Original Article

Observation and Modeling of Seawater Exchange in a Strait-Basin System in the Seto Inland Sea, Japan

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ABSTRACT

The seawater exchange is closely related to the spreading of pollutant and the water quality in coastal seas. The Seto Inland Sea is a semi-enclosed coastal sea which has a series of broad basins and narrow straits, and the along-channel outflows from the strait located at the center of the channel toward east and west may play an important role in seawater exchange. In this study, flows along the boundary between Bisan Seto which is located at the center of the Seto Inland Sea and the adjacent basin called Harima Nada were measured using a ship-mounted Acoustic Doppler Current Profiler and residual flows were obtained by removing tidal currents. The survey results showed significant volume flux of the along-channel outflows from Bisan Seto toward Harima Nada. A numerical model based on Princeton Ocean Model was also used in order to analyze the driving forces of the along-channel outflow. The outflow was well reproduced using the model which was driven by tide and horizontal density gradient between the strait and basin, suggesting that these possibly induce the seawater exchange in the Seto Inland Sea.

Keywords: water environment management, semi-enclosed seas, seawater exchange, acoustic doppler current profiler, strait-basin system

INTRODUCTION

The exchange flow, which consists of a surface outflow and subsurface inflow, is related to the residence time of seawater [1], which has been widely applied for water quality assessment, ecosystem management, and budget studies in coastal seas [2]. Outflows and inflows are commonly observed in Regions of Freshwater Influence (ROFI) [3], primarily in estuaries and river mouths [4–6], and along channels where horizontal density gradients are maintained [3].

One of the ROFI, the Seto Inland Sea, Japan, represents a semi-enclosed coastal sea connected to Pacific Ocean through two openings (Fig. 1a). The central part of the channel called Bisan Seto, is narrow and shallow (mean depth = 15 m) [7]. Relatively large rivers such as Takahashi River, Asahi River and Yoshii River flow into Bisan Seto thereby reducing

the salinity. Bisan Seto is occupied by relatively low-salinity and thus low-density water and the along-channel horizontal density gradients have been observed in summer [8]. The horizontal density gradients in coastal seas may induce gravitational circulation, with outflow of light water in the upper layer and inflow of heavy water in the lower layer [9].

The existence of surface outflow of the low-density water in summer from Bisan Seto toward both openings has been inferred from the results of drift card tracking [10]. It may play an important role in water exchange between the Seto Inland Sea and Pacific Ocean. The outflow was simulated by Murakami et al. (1985) stating that it might be induced by along-channel horizontal density gradient, however, it should be greatly affected by Earth's rotation according to the area in the Seto Inland Sea, where the widths across the channel are generally larger than Rossby's deformation

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Fig. 1 (a) Map of the Seto Inland Sea. Arrows show the locations of main rivers flowing into the study area (Takahashi River, Asahi River and Yoshii River). Dotted lines show the locations of the sections used in the ADCP observations, which conducted in 2005 and 2006, in addition to in 2007 (described in this study). (b) Map and bathymetry of the study area. Contours show water depth in meters (contour interval = 10 m). Black circles and triangles show the location of CTD measurements. The line between B1-B8 indicates the location of the section surveyed by ADCP measurements. A star mark and a square indicate the locations of the weather station and the station where harmonic constants of tidal currents were obtained, respectively.

diameter [11]. The surface outflow of the low-density water from Bisan Seto toward the adjacent basin is thus subjected to be quantified with the examination of the driving force of the outflow.

Moreover the volume fluxes associated with the surface outflow from Bisan Seto toward Hiuchi Nada (**Fig. 1a**) have been studied using the results from the observations and numerical model [12]. Those from Bisan seto toward the northern part of Harima Nada have also been studied using a ship-mounted Acoustic Doppler Current Profiler (ADCP) [13]. They found significant outflow of the low-density water through the surface layer of Hiuchi Nada and northern part of Harima Nada. The outflow from Bisan Seto toward the southern part of Harima Nada, however, has not been fully studied by cross-sectional observations using ADCP.

This study investigates the surface outflow and their associated volume flux using ocean observations along the boundary between Bisan Seto and the southern part of Harima Nada (**Fig. 1a**). Using ADCP measurements, we measures residual currents from Bisan Seto to the southern

part of Harima Nada. We then examine the relationship between the outflows and horizontal density gradients. Using the Princeton Ocean Model, we investigate the properties of the outflow, which may be driven by an exchange flow between the basin and straits.

MATERIALS AND METHODS

Tidal constituents and meteorological data

Harmonic constants of tidal current for M_2 , S_2 , K_1 and O_1 tidal constituents near the study area were obtained from the previous study [14]. The location of the station is indicated by a square in **Fig. 1b**. The temporal variation of the speed of tidal current at major axis during the observation period was predicted from those constants (**Fig. 2a**).

Wind velocity was obtained from a weather station of the Japan Meteorological Agency. The insignificance of regional variability of meteorological condition around the study area has been indicated by Guo et al (2004) [15]. One of the weather stations in the region was selected (Hiketa) and the

Fig. 2 Temporal changes in (a) predicted tidal currents (cm s^{-1}) and (b) observed wind velocity (m s^{-1}). Plots in **Fig. 2a** indicate the timing when the ship passed through B1 or B8 (the locations of the stations are indicated in **Fig. 1b**).

location is indicated by a star mark in **Fig. 1b**. The daily discharge from Yoshii River, Asahi River and Takahashi River flowing into Bisan Seto was obtained from the web site of the Ministry of Land, Infrastructure, Transport and Tourism [16]. Data at Miyasu, Makiyama, and Hiwa observatories were used as the discharges from Yoshii River, Asahi River and Takahashi River, respectively. The temporal variation of wind velocity on the date of the field observation was obtained from the web site of the Japan Meteorological Agency [17] and shown in **Fig. 2b**.

Field observations in the Seto Inland Sea

On 25 July 2007, hydrographic surveys have been carried

out in the boundary region between Bisan Seto and Harima Nada, using a conductivity-temperature-depth (CTD) profiler (AAQ1183; JFE-Advantech, Kobe, Japan). The locations of the stations are plotted in **Fig. 1b**. Hereafter the section along the boundary between Bisan Seto and Harima Nada (B1 ~ B8 in **Fig. 1b**) is called cross-channel section and the section perpendicular to the line (C1 ~ C6 in **Fig. 1b**) is called along-channel section.

In addition to the hydrographic surveys, the flow fields were measured on the section on a cross-channel section between Bisan Seto and Harima Nada indicated in **Fig. 1b**. The measurements were made using a ship-mounted ADCP (RD Instruments, Poway, U.S.A.) which operated at 300

neglected. The model time step was 40 seconds, with an integration period of 30 computer days. Passive tracers were released from both straits to visualize the flow between the basin and straits. To remove the tidal currents and obtain the residual flow, a harmonic analysis at the M_2 frequency to the horizontal velocity components was applied. The Princeton Ocean Model has the part of calculation of turbulence energy dissipation then it is useful to represents the difference of strength of stratification which induce by the difference of the width of the channel, so that it was applied for this study.

RESULTS AND DISCUSSION

Field observation results

The distributions of water temperature, salinity and density (σ_t) observed on 25 July 2007 on the along-channel section are shown in **Fig. 4**. Significant stratification was found at the station in Harima Nada (C6), while at the stations in Bisan Seto (C1 ~ C2), stratification was much weaker than that at C6. Relatively cold and saline water existed in the lower layer at C6, while warm and low-salinity water occupied its upper layer. The stratified water column was also found at the stations located around the boundary between Bisan Seto and Harima Nada (C3 ~ C5). The station C5 is on the ADCP observation line. The internal deformation radius ($Ro = \sqrt{g'D}/f$, $g' = g\Delta\sigma/\sigma$, where g is the gravitational acceleration (m s^{-2}), σ is the density (kg m^{-3}), $\Delta\sigma$ is the vertical density difference (kg m^{-3}), D is the thickness of upper layer (m) and f is the Coriolis parameter (s^{-1})) at station C5 was 5.4 km, using $g = 9.8$, $\sigma = 1022.0$, $\Delta\sigma = 2.0$, $D = 10$ and $f = 8.1 \times 10^{-5}$. The estimated value, 5.4 km, was less than the width of the channel.

The water at C3 is fresher and lighter than that in the east (**Fig. 4**). Horizontal gradients of salinity and density toward east were formed, with salinity increasing from 31.0 to 31.7 at the surface, and density increasing from 20.4 to 20.7 between C3 and C5. The horizontal gradients between those stations for salinity and density were ~ 0.05 (psu km^{-1}) and ~ 0.02 ($\text{kg m}^{-3} \text{ km}^{-1}$), respectively.

The distributions of water temperature, salinity and density observed on 25 July 2007 on the cross-channel section are shown in **Fig. 5**. The vertical gradients of temperature, salinity and density were significant almost throughout the section and thus low-salinity and low-density water occupied the upper layer. The horizontal gradients of salinity and density were also found. Below 10 m depth, salinity and density were the highest at station B5 and decreased southward, the

Fig. 4 Vertical distributions of (a) salinity (psu), (b) temperature (deg C) and (c) sigma-t observed in along-channel section on 25 July 2007. Ticks above each figure indicate observation points denoted by triangles in **Fig. 1b**.

corresponding isohalines and isopycnals sloped downward toward the south.

Figure 6 shows the residual currents normal and parallel to the cross-channel section. Positive and negative values in **Fig. 6a** indicate the outflow and the inflow from / into Bisan Seto, respectively. Outflows were dominant at the southern half of the section and their speeds reached $\sim 6 \text{ cm s}^{-1}$ at the uppermost layer (7.6 m), while inflows were dominant at the northern half of the section. The residual currents were relatively large around the southern and northern ends. The outflows at the southern part showed significant vertical gradients, whereas the inflows at the northern part

Fig. 5 Vertical distributions of (a) salinity (psu), (b) temperature (deg C) and (c) sigma-t observed in cross-channel section on 25 July 2007. Ticks above each figure indicate observation points denoted by black circles in **Fig. 1b**.

were vertically homogeneous. Positive and negative values in **Fig. 6b** indicate northward and southward along the section, respectively. The flows almost throughout the section

Fig. 6 Vertical sections of residual currents (cm s^{-1}) obtained from ADCP measurements on 25–26 July 2007. Velocities were resolved into two orthogonal directions; (a) normal and (b) parallel to the cross-channel section. Positive and negative values in **Fig. 6a** indicate the outflow and the inflow from / into Bisan Seto, respectively. Positive and negative values in **Fig. 6b** indicate northward and southward directions along the section, respectively.

were directed consistently toward the south along the section except for those at the northern end. The velocities were the largest at 7.6 m depth and gradually decreased toward the bottom.

Figure 7 shows the fluxes through each layer (F ; defined by equation (1)) estimated using the residual currents ($\bar{u}$) obtained from ADCP observations. Positive and negative values indicate the outflow and the inflow from / into Bisan Seto, respectively, same as **Fig. 6a**. The fluxes above approximately 23 m were positive (outflow), while those below

Fig. 7 Vertical profiles of the fluxes through each layer on cross-channel section ($\text{m}^2 \text{s}^{-1}$) estimated using the results shown in **Fig. 6a**. The definition of the flux is referred to in the text. Positive and negative values are outflows and inflows, respectively.

this depth were negative (inflow), indicating that significant volume transport was formed across the section. The volume flux (Q) of outflows obtained using equation (2) was $\sim 6,065 \text{ m}^3 \text{s}^{-1}$.

Numerical experiment results

Figure 8 shows the results of the numerical simulation at 1, 3, 4, 6, 9, 12, 15, and 30 days. Tracer concentration and velocity were averaged from the surface to 5-m depth to represent the bulk properties of the surface layer. A residual flow first developed near the straits, with currents steered towards the right (in the downstream direction) after 3–4 days. After 6, 9, and 12 days, the dominant flows were located along the right-hand boundaries of the straits. These along-coast residual flows were maintained even after 15 and 30 days, with the residual flows originating from the straits forming a horizontal circulation. The tracer released from the straits entered the basin along the right-hand boundary of each strait.

Figure 9 shows the distributions of temperature (**Fig. 9a**) and tracer (**Fig. 9b**) in the vertical along-channel (x - z plane) section. The locations of the x - z sections in **Fig. 9a** and **b** are shown in **Fig. 8e** by bold and dotted arrows, respectively. The distribution of temperature, which determines density because salinity is set to be homogeneous in this model case, was similar to the surface layer near the strait boundaries, while vertical stratification was maintained in the broad re-

gion representing the basin (**Fig. 9a**). As a result, significant horizontal density gradients developed in the surface layer at the boundary between the basin and the straits. In the along-channel section, the tracer primarily migrated to the surface (**Fig. 9b**).

Figure 10 shows the residual flow in the vertical cross-channel (y - z plane) section. The location of the y - z section is shown in **Fig. 8e** by a thin arrow. The upper and lower boundaries of the horizontal plane (**Fig. 8**) were defined to be oriented north and south, respectively. Velocities shown in **Fig. 10a** and **b** were resolved into two orthogonal directions (normal and parallel to the cross-channel section). Positive and negative values in **Fig. 10a** indicate the outflow and the inflow from/into the western strait, respectively. In the cross-channel section, a significant outflow from the strait into the basin was detected in the surface layer along the boundary (**Fig. 10a**). The direction and distribution of velocities were consistent with the field observations, where outflows from the strait into the basin dominated the southern half of the section, and inflows were dominant in the northern half (**Fig. 6a**). Positive and negative values in **Fig. 10b** indicate northward and southward currents along the section, respectively. Flows in the southern section were consistently directed toward the south, except those at the northern end (**Fig. 10b**), which is in agreement with the observations (**Fig. 6b**). We note that modeled velocity magnitudes were smaller than the field observations.

Driving force of the exchange flow in a strait–basin system

The results from the hydrographic surveys showed significant horizontal gradients of salinity and density were formed in the along-channel section (**Fig. 4**). The daily discharges from Yoshii River, Asahi River and Takahashi River on the date of the field observation were 62, 54 and 59 $\text{m}^3 \text{s}^{-1}$, respectively, which were comparable to the yearly normal value [16]. The salinity gradients indicate significant effect of river discharge into Bisan Seto. The density gradients can be understood as representing the effect of horizontal difference of temperature induced by that of intensity of stratification between Bisan Seto and Harima Nada, in addition to the effect of salinity gradients. The internal deformation radius at these stations was less than the width of the channel, indicating that the currents driven by wind or density gradients would be under the influence of Earth's rotation. Thus the observed density gradients possibly induce the southward currents along the cross-channel section.

The results from ADCP observation showed significant

Fig. 8 Model residual currents (cm s^{-1}) and tracer concentrations on a horizontal plane at (a) 1 day, (b) 3 days, (c) 4 days, (d) 6 days, (e) 9 days, (f) 12 days, (g) 15 days, and (h) 30 days. Thick, dotted and thin lines in **Fig. 8e** indicate the locations of the vertical sections shown in **Figs. 9 and 10**.

Fig. 9 The distributions of (a) temperature and (b) tracer along the vertical sections at 9 days. The locations of the sections in **Fig. 9a and b** are indicated by thick and dotted lines in **Fig. 8e**, respectively.

southward residual currents along the cross-channel section (**Fig. 6b**). The currents induced by the along-channel density gradients may be included in these southward currents. The southward flows in the cross-channel section had already been found in the previous studies using the observed residual flow and the numerical simulation [19–21], while the along-channel flow had not been shown in those large-scale study. The southward residual currents along the cross-channel section may transport low-salinity water toward the south. The results from the hydrographic surveys showed that low-salinity water distributed at the southern half of the cross-channel section and horizontal density gradients were formed along the section (**Fig. 5**). The observed density gradients possibly induced the eastward currents (outflows) under the influence of Earth's rotation.

The results of ADCP observations show significant eastward residual currents (outflows) in the southern half

of the cross-channel section (**Fig. 6a**). This is qualitatively consistent with the residual flows estimated from the numerical simulation (**Fig. 10a and b**), although observed velocity magnitudes are larger than those of the numerical model. One of the main reasons for the discrepancy in velocity magnitudes is possibly the differences in bottom and coastal topography between the field site and the idealized model domain. Despite these differences, the flow observed in the study region is consistent with the numerical simulation, which was conducted to investigate the forcing driving the observed currents. The residual flows that developed in front of the straits in the numerical simulation (**Fig. 8**) could be tidal residual currents, which may induce extrusions of seawater from the straits to the basin during model spin-up. As a result, horizontal density gradients formed along the open boundaries between the basin and straits, which may drive the residual flow. We highlight that tides and horizontal

Fig. 10 The distributions of the residual currents (cm s^{-1}) in the directions (a) normal and (b) parallel to the vertical section at 9 days. The location of the section is indicated by a thin line in **Fig. 8e**. Positive and negative values are as shown in **Fig. 6a and b**.

density gradients play an important role in the formation of the along-coast outflows from the straits to the basin.

The outflows described in the numerical simulation above showed time dependence in the development of the residual current. Residual flows in the real sea would be influenced by topography, surface heating and cooling, and the associated density field; e.g., the strength of the vertical density stratification would vary both temporally and spatially. The horizontal circulation shown in the numerical simulation (**Fig. 8g and h**) is in general agreement with the results from a previous numerical simulation that incorporated realistic bottom topography and the observed density structure in Hiuchi Nada [12]. In the numerical simulation with realistic topography [12], the straits and associated density field were

not located on opposite sides of the model domain at the same latitude (as in our simulation), which resulted in asymmetric residual flows that induced a significant flux of strait outflow into the upper layer of the basin. Although the large differences in topography between real sea and model domain, the facts that the residual currents from the strait to the basin were obtained in the numerical simulation, suggested that tides and the horizontal density gradients between the strait and the basin play essential role in driving those residual currents.

To isolate the influence of horizontal density gradients, this study did not include wind forcing. Wind-induced flows may contribute to residual currents, along with the density-driven flows described above. During the field study, the wind di-

rection changed every few hours with a maximum wind speed of $\sim 3 \text{ m s}^{-1}$ (**Fig. 2b**). Wind forcing from a consistent direction could drive a stable residual current; however, we would not expect these conditions in the field. Moreover, we this time focus on the intrusion of low-salinity water from strait to the basin, although understand that freshwater input from local rivers and point sources to Harima Nada are important. Although the forcing of the residual currents needs to be further investigated, our observational and computational results indicate that the along-channel outflow may be induced by horizontal density gradients. In summary, our results provide further evidence that gravitational circulation is one of the key processes that contributes to shelf-ocean exchange [22–25].

Our survey results provide the residual current components from Bisan Seto toward Harima Nada. The fluxes across the cross-channel section, estimated based on the observed residual currents, show a two-layer structure. Transports at depths shallower than $\sim 23 \text{ m}$ were directed toward Harima Nada, and at depths below $\sim 23 \text{ m}$ toward Bisan Seto (**Fig. 7**). While our observations are synoptic, they provide evidence of volume transport from Bisan Seto toward Harima Nada in the upper layer. We plan to further investigate exchange and mass transport in the Seto Inland Sea using more comprehensive 3-D models [21,26]. The results of this study, which quantified the outflow from Bisan Seto to the southern part of Harima Nada, along with previous results that provide evidence for outflows from Bisan Seto to the northern part of Harima Nada [13] and Hiuchi Nada [12], will be useful in validating future model results.

CONCLUSIONS

We investigated seawater exchange in the Seto Inland Sea, which is important for determining the spread of pollutants and water quality. Using ADCP observations, we quantified the outflowing flux in the surface layer of Bisan Seto, which is located at the center of the Seto Inland Sea, toward the adjacent basin of Harima Nada. The outflow from the strait to the basin was reproduced using an idealized numerical ocean model with a square basin and narrow straits on both sides of the model domain. Using only tidal forcing and homogenous seawater density at the strait boundaries, our model results suggest that outflows could be induced by horizontal density gradients between the basin and straits. We also anticipate that significant horizontal density gradients may be driven by surface heating and cooling, along with tidal stirring and terrestrial freshwater input. Therefore, the outflow from the

straits to the basin and the associated exchange flow may be important controls on exchange and residence time in this semi-enclosed sea.

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