Modular Ocean Model v6

Subgrid-scale horizontal physics

Presented by Andrew Shao (andrew.shao@noaa.gov)
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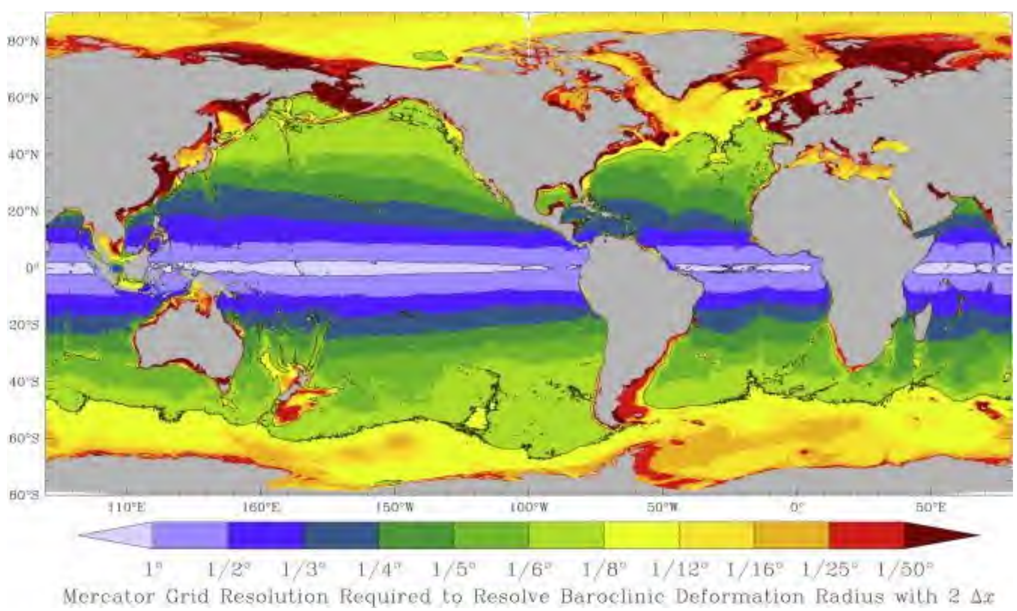
Material for slide series from:
Alistair Adcroft (Princeton), Scott Bachman (NCAR), Robert Hallberg (GFDL), Matthew Harrison (GFDL), Kate Hedstrom (University of Alaska-Fairbanks), Gustavo Marques (NCAR), and Andrew Shao (University of Victoria)

Overview of parameterizing horizontal physics

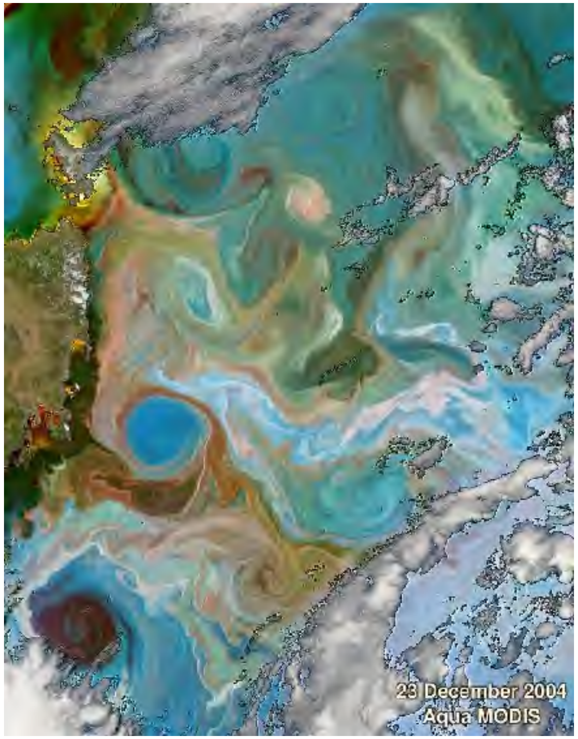
- Temporal and Horizontal discretization effectively **low-pass filters** the physics represented by a model
  - Typical IPCC-class global models use 110km spacing
  - Mesoscale eddies length scale determined by baroclinic deformation radius
- Water is an **inviscid** fluid, but kinetic energy dissipation in models needs to be **high**
  - Consider wind-forced ocean without viscosity, solution leads to unbounded accumulation of KE
- Some of kinetic energy goes into generating turbulence
  - Parameterized as a type of **mixing** momentum (viscosity) and tracers (diffusion)

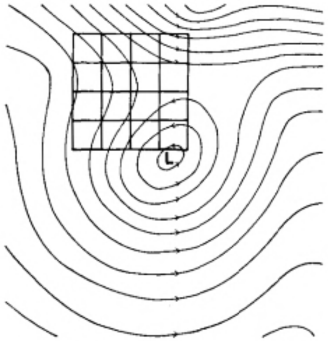


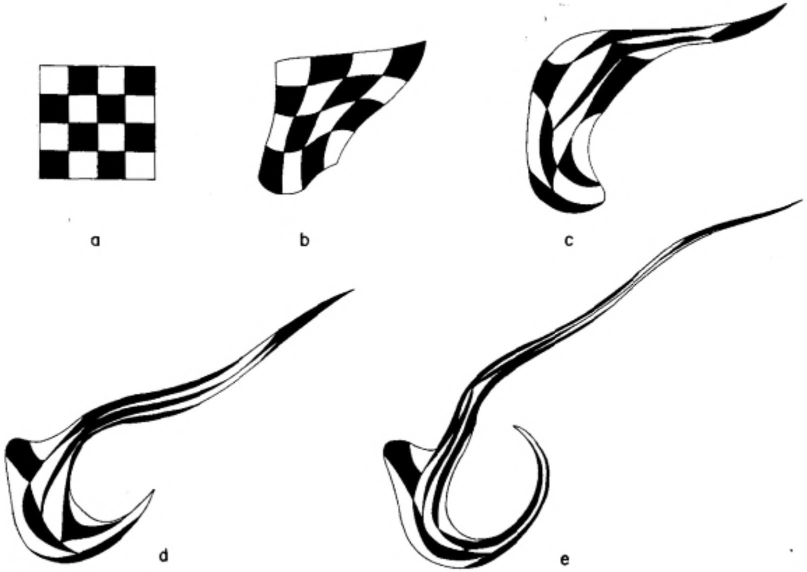
Hallberg [2013], Ocean Modeling

Effect of turbulence on a scalar field

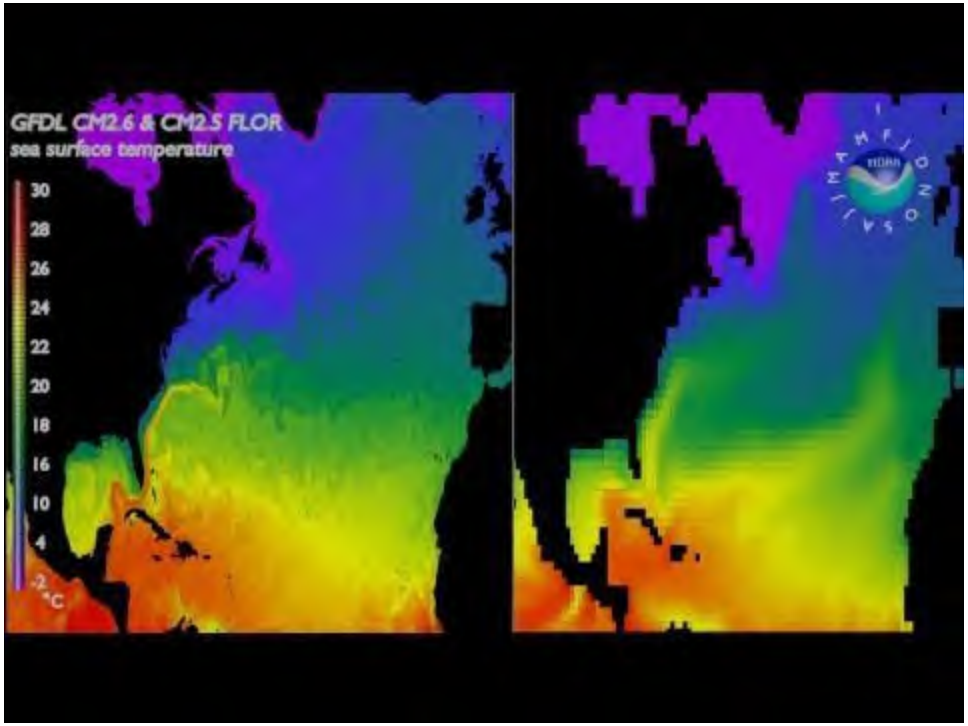
- Turbulence causes scalar field to deform
- Sharpens gradients
- Enhances efficiency of molecular diffusion







Goal of parameterizations: Capture the effect of subgrid-scale physics on the resolved flow



- Use **resolved** features of the flow to infer how the **unresolved** physics feedback onto the flow
- Ultimate goal of parameterizations, physics of low-resolution models resemble spatially-averaged high-resolution models

Horizontal parameterizations in MOM6

- Parameterizing eddy viscosity
- Mesoscale Eddy Kinetic Energy
- GM thickness diffusion
- Submesoscale
- Neutral diffusion

Reynolds averaging used to decompose resolved/unresolved physics

$$\rho_0(D_t\bar{\boldsymbol{u}} + f\hat{k}\wedge\bar{\boldsymbol{u}}) + \bar{\rho}\nabla_r\bar{\Phi} + \nabla_r\bar{p} = \nabla\cdot\boldsymbol{\tau} - \overline{\rho'\nabla_r\Phi'} - \nabla_r\cdot\overline{\boldsymbol{u}'\bigotimes\boldsymbol{u}'}$$

- Separate out the fast time-scale/small spatial scale features from the mean fields
  - Perturbations have zero time average
  - Retain perturbation terms which are multiplied
- Assume that resolved/unresolved physics can be decomposed
- Unresolved motions are a source/sink term for resolved motion
  - Redistributes momentum orthogonal to mean flow
  - Boussinesq hypothesis: effect of turbulence can be modeled as an additional viscosity
- Considerations when parameterizing perturbation terms
  - Perturbation terms can be continually split by spatial scale
  - How to parameterize the form of the perturbation terms
  - Strength of the parameterization
  - Avoid over-applying parameterizations when resolved

Main challenge of viscosity/diffusivity parameterizations

Problem:

- Models will need some level of viscosity to suppress noise
  - Acts as a form of unresolved turbulence closure
  - Reynolds number dictates a minimum level of vicosity needed to ensure resolved flow is laminar
- **But** viscosity suppresses *real* sharp gradients in flow
  - Western Boundary Currents are sharp in reality
  - Most GCMs have WBCs which are diffuse/slow even when total transport is right!

Solution:

- Choose the right level of viscosity/diffusivity based on physics and educated ‘guesses’ about the subgridscale
  - Smagorinsky, MEKE, Backscatter, Submesoscale
- Turn off parameterizations when turbulence is resolved
  - Resolution function approach

Parameterizing the downscale cascade of energy as eddy 'viscosity'

$$\overline{\boldsymbol{u}' \otimes \boldsymbol{u}'} = \begin{bmatrix} T_T & T_S \\ T_S & -T_T \end{bmatrix}$$

$$\text{Tension: } D_T = \partial_x \bar{u} - \partial_y \bar{v}$$

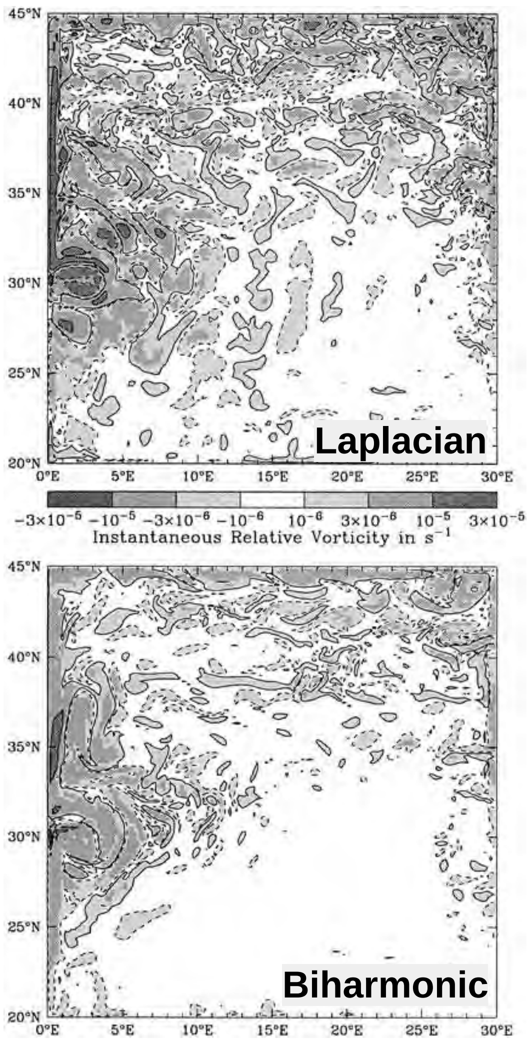
$$\text{Strain: } D_S = \partial_x \bar{v} - \partial_y \bar{u}$$

$$T_T = \overbrace{\nu(D_T)}^{\text{Laplacian}} + A\left(\partial_x[\hat{x} \cdot \nabla^2 \bar{\boldsymbol{u}}] - \partial_y[\hat{y} \cdot \nabla^2 \bar{\boldsymbol{u}}]\right)$$

$$T_S = \nu(D_S) + \underbrace{A\left(\partial_x[\hat{y} \cdot \nabla^2 \bar{\boldsymbol{u}}] + \partial_y[\hat{x} \cdot \nabla^2 \bar{\boldsymbol{u}}]\right)}_{\text{Biharmonic}}$$

Smagorinsky viscosity helps suppress flow-scale noise

Idealized “Gyre” experiment



Griffies and Hallberg, [2000]

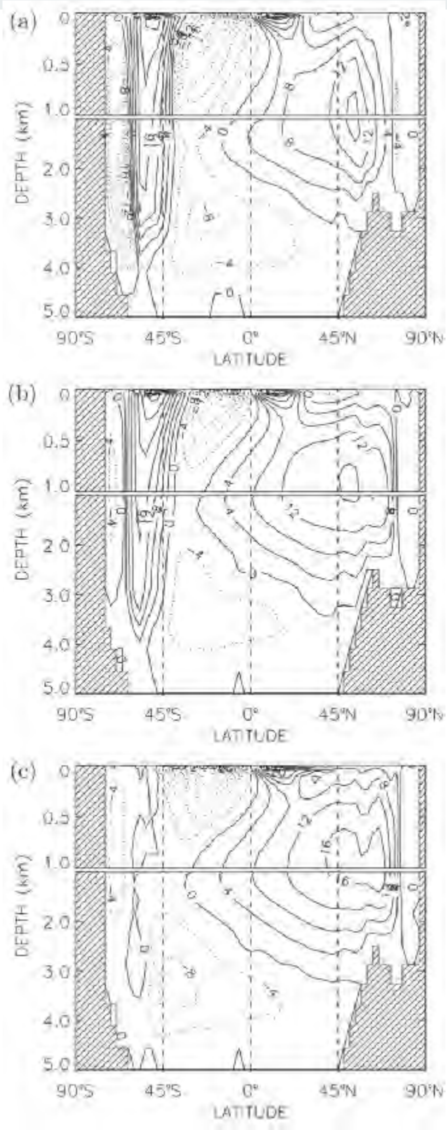
$$\nu_{Smag} = c_1 L^2 \sqrt{D_T^2 + D_S^2}$$

$$A_{Smag} = c_2 L^4 \sqrt{D_T^2 + D_S^2}$$

- Viscosity varies with the flow field
- Laplacian suppresses small-scale
- Biharmonic preserves smaller-scale features, acts more on larger-flow
- Biharmonic alone has no real ‘physical’ justification
- In practice, can use both to tune model
    - Global model uses Laplacian which may be scaled away and also Biharmonic

Brief over view of modeling eddy diffusion in models

- Parameterizations of mixing due to mesoscale eddies
  - Predominantly adiabiatic
  - Eddy stirring (Gent-McWilliams)
  - Eddy-mixing (Redi)
- Earliest models: horizontal diffusion along depth surfaces
  - Veronis effect: induces spurious upwelling and downwelling in mid-latitudes
  - Creates a shortcut for water, reducing overturning
- Gent-McWilliams
  - Parameterizes residual circulation
  - Behaves as a sink of available potential energy
- Both in combination allowed for first stable climate simulations without flux adjustment



Danabasalogu et al. [1994]

Extraction of available potential energy by *stirring* of eddies

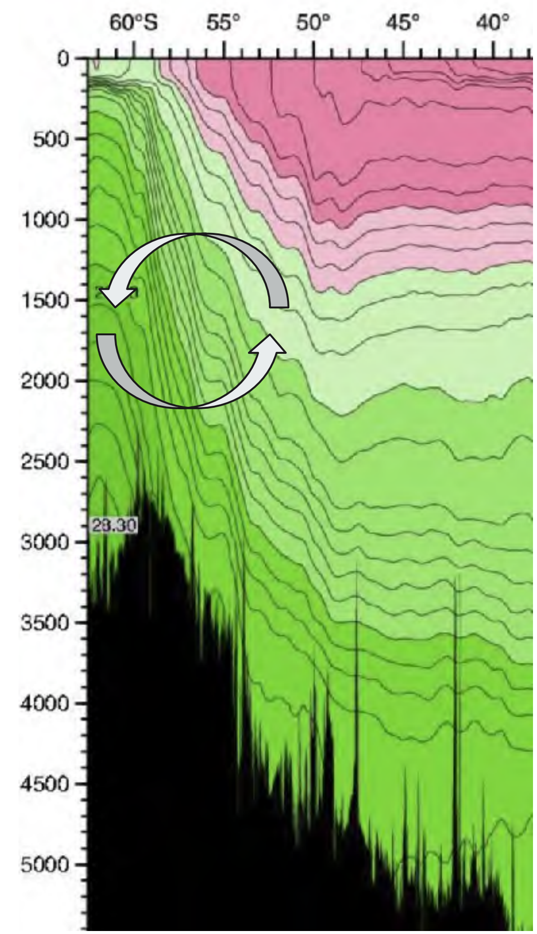
- Eady model
  - Sloping isopycnals represent available potential energy
  - Small perturbations lead to growing baroclinic instability
  - Eddies induce an overturning streamfunction flattening slopes
- Gent-McWilliams [1990,1995] cast this as a streamfunction

$$\Psi_{GM} = -\kappa \frac{\nabla_r \rho}{\partial_z \rho}$$

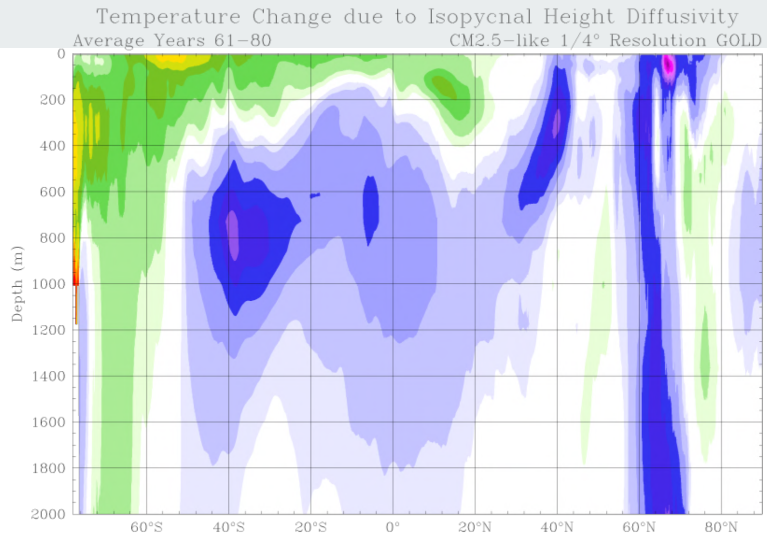
- Some numerical problems with this form in general coordinates, can tend to trap all transport near surface
- Ferrari et al. [2010] propose to solve the elliptic equation

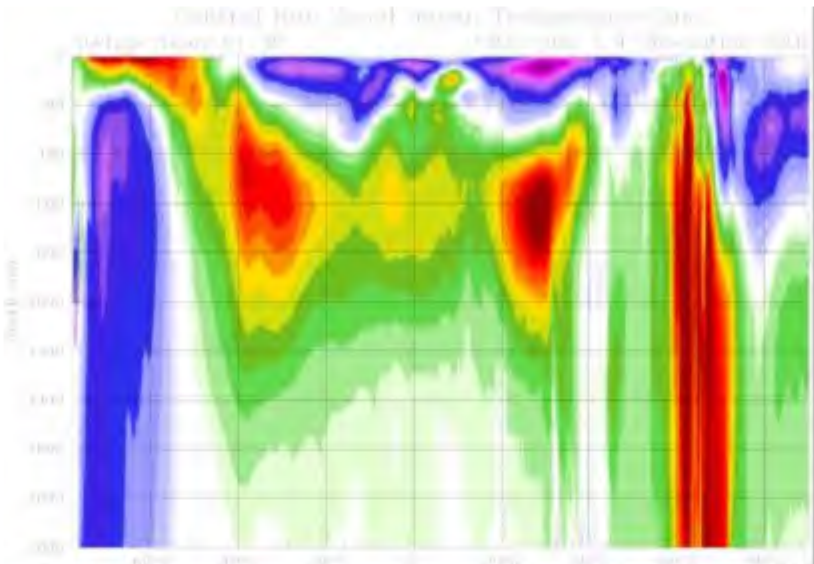
$$\gamma_F \partial_z c^2 \partial_z \psi - N_*^2 \psi = (1+\gamma_F)\kappa_h N_*^2 \frac{M^2}{\sqrt{N^4+M^4}}$$

- Gent-McWilliams (like viscosity) extracts energy from the large-scale fields to the mesoscale

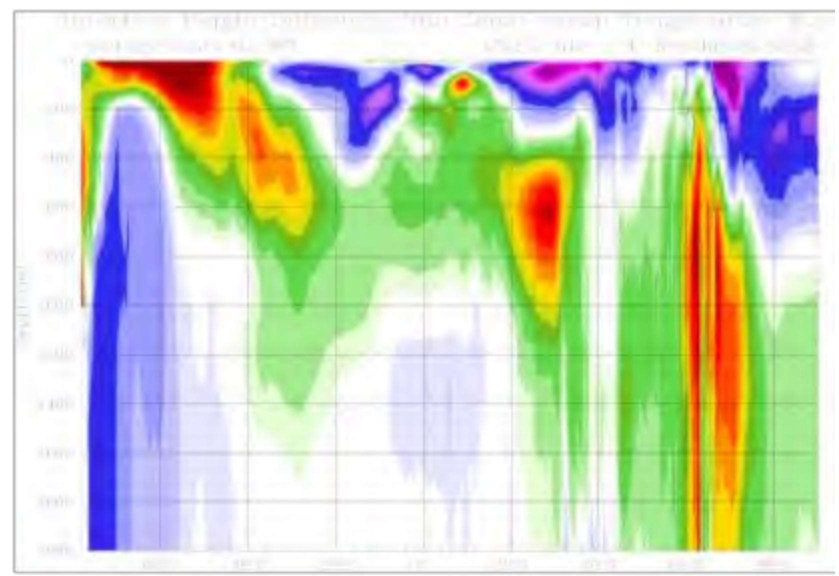


Gent-McWilliams reduces temperature bias



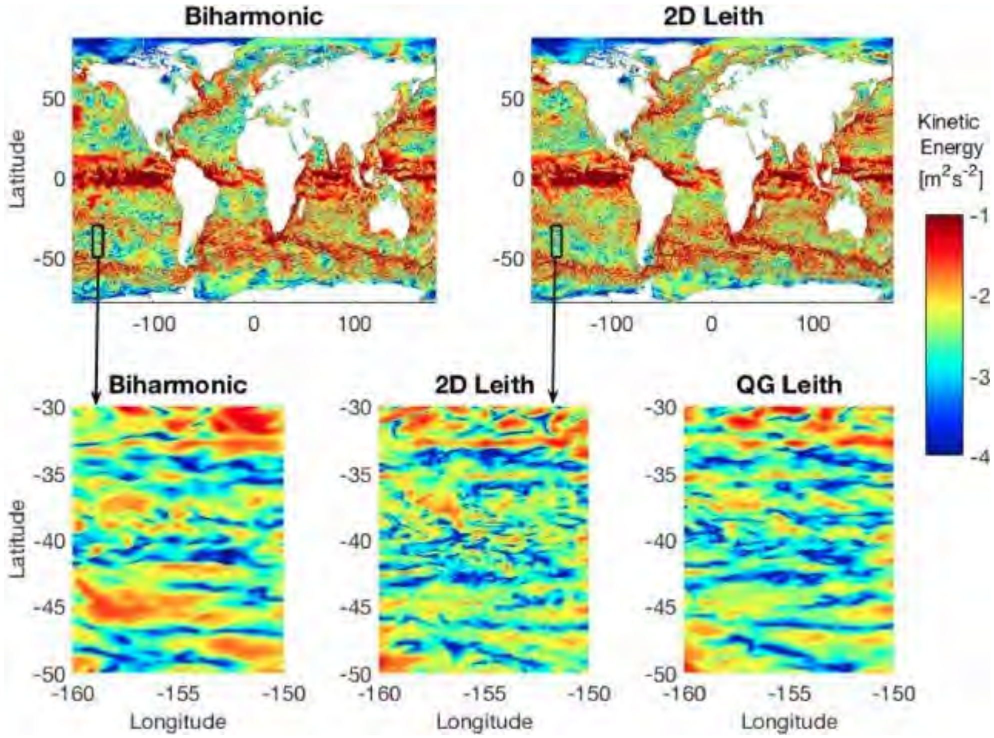


Difference from observations: No GM



Difference from observations: With GM

QG Leith is a mesoscale parameterization for both GM and viscosity

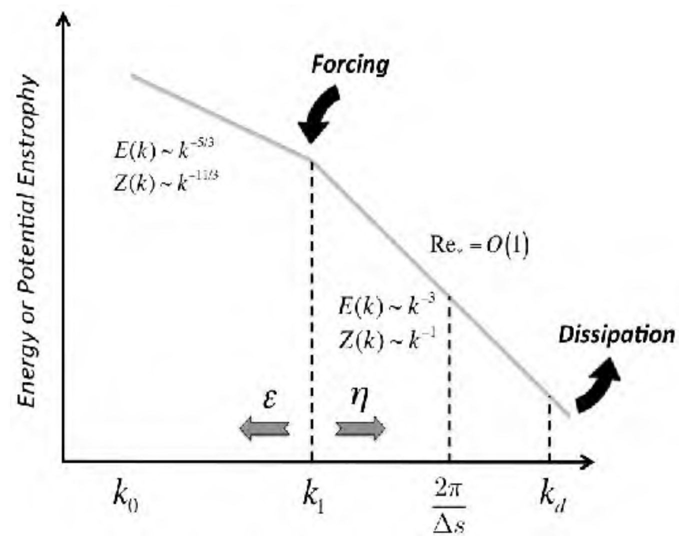


$$\nu_{Smag} = c_1 L^2 \sqrt{D_T^2 + D_S^2}$$

$$A_{Smag} = c_2 L^4 \sqrt{D_T^2 + D_S^2}$$

$$\nu_{QG2d} = c_3 L^3 \left(\beta + \nabla(D_S) + \partial_z \left[\frac{f}{N^2} \nabla b \right] \right)$$

- Recall: Smagorinsky viscosity is based on 3D turbulence
- QG Leith: based on ideas about mesoscale turbulence (more 2D)

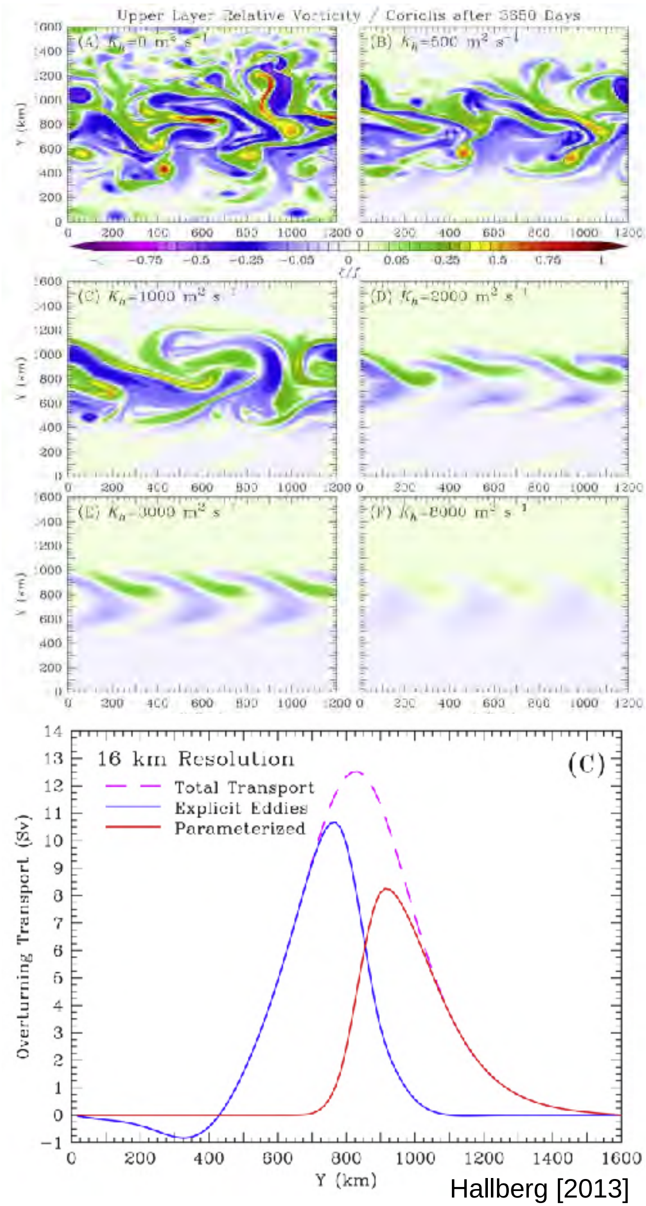


Bachman et al. [2017]

Explicitly suppressing eddy effects using a resolution function

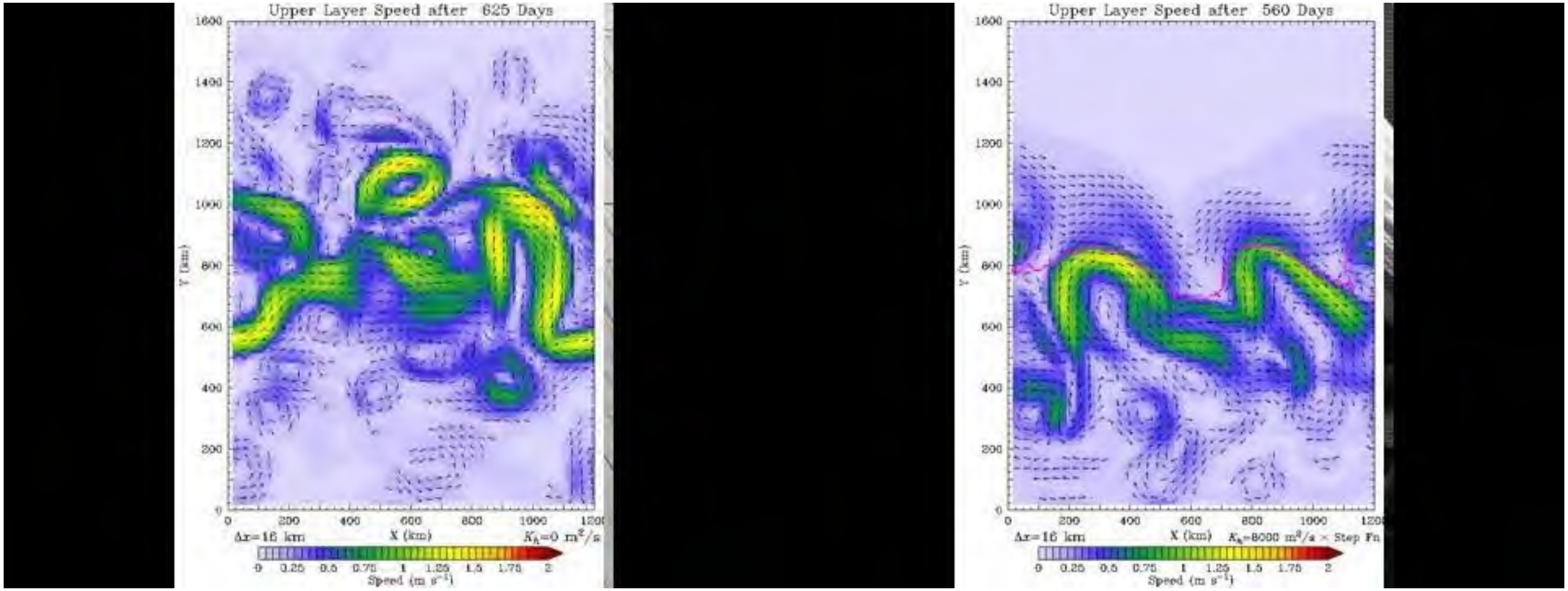
- Parameterizations extract energy from the system
  - Less energy available for the model to generate turbulence
- Model may sometimes resolve eddy field
  - Regionally enhanced resolution
  - Baroclinic radius of deformation
- Multiply diffusivities/viscosities by a step function (0,1) based on Rossby radius and grid size

$$\kappa = \begin{cases} \kappa_0 & \lambda_{def}/\Delta < R_{trans} \\ 0 & \lambda_{def}/\Delta \geq R_{trans} \end{cases}$$



Hallberg [2013]

Resolution function allows partial representation of eddies



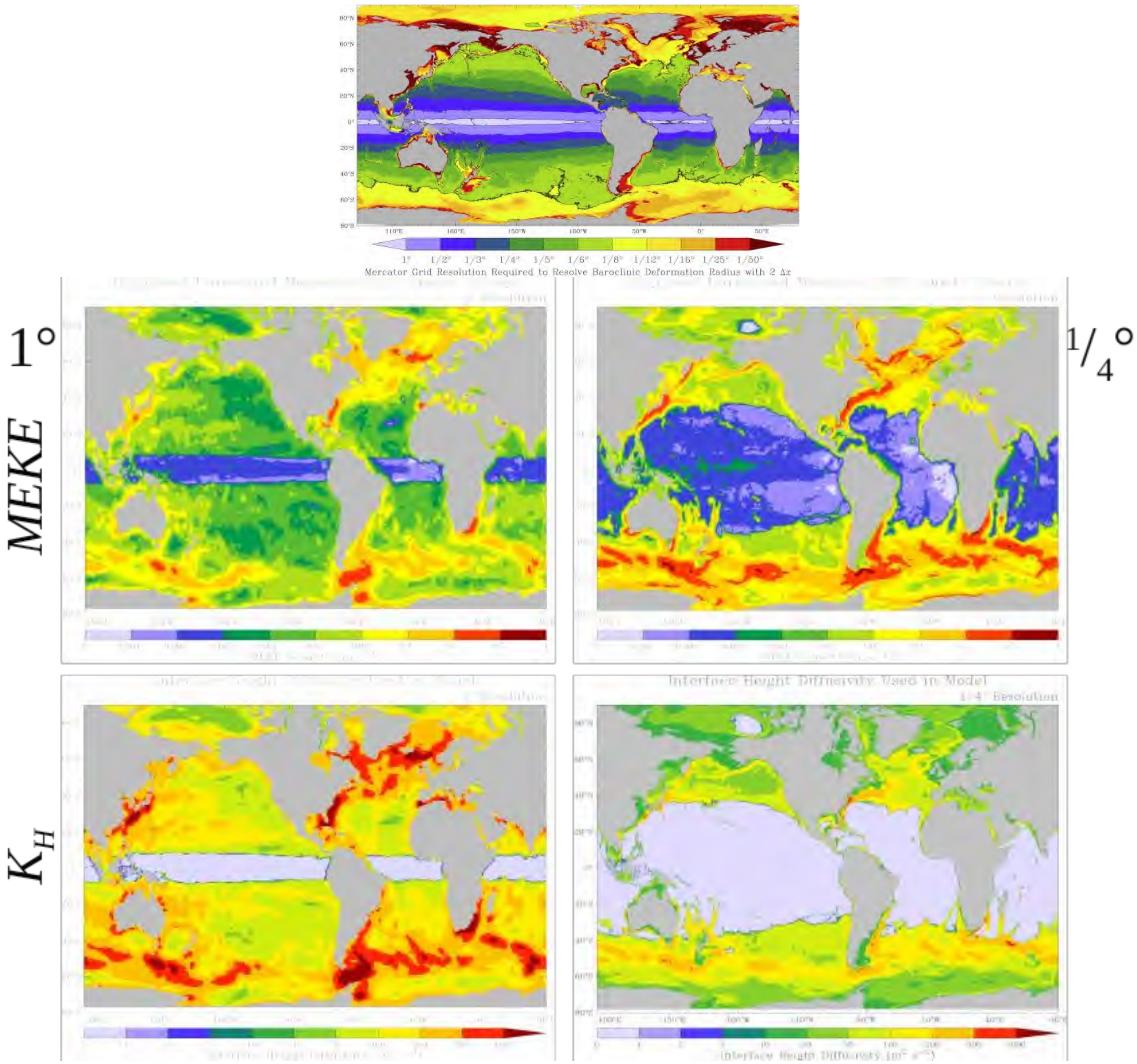
Devising an energetically-based scheme using an energy equation

$$\partial_t E = \overbrace{\dot{E}_b + \gamma_\eta \dot{E}_\eta + \gamma_v \dot{E}_v}^{\text{sources}} - \overbrace{(\lambda + C_d |U_d| \gamma_b^2) E}^{\text{local dissipation}} + \overbrace{\nabla \cdot ((\kappa_E + \gamma_M \kappa_M) \nabla E - \kappa_4 \nabla^3 E)}^{\text{smoothing}}$$

Jansen et al. [2015]

- Mesoscale eddies extract energy from large-scale fields
- Can keep track of how energy is either dissipated or gained (and transferred between points)
- Sources
    - Background energy
    - Extraction from GM
    - Extraction from viscosity
- Local dissipation
    - Linear damping
    - Bottom drag based amount of total column energy dissipated at the bottom
- Effective horizontal smoothing
    - Diffusion of energy (background + eddy)
    - Biharmonic viscosity

MEKE gives reasonable diffusivity and eddy-kinetic energy

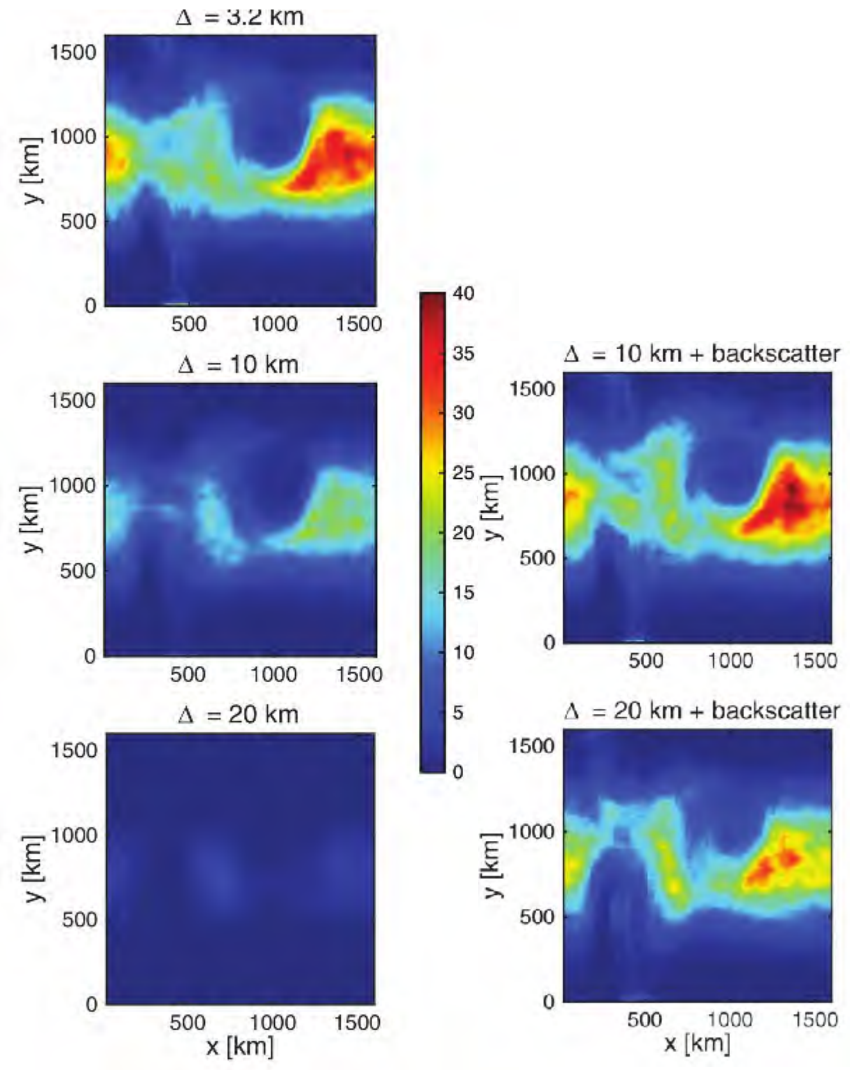


Using MEKE to infer diffusivity for tracers and/or viscosity for momentum

$$U_e = \sqrt{2E}$$

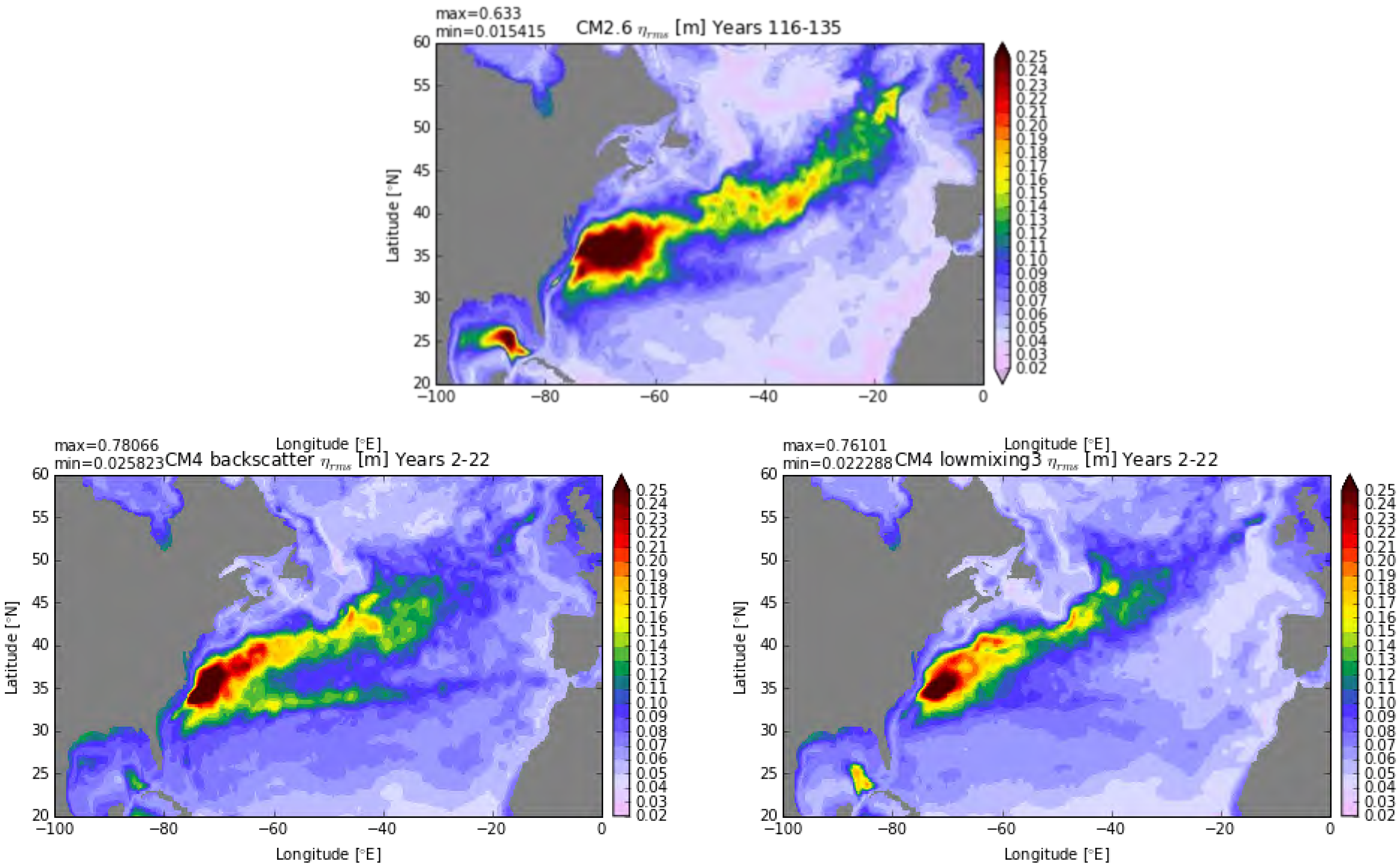
$$\kappa = \gamma_k l_M \sqrt{\left(1 + c_t \frac{c_g}{f} \frac{H}{c_d}\right)^{-1/4} U_e^2}$$

- Allows for a spatially varying viscosity coefficient for momentum equation, tracer diffusivity coefficient, and GM diffusivity
- Can be used to feed energy back into the resolved eddies (backscatter) by specifying a negative viscosity
  - Sharpens gradients instead of diffusing them



Jansen et al. [2015b]

Using backscatter to feed MEKE back to resolved flow strengthens eddy field



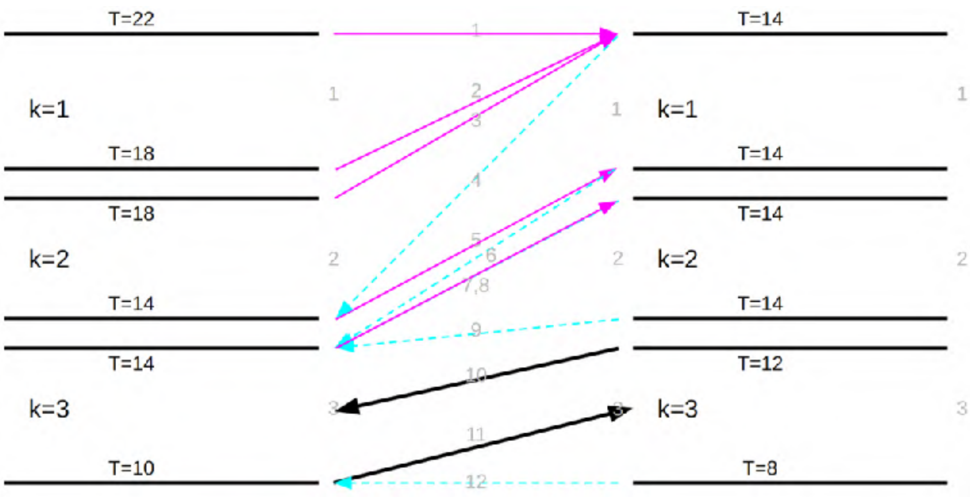
Restratification by mixed layer instabilities

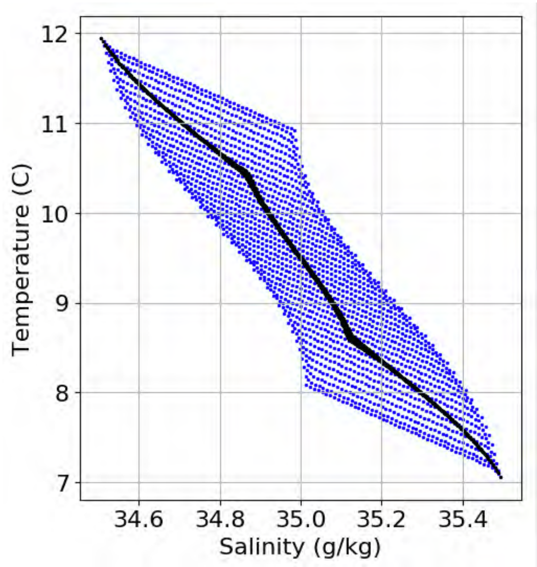
$$\Psi_{submeso} = C_e \Gamma_\Delta \frac{H^2 \nabla \overline{b^{H_{ml}}} \times \hat{\boldsymbol{z}}}{\sqrt{f^2 + \tau^{-2}}} \mu(z)$$

- Eady problem applied to a ageostrophic density front
  - Baroclinic instability grows
  - Isopycnals flatten
  - Mixed layers shoal
- Governing dynamics
  - Length scale of the front
  - Depth of the mixed layer
  - Horizontal buoyancy gradient
  - Inertial terms
  - Wind stress
- In combination with new boundary layer scheme, gives realistic depths

A general coordinate approach to epineutral diffusion

- Similar to GM, traditional rotated tensor approach can lead to numerical instabilities in general coordinates
- Known deficiencies in method motivate a new scheme
- General idea
  - Use piecewise polynomial reconstructions of T/S to determine neutral density surfaces
  - Perform diffusion along sublayers bounded by those surfaces
- Scheme is positive-definite and approximately density conserving





Summary of horizontal parameterizations

- Horizontal parameterizations attempt to capture effect of subgrid-scale physics on the resolved physics
    - Smagorinsky viscosity seeks to suppress flow ‘noise’
    - Mesoscale viscosity through MEKE can be used as momentum source or sink
- Scale-aware parameterizations allow for a given configuration to apply eddy effects only when necessary
    - Eventual goal could be to use the same ‘tunings’ for a range of horizontal resolutions
- Rewriting parameterizations in general coordinates represents a new challenge for the field
- Tomorrow: Vertical parameterizations