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Circulation in a bay influenced by flooding of a river discharging outside the bay

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ABSTRACT

To investigate the influence of a river discharging outside a bay on circulation in the bay, we carried out current and salinity measurements from mooring systems and hydrographic observations in Matsushima Bay, Japan, and off the Naruse River, which discharges outside the bay. Previously, enhancement of horizontal circulation in the bay induced by increased freshwater input from the Naruse River was reported to have degraded the seedling yield of wild Pacific oysters in the bay, but the freshwater inflow from the river was not directly measured. Our hydrographic observations in Katsugigaura Strait, approximately 3 km southwest of the Naruse River mouth, detected freshwater derived from the river. The mooring data revealed that freshwater discharged by the river flowed into Matsushima Bay via the strait and that the freshwater transport increased when the river was in flood. The inflow through straits other than Katsugigaura was estimated by a box model analysis to be 26–145 $m^3 s^{-1}$ under normal river discharge conditions, and it decreased to 6 $m^3 s^{-1}$ during flood conditions. During flood events, the salt and water budgets in the bay were maintained by the horizontal circulation: inflow occurred mainly via Katsugigaura Strait, and outflow was mainly via other straits.

1. Introduction

Circulation in a bay is typically induced by freshwater input from a river discharging at the bay-head (e.g., Bowden and Gilligan, 1971; Whitney and Garvine, 2006; Guo and Valle-Levinson, 2007). Such bays, which are created when erosion by a river results in the formation of a valley, are found worldwide (Gottschalk, 1945). A river discharging into the bay-head produces estuarine circulation in the bay, a density-driven circulation in which the flow in the upper layer is seaward and that in the lower layer is landward (Dyer, 1973; Fujiwara et al., 1997; Kakehi et al., 2012). In contrast, the influence of freshwater discharged outside a bay on circulation in the bay remains unclear. Of course, bays in which this occurs are comparatively rare, but the necessary topographic relationships can be created artificially, for example, by the construction of a canal.

Matsushima Bay and the Naruse River system in Japan is an example of the latter system. The Naruse River, one of the major rivers in the Tohoku region with a watershed area of 1133 km^2 and an average discharge along its lower reaches of 28 $m^3 s^{-1}$, flows through Miyagi Prefecture and into Sendai Bay, a large open bay with a width of 60 km (Fig. 1). Matsushima Bay is a highly enclosed embayment of Sendai Bay southwest of the Naruse River mouth. It has an area of 38 km^2 and an average depth of approximately 3.5 m. Watanabe and Sato (1972) stated that the bay is an estuary with moderate or intense mixing. The bay is connected to Sendai Bay by six straits: from west to east, Mahanashi, Kaneshima, Ishihama, Sabusawa, Wanigafuchi, and Katsugigaura straits. Kaneshima Strait is the largest strait that connects Matsushima Bay with Sendai Bay, and the tidal transport through this strait accounts for 64% of the total tidal transport of the bay (Watanabe et al., 1972). Katsugigaura Strait, which is 70–200 m wide and 2 m deep, is approximately 3 km southwest of the Naruse River mouth. This strait is not natural; it was constructed in 1963 as a canal. The Takagi River discharges into the head of Matsushima Bay. Its catchment area is 14 km^2 and its average discharge is 3 $m^3 s^{-1}$. The tsunami wave generated by the 11 March 2011 Tohoku earthquake was over 6 m high in the area adjacent to Matsushima Bay (Kakehi, 2011), and it altered the topography at the east end of Katsugigaura Strait, widening and deepening it where it entered Sendai Bay (Kakehi et al., 2016). In the Northern Hemisphere, freshwater discharging

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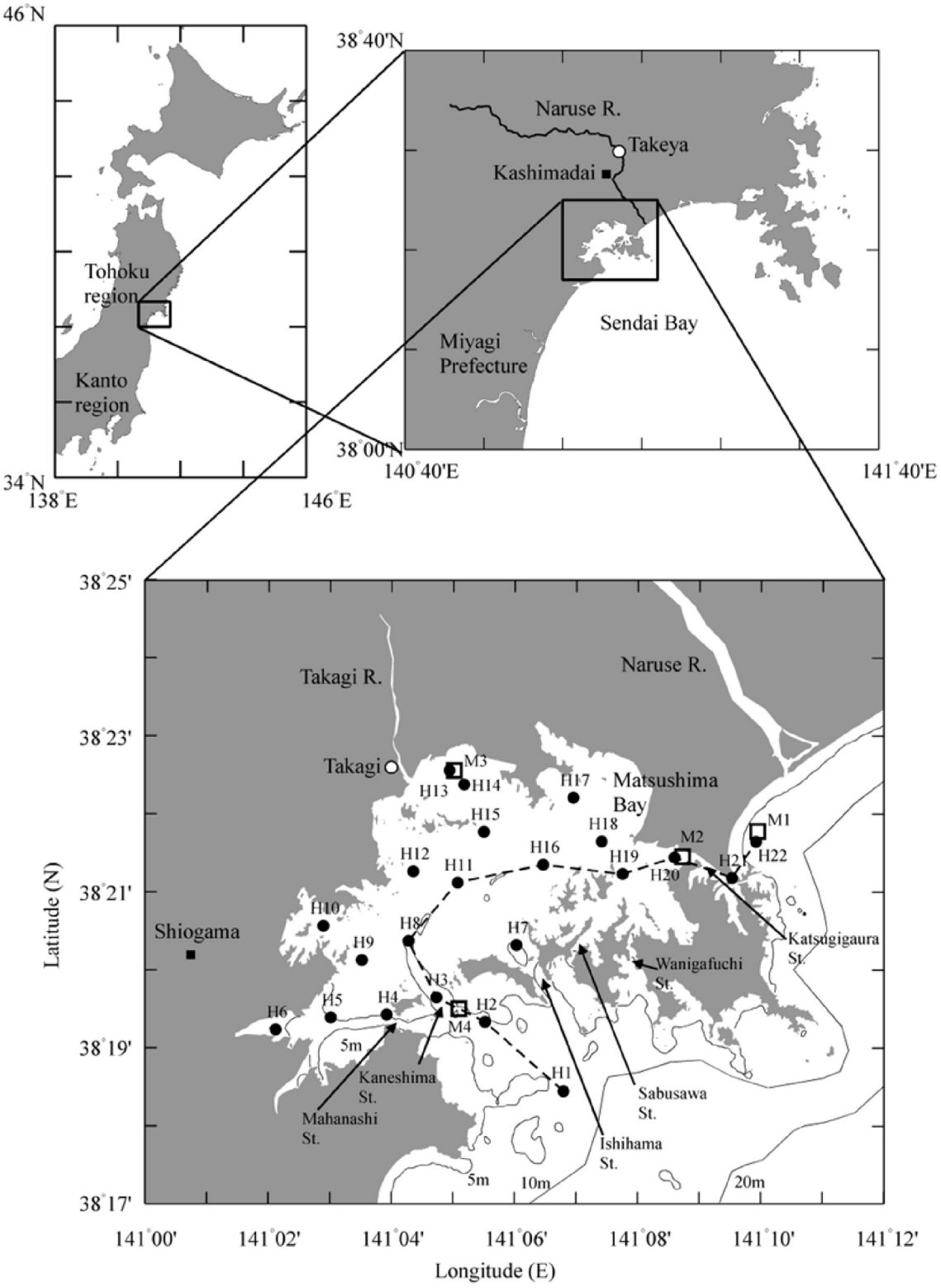

Fig. 1. Locations of Matsushima Bay and the Naruse River system, and observation stations. Open squares indicate the mooring system stations used for current and salinity measurements, and closed circles indicate the stations where hydrographic observations were conducted. Open circles (Takeya and Takagi) show the locations of the stations on the Naruse and Takagi rivers where water level was measured, and closed squares (Kashimadai and Shiogama) show the locations of AMeDAS stations. Arrows indicate the various straits connecting Matsushima Bay with Sendai Bay. Broken line indicates the longitudinal section shown in Fig. 3.

into the sea is deflected to the right by the Coriolis force (Simpson, 1997); therefore, freshwater discharged by the Naruse River tends to flow toward Matsushima Bay. Kakehi et al. (2016) suggested that freshwater from the river flows through Katsugigaura Strait into Matsushima Bay and enhances horizontal circulation in the bay. Aquaculture of the Pacific oyster (*Crassostrea gigas*) and red algae