Internal tide dynamics in a topographically complex region: Browse Basin, Australian North West Shelf

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Field observations and numerical circulation modeling revealed the spatial variability of the tidally driven dynamics in the topographically complex, continuously stratified, macrotidal environment of the Browse Basin on the Australian North West Shelf. Internal wave generation occurred at a number of discrete topographic features, and the resultant interaction of multiple waves led to a spatially variable internal wave climate. The generation of baroclinic energy was most intense in regions where the barotropic tide was aligned with steep topography. Generation of low-mode internal waves occurred at the inner-shelf break, where the ratio of tidal excursion distance to topographic length scale was large. In contrast, generation of high-mode beam-like internal waves occurred at the outer-shelf break, where the ratio of tidal excursion distance to topographic length scale was very small. The most efficient conversion from barotropic to baroclinic energy occurred at the outer-shelf break. The internal waves generated at the inner- and outer-shelf breaks interacted to produce a partly standing internal wave, resulting in a large along-shelf energy flux, and discrete locations with small ratios of horizontal kinetic energy to available potential energy. This phenomenon is likely to occur in other regions with semienclosed topography and multiple generation sites.


1. Introduction

Ocean mixing driven by internal waves, particularly those of tidal origin, is of importance in maintaining ocean stratification [Munk and Wunsch, 1998]. The transfer of energy from the barotropic tides into internal tides and, in turn, into turbulence and mixing is still not well understood [e.g., Ivey et al., 2008; Wunsch and Ferrari, 2004] and has been the focus of many studies, including recent work near the Hawaiian Ridge [Rudnick et al., 2003], on the European Shelf [Green et al., 2008], and on the Australian North West Shelf (NWS) [Katsumata, 2006]. The NWS has a strong barotropic tide with a semidiurnal spring-neap cycle [e.g., Holloway et al., 2001; Van Gastel et al., 2009] and is one of the most globally significant regions for tidal energy dissipation [Egbert and Ray, 2001]. The focus of this study is to understand the tidally driven dynamics and the internal wave generation, propagation and dissipation processes within the Browse Basin at the northern end of the NWS (Figure 1).

The generation of internal waves by tidal motions has been the focus of many studies, and recent reviews are given by Vlasenko et al. [2005] and Garrett and Kunze [2007]. Internal tides occur in stratified fluid when the oscillatory barotropic tide interacts with sloping topography to produce vertical motions and local internal pressure perturbations. These local perturbations can propagate as waves, leading to the transmission of energy to regions remote to the original generation site. Determining the conversion of energy from the barotropic to the internal tide and the proportion of the internal energy that is able to propagate away from the generation region is central to characterizing the internal wave dynamics of a region.

Garrett and Kunze [2007], for example, identified two main parameters influencing the type of internal wave response and the efficiency of conversion from the barotropic to the baroclinic tide: the slope criticality parameter \( \gamma \), and the tidal excursion parameter. The slope criticality parameter \( \gamma \) is the ratio of the local topographic slope \( S \) to the internal wave slope \( \alpha \):

\[
\alpha = \left( \frac{\omega^2 - f^2}{N^2 - f^2} \right)^{\frac{1}{2}}.
\]  

Here \( \omega \) is the forcing frequency, \( f \) the Coriolis frequency and \( N \) the buoyancy frequency. Although an internal response is
Figure 1. (a) Map of the Australian North West Shelf with 200, 500, and 1000 m isobaths indicated. The Browse Basin region is indicated by the dashed gray box, and the ROMS model domain is indicated by the black box. (b) Shaded gray-scale relief map of bathymetry (m) and important topographic features of the region indicated by dashed gray box in Figure 1a. Mooring locations are indicated by the black diamonds.

Possible for all values of $\gamma$, as $\gamma$ approaches one, the topography is termed critical and conversion is most efficient [e.g., Lim et al., 2010]. Internal wave beams can then radiate away in both upslope and downslope directions from the critical point. The tidal excursion parameter is defined as the ratio of the tidal excursion length $u_0/\omega$, where $u_0$ is the amplitude of the cross-isobath barotropic tide, to the characteristic length scale of the local topography, $L$. When the tidal excursion parameter $u_0/\omega L$ is less than one, a modal response is observed [e.g., Echeverri et al., 2009]. As $u_0/\omega L$ approaches one, the nonlinear advective terms become important and nonlinear features such as hydraulic jumps and enhanced dissipation and mixing may be observed [e.g., Legg and Klymak, 2008]. The mechanisms controlling both local mixing and energy loss versus baroclinic energy radiation from tidal generation sites requires further investigation.

Three-dimensional topography complicates the generation and propagation dynamics of the internal tide. Analytical solutions of the generation of internal tides using idealized topography, including seamounts and ridges [Baines, 2007; Llewellyn Smith and Young, 2002] have offered insight to the controlling mechanisms, but ocean environments often present far more complex topography. For example, many island chains and seamounts do not exist in isolation; instead, they can rise up from a continental slope. Numerical techniques are essential in such environments with complex topography. Numerical investigations of internal wave generation with three-dimensional topography have been conducted using idealized topography [e.g., Holloway and Merrifield, 1999; Munroe and Lamb, 2005] as well as realistic topography [e.g., Carter et al., 2008; Niwa and Hibiya, 2004].

In this study, we focus on the internal wave dynamics of the Browse Basin on the northern section of the Australian North West Shelf (NWS), a region where there is a rich and complex internal wave climate due to the combination of the persistent density stratification, the intensity of the barotropic tide and the three-dimensional complexity of the topography. The Browse Basin is characterized by both an inner- and outer-shelf break; in addition, Scott and Seringapatam Reefs rise steeply from 500 m depth at the outer-shelf break. Although the internal tide dynamics of the southern NWS have been the focus of some field [e.g., Holloway, 1994; Holloway et al., 2001] and numerical studies [e.g., Holloway, 2001; Katsumata, 2006; Van Gastel et al., 2009], the northern NWS has received little attention. The only previous study on the Browse Basin region, by Wolanski and Deleersnijder [1998], noted the presence of an internal tide, generated by Scott Reef; their two-layer numerical model was able to replicate some of the main flow features.

This paper describes the Browse Basin internal wave dynamics using data from both a recent field campaign and a three-dimensional numerical model. We utilized the numerical model to aid the interpretation of the spatially sparse field data, and to examine the generation, propagation and dissipation of internal waves over the entire region. Our paper is organized in the following way. We present the field site, the setup of the numerical model and the analysis methodology in section 2. Section 3 describes the background conditions at the study site. We describe the internal tide field observations and evaluate the model in section 4. In section 5, we use the numerical model to elucidate the mechanisms and regions of internal wave generation, and explore the internal wavefield over the Basin resulting from these multiple generation sites.

2. Methodology

2.1. Study Site

The Browse Basin, at the northern extremity of the NWS, is situated off the West Kimberley coast in far northern Western Australia, extending from the Rowley Shoals at 17°S northward to Ashmore Reef at 12.3°S (Figure 1). The topography of the region is complex, consisting of a wide continental shelf, two shelf breaks, and steep-sloped reef and island chains along the outer-shelf break. The Browse Basin has a steep, step-like feature
between 100 and 250 m depth, with a slope of 0.5–1.0° (the inner-shelf break), followed by a more gentle slope out to 600 m depth, where the slope increases to 3°–4° (the outer-shelf break) and runs down into the abyssal ocean, with depths greater than 2000 m. Upslope-aligned canyons, up to 3 km in width and 300 m in depth, pit this steep outer-slope region and extend from a water depth of 1500 m up to 700 m. These deepwater canyon features may enhance the upwelling movement of water near the outer-shelf break. Scott and Seringapatam Reefs rise very steeply, with a slope greater than 15°, from a depth of 500 m on the outer shelf all the way to the surface. Scott Reef, the larger of the two, is approximately 40 km from north to south at the surface and consists of two near-circular reefs separated by a 500 m deep channel.

The semidiurnal barotropic tidal components, M2 and S2, dominate the ocean dynamics of the region [Holloway, 1983]. On the NWS, the tidal elevations increase from southwest to northeast, with the greatest tidal ranges near the Kimberley coast (>10 m). The TPXOv7.1 global tidal model [Egbert and Erofeeva, 2002] reveals a constant phase line along the entire length of the North West Shelf with an amphidromic point, located in the Timor Sea to the north, which dictates a northern limit of the M2 elevation increase at Ashmore Reef (12.3°S, 123.0°E).

### 2.2. Field Experiment

In order to study the spatial variability of both the barotropic and internal tide dynamics of the Browse Basin, three moorings were deployed close to the dominant topographic features. Separated by a horizontal distance of 50–70 km, the moorings were located at: the outer-shelf break in 550 m of water (referred to as B2 herein), the base of the inner-shelf break in 200 m of water (referred to as G2 herein), and along the southeastern wall of Scott Reef in 300 m of water (referred to as H2 herein) (Figure 1 and Table 1).

On the mooring, instruments recorded current velocity (InterOcean CM04 current meters) and seawater temperature (Starmon Mini temperature loggers) at specific depths throughout the water column. Current meters were staggered over the depth, with the greatest resolution in the upper 250 m; vertical spacing ranged from 50 to 130 m (Table 1). Temperature loggers were spaced at 20 m intervals in the upper 250 m of the water column, and at 40 m intervals below this depth (Table 1). The instruments were deployed from September 2006–September 2007 and recorded at 1 min intervals; we focus primarily on the data from February 2007 in this manuscript.

We followed the methods outlined by Nash et al. [2005] to identify the internal wave induced perturbations of horizontal velocity \( \mathbf{u}'(z,t) \), and density, \( \rho'(z,t) \). The density perturbation is given by \( \rho'(z,t) = \rho(z,t) - \bar{\rho}(z) \), where \( \rho(z,t) \) is the measured value and \( \bar{\rho}(z) \) is the time mean value. The perturbation or baroclinic velocity is given by \( \mathbf{u}'(z,t) = \mathbf{u}(z,t) - \mathbf{u}_0(t) \), where \( \mathbf{u}(z,t) \) is the measured velocity, \( \mathbf{u}_0(z) \) is the time-mean component, and \( \mathbf{u}_0(t) \) the depth-independent or barotropic component of the velocity field. The barotropic component of the velocity is given by the condition \( \mathbf{u}_0(t) = \frac{1}{\rho_0} \int H_z |\mathbf{u}(z,t) - \mathbf{u}_0(z)| dz = 0 \).

The time-mean component of velocity and density was found by applying a low-pass 30 h third-order Butterworth filter to the raw data to remove any nontidal components. The velocity components were rotated to align with the local bathymetry at each of the mooring locations so that \( u = (u, v) \), where \( u \) is the cross-isobath and \( v \) the along-isobath component. Seasonal stratification conditions were determined by low-pass filtering the temperature data at mooring B2, removing oscillations with periods of motion less than 30 days, and, on the basis of CTD observations, we used a constant salinity of 34.6 to calculate density from temperature measurements.

Baroclinic energy fluxes \( \bar{E}_f = \langle \mathbf{u}' \cdot \mathbf{p}' \rangle \) were calculated using the methods outlined by Nash et al. [2005]. We included the contribution of the surface pressure to the vertical structure of the pressure perturbation by employing the fact that the depth integral of the pressure perturbation should equal zero. For the model data, we also removed the contribution to the pressure perturbation by the free surface displacement to leave the true baroclinic pressure perturbation [Kelly et al., 2010]. Testing revealed that removing the free surface induced pressure perturbation resulted in no significant changes to the magnitude of the energy fluxes at our sites. For the field data, no free surface measurements were available and we therefore assumed the density perturbation at the surface to be zero when calculating the pressure perturbation. We assumed the temperature at the uppermost thermistor (20 m below the surface) was representative to the free surface. Reconstruction of density and velocity profiles for imperfectly sampled vertical moorings using normal modes, as suggested by Nash et al. [2005], was not considered necessary given the high number of instruments and the full vertical coverage on the relatively shallow moorings. We used trapezoidal integration to compute the vertical integrals using the available sensors.

Using harmonic analysis, we calculated the amplitude and phase of the semidiurnal tidal components of the barotropic and baroclinic velocities and the isotherm displacements. Harmonic analysis was applied to 25 day periods for the barotropic tide, separating the relative contributions of the M2 and S2 semidiurnal constituents, but only 3 day periods for the baroclinic tide and only during spring tides.

### Table 1. Vertical Layout of the Instruments for the Three Moorings Used in This Study

<table>
<thead>
<tr>
<th>Mooring Name and Location</th>
<th>Total Depth (m)</th>
<th>Current Meter Locations (m ASB)</th>
<th>Thermistor Locations (m ASB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B2 (121.5934°E, 14.5108°S)</td>
<td>550</td>
<td>2.6, 130, 250, 330, 390, 450, 490, 530</td>
<td>2.6, 50, 90, 130, 170, 210, 250, 270, 290, 330, 350, 370, 390, 410, 430, 450, 470, 490, 510, 530</td>
</tr>
<tr>
<td>G2 (122.1923°E, 14.7309°S)</td>
<td>200</td>
<td>5, 100, 180</td>
<td>5, 10, 60, 80, 100, 120, 140, 160, 180</td>
</tr>
<tr>
<td>H2 (121.8922°E, 14.1886°S)</td>
<td>300</td>
<td>2.6, 80, 140, 220, 280</td>
<td>2.6, 20, 40, 60, 80, 100, 120, 140, 160, 180, 200, 220, 240, 260, 280</td>
</tr>
</tbody>
</table>

*ASB, above seabed.
Figure 2. Contour plot of the low-pass-filtered yearlong temperature data from the B2 mooring. The dotted line indicates the summer stratification that was the focus of this paper.

Contributions from all semi-diurnal constituents are present in the 3 day analysis. Isotherm displacements $\zeta$ were estimated by dividing the observed temperature perturbation by the local background temperature gradient $\zeta = T' / T^*$, estimates of the vertical displacement were affected by the relatively low vertical resolution of the temperature sensors. The vertical component of the barotropic tide ($w_{bt}$) was estimated by taking the product of the local components of the barotropic tide and the topographic slope and then linearly interpolating from the seabed to the surface:

$$w_{bt} = u_b \cdot \nabla H \left( \frac{z}{H} \right).$$

We estimated the tidally induced isopycenal displacement $\zeta_{bt}$ by integrating $w_{bt}$ over a tidal cycle. To estimate vertical energy flux from the model, $\langle w' p' \rangle$, we subtracted $w_{bt}$ from the modeled vertical velocity.

[15] We used modal decomposition to determine both the dominant vertical structure of the baroclinic motions and the relative contributions from the barotropic and baroclinic tides. Observed baroclinic velocity, pressure and displacement were separated into vertical modes by least squares fitting to theoretical modal profiles found by solving the eigenvalue problem $\frac{d^2 \psi}{d z^2} + N^2(z) \psi = 0$ for the observed mean vertical buoyancy frequency profile [e.g., Gill, 1982]. This assumes a flat bottom and, while not strictly valid at all of the field sites, it is useful for separating contribution from high and low vertical wave numbers [Nash et al., 2004]. The results are presented as the depth-integrated horizontal kinetic energy $\langle HKE \rangle$, available potential energy $\langle APE \rangle$, and horizontal energy flux in each mode, where $\langle HKE_n \rangle = \int 0.5 (u_n^2 + v_n^2) dz$ and $\langle APE_n \rangle = \int 0.5 N^2 \zeta^2 dz$ ($\langle \rangle$ denotes a wave cycle average.

The number of instruments on the moorings was limited (e.g., the G2 mooring had only three current sensors), limiting the number of baroclinic modes computed, and leading to the projection of energy from high modes onto low modes. This necessitated careful interpretation of the results.

2.3. Model Setup

[16] We used the Regional Ocean Modeling System (ROMS v3.1) to study the interaction between the tidally driven stratified flow and the complex shelf topography. ROMS solves the three-dimensional primitive Navier-Stokes equations using the Boussinesq and hydrostatic approximations; Schepetkin and McWilliams [2005] provide a complete description of the model equations and assumptions. In our application, the model grid used stretched curvilinear coordinates $(\xi, \eta)$, spanned approximately 500 km in the $\xi$ direction and 300 km in the $\eta$ direction. The domain included the region surrounding the moorings, the inner- and outer-shelf breaks and the associated slope regions, and Scott Reef (Figure 1). The grid, generated using the gridding package RFGGRID (Delft Hydraulics Software), was extended to the Kimberley coast, thus reducing the number of open boundaries to three. The horizontal resolution varied from $\sim 1$ to 3 km with the highest resolution used in regions where internal wave generation was likely to occur, such as the continental shelf break and Scott Reef. 50 vertical sigma layers were used, and the stretching parameters were chosen such that the vertical resolution was finer near the seabed, where internal wave beams are generated, and at the sea surface. A high vertical resolution ($\sim O(10)$ m) was deemed necessary to resolve the vertical wavelengths of the higher baroclinic modes [Johnston et al., 2003].

[17] Bathymetry for the model grid was taken from a combination of the Geoscience Australia 250 m data set and a high-resolution ($\sim 10$ m) data set provided by Woodside Energy Ltd., which covered Scott Reef and parts of the surrounding shelf break. To reduce the effect of the numerical pressure gradient error associated with steep bathymetry [Haney, 1991; Mellor et al., 1998], smoothing of the bathymetry was performed using a selective iterative filter [Martinho and Batteen, 2006] and the grid stiffness parameter was defined to be less than 0.2 everywhere.

[18] We ran the model for 28 d, allowing simulation of two spring-neap tidal cycles after a 3 d model spin-up time. The model was initialized with the measured average temperature profile from the month of February at site B2 (Figure 2) and a constant salinity. Below 550 m, the regionally and monthly averaged temperature fields from the Bluelink Reanalysis hindcast data (BRAN v2.1 [Schiller et al., 2008]) were used. We also used these temperature profiles as boundary conditions for the outer domain boundaries, thus the stratification remained relatively constant over the 28 day model run. All surface heat and momentum fluxes were set to zero with all forcing provided by the tide.

[19] Tidal amplitude and barotropic velocities from the TPXO7.1 global tidal model [Egbert and Erofeeva, 2002] for eight constituents (M2, S2, N2, K1, O1, P1 and Q1) were used to force the three open boundaries of the model. Flather [Flather and Heaps, 1975] and Chapman [Chapman, 1985] numerical conditions were used for the barotropic momentum and free surface open boundaries, and a passive-active radiation condition used for the baroclinic
velocity and tracer boundary conditions [Marchesiello et al., 2001]. A numerical sponge layer was applied along the boundaries by linearly ramping up the Laplacian horizontal eddy viscosity/diffusivity by a factor of 10 over the outer six grid points. Horizontal mixing was applied along geopotential surfaces for tracers and along sigma layers for momentum, and the generic length scale $k - \omega$ turbulence closure scheme was used to parameterize the vertical mixing in the model [Umlauf et al., 2003].

[20] We extracted the ROMS results at each of the mooring sites and compared them to the field data. Model–observation-derived M2 and S2 tidal harmonic constituents for the barotropic tidal velocity were compared by calculating the root-mean-square error:

$$\text{RMSE} = \sqrt{0.5(A_o^2 + A_m^2) - A_oA_m\cos(G_o - G_m)}.$$  (3)

Here $A_o$ and $A_m$ are the observed and modeled amplitudes, respectively, and $G_o$ and $G_m$ are the observed and modeled phases, respectively [Cummins and Oey, 1997]. We compared baroclinic velocity components and isotherm displacements by calculating the average RMSE through the water column for the semidiurnal constituent. We also compared the energy variables calculated from the field data with the model results.

3. Barotropic Tides and Stratification

[21] Power spectra of velocity data at site B2 reveal the important scales of motions for the region (Figure 3). A large peak was present at the semidiurnal frequency throughout the water column, highlighting the significance of this component of the barotropic tide. There was also significant energy at subinertial frequencies in the upper half of the water column, likely owing to the Indonesian throughflow and the seasonally variable winds (see Condie and Andrewartha [2008], and references therein, for a description of the mesoscale flows on the NWS).

[22] The tidal ellipses were determined via harmonic analysis of the barotropic currents, $\mathbf{u}(t)$, at each mooring (Table 2). The semidiurnal M2 and S2 constituents dominated the barotropic current signal: the S2 signal was approximately 70–80% of the amplitude of the M2 at both sites B2 and G2. The tidal form factor $F$ for the major barotropic ellipse, where $F = (K1 + O1)/(M2 + S2)$, was 0.15 and 0.08 at sites B2 and G2, respectively. The angle of the major ellipse axis, at both B2 and G2, aligned with the cross-shelf direction, approximately 145° anticlockwise from east (Figure 4). This indicates that fluid was forced across the steepest isobaths on the shelf break, maximizing the vertical velocities induced by the tidal motions, thereby enhancing internal tide generation. The observed orientation of the major ellipse axes is consistent with a barotropic wave propagating southeastward across the shelf, as indicated by the TPXO7.1 tidal solution. Along the southeastern wall of Scott Reef at station H2, the tidal ellipse angle was approximately 30° anticlockwise from east, indicating that the tide was strongly modified by the bathymetry within the immediate vicinity of the reef (Figure 4).

[23] Seasonal heating and cooling occurred in the upper 100 m of the water column during the 12 month period (Figure 2). The winter stratification consisted of a surface mixed layer down to approximately 100 m, with the peak

![Figure 3. Power spectra of eastward velocity from 6 months (September 2006 to February 2007) of data at site B2 for three depths. The 95% confidence intervals are indicated by the dashed lines. ASB, above seafloor.](image)
vertical temperature gradient located 150 to 200 m below the surface. The surface mixed layer was deepest during July–August 2007, with little seasonal variability below 300 m. In summer, the water column was continuously stratified to near the surface and the surface temperature peaked around February–March. The remainder of this paper focuses on the internal wave dynamics during this strongly stratified summer period.

We used the measured summer stratification and model bathymetry to estimate the slope criticality parameter \( g \) throughout the study region (Figure 4). The regions where the major axis of the tidal ellipse was aligned with steep slopes where \( g \geq 1 \), are likely to achieve relatively efficient barotropic to baroclinic energy conversion [e.g., Baines, 1982]. We calculated the parameters relevant to internal tide generation for the three different topographic features present in the Browse Basin (Table 3). Each mooring was within proximity of these features, namely the outer-shelf break (B2), the inner-shelf break (G2) and the south flank of Scott Reef (H2). All three features have critical and/or supercritical slopes \( (g \geq 1) \). The inner- and outer-shelf breaks have similar topographic height to water depth ratio \( (h_s/H = 0.65) \), while \( h_s/H \approx 1 \) for Scott Reef. The tidal excursion parameter \( (u_0/\omega l_s) \) was very large for the inner-shelf break \( (u_0/\omega l_s = 0.48) \), but small for both the outer-shelf break \( (u_0/\omega l_s = 0.03) \) and on the south flank of Scott Reef \( (u_0/\omega l_s = 0.04) \); at Scott Reef this is a result of the small upslope component of the barotropic tide \( (u_0 = 0.01 \text{ m/s}) \).

### 4. Observations of Internal Waves

Using both measured and modeled results, we first describe the amplitudes and phases of the internal wave motions at tidal frequencies, followed by the energy fluxes and energy density. We focus our attention on the dynamics during summer stratification and spring tide conditions when the semidiurnal internal wavefield dominates the observations. On average, 50% of the total variance in the baroclinic velocity signal, and 70% of the isotherm displacement signal, occurred at the semidiurnal frequencies, at all sites and depths. The rest of the variance resided at nontidal frequencies.

#### 4.1. Velocity and Displacement

**4.1.1. B2**

At the deepest site B2 (550 m), the largest baroclinic velocities of 10 cm s\(^{-1}\) occurred in the upper 150 m of the water column while the smallest amplitude was at middepth (Figure 5). The cross- and along-shelf components of

![Figure 4. Semidiurnal M2 barotropic tidal ellipses from the 25 day ROMS solution (gray) and moorings (white) for the corresponding period overlaid on a contour plot of the ratio of the internal wave characteristic slope to the topographic slope \( (\gamma) \). Internal wave characteristic slope was calculated for the summer stratification condition. Isobaths are at 100 m intervals to a depth of 500 m and 500 m intervals beyond this.](image-url)

### Table 3. Important Internal Wave Generation Parameters for Three Topographic Features in the Browse Basin

<table>
<thead>
<tr>
<th>Feature</th>
<th>Outer Shelf</th>
<th>Inner Shelf</th>
<th>Scott Reef (South Flank)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( l_s ) (m)</td>
<td>25,000</td>
<td>8000</td>
<td>2000</td>
</tr>
<tr>
<td>( h_s ) (m)</td>
<td>1300</td>
<td>100</td>
<td>500</td>
</tr>
<tr>
<td>( H ) (m)</td>
<td>2000</td>
<td>200</td>
<td>500</td>
</tr>
<tr>
<td>( S_{avg} )</td>
<td>0.05</td>
<td>0.0125</td>
<td>0.25</td>
</tr>
<tr>
<td>( \gamma_{max} )</td>
<td>4+</td>
<td>1</td>
<td>4+</td>
</tr>
<tr>
<td>( u_0 ) (m s(^{-1}))</td>
<td>0.10</td>
<td>0.55</td>
<td>0.01</td>
</tr>
<tr>
<td>( h_s/H )</td>
<td>0.65</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>( u_0/\omega ) (m)</td>
<td>700</td>
<td>3900</td>
<td>70</td>
</tr>
<tr>
<td>( u_0/\omega l_s )</td>
<td>0.03</td>
<td>0.48</td>
<td>0.04</td>
</tr>
</tbody>
</table>

*The \( l_s \) is the distance between the deepest and shallowest isobath; \( S_{avg} \) is the average slope between the two isobaths; and \( u_0 \) is the semidiurnal amplitude of the cross-isobath component of the modeled barotropic tide halfway up the slope.
velocity were similar in magnitude and, when the amplitude and phases were converted into elliptical parameters, the ratio of major to minor axes were approximately equal (not shown). The aspect ratio of major to minor axis for a single propagating wave should equal \( \frac{\omega f}{f} = 0.25 \) (for the M2 frequency at 14\(^\circ\)S). The observed near circular ellipses at B2 suggest the presence of multiple waves, as is often observed at deep ocean moorings [e.g., Eriksen, 1982].

The cross‐shelf component of velocity exhibits upward phase (downward energy) propagation in the upper 200 m of the water column, while the along‐shelf component has downward phase (upward energy) propagation throughout the water column. Finally, note the amplitude of the isotherm displacements \( \zeta \) are up to 25 m, and tend to increase with depth (Figure 5, bottom).

4.1.2. G2

At the shallower inner‐shelf site G2 (Figure 6) the amplitude of the semidiurnal baroclinic currents increased, with values exceeding 30 cm s\(^{-1}\), and the phase difference between the upper and lower half of the water column of 180\(^\circ\) shows the presence of a vertical mode‐one response. The isotherm displacements (Figure 6, bottom) increased with depth to a peak amplitude of 40 m, approximately 50 m above the seabed. The phase of \( \zeta \) was approximately equal throughout the water column and close to the phase of the barotropically induced isopycnal displacement \( \zeta_{bt} \).

Figure 5. The 3 day time series of (top) cross‐shelf baroclinic velocity, (middle) along‐shelf baroclinic velocity, and (bottom) isopycnal displacement at site B2 during spring tide and summer stratification conditions. Cross‐shelf is defined as 45\(^\circ\) clockwise from east. (a, b) The field‐ and model‐derived quantities are shown. (c, d) Semidiurnal amplitude and phase from fits to the time series are plotted. Black circles represent values derived from the measurements, and gray lines represent the model output. Dashed black and gray lines are the barotropic values from the field data and model, respectively. Barotropic induced displacements, \( \zeta_{bt} \) (see text), are also presented.
Near the seabed $z_{bt}/z_0 = 0.5$. Some of this underestimate is likely attributable to the error resulting from estimating the barotropic velocity from three discrete current meters, and we discuss this in more detail in section 4.2.3.

4.1.3. H2

The H2 mooring, located on the steep south flanks of Scott Reef, was dominated by baroclinic currents parallel to the isobaths, $v'$ (Figure 7). The maximum amplitude of 15 cm s$^{-1}$ was seen near the surface and 75 m above the seabed. The isotherm displacement $\zeta$ was greatest in the lower half of the water column exceeding 40 m. The $\zeta$ phase was constant below 100 m and was close to the phase of $z_{bt}$. The observed $\zeta$ amplitude near the seabed was more than twice the estimated $z_{bt}$. The very steep slopes ($S = 0.25$) indicate that an error of 1 cm s$^{-1}$ in the upslope component of the barotropic velocity will lead to an error of 18 m in the displacement. The large isopycnal displacements by the barotropic tide could indicate that H2 was within a region of barotropic to baroclinic energy conversion. We present an alternative explanation for the larger than predicted isopycnal displacement in section 5 using the numerical model output.

4.2. Energy Budget

4.2.1. Horizontal Kinetic and Available Potential Energy

From the modal fits to the baroclinic velocities and isotherm displacements, as shown in Figures 5–7, we computed the depth-integrated horizontal kinetic energy (HKE) and available potential energy (APE), and the results are shown in Figure 8. The majority of the total energy was in the first mode at all sites. For the HKE, 40% was in the first mode at site H2, 50% at G2, and less than 30% of HKE in the first mode at B2. For the APE, two-thirds was in the first mode at all sites. For a single progressive wave, theory [e.g., Gill, 1982] suggests the ratio of HKE/APE = $(\omega^2 + f^2)/$
\( (\omega^2 - f^2) = 1.13 \) for a wave at M2 frequency and latitude of 14°S. For both field data and model results, the ratio of HKE/APE was 0.75 at B2 and approximately 0.1 at G2 and H2. The small values of the ratio of HKE/APE at all sites suggests the presence of multiple waves possibly forming a standing internal wave, and we discuss this further in section 5.

### 4.2.2. Energy Flux

[30] Using the modal fits to the baroclinic velocities and isotherm displacements, we calculated the depth-integrated energy fluxes and, as shown in Figure 9, more than 70% of the energy flux was in the first mode at all sites. During these conditions of spring tide and summer stratification, the flux was in the ranges of 2–3 kW m\(^{-1}\) at B2, 5–6 kW m\(^{-1}\) at G2, and 6–7 kW m\(^{-1}\) at H2 (Figure 9). The dominant direction was approximately northwesterly at B2 (off-shelf), northwesterly to north at G2 (off-shelf), and east northeasterly at H2 (along-isobath). Stations G2 and H2 also had significant along-shelf (along-isobath) components of depth-integrated energy flux. At sites G2 and H2, the vertical distribution of the energy flux displayed peaks of the same sign near the surface and the seabed, with a mid-water column value of near zero (Figure 10), close to a theoretical mode one energy flux profile. In contrast, at site B2 the energy flux was confined to the upper 150 m (Figure 10).

### 4.2.3. Model Evaluation

[31] The barotropic current ellipse properties, derived from harmonic analysis of the ROMS solution, compared very well with the observations in terms of both the magnitude and orientation of the two semidiurnal tidal constituents (Figure 4 and Table 2). RMSE (equation (3)) for the M2 and S2 barotropic amplitude and phase are...
approximately 1 cm s$^{-1}$ at sites B2 and H2, and 3–4 cm s$^{-1}$ at G2 (Table 4). The average RMSE of both along- and cross-shelf baroclinic motions was 2–4 cm s$^{-1}$ at B2 and H2, and 20 cm s$^{-1}$ at G2. The larger RMSE for both barotropic and baroclinic currents at G2 is likely attributable to the lack of vertical resolution in the current measurements. The small number of discrete measurements likely projected some of the barotropic motion into baroclinic modes, resulting in the observation that the ROMS solution both underpredicts the observed barotropic currents and overpredicts the observed baroclinic currents. In other words, the model results may give a better representation of the actual barotropic tide than the estimate derived from a limited number of current meters.

[32] The model underpredicted the amplitude of the semidiurnal isotherm displacement at all three sites. However, the model was skilled at reproducing the vertical structure of both the isotherm displacements and baroclinic velocity profiles. For example, at site H2 the vertical structure and phase propagation of the modeled along-shelf velocity agreed well with the observations (Figure 6, middle). Furthermore, the model captured the mode one phasing of displacement observed at all sites (Figures 5–7).

[33] The modal distribution of HKE and APE revealed that, in general, the model tended to overpredict the proportion of energy in the first mode but underpredict the depth-integrated HKE and APE, by up to a factor of two (Figure 8). This results from the model underpredicting the amplitude of the baroclinic velocity and displacement. The model ratio of HKE/APE was similar to the observed at all sites. The model overestimated the magnitude of the energy flux vectors by a factor of two at site B2 and approximately 1.5 at sites G2 and H2 (Figure 10), and overestimated the proportion of energy flux in the first baroclinic mode. However, the model skillfully reproduced

**Figure 8.** Bar plot of HKE and APE derived from model fits to velocity and displacement profiles at sites (a) B2, (b) G2, and (c) H2. Field values are on the left, and model values are on the right. Numbers above each bar represent the percentage of total energy in each mode for the field and model (parentheses).

**Figure 9.** Cross-shelf and along-shelf depth-integrated energy flux derived from fits of velocity and pressure to vertical normal modes at sites (a) B2, (b) G2, and (c) H2. Cross-shelf direction is defined as 45° clockwise from east at B2, 60° clockwise from east at H2, and 45° clockwise from east at G2. Field-derived quantities are on the left, and model-derived quantities are on the right. Numbers represent the percentage of energy flux distributed in the first baroclinic mode for the field and model (parentheses).
the direction of the energy flux at all sites during the spring tide.

5. Spatial Variability of Internal Waves

As the field data was restricted to three sites, we used the ROMS solution to provide a greater spatial coverage of the dynamics and to identify the regions of internal wave generation, the directions of wave propagation and the areas of wave dissipation.

5.1. Generation, Propagation, and Dissipation Estimates

Following Niwa and Hibiya [2004] and Carter et al. [2008], the baroclinic energy conversion $C$ is equal to the sum of the horizontal energy flux divergence and the baroclinic energy dissipation:

$$ C \approx \nabla_H \cdot \mathbf{\bar{E}}_t - \text{diss}_{bc}. \quad (4) $$

The baroclinic energy conversion is calculated as the product of the near seabed vertical barotropic velocity, from equation (2), and the baroclinic pressure term, hence $C = \langle \omega_{bt} p'_{bc} - H \rangle$. The conversion term represents the work done on the baroclinic pressure field by the barotropic tide or the conversion of barotropic kinetic energy to baroclinic potential energy [Zaron and Egbert, 2006]. Equation (4) assumes that the advection of baroclinic energy is negligible.

We calculated $C$ and the flux divergence terms using the model output, and inferred the dissipation from the difference between the two terms (equation (4)). The dissipation is sensitive to the model setup, including the choice of turbulence closure scheme [Niwa and Hibiya, 2004] and grid resolution [Zilberman et al., 2009], so we only use the model results to highlight regions of relatively strong and weak dissipation. Additionally, the results can guide the selection of regions for future measurements of baroclinic dissipation and higher-resolution numerical modeling.

Figure 10. Through–water column horizontal baroclinic energy flux at sites (a, d) B2, (b, e) H2, and (c, f) G2, derived from harmonic fits to the baroclinic velocity and pressure perturbations. The black bars represent quantities derived from the field data, and gray patches represent quantities derived from the numerical model. Cross-shelf (Figures 10a–10c) and along-shelf (Figures 10d–10f) components are shown.

<table>
<thead>
<tr>
<th>Site</th>
<th>$u'$</th>
<th>$v'$</th>
<th>$\zeta$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B2</td>
<td>1.4</td>
<td>1.5</td>
<td>3.2</td>
</tr>
<tr>
<td>H2</td>
<td>1.0</td>
<td>0.9</td>
<td>2.1</td>
</tr>
<tr>
<td>G2</td>
<td>3.8</td>
<td>3.0</td>
<td>20.0</td>
</tr>
</tbody>
</table>

Table 4. RMS Errors of the Modeled Versus Observed M2 and S2 Tidal Harmonic Parameters at All Three Mooring Locations
5.2. Generation

Regions of intense generation (defined to be when \( C \geq 2 \, \text{W m}^{-2} \)) were limited to the steep outer-shelf break, both north and south of Scott Reef and to long sections of the inner-shelf (Figure 11). We note that all of the moorings were close to, but not within, the intense generation zones. As can be seen by comparing Figures 4 and 9, these sites of strong conversion or generation regions are characterized by both steep slopes (\( \gamma \geq 1 \)) and the cross-isobath alignment of the barotropic tidal ellipses. In regions where \( \gamma \geq 1 \) but the barotropic tidal ellipses were not aligned across the slope, for example the western side of Scott Reef, there was no generation.

5.3. Flux and Dissipation

In Figure 12 we plot the flux divergence term in equation (4) over the model domain. By comparing Figures 11 and 12, it is clear that zones of strong positive flux divergence also occurred in the regions of strong barotropic to baroclinic energy conversion. As seen by the vectors in Figure 12, internal waves generated from both the inner- and outer-shelf breaks were radiated mainly in a NW (offshore) direction. Conversely, internal waves generated along the southern and eastern flanks of Scott Reef radiated in a SE (onshore) direction. Over the continental shelf between the inner- and outer-shelf breaks, the direction of wave propagation was highly variable, but there were regions with relatively large along-shelf fluxes.

The relative amount of converted energy \( C \) that radiates away, compared with what is dissipated locally, is important as the energy that radiates away potentially becomes available for mixing in regions far from the local generation zone [e.g., St. Laurent and Garrett, 2002]. Following Carter et al. [2008] and Zilberman et al. [2009], we define the conversion efficiency \( \text{Eff}_{bt-bc} \) as the ratio of divergence term to the conversion term in equation (4), that is,

\[
\text{Eff}_{bt-bc} = \frac{\nabla H \cdot \int E^I/dz}{C}. \tag{5}
\]

The conversion efficiency in equation (5) was calculated for the three control volumes encompassing the dominant topographic features (Figure 11). For each region, we integrated \( C \) and the energy flux divergence over the control volume, the ratio therefore represents the average conversion efficiency over each defined region (Table 5). The conversion efficiency was 56% around Scott Reef, 52% at the inner-shelf break, and 74% at the outer-shelf break. By comparison, the Hawaiian Ridge, with similar characteristics to the outer-shelf break (\( \gamma > 1, \, h_s/H > 0.5, \, u_0/w \cdot l_s \sim 0.01 \)), is estimated to have a conversion efficiency of 85% [Carter et al., 2008]. The relatively low conversion efficiency observed here at the inner-shelf break may be explained by the locally larger tidal excursion parameter (\( u_0/w \cdot l_s \), Table 3), and we examine this in more detail in section 5.4.

We note that the conversion efficiency for Scott Reef (56%) may be an overprediction as we smoothed the bathymetry in order to make the 1 km grid resolution numerically stable owing to sigma coordinate pressure.
gradient issues on the steep slope. Zilberman et al. [2009] determined that horizontal smoothing of the Mid-Atlantic Ridge topography can result in changes in the conversion efficiency; in their case, the conversion rates were 48% for a 1.5 km grid, 50% for a 6 km grid and 57% for a 15 km grid. Accordingly, we anticipate that the Scott Reef conversion efficiency may decrease with a higher model resolution when more of the finer-scale topographic features are resolved.

5.4. Vertical Structure

5.4.1. Outer-Shelf Beam Structure

We examined the vertical structure of the wavefields along the two transects marked A and B in Figure 12. The outer-shelf generated beam shown in Figure 13 is reminiscent of the internal wave response observed at other sites (e.g., the European shelf [Pingree and New, 1991], the Hawaiian Ridge [Nash et al., 2006], and the southern part of the Australian NWS [Holloway, 2001]). A beam-like structure emanated from the convex section of the outer-shelf break, at a depth of 1000–1500 m, and propagated both upward (onshore) and downward (offshore) (Figure 13a). The shoreward and upward propagating energy reflected near the surface approximately 40 km inshore (121.7°E), approximately halfway between the inner- and outer-shelf breaks. A second reflection occurred from the seabed near the inner-shelf break (121.85°E). There was a local intensification of baroclinic currents in the model at both these surface and bottom reflection locations (not shown). The offshore propagating beam (downward phase velocity) appears to have first reflected from the seabed near the base of the shelf break (121.4°E), and subsequently from the near-surface region approximately 80 km from the outer-shelf break (121.05°E). Consistent with the depth-integrated picture in Figure 12, there was significant along-slope variation in the intensity of this beam/s (not shown) probably owing to multiple generation sites within the canyons along the outer-shelf break. The field observations at B2 showed a larger proportion of HKE in the higher modes (Figure 8a) and downward phase propagation (upward energy) in the

<table>
<thead>
<tr>
<th>Region Name</th>
<th>Area (km²)</th>
<th>Conversion (MW)</th>
<th>Divergence (MW)</th>
<th>Dissipation, ( \text{diss}_{bc} ) (MW)</th>
<th>Efficiency, ( \text{Eff}_{bc} ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer Shelf</td>
<td>909</td>
<td>600</td>
<td>444</td>
<td>156</td>
<td>74</td>
</tr>
<tr>
<td>Scott Reef</td>
<td>1353</td>
<td>367</td>
<td>206</td>
<td>161</td>
<td>56</td>
</tr>
<tr>
<td>Inner Shelf</td>
<td>934</td>
<td>489</td>
<td>252</td>
<td>237</td>
<td>52</td>
</tr>
</tbody>
</table>

Table 5. Baroclinic Energy Terms Integrated Over Finite Regions

Figure 12. Model-calculated depth-integrated baroclinic energy flux divergence, with energy flux vectors overlaid. Values were tidally averaged and are representative of spring tide conditions. Pink lines denote the locations of the transects presented in Figures 13 and 14.
along-shelf velocity component (Figure 5, middle). However, there were no peaks in the cross-shelf energy flux as would be expected from a propagating beam [e.g., Nash et al., 2006]. This suggests that a shoreward propagating wave may be interacting with an offshore propagating wave, and we examine this possibility below.

### 5.4.2. Inner-Shelf Low-Mode Structure

The baroclinic response at the inner-shelf break area exhibited a low-mode baroclinic response over the entire depth. This was apparent for both the model and in the G2 mooring observations; however, we note that the modal fits for the observations were derived from measurements at only three positions, inevitably projecting higher-mode energy onto modes one and two. The vertical energy flux profile at G2 corresponded to the structure predicted for a low-mode wave (Figure 9c). Furthermore, the majority of the HKE and APE was in the first vertical mode (Figure 8c). The low-mode response is consistent with the locally large tidal excursion parameter \((u_0/\omega l_s = 0.5)\). Echeverri et al. [2009] observed a similar modal response experimentally with a tidal excursion parameter of 0.15, \(\gamma > 1\) and \(h_s/H = 0.5\). They attributed this response to a rapid attenuation of the higher vertical modes close to the generation site. This reasoning suggests a lower conversion efficiency would be expected for this type of generation regime, which is consistent with our conversion efficiency estimate of 52% for the inner-shelf break versus 74% at the outer-shelf break.

### 5.4.3. Shelf Standing Mode

Both the observed low HKE/APE ratios and the large along-shelf component of the energy flux at the mooring sites are not consistent with a locally generated propagating wave. The model output revealed that the along-shelf energy flux varied between the outer- and inner-shelf break; the maximum in the along-shelf energy flux occurred just inshore of the outer-shelf break generation site (Figure 13b). Depth-integrated HKE and APE were 180° out of phase and oscillated sinusoidally between the outer- and inner-shelf break (Figure 13c). The moorings B2 and G2 were located (by chance) at points along this transect where the ratio of HKE to APE was small and the along-shelf energy flux was large.

These observations suggest the existence of a horizontally partly standing internal wave, resulting from the interaction of the onshore propagating wave generated at the outer-shelf break with the offshore propagating wave generated at the inner-shelf break [cf. Nash et al., 2004; Martini et al., 2007]. The equations for energy flux, APE and HKE describing the superposition of two mode one waves with equal amplitude, one propagating in the −x direction and the other in the +x direction but with the same horizontal wave.
number, can be derived from linear theory for a rotating, stratified flow [e.g., Nash et al., 2004]:

\[
\langle v'p' \rangle = \left( \frac{u_0' pf}{\omega} \right) \sin(2k_x x) \cos^2(k_z z),
\]

(6)

\[
\langle APE \rangle = \left( \frac{u_0'^2 N^2 f}{2 \omega^2} \right) \cos^2(k_x x),
\]

(7)

\[
\langle HKE \rangle = 0.5u_0^2 \left( 1 + \frac{f^2}{\omega^2} \right) \sin^2(k_x x).
\]

(8)

Here \(u_0'\) and \(p_0\) are the zonal velocity and pressure perturbation amplitudes of a mode one wave, and \(k_x\) and \(k_z\) are the horizontal and vertical wave numbers. Note the east-west component of energy flux (\(\langle u' p' \rangle\)) is zero and the HKE and APE are 180° out of phase. Oscillations of all terms occur at a scale twice that of the horizontal wave number \(k_x\). Representative summer condition values for the continental shelf region between the outer- and inner-shelf breaks (121.55°E to 122°E, Figure 13) are: \(N = 0.01\) s\(^{-1}\), \(H = 400\) m, \(f = -3.5 \times 10^{-5}\) s\(^{-1}\), \(\omega = 1.405 \times 10^{-4}\) s\(^{-1}\) (M2) and \(\lambda_x = 2H = 800\) m (mode one). We estimated the horizontal wavelength using the internal wave dispersion relation \(k_x = \alpha / k_z\), as approximately 60 km for the Browse Basin shelf. This means that 1.5 wave oscillations will occur over the width of the shelf (~90 km), in agreement with the observed three oscillations of HKE and APE over the shelf (Figure 13c). Assuming \(u_0' = 0.2\) m s\(^{-1}\) (Figure 5, top) results in similar magnitudes of energy flux, HKE and APE to those derived from the numerical model (Figure 13c).

The standing wave explains both the low HKE to APE ratio at all observation sites and the along-shelf component of the energy flux at B2. The overprediction of energy flux magnitude and underprediction of APE and HKE by the model at the B2 site is likely explained by a small offset (~10 km) in the standing wave position due to the ROMS model assuming horizontally uniform stratification. Seasonal variations in the vertical stratification are expected to modify the position and perhaps the existence of the standing wave. We note that, as \(\gamma > 1\) at the inner-shelf, incoming waves may be reflected and contribute to this partly standing internal wave pattern.

### 5.4.4. Influence of Scott Reef

The presence of the highly three-dimensional Scott Reef is a unique feature of the study region. The theoretical wave generation response from a supercritical seamount/island (\(h_s/H = 1\)) is still not well understood, making it difficult to compare our observations to theory. We observed a vertical low-mode response at the H2 mooring, propagating northeast (antclockwise) around Scott Reef. The downward phase of the along-isobath velocity at H2 (Figure 6, middle) implies upward energy propagation, as
also observed in the model (Figure 14a). While two-dimensional, supercritical topography cannot support the upsheie propagation of energy, the three-dimensional Scott Reef topography allows the energy to propagate upsheie. [47] The supercritical slopes of Scott Reef also affect the onshore and offshore propagation of internal waves. Along Transect B (Figure 12), we observe both an alongshelf energy flux and oscillations in the depth-integrated HKE and APE in the region between Scott Reef and the inner-shell break, both indicative of a horizontal standing internal wave (Figure 14). There were three peaks in the APE and along-shelf energy flux, suggesting the presence of 1.5 horizontal wavelengths (or \( \lambda_x = 50 \) km) between Scott Reef and the inner-shell break (a distance of 75 km). This spatial pattern of energy and energy flux is similar to transect A (Figure 13). These observations suggest that Scott Reef “trapped” baroclinic energy on the continental shelf by reflecting the offshore propagating waves, resulting in a horizontally standing internal wave.

6. Summary and Conclusions

[48] Internal waves of tidal frequency are a ubiquitous feature of the ocean dynamics in regions of large tidal forcing and steep topography [e.g., Holloway et al., 2001; Niwa and Hibiya, 2004; Pingree and New, 1989; Rudnick et al., 2003]. The Browse Basin, on the Australian NWS, includes all of the necessary properties for large amplitude internal tide generation: large tidal forcing, strong and persistent density stratification, and steep topography. We found that the generation of internal waves was most intense in regions where the tidal flow was directed across the steep isobaths. The most efficient conversion of barotropic to baroclinic energy (74%) occurred at the outer-shell break, where the ratio of the tidal excursion distance to topographic length scale was very small. The high conversion efficiency indicates that energy propagating away from this could thus influence mixing in regions far from the generation zone.

[49] We identified a horizontal partly standing internal wave, both between the inner- and outer-shell break and between Scott Reef and the inner-shell break. In the former location, this feature resulted from internal waves generated at the inner- and outer-shell breaks converging, whereas adjacent to Scott Reef this feature was most likely the result of offshore propagating waves being reflected by the steep topography of Scott Reef. This standing wave resulted in large along-slope energy fluxes and large spatial variability in velocity and vertical displacements and thus HKE and APE. This phenomenon may be common in regions where multiple generation zones and complex topography are present. Identifying the presence of a standing internal tide is difficult with sparse spatial sampling and we found that numerical modeling was a necessary aid to identify this process. The observations of Alford et al. [2006] indicate that the spatially variable vertical displacements and horizontal velocities resulting from the converging waves create conditions favorable for increased mixing. Quantifying the dynamics of internal tides is an important step toward identifying those regions characterized by relatively high rates of mixing compared to the background ocean conditions.

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References


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