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On the Circulation in the Jinhae Bay using the Princeton Ocean Model
I. Characteristic in Vertical Tidal Motion

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Circulation in the Jinhae Bay in the southern sea of Korea is examined using the Princeton Ocean Model (POM) with a free surface in a sigma coordinate, governed by primitive equations. The model well corresponds to the time series of the observed velocities at several layers obtained from a long-term mooring observation. In the residual velocity field of the model, persistent downward flow fields are formed along the central deep regions in the bay, and they are caused by bottom topographic effect. In addition, a comparison between a depth-averaged (2D) model and the POM is given, and a dependance of the results on bottom drag coefficient is also examined.

Key words: POM, Jinhae Bay, residual current, vertical motion, downwelling, bottom drag coefficient.

Introduction

Since 1980's the Jinhae Bay which is located at the southeastern sea of Korea (Fig. 1) has been noted due to abnormal conditions of sea water, such as red tide which has frequently occurred in the bay every year. This phenomenon may be primarily related to the circulation as well as ecological factors in the bay. A generation of red tide by its cyst which was buried at the bottom in the Jinhae Bay during winter (Kim, 1998) probably would be locally related to vertical flow in the bay. In the coastal ocean the vertical tidal motion has been nearly neglected due to dominant barotropic charateristic of tide but it is recently becoming important. According to Yanagi et al. (1997), vertical tidal flux plays important role in transporting suspended matter outward of the Tokyo Bay. The verification by the observation was also attempted (Noriki et al., 1997). Fujiwara (1997) reported that upward velocity in the esturarine circulation is a crucial factor to decide primary production or ecosystem. These studies indicate that vertical tidal motion may play important role in vertically transporting suspended or nutrient matter in a bay. In the Jinhae Bay, however, it seems that there are few studies concerned with the vertical motion.

Recently, Cho et al. (1998) observed the velocity field at the Jinhae Bay (St. J; see Fig. 1) using ADCP in the period of November 15 to December 3 in 1997, and presented the time series of the velocity at several layers as shown in Fig. 2. In this figure we can see that semi-diurnal tidal components are predominant in this period. In the upper layer (3 m depth) velocities are roughly ranged from 5 to 10 cm/s, though they are different in accordance with the tidal periods. As the depth deepens they decrease, and are reduced to the range from 2 to 5 cm/s in the lower layer (11 m depth). The main current is directed toward the northwest-southeast axis. Except for the periods of November 20 to 24 southward currents generally tend to be strong, and they seem to be largely related to wind in this period (Cho et al., 1998). This will be discussed at section 3.

The topographic configuration should influence the circulation in the Jinhae Bay which has three waterways; north and south of Kadokdo, and Kyeneryang. Most of the part (about 90 %) is exchanged through south of Kadokdo (Kim, 1984). Thus, the Jinhae Bay may be almost regarded as a semi-enclosed bay. It is noted that the bottom topography is roughly composed of being deeper over about 15 m depth along the central of the bay from Kadok waterway (see Fig. 1). A vertical motion of sea water in the bay will be discussed

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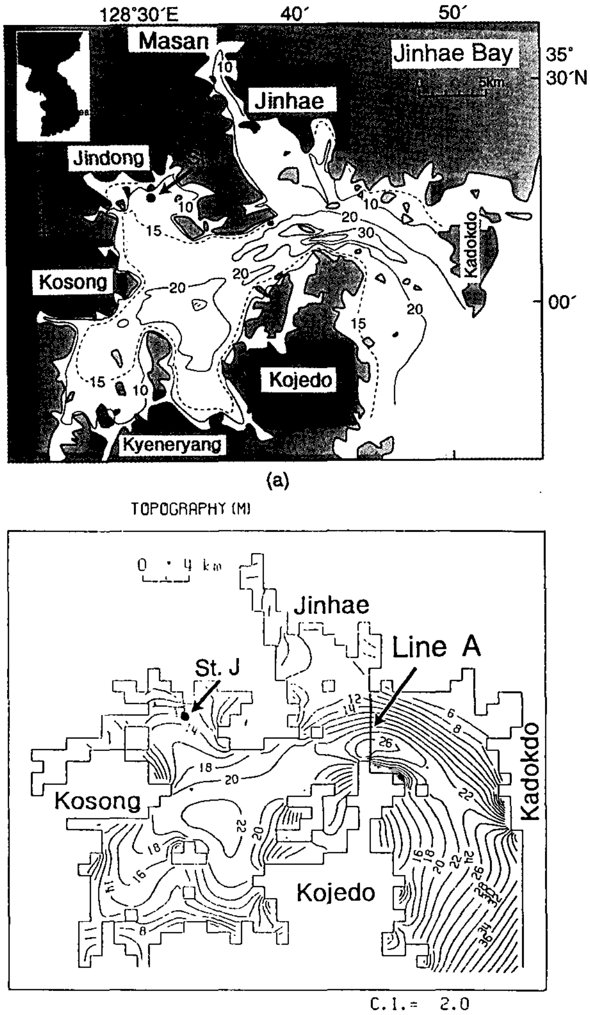


Fig. 1. The Jinhae Bay a). A long-term mooring observation was carried out at St. J. b) The model bathmetric map. Depths are in meter. The contour intervals are 2 m. Shown are vertical sections of variables along Line A.

later in accordance with this bottom topography (see Section 3).

Since the past decades, many numerical studies of the circulation in the Jinhae Bay have been conducted using depth-averaged (2D) models (KORDI, 1983; Kim, 1994, Kwoun, 1996). Three-dimensional (3D) models have been also employed; Kim et al. (1989) first attempted to apply 3D model to the Jinhae Bay; Kim (1994) investigated the effect of wind on tidal current in the bay; Bae (1997) examined the tidal current involving a baroclinic effect. However, most of their models seem to be too simply explained for the open boundary condition to understand how to calculate the variables in the open boundary, and also were not verified by vertically observed velocity field.

In this paper the circulation of the Jinhae Bay is examined using the Princeton Ocean Model (POM) which recently is widely used by many coastal oceanographers, and is focused on the vertical tidal motion. The numerical results are compared by the observation obtained by Cho et al. (1998) as mentioned above. Additionally, a comparison between a 2D model and the POM is given and discussed in relation with bottom friction effect.

Numerical Model

The model used here is the Princeton Ocean Model (POM), which is described in detail by Blumberg and Mellor (1987). It has been applied to coastal and estuarine oceanography (Blumberg and Mellor, 1983; Galperin and Mellor, 1990a, b; Oey et al. 1985a, b, c), the Gulf Stream (Mellor and Ezer 1991), and many other oceanic regions. A description of the model code can be found in Mellor (1996). The model configurations in the present study are basically similar to Hong et al. (1997) who studied a tidal circulation in the Deukryang Bay using the POM. It has a free surface in the sigma-coordinate, a split mode time step, and solves the following equations:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \qquad \cdots\cdots (1)$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}-fv= -\rho_0^{-1}\frac{\partial p}{\partial x}+\frac{\partial}{\partial z}\left(K_M\frac{\partial u}{\partial z}\right)+F^x \qquad \cdots\cdots (2)$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+u\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}+fu= -\rho_0^{-1}\frac{\partial p}{\partial y}+\frac{\partial}{\partial z}\left(K_M\frac{\partial v}{\partial z}\right)+F^y \qquad \cdots\cdots (3)$$

$$\rho g=-\frac{\partial p}{\partial z} \qquad \cdots\cdots (4)$$

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}= \frac{\partial}{\partial z}\left(K_H\frac{\partial T}{\partial z}\right)+F^T \qquad \cdots\cdots (5)$$

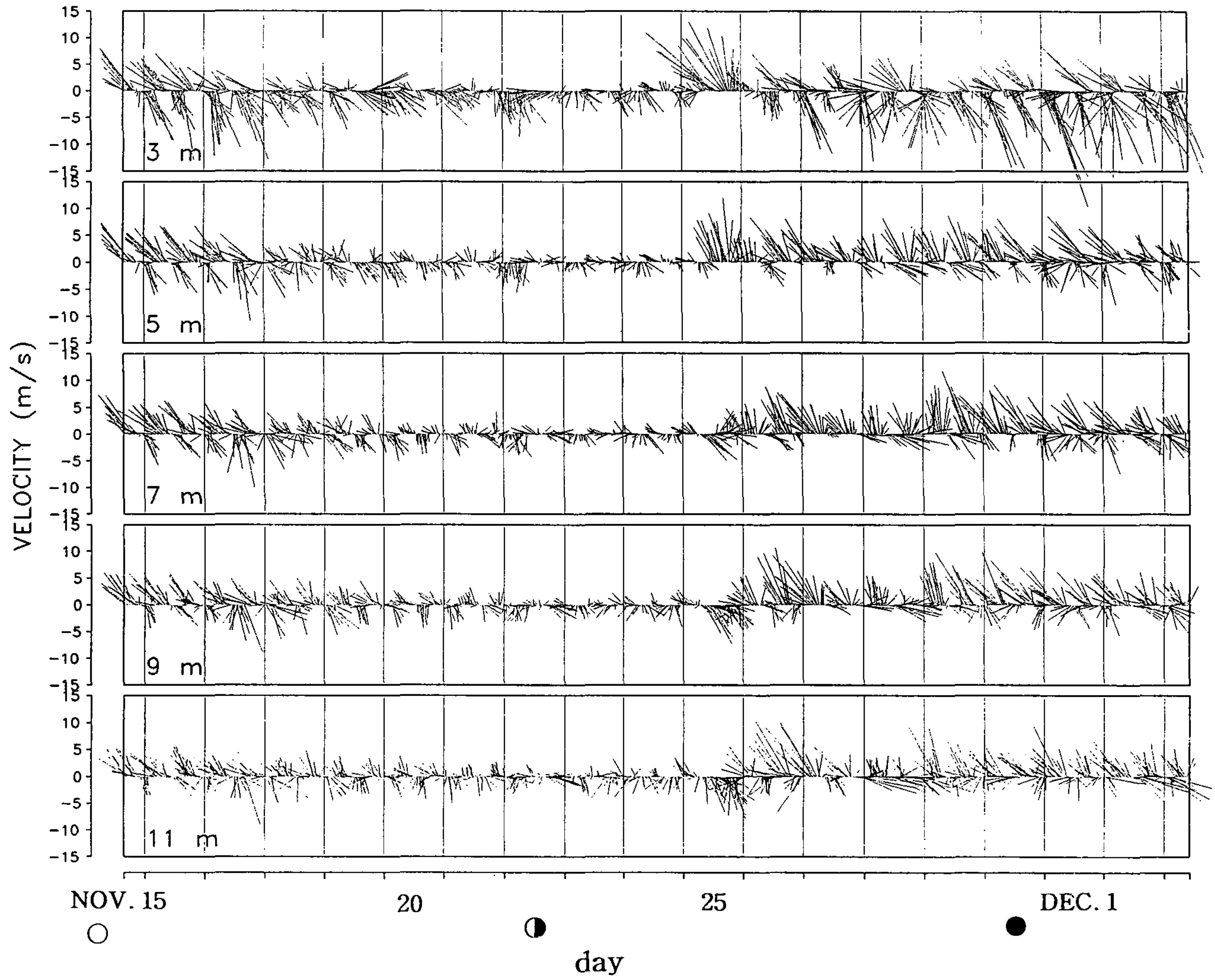


Fig. 2. Observed time series of the velocity (cm/s) at several layers at St. J of the Jinhae Bay using ADCP in a long-term mooring system obtained by Cho et al. (1998)

$$\frac{\partial S}{\partial t}+u\frac{\partial S}{\partial x}+v\frac{\partial S}{\partial y}+w\frac{\partial S}{\partial z}=\frac{\partial}{\partial z}\left(K_H\frac{\partial S}{\partial z}\right)+F^S \quad \cdots\cdots\cdots\cdots (6)$$

$$\rho=\rho\,(T,S). \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots (7)$$

The notations are conventional: ρ is in situ density, ρ_0 (=constant) the reference density, K_M the vertical eddy viscosity, K_H the vertical eddy diffusivity, $F^{(x,y)}$ the horizontal eddy friction terms, and $F^{(T,S)}$ the horizontal eddy diffusion terms. The Knudsen's equation is used for solving the equation (7). The K_M, K_H are determined by Mellor and Yamada level 2.5 turbulence closure model (Galperin et al., 1988). The sigma coordinate system is defined by $\sigma=(z-\eta)/(H+\eta)$, where η and H are the surface elevation and the water depth, respectively. We adopt 10 sigma levels (σ=0, −0.021, −0.042, −0.083, −0.167, −0.333, −0.500, −0.667, −0.833, −1.000). The bottom drag coefficient, γ, is given as

$$\gamma=MAX\left[\frac{k^2}{[\ln(1+\sigma_{kb-1})H/z_0]^2},\ 0.0025\right] \quad \cdots\cdots (8)$$

where k=0.4 is the von Karman constant and z_o is the roughness parameter (Mellor, 1996). For convenience, to discuss upwelling (or downwelling) phenomenon we here use the vertical velocity in the sigma coordinate, w (σ). More details in the model are given by Blumberg and Mellor (1987).

The model bathymetry of the Jinhae Bay is illustrated in Fig. 1b. The horizontal grid is fixed to 1 km in both x and y directions. They should be enough to represent main features in the circulation of the bay, although they are coarse to resolve the waterway of Kyeoneryang of which the width is about 1.2~1.4 km. However, it would not largely influence the circulation in the bay since the water exchange seems to be as small as negligible (Kim, 1984). Open boundaries at the south and the north of the Kadokdo, for convenience, are regarded as a closed boundary.

No normal flow condition is applied to the coastal boundary. At open boundary, the normal component of the external mode velocity to the boundary is given by a linearized momentum equation, and one of the internal mode velocity by a radiation condition of Orlanski (1976). The tangential components of both external and internal mode velocities are subject to free slip condition, $\partial\bar{u}/\partial y=\partial u/\partial y=0$. The same condition is also imposed for temperature and salinity. The initial temperature condition is horizontally homogeneous, and the values are exponentially decreased from 28℃ in the surface. Salinity distribution, on the other hand, is assumed to be equal everywhere to 34.5‰ and used as a check on the conservation properties of the finite difference technique. The initial sea level and velocities are set to be zero, $u=v=\eta=0$. For simplicity, the heat through open boundary is constantly given, and river discharges are not considered. The model is driven by M_2 tide (KORDI, 1996). Since semi-diurnal tidal components occupy over 90% of the tidal amplitude (M_2 tide is about 60%) in the Jinhae Bay (KORDI, 1981), the model will represent main features of circulation in the bay. Refer to Hong et al. (1997) for the details of the model.

Results

The model was run for six tidal periods. The results at the final period here are presented except for the time series of the velocity with the final two periods.

Figure 3 shows the 24-hours time series of the

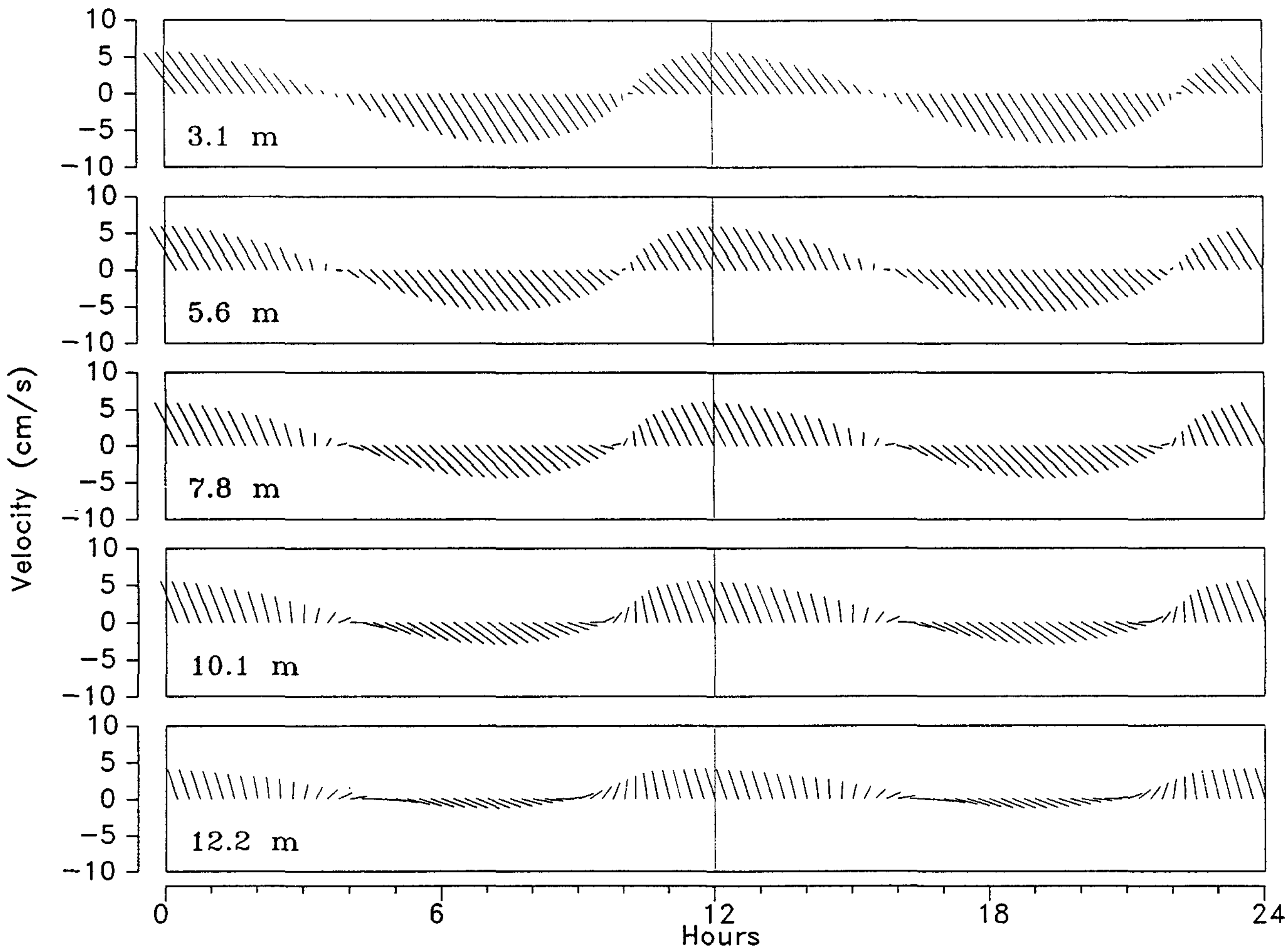


Fig. 3. Calculated time series of velocity (cm/s). Given is 24-hours time series.

calculated velocity at St. J (see Fig. 1) in depth. The model fairly reproduces the features of the observed velocity field as given in Fig. 2, although the depths are a little different from the observed depths; the surface maximum velocity in the model is about 8 cm/s and is comparable to the observation (see Fig. 2); as the depth deepens the velocity decreases and becomes about 5 cm/s at the lowest layer (12.2 m depth); the direction of the main axis of the current is in the northwest-southeast. In the lowest layer, the velocity direction in the model has been somewhat modified due to bottom friction. In general, the calculated velocity is slightly smaller than the observation, but it would be complemented when considering the wind effect and other tide components, such as S_2 or N_2, which were excluded in this study.

In the velocity fields of the flood tide (Fig. 4), the flows are stronger around the Kadok waterway at the northern end of Kojedo in both the upper (Fig. 4a) and lower layers (Fig. 4b). This tendency has also been shown in previous studies (e.g., KORDI, 1983; Kim, 1994; Bae, 1997). In the upper layer the maximum velocity is ranged between 45 and 50 cm/s, and these values were comparable to the surface maximum velocity (about 45~60 cm/s) observed by KORDI (1980) given in Fig. 5a. On the other hand, the velocity at the lower layer largely decreases, and is ranged between 20 and 25 cm/s in Kadok waterway. In the ebb tide (Fig. 6) the velocity field generally tends to be similar to the one in the flood tide (Fig. 4) except for the opposition of flow direction; the range of the maximum surface velocity (Fig. 6a) is between 45 and 50 cm/s, and these ranges correspond well to the observation in Fig. 5b.

In residual current fields (Fig. 7) a striking feature is found, i.e., many convergence zones are shown in the upper layer (Fig. 7a), for example, around the northern end of Kojedo, and they become divergence zones in the lower layer (Fig. 7 b). Vertical velocity fields in sigma coordinate, w (σ) (Fig. 8) show that downward velocities at the upper and the lower layers exist along the central parts of the bay. Note that these downward velocities mainly appear at regions where the depth is over about 15 m (see Fig. 1). In Fig. 9 vertical profiles of the residual currents along Line A in Fig. 1 show more clearly this phenomenon: the velocity components in the north-south direction (Fig. 9b) identifies that the convergence is active

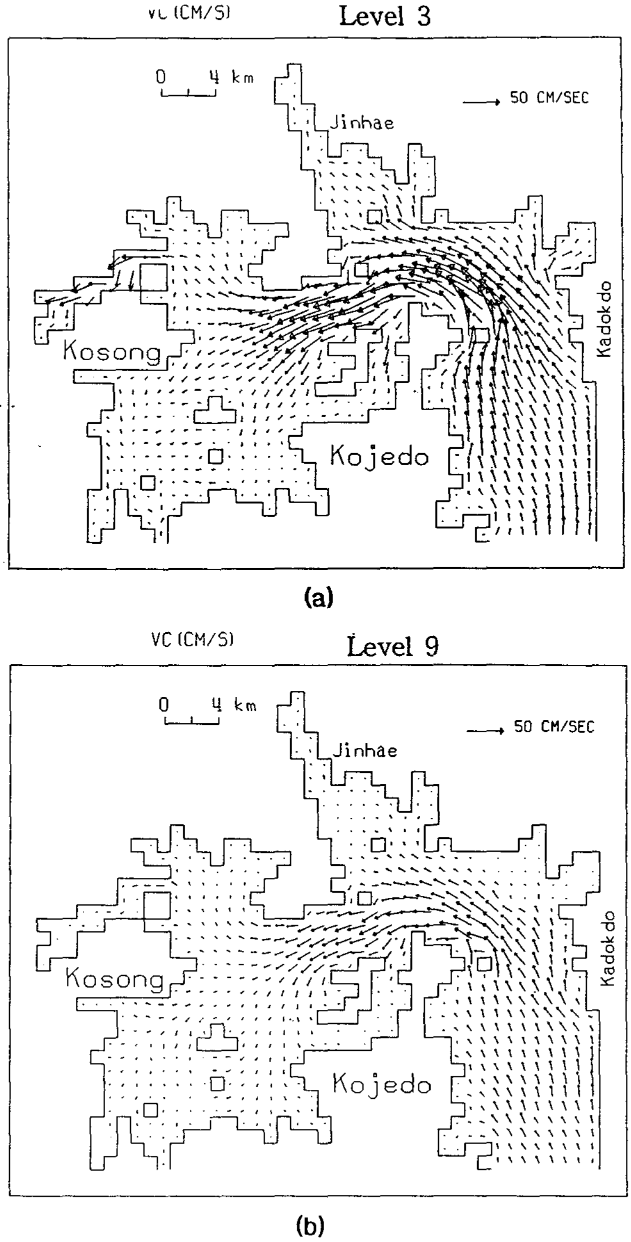
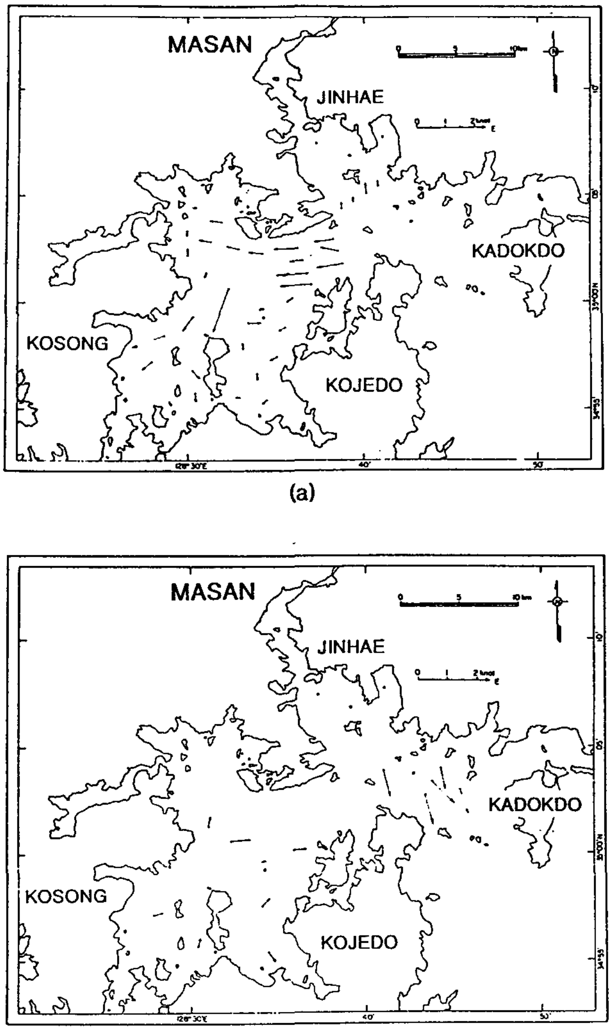


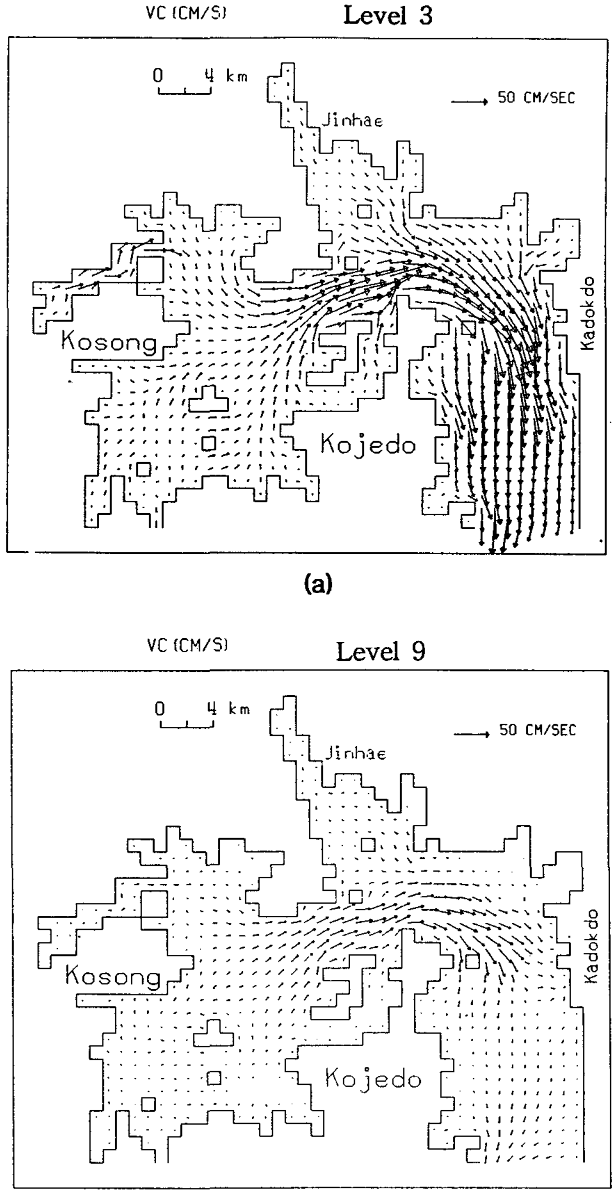
Fig. 4. Velocity fields (cm/s) in the flood tide of the model at the upper layer a), and at the lower layer b).

in the surface layer around the northern end of Kojedo, and the divergence in the lower layer. From the vertical velocity in sigma coordinate (Fig. 9c) we can estimate the downward velocity; about 30 m per day. Of course, this value should be varied by seasonal density condition or by considering wind, although they were excluded in the model. It would also be modified by improving open boundary conditions in which the south and the north of Kadokdo were closed. Nevertheless, this result strongly indicates that persistent downwelling may



(a) (b)

Fig. 5. Velocity fields (cm/s) in the Jinhae Bay observed by KORDI (1980), in the flood tide a), and in the ebb tide b).



(a) (b)

Fig. 6. Same as Fig. 4 except for in the ebb tide.

occur in the Jinhae Bay, particularly in the deeper zones, although it is not yet verified by the observation.

We noted above a close relation of downwelling velocity in the residual current field with bottom topography of the bay, and in order to examine such an effect of bottom topography, have been carried out a simple experiment. The conditions of the experiment are the same as the previous one (i.e., the depth-varied case) except for a constant depth with 20 m.

Under the constant depth (Fig. 10), there have been almost no convergence (divergence) zones at the upper (the lower) layer in horizontal residual current field, and the vertical velocity fields (Fig. 11) have been entirely changed. Also in vertical profiles along Line A (Fig. 12) any special features related to the downwelling have not been found. Note that the difference in vertical profiles along Line A has been clearly found in the deep place in the side of Kojedo. From these results, we can understand that the bottom topographic effect plays an important role in the formation of downwelling in the bay. Finally, we consider how a bottom drag coefficient (γ) influences the circulation in a depth-averaged (2D) model and the POM.

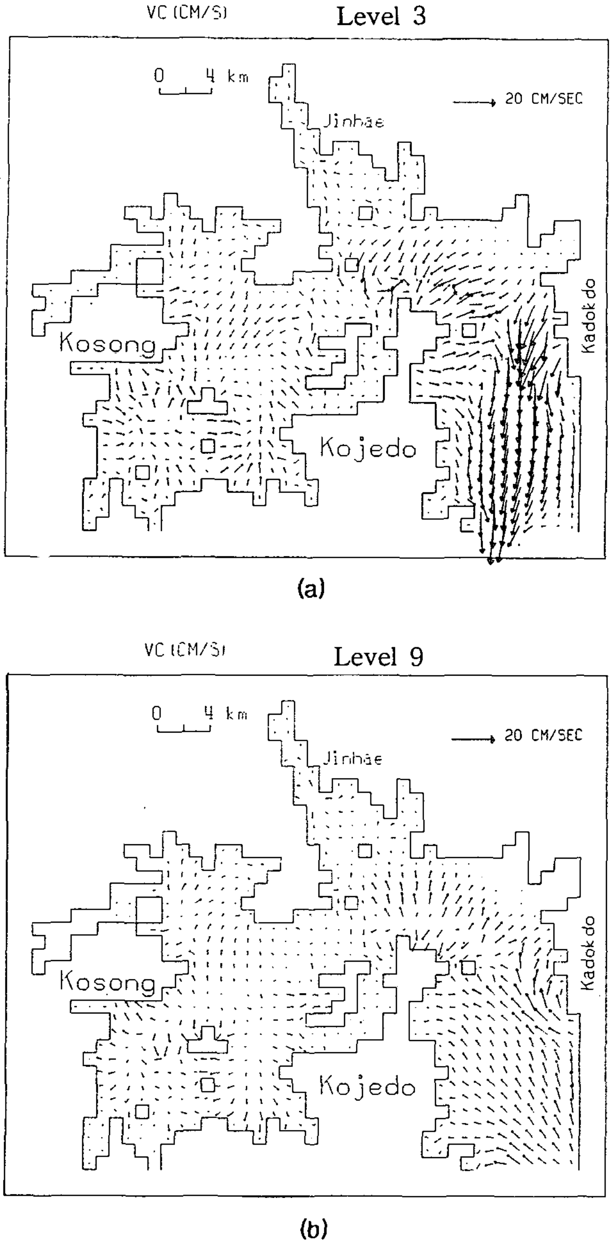


Fig. 7. Calcuated residual current fields (cm/s) in the upper layer a), and in the lower layer b).

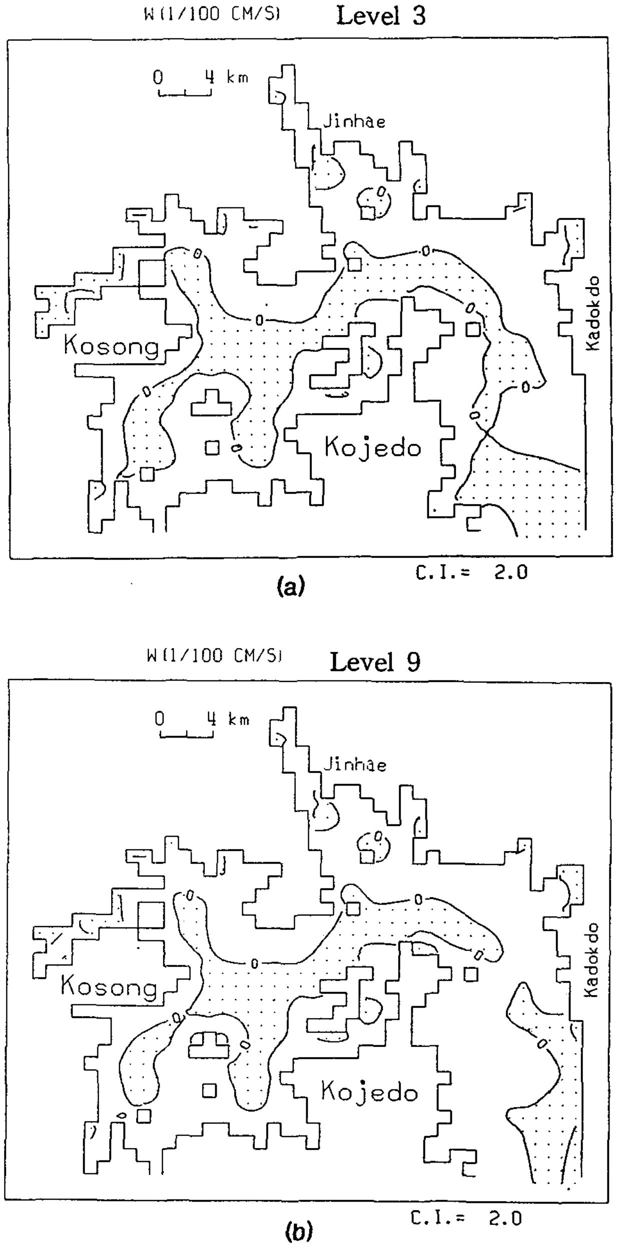


Fig. 8. Vertical velocity field in sigma coordinate in the upper layer a), and in the lower layer b). Unit is in cm/s $\times$ 10^{-2}.

Since the past decades, a bottom drag coefficient (γ) has been numerically employed as a constant by many authors (e.g., Kim, 1994; Bae, 1997). However, the current field in a shallow region, such as the Jinhae Bay, should be differently damped in time and in depth: the shallower the depth, the stronger the bottom friction, and vice versa. Thus, flow fields under a constant γ may be more overestimated than the real current field, especially in shallow regions. In a depth-averaged (2D) model, time series of velocity with a constant γ (0.0025) at St. J is given in Fig. 13a. The average speed is about 8 cm/s, and it seems to be more overestimated than the averaged observed velocity (roughly about 5 cm/s) in the vertical direction (Fig. 2). On the other hand, under γ depended on the depth (refer to equation 8) (Fig. 13b), the average speed has been about 4 cm/s and comparable to the observation. The residual current field (Fig. 14a) with the constant γ tends to be stronger than that with the

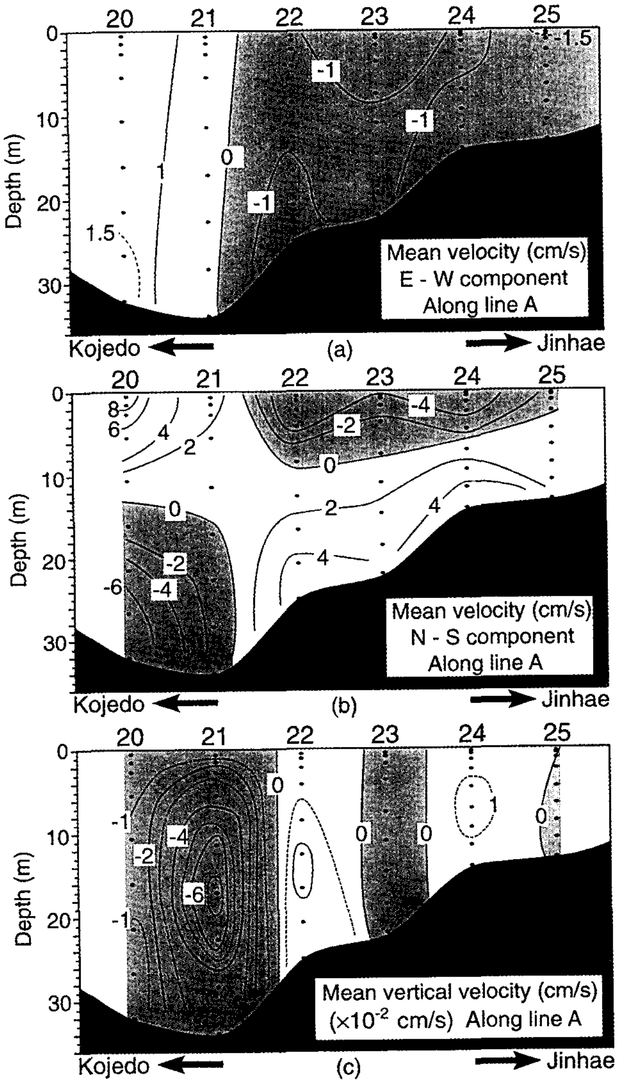


Fig. 9. Vertical profiles of residual currents along Line A (Fig. 1). East-west component a), north-south component b), and vertical velocity (cm/s × 10^{-2}).

depth-depended γ (Fig. 14b). (Note different unit-scales in the velocity each other.) Such a tendency is particularly remarkable around the south of Kosong which is relatively shallower (see Fig. 1). In the 3D model residual velocity field with constant γ in Fig. 15 has also been much increased at the lower layer, when comparing with the one in the case of the depth-depended γ (Fig. 7). Consequently, these results show that flow fields in the 2D and the 3D models can be significantly different by parameterizing bottom drag coefficient, especially near the bottom where the friction is more effective. Also, they imply that bottom drag coefficient evaluated from flow fields obtained by previous 2D models should not be adequate.

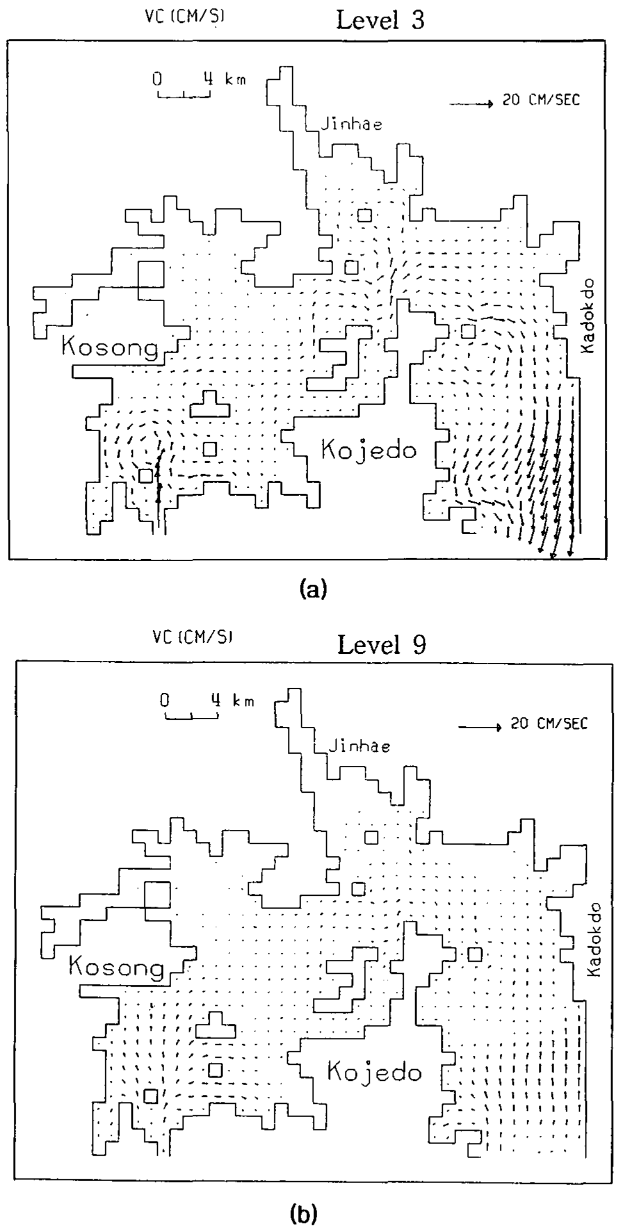


Fig. 10. Same as Fig. 7 except for the case of constant depth.

Discussion and Conclusions

The Princeton Ocean Model (POM) is used to examine the circulation in the Jinhae Bay in the southern sea of Korea. The conclusions are as follows:

1) The model well corresponds to the observed velocities at several layers in the Jinhae Bay obtained from a long-term mooring observation in the period of November 15 to December 3, 1997.

2) In the residual velocity field of the model convergence (divergence), zones are formed along deeper (shallower) regions in the bay, and are

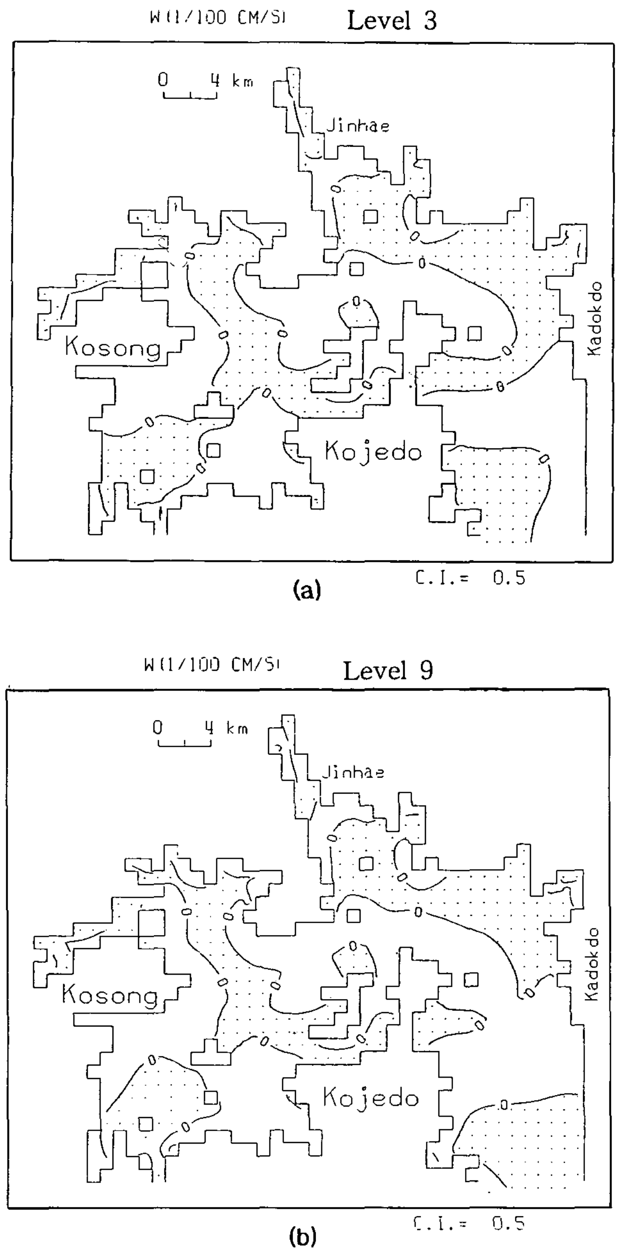


Fig. 11. Same as Fig. 8 except for the case of constant depth.

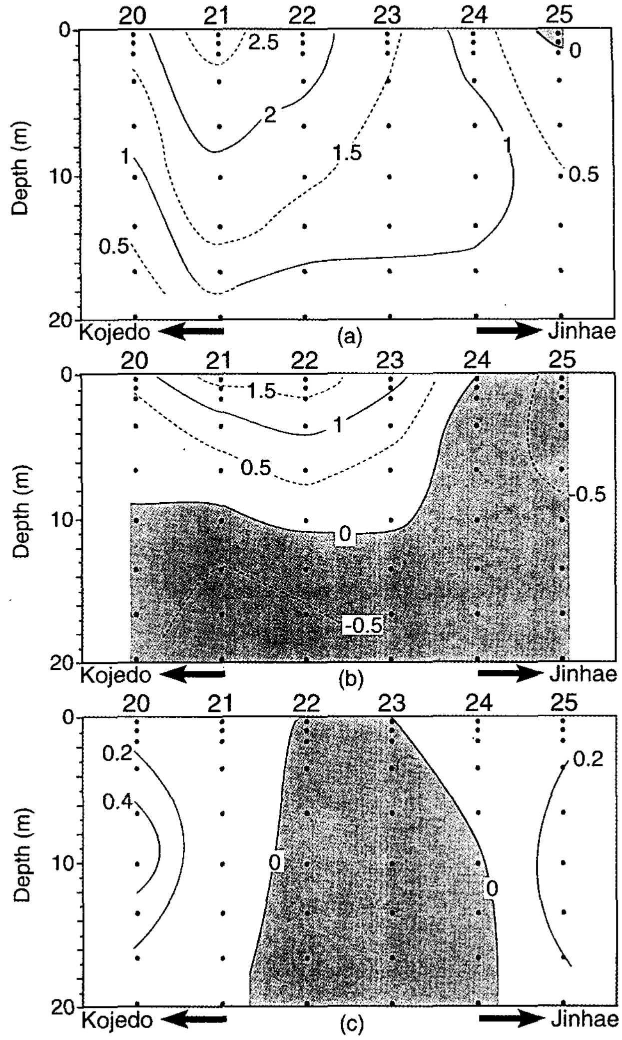


Fig. 12. Same as Fig. 9 except for the case of constant depth.

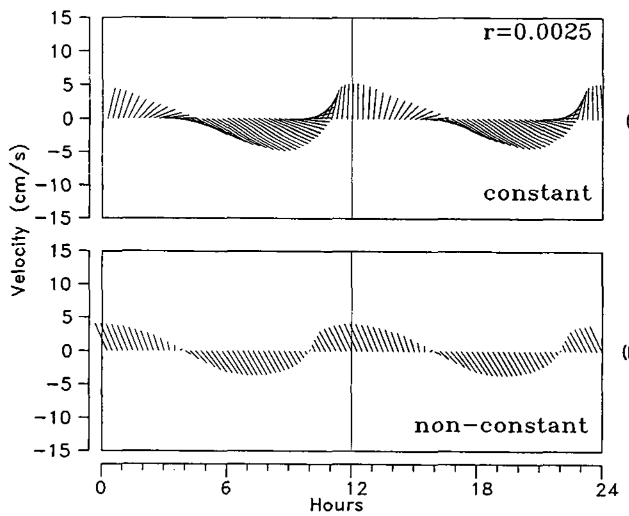


Fig. 13. Time series of velocity (cm/s) at St. J in 2D model with constant bottom drag coefficient (γ=0.0025) a), and with depth-depended γ b).

caused by bottom topographic effect.

3) By parameterizing bottom drag coefficient, flow fields in the 2D and the 3D models can be significantly different, especially near the bottom where the friction is more effective. This study implies that bottom drag coefficient evaluated from flow fields obtained by previous 2D models should not be adequate.

Yanagi (1992) proposed the 'tidal pump' to explain the temporal variation of the total vertical mass flux of the Tokyo Bay. The verification by the observation was also attempted (Yanagi et al., 1995; Noriki et al., 1997). Fujiwara (1997) reported that

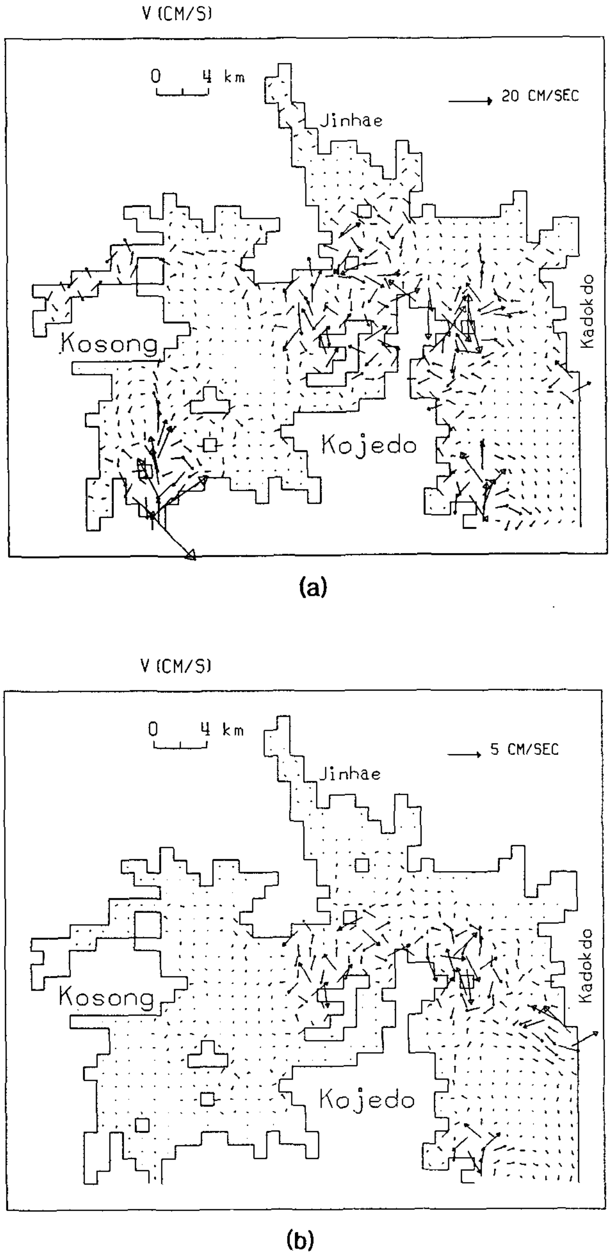


Fig. 14. Residual velocity fields (cm/s) in the 2D model with constant $\gamma(=0.0025)$ a), and with depth-depended γ b).

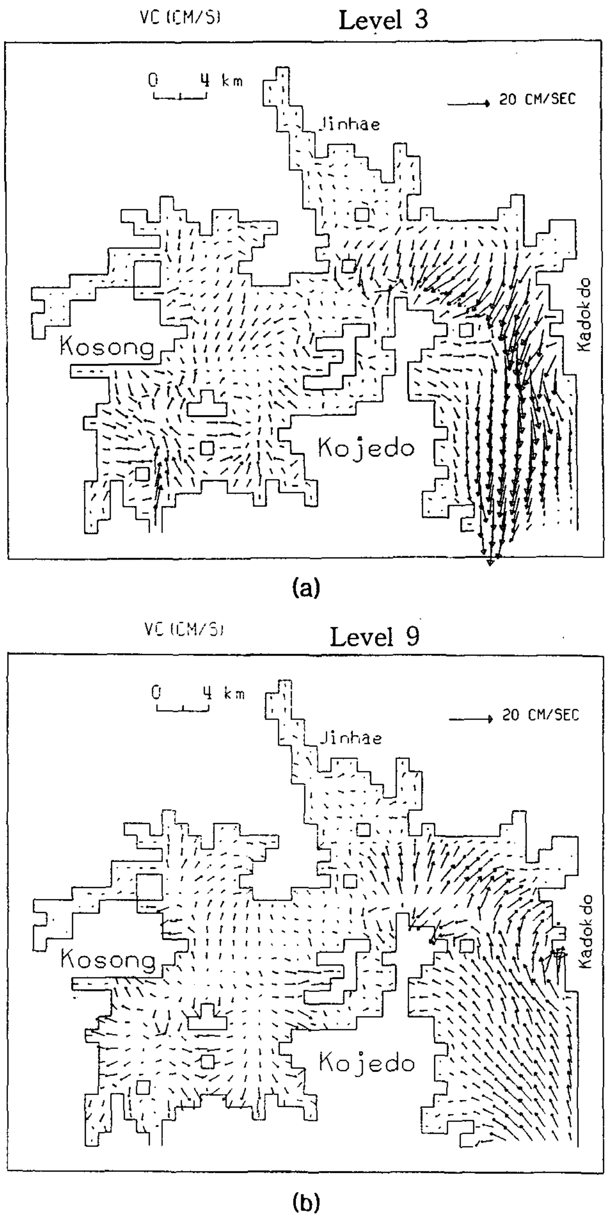


Fig. 15. Residual velocity fields (cm/s) in the 3D model with constant $\gamma(=0.0025)$ at the upper layer a), and at the lower layer b).

upward velocity in the estuarine circulation is a crucial factor to decide primary production or ecosystem. These studies indicate that vertical tidal motion may play important role in vertically transporting suspended or nutrient matter in a bay. In the present model a remarkable vertical motion along deep places in the Jinhae Bay was found (e.g., Figs. 8~9), and it may also influence the material transport in the bay. But it needs to be supported by the observation in the future. Especially the formation of dominant downwelling area in the Kadok waterway was caused by topographic effect but its dynamical process needs to study more in detail, probably concerning with vorticity dynamics.

Recently, Hong (1998) pointed out that in 2D model and 3D storm surge models based on POM, a constant bottom drag coefficient (γ) should be inadequate in terms of overestimating the real velocity field in a shallow bay. We also obtained similar results, e.g., Figs. 13~15, to his ones, i.e., more realistic flow field was obtained by using the

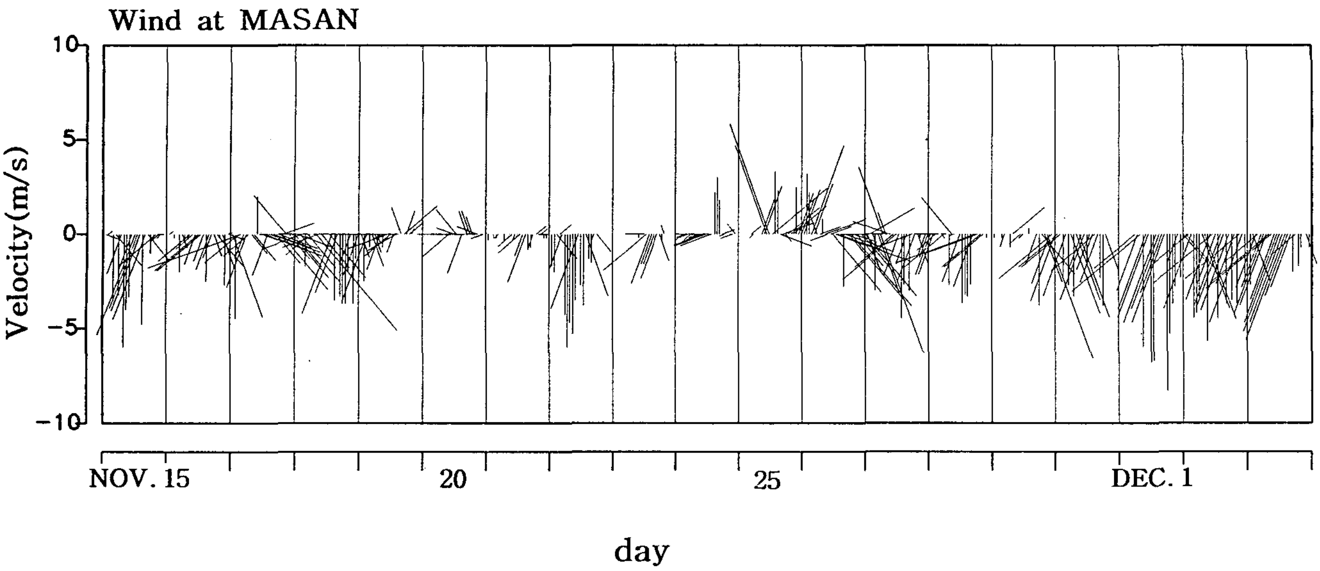


Fig. 16. Time series of wind (m/s) at Masan during November 15 to December 3, 1997.

depth-dependent γ. These results imply that in order to examine the circulation in a shallow bay where bottom friction is much effective, γ should be depended on the depth.

According to Cho et al. (1998), wind is likely to be effective in the circulation of the Jinhae Bay. They pointed out that there were strong current fields (Fig. 1) in the periods of north wind field at Masan as shown in Fig. 16. An interesting point is that a response of the current field to the wind is often baroclinic; as an example, the surface currents on November 25 flowed temporally northward with southwind in this period, but the currents at the lower layer was changed southward against of wind direction. This shows that the wind effect plays an important role in vertical structure of the circulation in the Jinhae Bay, and the model ought to involve the wind for the detailed vertical current structure, although the wind was excluded in this model.

In addition we must discuss limitations in the model. It was only driven by M_2 in order to capture basic oceanographic features of the bay, but the model should be improved by involving other components, e.g., S_2, O_1 or K_1 etc. The coarse spacial resolutions (1 km) in this syudy would be not enough to resolve Kyeneryang waterway (about 1.4 km) because the model has only one grid for that, thus an exchange of sea water through this waterway would be unrealistic in part. For convenience, we regarded the north and south of Kadokdo as closed boundaries, so that the flow fields would be somewhat modified around Kadokdo waterway. Nevertheless, the model would give us useful insights for the vertical tidal motion in the Jinhae Bay.

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