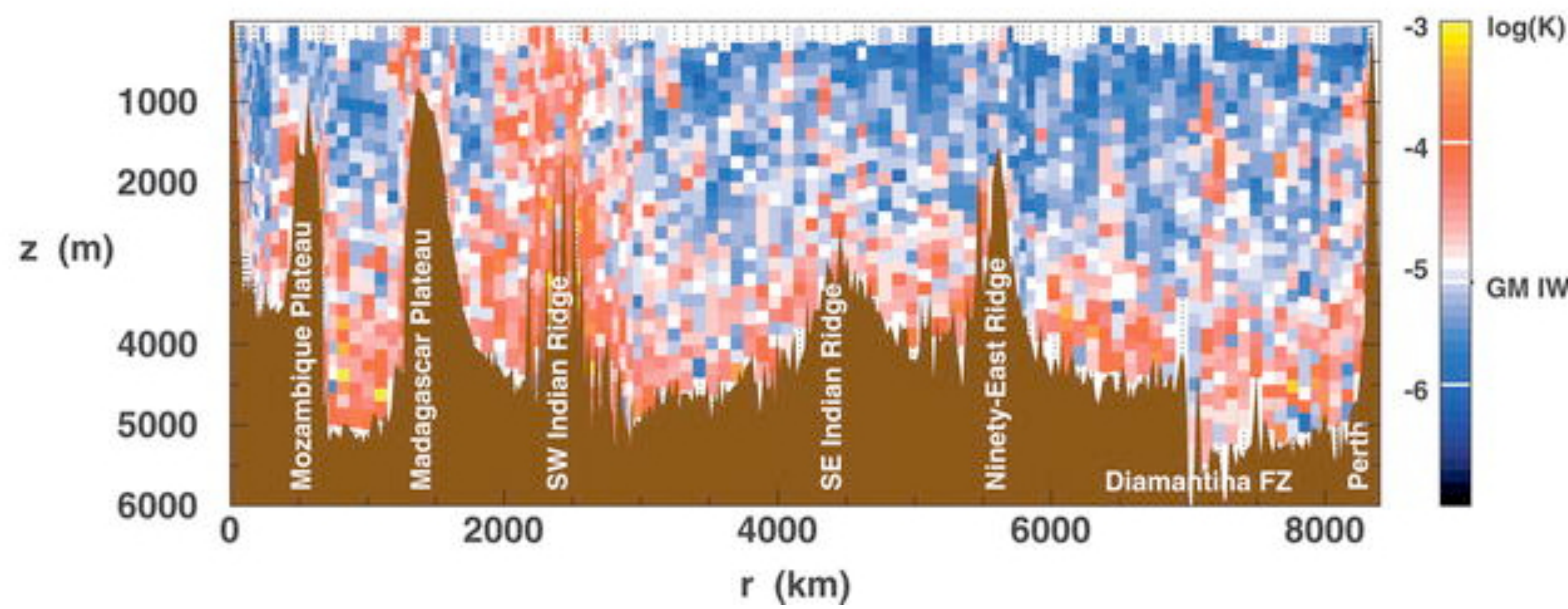
CPT: internal-wave driven mixing in global ocean models

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 the rates and patterns right.



Kunze et al 06

The Team

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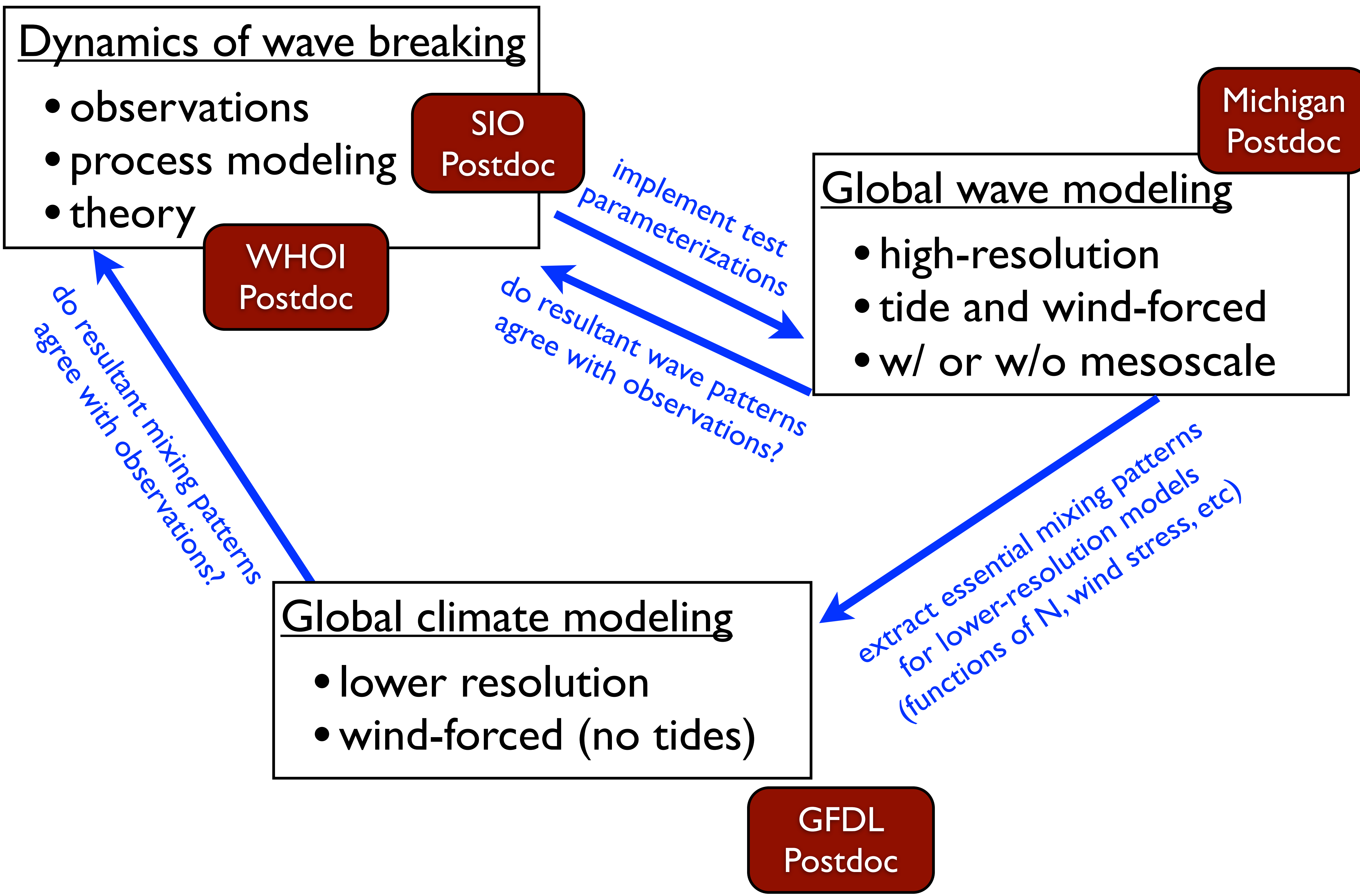
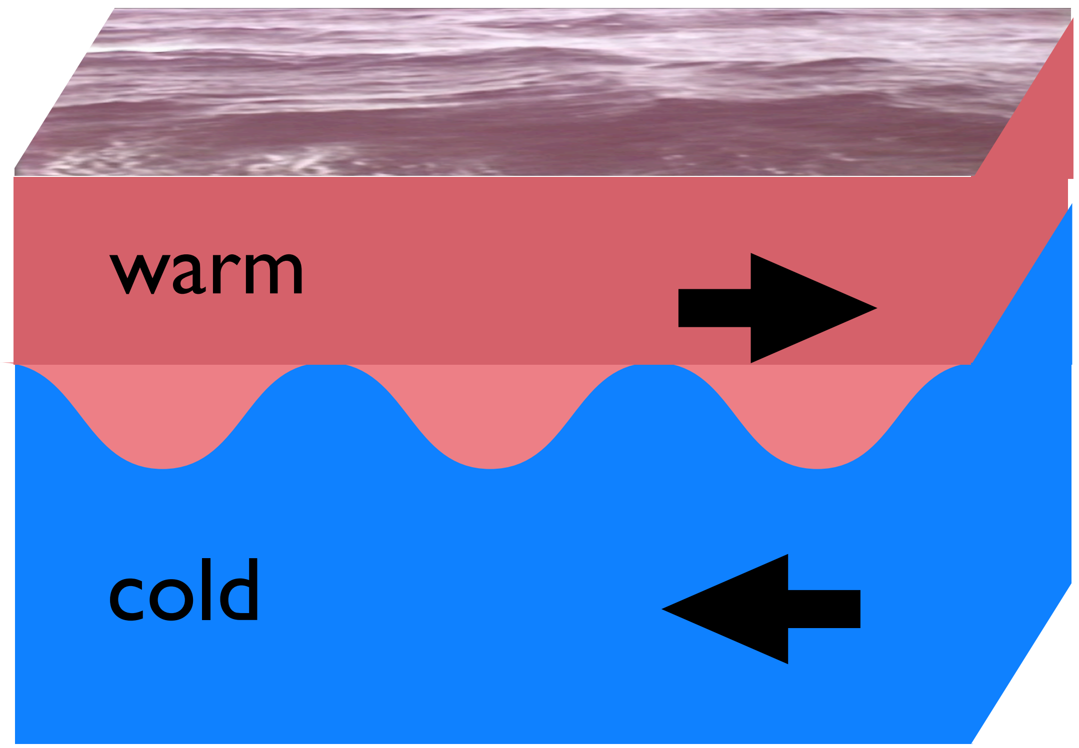
Our plan: use what we collectively know about internal wave physics to develop a dynamic parameterization of diapycnal mixing that can evolve in a changing climate.

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

Structure of CPT



Internal wave primer



- Low-mode ~interfacial waves
- High-mode ~ plane waves
- Fast $f \leq \omega \leq N$
- Breaking waves are at small scales: 1-10 m vertically, a few hundred horizontally (the later a larger constraint for model resolution)

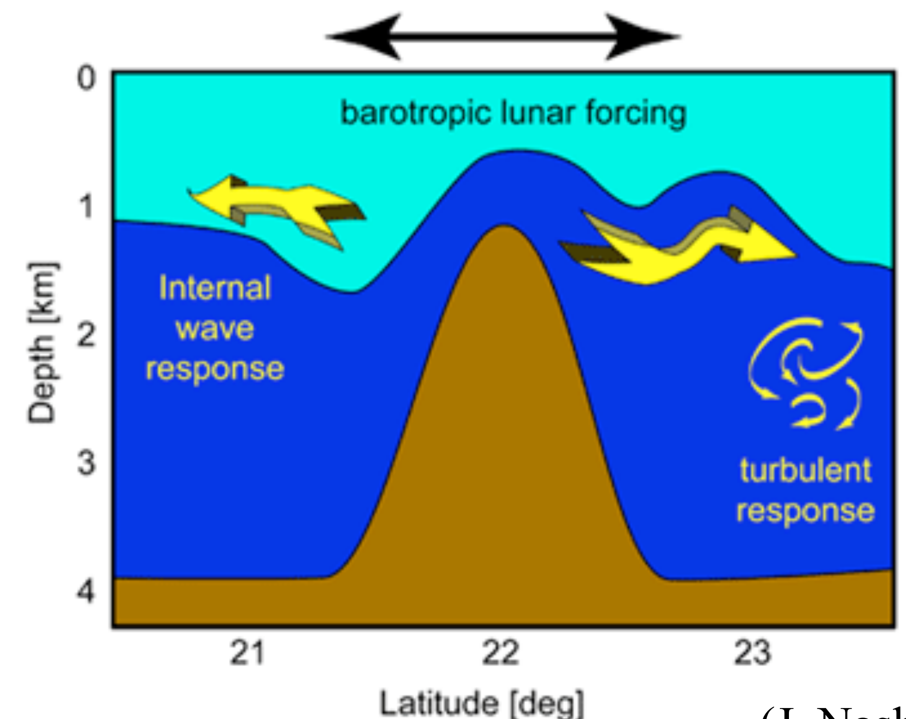
(Flierl)

Parameterizing mixing

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

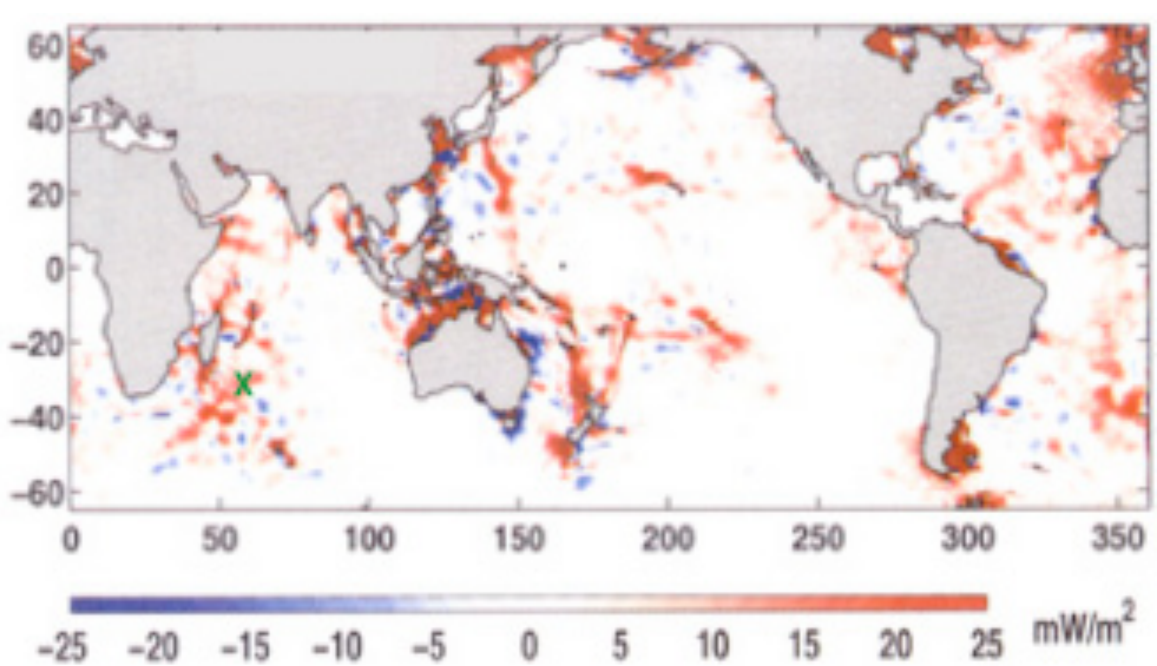
1) Wave generation: 3 different mechanisms

Internal Tides: generated by oscillatory tidal flow over topography. Waves have tidal frequencies. Not in climate models.



(J. Nash)

Internal-Tide Generation



Egbert and Ray 01

Geography of generation: where barotropic(astronomical) tides are large and topography is rough. Both of these things are predictable, so can create a static of internal tide production

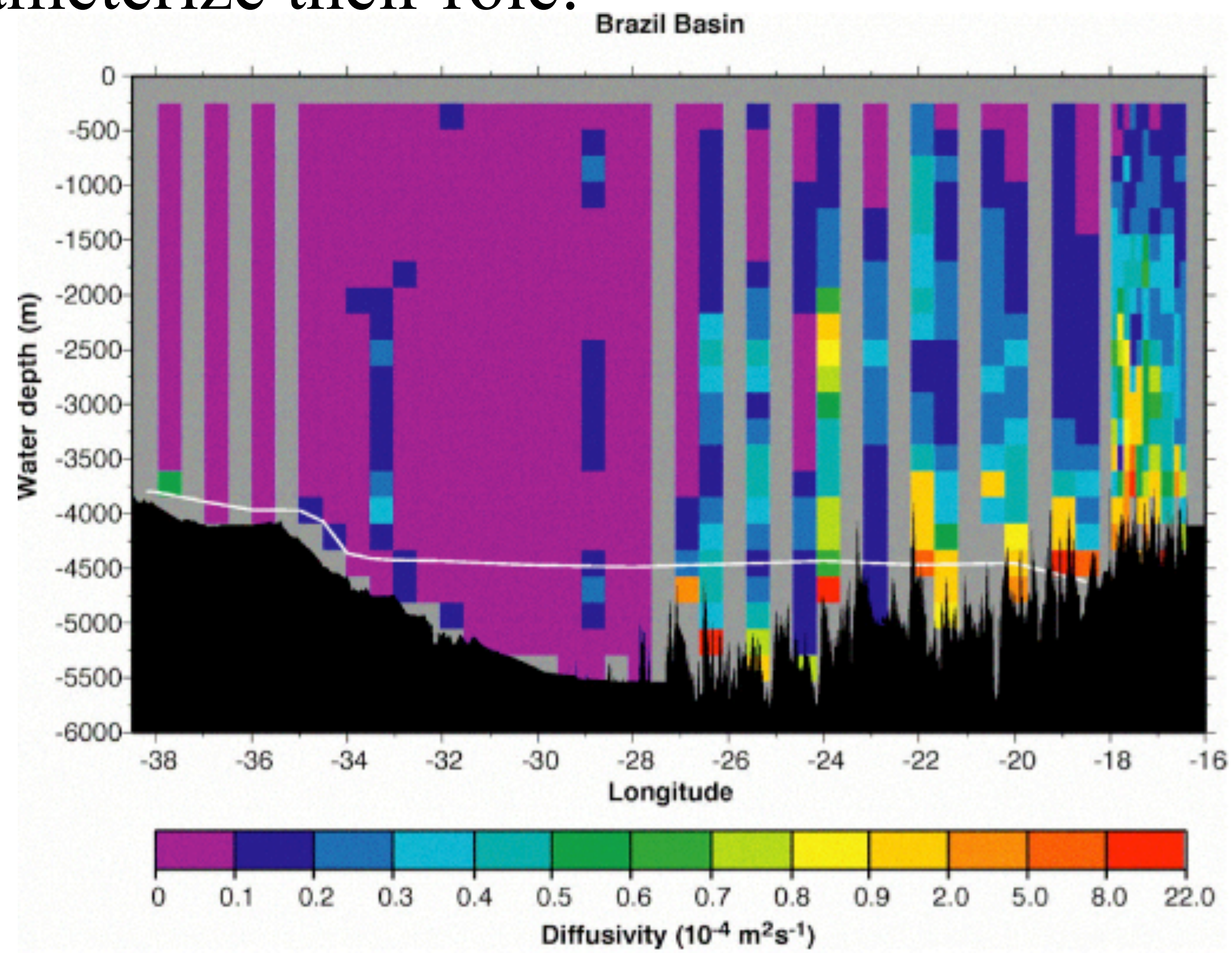
Parameterizing mixing

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

1) Wave generation

2) Some waves break "locally": the percent varies from place to place

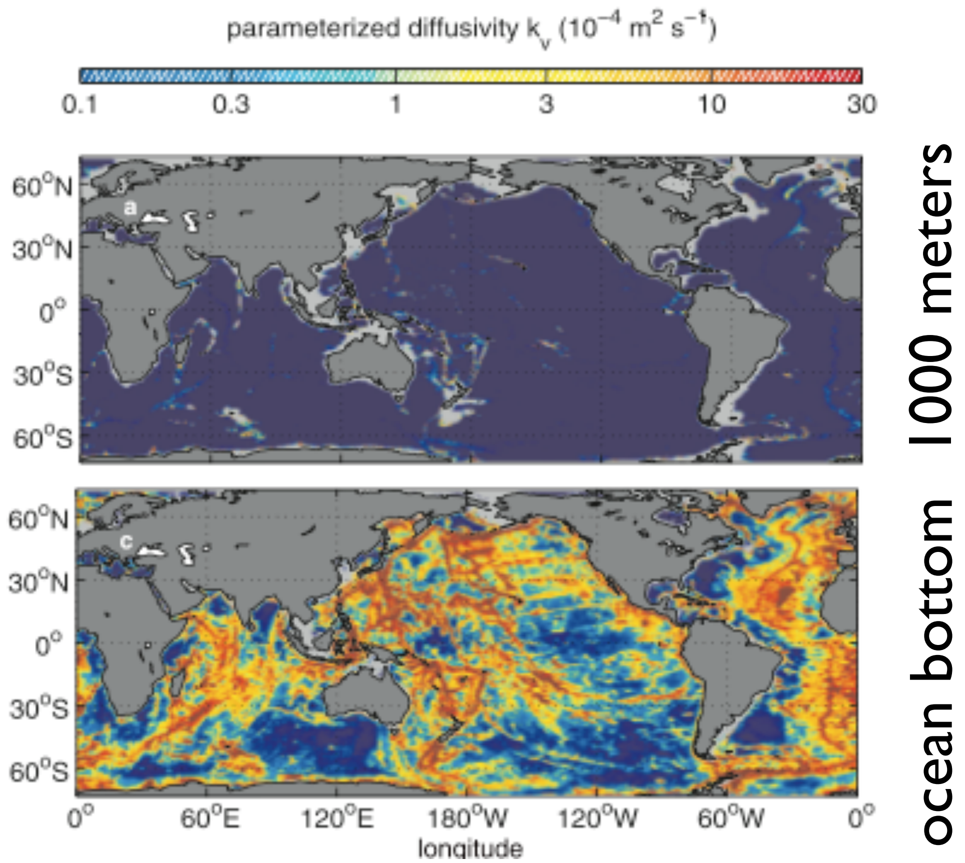
Internal tides propagating up from the rough (eastern) bathymetry steadily break, producing elevated mixing up into the main thermocline



Polzin et al. 97

Global pattern of mixing that mirrors wave generation

“Nearfield” tidal mixing



St Laurent et al 02

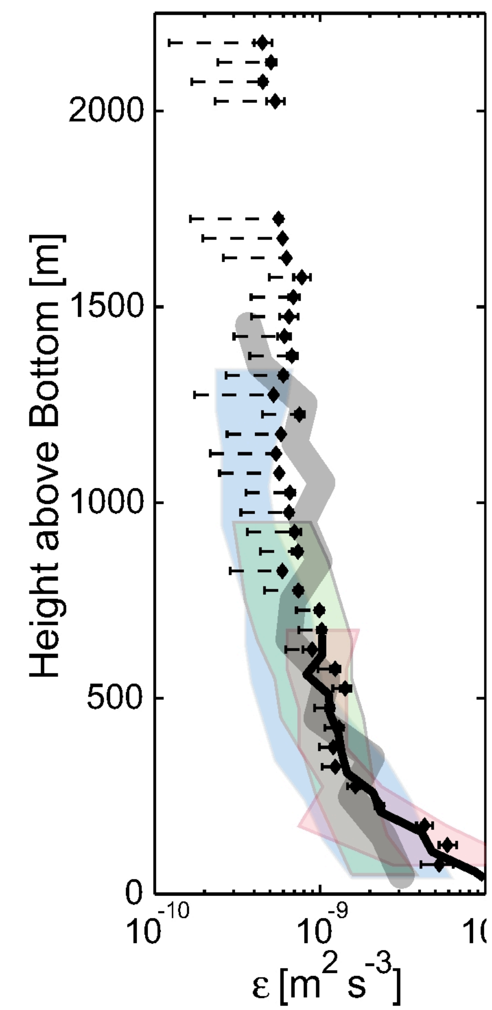
dissipation rate (related to diffusivity)

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

vertical structure (exponential decay)

$$\epsilon = \frac{\mathbf{qE(x,y)F(z)}}{\rho}$$

% of energy that dissipates locally



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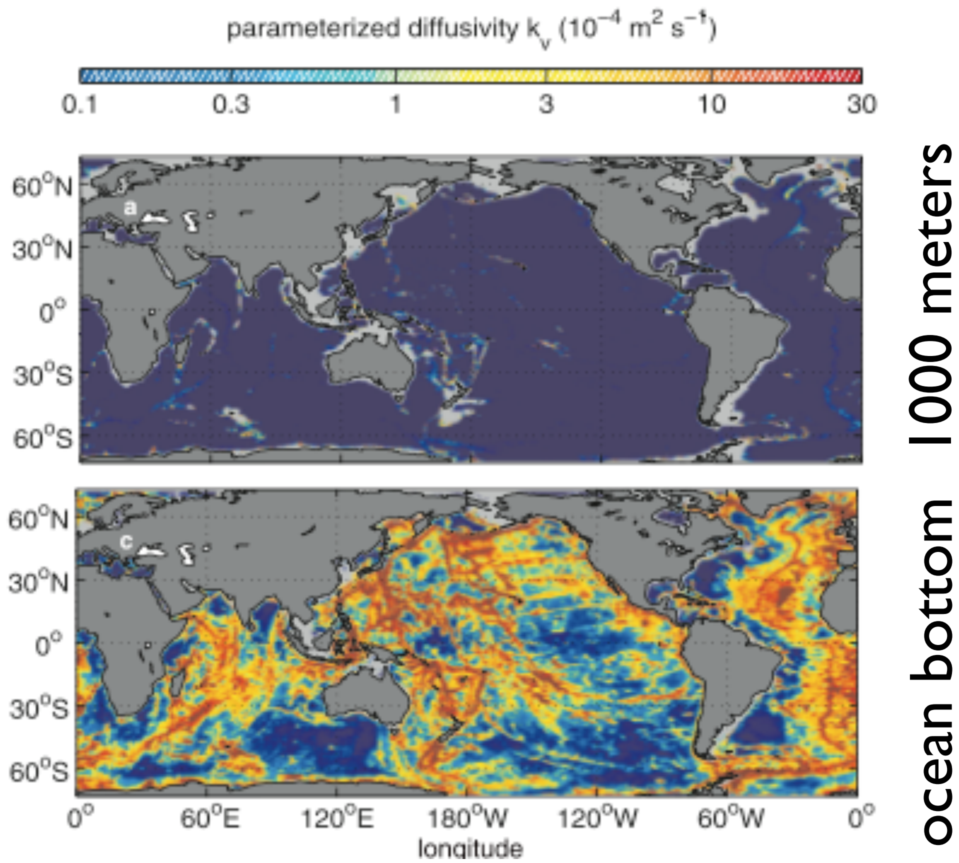

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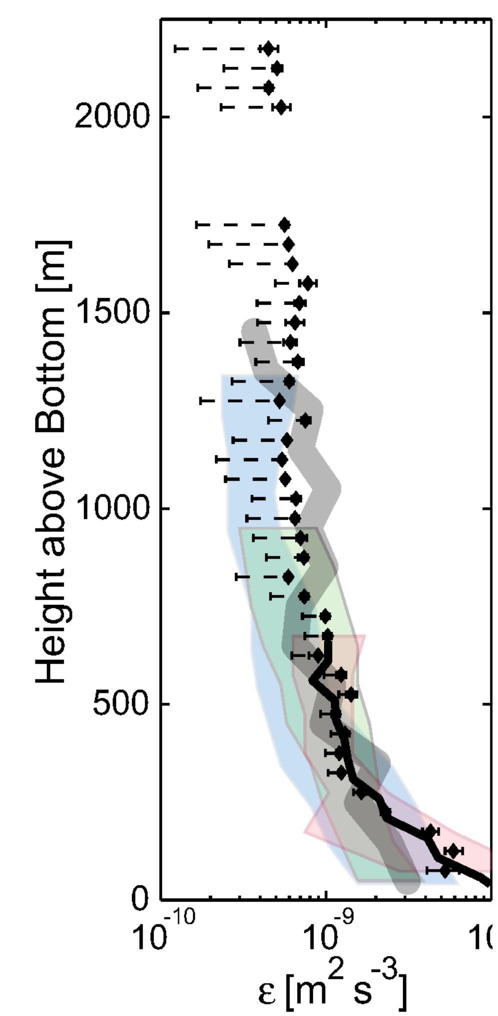
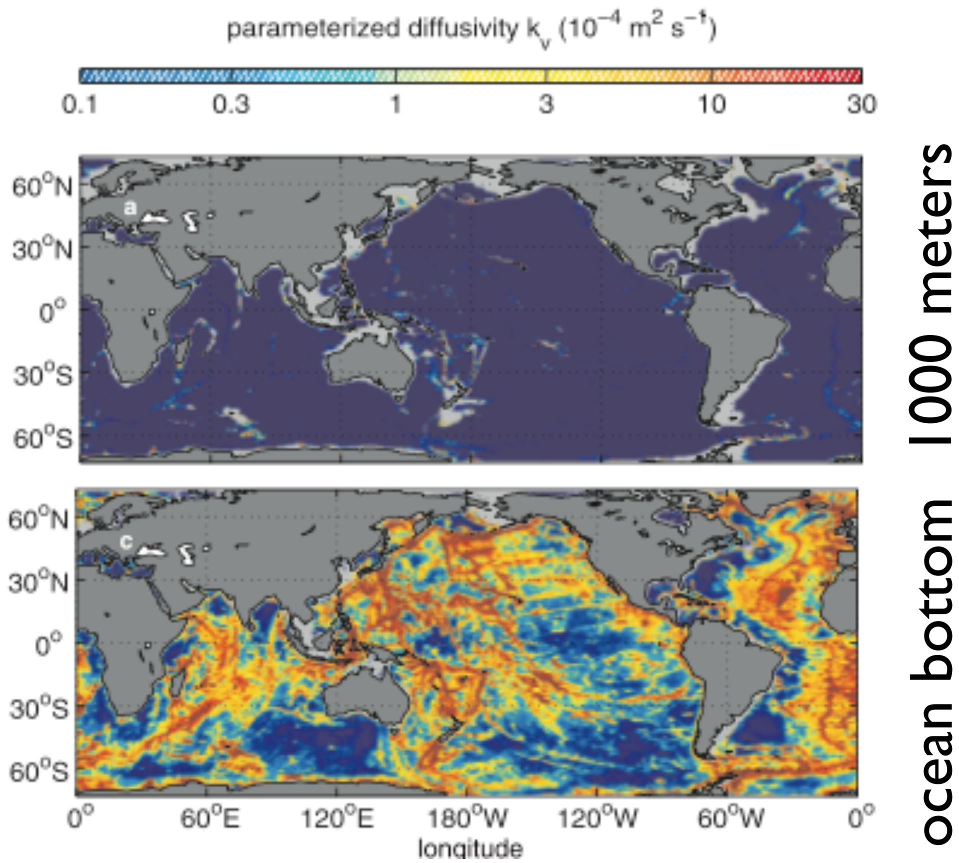


PLANNED WORK

Develop a vertical decay scale based on nonlinear dynamics of wave interaction and breaking. Essentially we’ve replaced the empirical F(z) vertical structure function from St. Laurent et al with a more dynamically based one and tested model sensitivity.

“Nearfield” tidal mixing



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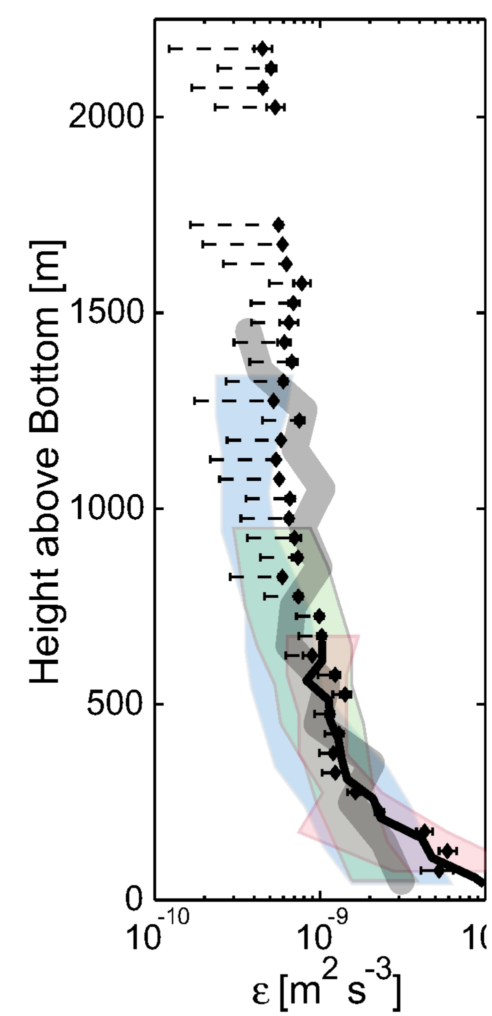
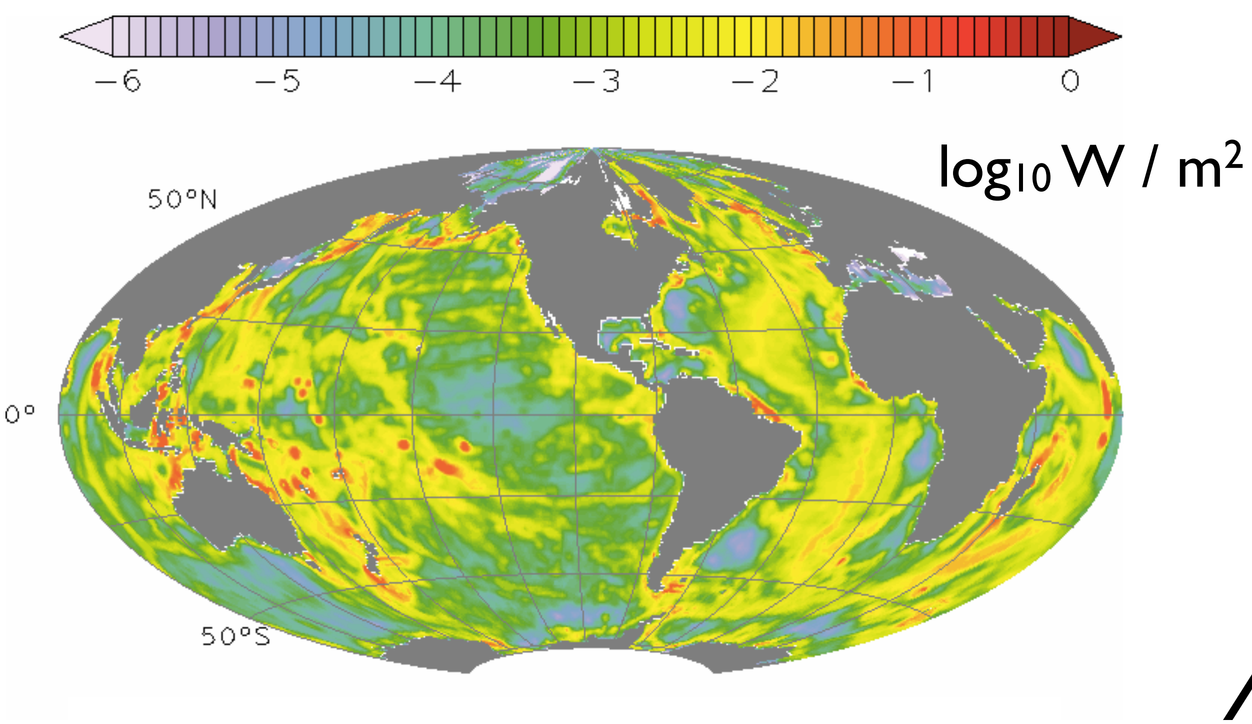
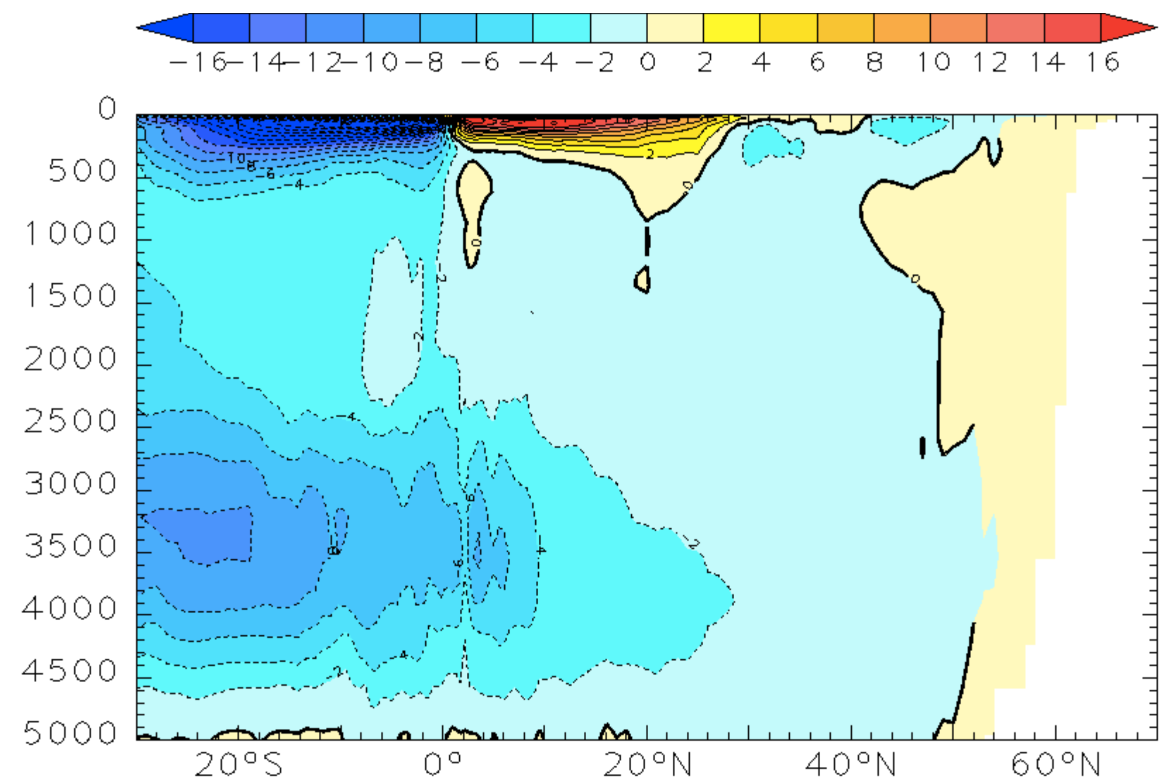


Nearfield: mixing over rough topography

Energy flux into internal tides in GFDL's GOLD isopycnal model (total = 1.5 TW)

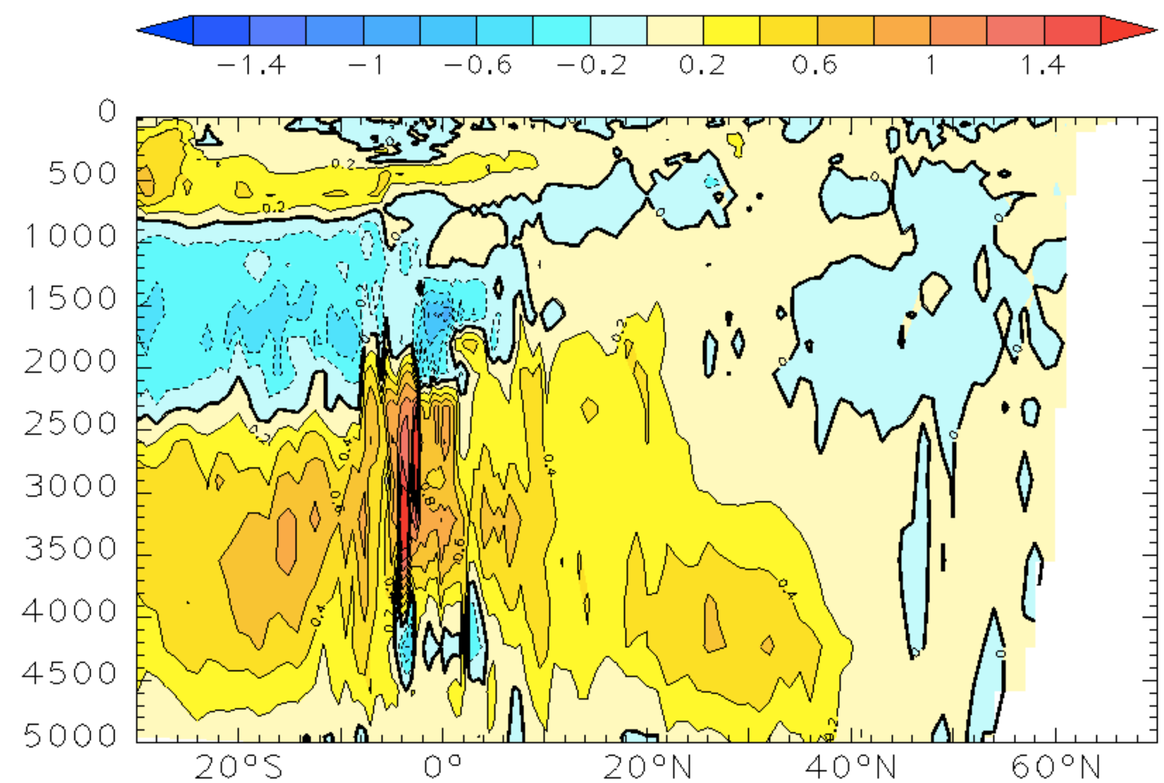




Sensitivity to the vertical structure of elevated mixing over rough topography:

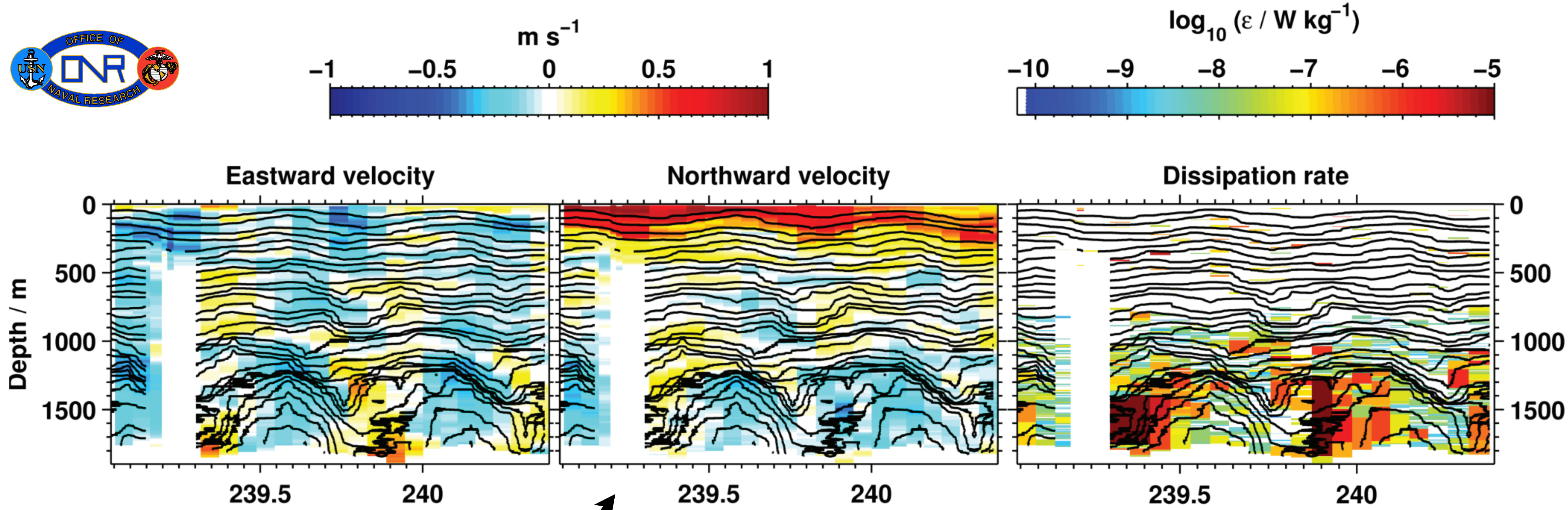
Total Indo-Pacific MOC (in Sv),

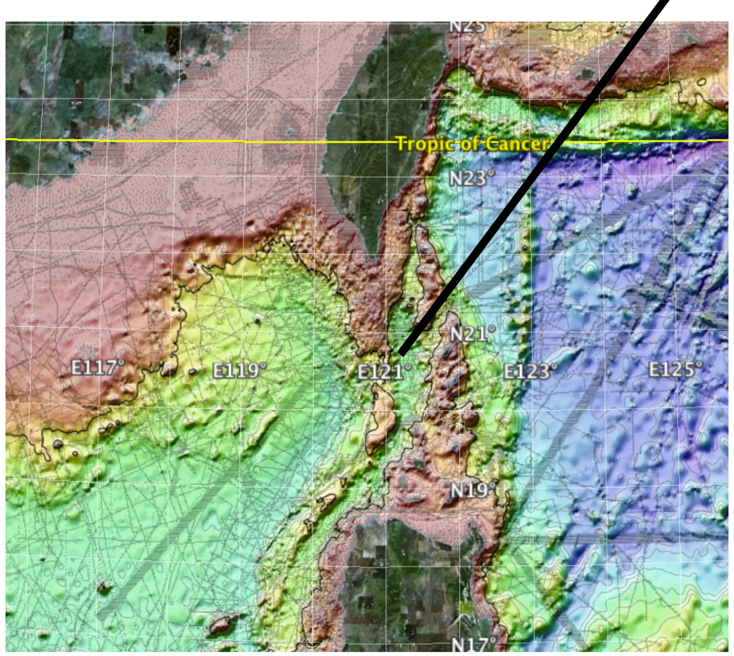
and change between two different formulations



Melet et al 12 (submitted)

Nearfield: EXTREME mixing over rough topography





Ongoing work by Legg and Klymak to parameterize elevated turbulence when topography is very steep and (tidal) flows very strong. Status: preliminary paramterization developed, working with GFDL to implement and test. Caveat - basic physics still not totally understood

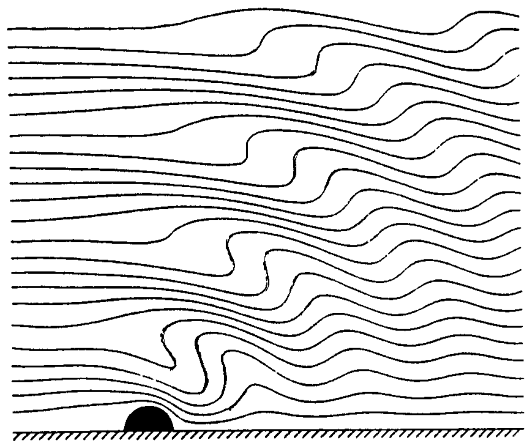
(Alford et al 11)

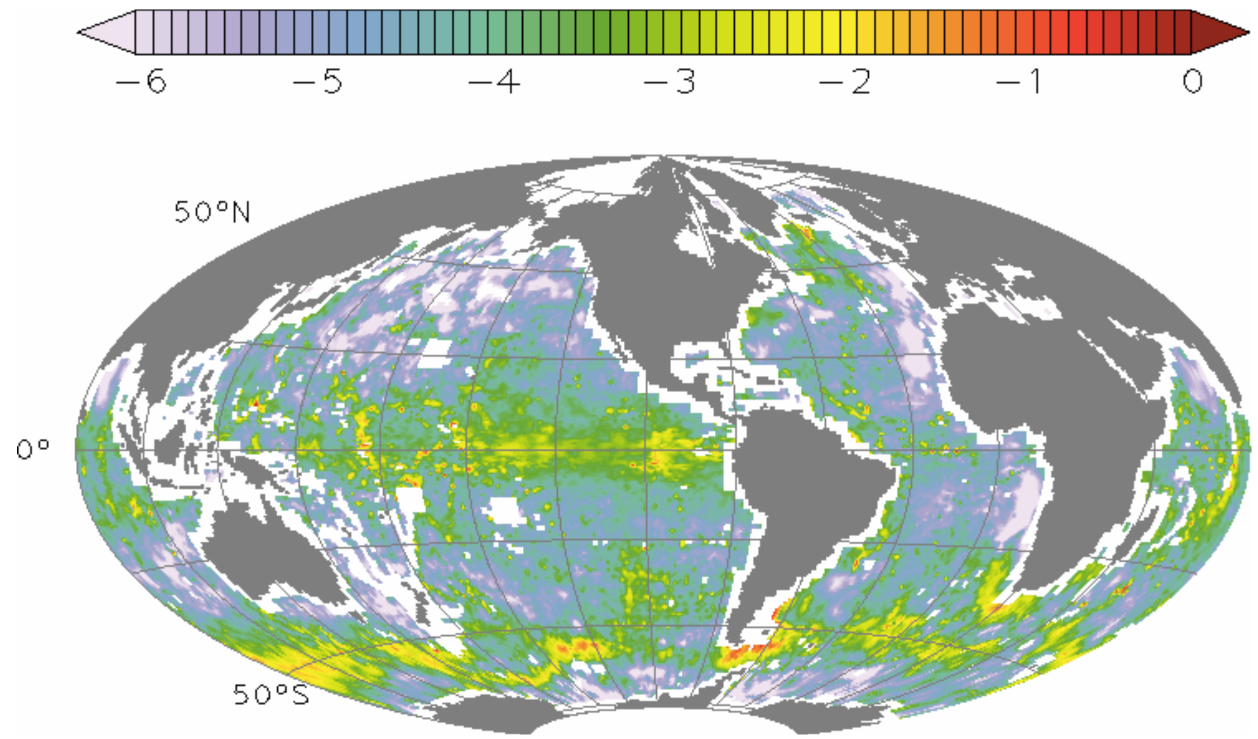
Internal lee waves

•Analogous to atmospheric mountain waves, where strong low-frequency flows encounter rough topography internal lee waves may be created, producing elevated mixing above the bottom, even when local tides are weak (e.g. Nikurashin and Ferrari 11).

•Effect is modest (0.2 TW in GOLD, compared to 1.5 TW for internal tide) but regionally important, especially in Southern Ocean and possibly the equator.

•Effect being implemented and studied by Melet et al with GFDL GOLD model.





Energy flux into internal lee waves in GOLD (Melet et al)

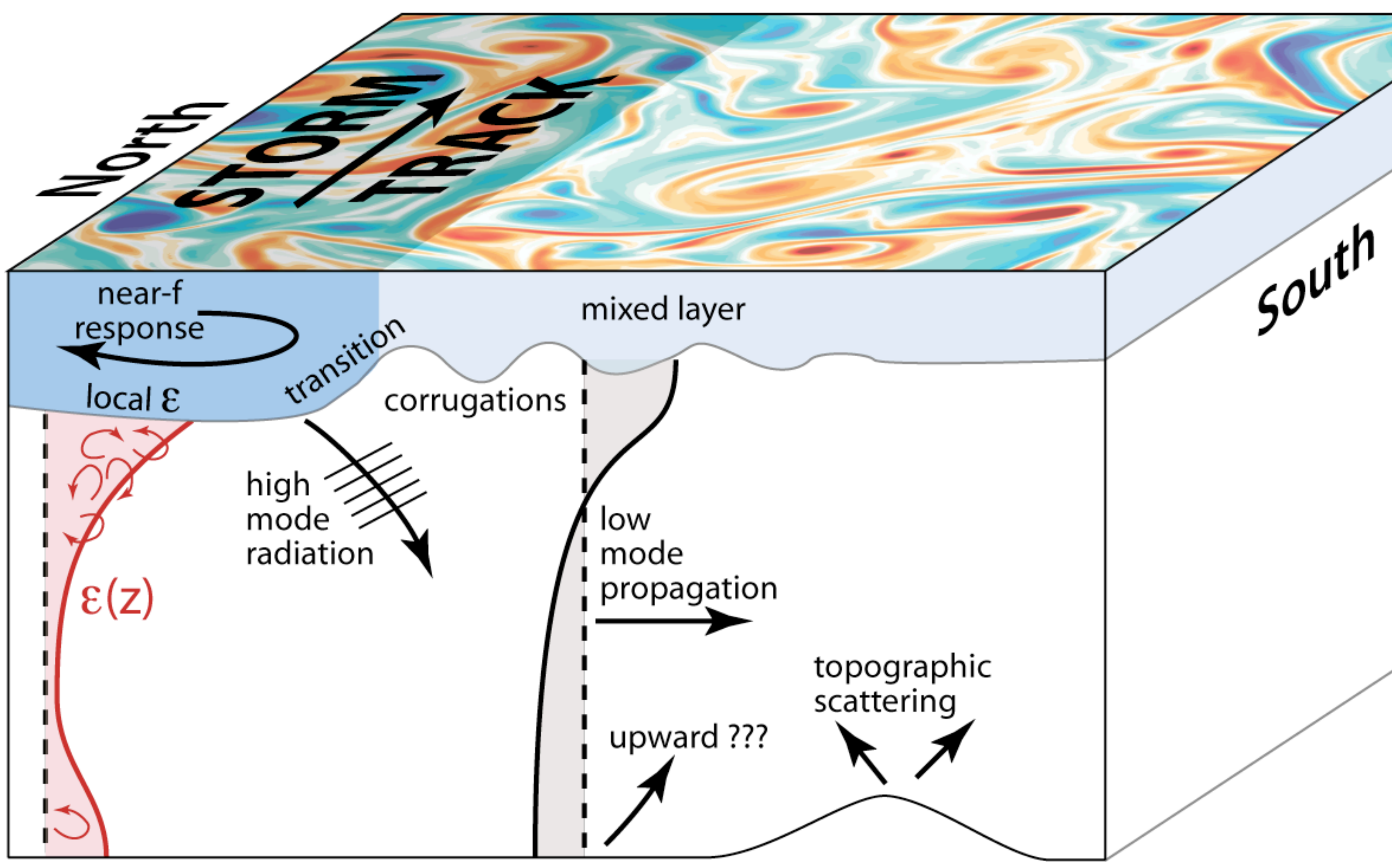
Near-inertial waves

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

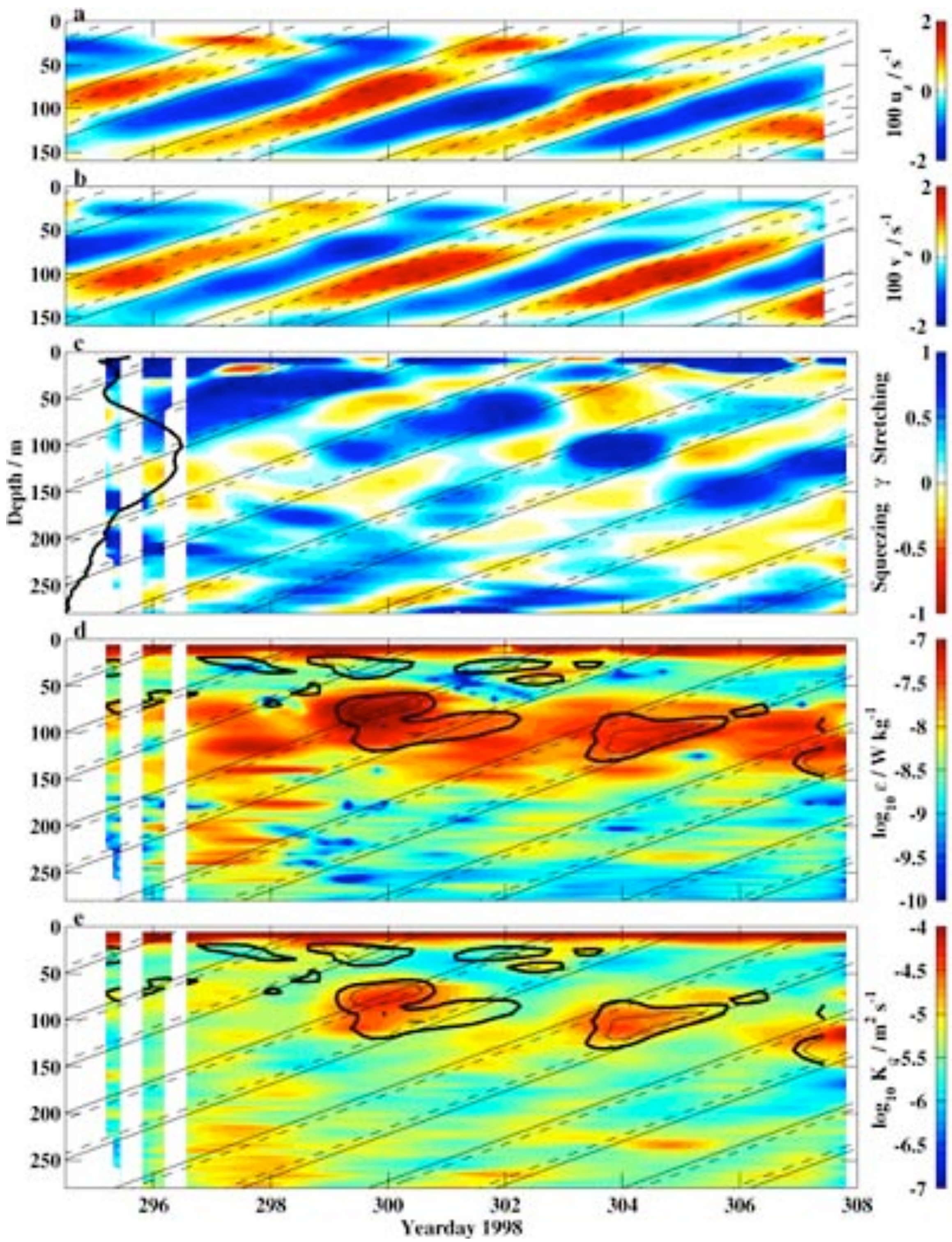
1) Wave generation: 3 different mechanisms

Near-inertial motions: Upper ocean inertial motions typically generated by time-variable component of wind stress have a frequency close to the local inertial frequency. Mixed-layer oscillations lose energy to propagating near-inertial internal waves. Typically large in mid-latitude storm tracks.

- As with internal tides, there is both a 'nearfield' and 'farfield' component to the internal wave breaking
- Upper ocean response sensitive to mesoscale vorticity, so hard to generate a static map, even given wind fields. Need a dynamic parameterization.



Example of near-inertial upper ocean mixing



S = du/dz

vertical strain

turbulent dissipation rate

turbulent diffusivity

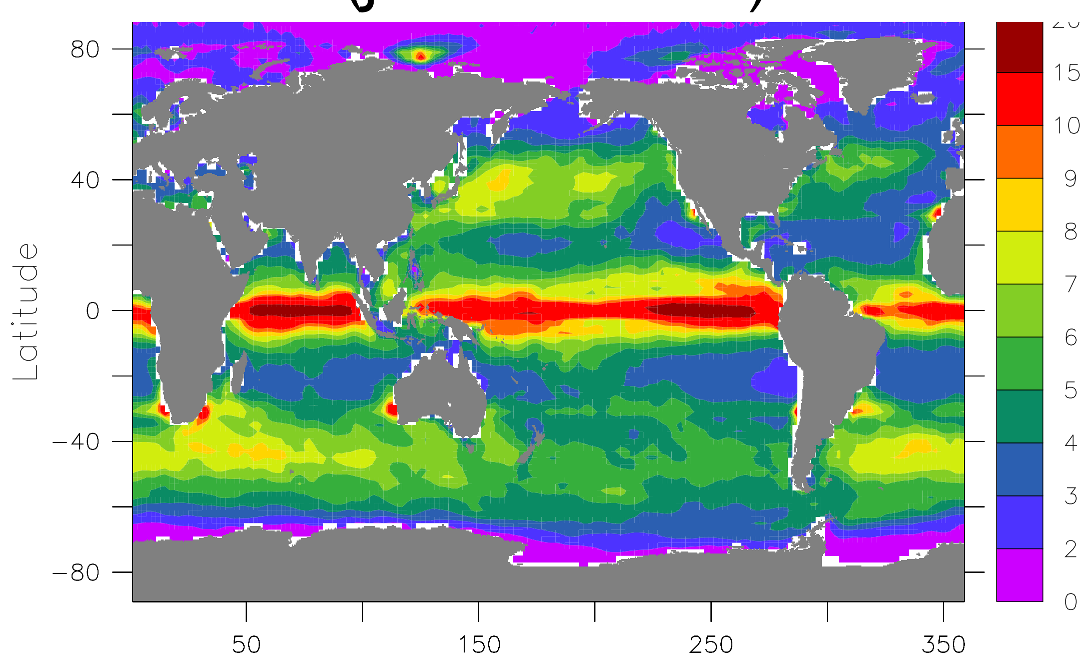
Example from the Banda Sea [Alford and Gregg 01]

Turbulence when $Ri = N^2/S^2$ is small

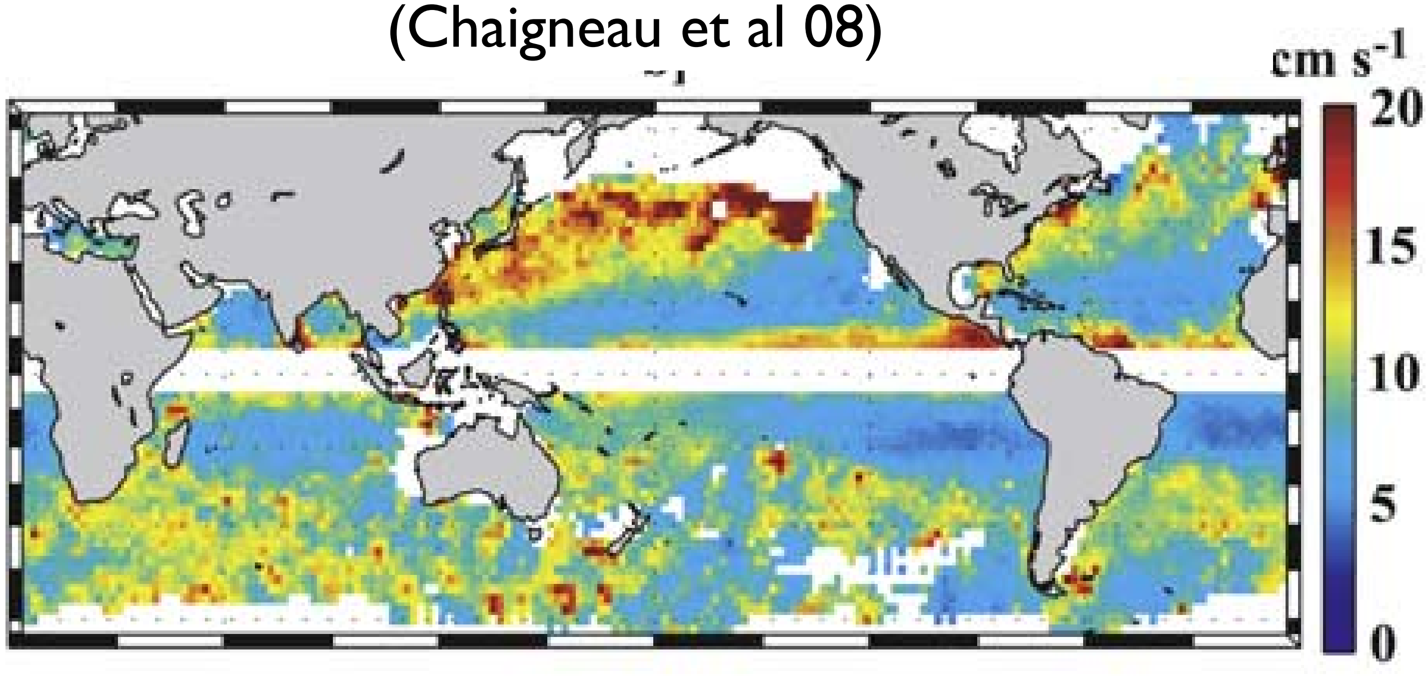
Parameterized near-inertial related mixing (NCAR)

- Change CCSM4 model to couple atmosphere to ocean every 2 hours => suddenly there are near-inertial motions everywhere! Particularly in mid-latitude storm tracks, Southern Ocean, and Arctic (the later sensitive to ice cover, which may be changing rapidly)

CCSM mixed-layer near-inertial speed (cm/s) (Jochum et al 12)



Observed near-inertial speed from surface drifters (Chaigneau et al 08)



Parameterized near-inertial related mixing (NCAR)

- Extra near-inertial shear at mixed layer base triggers KPP and deepens mixed layer 20-50% under storm track and trade winds.

- New upper ocean parameterization to account for mixing in upper ~500 meters of ocean due to radiating near-inertial internal waves

Internal tide parameterization

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

vertical structure (exponential decay)

$$\epsilon = \frac{\mathbf{q}\mathbf{E}(\mathbf{x},\mathbf{y})\mathbf{F}(\mathbf{z})}{\rho}$$

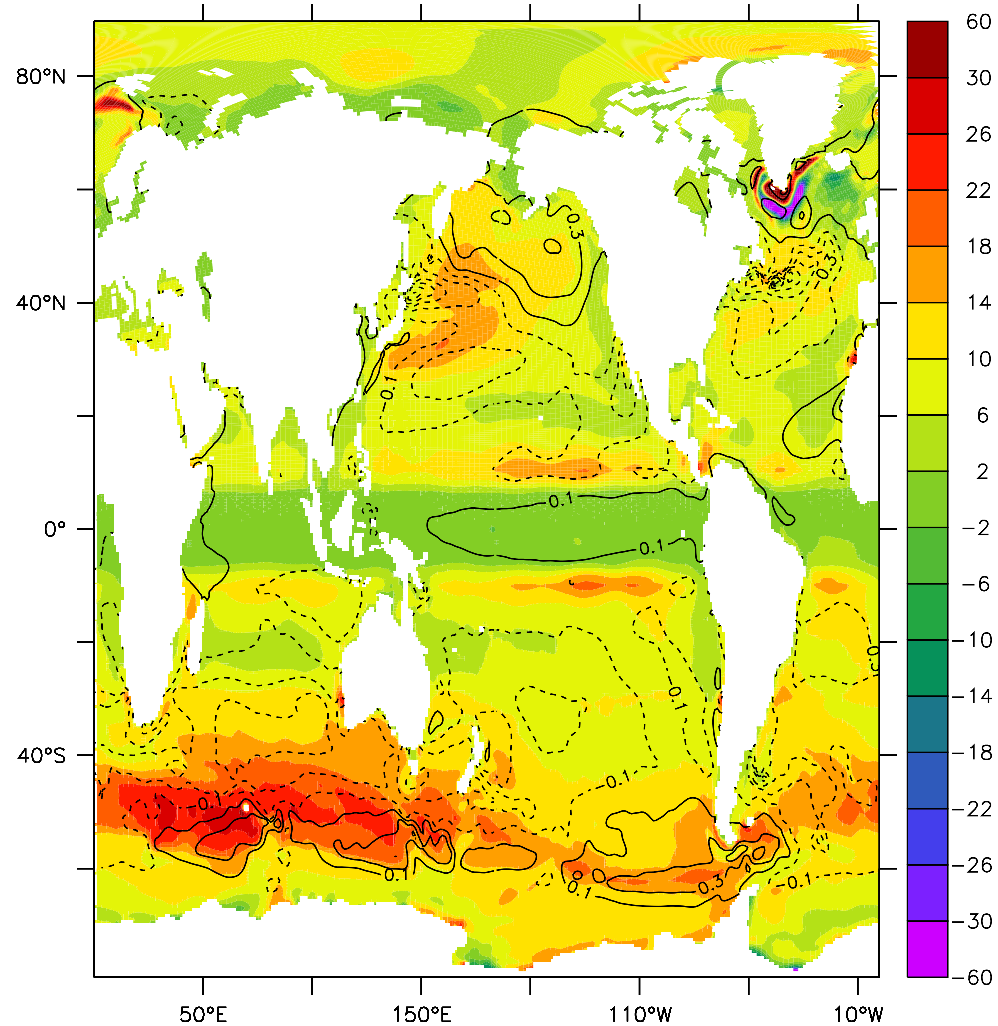
% of energy that dissipates locally

Here basically same thing, upside-down, where the power available is near-inertial mixed-layer energy, diagnosed by looking at difference in surface current between successive time steps.

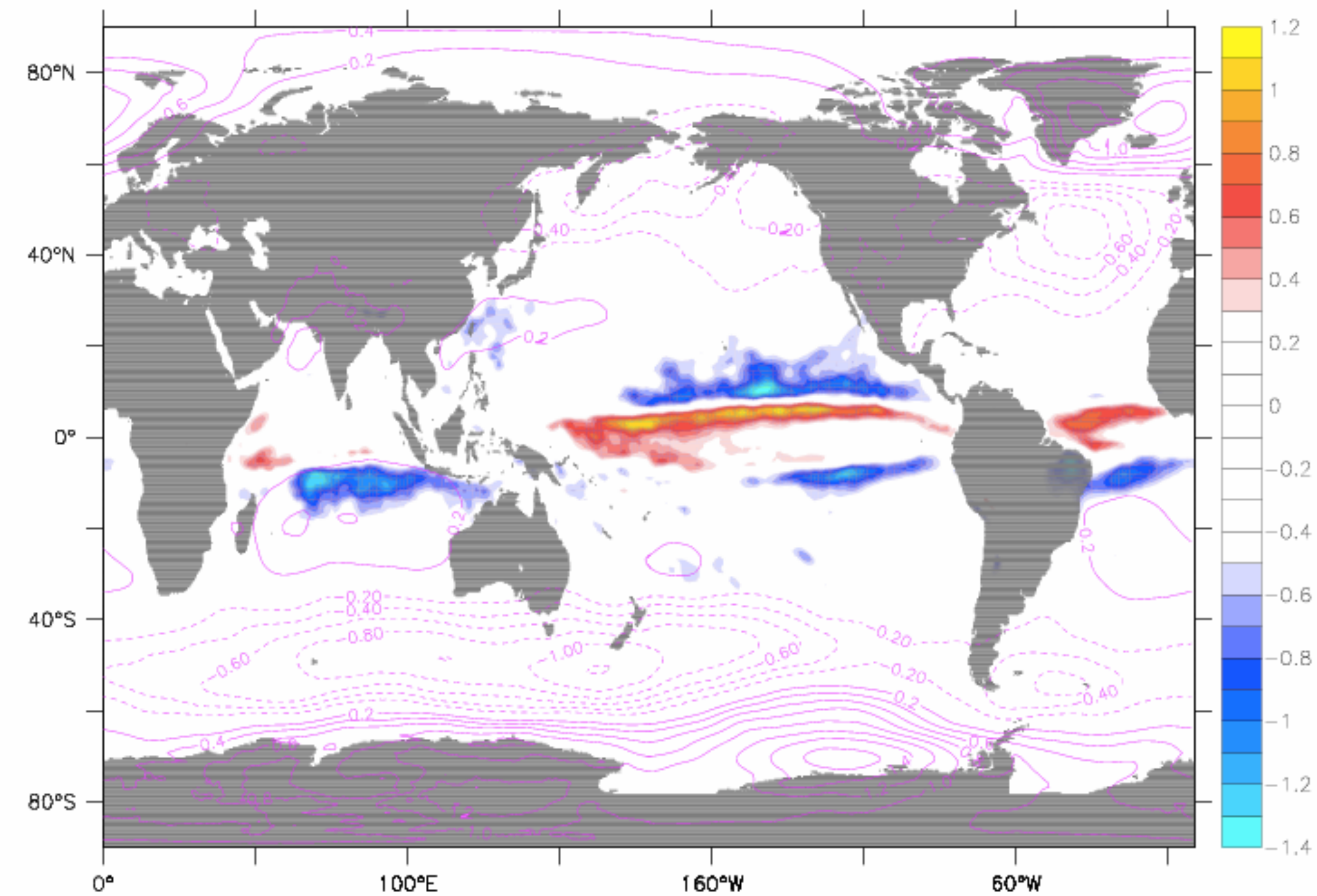
Current implementation is probably biased low in terms of power available, a lower bound.

Parameterized near-inertial related mixing (NCAR)

Differences in mixed-layer depth (color) and SST (contours)



Differences in annual mean precipitation (color) and sea level pressure (contoured)



Especially the tropical mixed-layer deepening leads to a cooler SST and a substantial shift in global precipitation, sea level pressure and the resulting surface winds . Since these changes project onto longstanding GCM biases we expect that much of the current GCM biases can be traced back to poorly represented mixed layer processes in the tropics. (Jochum et al 12)

Summary (so far)

Nearfield: diapycnal mixing is elevated near generation sites for internal waves, as recently generated high-mode waves slowly propagate into the interior and break. Previous and ongoing process studies have lead to some dynamical understanding, allowing parameterizations to be developed for the following:

- Internal tides: a mostly static map (needs model near-bottom N) implemented and being tested. Elevated in deep ocean where topography is steep and/or rough and barotropic tide is strong. Important for deep circulation.

- Internal lee waves: may be important in deep ocean in Southern Ocean and possibly the equator. Being implemented and tested, should compare to DIMES data.

- Near-inertial motions and internal waves: parameterization for near-inertial mixed-layer shear and upper ocean mixing being developed and tested. Inherently more dynamic, requiring ocean to be coupled to wind stress every ~2 hours. Shows significant effects on ocean mixed-layer depth and SST, especially in the tropics.

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Farfield: much of the energy going into internal waves radiates away from where they are generated. Where do they break and mix?

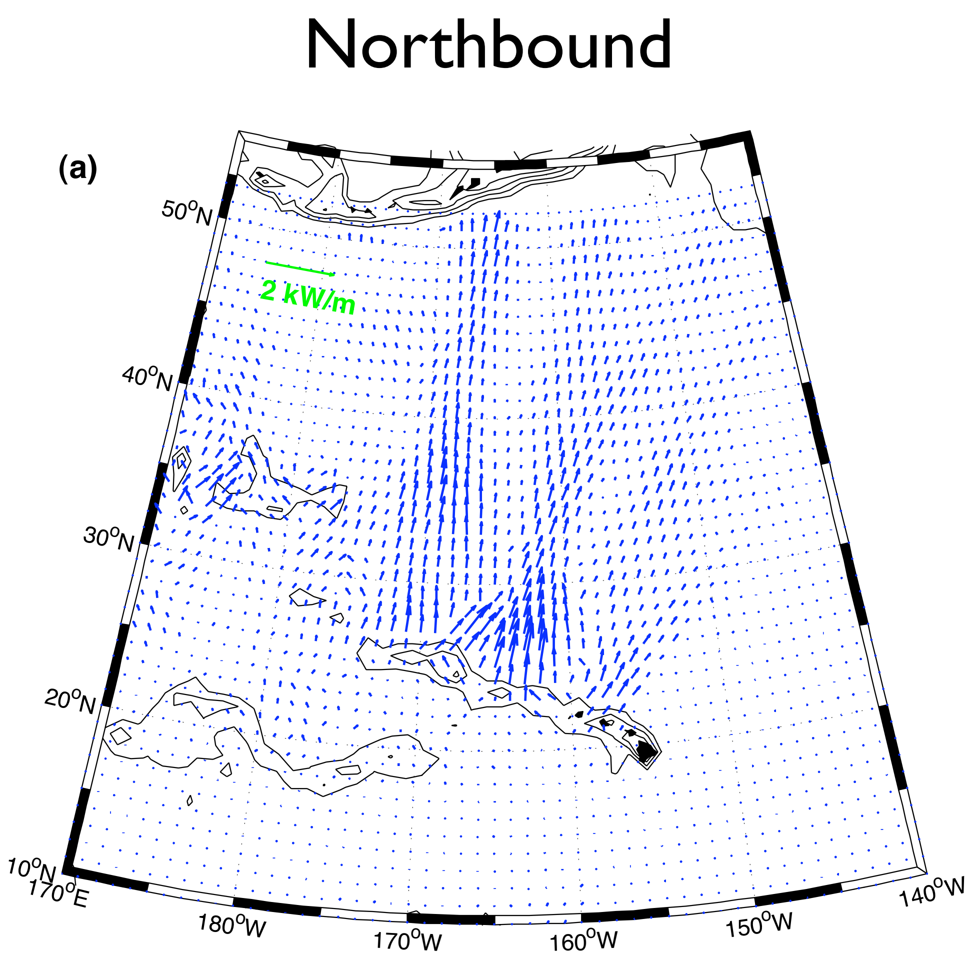
“Farfield” internal wave breaking / mixing

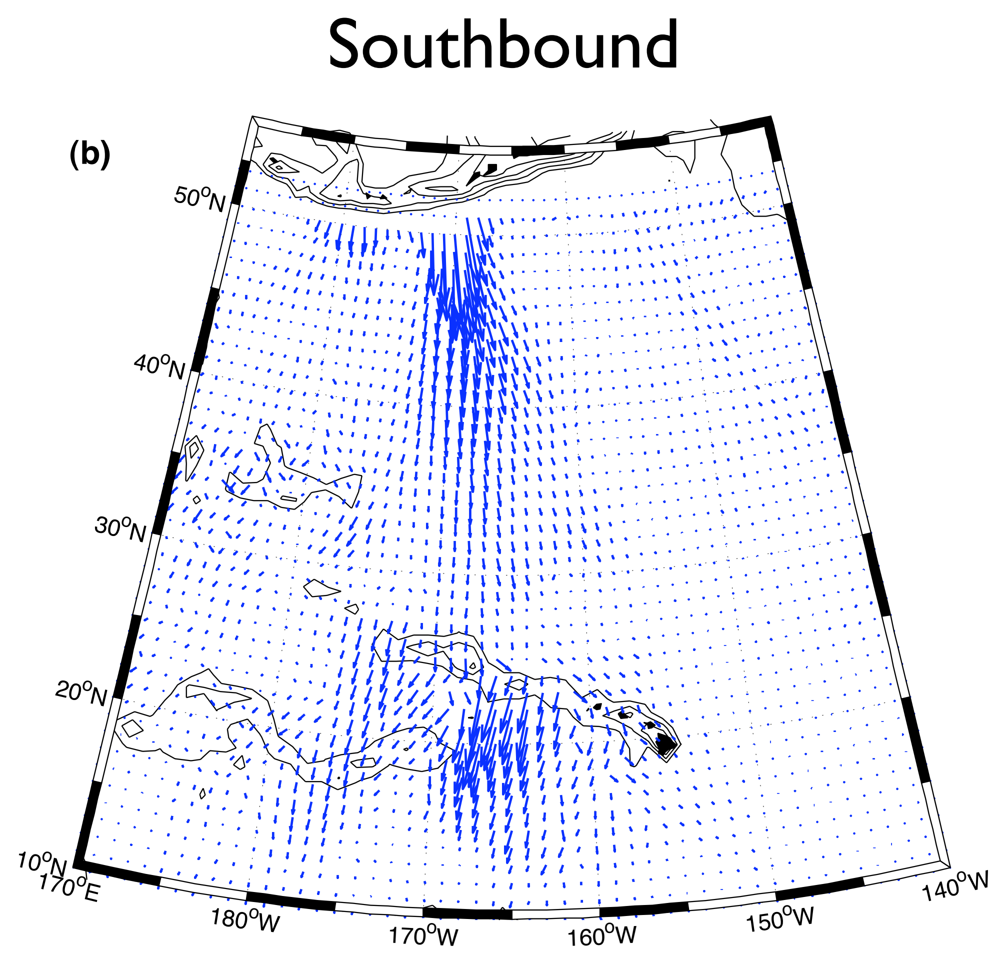
Most (70-90%) internal tide energy escapes to propagate thousands of km away.

Where do these waves break? [St. Laurent and Nash 04]

Altimetric tidal fluxes

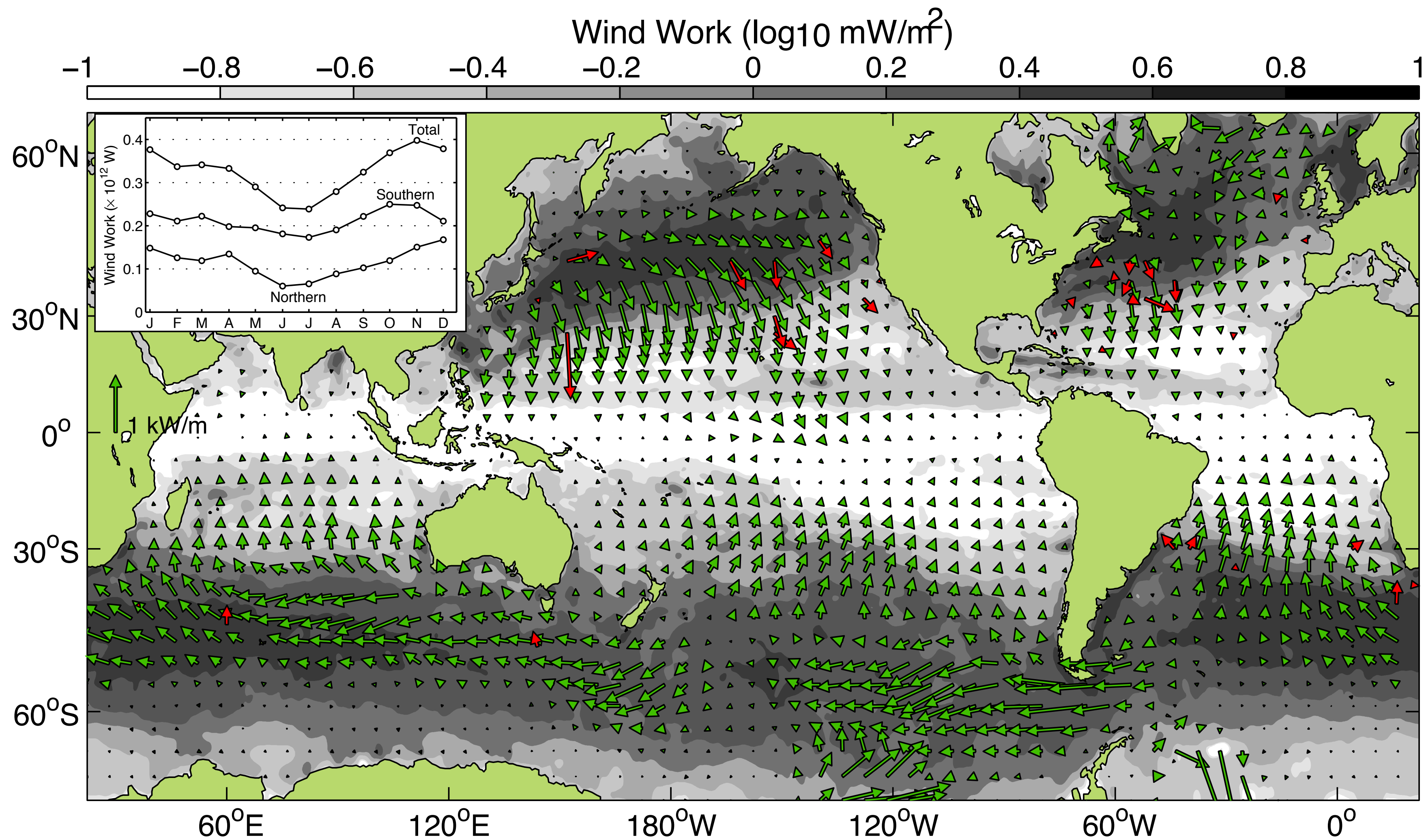
Zhongxiang Zhao, UW





Near-inertial wave farfield

Low-mode near-inertial internal waves can also radiate long distances. Comparison promising but limited. Model doesn't (properly) include wave breaking and data extremely sparse (hard), so hard to know how far they go.



Model depth-integrated annual mean baroclinic energy flux (green arrows) and mooring derived near-inertial fluxes from Alford 2003 (red arrows) over annual mean energy flux going into surface inertial motions (greyscale). From Simmons and Alford 2012 (in press).

Farfield wave breaking

The processes and geography of how propagating internal waves dissipate are open questions. Hypotheses include:

- Steady dissipation as they go through nonlinear wave-wave interactions (including PSI = parametric subharmonic instability, which may be enhanced near 29 N/S). Depth range: any.

- Enhanced dissipation (again) where waves scatter over rough mid-ocean topography. Depth range: deep

- Whatever doesn't dissipate as waves propagate through ocean basins likely crashes into continental slopes. Depth range: unknown - not clear whether this mixing would occur over the deep slope (mixing on deep isopycnals) or on the shelf (not as important to open ocean).

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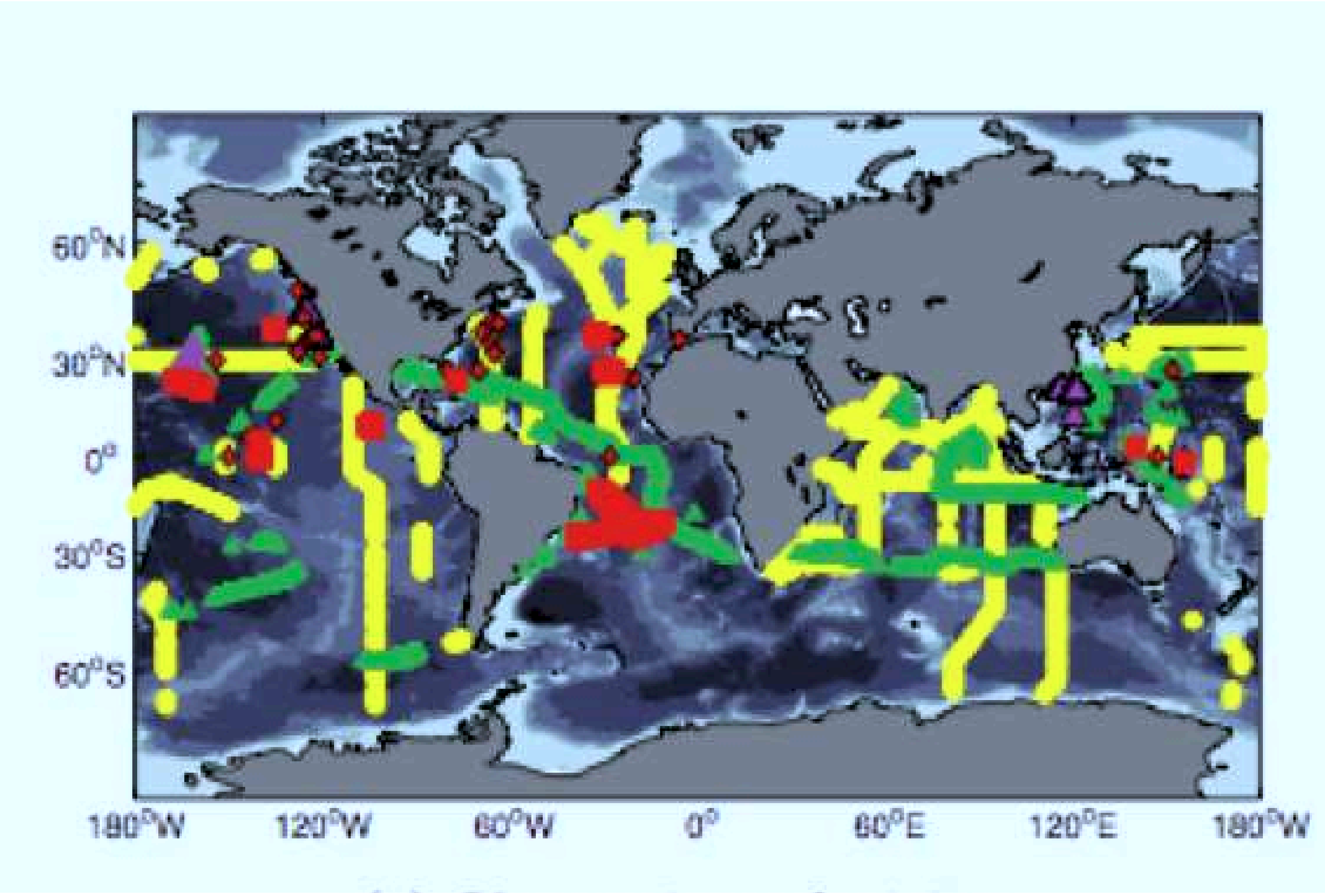
We are using all available mixing observations, combined with high-resolution global internal wave modeling (Simmons and Arbic), to try to constrain processes and patterns.

Using data to constrain farfield mixing patterns

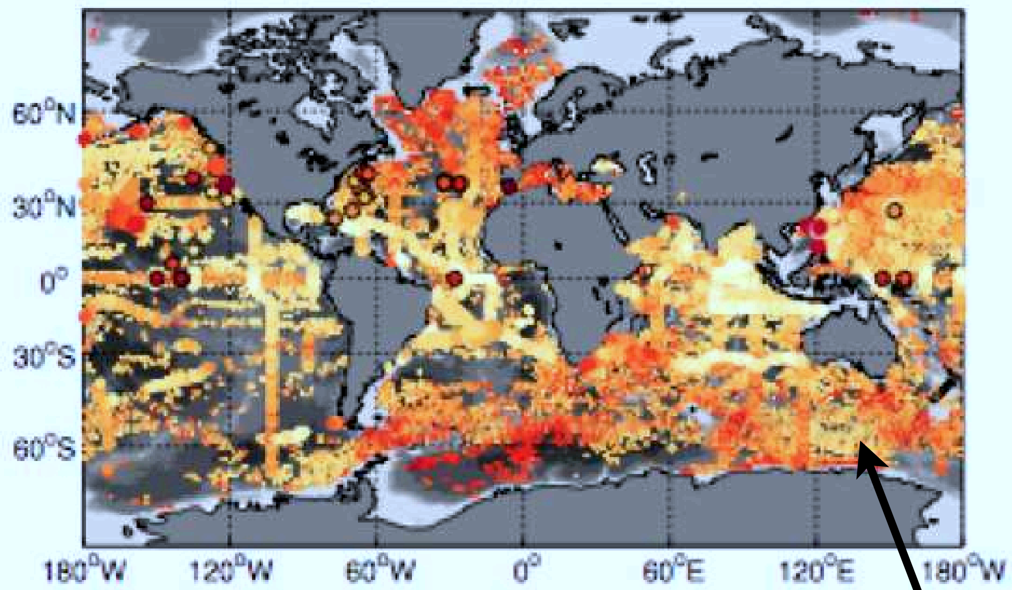
A major goal of the CPT was to put together all available microstructure data. Data available so far from CPT PIs and a few others (Moum) has been compiled. We are working to compile a standardized format database [Waterhouse and Sun]

- Red: published microstructure measurements
- Green: diffusivities inferred from shipboard finescale shear
- Yellow: inferred diffusivities from LADCP/CTD profiles of Kunze et al. [2006]
- Magenta: diffusivities calculated from overturns of density profiles from moored profilers



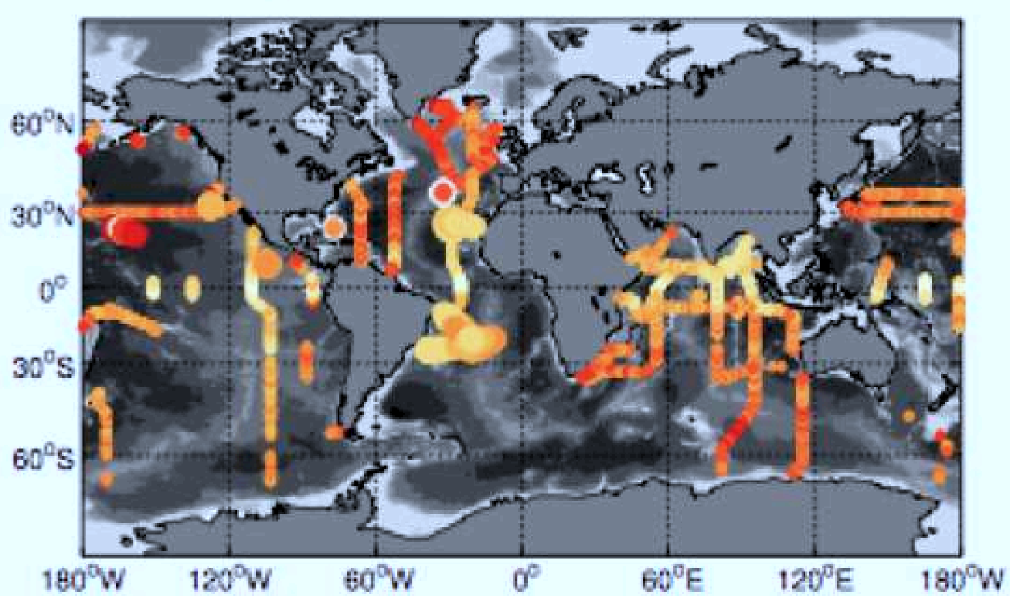
Location and type of available observational diapycnal diffusivity estimates

Using data to constrain farfield mixing patterns

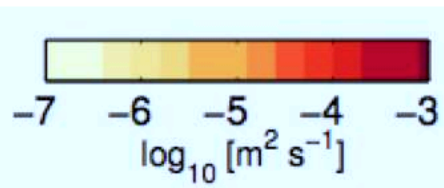


Upper 100 m κ (m^2/s)

Upper ocean diffusivity inferred from Argo data (Whalen et al 12)



Full depth κ (m^2/s)



- Overall average of depth-averaged observed diffusivity is 0.8 cm^2/s, and diffusivity below 1000 meters is 1.1 cm^2/s, in rough agreement with bulk estimates (Munk66 and various inverse models)
- Comparison of observed diffusivity to power input into internal waves suggests current sampling, is not unduly biased overall but too sparse to get the pattern pinned down, must use continuing process studies in target locations.
- Comparison of observations with maps of internal wave generation reveals that in some places (e.g. mid-Atlantic ridge) most energy is dissipated locally (nearfield params fine), while in other places (e.g. North Pacific) most energy radiates long distances likely to break at the continental slope.

[Waterhouse et al 12]

NEXT STEPS

- Continue final refinements and implementation of schemes for elevated mixing over topography and sensitivity testing. GFDL

- Improved near-inertial parameterization work, since upper ocean seems very sensitive and current implementation is a lower bound. Compare with tropical mooring data. NCAR.

- Farfield patterns of mixing. Use global internal wave process models as a middleman - implement test parameterizations for decay of propagating low-mode waves though wave-wave interaction (PSI), and topographic scattering, compare results to observations and implement patterns into GCMs. Consider effect of climactically altered stratification. (Arbic and Simmons models, data PIs).

- Think more about elevated mixing at continental slopes (combining available data, process models and simple theory). Consider what consequences such boundary mixing might have for larger-scale circulation. (Various team members).