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# Distribution of low saline water near the mouth of Tokyo Bay

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**Abstract** : Detailed CTD measurements were made in two lines in Sagami Bay to investigate a behavior of low saline water flowed out from Tokyo Bay near the bay mouth in May, September and November 1997. The low saline and high turbidity water were found near the tip of Miura Peninsula in Sagami Bay in all three observations. The low saline water distributed along the southern coast of the peninsula, and extended toward the center of Sagami Bay. Then the area occupied by the low saline water at the southern observation line was smaller than at the western one. ADCP measurements made in November 1997 shows the existence of the northwestward current in the southern line and west-northwestward current in the western line. The distribution of the low saline water flowed out from Tokyo Bay is strongly affected by the external force, i. e., the current circulation in Sagami Bay.

***Key words*** : *Tokyo Bay, Low saline water (LSW), Density current, Sagami Bay, Intrusion, CTD measurement, ADCP measurement, Internal radius of deformation*

## 1. Introduction

Low saline water (LSW) discharged from rivers is usually found in coastal zone of world's ocean and leads to formation of sharp density gradient, i.e., density front. Its behavior is often affected by external forcing, i.e., wind effect, ambient flow, bottom and coastal topography, and inflow properties. Existence of the buoyant's sources along the coastline represents one of the principle forcing mechanisms for coastal and shelf currents (YANKOVSKY and CAHAPMAN, 1997). When the width of LSW is equal to or larger than the internal radius of deformation in the coastal region, LSW has a characteristic of density current in the rotating fluid without external forces, that is, moving right on the coast in the northern hemisphere (e.g., GRIFFITHS, 1986). This characteristic is usually observed in coastal water in the world.

Tokyo Bay is a semi-enclosed bay with lots of river discharges. LSW discharged from Tokyo Bay is expected to flow out through the bay mouth into Sagami Bay to have a characteristic of density current in a rotating fluid. UNOKI and KISHINO (1977) reported from the long-term mean data that the low salinity and low transparency water distributes along the western coast of Tokyo Bay. MATSUIKE *et al.* (1986) also observed the high turbidity waters concentrated along Miura Peninsula, i. e., at the western side of the bay. But, the discharged water from the western side of the bay mouth is not clarified by the observation in detail. Both studies of field observation and numerical modeling are required to understand the behavior of LSW discharged from Tokyo Bay.

The present study was firstly focussed on the distribution of LSW in the vicinity of Miura Peninsula, i.e., western sides of the bay's entrance. The main purpose of this study is to obtain spatial and temporal scales of LSW distribution as a guide to build a gravity current model.

## 2. Observations

Figure 1 shows bottom topography of Tokyo and Sagami Bays, and the two observation

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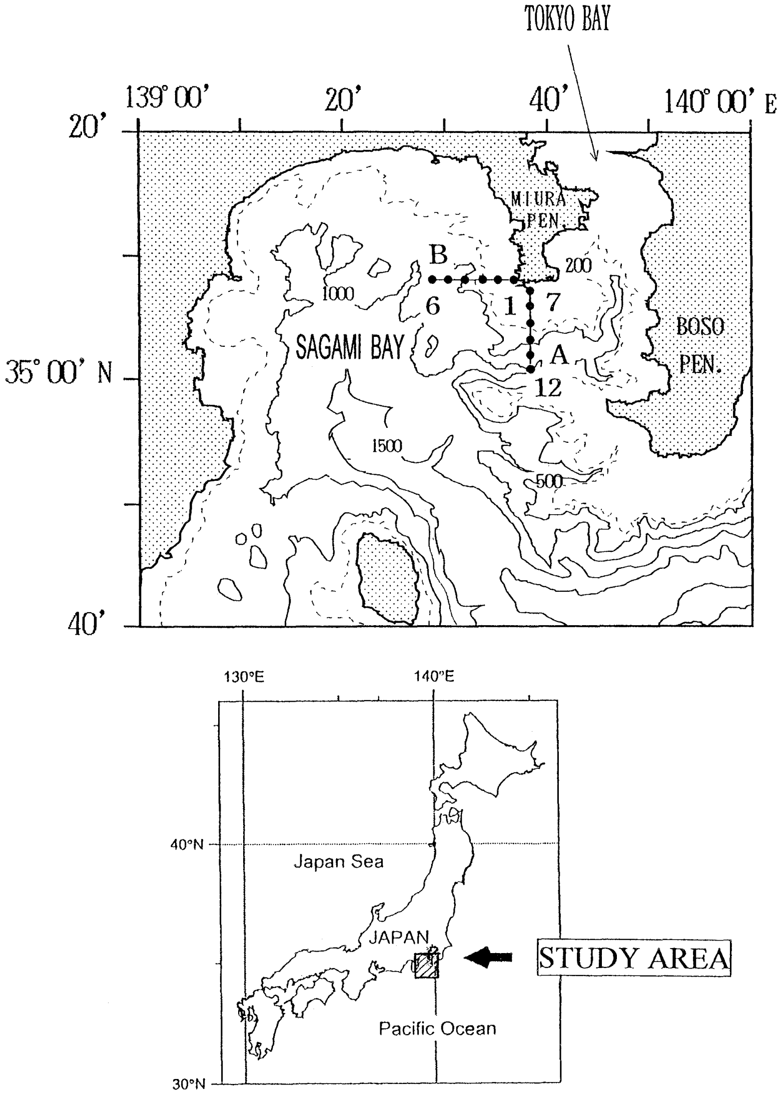

Fig. 1. Location of study area and bottom topography of Tokyo and Sagami Bays. A and B are CTD observation lines. Bottom contours are in meters.

lines (Line A and Line B) and each observational position. Each line consists of six stations. Line A faces to the south of the tip of Miura Peninsula in Sagami Bay, while Line B faces to the west. The distance between station and station is 1 miles (about 1.85 km) to 1.5 miles (about 2.8 km) and the nearest station to the coast is 0.9 km from shoreline in Line A and 1.2 km in Line B. The observations were made by T/V Seiyo-maru, belonging to Tokyo University of Fisheries. The CTD observations were made in May, September and November 1997 and the ADCP measurements were made in November, 1997.

## 3. Results

Figures 2 to 4 show temperature, salinity and density distributions on May 10, September 11, and November 15, 1997, respectively. The temperature and density distributions indicate the existence of the stratification due to the seasonal thermocline (e.g., IWATA, 1979; KAWABE

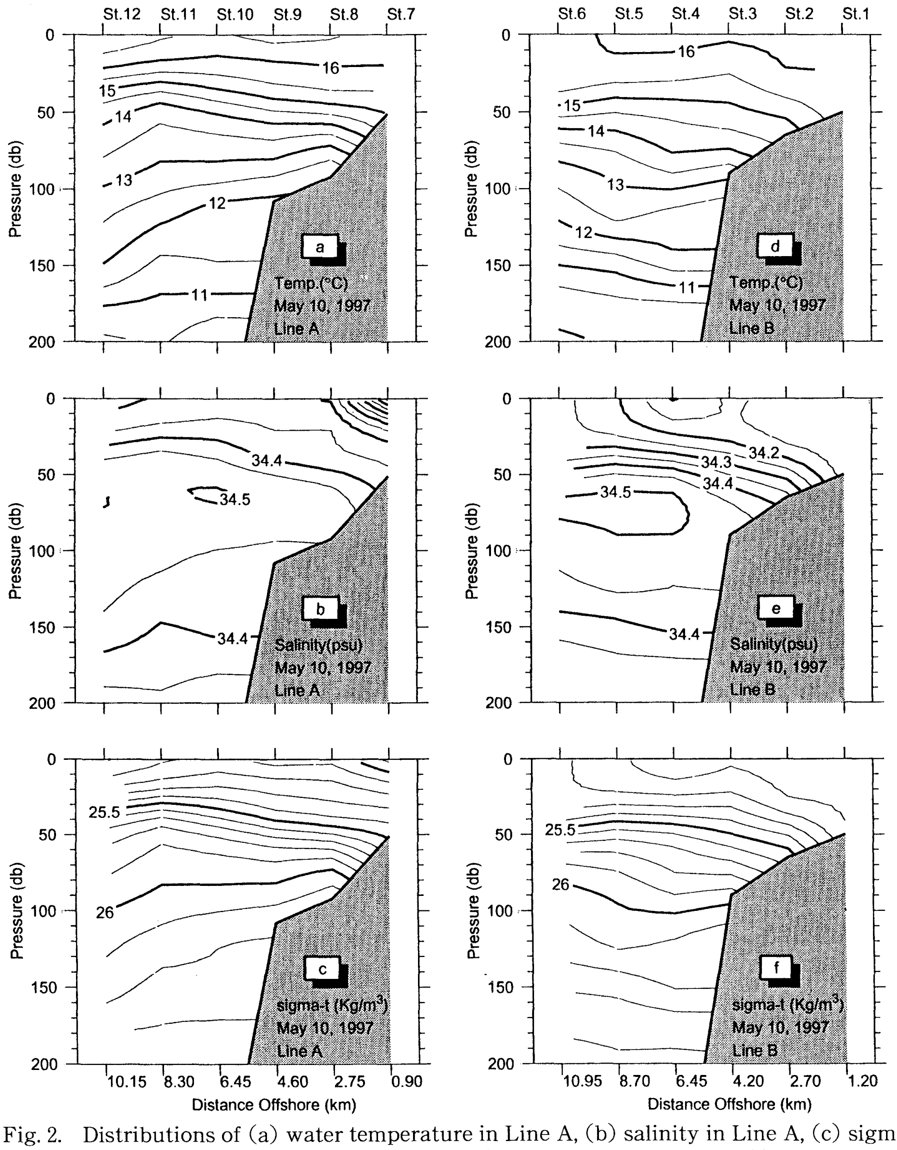

Fig. 2. Distributions of (a) water temperature in Line A, (b) salinity in Line A, (c) sigma-t in Line A, (d) water temperature in Line B, (e) salinity in Line B, and (f) sigma-t in Line B on May 10, 1997

and YONENO, 1987). In May (Fig. 2), the contours of the temperature and density in both Line A and Line B gradually decline toward the coast from the sea surface to about 100m depth. This indicates the existence of westward current in Line A and northward in Line B. The same feature is not found except near the coast in Line B in September (Fig. 3). In November (Fig. 4), the temperature and density distributions are complicated by the coastal water intrusion into the subsurface layer. The contour-line declination toward the coast is also recognized in the density distributions.

Salinity is variable in each observation, especially in the surface layer. The lowest value was observed at the sea surface in September among three observations. The subsurface layer is occupied by the higher salinity water of 34.5, originating from the Kuroshio water in

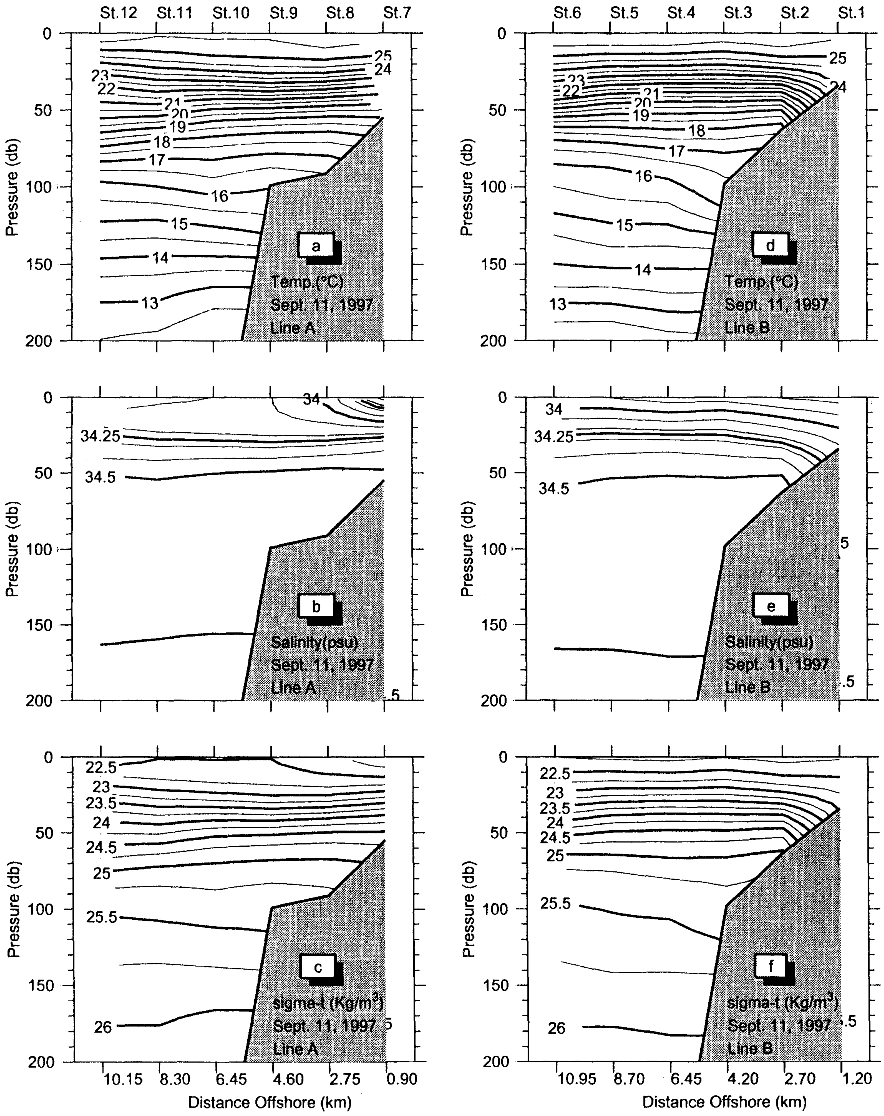

Fig. 3. The same as Fig. (2) except on September 11, 1997

every observation. The two common features are found from the comparison of Line A and Line B as follows. (1) The low salinity water concentrated in the surface layer near the coast in Line A. (2) The width of LSW was in Line B larger than in Line A. Then, LSW is trapped in the coast in Line A, while it extended offshore at Line B by the external forc. In November, the interesting feature is also found in the intrusion of the coastal water into the subsurface layer, i.e., the core depth of the intrusion is 30 m in Line A and 35m in Line B. The intrusion occurred along the density contour line. The separation of the temperature and density contour lines in Line A is due to the intrusion (Fig. 4). The intrusion into the subsurface layer observed in November is remarkably different from the dispersion at the sea surface in May and September.

LSW flowed out from Tokyo Bay into Sagami Bay is considered to be high turbidity water as well (MATSUIKE *et al.*, 1986, UNOKI and KISHINO, 1977). Figure 5 shows the salinity-transparency relation at every line in each

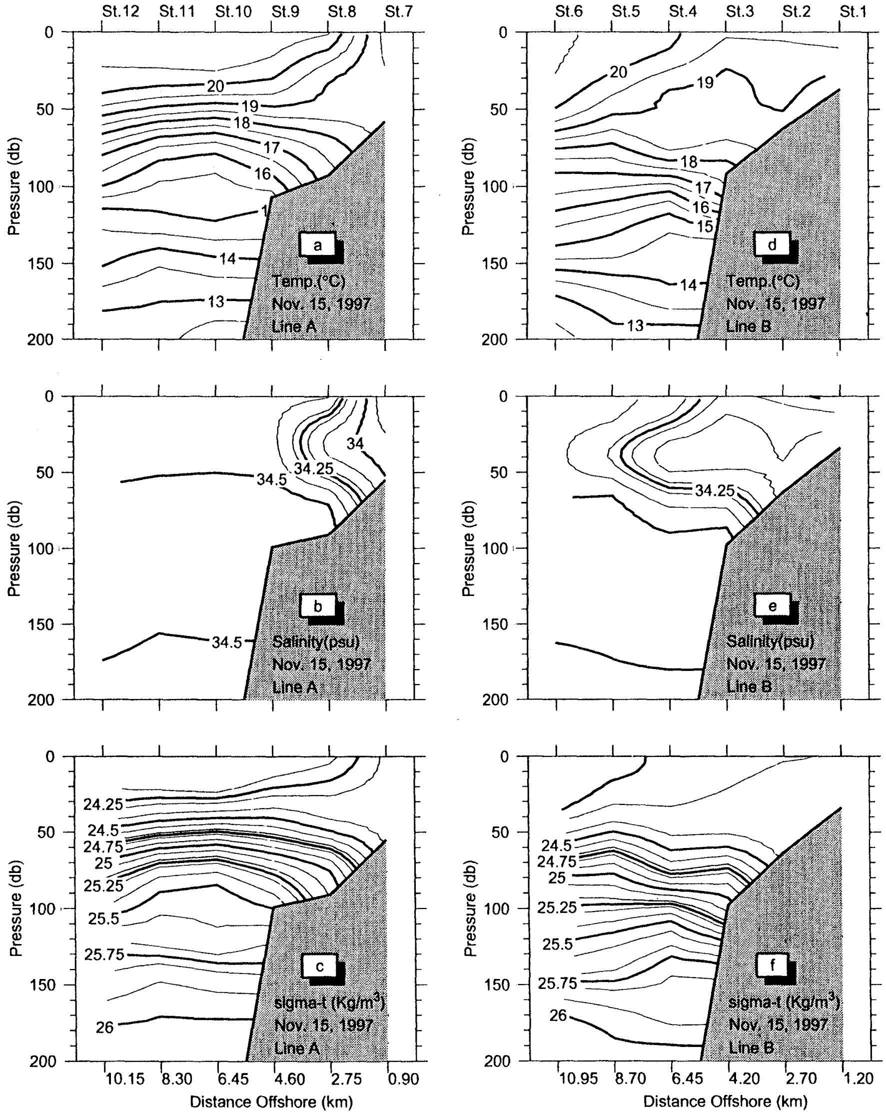

Fig. 4. The same as Fig. (2) except on November 15, 1997

observation. The value of transparency in May is relatively low in comparison with that in September and November. As the reason is not sufficiently explained, we treat as the relative relation of the salinity-transparency. The transparency is basically positive relation to the salinity except some data. The low salinity water indicates the low transparency water, i. e., highly turbidity water. The high salinity and low transparence water is found at St. 10 and at St. 4 in May, and at St. 4 and at St. 6 in November. The boundary mixing is possibly occurred near the sea bottom because the swift current in relation to the semidiurnal internal tide exists in this region (MATSUYAMA and IWATA, 1985, KITADE and MATSUYAMA, 1997). The detailed observations near the sea bottom will be required to clarify this phenomenon in future.

The ADCP measurements were made along Line A and Line B in November 15, 1997. Figure 6 shows the current distributions of 15m, 45m and 100 m depths, as the typical distributions in the surface, subsurface and middle

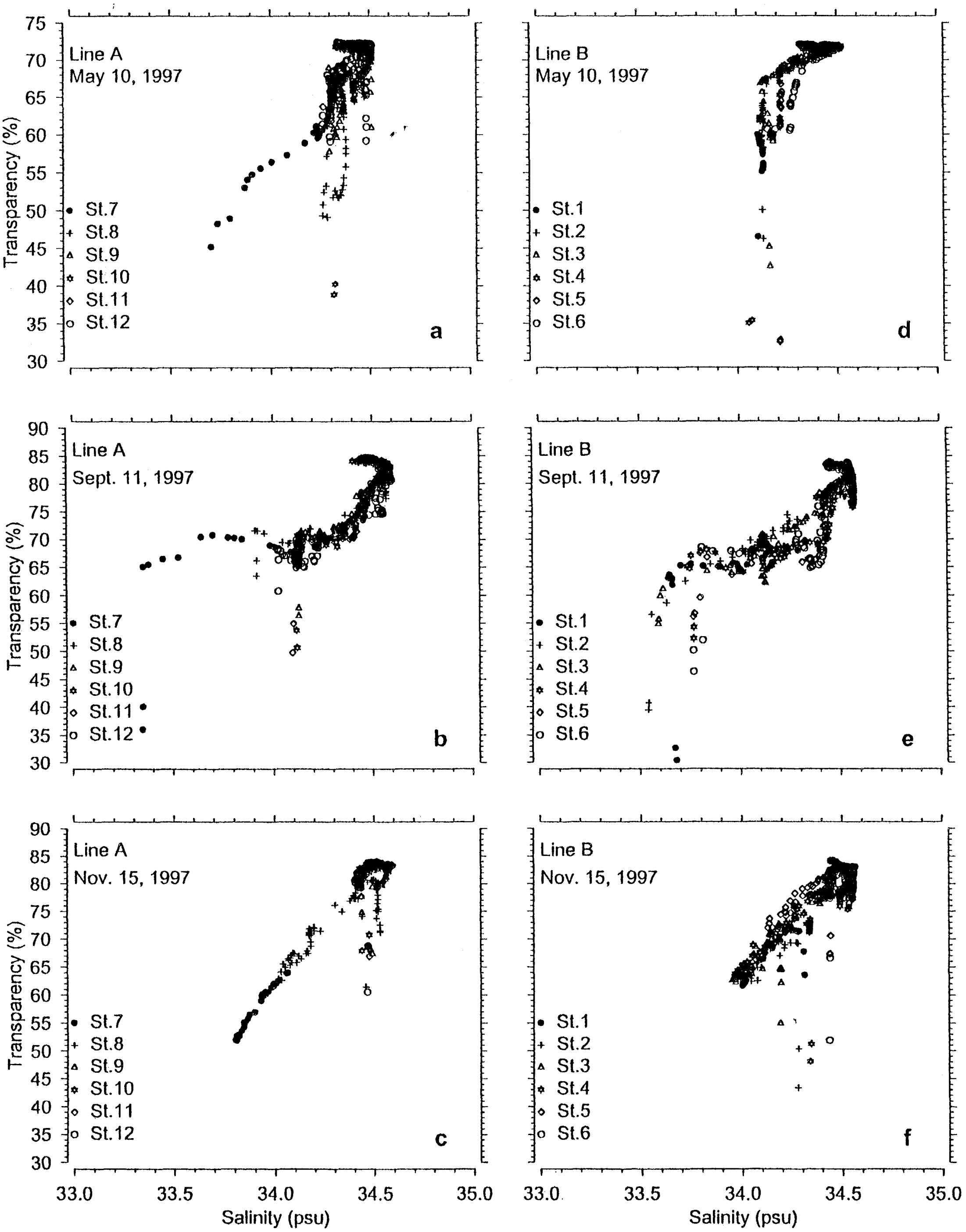

Fig. 5. Transparency - Salinity diagram of Line A and Line B in on May 10, September 11, and November 15, 1997

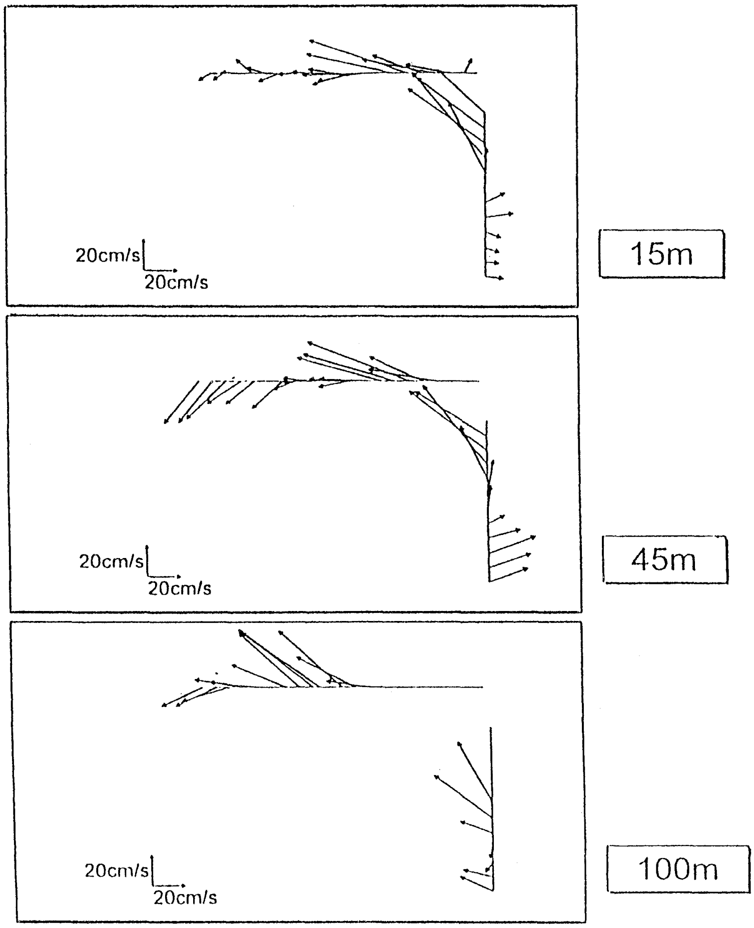

Fig. 6. Current at 15 m, 45 m and 100 m depths of Line A and Line B on November 15, 1997

layers, respectively. The strong current existed in the 15m and 45 m depths near the coast, i. e., the northwestward to west-northwestward direction in Line A and west-northwestward direction at Line B. The direction agrees with the current deduced from the density distributions (Fig. 4). The discharged low saline and high turbidity water moves westward through Line A and along Line B. As a result, the low saline water did not move northward along the eastern coast of Sagami Bay, but was dispersed toward the center of Sagami Bay. The current direction observed near the coast agrees with that obtained from the long-term current measurements on the shelf off Miura Peninsula by Iwata and MATSUYAMA (1989). They showed the mean current direction through 315° to 340° on the shelf west off Jogashima (the tip of Miura Peninsula). As a result, the low saline and high turbidity water flowed out from Tokyo Bay into Sagami Bay, trapping the coast of the tip of Miura Peninsula as a density current in a rotating fluid. After passing this area, the low saline water was extended to the westward to be affected by the external force in the field. The reason is speed of density current to be much less than that of the current in Sagami Bay.

## 4. Structure of LSW

### *Coastal Trapped Structure*

LSW was trapped along the coast at the southward line (Line A) from the tip of Miura Peninsula in all three observations. The observation shows the coastal-trapped structure in a rotating fluid (e. g., GRIFFITHS, 1986). So, we

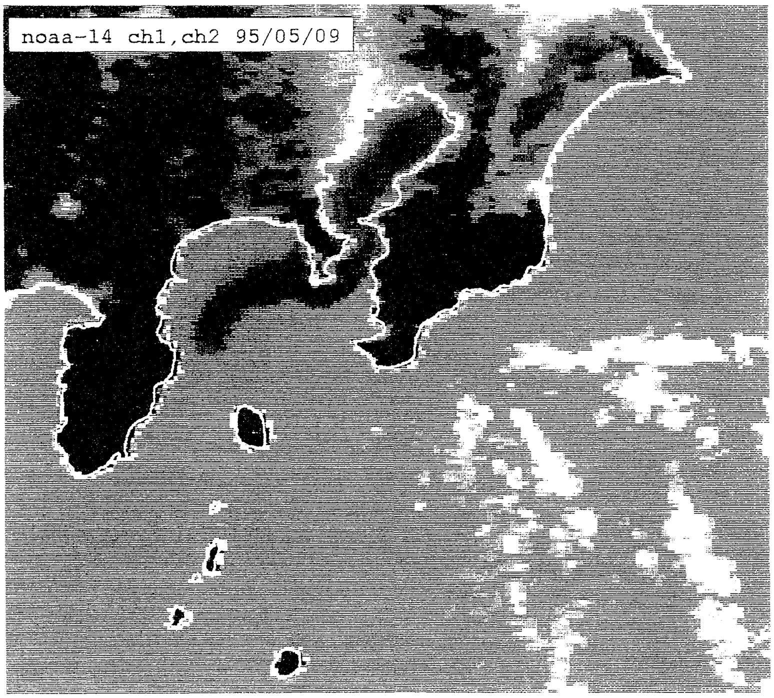

Fig. 7. Satellite image of the sea-surface chlorophyll of Tokyo and Sagami Bays on May 9, 1995 by NOAA-14.

examine to grasp a characteristic of the coastal-trapped mode by solving the basic equations under the hydrostatic and Boussinesq approximations in non-viscous fluid, following KUNDU *et al.* (1975). A rectangular coordinate system consists of $x$ eastward, $y$ northward with the origin at the coast and $z$ upward from the mean sea level. The fundamental equations are obtained as follows;

$$\begin{aligned} &\frac{\partial u}{\partial t}-fv=-\frac{1}{\rho_0}\frac{\partial p}{\partial x} \\ &fu=-\frac{1}{\rho_0}\frac{\partial p}{\partial y} \\ &\frac{\partial p}{\partial z}+\rho g=0 \\ &\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial x}=0 \\ &\frac{\partial \rho}{\partial t}+w\frac{\partial \bar{\rho}}{\partial z}=0 \end{aligned} \tag{1}$$

where $u$, $v$, and $w$ are the $x$-, $y$- and $z$-components of the velocity, respectively, $g$ the gravitational acceleration, $\rho_0$ the vertical mean density, $\bar{\rho}$ the equilibrium stable density, $\rho$ the perturbation density, $p$ the perturbation pressure, and $f$ the Coriolis parameter. The potential vorticity equation is derived from the set of fundamental equations (1) as

$$\frac{\partial}{\partial t}\left\{\frac{1}{f^2}\frac{\partial^2 p}{\partial y^2}+\frac{\partial}{\partial z}\left(\frac{1}{N^2}\frac{\partial p}{\partial z}\right)\right\}=0 \tag{2}$$

where $N^2=-\frac{g}{\rho_0}\frac{\partial\bar{\rho}}{\partial z}$ is the square of the buoyancy frequency. Assuming that $N$ is constant and initial potential vorticity is zero, Eq. (2) is written as

$$\frac{\partial^2 p}{\partial y^2}+\left(\frac{f^2}{N^2}\right)\frac{\partial^2 p}{\partial z^2}=0\,. \tag{3}$$

The vertical and horizontal modes can be separated from Eq. (3) as follow;

$$\begin{aligned} &\frac{d^2 Z_n}{dz^2}+\left(\frac{N^2}{f^2}\right)\alpha_n^2 Z_n=0 \\ &\frac{d^2 Y_n}{dy^2}-\alpha_n^2 Y_n=0 \end{aligned} \tag{4}$$

where $\alpha$ is separation constant, and $n$ the vertical mode number. We assume the dominant of the first mode from the distribution of the low salinity water at Line A (Figs. 2 to 4). The appropriate solution of the lower part of Eq. (4) is $Y_1 = A_1 \exp(\alpha_1 y)$ and of the upper part of Eq. (4) can be obtained as

$$Z_1 = B_1 \cos\left(\frac{N\alpha_1}{f} z\right)$$

under the boundary conditions at the sea surface and bottom, i. e., $w=0$ at $z=0$ and $z=-H$ (KUNDU *et al*., 1975). $A_1$ and $B_1$ are unknown constant. The internal radius of deformation is obtained as $\alpha_1^{-1} = \frac{NH}{f\pi}$. When we adapt $H=70$ m, $f=8.34\times10^{-5}s^{-1}$, the internal radius of deformation is estimated as 3.0 km in May, 4.9 km in September and 3.1 km in November.

On the other hand, if the salinity distributes as the coastal-trapped structure, the salinity is expressed as $S(y)=S_0-S'\exp(ay)$ where $a$ is the scale of the salinity variation, $S_0$ the salinity in open sea, and $(S_0-S')$ the salinity at the coast $(y=0)$. So, we estimate the radius of deformation as 3.2 km in May and 3.4km in September. In November, the estimation is not easy for the intrusion into the subsurface layer.

The internal radius of deformation is little difference from the scale of the salinity variation defined in this study, that is, there is little difference between the both values obtained from the different method. The radius of deformation ranged 3 km to 5 km in three observations.

### *Intrusion of LWS into the subsurface layer*

The salinity distributions are variable in time and space. The outflow mechanism may be different from each observation. The core of the low salinity was found at the sea surface in May and September, but at about 30m depth in November. As mentioned above, the density current is affected by the earth rotation (e. g., GRIFFTHS, 1986). Therefore, the core of low salinity at the sea surface can be explained as the outflow of low-density water moving southward along the western coast of Tokyo Bay. When the core of salinity minimum is 30 m depth, how can be explained the mechanism ? As shown in Fig. 6, the current distribution near the coast is nearly uniform in vertical. The distribution of the salinity minimum at about 30 m depth is speculated having already formed inside the mouth of Tokyo Bay. Recently KOIKE *et al*. (1997) reported the outflow in the subsurface layer through the bay mouth and the core of the coastal water at about 30 m depth. They explained the phenomenon due to the vertical circulation induced by the fairly strong northward wind during a few days. The salinity inversion in the surface layer is possible to occur by external forcing in Tokyo Bay, especially in late fall and winter when the density stratification is weaker than in summer. But, in future, we will continue the detailed observation in order to clarify whether or not the intrusion phenomenon is frequently found in weak density stratification and to grasp its formation.

## 5. Summary and Discussion

In order to investigate a behavior of low saline water flowed out from Tokyo Bay, the CTD observations were carried out in two lines, i. e., the southward and westward from tip of Miura Peninsula, in May, September and November 1997. The low saline water flowed out along the tip of Miura Peninsula into Sagami Bay in all three observations. The low saline water distributed along the southern coast of the peninsula, and extended toward the center of Sagami Bay. Therefore the area occupied by the low saline water at the southern observation line was smaller than at the western one. The ADCP measurements in November support the existence of the northwestward current at the southern line and west-northwestward current at the western line. Then, the low saline water flowed out from Tokyo Bay is strongly affected by the circulation in Sagami Bay. In November, the low saline water intruded into the subsurface layer in Sagami Bay. The internal radius of deformation, i. e., width of LSW, is estimated as 3–5 km from density stratification.

The coastal water flowed out from Tokyo Bay did not move along the western coast of Miura Peninsula, but extended toward the center of Sagami Bay, in all three observations. The west-northwestward current is clarified to be the most important role on behavior of the discharged water. Figure 7 shows a satellite image of the sea surface chlorophyll in Tokyo and Sagami Bay obtained on May 9, 1995. The distribution of the chlorophyll shows the pathway of the discharged water from Tokyo Bay and supports the above explanation.

The observed distributions of LSW near the tip of Miura Peninsula may be possible to be affected by tidal currents, especially semidiurnal internal tidal current (MATSUYAMA and IWATA, 1985; KITADE and MATSUYAMA, 1997). We examine the influence of the tidal current to the salinity distributions in Lines A and B. The first-mode internal tide is considered to dominate over higher modes ones, so the upper layer water moves with the same velocity. The tidal current excursion, $\eta$, is estimated as follows,

$$\eta = \int_0^{\frac{T}{2}} v_0 \sin\left(\frac{1\pi t}{T}\right) dt$$

where T is the semidiurnal period, and $v_0$ the current amplitude. When typical current amplitude is 0.2 m/s (MATSUYAMA and IWATA, 1985), the excursion, $\eta$, is estimated as 2.9 km. The current direction is mostly parallel to the coastline, so the tidal current effect should be considered to include the observation plan. It took about 4 hours to make CTD observations in the both lines; we will be required to shorten the observation time.

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