Sub-Rossby and Sub-Grid in Global Climate Models

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Below the Rossby Radius: Workshop on small-scale variability in the general circulation of the atmosphere and oceans
15.-17. September 2010 in Tremsbüttel, Germany

With Thanks to:

Scott Bachman, Adrean Webb, Andrew Margolin, & Bradley Cooper (students)

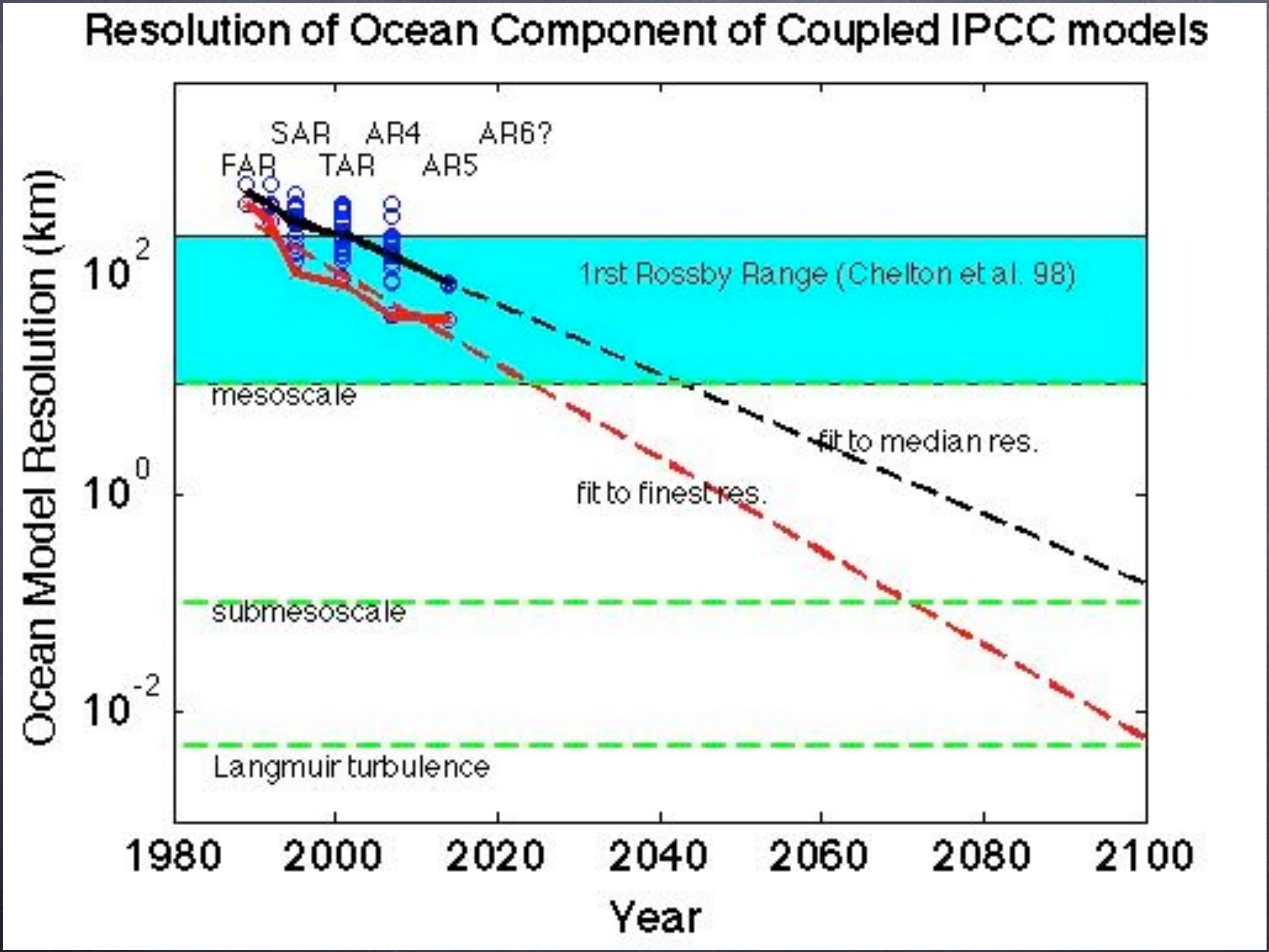
NCAR Oceanography Section

Raf Ferrari, Keith Julien

GFDL Oceanography Group

NSF (0825614, 0855010, 0934737)
IBM, NASA (NNX09AF38G)

How Small Before Irrelevant for Climate?



What's Smaller than First Rossby?

- I: Higher Modes/Advanced Mesoscale Eddies
- II: Submesoscale Eddies
- III: Langmuir Turbulence
- Not Today: Finestructure, IGW, SI, ...

What Makes Small Important for Climate?

- Nonlinear Terms Couple Across Scales
  - Eddy Fluxes
- The Ocean is Forced at the Surface
  - Mixed Layer Eddies
  - Langmuir Mixing
- Ubiquitous/Dynamical Import (not this talk)
  - Internal Waves, Deep Convection, Energy Sinks, PV Sinks & Sources

I: Mesoscale

(Capet et al., 2008)

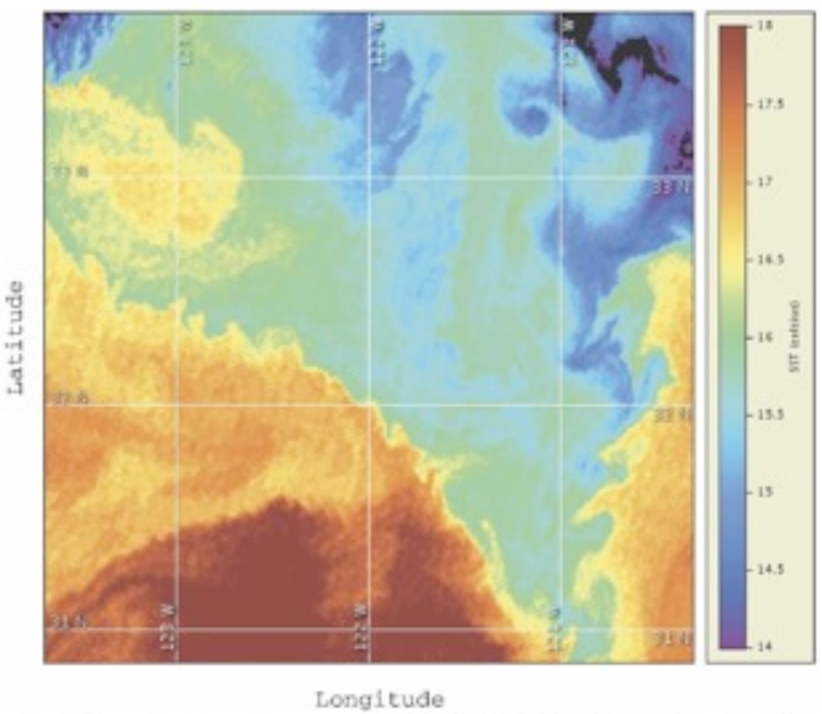


Fig. 16. Sea surface temperature measured at 1832 UTC 3 Jun 2006 off Point Conception in the California Current from CoastWatch (http://coastwatch.pfeg.noaa.gov). The fronts between recently upwelled water (i.e., 15°–16°C) and offshore water (≥17°C) show submesoscale instabilities with wavelengths around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

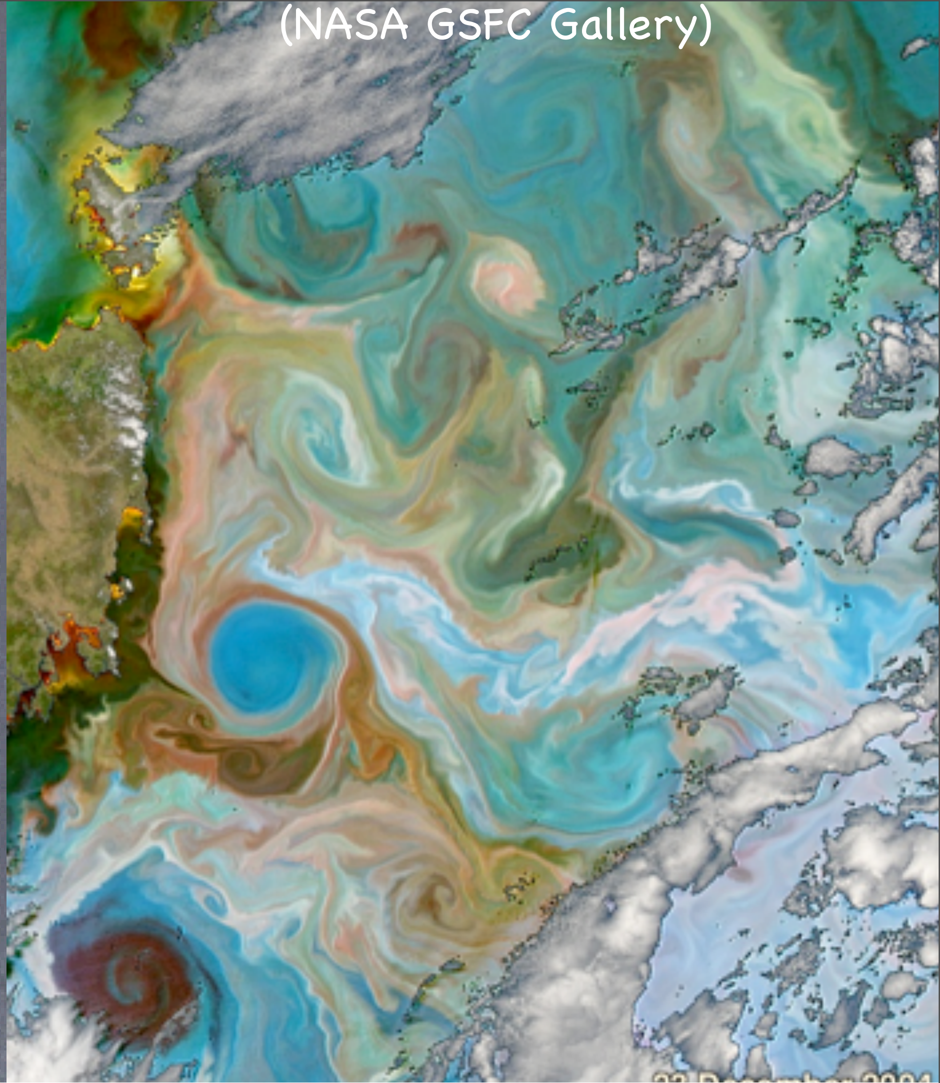
- Boundary Currents
- Eddies
- Ro=O(0.1)
- Ri=O(1000)
- Full Depth
- Eddies strain to produce Fronts
- 100km, months

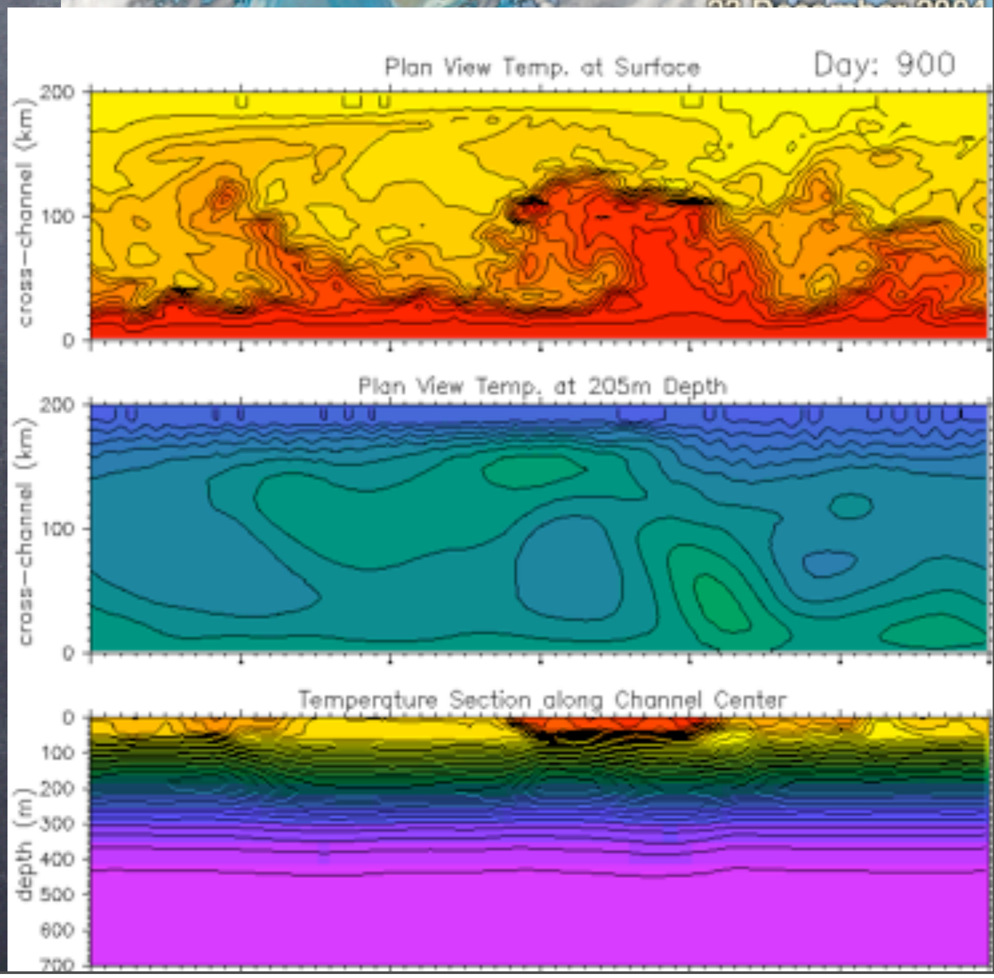
Eddy processes baroclinic & barotropic instability.

Parameterizations (GM, Visbeck, Eden & GB).

100 km

(NASA GSFC Gallery)





I: Mesoscale Variability

- Basics of Mesoscale:
  - Nearly Adiabatic
  - APE-Extracting
  - BC & BT Instab.
- Advanced Mesoscale
  - Higher Modes/ Vertical Variability
  - Horiz. Variability
  - Flow Dependence

Rossby Modes via WKB: Chelton et al 98

$$c_m \approx c_m^{\mathrm{WKB}} = \frac{1}{m\pi}\int_{-H}^{0} N(z)\,dz, \qquad m \geq 1. \quad (2.2)$$

Physically, the parameter c_m is the phase speed of long, mode-m gravity waves in a nonrotating, continuously stratified fluid (Gill 1982; LeBlond and Mysak 1978). Outside of the Tropics, the Rossby radius of deformation for mode m at latitude ϑ is determined from c_m by

$$\lambda_m = \frac{c_m}{|f(\vartheta)|} \qquad \text{if } |\vartheta| \gtrsim 5°. \quad (2.3a)$$

Within the equatorial band, the Rossby radius of deformation can be defined (see Gill 1982) as

$$\lambda_m = \left(\frac{c_m}{2\beta(\vartheta)}\right)^{1/2} \qquad \text{if } |\vartheta| \lesssim 5°, \quad (2.3b)$$

My Approach: Tracer Flux-Gradient Relationship

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

- Most subgridscale closures have this form: GM*, Redi, FFH** submesoscale, part of KPP & Langmuir mixing
- 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 closure

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

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

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)

Use a Natural, Mesoscale Eddy Environment to Test Out:

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

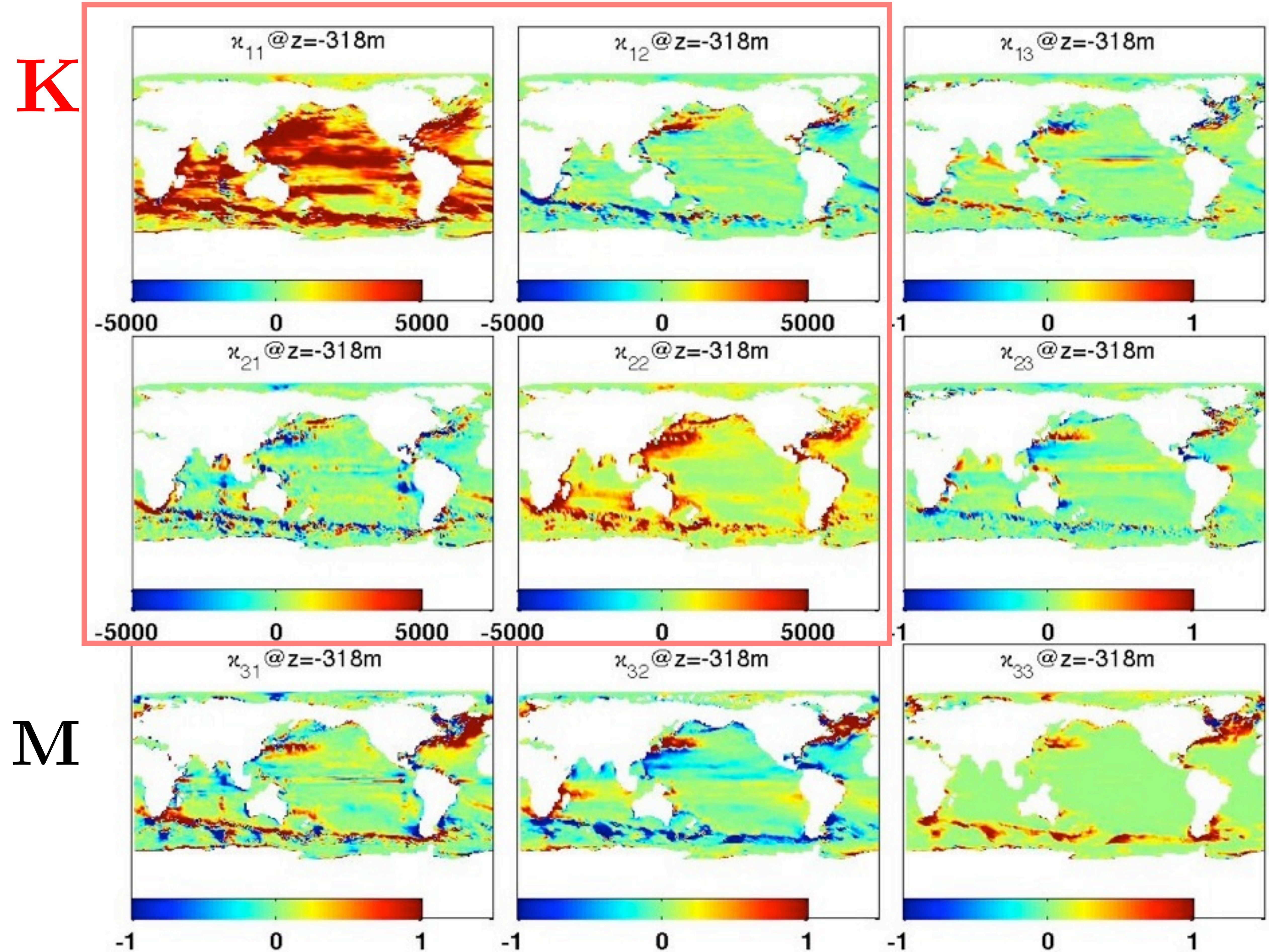
$$\begin{bmatrix} \overline{u'\tau'} \\ \overline{v'\tau'} \\ \overline{w'\tau'} \end{bmatrix} = -\begin{bmatrix} M_{xx} & M_{xy} & M_{xz} \\ M_{yx} & M_{yy} & M_{yz} \\ M_{zx} & M_{zy} & M_{zz} \end{bmatrix} \begin{bmatrix} \overline{\tau}_x \\ \overline{\tau}_y \\ \overline{\tau}_z \end{bmatrix}$$

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°, transient eddies, tracers to $\mathbf{M}$



Could you have guessed it?

Interpretation?

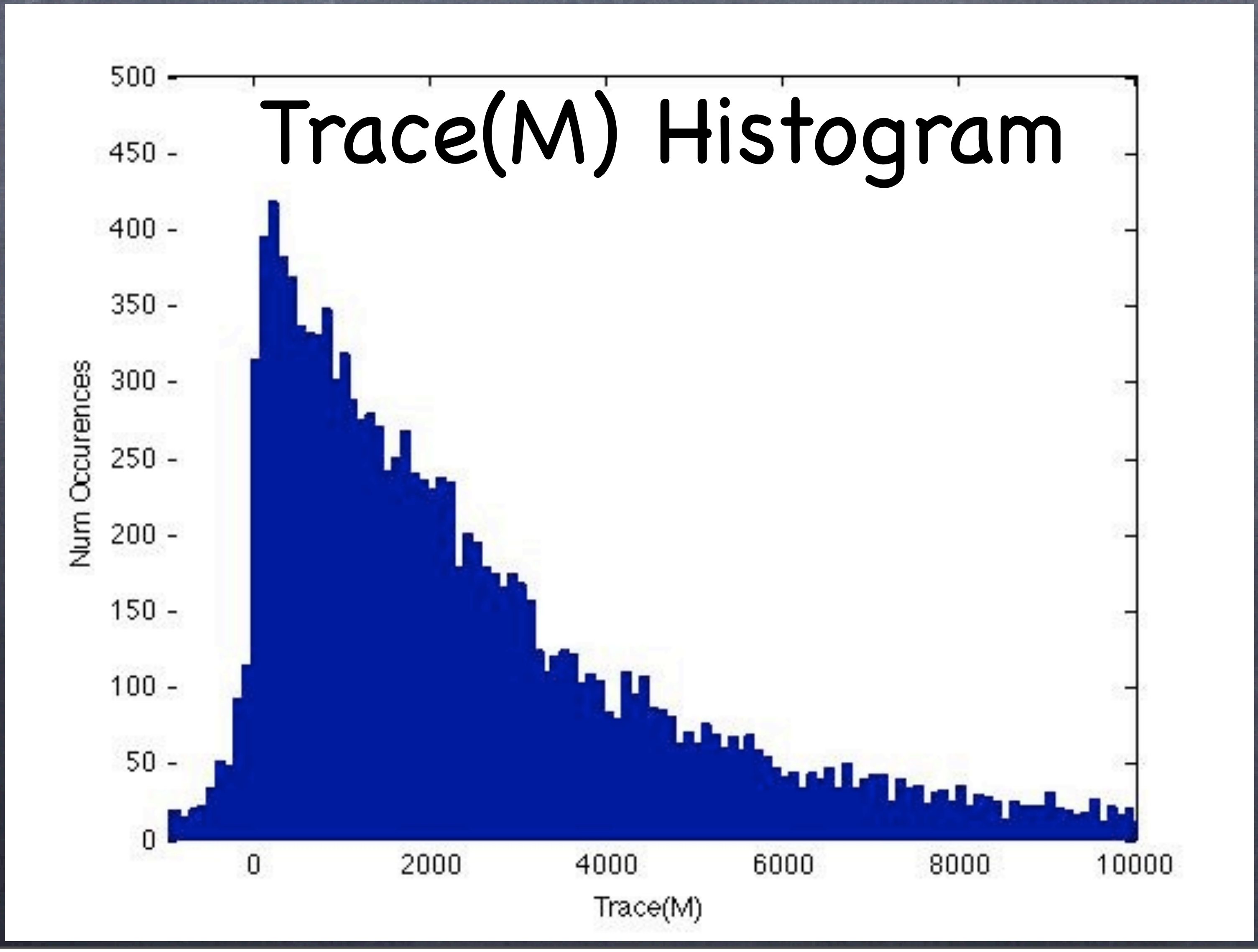
- Isoneutral diffusion or 'mixing': symmetric $\mathbf{K}$ with real, positive eigenvalues (neg->nonlocal)
- The eigenvalues of $\mathbf{M}$ are related, except there is one more involving the neutral to z coordinate conversion (in S&G theory, at least)
- The eigenvectors give the direction of the mixing 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!

Basics Validated

- Mesoscale Eddy Fluxes are Largely Adiabatic
- Mesoscale Eddy ‘Diffusivities’ are usually positive

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

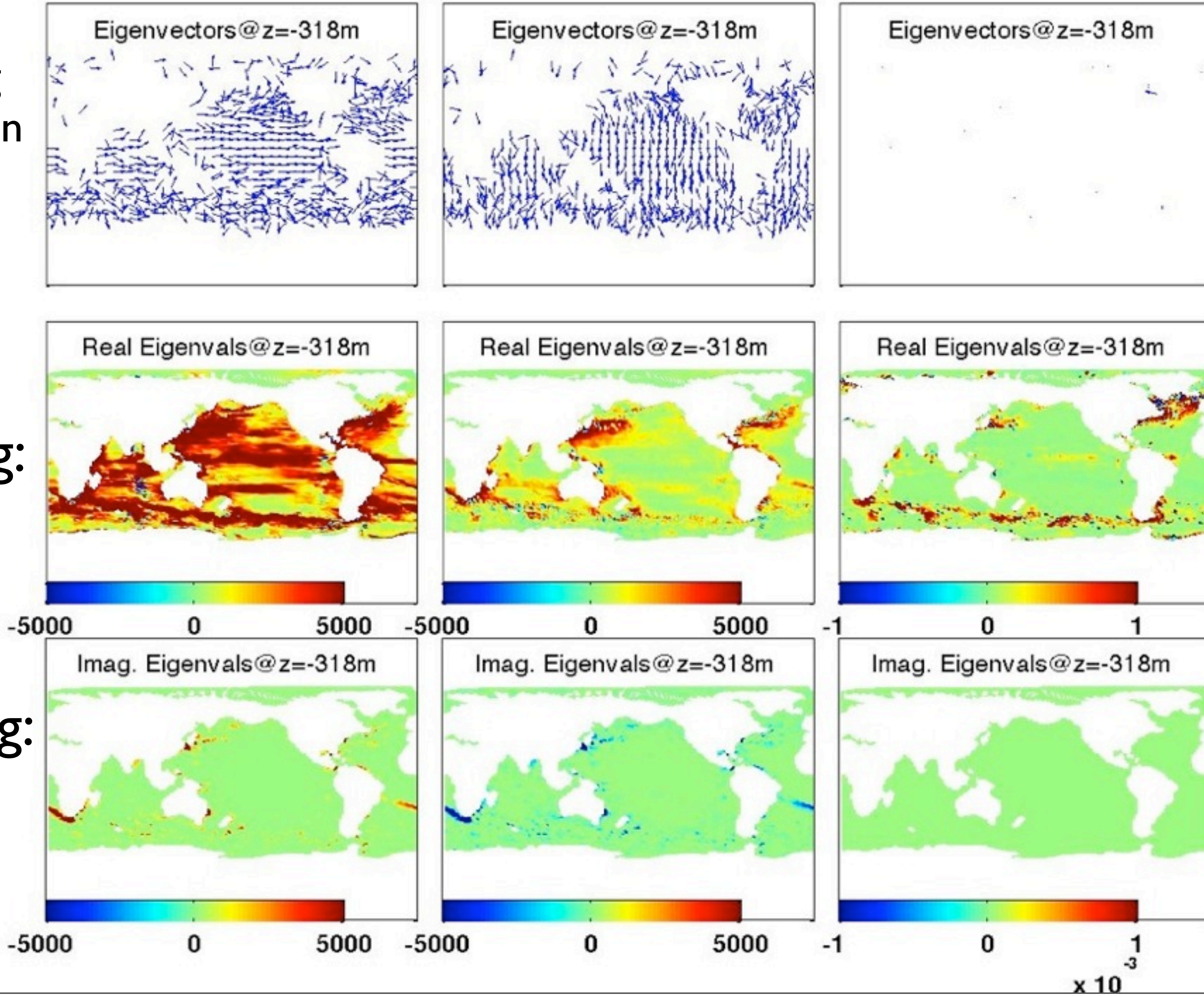
<6% negative

Result: Strong Anisotropy Along/Across Isopycnals

Mixing direction

Mixing:

Stirring:

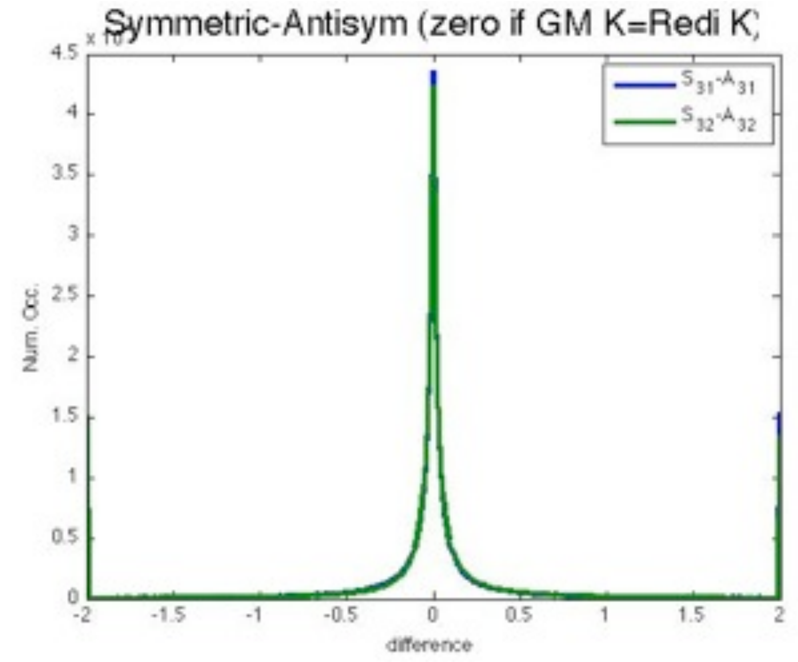


Advanced Mesoscale

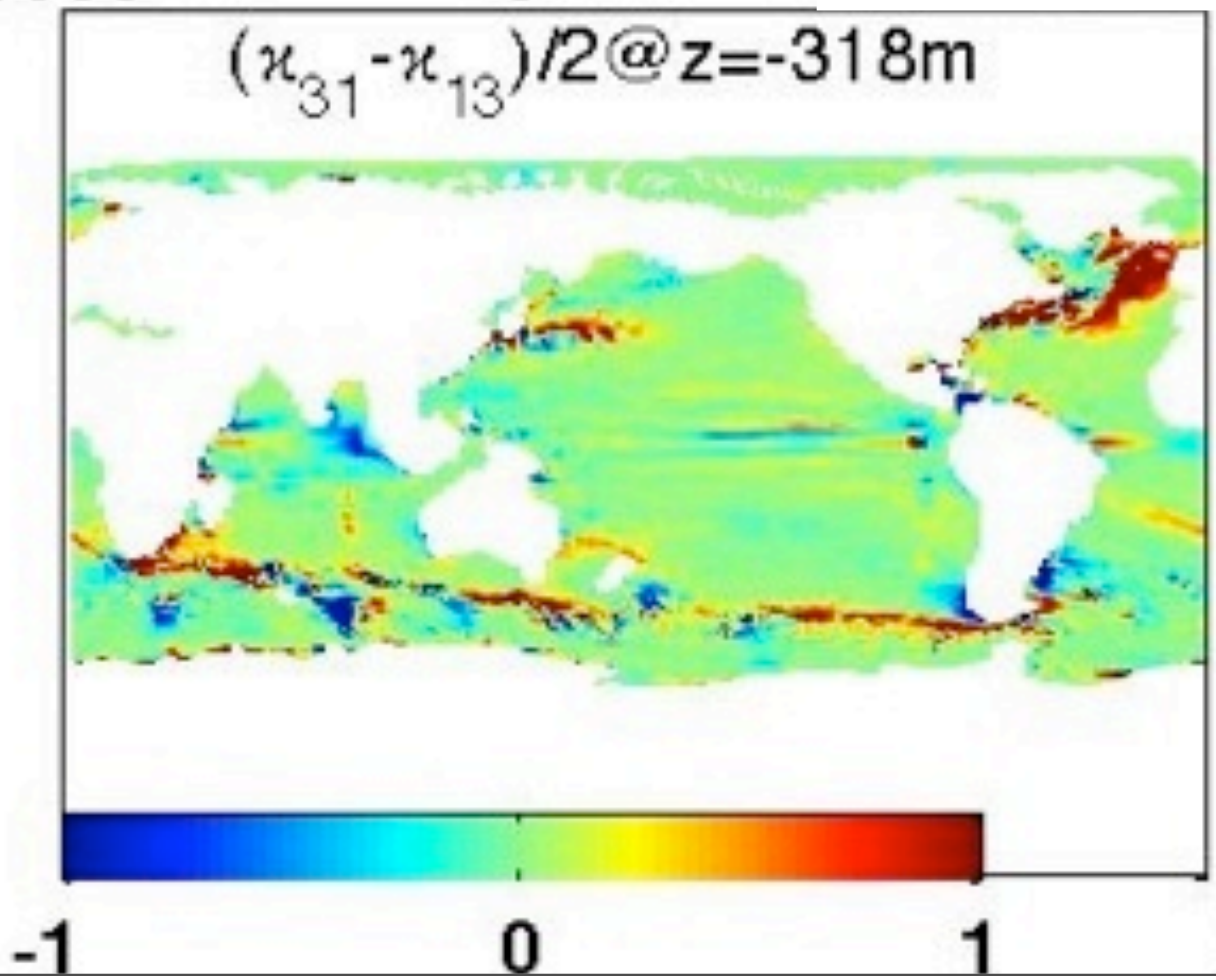
- GM=Redi
- Horizontal Variations
- Horizontal Direction (Anisotropy)
- Vertical Variations

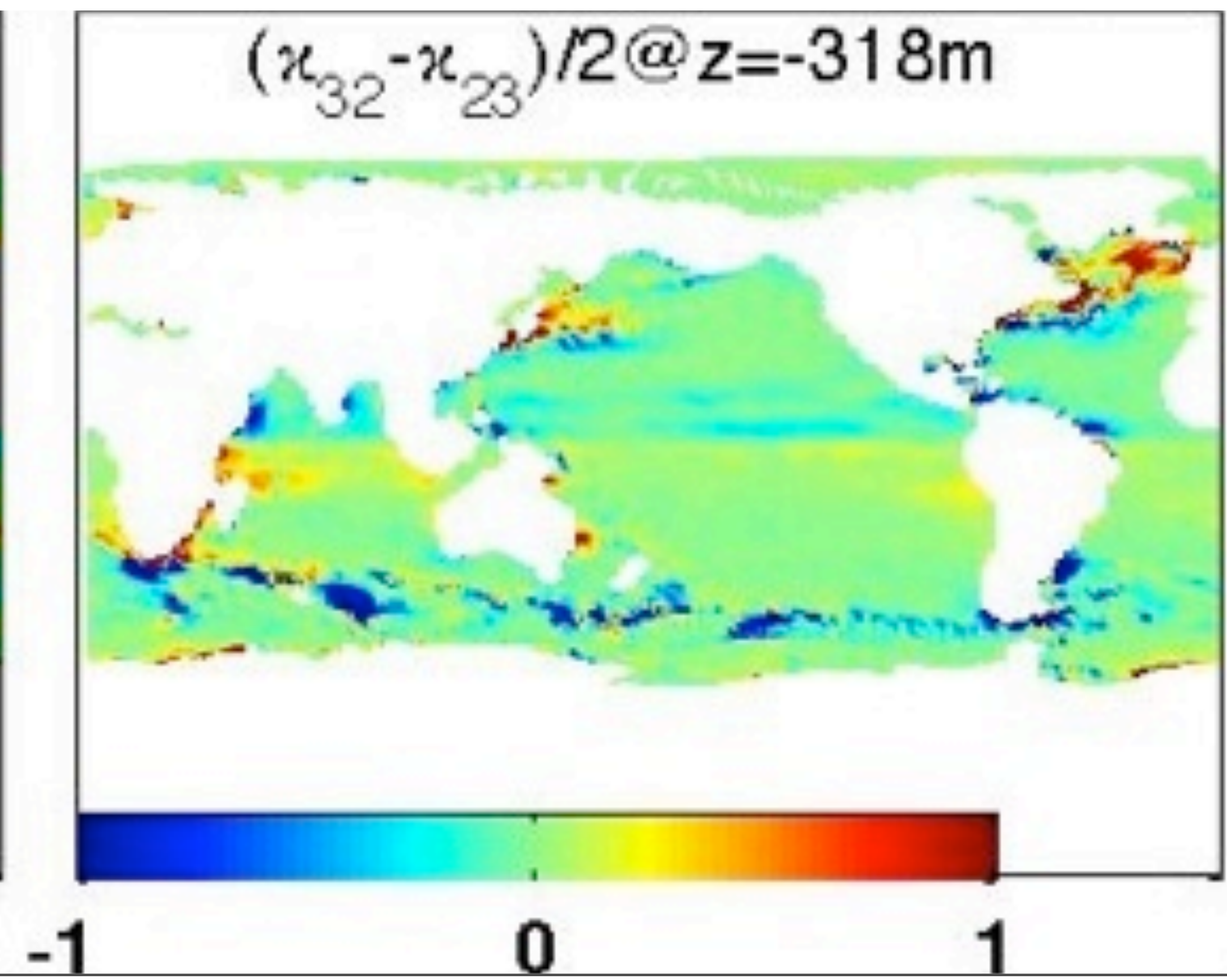
Result:

Redi K=GM K(mostly)



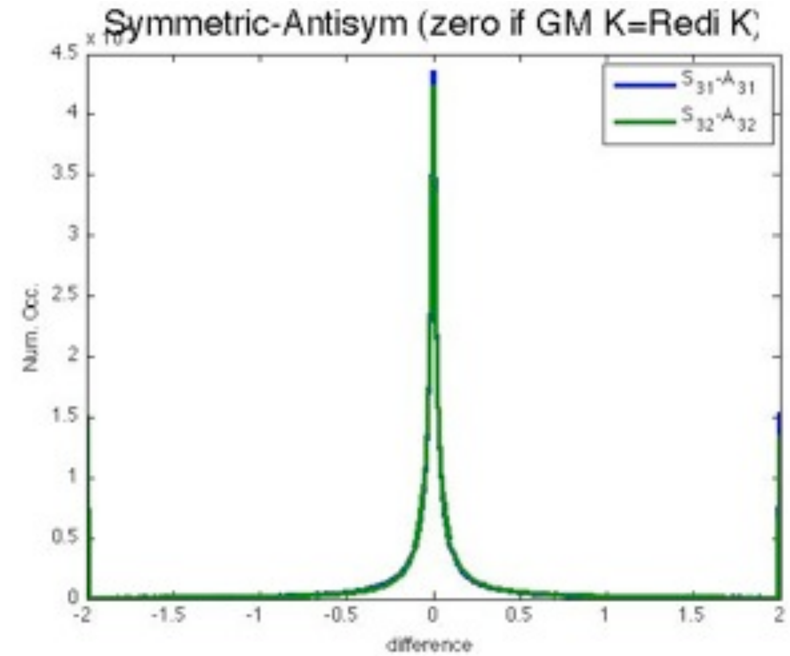
If so these 2 components should match in Sym & Antisym M



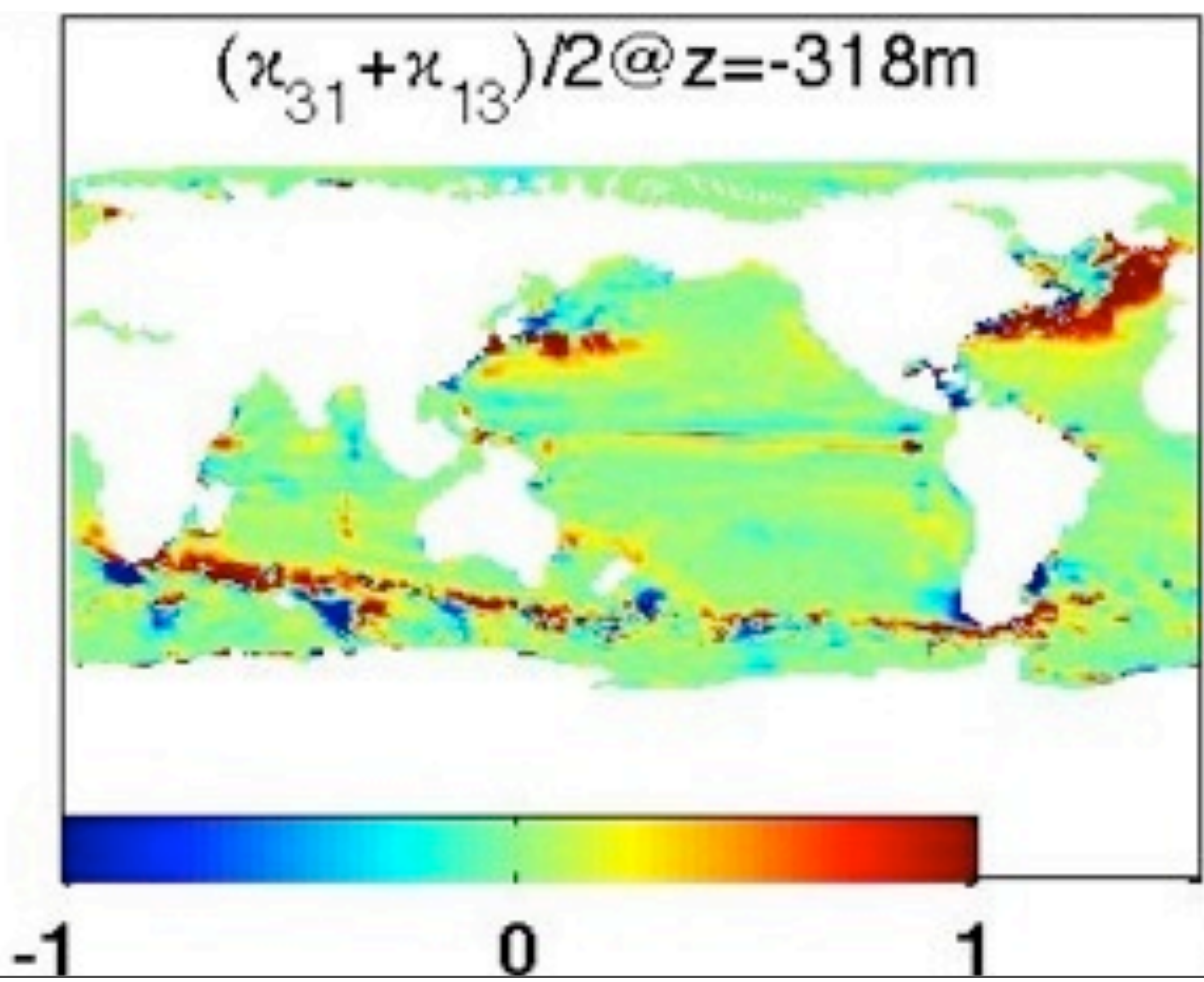


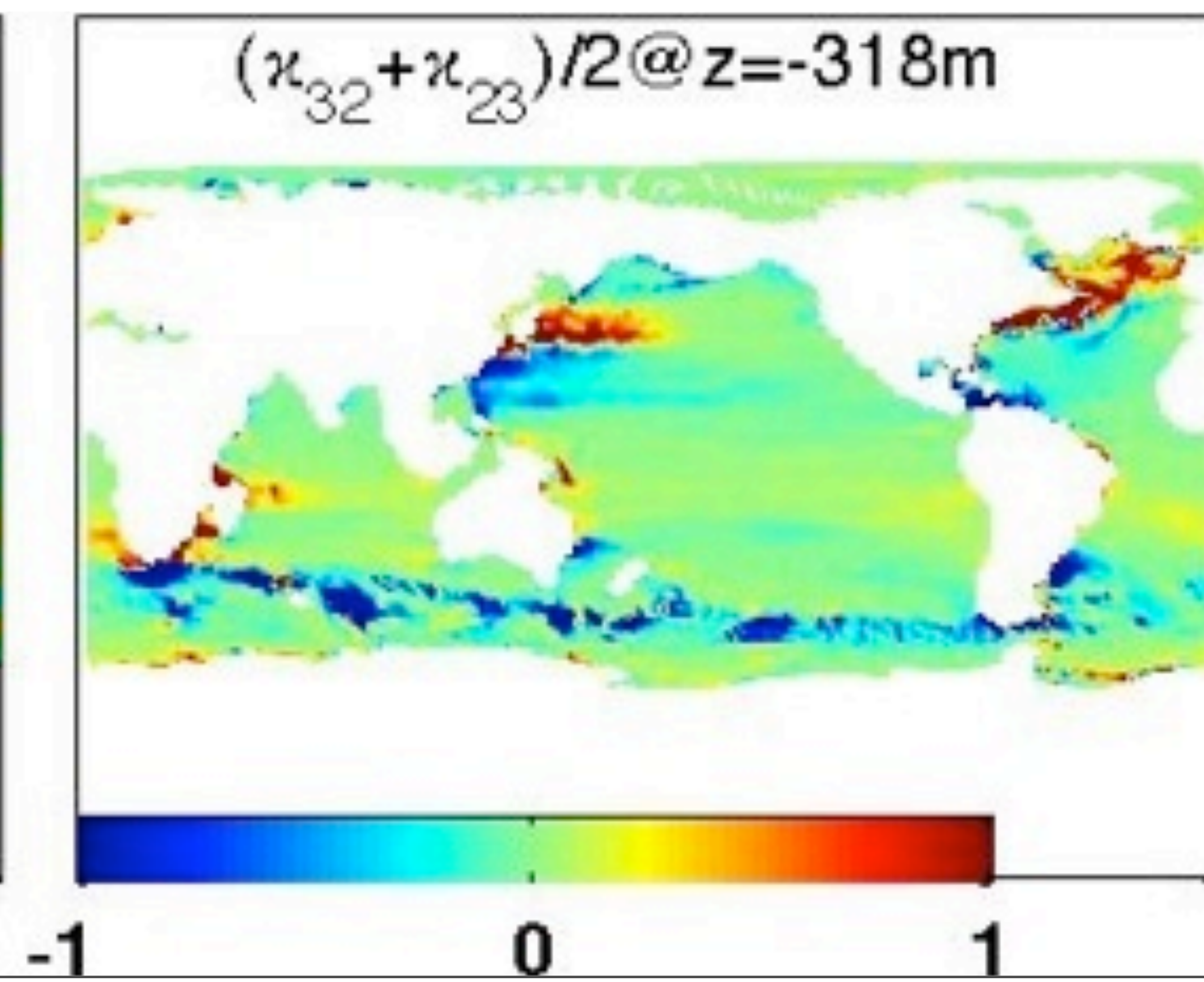
Result:

Redi K=GM K(mostly)



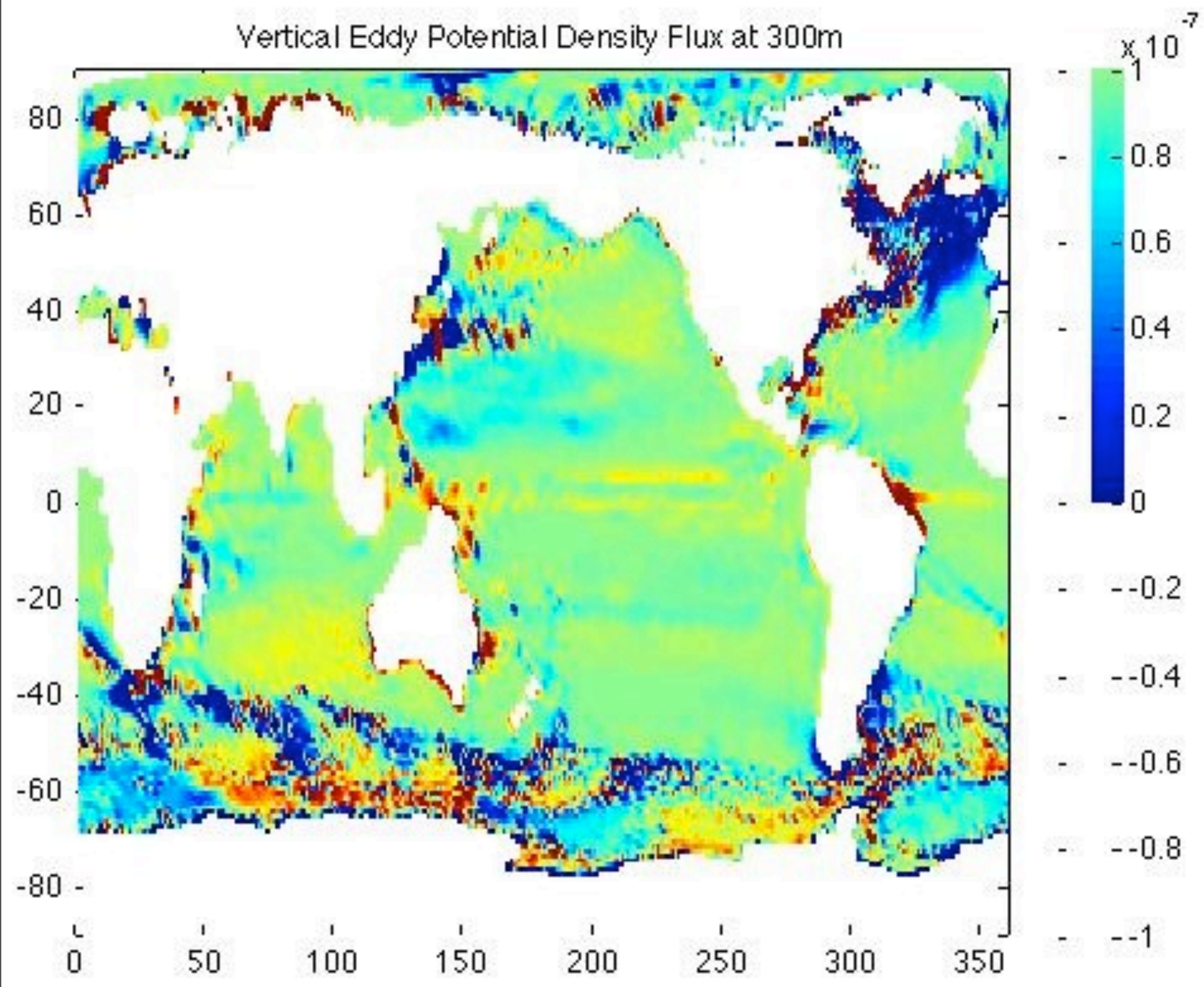
If so these 2 components should match in Sym & Antisym M



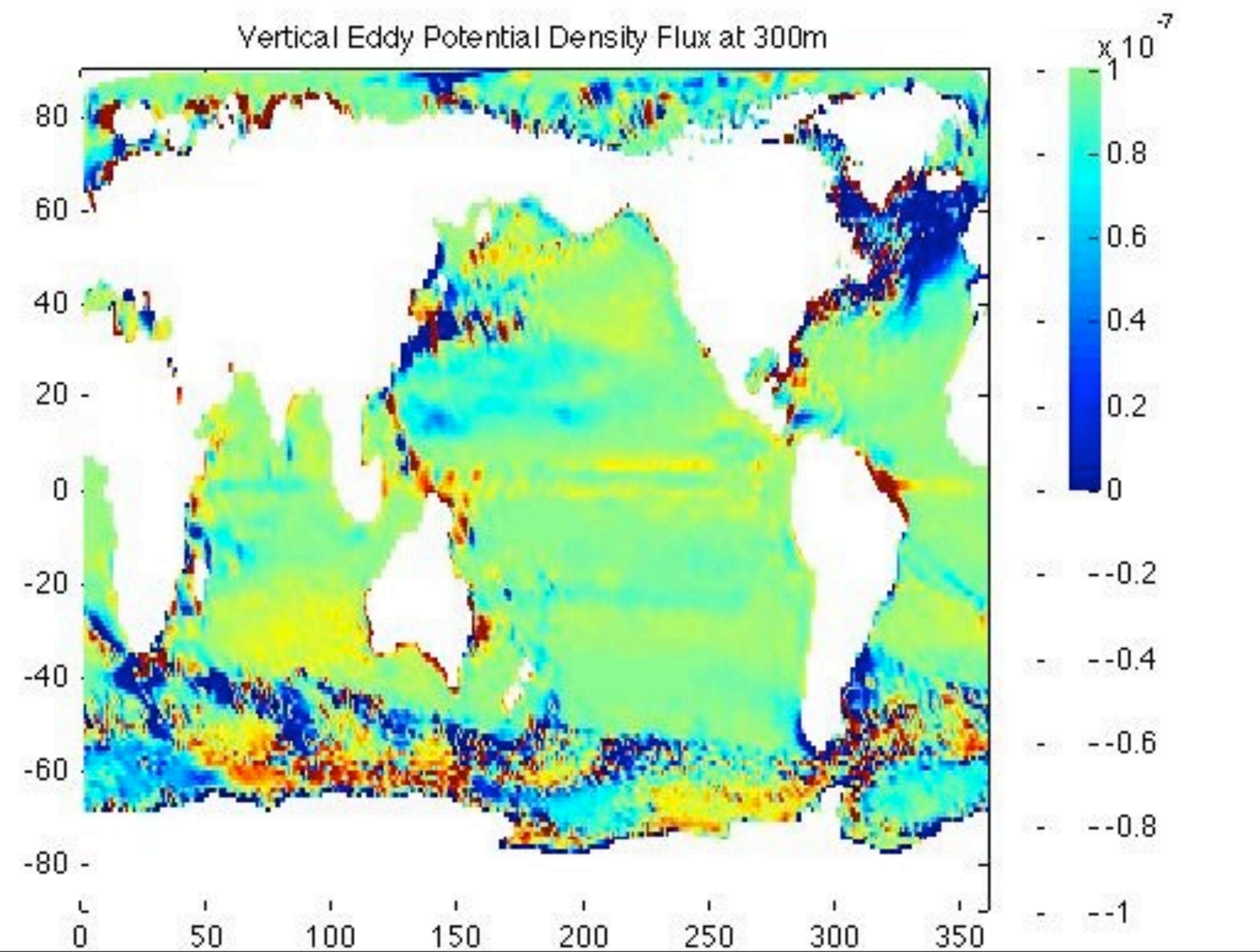


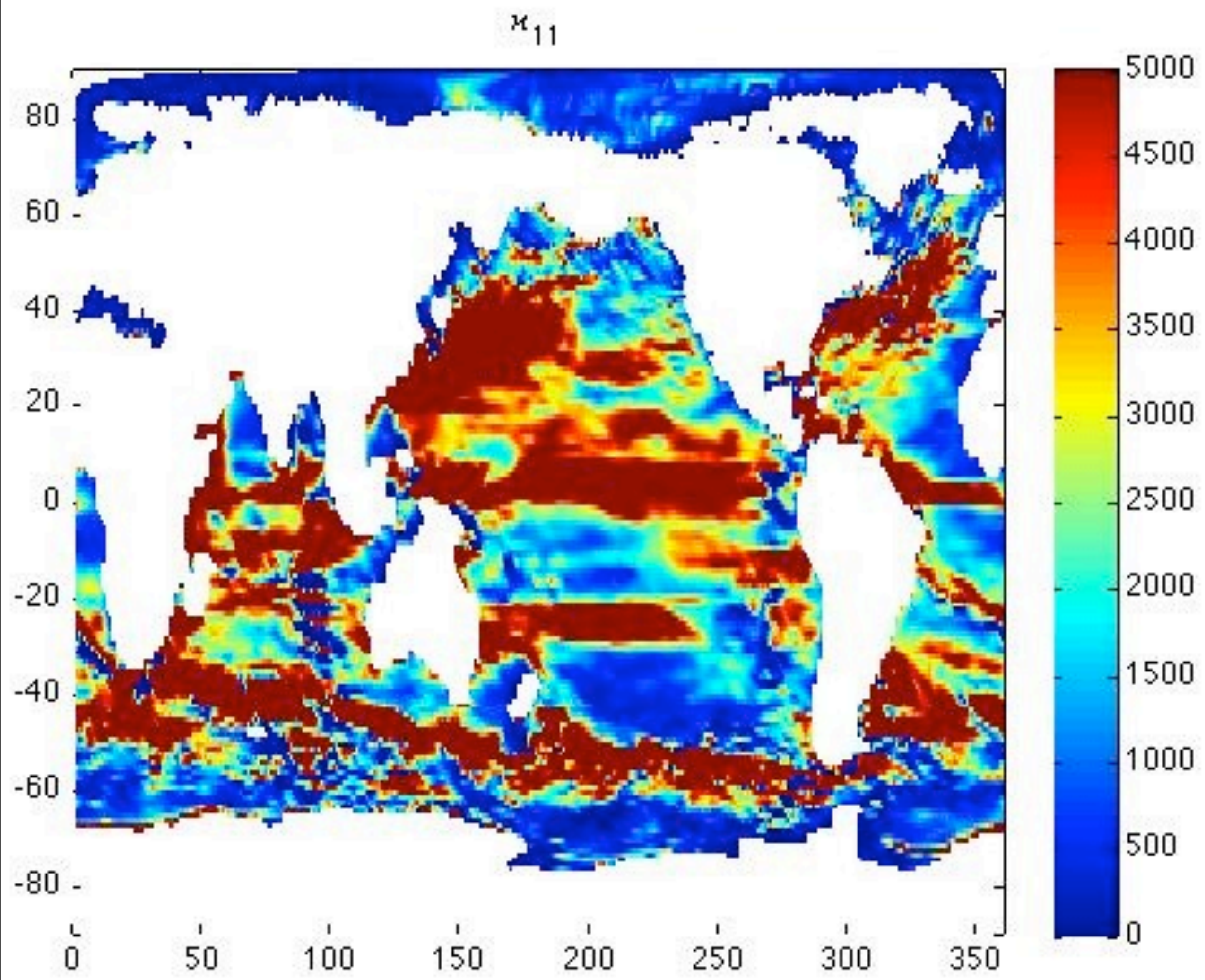
How do we explain the Horizontal Variations and direction of K?

Compare to vertical eddy density flux (PE Extraction)



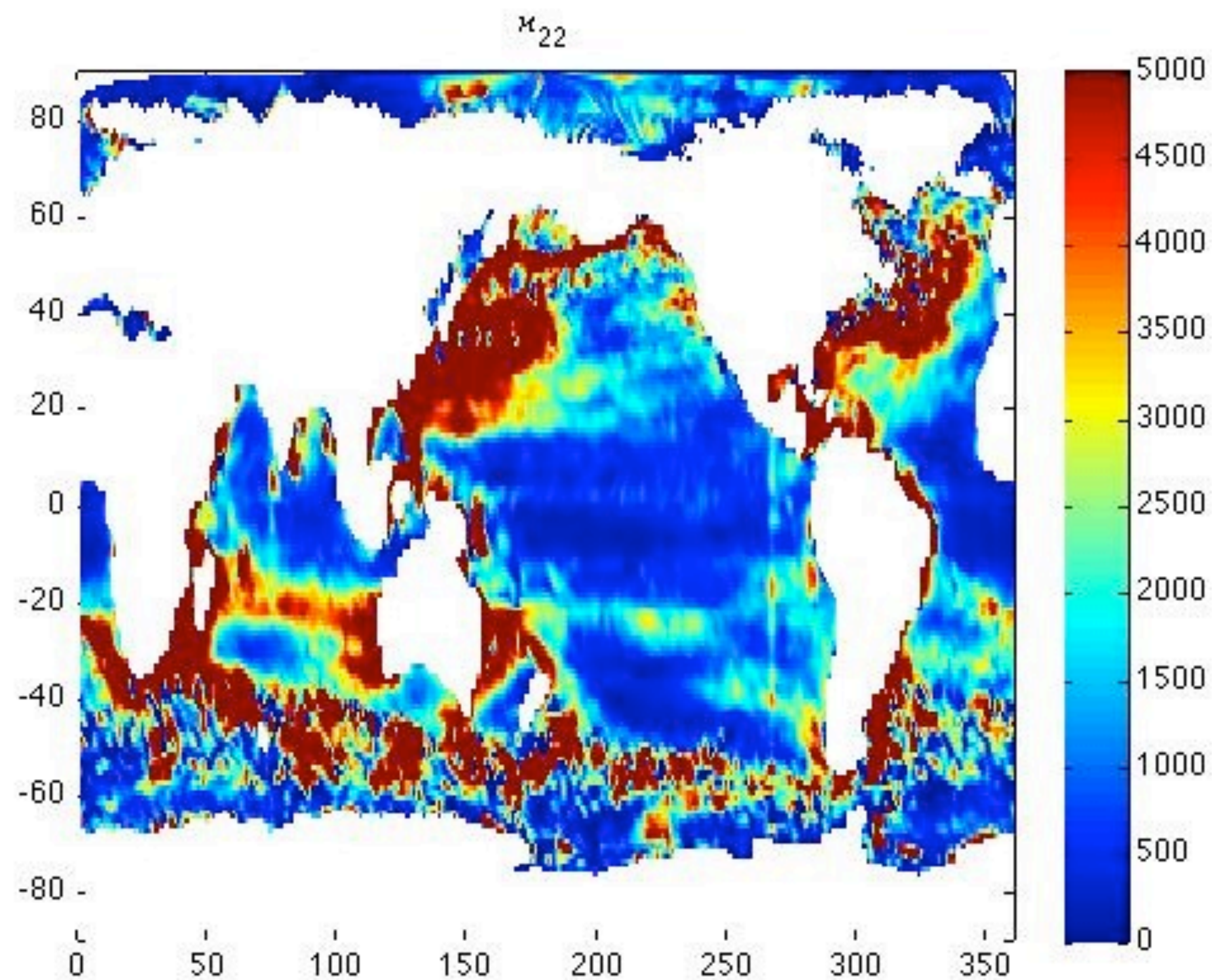
- Eden&Greatbatch (+others) propose that baroclinic instability's production of EKE from PE should guide M magnitude



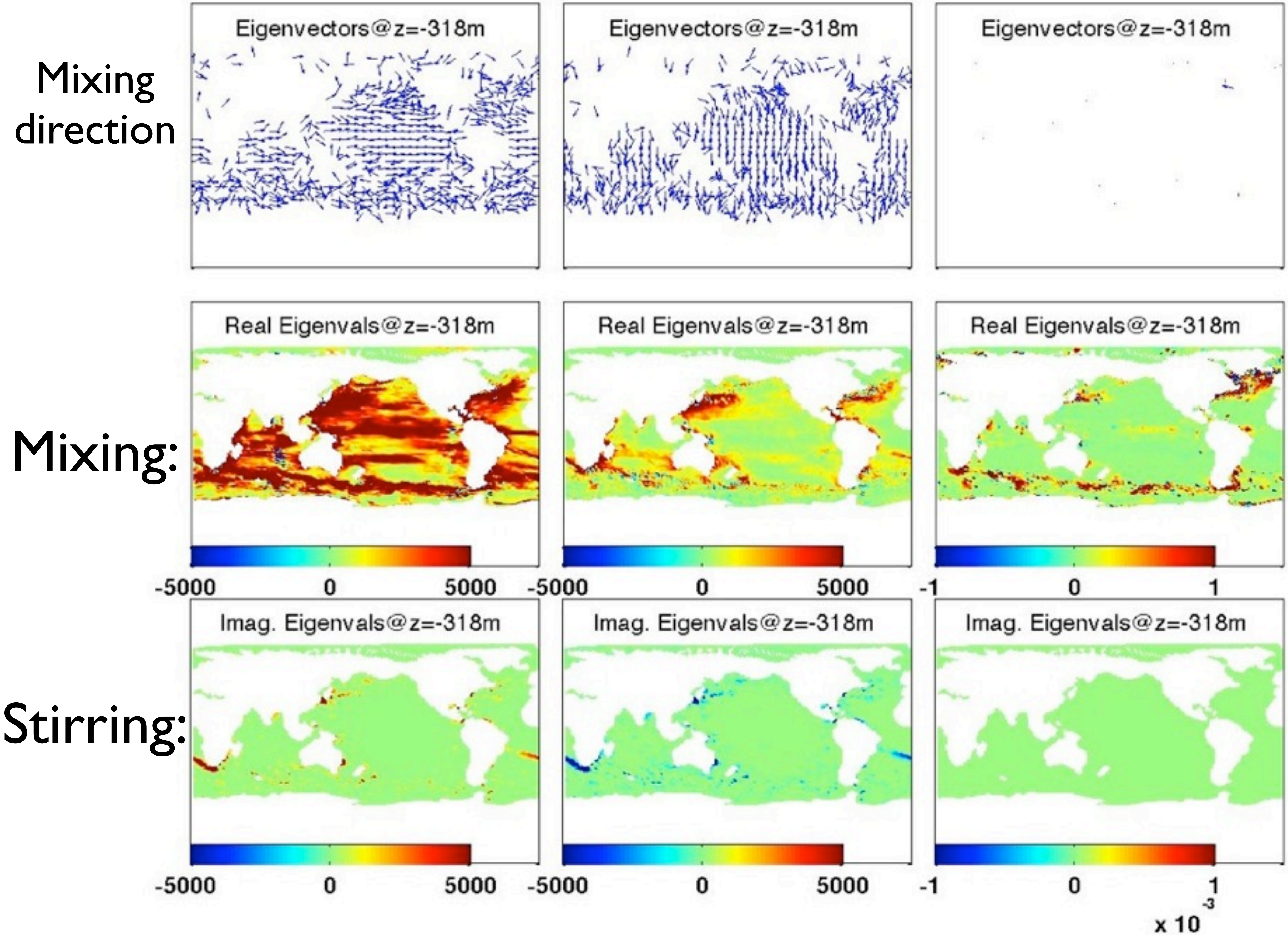


Locations of PE extraction are

Locations of large eigs of **K**



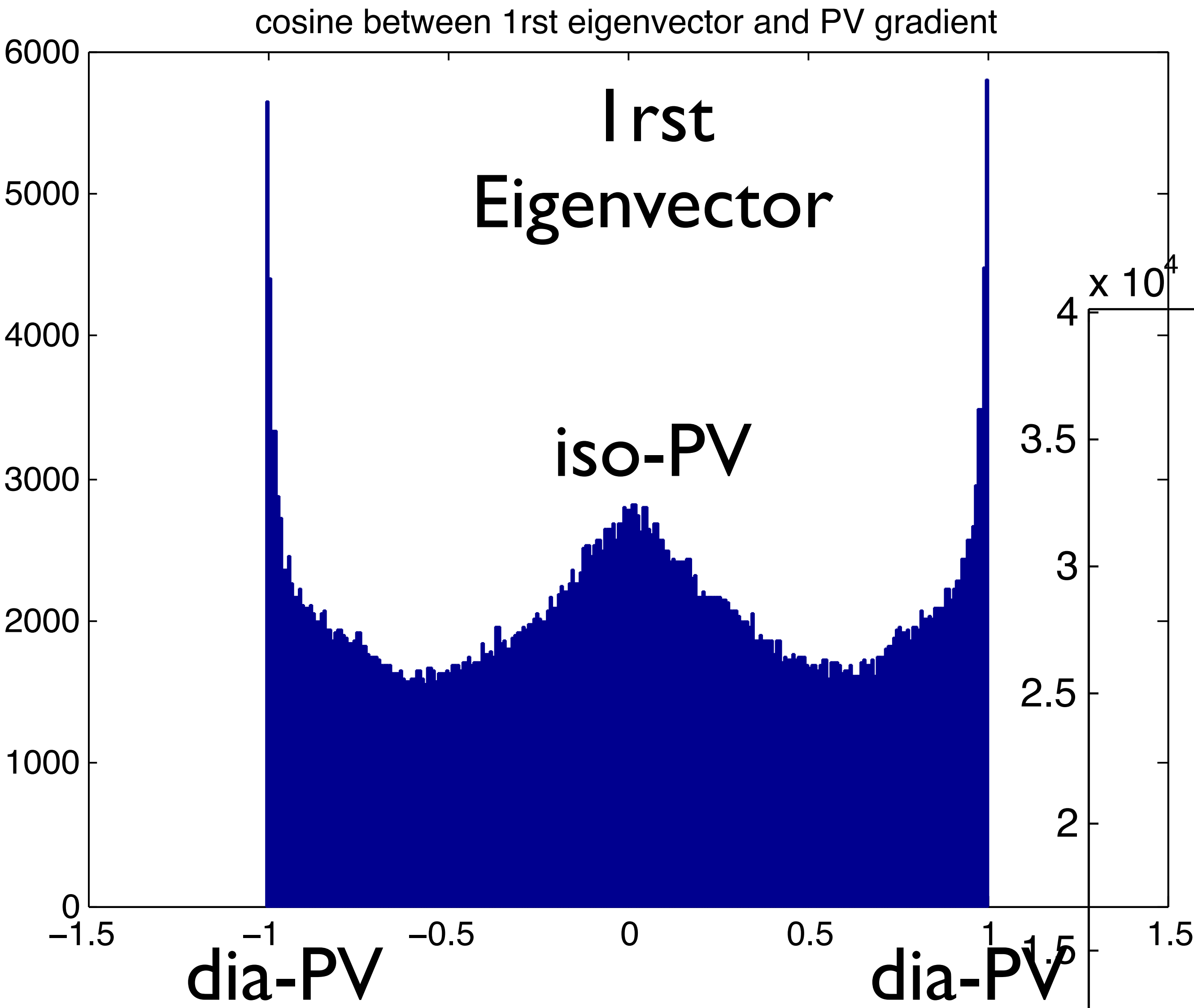
Result: Strong Anisotropy Along/Across PV Grads.



Result: Strong Anisotropy Along/Across PV Grads.

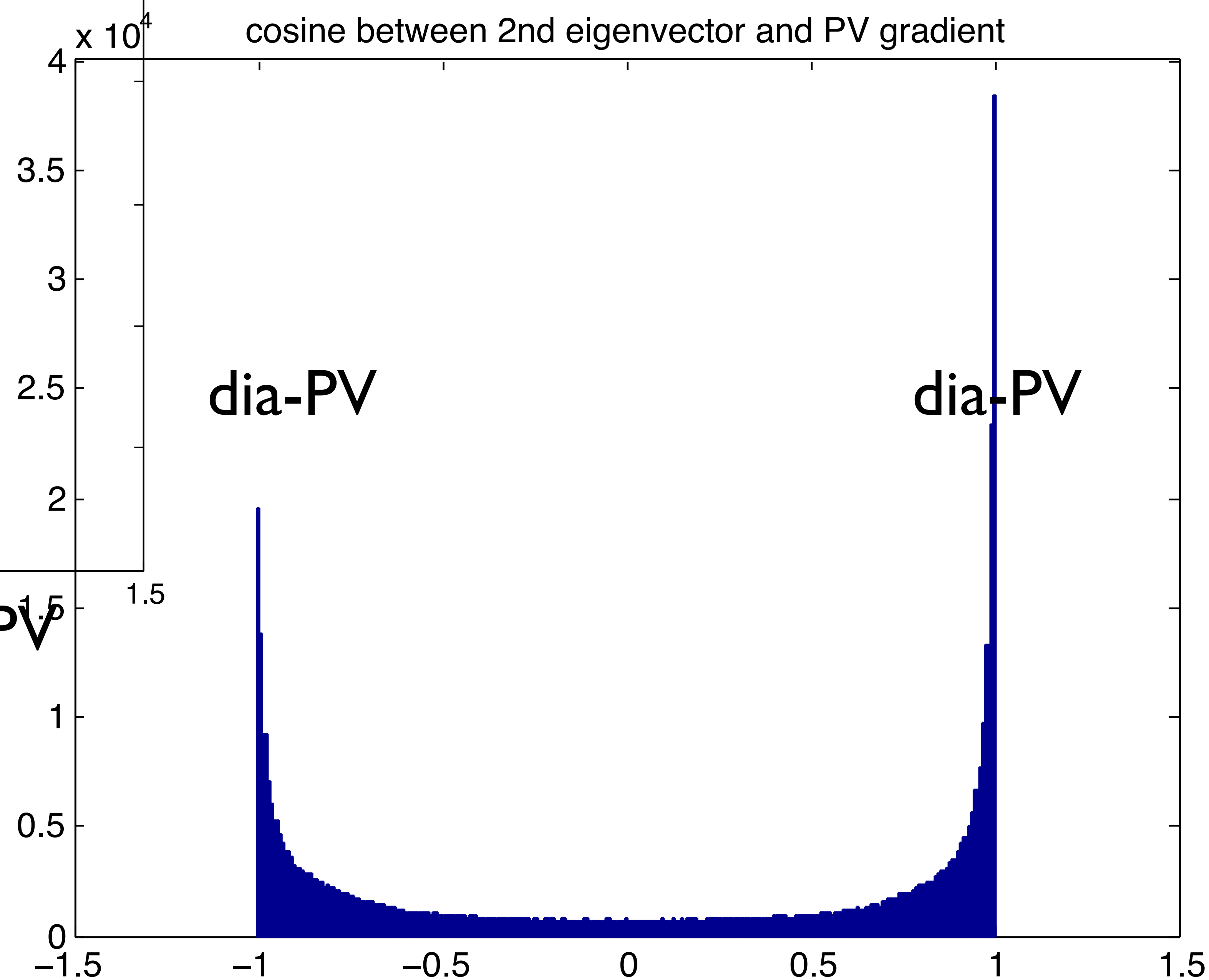
Mixing direction

Either along PV contours or across



2nd Eigenvector

Across PV contours



How do we explain the Vertical Variations of K?

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

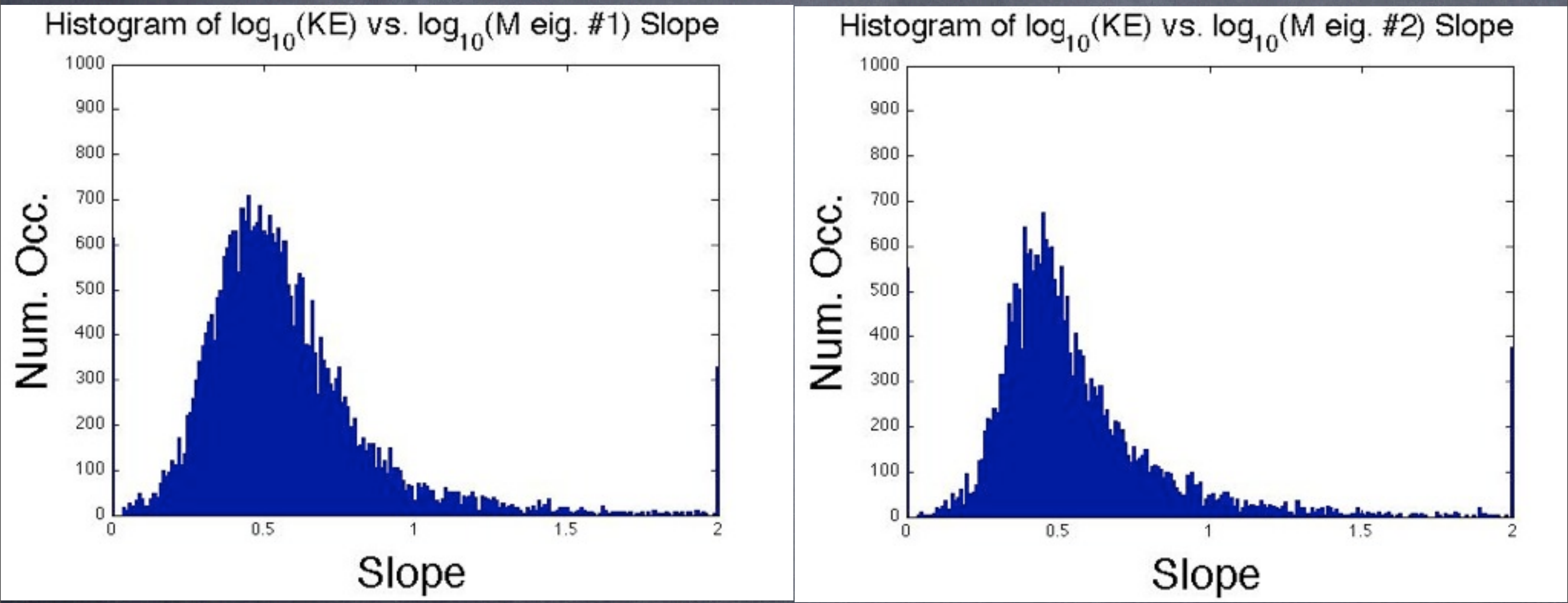
We expect: $$\mathbf{K} \propto \sqrt{\mathbf{EKE}}$$

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

Result:

coarse KE-> vertical structure of Mixing

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

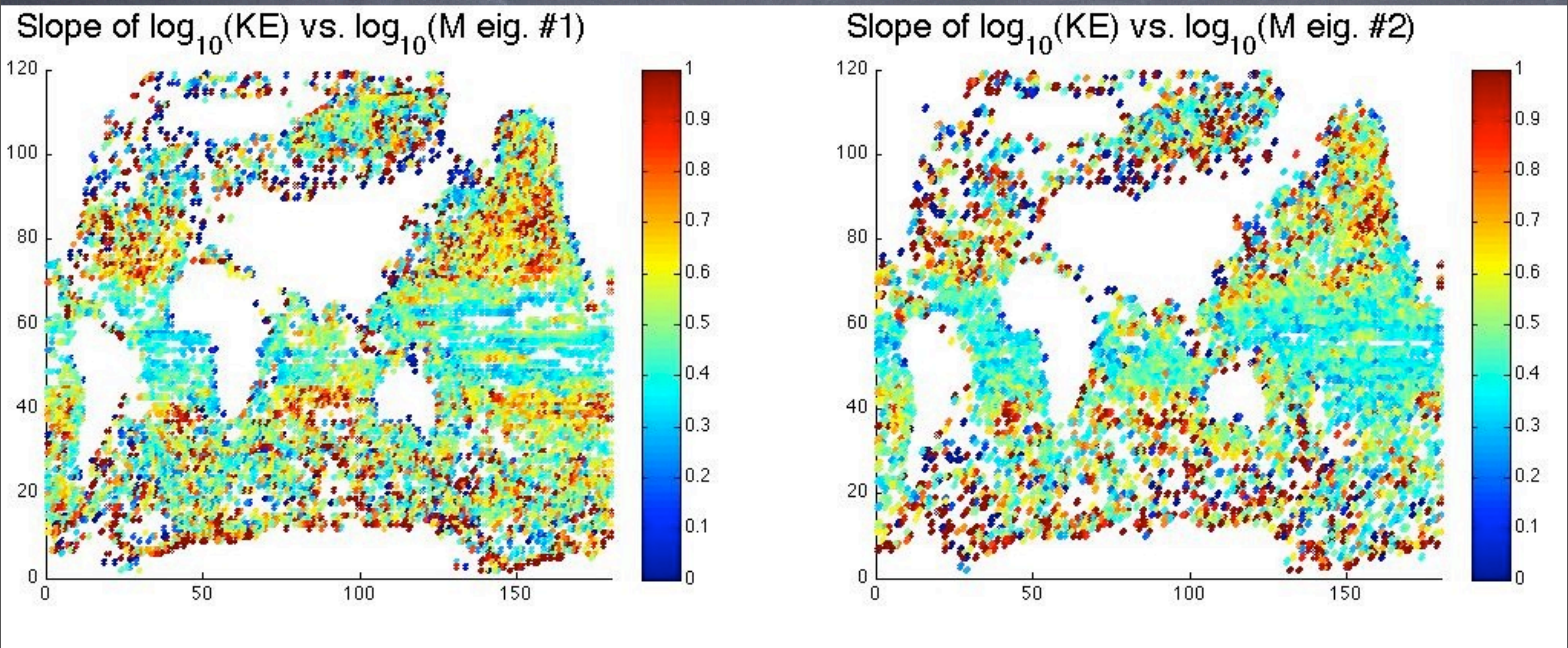


Even better with EKE!

Note--barotropic mode is in there!

Result:
power law not 'random'

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



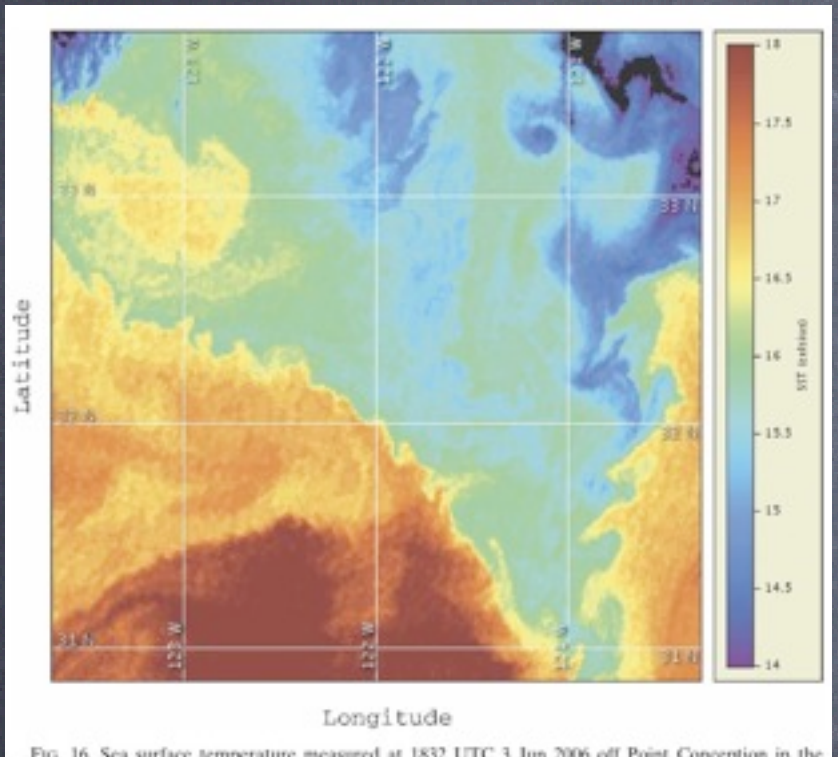
However, can probably do better!
Slopes not random.

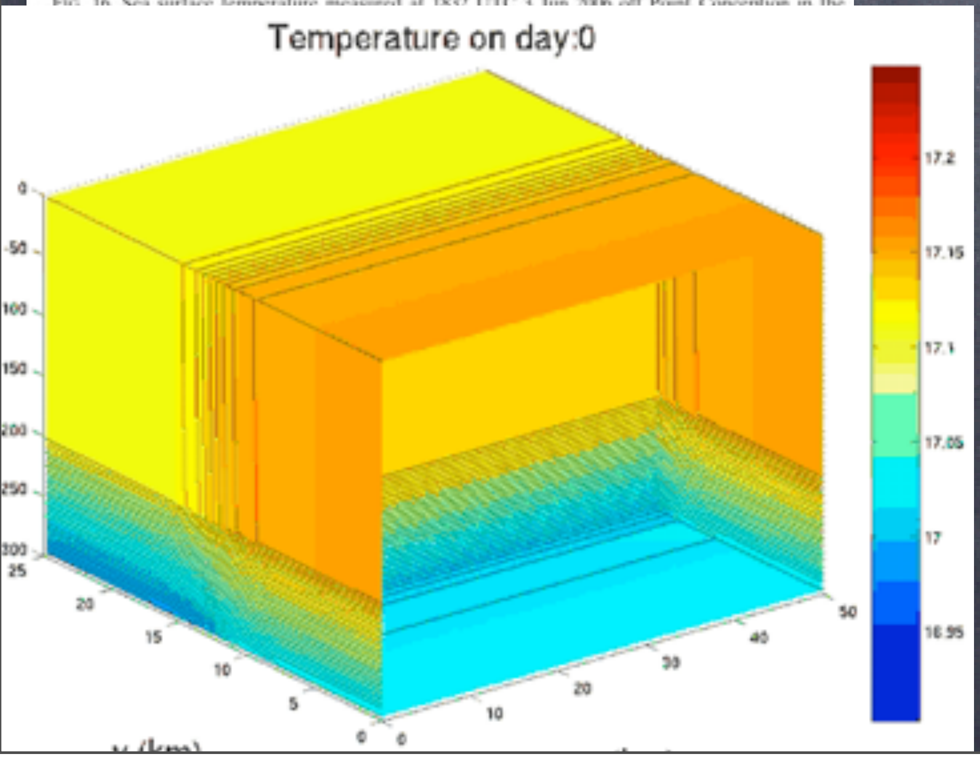
Conclusions

- 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 uniquely
- 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

2. Submesoscale

(Capet et al., 2008)



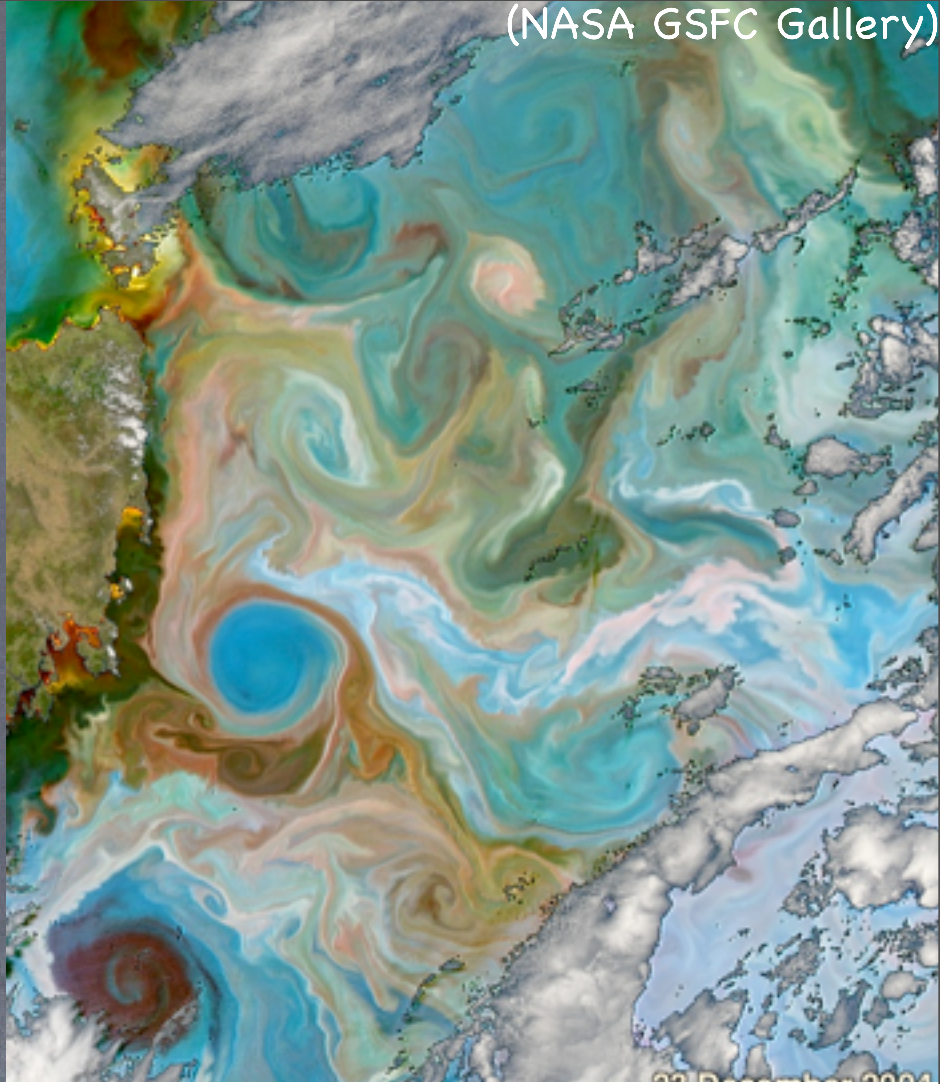


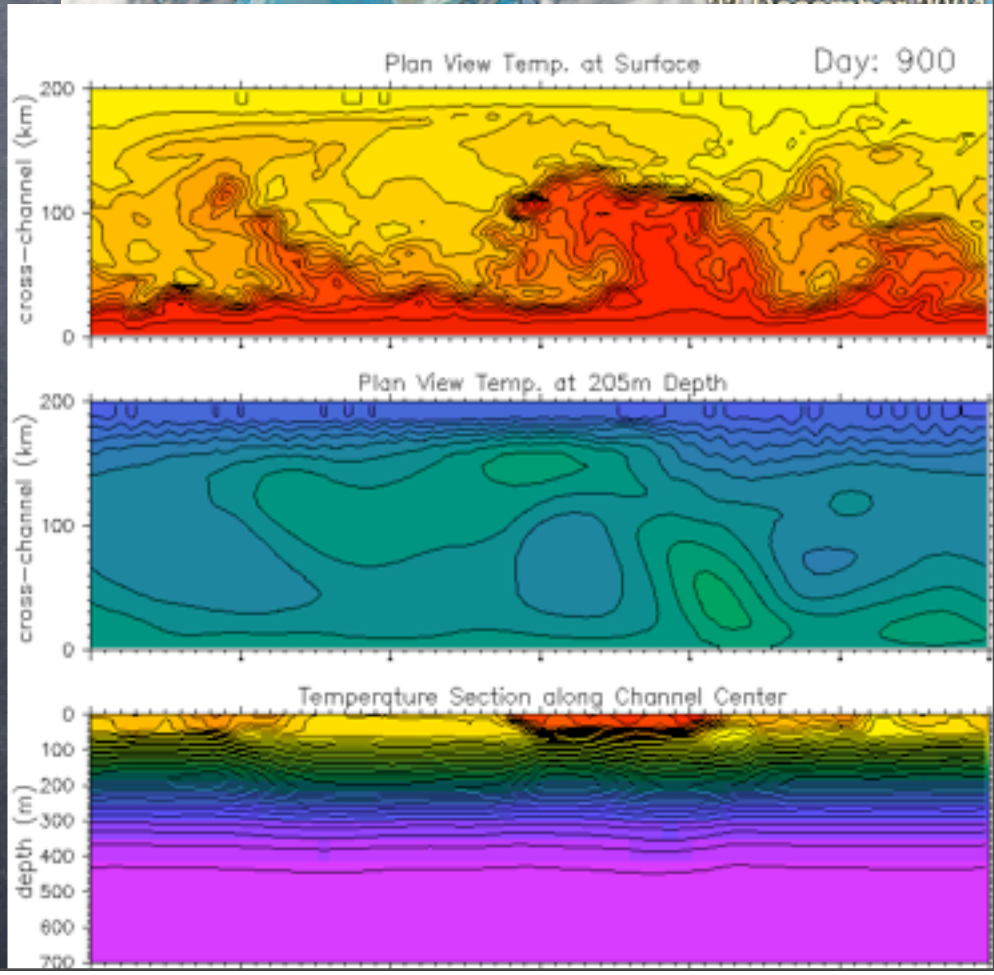
- Fronts
- Eddies
- Ro=O(1)
- Ri=O(1)
- near-surface
- 1-10km, days

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

< 10 km

(NASA GSFC Gallery)





A Global Parameterization of Mixed Layer Eddy Restratification with FLOW DEPENDENT M validated against simulations

Fox-Kemper, Ferrari, & Hallberg (2008) &
Fox-Kemper et al (2011, in press)

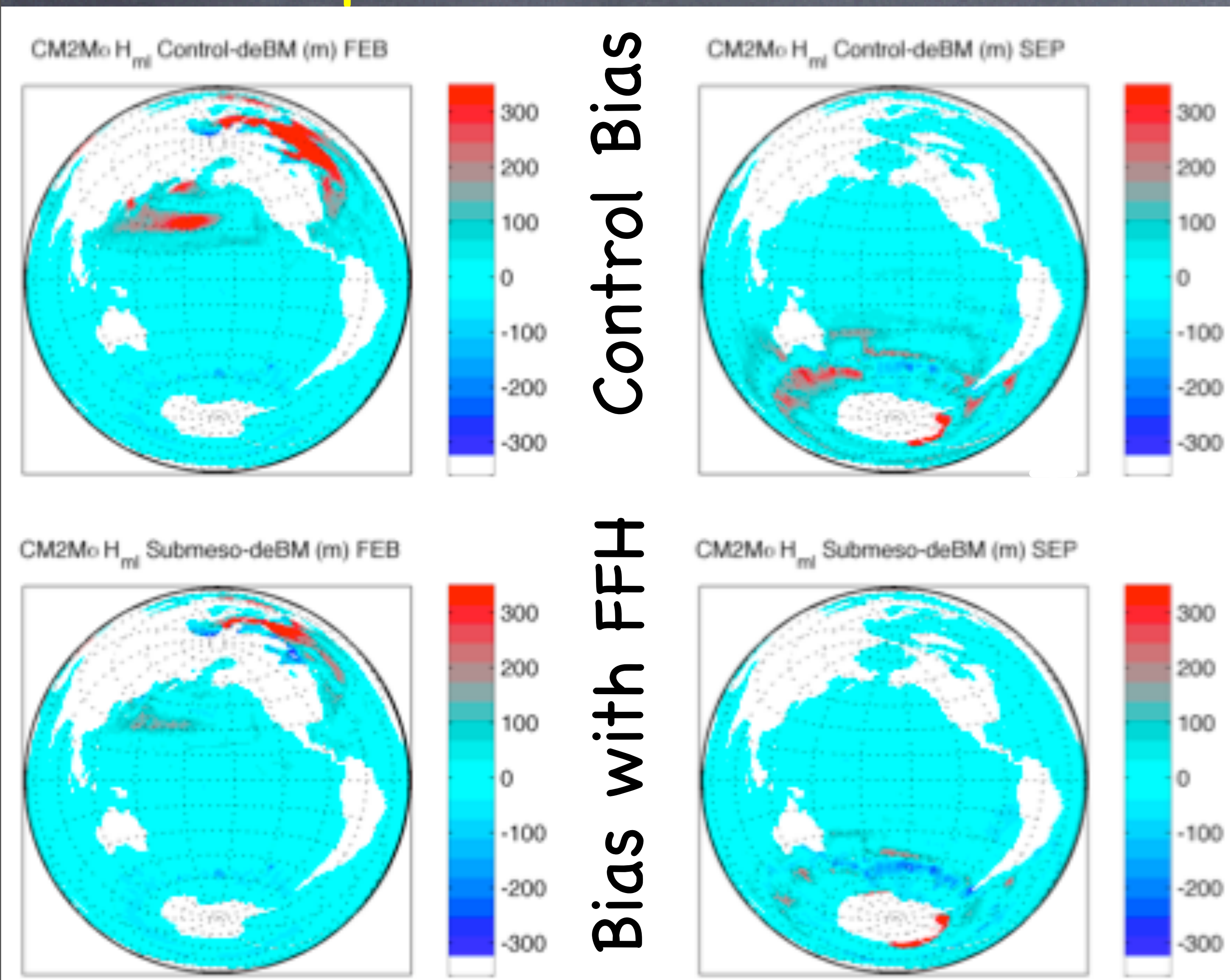
$$\begin{bmatrix} \overline{u'\tau'} \\ \overline{v'\tau'} \\ \overline{w'\tau'} \end{bmatrix} = -\begin{bmatrix} 0 & 0 & -\mathbf{\Psi_y} \\ 0 & 0 & \mathbf{\Psi_x} \\ \mathbf{\Psi_y} & -\mathbf{\Psi_x} & 0 \end{bmatrix} \begin{bmatrix} \overline{\tau}_x \\ \overline{\tau}_y \\ \overline{\tau}_z \end{bmatrix}$$

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

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

Physical Sensitivity of Ocean Climate to Submesoscale Eddy Restratification:

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

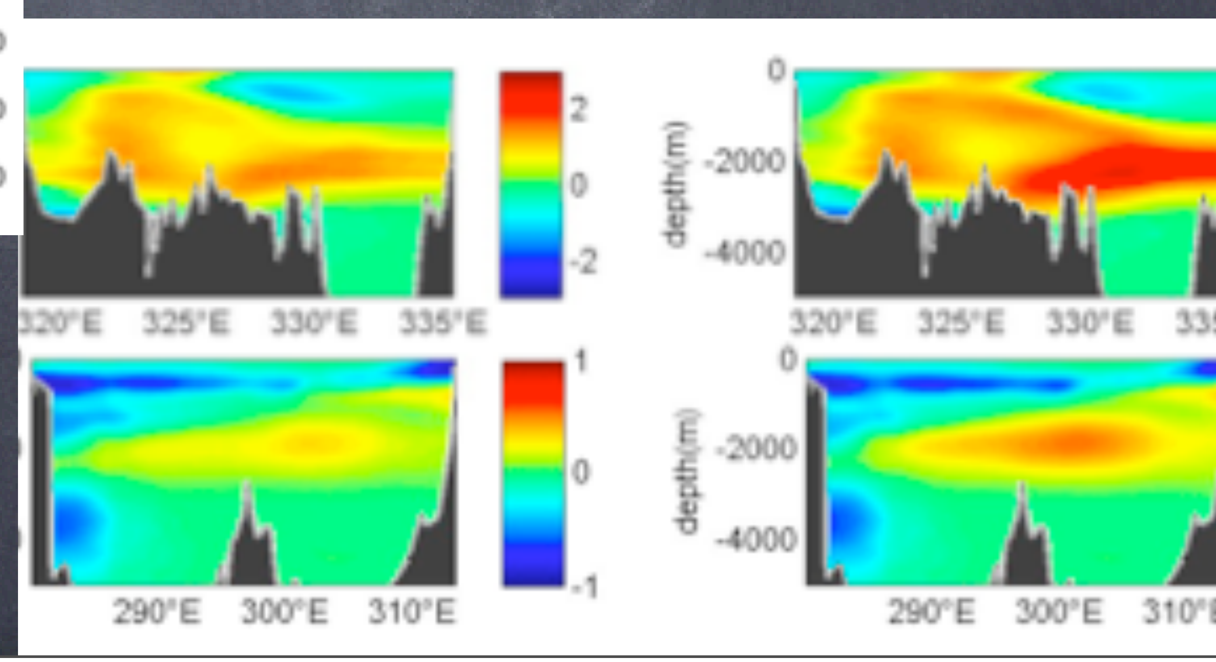


NO RETUNING NEEDED!!!

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

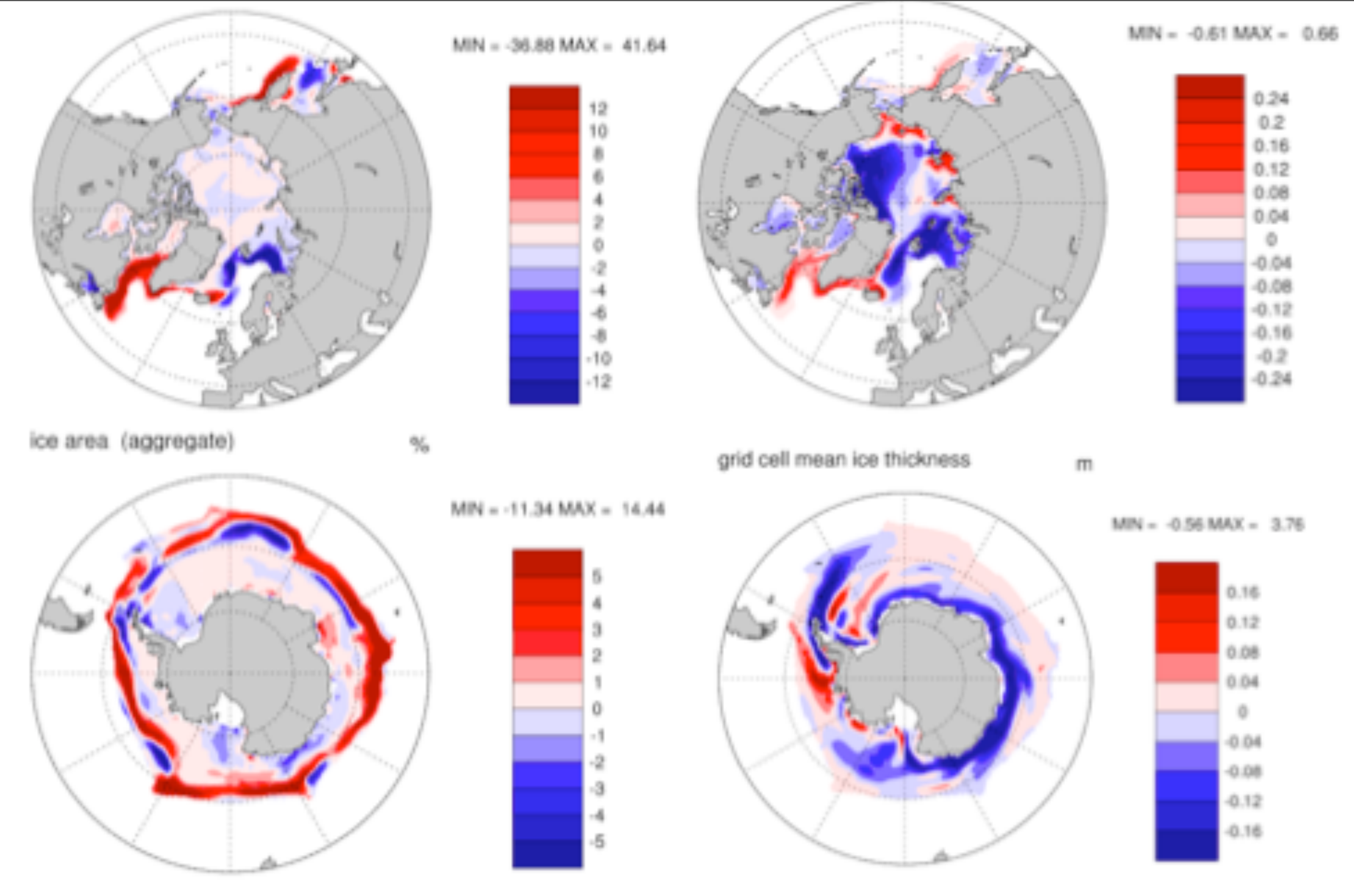
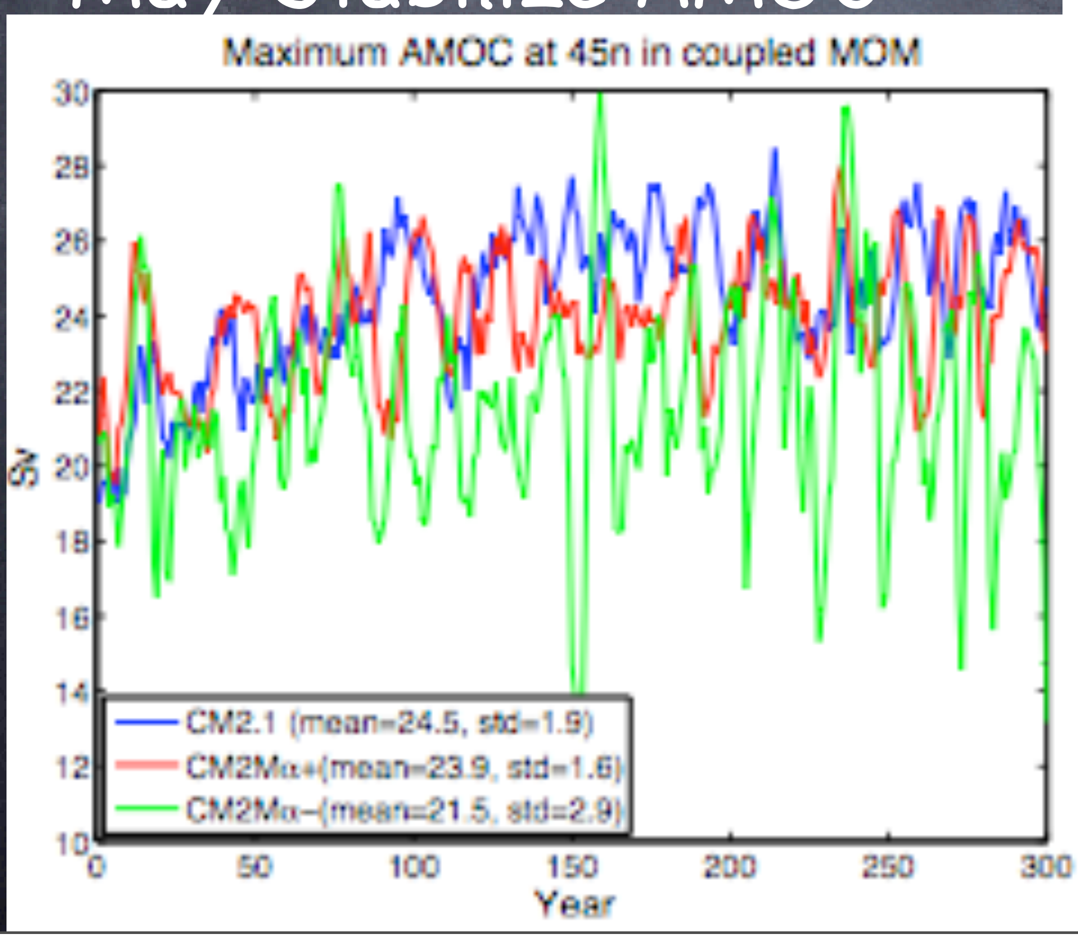


Figure 10: Wintertime sea ice sensitivity to introduction of MLE parameterization ($CCSM^+$ minus $CCSM^-$): January to March Northern Hemisphere a) ice area and b) thickness and July to September Southern Hemisphere c) ice area and d) thickness.

Affects sea ice

NO RETUNING NEEDED!!!

May Stabilize AMOC



These are impacts:
bias change unknown

Conclusions:

2. Submesoscale

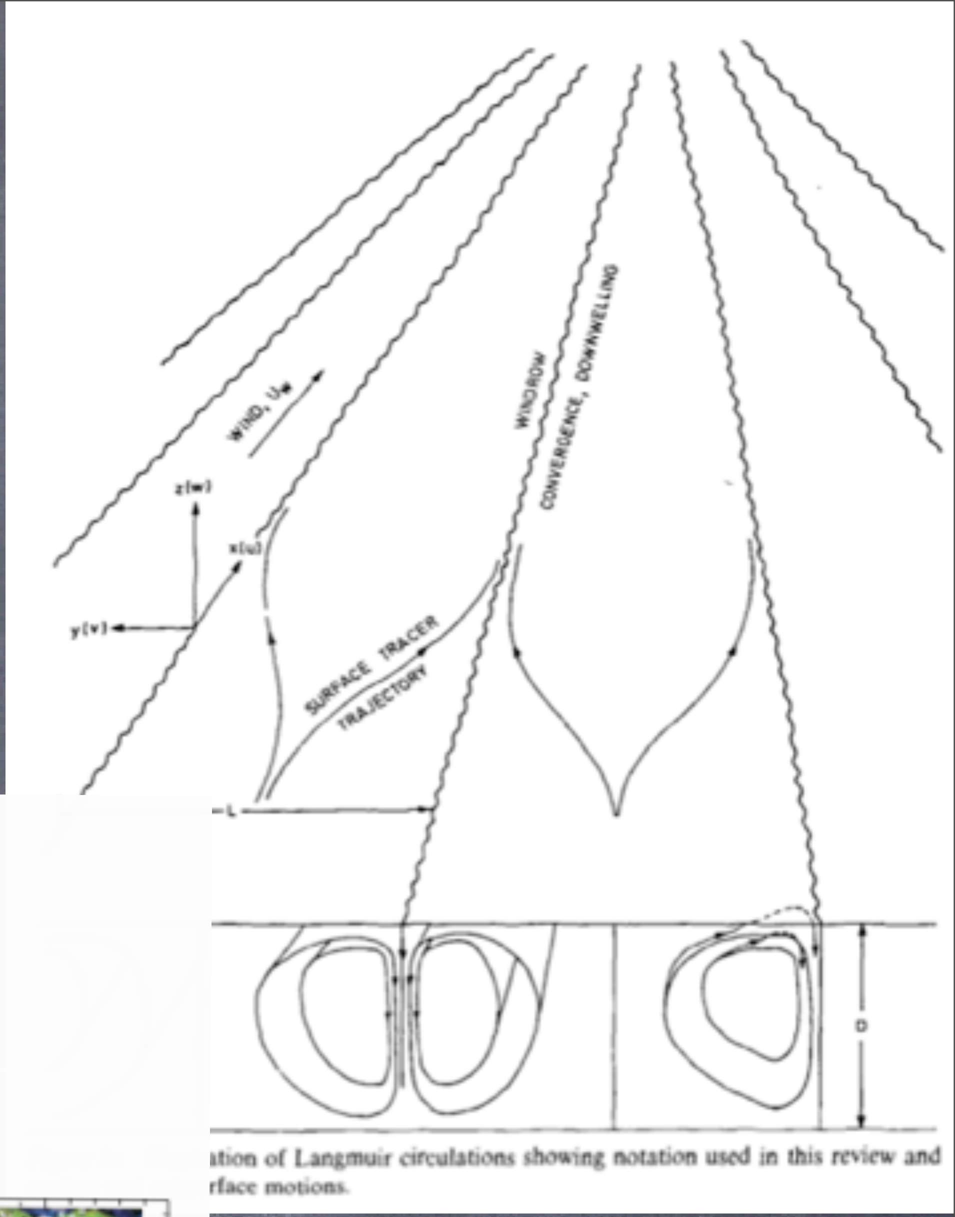
- FFH is used in at least 3 IPCC AR5 models
- Parameterization reduces bias in CFCs & Mixed Layer Depth
- Parameterization also affects ice, CFCs/Biology, & AMOC variability--need truth?
- Flow-dependent, nondimensional scalings validated against simulations *did not require retuning*

Review: Parameterization of Mixed Layer Eddies. III: Implementation and Impact in Global Ocean Climate Simulations, Fox-Kemper et al. 2011 Ocean Modelling in press for special issue

3: Langmuir Scale

- Near-surface
- Langmuir Cells & Langmuir Turb.
- Ro>>1
- Ri<1: Nonhydro
- 10-100m
- mins, hours
- w, u=O(20cm/s)
- Stokes drift
- Eqtns: Craik-Leibovich
- unused params exist (M&S,01 etc)

image: Leibovich, 83



...ation of Langmuir circulations showing notation used in this review and ...rface motions.

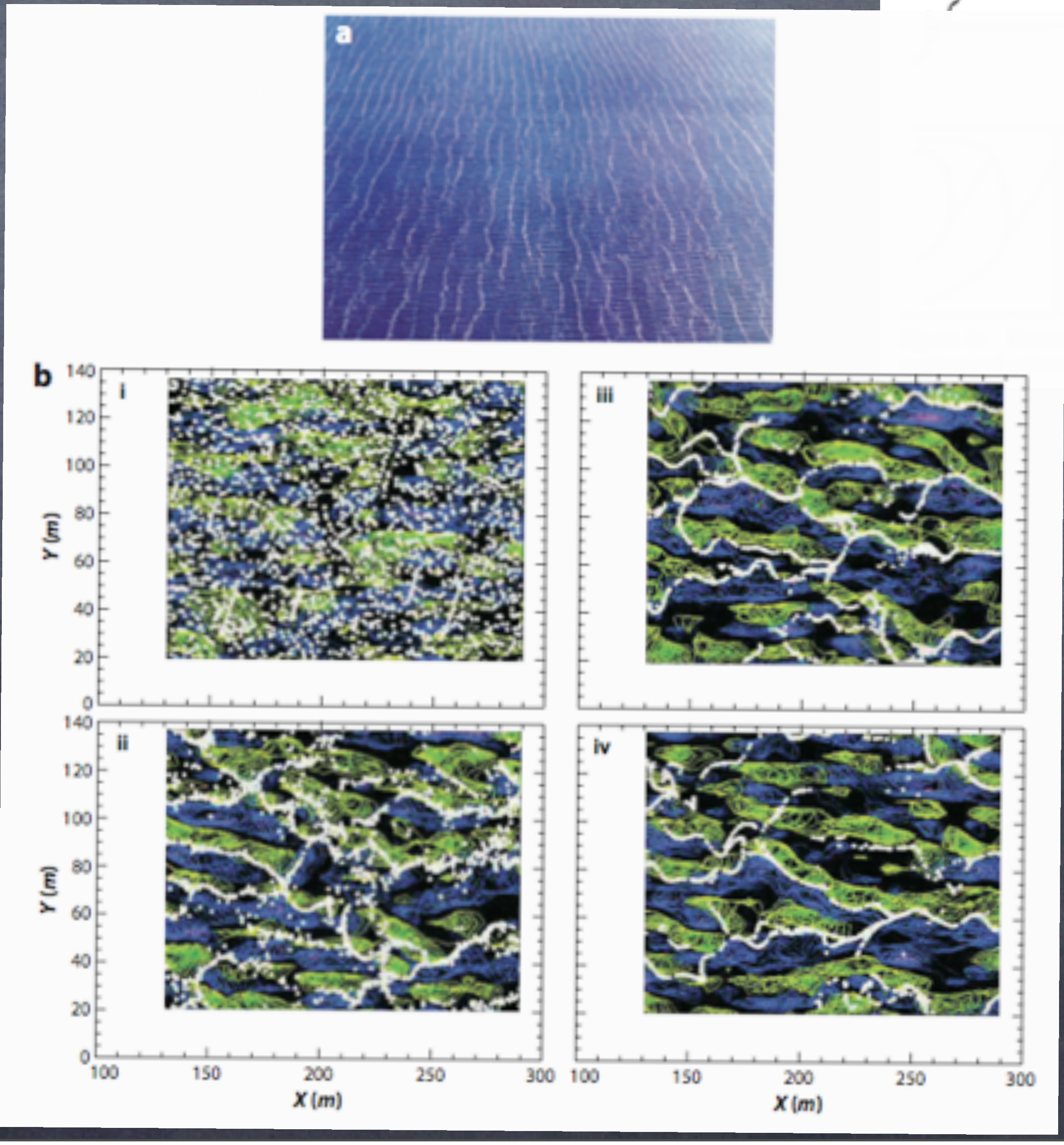
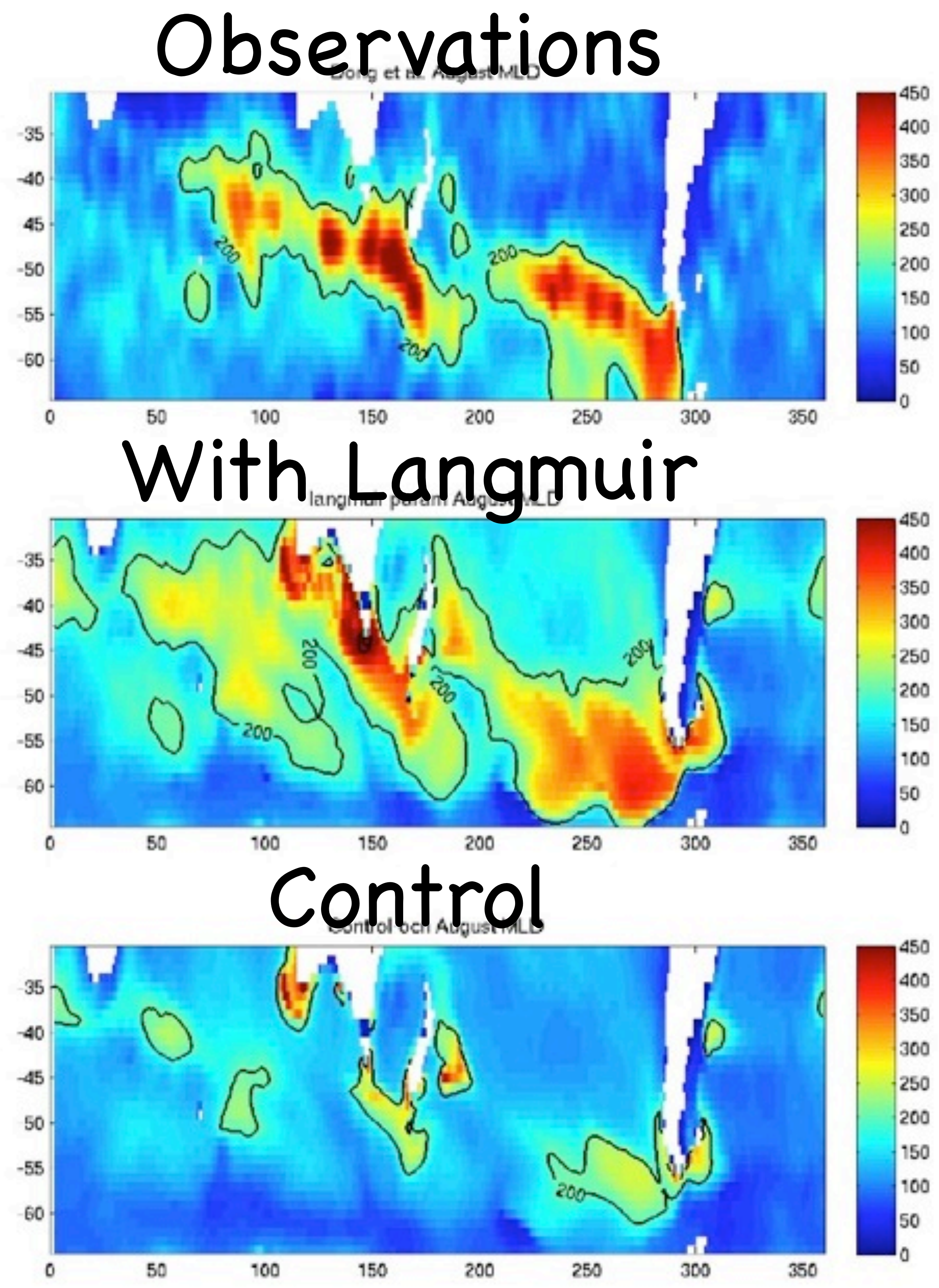


image: Sullivan & McWilliams, 10

CCSM3.5 Impact: MLD

- With reasonable parameters, Langmuir mixing parameterization produces deeper mixed layers in fully-coupled global climate models
- Often reduces bias in some regions, e.g., ACC

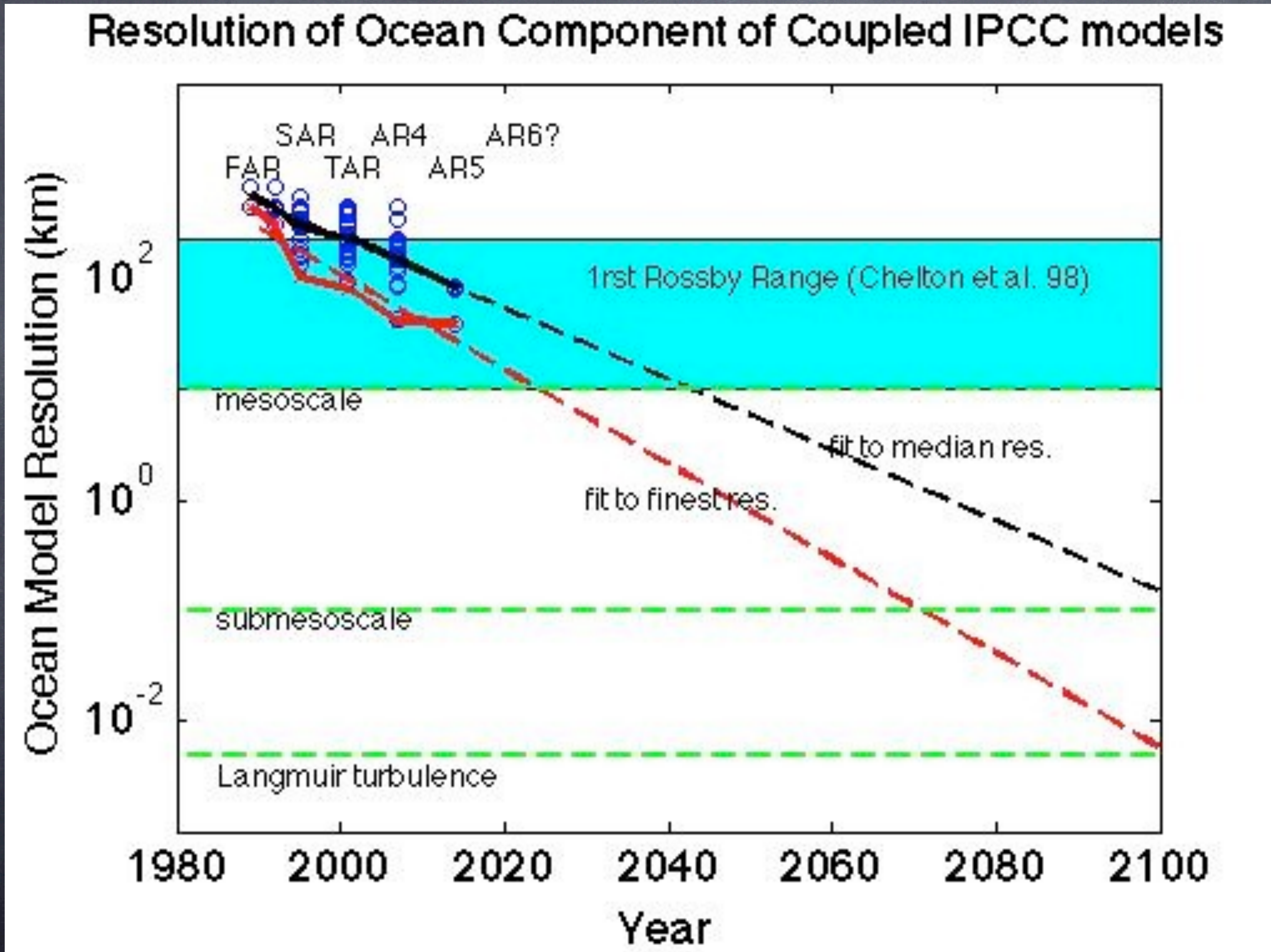


August mixed layer depths.

Conclusions: 3. Langmuir

- Like Mesoscale Variability and Submesoscale Restratification--Langmuir mixing has a nontrival impact on climate models
- However, we need better wave information, e.g., prognostic wave models as component of ESMs
- And results are sensitive to details--need better theory, too!

Parameterization is Here to Stay!



A Crude Scaling for Langmuir Depth/Entrainment:

(Li & Garrett, 1997)

$$Fr = \frac{\omega}{NH} \approx 0.6 \qquad \omega \approx \frac{V}{1.5} \approx \frac{\sqrt{u^* u_s}}{1.5}$$

CAM → u^*

related to CAM u* by WW3 Climatology → u_s

The Algorithm

Use Fr to determine H

If H is deeper than KPP Boundary Layer depth, use H

Large came up with clever choices for N, H that lead to a robust implementation in KPP

With these choices, H and BLD converge over time.

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

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

0. Climate Scale

- Gyres, MOC, ENSO
- Ro=O(0.01): geostropic
- Ri=O(1000): hydrostatic
- near-surface flux control
- full-depth transport
- 10,000km, decades
- Eqtns: PG, GCMs, Box Models

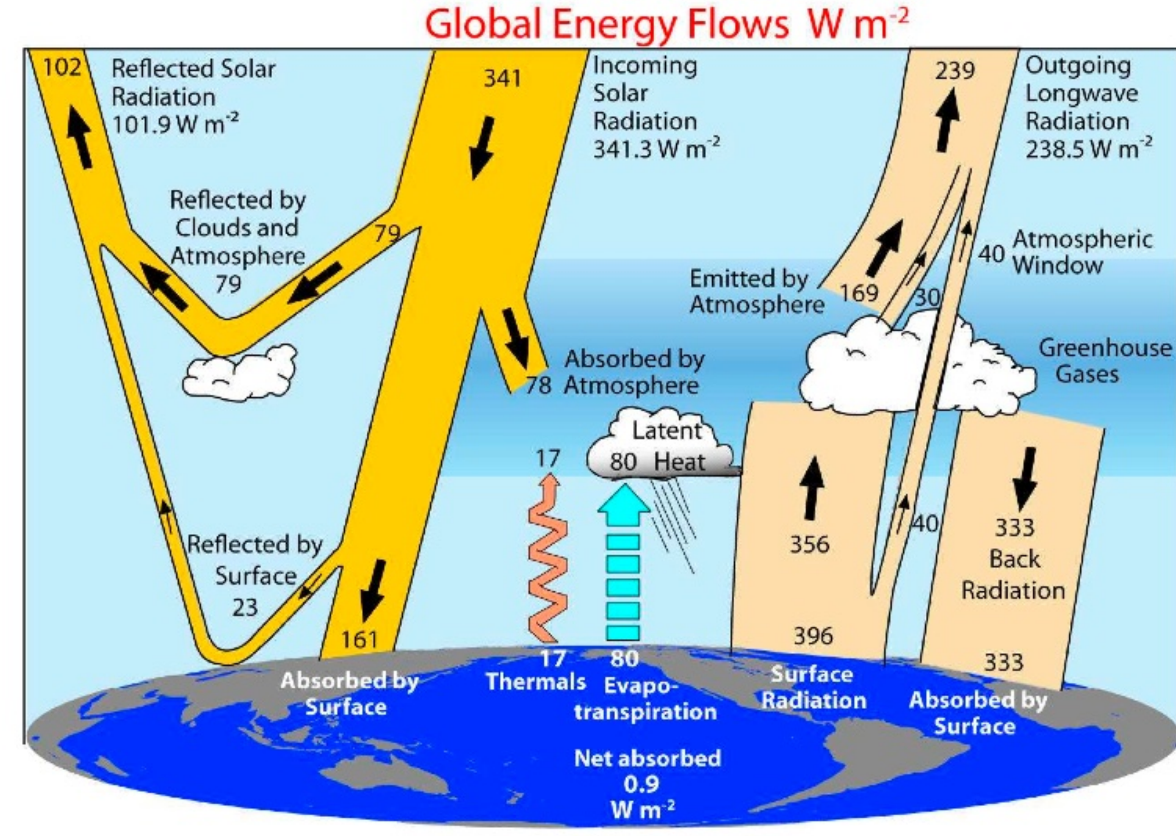


Figure 2.19: Estimate of the Earth's annual and global mean energy balance for the March 2000 to May 2004 period in W m^{-2}. Figure from Trenberth et al. (2009). Copyright 2009 American Meteorological Society (AMS).

Ocean Energy Flux

Images: Trenberth & Caron, IPCC AR4

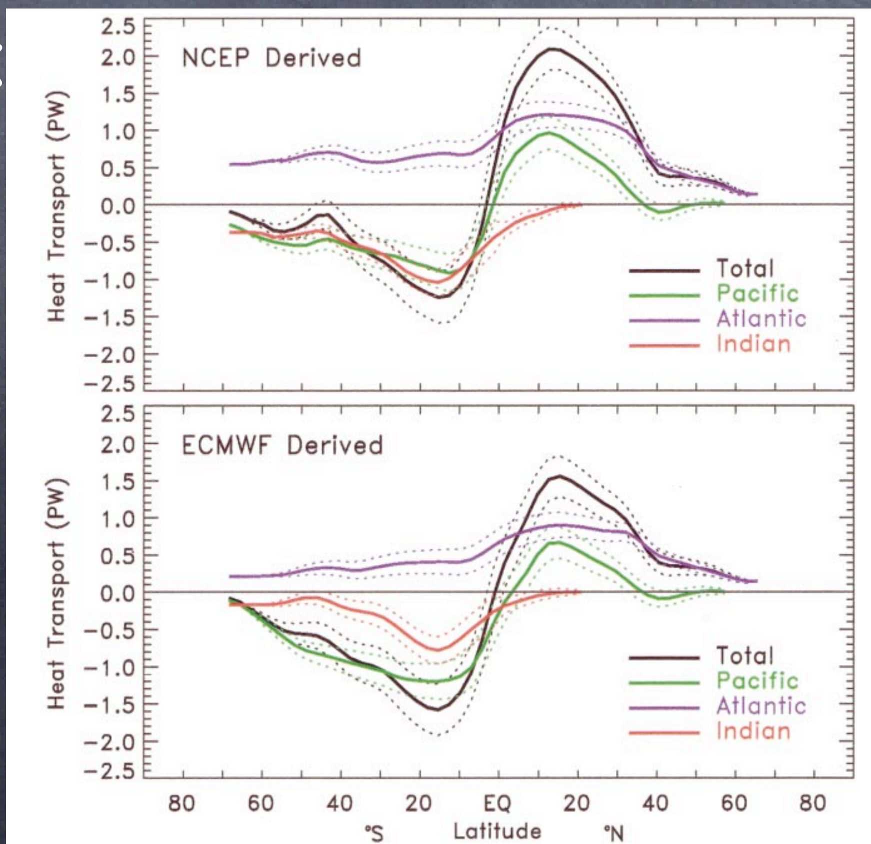
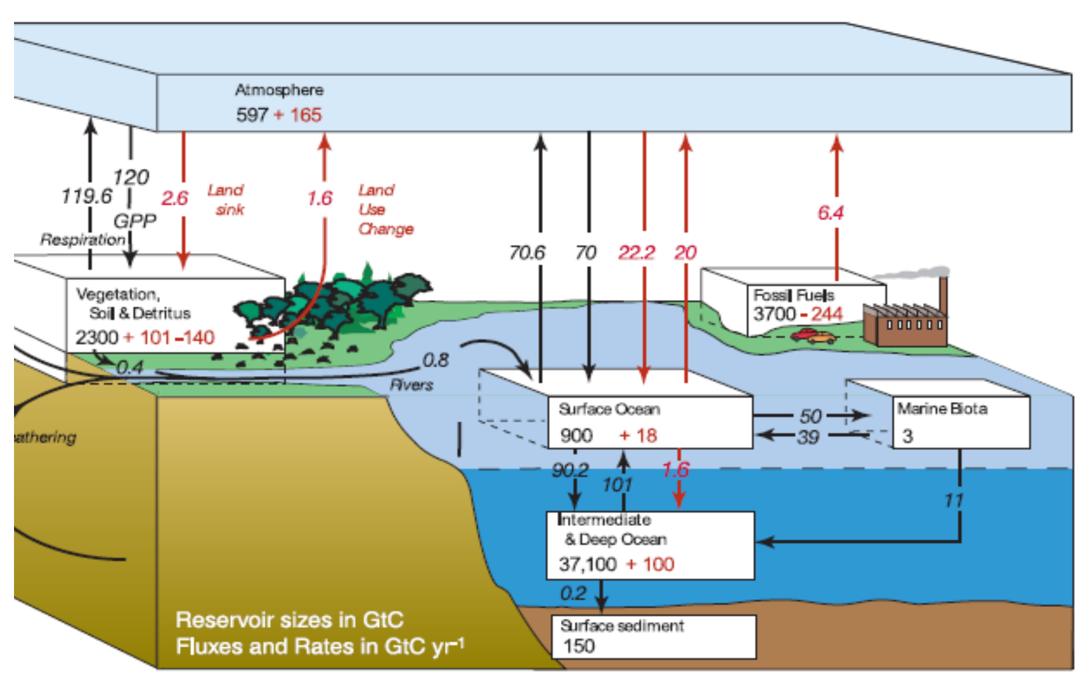
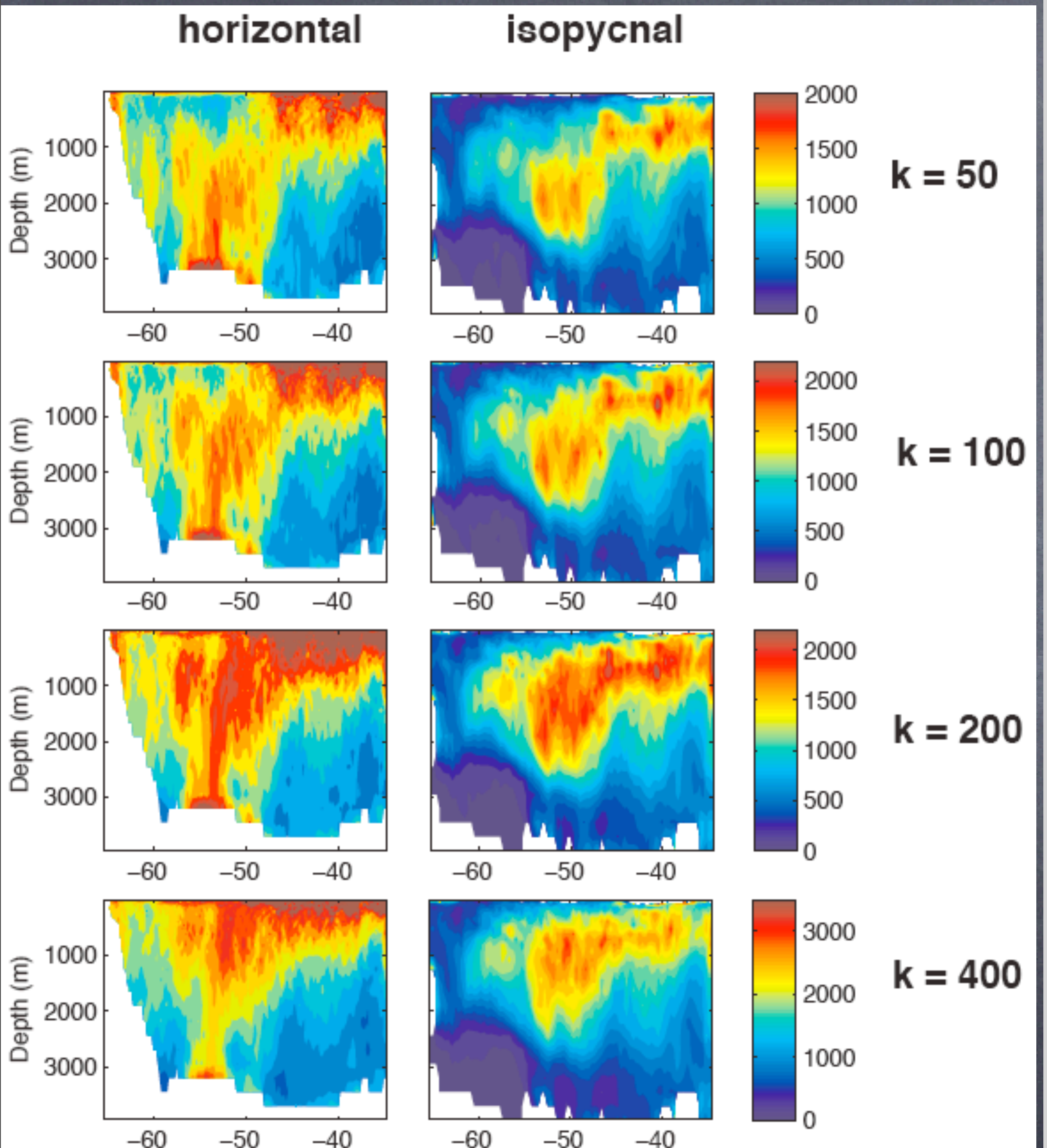


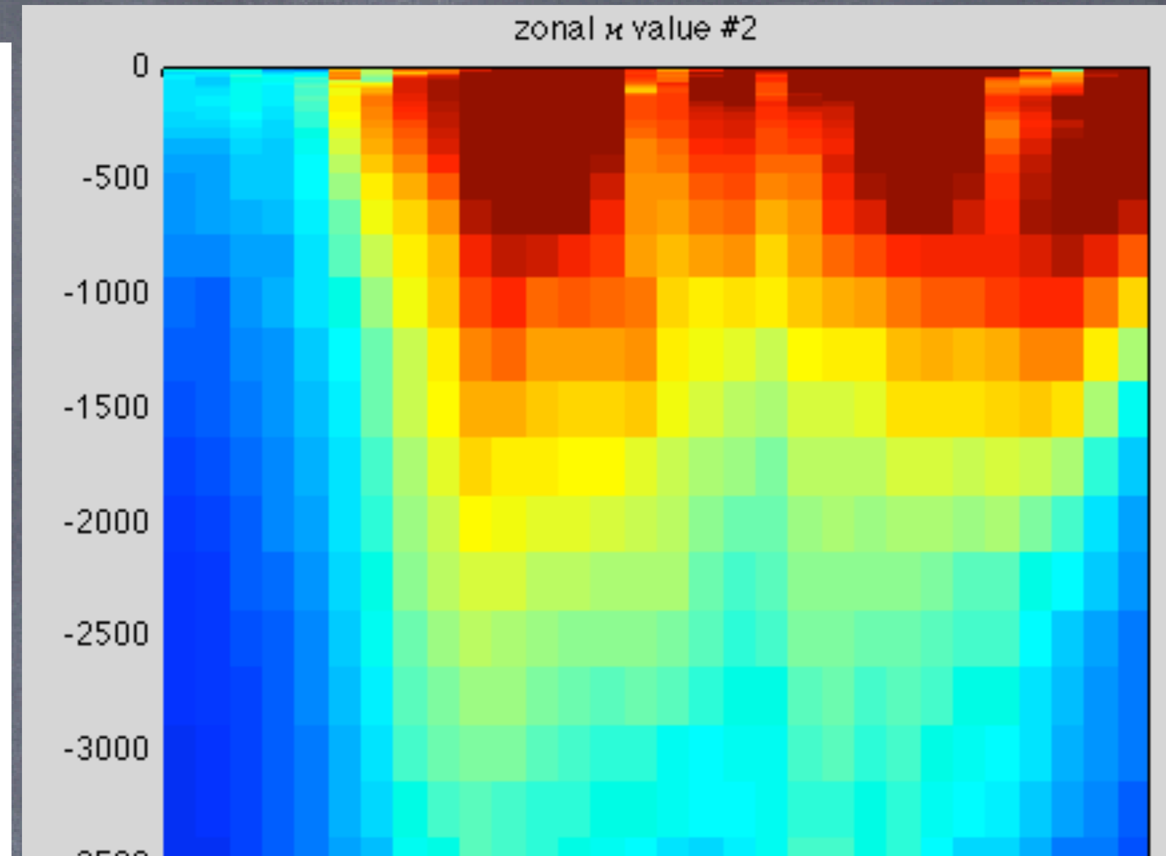
FIG. 5. Implied zonal annual mean ocean heat transports based upon the surface fluxes for Feb 1985–Apr 1989 for the total, Atlantic, Indian, and Pacific basins for NCEP and ECMWF atmospheric fields (PW). The 1 std err bars are indicated by the dashed curves.

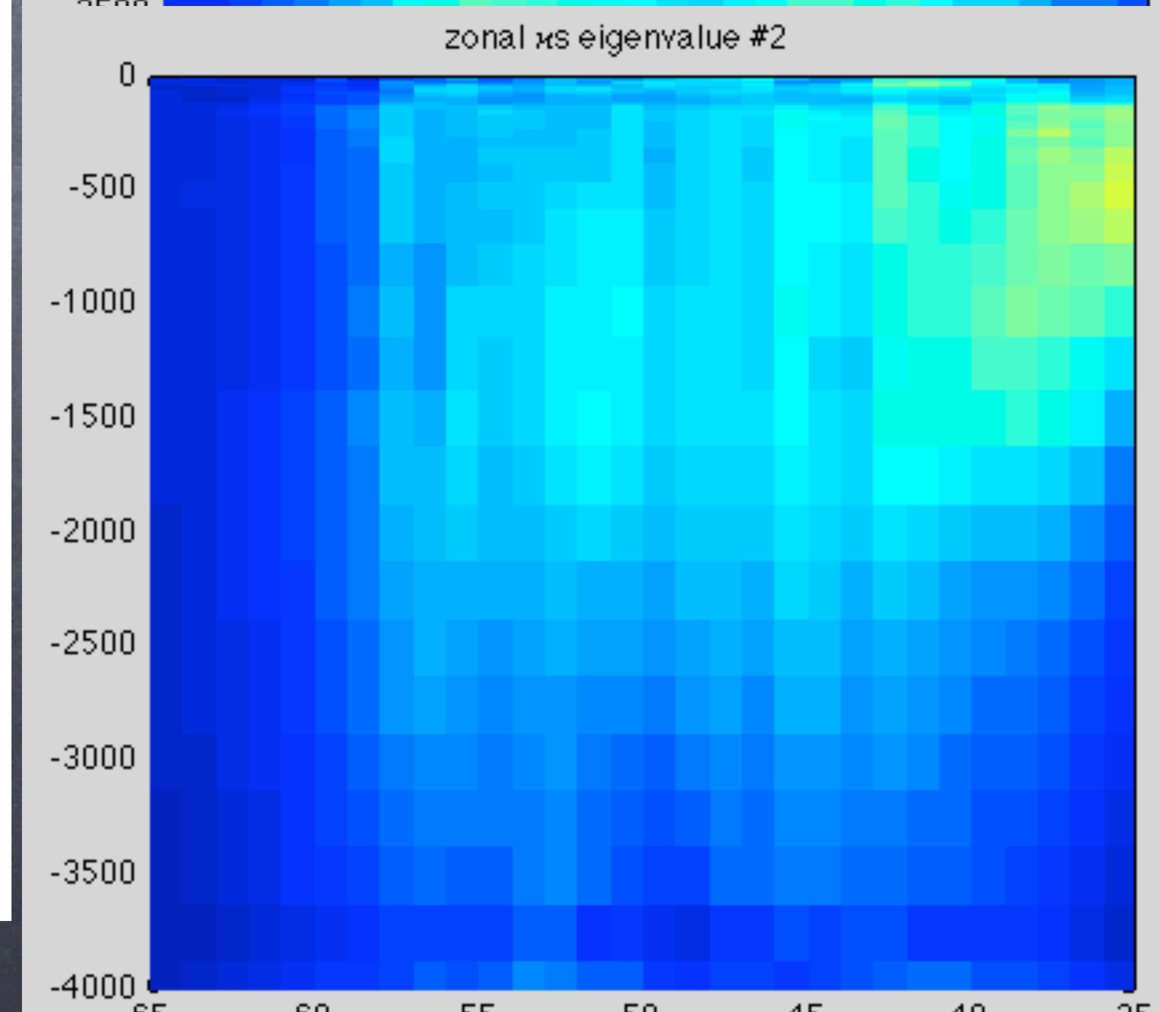
Ocean Carbon Uptake



Comparisons with Marshall et al.

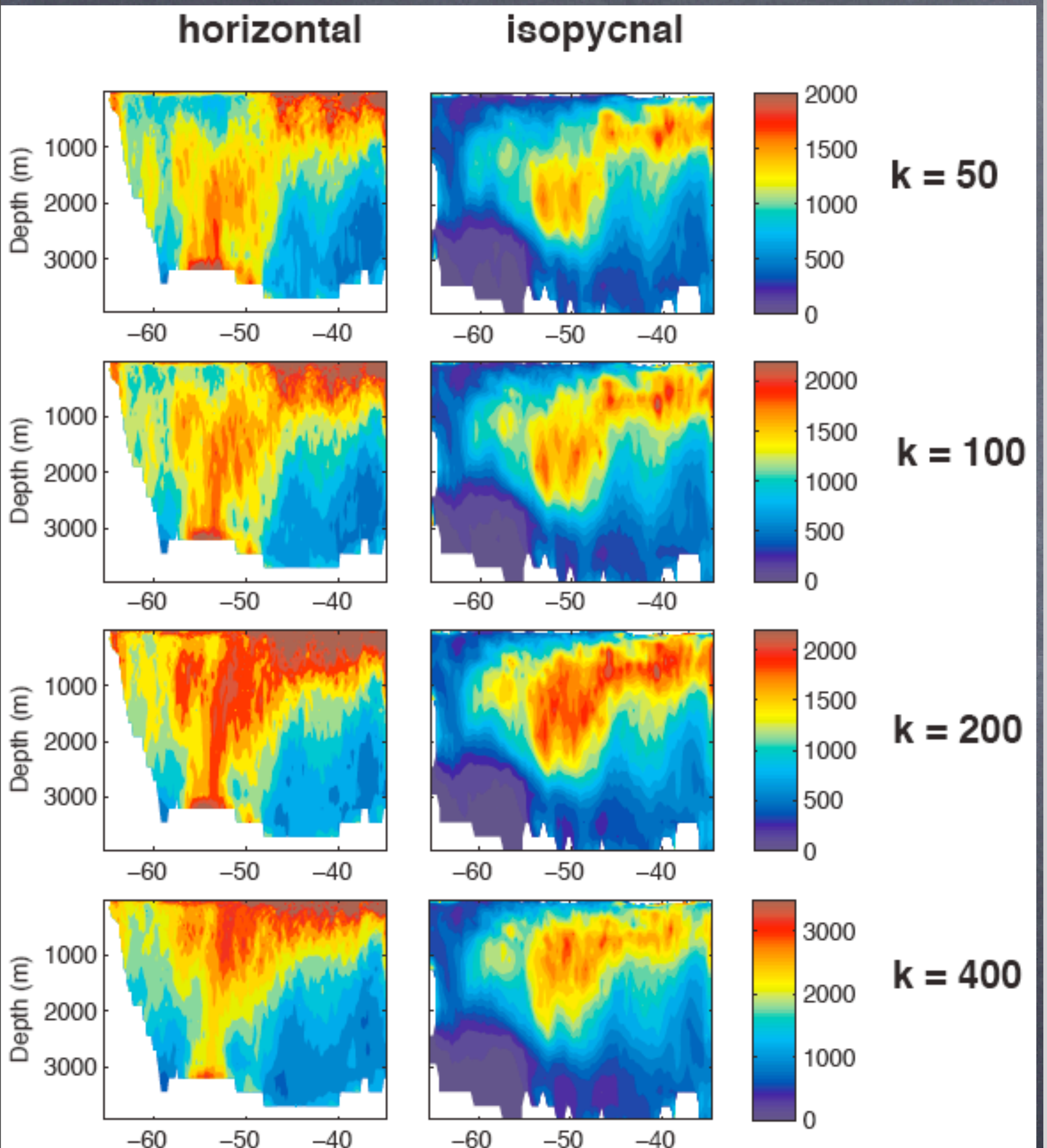




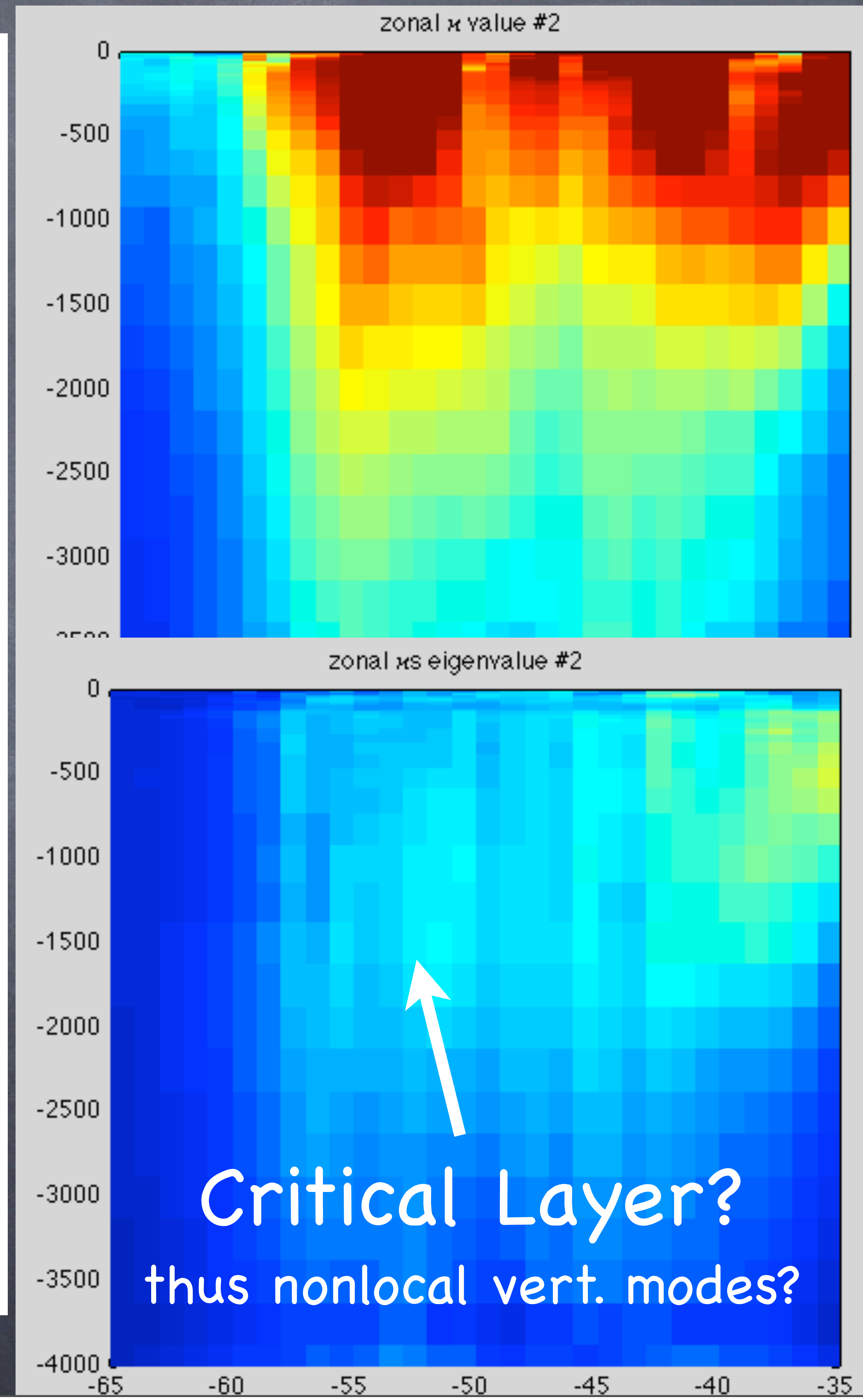


Abernathy et al 09

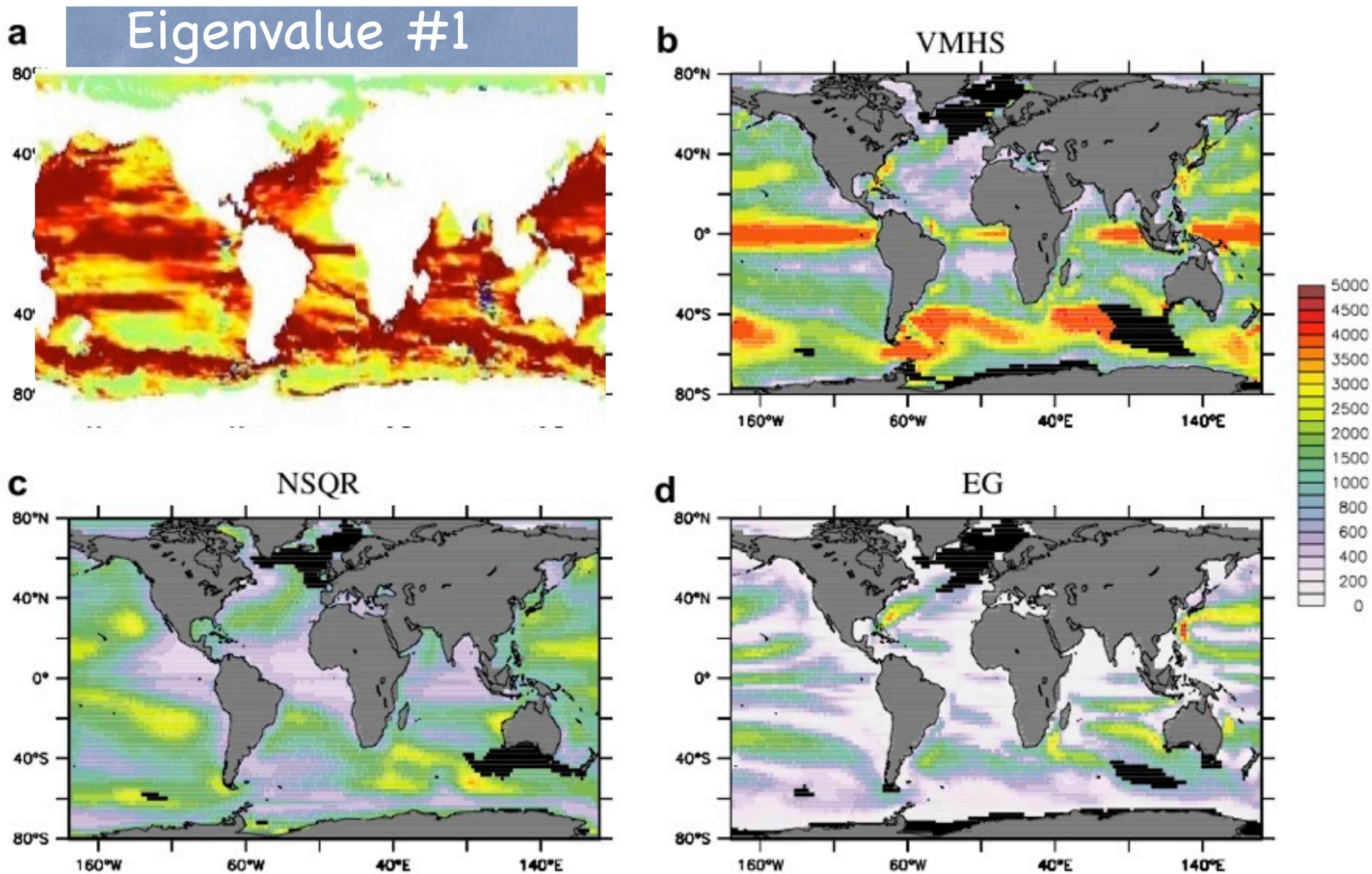
Comparisons with Marshall et al.



Abernathy et al 09

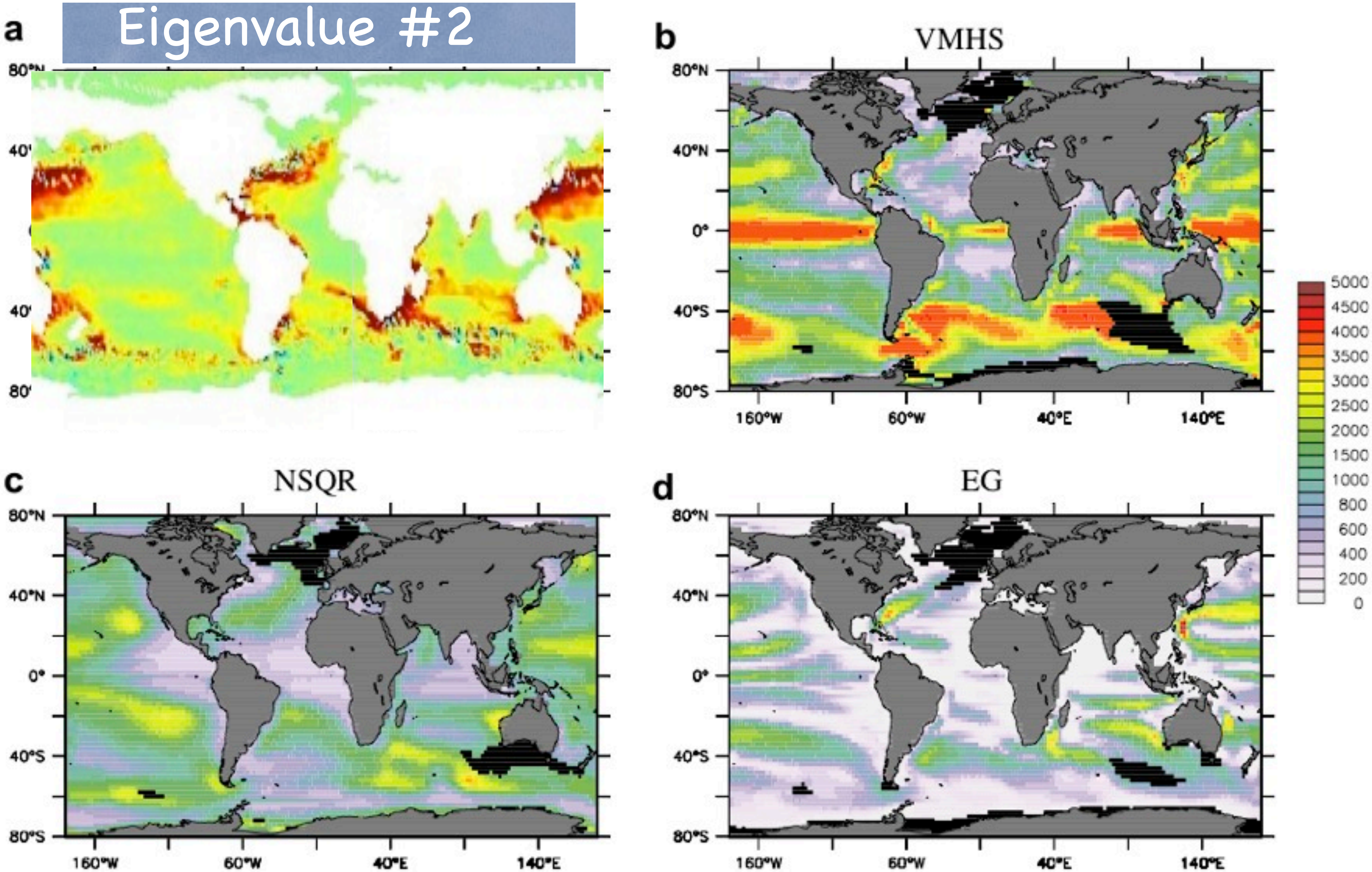


Compare with Eden, Jochum, Danabasoglu compilation of present parameterizations



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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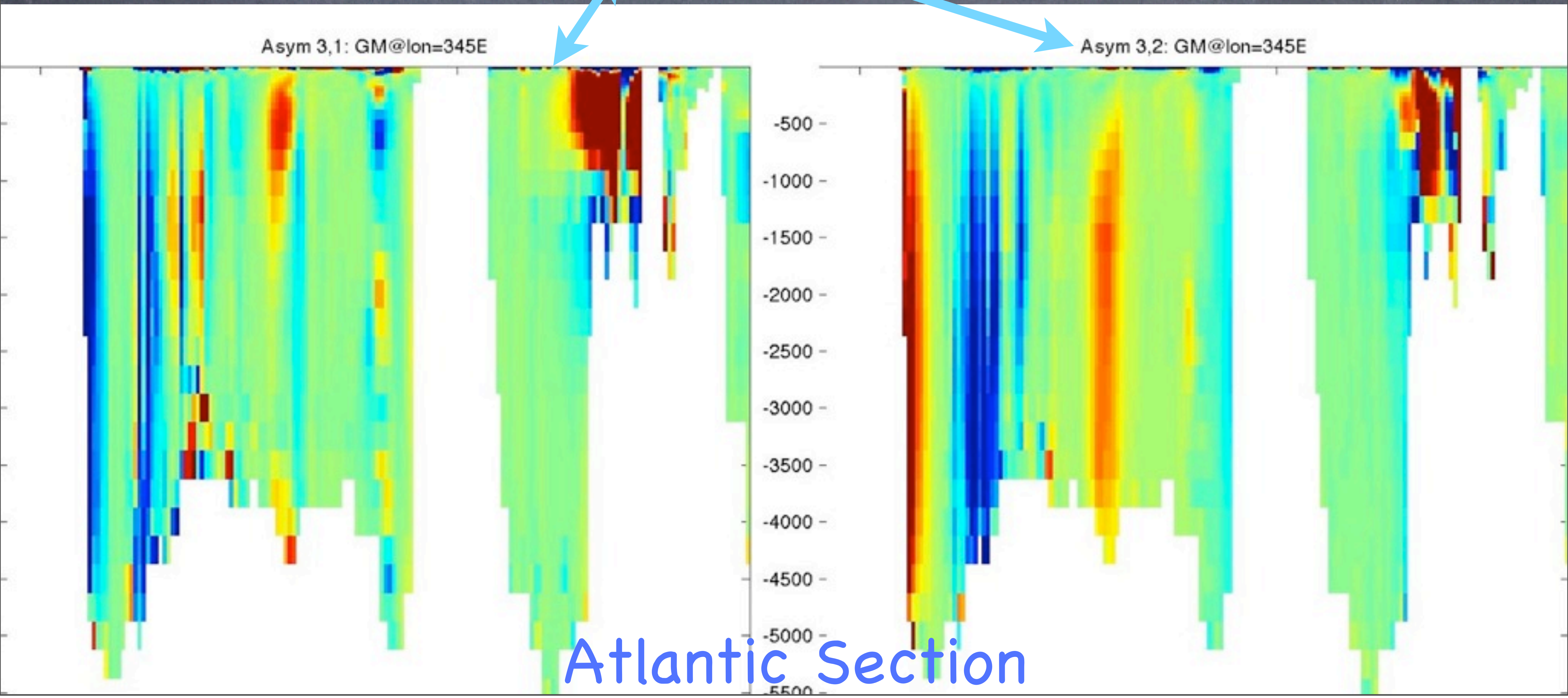
Use a Natural, Mesoscale Eddy Environment to Test Out:

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



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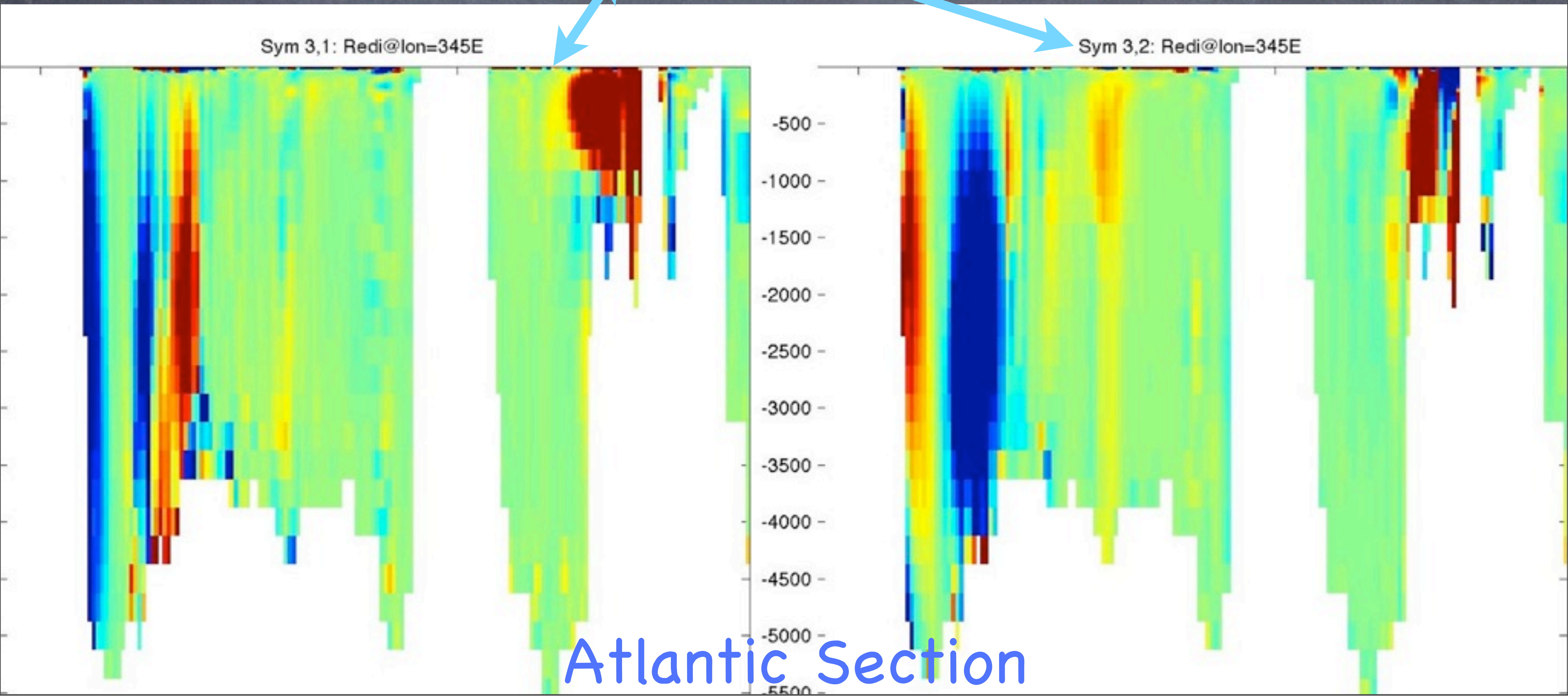
$$\begin{bmatrix} \overline{u'\tau'} \\ \overline{v'\tau'} \\ \overline{w'\tau'} \end{bmatrix} = - \begin{bmatrix} K_{xx} & K_{xy} & \hat{\mathbf{x}}\cdot\mathbf{K}\cdot\tilde{\nabla}\mathbf{z} \\ K_{yx} & K_{yy} & \hat{\mathbf{y}}\cdot\mathbf{K}\cdot\tilde{\nabla}\mathbf{z} \\ \hat{\mathbf{x}}\cdot\mathbf{K}\cdot\tilde{\nabla}\mathbf{z}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



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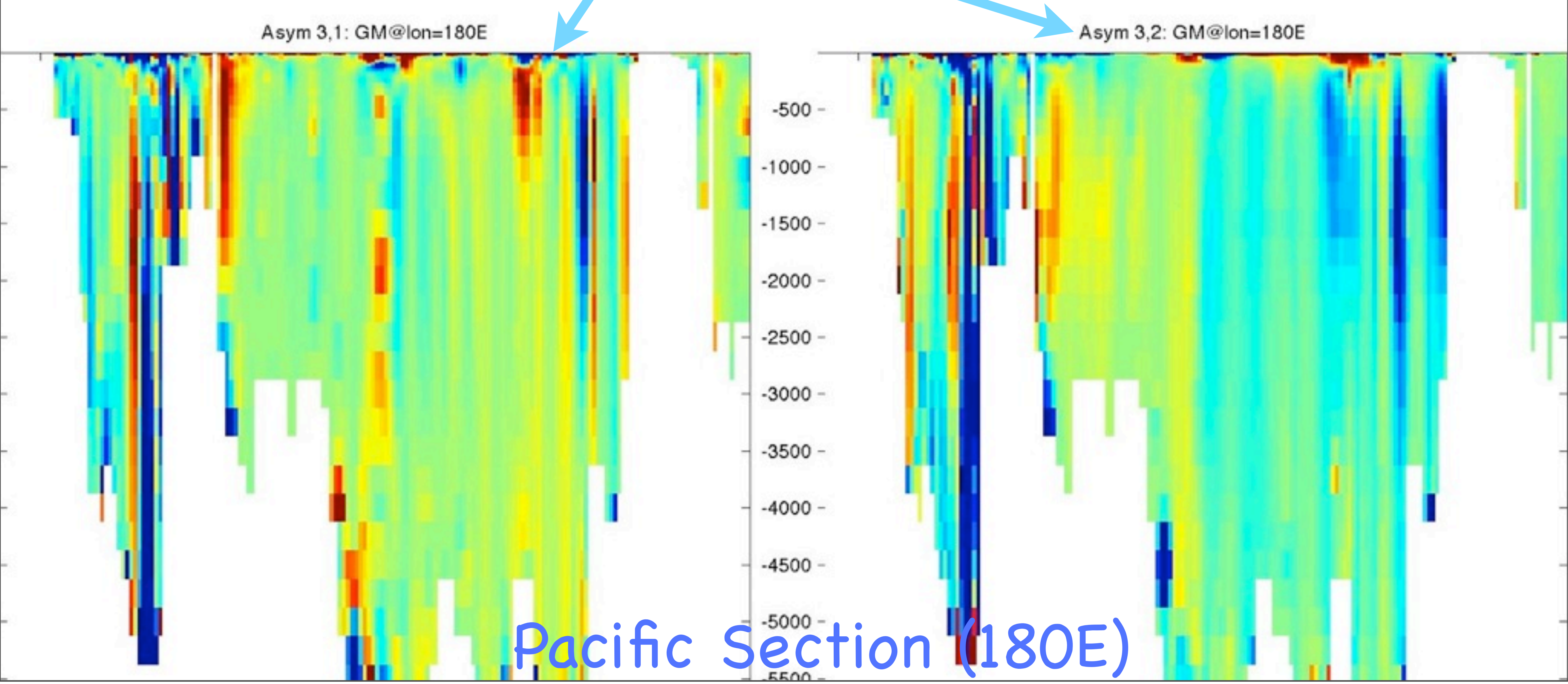
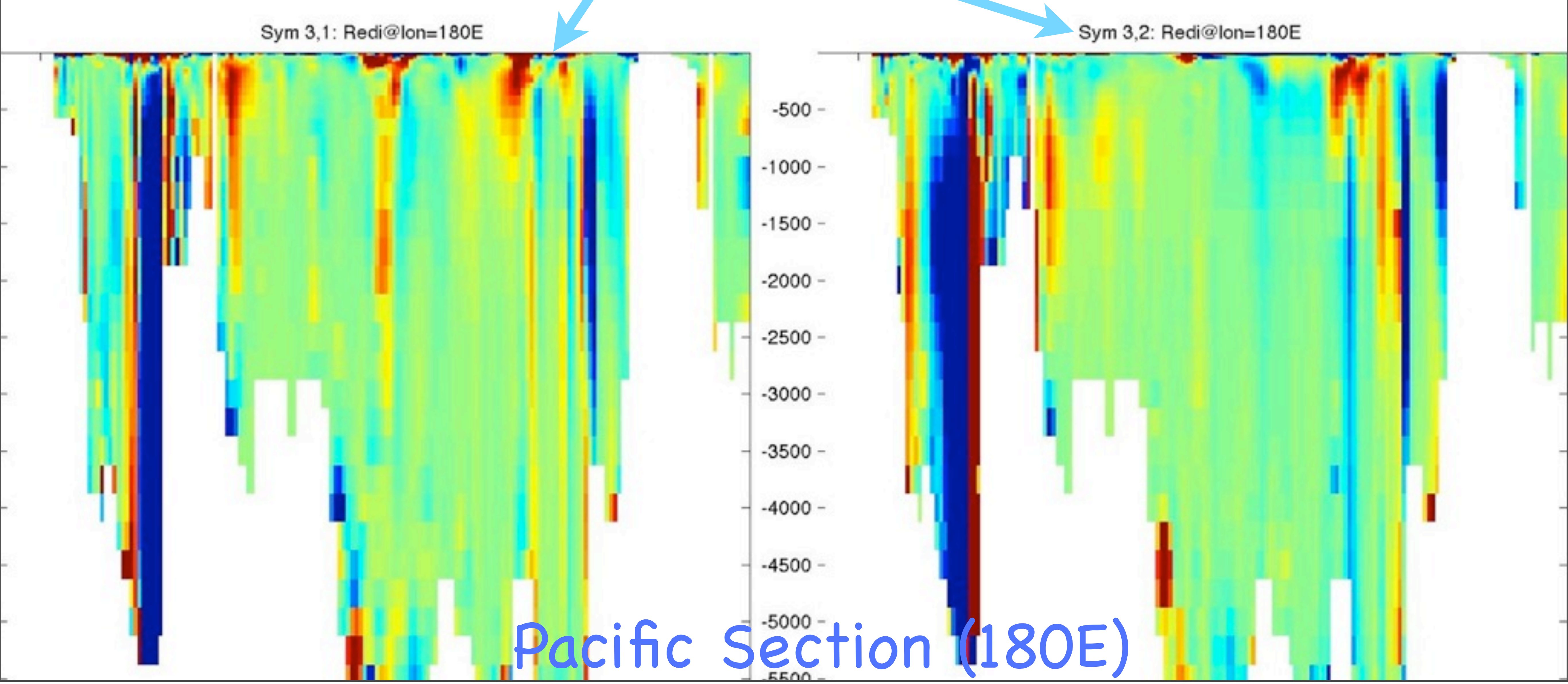


Pacific Section (180E)

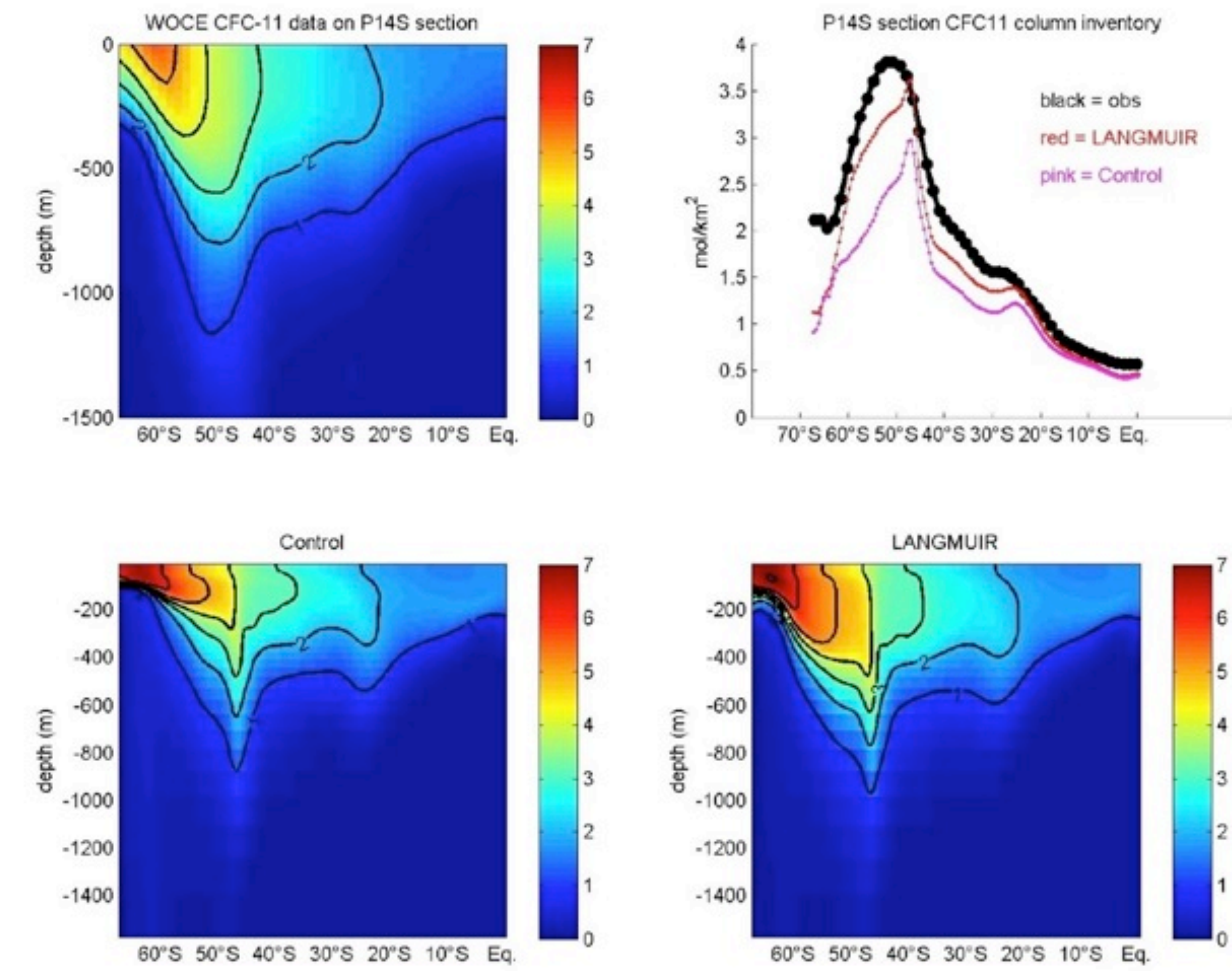
Use a Natural, Mesoscale Eddy Environment to Test Out:

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



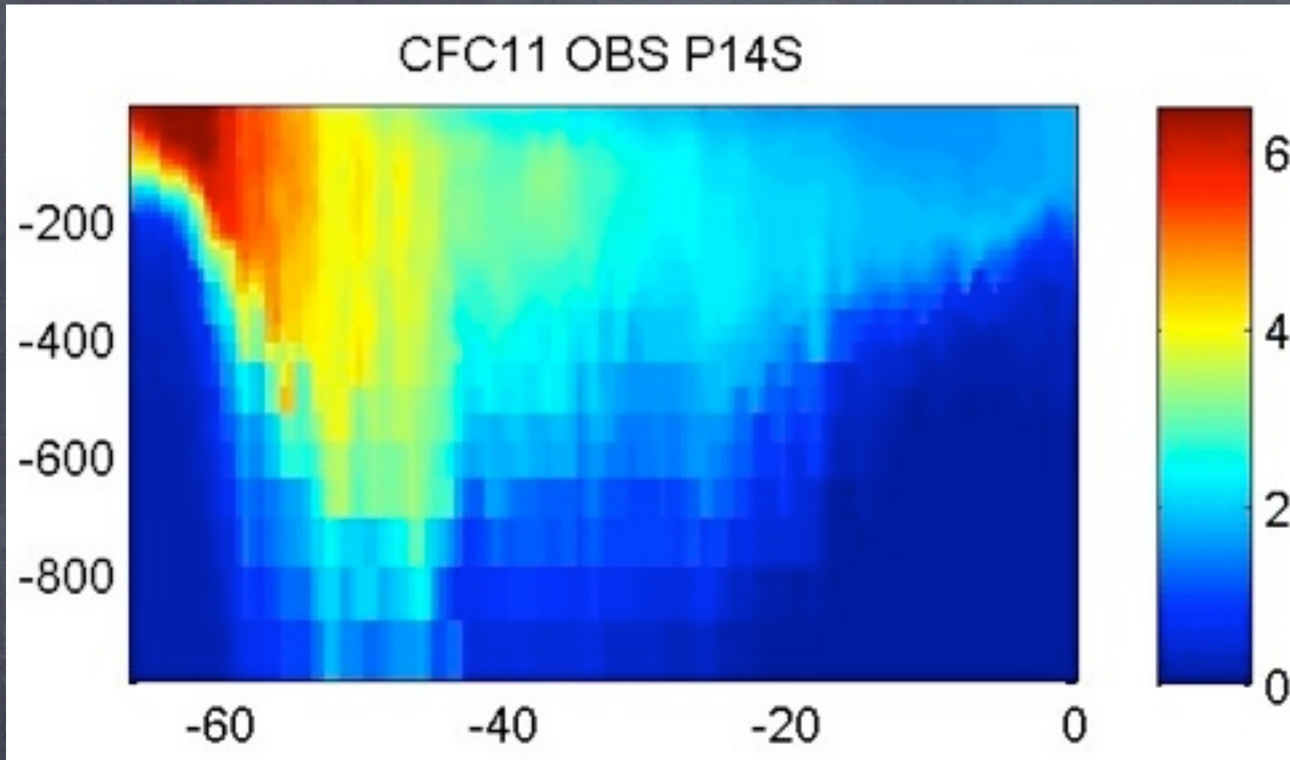
CCSM3.5 Langmuir Impact on Climate: CFCs

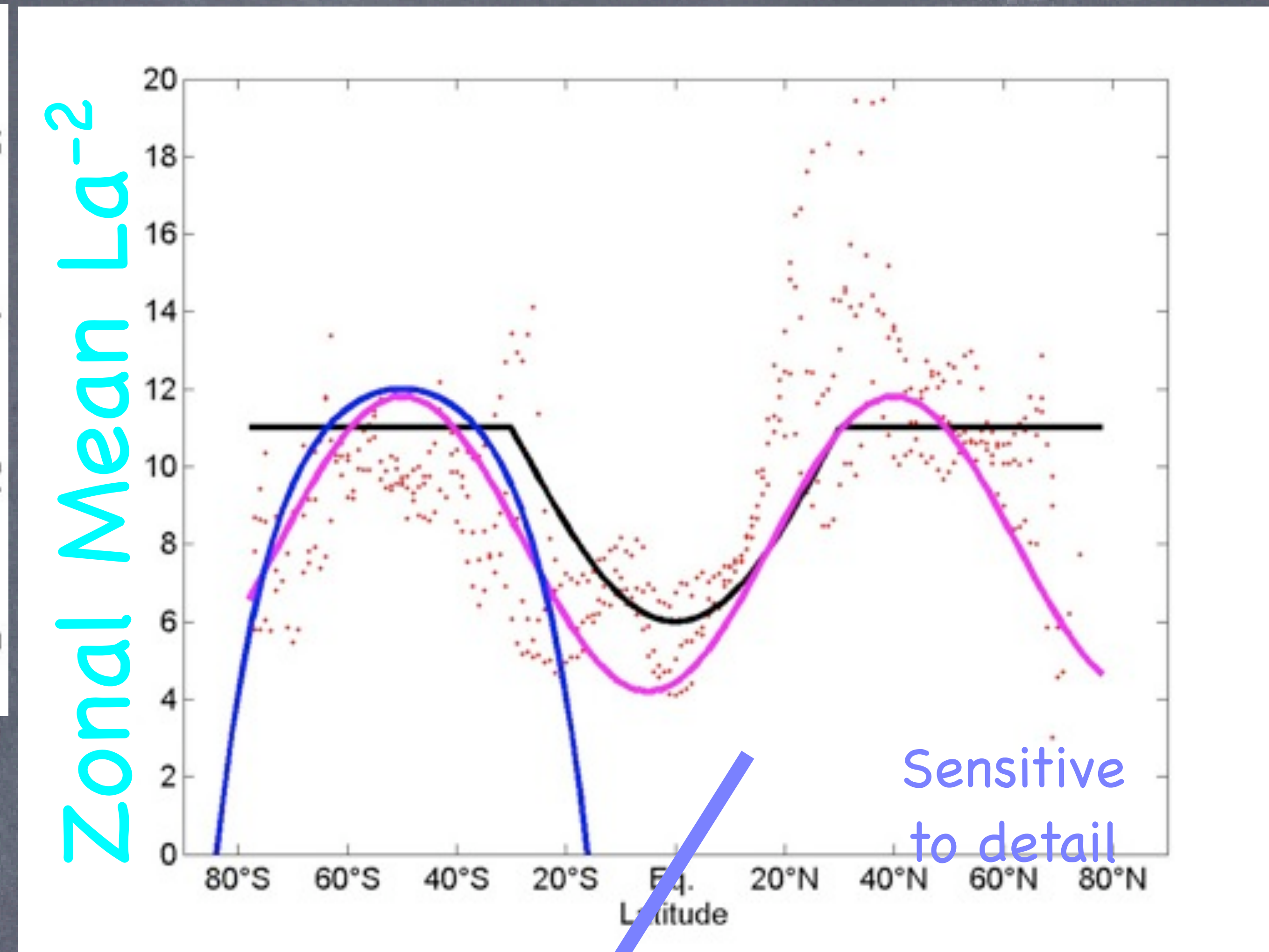
- With reasonable parameters, Langmuir affects CFCs
- Langmuir reduces bias in some regions, e.g., ACC versus WOCE
- Potentially large impact, change as large as bias

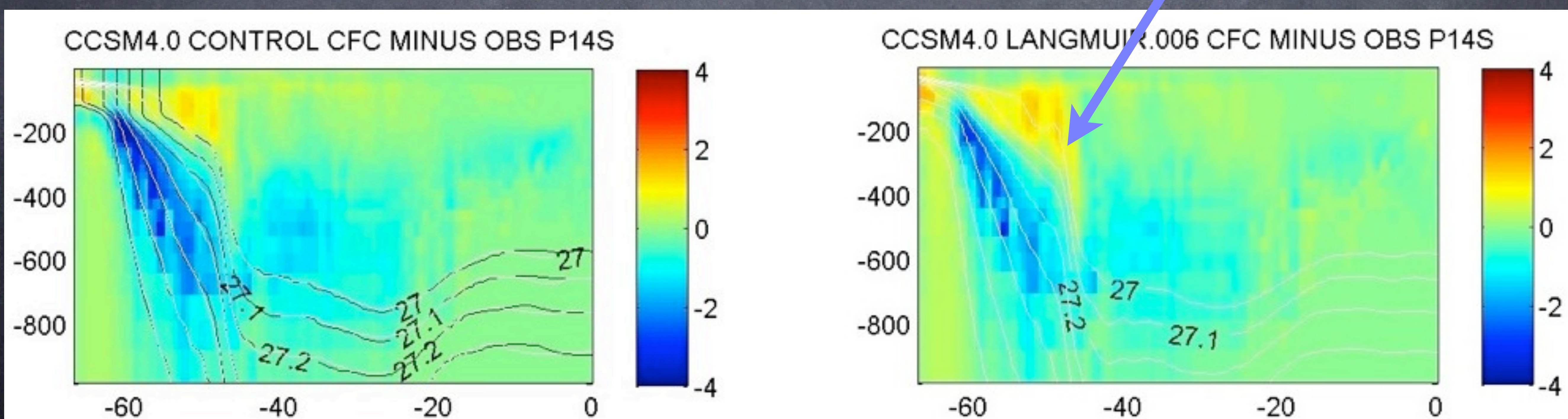


CFC in CCSM & P14S WOCE observations.

Nuance--CCSM3.5 and CCSM4.0







Nuance--CCSM3.5 and CCSM4.0