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Influences of the Kuroshio on the salinity budget of the Seto Inland Sea, Japan

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Abstract. The Seto Inland Sea (SIS) harbors abundant aquatic biological diversity, while its ecosystem has been affected by climate change in recent years. Previous studies have shown that the residual current in the SIS varies significantly under the influence of the Kuroshio. To isolate the open ocean influences, salinity transport and the associated salinity budget in the SIS were investigated, as a conservative variable characterizing the estuarine hydrodynamics, using a high-resolution, long-term 3D circulation model. Our findings indicate that the fluctuations of salinity fluxes were influenced by the position of the Kuroshio axis and were highly correlated with the associated volume fluxes. The clockwise eastward transport from Bungo to Kii varies seasonally with an increase in winter and a decrease or counterclockwise increase in summer. The total salinity in each of the eight sub-basins of the SIS was also correlated with the salinity fluxes at the straits connecting the sub-basins. The total salinity in the western sub-basins increased with the eastward clockwise transport and decreased with the westward counterclockwise transport, whereas the eastern sub-basins showed less correlations, resulting in a zonal difference of salinity response to the open ocean.

1 Introduction

The Seto Inland Sea (SIS), the largest estuary in Japan, provides an indispensable ground for the marine environment through its abundant aquatic biological diversity. As fishery and aquaculture industries are active in the SIS, its preservation is of great importance to human life and the marine-related economy. On the other hand, climate change has affected the SIS ecosystem in recent years, leading to declining fish catches. Therefore, it is essential to assess the factors controlling the SIS environment either by the open ocean or by local hydrodynamics in the sub-basins, whereas the former has not been fully investigated in previous studies.

The SIS is connected to the Pacific Ocean through the Bungo and Kii Channels. It has been studied that the inflow at the two channels results in the development of the residual throughflow from the Bungo Channel to the Kii Channel, which varies under the significant influence of the Kuroshio drifting south of the channels. This throughflow has been evaluated as volume flux or mass flux in previous studies. Komai et al. [1] reported that the influence of the average meandering and straightening of the Kuroshio on the volume flux in the SIS

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is estimated to account for approximately 30–40% of the seasonal variation. Furthermore, Uchiyama et al. [2] found that the variation of the outgoing and incoming volume flux in the SIS strongly depends on the degree of Kuroshio axis berthing at Cape Muroto and Cape Shionomisaki. However, it may not be accurate because the volume and mass of seawater in the SIS are noticeably affected by the fluctuating water temperature due to the heat budget, evaporation/precipitation, and inflows from rivers in the SIS. In contrast, salinity is a conservative variable and thus is considered to be straightforward to examine the influences of the open ocean and regional seawater mass balance in the SIS. Therefore, this study aims to understand influences on the SIS water from the open ocean by investigating the salinity transport process and the resultant salinity budget in the interior of the SIS.

2 Methods

The present study employed high-resolution, long-term 3D circulation model simulation results of the SIS model based on the Regional Ocean Modeling System (ROMS) [3] in a double-nested configuration with 600 m horizontal grid spacing forced by the Japan Coastal Ocean Predictability Experiment version 2M (JCOPE2M) [4] oceanic reanalysis at the outermost lateral boundaries (Figure 1). This SIS model is based on the model developed in Ubara et al. [5].

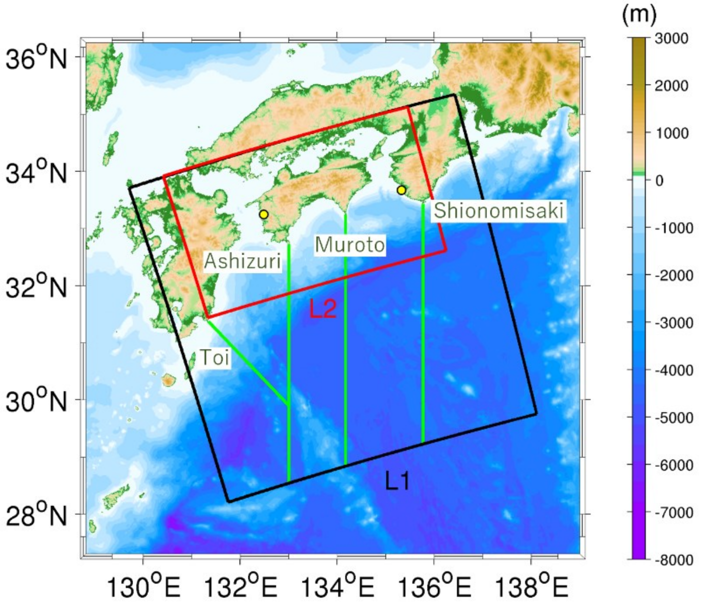

Fig. 1. ROMS-L1 and ROMS-L2 model domains indicated by black and red boxes. Green lines are the inspection transects for analyzing distances to the Kuroshio axis from the 4 capes, which are Cape Toi, Cape Ashizuri, Cape Muroto, and Cape Shionomisaki from left to right.

To analyze the salinity transport structures, 10 transects were introduced to divide the SIS into a total of 8 sub-basins (Figure 2). We computed cross-sectionally integrated salinity fluxes at the 10 transects and the total salinity content in the 8 sub-basins and examined the salinity budget. Since our primary interest is in the influences of the Kuroshio, the positions of the Kuroshio axis were also analyzed at several locations that are anticipated to alter the Kuroshio influxes to the SIS.

3 Results

3.1 Positions of the Kuroshio axis

Time series of the distances to the Kuroshio axis from Cape Toi, Cape Ashizuri, Cape Muroto and Cape Shionomisaki are shown in Figure 3. The inspection transects from the 4 capes are shown as the green lines in Figure 1. In this study, the position of the Kuroshio axis along the transects was defined as the location exhibiting the largest spatial gradient of sea surface height. Prior to 2016, the Kuroshio generally moved in a relatively close proximity to the coastline, although the distances from Cape Toi and Cape Ashizuri show approximately three times more fluctuations than those from the other two capes. However, following 2017, the Kuroshio began to deviate from the coastline and to meander. After 2019, the Kuroshio axis was observed to be 100–300 km away from the capes, which resulted in what is commonly referred to as “the Kuroshio Large Meander”.

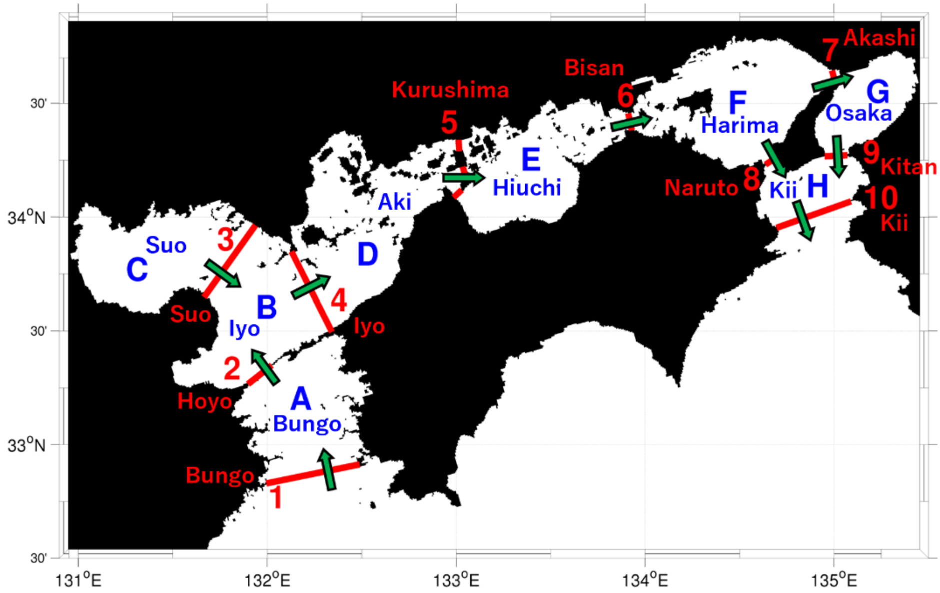

Fig. 2. Red lines are 10 transects (1: Bungo Strait, 2 : Hoyo Strait, 3 : Suo perimeter, 4 : Iyo perimeter, 5 : Kurushima Strait, 6 : Bisan Strait, 7 : Akashi Strait, 8 : Naruto Strait, 9 : Kitan Strait and 10. Kii perimeter) that separate the SIS into 8 sub-basins, where A : Bungo Channel, B : Iyo-nada Sea, C : Suo-nada Sea, D : Aki-nada Sea, E : Hiuchi-nada Sea, F : Harima-nada Sea, G : Osaka Bay, and H : Kii Channel. The salinity fluxes are defined as positive in the clockwise direction depicted by green arrows.

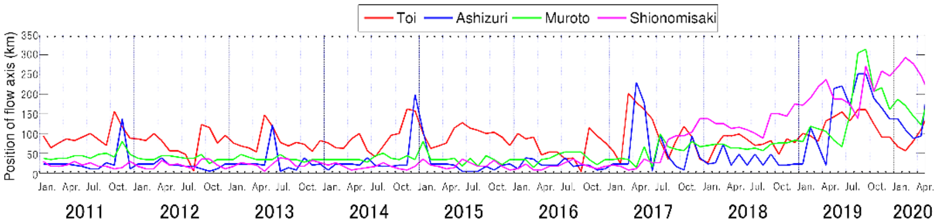

Fig. 3. The distances to the Kuroshio axis from the 4 capes (see Fig. 1).

3.2 Salinity flux

Figure 4 shows time series of the cross-sectionally integrated salinity fluxes evaluated at the ten transects defined in Figure 2. These salinity fluxes were highly correlated with those of the cross-sectional volume fluxes (not shown) and generally developed as a clockwise, eastward transport from Bungo (transect 1) to Kii (transect 10), consistent with the findings in Uchiyama et al. [2] and Ubara et al. [5]. This clockwise transport varied seasonally, with a clockwise increase in winter and a clockwise decrease or overturn to a counterclockwise transport in summer at all transects except Suo (transect 3), with a smaller increase in winter in 2019 during the Kuroshio large meandering period. While the salinity fluxes from Bungo to Kurushima (transect 5) were almost the same value, Naruto (transect 8) and Akashi (transect 7) had lower fluxes than that at the upstream Bisan transect, with a distribution of approximately 3:2 in winter. Furthermore, Naruto had smaller seasonal flux changes than the other transects. Akashi and Kitan (transect 9) exhibited particularly lower fluxes than the other transects, with almost the same value of flux in both.

A comparison of the salinity flux at Bungo with the distance to the Kuroshio axis from 4 capes in Figure 3 revealed that the position of the Kuroshio axis did not correlate with the seasonal change in the salinity flux. Nevertheless, we confirmed that the annual averages for both were negatively correlated at all four capes, suggesting that interannual salinity flux variability was controlled by the Kuroshio meandering and berthing.

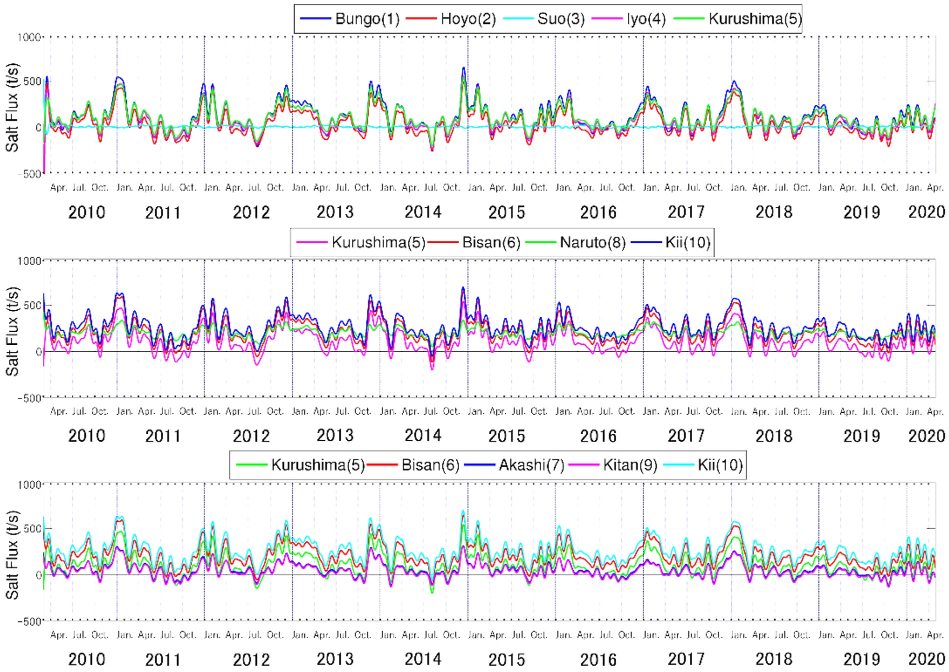

Fig. 4. Temporal variations of the salinity flux at each of the 10 transect shown in Figure 1. Note that clockwise, eastward transport is defined as positive. Upper panel: at western transects 1–5, middle panel: at southeastern transects 5, 6, 8 and 10, and lower panel: at northeastern transects 5, 6, 7, 9, and 10.

3.3 Total salinity

Figure 5 shows the volume-integrated, total salinity in each of the eight sub-basins. A long-term trend was observed with a gradual decrease until 2016, followed by a moderate increase during the meandering period, particularly in western sub-basins (from Bungo Channel to Harima-nada Sea). Seasonal variability is also more evident in western sub-basins. The total salinity was found to decrease in summer and increase in winter except in Osaka Bay, Kii Channel and Suo-nada Sea. In the western sub-basins from Bungo Channel to Hiuchi-nada

Sea, this seasonal difference was particularly conspicuous, and the effect of the Kuroshio meander was seemingly small. These tendencies suggest that total salinity was strongly correlated with the cross-sectional salinity fluxes, and that total salinity was largely influenced by the inflow into the SIS from Bungo Channel. On the other hand, in the eastern sub-basins, the seasonal difference between 2019–2020 during the Kuroshio meander was smaller, and the total salinity in Osaka Bay fluctuated much less because of the smaller salinity fluxes at the upstream Akashi Channel and the downstream Kii Channel.

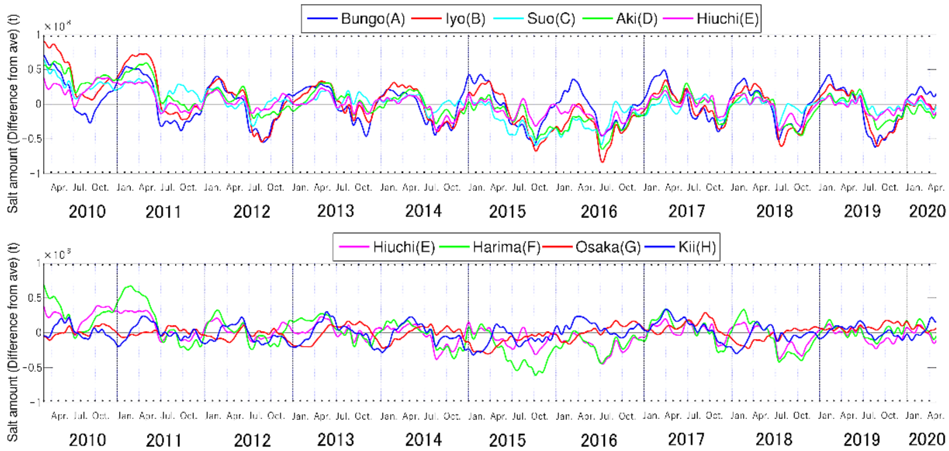

Fig. 5. Temporal variations of volume-integrated total salinity in each of the 8 sub-basins (see Figure 1). Note that deviations from the regional average for the entire analysis period are depicted. Upper panel: in western sub-basins (A : Bungo Channel, B : Iyo-nada Sea, C : Suo-nada Sea, D : Aki-nada Sea, and E : Hiuchi-nada Sea). Lower panel: in eastern sub-basins (E : Hiuchi-nada Sea, F : Harima-nada Sea, G : Osaka Bay, and H : Kii Channel).

4 Conclusion

In this study, the SIS model based on the Regional Ocean Modeling System (ROMS) was used to understand influences on the SIS water from the open ocean, viz., the Kuroshio, by investigating the salinity transport process and the resultant salinity budget in the interior of the SIS. First, the fluctuations of the cross-sectional salinity fluxes were highly correlated with those of the cross-sectional volume fluxes [2, 5]. Both salinity and volume fluxes were generally developed as an eastward, clockwise transport from Bungo Channel to Kii Channel. This clockwise transport varied seasonally with an increase in winter and a decrease or counterclockwise increase in summer. The increase of clockwise transport in winter was reduced during the large meandering periods of the Kuroshio path.

The total salinity in each sub-basin was also strongly correlated with the cross-sectional salinity fluxes. In particular, the western sub-basins (i.e., Bungo Channel, Suo-nada Sea, Iyo-nada Sea, Aki-nada Sea, and Hiuchi-nada Sea) were found to play a vital role in salinity transport and budget due to the influx from the open ocean through Bungo Channel. The total salinity in these western sub-basins increased with the clockwise transport, while it decreased when the counterclockwise transport developed. On the other hand, the eastern sub-basins (i.e., Hiuchi-nada Sea, Harima-nada Sea, Osaka Bay and Kii Channel) exhibited comparatively weaker correlations with the Kuroshio, leading to a notable zonal difference of the salinity response to the open ocean. In conclusion, it can be posited that the salinity transport process and the salinity budget within the SIS were significantly influenced by the Kuroshio.

These results could be used for further environmental studies in the SIS, including ecosystem modeling and coastal transport of Eulerian tracers (e.g. sewage effluents) and Lagrangian tracers (e.g., microplastic particles).

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