NOTES AND CORRESPONDENCE

A Numerical Experiment on Water and Salt Exchange through the Akashi and the Naruto Straits

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ABSTRACT

To study the relation between the water-volume exchange rates E_v and the salt-exchange rates E_s of the Akashi and the Naruto Straits in the Seto Inland Sea of Japan, we use an observed salt distribution near the straits, the calculated Eulerian velocity of the M_2 current and the calculated location of about 20 000 labeled particles tracked during an M_2 period. The salt-exchange rate E_s was about one-third and one-twelfth that of the water-volume exchange rate E_v for the Akashi Strait and the Naruto Strait, respectively. In general, the exchange rates of E_s and E_v do not equal each other, because E_s largely depends on the spatial distribution of salt near a strait. Therefore, E_s is not an adequate measure for the tidal exchange. We found that the salt distribution near the straits and the salt-exchange rates E_s were dependent on the deformation of a water column and that this deformation is produced not only by the velocity shear of the nonlinear tidal current but also by tide-induced transient eddies.

1. Introduction

Tidal exchange through a narrow channel is of importance in the study of coastal oceanography because river water discharged into an inner basin flows out through the channel to the open sea. Therefore, many studies have been undertaken to determine the tidal exchange rate and to clarify the physical mechanisms of this exchange. By assuming that there is a difference in salinity between two basins and that a large degree of water-mixing occurs, previous investigators (Hayami *et al.*, 1957; Parker *et al.*, 1972; Nakata and Hirano, 1976) have evaluated the tidal exchange rate on the basis of observations of salt flux across a cross section of a channel. Other investigators have studied the physical process in the salt flux across a cross-section in a channel (Bowden, 1963; Hansen, 1965; Fischer, 1972; Dyer, 1974), and reported that the so-called steady flow and its shear are of great importance in determining tidal exchange. Our group (Imasato *et al.*, 1980; Awaji *et al.*, 1980) studied the physical mechanism involved in the "water" exchange produced by a nonturbulent tidal current flowing through a narrow channel using a numerical model basin; the method of Euler–Lagrange was employed to track ~20 000 labeled particles during one M_2 period. It was found that the horizontal shear and the spatial change of the phase lag of a nonlinear tidal current flowing through a channel connecting two basins produce a large drift of water particles and as a result, water exchange between two basins occurs even when the current does not contain any turbulence or a steady flow.

Now, we have some problems: What is the difference between the salt-exchange rate E_s and the water-exchange rate E_v? How adequate is the salt-exchange rate E_s as a measure of tidal exchange through a narrow channel? If there is no difference in salinity between the water in two basins, the salt-exchange rate E_s becomes zero even though the volume exchange rate E_v is large. Therefore, it is questionable whether the salt exchange rate E_s can be the measure of tidal exchange of sea water. To explore these problems we investigated the tidal exchange of the Akashi and the Naruto Straits in the Seto Inland Sea of Japan, using observed data of salt-distribution (Water Quality Bureau, 1973), time-series of calculated locations of labeled particles and calculated Eulerian velocities (Imasato *et al.*, 1980; Imasato and Awaji, 1982).

2. Data

The Akashi Strait lies between the Harima-nada inner basin and Osaka Bay, and the Naruto Strait lies between the Harima-nada and the Kii Channel. The bottom topography near the Akashi and the Naruto Straits is shown in Fig. 1. The Naruto Strait is ~1.5 km wide and ~20 m deep, and it has narrow approaches on both sides; the northern approach is 4 km wide, 3 km long and 70 m deep; and the southern approach is ~4.5 km wide, ~6 km long and ~50 m deep. The Akashi Strait is ~4 km wide, ~6 km long and ~50 m deep. The speed of the tidal current flowing through both straits is very fast; the maximum speed reaches ~5 m s^{-1} in the Naruto Strait and ~3 m s^{-1} in the Akashi Strait.

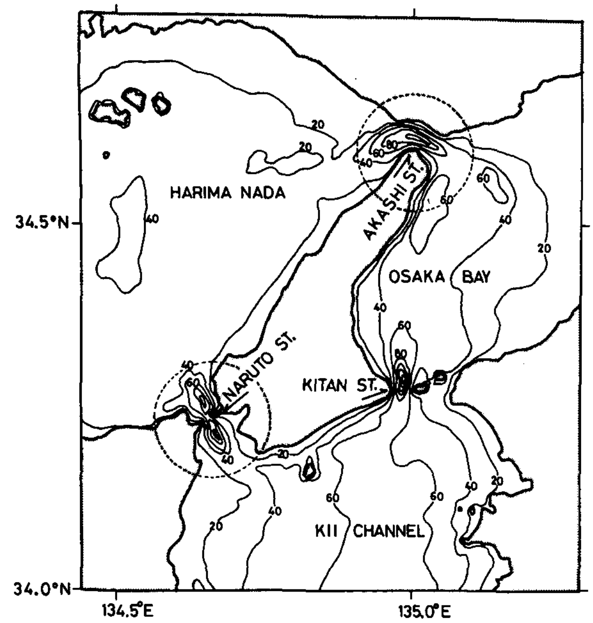

FIG. 1. Bottom topography near the Akashi and the Naruto Straits (dashed circles). Contour curves at 20 m intervals.

We use calculated time-series of current velocity and surface elevation, and locations of many labeled particles; in addition, we use the observed salinity distribution, i.e., the calculated data for the Akashi Strait (Imasato *et al.*, 1980), the calculated data for the Naruto Strait (Imasato and Awaji, 1982) and the salinity distribution (Water Quality Bureau, 1973). This salinity distribution, measured in January 1973, was used to assign an initial salinity to each particle (Fig. 2). In the first numerical model (Imasato *et al.*, 1980), the grid size was 1 km × 1 km, and 10 725 labeled particles (25 particles in each grid) were tracked; in the other numerical model (Imasato and Awaji, 1982), the grid size was ⅓ km × ⅓ km, and 17 852 labeled-particles (four particles in each grid) were tracked.

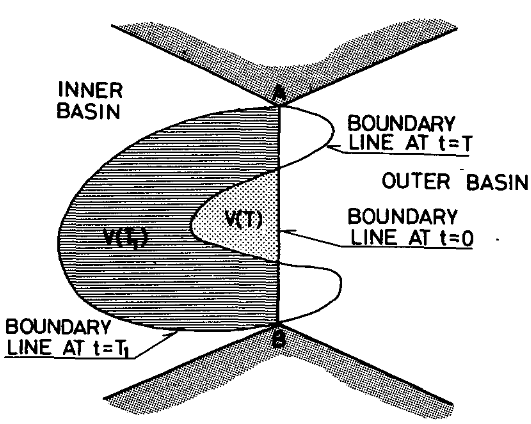

FIG. 2. Definition of water volumes $V(T)$ and $V(T_1)$.

3. The volume-exchange rate E_v and the salt-exchange rate E_s

The water-volume exchange rate E_v is defined as

$$E_v = \frac{V(T)}{V(T_1)}, \qquad (1)$$

where $V(T)$ is the volume of the outer (inner) water which exists in the inner (outer) basin at time t, T_1 denotes the time when the volume of outer (inner) water in the inner (outer) basin becomes maximum within a tidal cycle, and T denotes the tidal period. Then, $V(T)$ denotes the net volume transport across the cross-section or the exchanged water volume in a tidal cycle. Values of water volumes $V(T)$ and $V(T_1)$ were calculated by integrating the volume of water column represented by the outer (inner) water particles that exist in the inner (outer) basin at time $t = T$ and $t = T_1$, respectively (Fig. 2). Imasato *et al.* (1980) reported that the value of E_v depends on the tidal phase when tracking is started, and labeled particles must be released at the time of maximum flood (ebb) current, because the particle that lies on the boundary line $\overline{AB}$ (the straight line in Fig. 2) between the inner and the outer waters at $t = 0$ should move in the velocity fields of both the inner and the outer basins during a tidal cycle. Then, T_1 is the time near high (low) tide slack water. Volume-exchange rates E_v for the Akashi and the Naruto Straits that were reported by Imasato and Awaji (1982) are tabulated in Table 1.

Next, the salt-exchange rate E_s is defined as

$$E_s = \frac{\Delta FS}{FS}, \qquad (2)$$

where $\Delta FS = \int_0^T \int_A SUdAdt$ denotes the net salt flux across the cross-section $\overline{AB}$ (Fig. 2) during a tidal cycle, and $FS = \int_{T_1}^{T_2} \int_A SUdAdt$ denotes the salt flux across the cross-section during a flood (ebb) tide. Here S denotes the salinity, U the Eulerian tidal velocity normal to the cross-section $\overline{AB}$, $\int_A GdA$ the integration of a quantity G over the cross-section $\overline{AB}$, T_1 the time of high (low) tide slack-water and T_2 the time of low (high)-tide slack water.

TABLE 1. Salt- and water-exchange rates.

	Exchange rate	
	Salt	Water
	E_s (%)	E_v (%)
Akashi Strait	15.5	48.0*
Naruto Strait	6.2	76.9*

* Turbulent tidal current produced by M_2 tide. After Imasato and Awaji (1982).

To evaluate values of ΔFS and FS, we need to know the time change of Eulerian velocity and salinity at grid boxes along the cross-section. The trajectories of labeled particles and the Eulerian velocity have been already calculated by Imasato *et al.* (1980) and Imasato and Awaji (1982). Assuming that each particle moves in the basin and carries a salinity, we determine the salinity in a grid box at time t by mixing the salt that particles carry into the grid box at time t. Fig. 3 shows the initial distribution of the labeled particles and the isohalines; an open circle denotes a particle in the inner basin (the Harima-nada), and a solid square denotes a particle in the outer basin (Osaka Bay in panel A and the Kii Channel in panel B). At first, a salinity value was assigned to each particle by the method of linear interpolation using an isohaline distribution.

Figure 4 illustrates how salinity in the grid box A enclosed by thick solid lines is determined. Salinity $S8$ of the grid box A at time $t = n + 1$ h (n is an integer) is given by

$$S8 = \frac{\sum_{k=1}^{N} S_k V_k}{\sum_{k=1}^{N} V_k}, \quad (3)$$

where N is the number of particles in the grid box, S_k is the salinity of the kth particle in the grid box and V_k the volume of the water column represented by the kth particle. The operation indicates the mixing of salt in each grid box and was performed every lunar hour for grid boxes near the Akashi Strait and every 0.5 h for those near the Naruto Strait. Therefore, we have salinity diffusivities of $\sim 10^5$ and 10^6 cm^2 s^{-1} for the Akashi and the Naruto Straits, respectively. We assume that this operation changes the salinity value of a particle in the grid box and the salinity value in the grid box itself, but not the trajectory of each particle; i.e., this operation does not include mixing of the momentum of the particles, which was already considered by the addition of a turbulent velocity to the Lagrangian velocity of a particle. Then, N particles in grid box A in Fig. 4 have a new salinity $S8$ and continue to have the same salinity $S8$ for successive one or 0.5 lunar h, and they move along their own trajectories.

Figure 5 shows the calculated time change of salt flux $\int_A SUdA$ across the cross-section in the straits and that of salinity $S_A - \bar{S}_A$, where S_A is the salinity averaged over the cross-section and $\bar{S}_A$ the salinity S_A averaged over one tidal period; the salt flux across the Akashi Strait was twice that across the Naruto Strait. The calculated salt-exchange rate E_s is tabulated in Table 1 together with the volume-exchange rate E_v. The salt-exchange rate E_s for the Akashi Strait was 15.5% (about one-third the value of the volume-exchange rate E_v), and E_s for the Naruto Strait was 6.2% (about one-twelfth that of E_v). These values of salt-exchange rate E_s are smaller than those of E_v. Especially, E_s for the Naruto Strait is very small.

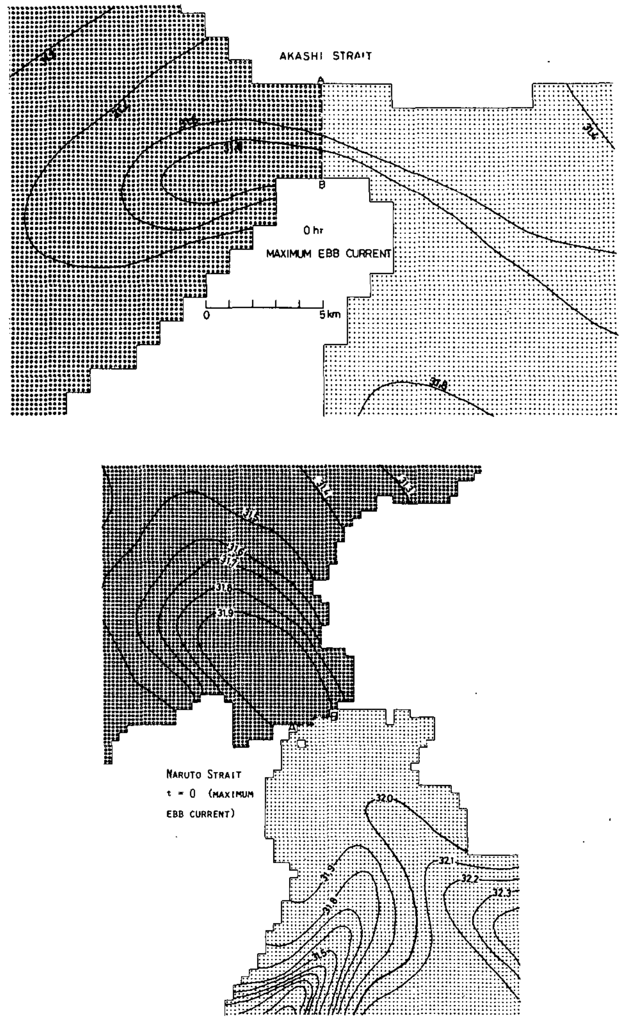

FIG. 3. Observed isohalines and initial locations of labeled particles: The heavy shading denotes a water particle in the inner basin (Harima-nada), and the light shading denotes a water particle in the outer basin (Osaka Bay in the top panel and Kii Channel in the bottom panel). Dashed line AB denotes the initial boundary between the inner- and the outer-water.

To account for these low values, it is necessary to study the movement of water particles. Figure 6 shows the initial locations of exchanged water particles together with the same observed isohalines shown in Fig. 1. In Fig. 6, the solid circles denote inner-water (water in the Harima-nada) particles and the open circles denote outer-water (water in the Osaka Bay in the panel A and in the Kii Channel in the panel B) particles. These particles move to the alternative basin through the cross-section shown by the dashed line and stay there after one tidal period. Fig. 6b shows that most of the water-particles exchanged through the Naruto

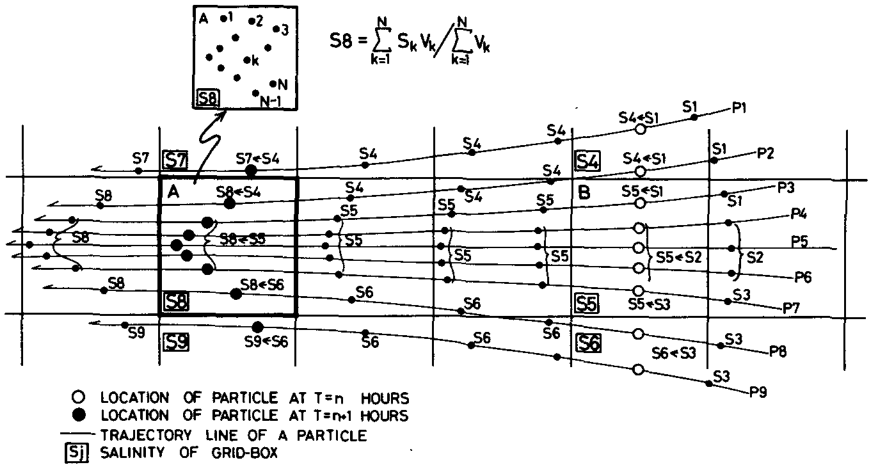

FIG. 4. The method of calculating an averaged salinity of grid box A, and that of a modified salinity of a labeled particle. The solid line denotes a trajectory of a particle, and the small solid circles a location of a particle. The large open and solid circles denote locations of a particle at time $t = n$ and $n + 1$ h, respectively; the symbol Sj ($j = 1, 2, \cdots$) denotes the salinity of a particle, and the symbol Sj within boxes ($j = 1, 2, \cdots$) the salinity in a grid box. $S8 \leftarrow S5$ means that salinity of a particle changes from $S8$ to $S5$ at time $t = n + 1$ h.

Strait are distributed in the area between the 31.9 and 32.0‰ isohalines. This explains why the salt-exchange rate E_s for the Naruto Strait is very small; a similar situation is also evident for the Akashi Strait.

The salt-exchange rate E_s and the volume-exchange rate E_v for the Naruto and the Akashi Straits indicate that the salt-exchange rates E_s largely depend on the spatial isohaline distribution. Therefore, the exchange rates E_s will change according to seasonal variations or some abrupt change in salt distribution even if the tidal current continues to be in a stationary state and the volume-exchange rate E_v is constant. The observed salt-exchange rates shown in Table 2 support our conclusion, because these observed values of exchange-rates are scattered in a fairly wide range according to the time of observation or the sea conditions. Thus, we conclude that the salt-exchange rate E_s is inadequate to measure the tidal exchange.

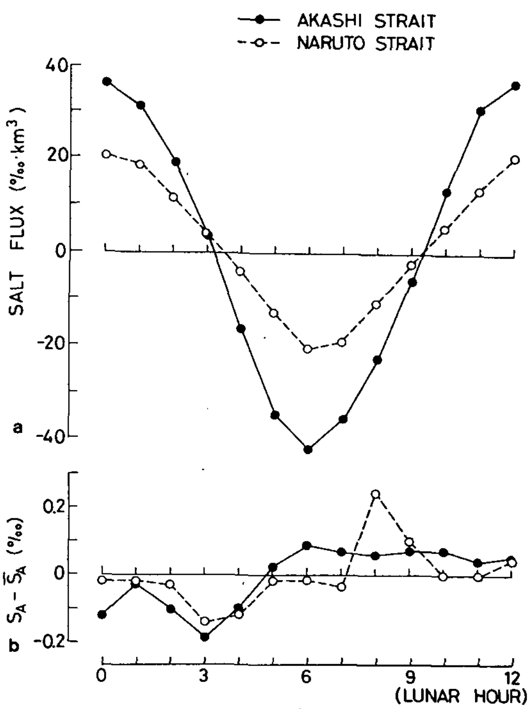

FIG. 5. Time change of (a) the salt flux across cross-section AB in Fig. 3; (top panel); and (b) the salinity averaged over cross-section AB.

4. Water-column deformation and salt exchange

Figure 6 also shows that the isohalines near the Akashi Strait run parallel to the coast of the channel, but, on the other hand, those near the Naruto Strait run across the channel, which is uniform in salinity. This fact shows that tidal mixing is very large near the Naruto Strait. This situation is supported by calculations of deformations of a water-column such as rotation, divergence, stretching deformation, and shearing deformation; *i.e.*, all of these deformations near the narrow channel of the Naruto Strait are ~10 times those in the Akashi Strait, although no figure is shown in this paper.

A large water-column deformation produces a large dispersion of particles or dye tracer in water. Now, we present some examples of dispersion of particles. For a grid box near the Akashi and the Naruto Straits, 1024 particles were instantaneously released at the time of maximum ebb current. These particles made a 1 km × 1 km patch near the Akashi Strait, and a 1/3 km

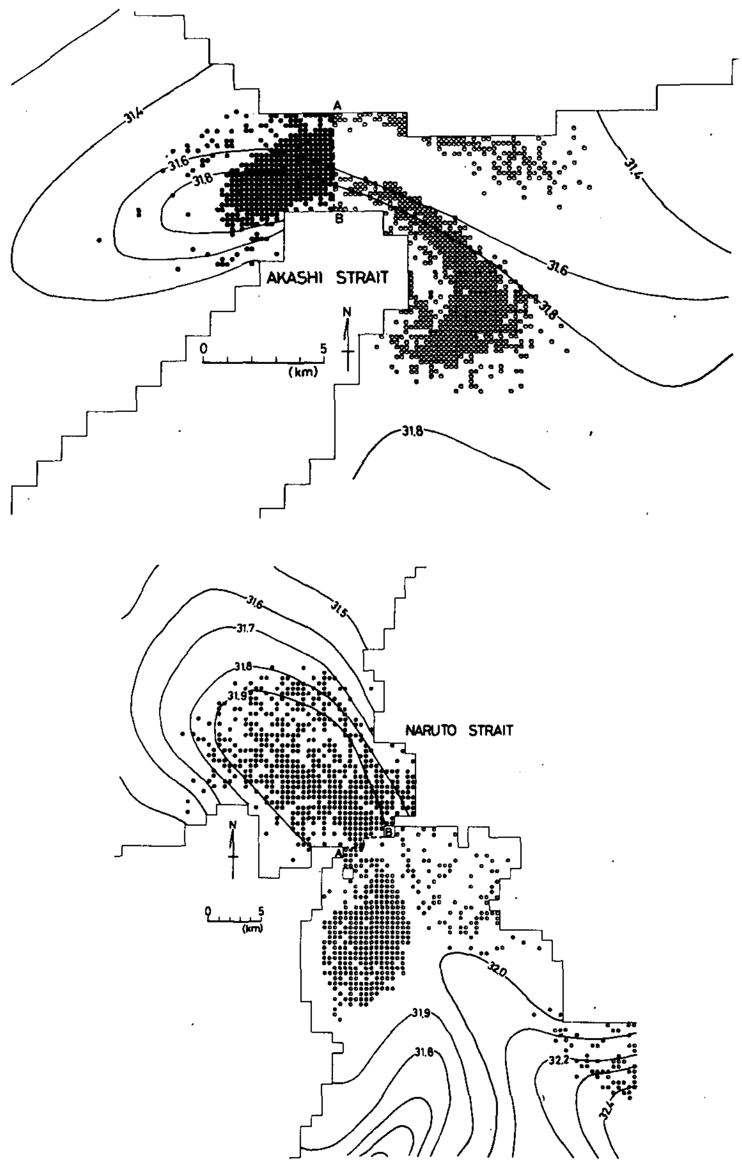

FIG. 6. Observed isohalines (as in Fig. 3) and the initial locations of exchanged particles near the Akashi (top panel) and the Naruto Strait (bottom panel). A solid dot shows the initial location of an inner-water particle which flows to the outer basin and remains after one tidal period, and an open circle shows the initial location of an outer-water particle which flows into the inner basin and remains after one tidal period.

TABLE 2. Observed salt-exchange rates.

	Salt exchange rate E_s (%)	Investigators
Golden Gate	17–36	Parker *et al.* (1972)
Hoyo Strait	11–21	Kawamura *et al.* (1975)
Akashi Strait	28–34	Shimizu and Kawamura (1981)
Kurushima Strait	7–26	Nakata and Hirano (1976)
Mekari Strait	20–50	Nakata and Hirano (1976)
Oguchi Strait	44–77	Nakata and Hirano (1976)

× ⅓ km patch near the Naruto Strait, and were dispersed during a tidal period. Figure 7 shows the seven examples of dispersions of particles; the initial location of a patch is represented by a square (e.g., $A1_0$), and the locations of particles after a tidal period is represented by a group of dots (e.g., $A1_{12}$). A square patch released near the Akashi Strait is deformed into the shape of a long line that runs parallel to the shoreline of the channel. On the other hand, the deformation of a square patch released near the Naruto Strait forms a circle and particles are widely dispersed.

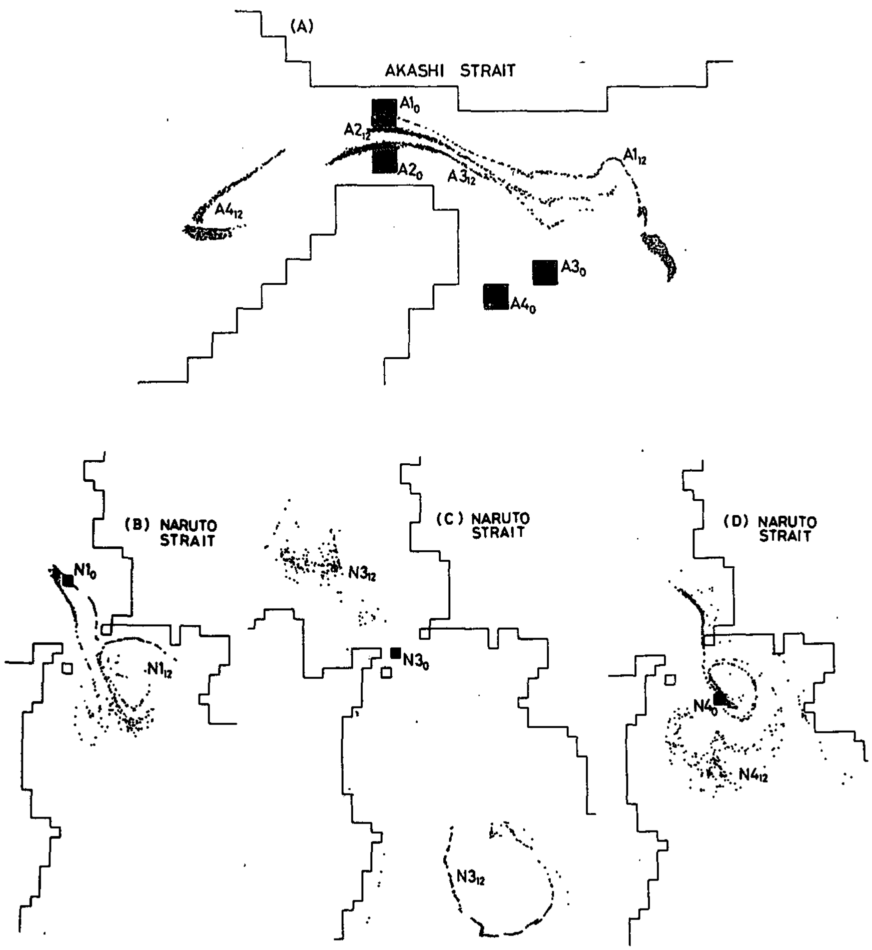

FIG. 7. Deformation or dispersion of a square patch released near the Akashi (panel A) and the Naruto Strait (panel B). A square (e.g., $A1_0$) shows the initial figure of a patch containing 1024 particles and a group of dots shows the locations of these 1024 particles after one tidal period.

Figure 8 presents a histogram of σ which is the measure of deformation of a patch, and both of the histograms consist of 20 patches that are nearly evenly spaced near the straits. σ is defined as

$$\sigma = \overline{\sigma_{ii}^2}/\overline{\sigma_{jj}^2}, \quad (4)$$

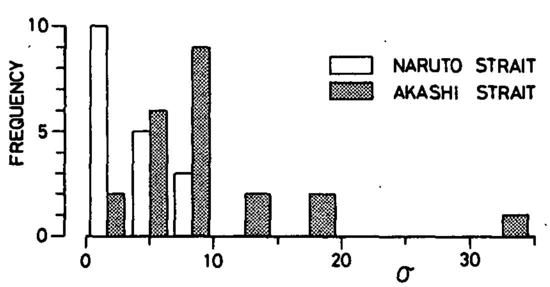

FIG. 8. Histogram of the deformation measure σ of a patch.

where $\overline{\sigma_{ii}^2}$ is the statistical dispersion coefficient in the direction of the long axis of a patch and $\overline{\sigma_{jj}^2}$ is that in the direction of the short axis. Therefore, σ represents the shape of a patch deformed during a tidal period. The Naruto Strait has a peak at $\sim\sigma = 1$ and the Akashi Strait has a peak at $\sim\sigma = 8.5$. These results show that the deformation and dispersion of many of the patches released near the Akashi and the Naruto Straits are identical to those shown in Fig. 7.

The interesting physical features of the Naruto Strait are the distribution of isohalines running across the channel and the formation of an area of a uniform salinity. As discussed above, these features are due to the large deformation of a water column which is produced not only by the large velocity shear of the tidal current but also by the tide-induced transient eddies (Imasato, 1983). These eddies are induced by the nonlinear tidal current in the area of the downstream side of line $\overline{AB}$ in Fig. 6b, and disappear soon after the beginning of the turn of the tidal current.

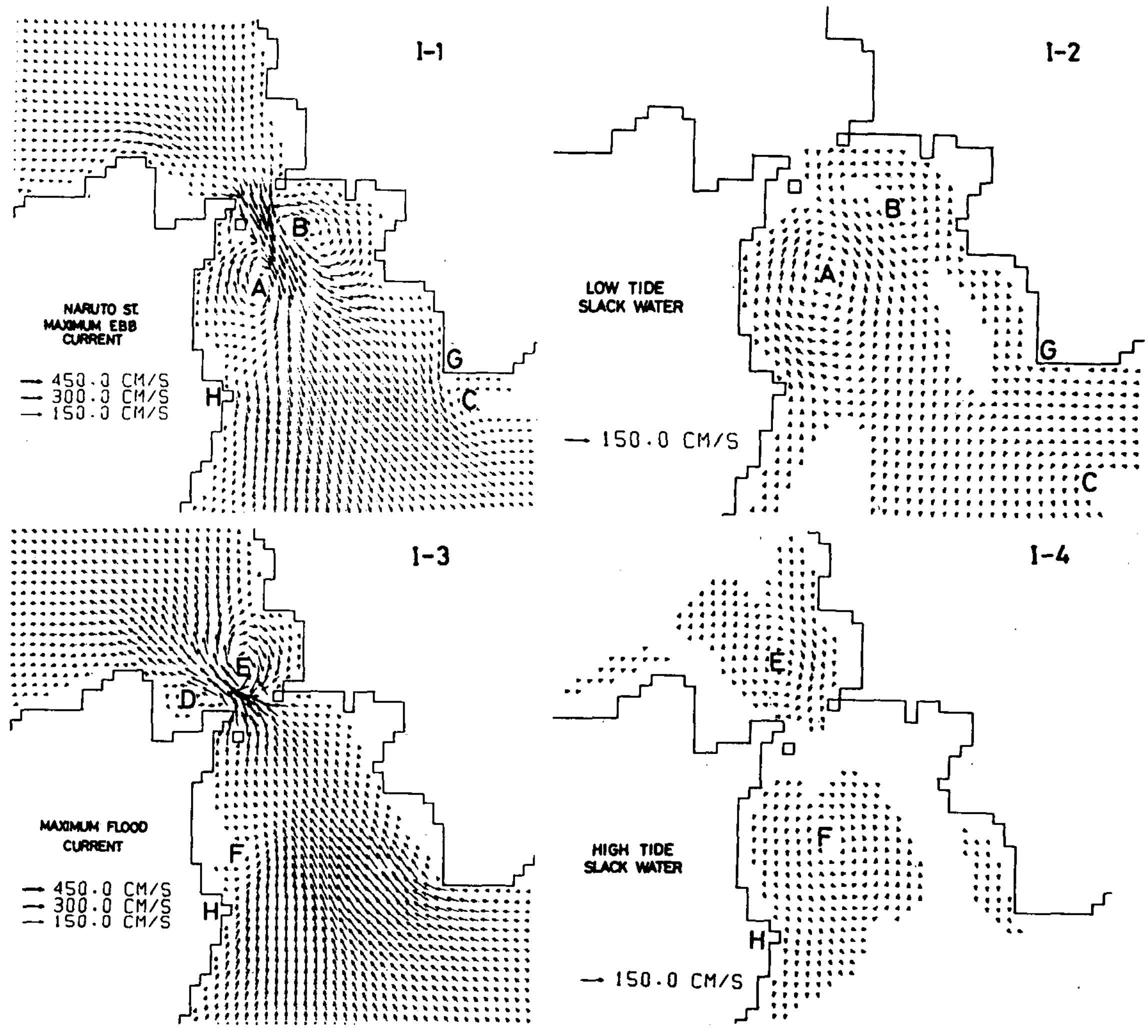

FIG. 9. Time change of the velocity field near the Naruto Strait (panels I-1–I-4) and the Akashi Strait (panels II-1–II-4).

Figure 9 shows the distributions of calculated velocity vectors at four tidal phases: maximum ebb current, low-tide slack water, maximum flood current, and high-tide slack water. Now, we examine the panels of the Naruto Strait. Circulations A and B are induced by the ebbing tidal current in the downstream area from the boundary line AB in Fig. 6b, and disappear soon after the turn of the tidal current. Panels I-1 and I-2 show that no circulation is induced in the Harima-nada (the upstream side) during the ebb tide. A situation similar to that during ebb tide is seen in panels I-3 and I-4 which show the velocity field during flood tide. Circulations C and F are induced behind Capes G and H, respectively. Circulation F (panel I-4) is located at the same position as circulation A (panel I-2), but these two circulations rotate in opposite directions. This fact shows that circulations A and F are time dependent. The features discussed for circulations A, B, D and E near the Naruto Strait are also evident for circulations I, J and K near the Akashi Strait. We called these time-dependent circulations "tide-induced transient eddy" and concluded that the so-called tide-induced residual current has no physical reality (Imasato, 1983).

Figures 6b and 9I show that the area of the tide-induced transient eddies overlaps both the area of initial locations of the exchanged particles and also the area of the uniform salinity near the narrow channel of the Naruto Strait (Fig. 6b). Therefore, we conclude that the distribution of isohalines near the narrow channel and the salt exchange through it largely depend on the deformation of the water column produced by velocity shear of the nonlinear tidal current and tide-induced transient eddies.

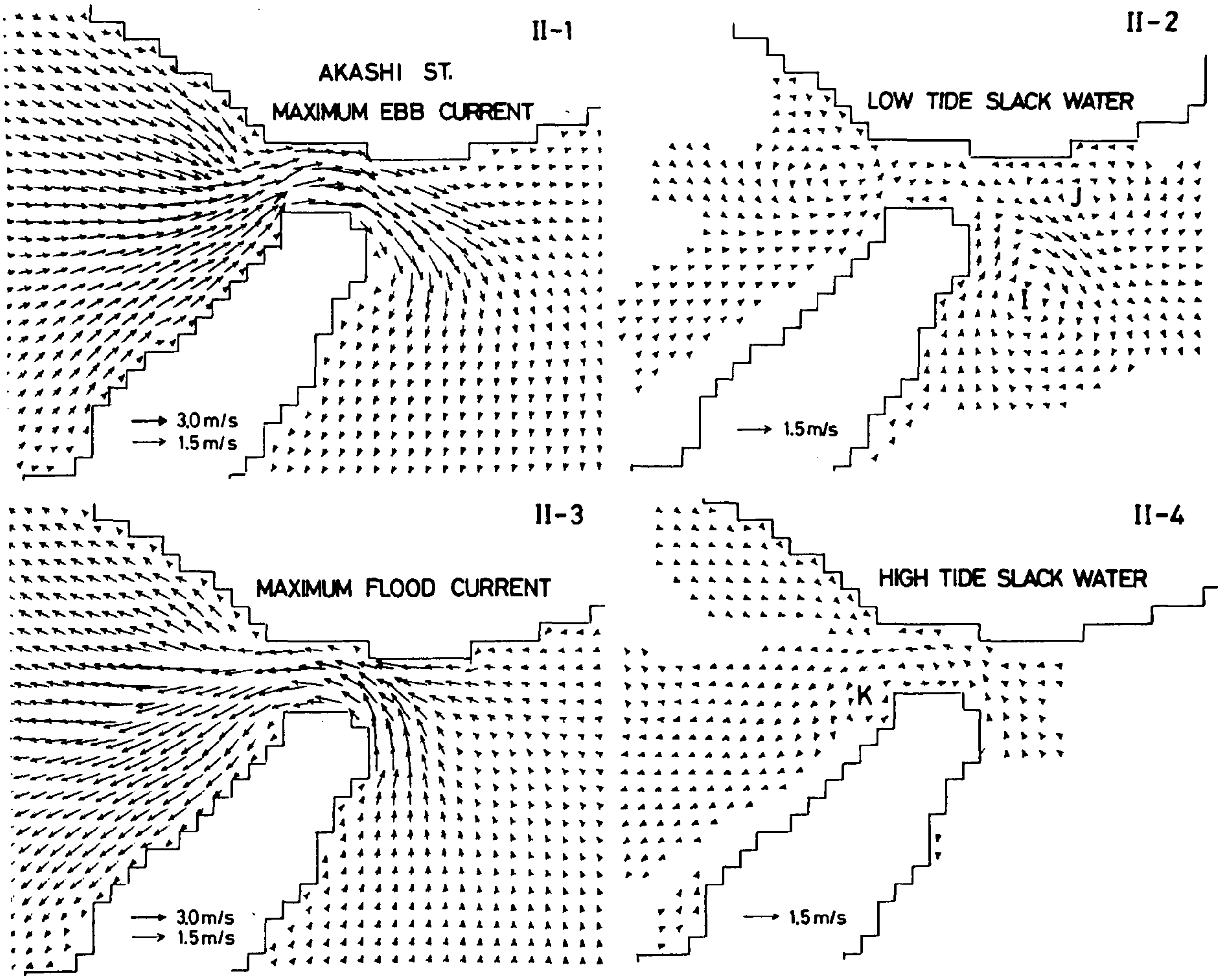

FIG. 9. (*Continued*)

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