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Numerical Experiment on the Fortnight Variation of the Residual Current in the Ariake Sea

Atsuyoshi MANDA, Atsuko YAMAGUCHI
and Hideaki NAKATA

*Faculty of Fisheries, Nagasaki University,
1-14 Bunkyo, Nagasaki 852-8521, Japan*

Abstract—The fortnight variations of the residual current in the Ariake Sea, a partly mixed estuary located in the western part of Japan, are investigated with a three-dimensional numerical ocean model. Regardless of season, lateral shear dominates at spring tide and vertical shear is intensified at neap tide. The density-driven current dominates the overall structure of the residual current. The Ekman number is the dominant parameter that controls the overall structure of the density-driven current, indicating that the magnitude of the tidal mixing is the most important factor that controls the structure of the density-driven current. The current structure is not sensitive to the Kelvin number, which suggests the bay width is not a constraint on the density-driven current.

Keywords: residual current, density-driven current, Ekman number, Kelvin number

1. INTRODUCTION

The residual current, defined as a de-tided current (i.e., tidal period velocity fluctuations are removed), plays a fundamental role in transporting various materials in estuaries and is therefore important for chemical-biological processes. The residual current consists of density- and wind-driven currents and a tide-induced residual current (TIRC; Tee, 1976; Yanagi, 1976). In this study, the TIRC is defined as the de-tided current with a constant density field.

The Ariake Sea is a macrotidal, partly mixed estuary, located in the western part of Japan (Fig. 1). In the Ariake Sea the density-driven current has been considered a dominant component of the residual current and one of the most important physical processes that transports various materials (Matsuno and Nakata, 2004). The density-driven current in the area varies greatly over time, but the available information on the current is qualitative and speculative. Quantitative description of the current is very limited.

Yanagi and Shimomura (2006) discuss the seasonal variation of the residual current in the Ariake Sea using a box model, based on the budgets of mass, salt, and temperature. They indicate that the transversal shear is intensified during summer, but the vertical shear dominates during winter. They propose that the Kelvin number, defined as the bay width scaled by the deformation radius (Simpson, 1997),

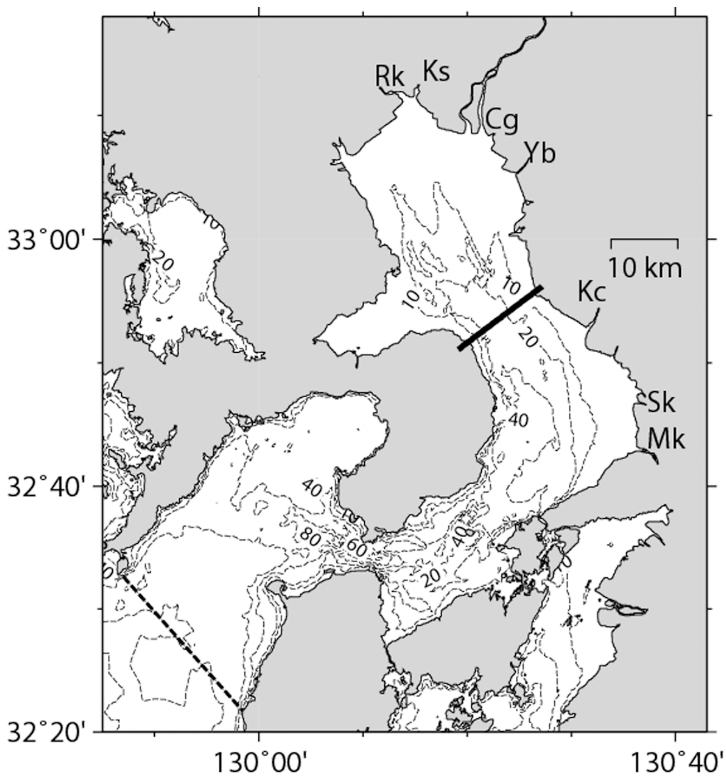

Fig. 1. Map of the Ariake Sea. Dashed contours are isobaths in meters. Thick solid and dashed lines indicate the locations of section A and the open boundary of the numerical model, respectively. Locations of the mouths of rivers, Rokkaku, Kase, Chikugo, Yabe, Kikuch, Shira-Kawa and Midori-kawa are indicated by Rk, Ks, Cg, Yb, Kc, Sk and Mk, respectively.

is an important parameter that determines the structure of the residual current.

Recent studies show evidence for fortnight variations in the residual currents in estuaries (e.g., Valle-Levinson, 2000). Yanagi and Shimomura's (2006) analysis in the Ariake Sea, however, neglects the fortnight variation of the residual current since they use the data sampled during only spring tides. If present, large fortnight variation of the tidal mixing in the Ariake Sea would result in the large modulation of the density-driven current, but little is currently known. In this study, numerical experiments are carried out in order to elucidate the fortnight variation of the spatial structure of the residual current in the Ariake Sea.

2. EXPERIMENT DESCRIPTION

The numerical model used in this study is the Princeton Ocean Model (Blumberg and Mellor, 1987). The horizontal grid employs a curvilinear orthogonal system with a variable resolution ranging from 350 m to 1170 m. The vertical coordinate is a sigma co-ordinate (terrain-following normalized coordinate) and the number of the vertical layer is 10. Bathymetry data are the same as in Manda and Matsuoka (2006). The model was forced by the M_2 and S_2 tides and river runoffs. Wetting and drying schemes (Oey, 2006) are employed for simulating water run-up and run-down across movable land-sea boundaries. Open boundary conditions are the same as in Oey and Chen (1992). The river discharge is modeled as a freshwater source from the river mouths in the continuity equation (Kourafalou et al., 1996). Temperature is held fixed in each experiment with density dependent only on salinity, this is a reasonable assumption in estuarine studies.

Three model runs were conducted in the numerical experiments. Runs 1 and 2 were designed so that the model reproduced the mean residual current in summer and winter, respectively. Run 3 was designed to reproduce the TIRC. The river discharge rate and the initial salinity conditions in Runs 1 and 2 were set to the representative values in July and January, respectively. River discharge rates are time invariant for simulating the seasonal mean fields with fortnight modulations. In Run 3, salinity is held fixed and river discharge rate is set to zero. The time integration of the model started from a state of rest and was carried out until the model reached the quasi-steady state. 25-hour averaged velocity was computed to obtain the residual current at the spring and neap tides in each run. The 25-hour averaged velocity in Run 3 is subtracted from the residual current in Runs 1 and 2 to calculate the velocity field of the density-driven current.

3. RESULTS AND DISCUSSION

Figure 2 shows the cross sections of the residual current along section A (see Fig. 1 for location). Lateral shear dominates at spring tide and vertical shear is intensified at neap tide during both summer and winter. Figure 3 shows the cross sections of the TIRC along the same section. The magnitude of the longitudinal component of the TIRC is small compared to the density-driven current (Fig. 4) and the cross sections of the density-driven current are very similar to those of residual current.

The Ekman number, which represents a ratio of the viscous to the Coriolis forces, and the Kelvin number are estimated using the model's output. The Kelvin number during winter is about three times larger than that during summer at both spring and neap tides (Fig. 4), which indicates the overall structure of the residual currents is not sensitive to the Kelvin number and the bay width is not a constraint on the lateral circulation as speculated by Yanagi and Shimomura (2006). The Ekman number during summer spring tides is five times larger than that of neap tides and the Ekman number during winter spring tides is three times larger than that of neap tides (Fig. 4). The current structures in spring and neap tides change accordingly, indicating that the Ekman number is the dominant parameter controlling the structure of the residual current.

Solutions for the analytical model by Kasai et al. (2000) are compared to the results of the numerical model in order to further investigate the dominant factor

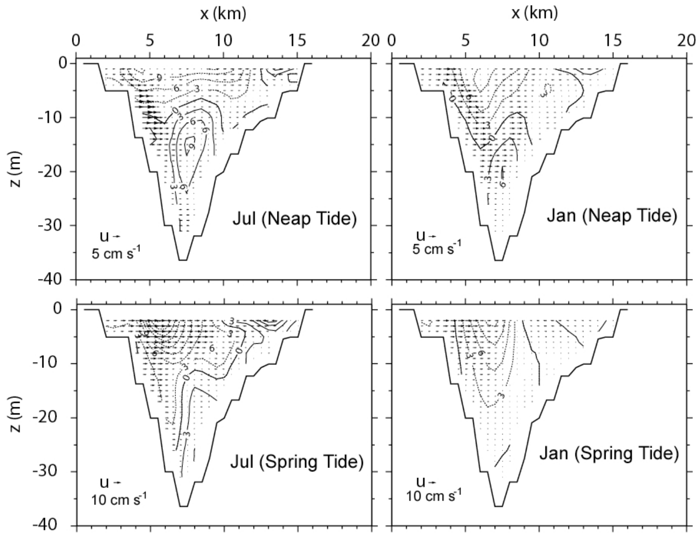

Fig. 2. Cross-sections of the residual currents at section A. Solid and dashed contours indicate landward and seaward currents in cm s^{-1}, respectively. Arrows indicate transversal components of current velocity.

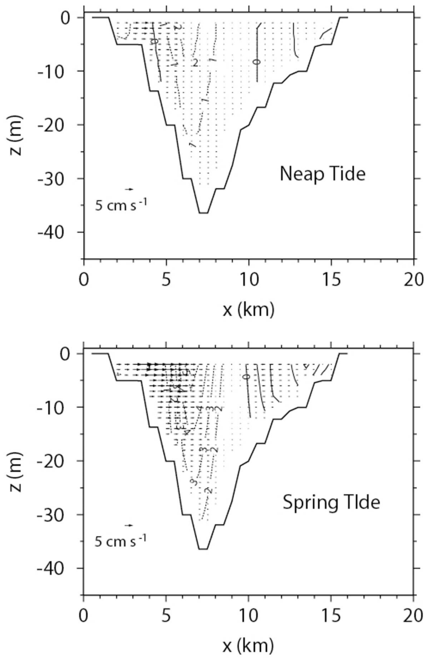

Fig. 3. Cross-sections of the tide-induced residual current at section A.

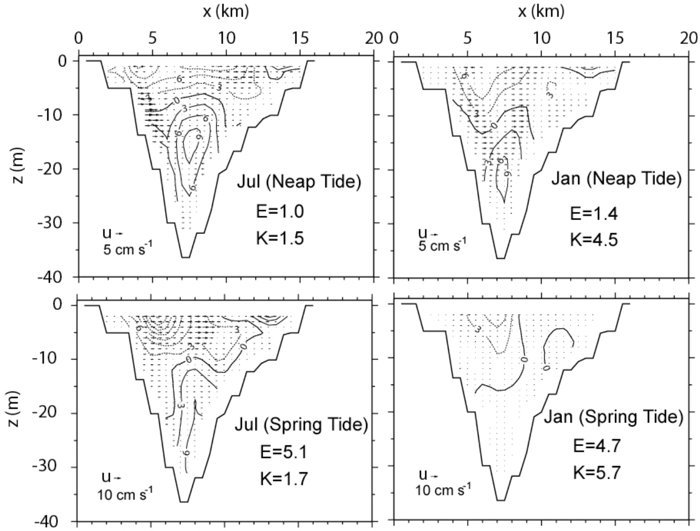

Fig. 4. Cross-sections of the density-driven current at section A. Solid and dashed contours indicate landward and seaward currents in cm s^{-1}, respectively. Arrows indicate transversal components of current velocity. E and K indicate the Ekman and Kelvin numbers, respectively.

that controls the structure of the density-driven current. Due to its simplicity, the analytical model is useful for isolating the most important factor that controls the current structure. The analytical model assumes a steady state and the dynamic balance among the Coriolis, viscous, and pressure-gradient forces. All the model parameters are time invariant and spatially constant. These assumptions greatly simplify the model's dynamics, compared to the numerical model. Figure 5 shows the cross sections of the density-driven current computed with the analytical model. The analytical model uses the cross sectional averages of the parameters in Figure 6. Although the parameters obtained by the numerical experiment show large transversal variation (Fig. 6), the analytical model reproduces well the overall current structure of the numerical model, i.e., lateral shear dominates at spring tide and vertical shear is intensified at neap tide during both summer and winter. It indicates that the dominant factor that controls the structure of the density-driven current is the magnitude of the cross sectional averages of these parameters.

The numerical model shows a northward current near the eastern coast at spring tide (Fig. 4), which is not reproduced by the analytical model (Fig. 5). After a slight modification of the analytical model, to take into account transversal variations of the model parameters (Fig. 6), the model reproduces the northward current near the eastern coast at spring tide (Fig. 7). Although the horizontal shear is stronger compared to the numerical model, this result indicates the deviations from the cross sectional averages of the model parameters affect the detailed structure of the density-driven current. Even though the river discharge rates of three rivers near

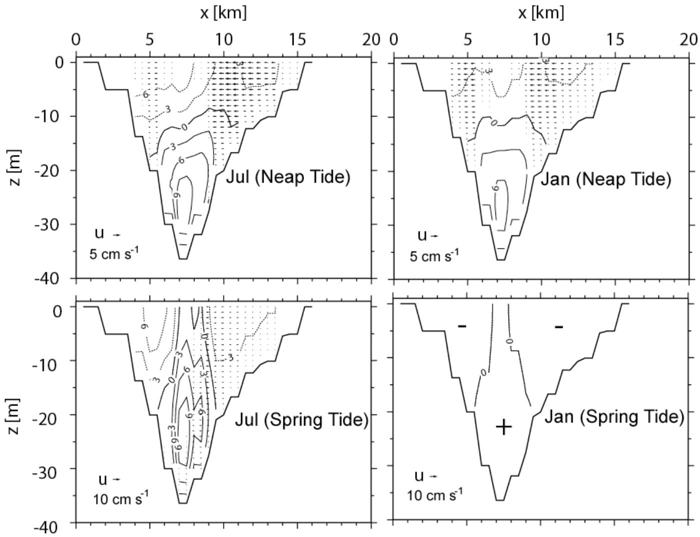

Fig. 5. Cross-sections of the density-driven current at section A computed with the analytical model.

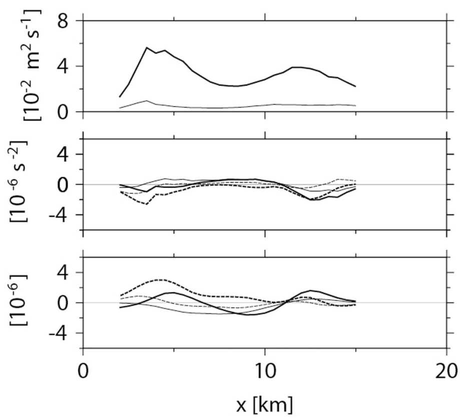

Fig. 6. Transversal variation of the 25-hour averaged model parameters in July. (Top) Vertically averaged vertical eddy viscosity, (middle) vertically averaged baroclinic pressure gradient, (bottom) gradient of surface elevation. Thick and thin lines indicate spring and neap tides, respectively, and solid and dashed lines indicate the transversal and longitudinal components, respectively.

section A (Kikuchi, Shira-Kawa, and Midorikawa rivers) are set to zero, the numerical model still shows the northward current (not shown), which suggests that the freshwater outflows of these rivers are not the dominant factors that control the

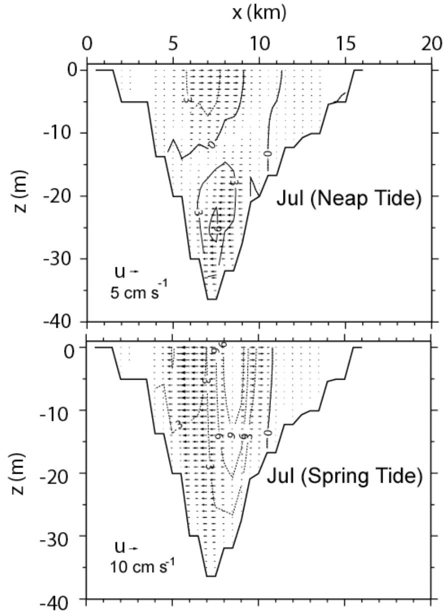

Fig. 7. Cross-sections of the density-driven current at section A in July computed with the analytical model with space-dependent model parameters.

cross sectional variations of the model parameters and the northward current near the eastern coast.

4. CONCLUSION

Fortnight variation of the residual current in the Ariake Sea is investigated using a three-dimensional numerical model (Princeton Ocean Model). Regardless of season, lateral shear dominates at spring tide and vertical shear is intensified at neap tide. The magnitude of the TIRC is small compared to that of the density-driven current. The Ekman number is shown to be the dominant parameter that controls the overall structure of the density-driven current. However, the current structure is not sensitive to the Kelvin number, which indicates the bay width is not a constraint on the density-driven current. Since the tidal current is the most energetic high-frequency velocity fluctuation that is parameterized by the eddy viscosity in estuaries, the magnitude of the tidal current is the most important factor that controls the structure of the density-driven currents. Although the transversal variations of the model parameters have secondary importance, they affect the detailed structure of the density-driven current.

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REFERENCES

Blumberg, A. F. and G. L. Mellor. 1987. A description of a three-dimensional coastal ocean circulation model. In: *Three-dimensional Coastal Ocean Models*, N. Heaps (Ed.), American Geophysical Union, Washington, D.C., pp. 1–16.

Kasai, A., A. E. Hill, T. Fujiwara and J. H. Simpson. 2000. Effect of the Earth's rotation on the circulation in regions of freshwater influence. *Journal of Geophysical Research* **105**: 16961–16969.

Kourafalou, V. H., L.-Y. Oey, J. D. Wang and T. N. Lee. 1996. The fate of river discharge on the continental shelf 1. Modeling the river plume and the inner shelf coastal current. *Journal of Geophysical Research* **101**: 3415–3434.

Manda, A. and K. Matsuoka. 2006. Changes in tidal currents in the Ariake Sea due to reclamation. *Estuaries and Coasts* **29**: 645–652.

Matsuno, T. and H. Nakata. 2004. Physical processes in the current fields of Ariake Bay. *Bulletin on Coastal Oceanography* **42**: 11–17.

Oey, L.-Y. 2006. An OGCM with movable land-sea boundaries. *Ocean Modelling* **13**: 176–195.

Oey, L.-Y. and P. Chen. 1992. A model simulation of circulation in the northeast Atlantic shelves and seas. *Journal of Geophysical Research* **97**: 20087–20115.

Simpson, J. H. 1997. Physical processes in the ROFI regime. *Journal of Marine Systems* **12**: 3–15.

Tee, K. T. 1976. Tide-induced residual current, a 2-D nonlinear numerical tidal model. *Journal of Marine Research* **34**: 603–628.

Valle-Levinson, A., K.-C. Wong and K. M. M. Lwiza. 2000. Fortnightly variability in the transverse dynamics of a coastal plain estuary. *Journal of Geophysical Research* **105**: 3413–3424.

Yanagi, T. 1976. Fundamental study on the tidal residual circulation I. *Journal of the Oceanographical Society of Japan* **32**: 199–208.

Yanagi, T. and M. Shimomura. 2006. Seasonal variation in the transverse and layered structure of estuarine circulation in Ariake Bay, Japan. *Continental Shelf Research* **26**: 2598–2606.

A. Manda (e-mail: manda@nagasaki-u.ac.jp), A. Yamaguchi and H. Nakata