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Changes in Tidal Currents in the Ariake Sound Due to Reclamation

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ABSTRACT: The Ariake Sound is a highly productive estuary located in the western part of Japan. The decline in fisheries and the frequent occurrence of red tides and hypoxia indicate a deterioration in the ecosystem of the sound. A change in tidal currents, which is one of the possible causes of the deterioration, was investigated by numerical experiments. Two major changes in the topography of the sound, which may have changed the tidal currents, are examined. These are the reclamation in the innermost part of the sound and the construction of a dyke in a subembayment called Isahaya Bay. The numerical experiments show that the reclamation caused the tidal currents to decrease by more than 10% over a large area in the innermost part of the sound. The influence of the dyke on the tidal currents is relatively local compared to the reclamation; the area where tidal currents significantly decrease is located mostly in the subembayment.

Introduction

Ariake Sound is a highly productive estuary located in the western part of Japan (Fig. 1). It is connected to another small basin (Tachibana Bay) by a narrow strait (Hayasaki-seto) and includes the small subembayment called Isahaya Bay. The sound is strongly influenced by tidal currents and freshwater outflow and can be categorized in the gulf-type region of freshwater influence (ROFI; Simpson 1997).

The Ariake Sound has shown a recent deterioration in its ecosystem. Hypoxia and red tides have occurred more frequently since the 1990s, and have caused serious damage to the fisheries. Two studies suggest that the changes in the ecosystem in the Ariake Sound started much earlier than this. Analyses of bottom sediments revealed that the dinocyst assemblage in the innermost part of the Ariake Sound has been changing since the end of the 1960s, which may indicate changes in primary production (Matsuoka 2004). Catch of the shellfish *Ruditapes philippinarum*, which is one of the commercially important species in the Ariake Sound, has decreased since the beginning of the 1980s (Kikuchi 2000).

Tidal currents have profound effects on the functioning of biological systems in the ROFI (Mann 2000). Vertical mixing due to turbulence in the water column caused by tidal currents is one of the main mechanisms for mixing the water column. Since the tidal range in the Ariake Sound is very large (3–5 m), tidal currents play a pivotal role in controlling the density stratification and phytoplankton production since the basic mechanism regulating production is the alternation of vertical mixing with stratification in the water column (Mann 2000).

During the last five decades, there were two major changes in the topography of the Ariake Sound that could have affected the tide and tidal currents. One is the reclamation in the innermost part of the sound that occurred from the 1960s to the mid 1970s; the other is the construction of a dyke in Isahaya Bay that occurred in the 1990s (Fig. 1). Since the longitudinal dimension of the Ariake Sound (ca. 100 km) is much shorter than the wavelength of barotropic tidal waves, the decrease in the area of the sound could reduce the amplitude of the tide as well as that of the tidal currents.

Some numerical experiments have been conducted in order to estimate the changes in tidal currents due to the construction of the dyke (e.g., Tsukamoto and Yanagi 2002; Fujiwara et al. 2004). No studies have been carried out on the changes in tidal currents due to the effect of the reclamation. This paper examines the influence of these changes in topography on the tidal currents in the Ariake Sound by numerical experiments. The main objective of this study is to assess the influence of the reclamation on the tidal currents in the Ariake Sound. Another objective is to compare the effect of the dyke with that of the reclamation. No comparative work has been carried out into the change in

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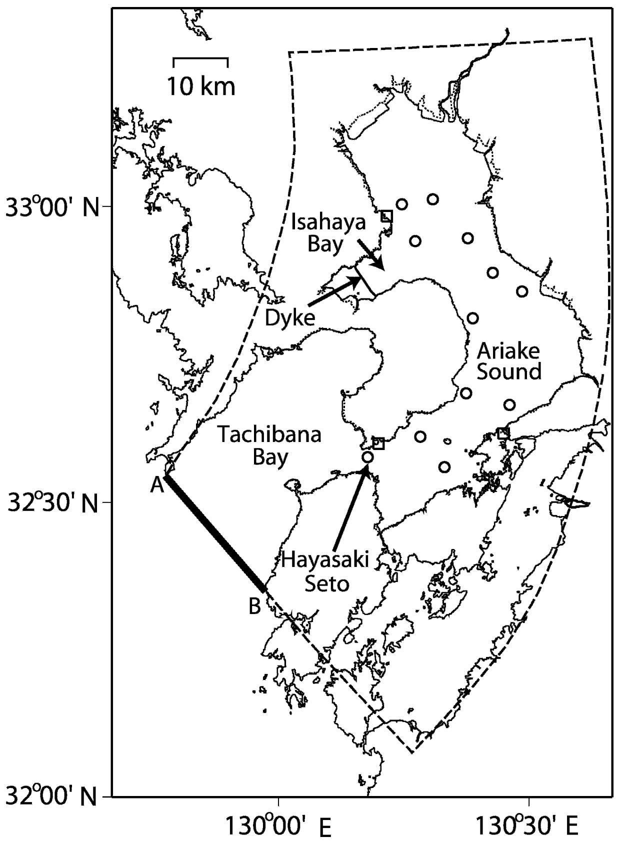

Fig. 1. Map showing the geographical location of the Ariake Sound. The dotted and solid lines indicate the coastlines in the 1940s and 1990s, respectively. The area enclosed by the dashed line shows the computational domain of the numerical model. The thick line AB indicates the open boundary. The circles and squares show the locations of the current meter moorings and tide gauges, respectively.

tidal currents due to the reclamation compared to that due to the dyke.

Materials and Methods

Data Source

In order to evaluate changes in tidal currents due to changes in bathymetry, we produced five model bathymetries, the details of which will be described later. The following data sets were used for producing the model bathymetries. The bottom topography data set J-EGG500 was used as the bottom topography data for the 1990s. This was distributed by the Japan Oceanographic Data Center (JODC). The World Vector Shoreline database distributed by National Oceanic and Atmospheric Administration (NOAA)/National Geophysical Data Center (NGDC) was employed for the coastline data in the 1990s. The historical chart for the 1940s provided by JODC was also used as the topographic data before the reclamation carried out in the 1960s. The bathymetric chart for the 1940s was digitized in order to produce the coastline and bottom topography data sets for the 1940s.

Sea level data at three tide gauges in the Ariake Sound, which were observed by the Japan Meteorological Agency (JMA) and distributed by the JODC, were used for the comparison of model results with observations. The locations of the gauges are indicated by the squares in Fig. 1.

The Numerical Model

The numerical model used in this study is the two-dimensional version of the Princeton Ocean Model (Blumberg and Mellor 1987). In this study, the model simulates the M_2 tide and tidal currents, which are predominant in the Ariake Sound. The area enclosed by the dashed line in Fig. 1 shows the domain of computation. The horizontal grid employs a curvilinear orthogonal system with a variable resolution ranging from 350 to 1,170 m. For specifying the bottom drag coefficient, we employ Manning's formula (e.g., Granger 1985), following Tsukamoto and Yanagi (2002). This formula reproduces well the tidal currents in the Ariake Sound for the 1980s and 1990s. The roughness coefficient is set to 0.02 unless otherwise stated.

All of the model bathymetries used in this study have been constructed with a grid generator called Seagrid (Denham unpublished data). Seagrid uses the conformal transformation for mapping the curved perimeter to a rectangle, after which a Poisson solver fills the interior with orthogonally distributed grid points. Figure 2 shows the model's bathymetries during the 1940s and 1990s produced with Seagrid and the difference in depth between these bathymetries. For convenience, we refer to the coastlines in the 1940s and 1990s as CL40 and CL90, respectively. Also, the bottom topographies during the 1940s and 1990s are referred to as BT40 and BT90, respectively.

The tidal elevation at the mouth of Tachibana Bay, which is indicated by the thick line in Fig. 1, is provided as the open boundary condition for the surface elevation. The tidal elevation is prescribed as the sinusoidal variation of the surface elevation. Since there are no tidal observations available on the open boundary, the amplitude of the tide on the open boundary was determined by a sensitivity experiment.

Sensitivity Experiment and Model Evaluation

In order to determine the tidal amplitude on the open boundary, a sensitivity experiment was conducted. The model is compared with the tide and tidal currents that occurred in 2001 since both tide

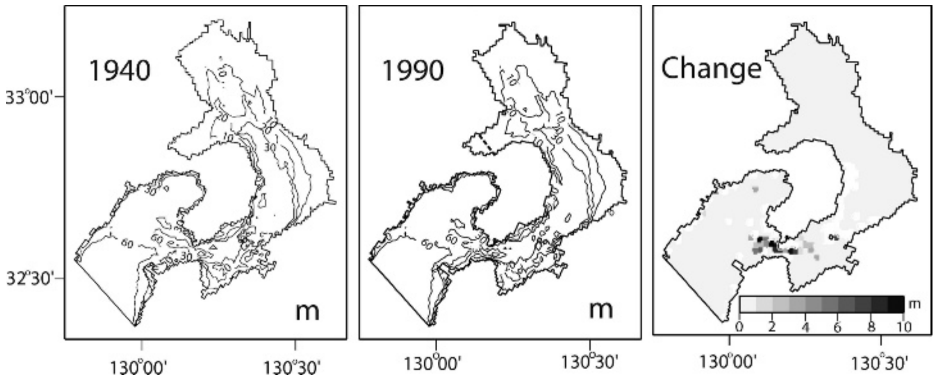

Fig. 2. Model's bathymetries in (left) the 1940s and (middle) 1990s, and (right) their difference in depth. Dashed line indicates the location of the dyke.

and tidal current data are available for that year. The use of two statistically independent data sets is indispensable to avoid overfitting the model. The model uses the CL90 and BT90 and has a dyke in Isahaya Bay so that the model simulates the tide and tidal currents of 2001. The cost function, which is used in this experiment to measure the model misfit, is based on the error estimator used by Davies et al. (1997) and is defined as

$$H_s = \frac{1}{n}\sum_{i=1}^{n}\left\{(HC_i)^2 + (HS_i)^2\right\}^{1/2} \quad (1)$$

where n is the number of tide gauges and

$$HC = h_o\cos(g_o) - h_c\cos(g_c) \quad (2)$$

$$HS = h_o\sin(g_o) - h_c\sin(g_c) \quad (3)$$

h_o and g_o are the observed amplitude and phase, and h_c and g_c are computed at a given tide gauge. The phase lag of the tide on the open boundary of the model is assumed to be constant for simplicity and set to 229 degrees, which is almost the same as that used in Tsukamoto and Yanagi (2002). The amplitude of the tide on the open boundary is assumed to be uniform and is optimized by computing H_s against many values of the amplitude. The result of this experiment is also used for the evaluation of the model performance in terms of velocity.

Effect of Bathymetry

In order to evaluate the changes in tidal currents due to the changes in bathymetry, five model runs with different model bathymetries (Runs 1–5) were performed. Run 1 employs CL40 and BT40, and Run 2 uses CL90 and BT90. Run 3 is the same as Run 2, except that there is a dyke in Isahaya Bay. Run 4 is the same as Run 1, except for the dyke. Run 5 uses CL90 and BT40 and was conducted to separate the effects of bottom and coastal topographies. Only the model bathymetry is changed throughout the experiment; all of the model parameters are the same as described earlier. The boundary condition is the same among all of the model runs. The tidal amplitude on the open boundary is uniform and set to 0.78 m, which is obtained by the sensitivity experiment, as illustrated later.

Results

Sensitivity Experiment and Model Evaluation

Figure 3 shows the cost function as a function of the tidal amplitude on the open boundary. The cost function is smallest when the tidal amplitude is 0.78 m, indicating that the value of 0.78 m is near optimal. The result is validated using the current velocity data, which is statistically independent of the tide data. The Hydrographic and Oceanographic Department of the Japan Coast Guard carried out current measurements in May 2001 and computed the harmonic constants of the tidal currents (Odamaki et al. 2003). The locations of the current meter moorings are shown in Fig. 1. The harmonic constants of the M_2 constituent obtained by the numerical experiment were compared with those of the observations in terms of the root mean square (RMS) errors of the length of the semi-major axes of the tidal ellipses, which indicate the maximum tidal current velocity. Figure 3 also shows that the RMS error is smallest when the tidal amplitude is 0.78 m. A tidal amplitude of 0.78 m once again seems to be the best choice among the values tested. Figure 3 shows that the RMS error of the model is approximately 2.2 cm s^{-1} when the amplitude is 0.78 m.

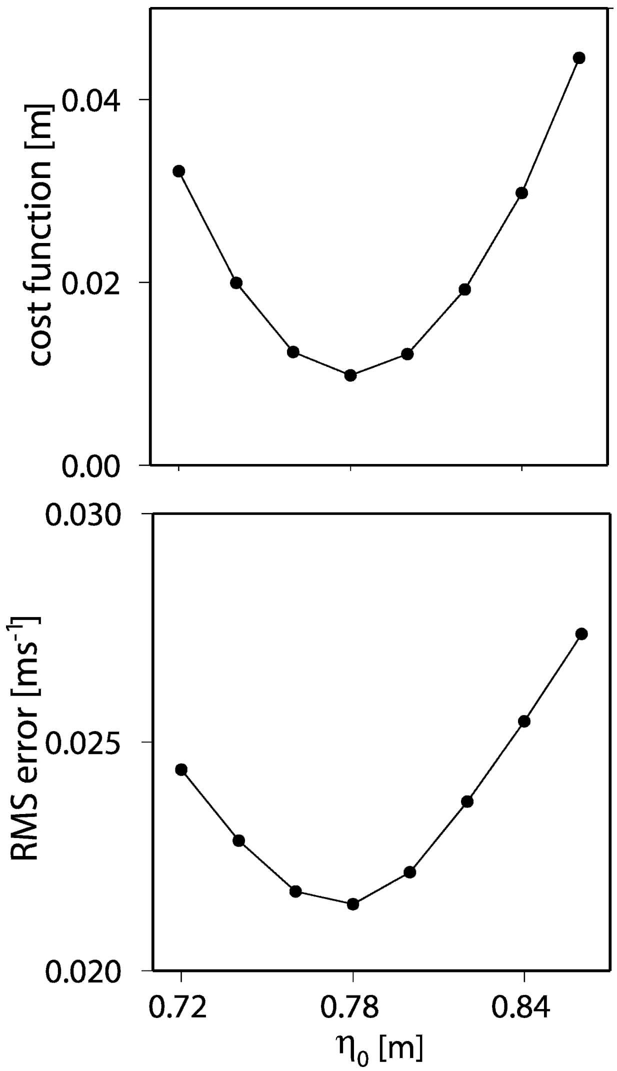

Fig. 3. (Upper) Dependence of the model error of the tidal amplitude on the tidal amplitude on the open boundary. (Lower) Dependence of the root-mean-square error of the tidal current velocity on the tidal amplitude on the open boundary (η_0).

Effect of Bathymetry

Figure 4 shows the ratio of the decrease in tidal currents in terms of the length of the semi-major axes of the tidal ellipses. Comparing Run 1 with Run 2, the areas with a large decrease in tidal currents are found in a large area in the innermost part of the sound. The ratio of the decrease in this area is 10–30%, except for the area closest to the coast. Comparing Run 2 with Run 3, the area of large decrease (>10%) is limited almost to Isahaya Bay, but the semi-major axes are slightly shorter (5–10%) in the middle part of the sound. The lower left panel compares Run 1 with Run 4 and is similar to the upper right panel. This indicates that the construction of the dyke affects the tidal currents mainly in Isahaya Bay, with or without the reclamation around the innermost part of the sound. In comparing Run 1 with Run 5, the tidal currents still decrease in the innermost part of the sound. A comparison of the upper left and lower right panels show that the decrease in the tidal currents in the innermost part of the sound is mainly caused by changes in the coastal topography rather than the bottom topography. The areas of negative decreasing ratio, which indicate an increase in tidal currents, are found in the upper left, but not in the lower right panel. This indicates that the areas of negative decrease in the ratio result from the local changes in the bottom topography from the 1940s to the 1990s.

Discussion

Mechanism of the Decrease in Tidal Currents

Since the tide in the Ariake Sound is primarily a standing wave, the head of the sound acts as an antinode of the tide, where the tidal current velocity remains at zero. The amplitude of the tidal currents may decrease near the head if the reclamation changes the location of the head towards the mouth. This can be demonstrated by a simple analytical model of the cooscillating tide in a rectangular basin (Officer 1973). Taking the x-axis in a longitudinal direction with the origin at the mouth, the amplitude of the tidal currents in the rectangular basin can be represented as:

$$A_u = \frac{a_0 \omega}{hk} \frac{\sin[k(l - x)]}{\cos kl} \tag{4}$$

where A_u is the amplitude of the tidal currents, the a_0 is the tidal amplitude at the mouth, ω is an angular frequency of the tide, h is the depth, l is the length of the basin, and k is the wave number. The longitudinal variation of the amplitude of tidal currents is represented by $\sin[k(l - x)]$. Since this term changes rapidly with x around the head, the change in the location of the head leads to a large change in the amplitude of the tidal currents in the innermost part of the basin. When the length of the basin decreases from l_1 to l_2 ($l_1 > l_2 > 0$), Eq. 4 gives the ratio of decrease in the amplitude of the tidal currents (R_u) as:

$$R_u = 1 - \frac{\cos kl_1}{\cos kl_2} \frac{\sin k(l_2 - x)}{\sin k(l_1 - x)} \tag{5}$$

In order to give the representative value for the Ariake Sound, the depth of the basin and the tidal period were set to 30 m and 12.42 h, respectively. The corresponding value of k is 8.2×10^{-6} m^{-1}, and the ratio of the reduction in the length of the basin is assumed to be 5%, i.e., $l_2 = 0.95 \times l_1$.

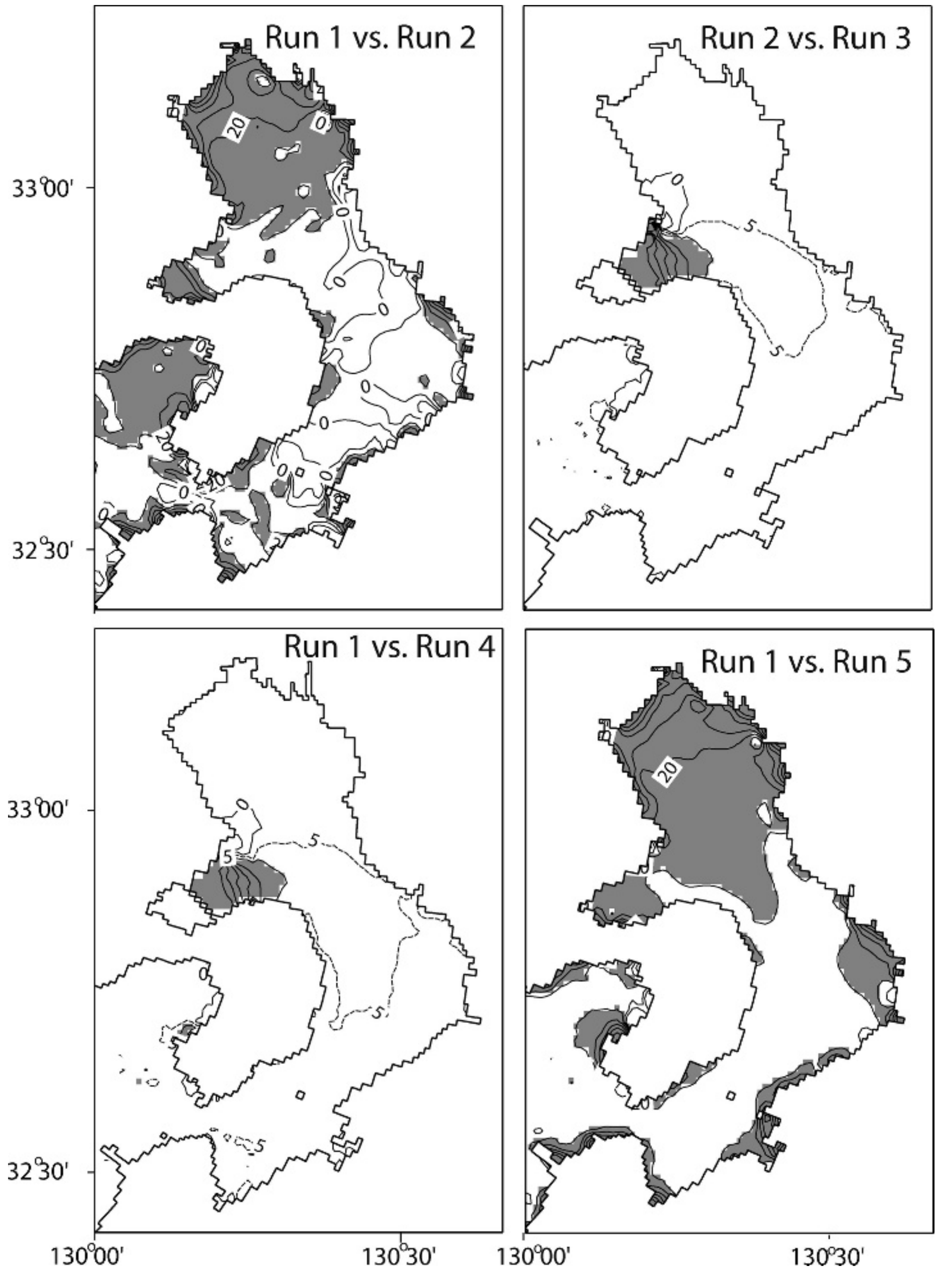

Fig. 4. Decrease in the length of the semi-major axis of the tidal ellipses in terms of percentage. The shaded area indicates the area where the length of the semi-major axis decreases by more than 10%.

Figure 5 shows a variation of R_u as a function of the dimensionless longitudinal coordinates and the decreases in ratios sampled from the lower right panel of Fig. 4 along the line in the lower panel of Fig. 5. R_u is not so large from the mouth to the middle part of the basin, but it increases rapidly with x near the head as expected. The numerical model results show good qualitatively agreement with that of the analytical model, which indicate that the change in the location of the antinode is a fundamental mechanism of the decrease in tidal currents in the innermost part of the Ariake Sound.

Effect of Long-term Variations of Tide, Bottom Roughness, and Mean Sea Level

There are three processes that might have caused the long-term variation in tidal currents, other than

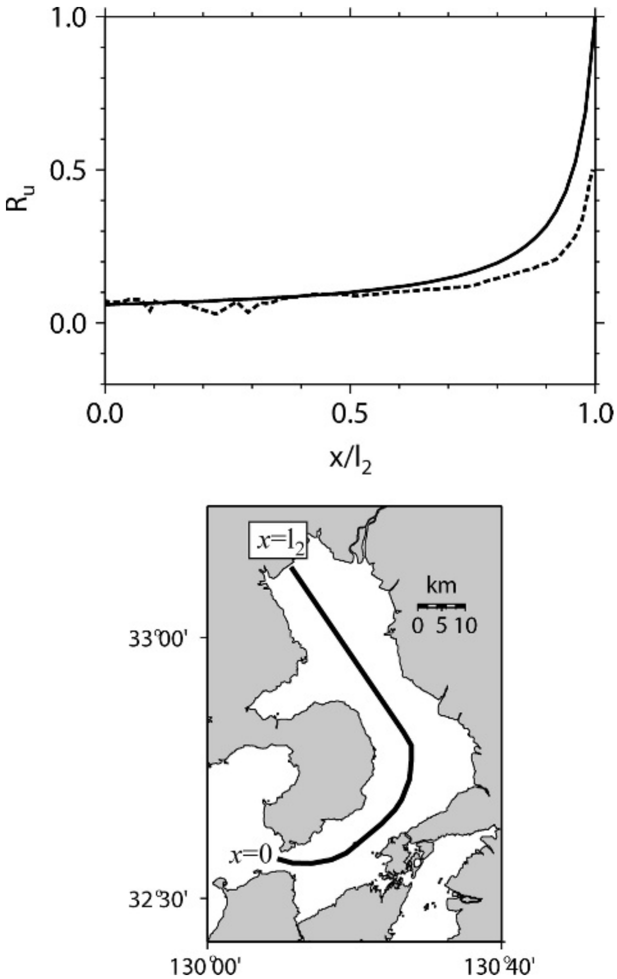

Fig. 5. (Upper) Ratio of decrease in the amplitude of tidal currents as a function of the dimensionless longitudinal coordinate. Solid line shows the decrease in ratio obtained by the analytical model. Dashed line shows the decrease in ratio sampled from the lower right panel of Fig. 4 along the line in the lower panel of this figure. (Lower) The line on which the decrease in ratio computed by the numerical model is sampled.

the changes in bathymetry: changes in tides due to a lunar nodal cycle, changes in bottom roughness, and changes in mean sea level. We examined whether these processes are important to tidal currents compared to changes in bathymetry. The lunar nodal cycle has a period of 18.6 yr, and might have caused the long-term variations in tidal currents in the Ariake Sound. The lunar nodal cycle causes the amplitude of the M_2 tide to vary by approximately $\pm$ 4%. Studies suggest that the median grain size of the bottom sediments around the innermost part of the Ariake Sound has been decreasing since the 1950s (Matsuoka unpublished data), so the bottom roughness could be larger than in the 1990s. Analysis of the sea level data around the Ariake Sound reveals that the mean sea level has increased by about 0.15 m since the 1970s (Tsukamoto and Yanagi 2002).

Additional model runs were conducted in order to assess the effect of these processes on tidal currents. Runs 1a and 1b are the same as Run 1 except for the tidal amplitude on the open boundary and the roughness coefficient around the innermost part of the sound. The tidal amplitude on the open boundary is decreased by 4% in Runs 1a and 1b. The roughness coefficient on the model grids north of 32°57′N is increased to 0.025 and 0.03 in Runs 1a and b in order to model the changes in the median grain size of the bottom sediments in the innermost part of the sound.

Run 2a is the same as Run 2 except for the tidal amplitude on the open boundary and mean sea level. The tidal amplitude on the open boundary is increased by 4%. The tidal amplitudes on the open boundary have been increased so that the maximum of the possible changes in the tides on the open boundary is taken into account. Mean sea level is increased by 0.15 m in Run 2a compared with Runs 1a and 1b in order to model the changes in mean sea level.

Figure 6 shows the changes in tidal currents in terms of the ratio of the decrease. The left panel compares Run 1a with Run 2a, and the right panel compares Run 1b with Run 2a. The overall pattern of the decrease in the ratio in this figure is similar to that in Fig. 4; the magnitude of the tidal currents still decreases in the innermost part of the sound. This result strongly suggests that tidal currents decreased in the innermost part of the sound during the 1940s to the 1990s and that the decrease in tidal currents is primarily due to the reclamation.

Influence of Changes in Tidal Currents on the Density Stratification

Tidal stirring is one of the most energetic mechanisms mixing the water column in the Ariake Sound. The decrease in tidal currents may intensify the density stratification, which may be of critical importance in controlling biological processes. The power available from the tidal stirring is proportional to u^3, where u is the amplitude of the tidal currents (Simpson et al. 1978). The decrease in tidal currents in the innermost part of the sound in Fig. 4 ranges from 10% to 30%, except for the area closest to the coast. The power available from the stirring decreases to about 35–70%, which may cause large changes in the density stratification around the innermost part of the sound. This could result in a significant effect on the biological processes occurring there.

As stated earlier, the Ariake Sound can be considered a gulf-type ROFI where the buoyancy is

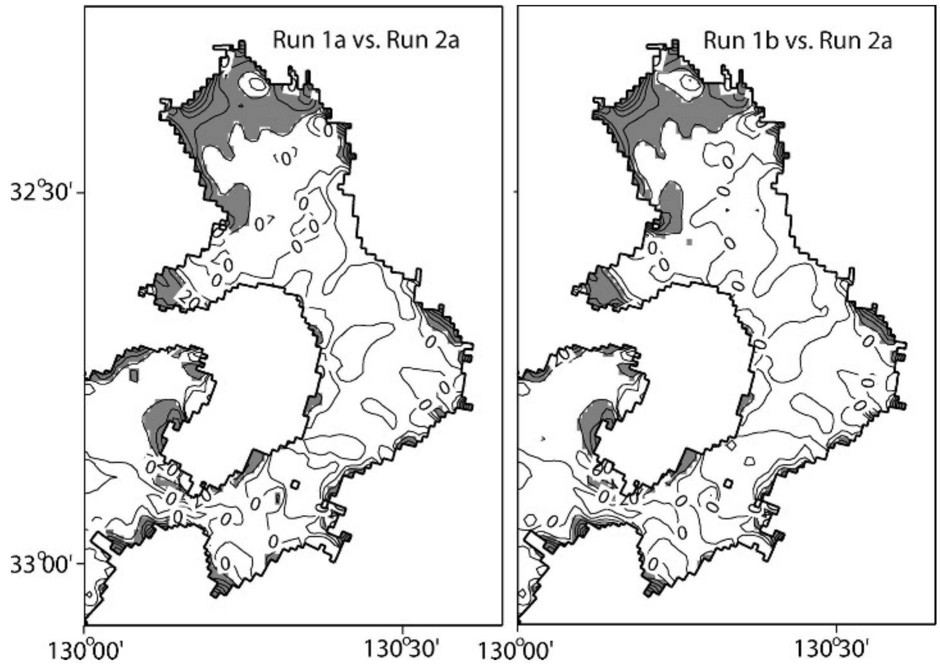

Fig. 6. Same as Fig. 4, except that (left) compares Run 1a with Run 2a and (right) compares Run 1b with Run 2a.

distributed horizontally by the local current system. The main controls on the stratification in the ROFI are tidal mixing, estuarine circulation, and tidal straining (Simpson et al. 1990). The contribution of the latter two depends on a local horizontal density gradient and the vertical velocity profile, which cannot be determined from external parameters such as the much-used h/u^3 criterion in the heating-stirring competition (Simpson et al. 1990). They must be determined by the internal dynamics in the ROFI. As stated in the classical theory of Hansen and Rattray (1965), the horizontal advection of density as well as the vertical diffusion are important in estuarine circulation, in contrast with the heating-stirring competition that is determined principally by the vertical energy balance.

The transversal current structure can dominate in the gulf-type ROFI as well as the changes in the vertical velocity profile (Wong 1994; Kasai et al. 2000). The horizontal distribution of the density gradient and velocity profile can be complex since circulation may vary considerably with a particular topography (Simpson 1997).

The use of a three-dimensional numerical model, which can deal with the inherent complexity in determining density stratification, would be of great help in understanding the influence of the change in tidal currents on the intensity of stratification. The numerical experiment with a three-dimensional model is underway in order to assess the changes in density stratification due to the changes in tidal currents.

Conclusions

The findings of the numerical experiments show that the reclamation has decreased by more than 10% the tidal currents over a large area in the innermost part of the Ariake Sound. The effects of long-term variations of tide, bottom roughness, and mean sea level were also been examined and did not significantly change the overall horizontal pattern of the decrease in tidal currents. The reclamation is the dominant reason for changes in tidal currents in this region. It was observed that the dyke constructed in Isahaya Bay plays a significant role in decreasing the tidal currents in Isahaya Bay. The influence of the dyke was local compared to the reclamation, contributing less than 5% to the decrease in tidal currents in the innermost part of the sound. Since a 10% decrease in tidal currents due to the reclamation corresponds to an approximately 30% reduction in the power available to mix the water column, any significant change in tidal currents due to the reclamation could have a large effect on the biological processes occurring there. The effects of the changes in tidal currents on the biological processes taking place in this area have not been fully understood, and need extensive investigations to bridge this gap.

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