Sea level variability along the Japanese coast forced by the Kuroshio and its extension

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Abstract
Sea level variability along the Japanese coast and its relation to the Kuroshio-Kuroshio Extension (KE) are investigated using ocean reanalysis data. The first mode of an empirical-orthogonal-function for the coastal sea-level represents a simultaneous sea-level change along the whole Japanese coast, which is synchronized with sea levels in the KE region, the Japan Sea and the East China Sea. The second mode is characterized by an east–west dipole pattern at the south coast. The first mode is correlated with the Kuroshio variations around the Izu–Ogasawara Ridge (IOR) and tends to be in a positive phase when the Kuroshio takes a nearshore path around IOR. The Kuroshio’s position around IOR is closely related to the KE dynamic state. When the KE jet is in a stable (unstable) state, a nearshore (meandering) Kuroshio path is formed around IOR. A composite analysis suggests that the sea level along the Japanese coast becomes high due to propagation of coastal trapped waves when the Kuroshio takes a nearshore path around IOR. That is why the first mode is synchronized with the KE decadal variability. The second mode has a close relation with the Kuroshio Large Meander (LM). The eastern positive anomaly at the coast between the Izu and Kii Peninsulas is formed by warm Kuroshio water brought by a westward branch flow along the coast. The western negative anomaly is attributed to a southward shift in the Kuroshio south of the Kii Peninsula associated with the LM.

Keywords Sea level • Kuroshio • Kuroshio Extension • Coastal trapped wave • Large meander

1 Introduction

Global mean sea level (GMSL) has been rising since the beginning of the 20th century (e.g. Church and White 2011; Jevrejeva et al. 2014). According to the sixth assessment report of the Intergovernmental Panel on Climate, GMSL increased by 0.15–0.25 m over the period 1901 to 2018 at an average rate of 1.3–2.2 mm year\(^{-1}\), and the rate in the GMSL rise has accelerated since the 1960s to 3.2–4.2 mm year\(^{-1}\) for the period 2006 to 2018 (IPCC 2021). The main factors contributing to the GMSL rise are ocean thermal expansion and inflow of water mass due to land ice melt and changes in land water storage (Horwath et al. 2022). However, the sea level rise is neither temporally nor spatially uniform because, in addition to the above factors, regional sea level is influenced by other factors such as changes in ocean circulation and atmospheric forcing (Carson et al. 2017; Qiu et al. 2015; Zhang and Church 2012).

Sea level along the Japanese coast exhibits prominent low-frequency variability unlike GMSL as shown in Fig. 1. Multi-decadal variability is dominant before the 1980s, whereas an increasing trend like GMSL superimposed with decadal variations is noticeable since the 1980s. The Japanese coastal sea level variations on decadal and longer timescales and their relation to changes in ocean circulation and atmospheric forcing have been investigated by former studies. Senjyu et al. (1999) carried out an Empirical Orthogonal Function (EOF) analysis using tide gauge data and indicated that the first EOF mode represents simultaneous sea level variations along the Japanese coast on bidecadal timescales. Yasuda and Sakurai (2006) pointed out that the bidecadal sea level variations along the Japanese coast are primarily brought about by meridional shift of the westerlies in the North Pacific and resulting shift in the boundary...
between the subtropical and subpolar gyres. Sasaki et al. (2017) suggested that the high sea level peak around 1950 is explained by weakening of the Aleutian low. The decadal sea level variations in recent decades have been shown to be in phase with the Kuroshio Extension (KE) decadal variability (Sasaki et al. 2014; Diabaté et al. 2021). Specifically, the Japanese coastal sea level increases (decreases) when the KE jet migrates northward (southward).

The Kuroshio path south of Japan, especially its bimodal path variations of the Kuroshio between the straight and large meander (LM) paths, also have a large impact on the sea level at the south coast of Japan (Kawabe 1980, 1989; Zhang and Ichikawa 2005). Sea level difference between Kushimoto and Uragami located to the west and east of the southern tip of the Kii Peninsula is known to be a good indicator of the Kuroshio LM (Kawabe 1995). The EOF analysis by Senjyu et al. (1999) showed that sea level variations associated the bimodal path variations of the Kuroshio are identified as the second mode. Our previous study (Usui et al. 2021) investigated the mechanism of an unusually high sea level event in September 2011 using a high-resolution assimilation model and indicated that sea level rise associated with this event, which was observed in the wide area along the Japanese coast, was caused by propagation of a coastal trapped wave (CTW) induced by a short-term fluctuation of the Kuroshio path south of Japan. In addition, Usui et al. (2021) pointed out that the Kuroshio-induced CTW could be a key process for the sea level variability along the Japanese coast.

To summarize the previous studies cited above, variations of the Kuroshio south of Japan and its extension are closely related to the sea level along the Japanese coast, although its underlying mechanism is still not yet fully understood. In this study, using a long-term high-resolution ocean reanalysis dataset covering the period 1982–2016, we therefore conduct a comprehensive analysis on the relation between the Japanese coastal sea level and the Kuroshio-KE variability for deeper understanding of the sea level variability along the Japanese coast.

This paper is organized as follows. Section 2 provides brief descriptions on the ocean reanalysis data and tide gauge observations used in this study. In Sect. 3 we conduct the EOF analysis of the Japanese coastal sea level using both the reanalysis and tide gauges. The relation between the leading EOF modes and the Kuroshio-KE variability is presented in Sect. 4 and its mechanism is discussed in Sect. 5. The findings from the present study are summarized in Sect. 6.

## 2 Data

Four-dimensional Variational Ocean Re-analysis for the Western North Pacific over 30 years (FORA-WNP30; Usui et al. 2017) is used in this study. FORA-WNP30 is the first-ever ocean reanalysis dataset covering the western North Pacific over three decades at eddy-resolving resolution. In-situ temperature and salinity profiles above 1500 m, gridded sea surface temperature, altimeter-derived sea level anomalies (SLAs), and sea ice concentration were assimilated using the four-dimensional variational (4DVAR) assimilation scheme version of the Meteorological Research Institute Multivariate Ocean Variational Estimation system (MOVE-4DVAR; Usui...
Sea level variability along the Japanese coast forced by the Kuroshio and its extension. The reanalysis period of FORA-WNP30 is from 1982 to 2016. More detailed descriptions and basic performance of FORA-WNP30 are summarized in Usui et al. (2017).

Tide gauge observations are also used to validate coastal sea level variability in FORA-WNP30. Daily mean SLAs are first calculated by averaging hourly SLAs, which are deviations from astronomical tide including seasonal change provided by JMA. Barometric pressure correction is applied to the daily mean SLAs using daily mean sea level pressure derived from JRA-25 (Onogi et al. 2007). Then, monthly mean SLAs are calculated from the daily mean SLAs with barometric pressure correction. SLAs at 34 tide gauge stations from 1993 to 2010 are used and their locations are plotted in Figs. 2 and 3.

3 Sea level variability along the Japanese coast

To investigate the sea level variability along the Japanese coast, we carry out the EOF analysis using both FORA-WNP30 and the tide gauge observations. For the tide gauge observations, EOF modes are calculated using the monthly SLAs from 1993 to 2010 at the 34 stations after removing a linear trend. EOF modes for FORA-WNP30 are also computed in the same manner as for the tide gauge data. Specifically, monthly SLAs for FORA-WNP30 are calculated as monthly mean sea surface height (SSH) anomalies from monthly mean climatologies from 1982 to 2016. Monthly time series of the FORA-WNP30 based SLAs at the tide-gauge locations are then created by a linear interpolation, and the EOF analysis is applied to the linearly interpolated monthly SLAs. For comparison, the EOF modes of FORA-WNP30 are calculated using the monthly SLAs from 1993

![Graph showing EOF analyses](image)

**Fig. 2** (a) PC1 time series for tide gauge observation and FORA-WNP30 shown by black and red lines. Spatial distribution of the first EOF mode for (b) tide gauge observation and (c) FORA-WNP30. Color indicates the amplitude of the EOF mode (unit in cm). Contribution rates of the first mode for tide gauge observation and FORA-WNP30 are 64.0 % and 62.8 %, respectively.
to 2010, the same period as the observations, and cor¬
responding principal components (PCs) are obtained for the
period 1982 to 2016 by projecting the monthly SLAs onto
the EOF modes. We have also conducted the EOF analysis
using FORA-WNP30 with different periods and confirmed
that similar EOF modes are obtained.

Figure 2a shows the time series of the principal compo-
nent (PC) and the horizontal pattern for the first EOF mode.
The first mode explains more than 60 % of the sea level
variability along the Japanese coast. The PC time series
and the horizontal pattern of EOF1 for FORA-WNP30 compares
well with those for tide gauge observation, indicating that
FORA-WNP30 captures the observed sea level variability
well as already shown by Usui et al. (2017). The PC time
series exhibits significant interannual to decadal variability.
It is worth emphasizing that the PC1 time series on decadal
time scale is synchronized with the coastal sea level time
series in Fig. 1. For example, positive phases appear around
1990, 2000, and the early 2010s. In contrast, the anomalies
tend to be negative in the mid-1980s, -1990s, -2000s, and
-2010s.

The first EOF mode has the same sign at the all tide
gauge stations (Figs. 2b and 2c), indicating that the first
mode represents a simultaneous sea level change along the
whole Japanese coast. The amplitude of EOF1 is large along
the south coast of Japan between the Boso Peninsula and
Kyushu, and is relatively small along the east coast of Japan
and the Hokkaido coast.

The second EOF mode shown in Fig. 3 explains around
17–19 % of the sea level variability along the Japanese coast.
FORA-WNP30 well reproduces the features of the second
mode sea level variability for the tide gauge observation
as well as the first EOF mode. One important feature of
the second EOF mode is that the PC time series becomes
high when the Kuroshio takes a LM path (see the periods
shown by gray shading in Fig. 3a), implying that the second
mode is closely related to variations of the Kuroshio path
south of Japan. The horizontal map of the EOF2 exhibits an
east–west dipole pattern, and its signals are confined at the
south coast of Japan. The boundary between the positive and
negative anomalies associated with the dipole EOF pattern
is located around the Kii Peninsula. It should be noted that

Fig. 3 Same as Fig. 2 but for the second mode. Gray shades in (a) indicate past LM periods
PC2 is high during some periods such as 2000, 2008 and 2013 even though the Kuroshio is in a non-LM state. We confirmed that the Kuroshio took a meandering path and the east–west dipole pattern was formed at the south coast of Japan during such periods although the criteria for the Kuroshio large meander (Yoshida et al. 2006) was not satisfied (not shown).

The features of the leading two modes described above are consistent with the result of Senjyu et al. (1999). The relationship between the leading EOF modes and circulation variability such as the Kuroshio and its extension will be further investigated in the next section.

4 Relationship between the Japanese coastal sea level and the Kuroshio-Kuroshio Extension variability

In the previous section, we identified the leading EOF modes of the sea level along the Japanese coast. To look into the relation between the leading EOF modes and large-scale circulation variability, SSH maps regressed to PC1 and PC2 are shown in Fig. 4.

The SSH map regressed to PC1 has large positive anomalies along the KE jet, and relatively uniform positive anomalies are distributed in the Japan Sea and over the continental shelf in the East China Sea. This means that the first EOF mode is synchronized with sea levels in the KE and marginal seas such as the Japan Sea and the East China Sea. The large positive SSH anomalies in the upstream KE region connect to the south coast of Japan, where EOF1 has large amplitude as mentioned in the previous section. In contrast, SSH anomalies associated with the second EOF mode shown in Fig. 4b are confined around the region south of Japan. The anomalies exhibit a tripolar structure. Positive anomalies are located to the south of Shikoku and at the upstream KE region, and negative anomalies distribute between the two positive ones. The positive anomaly in the upstream KE region connect to the eastern part of the coast south of Japan and the negative one extends to the coast west of Kii Peninsula, forming the east–west dipole pattern along the south coast of Japan associated with the second mode of the coastal sea level.

To examine more in detail the relation of the leading EOF modes with the Kuroshio path variations, we take correlation between the PC time series of the leading two modes and latitudinal variation in the Kuroshio axis defined as the position where the current velocity at 100 m is the strongest. We set meridional lines every 0.1 degree from 134.25°E to 141.85°E, and the correlation is calculated at each line. The calculated correlation coefficients are shown in Fig. 5b. It should be noted that negative PC2 is used in the calculation for the second mode to obtain positive correlations.

The PC1 time series has relatively high correlation with the Kuroshio path variation around the Izu–Ogasawara Ridge (IOR), and the correlation has a maximum value of 0.39 (statistically significant at a confidence level of 99%) at 140.55°E, where the Kuroshio axis is located to the south of the Boso Peninsula (Fig. 5a). This relation means that when the Kuroshio takes a nearshore path around the IOR (the axis migrates northward) PC1 tends to be positive and coastal sea level not only at the south coast of Japan but also at the whole Japanese coast becomes high. The correlation calculated after applying a 13-month
running mean filter still has a peak around the IOR, which exceed 0.6, suggesting that the latitudinal variations of the Kuroshio path around the IOR is responsible for the first mode sea level variations on both monthly and interannual time scales.

In contrast to the first mode, the second model is well correlated with the Kuroshio path variations from the Kii Peninsula to the southwest off the Izu Peninsula (Fig. 5). The correlations exceed 0.6 and 0.8 for the monthly time series (blue thick solid line) and the 13-month running mean filtered time series (blue thin solid line), respectively. The correlation around the IOR is, on the other hand, relatively low. The result of the correlation analysis suggests that when the Kuroshio takes a meandering path between the Kii Peninsula and the Izu Peninsula PC2 tends to be positive and the east–west dipole sea level anomaly appears along the south coast of Japan.

In the next section, we will discuss underlying mechanism responsible for the relation between the leading EOF modes of the coastal sea level and the Kuroshio-KE variability.

5 Discussion

5.1 EOF1 and Kuroshio Extension

The correlation analysis in the previous section indicated that the first EOF mode representing the simultaneous sea level change along the whole Japanese coast is closely related to the Kuroshio path variation around the IOR. To confirm this relation more clearly, PC1 and the latitude of the Kuroshio axis at 140.55°E are compared in Fig. 6a. Note that the 13-month running mean filter is applied to the time series of both PC1 and the latitude of the Kuroshio axis at 140.55°E.

Here a question arises how the meridional movement of the Kuroshio axis around the IOR causes the sea level variations not only at the south coast of Japan but also throughout the Japanese coast. Our previous study on an unusually high sea level event in September 2011 (Usui et al. 2021) gives a hint to answer this question. Usui et al. (2021) suggested that sea level rise associated with this event, which was observed...
Sea level variability along the Japanese coast forced by the Kuroshio and its extension in the wide area including the south coast of Japan and the coast of the Japan Sea, was brought about by propagation of a CTW caused by a short-term fluctuation of the Kuroshio path around the IOR. The first mode sea level variability along the Japanese coast would also be explained by the same mechanism.

Figure 7 shows composite maps of SSH and its anomalies for positive (PC1>1.5) and negative (PC1<-1.5) phases of

![Figure 6](image-url)

(a) Time series of PC1 (black line) and the latitudinal position of the Kuroshio axis at 140.55°E (red line). Note that the 13-month running mean filter is applied to the time series of both PC1 and the latitude of the Kuroshio axis.

(b) Time series of the latitudinal position of the Kuroshio axis at 140.55°E (red lines) and SSH anomaly (unit in cm) averaged over the KE region 31–36°N and 140–165°E (blue line). Thin red line in (b) is the same as the red line in (a), and thick red line is obtained by applying the running mean filter with 3-year time window.

![Figure 7](image-url)

Composite SSH anomalies for (a) PC1>1.5 and (b) PC1<-1.5. Black contour lines indicate mean SSH field with an interval of 10 cm, and green thick solid lines are the SSH contour line of 20 cm, which is regarded as a proxy of the mean Kuroshio axis. (c) Meridional distributions of zonally averaged SSH between 142°E and 152°E for (red line) PC1>1.5 and (blue line) PC1<-1.5.
the first mode. For the positive phase, positive SSH anomalies are pronounced in the KE region, the Japan Sea and the East China Sea like Fig. 4a. It is worth emphasizing that the positive anomalies are enhanced along the south coast of Japan, the west cost of Kyushu and the coast of the Japan Sea. Furthermore, the enhanced positive anomalies connect to those in the KE region through the coast around the Izu and Boso Peninsulas. These features strongly suggest that propagation of CTWs generated around the Izu and Boso Peninsulas play an important role in formation of the enhanced sea level anomalies along the Japanese coast associated with the first mode. The uniform positive SSH anomalies in the Japan Sea and the East China Sea seen in Fig. 4a could also be understood as the barotropic adjustment in response to the propagation of CTWs along the Japanese coast as suggested by Kida et al. (2016). Furthermore, taking a close look at the SSH map regressed to PC1 in Fig. 4a, there is a sea level difference between Kyushu and the Korean Peninsula (not shown), indicating a possibility that volume and heat transports of the Tsushima Warm Current change in association with the first mode variability of the Japanese coastal sea level as suggested by Kida et al. (2021). This should be addressed in future studies.

As expected from the correlation analysis in the previous section, the Kuroshio axis around the IOR in the positive phase is obviously located further north than that in the negative phase (see green lines around 140°E in Figs. 7a and 7b). Therefore, it is possible that CTW tends to be induced by the Kuroshio and propagate along the Japanese coast when the Kuroshio takes a nearshore path around the IOR. In fact, the Kuroshio axis was located near the coast around the IOR and PC1 was very high (1.90) in September 2011 when the Kuroshio-induced CTW caused the unusually high sea level (Usui et al. 2021).

The latitudinal position of the Kuroshio axis above the IOR is known to be closely related to the KE decadal variability (Qiu and Chen 2010; Sugimoto and Hanawa 2012; Usui et al. 2013). Actually, as shown in Fig. 6b low-frequency variability in the latitude of the Kuroshio axis at 140.55°E is well correlated with SSH anomaly averaged over the KE region (31–36°N, 140–165°E) on decadal time scale, which is a good indicator of the KE dynamic state and hence is called the KE index (Qiu et al. 2014). When the KE index is positive (negative) typically in 1990, 2002, and 2011 (1984, 1996, and 2006), the upstream KE path becomes stable (unstable) accompanied by positive (negative) SSH anomalies (Fig. 8).

It is also well known that the positive (negative) anomalies in the KE region, which are originally formed in the central North Pacific associated with wind-stress curl anomalies and propagate westward as the baroclinic Rossby waves, intensify (weaken) the KE jet and its southern recirculation gyre, while the KE jet migrates northward (southward) (Nakano and Ishikawa 2010; Qiu and Chen 2010). These features of the stable and unstable KE states can be found in the composite maps of SSH for positive and negative PC1 in Fig. 7. In the positive (negative) phase of PC1, positive (negative) SSH anomalies are found in the KE region, and the meridional SSH gradient across the KE increases (decreases) as shown in Fig. 7c, indicating the intensification (decline) of the KE jet and its recirculation gyre. Furthermore, the latitudinal position of the KE jet is more northerly compared to that in the negative phase (Fig. 7c).

### 5.2 EOF2 and Kuroshio path south of Japan

As shown in the previous sections, the second mode characterized by the east–west dipole sea level anomaly along the south coast of Japan is well correlated with the Kuroshio path variations from the Kii Peninsula to the southwest off the Izu Peninsula, and the PC2 time series becomes high when the Kuroshio takes a LM path. We, therefore, discuss the relation between the second EOF mode and the Kuroshio path south of Japan.

Figure 9 shows composite SSH maps for positive (PC2>1.5) and negative (PC2<-1.5) phases of the second mode. There is a clear difference in the type of the Kuroshio path south of Japan between the positive and negative phases of PC2. In the positive phase of PC2, The Kuroshio takes a LM path. In contrast, a straight Kuroshio path flowing along the south coast of Japan is formed in the negative phase. In association with the Kuroshio path type, significant SSH anomalies are formed off the southern coast of Japan. A tripolar structure of the SSH anomalies to the south of Japan in the positive phase, that are positive anomalies to the south of Shikoku and in the KE region and negative ones in the LM region, is consistent with the regression map in Fig. 4b. The positive anomalies to the south of Shikoku are attributed to a well-developed anticyclonic eddy and southwestward shift in the eddy’s position. The anticyclonic eddy is known to be strengthened during the formation of the LM (Tsujino et al. 2006; Usui et al. 2008). The negative SSH anomalies to the southeast of the Kii Peninsula correspond to a cyclonic eddy associated with the LM. When the LM is formed, the Kuroshio path around the IOR migrates northward to pass through a deep channel located around 34°N and 140°E (see Fig. 5) (Usui et al. 2013), forming the positive anomalies to the east of the LM. In the negative phase of PC2, the Kuroshio takes a straight path, leading to positive anomalies to the south of the Kuroshio axis except off the southeast of Kyushu. The anticyclonic eddy to the south of Shikoku shifts eastward compared to that in the positive phase, forming negative anomalies southeast of Kyushu.

One important feature in coastal waters south of Japan during a Kuroshio LM is significant warming due to warm Kuroshio water (Sugimoto et al. 2020). This significant
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Warming can be seen from southeast off the Kii Peninsula to the Boso Peninsula in Fig. 10a showing composite maps of temperature and horizontal velocity at 100 m for the positive phase of PC2 (PC2>1.5). When a Kuroshio LM occurs, a norward flow in the eastern flank of the meander brings warm Kuroshio water toward the coast. The northward flow then turns to the east off the Izu Peninsula, but a westward branch flow also appears along the coast between the Izu and Kii Peninsulas (Fig. 10a). The westward branch flow brings warm Kuroshio water, resulting in not only the significant warming there but also the positive SSH anomalies associated with the positive phase of PC2 (Figs 4b and 9a). In the negative phase of PC2, the Kuroshio water is rarely supplied to the eastern part of the south coast of Japan because of a straight Kuroshio path and consequently negative anomalies in temperature and coastal sea level are formed (Figs 9b and 10b).

Another feature in coastal waters associated with a LM is the negative sea level anomalies in the western part of the south coast of Japan, which is one component of the east–west dipole pattern associated with the second mode of the coastal sea level. The negative anomalies in coastal sea level connect to the negative anomalies off the southeast of the Kii Peninsula associated with the cyclonic eddy of the LM (Fig. 9a). Thus, the coastal sea level anomalies could be understood as a dynamical response to the changes in the Kuroshio position associated with the Kuroshio LM. In fact, Usui et al. (2021) indicated that the coastal sea level in the Seto Inland Sea located between the Japanese main islands of Honshu, Shikoku and Kyushu is sensitive to Kuroshio path variations to the south of the Kii Peninsula. According to Usui et al. (2021), the sea level in the Seto Inland Sea increases (decreases) when the Kuroshio off the south of the Kii Peninsula migrates north (south). There is a clear

Fig. 8 Yearly KE paths and SSH anomaly in typical (a) stable and (b) unstable years. Black solid lines denote monthly mean KE paths defined by 20-cm SSH contours. Shades indicate annual mean SSH anomalies (unit in cm)
difference in the latitudinal position of the Kuroshio axis between the positive and negative phases of PC2 (see green lines in Fig. 9). The Kuroshio path for the positive phase of PC2 is located to the offshore while the Kuroshio for the negative phase takes a nearshore path (Figs. 9 and 10). This interpretation is also consistent with the result of the correlation analysis in Fig. 5b that the latitudinal position of the Kuroshio axis to the south of the Kii Peninsula (longitude is around 136°E) has a high negative correlation with PC2.

We finally discuss the reason why the coastal sea level anomalies associated with the second EOF mode is localized at the south coast of Japan in contrast to those of the first mode distributed widely along the Japanese coast. As discussed in Sect. 5.1, we suggested that the first EOF mode representing the simultaneous sea level change along the whole Japanese coast is brought about by propagation of CTWs excited by the Kuroshio path variations around the IOR. Thus, we discuss possible reasons for the localized sea level anomalies associated with the second mode in terms of CTW propagation.
One possible reason would be that Kuroshio-induced CTWs are less likely to occur during a LM. If we assume that Kuroshio-induced CTWs tend to be caused by short-term fluctuations of the Kuroshio path as shown by Usui et al. (2021), the above inference is supported by Wang and Tang (2022), who showed that Eddy Kinetic Energy (EKE) south of Japan was low during the Kuroshio LM in 2004–2005. It should, however, be noted that the Kuroshio-induced CTW shown by Usui et al. (2021) is only one case and it is therefore still unclear under what conditions the Kuroshio tends to induce CTWs. For the negative phase of PC2 when the Kuroshio takes a non-LM path, on the other hand, the positive sea level anomalies in the western part of the south coast Japan extend to the west coast of Kyushu, implying propagation of CTWs induced around the Kii Peninsula, where the Kuroshio is located near the coast during the negative phase of PC2. The positive anomalies along the coast are, however, much smaller than those associated with the first mode. This might be because EKE associated with Kuroshio path variations to the south of the Kii Peninsula is smaller than that around the IOR (Wang and Tang 2022), where the Kuroshio-induced CTWs are likely to occur during the positive phase of the first mode as described in Sect. 5.1. Furthermore, even if CTWs are induced, sea level anomalies along the coast except for the south coast of Japan will be canceled out because of the positive and negative dipole anomalies associated with the second mode. This is another possible reason for the localized sea level anomaly of the second mode.

6 Summary

The sea level variability along the Japanese coast and its relation to the Kuroshio and its extension are investigated using the FORA-WNP30 ocean reanalysis data. We focus on the leading two modes obtained from an EOF analysis of the coastal sea level. The first mode explains more than 60% of the sea level variability along the Japanese coast, and represents a simultaneous sea level change along the whole Japanese coast, which is synchronized with sea levels in the KE and marginal seas such as the Japan Sea and the East China Sea. The second mode explaining about 19% of the total variance is characterized by an east–west dipole pattern at the south coast of Japan accompanied by eastern positive and western negative sea level anomalies. The first mode is correlated with the Kuroshio path variations around the IOR and it tends to be in a positive phase when the Kuroshio takes a nearshore path around the ridge. In contrast, the second mode has a good correspondence with latitudinal variations in the Kuroshio path from the Kii Peninsula to the southwest off the Izu Peninsula. When the Kuroshio migrates southward there to form a meandering path, the second mode becomes a positive phase.

We further investigate the relation between the leading modes of the Japanese coastal sea level and the Kuroshio-KE
variability, which is summarized in Fig. 11. The latitudinal position of the Kuroshio path around the IOR, which has a large impact on the first mode sea level variability along the Japanese coast, is closely related to the KE dynamic state on decadal time scale. When the KE jet is in a stable (unstable) state, the Kuroshio around the IOR migrates northward (southward) to form a nearshore (meandering) path. A composite analysis suggests that the coastal sea level not only at the south coast of Japan but also at the whole Japanese coast becomes high due to propagation of CTWs when the Kuroshio takes a nearshore path around the IOR. That is why the first mode of the Japanese coastal sea level is well synchronized with the KE decadal variability.

The second mode characterized by the east–west dipole structure at the south coast of Japan has a close relation with the Kuroshio LM. The eastern positive sea level anomaly at the coast between the Izu and Kii Peninsulas is formed by warm Kuroshio water brought by a northward flow in the eastern flank of the LM and a westward branch flow along the coast. The sea level along the coast to the west of the Kii Peninsula is sensitive to the meridional position of the Kuroshio path to the south of the Kii Peninsula. Thus, a southward shift in the Kuroshio path to the south of the Kii Peninsula, which is one of the features during the Kuroshio LM, leads to the western negative sea level anomaly associated with the second mode. In this way, the east–west dipole sea level anomaly at the south coast of Japan is formed in association with the second mode.

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