Mixed Layer Eddy Parameterization: Theory, Impact, and Comparison with Mesoscale Eddy Parameterizations.

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Tracer Flux-Gradient Relationship

$$\overline{\mathbf{u}'\tau'} = -\mathbf{M}\nabla\overline{\tau}$$

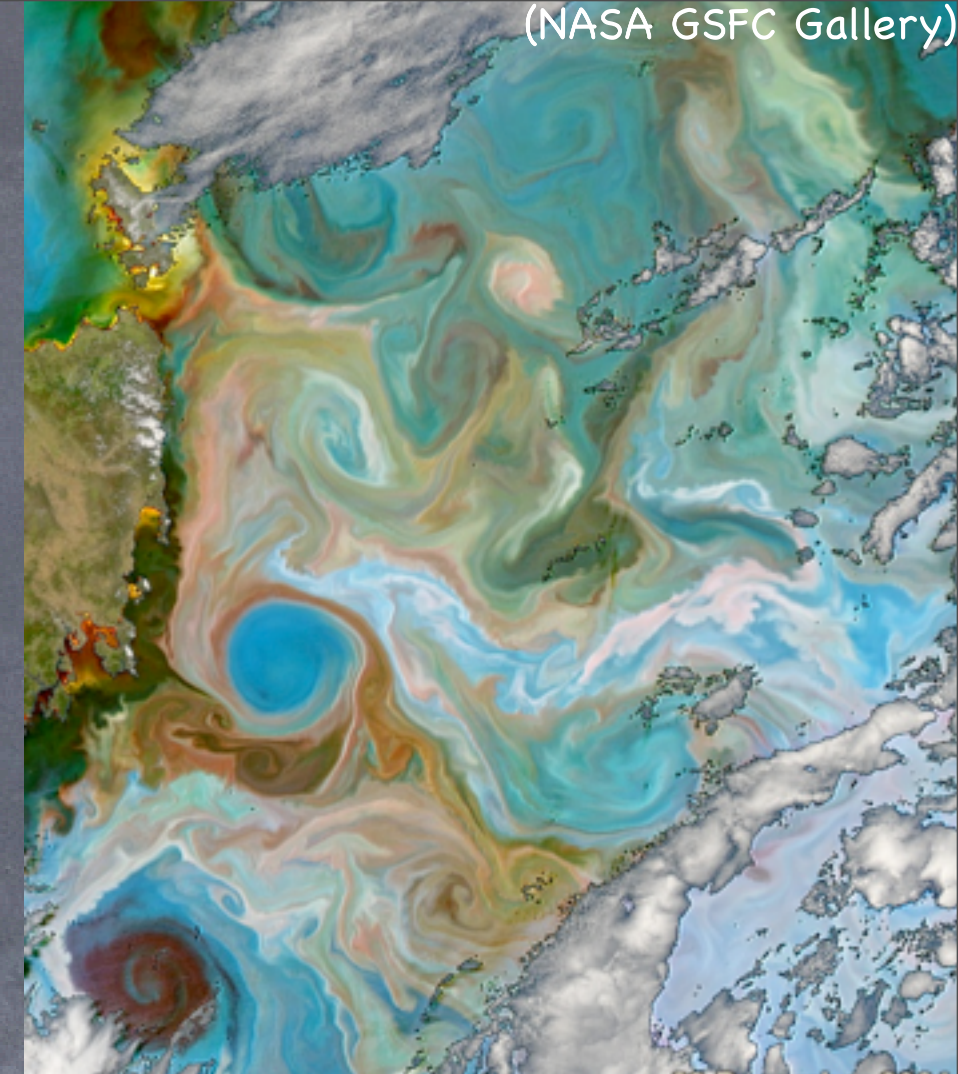
- Most subgridscale eddy closures have this form: GM*, Redi, FFH** submesoscale
- Relates the eddy flux to the coarse-grain gradients locally
- If we knew the dependence of $\mathbf{M}$ on the coarse-resolution flow, we'd have the optimal local eddy closure

*Gent & McWilliams (1990) **Fox-Kemper, Ferrari, Hallberg (2008)

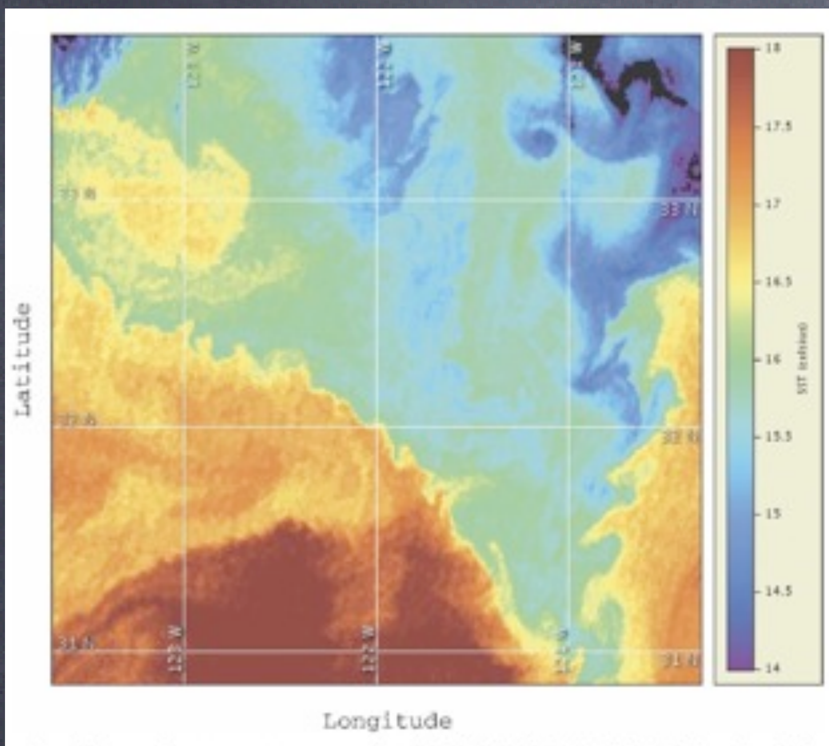
The Character of the Submesoscale

10 km

(NASA GSFC Gallery)

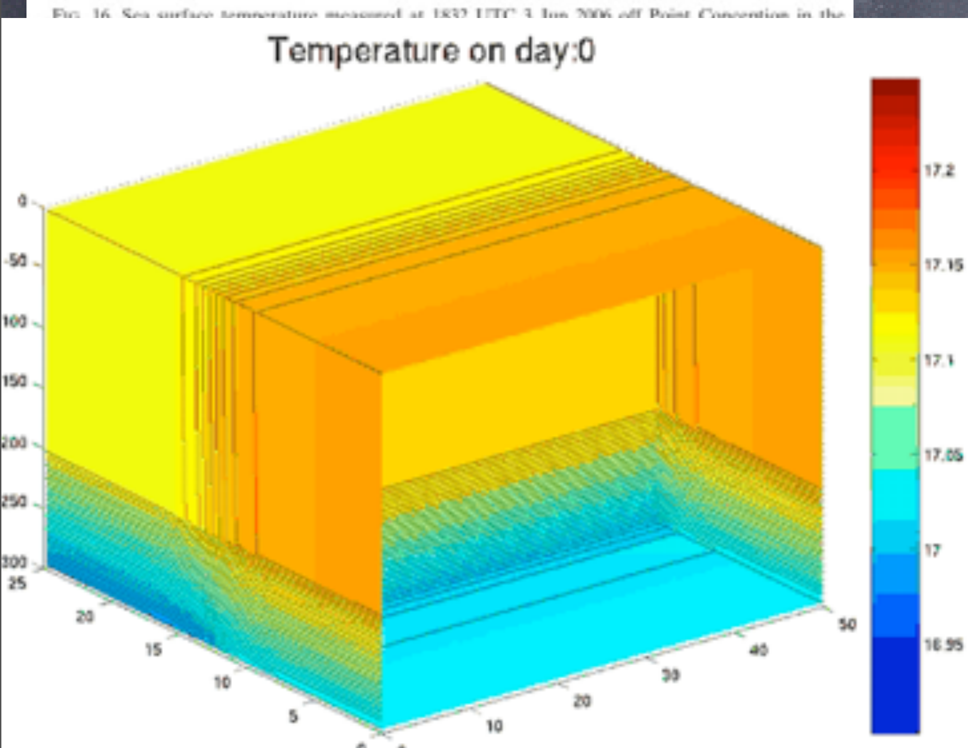


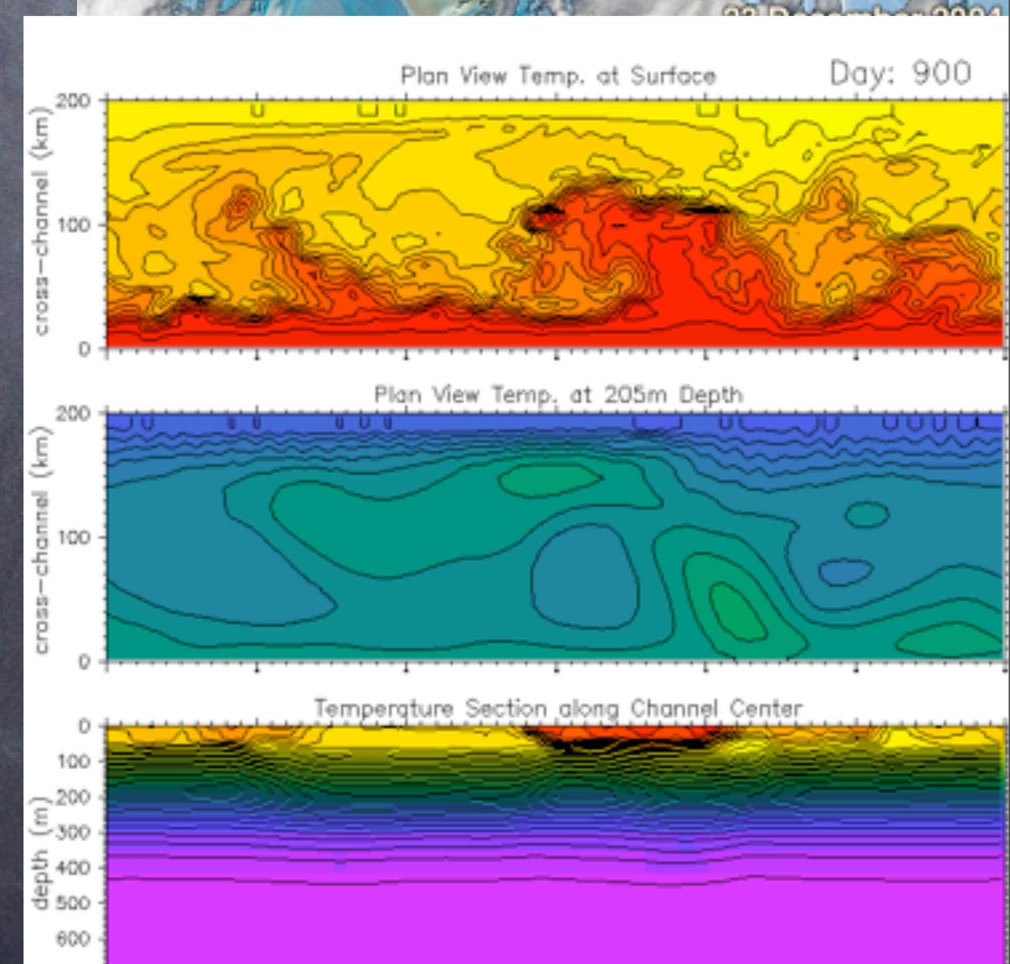
(Capet et al., 2008)



- Fronts
- Eddies
- Ro=O(1)
- Ri=O(1)
- near-surface
- 1-10km, days

Eddy processes mainly baroclinic instability (Boccaletti et al '07, Haine & Marshall '98). Parameterizations of baroclinic instability apply? (GM, Visbeck, FFH).





A Global Parameterization of Mixed Layer Eddy Restratification

with FLOW DEPENDENT M validated against simulations

Fox-Kemper, Ferrari, & Hallberg (2008) &

Fox-Kemper, Danabasoglu, Ferrari, & Hallberg (2008)

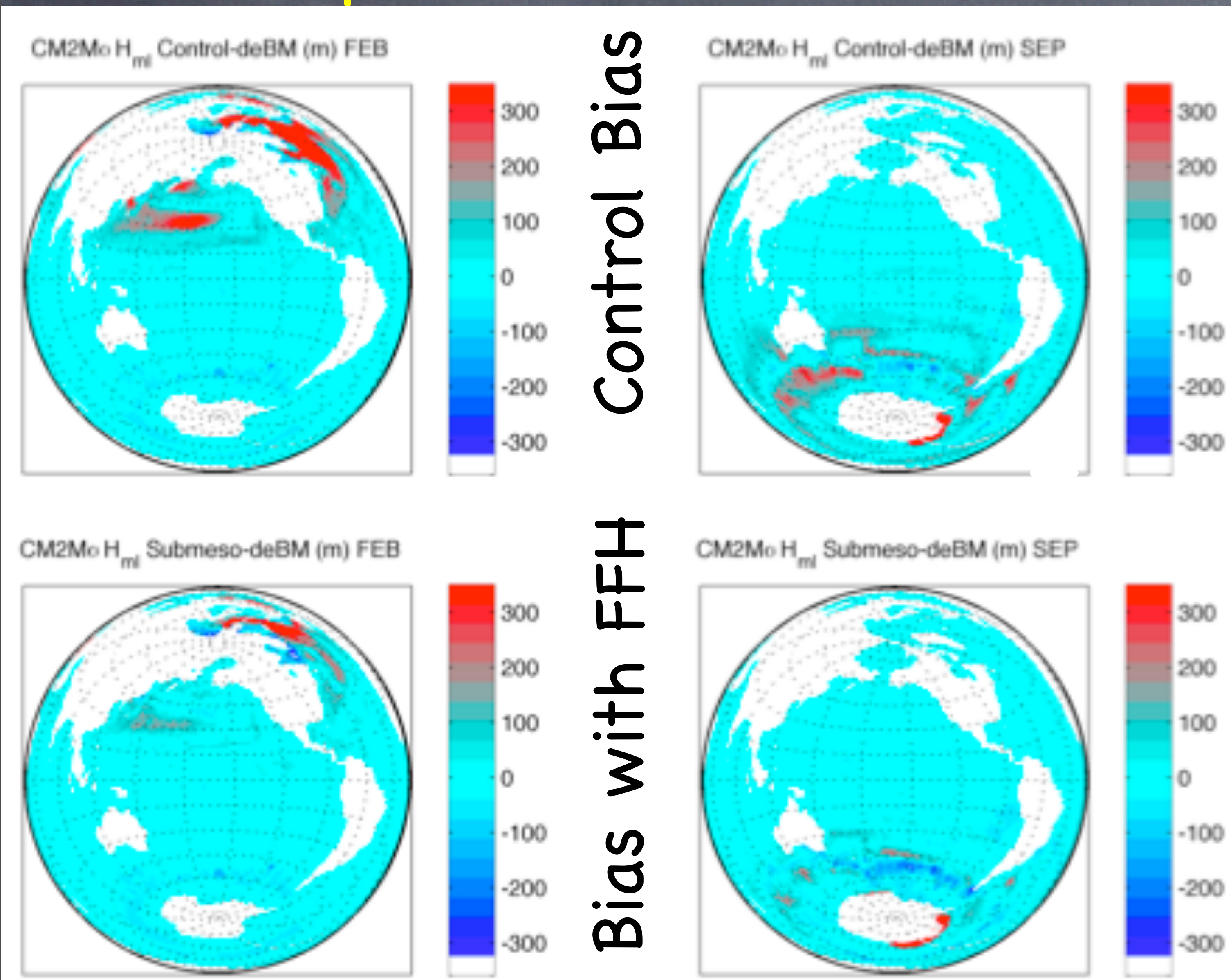
$$\begin{bmatrix} \overline{u'\tau'} \\ \overline{v'\tau'} \\ \overline{w'\tau'} \end{bmatrix} = - \begin{bmatrix} 0 & 0 & -\mathbf{\Psi_y} \\ 0 & 0 & \mathbf{\Psi_x} \\ \mathbf{\Psi_y} & -\mathbf{\Psi_x} & 0 \end{bmatrix} \begin{bmatrix} \overline{\tau}_x \\ \overline{\tau}_y \\ \overline{\tau}_z \end{bmatrix}$$

$$\mathbf{\Psi} = \left[\frac{\Delta x}{L_f}\right] \frac{C_e H^2 \mu(z)}{\sqrt{f^2 + \tau^{-2}}} \nabla \bar{b} \times \hat{\mathbf{z}}$$

$$\mu(z) = \left[1 - \left(\frac{2z}{H} + 1\right)^2\right] \left[1 + \frac{5}{21}\left(\frac{2z}{H} + 1\right)^2\right]$$

Physical Sensitivity of Ocean Climate to Submesoscale Eddy Restratification:

FFH implemented in CCSM (NCAR), CM2M & CM2G (GFDL)

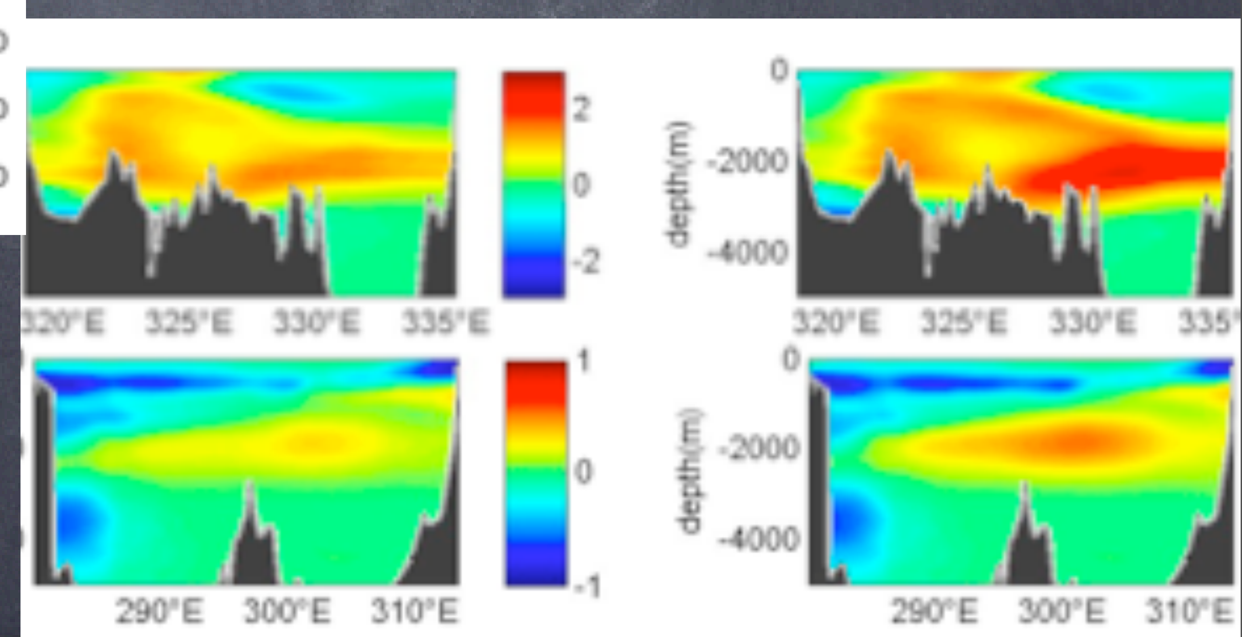


NO RETUNING NEEDED!!!

Improves CFCs

Bias with FFH

Control Bias



Deep ML Bias reduced

From Fox-Kemper et al., in prep

Sensitivity of Climate to Submeso: AMOC & Cryosphere Impacts

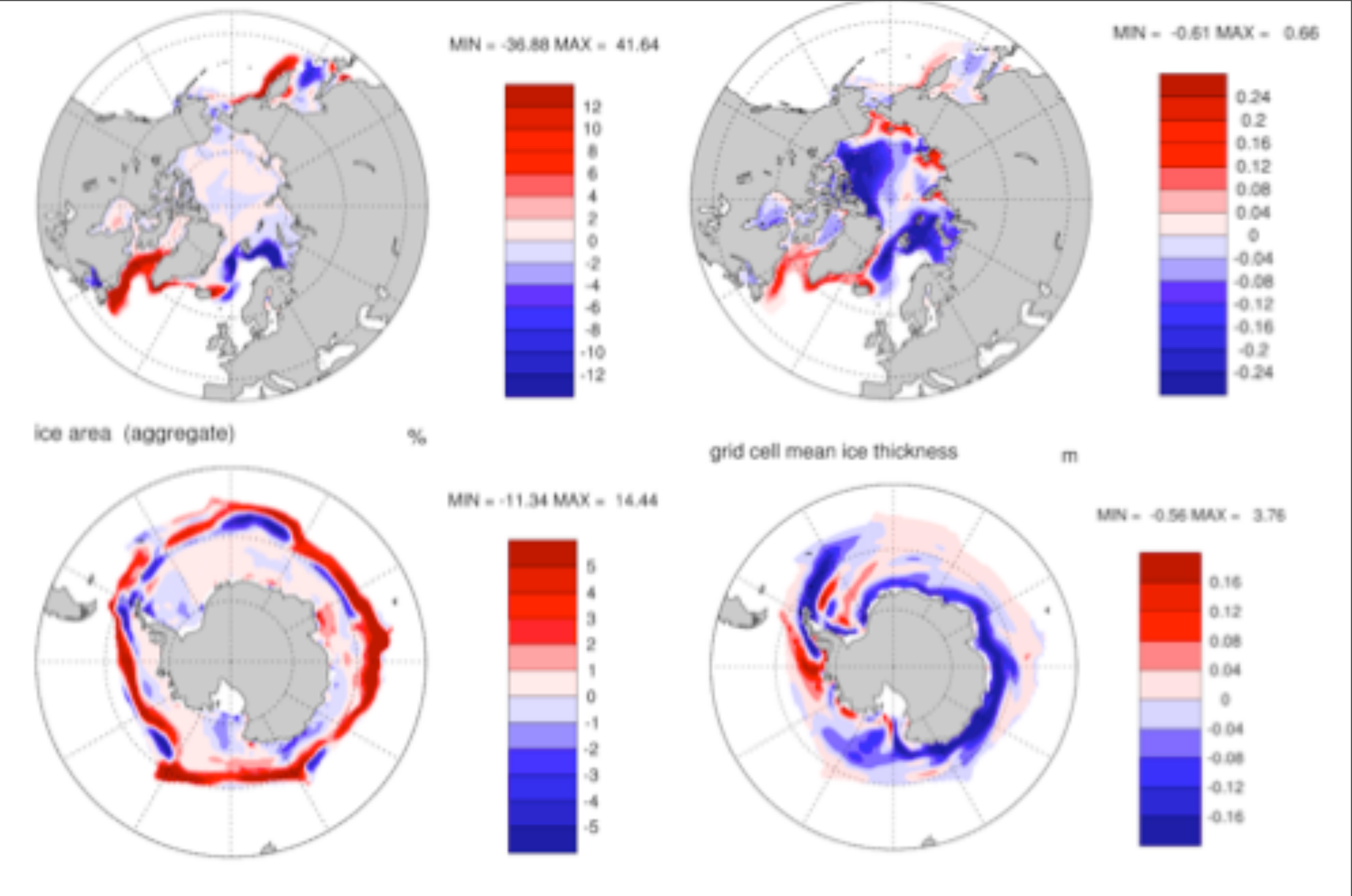
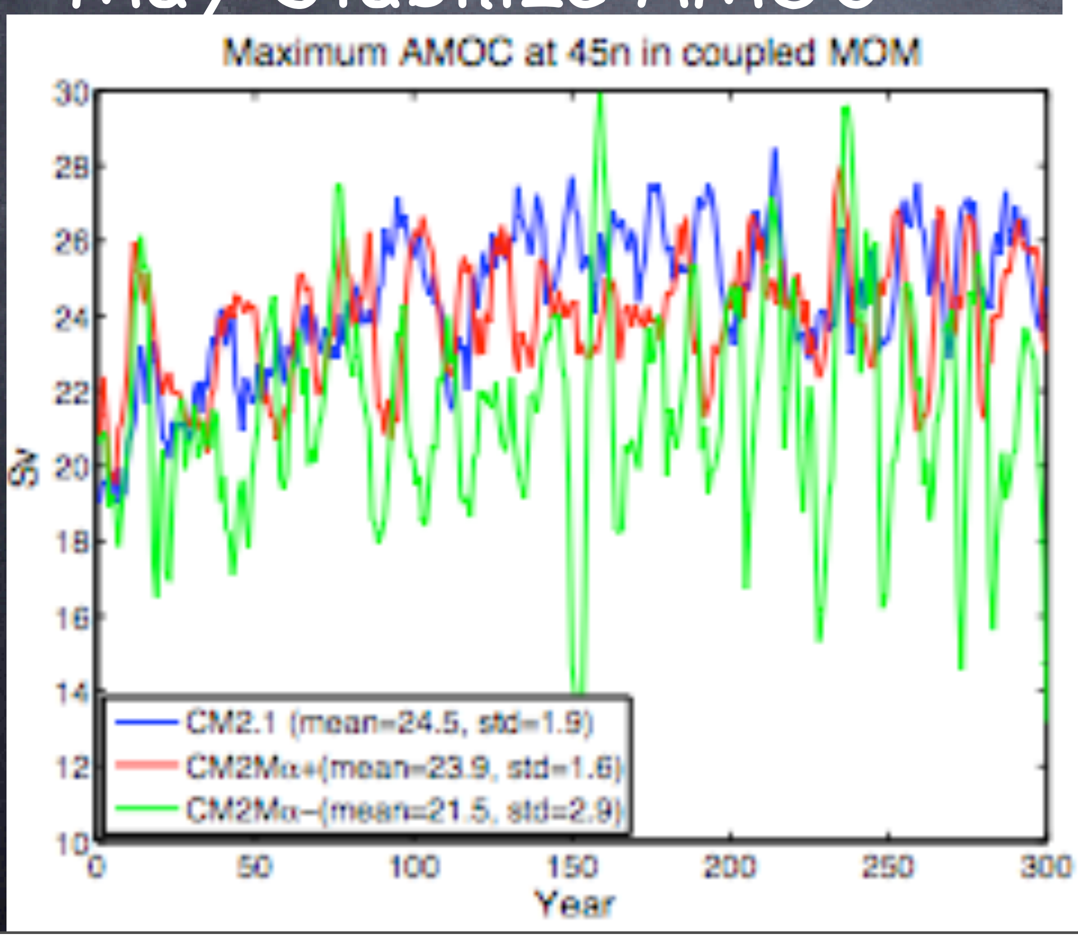


Figure 10: Wintertime sea ice sensitivity to introduction of MLE parameterization (CCSM$^+$ minus CCSM$^-$): January to March Northern Hemisphere a) ice area and b) thickness and July to September Southern Hemisphere c) ice area and d) thickness.

May Stabilize AMOC



Affects sea ice

NO RETUNING NEEDED!!!

These are impacts: bias change unknown

Conclusions Submesoscale

- FFH is implemented in at least 3 IPCC models
- Parameterization reduces bias in CFCs & Mixed Layer Depth
- Parameterization also affects ice & AMOC variability--need truth?
- Flow-dependent, nondimensional scalings validated against simulations *did not require retuning*

The Character of the Mesoscale

(Capet et al., 2008)

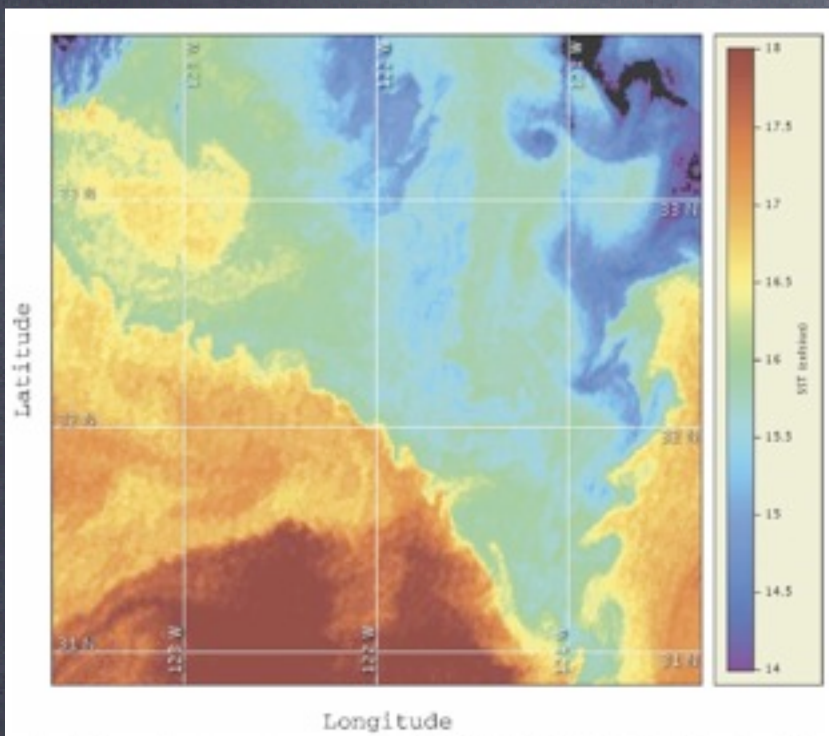


FIG. 16. Sea surface temperature measured at 1832 UTC 3 Jun 2006 off Point Conception in the California Current from CoastWatch (http://coastwatch.pfeg.noaa.gov). The fronts between recently upwelled water (i.e., 15°–16°C) and offshore water (≥17°C) show submesoscale instabilities with wavelengths around 30 km (right front) or 15 km (left front). Images for 1 day earlier and 4 days later show persistence of the instability events.

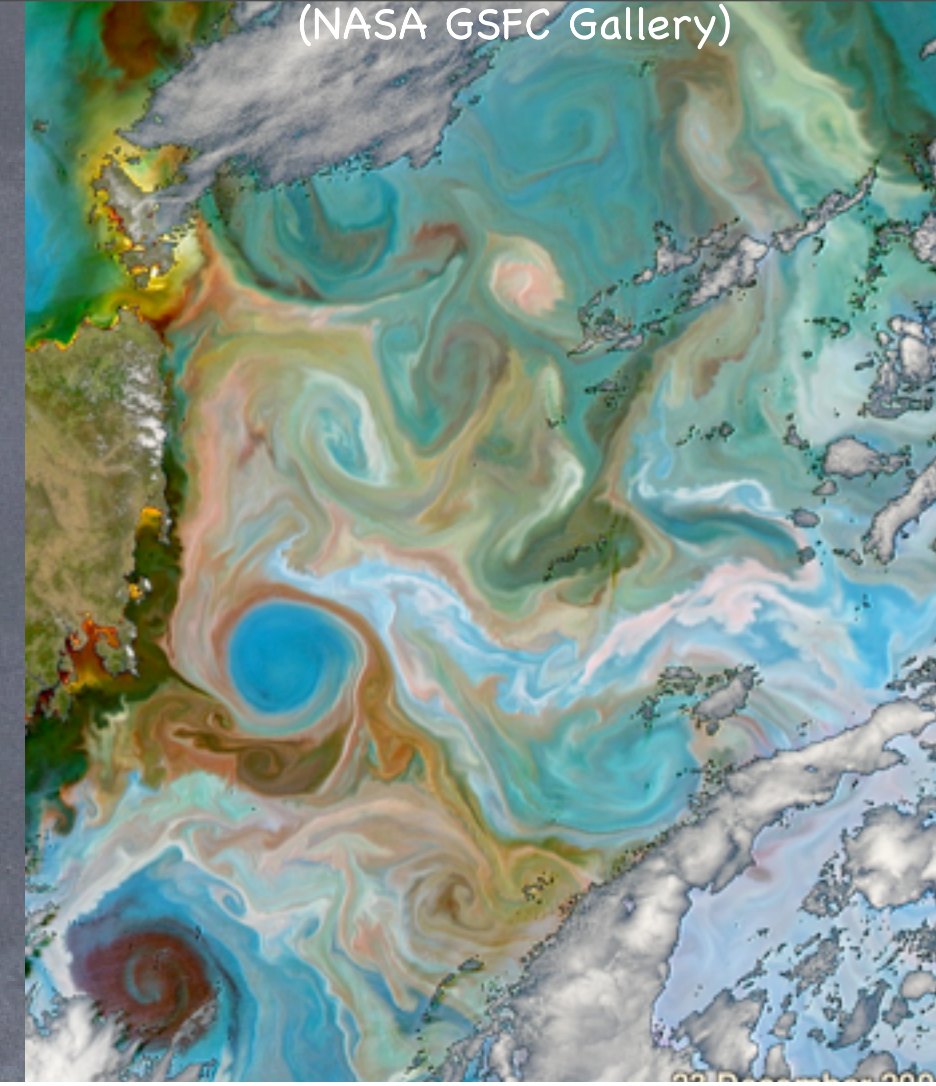
- Boundary Currents
- Eddies
- Ro=O(0.1)
- Ri=O(1000)
- Full Depth
- Eddies strain to produce Fronts
- 100km, months

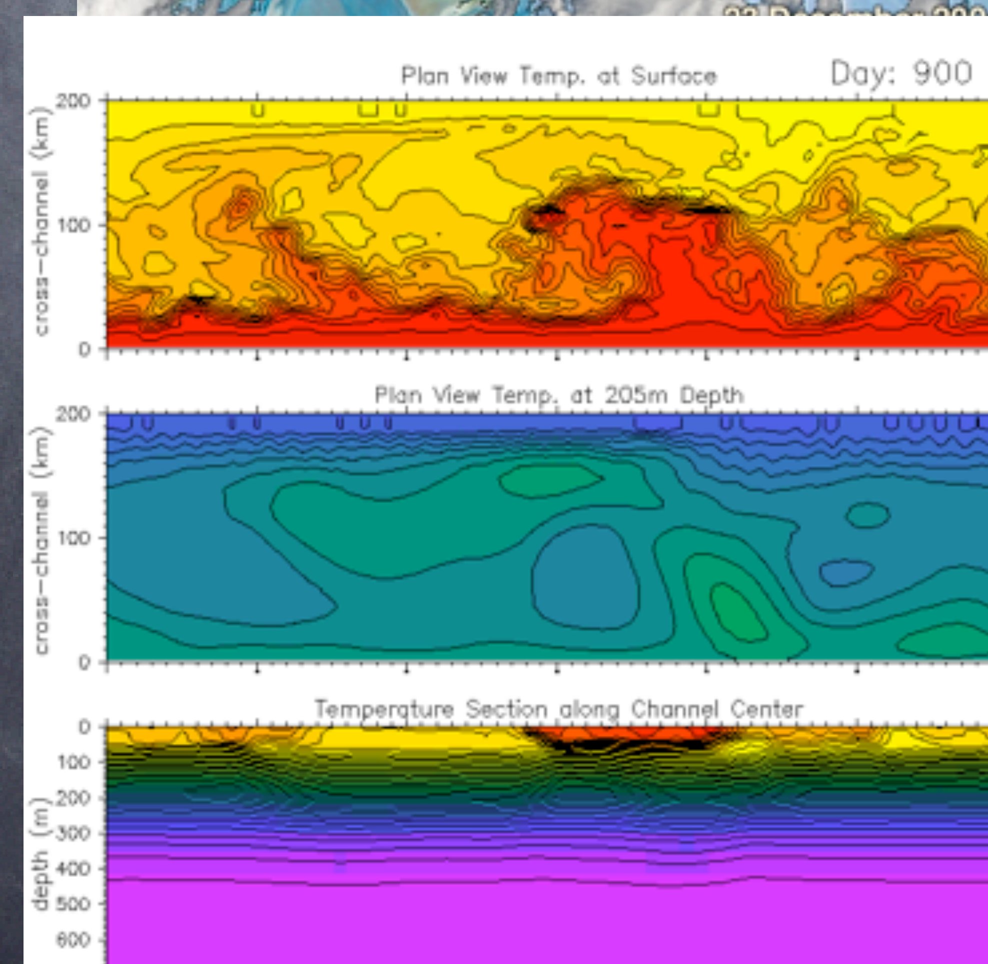
Eddy processes still baroclinic & barotropic instability.

Parameterizations (GM, Visbeck, Eden).

100 km

(NASA GSFC Gallery)





Tracer Flux-Gradient Relationship Diagnosis

$$\overline{\mathbf{u}'\tau'} = -\mathbf{M}\nabla\overline{\tau}$$

- Virtually all subgridscale eddy closures may be written as: GM, Redi, FFH Submesoscale
- Relates the eddy flux to the coarse-grain gradients $\nabla\overline{\tau}$ locally
- If we knew the dependence of $\mathbf{M}$ on the coarse-resolution flow, we'd have the optimal local eddy closure

$$\overline{\mathbf{u}'\tau'} = -\mathbf{M}\nabla\overline{\tau}$$

General Form

$$\begin{bmatrix} \overline{u'\tau'} \\ \overline{v'\tau'} \\ \overline{w'\tau'} \end{bmatrix} = - \begin{bmatrix} M_{xx} & M_{xy} & M_{xz} \\ M_{yx} & M_{yy} & M_{yz} \\ M_{zx} & M_{zy} & M_{zz} \end{bmatrix} \begin{bmatrix} \overline{\tau}_x \\ \overline{\tau}_y \\ \overline{\tau}_z \end{bmatrix}$$

Assume same $\mathbf{M}$ for all tracers:

3 equations per tracer

9 unknowns (components)+rot-parts (2/tracer)

BY USING 3 or MORE TRACER FLUXES, determine it!!!

(a la Plumb & Mahlman '87, Bratseth '98)

$$\overline{\mathbf{u}'\tau'} = -\mathbf{M}\nabla\overline{\tau}$$

Sym Part=Anisotropic* Redi

$$\begin{bmatrix} \overline{u'\tau'} \\ \overline{v'\tau'} \\ \overline{w'\tau'} \end{bmatrix} = - \begin{bmatrix} K_{xx} & K_{xy} & \hat{\mathbf{x}}\cdot\mathbf{K}\cdot\tilde{\nabla}\mathbf{z} \\ K_{yx} & K_{yy} & \hat{\mathbf{y}}\cdot\mathbf{K}\cdot\tilde{\nabla}\mathbf{z} \\ \hat{\mathbf{x}}\cdot\mathbf{K}\cdot\tilde{\nabla}\mathbf{z} & \hat{\mathbf{y}}\cdot\mathbf{K}\cdot\tilde{\nabla}\mathbf{z} & \tilde{\nabla}z\cdot\mathbf{K}\cdot\tilde{\nabla}\mathbf{z} \end{bmatrix} \begin{bmatrix} \overline{\tau}_x \\ \overline{\tau}_y \\ \overline{\tau}_z \end{bmatrix}$$

Yellow $\mathbf{K}$ 'are' horizontal stirring & mixing

Blue factors in Redi (1982) are symmetric

and scaled to make

eddy mixing along neutral surfaces

*Anistropic form due to Smith & Gent 04

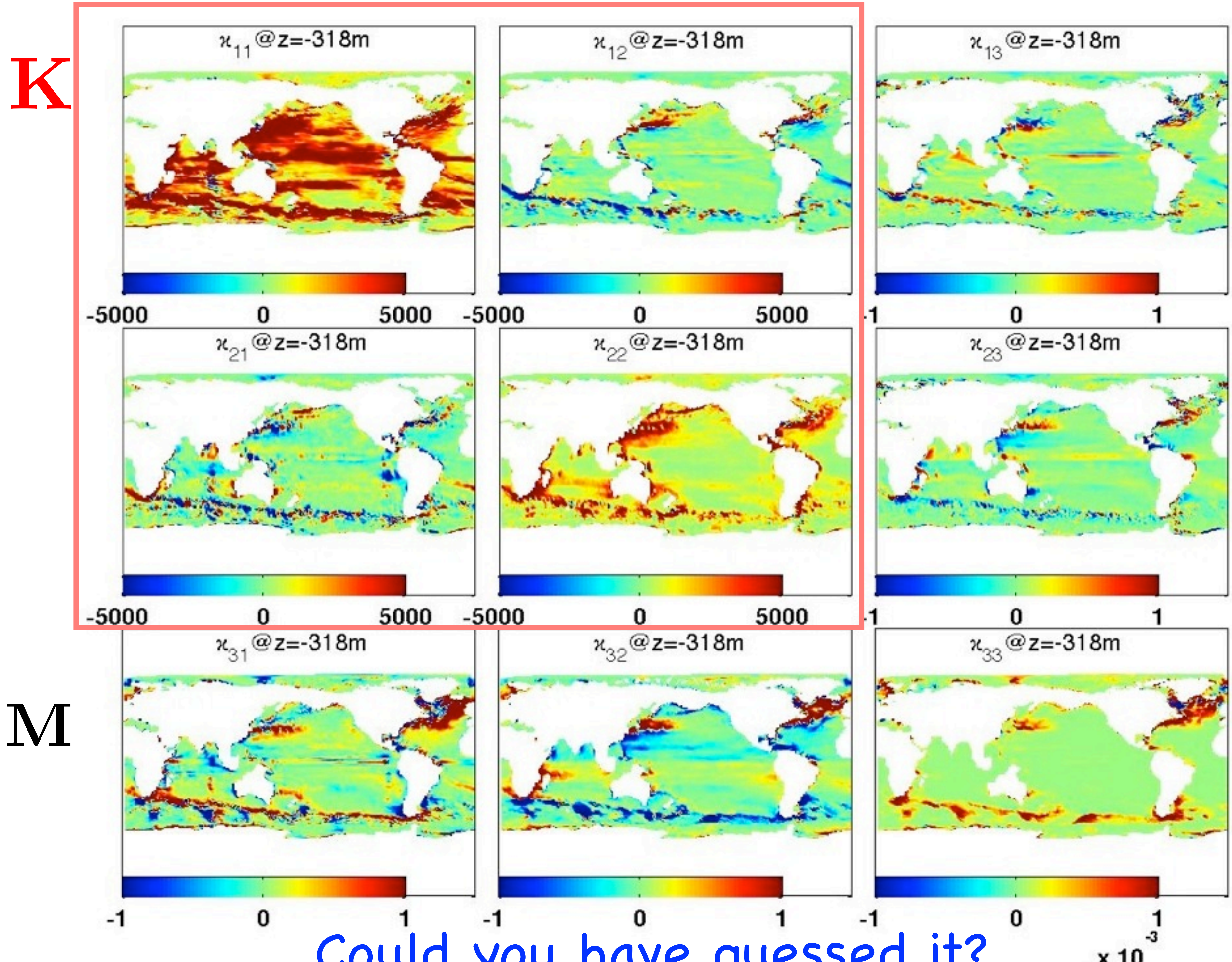
$$\overline{\mathbf{u}'\tau'} = -\mathbf{M}\nabla\overline{\tau}$$

AntiSym Part=Anisotropic* GM

$$\begin{bmatrix} \overline{u'\tau'} \\ \overline{v'\tau'} \\ \overline{w'\tau'} \end{bmatrix} = - \begin{bmatrix} 0 & 0 & -\hat{\mathbf{x}}\cdot\mathbf{K}\cdot\tilde{\nabla}\mathbf{z} \\ 0 & 0 & -\hat{\mathbf{y}}\cdot\mathbf{K}\cdot\tilde{\nabla}\mathbf{z} \\ \hat{\mathbf{x}}\cdot\mathbf{K}\cdot\tilde{\nabla}\mathbf{z} & \hat{\mathbf{y}}\cdot\mathbf{K}\cdot\tilde{\nabla}\mathbf{z} & 0 \end{bmatrix} \begin{bmatrix} \overline{\tau}_x \\ \overline{\tau}_y \\ \overline{\tau}_z \end{bmatrix}$$

Antisymmetric Elements in GM (1990)
are scaled to overturn fronts, make vertical fluxes
extract PE, and restratify the fluid
equivalent to eddy-induced advection
Q: Same horiz. mixing ($\mathbf{K}$) as Redi?

*Anistropic form due to Smith & Gent 04 *Tensor Form (Griffies, 98)



Could you have guessed it?

Validation: $\mathbf{M}$ Reproduces T-flux w/o negative eigs.

- Even though Temp not used as tracer to find $\mathbf{M}$

$$\overline{\mathbf{v}'T'} = -\mathbf{M}\nabla\overline{T} + O(0.1\%\mathrm{error})$$

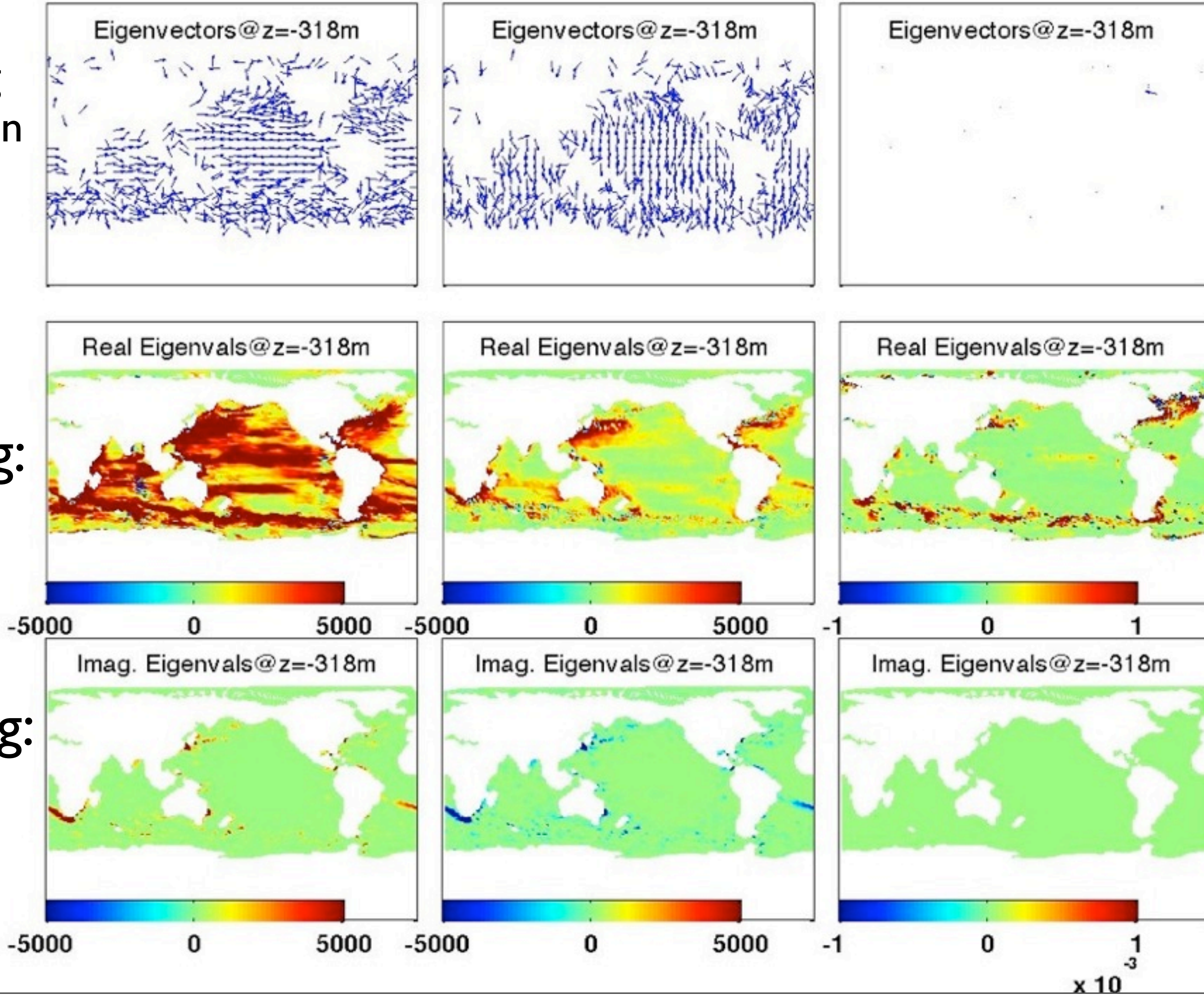
- Typically, diagnoses have problem with $\mathbf{K} < \mathbf{0}$
- Here, below the mixed layer only 6% of gridpoints have negative eigenvalues
- These few negative values are consistent with true nonlocal eddy fluxes

Result: Strong Anisotropy Along/Across Isopycnals

Mixing direction

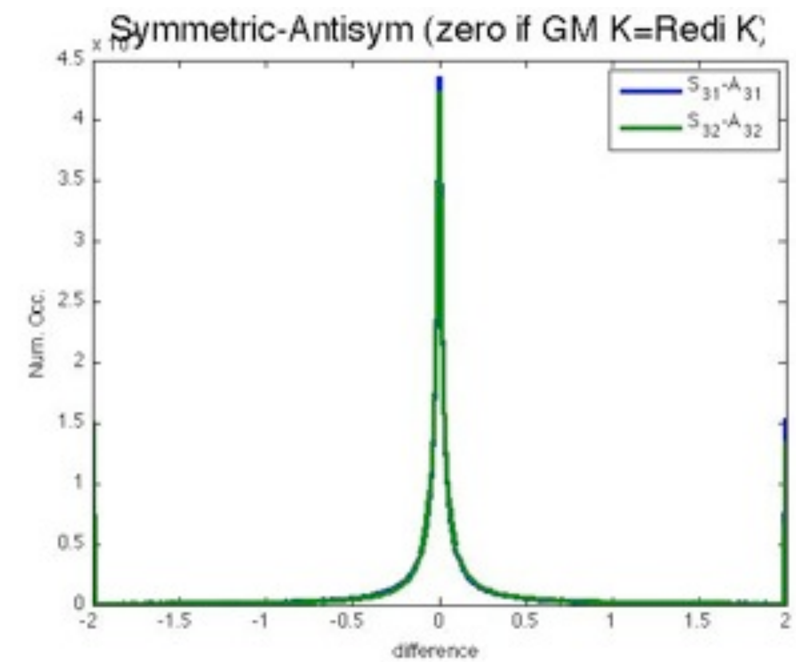
Mixing:

Stirring:

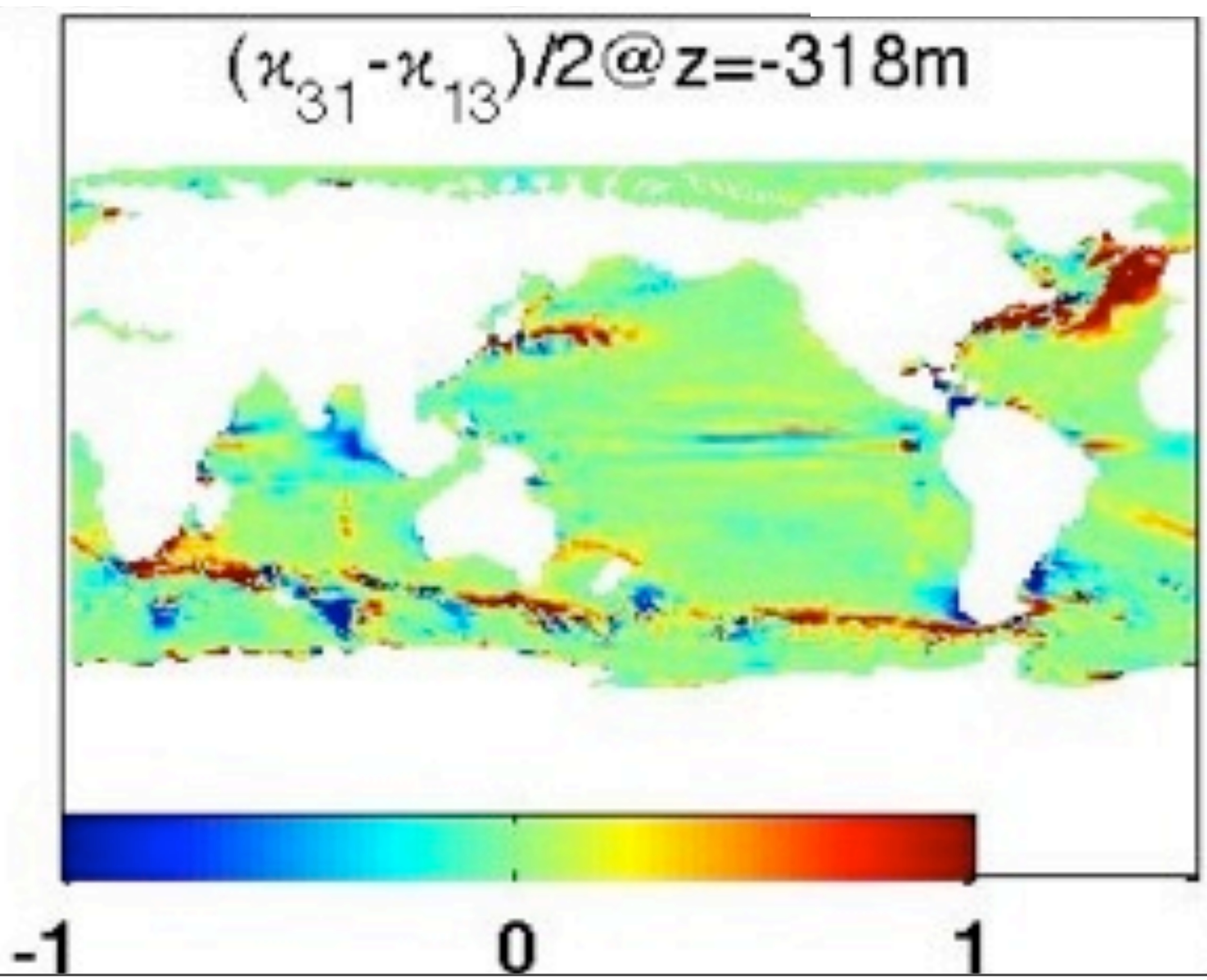


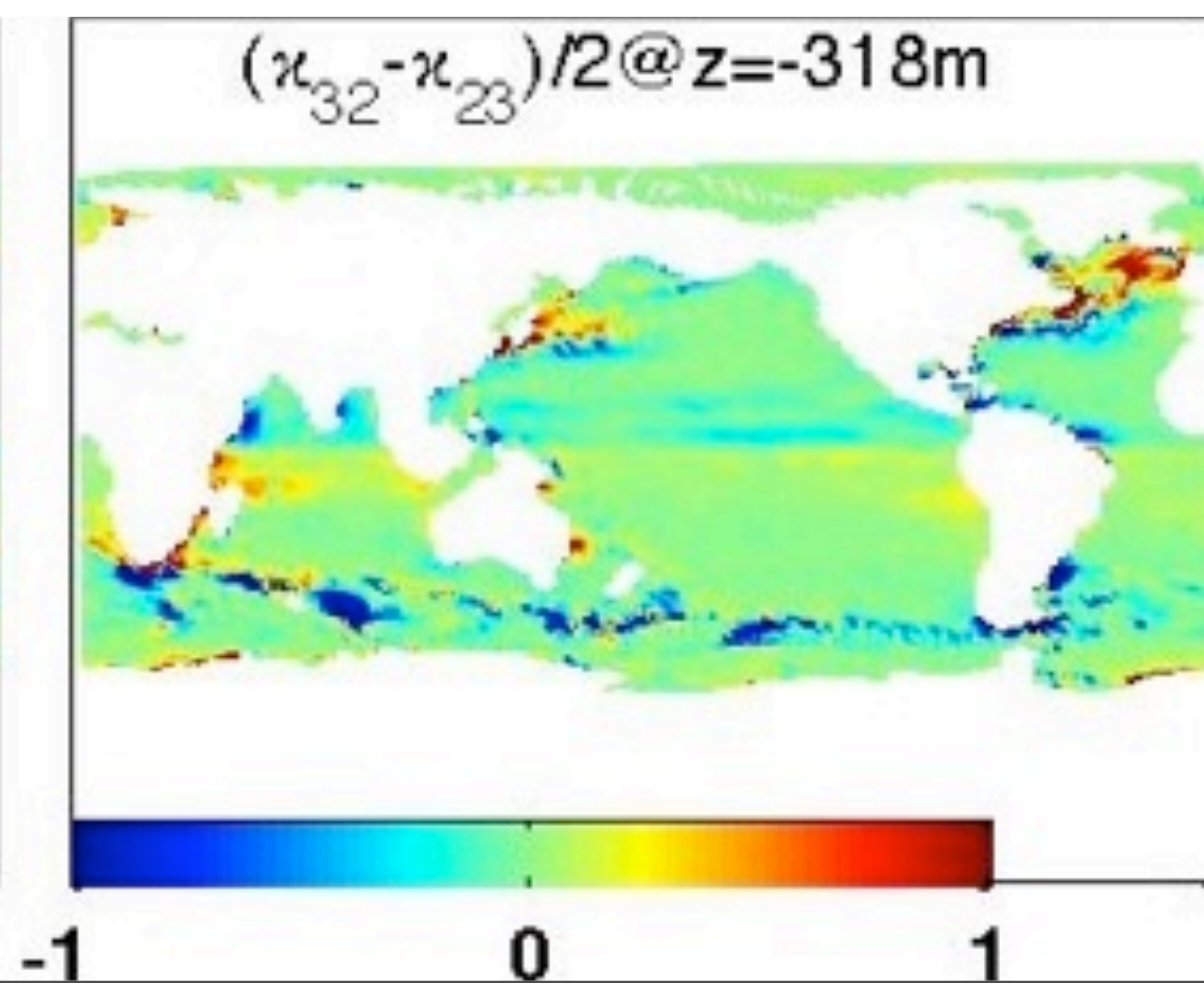
Result:

Redi K=GM K(mostly)



If so these 2 components should match in Sym & Antisym M





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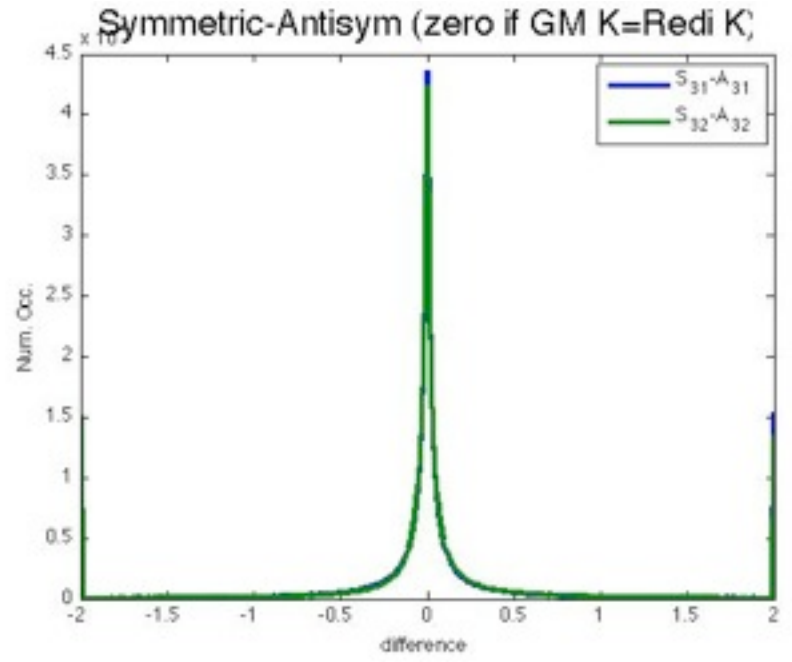
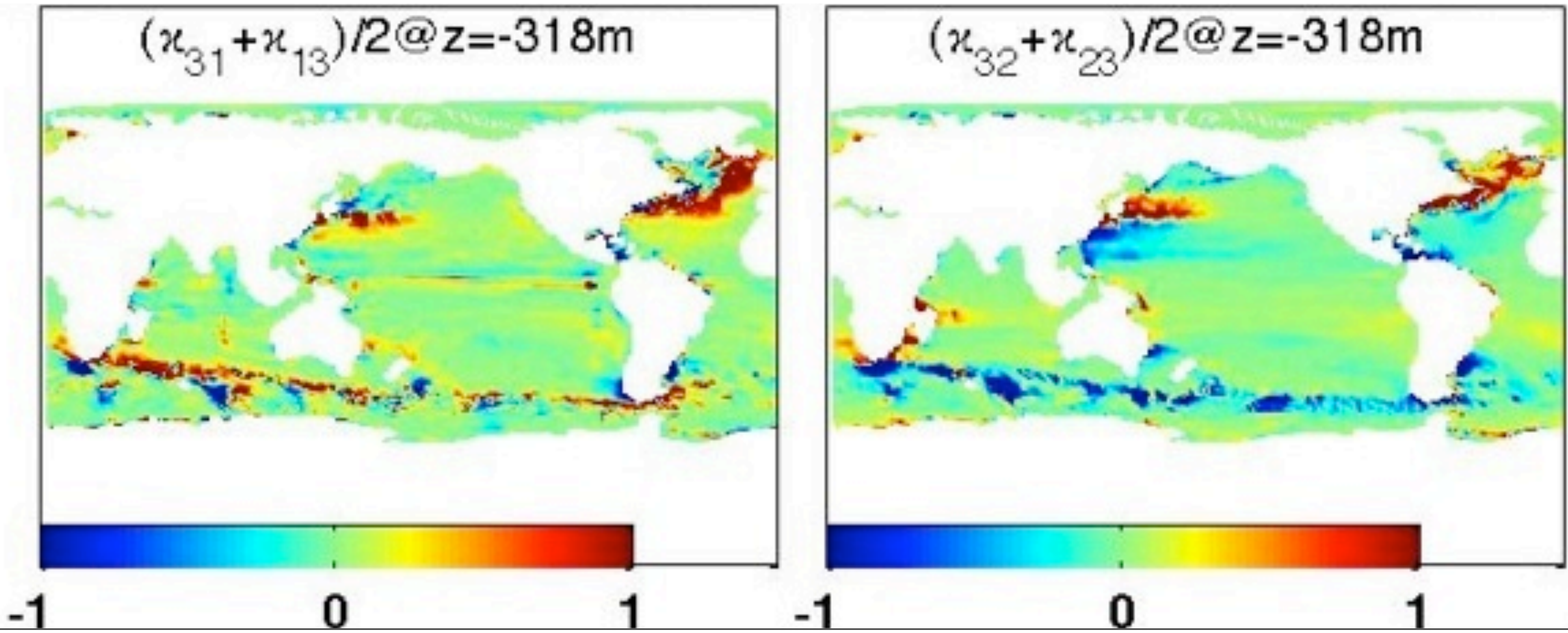


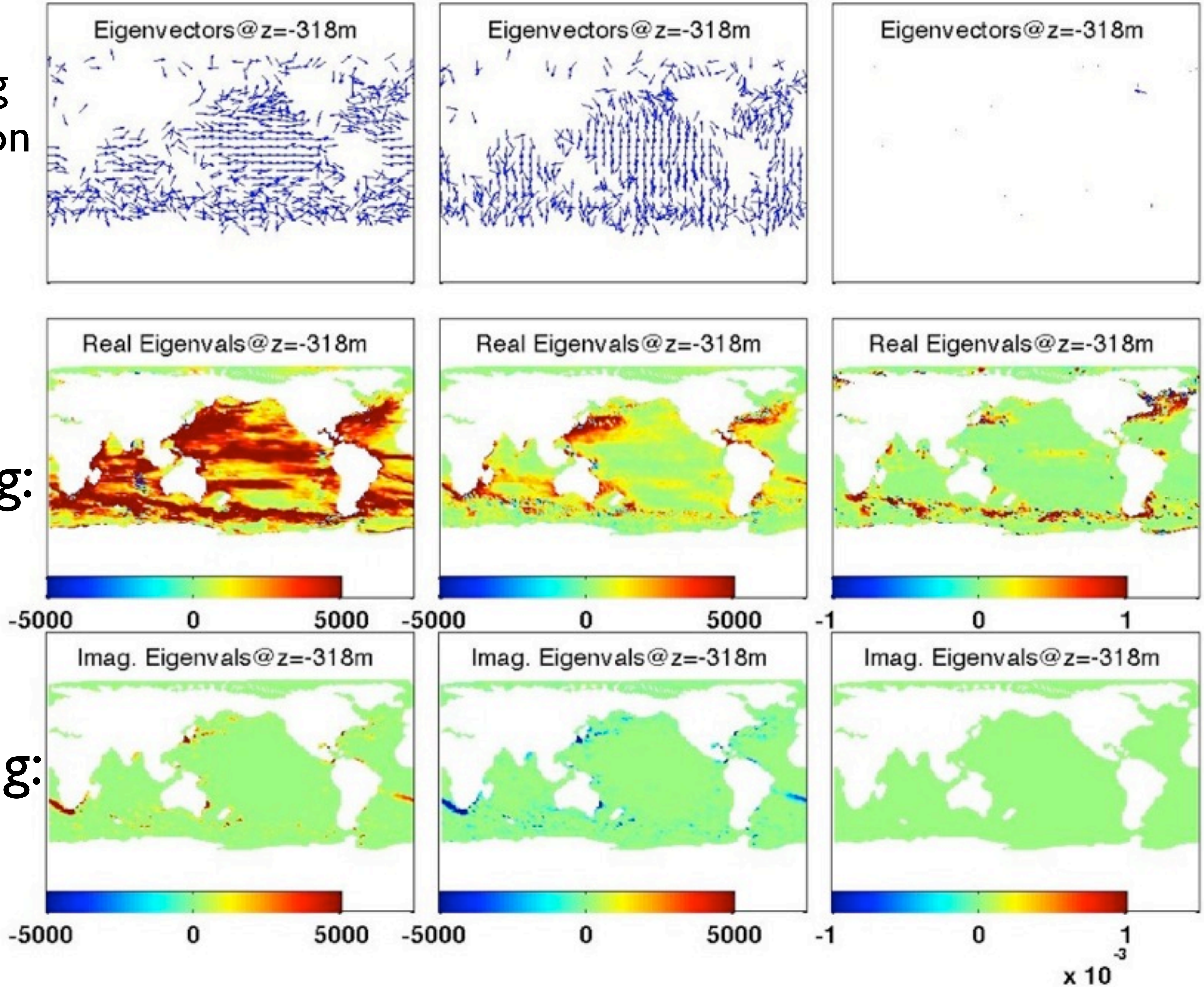


Result: Strong Anisotropy Along/Across PV Grads.

Mixing direction

Mixing:

Stirring:



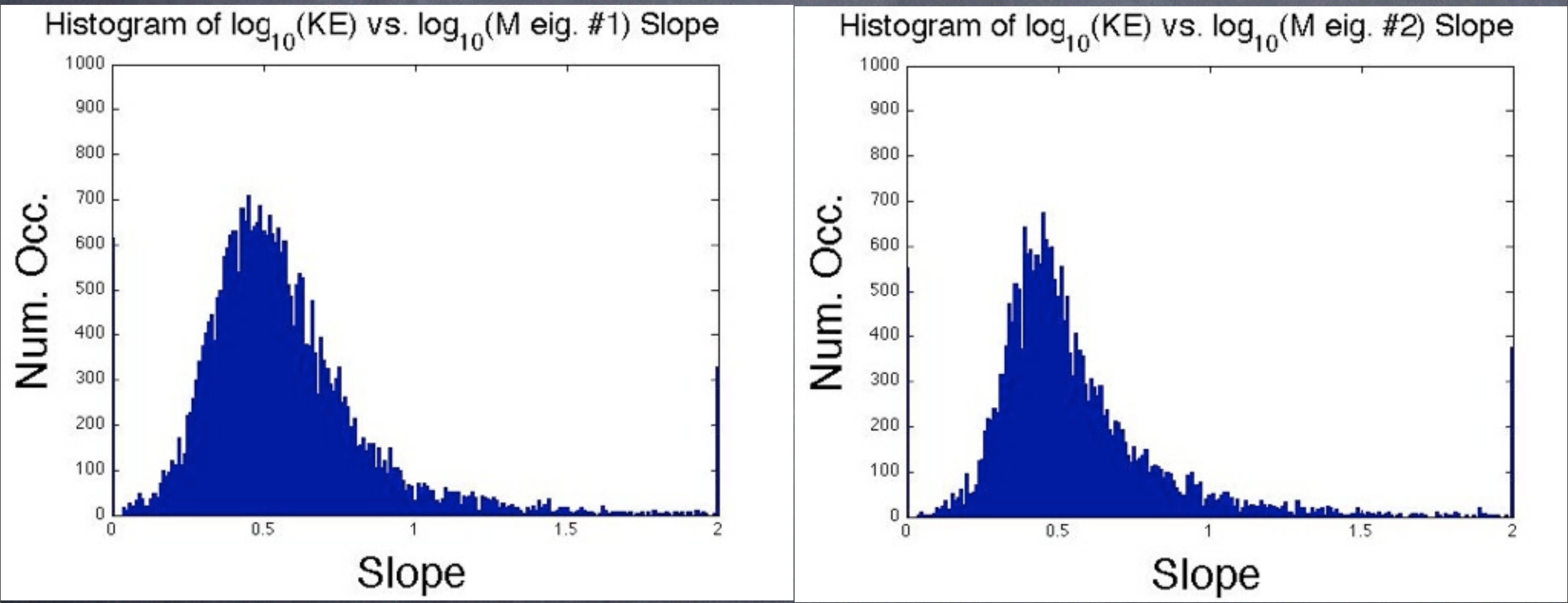
Result: eddy KE-> vertical power law w/ M eigs?

We expect: $$\mathbf{K} \propto \sqrt{\mathbf{EKE}}$$

But what about: $$\mathbf{K} \propto \sqrt{\langle \mathbf{KE} \rangle}$$

Result:
coarse KE-> vertical structure of Mixing

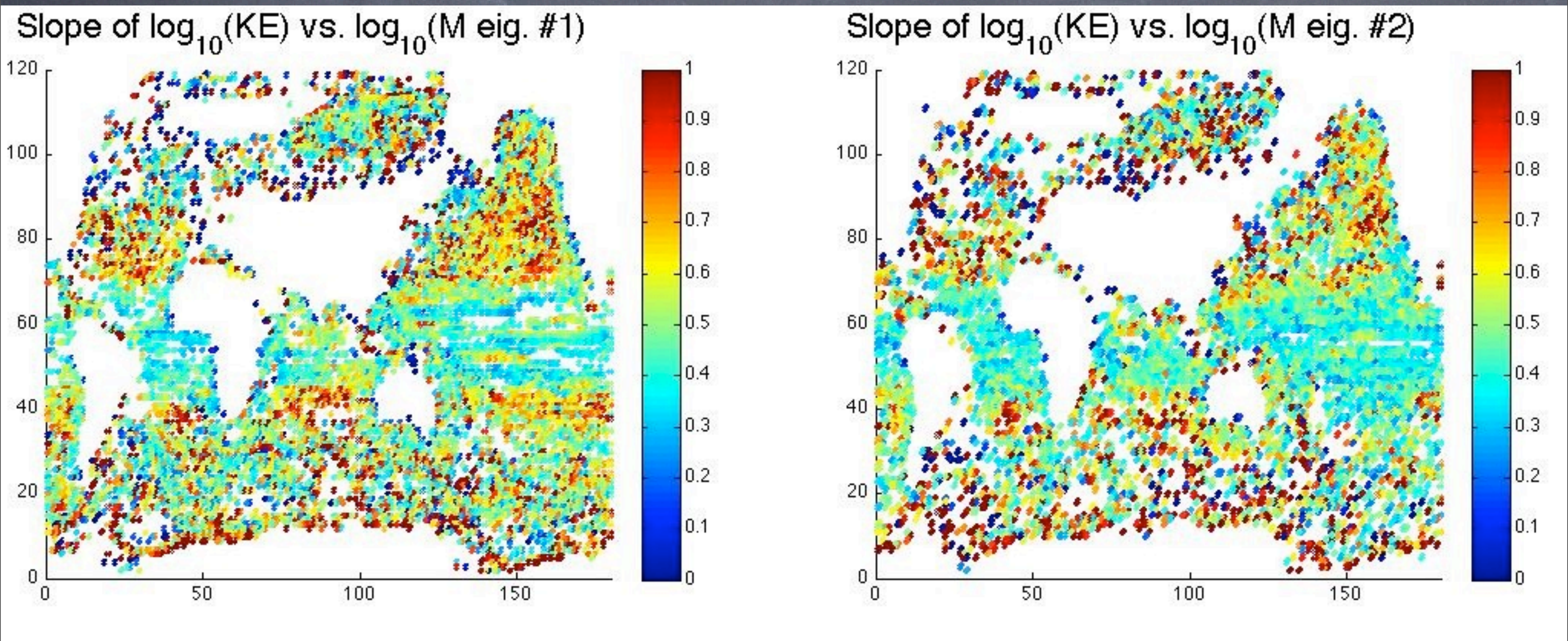
$$\mathbf{K} \propto \sqrt{\langle \mathbf{KE} \rangle}$$



You don't need to know EKE!

Result:
power law not 'random'

$$\mathbf{K} \propto \sqrt{\langle \mathbf{KE} \rangle}$$



However, can probably do better!

Slopes not random.

Coarse-graining--A matter of philosophy

- It would be nicest if when we diagnosed $\mathbb{M}$ it agreed with a theory
- However, if theory requires, e.g., scale separation, then it likely won't agree
- But, the approach here gives us the answer we need ($\mathbb{M}$), even if it's not the answer we want.
- Plumb & Mahlman's work suffers from the same theoretical issues--McDougall is working on it!

Conclusions Mesoscale

- Direct diagnosis of $\mathbf{M}$ is a valuable tool
- Gives validated tracer fluxes without negative eigenvalues or rotational issues
- Still, unfamiliar interpretation
- No clean comparison to theory (GLM? Scale Separation? Ensemble? Stochastics?)
- More to come!
  - (e.g., Ferrari et al '08 vs. Ferrari et al. '10)