Vertical structure of barotropic-to-baroclinic energy conversion on a continental slope

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Figure 1: Cross section of South China Sea at 21°N showing the processes of generation, breaking, propagation, steepening and dissipation of internal waves (Figure adopted from Alford et al. (2015)).
Figure 2. A sketch of the local generation of a vertically propagating internal tide at the shelf-break and the subsequent emergence of modal nonlinear solitary-like waves.
Internal Waves

Low frequency internal wave generation experiment (from https://www.phys.ocean.dal.ca/programs/doubdiff/demos/IW1-Lowfrequency.html).
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Hydrostatic, linear model calculation for the generation of the internal tide at the shelf break (from Griffiths and Grimshaw, 2007). The slope criticality $s = 0.5$, 1, and 2 from left to right. The figures show the isopycnal displacements at a fixed phase of the barotropic forcing period.

Parameter:

$$ s = \frac{\max|db/dx|}{\alpha}, \quad \text{where} \quad \alpha = \left(\frac{\omega^2 - f^2}{N^2 - \omega^2}\right)^{1/2} $$
Processes that transfer barotropic (BT) tidal energy to heat in the ocean (Kang and Fringer, 2012).

2. Evolution: disintegration of internal tide beams

Schematic of the M2 tidal energy budget in percentages (Kang and Fringer, 2012).
Energy equation

\[ \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -2\Omega \times \mathbf{u} - \frac{1}{\rho_0} \nabla P - \frac{g}{\rho_0} \mathbf{k} + \nabla_H \cdot (\nu_H \nabla_H \mathbf{u}) + \frac{\partial}{\partial z} \left( \nu \frac{\partial \mathbf{u}}{\partial z} \right), \]

\[ \frac{\partial \rho}{\partial t} + \mathbf{u} \cdot \nabla \rho = \nabla_H \cdot (\kappa_H \nabla_H \rho) + \frac{\partial}{\partial z} \left( \kappa \frac{\partial \rho}{\partial z} \right), \]

and

\[ \mathbf{v} \cdot \mathbf{u} = 0, \]

where

\[ \rho(x,y,z,t) = \rho_0 + \rho_b(z) + \rho'(x,y,z,t). \]

\[ p_h = p_0 + p_b + p', \]

\[ = \rho_0 g(n - z) + g \int_z^n \rho_b \, dz + \int_z^n \rho' \, dz \]

\[ \mathbf{u} = \mathbf{U} + \mathbf{u}'. \]
Horizontal distribution of energy conversion

(Guo et al., 2018.)

(Kang and Fringer, 2012)
Vertical distribution of energy conversion

\( C_{\text{int}} = 8.84 \text{ kW/m} \)

(Gerkema and Zimmerman 2008.)

(OMidvar et al., 2021.)
Figure 3. Shelf-slope topography and parameter ‘s’ (the ratio of the topographic slope to the internal wave characteristic slope).

Forcing:
-- \( u_0 = U_0 \sin(\omega t) \), \( \omega = 1.4 \times 10^{-4} \)

Open boundaries:
-- Sponge layers at the horizontal boundaries

Free surface, no-slip bottom

Run for 24 tidal periods
Figure 3. Shelf-slope topography and parameter ‘s’ (the ratio of the topographic slope to the internal wave characteristic slope).

- Topography is fixed with maximum parameter ‘s’ 1.38 for all cases.
- Density stratifications are classed to two groups.

Figure 4. Top 150 m (I) background density field and (II) buoyancy frequency for each case. Frequency under the depth of shelf (100 m) is uniform.
Exp 1: supercritical
Energy conversion

Figure 5. Vertical structure of energy conversion rate $C (I-VI)$ for cases a-f, averaged by six tidal periods. ($I'-VI'$) Depth-integrated energy conversion rate $C$, and ($I''-VI''$) cross-slope integral of $C$.

- The stronger the ‘energy patch’ the weaker the junction between ‘energy patch’ and ‘energy beam’.

Vertical distribution of energy conversion shows clear enhancement (‘energy patch’) at pycnocline.
Exp 1: supercritical
Energy conversion

• ‘Energy patch’ are weaker. Stratified lower layer can make a stronger intrusion and strengthen the ‘energy patch’.

Figure 6. Same as in figure 5 for cases a’-f’.
Velocity and density

Figure 7. Time varying barotropic vertical velocity and density anomaly at x=493 (critical point) and 499 km for cases b and b', respectively.

- Case b, stronger density anomaly occurs closer to shelf break, while anomalies near the critical point is weaker.
- Case b', density anomaly distributes more evenly. Anomalies near critical point is stronger than those at shelf break.
- More higher modes fluctuations in case b.
Energy flux

Figure 8. Baroclinic horizontal velocity, pressure anomaly, and energy flux (time-averaged by six tidal periods) for case b and b'.

- Stratified deep ocean is in favor of beam-like internal waves generation.
- Stratified upper ocean above the uniform lower layer leads to the generation of modal structure internal waves, mainly mode-1 waves here.
- Most of the energy converted near slope is reflected offshore.
- Energy converted at pycnocline propagates both onshore and offshore.
Wave profile

Figure 9. Wave profiles on the shelf.
Exp 2: subcritical
Energy conversion

• Positive and negative conversion is spaced in sequence with equivalent magnitude.

• Energy beam may not be the dominant part in energy conversion.

• Energy beam may weaken energy patch.

Figure 10. Same as in figures 5, 6 but for subcritical cases k-l and k’-l’.
Energy flux

Figure 12 Baroclinic horizontal velocity, pressure anomaly, and energy flux (time-averaged by six tidal periods) for subcritical cases k-l, k’-l’.

- Gentle topography restricts the generation of beam-like internal waves.
- Stratified deep water does not have an obvious contribution to onshore energy flux, weakening it instead.
Wave profile

Figure 13. Wave profiles on the shelf for subcritical cases k-l and k′-l′.
2. Disintegration of internal tide beams

2. Shelf depth

3. Topographic slope

4. Rotation

5. Incident beam
2. Disintegration of internal tide beams

Figure 14. Calculation of the internal tide generated by a M2 barotropic tidal flow over a Gaussian shelf using the linear, CELT-Q model (Kelly et al., 2013).
2. Disintegration of internal tide beams

Figure 15. MITgcm calculations of the internal tide generated by M2 barotropic tidal flow over a Gaussian shelf. Panels (a) and (b) show contours of the density fields after eight periods of forcing. The background density field is in (c). In (a) $f = 10^{-4}$ s$^{-1}$ and $f = 2 \times 10^{-5}$ s$^{-1}$ in (b).
2. Disintegration of internal tide beams

Figure 16. In(a)/(b) the slope width scale is 20/34.5 km. c) Instantaneous profiles of the horizontal velocity, \( u \), at \( x = 105 \) km. The short horizontal lines indicate the bottom location.
Revealing the vertical structure of BT to BC energy conversion rate, as well as the interaction between the near thermocline (subsurface) and near bottom region.

- Barotropic to baroclinic energy conversion $C$ can be significantly reinforced or weakened in the upper ocean (above shelf) near shelf-edge by stratified deep ocean.

- The negative and positive distribution of energy conversion for supercritical cases are due to phase lag of density anomaly.

- The structure of the stratification, particularly the characteristics that describe the mixed layer (depth, density jump and thermocline thickness) are crucial in the beam-to-mode scattering, disorganization, and subsequent solitary wave emergence.

- The ratio of the vertical scale of the beam to the depth of the shelf, is an important control on the beam evolution onto the shelf.

Thanks for listening.