有明海の重力循環流の季節変動

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Seasonal variation of the gravitational circulation in Ariake Sound

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The volume transport due to the gravitational circulation and the average residence time of freshwater in Ariake Sound are estimated employing a box model. The longitudinal volume transport in summer is about 1.5 times larger than that in winter if the model does not include the lateral circulation. The estimates of the vertical volume transport without the lateral circulation are larger than those with the lateral circulation. It indicates the vertical material flux (e.g., nutrient flux) can be overestimated if the vertical volume transports that are obtained by the vertically two-dimensional box model are used. Average residence time of freshwater in summer and that in winter are 25.2 and 42.3 days, respectively.

Key Words：Ariake Sound 有明海；gravitational circulation 重力循環流；
average residence time 平均滞留時間

1. Introduction

Ariake Sound is located in the western part of Japan (Figure 1). The environment in Ariake Sound shows remarkable deterioration recently. For example, the production of laver significantly decreased due to a bloom of diatoms in winter, 2001.[1)]

Intensity of the gravitational circulation is one of the key factors of the environment in estuaries. The gravitational circulation plays an important role in material transport in estuaries and flush the estuary with relatively unpolluted ocean water.[2)] In this study, the seasonal variations of the volume transport due to the gravitational circulation and the average residence time of freshwater are estimated employing a box model. The effect of the lateral circulation will also be examined, which might be important as well as the vertical circulation in the axial (longitudinal and vertical) plane.

2. Data sources

Temperature and salinity data, which have been compiled by Seikai National Fisheries Research Institute, were used in this study. These data consist of a series of conductivity-temperature-depth profiler (CTD) drops taken at fixed stations approximately once per month from 1990 to 2000. Locations of the stations are shown by filled circles in Figure 1. The CTD castings in each monthly survey were carried out around the spring tides. The spring-neap tidal variations in the data are thus expected to be small. However, these surveys were not synoptic relative to the diurnal and semidiurnal tides since they took 3-5 days.

Daily freshwater flow data of the six major rivers that flow into the sound were also used, namely Kase, Chikugo, Yabe, Kikuchi, Shira-Kawa, and Midori-Kawa Rivers. These data have been compiled by River Bureau of Ministry of Land, Infrastructure and Transport, Japan. Locations of these river mouths are indicated by arrows in Figure 1. The monthly means of freshwater outflows are shown in Figure 2. Chikugo River is the dominant source of freshwater in Ariake Sound.

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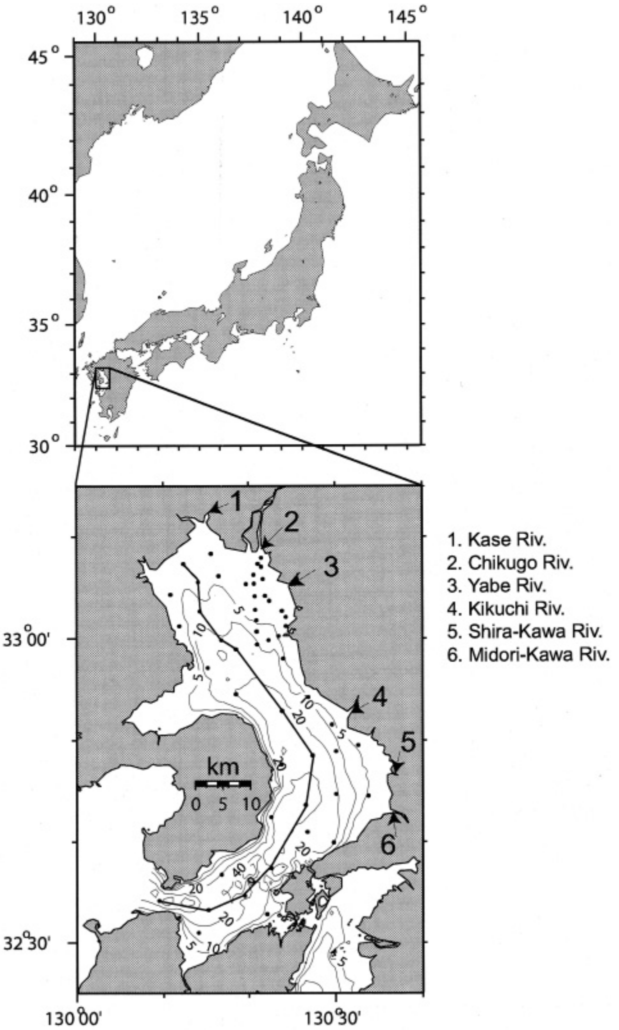

Figure 1. (Upper) geographical location of Ariake Sound. (Lower) bathymetry of Ariake Sound. Arrows show the locations of the mouths of rivers. Filled circles represent locations of the CTD casts. Solid contours are isobaths in meters.

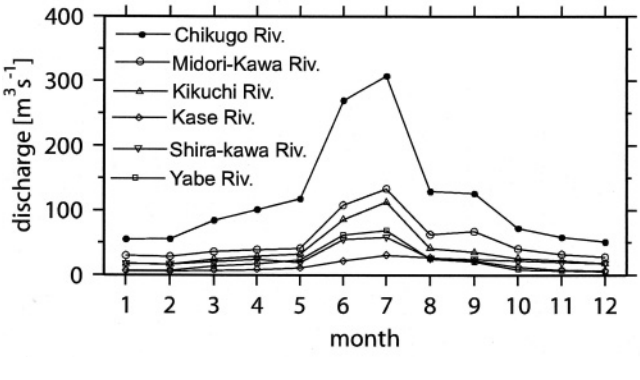

Figure 2. Monthly-averaged freshwater outflows.

3. Methods

The model is based on the conservation of water and salt. The schematic view of the model is shown in Figure 3. The model consists of four boxes: two boxes in the vertical direction and two boxes in the longitudinal direction. The model is divided into the inner and outer parts in the longitudinal direction as shown in Figure 4. Figure 5 shows the vertical distribution of the 11-year mean of density along the solid line in Fig. 1. The boundary of each box is determined from Fig. 5. Boxes 1 and 2 represent the inner part of Ariake Sound, and boxes 3 and 4 represent the outer part. The upper layer thickness is set to 10 m. It is also determined from the density filed as shown in Figure 5. Its validity will be discussed later.

Eleven-year averages of temperature and salinity in summer (July-September) and winter (January-March) were used for the computation in order to reduce the tidal-period signal, which may be contained in the raw data. The model thus provides the climatology of the gravitational circulation.

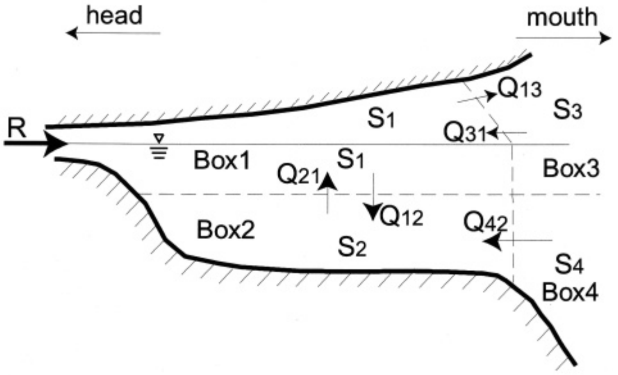

Figure 3. Schematic diagram of the box model.

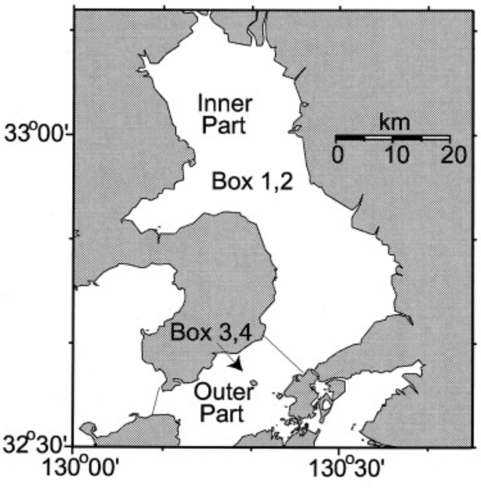

Figure 4. Domain of the boxes.

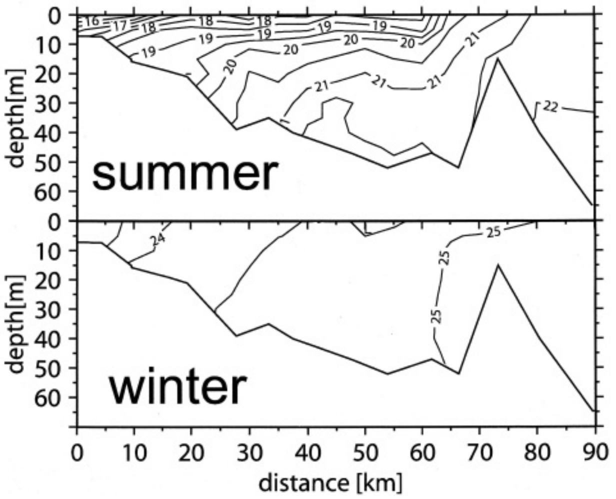

Figure 5. Vertical distribution of the mean density (sigma-t) along the solid line in Fig. 1.

Assuming the steady state, the conservation of water in the boxes 1 and 2 is described as:

$$R+Q_{21}+Q_{31}=Q_{13}+Q_{12}, \tag{1}$$

$$Q_{42}+Q_{12}=Q_{21}. \tag{2}$$

Similarly, the conservation equations of salt in the boxes 1 and 2 is,

$$S_2Q_{21}+S_3Q_{31}=S_1(Q_{12}+Q_{13}), \tag{3}$$

$$S_1Q_{12}+S_4Q_{42}=S_2Q_{21}, \tag{4}$$

where,

R : sum of the freshwater outflows,
S_i : salinity in the i-th box,
Q_{ij} : volume transport from the box i to j.

Vertical advective and diffusive fluxes are represented by Q_{12} and Q_{21}. Volume transports, Q_{13}, Q_{31} and Q_{42} represent the longitudinal transports due to the horizontal advective flux. The horizontal diffusive flux is neglected since its contribution is considered small compared to other fluxes. The validity of this assumption will be discussed later.

The set of equations (1)-(4) has more unknowns than the number of equations. To close the set of equations, the ratio of Q_{31} to Q_{13}, r_E is introduced. The ratio, r_E, represents the relative intensity of the lateral circulation. If there is no lateral circulation, r_E equals zero. From Equations (1)-(4), the volume transports are thus represented as follows:

$$Q_{42}=RY/(S_4-Y) \tag{5}$$

$$Q_{13}=\frac{RS_4}{(1-r_E)(S_4-Y)}, \tag{6}$$

$$Q_{21}=\frac{S_1R}{S_2-S_1}-r_E\left[\frac{R}{1-r_E}+\frac{RY}{(1-r_E)(S_4-Y)}\right]\frac{S_3-S_1}{S_2-S_1}, \tag{7}$$

$$Q_{12}=\frac{S_1R}{S_2-S_1}-\left[\frac{r_E}{1-r_E}\frac{S_3-S_1}{S_2-S_1}+1\right]\frac{RY}{S_4-Y}-\frac{r_E}{1-r_E}\frac{S_3-S_1}{S_2-S_1}R, \tag{8}$$

where, $Y=(S_1-r_ES_3)/(1-r_E)$. For given S_i, r_E and R, the volume transports, Q_{12}, Q_{21}, Q_{13}, and Q_{42} can be obtained using Equations (5)-(8).

The average residence time of freshwater in the inner part, T_f, is calculated by the following method. The volume of freshwater in the inner part, Q_f, can be calculated as,

$$Q_f=\sum_{i=1}^{2}V_i(S_o-S_i)/S_4, \tag{9}$$

where, V_i is the volume of the box i. If the steady state is assumed, the estimate of average residence time, T_f is then,

$$T_f=Q_f/R. \tag{10}$$

Table 1 shows the volume-averaged salinities. These are obtained by the gridded-salinity data, which have been calculated using the spline interpolation technique. The values of V_1 and V_2, are 0.759×10^{10} [m^3] and 0.714×10^{10} [m^3], respectively. The sum of the freshwater outflow, R is computed using the values in Fig. 2. The value of R in summer and that in winter are 440.87 and 150.81 [$m^3\ s^{-1}$], respectively.

Table 1. Salinity used in the box model.

	summer	winter
S_1	29.116	31.988
S_2	31.234	32.774
S_3	31.707	33.373
S_4	32.227	33.630

4. Results

a. Volume transports and average residence time

Figure 6 shows the volume transports as a function of r_E. If there is no lateral circulation (r_E=0), the longitudinal transport in the upper layer, Q_{13} in summer is 1.5 times larger than that in winter. In the lower layer, Q_{42} in summer is 1.4 times larger than that in winter. Although the vertical transport from

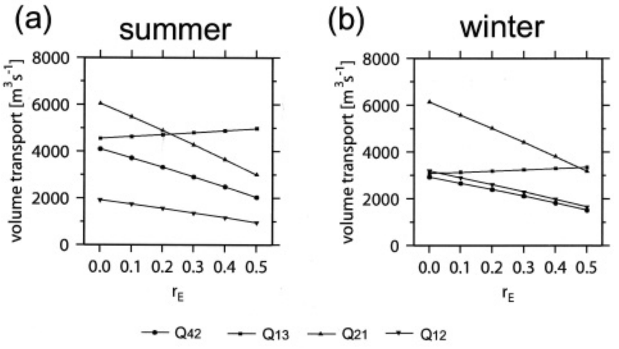

Figure 6. Volume transports as a function of r_E. The upper layer thickness of the model is 10 m.

the lower to upper layers (Q_{21}) in summer is nearly the same as that in winter, the vertical transport from upper to lower layers (Q_{12}) in summer is 60% of that in winter.

The volume transport, Q_{13} increases slightly as r_E increases. However, the values of Q_{42}, Q_{12} and Q_{21} decrease when r_E increases. The largest values are obtained when r_E equals zero. It indicates that the box model without the lateral circulation provides the largest vertical transports and the largest longitudinal transport in the lower layer.

By using of Equations (9) and (10), T_f in summer and that in winter were estimated to be 25.2 and 42.3 days, respectively. Thus, T_f in summer is 57% of that in winter.

b. Sensitivity to the upper-layer thickness

To examine the effects of the changes in the upper layer thickness, the volume transports and the average residence time are recomputed with the model whose upper layer thickness is 5 m. The mean salinity in each box and the volume of each box were recomputed accordingly (not shown). Figure 7 shows the recomputed volume transports. Although their values are a little smaller than those computed with the model whose upper layer thickness is 10m, dependence of the volume transport on r_E is qualitatively similar; Q_{13} increases slightly as r_E increases, and Q_{42}, Q_{12} and Q_{21} decrease when r_E increases. The average residence time of freshwater is also recomputed. The average residence time of freshwater in summer and that in winter are estimated to be 24.3 and 41.7 days, respectively. Those values are nearly the same as those computed with the model whose upper layer thickness is 10 m. It indicates the estimates of T_f are robust against the changes in the upper layer thickness.

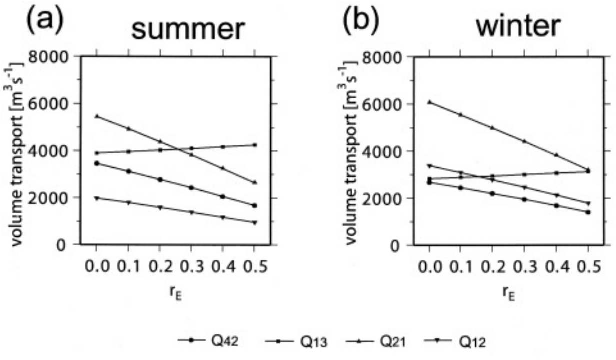

Figure 7. Same as Fig. 6 except that the upper layer thickness of the model is 5 m.

c. Comparison between the diffusive and advective fluxes

The horizontal diffusive flux between the inner and outer parts is neglected in this model. In order to validate this assumption, the order of the diffusive flux is compared with that of the advective flux. The area of the vertical section which divides the boxes 1 and 2, A_1 is about 1.5×10^5 [m^3]. We set K_x to 10^2 [m s^{-2}][3]. The along-estuary gradient of salt across the boxes 1 and 2, $\partial s/\partial x$ is 3.0×10^{-4} [m^{-1}]. We use relatively large values of K_x and $\partial s/\partial x$ in order to avoid an underestimation of the diffusive flux. The horizontal transport of salt due to the diffusive flux, A_1K_x $(\partial s/\partial x)$, is 4.5×10^3 [m^3 s^{-1}]. The representative values of S_1 and Q_{13} are set to 28.0 and 2,800 [m^3 s^{-1}], respectively. They are determined from Table 1 and Fig. 6. We choose the smallest values of S_1 and Q_{13} to avoid an overestimation of the advective flux. The horizontal transport of salt due to the advective flux, S_1Q_{13}, is 7.84×10^4 [m^3 s^{-1}]. It is more than 10 times larger than the horizontal transport due to the diffusive flux. It is thus reasonable that the horizontal diffusive flux is neglected.

5. Summary and discussion

The volume transports and the average residence time of freshwater are estimated employing the box model. The horizontal transport between the inner and outer parts in summer is about 1.5 times larger than that in winter if there is no lateral circulation. The estimates of the vertical volume transports with the model including the lateral circulation are smaller than those with the model excluding the lateral circulation. The average residence time of freshwater in summer and that in winter are estimated to be 25.2 and 42.3 days, respectively.

As mentioned above, the vertical transport can be overestimated with the vertically two-dimensional box model if there is lateral circulation. The transverse current structure in estuaries mainly depends on the two dimensionless numbers: the Kelvin and Ekman numbers. The Kelvin number is defined as the ratio of the bay width to the Rossby deformation radius.[4] If the Kelvin number is much larger than unity and the Ekman number is much smaller than unity, the lateral circulation can dominate.[4,5] These conditions are generally met in Ariake Sound. The acoustic Doppler current profiler survey in winter reveals that the residual currents in Ariake Sound show large transverse variation.[6] It indicates that we may overestimate the vertical material flux such as nutrient flux when the vertically two-dimensional box model is employed. Vertical nutrient transport is one of the important processes in the phytoplankton dynamics in estuaries. Care must be taken when estimating vertical material fluxes using the vertically two-dimensional box model.

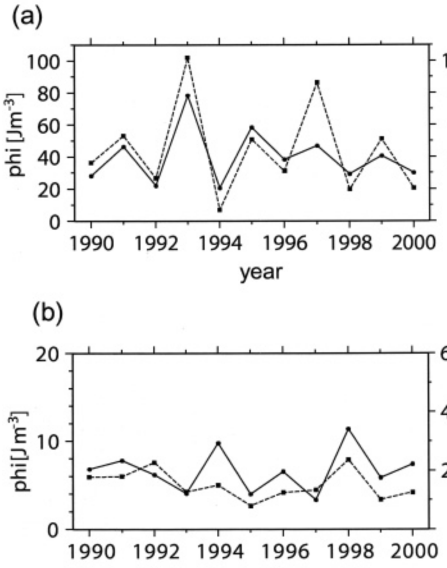

Figure 8. Temporal variations of the sum of the river discharge (dashed line) and the area-averaged stratification parameter (solid line) in (a) summer and (b) winter.

The gravitational circulation in Ariake Sound may have variations with different time scales. Figure 8 shows interannual variations of the area-averaged stratification parameter, which is an indicator of the level of the density stratification, along with the sum of the freshwater outflow. The stratification parameter, ϕ, is defined as follows:[7)]
where,

$$\phi = 1/h \int_{-h}^{0} (\overline{\rho} - \rho) gzdz \ ,$$

z : vertical coordinate (positive upward from the mean sea level),
h : depth of the water column,
ρ : density of seawater,
g : acceleration due to gravity,
$\overline{\rho}$: vertically-averaged density.

The stratification parameter and freshwater outflow vary significantly every year. The variation of freshwater outflow can cause the variation of the gravitational circulation. The change in the stratification parameter could be a reflection of an interannual variation of the gravitational circulation. Tidal period fluctuations in the raw data should be removed for the detailed analysis of the interannual variation. However, the sampling strategy for the data prevents us from removing the tidal signal and limits us to the analysis of the seasonal variation.

Figure 9 shows the power spectrum density of freshwater outflow of Chikugo River, which is the dominant source of freshwater, has remarkable peaks with periods of 20-100 days as well as the variation with a period of 1 year, i.e. the seasonal variation. The variations of freshwater outflow may cause the corresponding variations of gravitational circulation. Moreover, the spring-neap variations of tidal currents can cause the large variations of the density field and resultant currents,[8)] since the tidal range of Ariake Sound is large (3-5 m in the spring tide). The variations mentioned above are beyond our scope in this study, but should be studied for the further understanding of the physical impact on the biological process in Ariake Sound.

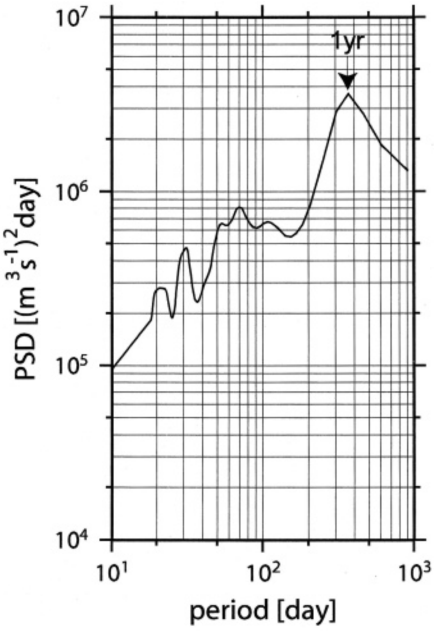

Figure 9. Power spectrum density of the freshwater outflow of Chikugo River.

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有明海の重力循環流の季節変動

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有明海の重力循環流による流量と河川水の平均滞留時間とをボックスモデルを用いて推定した。水平方向の循環を考慮に入れない場合，夏季の湾軸方向の流量は冬季の1.5倍と推定された。水平方向の循環を考慮に入れない場合には，考慮した場合と比べて鉛直方向の流量の推定値は大きくなる。この結果は，鉛直2次元のボックスモデルによって得られた鉛直流量をもとに鉛直方向の物質フラックスを計算した場合，その値が過大評価される可能性があることを示している。夏季および冬季における河川水の平均滞留時間は，それぞれ25.2日および42.3日と見積もられた。