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Seasonal Variation of Residual Current in Tokyo Bay, Japan —Diagnostic Numerical Experiments—

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The residual currents in Tokyo Bay during four seasons are calculated diagnostically from the observed water temperature, salinity and wind data collected by Unoki *et al*. (1980). The calculated residual currents, verified by the observed ones, show an obvious seasonal variable character. During spring, a clear anticlockwise circulation develops in the head region of the bay and a strong southwestward current flows in the upper layer along the eastern coast from the central part to the mouth of the bay. During summer, the anticlockwise circulation in the head region is maintained but the southwestward current along the eastern coast becomes weak. During autumn, the preceding anticlockwise circulation disappears but a clockwise circulation develops in the central part of the bay. During winter, the calculated residual current is similar to that during autumn. As a conclusion, the seasonal variation of residual current in Tokyo Bay can be attributed to the variation of the strength of two eddies. The first one is the anticlockwise circulation in the head region of the bay, which develops in spring and summer and disappears in autumn and winter. The second one is the clockwise circulation in the central part of the bay, which develops in autumn and winter, decreases in spring and nearly disappears in summer.

1. Introduction

Tokyo Bay is a semi-enclosed bay situated at the central part of Japan, which communicates with the Pacific Ocean through the narrow Uraga Strait (Fig. 1). Field observations (Unoki *et al*., 1980) show that the residual current in Tokyo Bay has a strong seasonal variable character.

Although many observations about the residual current in Tokyo Bay have been carried out (for a detailed review, see Unoki, 1985), the character of seasonal variation of residual current has not been known completely yet. On the other hand, a complete numerical calculation about the residual current system during four seasons in Tokyo Bay has not been found although there are some numerical researches about the wind-driven current or the formation process of the density-driven current in Tokyo Bay (e.g. Endoh, 1977; Ikeda *et al*., 1981; Guo and Yanagi, 1995). Thus, as one of the foundations of the material transport model of Tokyo Bay, the numerical calculations on the residual current systems during four seasons in Tokyo Bay are carried out in this paper.

From the viewpoint of physical processes, the seasonal variation of residual current should be brought by the variations in the river outflow, the heating or cooling through the sea surface, the prevailed wind field and the sea condition of open ocean. The first two factors can be reflected by the water density field in each season and the third factor can be considered easily in calculation by giving the wind field above the sea surface. Considering that the mouth of Tokyo Bay is very narrow and the influence of the open ocean on the residual current in the inner part

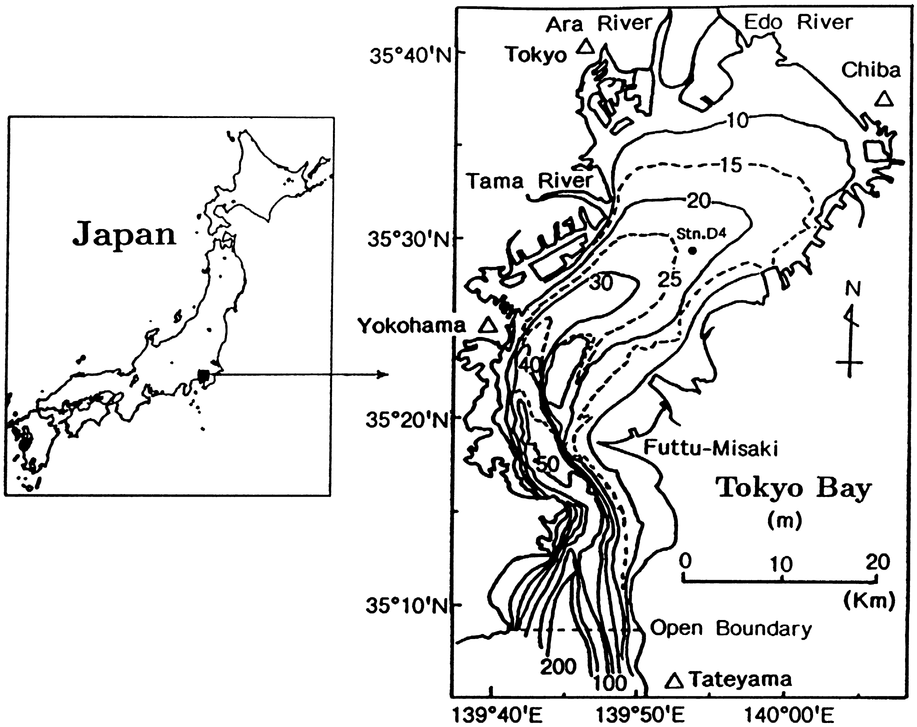


Fig. 1. Topography and rivers in Tokyo Bay.

of the bay is very small, we may adopt the diagnostic model to calculate the residual current in Tokyo bay.

As the crux of diagnostic calculation, a fine observed density field is necessary. The most detailed water temperature and salinity data should be the observed ones by each prefectural fisheries experimental station around Tokyo Bay. However, in these observations, the current is not measured at the same time. So the calculated residual current using such water temperature and salinity data can not be verified appropriately.

In view of verification, the water temperature and salinity data recorded simultaneously with the current data are preferred. For this purpose, the water temperature, salinity and wind data collected by Unoki *et al.* (1980) are adopted in this calculation because they are the most detailed available data set up to now in which the current was measured simultaneously with water temperature and salinity. However, these data have obvious weakness, that is, there are only two or three water temperature and salinity observation points on the vertical direction. As for this problem, we will mention its countermeasure later.

In the second section, the numerical model and its application to Tokyo Bay are described. The third section focuses on the comparison between the calculated and observed results in Tokyo Bay. On the forth section, we give some discussions about the seasonal variation characters of residual current and the forcing balance during each season. Finally, the results are summarized, the limitation and suggestion for the future work are presented.

2. Numerical Model

2.1 Equations

The governing equations on the Cartesian (*x*,*y*,*z*) coordinate system in which the horizontal coordinate is laid at the undisturbed sea surface, the vertical coordinate directs upwards, are as follows:

$$\frac{\partial u}{\partial t}+\vec{u}\cdot\nabla u-fv=-\frac{1}{\rho_0}\frac{\partial P}{\partial x}+\frac{\partial}{\partial x}\left(A_h\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(A_h\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial z}\left(A_v\frac{\partial u}{\partial z}\right)+T_x \tag{1}$$

$$\frac{\partial v}{\partial t}+\vec{u}\cdot\nabla u-fu=-\frac{1}{\rho_0}\frac{\partial P}{\partial y}+\frac{\partial}{\partial x}\left(A_h\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial y}\left(A_h\frac{\partial v}{\partial y}\right)+\frac{\partial}{\partial z}\left(A_v\frac{\partial v}{\partial z}\right)+T_y \tag{2}$$

$$P=\rho_0 g(\eta-z)+\rho_0 g\int_z^0\frac{\rho-\rho_0}{\rho_0}dz'\equiv P_1+P_2 \tag{3}$$

$$\frac{\partial \eta}{\partial t}+\frac{\partial}{\partial x}\int_{-h}^0 udz+\frac{\partial}{\partial y}\int_{-h}^0 vdz=0 \tag{4}$$

$$\rho=F(T,S) \tag{5}$$

where

$$\vec{u}=u\vec{i}+v\vec{j}+w\vec{k}$$

$$\nabla=\vec{i}\frac{\partial}{\partial x}+\vec{j}\frac{\partial}{\partial y}+\vec{k}\frac{\partial}{\partial z}$$

t = time,
u, *v*, *w* = the *x*, *y* and *z* components of residual current,
P = pressure,
T = observed temperature,
S = observed salinity,
ρ = observed density,
ρ_0 = reference density (the averaged value of all points),
h = undisturbed water depth,
η = sea surface elevation,
f = Coriolis parameter (8.469×10^{-5} s^{-1}),
g = acceleration due to gravity (980 cm/s^2).
T_x and T_y in Eqs. (1) and (2) are tidal stresses and defined as follows:

$$T_x = \left\langle u_0 \frac{\partial u_0}{\partial x} + v_0 \frac{\partial u_0}{\partial y} + w_0 \frac{\partial u_0}{\partial z} \right\rangle \tag{6}$$

$$T_y = \left\langle u_0 \frac{\partial v_0}{\partial x} + v_0 \frac{\partial v_0}{\partial y} + w_0 \frac{\partial v_0}{\partial z} \right\rangle \tag{7}$$

where, u_0, v_0, w_0 are the three components of tidal current that have been calculated in advance (Guo and Yanagi, 1994) and $\langle\,\rangle$ denotes the tidal average. Equation (5) is the well known Knudsen state equation.

The vertical and horizontal eddy viscosity coefficients A_v and A_h are related to the amplitude of tidal current according to the tidal mixing theory.

$$A_v = \alpha U_{\mathrm{amp}}^2 \tag{8}$$

$$A_h = \beta U_{\mathrm{amp}}^2 \tag{9}$$

where U_{amp} is the amplitude of tidal current and the parameters α and β are used to adjust the eddy viscosity coefficients locating in a reasonable range and explained later. By this way, the effect of tidal mixing can be considered partly, i.e., the stronger the tidal current, the larger the eddy viscosity coefficient.

The boundary conditions on the sea surface and bottom are:

$$z = \eta : A_v \frac{\partial}{\partial z}(u, v) = \frac{1}{\rho_0}\left(\tau_x^a, \tau_y^a\right) \tag{10}$$

$$z = -h : A_v \frac{\partial}{\partial z}(u, v) = \frac{1}{\rho_0}\left(\tau_x^b, \tau_y^b\right) \tag{11}$$

where, the wind stresses $\tau_x{}^a$, $\tau_y{}^a$ and sea bed stresses $\tau_x{}^b$, $\tau_y{}^b$ are calculated as:

$$\left(\tau_x^a, \tau_y^a\right) = \rho_a C_d \left(u_a, v_a\right)\sqrt{u_a^2 + v_a^2} \tag{12}$$

$$\left(\tau_x^b, \tau_y^b\right) = \rho C_b \left(u_b, v_b\right)\sqrt{u_b^2 + v_b^2}\,. \tag{13}$$

The symbols u_a and v_a denote the eastward and northward components of the wind velocity, ρ_a (=1.2×10^{-3} g/cm^3) is the density of air, C_d (=1.3×10^{-3}) is the non-dimensional drag coefficient at the surface, u_b and v_b is the velocity above the sea bed, C_b (=2.6×10^{-3}) is the drag coefficient at the sea bed.

Along the coastal line, no normal flow and no slip condition are allowed and a sponge condition is postulated at the open boundary.

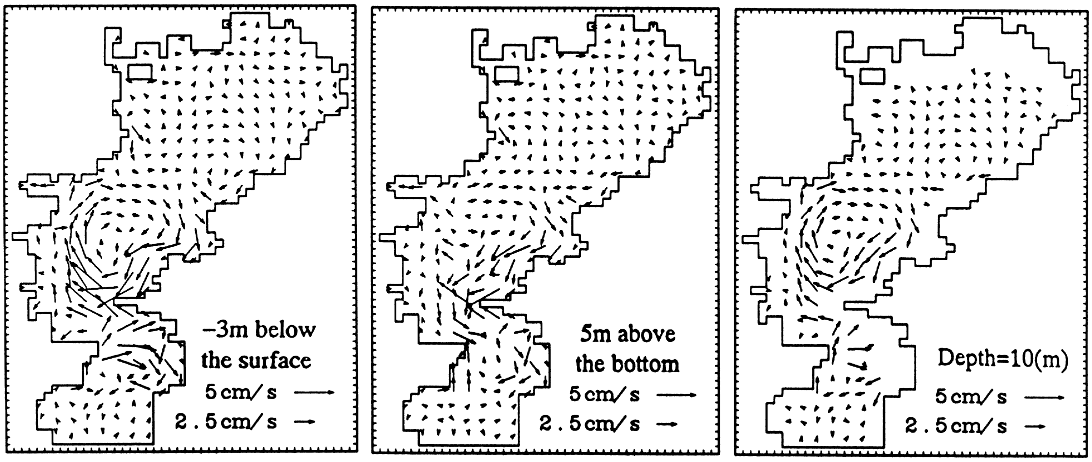


Fig. 2. The calculated tide-induced residual current.

The numerical solving method of above equations is nearly the same as that used in reproducing the wind-driven current in Tokyo Bay during winter (Guo and Yanagi, 1995). For the advective terms in Eqs. (1) and (2), we adopt the same difference scheme as that used in the Oonishi Model (Oonishi, 1978), which can ensure the conservation of the momentum and energy (Arakawa, 1966; Suginohara, 1978). Initially, a state of rest is assumed and the calculation lasts for 48 hours when the kinetic energy of the whole sea region reaches a steady state.

2.2 Application to Tokyo Bay

The topography of Tokyo Bay is shown in Fig. 1. The maximum depth in this calculation is taken as 200 m due to the computational economical viewpoint. The horizontal grid size is 1 km $\times$ 1 km and the water column is vertically divided into ten layers equidistantly at each horizontal grid point. This means that there are ten points on the vertical direction everywhere, no matter what depth they are. The time step is 36 seconds.

As a preparation of the diagnostic calculation, the tide-induced residual currents are calculated at first and the results at three depths are shown in Fig. 2. The calculated results show that a clear clockwise circulation is formed near the mouth of Tokyo Bay and the speed of this clockwise eddy can reach about 5 cm/s in the upper layer behind Futtu-Misaki. Except for this clockwise eddy, the tide-induced residual current in Tokyo Bay is weak. This calculated result is consistent with the existing knowledge about the tide-induced residual current in Tokyo Bay (Unoki, 1985). The tide-induced residual current is included in our calculations through tidal stress of Eqs. (6) and (7).

2.3 The observed water temperature, salinity and wind data

From November 1978 to August 1979, four times observations in Tokyo Bay were carried out by the Second Port and Bay Bureau, Japan and the observed results were collected and analyzed by Unoki *et al.* (1980). In these observations, besides of the current data, the water temperature and salinity were also measured by the current meter. These data allow us to do the following experiments: reproducing the residual current field through a diagnostic model by using the observed water temperature, salinity and wind data and verifying the calculated results

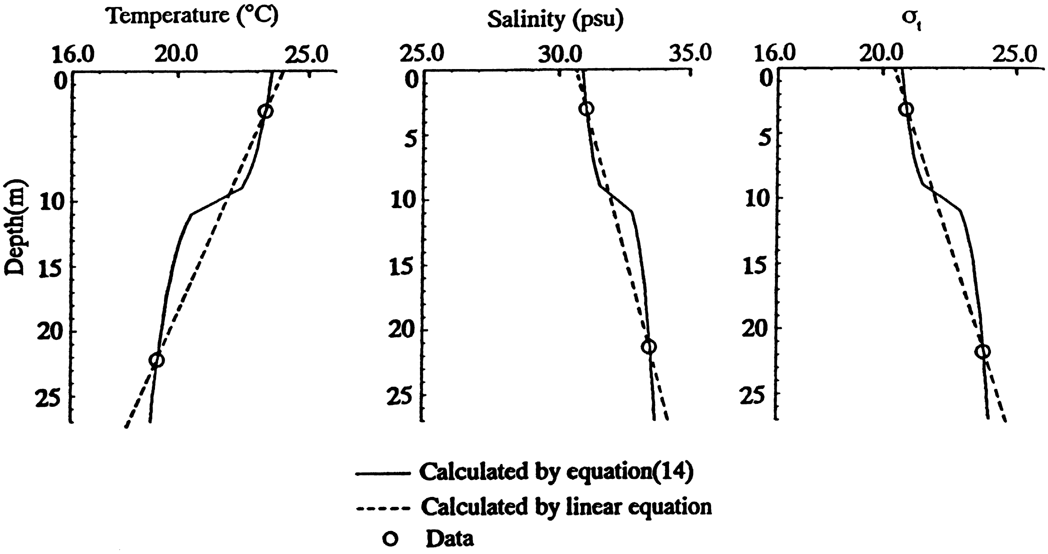


Fig. 3. The representation of stratification by one-third power function.

by the observed current data at the same time.

As a regrettable thing, the above field observation only provides two or three water temperature and salinity data on the vertical direction (3 meters below the sea surface and 5 meters above the sea bed). If there is no strong stratification such as the case of winter or autumn, a linear approximation can be used for the interpolation or extrapolation on vertical direction. But for the case of summer or spring when the density stratification has been formed, a method that can give an expression of the stratification effect is preferred than the linear approximation. Based on the fact that the depth of the pycnocline in most places of Tokyo Bay during summer has been 10 meters (Unoki, 1985; Yanagi *et al.*, 1991), the one-third power function is adopted to represent the vertical profile of observed water temperature and salinity as follows:

$$T = T_0 + \alpha_T (z - z_0)^{1/3} \tag{14}$$

where z_0 is the depth of the pycnocline (10 m in this case), T denotes temperature but can be replaced by salinity, T_0 and α_T are determined with the use of the two observed data. An example of Stn. D4 in the central part of the bay, whose position is denoted by a black circle in Fig. 1, is given by Fig. 3 from which an obvious improvements by Eq. (14) over the linear interpolation can be seen easily.

In the field observation, there are 8, 22, 9 and 22 observation points on the horizontal plane in spring, summer, autumn and winter, respectively. In the report of Unoki *et al.* (1980), only the averaged water temperature and salinity data at each point are given. Because there are two sets of observation points in summer and winter whose observation periods are different from each other (the longer one is about 33 days and the shorter one 17 days), some abnormal distribution of the observed water temperature and salinity can be found in some places, especially in summer. If we interpolate such data without any modification, some local unreal density distribution and density-driven current will be produced surely. Thus for avoiding such strange density current, we delete some temperature and salinity data whose maximum variation is obviously larger than other points. After this procedure, 8, 14, 8 and 20 points of temperature and salinity data for spring, summer, autumn and winter, respectively, are kept and interpolated at each mesh point. The interpolation method is the same as that used by Yanagi and Igawa (1992). The calculated horizontal distribution of temperature, salinity and density (σ_t) at three layers (3 m, 10 m and 15 m) in four seasons are shown in Figs. 4(a), (b), (c) and (d), respectively.

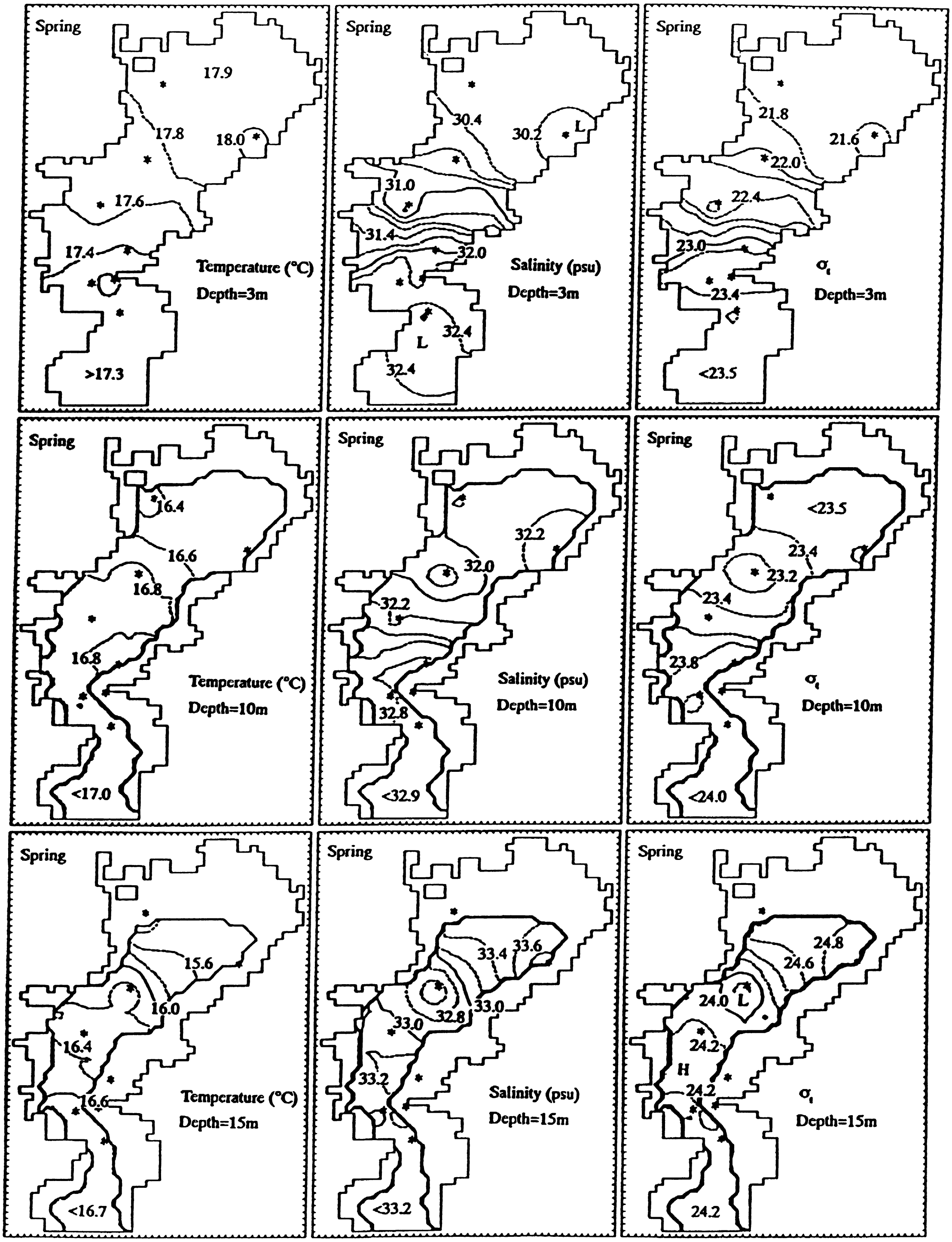
The spring case (Fig. 4(a)), whose data are collected from May 2nd to June 7th, 1979, shows that the water temperature and salinity vary a little in the head region of the bay but largely in the central part of the bay. The summer case (Fig. 4(b)), whose data are collected from July 13th to August 21st, 1979, shows that in the northern part of Tokyo Bay, an obvious light water mass exists in the upper layer that should be affected by the Ara, Edo and Tama Rivers (Fig. 1). On the whole, in the upper and middle layers the water in the western region is lighter than that in the eastern region but in the lower layer the water gives an opposite distribution with that mentioned above. The autumn case (Nov. 20th to Dec. 22nd, 1978, Fig. 4(c)) shows that the horizontal variation of water temperature, salinity is obviously less than those in summer and spring. In the winter case (Jan. 17th to Feb. 22nd, 1979, Fig. 4(d)), the water temperature, salinity and density structure at the mouth of bay is similar to that of the thermohaline front (Nagashima and Okazaki, 1979; Yanagi *et al*., 1989) and there is a light water mass in the upper layer of the northwestern part of the bay. The common character of the density distributions during four seasons in Tokyo Bay is that the water in inner part of the bay is lighter than that in outer part of the bay.

As mentioned before, the diagnostic calculation result depends on the observed density field closely and as a weak point of this research, only a few observed density data can be used in calculation, especially in spring and autumn case. However, it must be noticed that the dynamic role of the density field is manifested by its horizontal gradient, not by the density field itself. Thus few observed points can also give a basic description of the gradient field if the point’s positions are arranged well. Basing on this fact, we may believe that the density gradient along the main axis of Tokyo Bay is well represented by observation, even in spring and autumn case. The three points around the head region in spring and autumn may also give a basic description of the density gradient field there. The problem exists in the central part of the bay, especially in the western side, where the density gradient along the east-west direction can not be obtained correctly from the observation.

The wind data at four stations (Tokyo, Yokohama, Tateyama and Chiba, shown by triangle in Fig. 1), which were recorded every three hours during the above observation periods, were also collected by Unoki *et al*. (1980). We averaged these data over the observation period and interpolated them on the horizontal plane. The interpolated results (not shown in this paper because their spatial variation is very small) tell us that weak south, strong southwest, weak north and strong northwest wind prevails above Tokyo Bay during spring, summer, autumn and winter, respectively. The averaged wind speed is about 5 m/s in winter and summer, 3 m/s in spring and autumn.

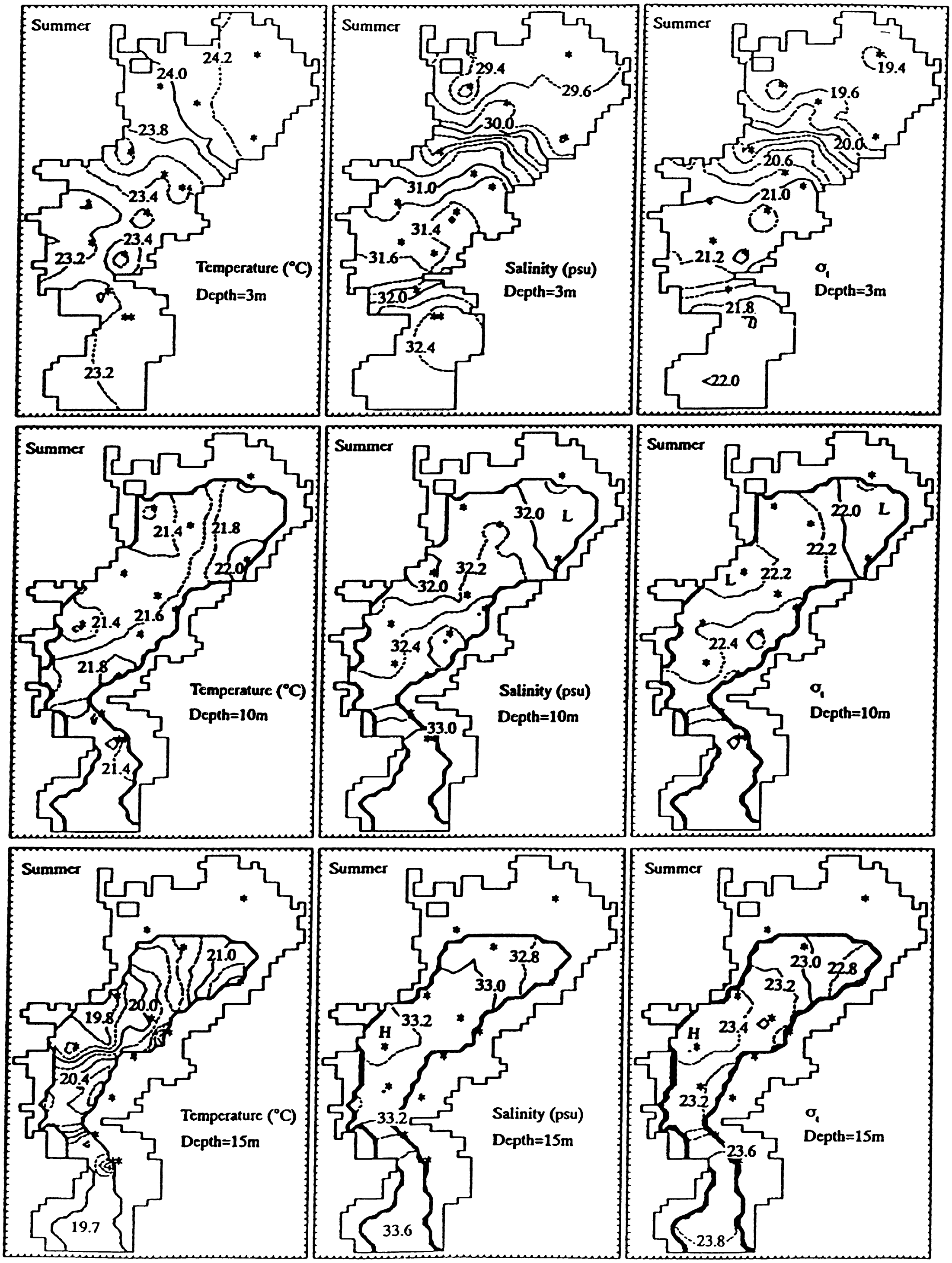
2.4 Determination of eddy viscosity coefficients

Considering that the amplitude of M_2 tidal current in Tokyo Bay is almost on the range of 5 and 50 cm/s (Guo and Yanagi, 1994), the parameter α in Eq. (8) is set as 0.06, 0.04, 0.06 and 0.08 for the residual current calculation in spring, summer, autumn and winter, respectively. So the calculated vertical eddy viscosity should be between 1 and 100 cm^2/s in summer, 2 and 200



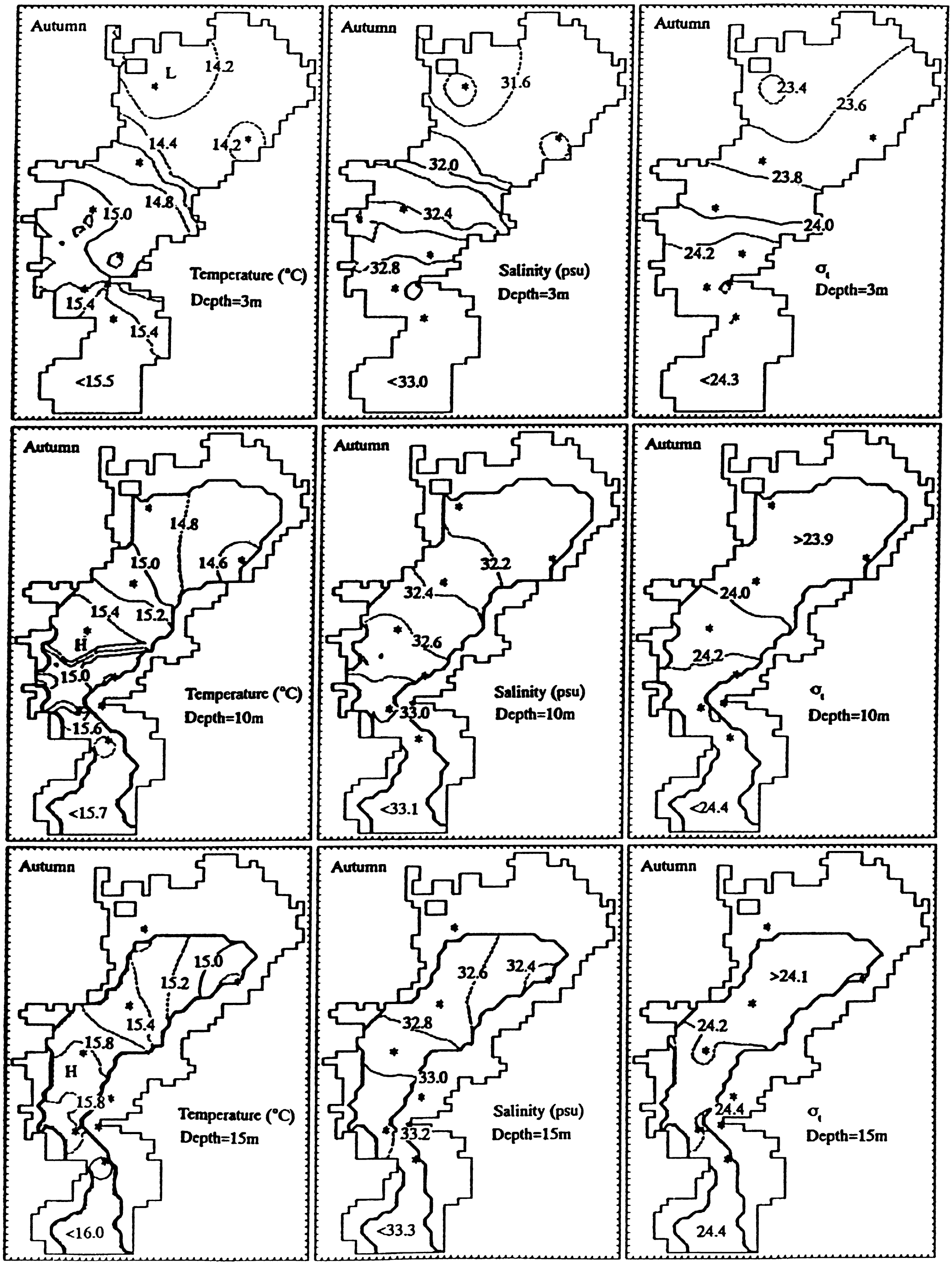
(a)

Fig. 4. (a) The horizontal distribution of temperature, salinity and density in spring. (b) The horizontal distribution of temperature, salinity and density in summer. (c) The horizontal distribution of temperature, salinity and density in autumn. (d) The horizontal distribution of temperature, salinity and density in winter.



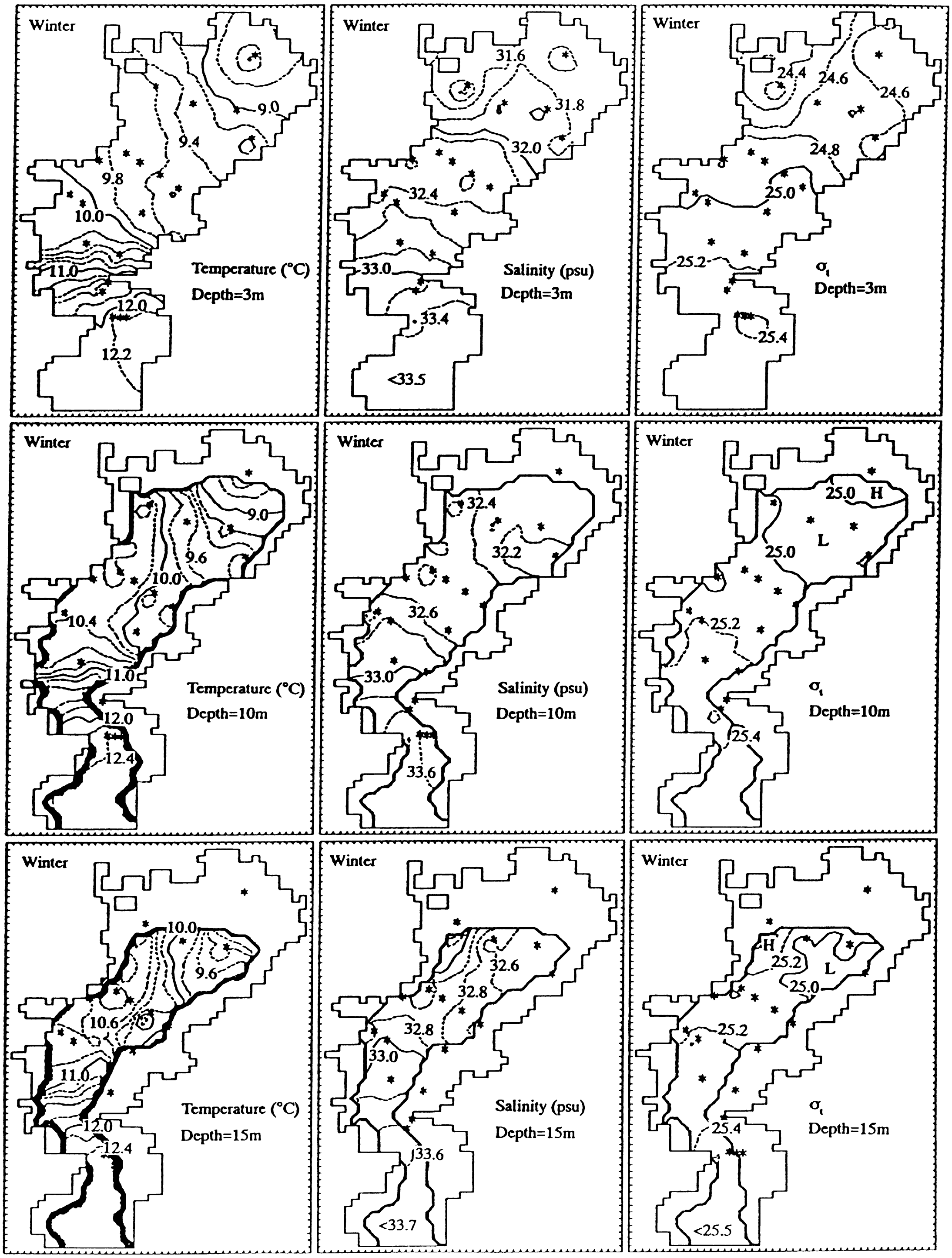
(b)

Fig. 4. (continued).



(c)

Fig. 4. (continued).



(d)

Fig. 4. (continued).

cm^2/s in winter, 1.5 and 150 cm^2/s in spring and autumn. Here its horizontal distribution is not shown because it should be the same as the distribution of M_2 tidal current amplitude essentially, which can be found in our previous paper (Guo and Yanagi, 1994). As used in the real calculation, its minimum value (1 cm^2/s in summer, 4 cm^2/s in winter, 2 cm^2/s in spring and autumn) has to be set to avoid the occurrence of abnormal surface current at the place where the tidal current amplitude is less than 5 cm/s. Parameter β in Eq. (9) is equated to 4×10^3 in all calculations so that the horizontal eddy viscosity is on the range of 1.0×10^5 and 1.0×10^7 cm^2/s. Such values can also be found on other researches (Ikeda *et al.*, 1981; Yanagi and Shimizu, 1993).

3. Results

3.1 Spring

The calculated and observed residual currents during spring are shown in Fig. 5. The calculated ones show that in the head region of the bay, a clear anticlockwise circulation develops in the upper layer and expands to the lower layer. In the upper layer of the central part of the bay, a strong southwestward residual current flows along the eastern coast from the central part to the mouth of the bay and turn to northwest partly as being obstructed by the narrow mouth. In the meanwhile, a northeastward residual current exists in the lower layer of the central part and joins into the anticlockwise eddy in the head region of the bay.

The observed result seems to be difficult to give a detailed description about the residual current in Tokyo Bay during spring because there are only nine observation points in the whole bay and five of them lies at the mouth region. Comparing the calculated and observed results, we would know that the southwestward flow in the upper layer along the eastern coast from the central part to the mouth of the bay and the northeastward flow in the lower layer seem to be

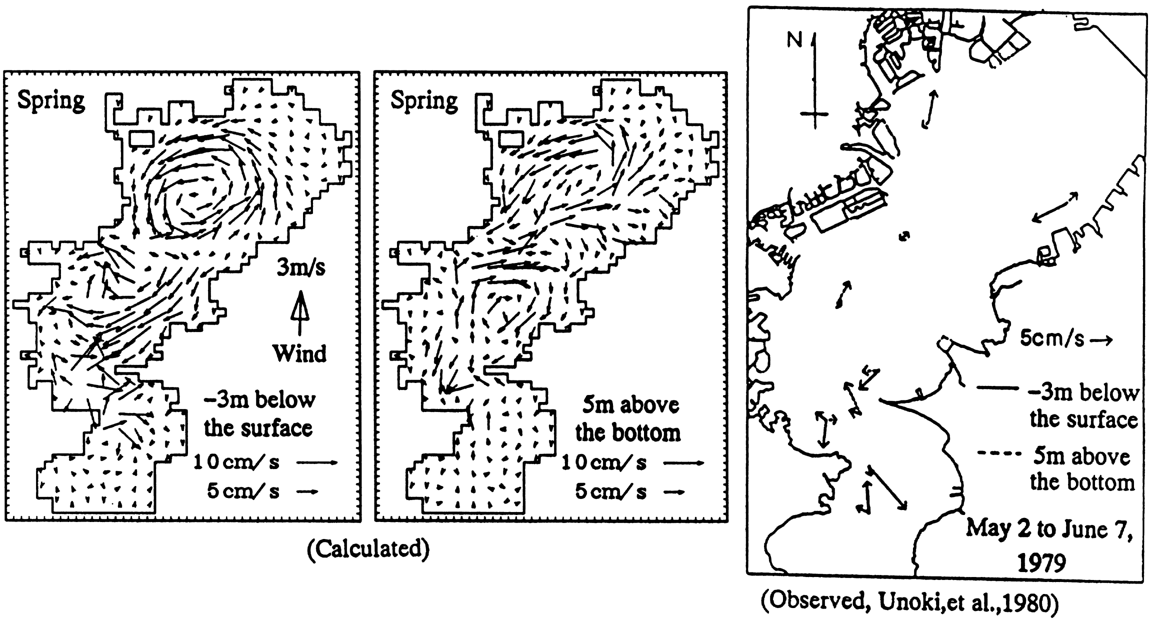


Fig. 5. Comparison between calculated and observed residual current in spring.

supported partly by the observed result. But the calculated anticlockwise eddy in the head region of the bay can hardly get some support from the observed result.

Here, we hardly discuss the difference between the calculated and observed results. However, we can try to give an interpretation on our calculated result. Considering the topography of the head region of the bay, we think that the calculated anticlockwise circulation there may be linked to a process similar to the topographic heat accumulation effect, i.e. during heating period such as spring and summer, the temperature of shallow water becomes higher than that of deep water and an anticlockwise circulation may develop in a nearly enclosed bay, where the water around the bay is shallower than that in the central part. The same mechanism has been found to play an important role on the formation and maintenance of the anticlockwise circulation in Lake Biwa during summer (Oonishi, 1975).

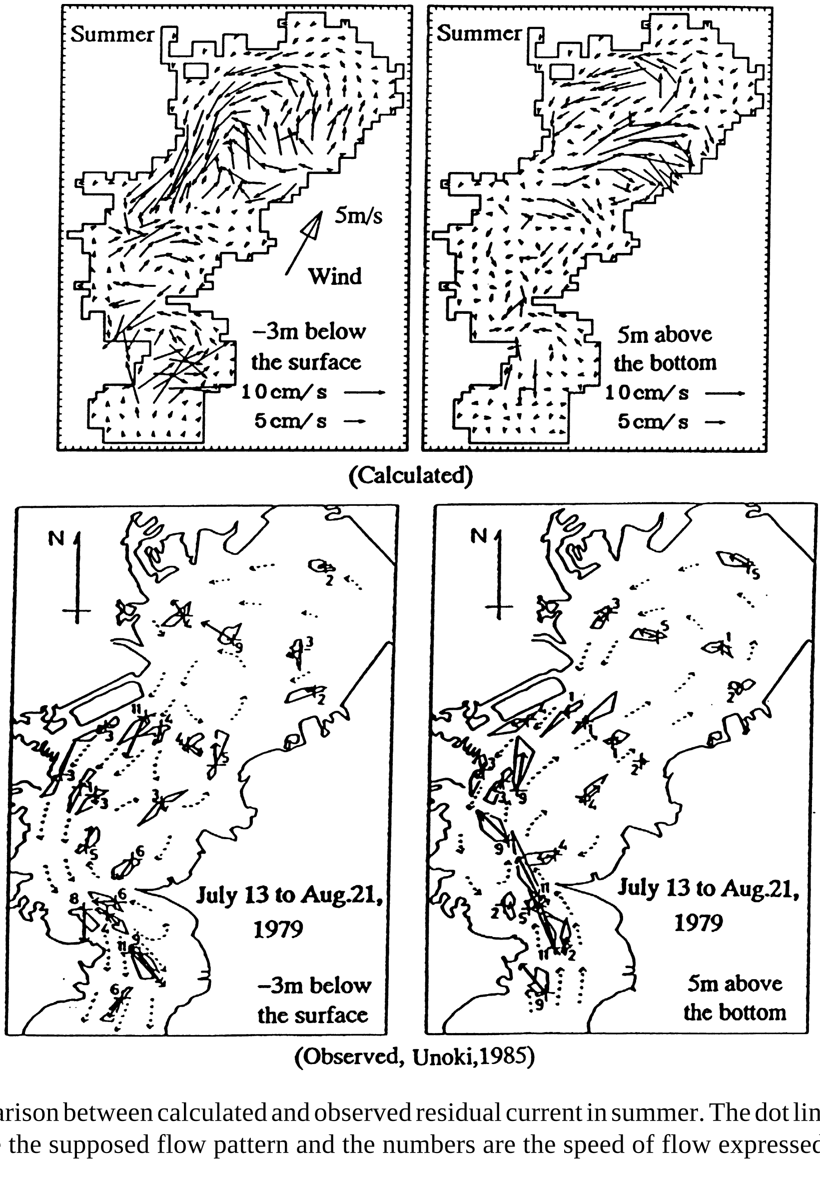


Fig. 6. Comparison between calculated and observed residual current in summer. The dot lines in observed results are the supposed flow pattern and the numbers are the speed of flow expressed in cm/s.

3.2 Summer

The most obvious character of the calculated residual current in the upper layer during summer (Fig. 6) is the strong southwestward current along the western coast from the head region to the central part of the bay, which should be brought by the fresh water from Ara, Edo and Tama Rivers (Fig. 1). In the meanwhile an anticlockwise circulation develops in the upper layer of the head region of the bay but does not close in the central part of the bay. The residual current in the lower layer is very similar to that during spring but stronger than that.

From the observed results, Unoki (1985) concluded that the residual current in Tokyo Bay during summer as: (i) an anticlockwise circulation exists in the head region of the bay; (ii) a southward current flows along the western coast; (iii) at the mouth of the bay, the water flow out at the western side in the upper layer and flow into in the lower layer. Compared with the observed results, the calculated ones can be said to reproduce the main character of residual current during summer. The difference in the southwestern coast from the central part to the mouth of the bay can not be discussed in detail because there is no observation point there. For the difference in the northwestern region of the bay where the river water concentrates (the calculated residual current flows southwestward but the observed one northwestward in the upper layer), we consider that one observed point is not enough to reproduce the density field well.

Although two dimensional numerical calculation shows that the south wind can produce an anticlockwise circulation in Tokyo Bay (Ikeda *et al.*, 1981), the south wind seems not to be the main cause for the anticlockwise circulation in the head region of the bay because the pattern of the south wind-driven residual current is very different from the observed one (Unoki, 1985). Considering that the topographic heat accumulation effect can also continue during summer, we still suggest that this effect should be responsible partly for the anticlockwise circulation in the head region of Tokyo Bay during summer. As for the fact that this eddy does not close in the

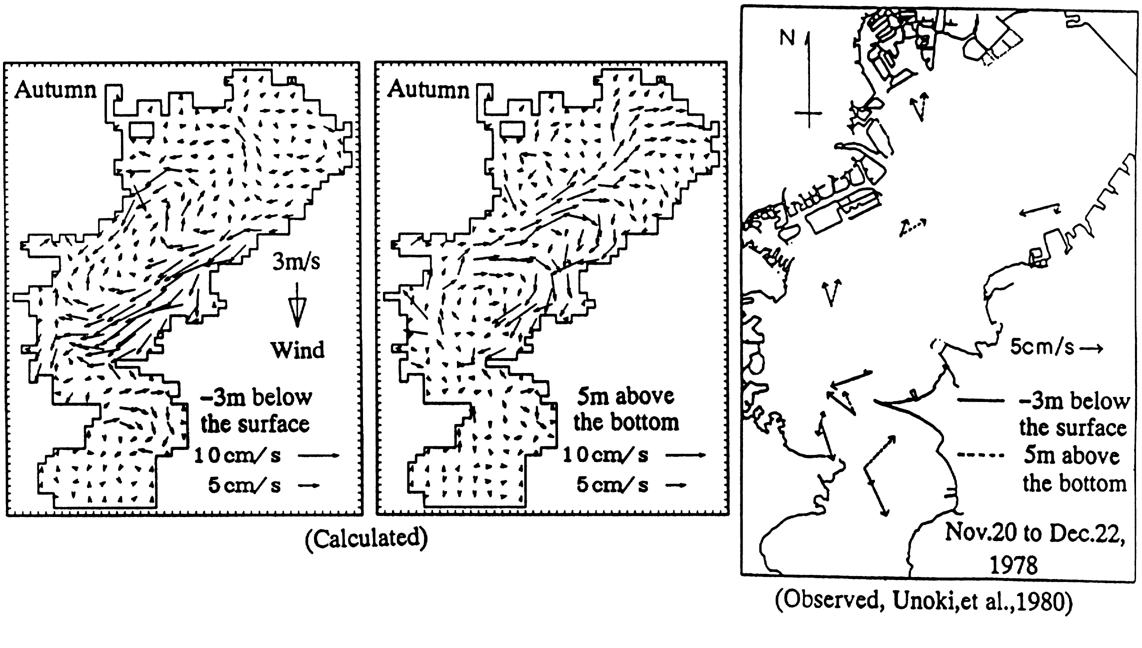


Fig. 7. Comparison between calculated and observed residual current in autumn.

central part of the bay, it should be caused by the different distribution patterns of water density in the central part of the bay during spring and summer as shown in Figs. 4(a) and (b). This difference should result from the large river outflow during summer. In other words, it may be the variation of river outflow to induce the anticlockwise circulation to be closed in spring but to flow southward in summer.

3.3 Autumn

The calculated residual current during autumn (Fig. 7) shows that in the upper layer, a strong southwestward current flows along the eastern coast from the central part to the mouth of the bay and another relatively strong southwestward current along the western coast from the head region

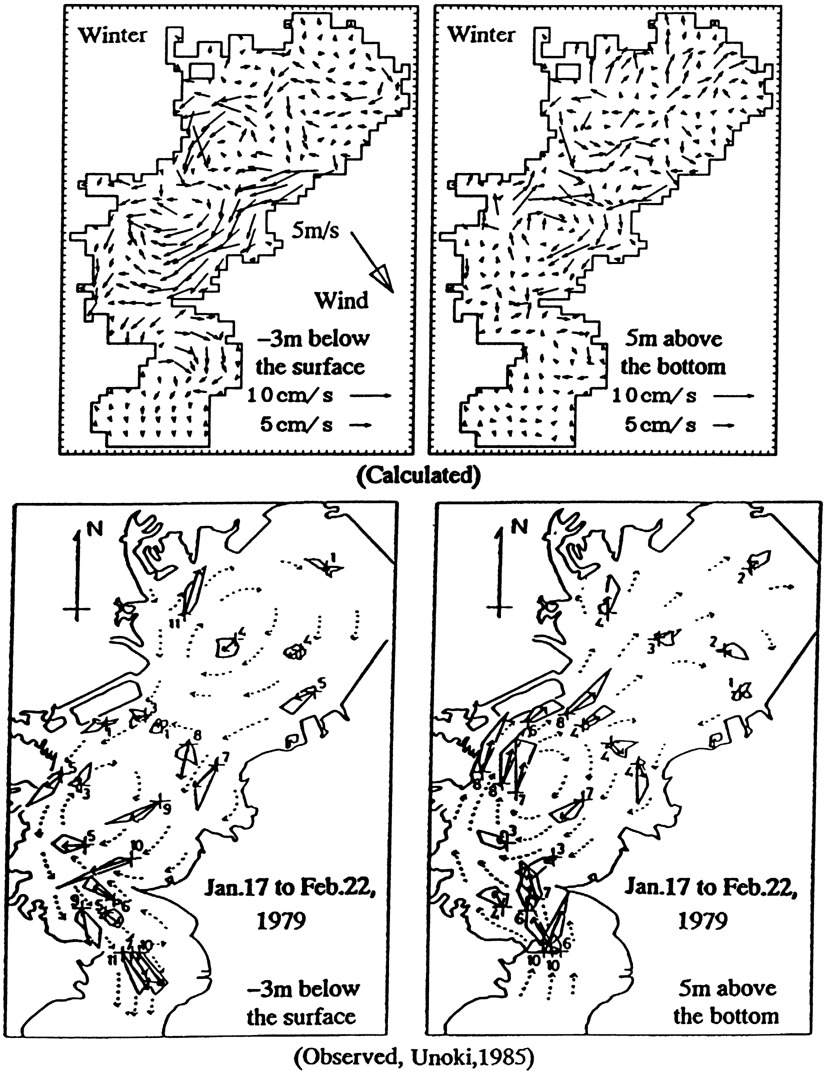


Fig. 8. Comparison between calculated and observed residual current in winter. The meaning of dot lines and numbers in observed results is the same as that in Fig. 6.

to the central part of the bay. At the same time, a northeastward current exists between these two southwestward currents. Apart from these characters, a weak clockwise circulation can be found in the eastern part of head region of the bay. In the lower layer, a branch of narrow and strong northeastward current exists from the mouth to the head of the bay and in the central part of the bay, a part of this northeastward current turns to the east and forms a clockwise circulation with the southwestward current along the eastern coast.

Compared with observed results, except for the southwestward current along the western coast from the head region to the central part of the bay, where no observation point exist, the main characters in the calculated result can almost be supported by the observation. Referring to other observed data, Unoki (1985) has suggested that the southwestward current along the western coast from the head region to the central part of the bay should exist all over the year. Our calculation is consistent with this suggestion (see Fig. 8 for the winter case).

3.4 Winter

On the whole, the calculated residual current during winter (Fig. 8) is similar to that during autumn. The difference exists in some local areas, especially in the head region of the bay. For example, in the upper layer, a branch of southward current appears in the middle of the head region, where an opposite current exists during autumn.

Unoki (1985) has also given a conclusion about the main characters of the residual current in Tokyo Bay during winter from the observed results, that is, (i) a clockwise circulation exists in the upper and lower layers; (ii) the relative strong residual current exists in the upper layer of the eastern coast and the lower layer of the western coast, respectively; (iii) in the upper layer a southwestward current flows along the western coast. Our calculation is consistent with the last two characters basically but shows different pattern in the head part of the bay where the clockwise circulation suggested by Unoki (1985) does not exist. The calculated result shows that a more complicated residual current exists there, which means that in the head region of the bay, especially in the western part of the head region, the influence of fresh water should be great, at least be the same order as the wind effect.

4. Discussion

4.1 The seasonal variation of residual currents in Tokyo Bay

We choose 10 m as the representative depth in Tokyo Bay and show the residual currents at this depth during four seasons in Fig. 9. Comparing these results, we attribute the seasonal variation of residual current in Tokyo Bay to the variation of the strength of two eddies. The first eddy is the anticlockwise circulation in the head region of the bay, which develops in spring and summer and disappears in autumn and winter. Such seasonal variation of this eddy can be related to the alternation of heating and cooling through the sea surface over one year and the variation of the fresh water coming from the rivers at the head of the bay (Fig. 1). During heating period such as spring and summer, the topographic heat accumulation effect may promote the formation of this eddy and during cooling period such as autumn and winter, the water temperature structure that the shallow place is warmer than the deep place is destroyed and this eddy can not be maintained. The second one is the clockwise circulation in the central part of the bay, which develops in autumn and winter, decreases in spring and nearly disappears in summer. This eddy is considered to be generated mainly by a combined effect of the tide-induced residual current and the density-driven current. However, the wind field influences greatly on this eddy, that is,

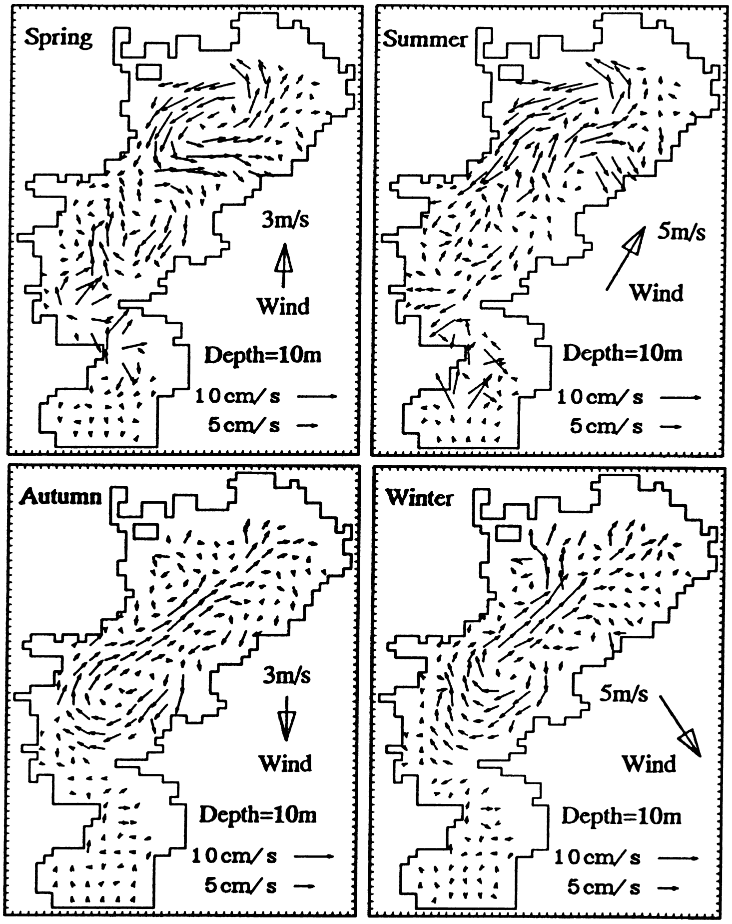


Fig. 9. Seasonal variation of the residual currents at 10 meters.

the north wind during autumn and winter promotes the formation of this eddy and the south wind during spring and autumn hinders the development of this eddy, respectively. In other words, it is the variation of the prevailed wind field to decide the fate of this eddy.

4.2 The forcing balance about the two eddies

The result shown here is that at the nearly steady state. In this case, the time variation terms in Eqs. (1) and (2) approach to zero and the other terms should balance with each other. In order to get an insight on the variation of the above two eddies, we plot the distribution of the main terms in Eq. (1) along the two lines shown in Fig. 10 (the balances in the Y-direction (Eq. (2)) along such lines are considered having no dynamic meaning to the maintenance of the two eddies). By this way, we find that the contributions from the advective term, the horizontal and vertical eddy viscosity terms are smaller than those from the other terms during four seasons and the results of spring and autumn case are very similar to those of summer and winter case, respectively. Thus, only the distribution of relatively large terms in summer and winter case are shown in Fig. 10.

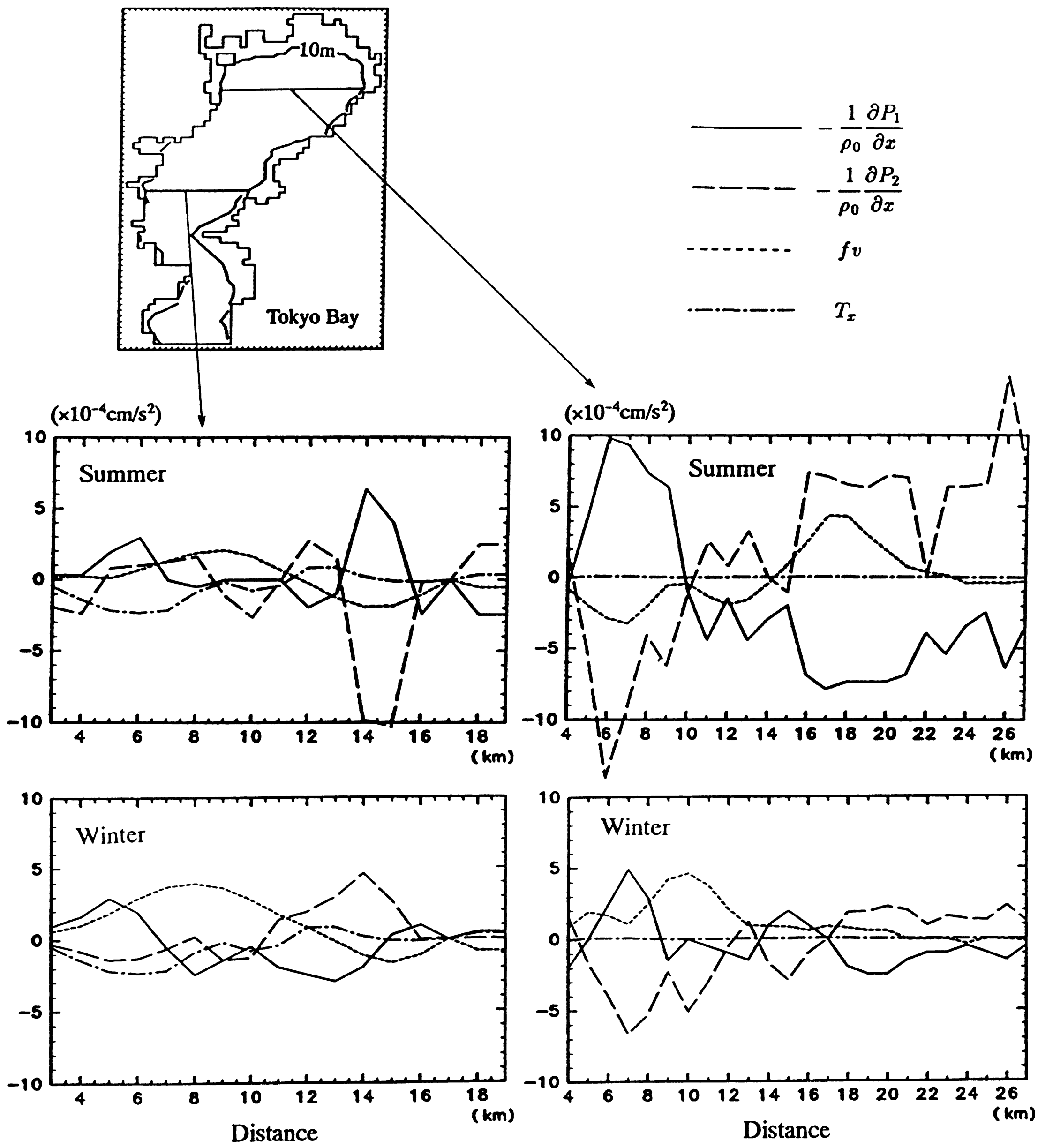


Fig. 10. The main forcing balance about the two eddied during summer and winter.

As expected, the tidal stress has no effect on the eddy existing in the head region of the bay during summer and the main balance about this eddy is the gradient of water elevation with the sum of Coriolis force and the density pressure coming from the horizontal density difference. The distribution that the density pressure is negative on the west side and positive on the east side means that the density of water above 10 meters in the middle place of the line is larger than that at two sides. Noticing that Coriolis force and the density pressure have the same function on the eddy, we suggest that a process similar to topographic heat accumulation effect should be responsible for the formation of this eddy. In fact, to clarify the generation mechanism of this eddy in detail, a prognostic calculation is needed. But the difference on the dynamic balance in summer and winter is obvious.

As for the eddy existing in the central part of the bay, it is difficult to discuss the detailed dynamic variation between summer and winter. But the role of tidal stress can be confirmed, i.e. the tidal stress promote the formation of this eddy, especially in the west side. Such effect should become strong as the position of the eddy approaches the mouth of the bay.

5. Conclusion and Suggestion

(1) The residual currents during four seasons in Tokyo Bay are calculated by a diagnostic numerical model and the calculated results reproduce the main characters of the observed residual current system and provide a detailed insight on it.

(2) The data of temperature, salinity and wind used in our calculation are the mean value over the observed period. In a nonlinear system, the calculated residual currents under this averaged data should be different from that obtained by averaging the field current data. Their good match suggests that the system is controlled mainly by a linear system. This conclusion can also be supported by the calculated forcing distribution during each season although they are not shown in this paper.

(3) As a limitation of the diagnostic model, we can not separate each process acting on the residual current system such as the river outflow and heating or cooling process. Thus, we can not do a deep research on the generation mechanism of the residual current in Tokyo Bay during each season. This problems will be tried by using a prognostic numerical model in the near future.

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References

Arakawa, A. (1966): Computational design for long-term numerical integration of the equation of motion: Two dimensional incompressible flow. Part 1. *J. Comput. Phys.*, **1**, 119–143.

Endoh, M. (1977): Formation of thermocline front by cooling of the sea and inflow of the fresh water. *J. Oceanogr. Soc. Japan*, **33**, 6–15.

Guo, X. and T. Yanagi (1994): Three dimensional structure of tidal currents in Tokyo Bay, Japan. *La mer*, **32**, 173–185.

Guo, X. and T. Yanagi (1995): Wind-driven current in Tokyo Bay, Japan during winter. *La mer*, **33**, 51–64.

Ikeda, K., M. Matsuyama and M. Tsuji (1981): Effect of the wind on the current in Tokyo Bay. *Umi to Sora*, **57**(1), 31–40 (in Japanese with English abstract).

Nagashima, H. and M. Okazaki (1979): Observations of temperature, salinity and current velocity at the mouth of Tokyo Bay in winter. *Bull. Coast. Oceanogr.*, **16**(2), 76–86 (in Japanese).

Oonishi, Y. (1975): Development of the current induced by the topographic heat accumulation (I). *J. Oceanogr. Soc. Japan*, **31**, 243–254.

Oonishi, Y. (1978): The numerical research—its methods. p. 246–271. In *Oceanography as an Environmental Science*, Vol. **2**, ed. by S. Horibe, Tokyo Univ. Press, Tokyo (in Japanese).

Suginohara, N. (1978): The numerical research—its methods. p. 234–245. In *Oceanography as an Environmental Science*, Vol. **2**, ed. by S. Horibe, Tokyo Univ. Press, Tokyo (in Japanese).

Unoki, S. (1985): Tokyo Bay—its physical aspect. p. 344–361. In *Coastal Oceanography of Japanese Islands*, Tokai University Press, Tokyo, 1106 pp. (in Japanese).

Unoki, S. and M. Kishino (1977): Averaged oceanic condition and water exchange in Tokyo Bay. *Report of Physical Oceanography Laboratory in Physical-Chemical Institute*, No. 1, 89 pp. (in Japanese).
Unoki, S., M. Okazaki and H. Nagashima (1980): The circulation and oceanic condition in Tokyo Bay. *Report of Physical Oceanography Laboratory in Physical-Chemical Institute*, No. 4, 262 pp. (in Japanese).
Yanagi, T. and S. Igawa (1992): Diagnostic numerical model of residual flow in the coastal sea—An example of adoption to Suo-Nada and Iyo-Nada. *Bull. Coast. Oceanogr.*, **30**(1), 12–19 (in Japanese with English abstract).
Yanagi, T. and M. Shimizu (1993): Sedimentation processes in Tokyo Bay, Japan. *La mer*, **31**, 91–101.
Yanagi, T., A. Isobe, T. Saino and T. Ishimaru (1989): Thermohaline front at the mouth of Tokyo Bay in winter. *Cont. Shelf Res.*, **9**, 77–91.
Yanagi, T., S. Okada, T. Ishimaru and T. Saino (1991): Behavior of high turbidity water outflow from Tokyo Bay in Summer. *La mer*, **29**, 45–51.