (blue box in Fig. 3b) from the mid-1970s to the mid-1980s on a 40–60-yr time scale (Fig. 5b), and the correlation coefficient with the basinwide integrated wind stress curl is 0.68, which exceeds the 95% significance level of 0.60 based on a two-tailed \(t\) test with 9 degrees of freedom. Furthermore, the changes in Kuroshio transport anomaly, which is estimated from wind stress curl averaged from 26° to 30°N according to Sverdrup theory, is significantly correlated to the PDO index (the correlation coefficient is 0.62) with a 95% confidence level and well described with this sea level change, resulting in spinup of the North Pacific subtropical gyre (Fig. 5c) correlated with 2-yr-lead PDO index (the correlation coefficient of 0.69). The large correlation coefficients suggest that wind stress change related to the PDO appear to cause the spinup and spindown of the subtropical gyre as shown in Fig. 2. The other distinctive feature in the first mode is related to the meridional shift of the boundary between the subarctic and subtropical gyre. The first baroclinic mode exhibits a bidecadal variation of the KE jet with a meridional shift of the maximum meridional gradient related to the KE (Fig. 4a). The bidecadal signals on the KE (green box in Fig. 3b) vary coherently with the changes in the basinwide integrated wind stress curl along the first baroclinic Rossby wave characteristic with a correlation coefficient of 0.61 with a 95% confidence level (Fig. 5a). These dynamical responses are consistent with the delayed ocean adjustment process due to the first baroclinic Rossby wave propagation (e.g., Qiu 2002; Schneider et al. 2002). Furthermore, the bidecadal signals narrow meridionally and increase, as they propagate westward along the KE (Fig. 4a). These features are consistent with the thin-jet theory (Sasaki and Schneider 2011).

The remaining baroclinic mode exhibits 40–60-yr fluctuations south of the KE (blue box in Fig. 3c) with large amplitude near 30°N and bidecadal fluctuations in the downstream regions of the KE (green box in Fig. 3c) near the international date line (Fig. 4b). The remaining baroclinic mode is related to positive (or negative) sea level change in the recirculation region of the KE after 1990 (or during the 1970s and 1980s). These fluctuations vary coherently with the thermosteric contribution in the upper 300 m (Fig. 5). The changes in the remaining baroclinic mode follow the changes in the first baroclinic mode related to the strength of the subtropical gyre (Figs. 2 and 5b). Their correlation coefficient is 0.70 with a time lag of about 7 years, which exceeds the 95% significant level of 0.67 with 7 degrees of freedom. This result suggests that the changes in heat transport via the Kuroshio related to the first baroclinic mode possibly influences the water mass density of the STMW related to the remaining baroclinic sea level variation in this region. Meanwhile, the signals of the bidecadal fluctuation of the remaining mode tend to expand downstream from the western edge of the KE to the
international date line and the maxima are seen from 170°E to 170°W (Fig. 4b). This fluctuation follows the sea level change of the first baroclinic mode reflecting the meridional shift of the KE with a time lag of about 2 years (Fig. 5a). The correlation coefficient is 0.63 for the period after 1980 and is reasonably large. However, it satisfies an 80% confidence level at most, assuming that the number of degrees of freedom is 4. The changes in the relationship between the first baroclinic mode and the remaining mode after 1980 might be related to the climatic regime shifts (see, e.g., Minobe 1999) during the 1970s. A similar eastward expansion of sea level anomalies appears in a climate model experiment, in which the signal is caused largely by eastward advection (Teng and Branstator 2011). Nonaka et al. (2006, 2008) also found similar eastward-propagating signals in the sea surface height and the sea surface temperature on the boundary between the subtropical and subarctic gyres (subarctic front) in a modeling study. They suggested that the advective effects and the migration of the boundary are likely contributors to the eastward propagation.

5. Conclusions and discussion

We described the distinctive features of the interdecadal baroclinic sea level change in the North Pacific using historical observations from 1951 to 2007. A strong variability of the observed baroclinic sea level changes is seen in the subtropical gyre, extending northeastward from the KE. This variability is separated into the first and remaining baroclinic modes. The observed sea level changes projected onto the first baroclinic mode and the remaining baroclinic mode zonally averaged from 140°E to 160°W, from 155° to 175°E, and from 170°E to 170°W. Areas where the analysis error is larger than half the interannual standard deviations are masked out. Contours indicate absolute baroclinic sea levels. Scale is in centimeters.
FIG. 5. (a) Sea level change represented by the first baroclinic mode (black) on the KE (32°–38°N, 140°–160°E) and basinwide integrated wind stress curl (dark blue) east of the KE along the first baroclinic Rossby wave characteristic. Sea level change represented by the remaining baroclinic mode (red) in the downstream region of the KE (36°–42°N, 170°E–170°W) and its related thermosteric contributions (green) at the upper depth of 300 m.

(b) Sea level change represented by the first baroclinic mode (black) in the recirculation south of the KE (26°–32°N, 140°–160°E) and basinwide integrated wind stress curl (dark blue) east of the recirculation region along the first baroclinic Rossby wave characteristic. Sea level change represented by the remaining baroclinic mode (red) in the recirculation region south of the KE (26°–32°N, 140°–160°E) and its related thermosteric contributions (green) at the upper depth of 300 m. Hatched area indicates the analysis error. Dotted lines indicate the 20-yr low-pass-filtered sea level changes.

(c) Kuroshio transport anomaly estimated from wind stress curl averaged over 26°–30°N according to Sverdrup theory (1 Sv = 10⁶ m³ s⁻¹; black line) and 5-yr running mean of the Pacific decadal oscillation index (red line).
thermosteric contribution in the upper ocean (Fig. 5). The changes of sea surface heat flux, using OAFlux, could not be used to explain the changes in the remaining baroclinic mode (not shown). As a result, it is suggested that the remaining baroclinic sea level variations related to the water mass density change might be influenced by changes in heat transport via the Kuroshio and the KE due to the changes in the ocean circulation represented by the first mode.

The bidecadal and 40–60-yr sea level fluctuations are associated with two different oceanic mechanisms: a meridional shift of the KE and spinup and spindown of the subtropical gyre. The coexistence of these on different time scales in the North Pacific sea level variations is consistent with previous studies [e.g., a wavelet analysis of the Pacific interdecadal variability of sea level pressure; Minobe (1999)]. The interdecadal fluctuations of the first baroclinic modes are explained by a dynamical response to the basin-scale wind stress change, and the following ocean heat transport change can induce the fluctuation of the remaining baroclinic mode.

The present analysis mainly focuses on areas near Japan because of the large variability of the baroclinic sea level fluctuation. In the meantime, there appear a characteristic “horseshoe” pattern of the northeastern Pacific in the remaining baroclinic mode as shown in Fig. 1 (1970–80) and Fig. 2 (lag = 0). This is regarded as the canonical pattern associated with the PDO. Some previous studies (i.e., Lagerloef 1995; Cummins and Lagerloef 2002; Cummins et al. 2005) suggests that this pattern is the local response of the main pycnocline to wind stress-curl forcing over the northeastern Pacific. However, we found that this pattern is represented by the remaining mode and, hence, the processes above the main pycnocline probably account for its variability. While the first baroclinic mode propagates westward as shown in this study, the higher baroclinic modes (i.e., the remaining baroclinic mode) stay there due to an intrinsically slow phase speed. Therefore, the remaining modes could be affected much by the local response to atmospheric forcing over the northeastern Pacific.

The observed hydrographic data do not cover a sufficiently long period to discuss these mechanisms. However, the results presented in this study will hopefully improve understanding of the more detailed processes of basin-scale sea level changes related to atmosphere–ocean coupled systems in the North Pacific.

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