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Wind-driven current in Tokyo Bay, Japan during winter*

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Abstract: The residual currents in Tokyo Bay driven by the southward wind during winter are calculated using a three-dimensional numerical model. On the basis of reproduced horizontal currents system, the verical current is examined. A vertical circulation with westward flow in the upper layer and eastward flow in the lower layer is induced by the Ekman transport along the east-west section. On the other hand, another vertical circulation with seaward flow in the upper layer and landward one in the lower layer induced by the sea surface gradient along the north-south sec-tion is thought to play a second role in the vertical circulation in Tokyo Bay during winter. The generation mechanism of the vertical flow is proposed to explain the different characters between the vertical current around the mouth area of the bay and that around the head area of the bay. The same mechanism is expected to take effect in other bays or straits with similar bottom topog-raphy to Tokyo Bay.

1. Introduction

Tokyo Bay is the semi-enclosed bay situated at the central part of Japan, which communicates with the Pacific Ocean through the narrow Uraga Strait. Averaged water depth is 17 meters and the surface area is about 1000km^2. From the mouth to the central part of the bay the sea bottom rises very rapidly. But from the central part to the head of the bay, the sea bottom rises gradually (Fig.1). Another character of the water depth is that the water depth distributes unsymmetrically to the main axis of the bay, where the water depth is deep along the western coast and shallow along the eastern coast. It will be seen that such unsymmetrical distribution of the water depth may affect the wind-driven current system there.

The circulation of Tokyo Bay in winter has been investigated by field observations for many times (NAGASHIMA and OKAZAKI, 1979; UNOKI *et al.*, 1980; MURAKAMI and MORIGAWA, 1988; SHIOZAKI *et al.*, 1988). Figure 2(a) is the residual currents system which was made on the basis of the observed data (UNOKI, 1985). By the analysis of cross-correlation between the residual currents and wind, it has been concluded that the clockwise circulation in Tokyo Bay during winter should be mainly due to the southward or southwestward wind above Tokyo Bay during winter (UNOKI *et al.*, 1980). This view has been supported by many numerical calculations in which the numerical model is horizontal two dimensional one (NAGASHIMA, 1982; IKEDA *et al.*, 1981) or three dimensional one (ODAMAKI *et al.*, 1990). Up to now, it can be said that we have understood the general pattern and the main generation force of the horizontal residual currents in Tokyo Bay during winter. However, for the research of material transport processes, it is not enough for us just to know the general pattern of the horizontal residual currents. We have to carry out more detailed works about the residual currents system, especially about the vertical residual circulation which has been thought to relate closely to the material transport processes, by three-dimensional numerical calculation.

The purpose of this paper is to present a unified analysis about the response of Tokyo Bay to the southward wind. With this aim in view, careful attention is paid to the vertical component of the wind-driven current.

In the second section of this paper, the model and its application to Tokyo Bay are described. The third section focuses on the comparison between the calculated results and the observed results in Tokyo Bay. In the fourth section, the generation mechanism of the vertical

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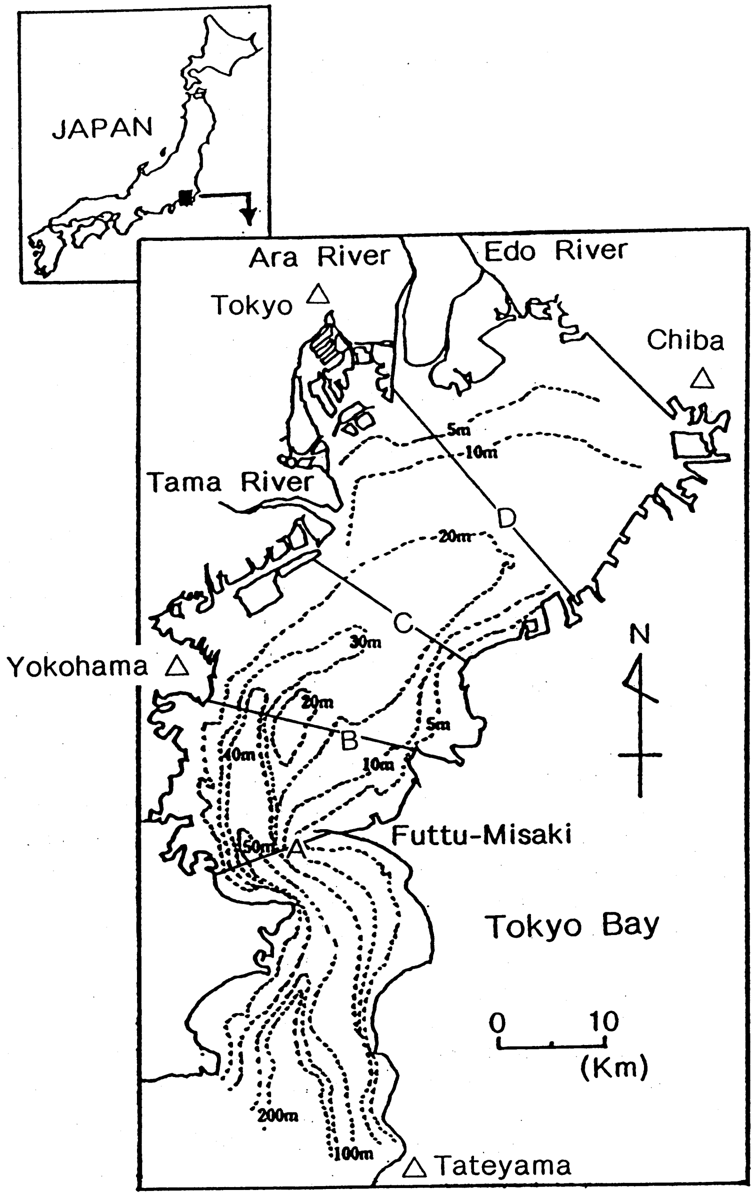

Fig. 1. The water depth distribution and the position of four transections in Tokyo Bay.

flow is analysed by some simple numerical models. Finally, the results of calculation are summarized, their limitations are discussed and suggestions for future work are presented.

2. Model

2.1. Formulation

Starting from the momentum equation in the f-plane and the continuity equation, assuming constant and uniform water density, and introducing hydrostatic approximation for linearzed motions, we get:

$$\frac{\partial u}{\partial t} - fv = -g\frac{\partial \zeta}{\partial x} + \frac{\partial}{\partial z}\left(A_v \frac{\partial u}{\partial z}\right) + A_h\left(\frac{\partial^2 u}{\partial^2 x} + \frac{\partial^2 u}{\partial^2 y}\right) \qquad (1)$$

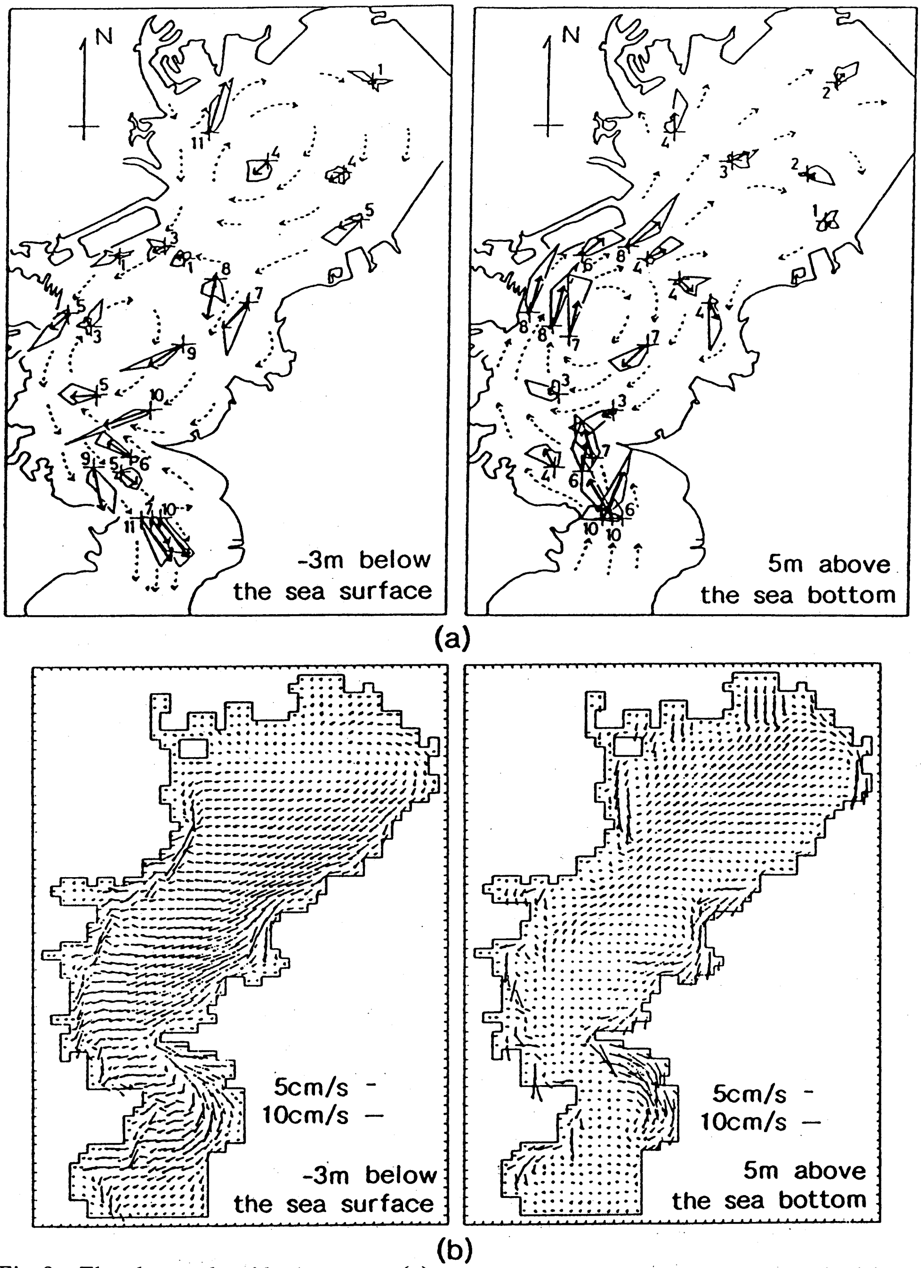

Fig. 2. The observed residual currents (a) and the calculated wind-driven currents (b) in Tokyo Bay during winter. The dot lines is the supposed flow pattern and the number is the speed of the residual currents expressed in cm/s. (UNOKI, 1985).

$$\frac{\partial v}{\partial t}+fv=-g\frac{\partial \zeta}{\partial y}+\frac{\partial}{\partial z}\left(A_v\frac{\partial v}{\partial z}\right)+A_h\left(\frac{\partial^2 v}{\partial^2 x}+\frac{\partial^2 v}{\partial^2 y}\right) \quad (2)$$

$$\frac{\partial \zeta}{\partial t}+\frac{\partial}{\partial x}\int_{-h}^{0} udz+\frac{\partial}{\partial y}\int_{-h}^{0} vdz=0 \quad (3)$$

where t=time,
ζ =sea surface elevation,
u,v=horizontal current components,

h=undisturbed water depth,
A_v=vertical eddy viscosity coefficient,
A_h=horizontal eddy viscosity coefficient,
f=Coriolis parameter,
g=acceleration due to gravity.

Equation (1) - (3) are written in the (x, y, z) coordinate system in which the horizontal coordinate is laid at the undisturbed sea surface, the vertical coordinate directs upwards.

Initially, a state of rest is assumed to exist. At the surface and bottom the following conditions are prescribed:

$$z=0:\ \rho A_v\frac{\partial u}{\partial z}=\tau_x, \rho A_v\frac{\partial v}{\partial z}=\tau_y \qquad (4)$$

$$z=-h: u=v=0 \qquad (5)$$

The wind stresses in equation (4) is defined as

$$\tau_x=C_d\rho_a u_a\sqrt{u_a^2+v_a^2},\ \tau_y=C_d\rho_a v_a\sqrt{u_a^2+v_a^2} \qquad (6)$$

The symbols u_a and v_a denote the wind velocity components, ρ_a is the density of air, ρ is the density of sea water, C_d is the non-dimensional drag coefficient. No normal flow and no slip condition are allowed along the coastal line. The problem is closed by postulating a sponge condition at the open boundary.

The numerical solving method of above equations is nearly the same as that when we used in reproducing the three-dimensional tidal currents in Tokyo Bay (GUO and YANAGI, 1994). The differences are just the open boundary condition and the condition applied on the sea surface, which bring no difficulty on changing our program of computation.

2.2. *Application to Tokyo Bay*

In order to calculate the response of Tokyo Bay to wind, we divide it by a mount of rectangular grids with the 1km size in both x (eastward) and y (northward) directions. With this grid size and a maximum depth of 200 meters, the Courant-Friedrichs-Lewy stability criterion gives the time step less than 16 seconds. As described in our last paper (GUO and YANAGI, 1994), our numerical model is not absolutely limited by this stability criterion. Thus we choose 30 seconds as the time step in our calculation.

The parameters f, g and ρ were set equal to $8.469\times10^{-5}s^{-1}$, $980cm/s^2$ and $1025kg/m^3$, respectively. Although there is no limit on the form of the vertical eddy viscosity coefficient in our numerical model, we still like to chose a constant vertical eddy viscosity model (A_v=10 cm^2/s) to enclose our problem at first. This value ($A_v=10cm^2/s$) has also been used by ODAMAKI *et al.* (1990) in the calculation of wind-driven current in Tokyo Bay. For the horizontal eddy viscosity coefficient, we do not have any experiences on deciding its value and just want to follow the experiences of former researchers (IKEDA *et al.*, 1981; ODAMAKI *et al.*, 1990) and take $10^5cm^2/s$ as its value in our calculation.

As for the non-dimensional drag coefficient in equation (6), ORLIC *et al.* (1994) have made a complete review about it and taken it as 2.5×10^{-3} in their numerical simulation. In our calcula-tion, we would like to calculate it according to the formula given by HONDA and MITSUYASU (1980) based on many experimental data. The averaged wind speed above Tokyo Bay during winter is about 5m/s and the calculated value C_d from the formula by HONDA and MITSUYASU (1980) is 1.17×10^{-3}. Considering the land/sea wind difference, we choose 1.3×10^{-3} as the value of C_d in our simulation. This value is the same as that used by IKEDA *et al.* (1981). The density of air is taken as $1.2\times10^{-3}g/cm^3$.

To be able to compare our calculated results with the observed ones (Fig. 2 (a)), we want to imposed a nearly real wind field in our simulation. The observation, according to which the winter residual current system shown in Fig. 2 (a) was drawn, was carried out from January 17th to February 22th in 1979 (UNOKI *et al.*, 1980). Meanwhile, the wind data at four stations (Tokyo, Yokohama, Tateyama and Chiba, see Fig. 1) was recorded every three hours, too. These wind data show clearly that the wind blew from north on the most days of that period and the averaged speed is about 5m/s. Basing on this fact we impose a southward wind field with the speed of 5m/s on the model at the start of the computaion and kept constant thereafter. The calculation was run for 48 hours after which a steady state is expected to reach.

3. Results

3.1. Comparison with observation

Firstly we would like to check the response time of Tokyo Bay to the wind. The averaged velocity $\tilde{u}$ of all grid points whose time-variation curve has the same meaning as that of the kinetic energy of Tokyo Bay is calculated by the following equation:

$$\tilde{u} = \frac{1}{N} \sum_{i=1}^{N} (u_i^2 + v_i^2)^{\frac{1}{2}} \quad (7)$$

where i represents the number of grid point and N is the whole numbers of grid in the bay. The time-variation curve of this averaged velocity (Fig. 3) shows that it just takes half a day for Tokyo Bay to reach a steady state as being blown by an uniform wind. In fact the observed results (UNOKI *et al.*, 1980) show that after a northward wind blowing above Tokyo Bay for 12 hours in winter, the residual currents pasttern becomes to an opposite one to Figure 2(a). Such fact demonstrates this time scale of 12 hours.

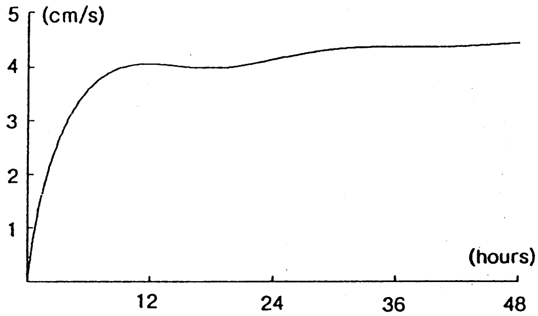

Fig. 3. The time-variation curve of the all points' averaged velocity.

The main characters of the winter residual currents system in Tokyo Bay described by UNOKI (1985) are: a clockwise horizontal circulation exists in Tokyo Bay and this circulation can be found either in the upper (-3m) or lower (5m above sea bed) layers; The relatively strong currents were found along the eastern side in the upper layer and along the western side in the lower layer; On the other hand, a southward current exists along the western coast, which usually should be due to the fresh water coming from the rivers locating along the western coast (Edo, Ara and Tama Rivers shown in Fig. 1) in Tokyo Bay; at the mouth of Tokyo Bay, a typical gravitational vertical circulation can be found, that is, south-

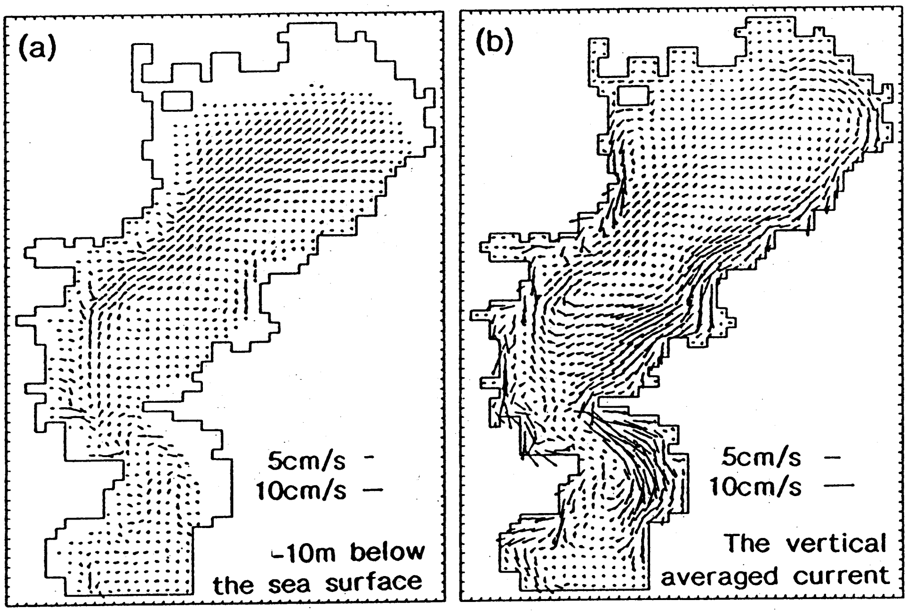

Fig. 4. The horizontal currents at the depth of 10 meters (left) and the vertical averaged currents (right) in Tokyo Bay.

ward current in the upper layer and the northward one in the lower layer (See Fig. 2(a)).

The calculated results at the same depth as the above observation is shown in Figure 2(b). From this figure, we can see: in the region such as the eastern part of the bay where the density current should be expected to be weak, the calculated results fit the observed ones well; In the region such as the western part of the bay where the river water may highly influence the residual currents system, the calculated results do not fit the observed ones very well. Figure 4(a) is the flow pattern at the depth of 10 meters which shows that the upwind current exists along the main axis of the bay where the water depth is deep and the downwind current exists along the coastal line where the water depth is shallow. Such flow pattrn is also found to exist in the Adriatic Sea by ORLIC *et al.* (1994). The mechanism of this flow pattern has been investigated by NAGASHIMA (1982) and was attributed to the water depth variation along the transection of the bay. Figure 4(b) is the vertically averaged currents which are nearly the same as those obtained by IKEDA *et al.* (1981) and NAGASHIMA (1982) using a

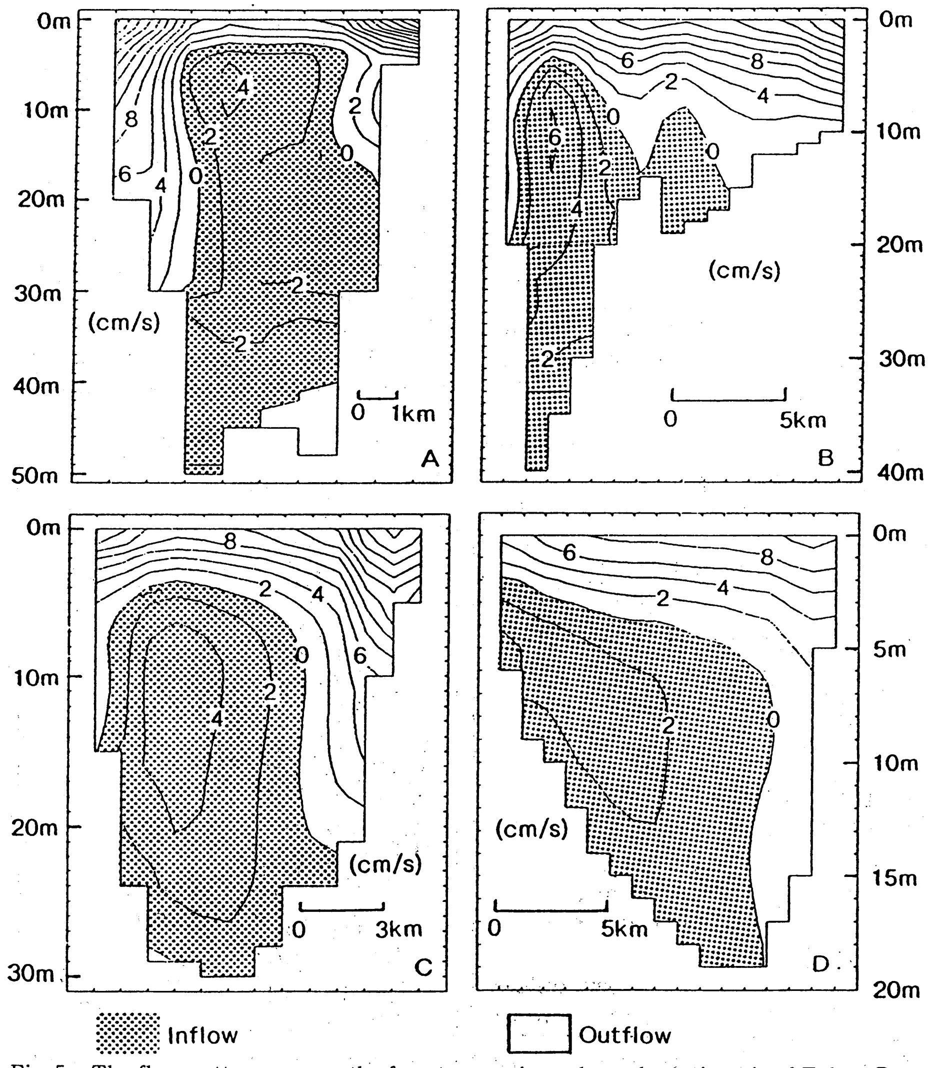

Fig. 5. The flow patterns across the four transections along the main axis of Tokyo Bay. The contouring interval is 2cm/s.

horizontal two dimensional numerical model. It is on this figure that a clockwise circulation can be seen clearly existing at the central part and at the head of the bay.

Figure 5 is the currents across four transections whose positions are shown in Figure 1. This figure tells us that along all transections the outflow currents exist in the surface layer and in the shallow part and the inflow currents exist in the deep part. Such circulation means that an upwelling and a downwelling region should exist around the head and the mouth of Tokyo Bay, respectively. However, to what extent such upwelling or downwelling develop, we do not know now. To answer this question we have to calculate the vertical residual current to see where the upwelling region is and where the downwelling region is. On the other hand, noticing the unsymmetrical distribution of the water depth to the main axis of the bay along the transection B, we can know the reason why the relatively strong currents were found along the eastem side of the bay in the upper layer and along the western side of the bay in the lower layer (NAGASHIMA, 1982).

3.2. Calculated vertical current

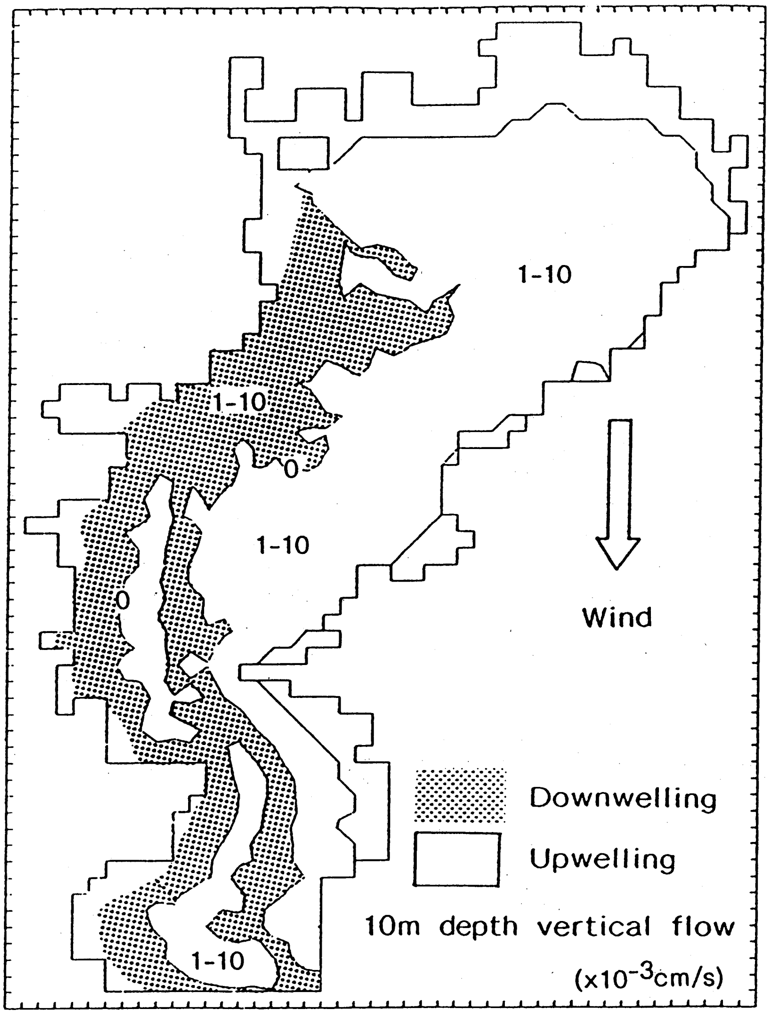

Fig. 6. The horizontal distribution of the calculated vertical current at the depth of 10 meters in Tokyo Bay under the condition of southward wind during winter.

Figure 6 is the horizontal distribution of the vertical residual current at the depth of 10 meters. In the northern part of the head of the bay, the upwelling region exists, which should be brought by the upwind residual currents in the deep layer and the rise of the sea bottom. In the southern part of the head of the bay, the upwelling region and the downwelling region exist along the eastern side and the western side, respectively. Such vertical circulation pattern should be due to the effect of the surface Ekman transport. Around the mouth of the bay, apart from the upwelling region at the eastern side and the downwelling region at the western side, there is another upwelling region existing along the western side where should be dominated by the downwelling flow. Such distribution character of vertical flow can not be explained by the surface Ekman transport. We guess that it is not other factors other than the water depth variation which may bring this difference because the generation force of the calculated residual current is the uniform sea surface wind. The detailed mechanism about it will be analysed in the next section using some simple model basins.

Here we want to point out that the previous studies about the vertical residual circulation in Tokyo Bay mainly focused on the vertical residual circulation in the direction from south to north which is produced by the gradients of sea surface elevation between the head and the mouth of the bay. Such vertical residual circulation with seaward flow in the upper layer and landward one in the lower layer will be identified by the southward or southwestward wind in Tokyo Bay duing winter (YANAGI, 1994). Thus a downwelling region will appear at the mouth of the bay and a upwelling region will appear at the head of the bay (UNOKI, 1985). Under this view the phenomenon named Aoshio in Japanese, which usually appears at the head of the bay after one or two days's blowing of the southward or southwestward wind in summer, is often related to this vertical residual circulation (MATSUYAMA *et al.*, 1990). However our calculation result shows that although the upwelling region exists in the most parts of the head area of Tokyo Bay, it should be mostly due to the Ekman transport. The upwelling currents due to the sea surface gradients between the mouth and the head of the bay just exist in a narrow region at the head of the bay. In other words, the vertical residual circulation in Tokyo Bay under the condition of southward wind is maintained mainly by the vertical residual circulation in the direction from east to west. In fact, the contour line of the observed sea water temperature in Tokyo Bay during summer after a southward wind blowing is nearly parallel to the coastal line (UNOKI, 1985). This observation may support our calculated vertical residual current distribution indirectly.

4. Discussion

4.1. The simple model basins.

To clear the reason why the horizontal distributions of the calculated vertical currents around the head and the mouth of the bay is different from each other, we carried out some numerical experiments by using some simple model basins. The transection of the model basins used in the following numerical experi-

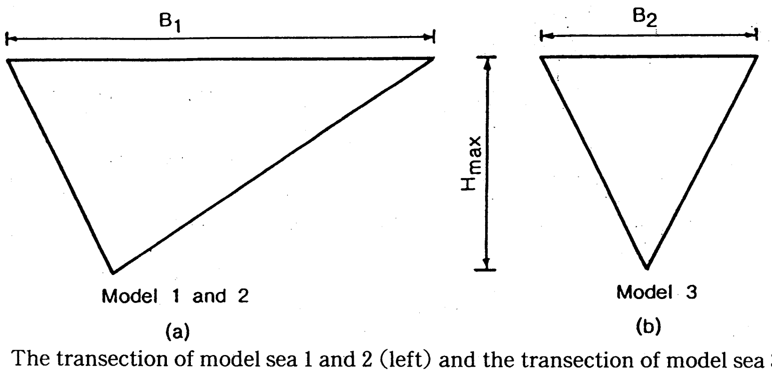

Fig. 7. The transection of model sea 1 and 2 (left) and the transection of model sea 3 (right).

ments are shown in Fig. 7, where (a) is the transection of model 1 and model 2 that reflects the unsymmetrical distribution character of the water depth in Tokyo Bay and (b) is the transection of model 3. The maximum depth of the model basin is 20 meters in model 1 that is nearly the same as the maxinum depth near the head of Tokyo Bay and 50 meters in model 2 that is nearly the same as the maxinum depth near the mouth of Tokyo Bay. The horizonatl scale, the length and the width of the model 1 and model 2, is taken as 50 km and 30 km, respectively, which are also nearly the same as those of Tokyo Bay, respectively. A southward wind field with the speed of 5 m/s is imposed to the model basin which is elongated to north-south direction. The other parameters and procedures of the calculations of the model basin are the same as those used in the calculation of section 2 of this paper. The results after two days of wind blowing will be shown hereafter.

4.2. Calculated results of model 1.

From the horizontal currents distribution at the depth of 10 meters (Fig. 8(a)), we can know that the downwind current exists in the shallow region and the upwind current exists in the deep region. This result is the same as the conclusion induced by NAGASHIMA (1982) by using a simple model in which the Coriolis force was ignored.

Figure 8(b) is the horizontal distribution of the vertical current at the depth of 10 meters. This figure shows that the east-westward vertical residual circulation exists in the most parts of the model basin. The upwelling and downwelling region caused by the sea surface gradient from bay mouth to head exists in a narrow areas near the southern and northern boundaries. Figure 8(c) is the flow pattern along the transection whose position is shown in Fig. 8(a).

4.3. Calculated results of model 2.

For investigating the effect of the variation in water depth, we calculated the response of model 2 to the southward wind. The horizontal currents distribution at the depth of 10 meters (Fig. 9(a)) shows no difference from that of

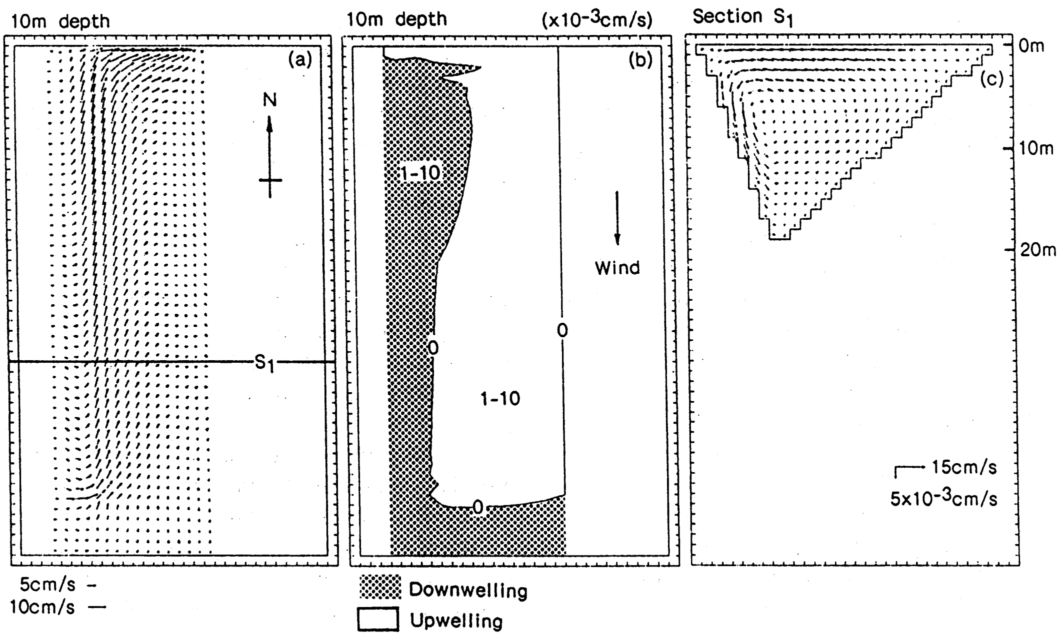

Fig. 8. The calculated results of model 1. Fig.(a) is the calculated horizontal currents at the depth of 10 meters; Fig.(b) is the horizontal distribution of the vertical current at the depth of 10 meters; Fig.(c) is the flow pattern along the transection of the model sea.

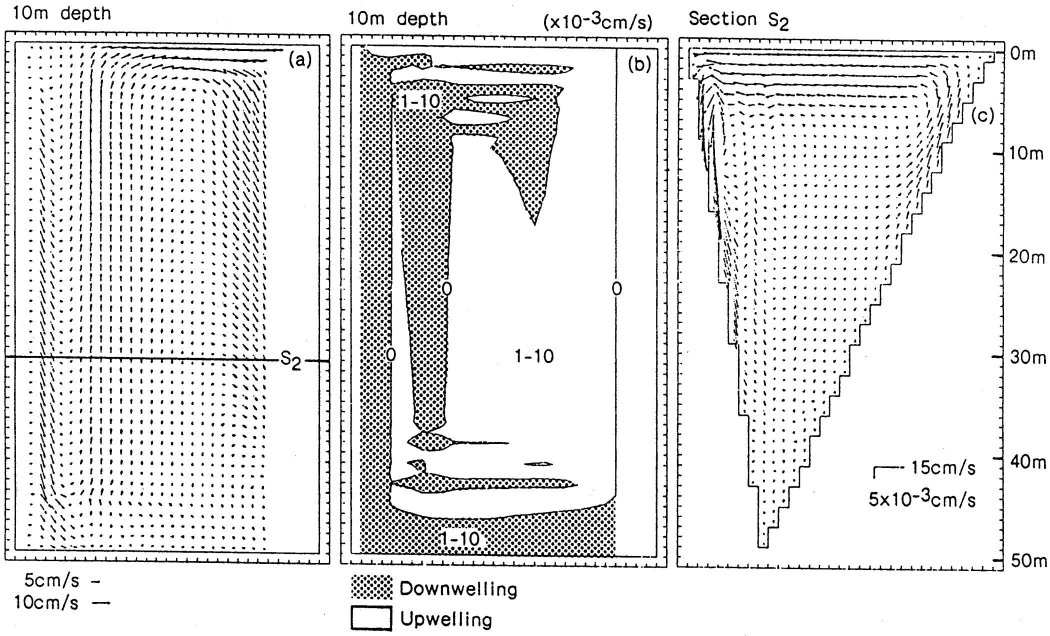

Fig. 9. The calculated results of model 2. The meaning of Fig.(a), (b) and (c) is the same as that in Fig. 8.

model 1 (Fig. 8(a)) in principle.

The horizontal distribution of the vertical residual current at the depth of 10 meters (Fig. 9(b)) shows some differences from that of model 1. Apart from the phenomenon which can be seen in model 1, there is another upwelling region existing on the west side where should be a downwelling region according to the Ekman transport theory. Such flow can be clearly seen in Fig. 9(c).

We suggest that this upwelling flow should be attributed to the Ekman pumping induced in the bottom boundary layer. In other words, on the western coastal area, the water column below the surface Ekman layer forced by the surface Ekman transport moves to the deep part from the shallow part and an anticlockwise eddy is produced in the internal flow region due to the conservation law of potential vorticity (PEDLOSKY, 1979). This anticlockwise eddy induces an upward flow in the bottom boundary layer and after this upward flow becomes stronger than the downward flow in the internal flow region, we can see an upward flow in that region. The same effect and another similar effect named Ekman suction will also be expected to take effect in the western side in model 1 and the eastern side in both model 1 and model 2, respectively. But we can not see this effect apparently. This can be explained by that whether the effect of Ekman pumping or Ekman suction can be seen in the internal flow region is decided by the balance between the speed of vertical current produced by such effects and the speed of vertical current coming from the residual current field along the transection in the internal flow region. The former depends on the eddy of the water column which is related to the variation of the water depth along the transection. The latter depends on the slope of the sea bottom and the horizontal residual current along the transection in the internal flow region which is nearly decided by the ratio of the Ekman transport in the surface Ekman layer to the height of the water column below the surface Ekman layer. At last the speed of vertical current coming from the residual current field along the transection in the internal flow region should be thorght to depend on the Ekman transport in the surface Ekman layer and the width of the slope sea bottom. In model 1, the gentle variation of the water depth along the transection induces the effect of Ekman pumping and Ekman suction to be weak and we can not see such effects in the internal flow region naturally. In model 2, the vertical flow contributed by the residual current field along the transection in the internal flow region keeps nearly the same as that in model 1 becouse of the same wind field. But the rapid variation of the water depth along the transection makes the effect of Ekman pumping to be larger than that in model 1 so we can see an upward flow in the western side. As for the effect of Ekman suction, the variation of the water depth in the eastern side is smaller than that in the western side, thus apparent downward flow can not be found in the internal flow region of model 2. We guess if we increase the slope of sea bottom in the eastern side as much as that in the western side of model 2, we will be able to see a downward flow in the eastern side. To verify this supposition we do another numerical experiment by using model 3.

4.4. Calculated results of model 3.

The transection of model 3 is symmetry to the direction from east to west (Fig. 7(b)). The maximum depth is kept as 50 meters but the width of the model sea is decreased to 15 km, half of the width of model 1 and model 2. By this way, we keep the same sea bottom slope gradient both in the western and eastern sides.

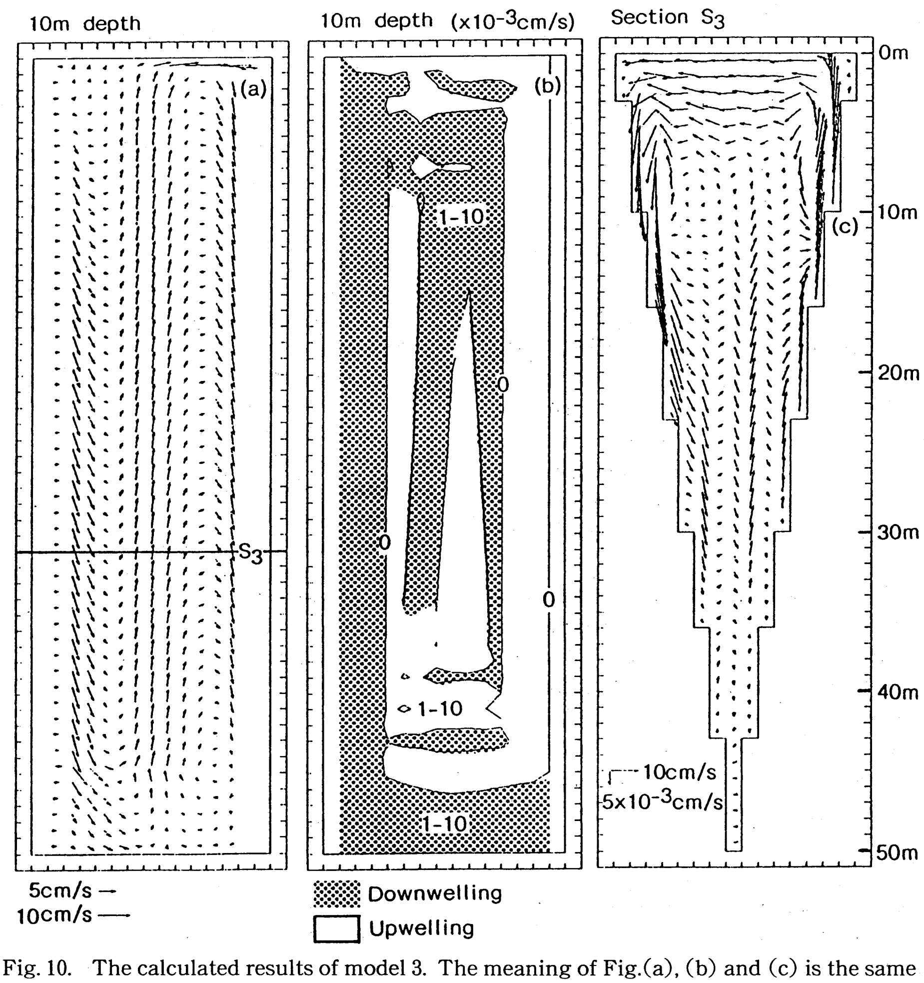

Fig. 10. The calculated results of model 3. The meaning of Fig.(a), (b) and (c) is the same as that in Fig. 8.

As described above, a symmetry upwelling and downwelling region will be expected to appear at the western and eastern sides of this model basin. The calculated results are shown in Fig. 10. The horizontal residual currents (Fig. 10(a)) show no difference from those of model 1 and model 2 in principle but the horizontal distribution of the vertical current (Fig. 10(b)) is different from those of model 1 and model 2. As expected, a nearly symmetrical upwelling and downwelling regions really appear in the western and eastern sides of this model basin, respectively. Such vertical flow can be more clearly imaged in Fig. 10(c). This result proves that under the same conditions the Ekman suction can also take effect as the Ekman pumping and the different horizontal distrbutions of calculated vertical residual current around the head and the mouth of Tokyo Bay are really due to the Ekman pumping effect happening around the mouth area of Tokyo Bay.

5. Conclusion and suggestion

(1). The basic characters of the horizontal wind-driven currents in Tokyo Bay during winter is reproduced well by a three-dimensional numerical model.

(2). The vertical residual circulation under the condition of southward wind in Tokyo Bay during winter is maintained mainly by that in the east-west direction. The vertical residual circulation in the north-south direction just plays a second role. The Ekman pumping takes effect around the mouth of the bay where the water depth varies rapidly along the transection of the bay.

(3). It can be expected that the calculated results depend on the parameters, especially the vertical viscosity coefficient, surely. In our model, the vertical viscosity coefficient is taken as a constant that could be said too simple. So about the correct choice of some parameters, especially the vertical viscosity coefficient, more works are needed in the future.

(4). Although we give an explanation about the generation of the vertical residual current, we have no method to verify it. We hope that in the future some field observation related to the vertical residual current could be carried out in Tokyo Bay or at someplace which has similar topography with Tokyo Bay. And also we suggest that the researches about the residual current in the future should pay some attentions to the vertical circulation because such circulation is an important factor when we discuss the material transport processes or the primary production.

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東京湾の冬季の吹送流

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要旨：冬季の東京湾において北風により発生する吹送流の特性を３次元数値モデルを用いて調べた．計算された水平的な流動が観測値をよく再現していることを確認した後，吹送流による鉛直流の特性を調べた．北風により表層で西向き，底層で東向きの流れが起こされるが，同時に表層で沖向き，底層で湾奥向きの鉛直循環流も起こっている．このような鉛直循環流に伴って励起される鉛直流は湾奥と湾口では，その海底傾斜の違いにより異なった特性を持つ．