Semidiurnal Internal Tides on the Continental Shelf off Abidjan

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16 April 1985 and 26 February 1986

ABSTRACT

Important semidiurnal internal tides with a maximum displacement of isotherms of about 30 m were observed on the continental shelf, near the submarine canyon Trou-Sans-Fond off Abidjan, Ivory Coast. It is proposed from a two-layer submarine canyon model experiment that the observed internal tides could have been generated by an interaction between the bottom topography of the submarine canyon and oscillatory longshore tidal currents and have propagated away on both sides of the canyon. The estimated wavelength and phase speed of the $M_2$ internal tides of the region were respectively 22 km and 0.5 m s$^{-1}$. The asymmetric profiles of isotherms and baroclinic currents were explained in terms of the nonlinear effects of the internal waves.

1. Introduction

During 1973 and 1976–77, the Centre de Recherches Oceanographiques (ORSTOM) in Ivory Coast conducted extensive hydrographic surveys and current measurements on the continental shelf on both sides of the submarine canyon Trou-Sans-Fond (hereafter, TSF), which cuts deeply across the continental shelf off Abidjan at a mean latitude of 5°10'N (Fig. 1). The ensemble of the graphic results from these data revealed distinctive semidiurnal oscillations in the depths of isotherms and isohalines as well as in the vertical current profiles. The hydrographic conditions and the current system in the region undergo a distinct seasonal variation (Morlière, 1970) and the $M_2$ surface tide is dominant at the coast (Picaut et al., 1979). It was suggested that the warm marine season (February–May and November), which has a strongly stratified water column, is more favorable for the generation of large-amplitude internal tides than the cold marine season (July–September and December–January), corresponding to the upwelling period of the region in a very weak stratification (Park, 1979). The $M_2$ principal lunar tide dominates temperature fluctuations during the warm season.

In this paper, we have two main purposes. First, we shall interpret the current profiling data obtained during the warm season in terms of internal tides. The periodic variation of baroclinic currents, which is one of the principal properties of internal tides, will be used as the best indicator of internal waves. Second, we shall examine a two-layer submarine canyon model in order to understand the mechanisms of the generation of internal tides and their propagation. The interaction between the abruptly changing bottom topography of the submarine canyon and the oscillatory barotropic currents will be considered as an effective mechanism for the generation of internal tides in this region.

2. Data

The current and temperature data used in this study were obtained at the anchor station TSF 13 (Fig. 1), using the current profiler (Düing et al., 1972) developed by the University of Miami. The station was occupied for four days (28 November–1 December 1973) on the continental shelf, 6 km offshore from the coast and 10 km westward from the edge of the submarine canyon TSF. The current profiler took about 10 minutes to descend freely from the surface to the deepest level of 48 m (bottom depth was 55 m). The repeated lowerings of the current profiler at intervals of about 30 minutes provided a time series of horizontal currents and temperatures at vertical intervals of 2.5 m. Since the raw data were randomly distributed in time with a time lag of 10 minutes between the surface and the deepest level, and there were differing intervals between each lowering, the interpolation of these data at a regular time interval of 10 minutes has been done by using the GPCP (General Purpose Contouring Program) developed by California Computer Program, Inc. The missing current data for the deepest level to the bottom were estimated by linear extrapolation.

3. Observation of semidiurnal internal tides

Figure 2 shows the semidiurnal oscillations in the vertical current profiles (a and b) and in the depths of isotherms (c) at TSF 13. The semidiurnal oscillation of isotherms with the maximum crest to trough displacement of about 30 m shows an asymmetric profile, having an abrupt rise and a slow descent. An asymmetric profile of this kind seems to be a general char-
characteristic of nonlinear internal waves approaching coastal shallow water (Cairns, 1967; Halpern, 1971; Stanton, 1977). The most striking feature is the presence of the strong semidiurnal baroclinic currents in addition to the barotropic component in the current data, which suggests the presence of strong semidiurnal internal tides.

In order to evaluate the contribution of individual internal wave modes to the observed currents, it is necessary to extract the baroclinic currents from the current measurements. The current measurements may be thought as composed of three principal components: baroclinic, barotropic and mean currents. First, the mean current at a fixed level can be estimated by averaging over several tidal periods, which will then be eliminated from the current measurements. Second, the vertical averaging will tend to suppress any baroclinic current fluctuations because the total flux by internal waves is zero, and all that remains is the barotropic current. Finally, the baroclinic current can be obtained after the elimination of the barotropic and mean currents from the original time series.

The major uncertainty in the evaluation of the barotropic and baroclinic components by the above procedure comes probably from the bottom boundary layer effects. We estimated the boundary layer thickness $\delta$ according to the semiparametric formula used around the British Isles by Soulsby (1983):

$$\delta = 0.0038(\bar{U}_a \sigma - \bar{U}_b f)(a^2 - f^2),$$

where $\bar{U}_a$ is the maximum depth-average current, $\bar{U}_b$ the minimum depth-averaged current with $\bar{U}_b$ positive (negative) for anticlockwise (clockwise) polarization, $\sigma$ the tidal frequency and $f$ the Coriolis parameter. For $\bar{U}_a < 25$ cm s$^{-1}$, $|\bar{U}_b| < 10$ cm s$^{-1}$, $\sigma = 1.4 \times 10^{-4}$ s$^{-1}$ for $M_2$, and $f = 1.3 \times 10^{-5}$ s$^{-1}$ for the latitude $5^\circ10'$, we obtain $\delta \approx 7$ m at TSF 13. We expect, therefore, that any significant boundary layer effects, such as the phase advance and the decrease in current amplitudes with approaching the bottom, will be limited to within around 10 m above the bottom. Owing to the relatively thin boundary layer depth compared to the total water depth (55 m) at TSF 13, the vertical averaging will cause a slight underestimate (overestimate) for the barotropic (baroclinic) component of currents in the upper layer. However, inside the bottom boundary layer, the vertical averaging could overestimate (underestimate) significantly the barotropic (baroclinic) component of currents.

Figure 3 shows the time series of the barotropic currents and the separated baroclinic currents at different levels. The semidiurnal baroclinic currents with a phase difference of 180° between the upper and lower layers suggest the lowest baroclinic mode. The saw-toothed asymmetry is remarkable especially in the E–W current component, while the barotropic currents show a nearly sinusoidal variation without any significant asymmetry. They are mostly in the E–W direction. Since internal tides commonly have much larger (internal) vertical displacements than surface tides, they will be influenced by amplitude and phase dispersion to a greater degree than surface tides. In the case corresponding to $(H/\lambda)^2 < a/H < 1$, where $H$ is the water depth, $\lambda$ the wavelength and $a$ the wave amplitude, amplitude dispersion dominates over phase dispersion and a crest travels faster than a trough, and the forward face of a wave steepens with propagation distance (Leblond and Mysak, 1978). Thus for $H = 55$ m, $a \approx 15$ m, and $\lambda \approx 22$ km, which were estimated $(H$ and $a)$ from the observed isothermal displacements and the model results $(\lambda)$ of section 4, the above inequality holds true in the case of TSF 13.

Hence the saw-toothed asymmetry shown in the isothermal displacements (Fig. 2) and the baroclinic currents (Fig. 3) is consistent with strong nonlinear effects of internal waves, in which amplitude dispersion dominates over phase dispersion.

The linear theory of internal waves states that the Fourier coefficients $a(z)$ and $b(z)$ of the baroclinic currents of the form,

$$u(z, t) = a(z) \cos \omega t + b(z) \sin \omega t,$$

can each be represented by a sum of eigenfunction $U_n(z)$

$$a(z) = \sum A_n U_n(z), \quad b(z) = \sum B_n U_n(z),$$

where $A_n$ and $B_n$ represent the contributions of the different modes $n$. The density distribution at TSF 13 was almost linear with the Brunt–Väisälä frequencies and the corresponding periods being about $2.6 \times 10^{-2}$ s$^{-1}$ and 4 min, respectively. The eigenfunctions $U_n(z)$ for the conditions at TSF 13 were calculated by a standard method (Krauss, 1966; Roberts, 1975). Using the orthogonality of eigenfunctions $U_n$ (Krauss, 1966), the
model contributions $A_n$ and $B_n$ were computed (Table 1). As expected, the first mode has a dominant contribution accounting for 70% of the total baroclinic fluctuation.

It is to be noted that the maximum amplitude of the baroclinic currents ($\sim 17$ cm s$^{-1}$) is stronger by a factor of 2 than that of the barotropic currents ($\sim 7$ cm s$^{-1}$). The mean orientation of the major axis of the baro-
clonic currents over the entire water column was found to be on the line bearing 105°, which is perpendicular to the axis of the submarine canyon TSF. This orientation and the possibility of the internal tide generation by an interaction between the submarine canyon and the oscillatory longshore tidal currents, suggest that the internal tides observed at TSF 13 could have been generated and propagated from the submarine canyon TSF.

4. Generation mechanism using a submarine canyon model

Generation of internal tides by tidal flows over a bottom irregularity, such as over a continental slope, at the sill or on a seamount has been considered in a number of experimental or theoretical works (e.g., Zeilon, 1934; Rattray, 1960; Rattray et al., 1969; Cavaniè, 1969, 1972; Baines, 1973, 1974; Prinsenberg et al., 1974). Recently Baines (1983) investigated the generation mechanisms of internal tides in submarine canyons with a laboratory experiment and a theoretical model. However, his model does not seem to be appropriate to interpret internal tides on the continental shelf outside a canyon, because it deals with internal tides generated inside a canyon by the onshore–offshore barotropic current. As previously noted, the internal tides observed at TSF 13 were probably generated by the stronger longshore barotropic currents interacting with the submarine canyon TSF. For mathematical simplicity, we shall examine a two-layer model for the generation of internal tides by oscillatory longshore barotropic currents across a submarine canyon. Although the two-layer approximation may not be a good description of the continuous stratification in the study area, the two-layer model is appropriate to examine a simple mechanism of internal tide generation, as long as there exists a predominant first mode internal wave.

### Table 1. Contribution of the lowest five modes to the E–W component of the M_2 baroclinic currents at TSF 13.

<table>
<thead>
<tr>
<th>Mode</th>
<th>$A_n$ (cm s$^{-1}$)</th>
<th>$B_n$ (cm s$^{-1}$)</th>
<th>$(A_n^2 + B_n^2)^{1/2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14.42</td>
<td>3.54</td>
<td>14.85</td>
</tr>
<tr>
<td>2</td>
<td>-1.15</td>
<td>-2.81</td>
<td>3.04</td>
</tr>
<tr>
<td>3</td>
<td>1.11</td>
<td>1.36</td>
<td>1.76</td>
</tr>
<tr>
<td>4</td>
<td>-0.73</td>
<td>0.25</td>
<td>0.77</td>
</tr>
<tr>
<td>5</td>
<td>-0.72</td>
<td>-0.32</td>
<td>0.79</td>
</tr>
</tbody>
</table>

a. Working equations

The governing equations and fundamental assumptions are the same as those of Cavaniè (1969), who has developed a nonlinear model for internal wave generation by the tidal currents over the sill at Gibraltar. The model is based on a two-layer system of perfect fluids and makes the long wave and rigid lid approximations, that is, it neglects the vertical acceleration and suppresses surface waves. Neglecting the earth's rotation since $f_0/\omega u \approx 0.02$ at TSF 13, the equations which describe the 2-D flow are

$$\rho_1(\partial u_1/\partial t + u_1\partial u_1/\partial x) = -\partial P_0/\partial x$$  \hspace{1cm} (1)

$$\rho_2(\partial u_2/\partial t + u_2\partial u_2/\partial x) = -\partial P_0/\partial x + g(\rho_2 - \rho_1)\partial h/\partial x$$  \hspace{1cm} (2)
\[ \frac{\partial h_i}{\partial t} + \frac{\partial (h_i u_i)}{\partial x} = 0 \]  
\[ d(t) = u_1 h_1 + u_2 (h_2 - h_1) \]

where \( u_1(x, t) \), \( u_2(x, t) \) and \( \rho_1, \rho_2 \) are the horizontal velocities and the densities respectively in the upper and lower layer; \( h_1(x, t) \) and \( h_2(x) \) are the depths of the interface and of the bottom with respect to the upper limit, which is a rigid horizontal boundary represented by the \( x \)-axis; \( d(t) \) and \( P_0(x, t) \) represent respectively the total flux and the pressure at the surface. Eliminating \( P_0 \) from (1) and (2) and then making the Boussinesq approximation, that is, replacing the ratio \( \rho_1/\rho_2 \) by unity except in the gravity term, we obtain

\[ \frac{\partial u_2}{\partial t} + u_2 \frac{\partial u_2}{\partial x} - (\partial u_1/\partial t + u_1 \partial u_1/\partial x) = g' \frac{\partial h_1}{\partial x} \]

where \( g' \) is the reduced gravity, defined by

\[ g' = g(\rho_2 - \rho_1)/\rho_2. \]

By the transformation due to C, Bellevaux (in Lacombe, 1965)

\[ \begin{align*} 
V^* \sqrt{2} & = g' H_0; \quad X = xH_0^{-1}; \quad T = tH_0^{-1} V^* \\
h_1(X, T) & = h_2(X) \{1 - C(X, T)\}/2; \quad h_2(X) = H_0 H(X) \\
d(T) & = D(T) V^* H_0; \quad u_2 - u_1 = V(X, T) V^* 
\end{align*} \]

where \( H_0 \) represents a constant characteristic depth, and assuming

\[ \begin{align*} 
C(X, T) & = \sin A(X, T), \\
V(X, T) & = H^{1/2}(X) \sin B(X, T). 
\end{align*} \]

Equations (3), (4) and (5) reduce to the following characteristic system of equations (for details, see Cavanié, 1969 and Park, 1979)

\[ \begin{align*} 
(dX/dT)_+ & = \alpha - \beta + 1/2 \gamma \\
(dX/dT)_- & = \alpha - \beta - 1/2 \gamma \\
d(A + B)/dT_+ & = \delta \{2\alpha - \gamma + \eta - (dX/dT)_+\} \\
d(B - A)/dT_- & = \delta \{2\alpha + \gamma + \eta - (dX/dT)_-\} 
\end{align*} \]

where plus and minus signs represent the two families of characteristic curves, and \( \alpha, \beta, \gamma, \delta \) and \( \eta \) are given by

\[ \begin{align*} 
\alpha & = D/H; \quad \beta = H^{1/2} \sin A \sin B; \quad \gamma = H^{1/2} \cos A \cos B \\
\delta & = (1/2H) \tan B(dH/dX); \quad \eta = H^{1/2}(1 - \sin A)/\sin B. 
\end{align*} \]

Specifying \( \rho_1, \rho_2, h_2(x), d(t) \) and \( H_0 \) and consequently \( V^*, H(X) \) and \( D(T) \) by (6), the solution of the characteristic system of equations (8) to (11) gives the values of \( A(X, T) \) and \( B(X, T) \) and therefore \( C \) and \( V \) by (7). The interface displacement, \( h_1(X, T) \) and the horizontal velocities in the two layers, \( u_1(X, T) \) and \( u_2(X, T) \) can then be obtained from (4) and (6).

b. Integration of equations

The bottom topography of the submarine canyon TSF has been modeled as shown in Fig. 4b. It consists of straight line segments of constant depth (CD and HI) on either side of the canyon and of variable depth (DE, EF, FG, and GH) in the canyon area. The water depths and the horizontal intervals between segments have been specified considering the typical bottom topography of the canyon

\[ \begin{align*} 
Z_1 & = Z_3 = 60 \text{ m}; \quad Z_2 = Z_4 = 120 \text{ m}; \quad Z_3 = 600 \text{ m} \\
L_1 & = 6 \text{ km}; \quad L_2 = L_3 = 2.4 \text{ km}; \quad L_4 = 4.2 \text{ km}. 
\end{align*} \]

The values of different parameters have been chosen as

\[ \begin{align*} 
\rho_1 & = 1024 \text{ kg m}^{-3}; \quad \rho_2 = 1026 \text{ kg m}^{-3}; \quad H_0 = 60 \text{ m}. 
\end{align*} \]

The total flux \( d(T) \) was assumed to undergo a sinusoidal variation,

\[ d(T) = d_0 \sin \sigma T \quad \text{or} \quad D(T) = [d_0/(V^* H_0)] \sin \sigma T \]

where \( d_0 \) is the amplitude of tidal flux and \( \sigma \) is a tidal frequency (e.g., the M2 frequency) in nondimensional units. For the case of a flat bottom \( (dH/dX = 0) \), \( A + B \) and \( B - A \) of (10) and (11) are constant in time along the families of positive and negative characteristics respectively. This means that the perturbations can be generated only by the variable depth of the submarine canyon, and they propagate, as wave fronts, to the continental shelf of constant depth on both sides of the submarine canyon. Figure 4a shows the integration domain in the space–time \((X-T)\) plane and the calculation grid net in the submarine canyon. The integration is limited between the two characteristic curves \( C_+ \) and \( C_- \) that travel to the right and to the left from the initial perturbations at both edges of the submarine canyon (points N and M). Since the integration on the flat bottom (zones II and III in Fig. 4a) is particularly simple, the integration on the variable depth (zone I) will be treated first.

1) Integration in the zone I

The integration of the characteristic system of equations (8)–(11) has been performed by the standard method written in Abbott (1966). The calculation grid net, having square elements with the mesh lengths in nondimensional units, \( X = 5, \Delta T = 5 \), was used (Fig. 4a). The choice of \( \Delta X \) and \( \Delta T \) was somewhat arbitrary but limited by the stability criterion \( \Delta T < \Delta X/C_{\text{max}} \), where \( C_{\text{max}} \) is the maximum speed of the perturbations in the submarine canyon. A value of \( C_{\text{max}} = 0.66 \) corresponding to \( 0.7 \text{ m s}^{-1} \) in dimensional units was estimated, according to the classic formula \( C^2 = g'(h_2 - h_1)h_1/h_2 \).

We supposed that the system is sufficiently linear for the characteristic slopes \((dX/dT_+ \text{ and } dX/dT_-)\) to remain constant over the time step \( \Delta T \). Suppose that
the two linear characteristics $C_+$ and $C_-$ are projected from the grid point $P(i, j)$ and cut the $X$-axis at points Q and R (Fig. 4a), at which the characteristic slopes at $P(i, j)$ are determined from (8) and (9) with the conditions at $P(i, j − 1)$. Knowing $A$ and $B$ at the grid points at time $j − 1$, $A$ and $B$ at points Q and R can

Fig. 4. Schematic of (a) the integration domain in the space–time ($X$–$T$) plane and the calculation grid net and (b) the bottom topography of the submarine canyon TSF for the model experiment.

Fig. 5. Results of the model experiment, showing the generation of perturbations of the interface over the canyon by alternating tidal currents and their propagation as internal waves on both sides of the canyon.
be obtained by interpolation. The integration of (10) and (11), with \( A \) and \( B \) obtained previously at points Q and R, gives \((A + B)_o\) and \((B - A)_o\), which in turn yields the first approximation for \( A \) and \( B \) at \( P(i, j) \). A better approximation can be achieved by successive iterations, taking the characteristic slopes at \( P(i, j) \) as the averaged values between the slopes at \( P(i, j) \) and those at points Q and R. Going through the same procedure, we find the better points Q and R, from which we obtain the better approximation for \( A \) and \( B \) at \( P(i, j) \). Thus we can calculate \( A \) and \( B \) and also \( h_1 \), \( u_1 \) and \( u_0 \) at the grid points at time \( j \), as long as \( A \) and \( B \) are known at the previous time step \( j - 1 \), which requires the fixed initial conditions. The initial conditions \((T = 0)\) were

\[
\begin{align*}
    h_1(X, 0) &= 20 \text{ m}; \quad u_1(X, 0) = u_0(X, 0) = d(0) = 0 \\
    A(X, 0) &= \sin^{-1}\left\{1 - 2h_1(X, 0) / [H_0 H(X)]\right\} \\
    B(X, 0) &= 0
\end{align*}
\]

where \( H(X) \) can be determined considering the bottom topography. At the boundaries of the zone I \((X = M \text{ and } X = N)\), one of the two characteristic families has to be specified. Since \((A + B)_x\) and \((B - A)_x\) are constant outside these boundaries,

\[
\begin{align*}
(A + B)_x &= A(M, 0) = A(M, T) \quad \text{on the } M-T \text{ axis} \\
(B - A)_x &= -A(N, 0) = -A(N, T) \quad \text{on the } N-T \text{ axis.}
\end{align*}
\]

2) Integration in Zones II and III

In these zones, \((A + B)_x\) and \((B - A)_x\) being constant, the values of \( A \) and \( B \) stay constant along the family of characteristics \( C_+ \) (for the zone II) and \( C_- \) (for the zone III). From the previous integration in zone I, the values of \( A \) and \( B \) at grid points along the \( M-T \) and \( N-T \) axes are known. It is sufficient, therefore, to calculate the arrival distance \( X_{T_n} \) at time \( T_n (=n\Delta T) \) by the perturbations that have left the edges of the submarine canyon \((X = M \text{ and } X = N)\) at time \( T_j (=j\Delta T) \). \( X_{T_n} \) in zone II can be obtained by integrating (8),

\[
X_{T_n} = d_0(\cos \sigma T_j - \cos \sigma T_n)/(V^* \sigma H_0)
\]

\[
+ \left( \frac{1}{2} \cos A \cos B - \sin A \sin B \right) (T_n - T_j)
\]

where \( A = A(N, T_j) \) and \( B = B(N, T_j) \).

In zone III \( X_{T_n} \) can be obtained by integrating (9),

\[
X_{T_n} = d_0(\cos \sigma T_j - \cos \sigma T_n)/(V^* \sigma H_0)
\]

\[
- \left( \frac{1}{2} \cos A \cos B + \sin A \sin B \right) (T_n - T_j)
\]

where \( A = A(M, T_j) \) and \( B = B(M, T_j) \).

If we repeat the integration from all the other grid points on the \( M-T \) and \( N-T \) axes, we can construct the instantaneous profiles of the propagation of perturbations on the continental shelf.

c. Model results

From several experiments using different amplitudes of the total flux \( \sigma_0 \), it was found that the displacements of the interface increase slowly with increasing \( \sigma_0 \). Figure 5 shows the profiles of the interfaces \((h_1/H_0 \text{ with } H_0 = 60 \text{ m})\) for the case of \( \sigma_0 = 10.2 \text{ m}^2 \text{ s}^{-1} \), at different tidal phases, with \( \sigma T = 0 \) and \( \pi \) corresponding to slack water and \( \sigma T = \pi/2 \text{ and } \pi \) corresponding to maximum currents to the east and to the west respectively. The value \( 10.2 \text{ m}^2 \text{ s}^{-1} \), corresponding to a barotropic current of 0.17 m s\(^{-1}\) over the flat bottom of 60 m, was found to be the upper limit of the total flux in order for the characteristic system to be applicable to the model. For an amplitude slightly larger than this value, the characteristic curves become zero near the axis of the submarine canyon. The maximum displacement of the interface from the model is about 7 m, which is less than half of the typical displacement of 15–20 m from the isothermal fluctuations (Fig. 2). We failed, therefore, to simulate the large-amplitude internal tides even though we have used stronger barotropic tidal currents than those observed at TSF 13. However, the model results permit a qualitative explanation of the generation of internal tides by alternating tidal currents over the submarine canyon TSF and their propagation onto both sides of the canyon (Fig. 5). The most striking feature of the model results is that the slope of the ascending interface steepens, and that of the descending interface attenuates with time, evolving internal bores after sufficient time has elapsed (indicated by the thin arrows in Fig. 5). These asymmetric profiles, which would be due to nonlinear terms, agree well with those observed in the isothermal displacements (Fig. 2) and in the baroclinic currents (Fig. 3). However, with the appearance of internal bores the present hydrostatic model loses its physical significance (the vertical accelerations can no longer be neglected) and should be replaced by a nonhydrostatic model. The mean wave length and the speed of the wave front for the Mz wave have been deduced from Fig. 5, giving respectively about 22 km and 0.5 m s\(^{-1}\). This speed of propagation of internal waves is in near-perfect agreement with the theoretical value of 50.5 cm s\(^{-1}\), according to the classic formula in a two-layer ocean.

5. Conclusions

Important semi-diurnal variations of isotherms with a maximum displacement of about 30 m have been observed on the continental shelf near the submarine canyon TSF off Abidjan. The presence of strong semi-diurnal baroclinic currents (-0.17 m s\(^{-1}\)) as well as the asymmetric profiles of isotherms and baroclinic
currents, which would be due to the nonlinear effects of internal waves, are convincing evidence of the existence of semidiurnal internal tides. The first mode internal wave was found to have a dominant contribution to $M_2$ baroclinic currents accounting for 70% of the total fluctuation.

We examined a two-layer submarine canyon model for the generation of internal tides by oscillatory longshore barotropic currents across a submarine canyon. The model provides a plausible explanation for the generation and the propagation of internal tides by alternating tidal flows across the submarine canyon TSF. The asymmetric profiles of the interface from the model appear to be consistent qualitatively with those observed in the isothermal displacements and in the baroclinic currents. The estimated values of the wavelength and the phase speed of the $M_2$ internal wave are respectively about 22 km and 0.5 m s$^{-1}$.

However, we failed to simulate the large amplitude internal tides by using the present two-layer model. The model gives a 7 m displacement which seems to be a much smaller value compared to a typical displacement of 15–20 m from Fig. 2. If we say that to first order the two-layer model predicts the potential energy of the internal wave field correctly, then to go to a continuous model we have

$$\Delta \rho gh = \alpha' \xi g \xi \quad \text{or} \quad \xi^2 = \Delta \rho h / \alpha'$$

where $h$ is the interfacial displacement in the two-layer model, $\xi$ is the displacement of an isopycnal surface in the continuous case and

$$\alpha' = \partial \rho / \partial z = \rho N^2 / g.$$

Using values given in this paper, we obtain

$$\xi \approx 14 \text{ m}.$$

So we expect larger waves in the continuous case in better agreement with the observations. Baines (1974) presented a numerical procedure for the calculation of internal tides generated by the interaction of surface tide with arbitrary bottom topography and a wide range of realistic density stratifications. A detailed comparison of the observed phenomena with Baines’ (1974) model which accounts for a submarine canyon topography would be required.

Acknowledgments. This study is based on thesis work completed by the author (Park, 1979). The author wishes to thank Dr. Picaut for his help in getting this work underway and for providing access to the data. I acknowledge Dr. Cavanaugh for his continuous encouragement and valuable discussions throughout the work. I am grateful for the financial support, during my stay in France, of the Centre National d'Exploitation des Océans de France.

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