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Numerical modeling of density-driven current in Tokyo Bay

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Abstract : Density-driven current induced by fresh water discharge from rivers in Tokyo Bay was numerically investigated by multi-level model. The experiment was focused on the density distribution and motion in the inner bay under the summer stratification by giving the monthly mean discharge. The low density water from the river mouth spreads asymmetrically in the surface layer of the basin by influence of Coriolis' force and moves along the coast on its right hand side with maximum velocity of 3–5 cm s^{-1}. In the surface layer, the low density water forms a coastal-trapped plume. The flow toward the river mouth is formed just beneath the surface layer, and is very weak in comparison with the surface outward flow. The inflows may be induced by the outward flow at the surface as the entrainment.

Key words : *Tokyo Bay, three-dimensional model, density-driven current, river discharge, salinity distribution, Coriolis effect, anticyclonic circulation*

Introduction

Tokyo Bay is located at the central part of the main island of Japan, facing to the Pacific Ocean (Fig. 1). The bay is separated in two parts, i.e., the inner and outer bays. The mean depth, bay length and width of the inner bay are 18 m, 80 km and 20–30 km, respectively.

The surface circulation consists of wind-driven, density-driven and tide-induced residual currents (UNOKI, 1993). The tide-induced residual current is not significant except the eastern area near the connection between the inner and outer bays. This is already clarified by the observation (UNOKI *et al.*, 1980) and numerical modeling (e.g., IKEDA *et al.*, 1981; GUO and YANAGI, 1994). The existence of wind-driven current was indicated by the moored current measurements(Hasunuma, 1979; UNOKI, 1985). SUZUKI and MATSUYAMA (2000) indicated that the main results of the observation at moored stations are simulated as the wind-driven current by using a three-dimensional model. They showed the importance of baroclinic response to the wind in the northern region of the stratified Tokyo Bay. On the other hand, FUJIWARA *et al.* (1997) showed that the anticyclonic circulation in the upper layer is formed near bay head of rectangular bay by freshwater discharge, and they suggested the importance of density-driven current in the surface circulation near the bay head. They explained an anticyclonic circulation in the upper layer to be caused by horizontal divergence associated with upward entrainment, which is a part of the estuarine circulation and means the importance of stratification by earth's rotation. We wonder how mechanism of the strong upward entrainment is induced by the weak discharged flow. Their study didn't sufficiently evaluate contribution of density-driven current due to river discharge to residual current. Therefore, the study of density-driven current induced by the river discharge in Tokyo Bay is required to understand the residual current, which advects various properties from the bay to the open sea.

In the present study, we try to investigate the density current induced by the discharged water from the rivers in Tokyo Bay, using the three-dimensional numerical model. We focus on the behavior and structure of low density water around the estuary.

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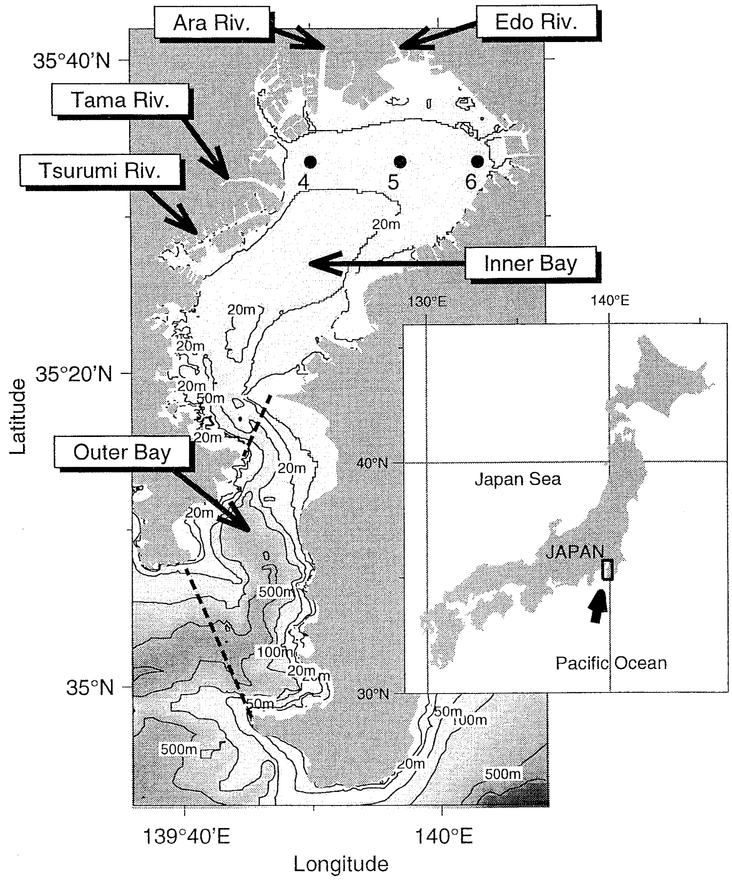

Fig. 1. Bottom topography of Tokyo Bay and location of the observation sites in Tokyo Bay. Numerals on bottom contours are in meters. Station K is the CTD station of Kanagawa Prefectural Fisheries Research Institute. The filled circles with station numbers indicate the CTD stations of the 3rd Regional Coast Guard Headquarters, Japan Coast Guard.

River discharge in Tokyo Bay

The data of river discharge are mostly observed at the mouth of each river. We need the data of river discharge for the boundary condition of the numerical modeling as forcing. The discharge data at main four rivers, i.e., Edo, Ara, Tama and Tsurumi Rivers, are used for experiments. In this study, we focus on the low salinity water at the sea surface along the western coast of Tokyo Bay in August. Figure 2 shows the daily-mean discharge volume of each river and total discharge volume during the period from August 1 to 31, 1995, from the "Report of River Discharge Data 1995". The largest discharge volume was Edo River, and the smallest was Tsurumi River. The monthly mean of total volume discharged into Tokyo Bay was 110 m^3s^{-1}, and it ranged from 75 m^3s^{-1} to 250 m^3s^{-1} in this period. Based on Annual Report on River Discharge data in Japan in 1979, GUO and YANAGI (1998) used the total freshwater volume of 130 m^3s^{-1}, i.e., Edo River, Ara River, Tama River and Tsurumi River are 70, 30, 20 and 10 m^3s^{-1}, respectively.

Model description

We consider a stratified, rotating, incompressible fluid, and use a rectangular coordinate system on an f-plane. Figure 3 shows the model configuration of Tokyo Bay. The x, y, and z-axes are taken in southeastward, northeastward and vertically upward from the mean

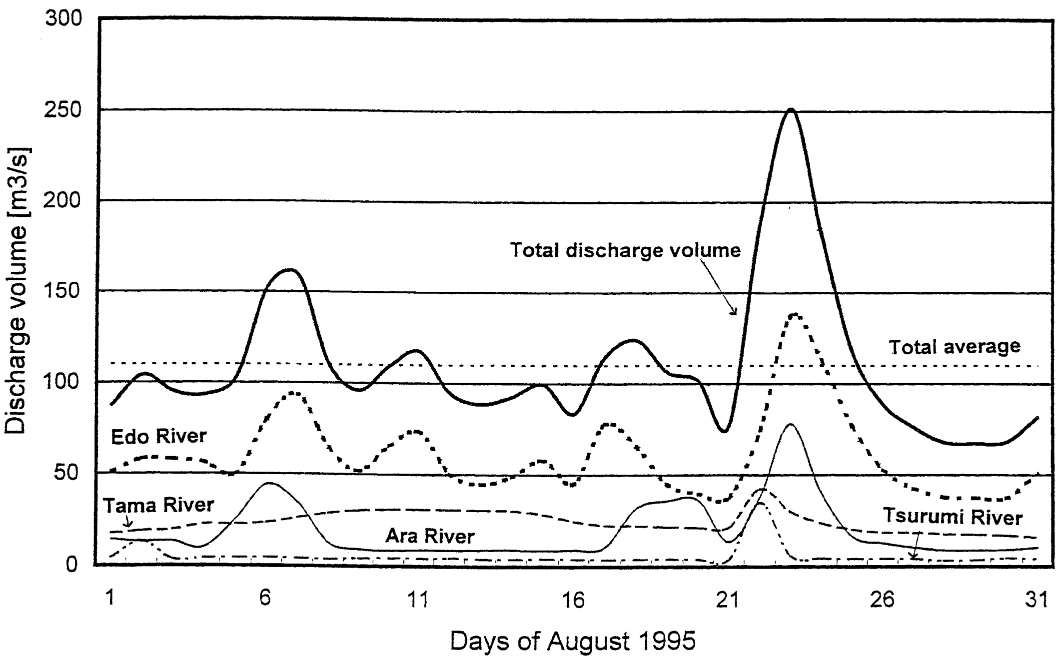

Fig. 2. Daily-mean river discharged volume of main rivers in Tokyo Bay during August 1995.

sea-surface level, respectively. The basic equations are as follows;

$$\vec{u}_t+\vec{u}\cdot\nabla\vec{u}+w\vec{u}_z+f\vec{k}\times\vec{u} = -\frac{1}{\rho_0}\nabla p+A_h\nabla^2\vec{u}+A_v\vec{u}_{zz}$$

$$\rho g = -p_z$$

$$\nabla\cdot\vec{u}+w_z=0$$

$$\rho_t+\vec{u}\cdot\nabla\rho+w\rho_z = K_h\nabla^2\rho+\frac{K_v}{\delta}\rho_{zz}$$

where $\vec{u}$ is the horizontal velocity vector (u,v), w the vertical velocity, ∇ the horizontal gradient operator, ∇^2 the Laplacian operator, f the Coriolis' parameter, $\vec{k}$ unit vector of vertical axis, ρ_0 the reference density, ρ the density, p the pressure and g the gravitational acceleration. A_h, A_v, K_h, and K_v are the coefficients of the horizontal and vertical eddy viscosity and the coefficients of the horizontal and vertical diffusivity, respectively. The symbol δ is the instantaneous convective adjustment parameter and is used to maintain a stable stratification in the model (SUGINOHARA, 1982). It is defined as follows:

$$\delta=\begin{cases}1 & for\ \dfrac{\partial\rho}{\partial z}\leq 0\\[2ex] 0 & for\ \dfrac{\partial\rho}{\partial z}>0\end{cases}$$

A non-slip and no normal density flux conditions are adopted at the coastal boundary as follows:

$$\vec{u}=0,$$

$$\frac{\partial\rho}{\partial n}=0,$$

where n denotes the normal component to the coast. The bottom boundary conditions are adopted as follows:

$$\frac{\partial\rho}{\partial z}=0,$$

$$A_v\left(\frac{\partial u}{\partial z},\frac{\partial v}{\partial z}\right) = C_b U_B(u_B, v_B)$$

where $U_B=\sqrt{u_B^2+v_B^2}$ is the current speed, with u_B and v_B the velocity components just above the sea bottom in the x and y directions, respectively, and C_b is the coefficient of bottom friction. At the sea surface $(z=\eta)$, no wind stress is given.

An Orlanski Radiation Condition (ORLANSKI,

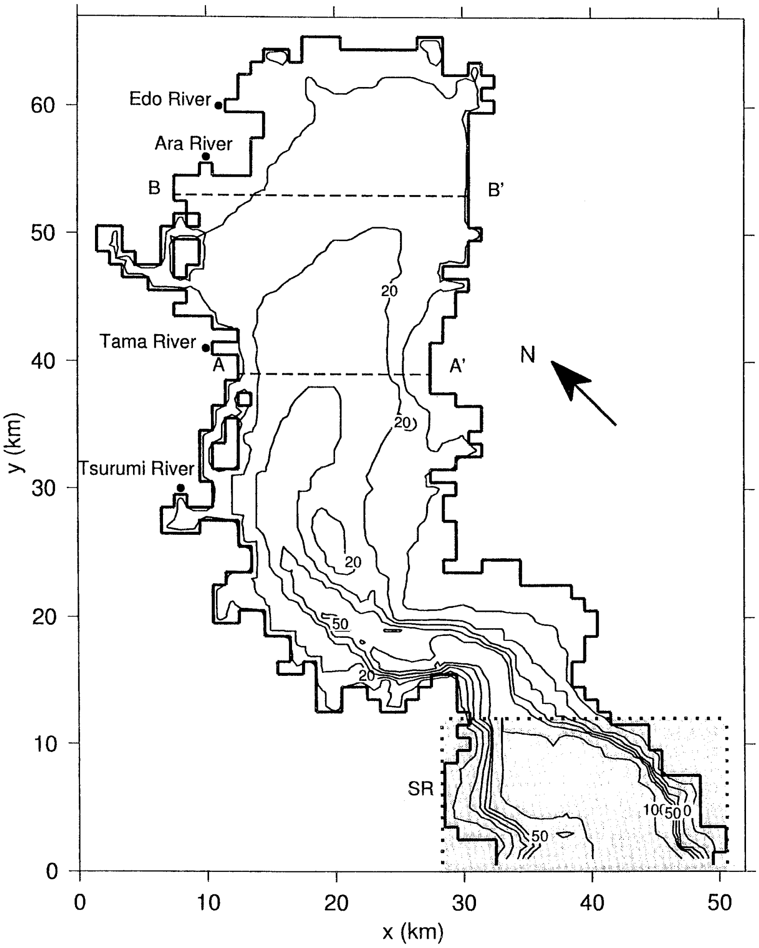

Fig. 3. Schematic view of the model. Numerals on bottom contours are in meters. The sponge region (SR) is imposed at $0<y<12$km and the area is drawn by the dotted lines. The filled circle indicates the mouth of the main river. Dashed lines (A–A' and B–B') are used for model cross sections.

1976) is imposed to velocity components, u, v and elevation of sea surface η at the bay mouth, i.e., the southern boundary at $y=0$.

$$\frac{\partial\phi}{\partial t}\pm c\frac{\partial\phi}{\partial y}=0$$

where

$$c=\begin{cases}\dfrac{\Delta y}{\Delta t} & if \quad \mp\dfrac{\partial\phi}{\partial t}/\dfrac{\partial\phi}{\partial y}\geq\dfrac{\Delta y}{\Delta t}\\ \mp\dfrac{\partial\phi}{\partial t}/\dfrac{\partial\phi}{\partial y} & if \quad 0<\mp\dfrac{\partial\phi}{\partial t}/\dfrac{\partial\phi}{\partial y}\geq\dfrac{\Delta y}{\Delta t}\\ 0 & if \quad \mp\dfrac{\partial\phi}{\partial t}/\dfrac{\partial\phi}{\partial y}\leq 0\end{cases}$$

where Δt and Δy are a time step and grid size of y-direction, respectively. Moreover the sponge region of 12 km length from the bay mouth is added. Within this region the bottom friction coefficient is exponentially increased from its interior value to four times that value at the open boundary (RØED and COOPER, 1987).

The basic density stratification is given in Fig. 4 as a representative one in summer. The data were obtained at Stn. K (Fig. 1) by Kanagawa Prefectural Fisheries Research Institute on August 6, 1979. The observed density stratification from the sea surface to 30m depth is used in this model. The density beneath 31m depth is assumed as uniform, and it is the same value as that at 30m depth. Density of

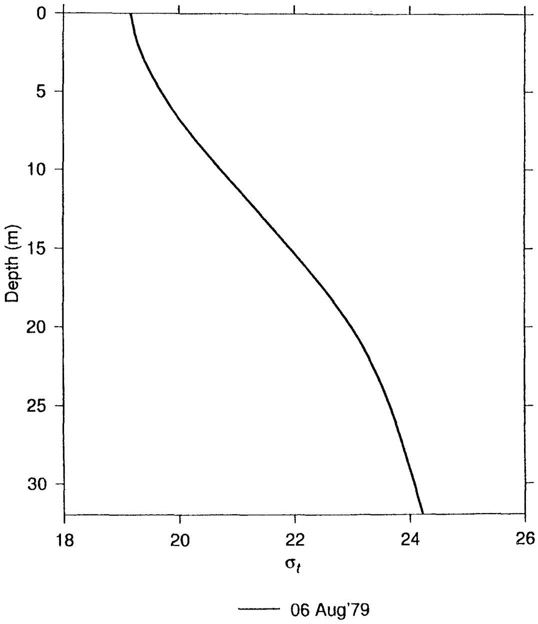

Fig. 4. Basic density (σ_t) stratification at the hydro-cast station observed by Kanagawa Prefectural Fisheries Research Institute on August 16, 1979.

Table 1. Discharge volume (m^3s^{-1}) of each river used in the model.

Riber Name	Case 1 (typical case)	Case 2 (flood case)
Edo River	70	200
Ara River	30	70
Tama River	20	40
Tsurumi River	10	15
Total	130	325

freshwater at each river mouth is assumed as 1.0100 g cm^{-3}, while the ambient density at the sea surface is 1.0192 g cm^{-3}. Two cases of the numerical experiments were performed;(1) Case 1 is the typical volume of discharge water in summer, and (2) Case 2 is the flood case (Table 1). Water in the whole bay is at rest initially. To avoid the initial shock waves, the river velocity is gradually increased in two hours from zero to the given value. The horizontal grid size is 1km and vertical grid is 1m from the sea surface to 31m depth. The bottom layer is taken from 31m to the sea bottom in the model. Time step is 10 seconds. To get well-established plume shape, the model is running for 12 days. For computational efficiency, the maximum water depth is limited by 100m depth.

The following values are used for numerical computations; $f=8.44\times10^{-5}$ s^{-1} (at 35.5°N), g = 980 cm s^{-2} and $\rho_0 =$ 1.0000g cm^{-3}. The following coefficients for the calculation are based on the previous numerical studies (SUGINOHARA 1982; SUZUKI and MATSUYAMA, 2000); A_h = $1.0\times10^6 cm^2 s^{-1}$, $A_v = 1.0 cm^2 s^{-1}$, $K_h = 1.0\times10^5$ $cm^2 s^{-1}$, $K_v = 1.0$ $cm^2 s^{-1}$ and $C_b = 2.6\times10^{-3}$. The basic equations are numerically solved by a semi-implicit finite-difference method using a non-staggered Arakawa-C grid.

Results

Figure 5 shows the distributions of horizontal current vector and density at 0.5m depth from 0.5 day to 12days after the initial state. At

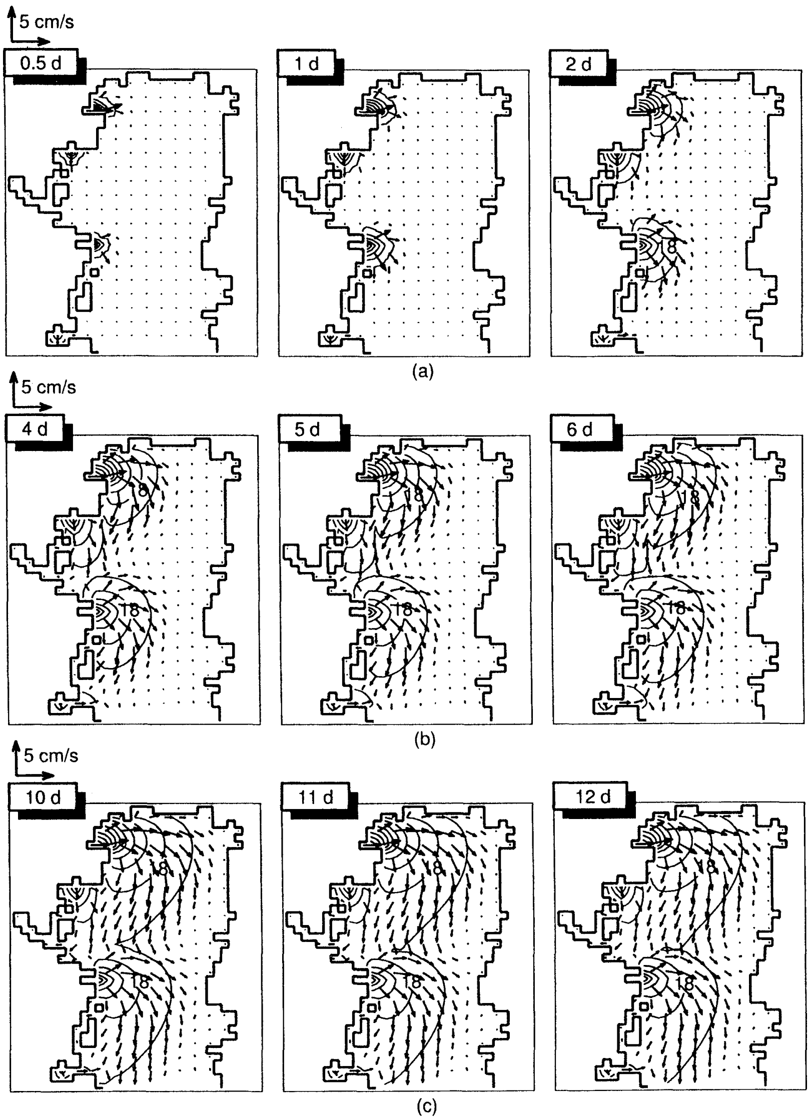

Fig. 5. Evolution of density and velocity distributions at 0.5 m depth after 0.5, 1, and 2 days (upper panel), after 4, 5 and 6 days (middle panel), and after 10, 11 and 12 days (lower panel) from initial stage for Case 1 (typical case). Isopycnal interval is σ_t of 1.0.

0.5 and 1day, low density water can be found in the limited region near the mouth of the Edo, Ara and Tama rivers. At 2 days, the low density region is clearly formed near the mouth of the rivers, and the contour lines mostly form the semicircle plume. The low density region slightly extends toward the bay mouth. At 4, 5 and 6 days, the low density region still grows in horizontal and slightly extends along the western coast. The current vector has a right angle with the density contours near the river mouth, while it diagonally crosses the contours in the offshore region. Maximum velocity is 3 –5 cm s^{-1} and it is not so large. These current patterns show almost steady state at 6 days except near boundary between the low density water and bay water, but the density contour lines slowly extend toward the east and south

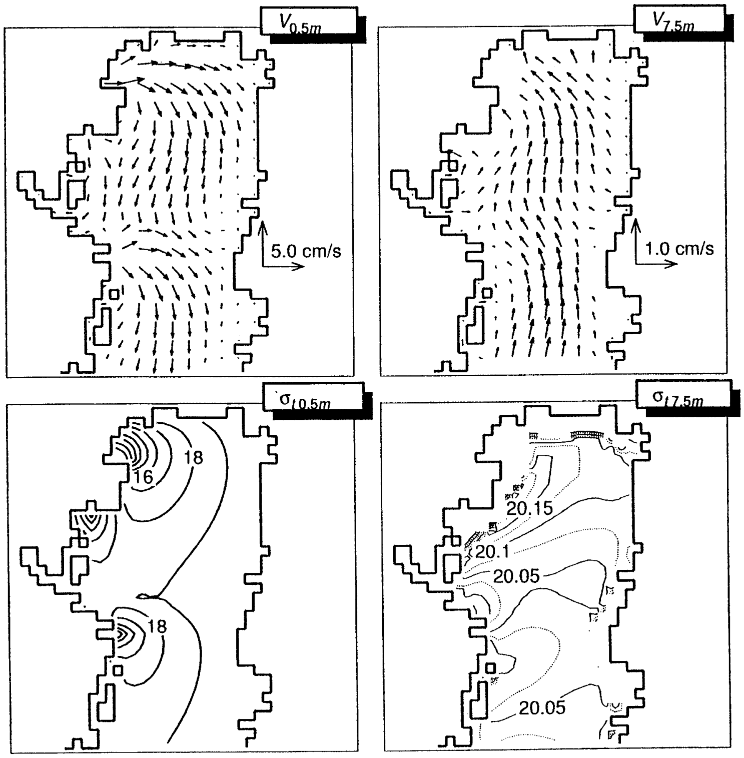

Fig. 6. Horizontal distribution current and density at 0.5m (upper) and 7.5m (middle) depths after 12 days. Isopycnal interval is as follows: st of 1.0 for st<19.00 and st of 0.025 for σ_t>19.00.

even at 12 days. The low density water moves toward the bay mouth along the western coast. The large cells are formed near the river mouth and both cells have nature of the clockwise circulation. The high pressure, i.e., high sea level region is formed by the river discharge as indicated by the hydraulic model experiments (MICHIDA, 1983; KITAMURA and NAGATA, 1983).

Figure 6 shows the horizontal distributions of velocity and density at two depths for the inner bay at 12 days. Two depths of 0.5m and 7.5m are selected as the representative of the surface and middle layers, respectively, to describe the current and density patterns. In the surface layer, the current direction is southward along the western coast following the geometric shape of the bay. Maximum velocity is found nearby the river mouth in the western part of the bay. The low density water flows out in the surface layer near the river mouths, and low density region is formed along the western coast. In the middle layer, the current vector direction is toward the bay head beneath the outward flow. This inward current may be induced by the outward flow in the surface layer. But this inward current is very weak in comparison with the surface outward one. The density in the middle layer is slightly higher near the mouth of the rivers than other region, suggesting existence of upwelling associated with entrainment.

Figure 7 shows the vertical sections of density, cross-bay and along-bay components of current across the bay at y = 38km (A–A' section shown in Fig. 3) after 12 days from the initial stage. The section is selected as the representative one to observe the density current affected by the Edo River, Ara River and Tama River. The density contour lines above 5m depth rise up from the west to the east in the bay. Below this depth, the contour lines are almost in horizontal. The contour lines of σ_t = 19 and below this value outcrop at the sea surface in the region between the west coast and

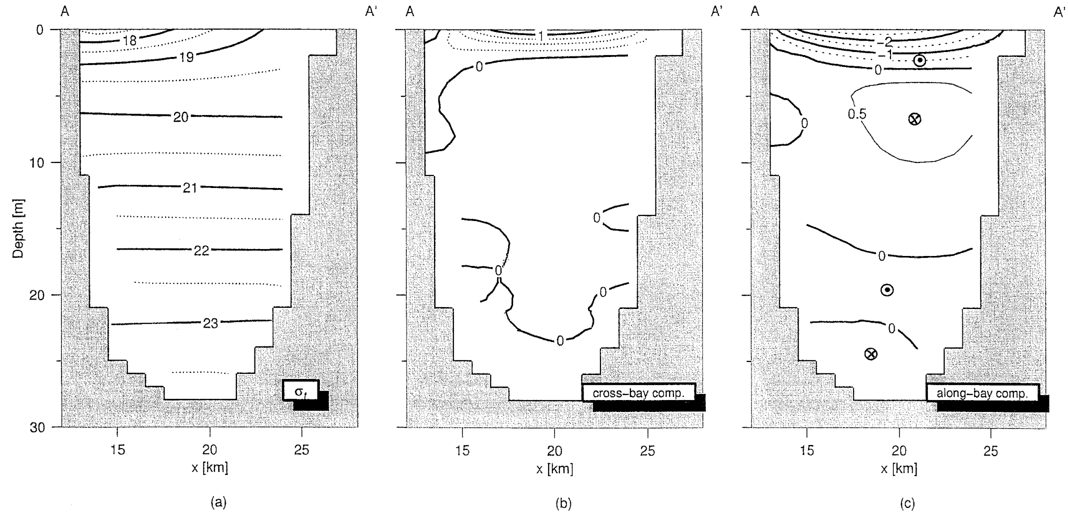

Fig. 7. Cross sections along A–A' line (y =40 km) for σ_t(a), cross–bay current (b) and along–bay current (c) after 12 days. Contour intervals are σ_t of 0.5 for density distribution, 0.25 cm s^{-1} for cross–bay current and 0.5 cm s^{-1} for along–bay current. Negative and positive velocity indicates outflow and inflow direction, respectively.

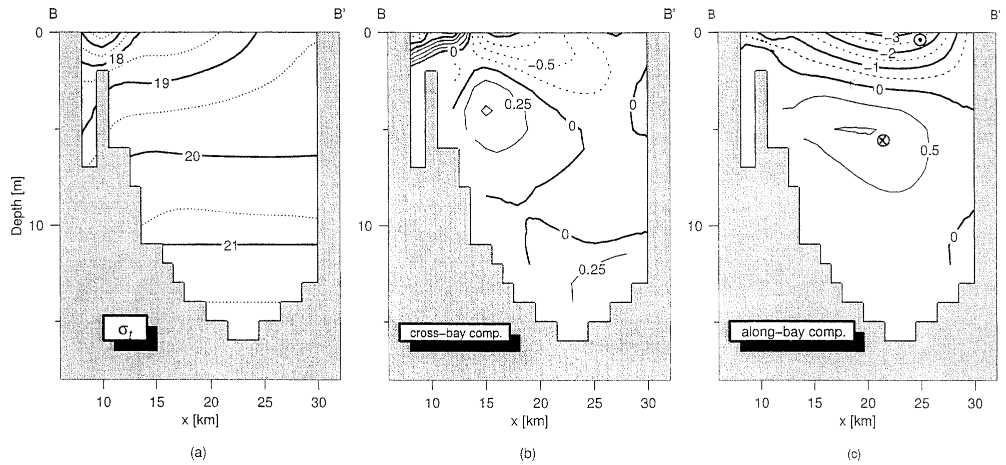

Fig. 8. Same as Fig. 7, but for the section along B–B' line.

center in the bay, that is, the weak density front is formed at the edge of the plume. The horizontal scale of the plume is 5–10 km, longer than the internal radius of deformation of 2–4 km (SUZUKI and MATSUYAMA, 2000). In the surface layer with about 3m thickness, the current is directed to the bay mouth. The strong current is found inside the plume.

Figure 8 shows the cross section at y = 53 km (Section B–B' shown in Fig. 3), which is located 2 km from Ara River at the bay head. The contour lines of the low density water cover wide region at the sea surface. The lines of lower density than σ_t=18.0 concentrate in the narrow region of the west coast. The region of eastward flows in the surface layer mostly agrees with that of the lower density water. The core of southward flow toward the bay mouth exists center of the bay off the low density water and the southward current takes together with weak westward component. This southward or south-southwestward current near the central region is induced by the discharge from Edo River. The frontal structure is

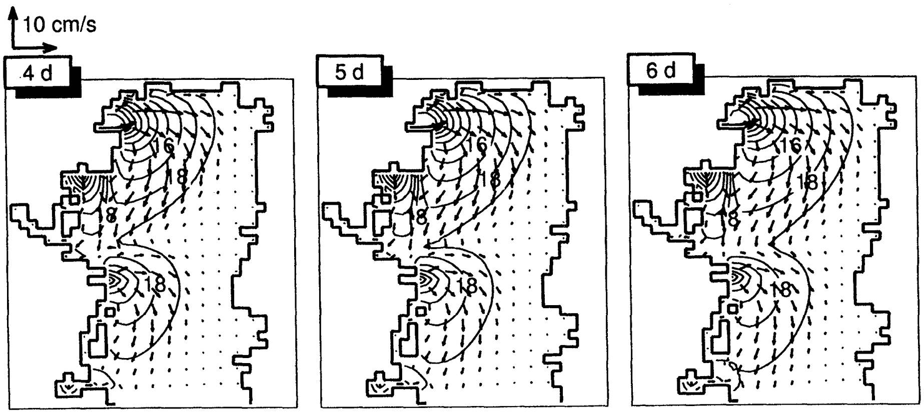

Fig. 9. Density and current distributions near the sea surface after 4, 5 and 6 days for Case 2 (flood case). Isopycnal interval is σ_t of 1.0.

clearly formed near the mouth of Ara River.

Figure 9 shows the current and density distributions at 4, 5 and 6 days for Case 2 (flood case). The low density water spreads faster and occupies wider region in comparison with that for Case 1 (typical case), but their patterns are not different from each other. Maximum velocity is also found near the mouth of rivers and its value is about 10 cm s^{-1}.

The results of numerical experiments using three-dimensional model are summarized as follows. The low density water formed by the river discharge distributes around and off the river mouth in the surface layer along the western coast of the bay in summer. This water flows toward the bay mouth with speed of 3–5 cm s^{-1} in the upper layer for monthly mean discharge, while the inward flows exist just beneath the very weak outward flows for the compensation. We suppose that the current is not easy to be detected by the current measurements at the moored station because of the weak velocity, but the salinity distribution offers the density current pattern.

Discussion

The density-driven current induced by the river discharge is found along the western coast of Tokyo Bay. The low density region in the surface layer is firstly formed in estuary, i.e., off the mouth of rivers and progresses toward the bay mouth along the western coast (Fig. 5). Such features are similar to the behavior of the discharged high temperature water in the coastal area from the power plant (MATSUNO and NAGATA, 1987). The pressure gradient balances to the Coriolis force in the offshore direction, so the low density water progresses along the coast on the right hand side in northern hemisphere for conservation of potential vorticity (e.g., GRIFFITHS, 1986). Figure 10 shows the vertical section of the salinity distribution near the bay head on August 7, 1995, observed by the 3rd Regional Coast Guard Headquarters, Japan Coast Guard. The location of the observation is shown in Fig. 1. The observation line is not taken cross the bay, but is diagonal to the bay axis, i.e., along the latitude line. Although it was the coarse interval from station to station for the observation, the numerical model results (Fig. 8) is similar to the observational ones except for small salinity variation in the eastern side.

Figure 11 shows the salinity distribution at 1m depth in August 7 to 8, 1995, observed by the 3rd Regional Coast Guard Headquarters, Japan Coast Guard, as well. The temperature distribution at the sea surface is not so large difference in the inner bay in summer. The salinity distribution agrees with the density one in the surface layer. The low salinity is found near the mouth of main three rivers along the western side of the bay. The observational result closely resembles the numerical one except near the mouth of Ara River (Fig. 5 and Fig. 9). In Fig. 11, the lowest salinity region is

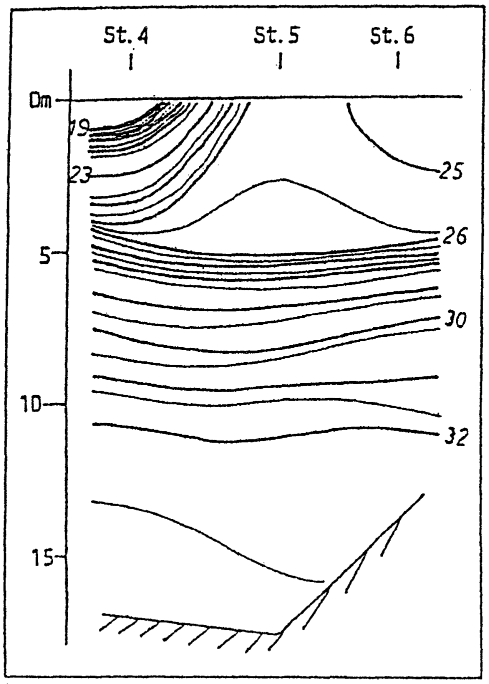

Fig. 10. Vertical distribution of salinity along latitude line at station number 4, 5 and 6 (see Fig. 1) in Tokyo Bay on August 7 to 8, 1995 (after the 3rd Regional Coast Guard Headquarters, Japan Coast Guard).

found off the mouth of Ara River, but not off the mouth of Edo River (Fig. 5). As shown in Fig. 2, Edo River is the largest discharge of the fresh water among the four main rivers, so that the numerical experiments (Fig. 5) shows the low density distributions off the mouth of Edo River. What is reason of the different distributions between observational and numerical results? The observational results are not only affected by the river discharge but also by wind and tide, while the numerical results are affected only by the river discharge. SUZUKI and MATSUYAMA (2000) indicated the important role of the wind-driven current in the inner bay of Tokyo Bay in summer. So, we investigate the wind data at Chiba in August 1995 because tide-induced residual current is not so significant near the bay head. Figure 12 shows the time series of wind vector at Chiba (AMeDAS). The westward wind blows from the morning of August 4 to the afternoon of August 6 and wind direction changes toward southeast after this period. Except about 6 hours in early morning of August 7, the southeastward wind continues during 4–5 days. This wind blows the parallel to the bay head coast, so it is possible to generate an outward Ekman transport. The surface water near the bay head may be moved toward the offshore. This surface water movement may give the explanation for the disappearance of the low salinity water off the mouth of Edo River in the observation.

The numerical experiments also supply a significant feature in the density-driven current induced by the river discharge into Tokyo Bay. It is an upwelling generated by the entrainment of the lower layer water due to the surface outflow. As expected, the inward flow of the lower layer is very weak. The anticyclonic circulation around the river mouth is closely related to the high-pressure region at the sea surface generated by the outflow from rivers. The anticyclonic circulation induces the upwelling in the middle layer. The high density water was found in the middle layer near the river mouth, suggesting the upwelling associated with the entrainment (Fig. 6). The

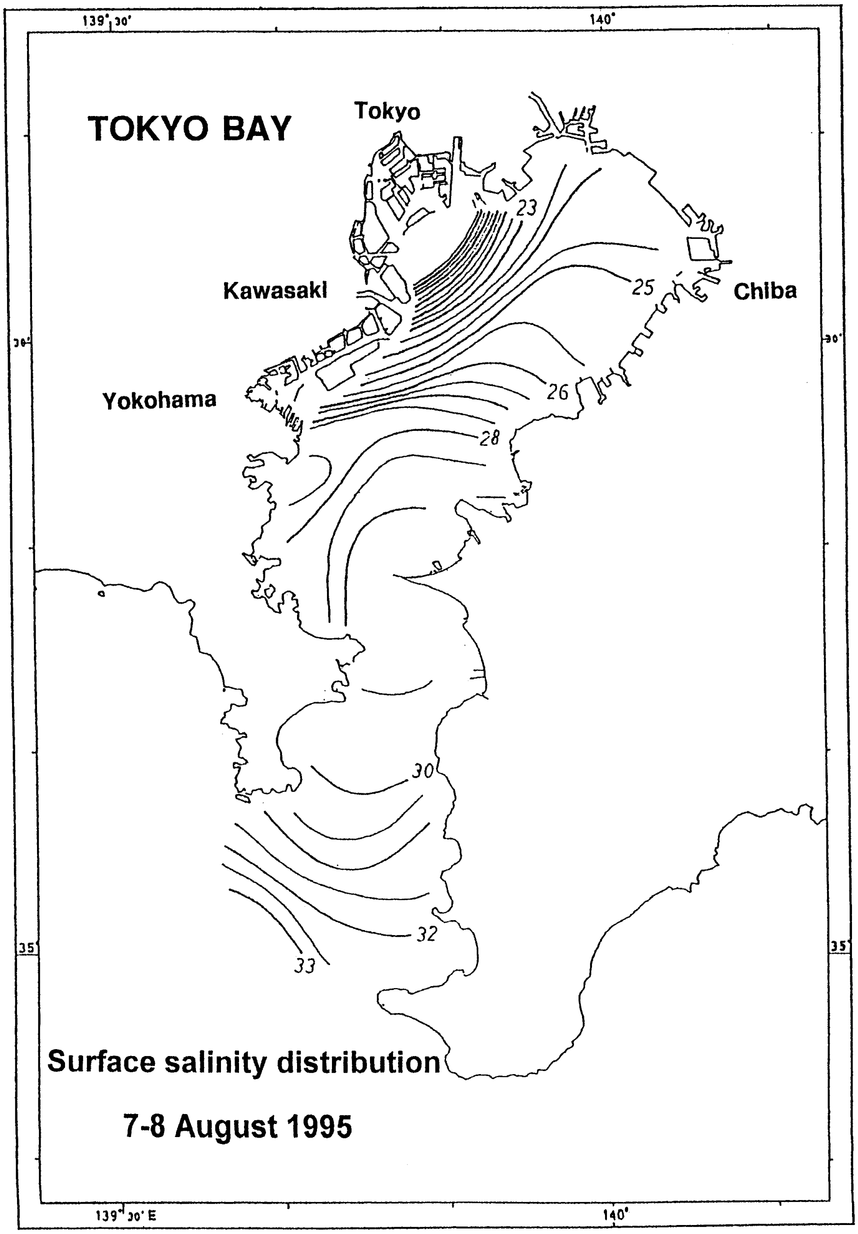

Fig. 11. Horizontal distribution of salinity at 1m depth on August 7 to 8, 1995 in Tokyo Bay (after the 3rd Regional Coast Guard Headquarters, Japan Coast Guard).

detailed discussion will be required to clarify the local upwelling near the mouth by using a simple model.

Summary

The density-driven current is examined as the behavior and structure of the low density water discharged from the rivers, using the three-dimensional numerical model. The low density water spreads in the surface layer from river mouth to the inner bay and makes the anticyclonic circulation after 2–4 days from the

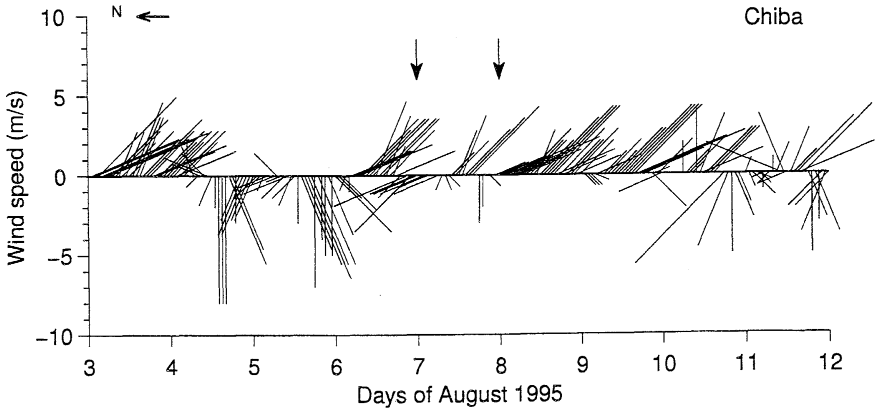

Fig. 12. Time series of wind vectors at Chiba AMeDAS Station during August 3–12, 1995. Two thick arrows indicate the observation time of data sampling of salinity and temperature as shown in Fig. 10 and Fig. 11.

initial state for the mean volume of river discharge. After this time, the water moves toward the bay mouth along the western coast with maximum velocity of 3–5 cm s^{-1}. The flow toward the river mouth is formed just beneath the surface layer, and is very weak in comparison with the surface outward flow. The inflows may be induced by the outward flow at the surface as the entrainment.

The density distribution calculated from the numerical experiments almost resembles the observed salinity distribution at the surface layer along the western coast of the bay except near the mouth of Ara River. Therefore the three-dimensional model is suitable to clarify salinity and temperature distribution in detail for fresh water injection from rivers and power plant. GUO and YANAGI (1998) and TANAKA *et al.* (1998) studied the residual current in the stratified Tokyo Bay by the three-dimensional model. Both papers included all factors such as wind, tide and river discharge in the model, so that the numerical model did not effectively extract the characteristics of density-driven current. The detailed numerical study is required to comprehend an individual phenomenon, i.e., wind-driven current, density-driven current and tidal current.

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