CPT: Representing internal-wave driven mixing in global ocean models

The Team:
Matthew Alford (UW)
Brian Arbic (U Michigan)
Frank Bryan (NCAR)
Eric Chassignet (FSU)
Gokhan Danabasoglu (NCAR)
Peter Gent (NCAR)
Mike Gregg (UW)
Steve Griffies (GFDL)
Robert Hallberg (GFDL)
Steve Jayne (WHOI)
Markus Jochum (NCAR)
Jody Klymak (UVic)
Eric Kunze (Uvic)
William Large (NCAR)
Sonya Legg (GFDL/Princeton)
Jennifer MacKinnon (SIO)**
Rob Pinkel (SIO)
Kurt Polzin (WHOI)
Harper Simmons (UAF)
Lou St. Laurent (WHOI)

Patchy mixing in the Indian Ocean
Kunze et al 06

http://www-pord.ucsd.edu/~jen/cpt/

We’re hiring 4 post-docs. Not too late to submit an application...
1. Most diapycnal (vertical) mixing in the ocean interior is due to breaking internal gravity waves.

2. Mixing is patchy in space and time, reflecting the complex geography of internal wave generation, propagation, and dissipation.

3. Patchy mixing matters for ocean circulation and fluxes. It’s important to “get it right”.

4. Our plan: use what we collectively know about internal wave physics to develop a dynamic parameterization of diapycnal mixing that can evolve in a changing climate.
Internal wave primer

- Low-mode \sim interfacial waves
- High-mode \sim plane waves
- Fast \quad f \leq \omega \leq N
- Breaking waves are at small (1-10 m) scales
The zoo of internal waves in the ocean

Two frequencies dominate energetically
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Near-inertial waves: often wind generated, have a frequency close to the local inertial frequency (latitude dependent)
The zoo of internal waves in the ocean

Two frequencies dominate energetically:

- **Internal Tides**: generated by oscillatory tidal flow over topography. Waves have tidal (often $M_2=12.4$ hour) period.

- **Near-inertial waves**: often wind generated, have a frequency close to the local inertial frequency (latitude dependent).
Parameterizing mixing

Can’t explicitly resolve internal waves in climate models.
3 steps to parameterize their role:

1) Wave generation

Internal-Tide Generation

Generation where barotropic (astronomical) tides are large and topography is rough

Wind-generated near-inertial internal waves

Generation by rotating component of wind stress, mirrors storm tracks

Egbert and Ray 01

Alford 01
Cant’ explicitly resolve internal waves in climate models. 3 steps to parameterize their role:

1) Wave generation

2) Some waves break “locally”

Internal tides propagating up from the rough (eastern) bathymetry steadily break, producing elevated mixing up into the main thermocline

Global pattern of mixing that mirrors wave generation

Polzin et al. 97
“Nearfield” tidal mixing

\[ \epsilon = \frac{qE(x, y)F(z)}{\rho} \]

St Laurent et al 02

map of internal tide generation (\(U_{bt}, N\))

dissipation rate (related to diffusivity)

vertical structure (exponential decay)

Tidal Energy Dissipated Near Topography, 'Aha Huliko'a Proceedings, January 2003

well et al., 2000), and the 3000-m isobath of the Hawaiian Ridge (Kunze et al., 2002b). The latter was averaged from 16 stations spanning roughly \(\sim 1000\) km along the Hawaiian Ridge. These stations were occupied over a 3 week period during 2000 and capture energy flux radiated from both strong and weak sites of internal tide generation along the ridge. A profile from the Virginia Slope is also shown, as turbulence at this site is likely supported by low-mode internal tides dissipating in the far field (Nash et al., 2003).

At all sites, the dissipation rates are maximum along the topography, and decay away from the topography with height. Enhanced turbulence levels are found to extend up to 1000 m from the bottom.

The energy flux carried by the internal tide can radiate as propagating internal waves, and these waves are subject to a collection of processes that will eventually lead to dissipation. Shear instability, wave-wave interactions, and topographic scattering all act to influence the rate of dissipation and control whether the internal tide dissipates near the generation site or far away. Understanding the physical cascade that allows energy in the internal tide to power turbulence is one goal of ocean mixing research.

2. Internal tide energy flux

Several nondimensional parameters are needed to model the physical regime of internal tide generation. One parameter, 

\[ \frac{kU_0}{\omega} \]

measures the ratio of the tidal excursion length scale \(U_0/\omega\) to the length scale of the topography \(k^{-1}\). This parameter is discussed by Bell (1975) and others, and distinguishes a wave response dominated by the fundamental tidal frequency \((kU_0/\omega < 1)\) from a lee-wave response involving higher tidal harmonics \((kU_0/\omega > 1)\).

A second parameter, 

\[ \delta = \frac{h_0}{H} \]

measures the ratio of the topographic amplitude \(h_0\) to the total depth \(H\).

A third parameter, 

\[ \frac{s}{\alpha} \]

measures the ratio of the maximum topographic slope \(s = |\nabla h|\) to the ray slope given by 

\[ \alpha = \sqrt{\frac{\omega^2 - f^2}{N^2 - \omega^2}} \]

This parameter also distinguishes two regimes. In the case of \(s/\alpha < 1\), the topographic slopes are less steep than the radiated tidal beam, and internal wave generation is termed subcritical. In the case of \(s/\alpha > 1\), the topographic slopes exceed the steepness of the radiated beam and the internal wave generation is termed supercritical. The critical generation condition is met when the radiated tidal beam is aligned with the slope of the topography.

The subcritical generation of internal tides was first considered by Cox and Sandstrom (1962), Baines (1973), and Bell (1975). These studies examined subcritical topography in the limit of \(\delta \gg 1\) and \(s/\alpha \ll 1\), for which the bottom boundary condition can be linearized to 

\[ w(-H) = U \cdot \nabla h. \]

In this case, the internal tide generation problem can be

Figure 1. Average profiles of turbulent dissipation from several sites where internal tides support mixing. Oregon Slope data are shown with 95% confidence intervals, as described by Moum et al. (2002). Virginia Slope data (Nash et al., 2003) show mixing supported by the dissipation of low mode internal tides. The 95% confidence intervals for data from Brazil Basin fracture-zone valleys, crests, and slopes are shown as blue, green, and red shaded bands, respectively, as described by Ledwell et al. (2000). Dissipation at the 3000-m isobath of the Hawaiian Ridge was derived from data described in the text.
“Nearfield” tidal mixing

St Laurent et al 02

map of internal tide generation \( (U_{bt}, N) \)

dissipation rate (related to diffusivity)

vertical structure (exponential decay)

\[ \epsilon = \frac{qE(x, y)F(z)}{\rho} \]

PLANNED WORK

Develop a vertical decay scale based on nonlinear dynamics of wave interaction and breaking

Thursday, July 8, 2010
“Nearfield” tidal mixing

**St Laurent et al 02**

![Map of internal tide generation](image)

**vertical structure (exponential decay)**

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Develop a similar representation for elevated mixing in the upper ocean under storm tracks

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St Laurent et al 02

**map of internal tide generation (U_{bt}, N)**

**vertical structure (exponential decay)**

\[
\epsilon = \frac{qE(x, y)F(z)}{\rho}
\]

% of energy that dissipates locally

Dissipation rate (related to diffusivity)

``PLANNED WORK``

``PLANNED WORK``

``parameterized diffusivity k_{\alpha} (10^{-3} m^2 s^{-1})``
“Farfield” wave breaking / mixing

Most (70-90%) internal tide energy escapes to propagate thousands of km away.
Where do these waves break? [St. Laurent and Nash 04]

Altimetric tidal fluxes

Zhongxiang Zhao, UW
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Propagating waves steadily lose energy due to interaction with other internal waves and mesoscale eddies. Apply existing wave-wave interaction theory to develop a map of dissipation for low-mode internal waves.
Turbulent mixing makes the ocean go round

- Turbulence occurs at small scales: cm to m
- Determines large scale vertical transport of heat, CO2, nutrients, etc.
- Drives meridional overturning circulation by creating potential energy.

Low Latitudes

High Latitudes

nature (May 2007)

Churn, churn, churn

How the oceans mix their waters is key to understanding future climate change. Yet scientists have a long way to go to unravel the mysteries of the deep.
Turbulent mixing makes the ocean go round

Heat conveyor

Low Latitudes

High Latitudes

PE → KE

simmons et al

Thursday, July 8, 2010
Turbulent mixing makes the ocean go round

But patchy mixing changes the story

Fig. 5. Diapycnal mass flux ($w^*$) through the 3300 m depth level.
Expectation: freshwater flux will slow down MOC. But if mixing increases in a windier climate, maybe not (Schmitt et al, Ocean Obs)
Changing strength of regional overturning

Palmer et al 07: Modeled Indian Ocean overturning streamfunction

Constant $\kappa = 1.2 \times 10^{-4}$

Bottom enhanced diffusivity
Sensitivity to changes in mixing in the thermocline. The bias in the depth of the $\sigma_{\theta}$ surface (which has a typical subtropical depth of ~400 m) in the GOLD-based model CM2G (also to be used in AR5) is greatly reduced (30%) by using a background thermocline diffusivity with a latitudinal dependence suggested by early studies of internal gravity wave interactions, compared with a constant background diffusivity of the same average magnitude [Harrison and Hallberg 08].

**Zonal mean Atlantic temperature bias**

**Elevated mixing over rough topography**

Hallberg
Successful application of wave-wave interaction theory: breaking of ambient internal wave field scales with latitude because of changing internal wave frequency band ($f<\omega<N$).

**Patchiness of Upper Ocean Mixing matters**

**Observational confirmation**

Gregg et al 03

**Modeled implication**

Harrison and Hallberg 08
**Planned Work**

**Dynamics of wave breaking**
- observations
- process modeling
- theory

**Global wave modeling**
- high-resolution
- tide and wind-forced
- w/ or w/o mesoscale

**Global climate modeling**
- high-resolution
- tide and wind-forced
- w/ or w/o mesoscale

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