Water exchange between Ikushima Bay and Seto Inland Sea, Japan based on numerical experiment

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Introduction

Tidal flats and seagrass beds are essential components of coastal ecosystems, playing a crucial role in the efficient cycling of materials within coastal seas. However, these habitats have been steadily declining worldwide, including in the Seto Inland Sea, the largest enclosed sea in Japan. Surveys indicate that both habitats have shrunk to less than half of their original extent (Tada et al., 2019). Despite their ecological significance, a comprehensive understanding of the material cycling processes within these environments remains lacking. The specific functions of these habitats, as well as their contributions to the broader ecosystem, are not yet fully understood, making it imperative to deepen our knowledge for effective conservation and restoration strategies.

Ikushima Bay is a small tidal inlet covering 420,000 m², with extensive coverage of *Zostera marina* across nearly its entire area. Located in the eastern part of the Seto Inland Sea, Japan, the bay is connected to Bisan-Seto, one of the country's most significant *Z. marina* habitats. Water exchange in Ikushima Bay is primarily driven by tidal currents, with minimal influence from river or canal discharge. A previous study (Asahi et al., 2019) investigated nutrient budgets in this seagrass bed system but was unable to fully account for the nutrients required to sustain seagrass growth. A deficiency in key nutrients, particularly nitrogen, was identified as a limiting factor for seagrass health in this area. This underscores the need for further research into the physical, chemical, and biological processes governing nutrient cycling in seagrass ecosystems, as these dynamics may also influence broader nutrient exchanges along the coastal zone.

This study presents a preliminary exploration of the physical mechanisms governing water exchange between Ikushima Bay and the external sea using numerical simulations. The findings provide essential baseline data for future research on nutrient exchange processes within and beyond the bay, contributing to a more comprehensive understanding of seagrass ecosystem dynamics and informing conservation efforts.

Procedure

This study investigates the circulation of tidal currents in Ikushima Bay using a hydrodynamic model, specifically the Princeton Ocean Model (POM). The study area is defined within the longitude range of 133.9592°N to 133.9766°N and the latitude range of 34.36227°E to 34.37767°E (Figure 1). The northern boundary of the model domain is an open boundary connected to Bisan-Seto, which is adjacent to Harima-Nada, a significant body of water in the eastern Seto Inland Sea, Japan. The model resolution is set at 50 meters, ensuring a detailed representation of hydrodynamic processes within the bay. Bathymetric data used in the model were obtained from a bottom topography digital dataset of Japan Hydrographic Association, providing an accurate seabed profile essential for simulating water movement. The tidal forcing applied in the model includes the M_2, S_2, O_1, and K_1 tidal constituents, which were derived from a two-dimensional hydrodynamic model of Harima-Nada (Thong-u-dom, 2024).

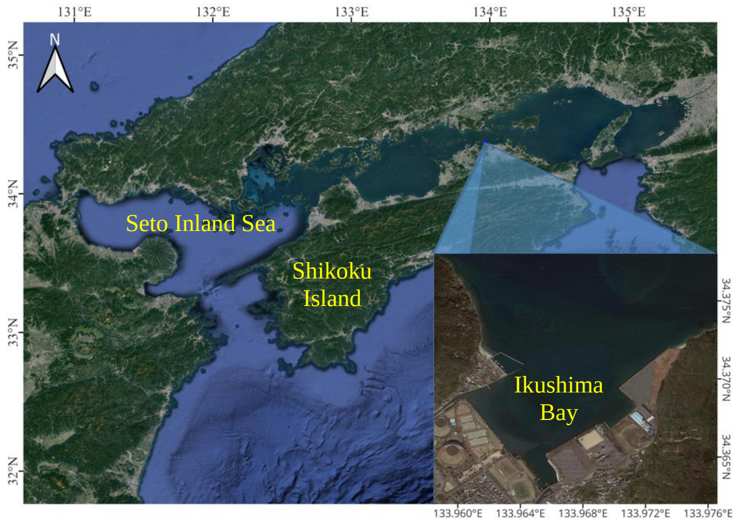

Figure 1 Ikushima Bay

Hourly current simulations were conducted, and the results were subsequently averaged on daily and weekly timescales to analyze variations in tidal circulation patterns within Ikushima Bay. Additionally, to assess the exchange of water masses, a bay boundary division was established near the bay's mouth. This allowed for the quantification of water inflows and outflows over different tidal cycles, providing insight into the physical mechanisms driving water exchange in this enclosed coastal system. The findings of this study will serve as a fundamental dataset for further research on nutrient transport, water quality, and ecosystem dynamics in seagrass-dominated habitats within Ikushima Bay and other similar coastal environments.

To analyze the movement of water entering and leaving the bay, a boundary was defined along the bay mouth (Figure 2). The volume of water crossing this boundary was calculated to understand the exchange of water mass between the bay and the open sea. A positive volume value (+) represents water flowing out of the bay, while a negative volume value (–) indicates water entering the bay. The unit used for these measurements is m^3/s.

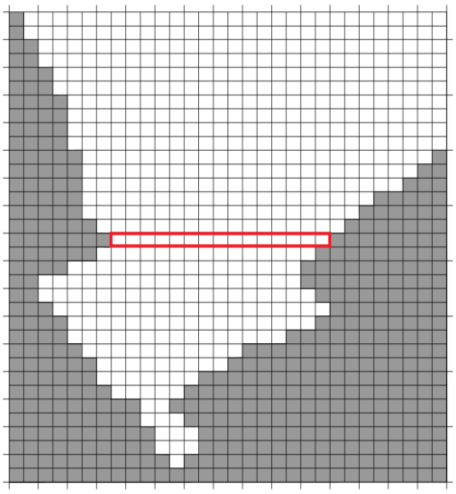

Figure 2 Computational grid domain of Ikushima Bay, with the grids inside the red rectangle representing the area used for calculating volume transport at the bay mouth.

Results and discussion

The results from the hydrodynamic model simulation show that water moves more slowly inside the bay compared to outside it. The northern part of the study area, which is located outside the bay, experiences stronger currents, while the southern part, inside the bay, has weaker currents. Throughout the simulation, different patterns of eddy formation were observed, highlighting how the water circulation within the bay continuously changes over time.

At the entrance of the bay, a counterclockwise eddy forms first. Here, water flows into the bay from the west and exits to the east (Figure 3). As time progresses, the current pattern shifts, leading to the development of two separate eddies—one on the left side rotating clockwise and another on the right side rotating counterclockwise. The western eddy slowly moves toward the center of the bay, while the eastern eddy remains near the entrance. Over time, the western eddy drifts further east, and a new eddy forms again in the west, repeating this cycle. At the same time, coastal currents begin to develop along both shorelines, flowing southward before merging and exiting through the center of the bay. This pattern continues, with newly formed eddies in the west gradually growing larger while the older eddies continue shifting eastward. The ongoing formation and movement of these eddies highlight how dynamic and ever-changing the water circulation within the bay is.

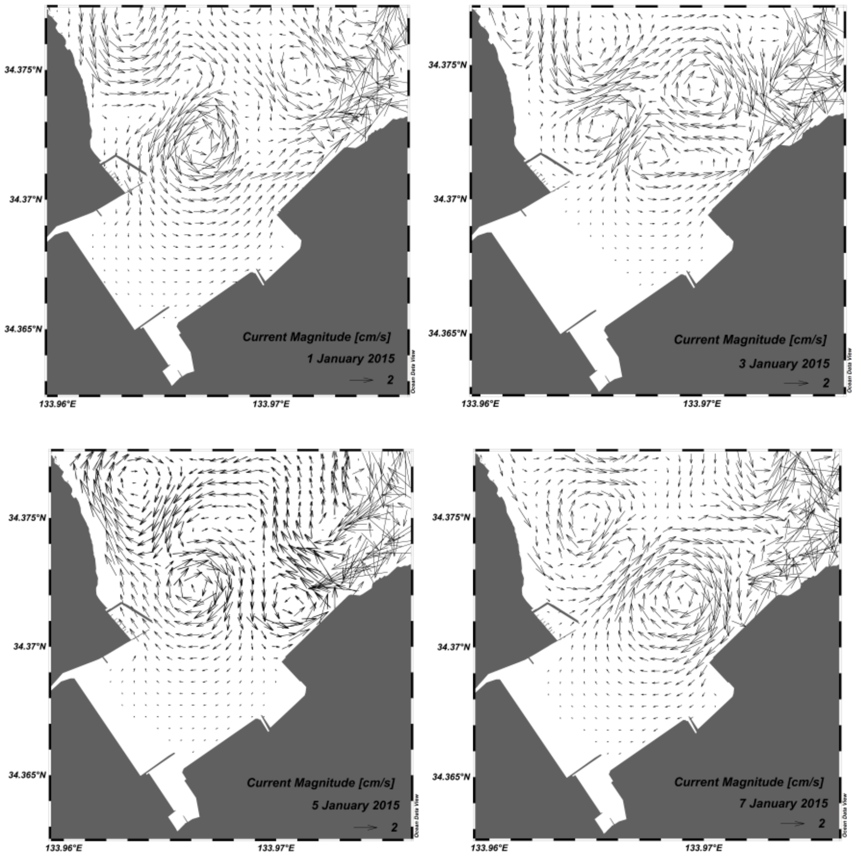

Figure 3 Simulate residual circulation averaged 25 hours on Day 1, 3, 5, and 7 of the simulation with arrow represent current, magnitude, and direction.

By computing the tidal-cycle-average water volume for each grid cell, distinct exchange patterns were observed (Figure 4). During days 1 to 3 of January 2015, water entered the bay in the west and exited in the east of the bay mouth. As the circulation evolved, another shift occurred, where water started entering from the east and exiting through the central part of the bay, before eventually transitioning to a pattern where inflow occurred from the west, and outflow was directed toward the east (Figure 6). These alternating flow patterns highlight the dynamic nature of water exchange within the bay, influenced by tidal oscillations.

Analysis of the daily average water mass volume through the mouth boundary reveals that the movement of water in and out of the bay fluctuates over time (Figure 5). The highest recorded outflow was 2.79 m^3/s on Day 14, while the largest inflows were -2.28 m^3/s on Day 7 and -2.02 m^3/s on Day 20. When averaging the data over the entire 31-day period, the net volume transport was 0.23 m^3/s, indicating a slight overall outflow from the bay.

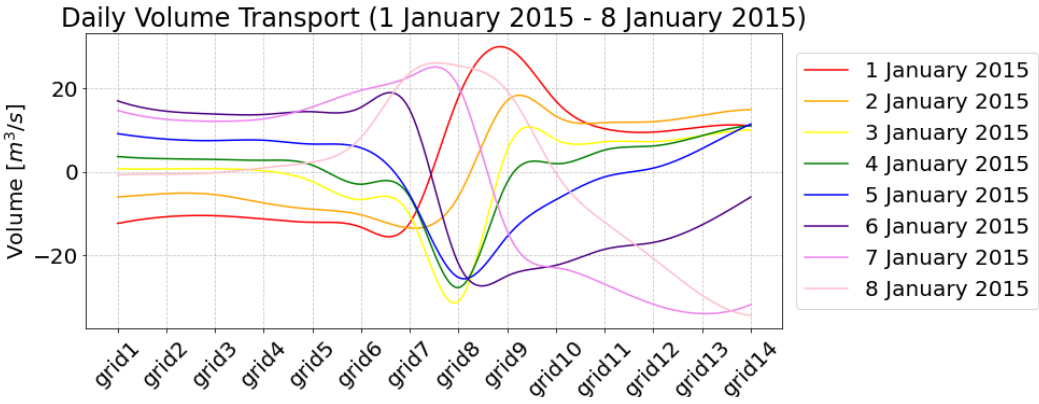

Figure 4 Daily average volume transport in (-)/out (+) the Ikushima Bay in each grid from 1 to 8 January 2015

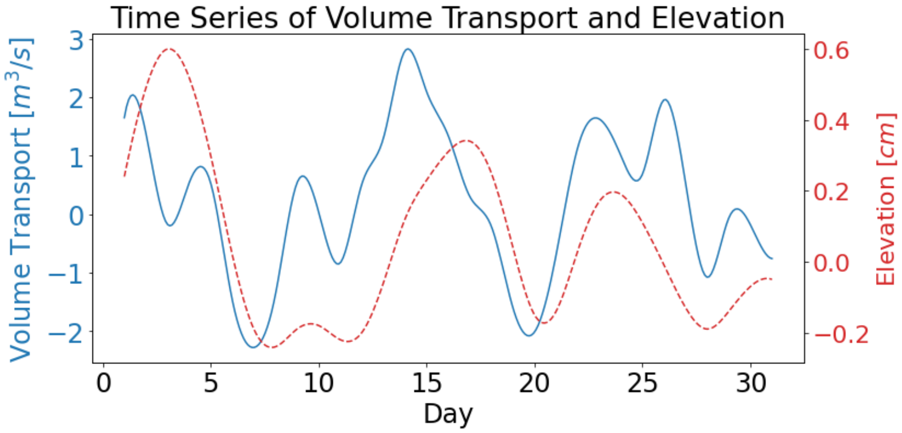

Figure 5 A tidal-cycle-average volume transport and elevation in 31 days in January 2015

The fluctuations in water exchange closely follow the tidal elevation averaged in a tidal cycle (Figure 5). When the mean water level rises, water flows out of the bay, whereas when the water level drops, water flows into the bay. This relationship suggests that tidal forces play a dominant role in controlling the water exchange at the bay mouth. Understanding these variations is essential for assessing water renewal, sediment transport, and ecological dynamics within the bay.

Perspectives on the future

In the next phase of our study, we will enhance this circulation model by coupling it with an ecosystem model to assess nutrient budgets under scenarios that include seagrass beds in Ikushima Bay. This integration will allow for a more comprehensive evaluation of how water circulation interacts with biological and chemical processes, providing valuable insights into nutrient dynamics and ecosystem functioning within the bay.