Modular Ocean Model v6:
Boundary layers and parameterizing vertical turbulence

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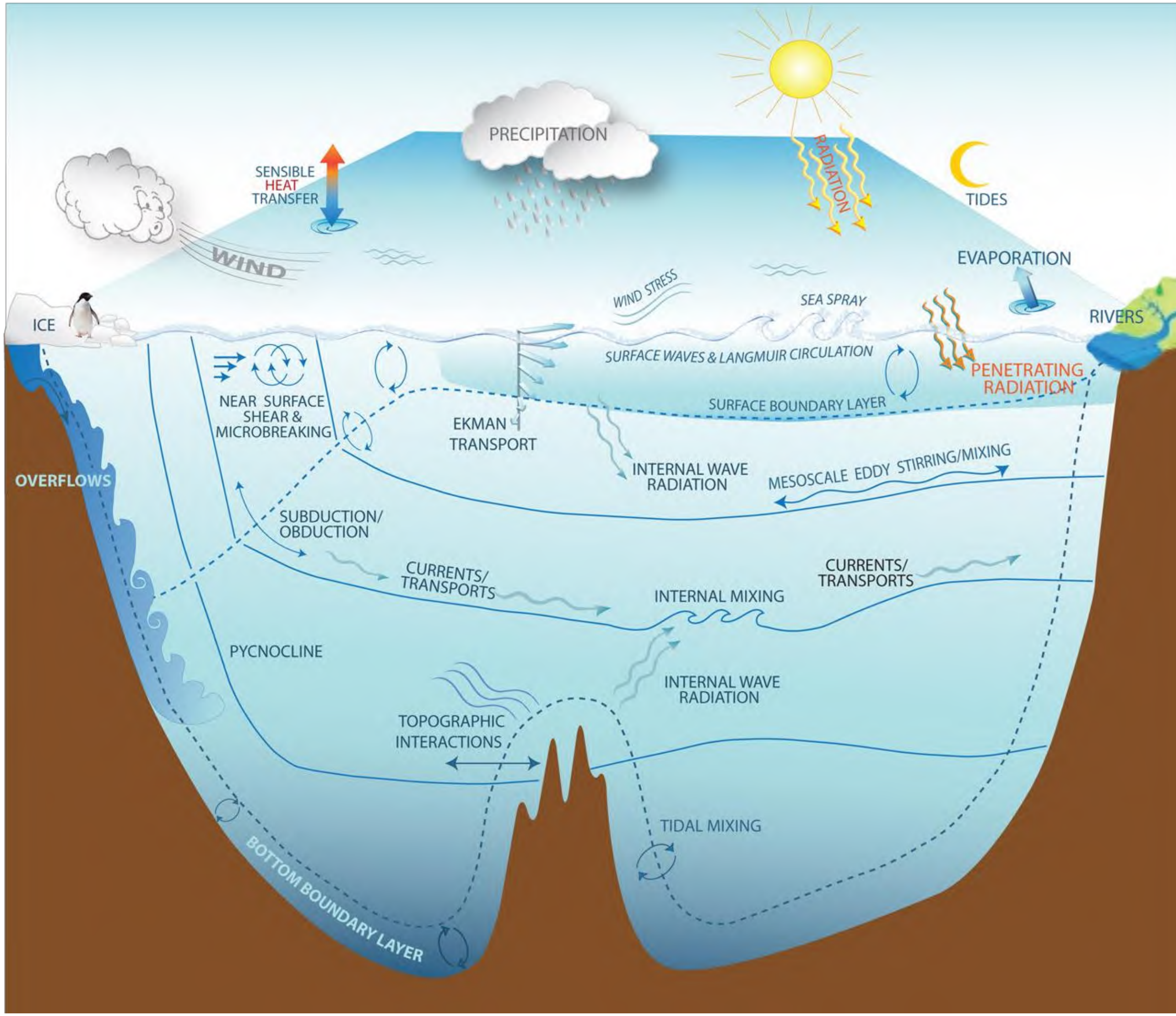


Sources of ocean mixing

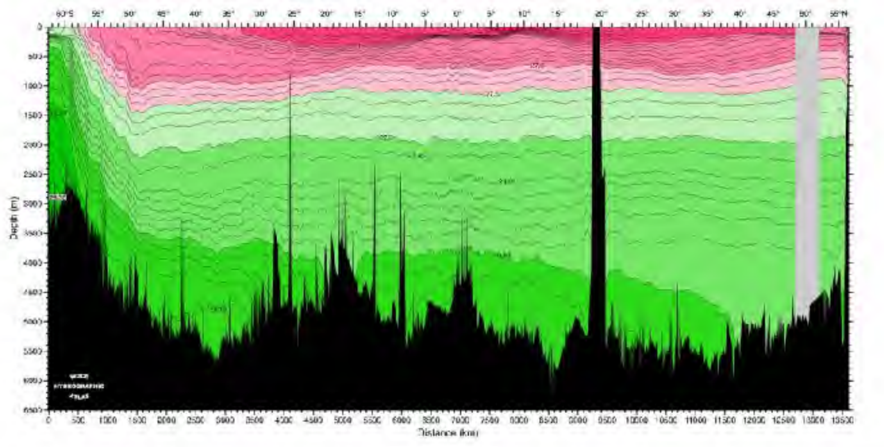
The problem of resolving vertical mixing

- Much of the shear-driven turbulence happens at O(1m) or even less
  - In global model, highest near-surface resolution aroudn 1m
- Timescales are also very short O(1-100s)
  - Typical model ‘mixing’ timestep 3 hours
- **Hydrostatic primitive equations assume small vertical motion**
  - Any nonhydrostatic process **MUST** be parameterized

Separating the physics within a water column

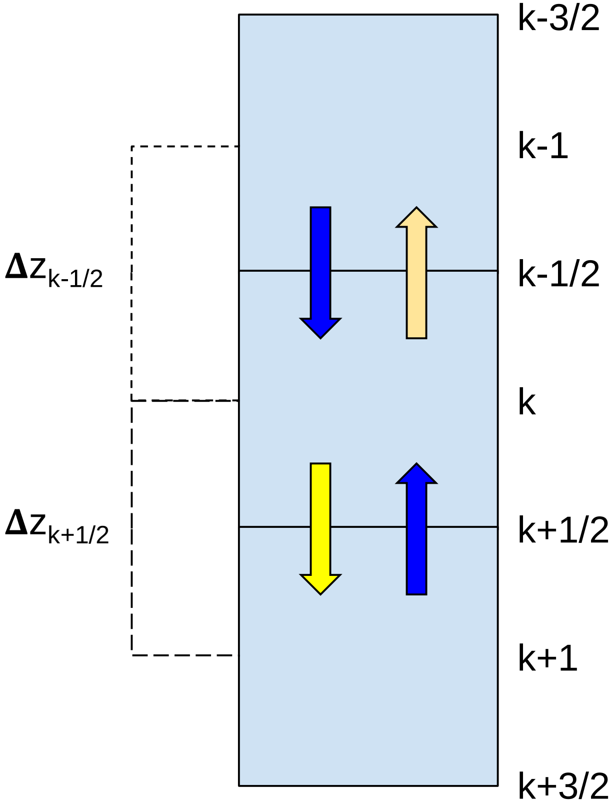
- Full water column (*Internal Mixing*)
  - Background (unresolved or molecular)
  - Convection
  - Double-diffusion
- Bottom driven physics
  - Interaction of flow with topography
    - Lee wave generation/dissipation
    - Internal tide generation/dissipation
    - Law of the wall
- Surface boundary layer
  - Crucial for coupling atmosphere and ocean
  - Surface buoyancy-loss driven convection
  - Mechanical stirring
  - Vertical Shear driven-mixing
- Note: Diffusion also applies to viscosity and affects momentum transfer between model layers

Numeric considerations for diffusion in GCMs



- Parameterizations either return a diffusivity or energy dissipation
    - Osborne [1980] relation provides a simple relationship to describe a mixing ‘efficiency
- Diffusivities (and mixing) occur at interfaces of cells (C-grid)
- Discretization in the vertical implies that there exists a maximum amount of turbulent kinetic energy that is required to fully mix to layers
    - Consider unstratified case, zero TKE required
    - Stratified case: TKE must erode potential energy in stratification
- Accumulate diffusivities at the interfaces from all processes
- Do one pass to actually diffuse momentum/tracer
- Explicit methods for diffusion not suitable for climate timescales
    - Require relatively small timesteps for diffusivity
    - Very difficult especially when there might be vanished layers!

Finite volume implicit method for diffusion



- Explicit methods calculate the the next state of the model from the current state
    - Euler forward f(t+Δt) = f(t) + Δt×f'(t)
- Implicit methods solve an equation involving both the current state and present state
    - Below method for diffusion is unconditionally stable
    - **BUT** might not be accurate

$$h_k \frac{T_k^{n+1} - T_k^n}{\Delta t} = \frac{\kappa_{k-1/2}}{\Delta z_{k-1/2}} \left(T_{k-1}^{n+1} - T_k^{n+1}\right) + \frac{\kappa_{k+1/2}}{\Delta z_{k+1/2}} \left(T_k^{n+1} - T_{k+1}^{n+1}\right)$$

$$a_{k+1/2} \equiv \kappa_{k+1/2} \frac{\Delta t}{\Delta z_{k+1/2}}$$

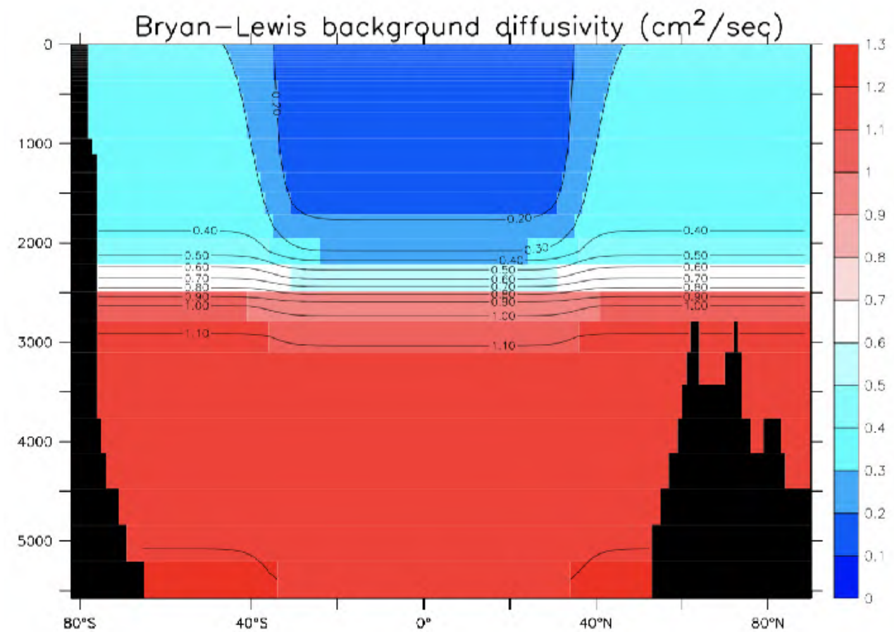
$$\left(h_k + a_{k+1/2} + a_{k-1/2}\right) T_k^{n+1} = h_k T_k^n + a_{k-1/2} T_{k-1}^{n+1} + a_{k+1/2} T_{k+1}^{n+1}$$

$$\boldsymbol{\Lambda} T^{n+1} = \boldsymbol{A} T^n$$

State-independent diffusivities

$$\kappa(z) = \left[\kappa_{surface} + \frac{\kappa_{deep}}{\pi}\tan^{-1}\left(\frac{z - z_{trans}}{H_{trans}}\right)\right] \times 10^{-4}$$

- Static diffusivities inherently assume no change in energy available for mixing
- Simplest choice is to use a constant
  - 10^{-4} m^2s^{-1} based on Abyssal Recipes
- Real ocean has vertical structure
  - Largely due to internal waves
    - Low diffusivity within thermocline
    - Increases near bottom
  - Specifying a shape Bryan and Lewis [1979]
  - Scale by a buoyancy frequency Gargett [1984]
- Latitudinal dependence (wave-wave)
  - Henyey et al. [1986]
- Latitudinal and depth

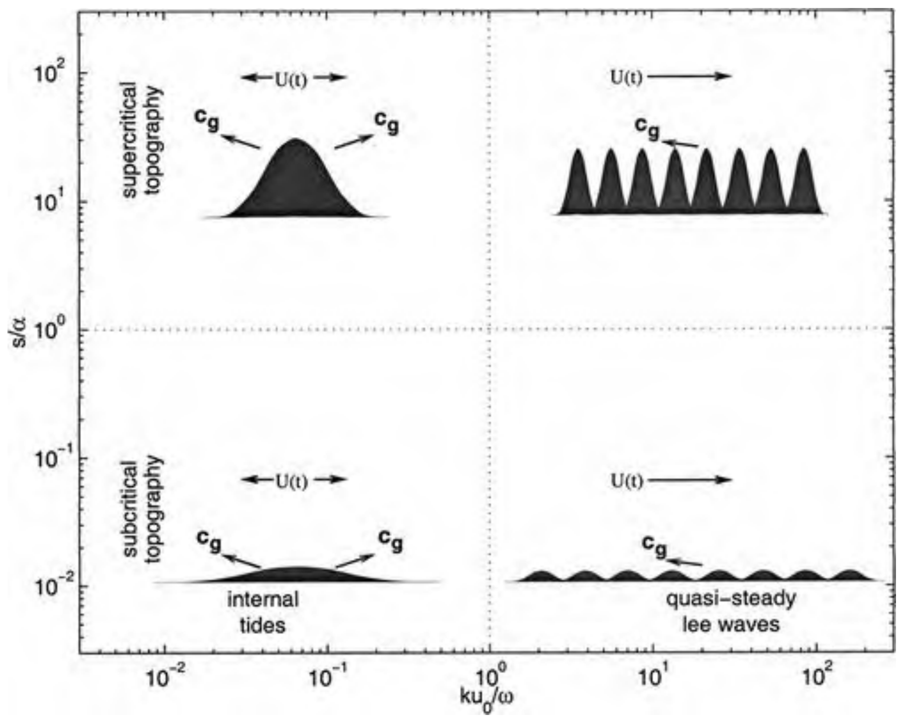


$$\kappa(\phi) = \kappa_0 f / f_{30} \cosh^{-1}(1/f_{30})$$

$$\kappa = \frac{e_0}{N^2}\frac{f}{f_0}\frac{\cosh^{-1}(N/F)}{\cosh^{-1}(N_0/f_0)}$$

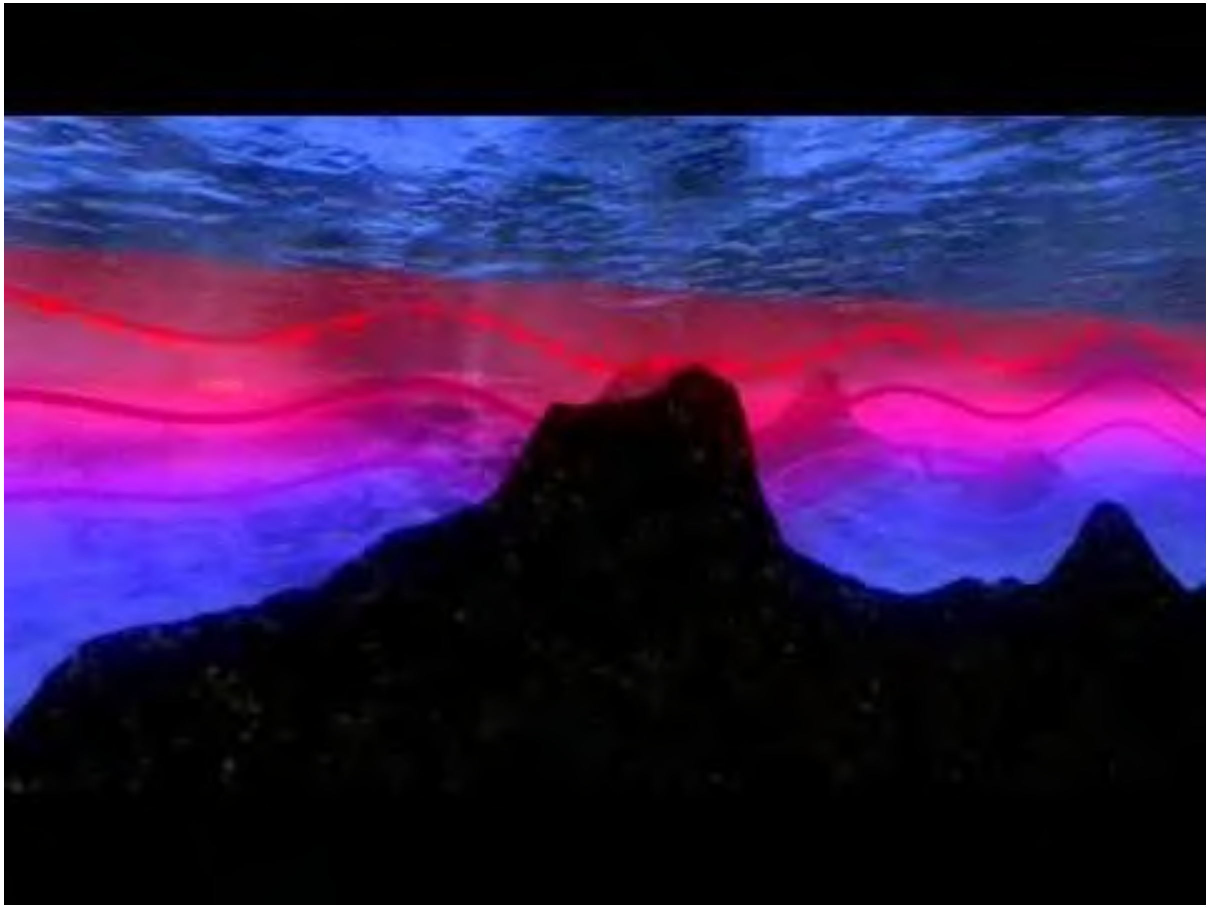
Internal waves generated by topography

- Flow over topography leads to internal wave generation
- Tides generate waves
    - Generated at specific sites
    - Local/remote dissipation
- Propagation/dissipation
    - Topography
    - Stratification
    - Coriolis
- Standing lee waves generated by geostrophic flow
- Internal wave energy is dissipated and leads to mixing



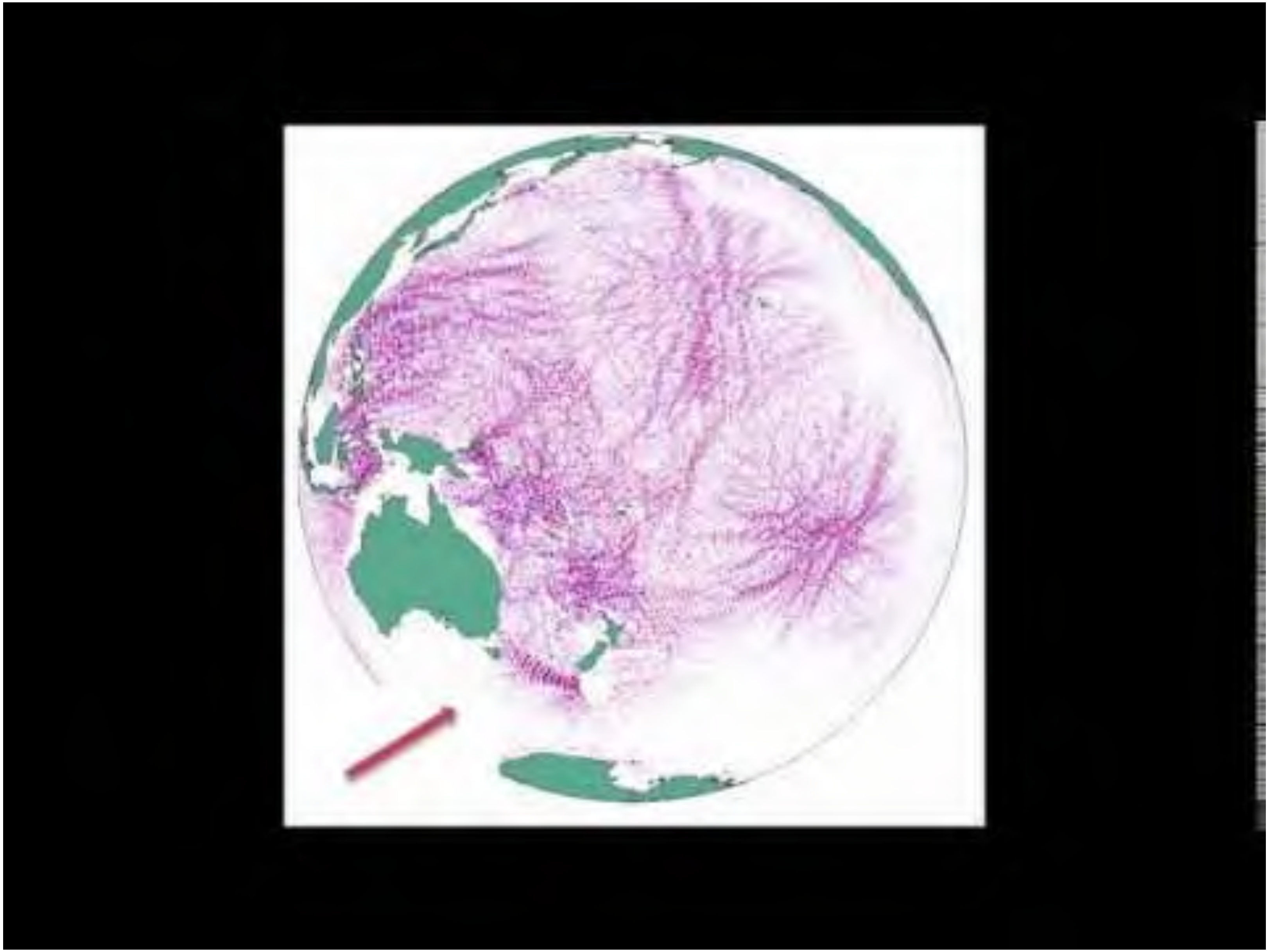
Simmons et al. 2004

Generation of internal waves in Luzon Strait



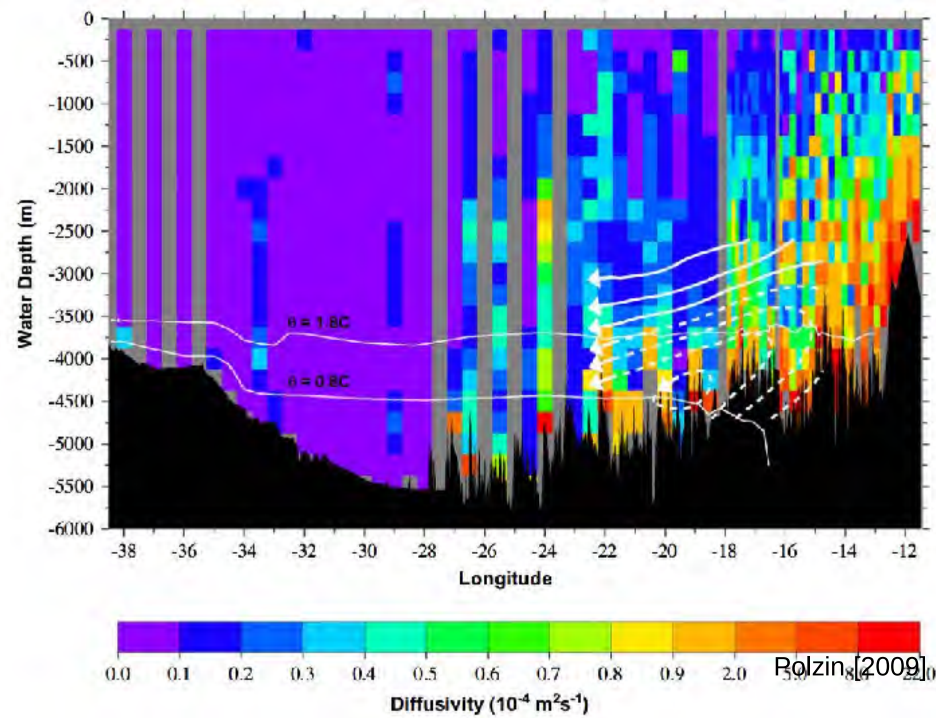
Visualization from Internal Waves in Straits Experiment (IWISE)

Simulations of tidally generated internal waves



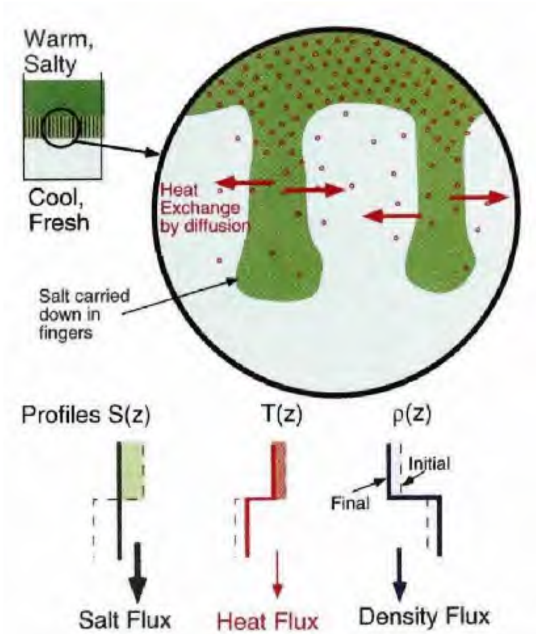
Parameterizing local mixing by topographically generated internal waves

- Some of the internal tide is dissipated locally
- Portion that is propagated away parameterized as ‘background’
- MOM6 always cast in terms of a dissipation
    - Draw down the maximum TKE that would erode layer
    - Convert dissipation to a diffusivity
- Energy is distributed in the vertical via vertical structure function
    - Simmons et al. [2004]
    - Polzin 2009

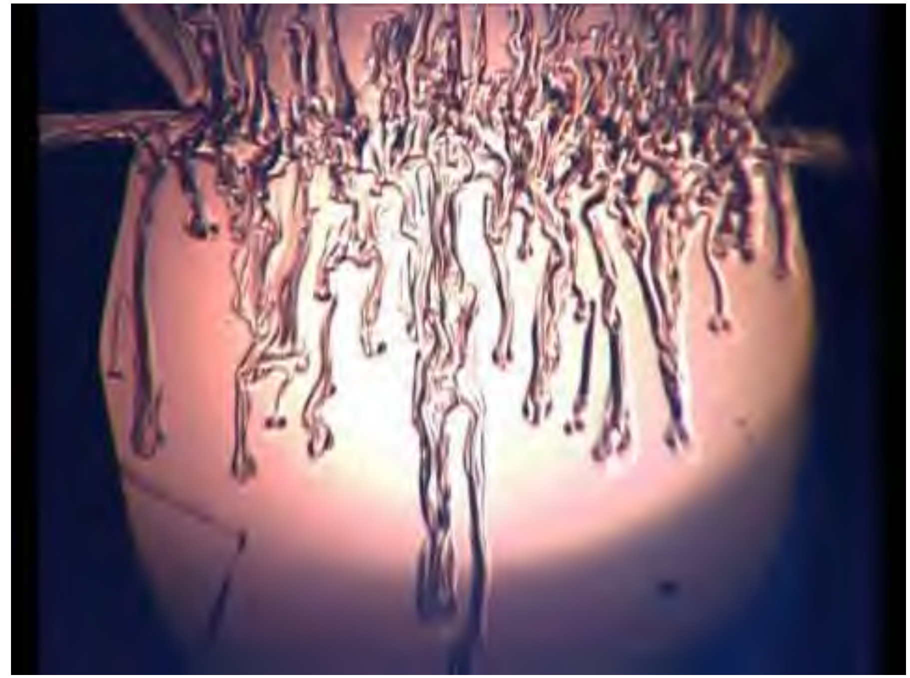


$$E_{tides} = \frac{\rho_0}{2}(\alpha_s \mathrm{Var}(h))(k_{topo}U^2_{tide}$$

Differing molecular diffusion of T/S leads to apparent vertical mixing



Ruddick [1997]



- Ocean has two active tracers
  - Temperature
  - Salinity
- Recall from thermodynamics that temperature is average energy of a system
  - Diffusion is an energy transfer
- Recall from chemistry that salt is a molecule
  - Diffusion is transfer for discrete particles
- Heat diffusion is about 70x higher than salt diffusion

Parameterizing Double Diffusive mixing

- Generally with depth
  - Temperature decreases
  - Salinity increases
- But parts of ocean strongly stratified by temperature or salinity
  - Fresh below salty
  - Warm below cold
- Two regimes of:
  - Salt fingering
  - Diffusive convection
- Governing parameter function of thermal expansion and haline contraction

$$R_\rho = \frac{\alpha}{\beta}\left(\frac{\partial\Theta/\partial z}{\partial S/\partial z}\right), \quad \alpha = -\frac{1}{\rho}\left(\frac{\partial\rho}{\partial\Theta}\right), \quad \beta = \frac{1}{\rho}\left(\frac{\partial\rho}{\partial S}\right).$$

Salt-fingering regime

$$\frac{\partial S}{\partial z} > 0$$

$$1 < R_\rho < R_\rho^0 = 2.55.$$

$$\kappa_d = \kappa_d^0\left[1 - \frac{R_\rho - 1}{R_\rho^0 - 1}\right]^3.$$

$$\kappa_d^0 = \begin{cases} 1\times10^{-4}\ \mathrm{m^2\ s^{-1}} & \text{for salinity and other tracers} \\ 0.7\times10^{-4}\ \mathrm{m^2\ s^{-1}} & \text{for temperature.} \end{cases}$$

Diffusive convection regime

$$\frac{\partial\Theta}{\partial z} < 0$$

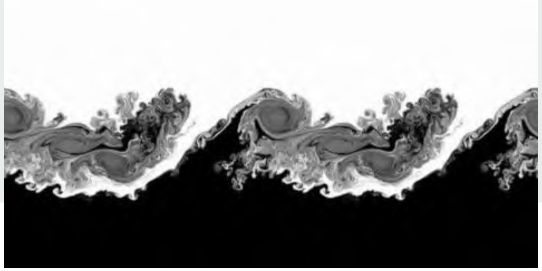
$$0 < R_\rho < 1$$

$$\kappa_d = \nu_{\text{molecular}} \times 0.909 \exp\left(4.6 \exp\left[-.54\left(R_\rho^{-1} - 1\right)\right]\right),$$

$$\nu_{\text{molecular}} = 1.5 \times 10^{-6}\ \mathrm{m^2\ s^{-1}}$$

$$\text{factor} = \begin{cases} \left(1.85 - 0.85R_\rho^{-1}\right)R_\rho & 0.5 \le R_\rho < 1 \\ 0.15R_\rho & R_\rho < 0.5, \end{cases}$$

Mixing arising from vertical shear of horizontal velocity

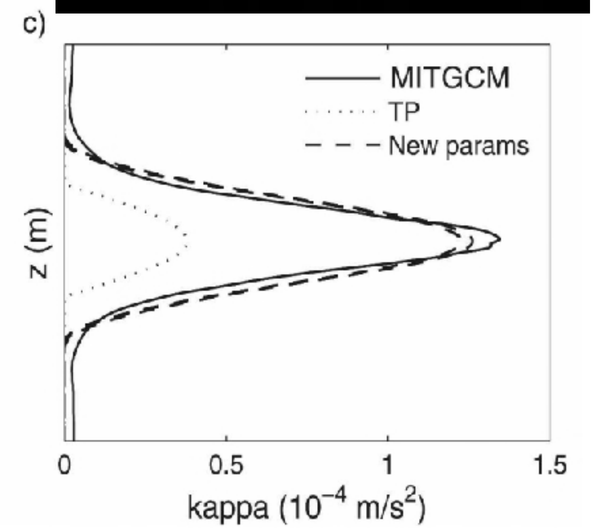


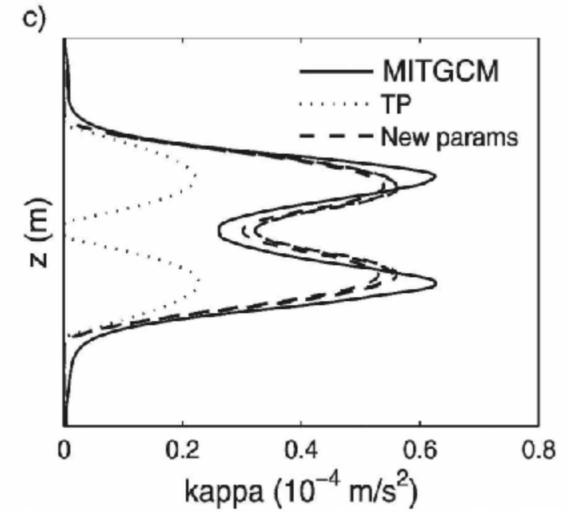
$$\partial_{zz}\kappa - \kappa L_d^{-2} = -2Sf(Ri)$$

$$L_d = \lambda Q^{1/2}/N$$

$$\partial_z[(\kappa + \nu_{mol}))\partial_z Q] + \kappa(S^2 - N^2) - Q(c_N N + c_S S) = 0$$

- Richardson number predicts growth of Kelvin-Helmholtz instabilities
  - Cannot be resolved in the model
- Want to derive a diffusivity that represents the steady-state mixing of momentum/tracers
- First equation allows for non-local effects of regions with high turbulence
- Second equation is energetics based
  - Interpreted as a “conservation” of diffusivity
  - Represents effects of diffusion of Q
  - Dissipation of shear and stratification by mixing
  - Drawdown of TKE by internal wave production and turbulence



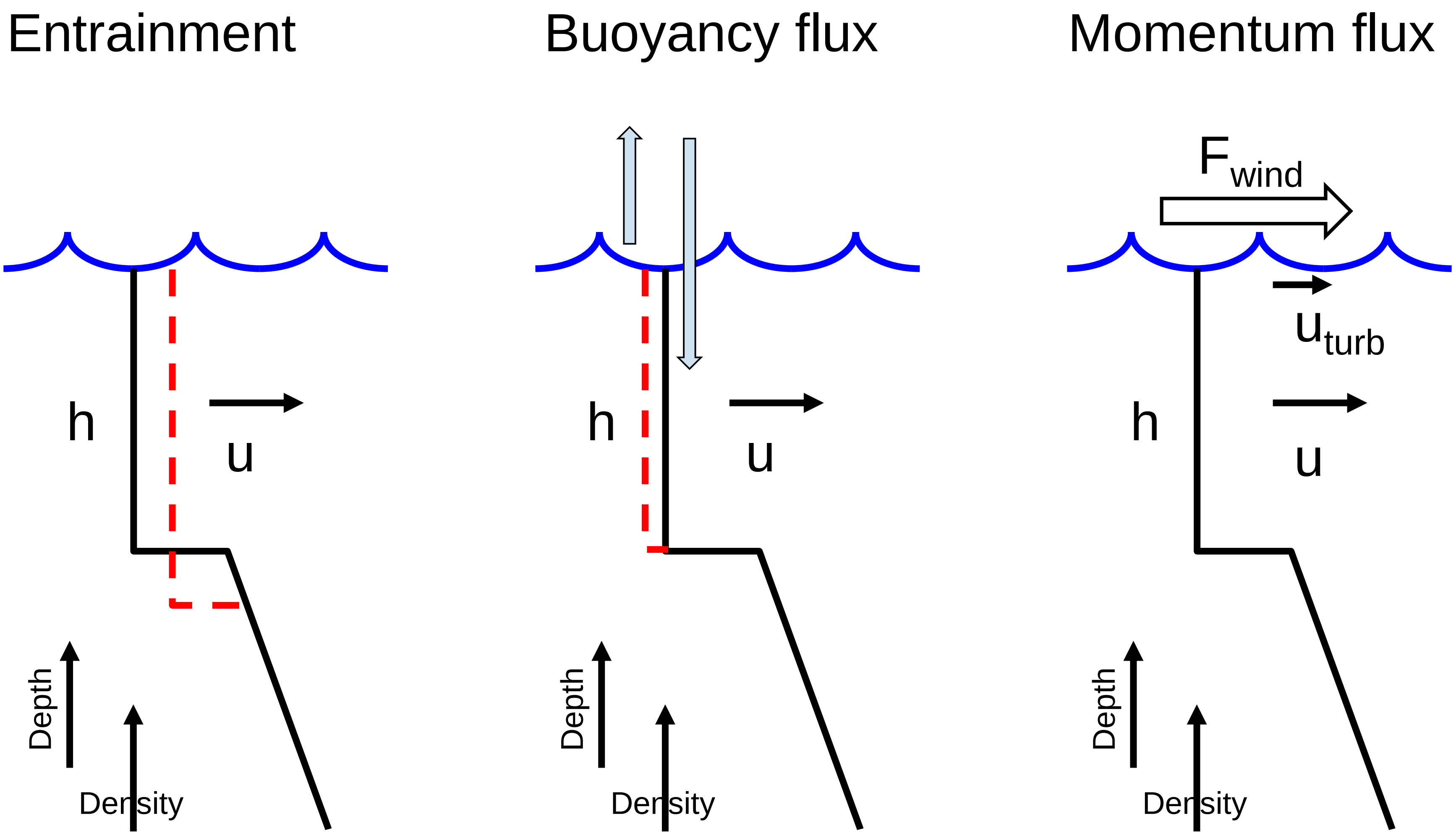


Jackson et al. 2008

Atmosphere-ocean boundary layer schemes

- Clarifying notation
  - Mixed layer implies a homogeneous fluid
  - Boundary layer is an actively mixing part of the ocean
- Atmospheric point of view
  - Ocean exchanges heat/water at the surface
  - Depth of boundary layer sets heat capacity
- Depth of mixed layer important controller of oceanic ventilation
- Bulk mixed layer (isopycnal mode)
  - Uniform in tracer but not in momentum
  - Use a TKE budget to balance shear/convection against erosion into interior stratification
  - Buffer layers allow transport to/from isopycnic interior
- Energetic Planetary Boundary Layer
  - Similar in concept to bulk mixed layer in balancing TKE production and mixing
  - But diagnose a diffusivity profile (like KPP)
    - KPP requires dimensional and global parameters

Sources and sinks of energy in the near-surface
(Bulk mixed layer model)

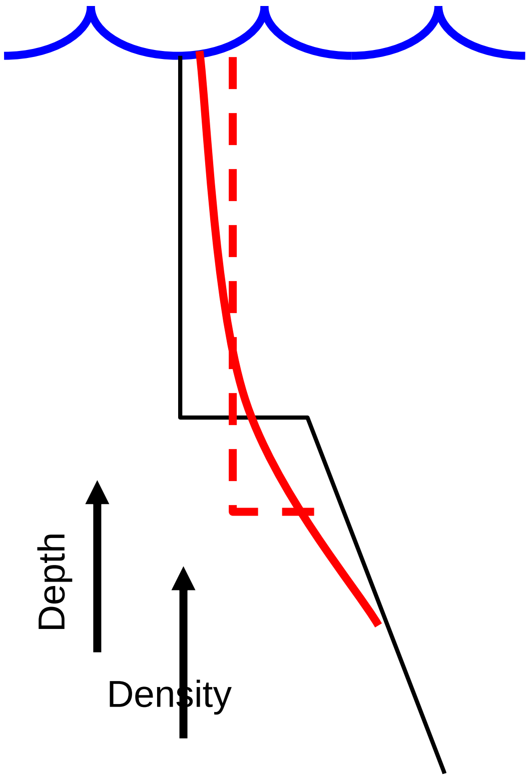


ePBL as a continuous analogue of a bulk mixed layer

$$\frac{H_{bl}}{2}\frac{\partial H_{bl}}{\partial t}B^{-} = m_* u_*^3 - \frac{n_*}{2} H_{bl} B^{+}(H_{bl})$$

$$\int_{-H_{bl}}^{0} \kappa(z)\max(N^2,0)\ dz = m_* u_*^3 - n_* \int_{-H_{bl}}^{0} \kappa(z)\min(N^2,0)\ dz$$

- Bulk mixed layer assumes that mixing is perfect in the interior
- ePBL uses estimates of actively mixing layer to solve for diffusivity profile
- m^* represents conversion from surface stress to TKE
- n^* unstable convection (near-surface buoyancy loss)



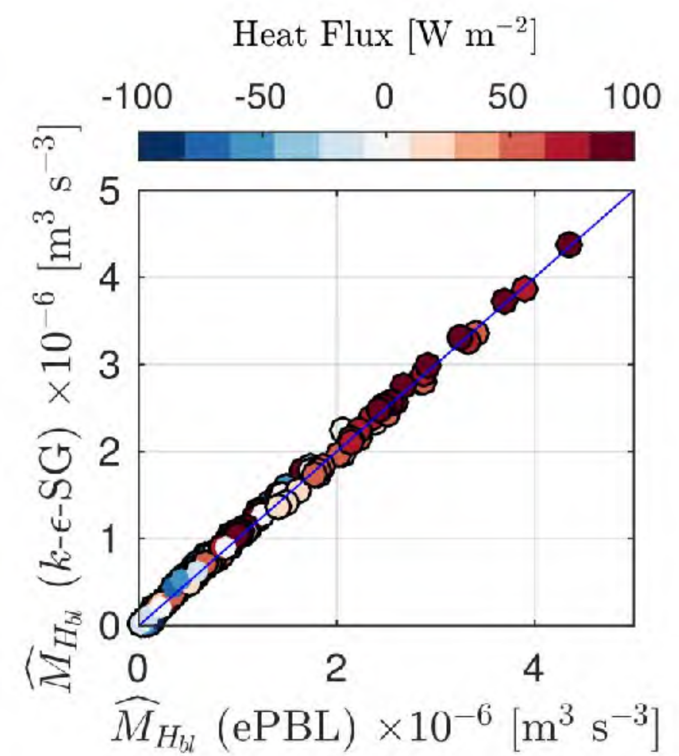
Constraining the free parameters of ePBL

$$m_* = m_*^{neutral} + m_*^{B^+} - m_*^{B^-}$$

$$n^* = 0.066$$

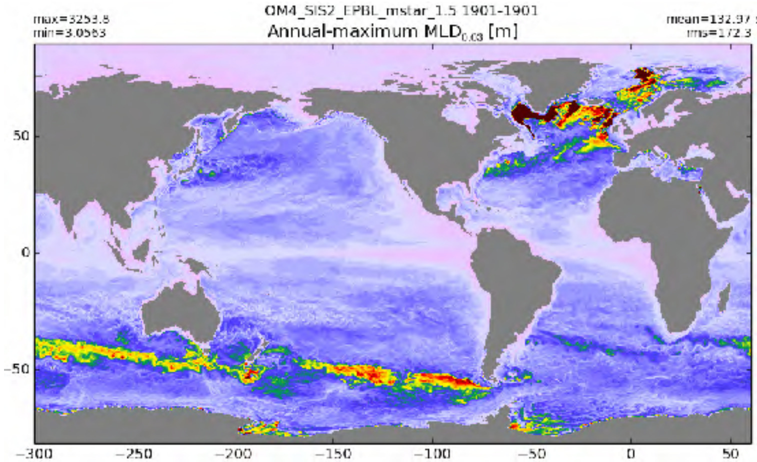
$$\kappa(z) = l_{mix} w_{mix}$$

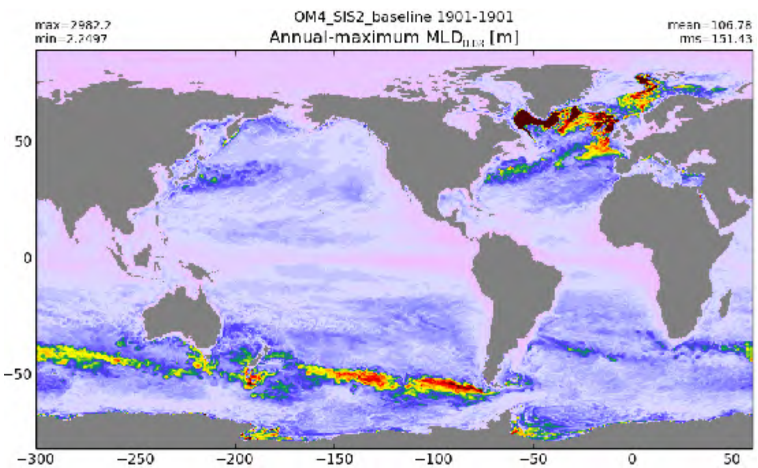
- Free parameters tuned by idealized test cases using k-epsilon
- m* contains three components
  - Neutral conditions
  - Stabilzing buoyancy fluxes
  - Destabilizing fluxes
- n* found to be insensitive to wide range of fluxes
- Specifically chosen to handle rotating convection case
- Used in conjunction with shear-driven mixing
- Can also add Langmuir turbulence as an extra energy source



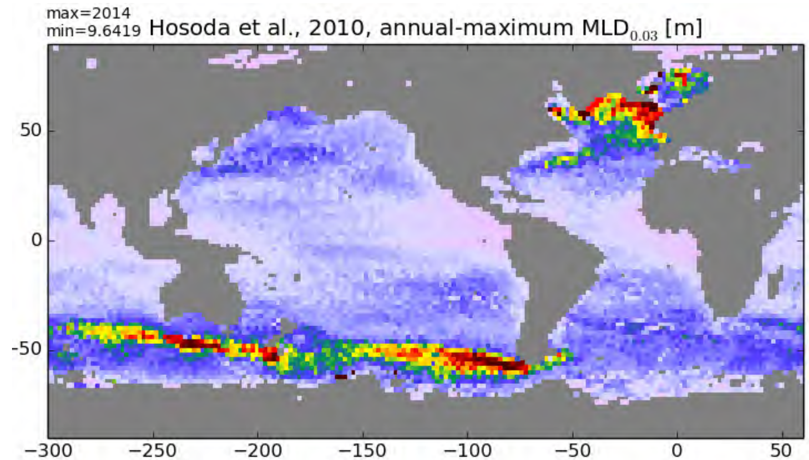
ePBL vs KPP: Maximum mixed layer depths

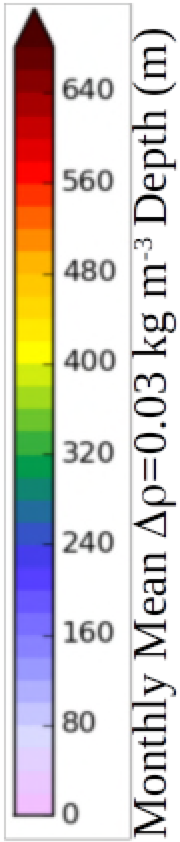
ePBL





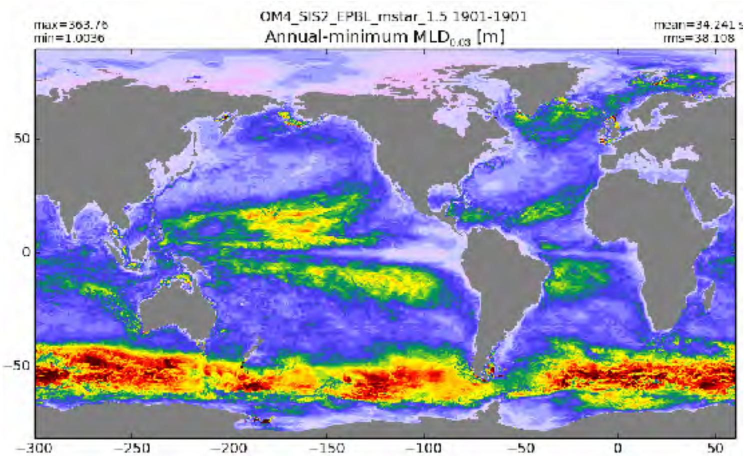
KPP

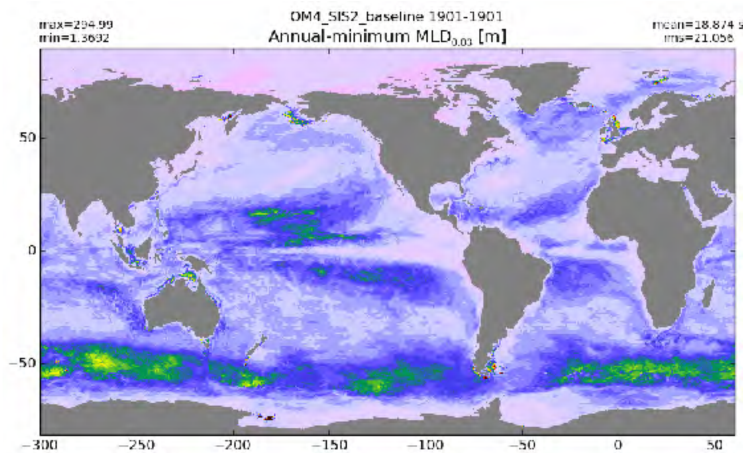




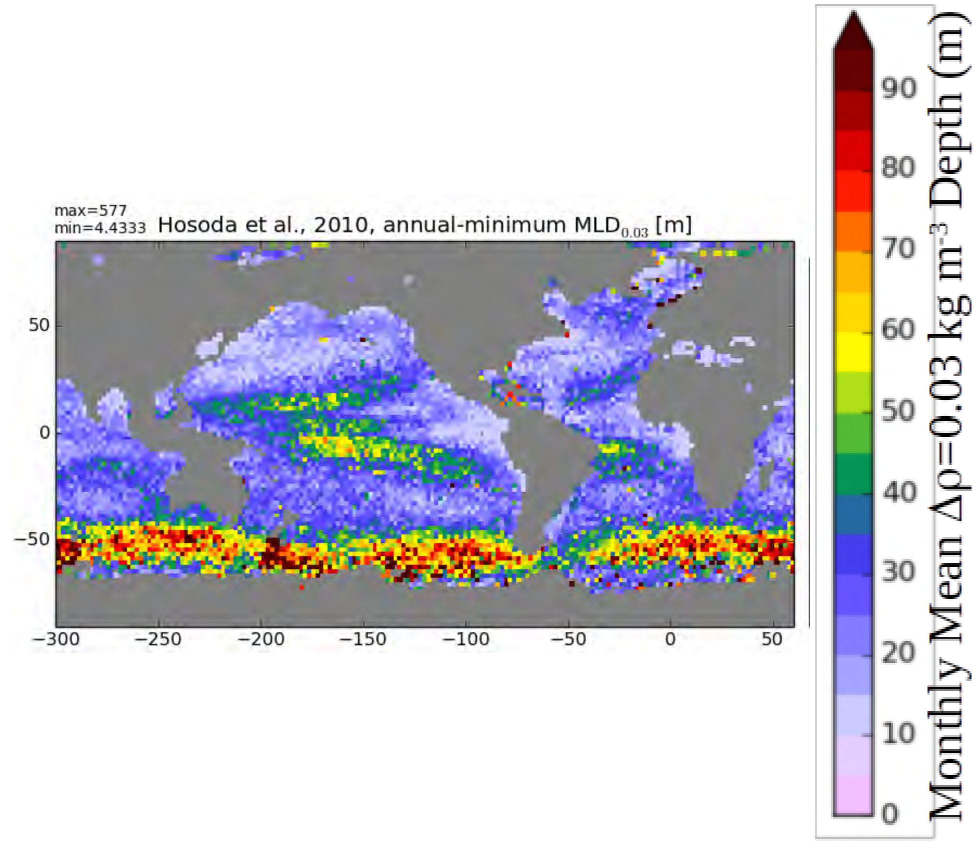
Comparing skill of ePBL to KPP: Minimum mixed layer depths

ePBL





KPP



Other parameterizations part of CVMix

- Community Vertical Mixing Project
- Implements a number of vertical mixing parameterizations
  - Lee wave/tidal mixing
  - Shear-driven mixing
  - K-profile parameterization (KPP)
- Model agnostic
  - Compare effects of different parameterizations across models
  - Reduces redundant code development
- Collaboration between
  - NCAR
  - Los Alamos
  - GFDL

Summary of vertical parameterizations

- Scales of vertical turbulence unlikely to be resolved in global models in the near future
  - Physics resolved need nonhydrostatic models
  - Vertical length scales too small to be resolved
  - Time scale to short to be practical
- Parameterizations capture the effect of
  - Remote internal tide dissipation
  - Local internal tide dissipation
  - Double-diffusive processes
  - Shear-driven mixing
- Boundary layer schemes crucial in ventilating the ocean and for ocean-atmosphere coupling
  - New ePBL scheme is energetically consistent
  - Combined with shear-driven mixing scheme has good skill