Including small-scale processes and their interactions in ocean climate models

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Includes material from Climate Process Team on Internal wave-driven mixing, led by Jennifer MacKinnon (BAMS 2017)
Small-scale ocean processes
Winds, tides and subinertial flow generate internal waves, which propagate, and eventually break. Some of the wave energy leads to diapycnal mixing, both near and far from the wave generation site.

McKinnon et al, 2017, BAMS

*Internal wave driven mixing*

*Climate Process Team*

Nonlocal global problem
Can we just resolve internal waves?

Global simulations of the propagating internal tide are possible, but energy loss to both barotropic and baroclinic tide must be parameterized.

M2 tidal amplitude  
*Ansong et al, 2015*

Observations

1/12.5° Hycom simulation with wave drag on both barotropic and baroclinic tide

1/12.5° Hycom simulation with no parameterization
How do we currently parameterize mixing by tidally-generated internal waves?

Mixing is represented by a diapycnal or vertical eddy diffusivity $\kappa$

$$\kappa = \varepsilon \frac{\Gamma}{N^2}$$

Farfield dissipation: $\kappa = \kappa_b = \text{constant}$

Local dissipation

$$\varepsilon = \frac{1}{\rho} E(x, y) \cdot q \cdot F(z)$$

Rate of energy conversion from barotropic tide to baroclinic per unit area.

St Laurent et al, 2002

Fraction of local dissipation. Set (arbitrarily) to 1/3 in current implementations

Vertical structure function

$$\int_{-H}^0 F(z) dz = 1$$

Exponential decay with (arbitrary) constant vertical scale in current implementations

Mixing efficiency ($\approx 0.2$)
Barotropic to baroclinic energy conversion

Current climate model parameterization (Jayne and St Laurent, 2001)

\[ \varepsilon = \frac{1}{\rho} E(x, y) \cdot q \cdot F(z) \]

\[ E(x, y) = \frac{1}{2} \rho_0 N_b k h^2 \langle u^2 \rangle \]

rms tidal velocity: from offline barotropic tidal model

rms topographic variation: from gridded bathymetric products

Bottom stratification: from ocean model

Topographic wavelength: treated as a global tuning parameter

Based on linear theory, assuming small tidal excursion parameter, small relative topographic steepness

Alternative: Nycander 2005 eliminates need to specify k, by using topographic gradients \( \partial h / \partial x \)

\[ E_f^+ (r) = \frac{\rho_0 N_B U^2}{4\pi} \sqrt{1 - \frac{f^2}{\omega^2} \frac{\partial h(r)}{\partial x}} \int \int \left( g_a(|r-r'|) \frac{\partial h(r')}{\partial x'} \right) d r' \]

\( E_f^+ = \) energy conversion due to \( U^+ \), amplitude of semi-major axis of tidal flow ellipse
Barotropic to baroclinic energy conversion: Observational constraints

Energy conversion from barotropic to baroclinic tide, from parameterization.

\[ E(x, y) = \frac{1}{2} \rho_0 N_b kh^2 \langle u^2 \rangle \]

Jayne and St Laurent, 2001

Energy loss from M2 tide, deduced from Topex-Poseidon SST: frictional dissipation in shallow seas, conversion to baroclinic tide in deep ocean.

Egbert and Ray, 2000
Improvements to barotropic to baroclinic energy conversion

Increase in energy conversion, using Nycander 2005 formula, when spectral representation of small-scale topography is included. *Melet et al, 2013b*

Inclusion of small-scale <O(10km) topography can increase energy conversion. At steep sinusoidal/rough topography, interference reduces energy conversion.

Dependence of energy conversion on topographic steepness *(Zhang and Swinney, 2014)*
The local dissipation fraction \( \varepsilon = \frac{1}{\rho} E(x, y) \cdot q \cdot F(z) \)

Current climate model parameterizations: \( q = \) constant \((1/3)\)

Observational evidence: \( q \) varies from 100\%-20%

(Waterhouse et al, 2014)
The local dissipation fraction: what are the controlling factors?

At tall steep isolated topography, $q \sim U$ (Klymak, Legg and Pinkel, 2010)

At small-scale rough topography $q$ depends on latitude (Nikurashin and Legg, 2011)

The net fraction of energy dissipated locally depends on the nonlinearity of the waves, leading to local wave breaking. Several different mechanisms lead to nonlinearity.
The vertical profile of near field dissipation

$$\varepsilon = \frac{1}{\rho} E(x, y) \cdot q \cdot F(z)$$

Current climate model parameterizations:

(St Laurent et al, 2002, Simmons et al, 2003)

(Polzin 2009, Melet et al, 2013a)

$$F(z) = \frac{e^{-z/z_s}}{z_s(1 - e^{-H/z_s})}$$

$$z_p = \mu (N_b^{\text{ref}})^2 \frac{U}{h^2 \kappa^2 N_b^3}$$

$$z^*(z) = \int_0^z \left[ \frac{N^2(z')}{{N_b}^2} \right] dz'$$

Indo-Pacific overturning, difference between Polzin, and Simmons et al

Redistributing dissipation in vertical has an impact on global circulation
The vertical profile of dissipation: Examples

Compiled observations

(Waterhouse et al, 2014)

Brazil basin obs and wave-saturation model

(Lefave et al, 2015)

Coriolis dependence in simulations

(Yi, Legg and Nazarian, 2017)

Vertical distribution of dissipation depends on topography, Coriolis, stratification.
Mixing efficiency

Current climate model parameterizations:
\[ \Gamma = 0.2, \text{ with modifications for very low } N \]

Variable mixing efficiency (DeLavergne et al. 2016): depends on buoyancy Re

\[ \Gamma = \frac{\kappa \rho}{\nu Re_b} \]

Impact of variable mixing efficiency on near-field tidal diffusivity

Variable \( \Gamma \) tends to reduce \( \kappa \) in deep ocean.
Far-field tidal dissipation

Local and remote dissipation: globally require \( \int \varepsilon dV = \frac{1}{\rho} \int E(x, y) dx dy \)

\((1 - q) \times \) baroclinic tide energy propagates away from generation site

Modeled energy flux \((Ansong \ et \ al, \ 2017)\)

Current climate model parameterization: Constant or latitude dependent \( \kappa_b \)

Violates energy conservation!

Breaking of propagating waves → farfield dissipation.

Processes leading to breaking include: wave-wave interactions, scattering from topography, interaction with subinertial flow.

To represent farfield dissipation, we need to understand horizontal distribution and vertical profile.

2D low-mode ray-tracing models can provide time-evolving horizontal distribution of internal tide energy \((Mater \ in \ prep; \ Eden \ and \ Olbers, \ 2014)\).

Internal wave breaking at continental slope \((Legg \ and \ Adcroft, \ 2003)\)
Impact of vertical structure of farfield mixing: overturning strength (ESM2G coupled model simulations, Melet et al, 2016)

- Less near-surface mixing: \( \rightarrow \) weaker subtropical overturning
- More mixing at depth: \( \rightarrow \) stronger deep overturning

Global meridional overturning circulation (Sv)

\[ \varepsilon \sim N^2 \]

\[ \varepsilon \sim N \]

\[ \varepsilon \sim e^{-\frac{z}{z_s}} \]
Impact of horizontal location of farfield mixing: Atlantic overturning

Reference: 20% local, 80% uniform diffusivity

• Mixing on shelves/straits weakens AMOC
• Deep mixing strengthens/deepens AMOC

All have $\epsilon \sim N$ (Melet et al, 2016)
Summary of progress and gaps in tidal mixing parameterization

\[ \kappa = \frac{\Gamma}{N^2} \quad \varepsilon = \frac{1}{\rho} E(x, y) \cdot q \cdot F(z) \]

Locally \[ \int \varepsilon dV = \frac{1}{\rho} \int E(x, y) dx dy \]

E(x,y) depends on:
- tidal velocities, f, \( \omega \), stratification – well understood
- topography – less well understood.

q, F(z) depend on:
- different processes responsible for dissipation – spatially highly variable.

Farfield:
- Horizontal distribution depends on wave propagation
- Vertical distribution depends on wave-breaking process.
How to proceed?

What is most important?
Distribution of mixing in water column, and relative to dense water sources.

Constraints
- Total energy lost from barotropic tide
- Spatial distribution of barotropic energy loss (approximate)
- Spatial distribution of dissipation (incomplete)
- Emergent properties of flow, e.g. MOC, stratification (indirect)
- Paleo reconstructions of energy loss, flow properties (indirect)

- Current practice is to tune one parameterization component at a time and progressively layer on additional improvements.
- Can we optimize all parameterizations concurrently, using all available constraints?

(Waterhouse et al, 2014)
Building the ESM of the future requires the team of the future

• Climate scientists need to incorporate social science evidence to form and manage better teams.
• When 80% of the people in the room come from 25% of the population, we are under-using the talent of the remaining 75% of the population.
• Diverse teams do better work.