Beyond GM
A Symposium on Oceanic Eddy Fluxes

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NCAR CGD Symposium, Th. 3/4/2010 3-5PM

he Character of the Mesoscale

100 km

(Capet et al., 2008)

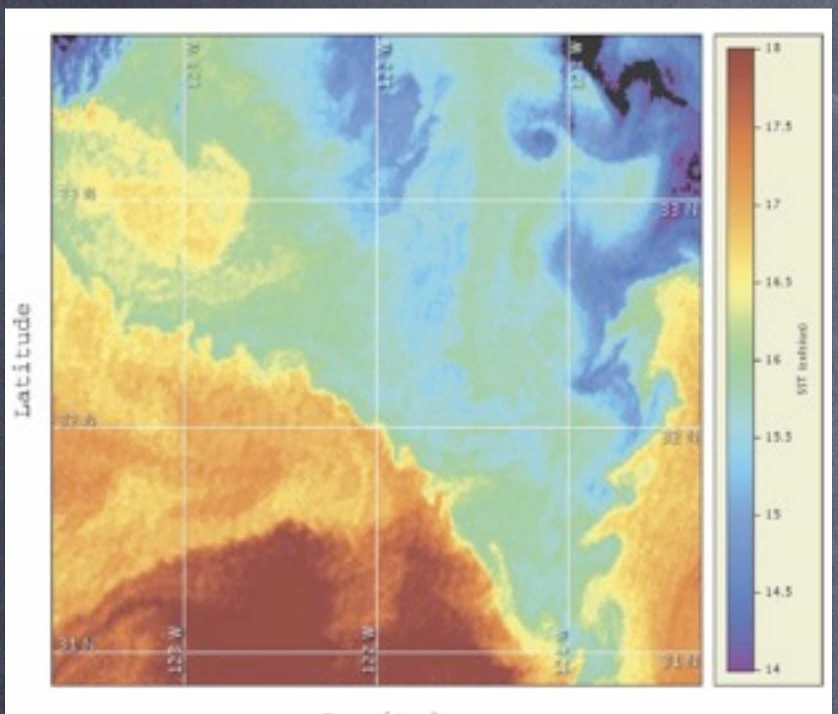
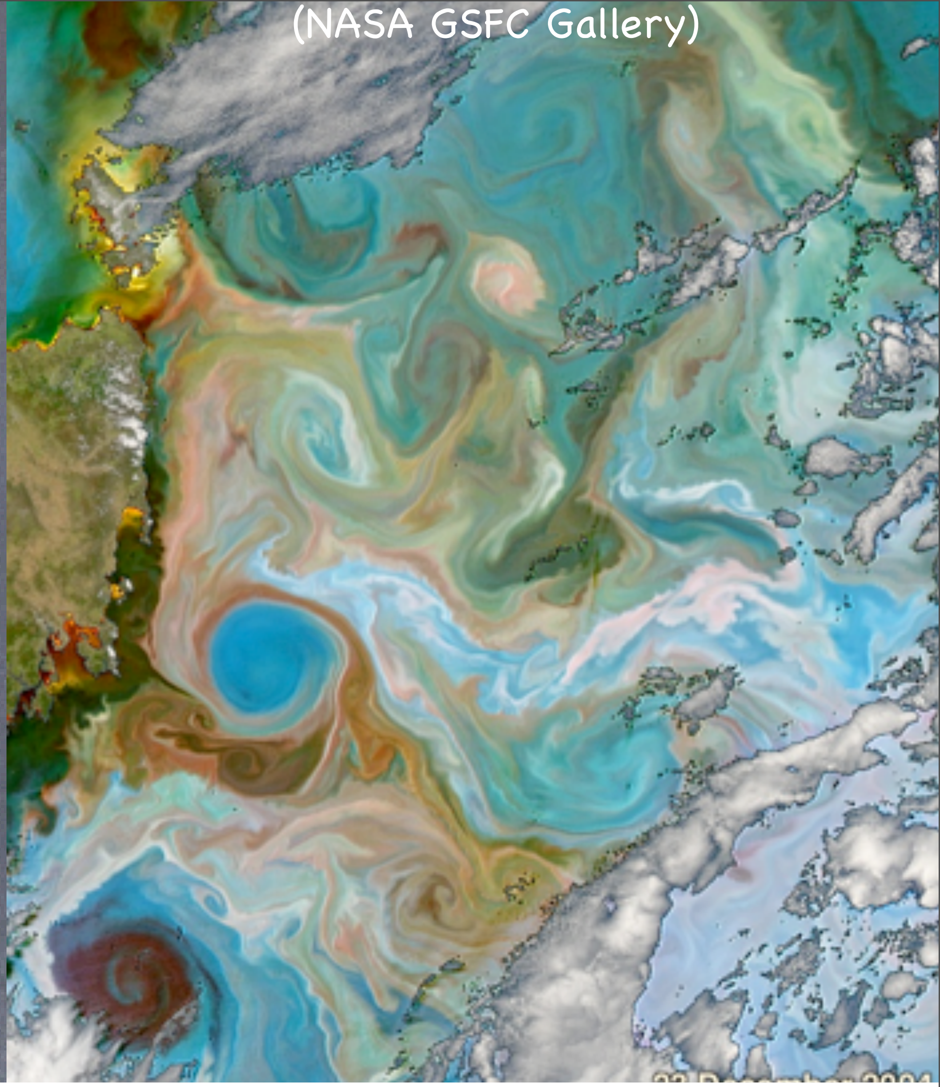


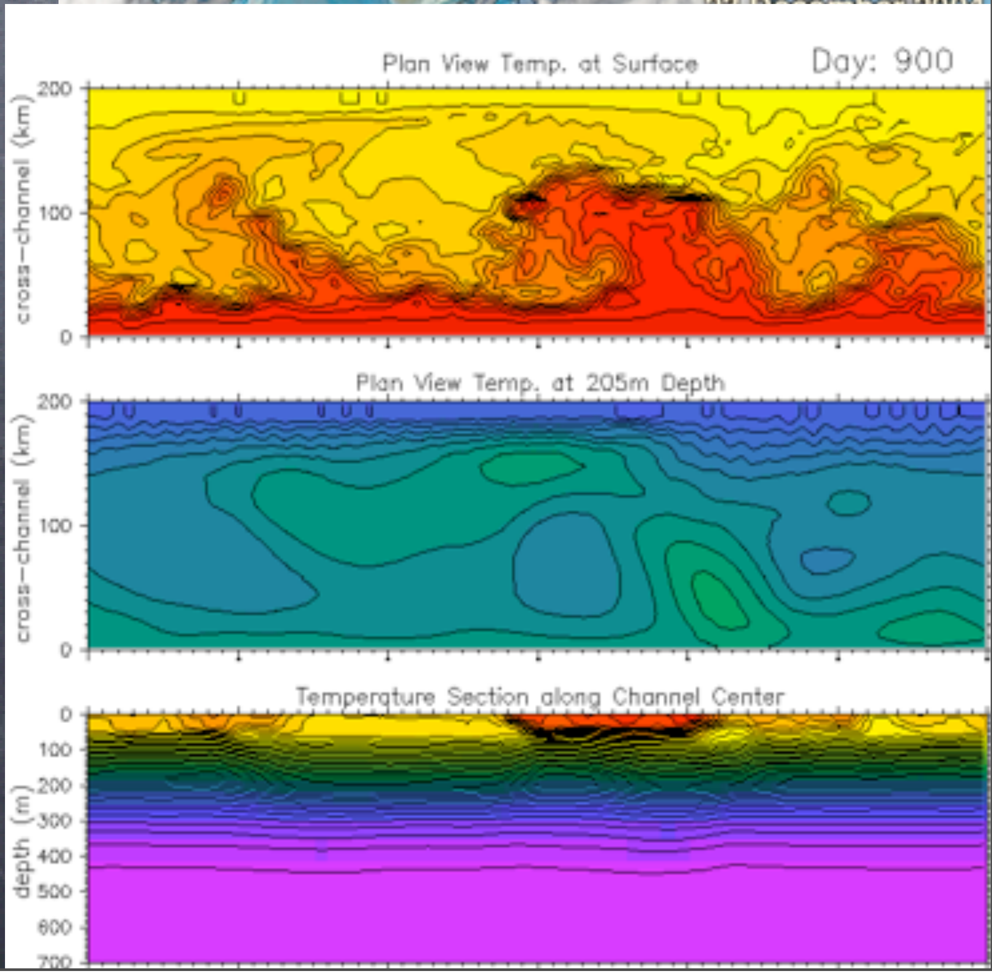
Fig. 16. Sea surface temperature measured at 1832 UTC 3 Jun 2006 off Point Conception in the California Current from CoastWatch (http://coastwatch.pfeg.noaa.gov). The fronts between recently upwelled water (i.e., 15°–16°C) and offshore water (≥17°C) show submesoscale instabilities with wavelengths around 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 mainly baroclinic & barotropic instability. Parameterizations of baroclinic instability (GM, Visbeck...).

(NASA GSFC Gallery)

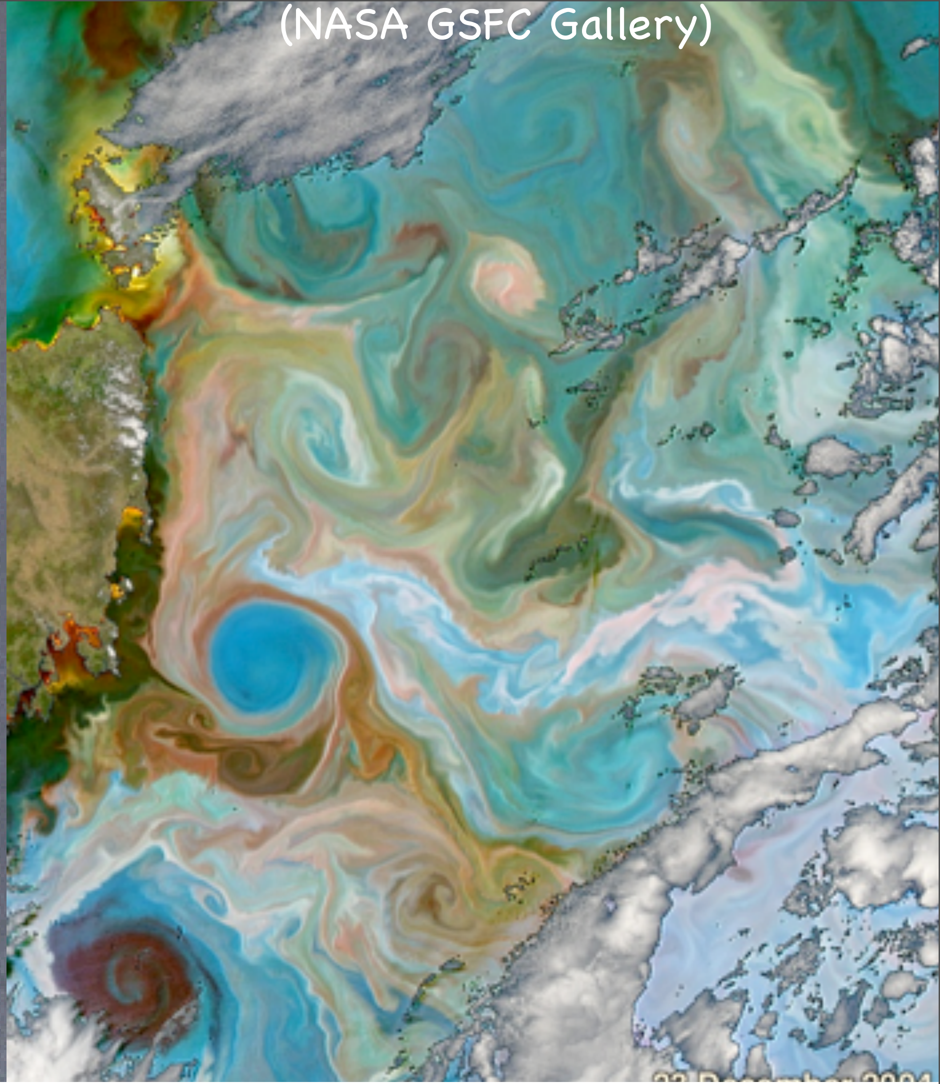




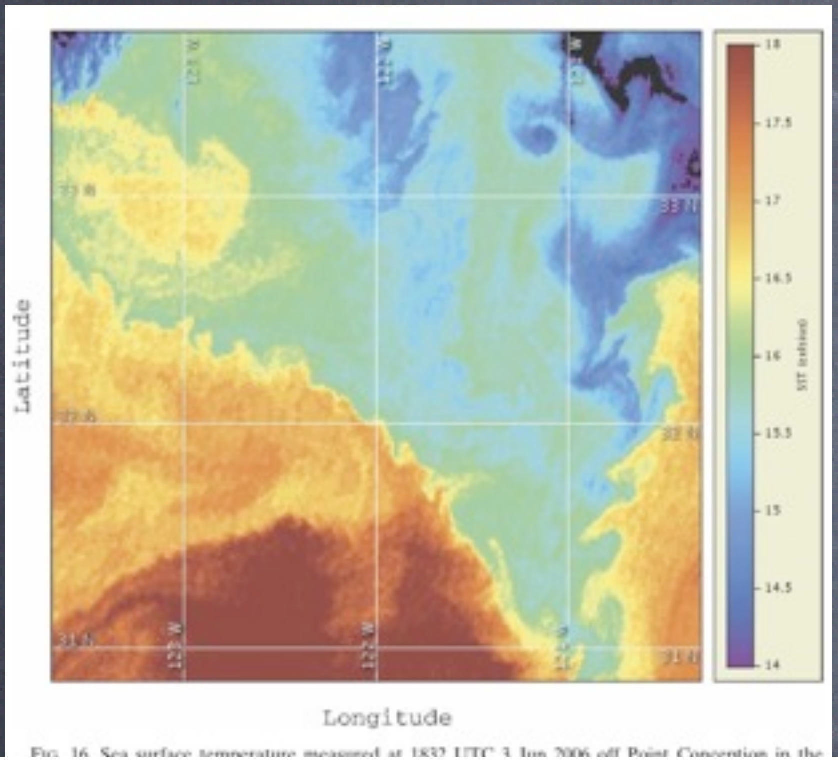
The Character of the Submesoscale

10 km

(NASA GSFC Gallery)

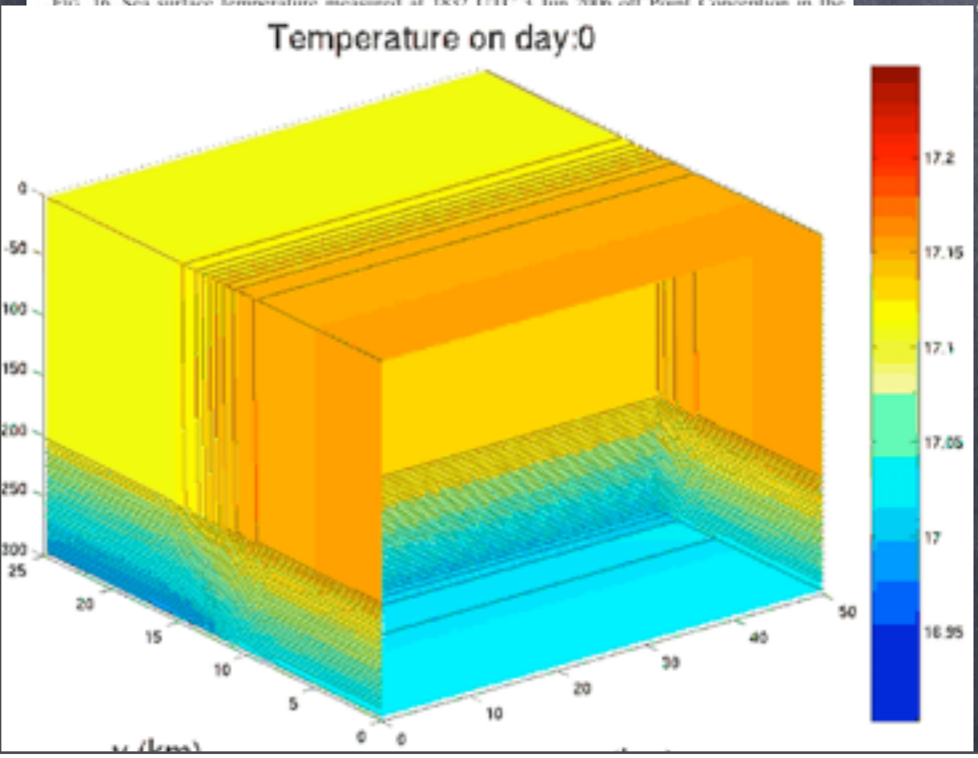


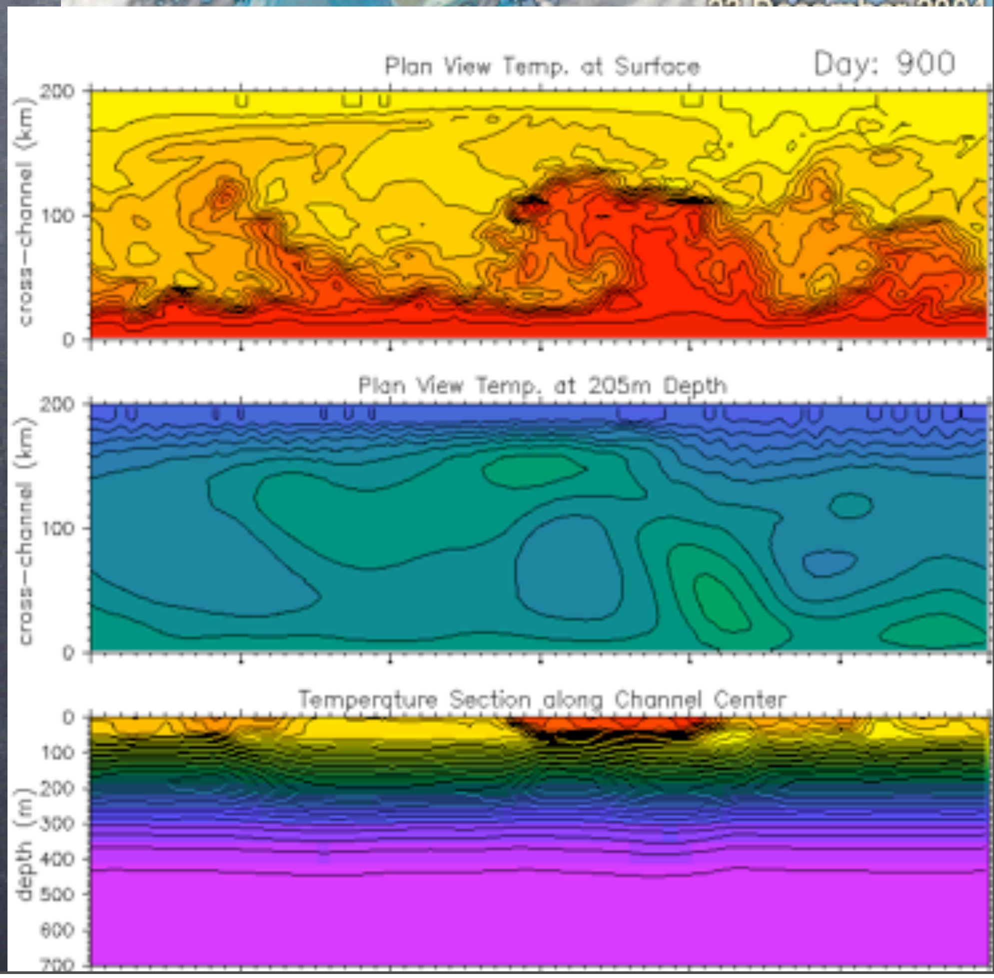
(Capet et al., 2008)



- 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...).





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)

A bit of theory...

- Dukowicz & Smith (97) and Smith (99) lay out the form of a stochastic, adiabatic relocation of particles
- The resulting Fokker-Planck Equation for the probablility density of the particles gives a K and a v, which are closely related to the Lagrangian mean transport and the diffusion of probability.

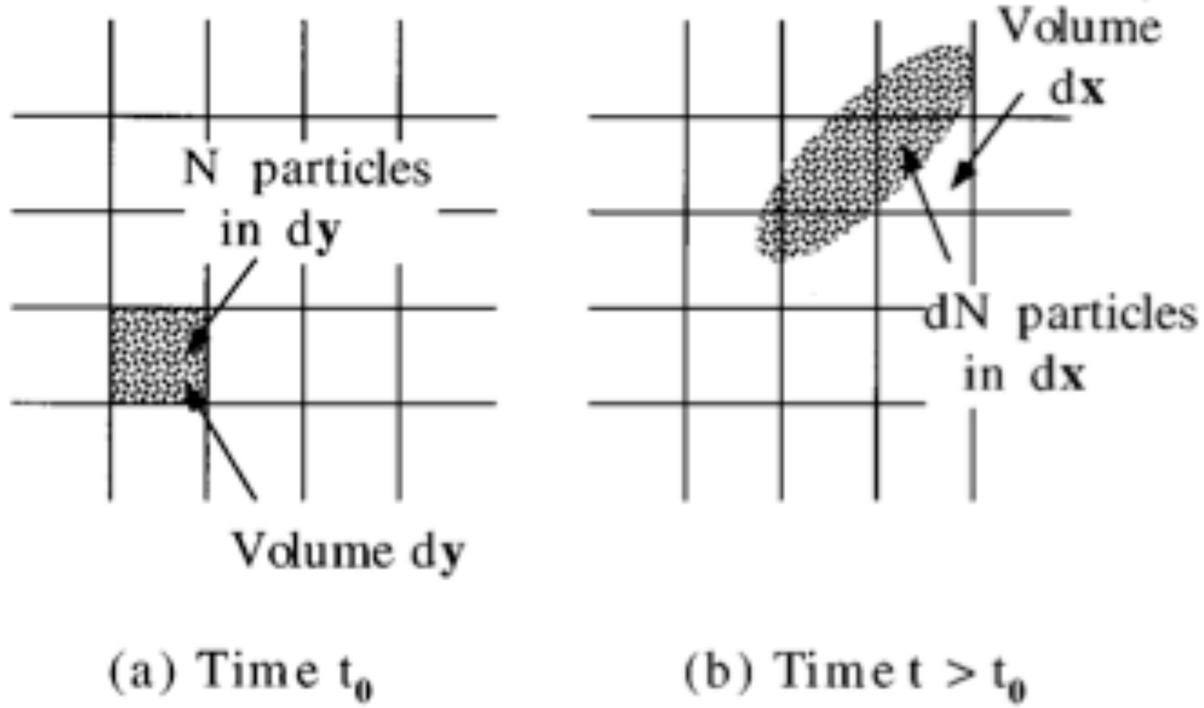


FIG. 1. A schematic illustration of the turbulent transport of a cloud of particles originating in dy at time t_0, and the fraction dN/N which arrives in dx at a later time t.

$$\partial_t p(\mathbf{x}, t|\mathbf{y}, t_o) + \boldsymbol{\nabla}\cdot \mathbf{U} p(\mathbf{x}, t|\mathbf{y}, t_o) = \boldsymbol{\nabla}\cdot\mathbf{K}\cdot\boldsymbol{\nabla} p(\mathbf{x}, t|\mathbf{y}, t_o) \qquad (50)$$

$$\mathbf{U} = \mathbf{v} - \boldsymbol{\nabla}\cdot\mathbf{K} \qquad (51)$$

$$\mathbf{v}(\mathbf{x},t) = \lim_{\Delta t\to 0}\frac{1}{\Delta t}\int d\mathbf{x}'(\mathbf{x}'-\mathbf{x})p(\mathbf{x}', t+\Delta t|\mathbf{x}, t) \qquad (52)$$

$$\mathbf{K}(\mathbf{x},t) = \lim_{\Delta t\to 0}\frac{1}{\Delta t}\int d\mathbf{x}'\frac{1}{2}(\mathbf{x}'-\mathbf{x})(\mathbf{x}'-\mathbf{x})p(\mathbf{x}', t+\Delta t|\mathbf{x}, t). \qquad (53)$$

Since the pdf is positive, it is clear from (53) that **K** is a 2×2 symmetric positive-definite tensor. We will refer to **v** as the Lagrangian mean velocity, although this identification is not exact (see Bennett 1996, p. 7). In (52)

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

General Form

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

- Small slope approximation converts the horizontal stochastic reshuffling along neutral surfaces to a GM+Redi like form
- Could vary tracer by tracer, or active tracer vs. passive, etc. In practice we don't let it.
- Using the same form for all tracers amounts to 'labeling' fluid with tracer, neglecting sources, etc.

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

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

Monday, June 13, 2011

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

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)

An example of what a (submeso) subgrid parameterization looks like

with FLOW DEPENDENT $\mathbb{M}$:

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

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

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

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

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

Sym Part=Anisotropic* Redi

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

AntiSym Part=Anisotropic* GM

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

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

Need a Natural, Mesoscale Eddy Environment to Test Out:

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

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

3 equations/tracer

9 unknowns ($\mathbf{M}$ components)

BY USING 3 or MORE TRACERS, can determine $\mathbf{M}$!!!

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

No assumptions about symmetry required.

Need a Natural, Mesoscale Eddy Environment to Test Out:

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

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

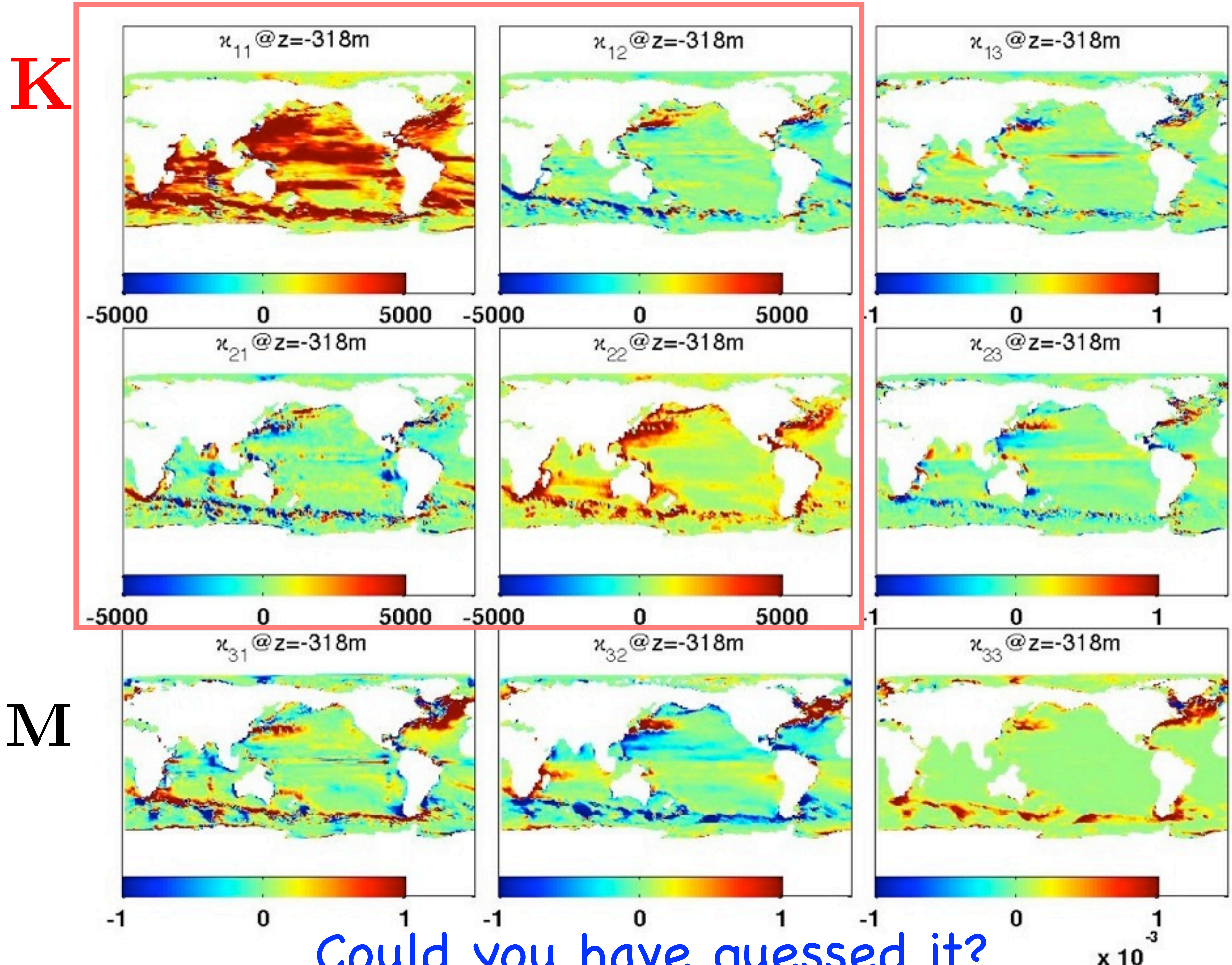
With John Dennis & Frank Bryan, we took a POP0.1° Normal-Year forced model (yrs 16-20 for anal.)

Added 9 Passive tracers--restored to x,y,z @ 3 rates

Kept all the eddy fluxes for passive & active tracers

Coarse-grained to 2°, passive tracers to find $\mathbf{M}$

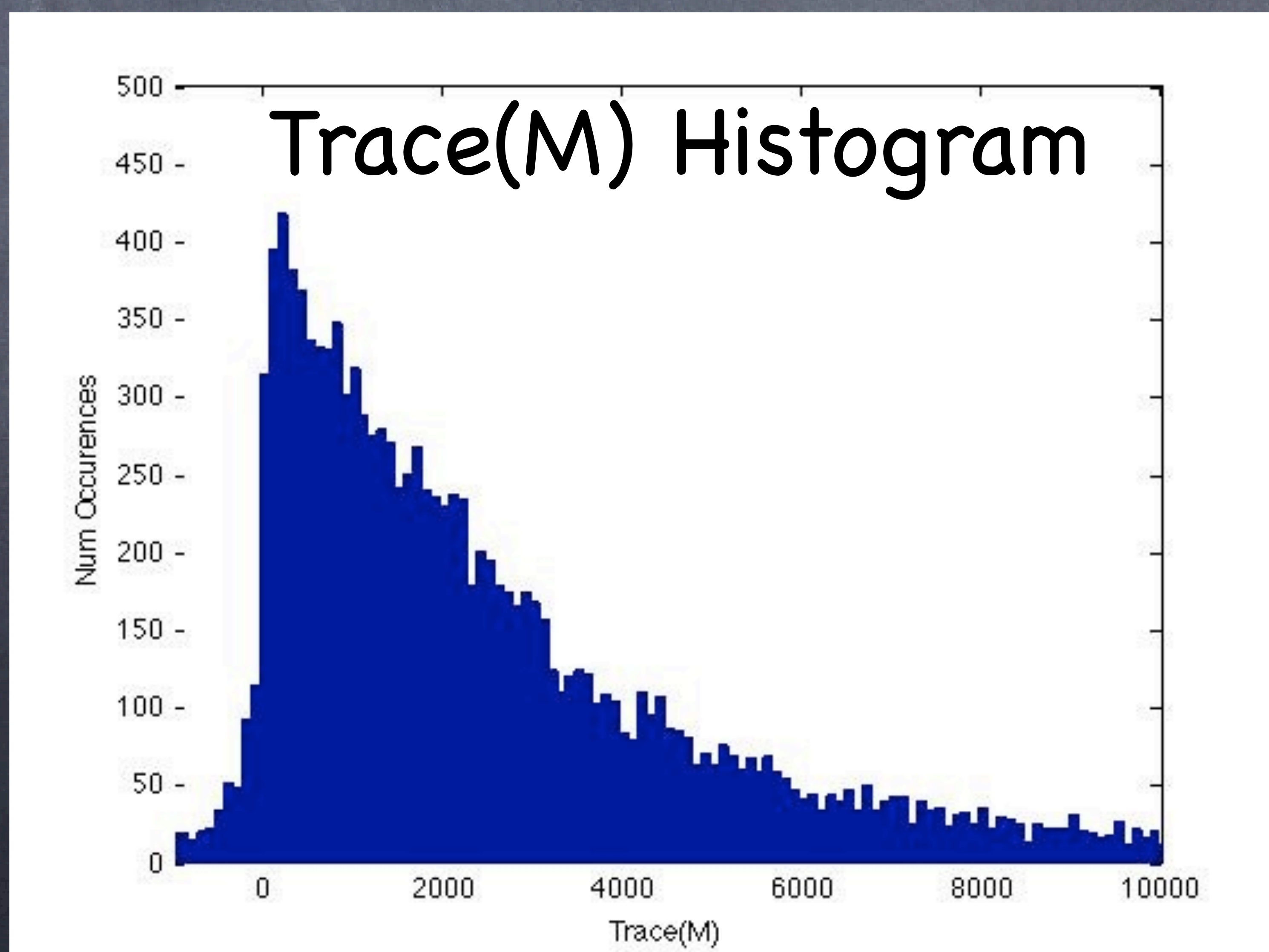
Monday, June 13, 2011



Could you have guessed it?

Use a Natural, Mesoscale Eddy Environment to Test Out:

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



Hor. Diffusivity is roughly Trace(M)/2

Peak of Diffusivity near 250 m^2/s

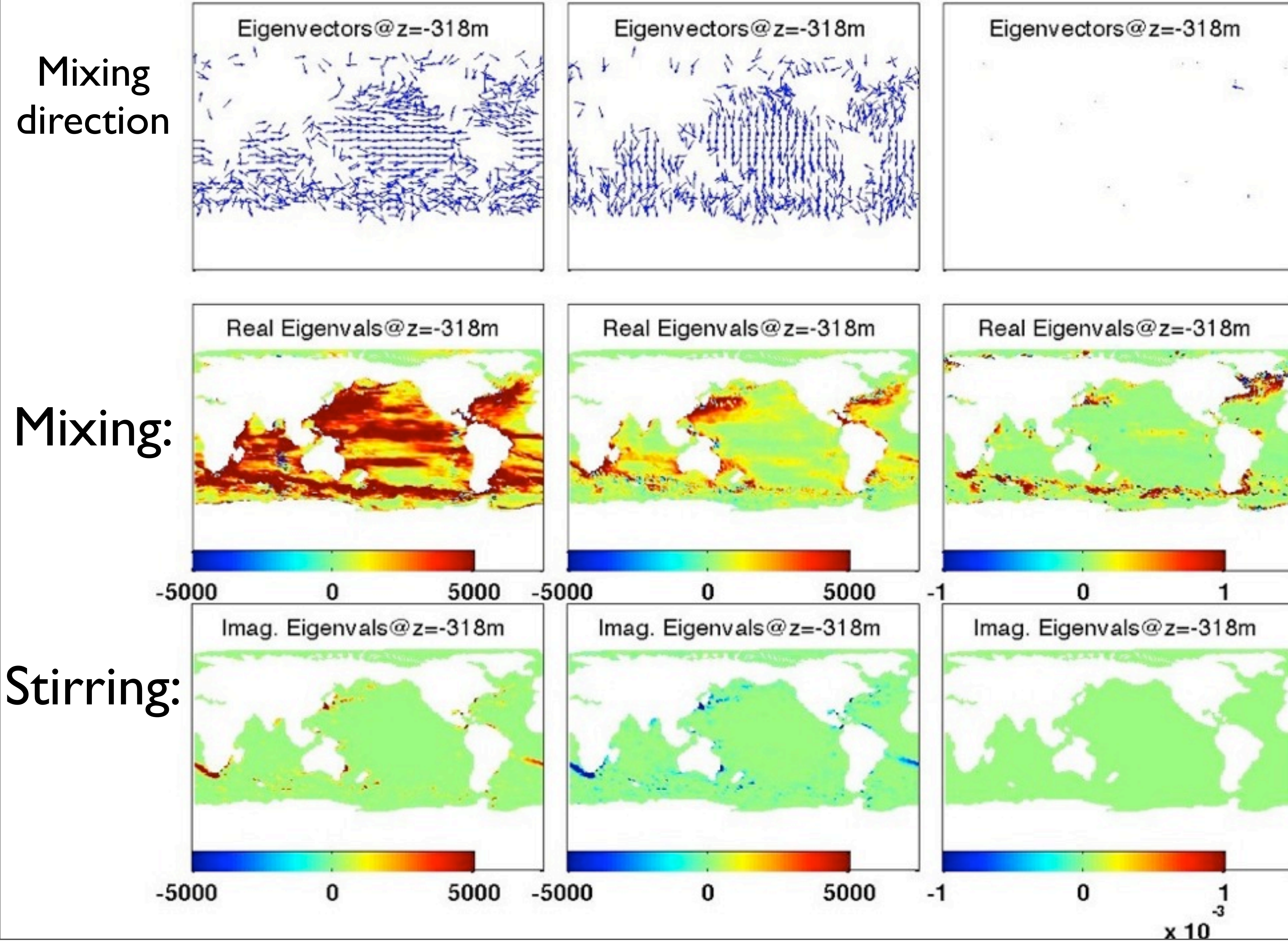
Median Diffusivity near 1000m^2/s

<6% negative

Interpretation?

- Isoneutral diffusion or 'mixing': symmetric $\mathbf{K}$ with real, positive eigenvalues (neg->nonlocal)
- The eigenvalues of $\mathbf{M}$ are related, except there is one more involving the neutral to z coordinate conversion (in S&G theory, at least)
- The eigenvectors give the direction of the mixing associated with each eigenvalue
- Antisymmetric $\mathbf{K}$ & $\mathbf{M}$ are stirring/overturning by an eddy-induced (quasi-stokes) streamfunction--non-orthogonal eigenvects and imaginary eigenvalues possible!

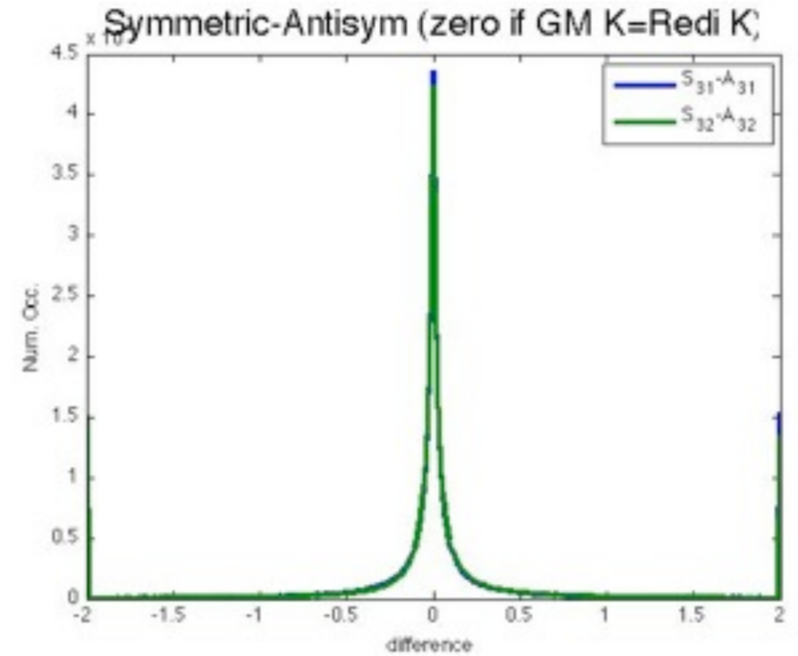
Result: Strong Anisotropy Along/Across Isopycnals

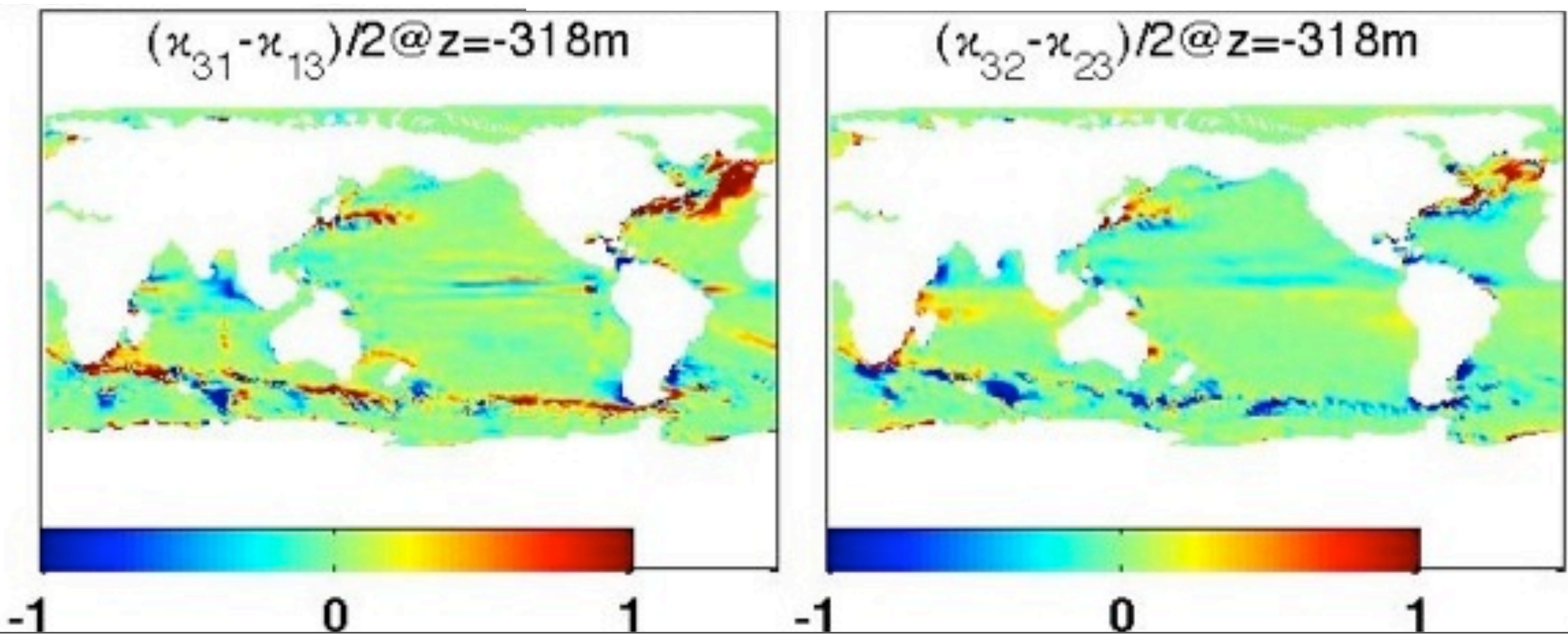


Result:

Redi K=GM K(mostly)

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





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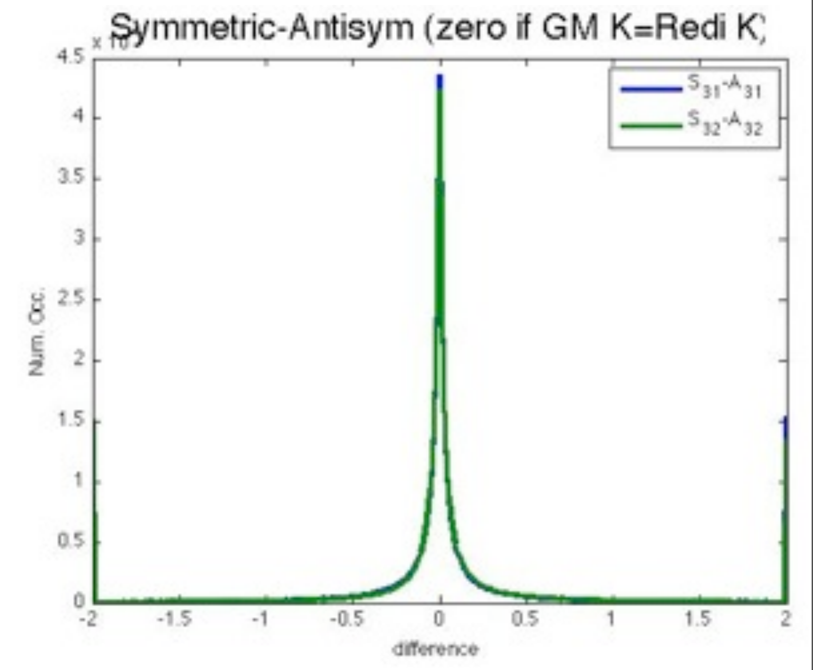
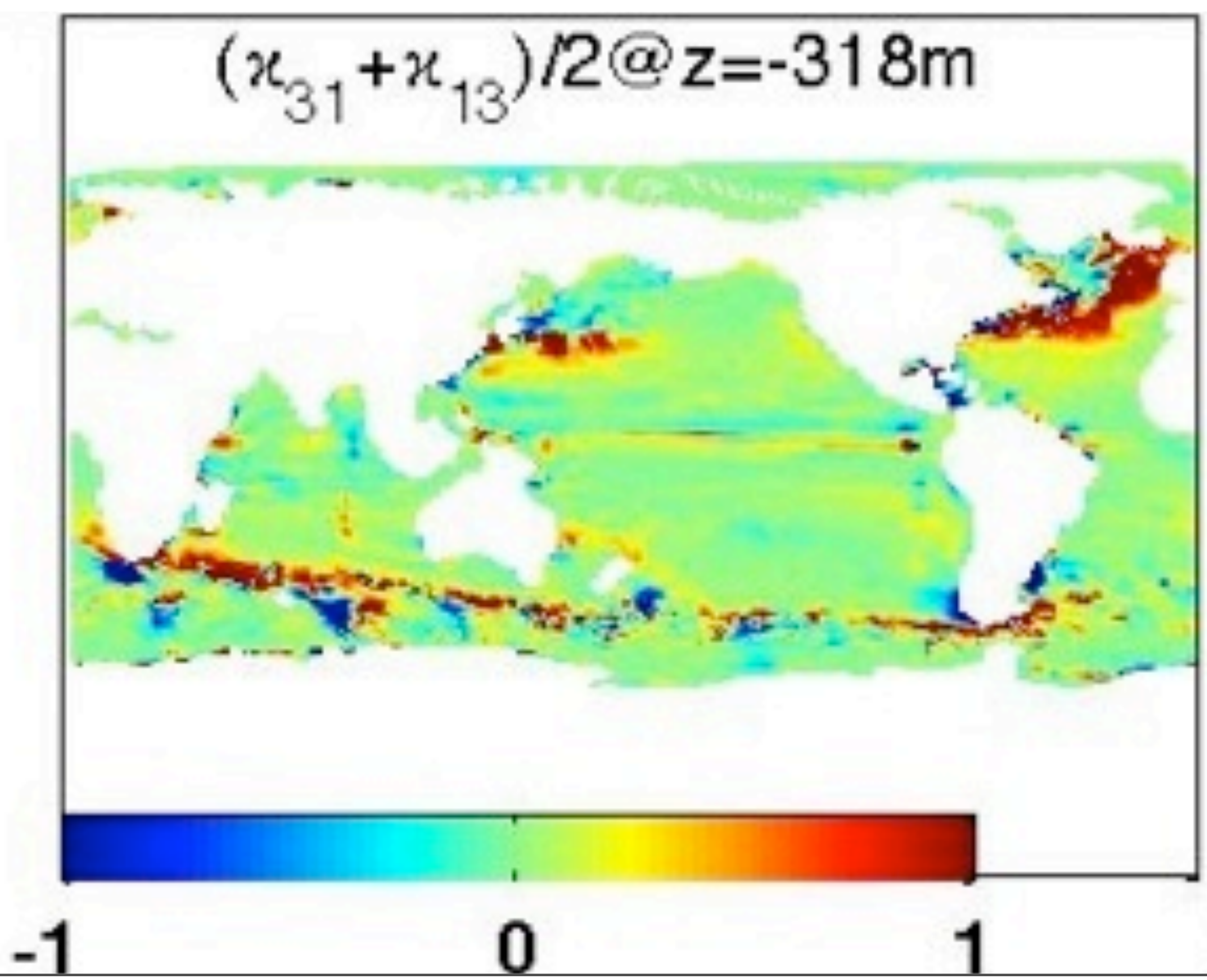
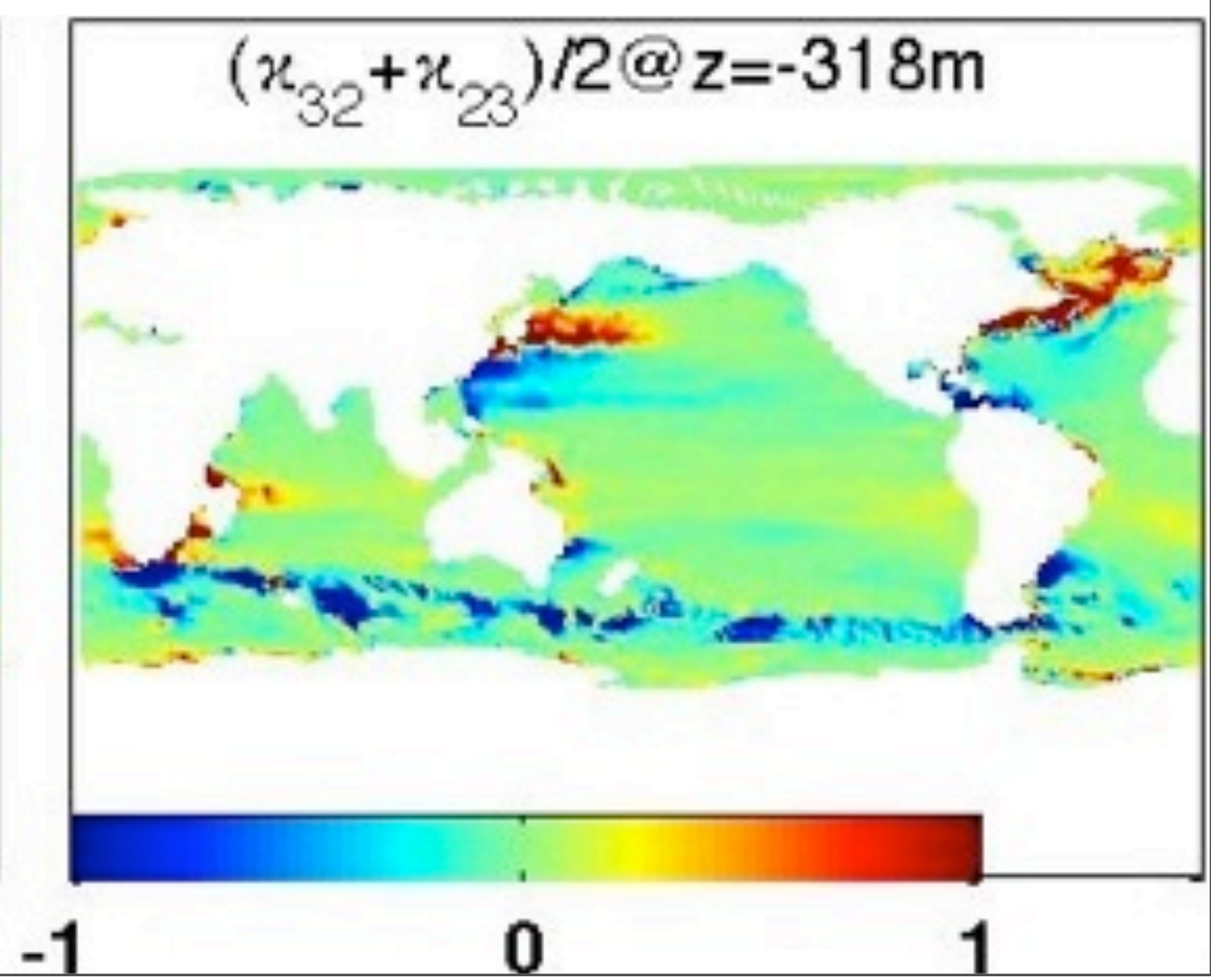
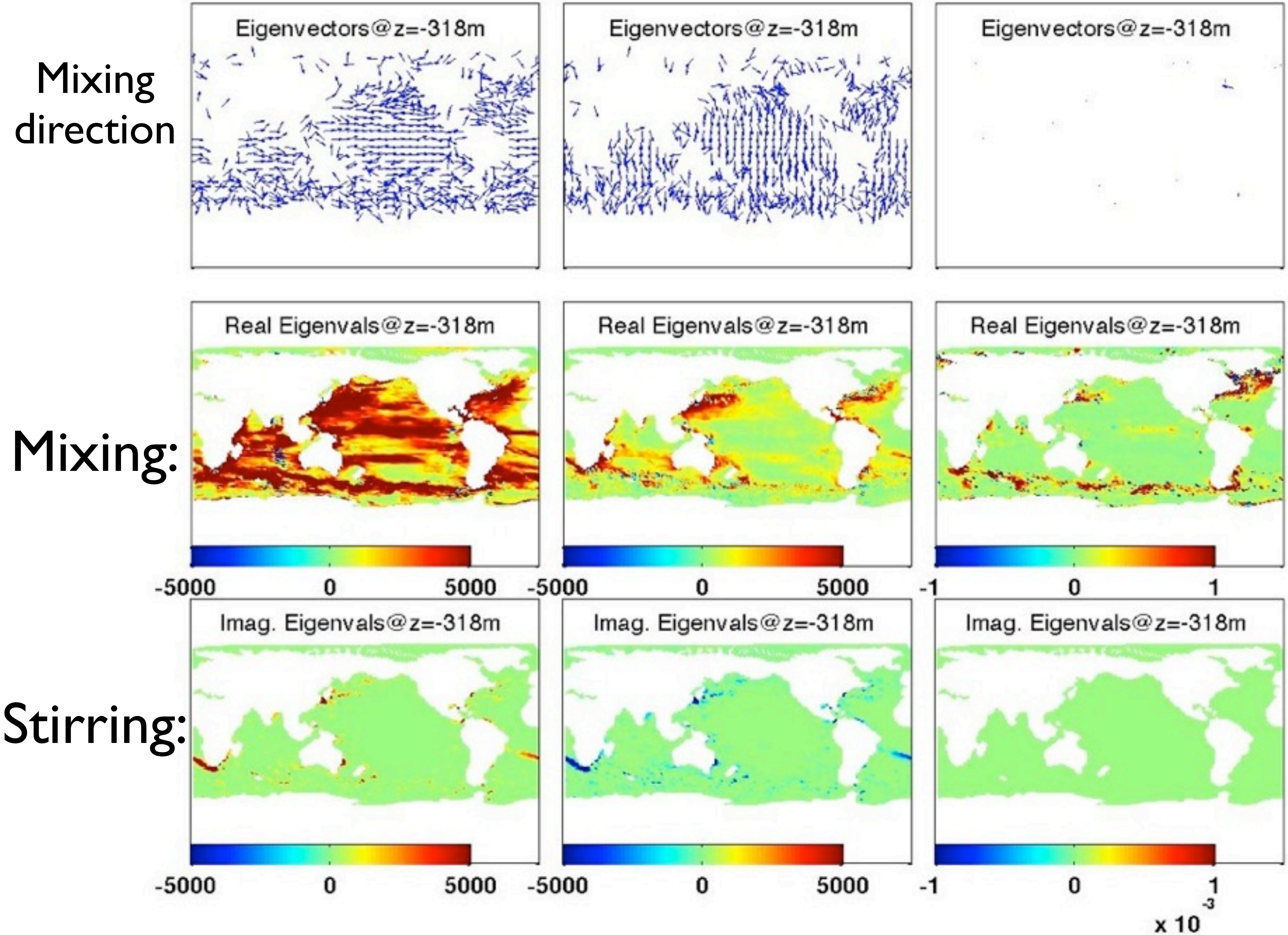






Result: Strong Anisotropy Along/Across PV Grads.



Comparisons with Marshall et al.

Realistic negative eigs. vs. spurious?

Ferreira, Marshall, Heimbach 05

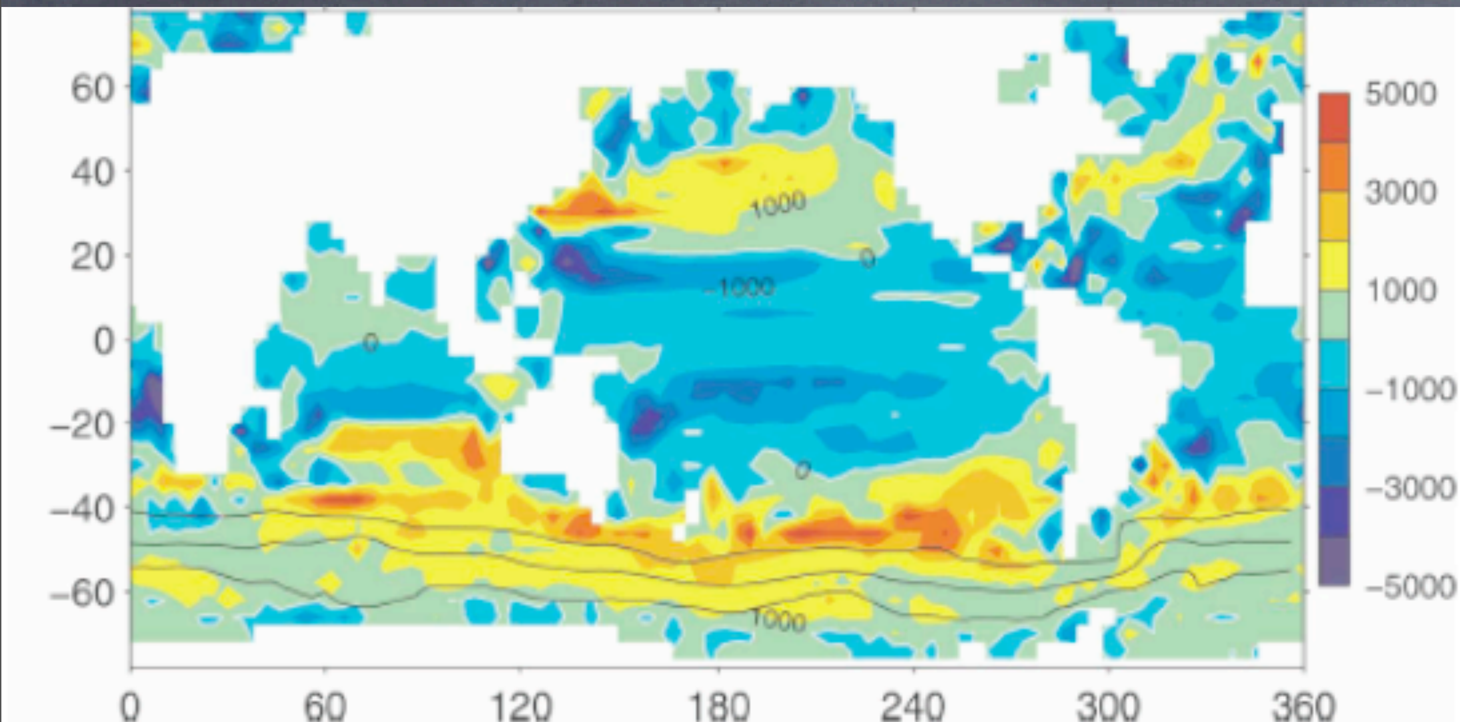
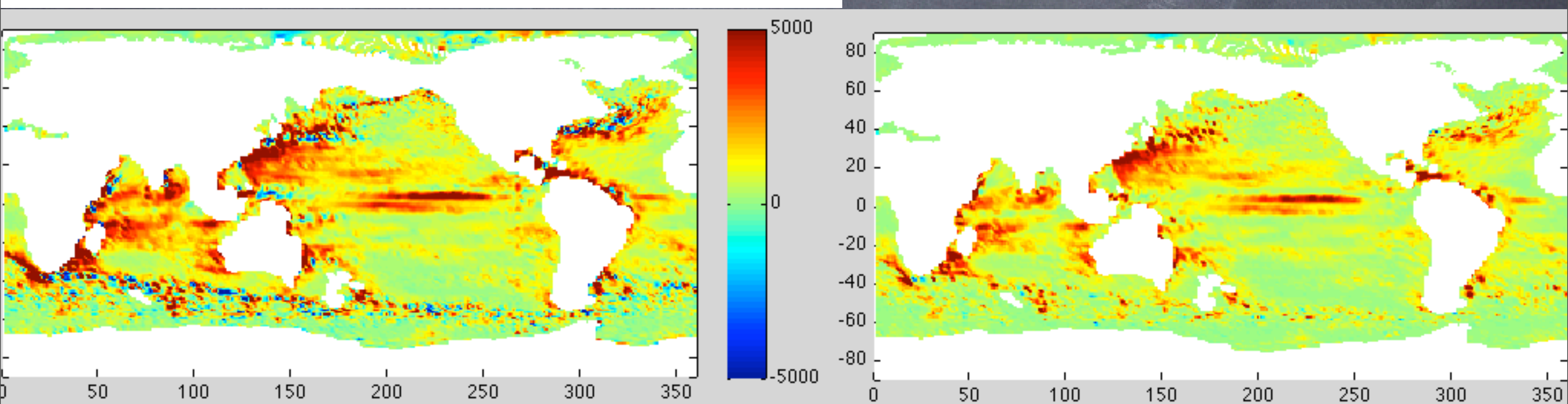
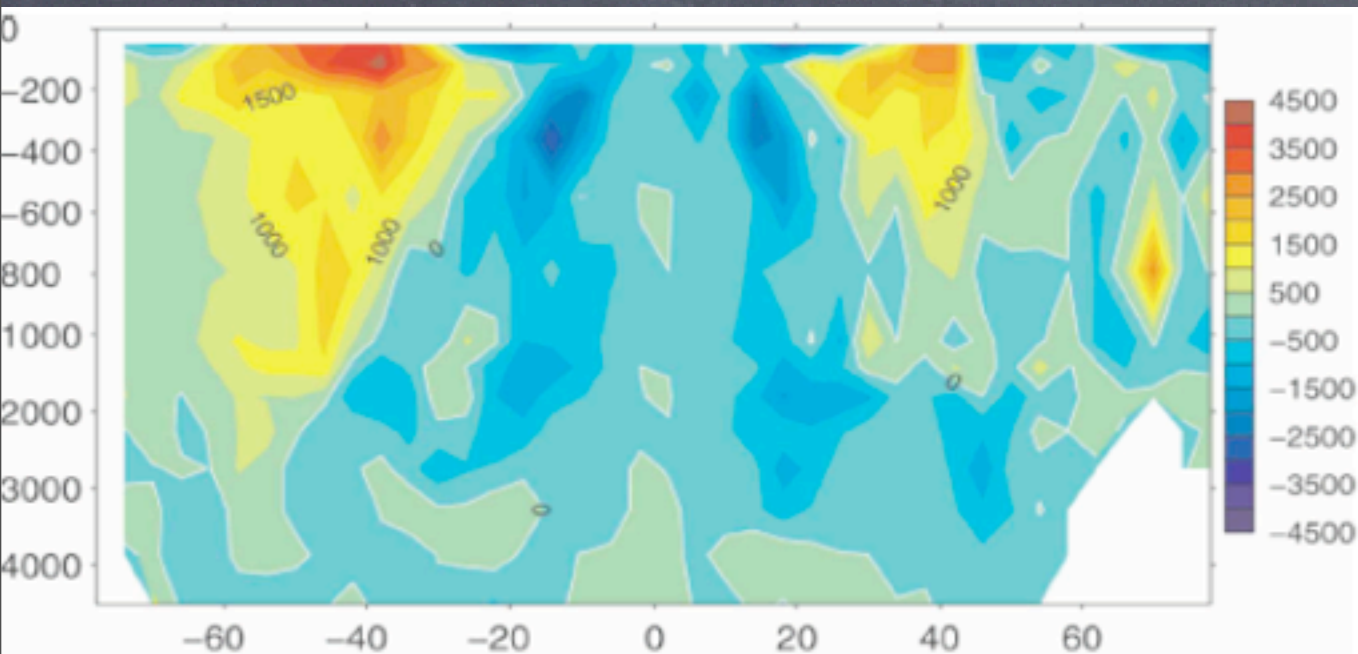


FIG. 12. Inferred horizontal eddy diffusivity κ ($m^2 s^{-1}$): (top) zonal mean and (bottom) vertical mean over the thermocline (0–1200 m). The contour intervals are (top) 500 and (bottom) 1000 $m^2 s^{-1}$. The thick line indicates the zero contour. Also indicated in the bottom panel are the 10-, 70-, and 130-Sv contours of the barotropic streamfunction.



Re(2nd eigenvalue) (2nd eigenvalue of symmetric M)

Comparisons with Marshall et al.



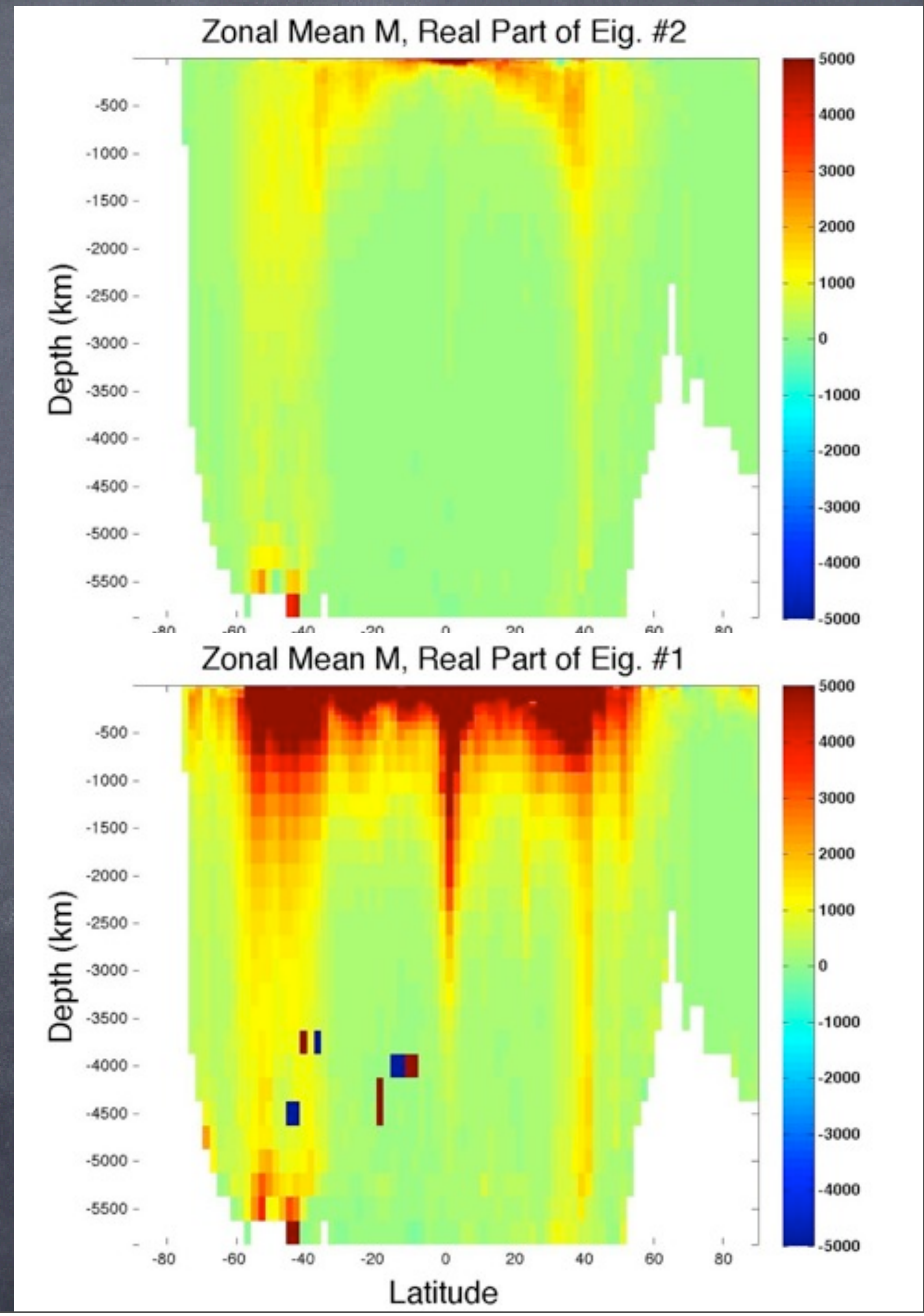
Ferreira, Marshall, Heimbach 05

Zonal mean (scalar) diffusivity

vs.

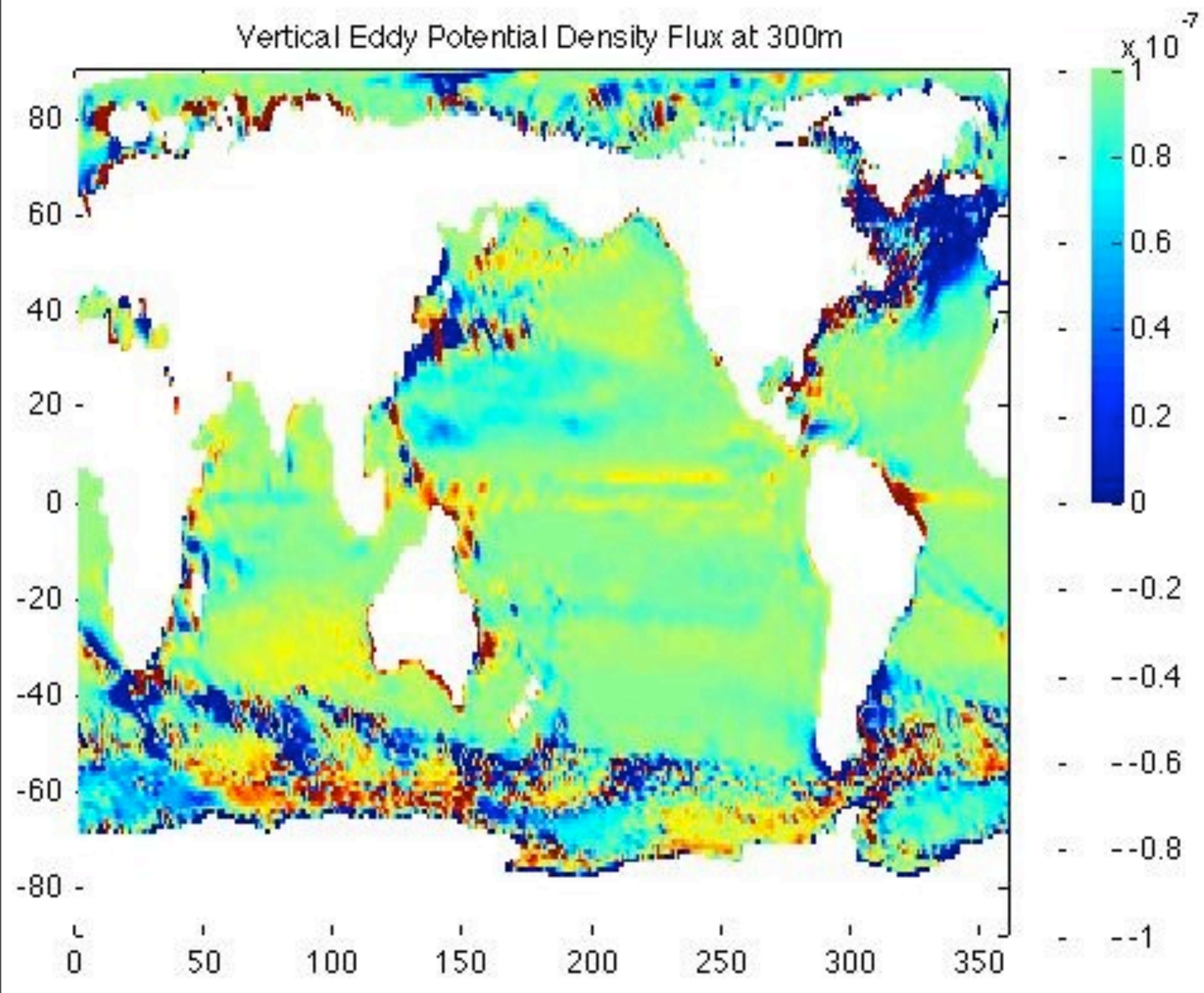
Eigenvalues of $\mathbf{M}$

Same shape--few negatives!

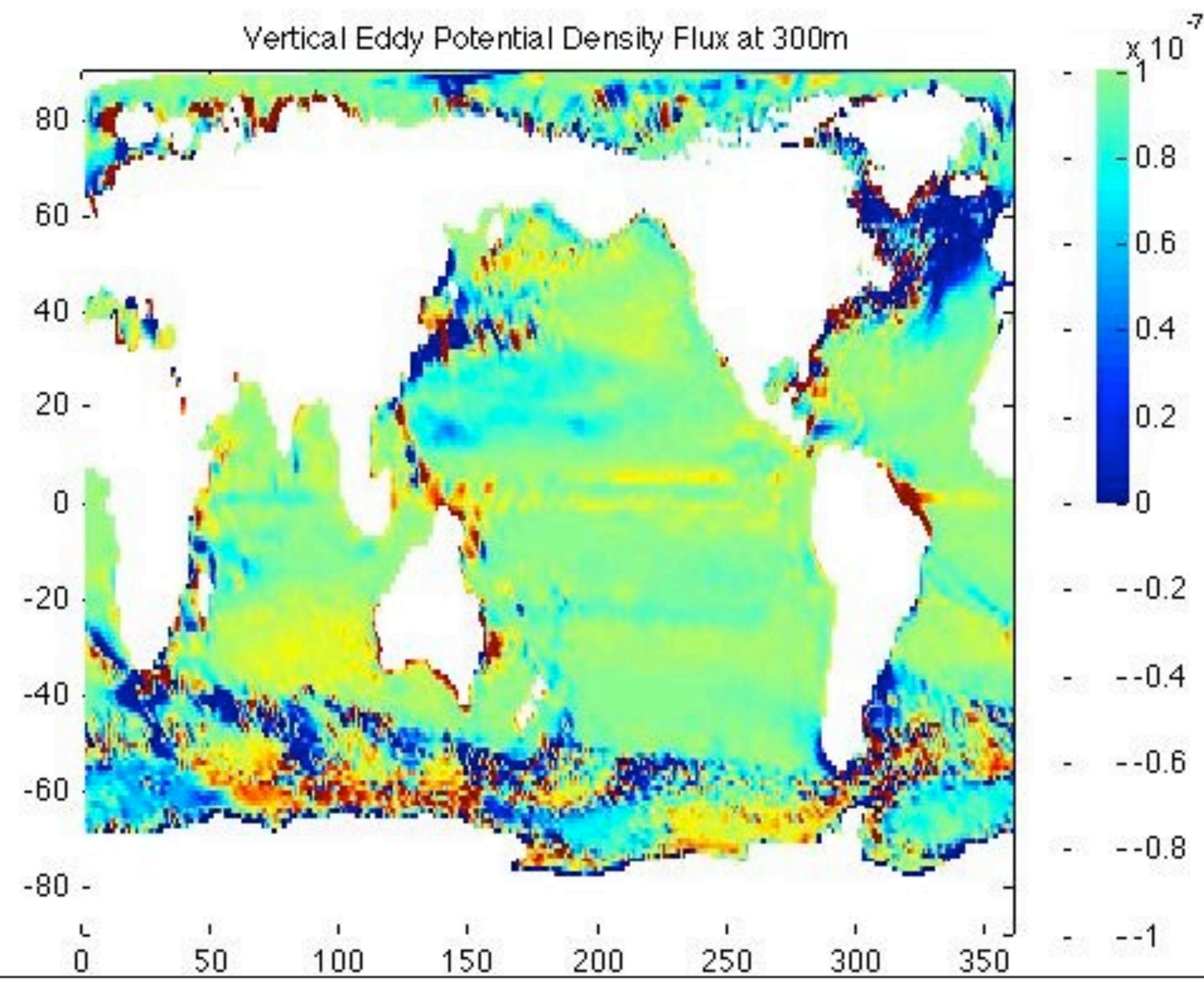


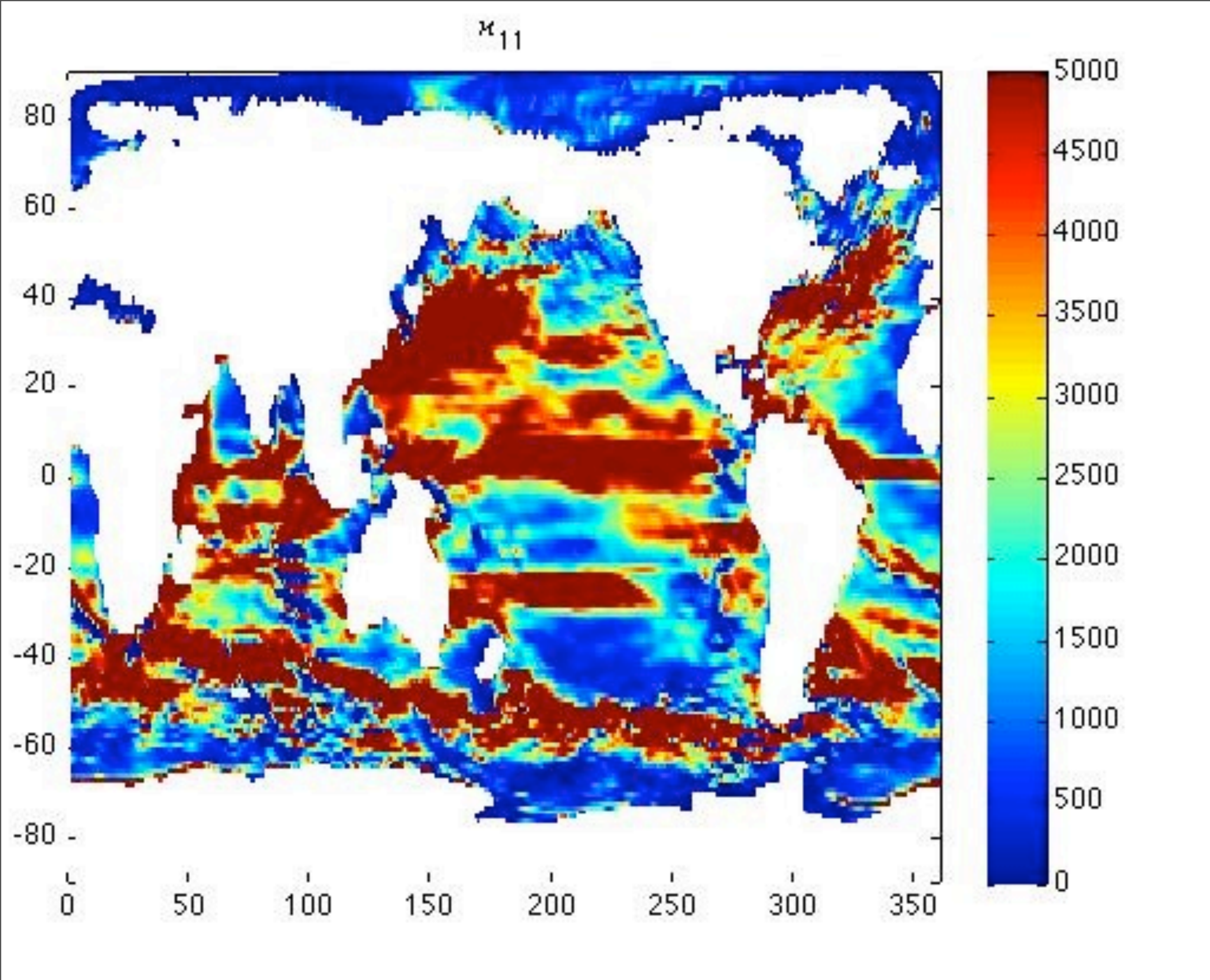
How do we explain the Horizontal Variations of K?

Compare to vertical eddy density flux (PE Extraction)



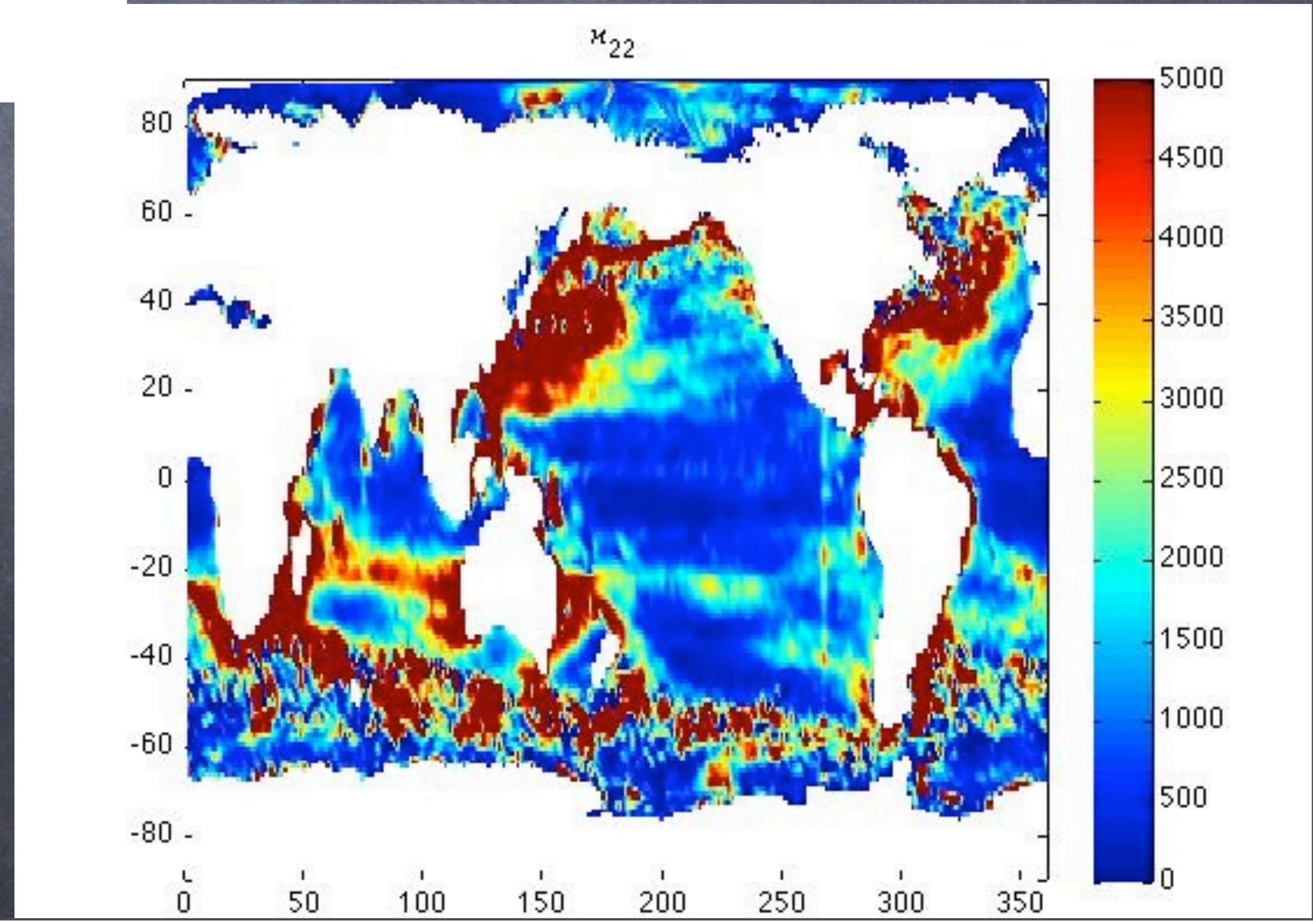
- Eden&Greatbatch (+others) propose that baroclinic instability's production of EKE from PE should guide M magnitude





Locations of PE extraction are

Locations of large eigs of **K**



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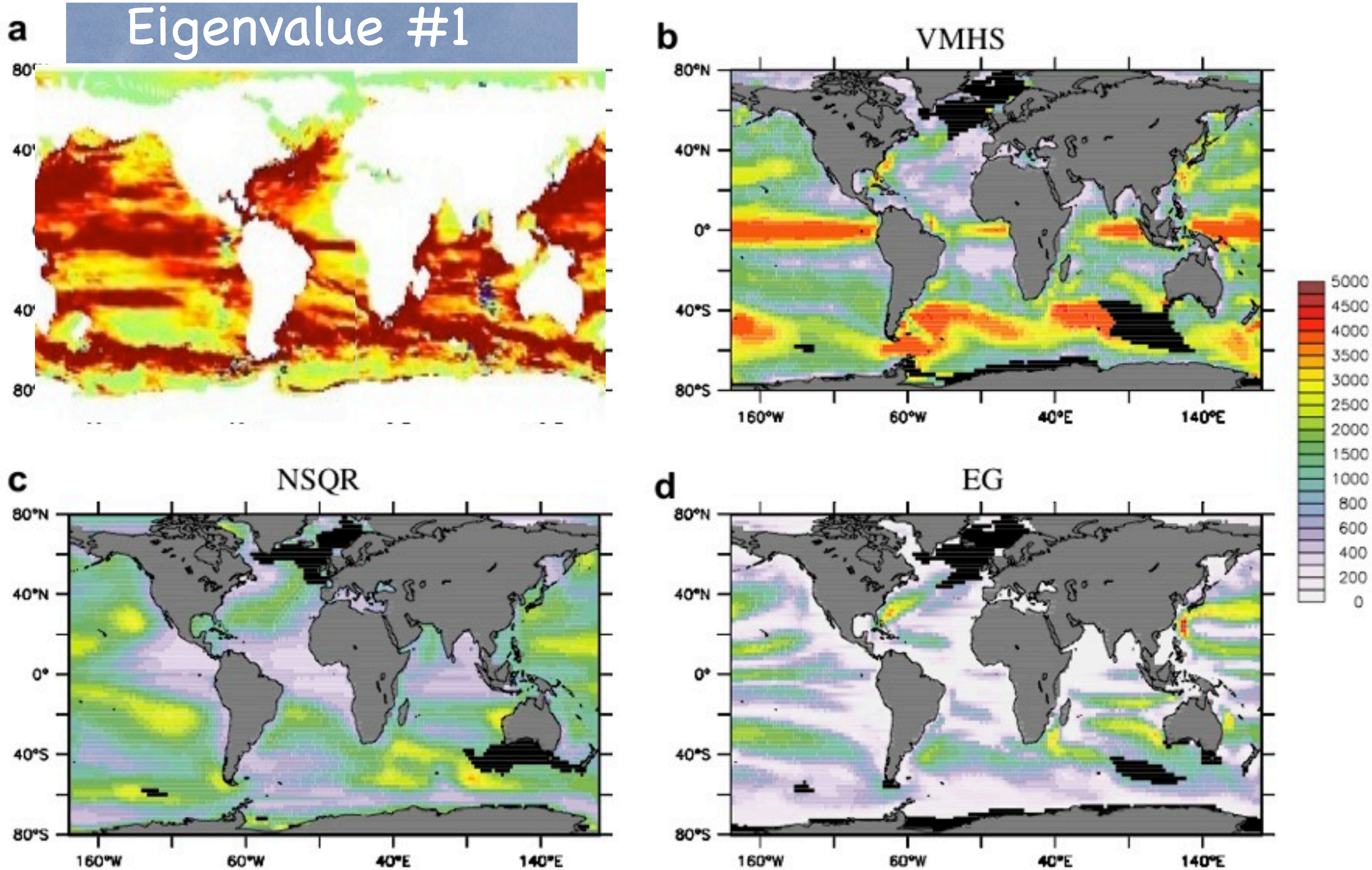
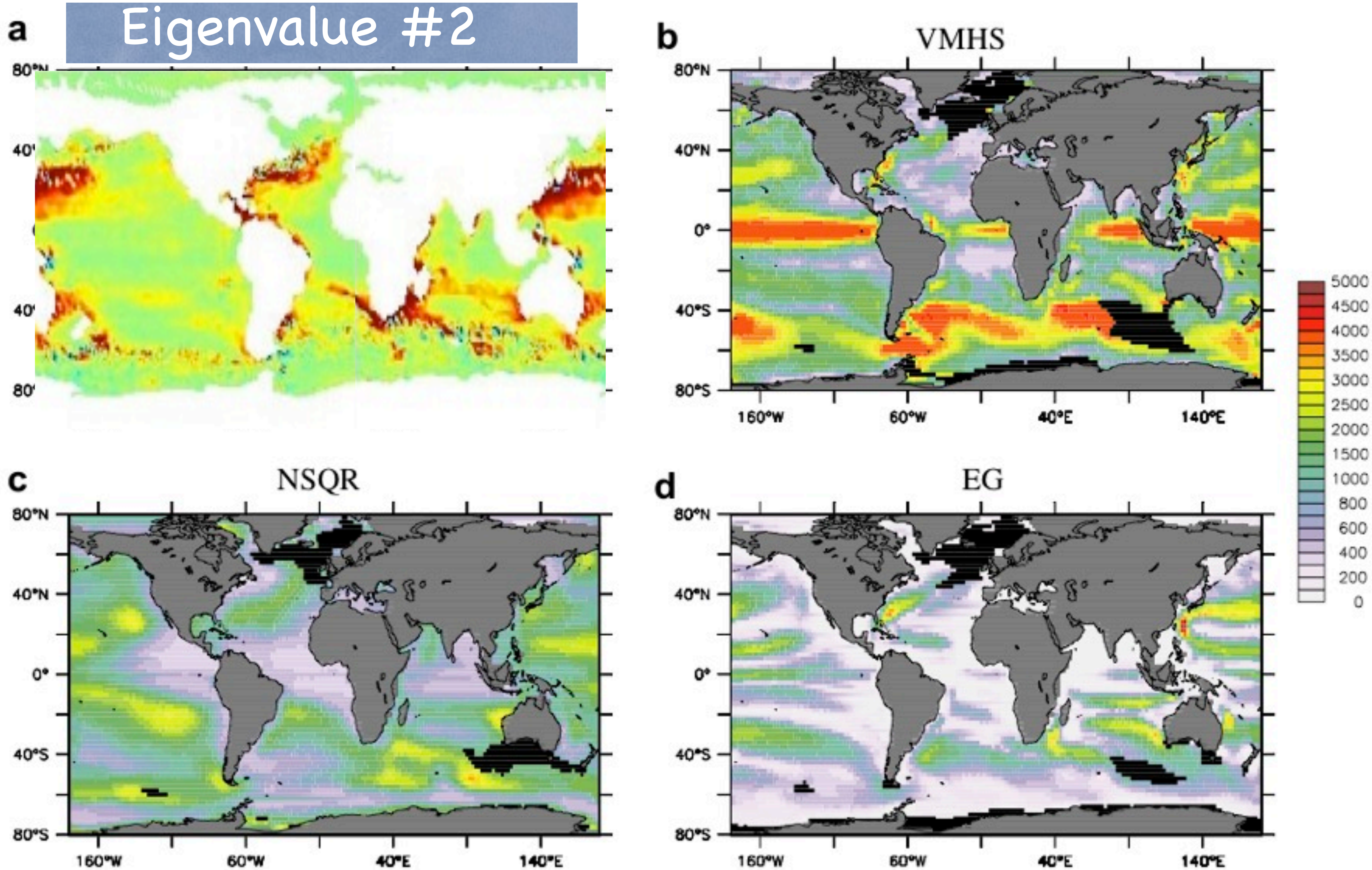
Compare with Eden, Jochum, Danabasoglu compilation of present parameterizations



g. 1. Annual mean thickness diffusivity (K) in m^2/s at 300 m depth in experiment CONST (a), VMHS (b), NSQR (c) and EG (d) after 500 years integration. Values of K are own for the interior region only, i.e. values of K in the (seasonal maximum) diabatic surface and transition layer are not shown and shaded black. Note the non-linear colour ale for the thickness diffusity. Note also that the data have been interpolated from the model grid to a regular rectangular grid of similar resolution prior to plotting. The nd mask in the figure (taken from Smith and Sandwell (1997)) differs therefore slightly from the model's land mask.

Compare with Eden, Jochum, Danabasoglu compilation of present parameterizations



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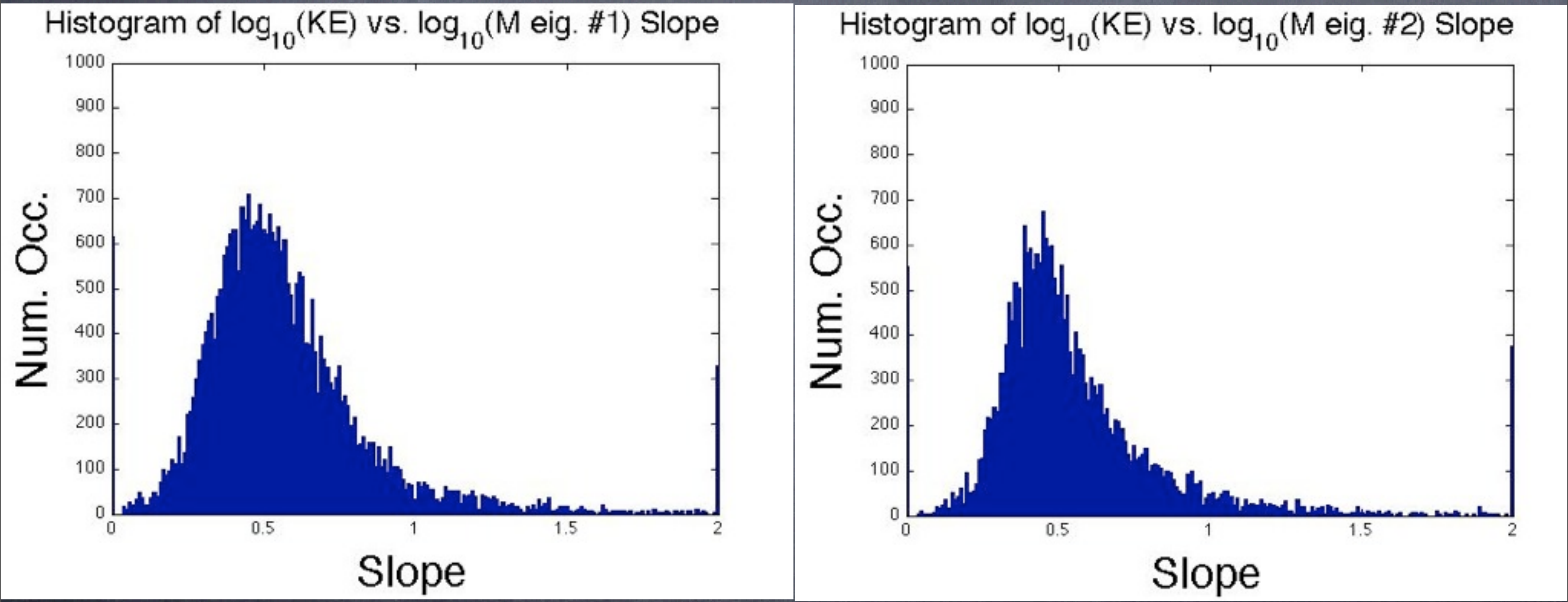
How do we explain the Vertical Variations of K?

Result:

coarse KE-> vertical structure of Mixing

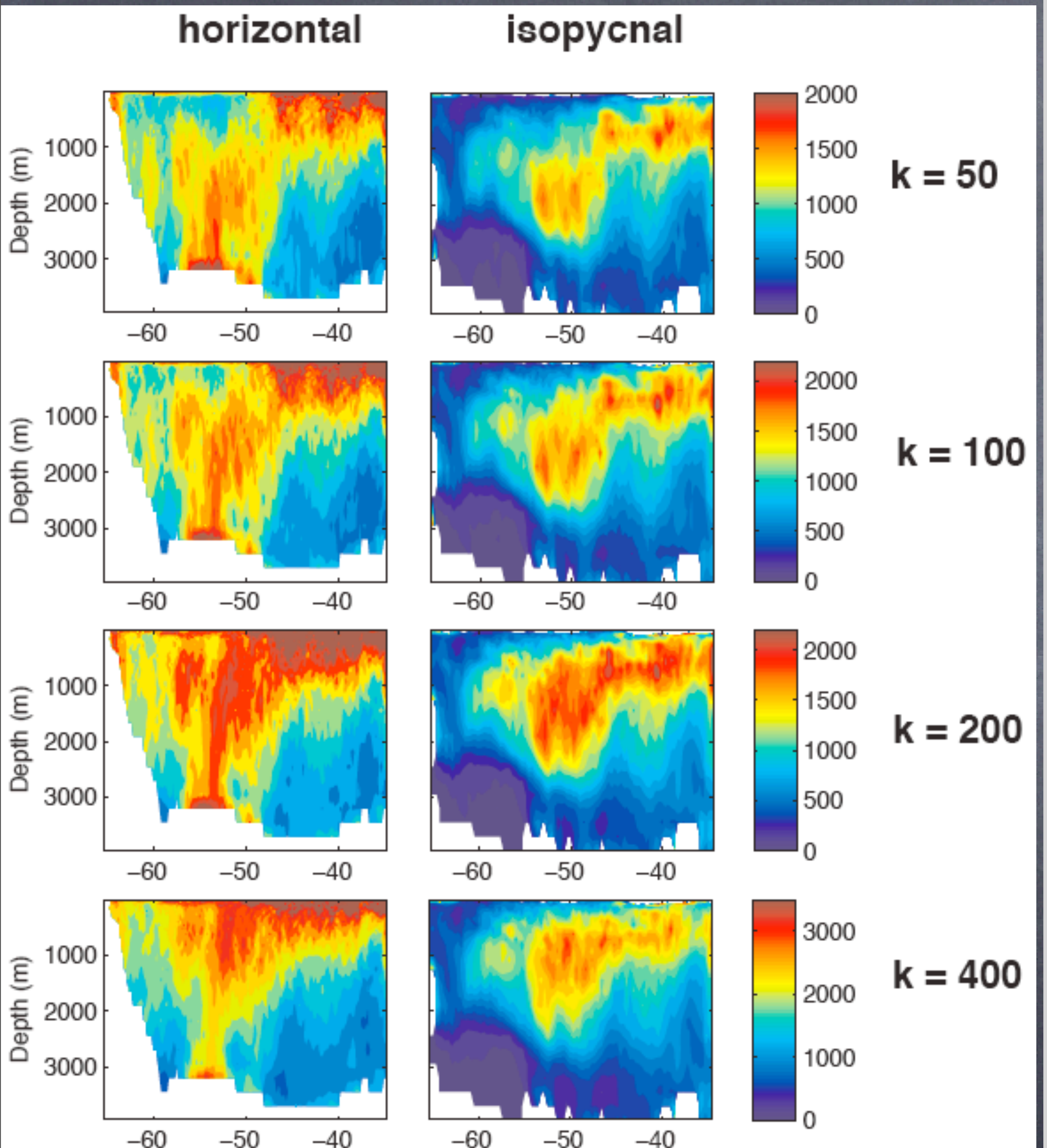
$$\mathbf{K} \propto \sqrt{\langle \mathbf{KE} \rangle}$$



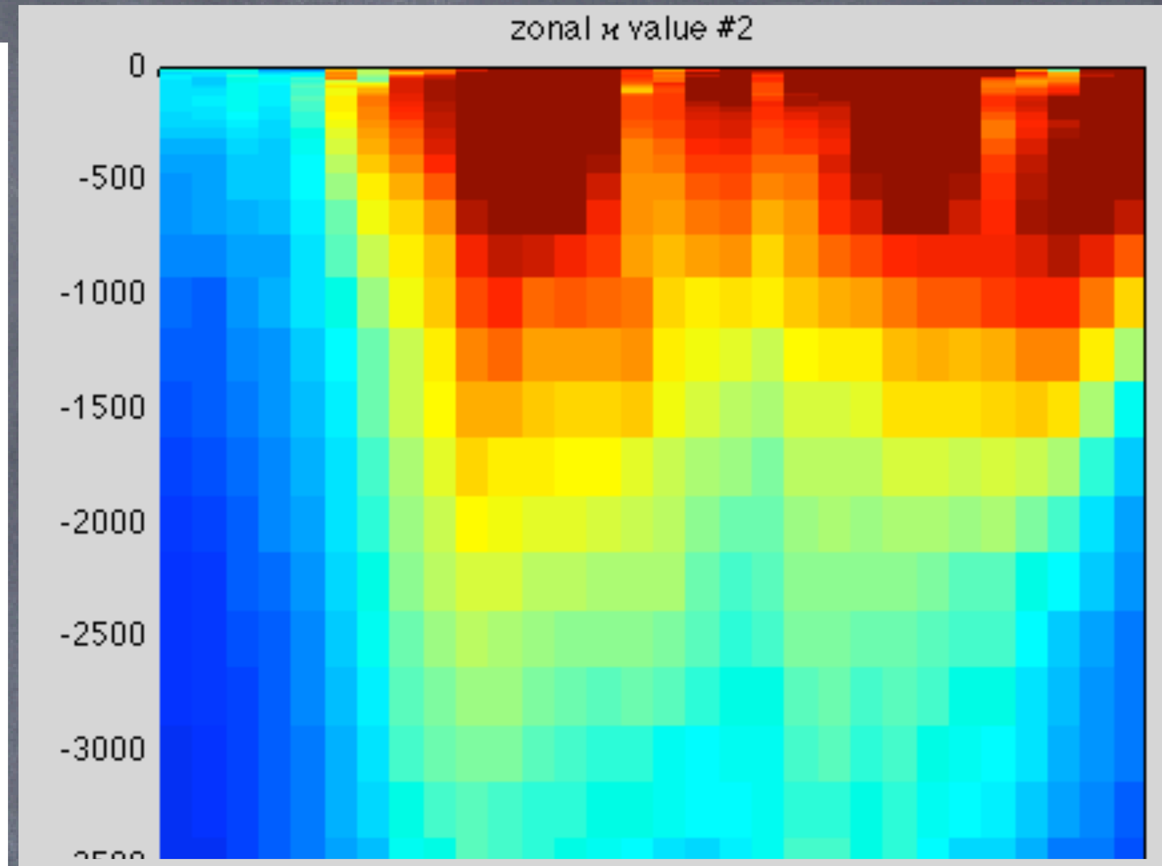
Even better with EKE!

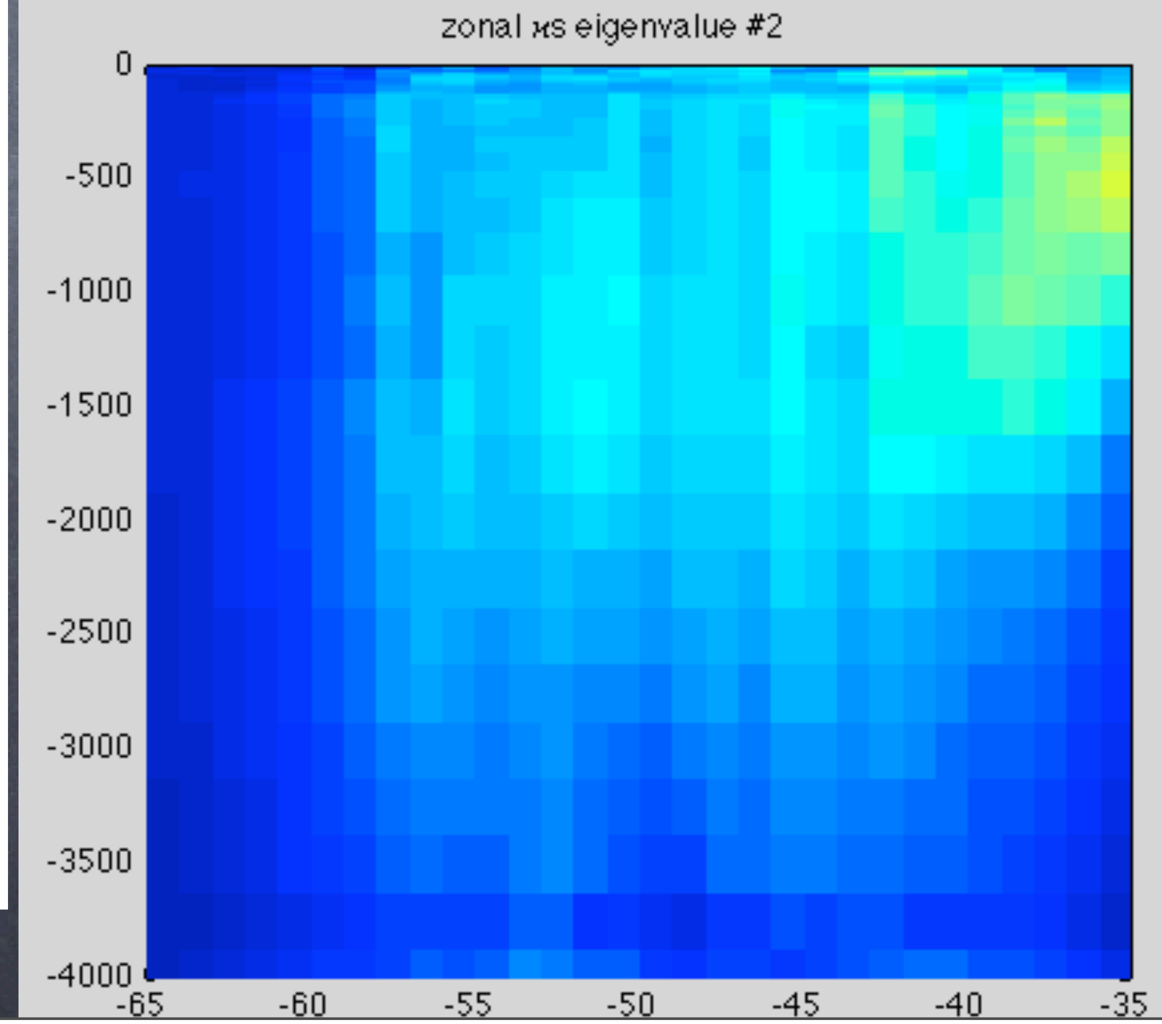
Note--barotropic mode is in there!

Comparisons with Marshall et al.



Abernathy et al 09





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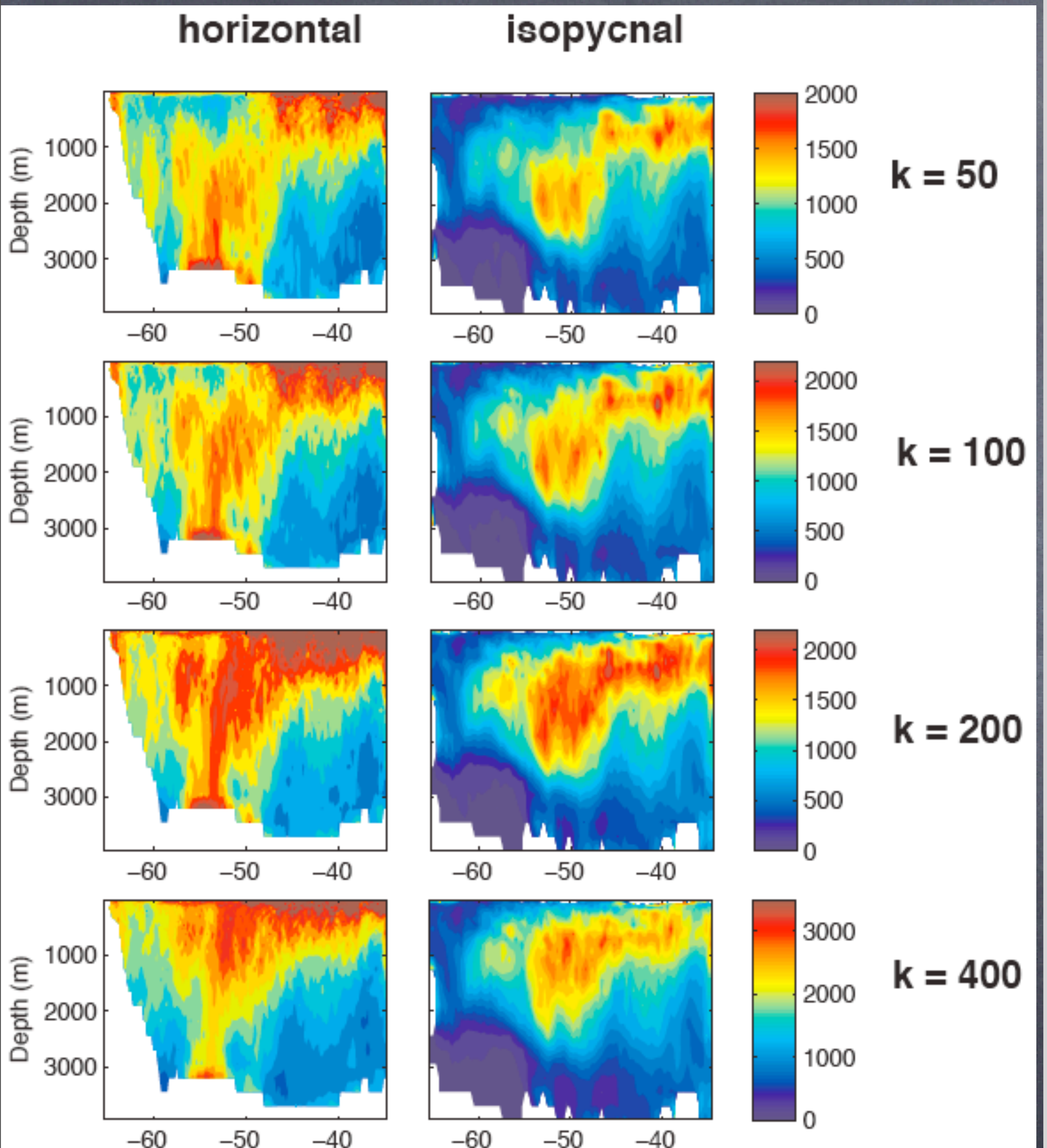
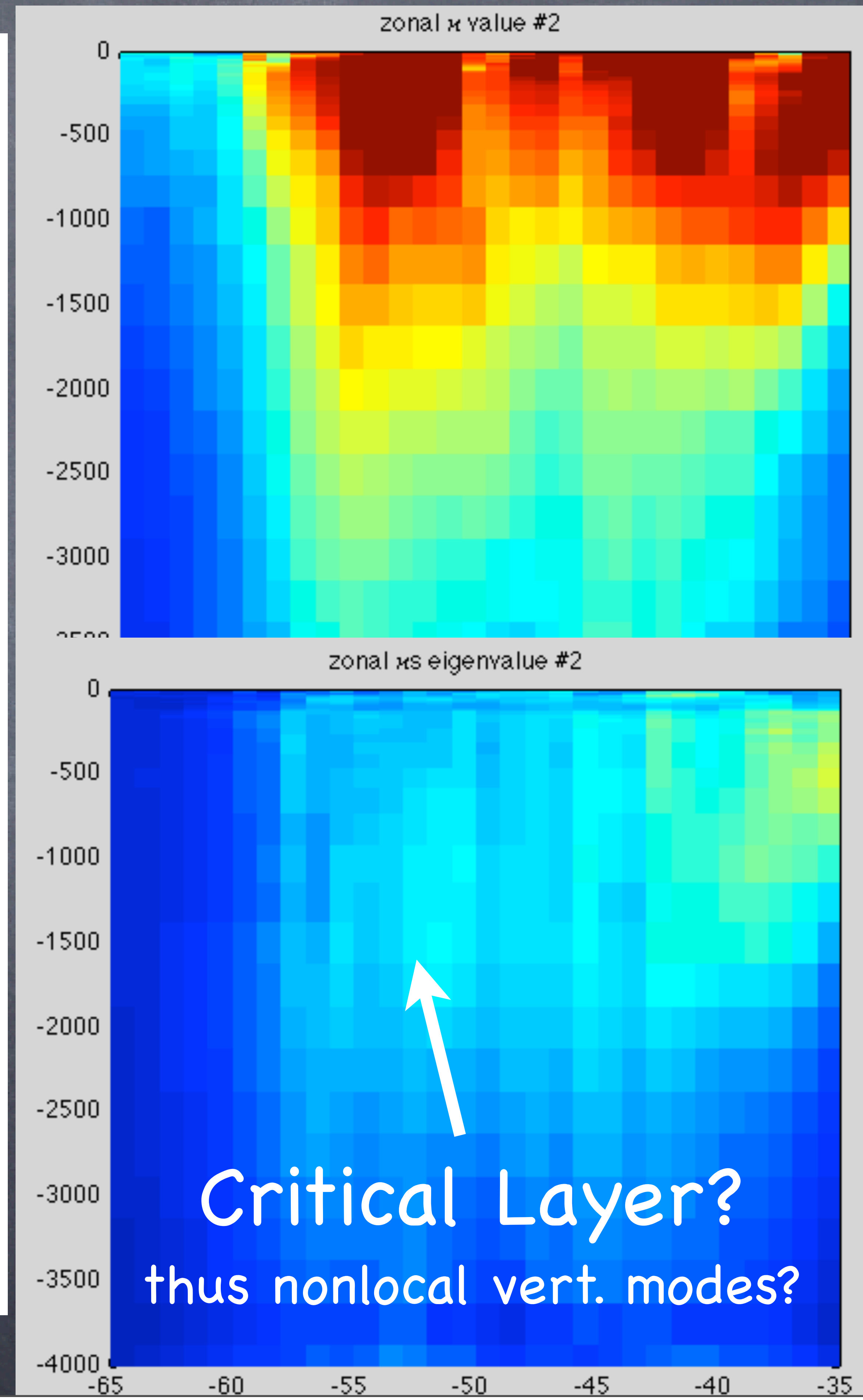


Abernathy et al 09



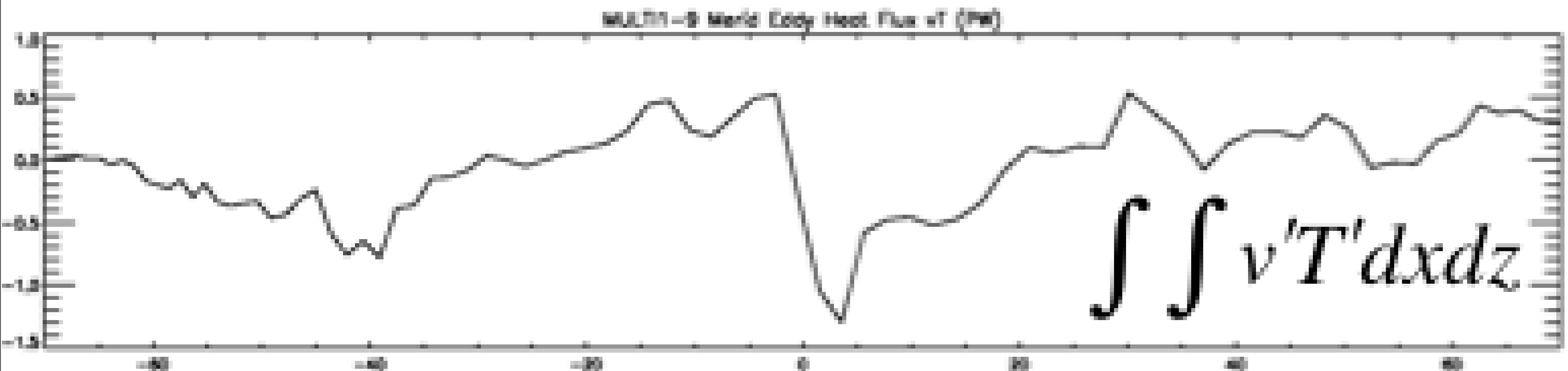
Conclusions

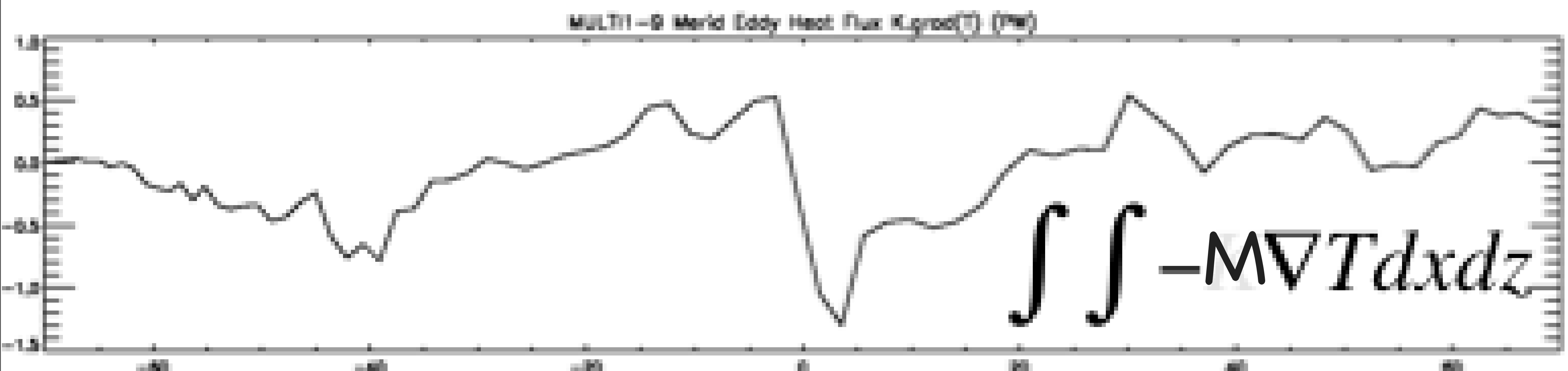
- A method for diagnosing the eddy stirring associated with fluxes represented in a 0.1° model but not a 2° model is presented
- It estimates the tracer-type-independent transport of tracer
- The shape and structure agrees roughly with Griffies (98) and Gent & Smith (04) analyses of GM & Redi isoneutral fluxes with *equal* anisotropic mixing & stirring.
- No gauge/rot. fluxes are needed to eliminate negative spurious eigenvalues

Use a Natural, Mesoscale Eddy Environment to Test Out:

Testing the Diagnosis:

Note: T not used for diagnosis, active tracers are apparently transported as passive ones are!





Difference: Diffusive - Eddy

Use a Natural, Mesoscale Eddy Environment to Test Out:

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

Result 1: Antisymmetric (GM) Elements scale with corresponding Symmetric (Redi) elements in extratropics.

Thus, GM/Redi basic shape of M is roughly correct (some detailed validation remains)

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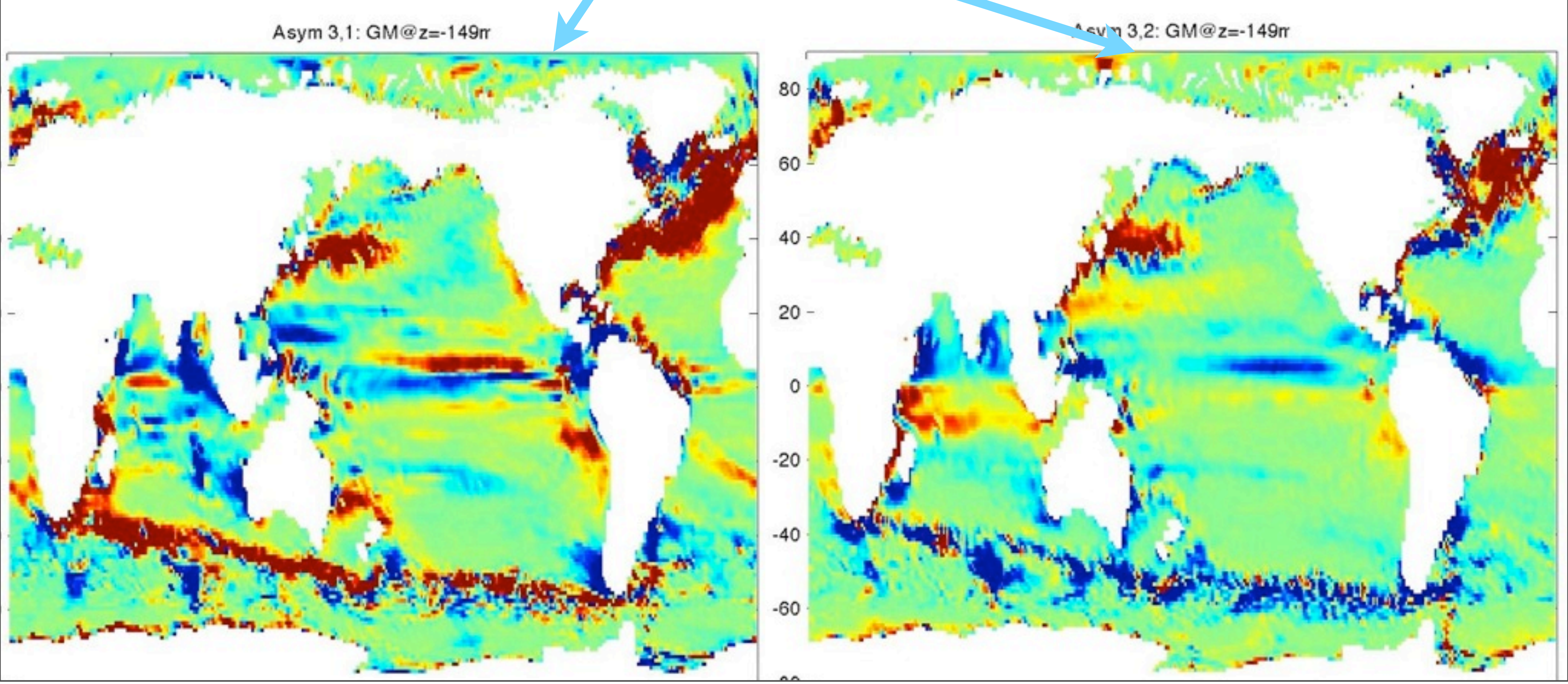

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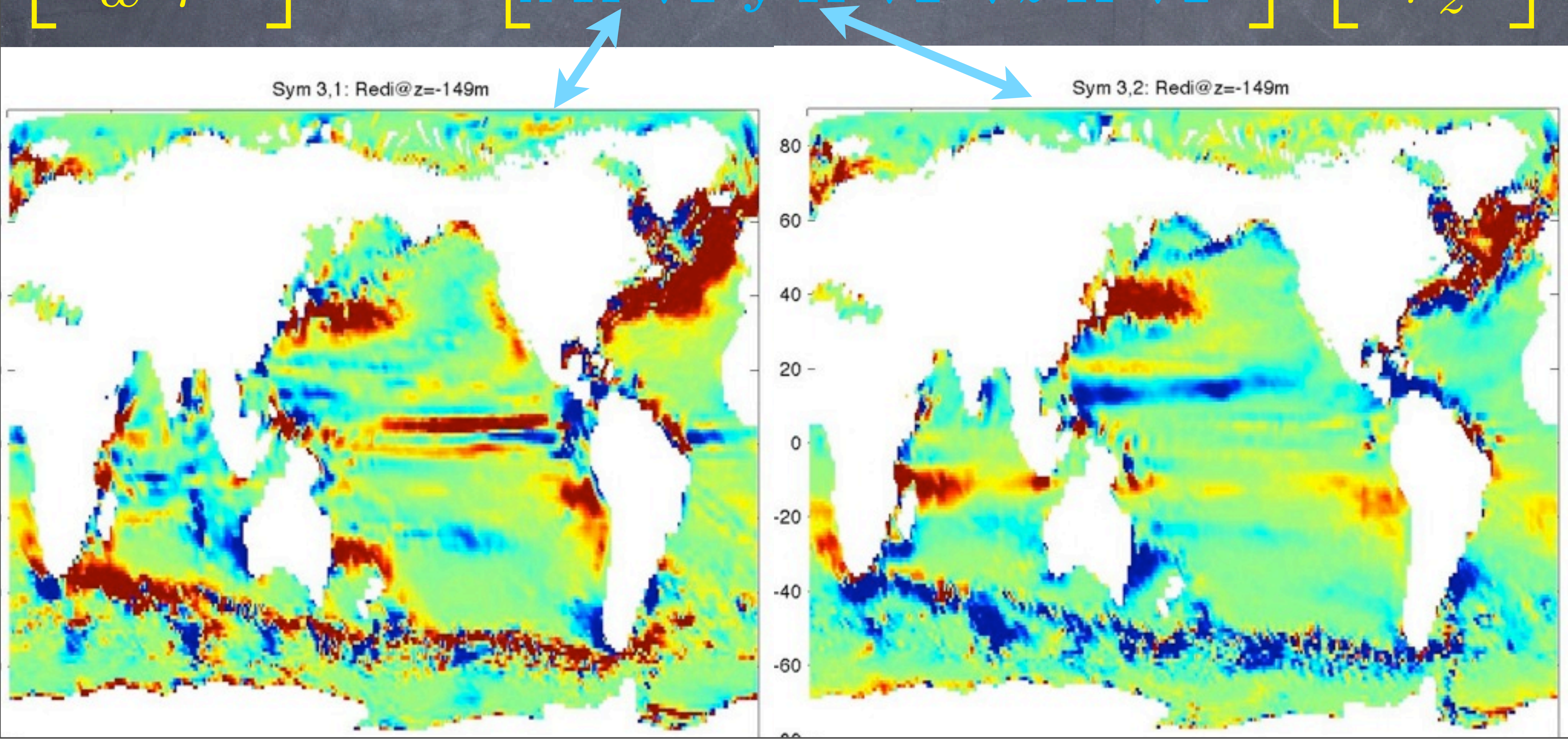

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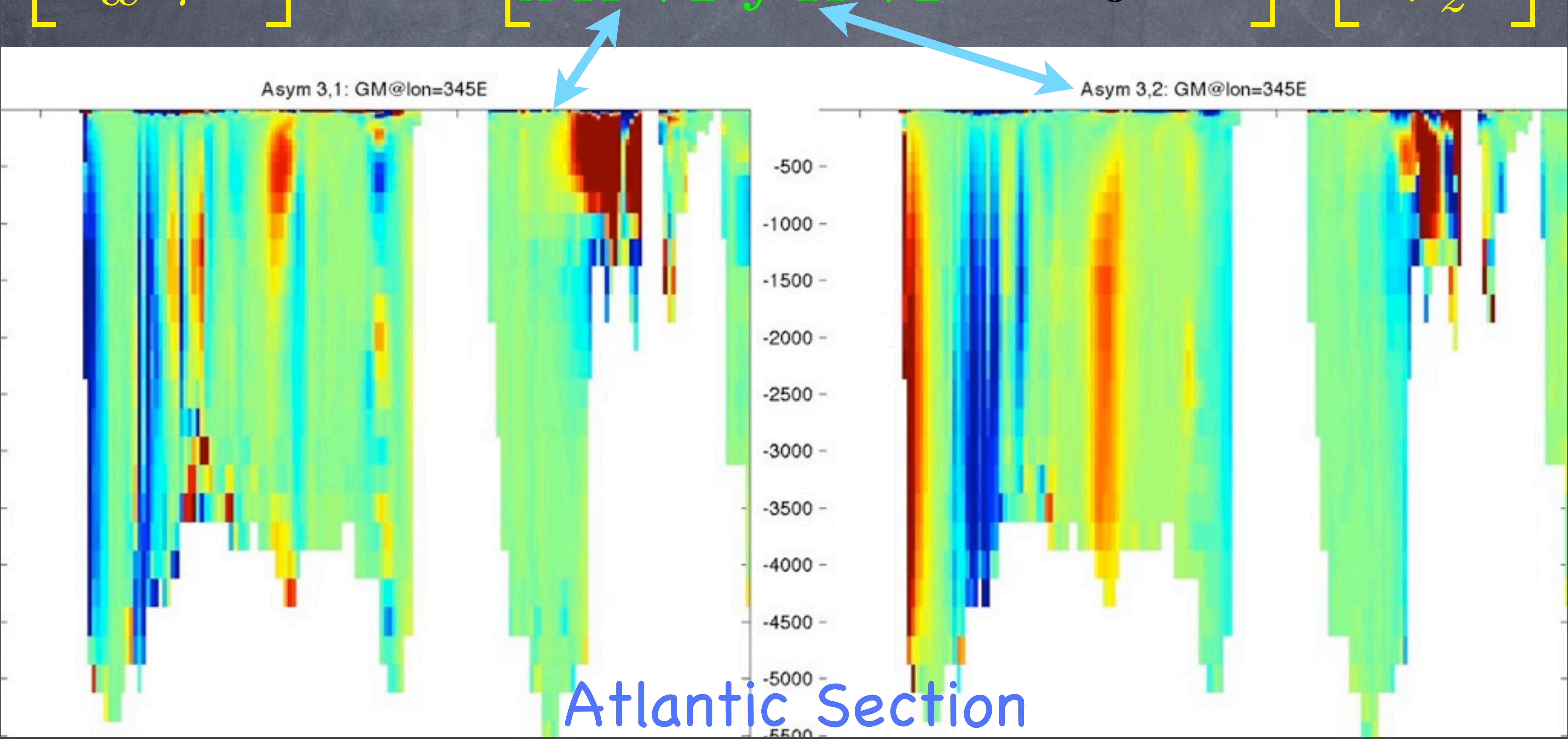

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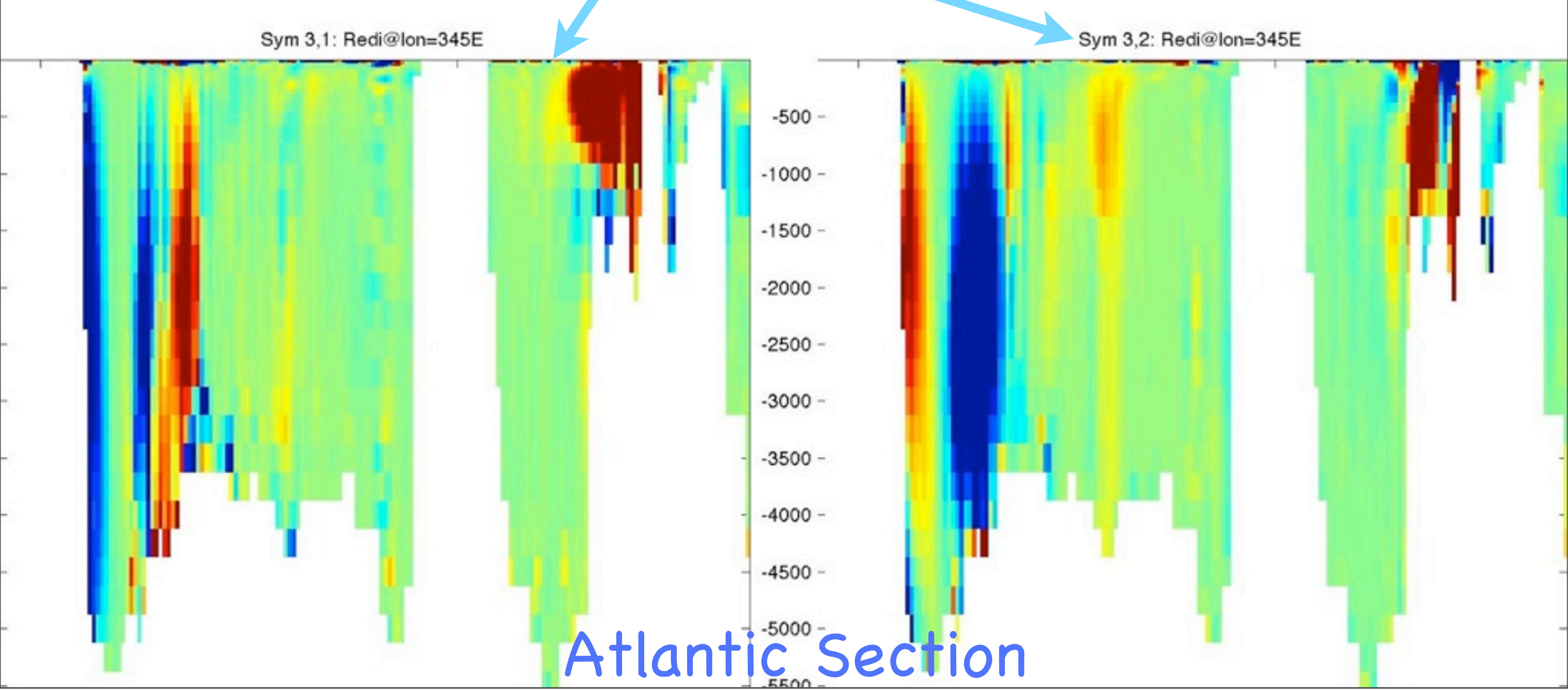

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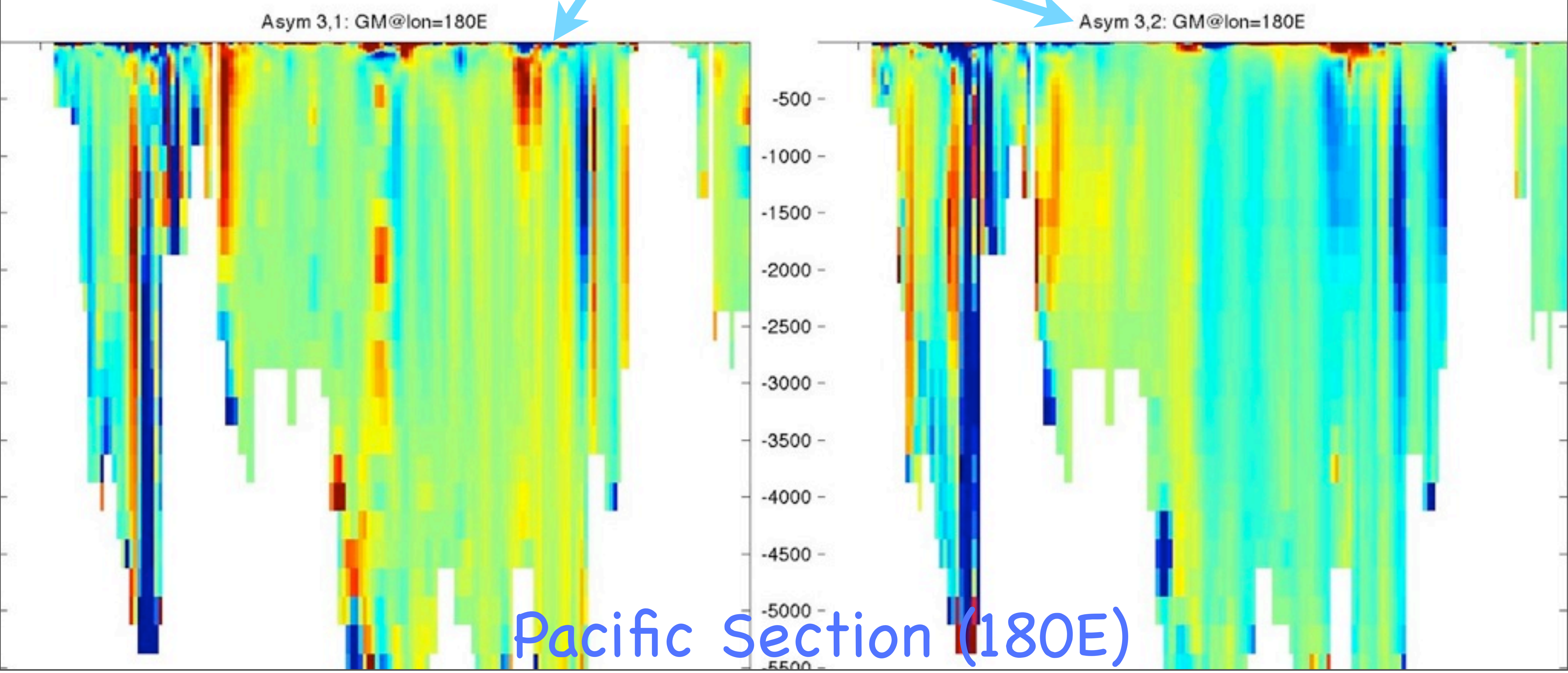

Pacific Section (180E)

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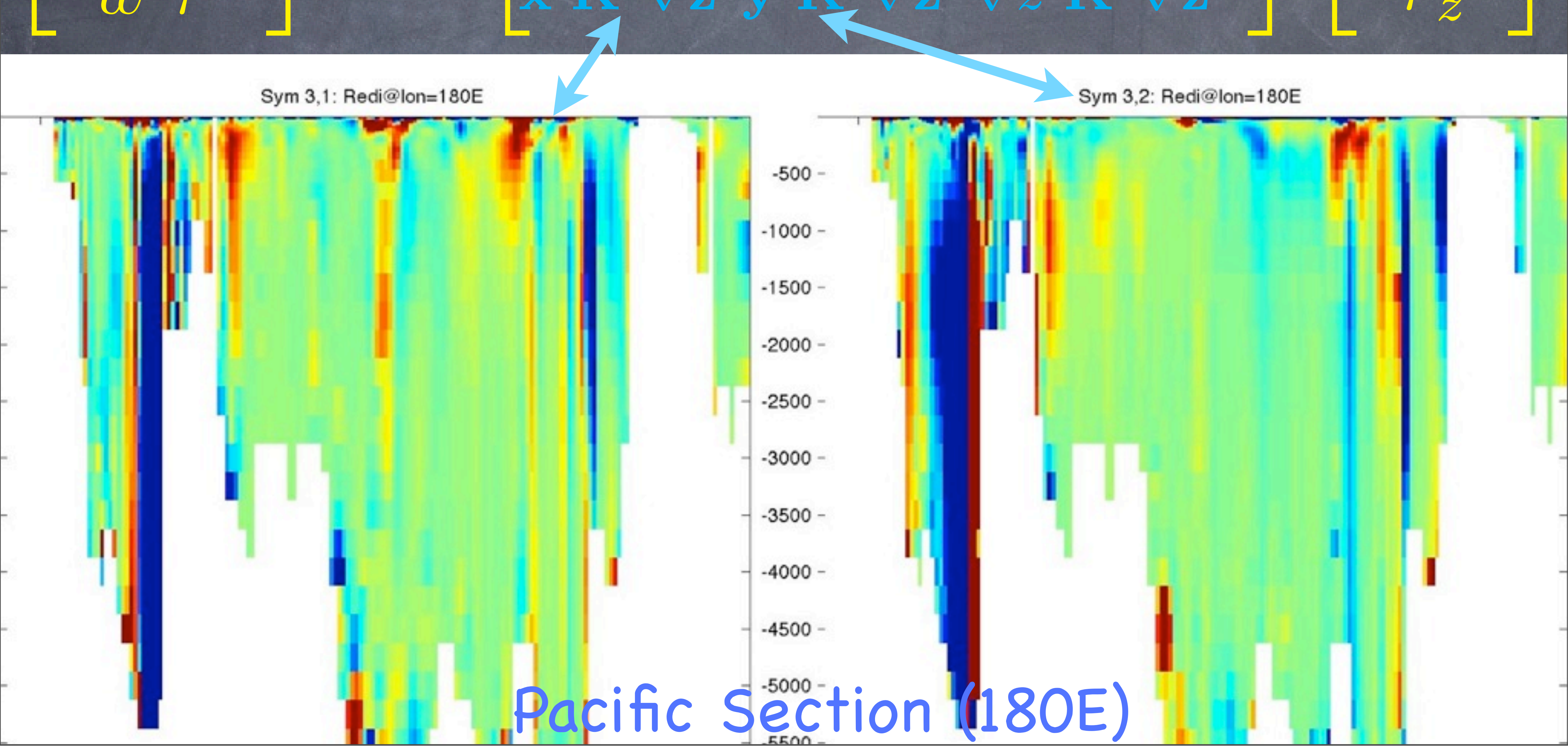


NSEF & Diabatic/ Transition Layer

- Danabasoglu & Marshall
- Danabasoglu, Ferrari & McWilliams
- Ferrari, McWilliams, Canuto, Dubovikov
- Surface-intensified GM, no boundary condition issues, no over-restratificiation of Mixed Layer by Eddies

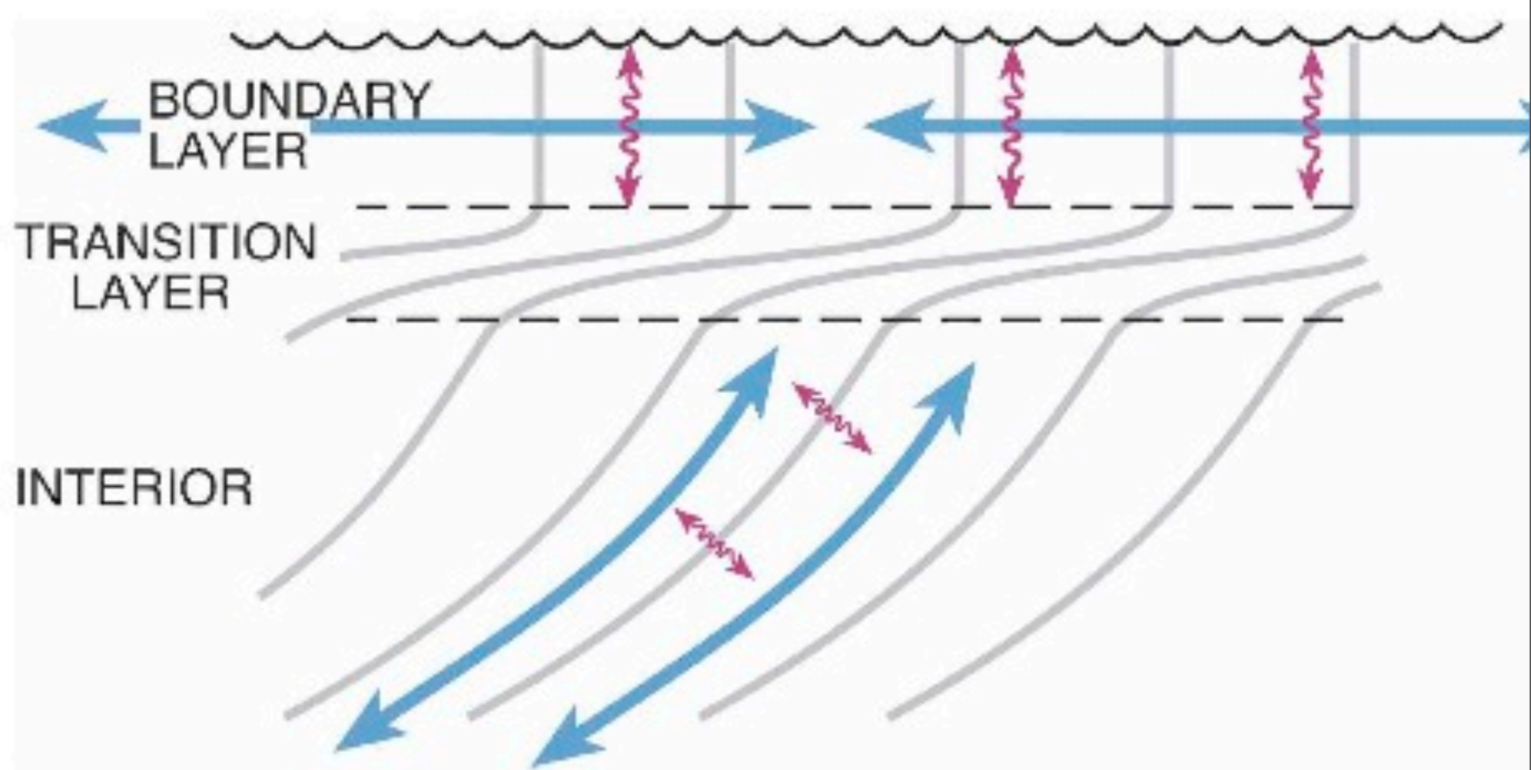
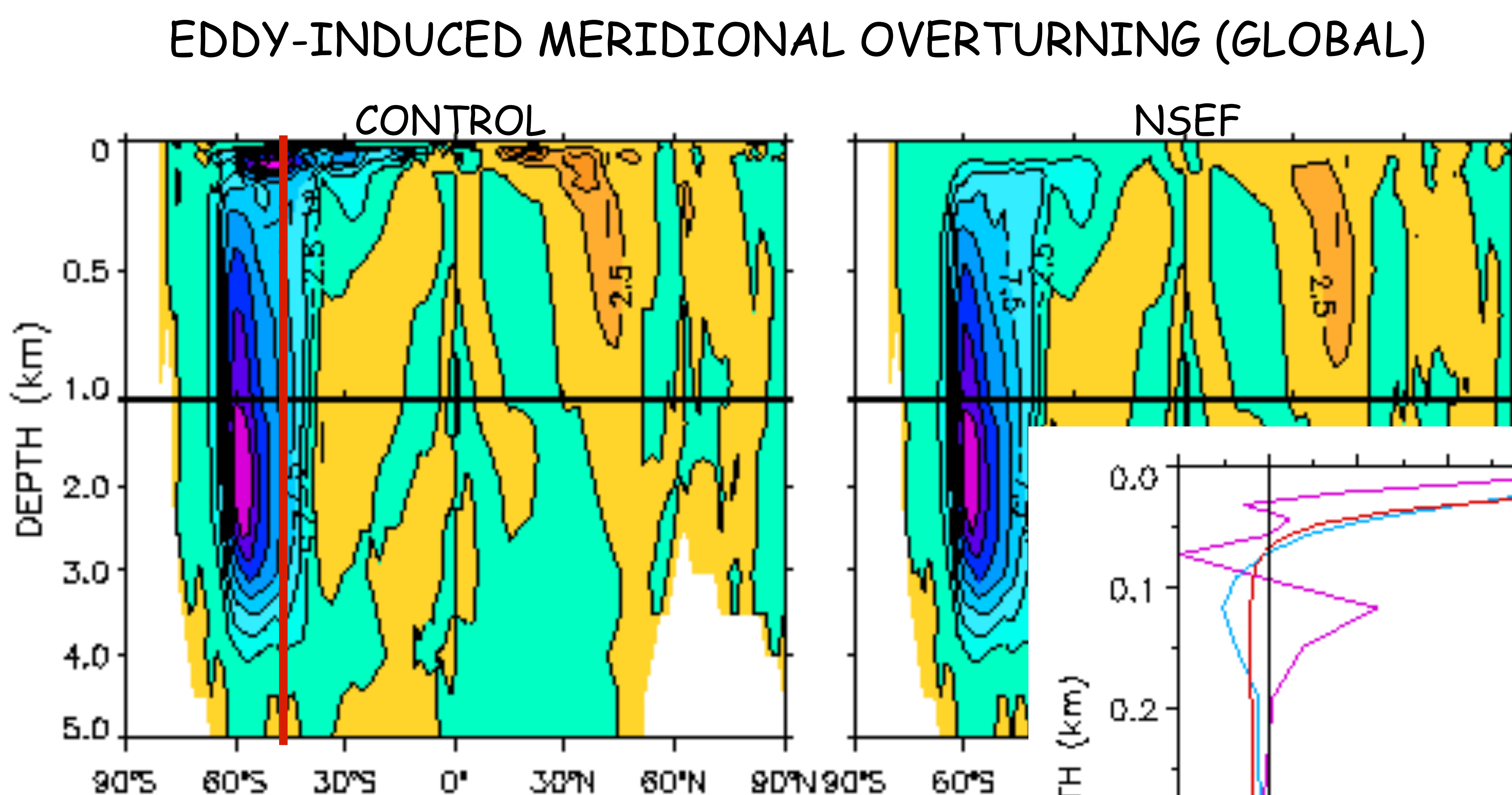
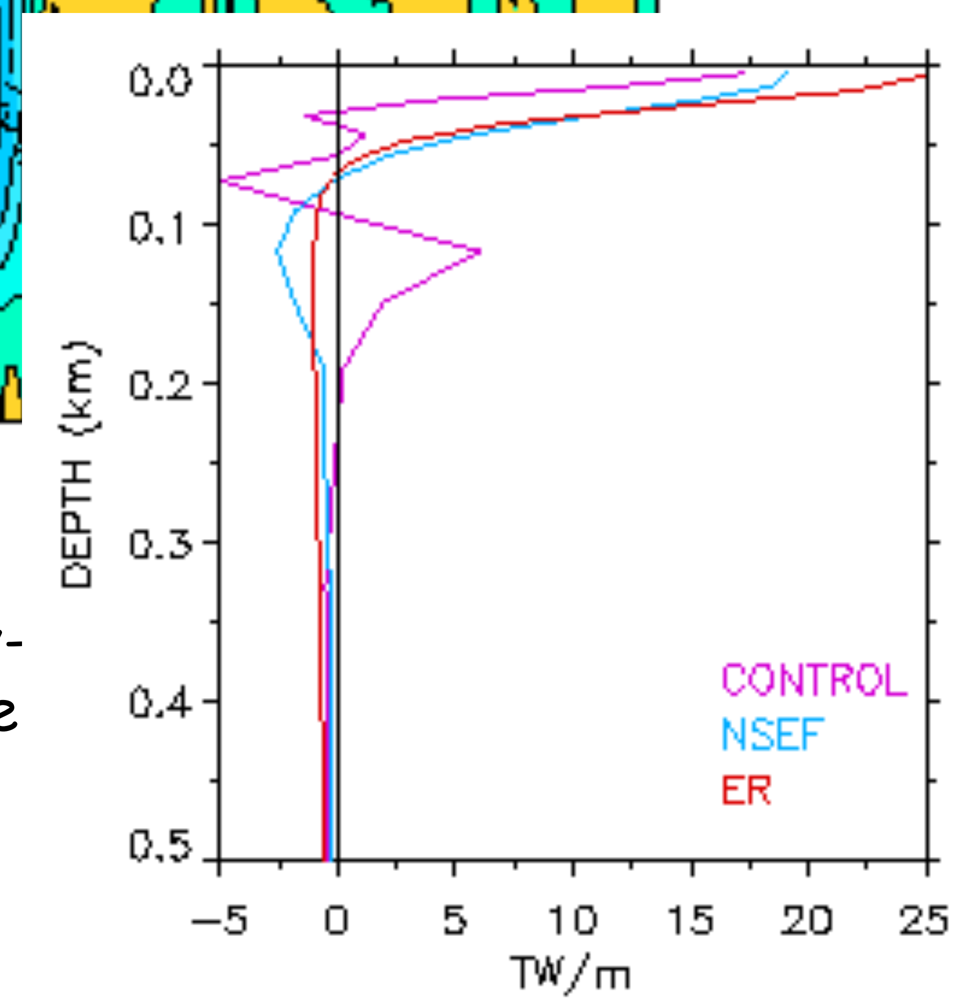


FIG. 2. A conceptual model of eddy fluxes in the upper ocea
Mesoscale eddy fluxes (blue arrows) act to both move isopycn
surfaces and stir materials along them in the oceanic *interior*, b
the fluxes become parallel to the boundary and cross density su
faces within the *BL*. Microscale turbulent fluxes (red arrows) m

Near-surface eddy flux scheme (Ferrari, McWilliams, Canuto, Dubovikov)





Vertical profile of zonally-integrated total advective heat flux at 49°S

A new eddy parameterization (Ferrari, Griffies, Nurser & Vallis)

- The eddy streamfunction is given by the elliptic problem

$$\left(c^2\frac{\mathrm{d}^2}{\mathrm{d}z^2} - N^2\right)\widetilde{\boldsymbol{\Psi}} = -\kappa\nabla\bar{b}$$

$$\widetilde{\boldsymbol{\Psi}} = 0, \quad z = 0, -H$$

Properties of the new parameterization

- releases mean available potential energy
- the eddy transport vanishes at the ocean boundaries
- the eddy transport is dominated by the first baroclinic mode (if c is set to speed of first baroclinic mode)
- does not require any tapering function
- reduces to GM for c=0

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