Internal Tides in the Southwestern Atlantic off Brazil: Observations and Numerical Modeling

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(Manuscript received 18 February 2005, in final form 26 September 2006)

ABSTRACT

Data collected from moored instruments, deployed over the southeastern Brazilian continental shelf during the summer and winter months of 2001, show internal tide activity near the shelf break. To help to elucidate the observations, a fully three-dimensional nonlinear primitive equation model is applied to simulate the regional barotropic and baroclinic tides. Two semidiurnal ($M_2$ and $S_2$) and two diurnal ($K_1$ and $O_1$) tidal frequencies are considered. Tidal surface elevations are relatively small over the whole modeled area, reaching maximum values of about 0.40 m for $M_2$ and 0.11 m for $O_1$. Comparison between observed and computed tide elevation and Greenwich phase shows reasonable agreement. When the baroclinic response of the model is investigated, stratification is prescribed using summer and winter climatology data of potential density. In this case, the model response to summer and winter stratifications is very similar and internal tides are generated over the shelf break and slope, with vertical displacements up to 25 m, and seaward propagation. Modeled semidiurnal tidal ellipses agree well with winter and summer observations. Observed diurnal tidal ellipses in the middle of the continental shelf and close to the shelf break during summer show an intensification through the water column that could not be represented by the model. Estimates of the total baroclinic $M_2$ offshore energy flux are about 3.5 and 0.5 MW considering winter and summer stratifications, respectively. Although these quantities are three orders of magnitude less than that estimated for regions known for intense internal tides, they refer to offshore fluxes computed for a very small section of the southeastern Brazilian shelf. This is the first published investigation into internal tides in the southwestern Atlantic Ocean off Brazil.

1. Introduction

Internal tides over continental margins are, in many locations, energetic flows that can influence mixing, sediment transport, biological productivity, and spatial and temporal variation in current flows. In thermally stratified tropical waters, the vertical and horizontal excursions associated with internal tides may be sufficient to contribute to significant nutrient fluxes onto the continental shelf (e.g., Holloway et al. 1985).

Numerous observations from many regions around the world have shown the existence of internal tides (see review by Huthnance 1989). But, as already pointed out by Sherwin et al. (2002), the eastern coast of South America has not been surveyed for this kind of internal wave. In this study, we focus on the region of the Dinâmica do Ecossistema da Plataforma da Região Oeste do Atlântico Sul (DEPROAS) project, localized in the northern part of the South Brazil Bight (Fig. 1). In this area, frequent coastal upwelling events occur within the coastal band between 21° and 23°S (Mascarenhas et al. 1971), especially during summer, associated with the prevailing easterly–northeasterly winds (Castro and Miranda 1998). One of their consequences is the intrusion of South Atlantic Central Water (SACW), bringing cold and nutrient-rich water toward the coast.

In this paper, baroclinic tides on the southeastern Brazilian continental shelf and slope based on observational data and numerical modeling are described. The manuscript is organized as follows. In section 2, the description and a preanalysis of the observed data used for model evaluation are given; the full three-dimensional model configuration is presented in section 3. In sections 4a and 4b, modeled surface elevations, barotropic and baroclinic currents, and energy fluxes...
are discussed in detail; in section 5, a summary and the conclusions are presented.

2. Observational data

The DEPROAS project is part of the Global Ocean Ecosystem Dynamics (GLOBEC). As part of this program, during cruises on board the Research Vessel (RV) Prof. W. Besnard in February and June 2001, three moorings were deployed across the northern part of the South Brazil Bight, off Cabo Frio (22.93°S, see Fig. 1). These moorings, placed for a period of approximately 30–60 days, were equipped with three, four, or five Falmouth Scientific, Inc., (FSI) acoustic current meters deployed at different depths with a 15-min sampling rate. In Table 1, details of the moored instrumentation are listed.

Data recovery from the current meters was good, with all them returning data. The mooring array provided results ranging from 200 m near the shelf break (Fig. 1, site 3) to 50-m depth on the inner shelf (Fig. 1, site 1) with satisfactory vertical coverage.

The most remarkable tidal feature observed in the data is the presence of large semidiurnal internal tides at site 3. Figure 2 shows snapshots of depth–time contoured distributions of temperature and cross-shelf currents at the site mentioned. At this point, located near the shelf break, isotherms at middepths oscillate with a height of about 30 (summer) and 20 (winter) m and with a period of approximately 12 h (Fig. 2, left). Although there is some higher-frequency variation in the first 30 m of the water column during summer, there is clearly, in both seasons, a semidiurnal internal tide oscillation that is approximately sinusoidal. The velocities (Fig. 2, right) show a phase reversal as between the

<table>
<thead>
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<th>Mooring</th>
<th>Water depth (m)</th>
<th>Current-meter and temperature sensor depths (m)</th>
<th>Period</th>
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<td>27 Jun–11 Aug 2001</td>
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<td>W2</td>
<td>99</td>
<td>22, 75, 85, 95</td>
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</tr>
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<td>W3</td>
<td>201</td>
<td>22, 85, 155, 185, 201</td>
<td>29 Jun–12 Aug 2001</td>
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</table>

Fig. 1. Map of the southeastern Brazilian shelf and adjacent waters, showing bottom topography (m). Numbered black triangles indicate mooring positions. The location of Cabo Frio is indicated by the white star, and the tide gauge observation site is marked with the black circle. The area investigated with the numerical model is delimited with a solid black line, forming a closed polygon. The dotted line indicates the slice for which the modeled internal tide results are presented in the following figures.
upper and lower layers of the water column and correspond well with the elevations seen on the time sequence of isothermal depths. The phase relationship between elevations and velocities (shoreward middepth flow at the peak of the wave) shows the waves to be propagating seaward.

At mooring 2, located on the middle shelf, the data show no semidiurnal internal tide activity, as observed at site 3, but power spectrum analysis of the temperature data indicates the presence of a diurnal period oscillation during summer (Fig. 3). Only near the bottom (Fig. 3, bottom) is its amplitude less evident, probably resulting from the effect of bottom friction. During winter (Fig. 4), subtidal oscillations (of periods greater than 2 days), associated with the passage of frontal systems (Castro and Miranda 1998), are dominant in the spectrum.

Site 1 was located near the coast. During both seasons, temperature data (not shown) do not indicate any significant stratification through the water column. Probably for this reason, tidal currents, discussed later in the paper, show little depth dependence above the bottom Ekman layer.

An indication of the potential generation sites of internal tides may be deduced from the linear internal wave theory, whereby the bottom slope $b_s$ is compared with the slope of the internal wave characteristics $c$, as defined by (Baines 1982; Craig 1987)

$$c^2 = \frac{\omega^2 - f^2}{N^2 - \omega^2},$$

provided that $\omega^2 > f^2$; here, $f$, $N$, and $\omega$ are the inertial, Brunt–Väisälä, and tidal frequencies, respectively. Regions where the ratio $\alpha$ between $b_s$ and $c$ is equal to 1 (critical slopes), or where the seafloor is steeper than the characteristics (supercritical slopes), are likely sites for internal tide generation. Where the ratio $\alpha$ is less than 1 (subcritical slopes), it is not to be expected that internal tides should be generated. If $\alpha = 1$, the internal tide generated will propagate along slope and if $\alpha > 1$, it will propagate in an offshore direction.

Using summer and winter climatology data of temperature and salinity (Levitus 1982), the ratio $\alpha$ related to $M_2$, $S_2$, $O_1$, and $K_1$ tidal frequencies was computed for a cross-shelf slice through the mooring positions (see Fig. 1). Figure 5 presents $\alpha$ values taking $M_2$ and $K_1$ into consideration; similar results were obtained for $S_2$ and $O_1$, compared, respectively, with $M_2$ and $K_1$. In general, summer and winter stratification resulted in similar $\alpha$ values for each frequency. On the inner and middle continental shelf, $\alpha$ varies from supercritical to

Fig. 2. Time sequence of (left) isothermal depths (°C) and (right) cross-shelf component of velocity (cm s$^{-1}$) over a 25-h period from thermistor and current-meter measurements at location 3 during (top) summer and (bottom) winter. Negative velocities (broken contours) indicate onshore and positive (solid contours) offshore propagation.
subcritical, respectively, for $\omega$ corresponding to the $M_2$ tidal frequency. It becomes supercritical closer to the shelf break and on the slope, indicating regions of internal tide generation and seaward propagation. Such a result is consistent with the observed data at 200 m (site 3). On the middle slope (170 km, 1500-m depth), a small area becomes critical under summer stratification. Over most of the lower slope, $\alpha$ is subcritical for both seasons but an area located between 100 and 125 km is supercritical under summer stratification. In the case of the $K_1$ frequency, the slope is supercritical for much of the cross-shelf transect, indicating that it is a potential region for the generation of internal waves with diurnal period. Seasonal differences related to $\alpha$ are found mainly on the lower slope between 50 and 100 km, where $\alpha$ is close to critical during winter but supercritical during summer.

Although the theory used above may be useful for the interpretation of observations, it has some limitations, for example, its assumption of linear dynamics and its omission of any consideration of along-slope variations of bottom topography. Moreover, internal tide generation also requires barotropic tidal flow across the topographic slope on critical and supercritical slopes. Because of the lack of observations within the region of the slope, it is impossible to identify generation sites accurately and the propagation characteristics of the semidiurnal internal tides. For these reasons, and so as better to understand the internal tide activity in the region, use will be made of a full three-dimensional numerical model to help elucidate the observations made.

The observed data will be used for model comparison. Both summer and winter current-meter data were harmonically analyzed using the algorithms developed by Foreman (1977, 1978) and will be discussed in detail when comparing them with the model results. Tidal analyses were performed using hourly raw data for the entire length of each record. Oceanographic processes other than tidal currents have not been removed from the raw data.

3. Model configuration

a. The numerical model

The numerical modeling has been undertaken using the S-Coordinate Rutgers University Model (SCRUM; Song and Haidvogel 1994), a hydrostatic, free sea surface, primitive equation ocean circulation model. This model was applied in the investigation of tides and tidal mixing in the southern Weddell Sea, Antarctica (Pereira et al. 2002). One single modification has been...
made, including the tide-generating force for the four main tidal constituents ($M_2$, $S_2$, $K_1$, and $O_1$) in the model's equations. Because the form of this term is standard (see Schwiderski 1980) it will not be described here.

The governing equations are discretized on an Arakawa C grid using a horizontal orthogonal curvilinear system, and in the vertical a sigma (terrain following) coordinate system that avoids a steplike representation of the seafloor and the lateral boundaries is employed. The reader is referred to Haidvogel and Beckmann (1999) for a full description of the standard equations and their numerical implementation. For our regional application, potential density is the only state variable.

The subgrid-scale parameterizations are equal to that described in Pereira et al. (2002) and are briefly set out here.

The vertical eddy viscosity and diffusivity coefficients are computed using the Mellor–Yamada level-2.5 turbulence closure scheme (Mellor and Yamada 1982) with modification by Galperin et al. (1988). The background vertical viscosity and diffusivity are set at $10^{-5}$ m$^2$ s$^{-1}$.

The lateral viscosity and diffusivity coefficients are chosen to be a quadratic function of the horizontal grid spacing. At the bottom, a velocity-dependent quadratic bottom friction is used.

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Fig. 4. Same as Fig. 3, but during winter.

![Fig. 4](image_url)

Fig. 5. Ratio $\alpha$ considering summer (solid line) and winter (dotted line) stratification related to $M_2$ and $K_1$ tidal frequencies plotted together with bottom topography (m; dashed line) of a transect joining the mooring positions (see Fig. 1). The thick line marks $\alpha = 1$. 

![Fig. 5](image_url)
b. Model domain, bathymetry, and grid resolution

The model domain covers the region delimited by the solid black line in Fig. 1. Because the character of the internal tides has high spatial variability, the horizontal grid must be fine enough to resolve an internal tide wavelength. Taking wavelength scales as \( \frac{NHT}{\pi} \), where \( H \) is water depth and \( T \) is the wave period (12.42 h for the \( M_2 \) tidal constituent), and given typical values of these variables for the region (\( \frac{N}{H} = 0.007 \text{ s}^{-1} \), see Fig. 7), wavelengths will vary from 100 km at 1000 m to 5 km at 50 m. Figure 6 shows the orthogonal curvilinear grid that has 70 grid points in the \( x \) direction and 50 grid points in the \( y \) direction. Such a grid leads to a resolution of about 5–7 km over most of the model domain in both directions, which is a grid spacing that combines fine resolution with coverage of a large domain. Maximum and minimum grid spacings of 10 and 3 km, respectively, are to be found near the coast. The \( x \) and \( y \) directions of the orthogonal grid are not aligned with the latitude and longitude coordinates so as to avoid land points within the model domain. Each grid point has a different rotation angle in relation to the north–south and east–west directions that will be used to place the model’s results and observations within a common coordinate system.

Vertically, the domain is divided into 24 sigma levels nonequidistantly distributed over the water column, with high resolution near the bottom and pycnocline. The nonlinear stretching employed led to a vertical grid spacing near the upper and lower boundaries of 1 m on the shelf and 30 m in the deep ocean.

Bottom topography was taken from the 2′ resolution dataset of Smith and Sandwell (1997) based on satellite gravimetry. The minimum water column thickness was set to 10 m. The domain is open on the two-shelf boundaries and on the offshore boundary.

c. Initialization, forcing, and model parameters

In this study, the following three numerical experiments have been made: a barotropic and two baroclinic cases, considering summer and winter stratifications. When the baroclinic response of the model is examined, the potential density is initialized as a horizontally and vertically stratified field. Thus, the seasonal climatology of temperature and salinity (Levitus 1982) was interpolated on the numerical grid and the potential density was then calculated. Horizontally a bilinear interpolation was used, and vertically the spline interpolation was employed. Figure 7 shows typical density and buoyancy profiles for the region.

The model is forced through the open boundaries with a barotropic tidal wave computed with tide height coefficients obtained from the Ocean Topography Experiment (TOPEX)/Poseidon global tidal model TPXO.5 (Egbert and Erofeeva 2002), coupled with the numerical model. The four main tidal constituents \( M_2 \), \( S_2 \), \( K_1 \), and \( O_1 \) are considered.

For the barotropic and baroclinic flows, a gradient condition is applied along the open boundaries. A relaxation scheme (Martinsen and Engedahl 1987) is applied to the tracer field, relaxing the density value to its initial value. This condition is applied to the last three grid points of all the open boundaries.

The buoyancy and momentum fluxes through the sea surface are set at 0.

Each model calculation begins from rest and is integrated for a period of 60 days. The forcing is gradually increased to its full strength within the first 5 days of model integration to reduce the effect of inertial wave excitation. The model time step is limited by grid resolution; it is set at 10 s for the depth-dependent mode and 5 s for the depth-averaged mode.

Hourly fields from the last 30 days of model results (velocities and free surface elevation) are harmonically analyzed (Foreman 1977, 1978) to separate the response at the four tidal frequencies.

4. Model results and discussion

a. Barotropic tides

In this section, we present the model’s results for the barotropic case, that is, considering a homogeneous ocean.
The amplitude and phase of the surface elevation field at the semidiurnal ($M_2$ and $S_2$) and diurnal ($K_1$ and $O_1$) frequencies are presented in Figs. 8 and 9, respectively. The $M_2$ tide propagates northeastward with amplitudes varying from 20 to 28 cm in the deep ocean. Along the coastline, the $M_2$ amplitude is nearly 1.5 times higher from south to north. Its amplitude ranges from 26 cm in the southern corner of the model domain to up to 40 cm in the northern part where the continental shelf is shallower. The $S_2$ constituent (Fig. 8, right) exhibits similar spatial features but with smaller amplitudes. The mean ratio over the whole model domain from $S_2$ amplitudes to $M_2$ amplitudes is 0.6. For both semidiurnal tides, their coamplitude and cophase distribution are characterized by a coastal Kelvin wave with amplitudes decreasing away from the coast.

The diurnal ($K_1$ and $O_1$) tidal waves propagate equatorward, decreasing the amplitude northward (Fig. 9). Higher amplitudes are found near the coast, reaching 6.6 and 11 cm for $K_1$ and $O_1$, respectively. The mean
ratio between $K_1$ and $O_1$ amplitudes is 0.58, a value very similar to that of the semidiurnal ratio.

Observations from one single tide gauge station located on the continental shelf (Fig. 1) were available for comparison with model results (Mesquita and Harari 2000). Table 2 lists observed and calculated elevation amplitudes and Greenwich phases for the four tidal constituents considered. Modeled semidiurnal amplitudes are a few centimeters higher than the observations; this is also true for the $O_1$ computed elevation. Such differences are attributed to discrepancies between the real bottom topography and its representation in the numerical grid.

Barotropic tidal current ellipses are presented in Fig. 10 for the $M_2$ and $K_1$ constituents. A similar pattern was obtained for $S_2$ and $O_1$ tidal ellipses as compared with $M_2$ and $K_1$, respectively. In deep regions, tidal currents are small [$O(2 \text{ cm s}^{-1})$ for $M_2$ and $O(0.5 \text{ cm s}^{-1})$ for $K_1$], and ellipses have great eccentricity (ratio of semiminor axis to semimajor axis). Whereas $M_2$ barotropic ellipses rotate clockwise, $K_1$ rotate counterclockwise.

Only over the shelf do the ellipses assume a significant magnitude. The $M_2$ tidal currents reach 8 cm s$^{-1}$ northward from Cabo Frio. Most of the ellipses rotate counterclockwise and have their major axes almost perpendicular to the cross-shelf bottom topography, indicating strong currents across the topographic slope, especially southward from Cabo Frio. In such regions, the stratified fluid is forced more vigorously up and down the topographic gradient and the forcing mechanism for the generation of internal tides is at its strongest. Diurnal barotropic ellipses reach 1.5 cm s$^{-1}$ on the shelf and, over most of the model domain, their major axes are parallel to the coast (Fig. 10, right).

b. Baroclinic tides

In this section, we examine the vertical structure of computed baroclinic currents closely and compare them with the current-meter observations presented in section 2. Baroclinic tides are discussed in terms of the horizontal baroclinic current and vertical displacement. Results are presented along the transect joining the mooring positions (y–z, see Fig. 1) that intersect the continental margin. The discussion is limited to $M_2$ and $K_1$ tidal frequencies. Respectively, $S_2$ and $O_1$ baroclinic currents were similarly affected by stratification as compared with $M_2$ and $K_1$.

1) $M_2$ FREQUENCY

Figure 11 shows modeled $M_2$ semimajor axis (left) and vertical displacement (right), considering summer (top) and winter (bottom) stratifications along the selected vertical transect. Although baroclinic tidal currents were slightly increased for the winter simulation, very similar numerical results were obtained for both seasons. There is clearly a semidiurnal internal tide with its strongest motion centered on the upper

<table>
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<td>Frequency</td>
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</tr>
<tr>
<td>$K_1$</td>
<td>6.0</td>
</tr>
<tr>
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<td>9.4</td>
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</table>
continental slope. The motion appears to propagate down the continental slope, reaching the 1800-m isobath.

Semidiurnal $M_2$ vertical displacements (Fig. 11, right) in excess of 25 m are obtained over the steepest parts of the continental slope near the seabed. These large values result from the direct forcing of vertical motions over the slope by the barotropic tide and indicate generation regions for the internal tide. Along the slope of the considered cross section, the topographic slope is steeper than the slope of characteristics ($\alpha > 1$) and propagation is directed toward deep water. Figure 12 shows the paths of the internal tide characteristics [Eq. (1), section 2] for summer and winter stratifications, and the paths confirm the offshore propagation of the internal tide.

Figure 13 (left) shows the modeled depth-integrated $M_2$ baroclinic energy flux for the considered cross section computed in accordance with Holloway (1996). Over most of the slope, the flow of energy is offshore with peak values of between around 20 and 10 W m$^{-2}$ for winter and summer, respectively. Over the upper slope near the shelf break there is a net onshore energy flux of approximately 5 W m$^{-2}$, and this is rapidly dissipated with very little energy propagating far onto the shelf. Although internal tidal currents and vertical displacement amplitudes follow a similar pattern for summer and winter stratifications, the depth-integrated energy flux in summer is significantly weaker than in winter (i.e., about half that seen in winter).

As a means of verifying the model, comparisons between observed and modeled $M_2$ tidal ellipses are shown in Figs. 14, 15, and 16 (left). In these figures, the barotropic component was not separated from the baroclinic component of the current. As expected from a preanalysis of the observations (see section 2), $M_2$ tidal currents are barotropic at station 1 (Fig. 14, left), with little variation across the water column. They reach 3 cm s$^{-1}$ and rotate counterclockwise as shown by the modeled barotropic ellipses (section 4a). Modeled winter and summer tidal ellipses are very similar, although, when winter stratification is considered, the eccentricity of the tidal ellipses is little increased. Model winter and summer ellipses capture the observed rotation direction, ellipse inclination, and barotropic behavior.

At site 2 (Fig. 15, left), a small seasonal variation of the baroclinic tidal current is present with greater velocities during winter. The model captures this variation. Modeled and observed $M_2$ tidal ellipses have a
counterclockwise rotation through the whole water column and are about 3 and 2.5 cm s\(^{-1}\), considering winter and summer stratifications, respectively.

Observed \(M_2\) tidal ellipses at station 3 (Fig. 16, left) exhibit considerable vertical variation, confirming the internal tide signal seen in depth–time contoured distributions of temperature and cross-shelf currents (Fig. 2). Although the internal tide intensity is very similar for both seasons, differences in the ellipse inclination, phase, and eccentricity are found between summer and winter observations, indicating a seasonal variation of the internal tide. The model could better represent the major features of the tidal ellipses observed during winter months. When summer stratifica-

![Diagram](image1)

Fig. 11. Modeled \(M_2\) (left) semimajor axis (cm s\(^{-1}\)) and (right) vertical displacement (m) considering (top) winter and (bottom) summer stratification across the vertical slice \((y-z)\; \text{see Fig. 1}\).

![Diagram](image2)

Fig. 12. Paths of the \(M_2\) characteristics for (left) summer and (right) winter stratifications across the vertical slice \((y-z)\; \text{see Fig. 1}\).
tion was considered, discrepancies of the ellipse eccentricity are found through the upper water column.

2) $K_1$ FREQUENCY

The $K_1$ semimajor axis and vertical displacements are shown in Fig. 17 for the selected cross section indicated in Fig. 1. When winter stratification was considered (top), slight increased baroclinic tidal currents were modeled comparing them with that obtained for summer stratification (bottom). However, their spatial structures were very similar. For both seasons, the strongest currents [$O(0.5 \text{ cm s}^{-1})$] are found near the seabed and surface over the slope and continental rise. Little motion appears to propagate across the outer and middle continental shelf. The vertical displacement (Fig. 17, right) show a series of cell-like structures over the slope and continental rise with the maximum amplitude occurring near the seabed around 1000 m.

The depth-integrated energy flux (Fig. 13, right) is very low (peak value of less than 1 W m$^{-2}$) for summer and winter. There is no energy flowing onto the shelf.

At all three mooring positions model results have a
satisfactory agreement only with the observations made during winter. In this case, the vertical structure of modeled and observed current ellipses is dominated by the barotropic component. Ellipses rotate clockwise at site 1 and counterclockwise at sites 2 and 3, as predicted from the barotropic simulation (section 4a).

During summer, observed diurnal tidal ellipses show a strong variation through the water column, especially at stations 2 (Fig. 15, right) and 3 (Fig. 16, right); this is not represented by the model. From the temperature time series plotted in Fig. 3 at different depths, it may be seen that stratification is very weak at site 2 during summer and thus probably unable to sustain an internal wave. Furthermore, α values (Fig. 5) do not indicate internal tide generation with diurnal periods over the continental shelf or onshore propagation of waves gen-

![Fig. 15. Same as Fig. 14, but for site 2.](image1)

![Fig. 16. Same as Fig. 14, but for site 3.](image2)
erated over the slope. Such notable differences between the model and observations can arise from non-linear interactions between tides and buoyancy-driven currents. The presence of a diurnal period signal in the summer temperature data (see Fig. 3) may be related to the diurnal cycle resulting from the greater absorption of solar shortwave radiation during summer than winter.

5. Summary and conclusions

In February and June 2001, three moorings were deployed across the southeastern Brazilian shelf. The observations obtained from them indicated the presence of semidiurnal internal tides near the shelf break and the existence of a strong diurnal period signal in the temperature data in the middle of the continental shelf and on the shelf break, during summer. To investigate the generation and propagation of the internal tide, a three-dimensional tidal model with two basic configurations—one with a homogeneous ocean and the second with stratified fluid—was used. Four tidal frequencies were considered, $M_2$, $S_2$, $K_1$, and $O_1$.

Tidal surface elevations are relatively small over the whole region, reaching maximum amplitudes of about 40 cm near the coast for $M_2$. Modeled tidal amplitudes and Greenwich phases agree reasonably well with the available observations. Tidal currents in the unstratified case are small in the deep ocean [$O(2 \text{ cm s}^{-1})$ for $M_2$ and $O(0.5 \text{ cm s}^{-1})$ for $K_1$], reaching a significant magnitude only over the continental shelf (about 8 cm s$^{-1}$ for $M_2$ and 1.5 cm s$^{-1}$ for $K_1$).

When stratification was included, internal tides were generated over the slope and propagated seaward for all four frequencies considered. Modeled tidal ellipses were compared with the observations made. In general, the model retained the essential characteristics of semidiurnal and diurnal tidal currents at station 1. At station 2, reasonable agreement was found between the observed and modeled semidiurnal tidal currents but large discrepancies were obtained for diurnal tidal currents when summer stratification was considered. Internal tides modeled at station 3 had a similar current intensity to those observed, but the model did not adequately represent the inclination and phase of the observed tidal ellipse. It should be kept in mind that the
high degree of spatial and temporal variability seen in the internal tide observation and modeled fields constitutes a demanding test for a comparison between observations and model predictions.

The observed diurnal period oscillation observed in the summer temperature data is not related to internal tide activity. It might be related, rather, to the greater absorption of solar shortwave radiation during summer than winter. The result is the generation of buoyancy currents that interact non-linearly with tidal currents, thus contaminating the diurnal signal. Because the model does not include buoyancy and momentum fluxes through the sea surface, such conditions cannot be represented by the model’s results.

Baroclinic energy fluxes computed from the model indicate that semi-diurnal baroclinic tides radiate offshore along the continental slope. Estimates of the depth-integrated energy fluxes were typically $O(10 \text{ W m}^{-2})$. To estimate the offshore flux for the model domain, the depth-integrated energy flux is summed along the offshore model boundary (just outside the relaxation zone). The integrated offshore flux for the $M_2$ frequency is about 3.58 and 0.51 MW ($1 \text{ MW} = 10^6 \text{ W}$) for winter and summer, respectively. Although these values refer to the power contained in internal tides generated in a very small section of the southwestern Atlantic Ocean, these flux quantities are three orders of magnitude less than those estimated for several other regions of the world; for example, on the Australian northwest shelf, Holloway (2001) has estimated offshore fluxes between 1.01 and 1.77 GW ($1 \text{ GW} = 10^9 \text{ W}$), depending on stratification; on the shelf off northern British Columbia, Cummins and Oey (1997) found an offshore baroclinic energy flux of about 0.60 GW. Baines (1982) has also estimated offshore baroclinic fluxes for different regions around the world. The values obtained by him were also of the order of 10$^9$ GW. In all the areas cited, internal tides with intense horizontal and vertical currents were modeled. This was not the case here, where baroclinic currents are just a few centimeters per second, and, consequently, the power contained in the internal tide is comparatively reduced.

Growing evidence suggests that internal tides provide much of the power for mixing and the accompanying vertical circulation in the deep ocean (e.g., Sjöberg and Stigebrandt 1992; Munk and Wunsch 1998); however, theoretical estimates of tidal mixing still lack observational verification in various regions of the world, such as the eastern coast of South America. This paper is the first to have reported on and investigated internal tides in the area mentioned.

6. Outlook

Internal tides over the continental shelf and slope regions are characterized by high spatial and temporal variability, propagating both shoreward and seaward. The waves are often energetic and can contribute significantly to ocean mixing (Polzin et al. 1997). Furthermore, they can lift water parcels up to 40 m up the water column.

As mentioned in the introduction, the southeastern Brazilian coast is subject to upwelling events, especially during summer, with the penetration of the South Atlantic Central Water extending far onto the shelf. These events are really important for the local ecosystem, bringing cold water rich in nutrients on to the continental shelf (e.g., Metzler et al. 1997). The existence of internal tides in this region may also contribute to the enrichment of coastal waters with nutrients through the upwelling of subthermocline waters and mixing, which are subjects to be investigated in the near future.

Acknowledgments. We thank André Belém for his helpful discussions. The DE-PROAS project is supported by Programa de Núcleos de Excelência (PRONEX), Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), and Financiadora de Estudos e Projetos (FINEP). This project was funded by a CNPq grant (Contract 301379/01-7) and Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP; Contract 03/12985-0).

REFERENCES

Haidvogel, D. B., and A. Beckmann, 1999: Numerical Ocean Cir-