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***Abstract*:** The tidal water mass exchange in an inland sea with archipelago is numerically studied adopting the control volume based 2-dimensional finite element method to cope with the complex coastline. Yatusiro Sea situated in the south-west of Kyushu, Japan is the model inland sea of our study. Water mass exchange by semi-diurnal (M_2) tidal flow is investigated by the dispersion of Lagrangean particles and by the Eulerean tidal residual flow. Main results are as follows: i) Except the southern part of Ariake Sea and Nagashima Strait, the most part of Lagrangean particles still stay in the areas after 20 periods. ii) The particles in Ariake Sea (Yatusiro Sea) flow into Yatusiro Sea (Ariake Sea) through Yanagi-seto (Misumi-seto). iii) The particles in Hachiman-seto flow into Yatusiro Sea through Oh-seto and Gannojiri-seto. iv) The particles in the south part of Yatusiro Sea flow into Nagashima Strait through Mebuki-seto and Ikara-seto. v) In the Eulerean tidal residual flow, there exists a clock-wise vortex around Shishijima island in Yatusiro Sea.

***Keywords*:** water mass exchange, finite element method, tidal flow, Lagrangean particle dispersion, archipelago, inland sea.

The water mass exchange in an inland sea is one of the important elements for the environmental situation of the sea. The circulation of water mass in an inland sea is mainly caused by the tidal and tidal residual flow (Ketchum, 1951), wind stress (Chase, 1975) and density flow (Kikukawa et al., 1997). We study, in this article, the water mass exchange by the tidal and tidal residual flow in Yatusiro Sea situated in the south-west of Kyushu, Japan (Fig.1). Yatusiro Sea is the good fishing ground and for migratory birds, good resting point. On low tide, large tidelands appear in the northern part of Yatusiro Sea and many peculiar livings are observed in the mud flats. Also included are many fishing farms and Minamata Bay which was polluted by organic mercury.

Yatusiro Sea contains archipelago and its coastline is complex. When an inland sea contains archipelago, finite element method (FEM) has the advantage to trace its complex coastline. Tidal water mass exchange can be studied by the dispersion of the Lagrangean particles as well as the Eulerean tidal residual flow. However, so far as we know, the Lagrangean particle dispersion has not been investigated by FEM. We adopt, in this article, the control volume based 2-dimensional FEM and calculate the Lagrangean particle dispersion. For the purpose to avoid the false viscous difficulties, the dependent variables are interpolated exponentially in the direction of the element average velocity vector and linearly in the normal direction according to Baliga and Patankar (1983).

The aim of this article is to perform a numerical simulation of the tidal water mass exchanges of 6 areas in Yatusiro Sea and between the outer ocean and the inland sea through three straits. The density flow and wind stress

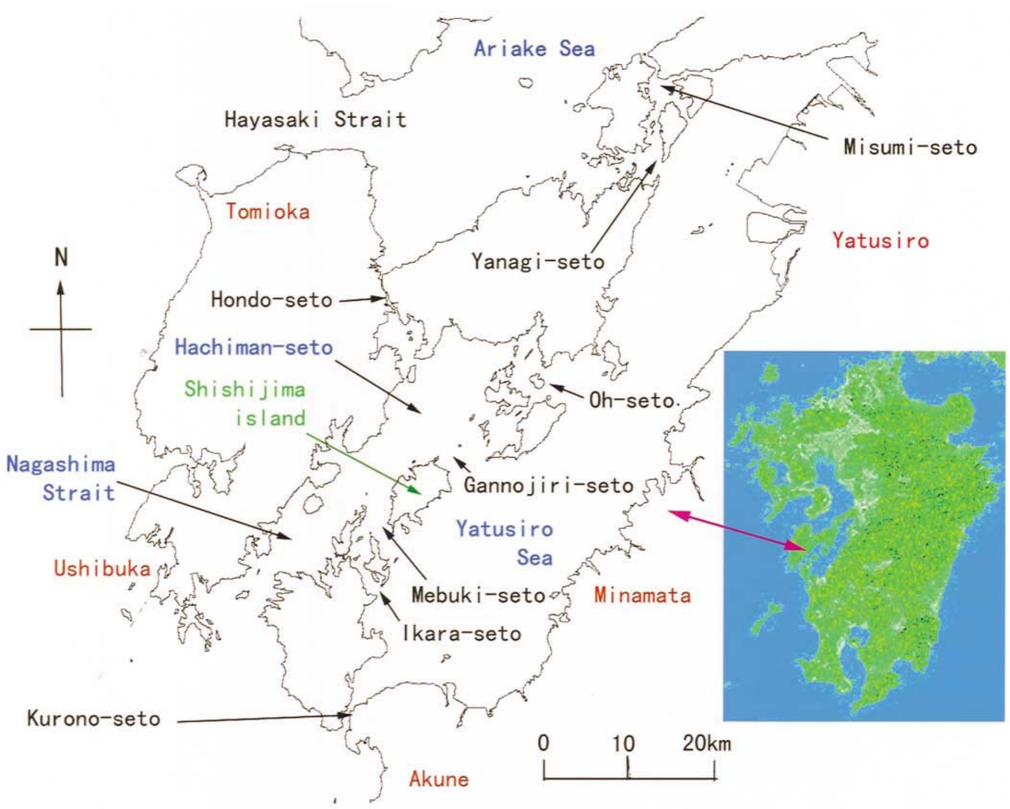

Fig.1. Map of inland seas around Yatusiro Sea.

might also play important roles for water mass exchange in the inland sea. These processes, however, have seasonal variations and the three dimensional effects are essential. These will be treated separately.

This article is only concerned with the horizontal 2-D problems of semi-diurnal tidal flow. Although our interest is mainly concerned with Yatusiro Sea, calculation is perfomed including Ariake Sea for the purpose to study the water mass exchange between two inner seas. The bay is divided into triangular elements (Fig.2). For the purpose to reduce the boundary effects of numerical simulation, open boundaries are extended about 20km outside the straits. The number of nodes (elements) is 10194 (17701). The depth at every node is read from the bathymetric chart (Fig.3).

The governing equations adopted in this article are

$$\frac{\partial hu}{\partial t}+\frac{\partial huu}{\partial x}+\frac{\partial hvu}{\partial y}-fhv=-\boldsymbol{g}h\frac{\partial \eta}{\partial x}+\frac{\partial hR_{xx}}{\partial x}+\frac{\partial hR_{xy}}{\partial y}-c_f u\sqrt{u^2+v^2}, \quad (1)$$

$$\frac{\partial hv}{\partial t}+\frac{\partial huv}{\partial x}+\frac{\partial hvv}{\partial y}+fhu=-\boldsymbol{g}h\frac{\partial \eta}{\partial y}+\frac{\partial hR_{yx}}{\partial x}+\frac{\partial hR_{yy}}{\partial y}-c_f v\sqrt{u^2+v^2}, \quad (2)$$

$$\frac{\partial h}{\partial t}+\frac{\partial hu}{\partial x}+\frac{\partial hv}{\partial y}=0, \quad (3)$$

where $(x, y) = (x_1, x_2)$ are the horizontal coordinates, t denotes time, $v = (u, v) = (v_1, v_2)$ the vertically averaged velocities, η the sea surface elevation, $h \equiv h_0 + \eta$, h_0 the depth, $R_{ij} = \nu_e\left(\frac{\partial v_i}{\partial x_j}+\frac{\partial v_j}{\partial x_i}\right)$, $\boldsymbol{g}$ the gravitational

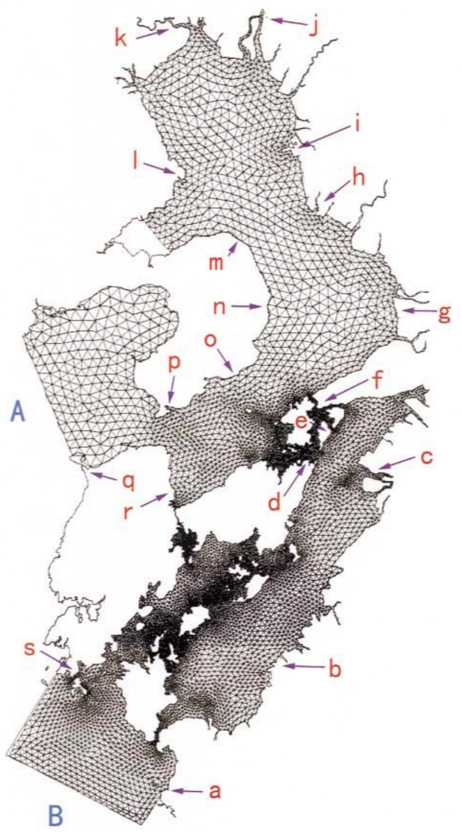

Fig.2. Division of Yatusiro and Ariake Seas by triangular elements. A and B denote open boundaries where tidal levels are forced. Small alphabets denote local points where M_2 tidal level coefficients are compared with the calcutaled ones.

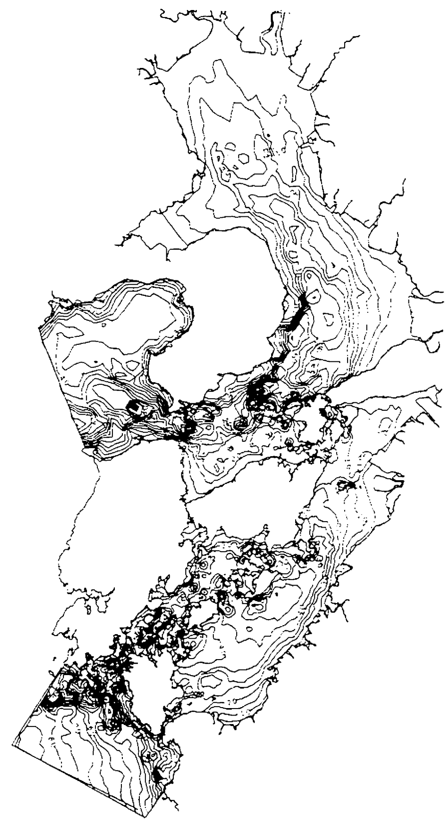

Fig.3. Depth distribution used in our simulation.

acceleration, f (= $2\omega\sin(\theta)$, $\omega = 2\pi/86400\text{s}^{-1}$, θ = 32.3 degree) is the Coriolis coefficient and c_f (= $0.0026/h$) is the bottom friction parameter. For horizontal eddy viscosity ν_e, we adopt Smagorinsky's model

$$\nu_e = \left(C_s\Delta\right)^2\sqrt{2\overline{S_{ij}}\ \overline{S_{ij}}}\ . \qquad (4)$$

In Eq. (4), $S_{ij} = \frac{1}{2}\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right)$ are the rate-of-strain tensors and overline denotes space averaging, Δ denotes space filter width, for which the element size is used and C_s = 0.25 is adopted. Equation (4) is widely used for fundamental sub-grid-scale stress model of large eddy simulation.

We have solved Eqs. (1) to (3) improving the FEM developed by Baliga and Patanlar (1983) to be available for evolutive equation, which is one of the control volume based up-wind methods. The characteristic of the method is to use different interpolation functions for the direction of element average velocity vector and its normal direction. A new coordinates (X, Y) are introduced in an element (Fig.4), X is directed to element average velocity vector and Y to its normal direction. In the advective and the viscous terms in Eqs. (1) and (2), u and v are interpolated exponentially for X direction and linearly for Y direction

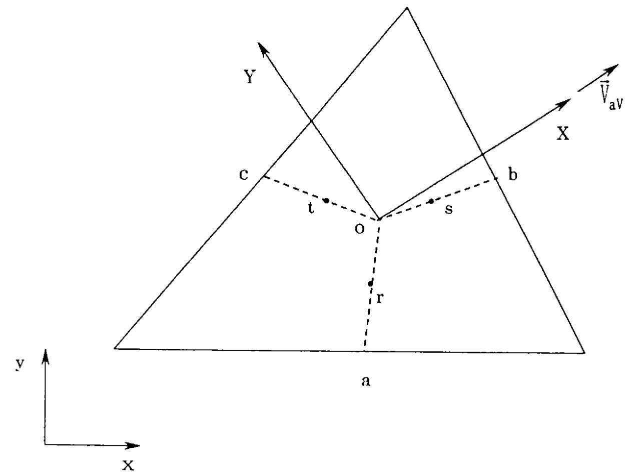

Fig.4. Relationship between the global (x, y) and flow-oriented local (X, Y) coordinate systems for a typical element. See the text for the detailed explanation.

$$u = A_u \exp\left(\frac{U_{av} X}{\nu_e}\right) + B_u Y + C_u, \quad v = A_v \exp\left(\frac{U_{av} X}{\nu_e}\right) + B_v Y + C_v, \tag{5}$$

where $U_{av} = |\vec{V}_{av}|$ is the magnitude of average velocity vector in the element. u and v except the advective and the viscous terms and the sea surface elevation η are interpolated linearly.

At the open boundaries of A and B in Fig.2, the sea surface elevations are forced to be

$$\eta_i = a_i \sin(\omega_{M_2} t - \delta_i), \quad i = A, B \quad \omega_{M_2} = 2\pi/45000(\mathrm{s}^{-1})$$
$$a_A = 96.0(\mathrm{cm}), \quad \delta_A = 230.0(\mathrm{degree}), \quad a_B = 79.7(\mathrm{cm}), \quad \delta_B = 221.1(\mathrm{degree}). \tag{6}$$

Slip boundary condition is adopted at the coast. Initially, still sea water and flat sea surface are assumed. Calculated velocity v and the sea surface elevation η became stable after 10 periods.

In Fig.5, calculated sea levels at several points are compared with tidal harmonic constants of semi-diurnal tide. Abscissa in Fig.5 denotes the points shown in Fig.2. We can see from Fig.5, the calculated amplitudes are a little larger than the harmonic amplitudes and the calculated phases ought to delay at inner bay. However, the differences are not so large and the calculated sea levels might be satisfactory in spite of the assumption that the sea level change is produced only by M_2 tidal level at the open boundary.

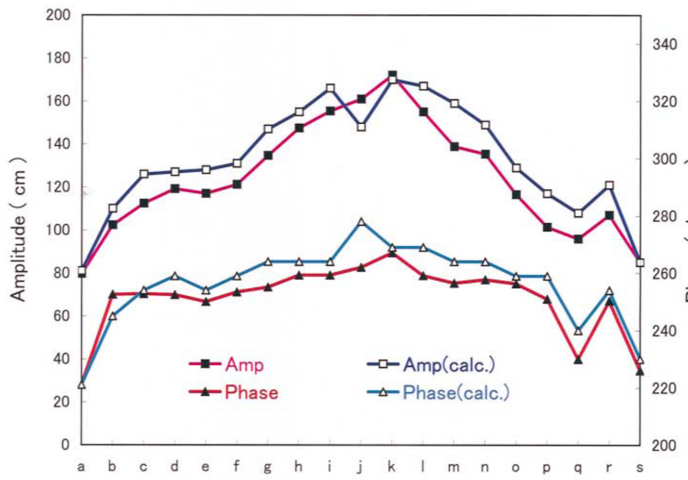

Fig.5. Comparison of M_2 tidal coefficients between the observation and the simulation. Abscissa denotes the points shown in Fig.2.

In Fig.6 the calculated M_2 tidal residual flow is given. Many vortices are found around straits and islands in Fig.6. At the north-west (north-east) of Hayasaki Strait, a clockwise (anti-clockwise) vortex exists and at the south-east, a large clockwise vortex appears. The maxima velocities of these vorticies exceed 20cm/s. More than 7 vorticies exist side by side in Nagashima Strait and at the south of Kurono-seto, a clockwise and an anti-clockwise vorticies appear. The most conspicuous vortex is the one around Shishijima island. Owing to this vortex, the sea water in Hachiman-seto flows into Yatusiro Sea through Gannojiri-seto and the sea water in Yatusiro Sea flows out to Nagashima Strait through Mebuki-seto and Ikara-seto. The residual velocities are small at the north and east areas in Yatusiro Sea and at the north area in Hachiman-seto. The sea water must be stagnant in these regions. The water mass exchanges through Hayasaki Strait, Nagashima Strait and Kurono-seto as well as between Yatusiro Sea and Ariake Sea are not decisive in Fig.6.

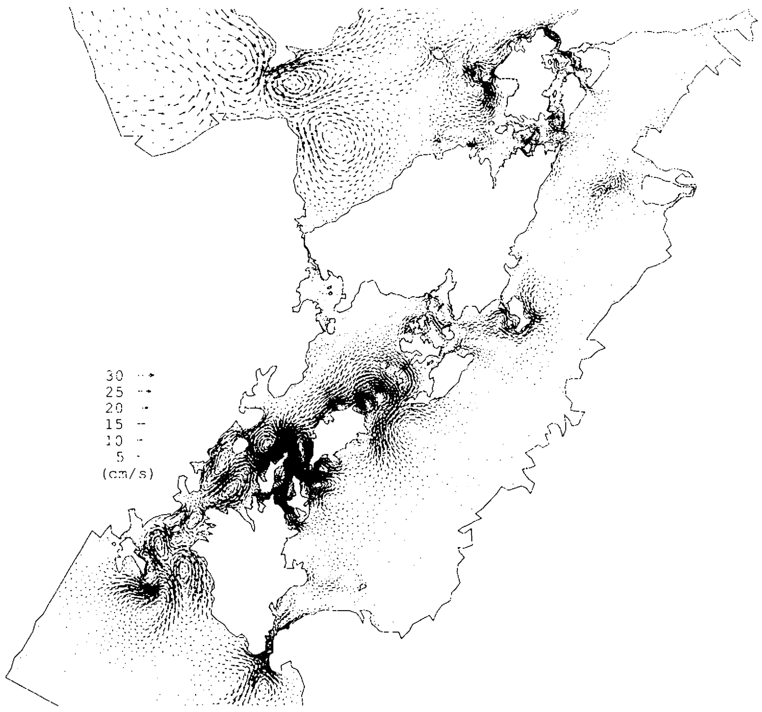

Fig.6. Calculated tidal residual flows.

We will see, in this section, the dispersion behaviors of Lagrangean particles dispersed into the sea. They are distributed in 6 areas shown in Fig.7 at time of almost low tide. Figure 8 shows the location of particles at the end of several periods.

At period 2, the outer ocean water flows into Ariake Sea through the middle of Hayasaki Strait. The particles in the semicircular east area of Shishijima island flow out to Nagashima Strait through Mebuki-seto. The particles in Nan and Yam flow into the semicircular east area of Shishijima island through Gannojiri-seto. The particles in Yan stagnate and the some particles in Nas flow out to outer ocean.

At period 5, the particles in Ars flow out to outer ocean through the north part of Hayasaki Strait and begin to flow into Yatusiro Sea through Yanagi-seto. At the semicircular east area of Shishijima island, there exist the particles dispersed in Nan, Yam and Nas. The particles in Nan (Yas) begin to flow out to outer ocean through Nagashima Strait (Nagashima Strait and Kurono-seto).

At periods 8 and 12, the outer ocean water flowed in through the south part of Hayasaki Strait turns out the particles dispersed in the south-east area of Hayasaki Strait and the particles flowed into Yatusiro Sea through

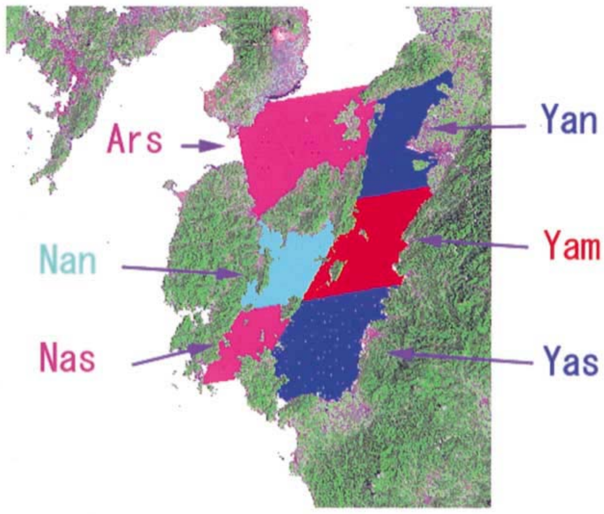

Fig.7. Initial locations of Lagrangean particles distributed in the 6 areas.

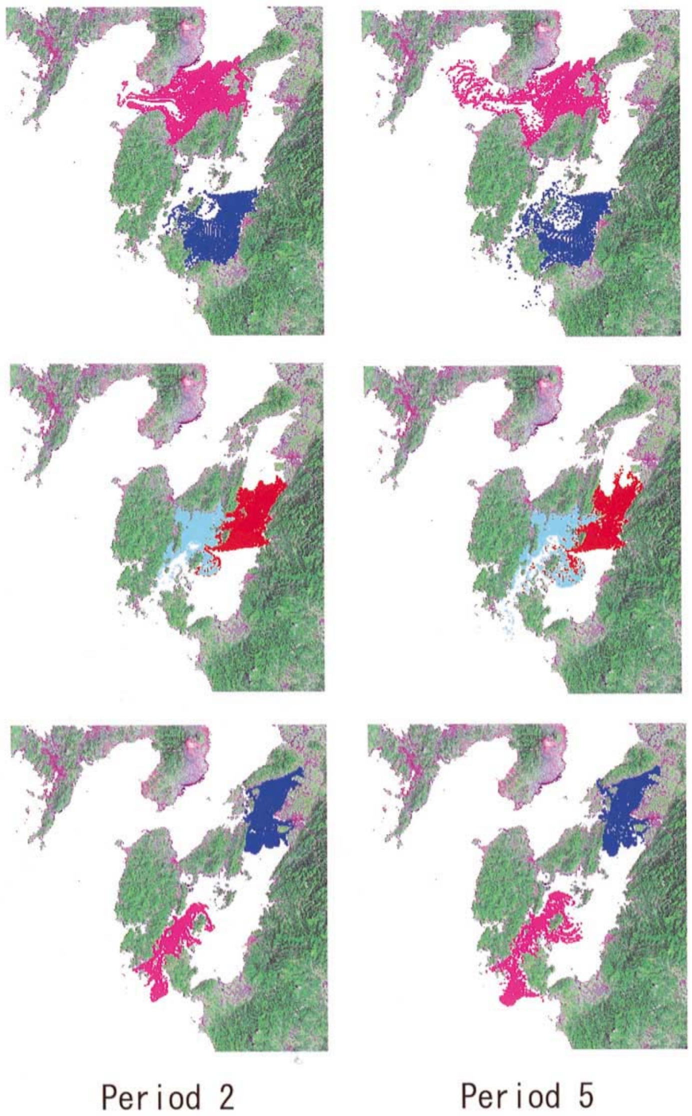

Fig.8. Locations of Lagrangean particles at the end of 2, 5, 8, 12, 16 and 20-th periods.

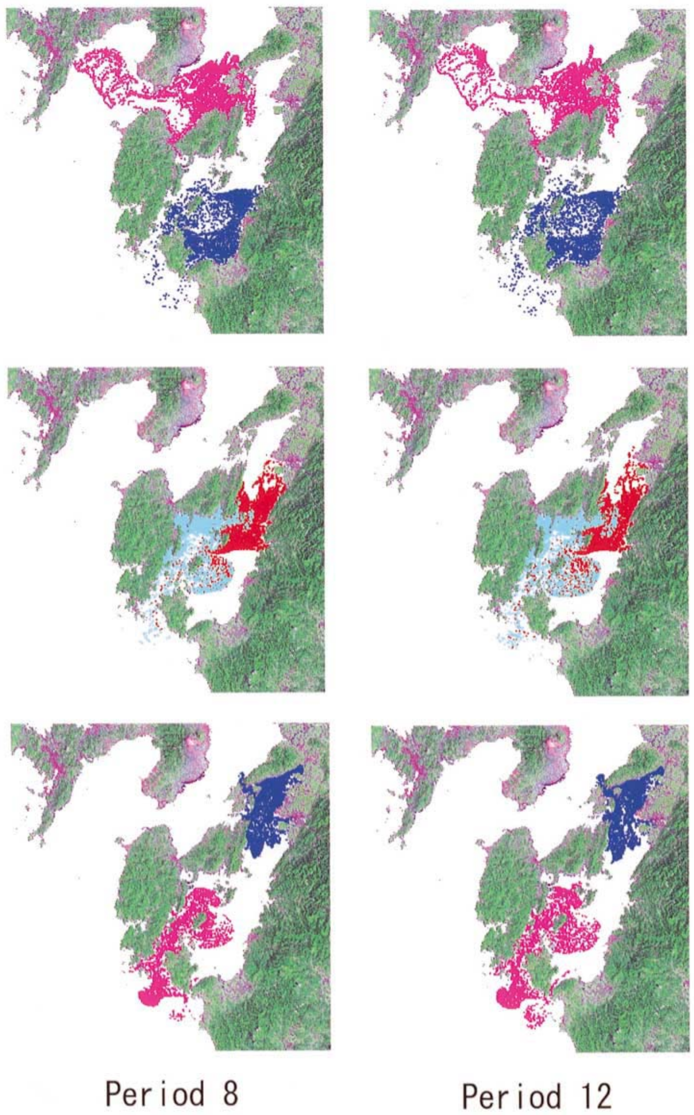

Fig.8. (continued)

Yanagi-seto begin to go southward. At the semicircular east area of Shishijima island, the particles dispersed in Yas returned in addition to the particles dispersed in Nan, Yam and Nas. The particles in Nan flow into the area of Yam through Oh-seto and the particles in Yam begin to go northward along the east coast of Yatusiro Sea. A few particles in Yan flow into Ariake Sea through Misumi-seto. The particles of Nas once flowed out from Nagashima Strait, begin to go into Yatusiro Sea through Kurono-seto.

At periods 16 and 20, many particles in Ars flow out to outer ocean through the north part of Hayasaki Strait and flow into Yatusiro Sea through Yanagi-seto. A few particles in Ars also flow into Hachiman-seto through Hondo-seto. At the semicircular east area of Shishijima island, the particles in Nan, Yam, Yas and Nas are mixed. The particles in Yan (Yam) flow southward (northward) along west (east) coast of Yatusiro Sea.

The characteristic features of particle dispersion are: 1) The particles in Ariake Sea flow out from the north part of Hayasaki Strait and the ocean water flowed into Ariake Sea from the south part turns out the particles dispersed in the south-east area of Hayasaki Strait. 2) The particles in Ariake Sea (Yatusiro Sea) flow into Yatusiro Sea (Ariake Sea) through Yanagi-seto (Misumi-seto). 3) The particles in Hachiman-seto flow into Yatusiro Sea through Oh-seto and Gannojiri-seto. 4) The particles in the south part of Yatusiro Sea flow out to Nagashima Strait through Mebuki-seto and Ikara-seto. 5) Some particles which go out from Nagashima Strait flow into the south part of Yatusiro Sea through Kurono-seto. 6) A few particles in Ariake Sea flow into Hachiman-seto through Hondo-seto.

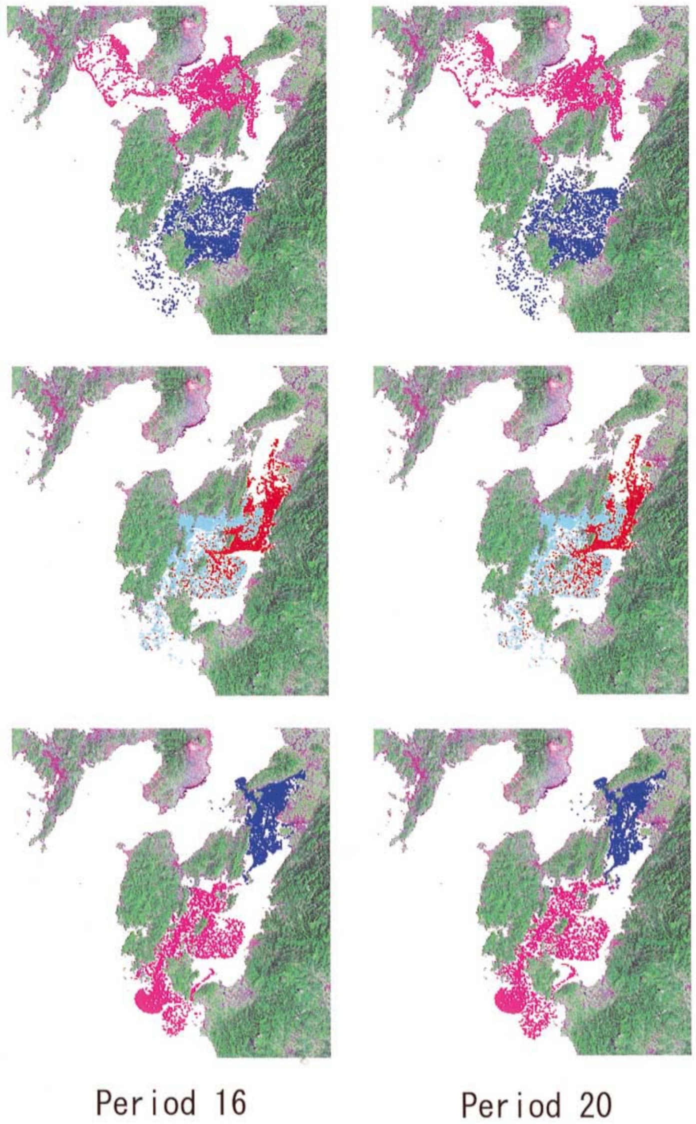

Fig.8. (continued)

As an example, the trajectories of three particles, each given at the centers of Hayasaki Strait, Nagashima Strait and Kurono-seto, are shown in Fig.9. The particle dispersed at the center of Hayasaki Strait slowly goes southward, oscillating east-west wards. The particle dispersed at the center of Nagashima Strait flows northeast ward, goes into Yatusiro Sea through Gannojiri-seto and returns to Nagashima Strait through Ikara-seto. The particle dispersed at the center of Kurono-seto goes in and out from Yatusiro Sea. These particle behaviours, however, change in a large way when the dispersed positions are shifted for a short distance.

In Fig.10 is given net out-flow particles through straits and setos during 20 periods. The figure shows: 1) About 28% (5%) of the particles in Ars flows out from Hayasaki Strait (Yanagi-seto) to outer ocean (Yatusiro Sea). 2) Only 6% (3%) of the particles in Yas flows out from Nagashima Strait (Kurono-seto). 3) Most particles in Yam and Nan stagnate. Only 6.5% (1.5%) in Nan (Yam) flows out from Nagashima Strait. 4) About 42% (15%) of the particles in Nas (Yan) flows out from Nagashima Strait (Misumi-seto) to outer ocean (Ariake Sea).

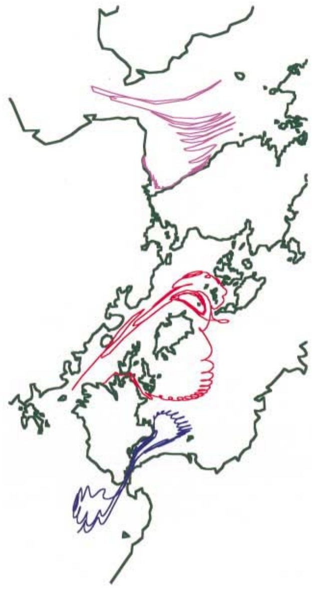

Fig.9. Example of particle trajectories given in Hayasaki Strait, Nagashima Strait and Kurono-seto.

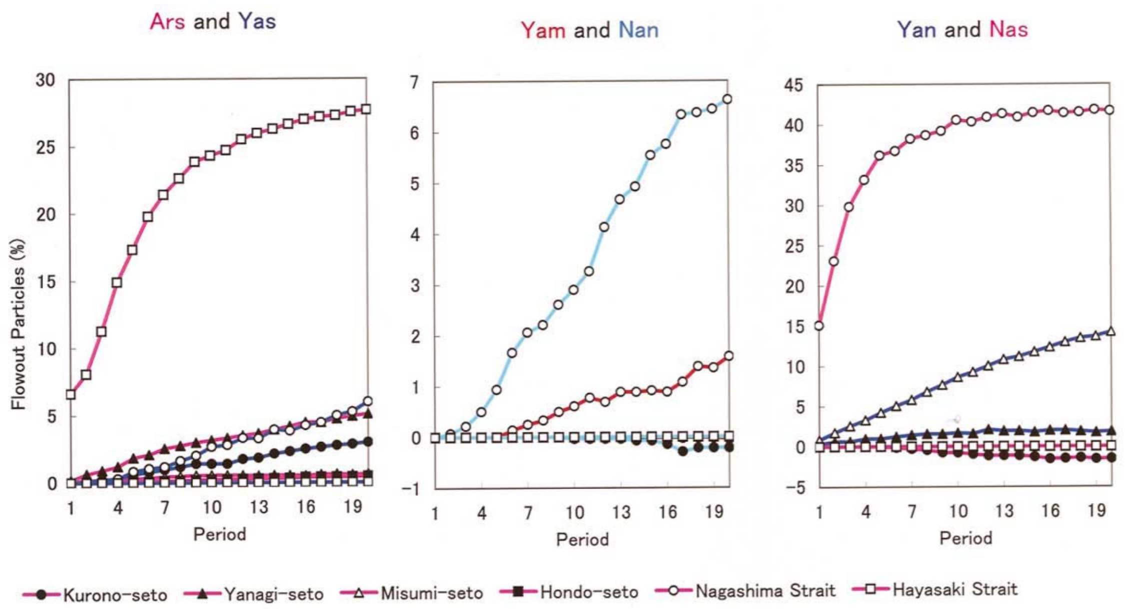

Fig.10. Ratios of net escaped particles from the 6 areas defined in Fig.7 through straits and setos during 20 periods.

Yatusiro Sea located at south-west of Kyushu, Japan is a semi-enclosed coastal bay with complex coastline and archipelago. Water mass exchange in the sea by M_2 tidal flow is numerically studied by the control volume based 2-dimensional FEM. Exchange of water mass is visualized by tracing floating fictitious particles distributed in 6 areas in the sea. Except the south areas of Ariake Sea and Nagashima Strait, only less than 7% of the particles flows out to the outer ocean during 20 periods.

From the behaviours of Lagrangean particles as well as the Eulerean tidal residual flow, a large clock-wise vortex is found around Shishijima island. The water mass exchange between Yatusiro Sea and Ariake Sea is also observed.

It is important to estimate the water mass exchange due to density flow and wind-driven flow in the next step. Three dimensional FEM will be devised for this purpose.

Acknowledgments

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