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

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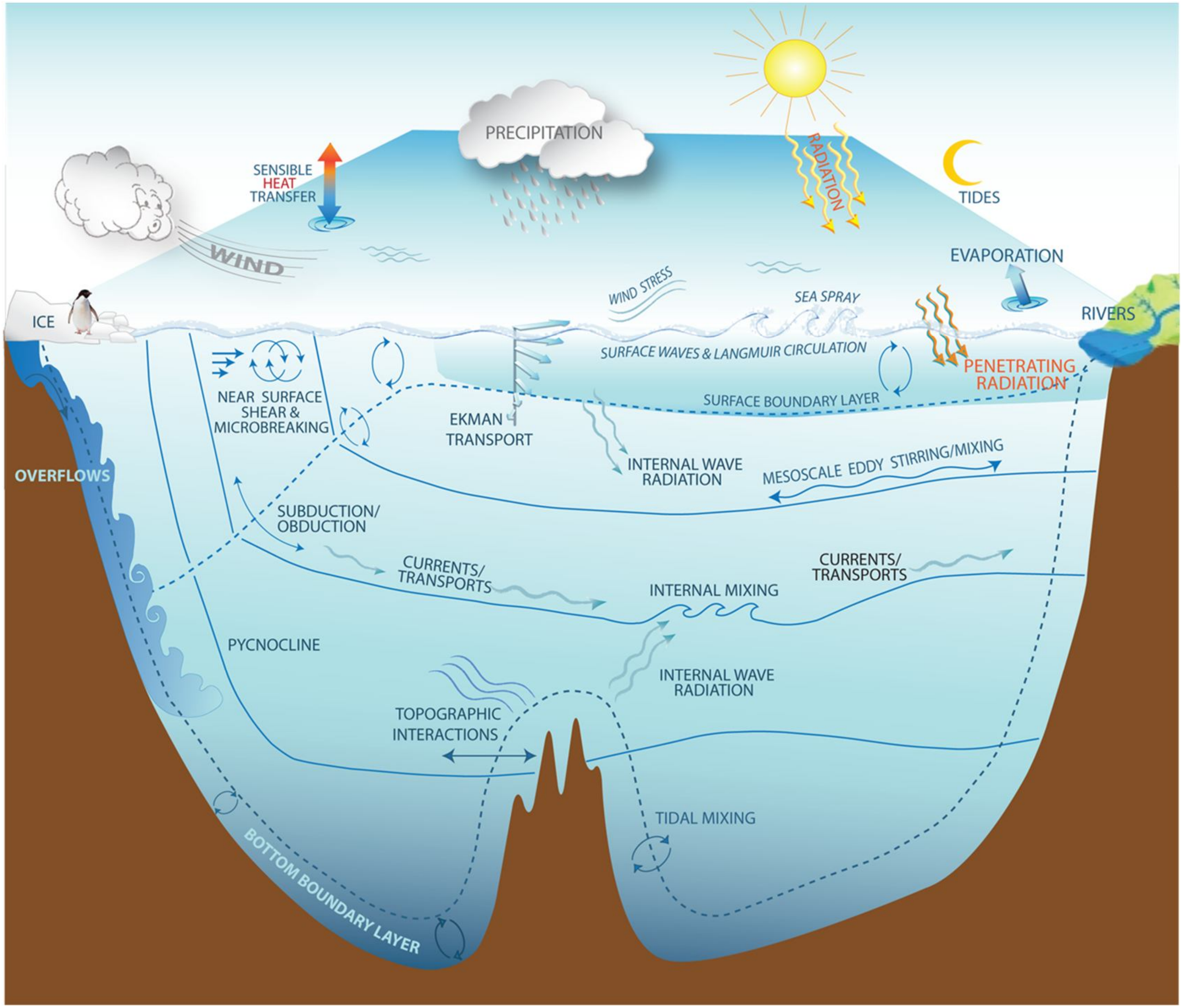
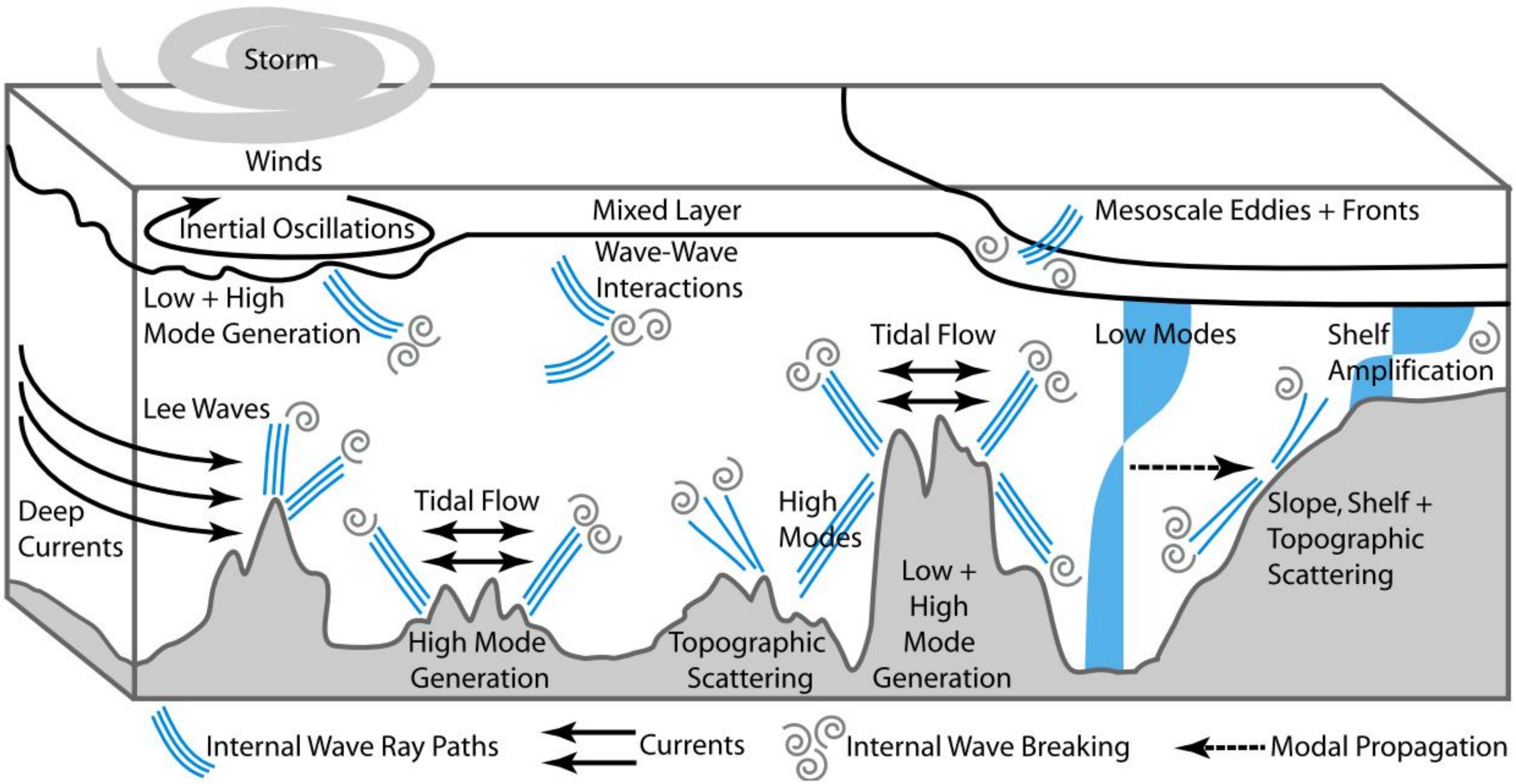
Includes material from Climate Process Team on Internal wave-driven mixing, led by Jennifer MacKinnon (BAMS 2017)

Small-scale ocean processes



Focus on internal wave driven mixing

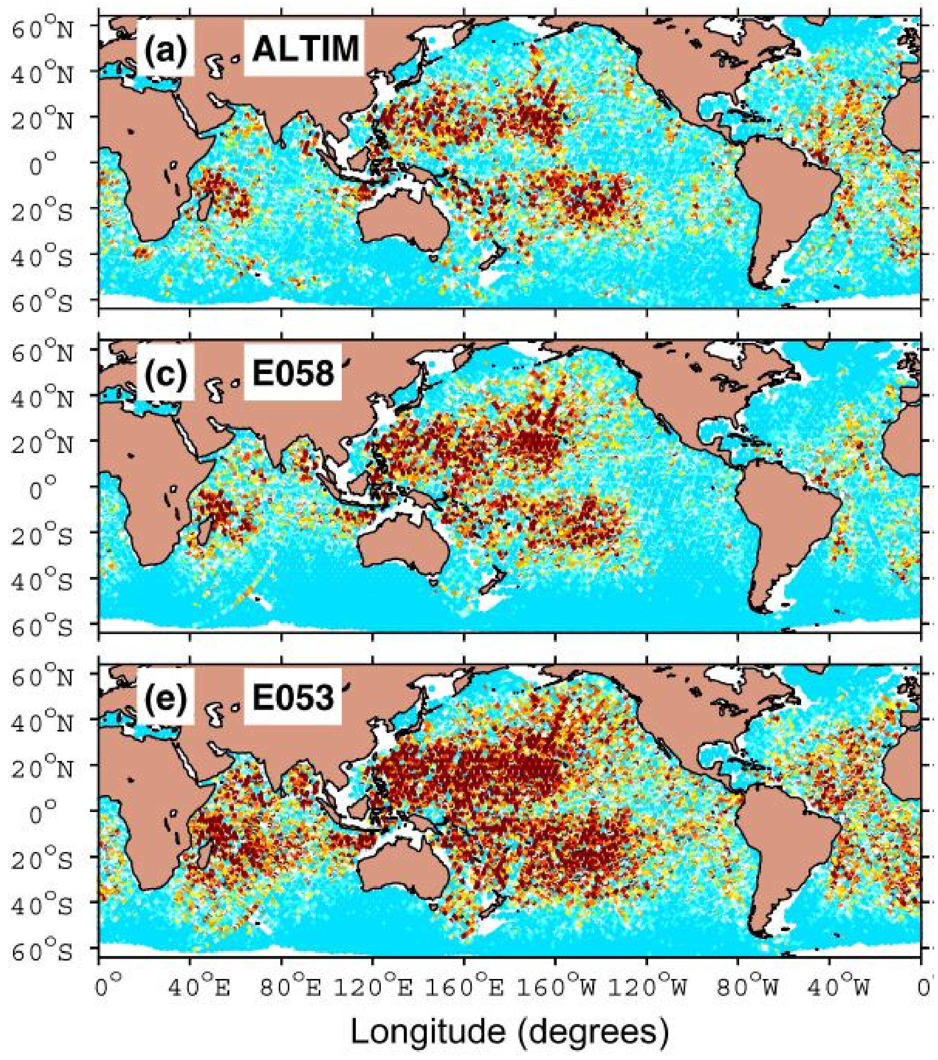


McKinnon et al, 2017, BAMS
Internal wave driven mixing
Climate Process Team

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.

Nonlocal global problem

Can we just resolve internal waves?



Observations

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

1/12.5° Hycom simulation with no parameterization

M2 tidal amplitude

Ansong et al, 2015

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

How do we currently parameterize mixing by tidally-generated internal waves?

Mixing is represented by a diapycnal or vertical eddy diffusivity κ

Local dissipation

St Laurent et al, 2002

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

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

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

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

Mixing efficiency (~0.2)

Farfield dissipation: $\kappa = \kappa_b$ = constant

Barotropic to baroclinic energy conversion

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

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

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

rms tidal velocity: from offline barotropic tidal model

Bottom stratification: from ocean model

rms topographic variation: from gridded bathymetric products

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** $\partial h / \partial x$

$$E_f^+(\mathbf{r}) = \frac{\rho_0 N_B U_+^2}{4\pi}\sqrt{1-\frac{f^2}{\omega^2}}\frac{\partial h(\mathbf{r})}{\partial x}\iint \left(g_a(|\mathbf{r}-\mathbf{r}'|)\frac{\partial h(\mathbf{r}')}{\partial x'}\right) d\mathbf{r}'$$

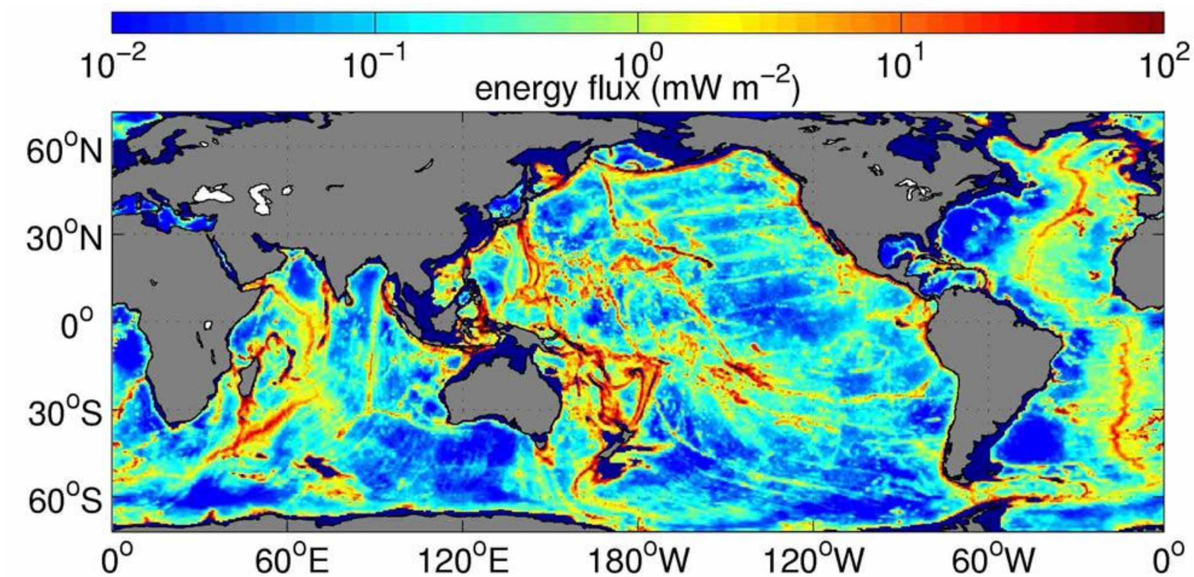
E_f^+ = energy conversion due to U^+, amplitude of semi-major axis of tidal flow ellipse

Barotropic to baroclinic energy conversion: Observational constraints

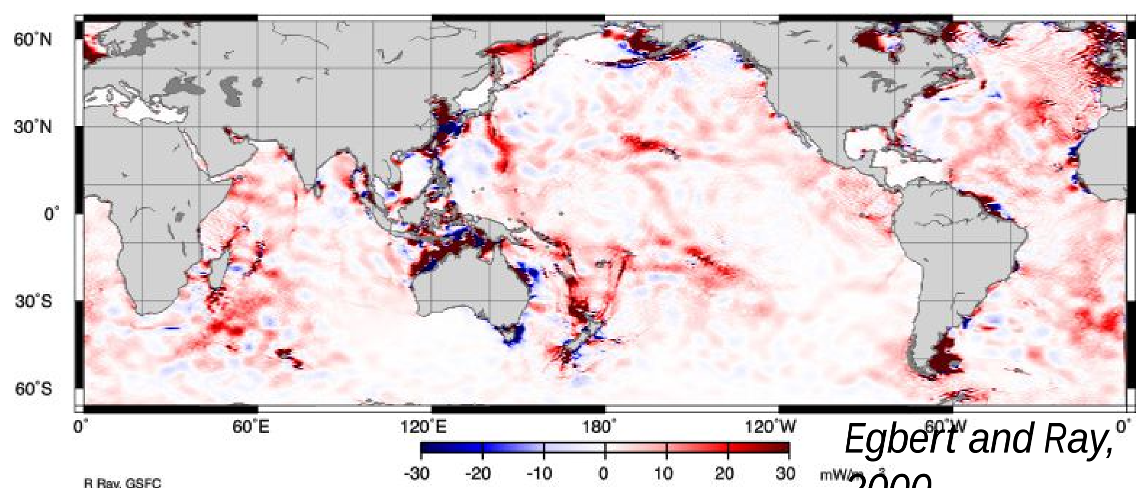
Energy conversion from barotropic to baroclinic tide, from parameterization.

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

Jayne and St Laurent, 2001



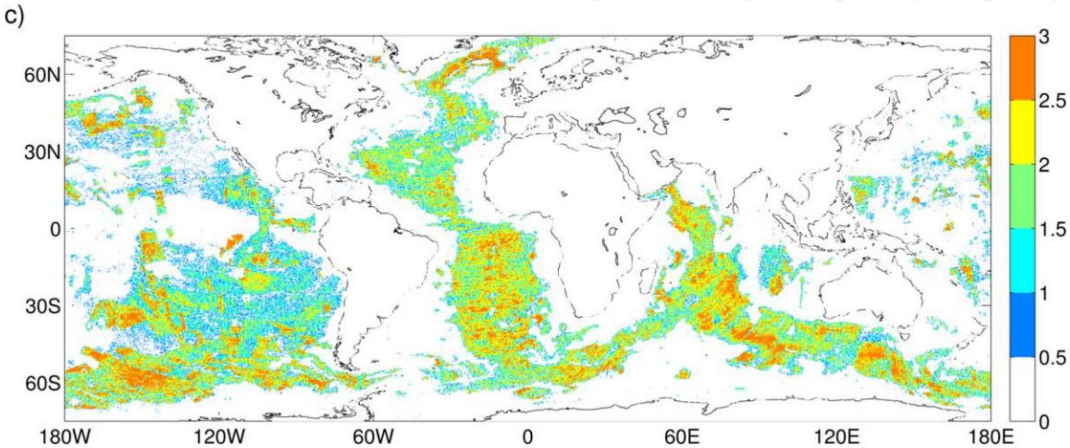
Energy loss from M2 tide, deduced from Topex-Poseidon SST: frictional dissipation in shallow seas, conversion to baroclinic tide in deep ocean.



Egbert and Ray, 2000

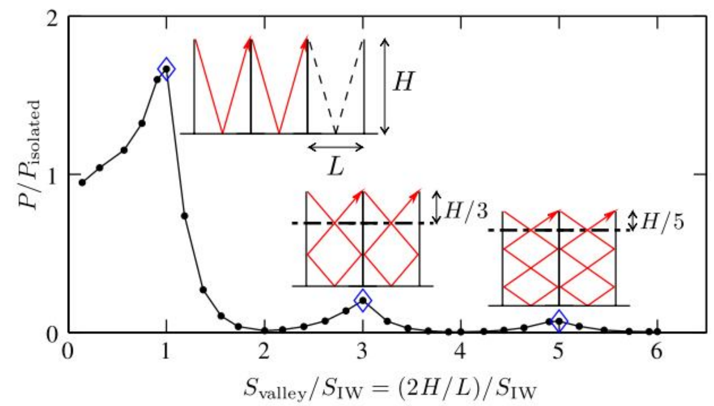
Improvements to barotropic to baroclinic energy conversion

Include small-scale <O(10km) topography



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

Account for steep topography



Dependence of energy conversion on topographic steepness *(Zhang and Swinney, 2014)*

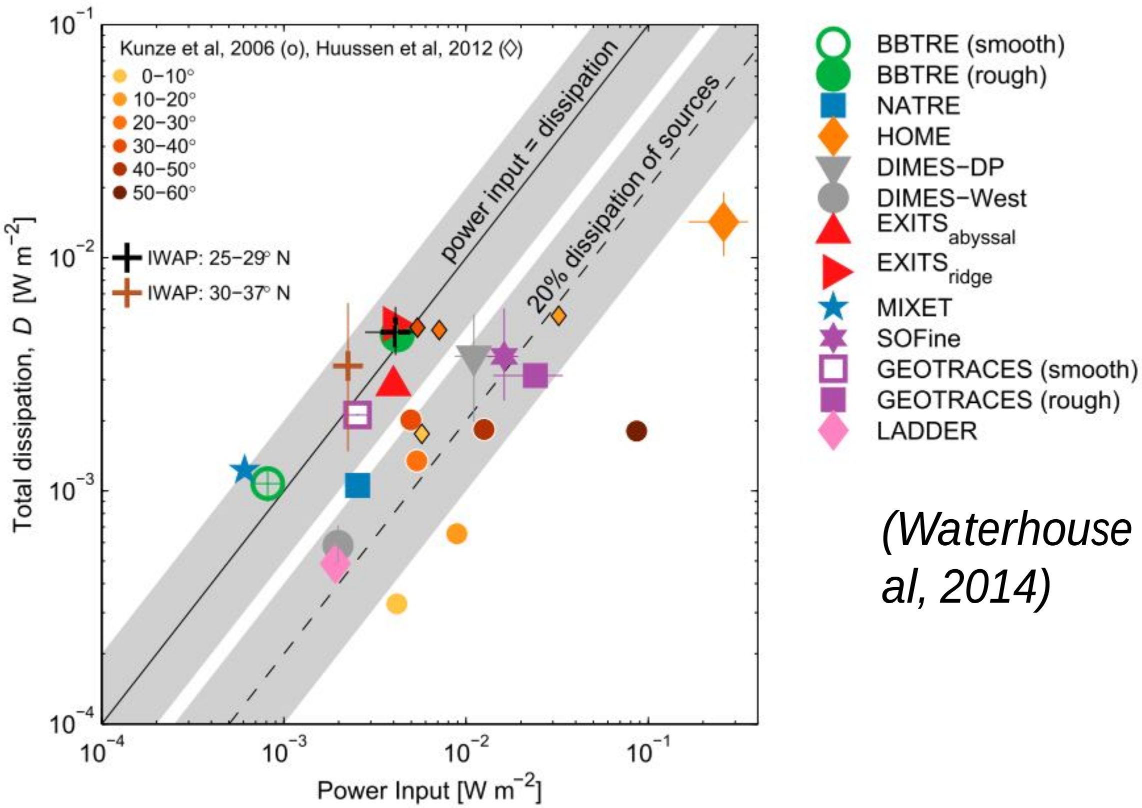
Inclusion of small-scale abyssal hills can increase energy conversion

At steep sinusoidal/rough topography, interference reduces energy conversion.

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

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

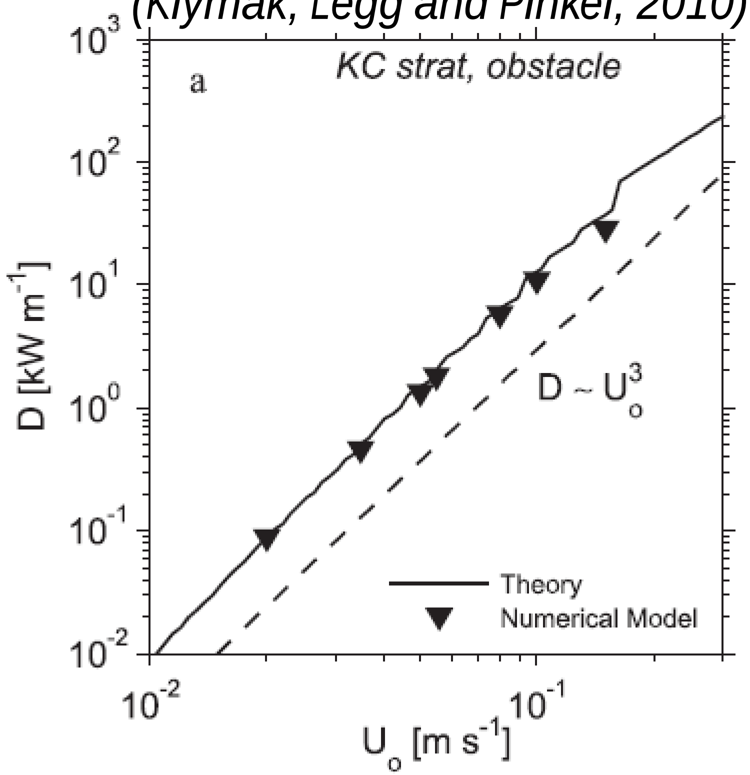
Observational evidence: q varies from 100%-20%



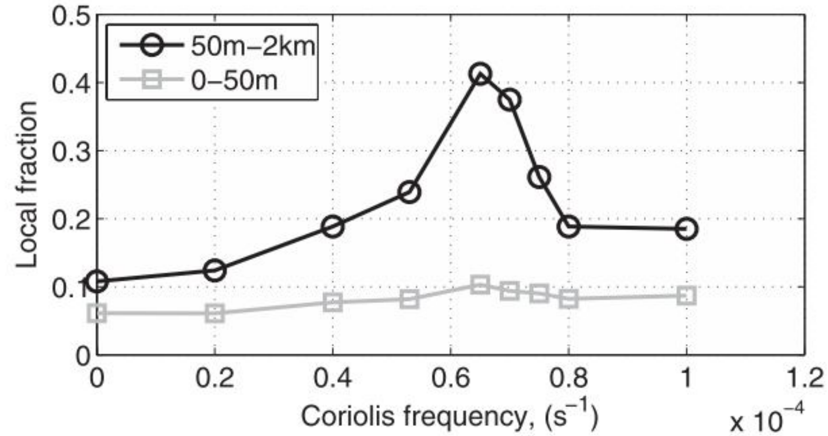
(Waterhouse et al, 2014)

The local dissipation fraction: what are the controlling factors?

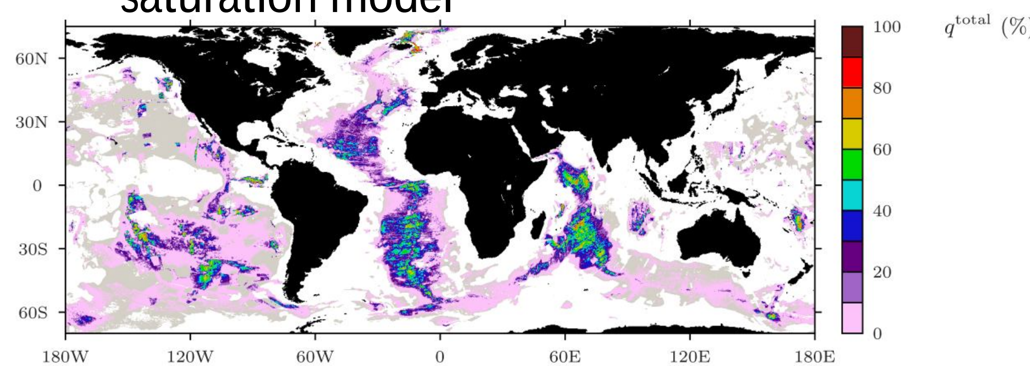
At tall steep isolated topography, $q \sim U$ *(Klymak, Legg and Pinkel, 2010)*



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



q predicted by wave-saturation model *(Lefauve et al 2015)*



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)

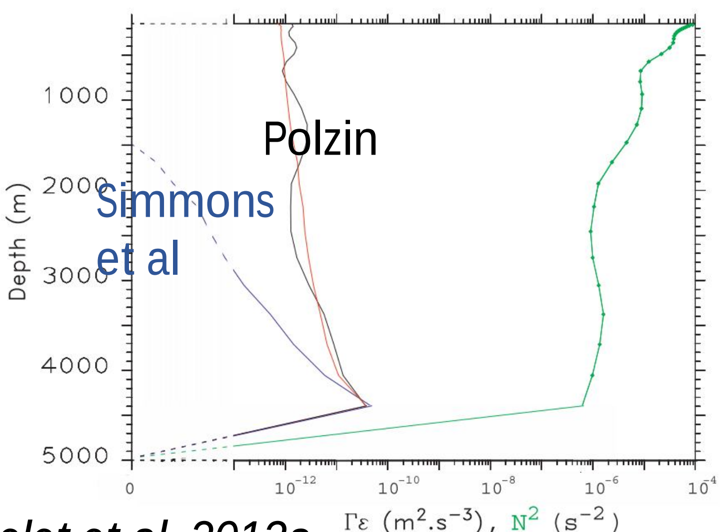
$$F(z) = \frac{e^{-z/z_s}}{z_s(1 - e^{-H/z_s})}$$

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

(Polzin 2009, Melet et al, 2013a)

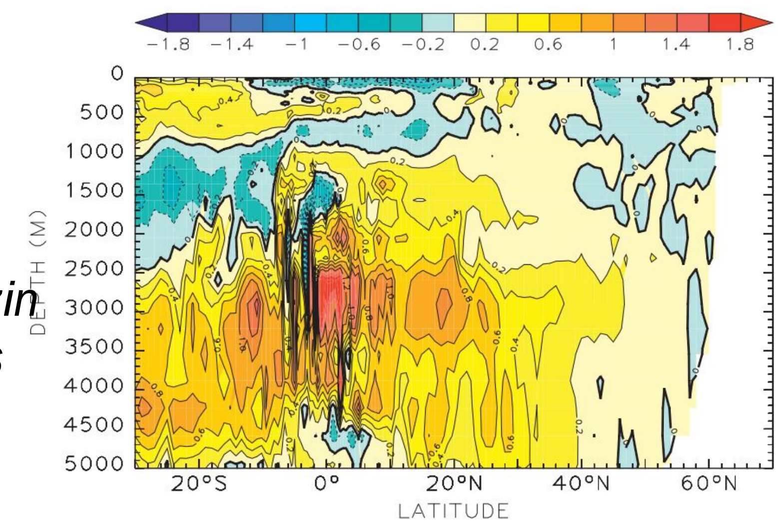
$$F(z) = \frac{1}{[1 - (z^*/z_p^*)]} \frac{N^2(z)}{\overline{N^2}} \left(\frac{1}{H} + \frac{1}{z_p^*} \right)$$

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



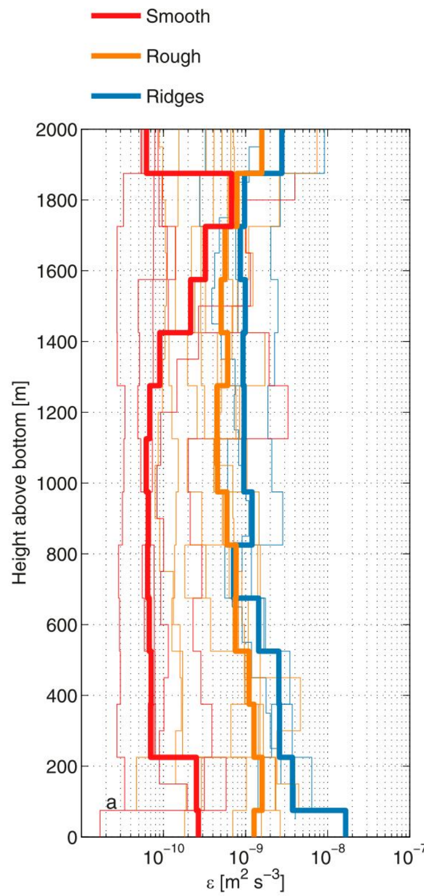
Melet et al, 2013a

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



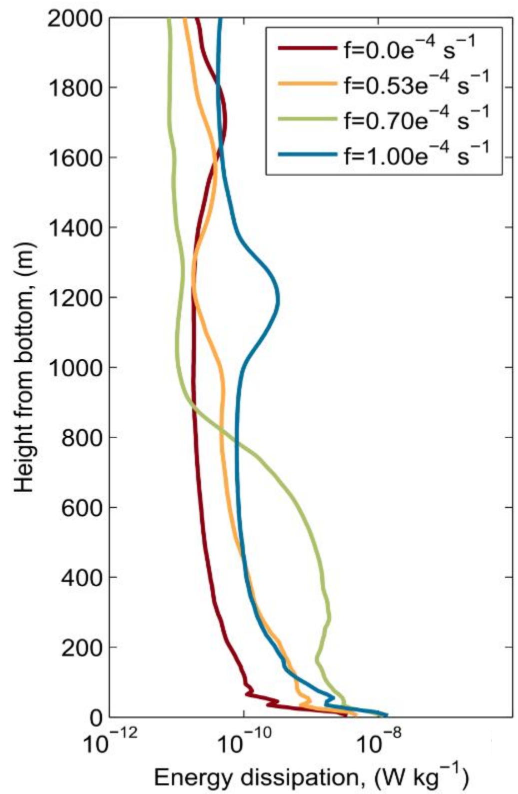
Redistributing dissipation in vertical has an impact on global circulation

The vertical profile of dissipation: Examples



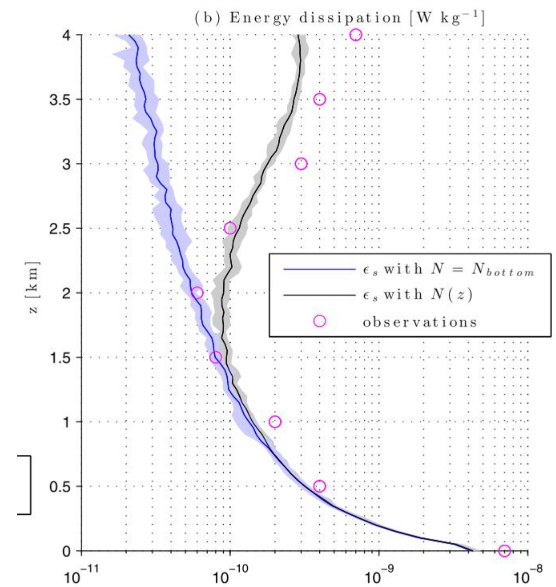
Compiled observations

(Waterhouse et al, 2014)



Coriolis dependence in simulations

(Yi, Legg and Nazarian, 2017)



Brazil basin obs and wave-saturation model *(Lefave et al, 2015)*

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

Mixing efficiency

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

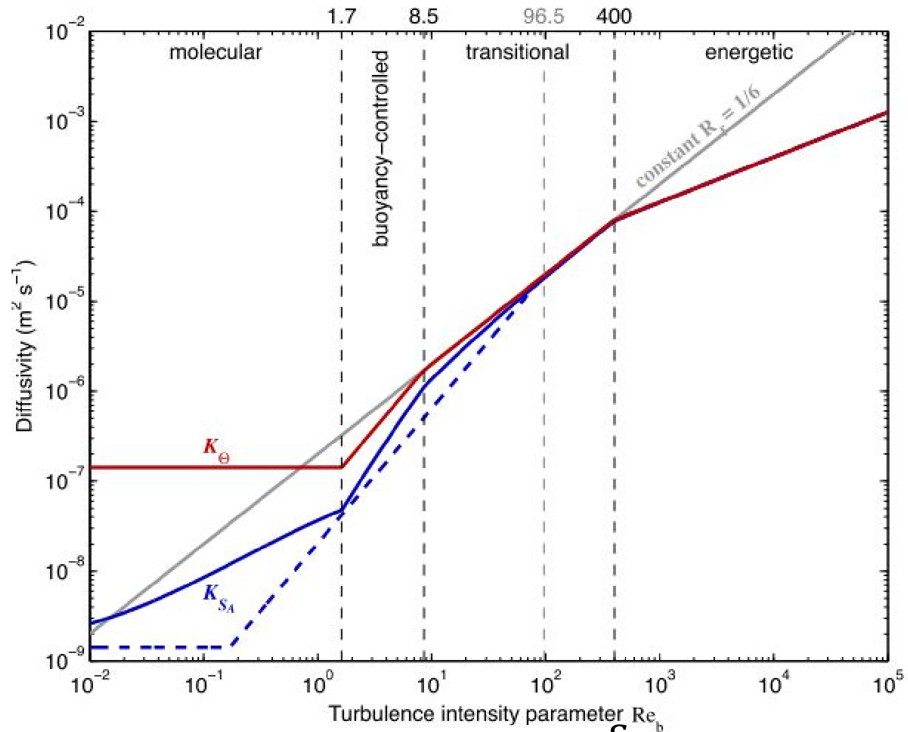
Current climate model parameterizations:

Γ = 0.2, with modifications for very low N

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

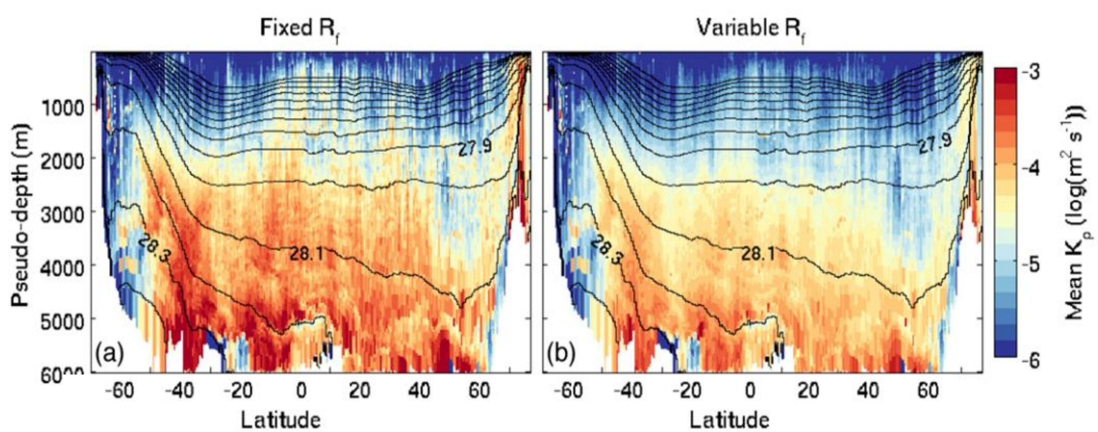
$$\Gamma = \frac{\kappa_\rho}{\nu Re_b}$$

κ



$$Re_b = \frac{\varepsilon}{\nu N^2}$$

Impact of variable mixing efficiency on near-field tidal diffusivity

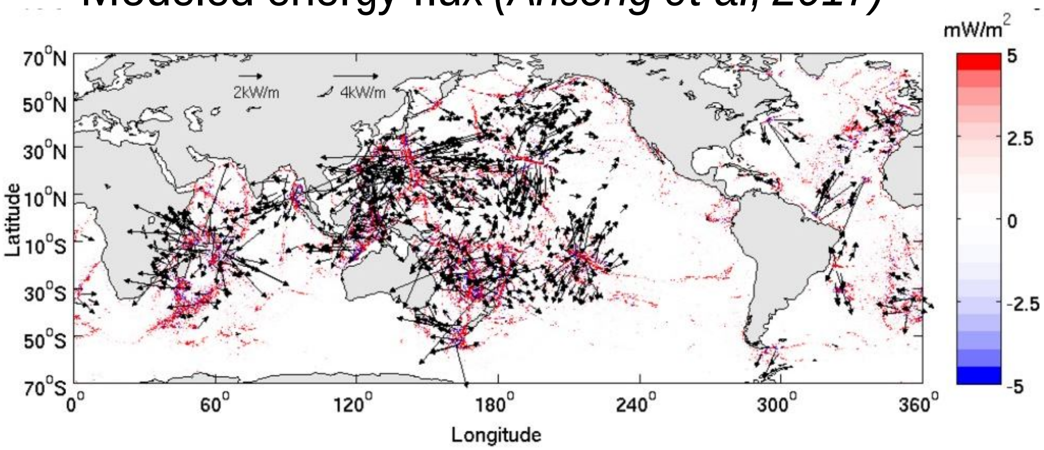


Variable Γ tends to reduce κ in deep ocean.

Far-field tidal dissipation

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

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



$(1-q)$ × baroclinic tide energy propagates away from generation site

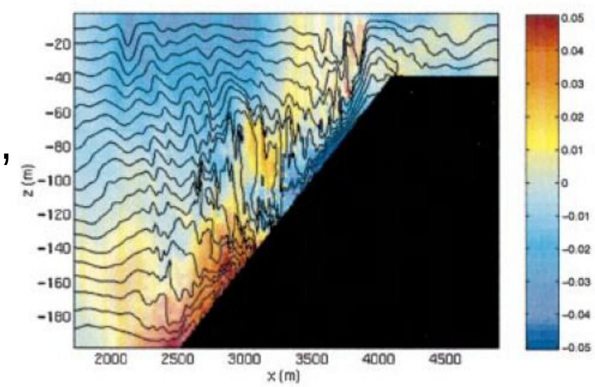
Current climate model parameterization: Constant or latitude dependent κ_b
Violates energy conservation!

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).

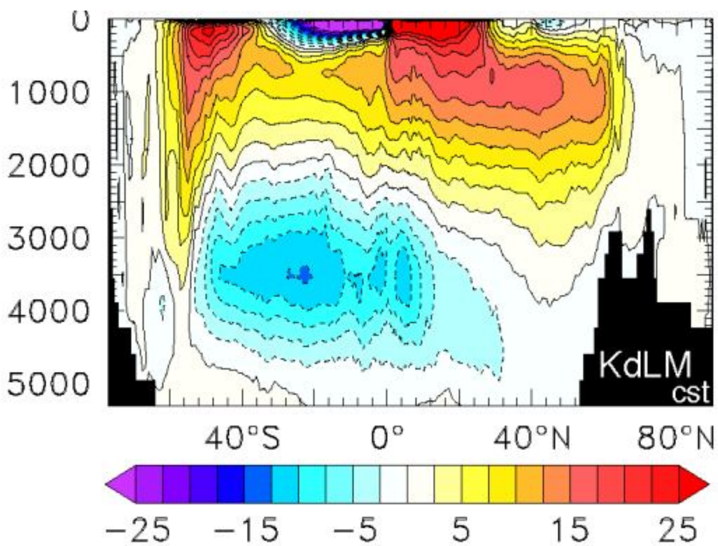


Internal wave breaking at continental slope
(Legg and Adcroft, 2003)

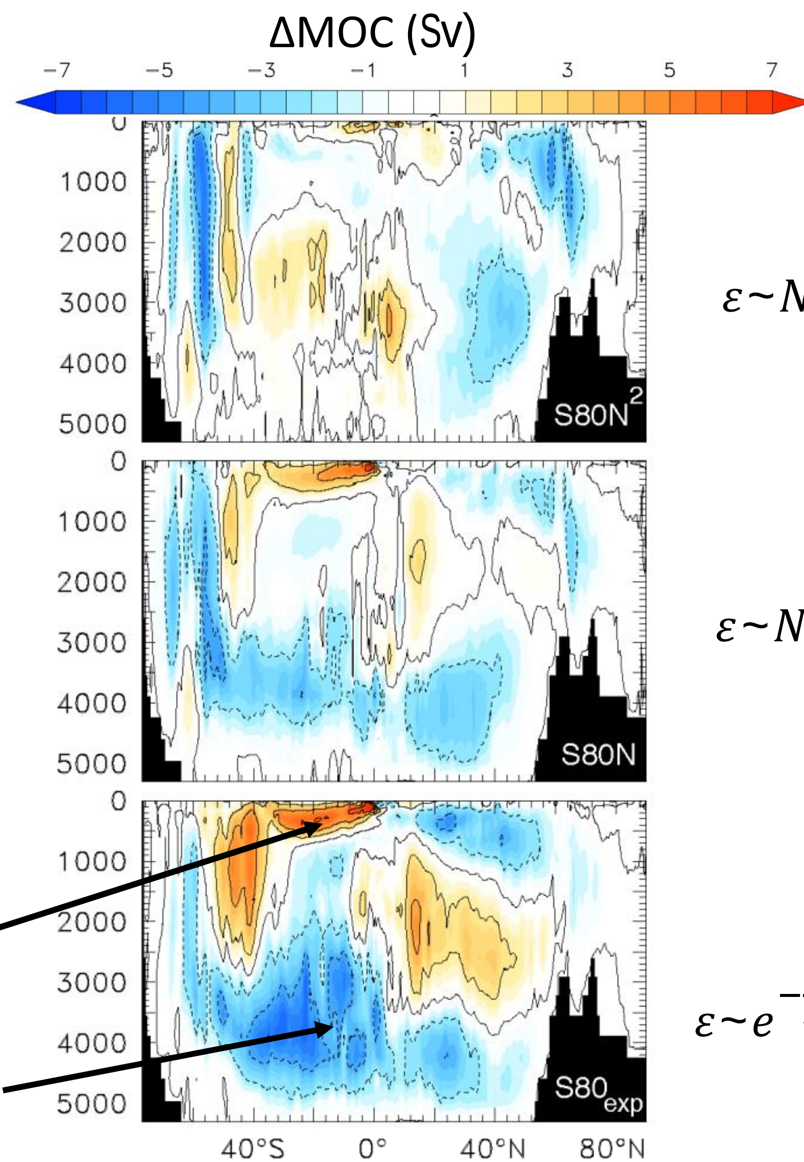
Impact of vertical structure of farfield mixing: overturning strength

(ESM2G coupled model simulations, *Melet et al, 2016*)

Reference: 20% local,
80% uniform diffusivity



Global meridional overturning circulation (Sv)



$\varepsilon \sim N^2$

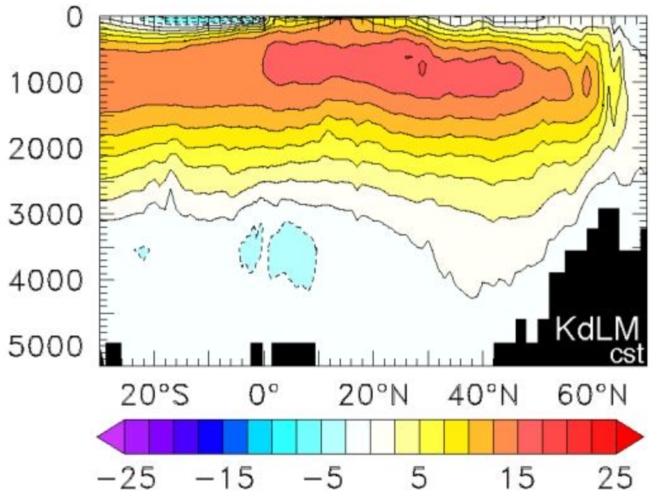
$\varepsilon \sim N$

$\varepsilon \sim e^{-\frac{z}{z_s}}$

20% local, 80% slopes

- Less near-surface mixing:→ weaker subtropical overturning
- More mixing at depth:→ stronger deep overturning

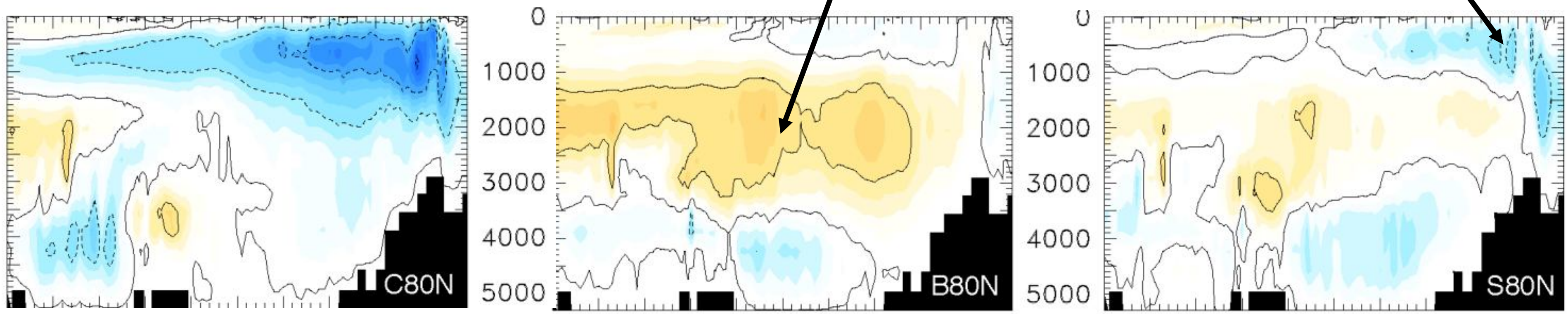
Impact of horizontal location of farfield mixing: Atlantic overturning



Atlantic MOC (Sv)

Reference: 20% local, 80% uniform diffusivity

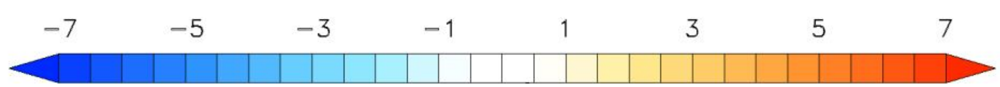
- Mixing on shelves/straits weakens AMOC
- Deep mixing strengthens/deepens AMOC



20% local, 80% coasts

20% local, 80% basins

20% local, 80% slopes



ΔAMOC (Sv)

All have $\varepsilon \sim N$

(Melet et al, 2016)

Summary of progress and gaps in tidal mixing parameterization

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

Locally

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

Globally require

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

E(x,y) depends on:

- tidal velocities, f, ω, 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.

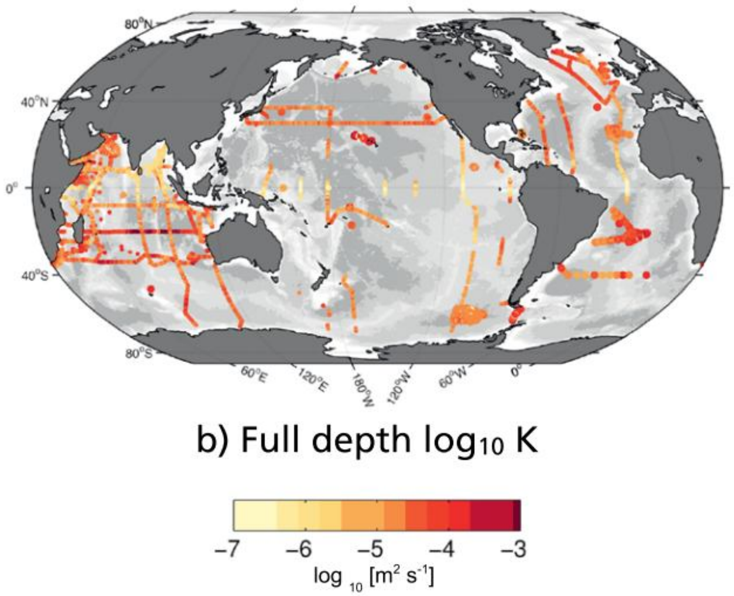
How to proceed?

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)



(Waterhouse et al, 2014)

- 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?

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.