The Kuroshio Extension: A Leading Mechanism for the Seasonal Sea-level Variability along the West Coast of Japan

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Abstract

Sea level changes coherently along the two coasts of Japan on the seasonal time scale. AVISO satellite altimetry data and OFES (OGCM for the Earth Simulator) results indicate that the variation propagates clockwise from Japan's east coast through the Tsushima Strait into the Japan/East Sea (JES) and then northward along the west coast. In this study, we hypothesize and test numerically that the sea level variability along the west coast of Japan is remotely forced by the Kuroshio Extension (KE) off the east coast. Topographic Rossby waves and boundary Kelvin waves facilitate the connection. Our 3-d POM model when forced by observed wind stress reproduces well the seasonal changes in the vicinity of JES. Two additional experiments were conducted to examine the relative roles of remote forcing and local forcing. The sea level variability inside the JES was dramatically reduced when the Tsushima Strait is blocked in one experiment. The removal of the local forcing, in another experiment, has little effect on the JES variability. Both experiments support our hypothesis that the open-ocean forcing, possibly through the KE variability, is the leading forcing mechanism for sea level change along the west coast of Japan.

1. Introduction

The Kuroshio and Oyashio Currents are two major western boundary currents (WBCs) in the North Pacific Ocean. Flowing toward each other along the continental slope off the Asian Marginal Seas, there is a mixed water region between the two off the coast of Honshu – the largest Japanese Island. The merged currents transport the WBCs water offshore and form the Kuroshio Extension (KE) (Talley et al., 1995; Qiu, 2003). The KE, like its counterpart the Gulf Stream Extension (GSE) in the North Atlantic Ocean, is a meandering current (Kawabe, 1995; Mitsudera et al., 2001, among others) with high eddy variability as observed by satellite altimeters (e.g., Qiu, 2000; Qiu and Chen, 2005). From the perspective of ocean dynamics, it is expected that the sea surface height (SSH) along the east coast of Honshu would be influenced directly by the KE variability because mesoscale eddies transport energy westward. Where does the KE-induced coastal variability propagate and how does it force remote regions, however, have been less examined. In this study, we will investigate the KE forcing of the seasonal SSH variability along the west coast of Honshu inside the Japan/East Sea (JES).

The JES is a deep semi-enclosed sea which is bounded by the Asian continent to the west and the Japanese Islands to the east. The Tsushima Warm Current (TSWC), which is generally considered as a branch of the Kuroshio, especially in winter, flows into the JES through the Tsushima Strait from the East China Sea. The water flows out of the JES into the Pacific Ocean through the Tsugaru Strait and into the Sea of Okhotsk through the Soya and Tartar Straits. The Tartar Strait is very narrow and shallow, and seasonally frozen. So the Tsushima, Tsugaru and Soya Straits are the main passages for the JES inflow and outflow.

As for variability inside the JES, most of the previous studies focused on local forcing (Seung and Yoon, 1995; Teague et al., 2005) and on the transport of the TSWC (Isobe et al., 1994; Teague et al., 2002; Takikawa et al., 2005). In addition, variability in the Pacific Ocean would inevitably affect the TSWC and the JES (e.g., Lyu and Kim, 2003). SSH interannual variability within the JES is in phase with the Pacific Decadal Oscillation via the Kuroshio (Gordon and Giulivi, 2004). The TSWC is forced by the Subtropical and Subpolar Gyres in the North Pacific Ocean (Yang et al., 2006).

In this study, we will demonstrate that the seasonal variability along the west coast of Honshu is remotely forced by the KE variability and topographic Rossby waves, and boundary-trapped Kelvin waves may be responsible for this connection. The time evolution of the SSH along the Honshu coast from satellite altimetry data (AVISO, 2008) indicate that the signal of anomalous SSH appeared coherently along the coast from the KE area into the JES (Figure 1a). To show the linkage we chose a grid between 148°-150°E, 34°-36°N, which located in the KE region, and two tidal stations-Kushimoto and Hamada, which are located in the east and west coast of Honshu respectively and marked in Figure 1a. The SSH variability averaged from AVISO data in the grid and measured at these two stations varied coherently from intra-seasonal to interannual time scales (Figure 2), indicating that the variability at KE region and these two stations may indeed be related to each other. The correlation coefficient of the two stations is 0.722 and above the 99% confidence level. But there is not significant phase lag, which may attribute to the rapid signal propagation and 1-month data interval.

In this study, we will analyze AVISO altimetry data and OFES (OGCM for the Earth Simulator) results, and use a three-dimensional model to examine whether the KE variability remotely forces the seasonal SSH variability along the west cost of Honshu. The paper is organized as follows: the data and model results will be presented in section 2, and discussed and summarized in section 3.

2. Data analyses and model simulations

Satellite altimetry has played an increasingly important role in observing variability of the global sea level, and the altimeter data have been widely utilized in examining the spatial scales, generation mechanisms, propagation and kinetic energy distributions of various oceanic modes of variability (e.g., Ichikawa and Imawaki, 1994; Fu and Chelton, 2001; Fu and Qiu, 2002). The newly merged product of altimeter data (AVISO, 2008) provides observations of SSH variations since October 1992, with a relatively high spatial resolution (1/4° by 1/4°) at short time intervals (7 days). In this study, we are primarily interested in the seasonal variability and so we have compiled a monthly climatology based on the 7-day AVISO data. Figure 1a shows the SSH deviation in September. The sea level in the whole eastern JES and particularly along the west coast of the Japanese Islands, from Kyushu to Hokkaido, is seasonally higher than the annual mean (which is removed in Figure 1a). The high SSH apparently extends to the southeastern coast of Japan. Interestingly, there are two large anti-cyclones with high SSH to the east of Japan, one in the KE region at 146°E, 35°N and the other off Kyushu Island at 135°E, 30°N.

The OFES model, described in detail by Masumoto et al. (2004), is based on the MOM3 with a horizontal grid spacing of 1/10°. It was run starting from the World Ocean Atlas 1998 annual mean for more than 50 model years, forced by monthly mean wind stresses averaged from 1950 to 1999 from the

NCEP/NCAR reanalysis data (Sasaki et al., 2004; 2007). The high resolution and realistic coastline of OFES data could improve the understanding of the SSH variability around the Japanese Islands. The fifteen years (1990-2004) output of 3-day snapshots of the SSH are used in this study, which is comparable with the time span of altimetry data. We also removed annual mean and compiled a monthly climatology based on the OFES data. Figure 1b shows the SSH deviation in September as well. And the result is consistent with that from altimeter data: there is high sea level all the way from the southeastern coast to the western coast of Japan through the Tsushima Strait.

To examine whether the high SSH along the two coasts of Japan are related to each other, we drew a temporal-spatial section of sea level anomaly along PV contour near the coast of Japanese Islands as marked from A to E in Figure 3a. There is a distinct seasonal change of the SSH around the Honshu and Kyushu Islands (Figure 3b is from AVISO altimetry data, Figure 3c is from OFES results). The change appears to be coherent along the entire coastline. The sea level is high in the late summer and early fall around September and October, and low in the late winter in March. There is a clear indication from these two figures that seasonal SSH anomaly propagates clockwise starting from A, though B and C along the southern coast of Honshu Island, then pass D to E along the west coast of Honshu Island. The phase lags between sea level variations at station pairs of A and B, B and C, and C and D are nearly 1 week, and the correlation coefficient passed 95% confidence level. The time scale of the propagation around one path shown in Figure 3a is roughly one month and the speed is about 1.5 m/s.

We estimated theoretical coastal Kelvin wave and topographic Rossby wave speed. Here, we used the long Rossby wave approximation in calculation of the phase speed (Pedlosky, 1979),

$$c_K = \sqrt{g'h}$$

$$c_R = -(\beta + \frac{f}{h}s)R_d^{\ 2}$$

where g' is the reduced gravity, h is the water depth, s is the bottom slope, R_d is Rossby deformation radius. In application to Japan Islands, $\beta = 1.9\times10^{-11}m^{-1}s^{-1}$, $f = 8.3\times10^{-5}s^{-1}$ (the latitude is 35°N), $g' = g\times1e^{-3}$, $h\approx1000m$, $s\approx0.1$. Thus, the theoretical Kelvin wave speed is about 3.1 m/s, while the theoretical topographic Rossby wave speed is about 1.2 m/s, which is more comparable with the satellite observation.

In order to examine the mechanism of seasonal variability along Japan's coast, a 3-D full forcing model was used. The model is the latest version of the Princeton Ocean Model (POM). The simulation domain is 100°-150°E, 0°-50°N with a resolution of 1/6° by 1/6° horizontally, and 16 sigma levels vertically. The bathymetry used in the model is interpolated from ETOPO5 5-minute gridded elevation data (NOAA, 1988). The model is initialized with temperature and salinity fields for January from the National Oceanographic Data Center (Levitus et al., 1994; Levitus and Boyer, 1994), and is forced by monthly mean climatologic atmospheric fields. The wind stress is from the National Center for Environmental Prediction (NCEP, Kistler et al., 2001). Along the boundaries, we specify model variables from the results of a global model (Qiao et al., 2004).

In the standard run, the model was integrated for 10 years until it reached a statistically steady seasonal cycle. The spin-up time scale for a baroclinic ocean with the size of the Pacific is much longer than 10 years, especially in higher latitudes within the model domain. The relatively short spin-up time in our model integration is due to the use of a small model domain. The boundary condition prescribed from a coarse-resolution global model already contains the spin-up information in the vast interior ocean. The main features of the circulations in the region are well simulated and consistent with observation-based description (Su, 2001). In this study, we will concentrate on the seasonal variability along the coast of Japan. The SSH deviation from the annual mean in the month of September is shown in Figure 4a. There are noticeable differences in the details between the model simulation (Figure 4a) and the altimetry data (Figure 1a) or the OFES results (Figure 1b). For instance, the anti-cyclone off Kyushu's coast is weaker in the model. But there is broad similarity between the model and data. The high SSH along Japan's coast is well simulated. The SSH anomaly pattern off the east coast of Japan is comparable with the data. We calculated the temporal-spatial evolution of SSH around Honshu and Kyushu from the model output (Figure 3d). The pattern is similar to that from the altimetry data (Figure 3b) and OFES results (Figure 3c) except that the seasonal cycle is slightly ahead in the model than in the data. Overall, the results from the standard run are reasonably consistent with satellite observations. This gives us some confidence to use the model to examine mechanisms. Two additional experiments are designed here: (1) block the Tsushima Strait; (2) remove the local forcing of wind stress. The results will be compared with the standard run.

In the first sensitivity experiment, the Tsushima Strait is blocked and everything else remains unchanged from the standard run. The sea level anomaly of September is shown in Figure 4b. The most noticeable difference from the data (Figure 1) or our standard run (Figure 4a) is the absence of the high SSH along the west coast of Japan inside the JES. It should be noted here that the JES is still connected to the other basins through the Tsugaru and Soya Straits even though the Tsushima Strait is blocked in this run. Both boundary Kelvin waves and topographic Rossby waves propagate clockwise around the Honshu and Kyushu Islands (a topographic Rossby wave in the northern hemisphere propagates along constant potential vorticity (PV) contours with a high PV or shallower bathymetry to its right hand side). So the variability originated along the east coast of Japan does not propagate directly into the JES through the Tsugaru Strait.

Another interesting feature in Figure 4b is that the high SSH along the west coast of Korea is heightened when the Tsushima Strait is blocked (compared Figure 4b and Figure 4a). When the Tsushima Strait is blocked, Kelvin and topographic Rossby waves cannot enter the JES and so they travel along the boundary into the Yellow Sea. This change further supports our hypothesis that wave propagation is responsible for the SSH changes along the west coast of Japan.

Next, we will examine the role of the local wind stress forcing. We remove the forcing within our model domain. The model is forced entirely by specifying the open-boundary conditions from a global run (Qiao et al., 2004). This represents the open-ocean forcing since the information from the vast interior is passed into the smaller domain through the open boundaries. The Kuroshio and Oyashio Currents, including the KE, remains robust since they are forced by the wind-stress curl in the vast interior ocean. The SSH anomaly in September (and all other months) is very similar to that from the standard run (Figure 4c vs. Figure 4a). This experiment demonstrates that the seasonal SSH variability along the west coast of Japan inside the JES is forced primarily by the open-ocean process instead of the local wind stress.

3. Discussion and Summary

Altimetry data and OFES results show that the SSH along the east and west coasts of Japan varies coherently with seasons, and indicate that the signal of such seasonal variability propagates clockwise from the southeastern coast of Honshu Island. This pattern was simulated well by a three-dimensional ocean model. In this study, we hypothesize and test that the seasonal SSH variability along the west coast of Japan inside the JES is forced remotely by the SSH changes along the east coast. The remote forcing is through topographic Rossby and/or boundary Kelvin waves, but much more prefer to the former according to the comparison between observed and theoretical values.

The open ocean responds to atmospheric forcing or adjusts to the internal oceanic interactions through the propagation of Rossby waves, eddies and meanders. These transient features typically move westward and would eventually feel the changing bathymetry as they approach the continental slope and shelf. In the absence of strong external forcing, they tend to move along the PV contours as topographic Rossby waves. In the northern hemisphere, they move in the direction with shallower bathymetry (higher PV) on their right hand side. In our application to the JES, topographic Rossby waves propagate clockwise around the Honshu and Kyushu Islands. Ageostrophic processes, such as friction, nonlinearity and external forcing, may force the flow to across the PV contours toward the land-sea boundary. So boundary Kelvin waves may also play a role in the remote forcing of SSH in JES.

Both the observation and models show mighty SSH variability in the KE region. So it may act as the energy source of remote forcing mentioned above. The KE has been considered to be an eastward inertial jet (Kawai, 1972; Yasuda et al., 1992) which is accompanied by large meanders and energetic eddies. Due to its abundance of mesoscale eddy variability, the KE region is one of the regions with the highest eddy kinetic energy (Wyrtki et al., 1976). So the KE variability, as we hypothesize in this study, may be the leading mechanism for the seasonal SSH variability along the west coast of Japan inside the JES.

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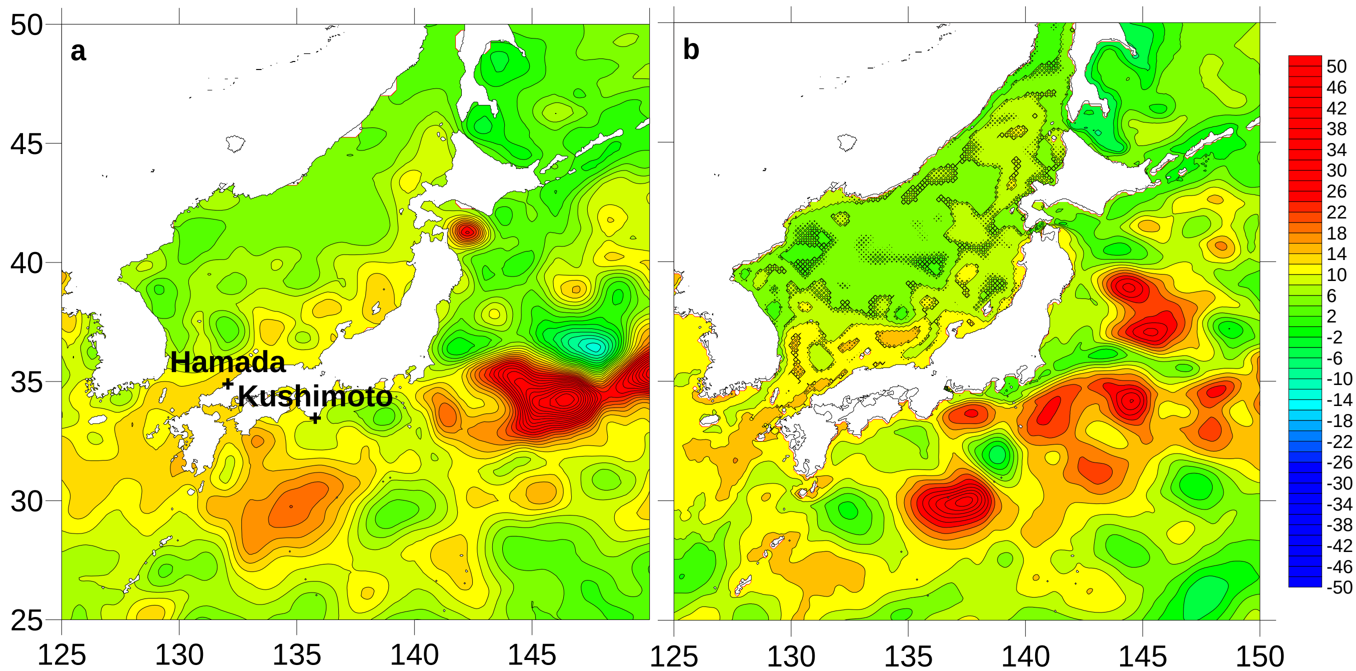

Figure 1: The September deviation of SSH from the annual mean (the contour interval is 2 cm). The left panel is from AVISO MSLA data and the right is from OFES results. The SSH along the entire west coast of Japan inside the JES is seasonally high and appears to be related to the positive anomaly along the southeast coast of Japan. This correlation of the SSH variability on two Japanese coasts is strong for the whole annual cycle as to be discussed later. Sea level data from two tidal stations at Hamada and Kushimoto, as marked in the Figure, will be used in the following analyses.

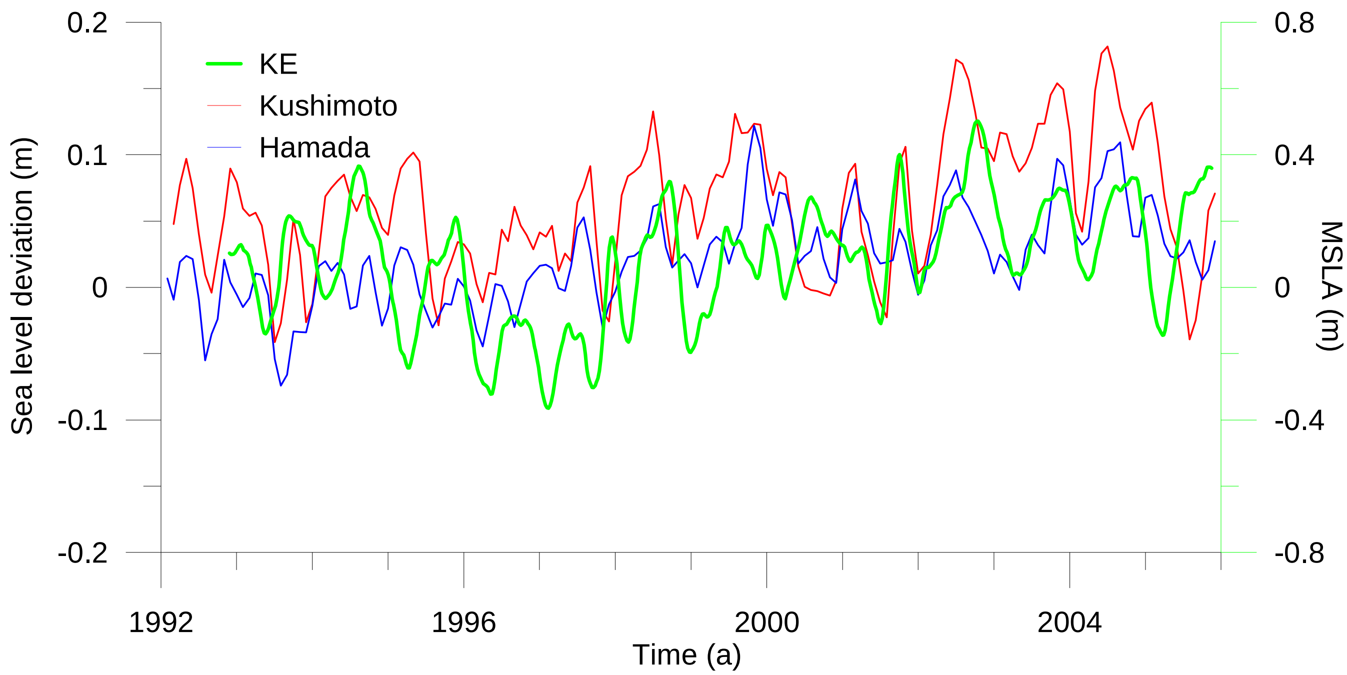

Figure 2: Monthly SSH anomaly averaged from AVISO data in the KE region (148°-150°E, 34°-36°N) and SSH deviation from the 15-year (1992-2006) mean measured at two tidal stations, marked in Figure 1a. The left axis is for SSH deviation at the two tidal stations and the right is for SSH averaged over KE region. A 6-month running mean is used to remove high-frequency variations. Both stations showed upward trends. They were associated with global sea-level rise and beyond the scope of this study. We are interested in the seasonal and interannual changes which were coherent at KE region and these two stations. It indicates that the sea-level variability along the two coasts of Japan is likely related.

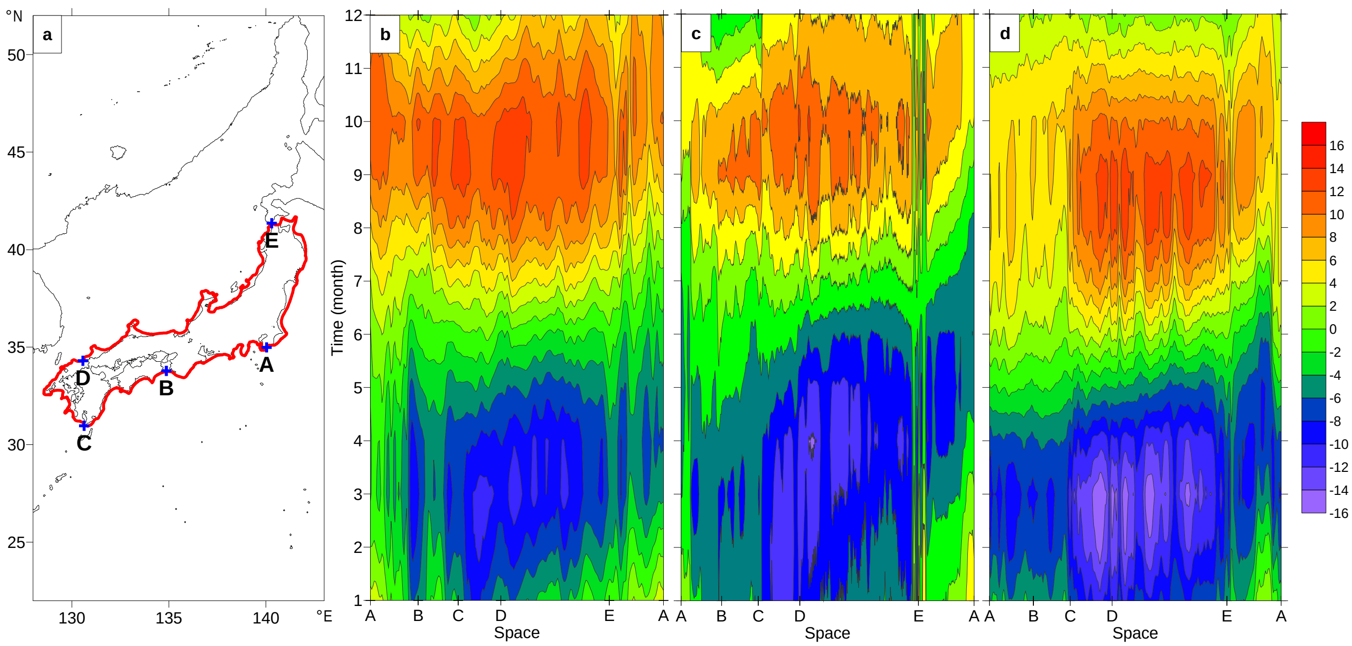

Figure 3: To investigate the relationship of variability along two coasts of Japan, we plot the time evolution of the seasonal SSH anomaly clockwise from the east coast of Japan at about 35°N. The path is the PV contour (8×10^{-6} $m^{-1}s^{-1}$), and the direction is ABCDEA, as marked in the Figure 3a. The Figure 3b is from the altimetry data and clearly shows the clockwise propagation of SSH anomaly around Honshu and Kyushu Islands. The Figure 3c is from OFES results and also shows the clockwise propagation of SSH anomaly. The similar pattern of propagation was reproduced by the model except that there is 1-month lead of the seasonal cycle in the model (Figure 3d) as compared to altimetry data. The contour interval of SSH anomaly is 2 cm.

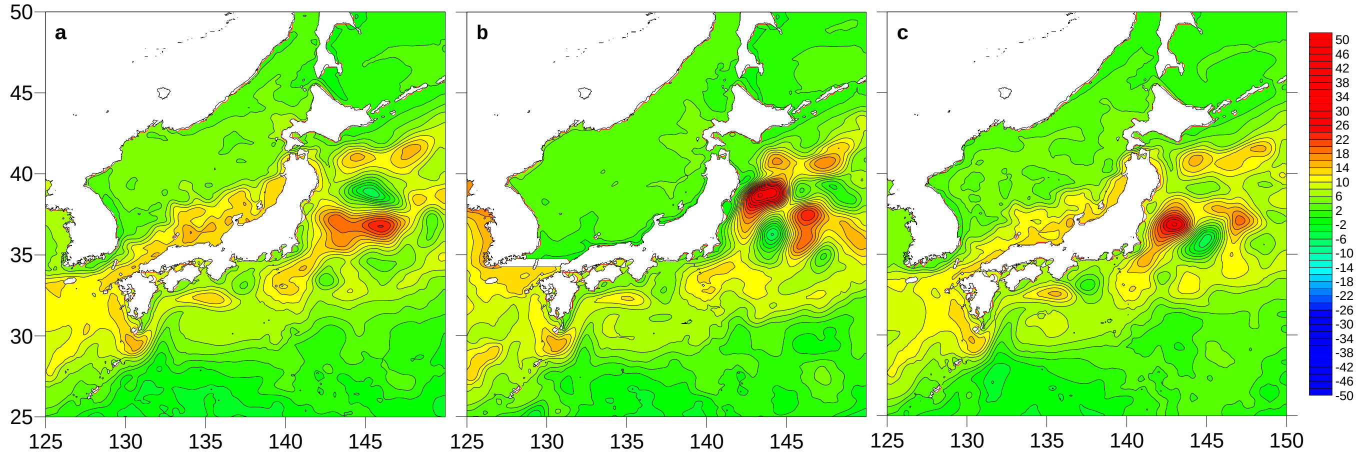

Figure 4: In addition to the standard run, two sensitivity experiments were conducted to test the connectivity of the SSH variations between two Japanese coasts. The left panel is the monthly SSH deviation in September from the standard run. It compares well with the altimetry data and OFES results shown in Figure 1. In the first sensitivity experiment, the Tsushima Strait is blocked and everything else remains unchanged. The SSH variability along the west coast of Japan virtually removed (middle panel), indicating strongly that the SSH variability there is transmitted through the Tsushima Strait. In the second sensitivity experiment, the local forcing within the model domain is removed and the model is forced by the open boundary conditions from a coarser and basin-scale model. The SSH variability along the west coast of Japan is robust even though there is no direct forcing within the JES (right panel). This further supports our remote-forcing hypothesis.