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Seasonal Variation of the Material Transport Processes in the Ariake Sea

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Abstract—Seasonal variation of the salt fluxes in the middle part of the Ariake Sea have been investigated by modeling with hydrographic and meteorological data. The salt flux due to the seasonally averaged density-driven currents accounts for approximately 60% of the total salt flux during summer. The salt flux due to the other processes, that are not treated explicitly, such as the tidal pumping, tide-induced residual currents, and short-term variations of the density- and wind-driven currents dominates during winter. It is suggested that the recent decrease in tidal currents increases the salt flux due to the density-driven currents during summer but decreases the salt flux due to the tidal pumping and/or tide-induced residual currents during winter.

Keywords: density-driven current, wind-driven current, salt flux

1. INTRODUCTION

The Ariake Sea is a highly productive estuary located in the western part of Japan (Fig. 1). A study using the current meter moorings (Nishinokubi et al., 2004) and numerical model studies (Nadaoka and Hanada, 2002; Takigawa and Tabuchi, 2002; Tanaka et al., 2002; Tsukamoto and Yanagi, 2002; Fujii et al., 2004; Manda and Matsuoka 2006) indicate that the amplitude of the tidal current velocity in the Ariake Sea has been decreasing. A decrease in the amplitude of the tidal currents could have weakened the tidal pumping (Simpson et al., 2001) and tide-induced residual currents (Tee, 1976; Yanagi, 1976). On the other hand, a decrease in the amplitude of the tidal currents could have intensified the vertical stratification of the water column, resulting in an increase in the velocity of the density-driven currents (Hansen and Rattray, 1965). In order to clarify the effects of the decrease in the amplitude of the tidal currents on the material transport in the Ariake Sea, the dominant physical processes that transport the materials in the Ariake Sea must be elucidated.

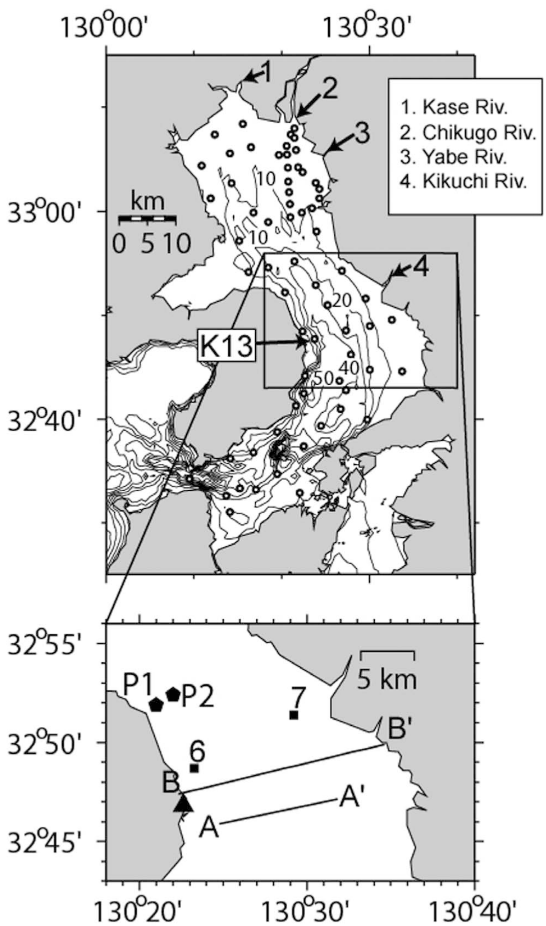

Fig. 1. (Upper) Map showing the geographical location of the Ariake Sea. Solid contours are isobaths (contour interval is 10 m). Arrows indicate the locations of the river mouths. Circles show the locations of the hydrographic stations. Sta. K13 is the station where the representative value of the density difference between the bottom and surface waters was computed. (Lower) Mooring sites carried out by the Japan Coast Guard (square), weather station of the Japan Meteorological Agency (triangle), ADCP transect (line AA′) and the location of the cross section where the salt flux was estimated (line BB′). The numerals on the squares indicate the number of the mooring sites by the Japan Coast Guard. P1 and P2 indicate the mooring sites of Nishinokubi et al. (2004). (Reprinted with permission from *Oceanography in Japan*, **15**, Manda et al., 465–477, Fig. 1. © 2006, The Oceanographic Society of Japan.)

Salt is one of the conservative materials in estuaries and can be considered representative of the dissolved matters in estuaries. Density-driven currents have been considered one of the most important physical processes that transport various materials in the Ariake Sea (Matsuno and Nakata, 2004). However, its magnitude could significantly vary throughout a year due to vertical stratification and freshwater outflow. Accordingly the contribution of the density-driven currents to the salt flux in the Ariake Sea would vary significantly throughout a year.

Currently there has been no study estimating the contribution of the density-driven currents to the salt flux and its seasonal variability, in the Ariake Sea. Higuchi (1967) and Yanagi and Abe (2005) estimated the dispersion coefficients in the Ariake Sea, but they examined neither the seasonal variation nor the contribution of the density-driven currents to the total salt transport.

In this study, the velocity fields of the density- and wind-driven currents are estimated by modeling with hydrographic and meteorological data. The salt fluxes due to these currents are also estimated. Moreover contributions of the currents to the salt fluxes and their seasonality are computed from the salt budget.

2. DATA

In this study in-situ salinity and temperature data from 1990 to 2000 have been used (provided by the Seikai National Fisheries Research Institute, Fisheries Research Agency). These data were recorded once a month by individual CTD casts. The circles in the upper panel of Fig. 1 show the locations of the CTD casts. The river discharge rate data has been obtained from the Ministry of Land Infrastructure and Transport. Harmonic constants obtained by the current meter moorings by Odamaki et al. (2003) have been employed (shown by squares in Fig. 1). Wind speed and direction data at a meteorological observation site have been used for estimating the wind-driven currents (shown by triangles in Fig. 1).

3. METHOD

In gulf-type regions of freshwater influence Kasai et al. (2000) obtained the solution of an analytical model that can reproduce well the structure of the density-driven current (Simpson, 1997). In this study, a modified version of this model (Valle-Levinson et al., 2003) has been employed for estimating the density-driven currents in Ariake Sound. The wind-driven currents have been estimated using an analytical model, a modified version of the model by Wong (1994), which incorporates the effects of the rotation of the earth.

The vertical viscosity used in the models is determined by the empirical formula by Garrett and Loder (1981), using the vertical profile of density at Station K13 and harmonic constants as Stations 6 and 7 (Fig. 1). Measuring the longitudinal gradient of the sea surface used in the Vale–Levinson's model is not feasible. It is determined so that the estimated longitudinal gradient of the sectional mean of density matches the observed gradient.

Assuming the steady state, the salt budget can be represented by the following equation:

$$\rho_0 S_a Q_f / A + \rho_0 \overline{u_S S_S} + \rho_0 \langle u_C S_C \rangle + \rho_0 \left\langle \overline{u' S'} \right\rangle = 0, \tag{1}$$

where overbar and angle bracket denote the sectional and time averages, respectively, ρ_0 is the mean density, S_a is the sectional mean of time-averaged salinity, Q_f is the

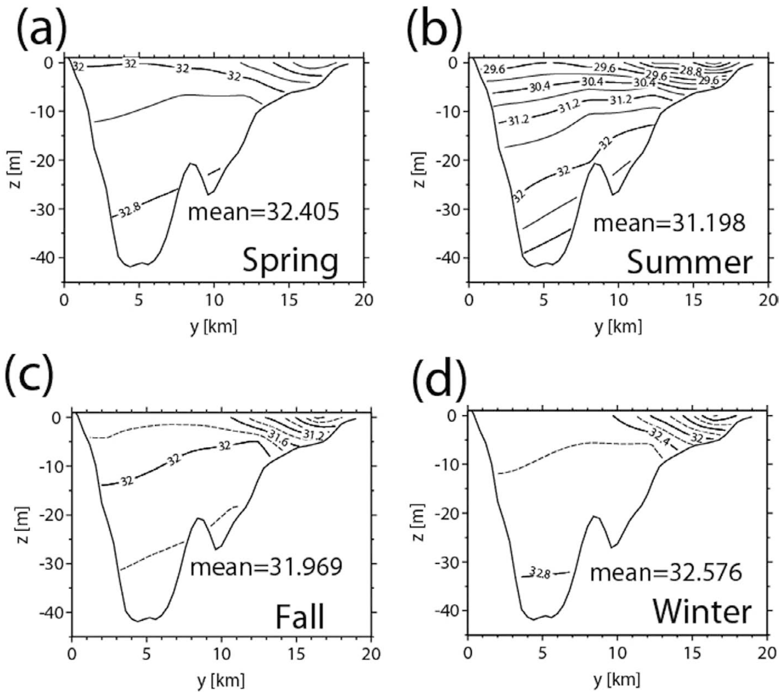

Fig. 2. Salinity profiles at Section BB' during (a) spring, (b) summer, (c) fall, and (d) winter. (Reprinted with permission from *Oceanography in Japan*, **15**, Manda et al., 465–477, Fig. 6. © 2006, The Oceanographic Society of Japan.)

river discharge rate, u_S is the anomaly from the sectional mean of longitudinal components of the time-averaged currents, u_C is the sectional mean of the deviation from the time mean of the longitudinal component of currents, u' is the deviation from the sectional and time averages of longitudinal component of the currents, S_S is the anomaly from the sectional mean of the time-averaged salinity, S_C is the sectional mean of the deviation from the time mean of salinity, S' is the deviation from the sectional and time averages of the currents. Since the seasonal variations are considered in this study, the interval for taking time-average is three months. The fourth term in the left hand side of Eq. (1) consists of the tidal pumping and advective flux due to the tide-induced residual currents and short-term variations of density- and wind-driven currents. The second term of the left hand side of Eq. (1) can be further decomposed into:

$$\rho_0 \overline{u_S S_S} = \rho_0 \overline{u_D S_S} + \rho_0 \overline{u_W S_S} + \rho_0 \overline{u_{TR} S_S}, \tag{2}$$

where u_D, u_W, and u_{TR} are the longitudinal components of time-averaged density- and wind-driven currents, and tide-induced residual currents, respectively. Defining $F_A = \rho_0 S_a Q_f / A$, $F_D = -\rho_0 \overline{u_D S_S}$, and $F_W = -\rho_0 \overline{u_W S_S}$, Eq. (1) can be represented as:

Table 1. Parameters used for the estimation of current velocity. (Reproduced with permission from *Oceanography in Japan*, **15**, Manda et al., 465–477, Table 1. © 2006, The Oceanographic Society of Japan.)

Parameter		Spring	Summer	Fall	Winter
$\Delta\rho$	(kg m^{-3})	0.7	2.5	0.3	0.1
A_v	(10^{-2} m^2 s^{-1})	1.3	1.0	1.5	1.8
$\partial\rho/\partial x$	(10^{-5} kg m^{-4})	2.4	4.8	1.8	1.4
k	(10^{-4} m^{-1})	2.7	1.4	4.0	7.2
N_{D0}	(10^{-7})	3.0	6.0	2.3	1.8

$$F_A = F_D + F_W + F_T, \tag{3}$$

where $F_T = -\rho_0 \overline{u_{TR} S_S} - \rho_0 \langle u_C S_C \rangle - \rho_0 \langle \overline{u' S'} \rangle$, which indicates the salt flux due to the tide-induced residual currents, tidal pumping, and short-term variations of density- and wind-driven currents. The procedure for estimating the salt fluxes is as follow:

- Time-averaged density- and wind-driven currents by the section BB′ shown in Fig. 1 are estimated by the analytical model.
- F_D and F_W are computed using the salinity profile data and the estimated current fields,
- F_A is estimated using salinity and freshwater outflow data,
- Compute F_T by subtracting F_D and F_W from F_A.

Figure 2 shows the vertical profile of salinity at Section BB′ for estimating the salt fluxes.

In order to validate the estimated currents, A 25-hour acoustic Doppler current profiler (ADCP) survey (BBVM300 of Teledyne RD Instruments) was conducted from August 3rd to 4th, 2005 along the line AA′ shown in Fig. 1. The current velocity data were de-tided using the method by Simpson et al. (1990).

4. RESULTS

The parameters used for estimating the density- and wind-driven currents are shown in Table 1. The parameter, $\Delta\rho$ indicates the density difference between the bottom and the surface waters. The inverse of the internal deformation radius, k, is in the order of 10^{-4} m^{-1}. The longitudinal gradient of the sea surface is represented by N_{D0}. The vertical eddy viscosity, A_v, is one of the most important parameters and is in the order of 10^{-2} m^2 s^{-1}. The value of the vertical eddy viscosity during summer is approximately half that during winter, due to density stratification.

The modeled and observed density-driven currents in summer at Section AA′ are shown in Fig. 3. The density-driven current is considered the dominant component of the residual currents during the ADCP survey since the wind was very weak. The model reproduced well the observed residual currents, therefore, supporting the validity of the model.

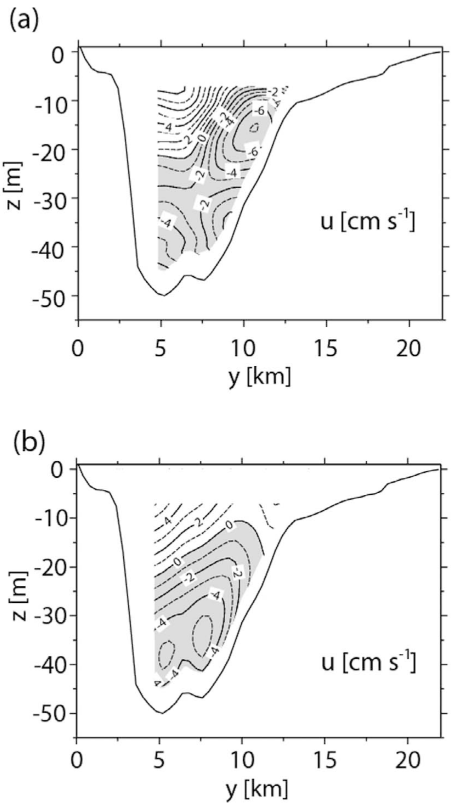

Fig. 3. (a) Longitudinal component of the ADCP-measured residual currents on August 3–4, 2005 at Section AA′. (b) Longitudinal component of the estimated residual currents during summer at Section AA′. Shaded areas indicate landward currents. (Reprinted with permission from *Oceanography in Japan*, **15**, Manda et al., 465–477, Fig. 7. © 2006, The Oceanographic Society of Japan.)

The modeled density-driven currents at Section BB′ are shown in Fig. 4. The landward current in the lower layer and seaward current in the upper layer, typical in estuaries, are observed. The horizontal velocity shear is also found, which cannot be reproduced by the classic two-dimensional model of Hansen and Rattray (1965) and is a recent focus in estuarine studies (e.g., Simpson, 1997). The modeled longitudinal components of the wind-driven currents at Section BB′ are shown in Fig. 5. The wind velocity is one order smaller than the density-driven currents. The landward currents in the upper layer and seaward currents are found in summer, due to the southerly (northward) wind dominating during this season.

Figure 6a shows the seasonal variation of the salt fluxes. During summer, the salt flux due to the time-averaged density-driven currents, F_D reaches its maximum of 2.2×10^{-3} g cm^{-2} s^{-1}; which is 40 times larger than that during winter. The salt flux

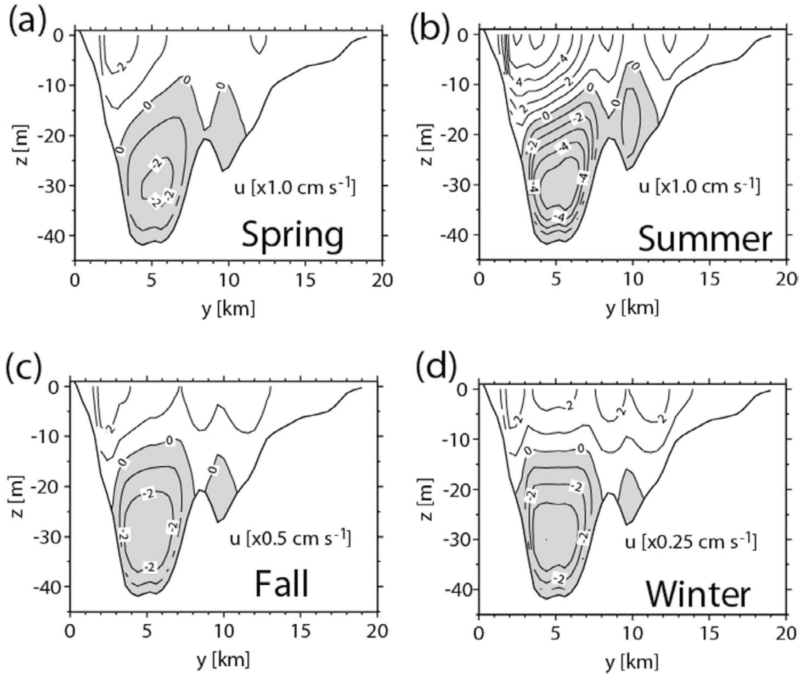

Fig. 4. Longitudinal components of the estimated density-driven currents at Section BB' during (a) spring, (b) summer, (c) fall, and (d) winter. Shaded areas indicate landward currents. (Reprinted with permission from *Oceanography in Japan*, **15**, Manda et al., 465–477, Fig. 8. © 2006, The Oceanographic Society of Japan.)

due to the time-averaged wind-driven currents during summer is very small and can be neglected. The salt flux due to the physical processes other than time-averaged density- and wind-driven currents, F_T is virtually constant (1.0×10^{-3} g cm^{-2} s^{-1}) throughout a year. If the dominant processes in F_T are the tidal pumping and tide-induced residual currents, F_T is almost constant since they are virtually steady. The ratios, $R_D = F_D/F_A$, $R_W = F_W/F_A$, and $R_T = F_W/F_A$, which represent the contribution of each flux to the total flux, are shown in Fig. 6b. The contribution of the time-averaged density-driven currents, R_D accounts for approximately 60% of the total salt flux during summer. On the other hand, R_T dominates during winter ($R_T = 0.9$). These results indicate that the dominant process in the transport of material varies significantly throughout a year and depends heavily on the season.

5. DISCUSSION

Nishinokubi et al. (2004) showed that the amplitude of the tidal currents in 2001 decreased by about 10 and 27% at the mooring sites, when compared with those in 1993 (see Fig. 1 for their locations). This study shows the salt fluxes due to the

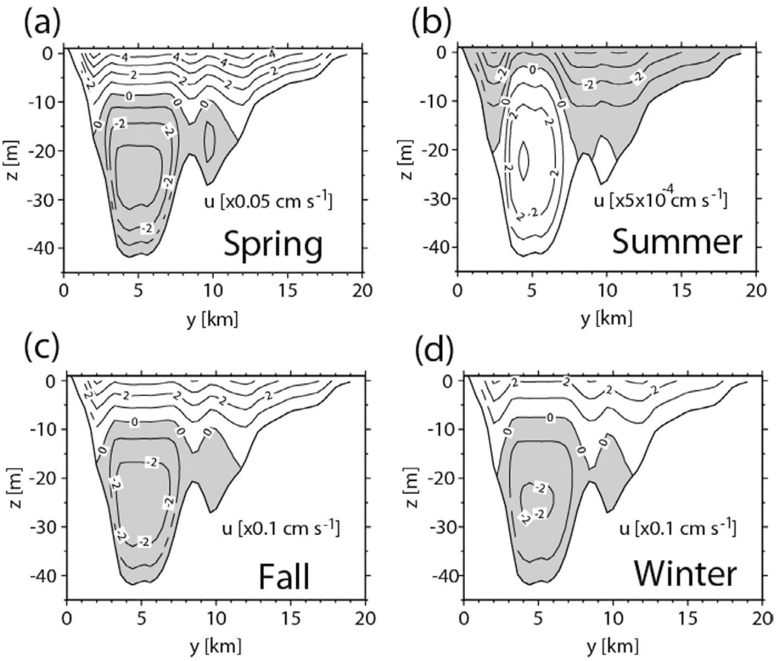

Fig. 5. Longitudinal components of the estimated wind-driven currents at Section BB' during (a) spring, (b) summer, (c) fall, and (d) winter. Shaded areas indicate landward currents. (Reprinted with permission from *Oceanography in Japan*, **15**, Manda et al., 465–477, Fig. 9. © 2006, The Oceanographic Society of Japan.)

time-averaged density-driven currents when the amplitudes of the tidal currents are increased by 10 and 27% (Fig. 7). An increase in the amplitude of the tidal currents decreases, F_D, indicating that the salt flux in 1993 was smaller than that in 2001. However, F_D does not change much during other seasons, which suggests that the salt fluxes due to the tidal pumping and tide-induced residual currents have been decreasing since 1993. In addition to tidal currents and tide-induced residual currents, F_T consists of several current components, such as short-term variations of density- and wind-driven currents. A decrease in salt fluxes due to the tidal pumping and tide-induced residual currents could be compensated by the short-term fluctuations of density- and wind-driven currents. Year-to-year variations of the amplitude of these short-term fluctuations have not been elucidated and should be investigated for a better understanding of material transport processes in the Ariake Sea.

6. CONCLUSIONS

Seasonal variations of the salt fluxes in the middle part of the Ariake Sea have been investigated by modeling with hydrographic and meteorological data. During

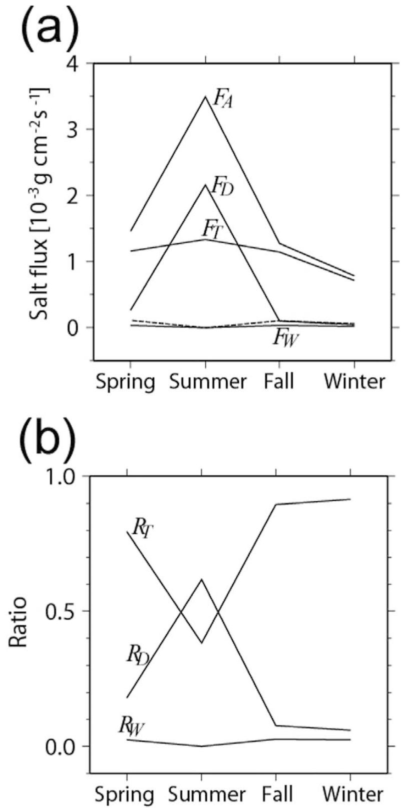

Fig. 6. (a) Estimated salt fluxes and (b) fraction of the upstream salt fluxes. Subscript A indicates total salt flux. Subscripts D and W indicate the salt fluxes due to the time-averaged density and wind-driven currents, respectively. Subscript T indicates the salt flux due to the physical process other than time-averaged density and wind-driven currents. The dashed line indicates the salt flux due to the time-averaged wind-driven currents when the wind speed is doubled. (Reprinted with permission from *Oceanography in Japan*, **15**, Manda et al., 465–477, Fig. 10. © 2006, The Oceanographic Society of Japan.)

summer, the salt flux due to the time-averaged density-driven currents reaches its maximum of 2.2×10^{-3} g cm^{-2} s^{-1}, which is 40 times larger than that recorded during winter. The salt flux due to the time-averaged wind-driven currents during summer can be neglected. The contribution of the time-averaged density-driven currents accounts for approximately 60% of the total salt flux during summer. On the other hand, the contribution of the other processes that are not treated explicitly such as the tidal pumping, tide-induced residual currents, and short-term variations of the density- and wind-driven currents dominate during winter. It is suggested that the recent decrease in tidal currents increases the salt flux due to the density-driven

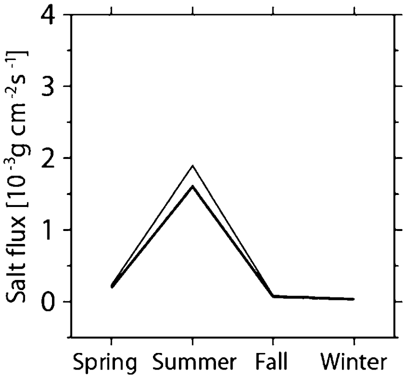

Fig. 7. Salt fluxes due to the time-averaged density-driven currents when the amplitudes of the tidal currents are increased by 10% (thin solid) and 27% (thick solid), respectively. (Reprinted with permission from *Oceanography in Japan*, **15**, Manda et al., 465–477, Fig. 11. © 2006, The Oceanographic Society of Japan.)

currents during summer but decreases the salt flux due to the tidal pumping and/or tide-induced residual currents during winter.

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