Numerical Simulation of Baroclinic Tidal Currents in Suruga Bay and Uchiura Bay Using a High Resolution Level Model

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Numerical simulation of baroclinic tidal currents in Suruga Bay and Uchiura Bay has been carried out using a 3-D, high resolution numerical model. It is shown that internal tides in Suruga Bay originate from the localized area in the northern part of Izu Ridge where strong tidal advection effects play crucial roles. The amplitude of calculated baroclinic tidal currents in Suruga Bay becomes more than double the value previously estimated from the numerical model, in which nonlinear effects were not taken into account. The internal tides thus generated have low-vertical-mode structures where the interface can be found at a depth of 200–300 m. The amplification of baroclinic tidal currents below a depth of about 800 m toward the bottom of Suruga Trough observed by Matsuyama et al. (1993) can be interpreted in terms of the low-vertical-mode structure of the propagating internal tides. The low-vertical-mode internal tides propagate into Uchiura Bay, located at the head of Suruga Bay, exciting significant isopycnal oscillations.

Although the semidiurnal internal tide of the first vertical mode in Uchiura Bay is shown to be amplified through the resonant coupling to the internal seiche in the bay, the interface is found at a depth of 50–70 m, which is much shallower than the depth of the interface outside Uchiura Bay. The occurrence of a strong vertical velocity on the bottom at the mouth of Uchiura Bay implies that internal tides observed in Uchiura Bay are generated near the bay mouth through the interaction between the shelf slope and strong baroclinic tidal currents associated with low-vertical-mode internal tides propagating from the northern part of Izu Ridge. In order to reproduce the generation and propagation features of internal tides in Suruga Bay, including the excitation processes of internal tides in Uchiura Bay, we need at least a three-layer numerical model that takes account of nonlinear tidal advection effects.

1. Introduction

Suruga Bay is a representative deep bay in Japan, its depth reaching a maximum of about 2500 m at the bay mouth and being more than 1000 m even near the bay head, where the Suruga Trough is deeply incised. A shallow inlet with nearly constant depth of about 100 m, Uchiura Bay is located at the north-eastern corner of Suruga Bay (Fig. 1). Previous current measurements made in the surface layers shallower than 100 m in Suruga Bay showed that the amplitude of tidal currents reaches more than 20 cms⁻¹, though it varies depending on the phase of the moon and the season (Inaba, 1981, 1984). As mentioned above, Suruga Bay is a very deep bay so that the amplitude of barotropic tidal current for each tidal constituent is less than 1 cms⁻¹ (Ohwaki et al., 1991). Therefore observed tidal currents in surface layers are considered to be attributed to internal tides. Harmonic analysis showed that the prevailing period of surface elevation is semidiurnal, whereas the prevailing period of tidal currents is diurnal in Suruga Bay. Furthermore, current and temperature measurements carried out in Uchiura Bay indicated the existence of baroclinic tidal currents with amplitudes reaching about 20–40 cms⁻¹ (Matsuyama and Teramoto, 1985). The internal tides have vertical two-layer structures with the phase difference between the variation of lower layer current and that of isopycnal displacement being very close to 90 degrees, which is a characteristic feature of standing waves.

To explain the observed features in Uchiura Bay, Matsuyama (1985) performed a numerical experiment by...
using a two-layer model with a barotropic forcing specified at the mouth of Suruga Bay. The calculated current amplitudes in Uchiura Bay were too small to be compared with the observed one, and baroclinic forcing was also necessary at the mouth of Suruga Bay to reproduce strong baroclinic tidal currents in Uchiura Bay. Matsuyama (1985) demonstrated that the amplitude of interfacial displacement at the head of Uchiura Bay became 4–12 times that at the mouth of Suruga Bay depending on the density stratification as a result of resonant coupling to the longitudinal internal seiche in Uchiura Bay, the eigenperiod being very close to 12 h.

Ohwaki et al. (1994) carried out numerical experiments by using a two-layer model which covered a much larger area than the model of Matsuyama (1985). They found that the internal tides were generated over the northern part of Izu Ridge, thereafter propagating into Suruga Bay along the west-coast of Izu Peninsula as either internal Kelvin waves with semi-diurnal and diurnal frequencies, or inertio-gravity waves with a semi-diurnal frequency. However, significant baroclinic tidal currents in Uchiura Bay were not reproduced in the calculated results of Ohwaki et al. (1994) and the amplitudes of semi-diurnal and diurnal tidal currents in Suruga Bay reproduced in their numerical model were about 5 cm s\(^{-1}\) and 7 cm s\(^{-1}\), respectively, under typical density stratification during summer, which is obviously smaller than the observed values (Inaba, 1981, 1984). Two-layer linear numerical models were used in these previous numerical studies (Matsuyama, 1985; Ohwaki et al., 1994). Considering the fact that barotropic tidal flow is significantly enhanced over the northern part of Izu Ridge due to the topographic constriction effects, however, we might need a numerical model that takes account of nonlinear tidal advection effects (Hibiya, 1986, 1988).

Matsuyama et al. (1993) carried out current measurements at two or three depths at two stations along the main axis of Suruga Trough during about 70 days from August to October 1988. From this field observation, they showed the existence of strong semi-diurnal and diurnal tidal currents near the bottom. The orientation of the major axis of each tidal ellipse was shown to be nearly coincident with that of
the main axis of Suruga Trough. Furthermore, they indicated that the amplitudes of these tidal currents below a depth of about 800 m were seen to increase toward the sea bottom, suggesting the concentration of internal wave energy propagating vertically downward along the ray. To confirm such vertical propagation processes of internal wave energy along the ray, we definitely need numerical models with high vertical resolutions.

In the present study, we have carried out numerical experiments by using a 3-D, high resolution, nonlinear numerical model to clarify the generation mechanism of strong baroclinic tidal currents observed near the bottom of Suruga Trough and inside Uchiura Bay.

2. Numerical Experiments

We used a 3-D, high resolution level model that takes account of realistic topography. Under the Boussinesq, $f$-plane and hydrostatic approximations, the equations of motion and continuity for an incompressible fluid can be written as

$$\frac{Du}{Dt} = f v - \frac{1}{\rho_0} \frac{\partial \rho}{\partial x} + A_v \frac{\partial^2 u}{\partial z^2} + A_H \nabla^2 u, \quad (1)$$

$$\frac{Dv}{Dt} + fu = \frac{1}{\rho_0} \frac{\partial \rho}{\partial y} + A_v \frac{\partial^2 v}{\partial z^2} + A_H \nabla^2 v, \quad (2)$$

$$\frac{\partial \rho}{\partial z} = -g \rho', \quad (3)$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0, \quad (4)$$

$$\frac{D\rho'}{Dt} = -w \frac{\partial \rho}{\partial z} + K_V \frac{\partial^2 \rho'}{\partial z^2} + K_H \nabla^2 \rho' \quad (5)$$

where $D/Dt = \partial/\partial t + u \partial/\partial x + v \partial/\partial y + w \partial/\partial z$ is the total time derivative with $u$, $v$, and $w$ being the eastward, northward and vertical upward velocity components, respectively; $\nabla^2 = \partial^2/\partial x^2 + \partial^2/\partial y^2$; $f$ is the Coriolis parameter; $A_h$ and $A_v$ are coefficients of the horizontal and vertical viscosities, respectively; $K_H$ and $K_V$ are coefficients of the horizontal and vertical diffusivities, respectively; $\rho$ is the basic density field; $\rho_0$ is the reference density and $\rho'$ is the density perturbation. The values of the parameters used in the present numerical experiment are $f = 8.35 \times 10^{-5}$ s$^{-1}$, $A_H = K_H = 2.0 \times 10^6$ cm$^2$s$^{-1}$ and $A_V = K_V = 1.0$ cm$^2$s$^{-1}$.

Numerical simulation is done by integrating Eqs. (1)–(5) with suitable initial and boundary conditions. For this purpose, Eqs. (1)–(5) are replaced with a finite difference scheme by applying the centered difference and leapfrog schemes.

Figure 1 shows a domain of the present numerical model, in which water depths less than 10 m are assumed to be 10 m, whereas water depths greater than 2500 m are assumed to be 2500 m. The number of horizontal grid points in this numerical model is 100 in the north-south direction and 103 in the east-west direction with a horizontal grid size of 1 km, whereas the number of vertical grid points is 64 with a vertical grid size of 10 m from the surface down to 100 m depth, 20 m for the depths range of 100–200 m and 50 m from 200 m depth down to the bottom.

The buoyancy frequency defined for the basic vertical density stratification $N(z) (N^2 = -(g/\rho_0)\partial \rho/\partial z)$ is approximated as shown in Fig. 2, where vertical density profile in the upper layer (0–200 m) is determined on the basis of the results from field observations in October 1973 (see figure 13 of Inaba (1981)) and that in the lower layer (200–2500 m) is determined on the basis of the results from field observations in October 1988 (see figure 3 of Matsuyama et al. (1993)).

Since the $M_2$ and $K_1$ barotropic tides dominate the $S_2$ and $O_1$ barotropic tides, we specify only the $M_2$ and $K_1$...
Fig. 3. The calculated horizontal current velocity field in the surface layer (5 m in depth) of Suruga Bay at intervals of 2 h from $t = 218$ h to $t = 240$ h. The unit vector shown on the lower right-hand side of each figure corresponds to 50 cm s$^{-1}$. The interval of contours superimposed on each figure is 20 cm s$^{-1}$. 

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The numerical computation proceeds from an initial state of rest up to \( t = 240 \) h with a time step of 120 s. In order to avoid numerical instability, the Euler-backward scheme is applied every 20 time steps.

3. Results

Figure 3 shows the horizontal velocity field in the surface layer of Suruga Bay at intervals of 2 h from \( t = 218 \) h to \( t = 240 \) h. We can see that strong currents with an amplitude approaching about 50 cm/s occur in the area just off the south-eastern coast of Izu Peninsula, namely in the northern part of Izu Ridge. The disturbance thus generated is seen to propagate into Suruga Bay, being confined within a scale of the internal deformation radius, namely about 30 km from the west coast of Izu Peninsula. From Fig. 3, the propagation speed of this disturbance is estimated to be of the order of 300 cm/s, which is comparable to the theoretically estimated phase velocity of an internal Kelvin wave of the first vertical mode.

The amplification of tidal currents toward the bottom at Stns. NB and SB (Fig. 1) in Suruga Trough, as observed by Matsuyama et al. (1993), is well reproduced in the present numerical experiment where the total range of calculated current fluctuations is shown to reach about 30 cm/s. In order to check the validity of the numerical results in more detail, we have calculated the spectrum of horizontal current velocity. Figure 4 shows the vertical distributions of the calculated horizontal kinetic energy for semi-diurnal and diurnal tidal constituents at Stns. NB and SB, respectively, where the energy level for the semi-diurnal tidal constituent is seen to be amplified below a depth of about 500 m toward the bottom at both stations. In particular, the observed feature that the amplification factor toward the sea bottom is larger at Stn. NB than that at Stn. SB is also well reproduced in the present numerical experiment.

Figure 5 shows a time series of the vertical structure of the east-west component of horizontal current velocity (upper panel) and that of the isopycnal displacement (lower panel) at Stn. UA in Uchiura Bay (for the geographical location, see Fig. 1) obtained from the present numerical experiment. The two-layer structure with the interface found at a depth of about 60 m can be seen in the current velocity field. The total range of tidal velocity variations reaches nearly 40 cm/s, whereas the total range of isopycnal displacements reaches nearly 30 m. The baroclinic tidal field in Uchiura Bay thus reproduced is consistent with the results from field observations (Matsuyama and Teramoto, 1985).

![HORIZONTAL KINETIC ENERGY](image1)

**Fig. 4.** The vertical distribution of the calculated horizontal kinetic energy for the semi-diurnal tidal constituent (solid line) and that for the diurnal tidal constituent (dashed line) at Stns. SB (left figure) and NB (right figure) in Suruga Trough, respectively.
4. Discussion

In the calculated results, tidal current is found to be significantly amplified near the south-eastern coast of Izu Peninsula where tidal current in the surface layer reaches about 50 cms\(^{-1}\) (see Fig. 3). On the basis of the barotropic model, Ohwaki et al. (1991) showed that the amplitude of \(M_2\) barotropic tidal current is about 20 cms\(^{-1}\), whereas the amplitude of \(K_1\) barotropic tidal current is about 15 cms\(^{-1}\) in this localized area. Even if both constituents of the barotropic tidal currents are additively superimposed, the amplitude of the composite barotropic tidal current still falls short of that of the tidal current reproduced in the present numerical model. The calculated strong tidal currents, therefore, cannot be explained as being caused only by the barotropic tides.

Considering the existence of a prominent topographic feature in this area, we can expect that large amplitude internal tides might be generated by strong tide-topography interactions (Hibiya, 1986). Figure 6 shows the time variation of isopycnal displacements across section A (see Fig. 1) from \(t = 216\) h to \(t = 221\) h. On the downstream side of the
Fig. 6. The calculated time variation of the isopycnal displacement across section A near the south-eastern coast of Izu Peninsula (see Fig. 1) from $t = 216$ h to $t = 221$ h. Contour interval is $1.0 \times 10^{-4}$ g cm$^{-3}$. The numeral and arrow at the top of each figure indicate the magnitude and direction of barotropic tidal flow over the sill crest, respectively.
sill crest, the isopycnal depression with a horizontal scale of about 5 km is seen to increase its amplitude up to about 25 m as the barotropic tidal flow approaches its maximum of about 35 cm s⁻¹ (t = 217 h). With the decrease of the barotropic tidal flow, the internal disturbance thus amplified starts to propagate westward over the sill crest (t = 221 h) (Hibiya, 1986, 1988). Since the generation region of the internal disturbance is fairly close to the south-eastern coast of Izu Peninsula, the internal disturbance thus generated propagates into Suruga Bay while being trapped along the coast on its right-hand side, with the horizontal wavelength increasing rapidly due to the dispersion effects (Fig. 3).

As mentioned earlier, Matsuyama et al. (1993) suggested that strong semidiurnal tidal currents observed near the bottom of Suruga Trough are caused by the concentration of internal wave energy which propagates vertically downward along the ray while reflecting at the steep side slopes of Suruga Trough. However, as is seen in the time series of the vertical profile of the calculated north-south component of horizontal current velocity at Stns. NB and SB (Fig. 7), the velocity field in Suruga Trough seems to consist of low vertical modes where vertical propagation of internal

![N-S Velocity field Stn NB](image1)

![N-S Velocity field Stn SB](image2)

Fig. 7. The time series of the vertical structure of the calculated north-south component of horizontal current velocity at Stns. NB (upper panel) and SB (lower panel) in Suruga Trough. Contour interval is 2 cm s⁻¹. Shaded areas correspond to the southward horizontal current velocity.
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wave energy along the ray, as suggested by Matsuyama et al. (1993), cannot be recognized at all, even though the vertical resolution of the present numerical model is high enough to reproduce such a ray structure if it exists.

To examine the vertical structure of internal tides at Stns. NB and SB more closely, modal decomposition was carried out for the calculated horizontal velocity and isopycnal displacement such that

\[
    u(z,t) = \sum_{n=1}^{\infty} U_n(t) \frac{dW_n(z)}{dz},
\]

\[
    v(z,t) = \sum_{n=1}^{\infty} V_n(t) \frac{dW_n(z)}{dz},
\]

\[
    \eta(z,t) = \sum_{n=1}^{\infty} Z_n(t) W_n(z)
\]

where \( W_n(z) \) and \( dW_n(z)/dz \) are the \( n \)th-vertical-mode eigenfunctions for the isopycnal displacement and horizontal current velocity, respectively. Figure 8 shows \( dW_n/dz \) for the lowest four vertical modes at Stn. SB. The kinetic energy (K.E.) and potential energy (P.E.) for each vertical mode internal wave are given by

\[
    (K.E.)_n = \frac{1}{2} \rho_0 \int_0^H \left( U_n^2 + V_n^2 \right) \frac{dW_n(z)}{dz}^2 dz,
\]

\[
    (P.E.)_n = \frac{1}{2} \rho_0 \int_0^H N^2(z) W_n^2(z) dz
\]

where \( H \) is the total water depth at each location. Table 1 shows the values of K.E. and P.E. for semidiurnal and diurnal constituents of the lowest four vertical modes at Stns. NB and SB. The calculated internal wave field mostly consists of the lowest three vertical modes. For the semidiurnal tidal constituent, most of the kinetic energy is seen to reside in the first vertical mode, making a dominant contribution to the total internal wave energy. For the diurnal tidal constituent, however, a considerable fraction of kinetic energy is found in the third vertical mode. The fact that the potential energy, in contrast, mostly resides in the first vertical mode implies that such modal dependency of the kinetic energy might result from the interference be-

![Fig. 8. The eigenfunctions of the lowest four vertical modes for the horizontal current velocity at Stn. SB in Suruga Trough (see Fig. 1). Calculated phase velocity of each vertical mode is also shown.](image)

Table 1. The fraction of internal wave energy of the lowest three vertical modes for diurnal and semidiurnal components at Stns. NB and SB.

<table>
<thead>
<tr>
<th></th>
<th>Diurnal component</th>
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<th>Semi-diurnal component</th>
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<td>K.E. (grs⁻²)</td>
<td>P.E. (grs⁻²)</td>
<td>Total</td>
<td>K.E. (grs⁻²)</td>
<td>P.E. (grs⁻²)</td>
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<td>213.3E + 4</td>
<td>224.2E + 4</td>
<td>149.4E + 4</td>
<td>76.7E + 4</td>
<td>226.1E + 4</td>
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<td>18.9E + 4</td>
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<td>19.6E + 4</td>
<td>2.9E + 4</td>
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Fig. 9. The time series of the calculated vertical velocity field across section B in Uchiura Bay (see Fig. 1) at intervals of 2 h from $t = 218 \text{ h}$ to $t = 240 \text{ h}$. Solid (dashed) contours show upward (downward) current velocity. Contour interval is 0.07/cms$^{-1}$. Shaded areas indicate the magnitude of vertical current velocity is more than 0.1 cms$^{-1}$. The areas where the magnitude of vertical current velocity exceeds 0.175 cms$^{-1}$ are heavily shaded.
tween the incoming (northward propagating) and outgoing (southward propagating) internal tides. The dominance of low-vertical-mode internal tides in Suruga Bay is consistent with the theoretical results of Hibiya (1986), who found that, under strong tidal advection effects, internal waves generated over topographic features are mostly of low vertical modes. Actually, over the prominent topographic feature in the northern part of Izu Ridge where most baroclinic tidal energy in Suruga Bay originates, the maximum internal Froude number of the barotropic tidal flow is estimated to reach about 2.5 with respect to the first vertical mode. The observed amplification of tidal currents below a depth of about 800 m toward the bottom of Suruga Trough is considered as reflecting just such low-vertical-mode structures of the internal tides propagating from the northern part of Izu Ridge.

The results from the present numerical experiment show that, though the internal tide in Uchiura Bay has a two-layer structure, the interface is found at a depth of 50–70 m which is much less than that outside Uchiura Bay. Furthermore, the horizontal wavelength of the first-vertical-mode internal tide outside Uchiura Bay becomes about 130 km for the semidiurnal tidal constituent and about 260 km for the diurnal tidal constituent, both of which are much larger than the horizontal scale of the shelf slope at the mouth of Uchiura Bay, which is about 10 km. Under such situations, it is very hard to imagine that the low-vertical-mode internal tides in Suruga Bay can propagate into Uchiura Bay while maintaining their vertical mode structures. Figure 9 shows a time series of the vertical velocity field across section B (see Fig. 1) at intervals of 2 h from \( t = 218 \) h to \( t = 240 \) h. A strong vertical velocity is seen to occur on the bottom at the mouth of Uchiura Bay, suggesting that the upper shelf slope at the mouth of Uchiura Bay is acting as a strong forcing area for internal tides.

In order to examine the temporal and spatial features of internal tides in Uchiura Bay, harmonic analysis and vertical mode decomposition have been carried out, respectively. The eigenfunctions \( dW_d/dz \) (see Eqs. (6) and (7)) for the lowest four vertical modes at Stn. U1 in Uchiura Bay are shown in Fig. 10. Figure 11(a) shows the theoretically predicted fraction of internal wave energy of each vertical mode excited by the barotropic forcing at the shelf edge, given by

\[
F = -z Q N^2(z) \omega (h'/h^2) \sin \alpha \hat{z}
\]

where \( z \) is the vertical coordinate with the origin at the undisturbed sea surface; \( \hat{z} \) is the unit vector directed vertical upward; \( Q \) is the transport of barotropic tidal flow; \( h \) and \( h' \) are the water depth and bottom slope at the shelf edge, respectively; and \( \omega \) is diurnal or semidiurnal tidal frequency (Baines, 1982). Although the fraction of each vertical mode wave energy for the diurnal tidal constituent follows the theoretically predicted one (Fig. 11(c)), that for the semidiurnal tidal constituent is determined more independently on the forcing field, where most of the semidiurnal tidal energy is seen to be occupied by the lowest vertical mode (Fig. 11(b)).

Figure 12 shows the time series of the east-west component of horizontal current velocity \( U_h(t) \) (solid lines) and that of the isopycnal displacement \( Z_h(t) \) (dashed lines) for the semidiurnal tidal constituent of the lowest three vertical modes at Stns. U1–U4 (see Fig. 1) in Uchiura Bay, which are defined in Eqs. (6) and (8). We can see that the phase difference between \( U_h(t) \) and \( Z_h(t) \) becomes close to 90 degrees only for the first vertical mode, where \( U_h(t) \) or \( Z_h(t) \) at Stns. U1–U4 are found to occur almost in phase. Furthermore, on approaching the head of Uchiura Bay, the amplitude of \( U_h(t) \) decreases, whereas the amplitude of \( Z_h(t) \) increases, showing that the semidiurnal internal tide of the first vertical mode behaves as a standing wave, consistent with the observed features pointed out by Matsuyama and Teramoto (1985).
excited is resonantly coupled to the longitudinal internal seiche in Uchiura Bay with an eigenperiod very close to the semidiurnal tidal period. A schematic view showing the generation processes of internal tides over the shelf slope at the mouth of Uchiura Bay is illustrated in Fig. 13.

5. Conclusion

In the present study we have succeeded in reproducing the strong baroclinic tidal currents observed near the bottom of Suruga Trough and inside Uchiura Bay. It has been shown that internal tides in Suruga Bay originate from the localized area in the northern part of Izu Ridge where strong tidal advection effects play crucial roles in the generation processes of internal tides. The present numerical experiment has also shown that the amplitude of baroclinic tidal current in Suruga Bay reaches more than double the value previously estimated from the numerical model, in which nonlinear tidal advection effects are not taken into account. The internal tide thus generated has low-vertical-mode structures where the interface can be found at a depth of 200–300 m. The amplification of baroclinic tidal currents toward the bottom of Suruga Trough pointed out by Matsuyama et al. (1993) can be interpreted in terms of the low-vertical-mode structures of the propagating internal tides.

Although the semidiurnal internal tide of the first vertical mode in Uchiura Bay has been shown to be resonantly coupled to the internal seiche in the bay, the interface is found at a depth of 50–70 m, much shallower than the interface outside Uchiura Bay. Furthermore, the horizontal wavelength of the low-vertical-mode internal tides outside Uchiura Bay is more than 100 km, which is much larger than the horizontal scale of the shelf slope at the mouth of Uchiura Bay which is about 10 km. Putting all these facts together, we can conclude that prominent internal tides observed in Uchiura Bay are mostly generated through the interaction between the shelf slope at the mouth of Uchiura Bay and strong baroclinic tidal currents associated with the low-vertical-mode internal tides propagating from the northern part of Izu Ridge.

The generation and propagation features of internal tides thus clarified are quite different from the ones demonstrated in the previous numerical studies on the basis of a linear two-layer model (Matsuyama, 1985; Ohwaki et al., 1994) in which the internal tidal disturbance propagating from the mouth of Suruga Bay as an interfacial mode was shown to be amplified by up to a factor of 4–12 through resonant coupling to the internal seiche in Uchiura Bay. In order to reproduce the generation and propagation features of internal tides in Suruga Bay, including the excitation processes of internal tides in Uchiura Bay, we need at least a three-layer numerical model that takes account of nonlinear tidal advection effects (see Fig. 13).

It has been shown that the nonlinear dynamics in the localized forcing area in the northern part of Izu Ridge strongly controls the baroclinic tidal current field in Suruga Bay. Detailed field studies in this forcing area are therefore
Fig. 12. The time series of the calculated east-west component of horizontal current velocity (solid line) and that of the calculated isopycnal displacement (dashed line) for the semidiurnal tidal constituent of the lowest three vertical modes at Stns. U1–U4 (see Fig. 1) inside Uchiura Bay.
desirable for a more complete understanding of the baroclinic tidal current field in Suruga Bay.

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**References**


