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Three Dimensional Structure of Tidal Currents in Tokyo Bay, Japan*

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Abstract: Tides and tidal currents in Tokyo Bay are calculated by using a three dimensional numerical model, where vertical eddy viscosity coefficient is computed by the Prandtl's mixing length theory. The results well reproduce the two-dimensional structure of tides and tidal currents in Tokyo Bay, Japan. On the basis of these results, we calculate the vertical tidal current whose amplitude is smaller than 10^{-2}cm/s in the most places of Tokyo Bay. At the mouth of Tokyo Bay, where water depth varies rapidly, the amplitude of vertical tidal current attains to the order of 10^{-2}cm/s. The tidal stresses calculated in two ways, e.g. two dimensional and three dimensional methods, have no differences in principle in most places of Tokyo Bay.

1. Introduction

It is well known that the currents play an important role in the material transport processes and the tidal currents consist of the major parts of the movements of water in coastal seas. Because the tidal currents have some potential effects to the primary production, the structure of tidal currents, especially its three dimensional structure is worth to study.

The tides and tidal currents in Tokyo Bay have been studied by YAMADA (1971), UNOKI *et al.* (1980) and NAGASHIMA and OKADA (1984) based on the observed data. YANAGI and SHIMIZU (1993) calculated the two dimensional tidal currents as a part of the research on the sedimentation processes in Tokyo Bay.

It can be said that we have known the general characters of tides and tidal currents in Tokyo Bay. But as for the vertical tidal currents we have neither observed data nor calculated results about its order or the place where the vertical tidal current is large. And for the research of material transport processes, we need a basic three dimensional current field. For these purposes, we calculate the three-dimensional structure of tides and tidal currents in Tokyo Bay in this paper.

2. Model

2.1 Formulation

Based on the fact that tidal waves are gravitaional long-waves (by nature), the first order linear equations is:

$$\frac{\partial u}{\partial t}-fv=-g\frac{\partial \zeta}{\partial x}+\frac{\partial}{\partial z}\left(\nu\frac{\partial u}{\partial z}\right), \qquad (2\text{-}1\text{-}1)$$

$$\frac{\partial v}{\partial t}+fu=-g\frac{\partial \zeta}{\partial y}+\frac{\partial}{\partial z}\left(\nu\frac{\partial v}{\partial z}\right), \qquad (2\text{-}1\text{-}2)$$

$$\frac{\partial \zeta}{\partial t}+\frac{\partial}{\partial x}\int_{-h}^{0}udz+\frac{\partial}{\partial y}\int_{-h}^{0}vdz=0, \qquad (2\text{-}1\text{-}3)$$

where the continuity equation (2-1-3) has been integrated from the sea bed to the sea surface.

The boundry conditions are:

$$z=-0:\ \frac{\partial u}{\partial z}=\frac{\partial v}{\partial z}=0, \qquad (2\text{-}1\text{-}4)$$

$$z=-\mathrm{h}:\ u=v=w=0, \qquad (2\text{-}1\text{-}5)$$

along the shore boundary C_1:

$$\cos\alpha_x\int_{-h}^{0}udz+\cos\alpha_y\int_{-h}^{0}vdz=0, \qquad (2\text{-}1\text{-}6)$$

along the open boundary C_2:

$$\zeta=S. \qquad (2\text{-}1\text{-}7)$$

In the above, x, y, z constitute a Cartesian coordinate system at the right-hand side, the plane x, y coinsides with the undisturbed sea surface, and z is positive upward; t denotes the time; u, v denote the components of tidal currents in x,

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y directions, respectively, and w represents the vertical component; ζ is the elevation of the tide measured from the undisturbed sea surface; f is the Coriolis parameter ($=8.469\times10^{-5}\mathrm{sec}^{-1}$); ν is the coefficient of vertical eddy viscosity; g is the gravitational acceleration($=980\mathrm{cm/sec}^2$); S denotes the tidal elevation along the open boundary; h is the water depthe; $\cos\alpha_x$, $\cos\alpha_y$ denote the direction-cosines normal to the boundary.

Before calculation, we have to make a turbulence closure model to decide the value of ν. The simplest one is to take up the vertical eddy viscosity coefficients as a constant (Yanagi *et al.*, 1983; Fang and Ichiye, 1983) or a variable which can vary in the vertical direction according to a given function (Wang , 1989; 1992) or vary in horizontal direction by given different values at different horizontal positions (Yanagi and Igawa, 1993). But such ways include too many factors of mankind and usually fail to give a correct vertical profile of the tidal currents near the sea bed (Fang and Ichiye, 1983). If we use the high level turbulence closure models such as the first order model or second order model of turbulence described by Koutitas (1987), we must solve another one or two different equations of the turbulent kinetic energy or the rate of dissipation of the turblulent kinetic energy besides the above equations. Considering the boundary layer character of the coastal water (Yang, 1992) and reasonable time consumption in computer, we would like to choose the zero order turbulent model, that is the Prandtl's mixing length theory as our turbulence closure model. It will be shown that in our numerical schemes the Prandtl's mixing length theory will not cost much calculating time than the model where the vertical eddy viscosity coefficient is a constant and this model really improve the accuracy of calculated results. The another reason why we choose the Prandtl's mixing length theory is that two papers (Fang and Ichiye, 1983; Yang, 1992) show that the mixing length theory suits to the study of tides and tidal currents.

Using the same denotations as the above equations, we have

$$\nu=\nu_0+l^2\left[\left(\frac{\partial u}{\partial z}\right)^2+\left(\frac{\partial v}{\partial z}\right)^2\right]^{1/2} \quad (2\text{-}1\text{-}8)$$

the mixing length l is

$$l=\kappa_0(z+h+z_0)\left[1-\frac{z+h}{(1+s)h}\right] \quad (2\text{-}1\text{-}9)$$

Where κ_0 is the Karman constant approximately equal to 0.4, and z_0 is the sea bed roughness length, s is a parameter introduced by Fang and Ichiye (1983) which express the roughness of sea surface. ν_0 is a small number ($=2.0\mathrm{cm}^2/\mathrm{sec}$) which prevent the vertical eddy viscosity coefficient from equaling to zero.

2.2 Procedure

The above equations with the constant vertical eddy viscosity coefficient had been solved by means of the splitting velocity method (Sun, 1992) which was applied to tidal problem in Bohai Sea (Wang, 1989) or the East China Sea (Wang, 1992). In their calculations, the authors mainly follow the line of Hansen's boundary-value problem which need many observed data along the coatal line. Usually this is very difficult. By the thought that a correct tidal currents field could produce a correct tidal elevation, we would like to follow the idea of hydrodynamics numerical methods. Along this line, Yang (1992) has calculated the tide in Bohai Sea. In our paper, we made some improvements over his works and calcutated the tides in Tokyo Bay.

Here, we want to use the A.D.I method (Leendertse *et al.*, 1973), which had been proved as an effective and corrective method in coastal numerical calculations, to treat the time-depending differential terms in the above equation. In the first half time step, we have:

$$\frac{u^{n+1/2}-u^n}{0.5\Delta t}-fv^{n+1/2}=-g\left(\frac{\partial\zeta}{\partial x}\right)^{n+1/2}+\frac{\partial}{\partial z}\left(\nu\frac{\partial u^{n+1/2}}{\partial z}\right), \quad (2\text{-}2\text{-}1)$$

$$\frac{v^{n+1/2}-v^n}{0.5\Delta t}-fu^n=-g\left(\frac{\partial\zeta}{\partial y}\right)^n+\frac{\partial}{\partial z}\left(\nu\frac{\partial v^{n+1/2}}{\partial z}\right), \quad (2\text{-}2\text{-}2)$$

$$\frac{\zeta^{n+1/2}-\zeta^{n}}{0.5\ \Delta t}+\frac{\partial}{\partial x}\int_{-h}^{0}u^{n+1/2}dz$$
$$+\frac{\partial}{\partial y}\int_{-h}^{0}v^{n+1/2}dz=0, \qquad (2\text{-}2\text{-}3)$$

In the second half time step, we have:

$$\frac{u^{n+1}-u^{n+1/2}}{0.5\Delta t}-fv^{n+1/2}=-g\left(\frac{\partial\zeta}{\partial x}\right)^{n+1/2}$$
$$+\frac{\partial}{\partial z}\left(\nu\frac{\partial u^{n+1}}{\partial z}\right), \qquad (2\text{-}2\text{-}4)$$

$$\frac{v^{n+1}-v^{n+1/2}}{0.5\Delta t}-fu^{n+1}=-g\left(\frac{\partial\zeta}{\partial y}\right)^{n+1}$$
$$+\frac{\partial}{\partial z}\left(\nu\frac{\partial v^{n+1}}{\partial z}\right), \qquad (2\text{-}2\text{-}5)$$

$$\frac{\zeta^{n+1}-\zeta^{n+1/2}}{0.5\Delta t}+\frac{\partial}{\partial x}\int_{-h}^{0}u^{n+1}dz$$
$$+\frac{\partial}{\partial y}\int_{-h}^{0}v^{n+1}dz=0, \qquad (2\text{-}2\text{-}6)$$

By this way, in each time step we only need to solve a triangle matrix which can be easily done by the Thomas algorithm (ROACHE, 1976).

Other than the finite-difference of the space-depending terms directly, we would like to split the horizontal velocities in advance as follows:

in the first half time step,

$$u^{n+1/2}=g\left(\frac{\partial\zeta}{\partial x}\right)^{n+1/2}Pe^{n+1/2}+Pv^{n+1/2}, \qquad (2\text{-}2\text{-}7)$$

$$v^{n+1/2}=g\left(\frac{\partial\zeta}{\partial y}\right)^{n}Ge^{n+1/2}+Gv^{n+1/2}; \qquad (2\text{-}2\text{-}8)$$

in the second half time step,

$$u^{n+1}=g\left(\frac{\partial\zeta}{\partial y}\right)^{n+1/2}Pe^{n+1}+Pv^{n+1}, \qquad (2\text{-}2\text{-}9)$$

$$v^{n+1}=g\left(\frac{\partial\zeta}{\partial y}\right)^{n+1}Ge^{n+1}+Gv^{n+1}. \qquad (2\text{-}2\text{-}10)$$

By this way, we separate the velocity into two parts, in which one is connected to the gradient of tidal elevation and another one is connected to other force such as the Coriolis force. This method had been successfully used in many aspects of coastal calculations such as storm surge, tide and circulations (SUN, 1992) and were called as the velocity splitting method in China.

Here Pe, Pv, Ge, Gv represent the vertical profile functions of the tidal currents respectively and superscripts n, $n+1/2$, $n+1$ represent different time levels. Substitute (2-2-7) and (2-2-8)into the momentum equations (2-2-1) and (2-2-2)in the first half time step or substitute (2-2-9)and (2-2-10) into the momentum equations(2-2-4) and (2-2-5) in the second half time step, we can get a series of one dimensional differential equations about the vertical profile functions Pe, Pv, Ge, Gv as follows:

$$\frac{\partial}{\partial z}\left(\nu\frac{\partial F}{\partial z}\right)-\frac{2}{\Delta t}F=\mathrm{B}, \qquad (2\text{-}2\text{-}11)$$
$$z=0:\ \frac{\partial F}{\partial z}=0,$$
$$z=-h:\ F=0,$$

where as $\mathrm{F}=Pe^{n+1/2}$, $Ge^{n+1/2}$, Pe^{n+1}, or Ge^{n+1}, $\mathrm{B}=1$;

as $F=Pv^{n+1/2}$, $\mathrm{B}=-fv^{n+1/2}-\frac{2}{\Delta t}u^{n}$;

as $F=Gv^{n+1/2}$, $\mathrm{B}=fu^{n}-\frac{2}{\Delta t}v^{n}$;

as $F=Pv^{n+1}$, $\mathrm{B}=-fv^{n+1/2}-\frac{2}{\Delta t}u^{n+1/2}$;

as $F=Gv^{n+1}$, $\mathrm{B}=fu^{n+1}-\frac{2}{\Delta t}v^{n+1/2}$.

This equation is just a one-dimensional differential equation which can be solved by many methods (SUN, 1992). If we have some interests about the profile of tidal currents near the sea bed, we can use the logarithm coordinate transfer in the vertical direction such as FANG and ICHIYE (1983). Here, we just use the general methods to solve these equations in which we replace the unknown vertical eddy viscosity coefficient by using the upper time level's value. If we take the vertical eddy viscosity coefficient as a constant, we will need not calculate it and even can get the analytical solotuin about Pe and Ge. In fact, apart from the calculation of the vertical eddy viscosity coefficient in each time step, there is no difference between the Prandtl's mixing length theory and constant vertical eddy viscosity coefficient model in our numerical model.

As for the water elevations, we can substitute (2-2-7) and (2-2-8) into the continuity equations (2-2-3) in the first half time step or substitute (2-2-9) and (2-2-10) into the continuity equations (2-2-6) in the second half time step and get a two dimensional differential equation only about the water elevations as follow:

in the first half time step,

$$A_{i-1,j}\zeta_{i-1,j} + B_{i,j}\zeta_{i,j} + C_{i+1,j}\zeta_{i+1,j} = T_{i,j} \qquad (2\text{-}2\text{-}12);$$

in the second half time step,

$$D_{i,j-1}\zeta_{i,j-1} + E_{i,j}\zeta_{i,j} + F_{i,j+1}\zeta_{i,j+1} = S_{i,j} \qquad (2\text{-}2\text{-}13);$$

where the coefficients of these algorithm equations are the integrated values of Pe, Ge, Pv and Gv from the sea bed to the sea surface. By the Thomas Algorithm, we can solve these algorithm equations just on the lines parallel to X-axis in the firt half time step and on the lines parallel to Y-axis in the second half time step.

The process in which we solve the equations is that at first, we solve $Ge^{n+1/2}$, $Gv^{n+1/2}$ and we can get the value of $v^{n+1/2}$, according to (2-2-8). After this step, we solve the $Pe^{n+1/2}$, $Pv^{n+1/2}$, and substitute these values into the tidal elevation equation (2-2-12) to get the values of $\zeta^{n+1/2}$. Then we can get the value of $u^{n+1/2}$ according to (2-2-7). At the second half time step, we make some changes on the order of the solving processes and almost repeat the same procedure as that at the first half time step.

By this way, it can be known that instead of solving a three dimensional tidal problem, we may solve a two dimensional finite-difference equation and a series of one dimensional differential equation at each horizontal point. And also, if we need, we can get a detail vertical profiles of the tidal currents without too much increase of calculating time.

3. Results

The size of horizontal mesh is 1km in X-direction and Y-direction and we divide the water depth into 10 layers. The time step is 45 seconds which is 2.8 times longer than Courant-Friedrichs-Lewy condition. The sea bed roughness length z_0 is taken as 0.04 cm according to MATSUMOTO (1983) and SOULSBY (1983). The parameter of s is taken as 0.1 according to FANG and ICHIYE (1983). The whole time of calculation is four tidal periods.

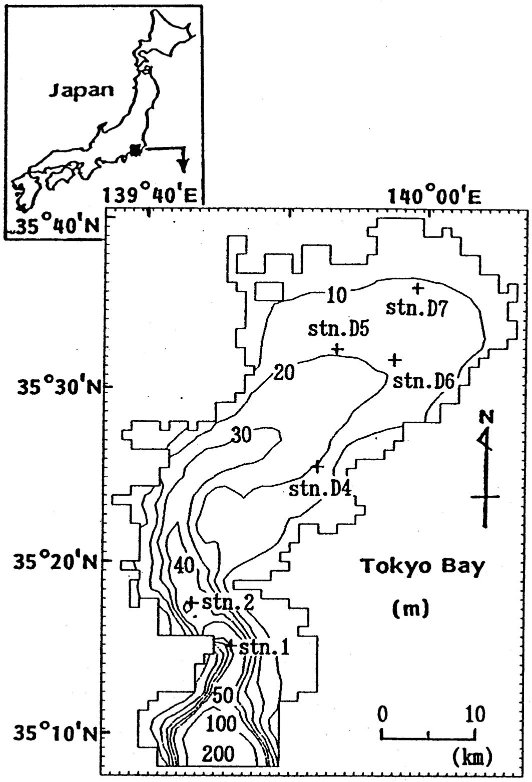
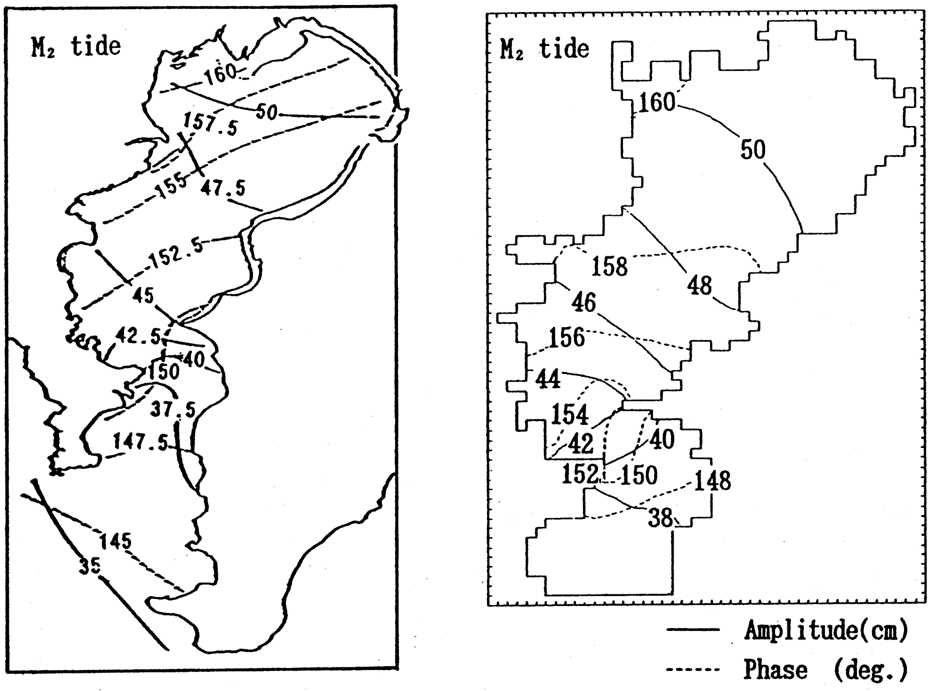


Fig. 1. Water depth in Tokyo Bay.

Figure 1 is the contour line of water depth of Tokyo Bay which is produced by the water depth data used in calculation.

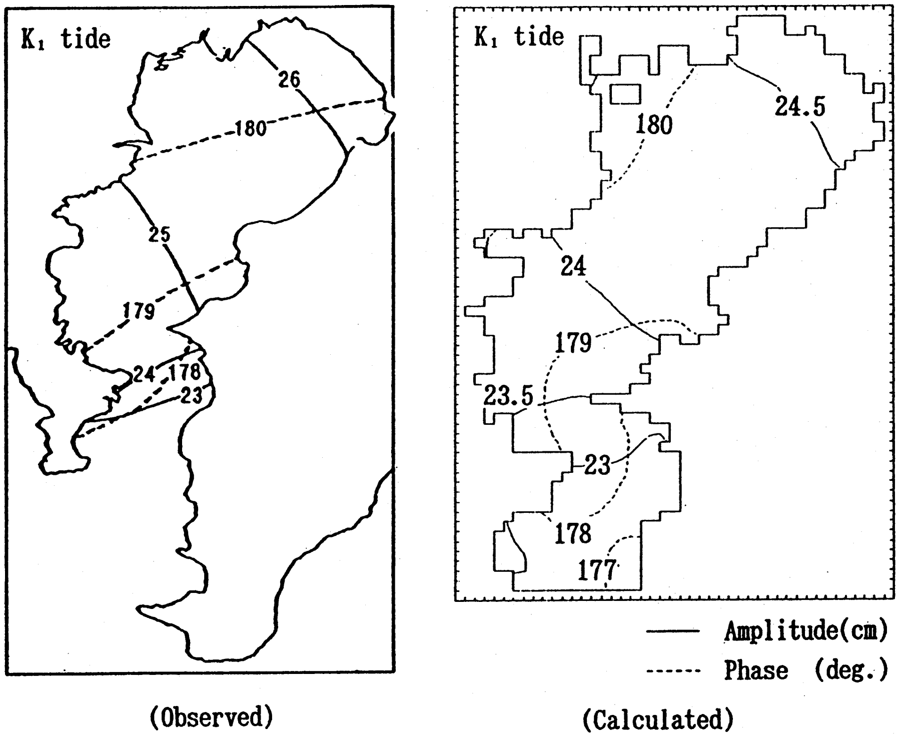
The observed and calculated co-range and co-tidal charts of M_2 and K_1 are drawn in Figs. 2 and 3, respectively. As for the M_2 tide, the calculated amplitudes agree to the observation very well but the phases have some difference with the observation. This may be brought by the no slip condition at the sea bed which lead to a large velocity gradient near the sea bed in the vertical direction and then lead to a large sea bed friction. From Fig. 3, it can be seen clearly that the calculated phases of K_1 tide are nearly the same as the observed ones, but in the head of the bay the calculated amplitudes are smaller than the observed ones. We guess that the less increase of the tidal elevation may be brought by the large dissipation of the kinetic energy caused by the large vertical eddy viscosity coefficient.

The M_2 tidal current ellipses in Tokyo Bay



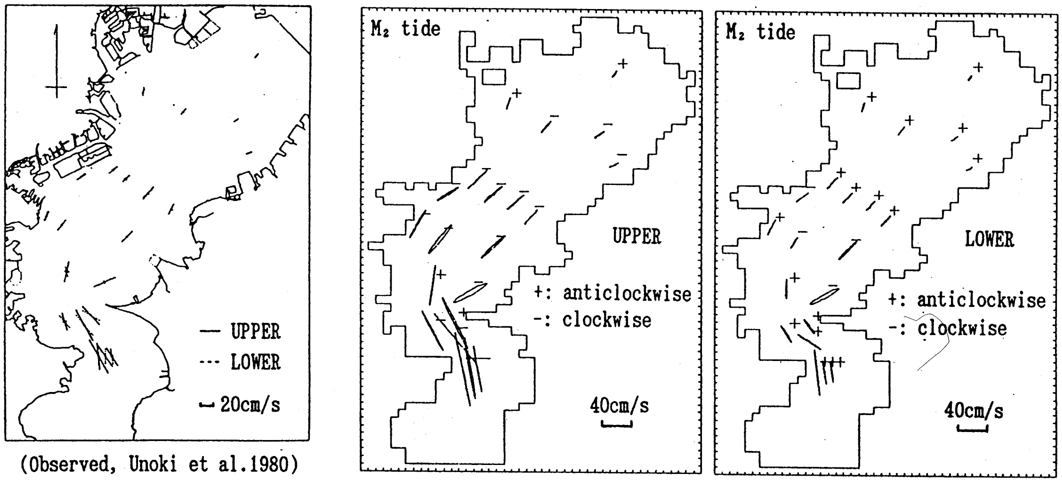
(Observed) (Calculated)

Fig. 2. Observed and calculated co-range and co-tidal chart of M_2 tide.



(Observed) (Calculated)

Fig. 3. Observed and calculated co-range and co-tidal chart of K_1 tide.



(Observed, Unoki et al.1980)

(Calculated)

Fig. 4. Horizontal distribution of observed and calculated M_2 tidal current ellipses.

have been drawn by UNOKI *et al.* (1980). Here we reprint their chart of tidal current ellipses in winter season, and draw the calculated M_2 tidal current ellipses at the same points in Fig.4 where "upper" represents the results at the depth of 3 meters below the sea surface and "lower" represents the results at the 5 meters over the sea bed. By this way we can know that the calculated horizontal distribution of M_2 tidal current ellipses are similar to the observed results. Noticing the characters of the rotation direction of M_2 tidal current ellipses, we can find easily that the rotation direction varies from clockwise in the upper layer to the anticlockwise in the lower layer or keeps anticlockwise from the upper layer to the lower layer in the most part of Tokyo Bay. This character is the same as the conclusion of NAGASHIMA and OKADA (1984).

Figure 5 is the vertical distribution on M_2 tidal current ellipses at the points shown in Fig. 1. The left ones is the observed results (reprinted from the book of *Tokyo Bay*, ed. by OGURA, 1993) and the right ones is the calculated results. From this figure we can see that apart from the rotation direction of the tidal currents, the calculated tidal currents are nearly the same as the observed ones. In fact, we can not know the rotation direction of the observed tidal currents from the observed tidal currents ellipses, so we can not say anything about this point.

The amplitude and phase of calculated M_2 and K_1 tidal currents at the depth of 10 meters are shown in Fig. 6 which show that the amplitude of M_2 tidal currents is 30–40 cm/s at the mouth of Tokyo Bay, 15 cm/s in the central part of the bay and 5–10 cm/s in the head of the bay. This result is the same as the observed ones (UNOKI *et al.*, 1980). From Fig. 6, we can also know that the tidal currents along the west coast are stronger than those along the east coast of Tokyo Bay. This phenomenon had been found by YAMADA (1970). The phase distribution of M_2 and K_1 tidal currents show that the shallower the water depth is, the earlier the turn of tidal current is.

After the above comparisions, it can be said that we have well reproduced the tides and tidal currents in Tokyo Bay by a three dimensional scheme.

The vertical component of tidal currents have been thought to have some potential effects on the primary production in the coastal sea. It is valueable for us to calculate the vertical component of tidal currents in Tokyo Bay. The formula used in the calculation of w is

$$w|_z = -\int_{-h}^{z} \frac{\partial u}{\partial x}\, dz' - \int_{-h}^{z} \frac{\partial v}{\partial y}\, dz' \tag{3-1}$$

Figure 7 is the calculated amplitude of the

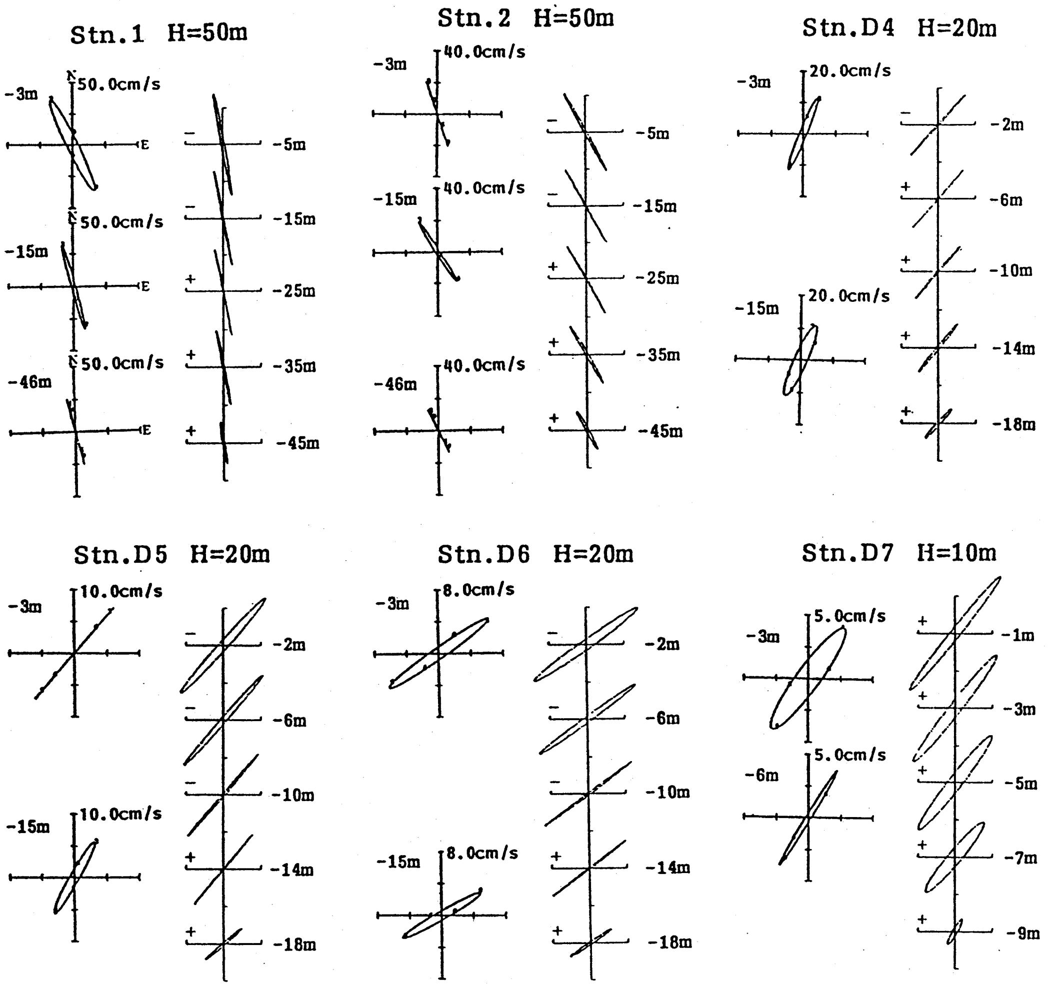


Fig. 5. Vertical distribution of observed (left) and calculated (right) tidal current ellipses at 6 points shown in Fig.1

vertical tidal currents. From this figure, we can know that the order of vertical tidal current in most of Tokyo Bay is smaller than 10^{-2}cm/s. In the region such as the mouth of the bay where the water depth varies rapidly, the vertical tidal current can get the order of 10^{-2}cm/s. If we divide the speed of horizontal tidal currents to that of vertical tidal current, we can know the ratio is about 10^3. This order is the same as the aspect ratio of the horizontal length scale of Tokyo Bay, 60km, to the characteristic depth of Tokyo Bay, 20 m, which is usually used to estimate the order of the vertical tidal currents.

4. Discussion

It is a difficult point to decide the values of the vertical eddy viscosity coefficient in the numerical calculation of coastal oceanography. In our calculation, we take the vertical eddy viscosity coefficient as a constant (50 cm^2/s) at first and get the co-range and co-tidal chart of M_2 tide as shown in Fig. 8 which could be said having the same distributing tendency as the observed ones. But as trying other constants such as 10 cm^2/s or 100 cm^2/s, we got some little different results from Fig.8. This suggests that we have to choose a high level turbulence closure model such as the Prandtl's mixing length theory to enclose our turbulent model.

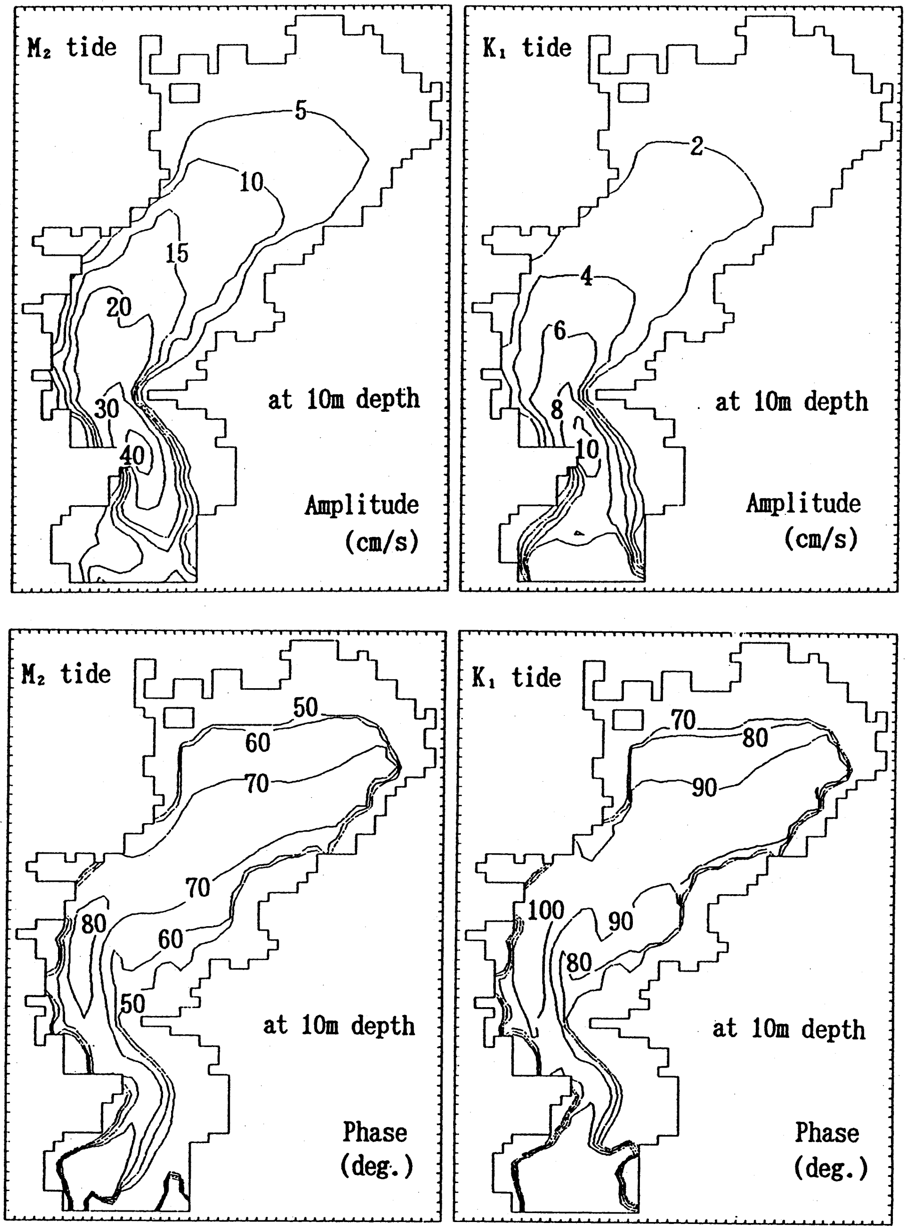


Fig. 6. Horizontal distribution of the amplitude and phase of horizontal M_2 and K_1 tidal currents at the depth of 10 meters.

Here we show the horizontal distribution of calculated $\langle v \rangle$ at the depth of 10 meters in Fig.9 and the vertical distribution of calculated $\langle \nu \rangle$ for M_2 tide at one point with the depth of 29 meters in Fig. 10 whose horizontal position is expressed by "+" in Fig. 9. Here $\langle\ \rangle$ expressed the average over one tidal period. On the fact that we have well reproduced the tides and tidal currents in Tokyo Bay, we think that the value of $\langle v \rangle$ calculated by the Prandtl's mixing length theory can be accepted although these values are larger than the general concept. In fact the order of 10 cm/s has been used for many times (WANG, 1989, 1992) and the result of

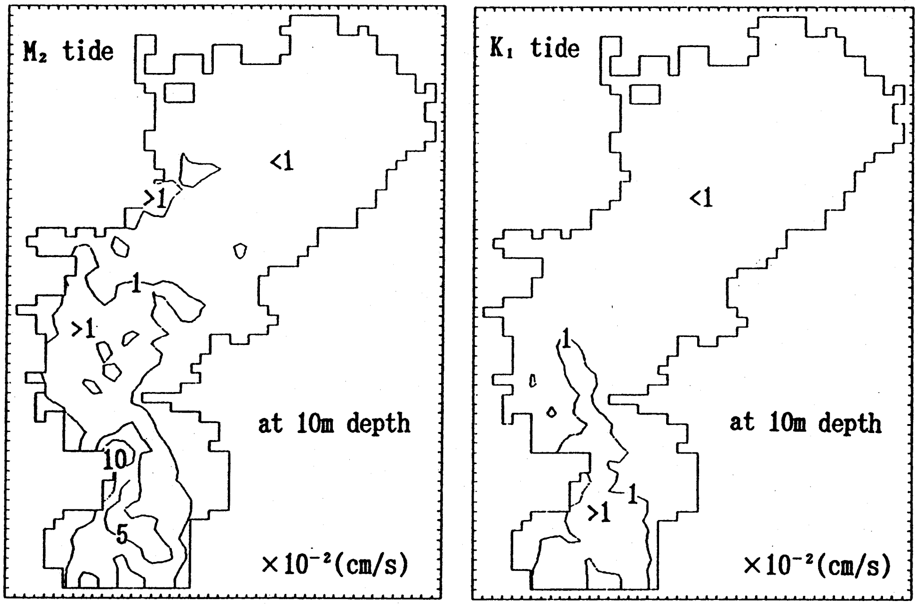
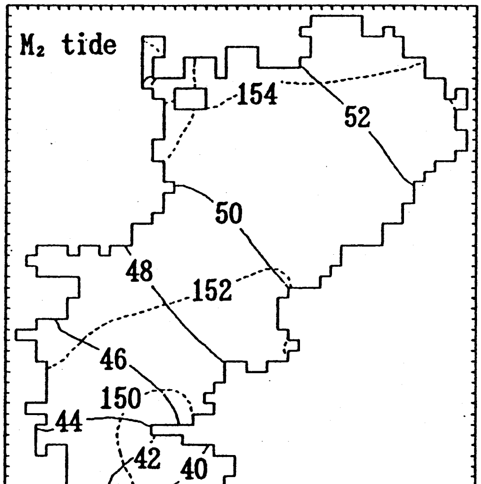


Fig. 7. Horizontal distribution of the amplitude of M_2 and K_1 vertical tidal currents at the depth of 10 meters.

FANG and ICHIYE (1983) has also been this order. From Fig. 9, we can see that at the mouth of bay where the tidal currents and water depth vary rapidly the value of $\langle v \rangle$ is large. From Fig.10, we can see that below the middle layer of the whole water depth, the $\langle v \rangle$ take its maximal value and the distribution curve from the sea bed to the sea surface approach a parabola which is similar to the experimental result reported by SUMI (1991). In fact, this form is also usually used in three dimensional coastal ocean models (NIHOUL, 1977; TEE, 1979). From this chart, we can also see that because the number of mesh points in vertical deirection is just 10, there is a little anomalous near the sea bed.

It is well known that the tide-induced residual current, which has important effects on the material transports processes in the coastal sea, is produced by the nonlinear effects of the tidal current. The tidal stress has been accepted as a force which have the same effects to the sea water as the wind or the buoyancy (NIHOUL and RONDAY, 1975; YANAGI, 1989). In a two dimensional tidal model, the tidal stress is calculated by:



(Calculated)

Fig. 8. Calculated co-range and co-tidal of M_2 tide as $v=50cm^2/s$.

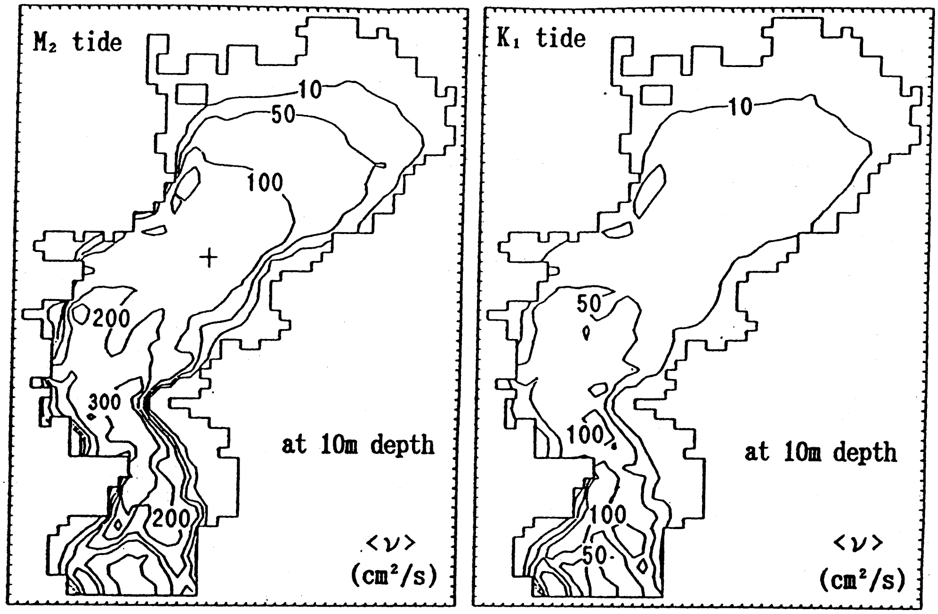


Fig. 9. Calculated horizontal distribution of $\langle \nu \rangle$ at the depth of 10 meters.

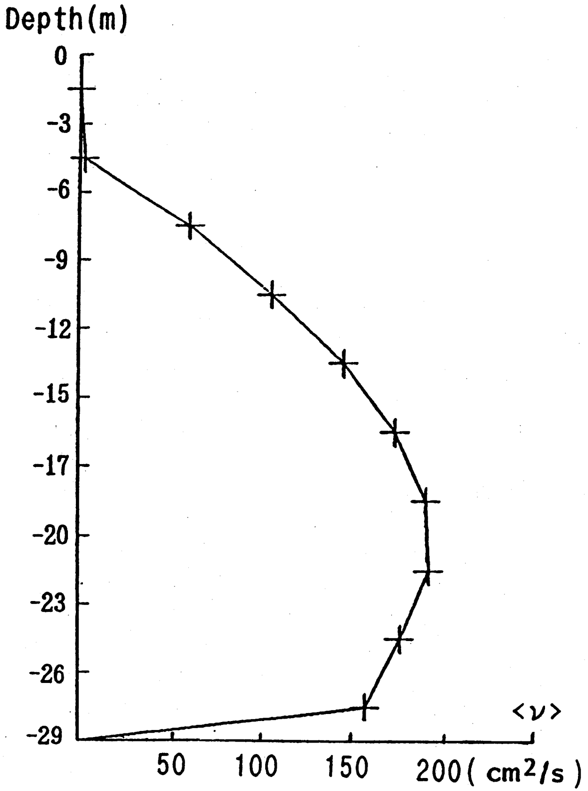


Fig. 10. Vertical distribution of $\langle \nu \rangle$ for M_2 tide at the central part of Tokyo Bay calculated by Prandtl's mixing length theory.

$$S_x = \left\langle \tilde{u}\frac{\partial \tilde{u}}{\partial x} + \tilde{v}\frac{\partial \tilde{u}}{\partial y} \right\rangle \qquad (4\text{-}1)$$

$$S_y = \left\langle \tilde{u}\frac{\partial \tilde{v}}{\partial x} + \tilde{v}\frac{\partial \tilde{v}}{\partial y} \right\rangle \qquad (4\text{-}2)$$

where $\tilde{u}$, $\tilde{v}$ represent the water depth averaged velocity, $\langle\ \rangle$ represent the average over one-tidal cycle. In a three dimensional tidal model, the tidal stress is

$$S_x = \left\langle u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} \right\rangle \qquad (4\text{-}3)$$

$$S_y = \left\langle u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} \right\rangle \qquad (4\text{-}4)$$

As these two ways are usually used in the calculation of tidal stress, we would like to check the difference between these two ways. Figure 11 is the results we get by these two ways in which "2-D" represents the results calculated by formula (4-1) and (4-2), "3-D" represents the results at the depth of 10 meters calculated by formula (4-3) and (4-4), "3-D'" represents the results at the same depth calculated by the first two terms in formula (4-3) and (4-4). From these results we can know that the difference between 2-D and 3-D models is very small in most parts of Tokyo Bay. The contribution coming

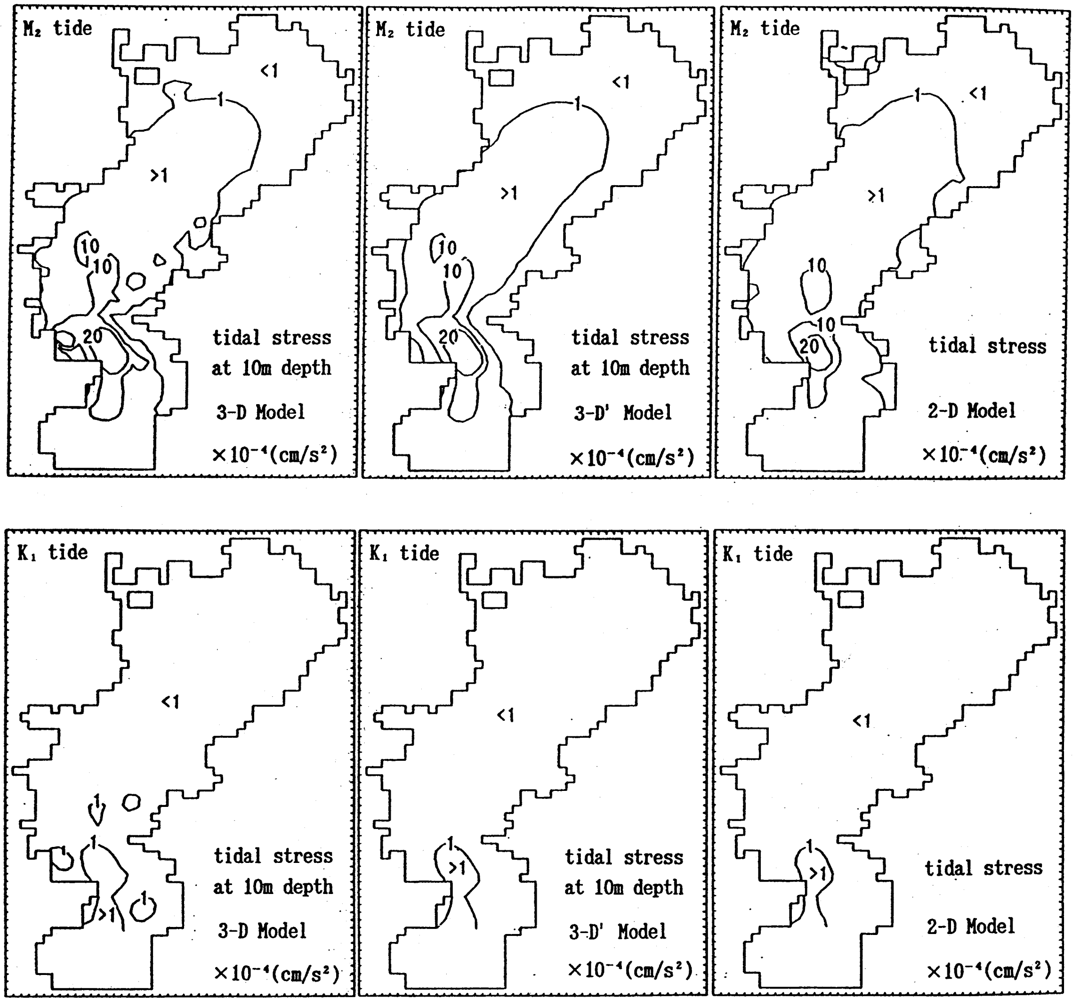


Fig. 11. Tidal stress produced by M_2 and K_1 tidal currents.

from the last term of formula (4-3) and (4-4) is also small in most parts of Tokyo Bay. By comparing to the tidal stress in Osaka Bay (YANAGI and TAKAHASHI, 1995), we can also know that the tidal stress in Tokyo Bay is smaller than that in Osaka Bay by one or two orders. On the other hand, it is clear that we can ignore the contribution of K_1 tidal currents when we calculate the tide-induced residual currents in Tokyo Bay.

5. Conclusion

(1) The tides and tidal currents in Tokyo Bay calculated by a three dimensional model well reproduce the observed ones. The vertical eddy viscosity coefficient has a great influence on the accuracy of calculated results.

(2) The vertical tidal current is smaller than 10^{-2}cm/s in most parts of Tokyo Bay. In the places such as the mouth of Tokyo Bay, where the water depth varies rapidly, the vertical tidal current can attain to the order of 10^{-2}cm/s.

(3) The tidal stress calculated by two dimensional model and three dimensional model have no difference in principle in most parts of Tokyo Bay. The tidal stress caused by M_2 tide in Tokyo Bay suggests that the tide-induced residual current is large near the bay mouth but small in most parts of Tokyo Bay. The tide-induced residual current caused by K_1 tide can be ignored in Tokyo Bay.

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Refferences

Coastal Oceanography Research Committee, the Oceanographical Society of Japan (ed.) (1985): Coastal Oceanography of Japanese Islands. Tokai Univ. Press, Tokyo, 1106pp.

FANG, G. and T. ICHIYE (1983): On the vertical structure of tidal currents in a homogeneous sea. Geophys. J. Roy. Astr. Soc., **73**, 65–82.

FENG, S.(1977): A three dimensional nonlinear model of tides. Scientia Sinica, **20**, 436–446.

KOUTITAS, C. (1987): Three dimensional models of coastal circulation: An engineering viewpoint. *In*, Three Dimensional Coastal Ocean Models (Coastal and Estuarine Sciences 4), p.107–124, HEAPS, N.S.(ed.), American Geophysical Union, Washington.

LEENDERTSE, J.J., R.C. ALEXANDER and S.K. LIU (1973): A three dimensional model for estuaries and coastal seas, Vol. 1, Principle of computation. The Rand Corporation, R-1477-OWRR, 57pp.

MATSUMOTO, E. (1983): Sediment environments in Tokyo Bay. Geochemics, **17**, 27–32(in Japanese).

NAGASHIMA, H. and K. OKADA (1984): The tidal currents in Tokyo Bay-its vertical distribution. Abstract in the spring meeting of the Oceanographical Society of Japan, 118–119 (in Japanese).

NIHOUL, J.C.J. and R.C. RONDAY (1975): The influence of the tidal stress on the residual circulation. Tellus, **27**, 484–489.

NIHOUL, J.C.J. (1977): Three-dimensional model of tides and storm surges in a shallow well-mixed continetal sea. Dyn. Atmos. Ocean, **2**, 29–47.

OGURA, N.(ed.)(1993): Tokyo Bay, Koseisha Koseikaku, Tokyo, 193pp.

ROACHE, P.J. (1976): Computational Fluid Dynamics, Hermosa, Albuquerque, 446pp.

SOULSBY, R.L. (1983): The bottom boundary layer of shelf seas. *In*, Physical Oceanography of Coastal and Shelf Seas, p.189-266, JOHNS, B.(ed.), Elsevier, Amsterdam.

SUMI, K. (1991): The turbulent structure in the bottom boundary layer on the shallow sea. 38th Proceedings on the Ocean Engineering, 176–180 (in Japanese).

SUN, W. (1992): A numerical method in three dimensional shallow sea hydrodynamics-the velocity splitting method. *In*: Numerical Calculation in Physical Oceanography, p.100–195, FENG, S. and W. SUN (ed.), Henan Scientific Press, Luoyang, China(in Chinese).

TEE, K.T. (1979): The structure of three-dimensional tide-generating currents, Part I : Oscillating currents. J. Phys. Oceanogr. **9**, 930–944.

UNOKI, S., M. OKAZAKIand H. NAGASHIMA (1983): The circulation and hydrographic conditions in Tokyo Bay. Tech. Rep. No.4, Inst. of Phys. and Chem. Res., Japan, 262pp.(in Japanese).

WANG, H. (1989): Numerical calculation of the wind-driven, thermocline and tide-induced Lagrangian residual current in Bohai sea. MS. thesis, Ocean Univ. of Qigdao Press, Qindao, China, 52pp. (in Chinese).

WANG, H. (1992): On the research of shelf circulation and transport processes. Ph. D. thesis, Ocean Univ. of Qindao Press, Qindao, China, 300pp. (in Chinese).

YAMADA, T. (1971): The tidal current in Tokyo Bay. Report of hydrographic Department, Japan, **91**, 85–90 (in Japanese).

YANAGI, T., M. Nishii and H. Higuchi (1983): The vertical structure of tidal ellipse. 30th proceeding on the Ocean Engineering, 495-499 (in Japanese).

YANAGI, T. (1989): Coastal Oceanography. Koseisha-Koseikaku, Tokyo, 154pp.(in Japanese).

YANAGI, T. and M. SHIMIZU (1993): Sedimentation processes in Tokyo Bay, Japan. La mer, **31**, 91–101.

YANAGI, T. and S. IGAWA (1993): Diagnostic numerical model of residual flow in the coastal sea-an example of adaption to Suo-Nada and Iyo-Nada. Bull. Coast. Oceanogr., **30**, 12–19(in Japanese).

YANAGI, T. and S. TAKAHASHI (in press): Variability of the residual flow in Osaka Bay, Japan. Memoir of Dept. Engineering, Ehime Univ.

YANG, Z. (1992): On the theoretical and numerical models of shallow water circulation and mass transport processes. Ph. D. thesis, Ocean Univ. of Qindao Press, Qindao, China, 150pp.(in Chinese).

東京湾の潮流の3次元構造

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要旨：三次元数値モデルを使って，東京湾の潮汐と潮流を計算した。鉛直渦動粘性係数は Prandtl's 混合距離論によって求めた。計算の結果は東京湾の潮汐と潮流の水平二次元構造をよく再現した。これらの結果をもとに潮流の鉛直成分を計算した。東京湾の大部分の所では潮流の鉛直成分の振幅は 10^{-2}cm/s より小さいが，湾口のような水深の変化が激しい所では 10^{-2}cm/s を越えることがある。三次元モデルと二次元モデルにより計算した潮汐応力を比べると，東京湾の大部分の所では両者に本質的な差がないということが分かる。