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Relative contributions of external forcing factors to circulation and hydrographic properties in a micro-tidal bay

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ABSTRACT

The dominant external forcing factors influencing estuarine circulation differ among coastal environments. A three-dimensional regional circulation model was developed to estimate external influence indices and relative contributions of external forcing factors such as external oceanic forcing, surface heat flux, wind stress, and river discharge to circulation and hydrographic properties in Tango Bay, Japan. Model results show that in Tango Bay, where the Tsushima Warm Current passes offshore of the bay, under conditions of strong seasonal winds and river discharge, the water temperature and salinity are strongly influenced by surface heat flux and river discharge in the surface layer, respectively, while in the middle and bottom layers both are mainly controlled by open boundary conditions. The estuarine circulation is comparably influenced by all external forcing factors, the strong current, surface heat flux, wind stress, and river discharge. However, the influence degree of each forcing factor varies with temporal variations in external forcing factors as: the influence of open boundary conditions is higher in spring and early summer when the stronger current passes offshore of the bay, that of surface heat flux reflects the absolute value of surface heat flux, that of wind stress is higher in late fall and winter due to strong seasonal winds, and that of river discharge is higher in early spring due to snow-melting and summer and early fall due to flood events.

1. Introduction

Regions of freshwater influence (ROFI; Simpson et al., 1993) form transition zones between oceanic and riverine environments and are one of the most productive marine ecosystems (McLusky and Elliott, 2004). ROFI ecosystems are driven by complex interactions of physical and biochemical processes, and the physical processes such as estuarine circulation have a major influence on the biochemical processes through the transport of nutrients and organisms (Mann and Lazier, 2005). The physical processes are under the combined influences of external forcing: oceanic (such as tides, waves, and the intrusion of high salinity water), atmospheric (such as surface heat flux and wind stress), and riverine (such as river discharge) forcing (reviewed by Uncles, 2002). Extensive studies on the influences of external forcing on ROFIs have shown that they are dominated by forcing factors such as tides (e.g., Sylaios et al., 2006), wind stress (e.g., Geyer, 1997; Carniello et al., 2011), and river discharge (e.g., Liu et al., 1997), or a balance between/among these forcing factors (e.g., Niedda and Greppi, 2007). The dominant forcing factor changes in different ROFI environments, and the degree of influence of each forcing factor varies with temporal variations in external forcing factors (reviewed by Llebot et al., 2014).

Wakasa Bay (Fig. 1), located in western Honshu Island, Japan, is one of the largest bays along the Japanese coast of the Sea of Japan. The bottom depth is 50–100 m over a large section of the bay, being deepest in the mouth of the bay. It is well known that the tide is small in the Sea of Japan, and the tidal range is less than 50 cm at the Maizuru tidal station of the Japan Meteorological Agency. The Tsushima Warm Current enters the Sea of Japan through the Tsushima Straits and flows at depths shallower than 200 m offshore of Wakasa Bay (Hase et al., 1999). Strong northwesterly winds prevail in late fall and winter, whereas in summer winds are weak except during sporadic events such as typhoons. Two large rivers, the Yura River and the Kita River, flow into the bay. The ROFI of the Yura River (Tango Bay; Fig. 1c) is located in the southwestern part of

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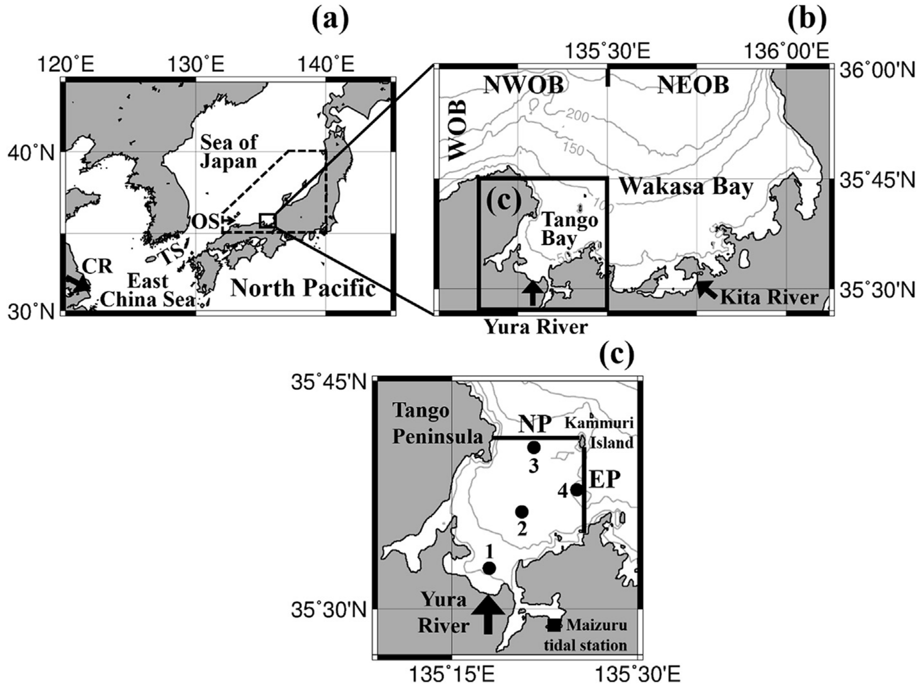

Fig. 1. (a) Location of the study area. CR, TS, and OS indicate Changjiang River, Tsushima Straits, and Oki Strait, respectively, and the dashed polygon indicates the domain of the DR_C model develop by Hirose et al. (2016). (b) Model domain and bathymetry with a contour interval of 50 m. WOB, NWOB, and NEOB indicate the western, northwestern, and northeastern open boundary, respectively. (c) Observation stations with bathymetry with a contour interval of 25 m. Lines NP and EP indicate the northern and eastern passage of Tango Bay, respectively. Numbers represent station numbers.

Wakasa Bay and is connected through two passages, the northern (NP) and eastern (EP) passages, which are east and south of the Kammuri Island (ca. 22 km from the river mouth), respectively. This ROFI is an important spawning and nursery ground for several fishes such as seabass (*Lateolabrax japonicus*) and flounder (*Paralichthys olivaceus*), and the estuarine circulation plays an important role in the transport of eggs and larvae (Fuji et al., 2010, 2014; Watanabe et al., 2014).

Several physical oceanographic surveys in and around Wakasa Bay have been conducted. Yamagata et al. (1984) and Umatani et al. (1986) reported the intrusion of a warmer and less saline water mass, derived from the Tsushima Warm Current, into Wakasa Bay in summer. Hashimoto (1982) and Hara et al. (1992) reported the occurrence of anticyclonic circulation in Wakasa Bay in summer caused by the Tsushima Warm Current. Kumaki et al. (2005, 2012) reported the occurrence of a strong coastal current related to the increase and decrease in water temperature around the Tango Peninsula after and before the passage of a typhoon, respectively. Although previous studies mainly focused on short-term fluctuations, Itoh et al. (2016) conducted a long-term mooring and hydrographic survey at four stations (corresponding to St. 1–4 shown in Fig. 1c) between 2012 and 2014 in order to clarify the seasonal circulation pattern in Tango Bay and the forces driving this flow. As their results show, the anticyclonic circulation flows across the bay with the inflow and outflow at the eastern and northern openings, respectively, and this flow intensifies in winter. They carried out correlation analysis between mooring data (velocity and salinity) and forcing factors (river discharge, wind speed and direction, and Tsushima Warm Current index), and concluded that the circulation in the bay is strongly affected by seasonal winds and the Tsushima Warm Current.

Numerical simulations also have been conducted in coastal regions including Wakasa Bay. Igeta et al. (2007) and Kumaki et al. (2012) used a three-dimensional hydrodynamic model with a horizontal resolution of 1 km to explain the generation mechanism of the strong coastal current around the Tango Peninsula before and after the passage of a typhoon. The model results showed that the "before" current was generated by continuous strong easterly winds (Kumaki et al., 2012), and the "after" one was caused by the backwash from waves breaking in the swash zone (Igeta et al., 2007). While both previous models considered only wind stress as forcing, Hirose et al. (2016) developed a three-dimensional coastal ocean model (called DR_C) with a horizontal resolution of 1.5 km considering a realistic open boundary condition obtained from a regional data assimilation system (Hirose et al., 2013), surface heat flux, wind stress, and river discharges. The polygon in Fig. 1a indicates the DR_C model domain. The DR_C simulated rapid changes in the coastal current mostly associated with strong wind events, and the model results showed good agreement with in-situ velocity observations. The model also simulated the anticyclonic circulation in Wakasa Bay, which was developed from a vortex separated from the Tango Peninsula.

Physical processes in an open bay, which is influenced by river water, are generally complex and highly localized (Simpson, 1997; Itoh et al., 2016). Although previous studies reported that Wakasa Bay is significantly influenced by the Tsushima Warm Current and wind stress, the relative contribution of each forcing factor has not been evaluated as compared with the other factors such as surface heat flux and river discharge. In this study using a three-dimensional regional circulation model, therefore, we evaluated the relative contributions of external forcing factors such as external oceanic forcing, surface heat flux, wind stress, and river discharge to circulation and hydrographic properties (i.e., water temperature, salinity, and velocity) in Tango Bay on a monthly and annual time scale.