Eddies, Mixing and all that: Ocean Parameterization Developments from 4m to 400km

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with
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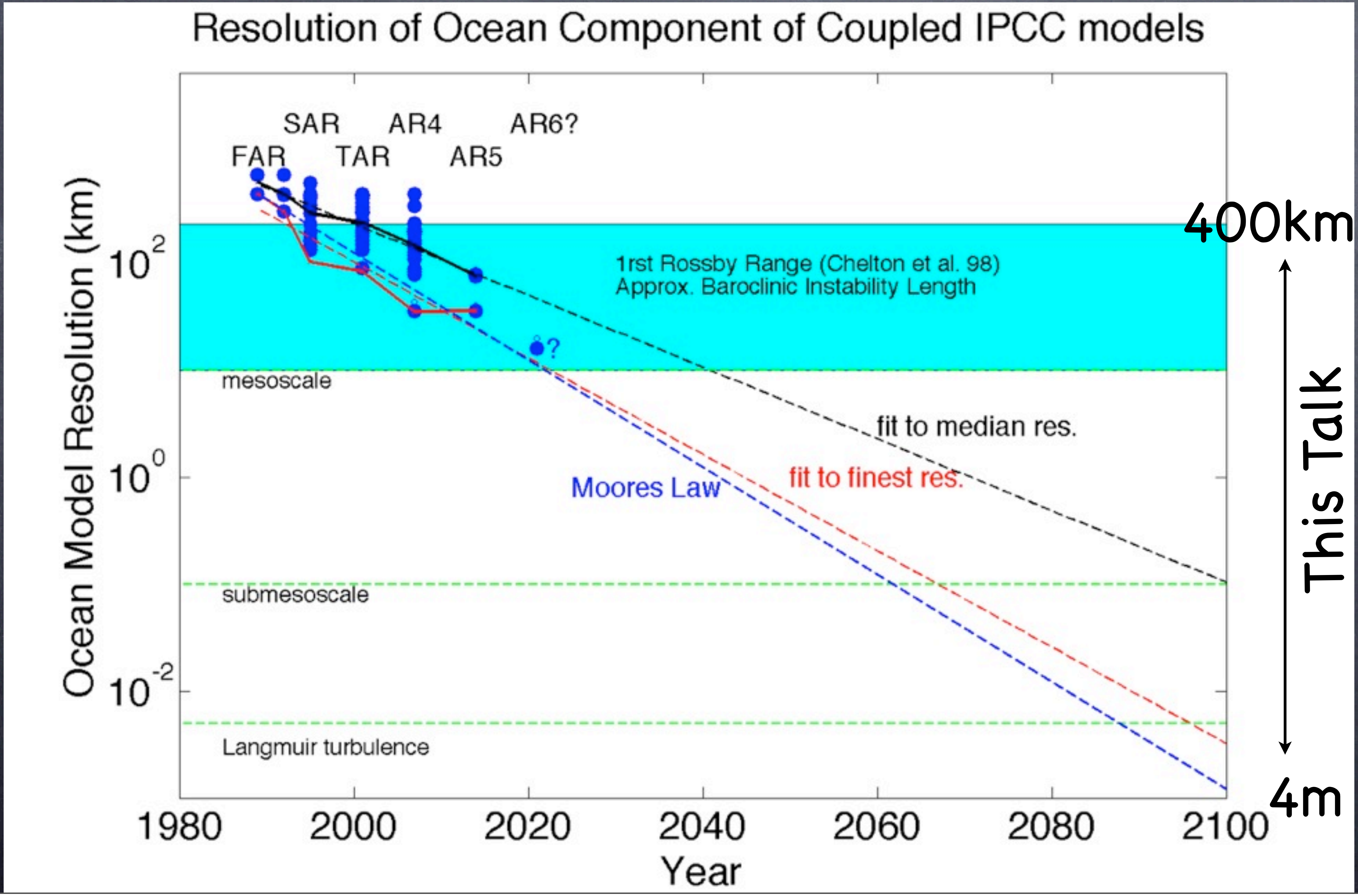
TeraGRID, IBM, UCAR, CIRES, CU-Boulder

Climate Forecasts (IPCC/CMIP Runs) have a very coarse ocean gridscale (>100km)



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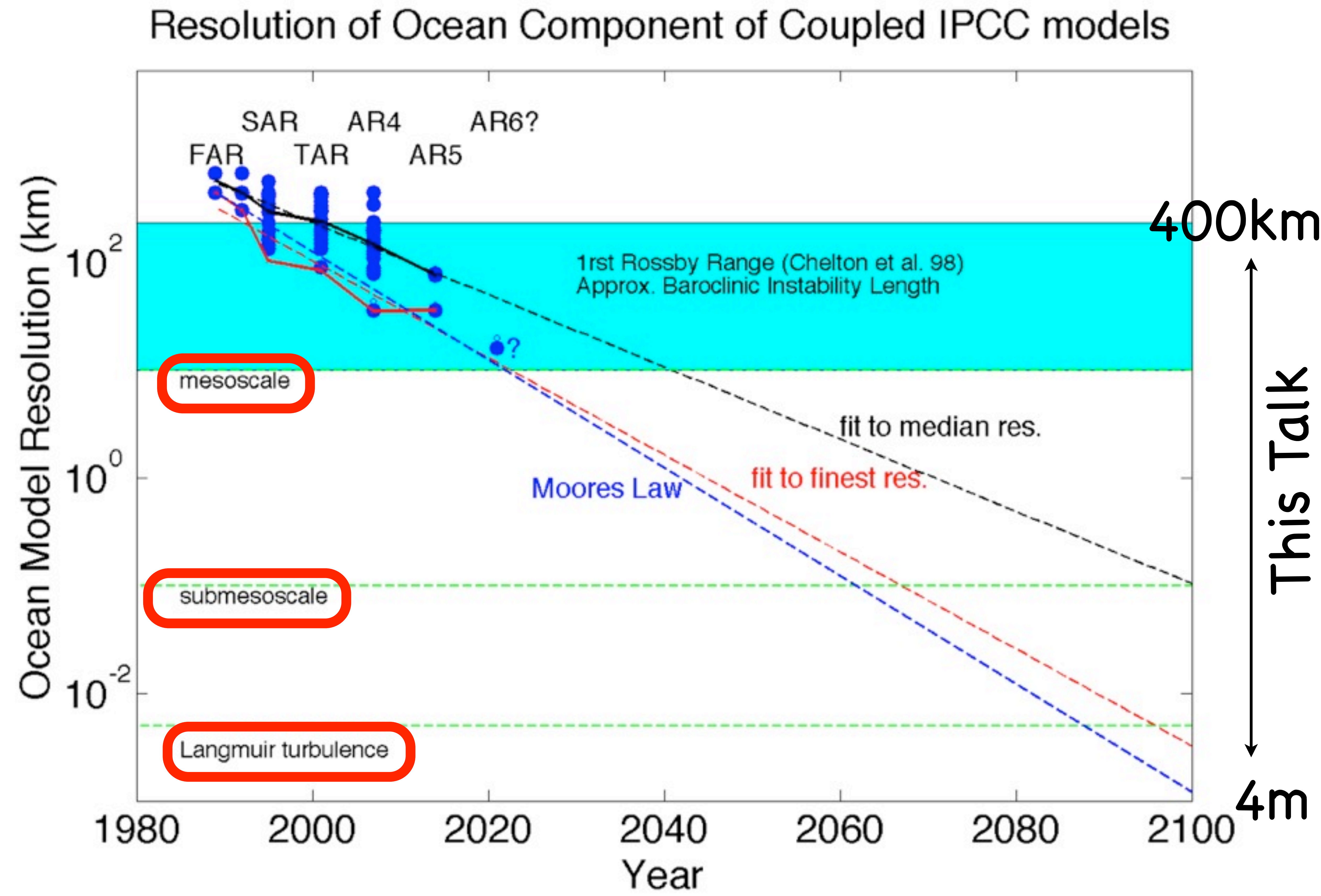
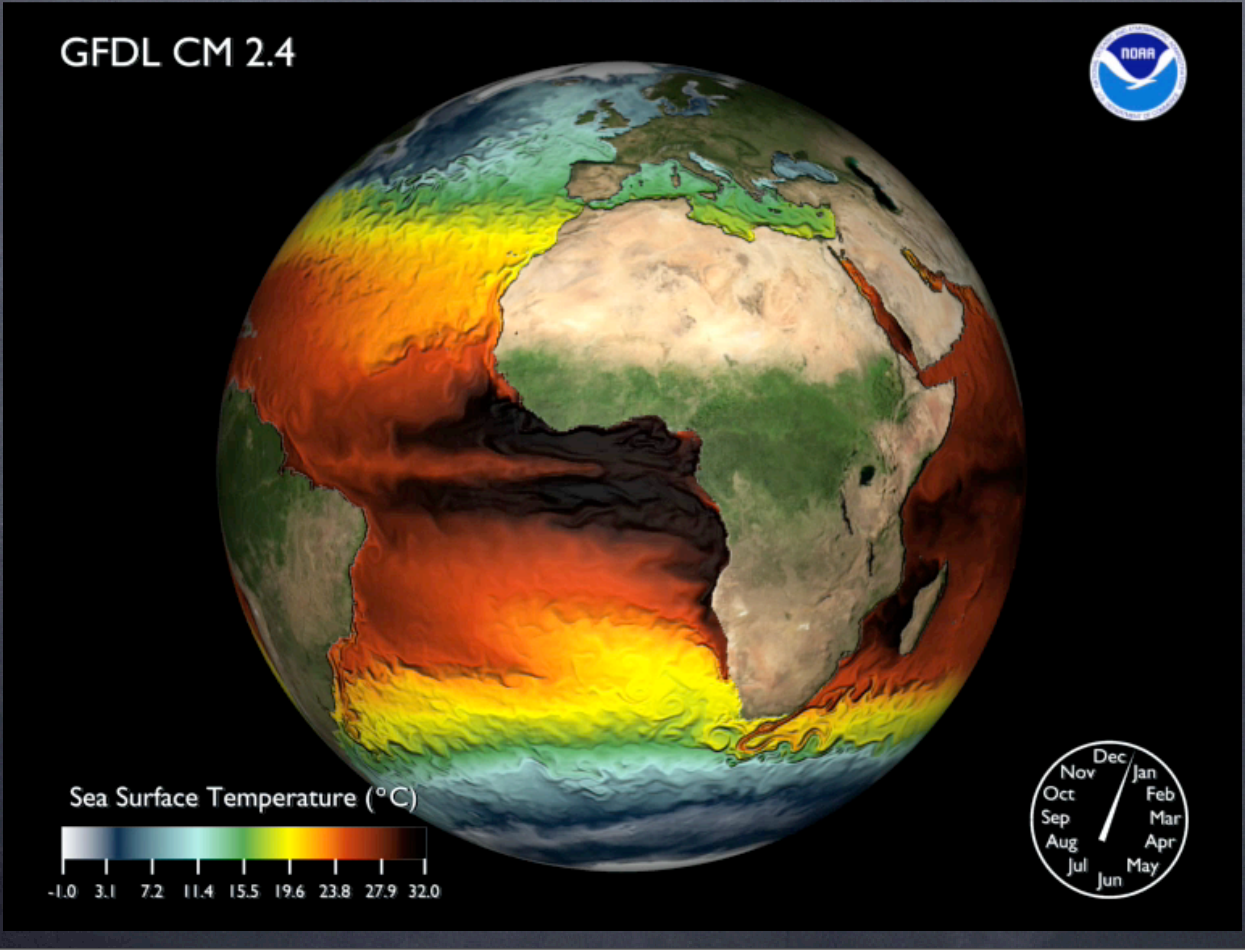


A Bleeding-Edge Climate Model (in terms of ocean resolution) Has some ocean mesoscale instabilities:



Ocean Equations*:
Boussinesq Fluid on Tangent Plane to a Rotating Sphere

$$\partial_t \mathbf{u} + \mathbf{u} \cdot \nabla_h \mathbf{u} + w \partial_z \mathbf{u} + Ro^{-1} \mathbf{f} \times \mathbf{u} = -\overline{P} \nabla_h p + \boxed{Re^{-1} \nabla^2 \mathbf{u}}$$

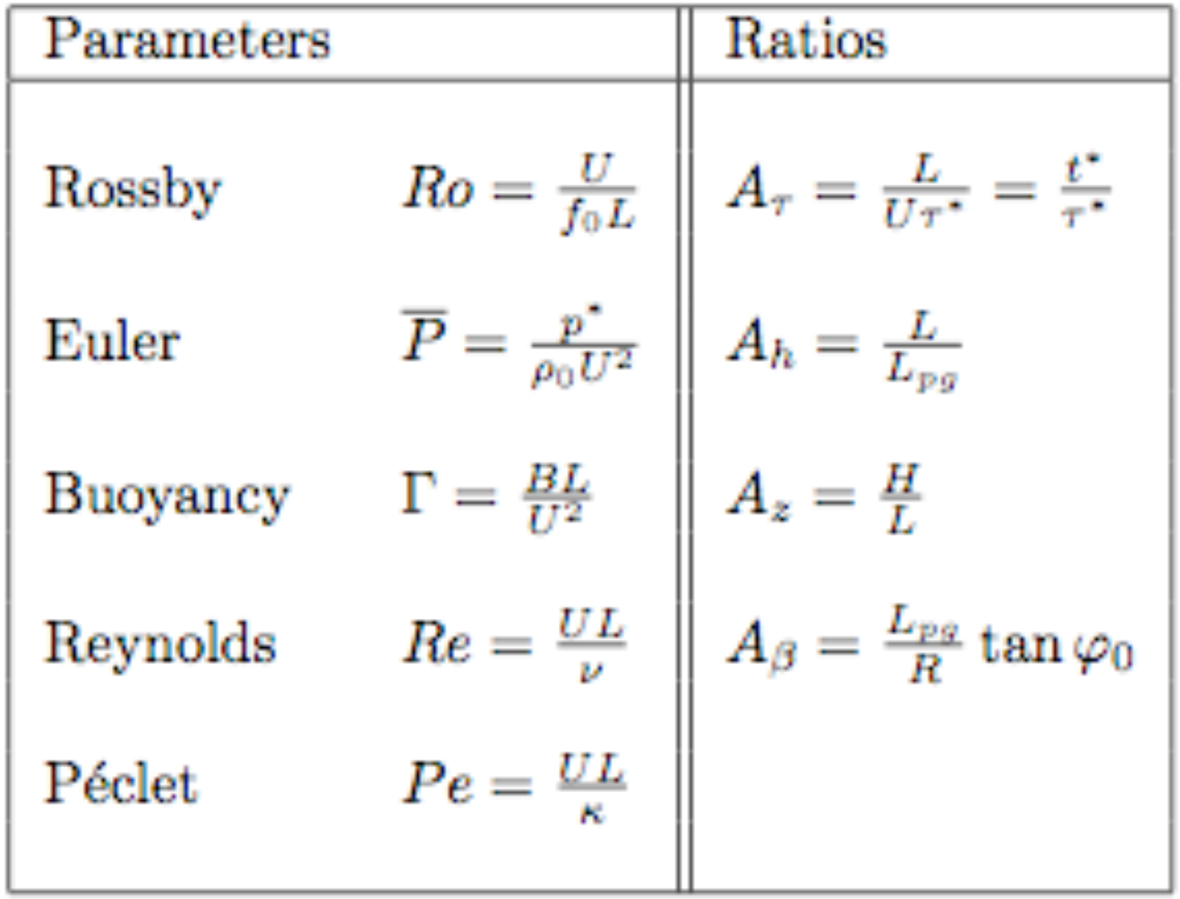
$$\partial_t w + \mathbf{u} \cdot \nabla_h w + w \partial_z w = -\overline{P} \partial_z p + \Gamma b \hat{\mathbf{z}} + \boxed{Re^{-1} \nabla^2 w}$$

Buoyancy (or S, T): $\partial_t b + \mathbf{u} \cdot \nabla_h b + w \partial_z b = \boxed{Pe^{-1} \nabla^2 b}$

$$\nabla_h \cdot \mathbf{u} + \partial_z w = 0$$

Re, Pe for an affordable gridscale are 10^6 to 10^{11}

Numerics require O(1)



Parameters		Ratios
Rossby	$Ro = \frac{U}{f_0 L}$	$A_\tau = \frac{L}{U\tau^*} = \frac{t^*}{\tau^*}$
Euler	$\overline{P} = \frac{p^*}{\rho_0 U^2}$	$A_h = \frac{L}{L_{pg}}$
Buoyancy	$\Gamma = \frac{BL}{U^2}$	$A_z = \frac{H}{L}$
Reynolds	$Re = \frac{UL}{\nu}$	$A_\beta = \frac{L_{pg}}{R} \tan \varphi_0$
Péclet	$Pe = \frac{UL}{\kappa}$	

*From Grooms, Julien, & F-K, 11

What is a subgrid model?

- Express the coarse-grain averages of quantities (including the subgrid effects), e.g.:

$$\overline{\frac{\partial \tau}{\partial t}} \qquad \overline{\frac{\partial u}{\partial x}} \qquad \overline{\frac{\partial u\tau}{\partial x}}$$

- As a function of the resolved coarse-grain fields

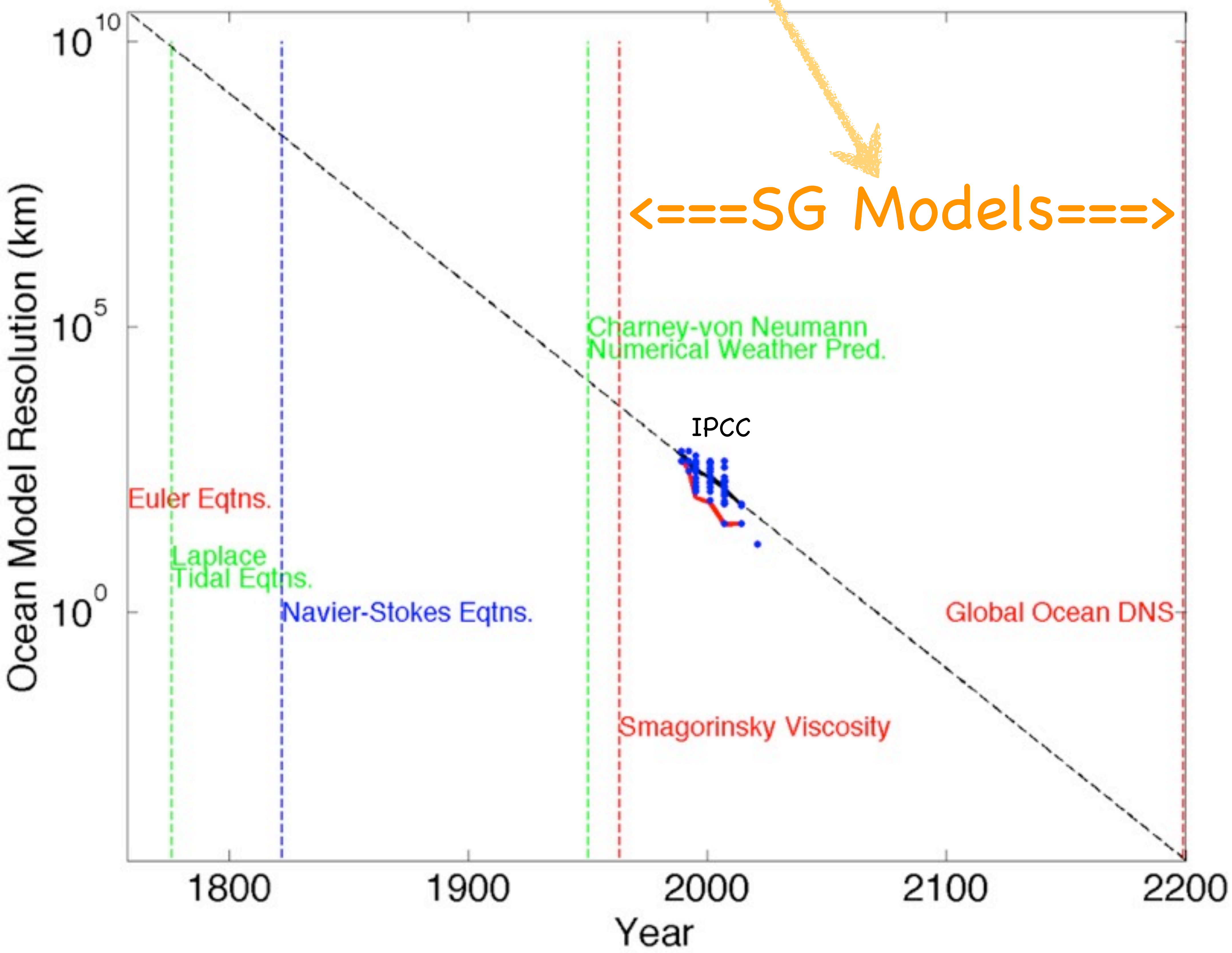
$$\overline{\frac{\partial \tau}{\partial t}} = \frac{\partial \overline{\tau}}{\partial t} \qquad \overline{\frac{\partial u}{\partial x}} = \frac{\partial \overline{u}}{\partial x} \qquad \overline{\frac{\partial u\tau}{\partial x}} = \frac{\partial \overline{u}\;\overline{\tau}}{\partial x} + \frac{\partial \overline{u'\tau'}}{\partial x}$$

- Note that nonlinear terms require special treatment
- And Couple different scales, small talks to large!

Different Uses, Different Needs

- MOLES (e.g., the CM2.4 movie before; grid 5-25km)
  - Mesoscale Ocean Large Eddy Simulation
  - Largest eddies are resolved--need smooth cutoff in mesoscale range
- MORANS (e.g., typical IPCC/CMIP models; grid>50km)
  - Mesoscale Ocean Reynolds-Averaged Navier-Stokes
  - Nothing resolved, unresolved to be parameterized
- SMORANS (e.g., Fox-Kemper et al., 2011; grid 1-10km)
  - Submesoscale Ocean...
  - Mesoscale resolved, submesoscale unresolved...
- NOTE: RANS contains all smaller scales that couple!

Extrapolate for historical perspective:
The Golden Era of Subgrid Modeling is Now!



<===SG Models===>

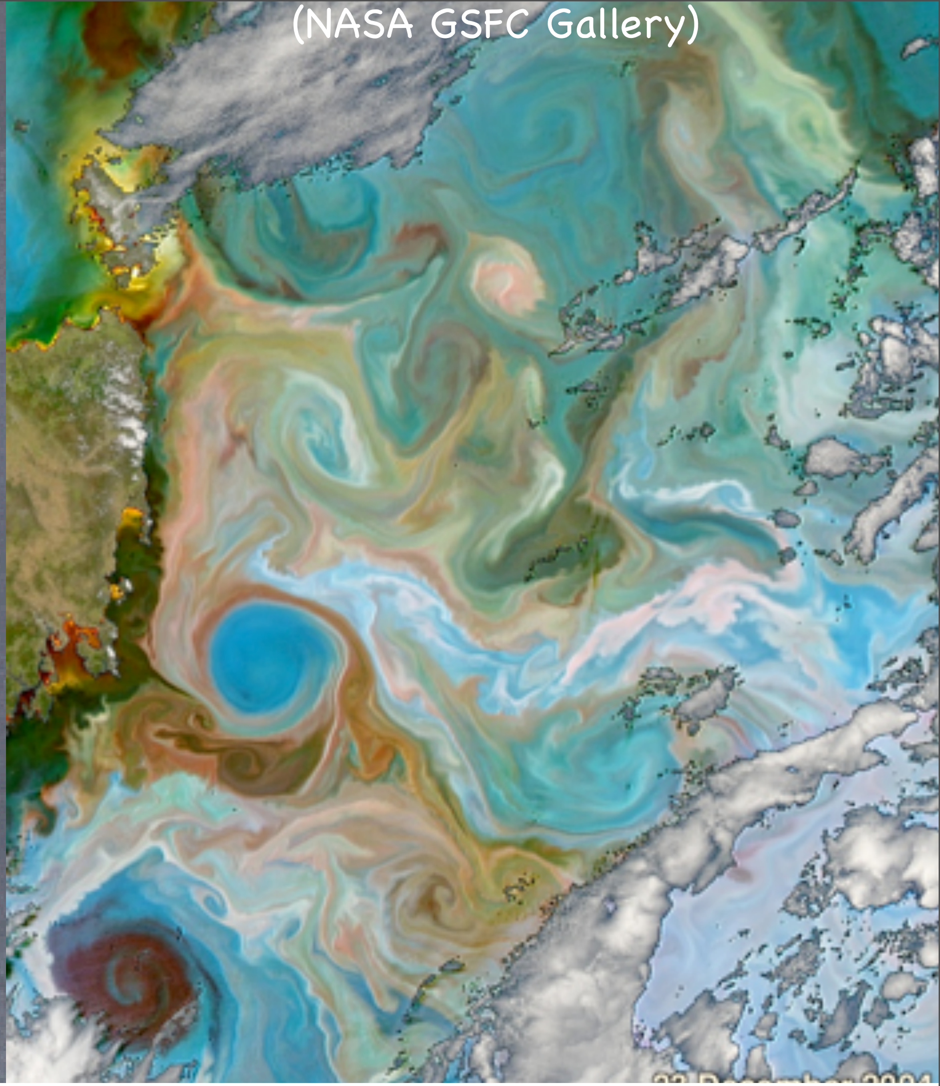
Mesoscale Parameterizations

- Researchers have already cast much darkness on this subject and if they continue their investigations we shall soon know nothing at all about it.
  - --Mark Twain

The Character of the Mesoscale

100 km

(NASA GSFC Gallery)



(Capet et al., 2008)

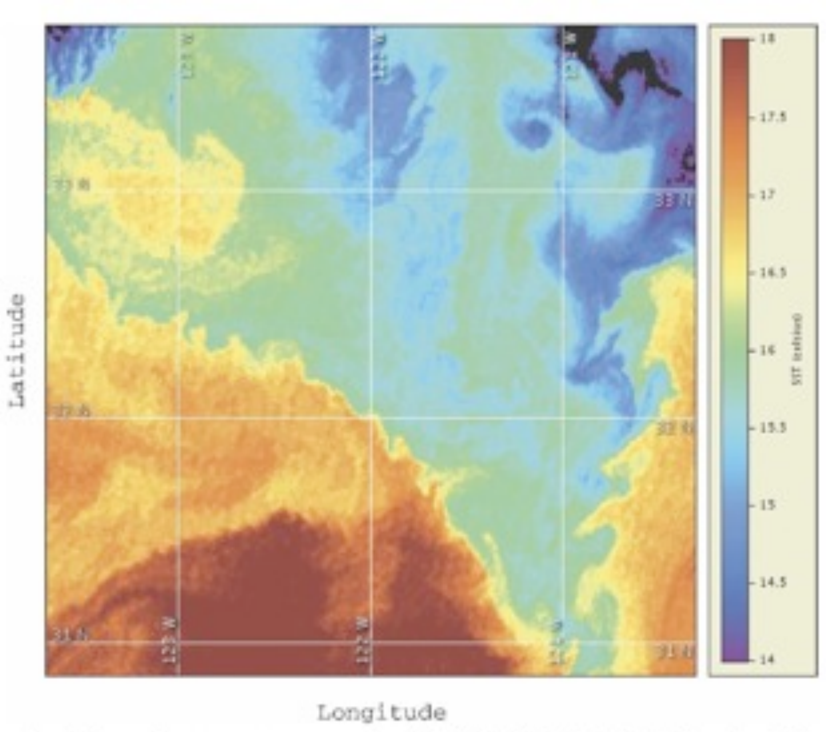
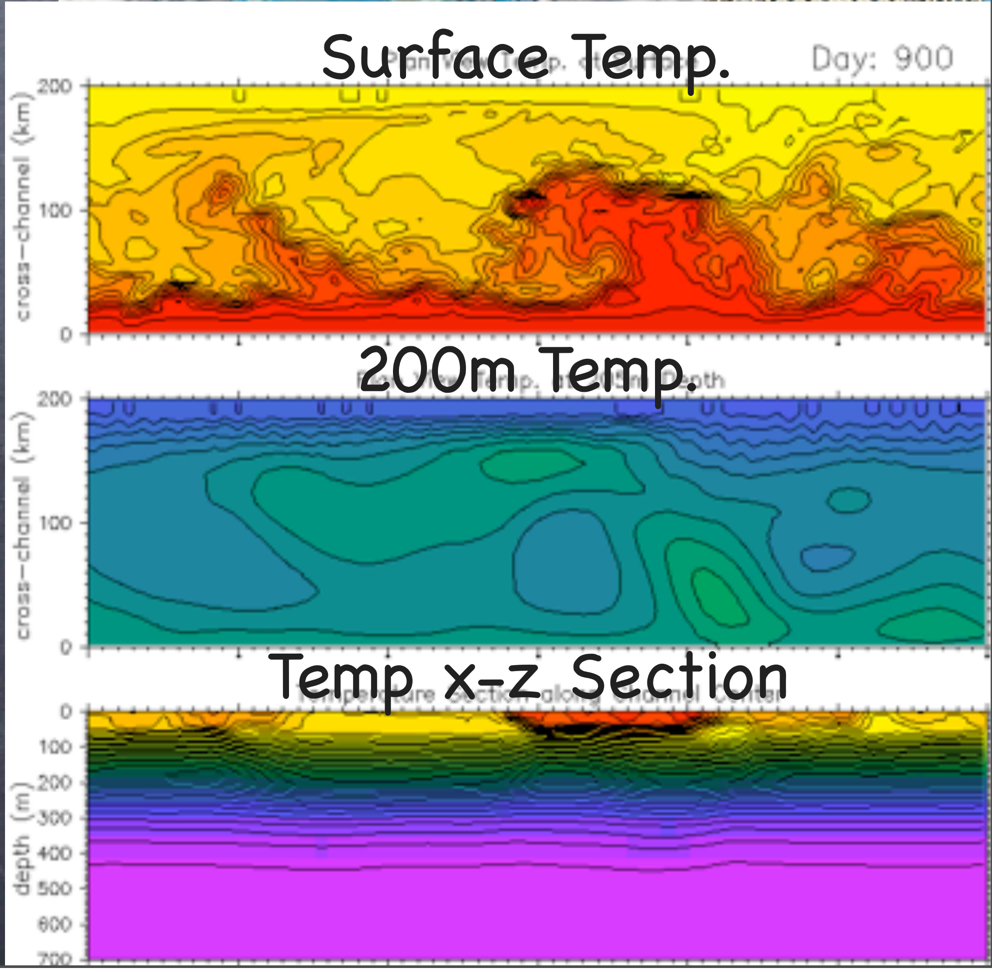


FIG. 16. Sea surface temperature measured at 1832 UTC 3 Jun 2006 off Point Conception in the California Current from CoastWatch (http://coastwatch.pfeg.noaa.gov). The fronts between recently upwelled water (i.e., 15°–16°C) and offshore water (≥17°C) show submesoscale instabilities with wavelengths around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

A MOLES Closure:

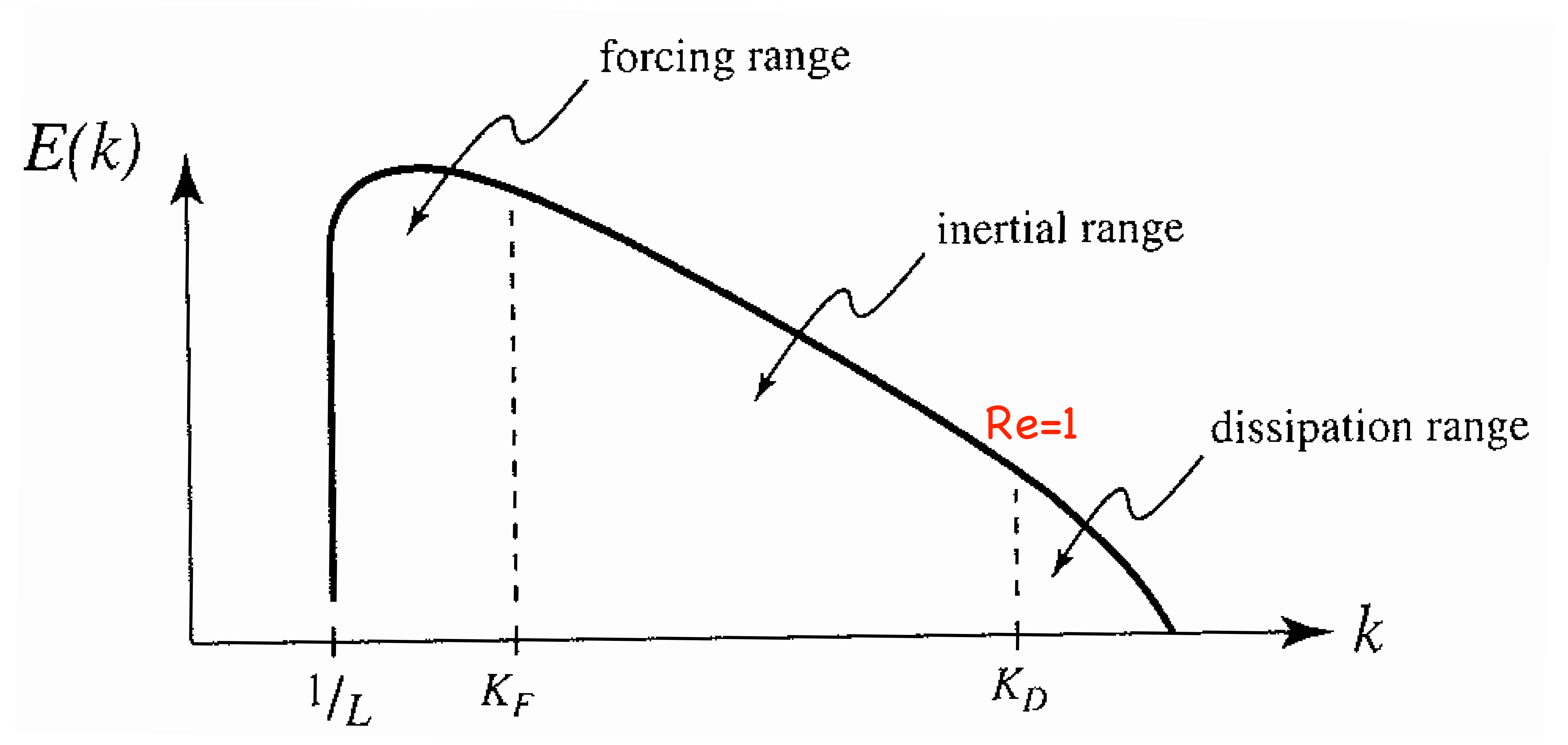
Smagorinsky & Kolmogorov
vs.
Leith & Kraichnan

Idea: Replace Eddy Momentum Fluxes with Artificially Inflated Viscosity

Relies on:

Energy Source, Dissipation, Flow & Dimensional Analysis

Truncation of Cascades

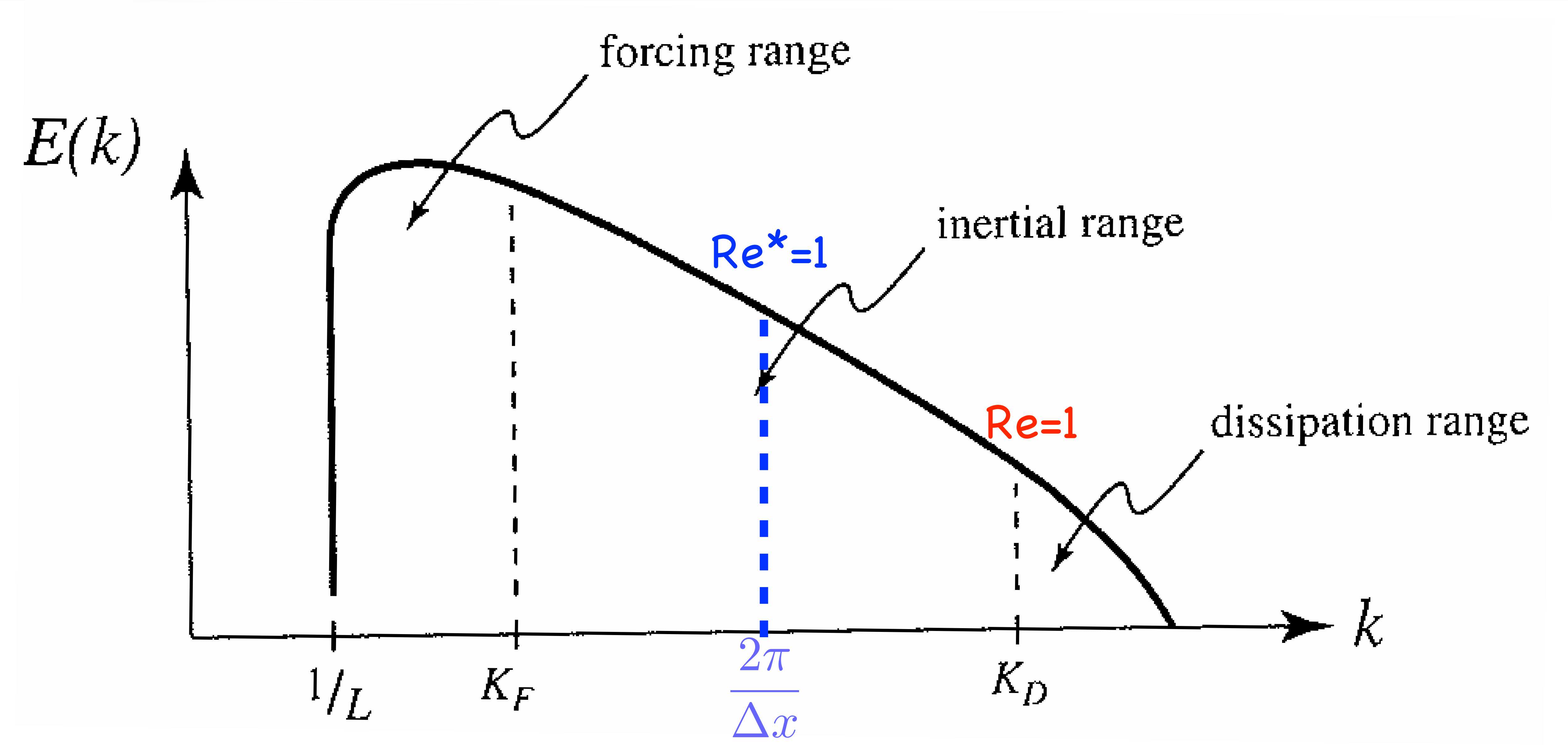


Power Spectrum:
Energy/Wavenumber

$$\langle E\rangle = \frac{1}{V}\iiint \frac{1}{2}(\mathbf{u}\cdot\mathbf{u})\,\mathrm{d}V = \int_0^\infty E(k)\mathrm{d}k.$$

1941: Kolmogorov Envisions the Inertial Range

Truncation of Cascades



1963: Smagorinsky Devises Viscosity Scaling,
So that the Energy Flow is Preserved,
but order-1 gridscale Reynolds #: $Re^* = UL/\nu_*$

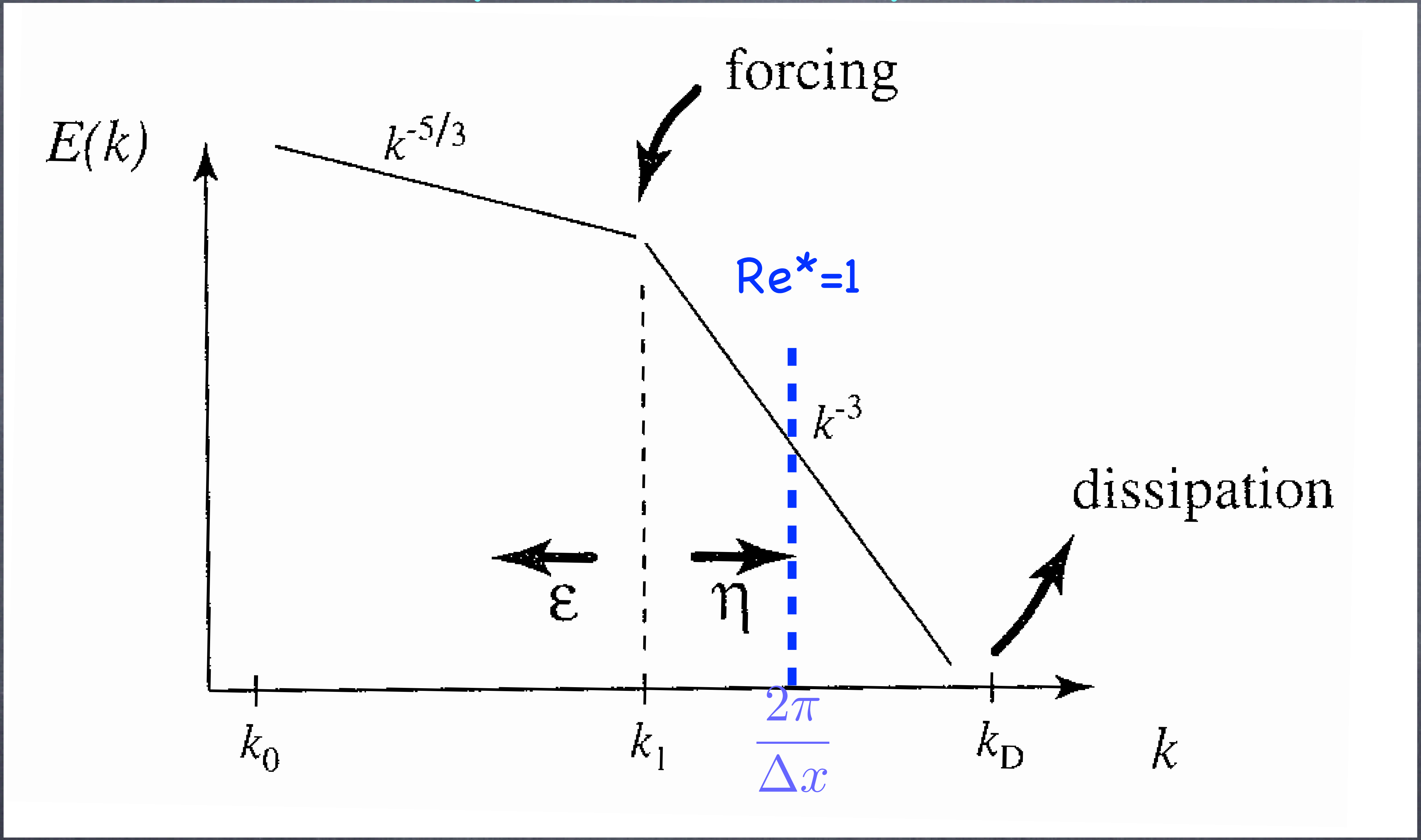
$$\nu_{*h} = \left(\frac{\Upsilon_h \Delta x}{\pi}\right)^2 \sqrt{\left(\frac{\partial u_*}{\partial x} - \frac{\partial v_*}{\partial y}\right)^2 + \left(\frac{\partial u_*}{\partial y} + \frac{\partial v_*}{\partial x}\right)^2}.$$

Except... Ocean Turbulence isn't 3d Turbulence at the Gridscale

- The ocean is wide (10000km)
- But not deep (4km)
- So motions are largely 2d
- The layer of blue paint on a globe has roughly the right aspect ratio!
- MOLES grid aspect is similar

2d Turbulence Differs

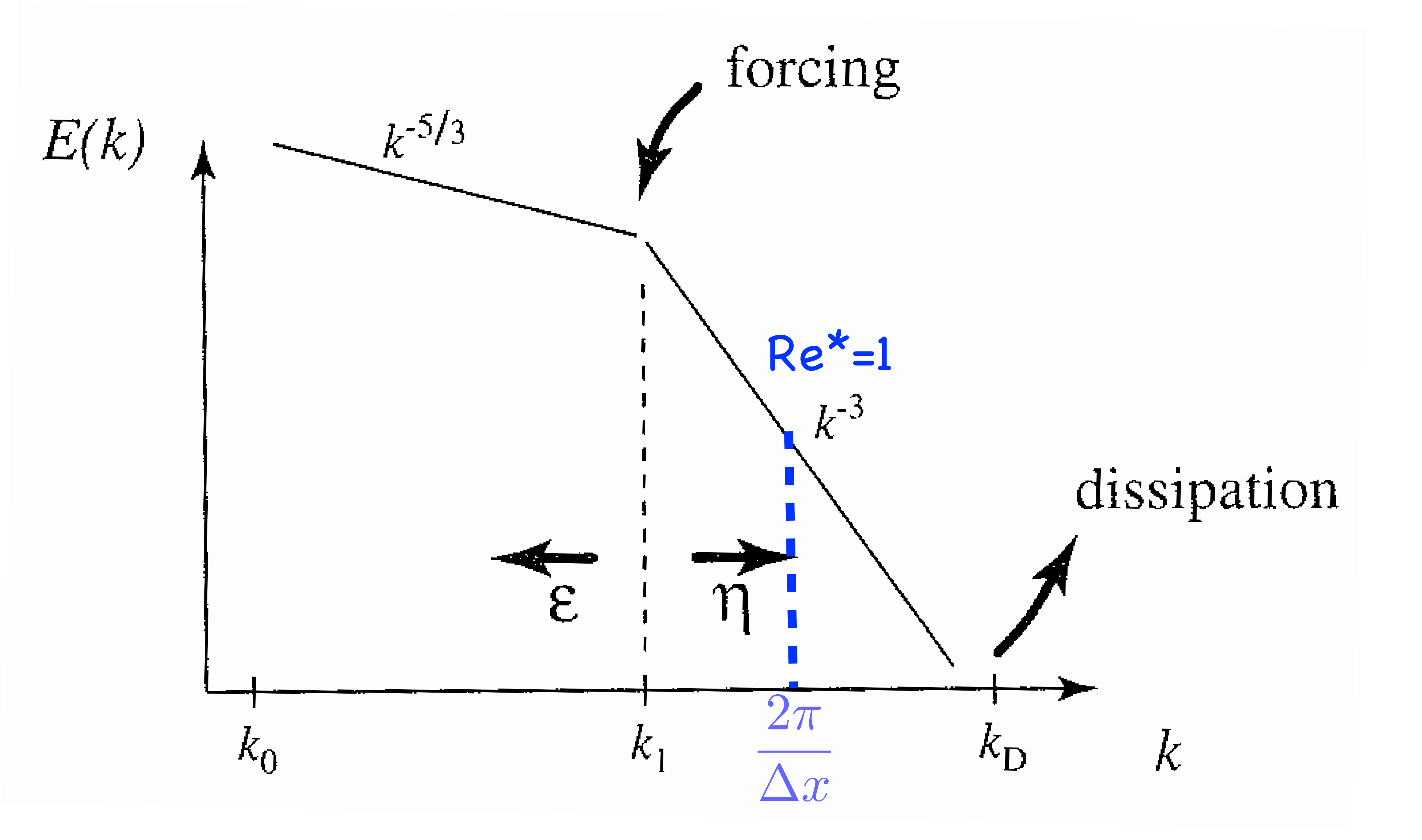
(Kraichnan, 67)



2 Conserved Quantities: Energy and Enstrophy (vorticity variance)

Energy Cascades Upscale, Enstrophy Downscale...

2d Turbulence Differs



1996: Leith Devises Viscosity Scaling,
So that the Enstrophy Flow is Preserved

$$\nu_* = \left(\frac{\Lambda\Delta x}{\pi}\right)^3 \left|\nabla_h \left(\frac{\partial u_*}{\partial y} - \frac{\partial v_*}{\partial x}\right)\right| .$$

2-d Turbulence is different from Atmosphere (Ocean*?) macro-turbulence

Figure adapted from Nastrom & Gage (85)

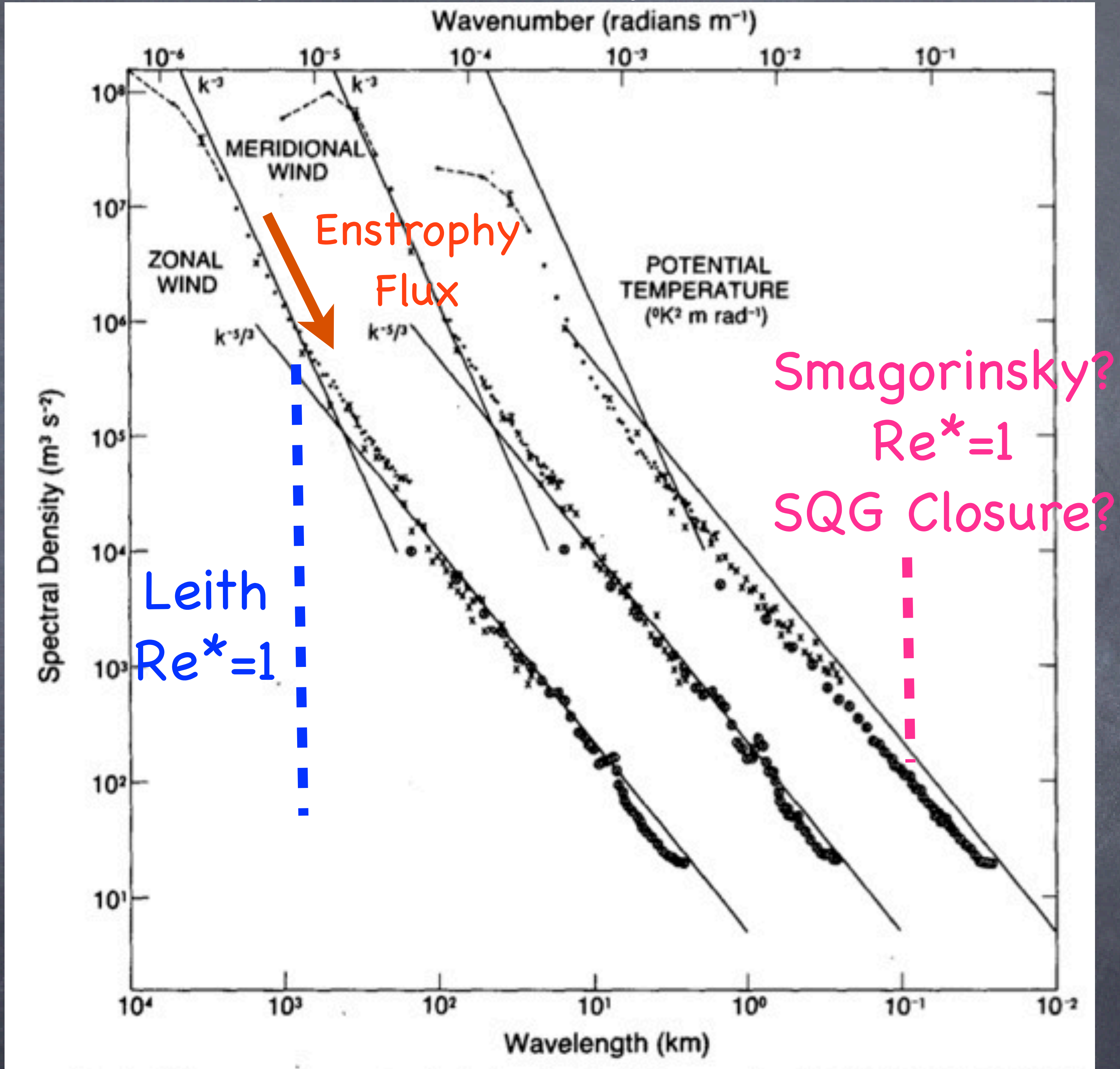
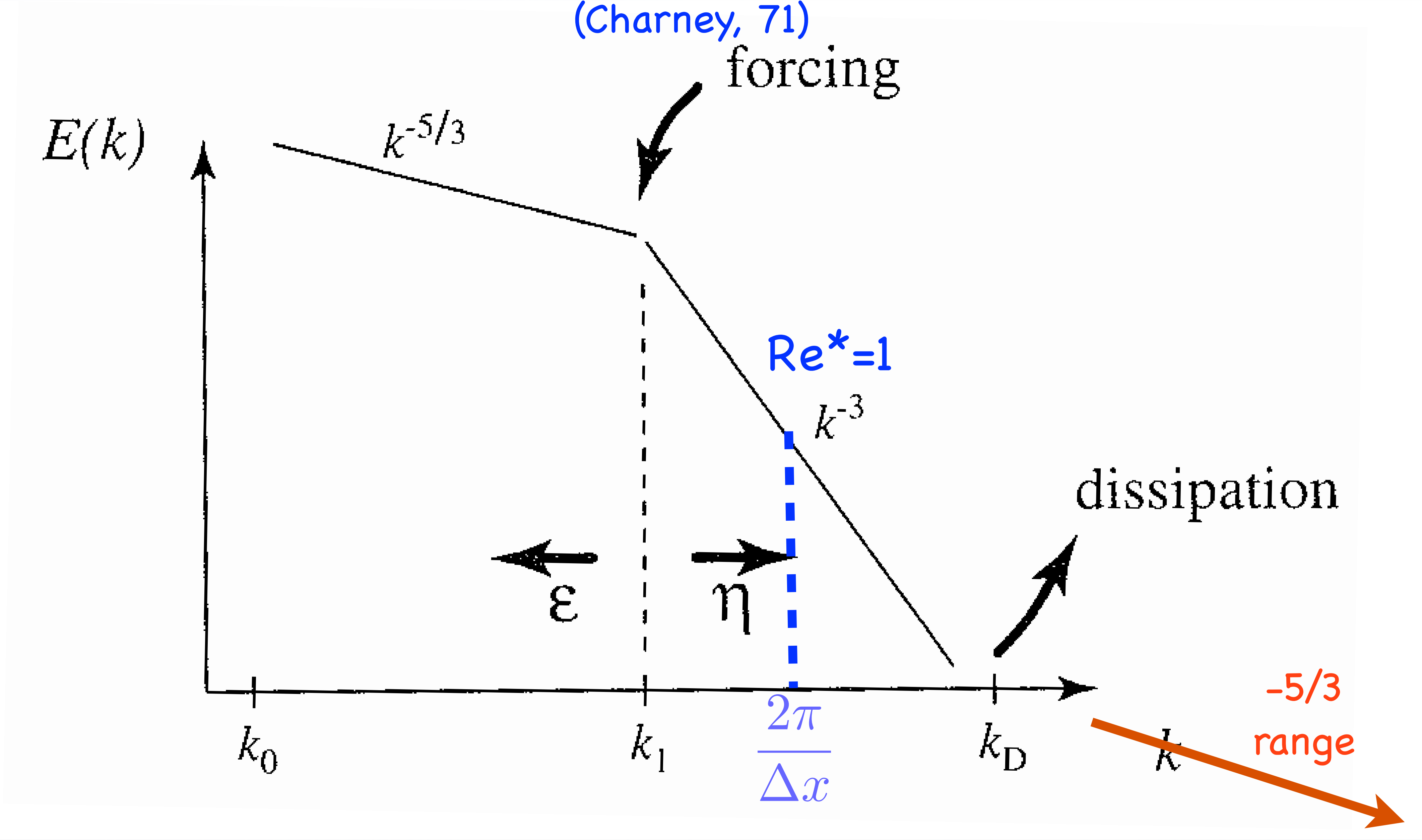


FIG. 3. Variance power spectra of wind and potential temperature near the tropopause from GASP aircraft data. The spectra for meridional wind and temperature are shifted one and two decades to the right, respectively; lines with slopes −3 and −⁵⁄₃ are entered at the same relative coordinates for each variable for comparison.

Kolmogorov
Re=1

* My student, Katie McCaffrey, is working on ocean spectra from obs.

MOLES Turbulence Like Pot'l Enstrophy cascade, but divergent

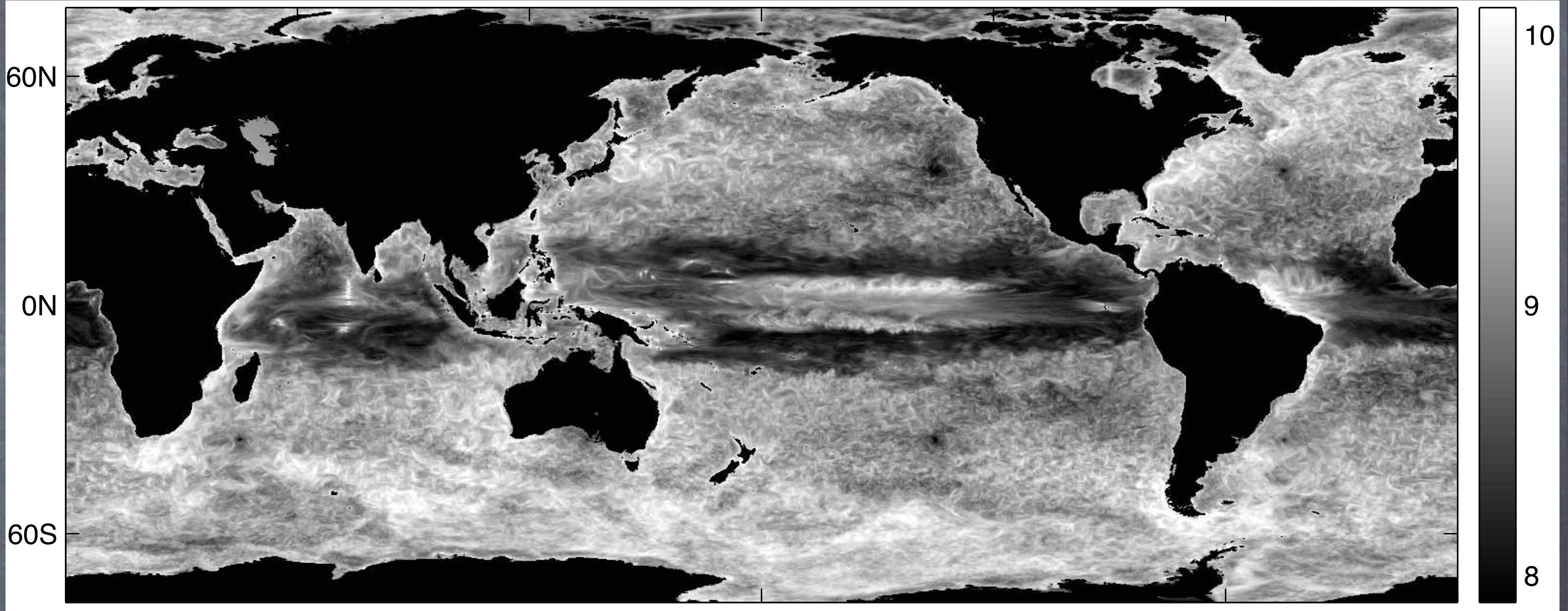


2008: F-K & Menemenlis Revise Leith Viscosity Scaling,
So that diverging, vorticity-free, modes are also damped

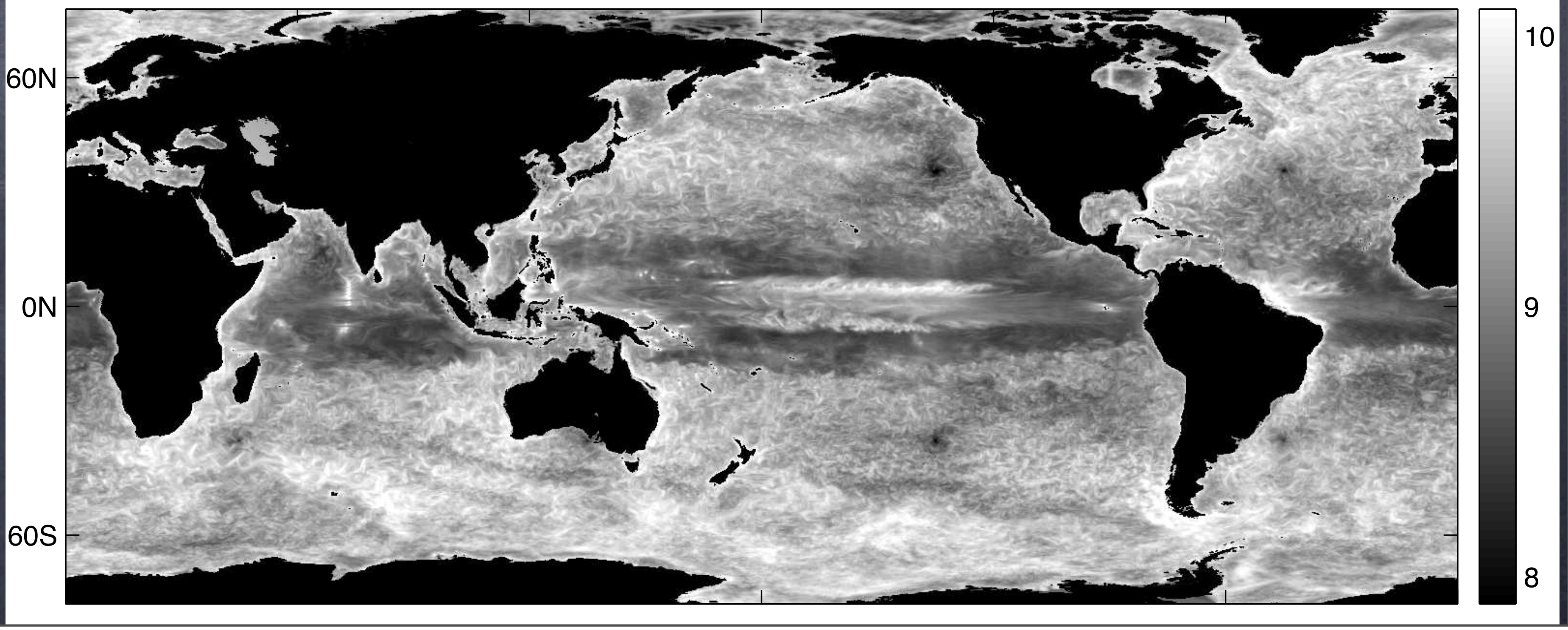
$$\nu_* = \left(\frac{\Delta x}{\pi}\right)^3 \sqrt{\Lambda^6|\nabla_h q_{2d}|^2 + \Lambda_d^6|\nabla_h(\nabla_h \cdot \mathbf{u}_*)|^2}.$$

Makes viscosity a bit bigger, especially near Eq.

Leith



F-K&M



But matters a lot for stability!

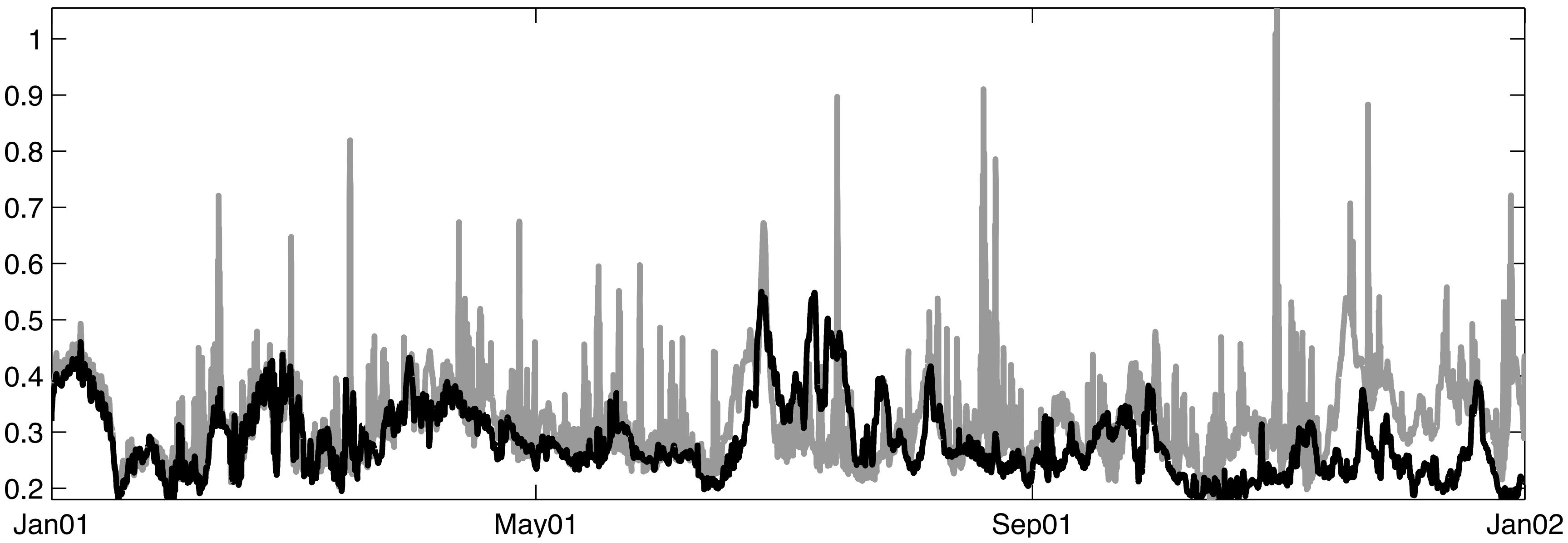


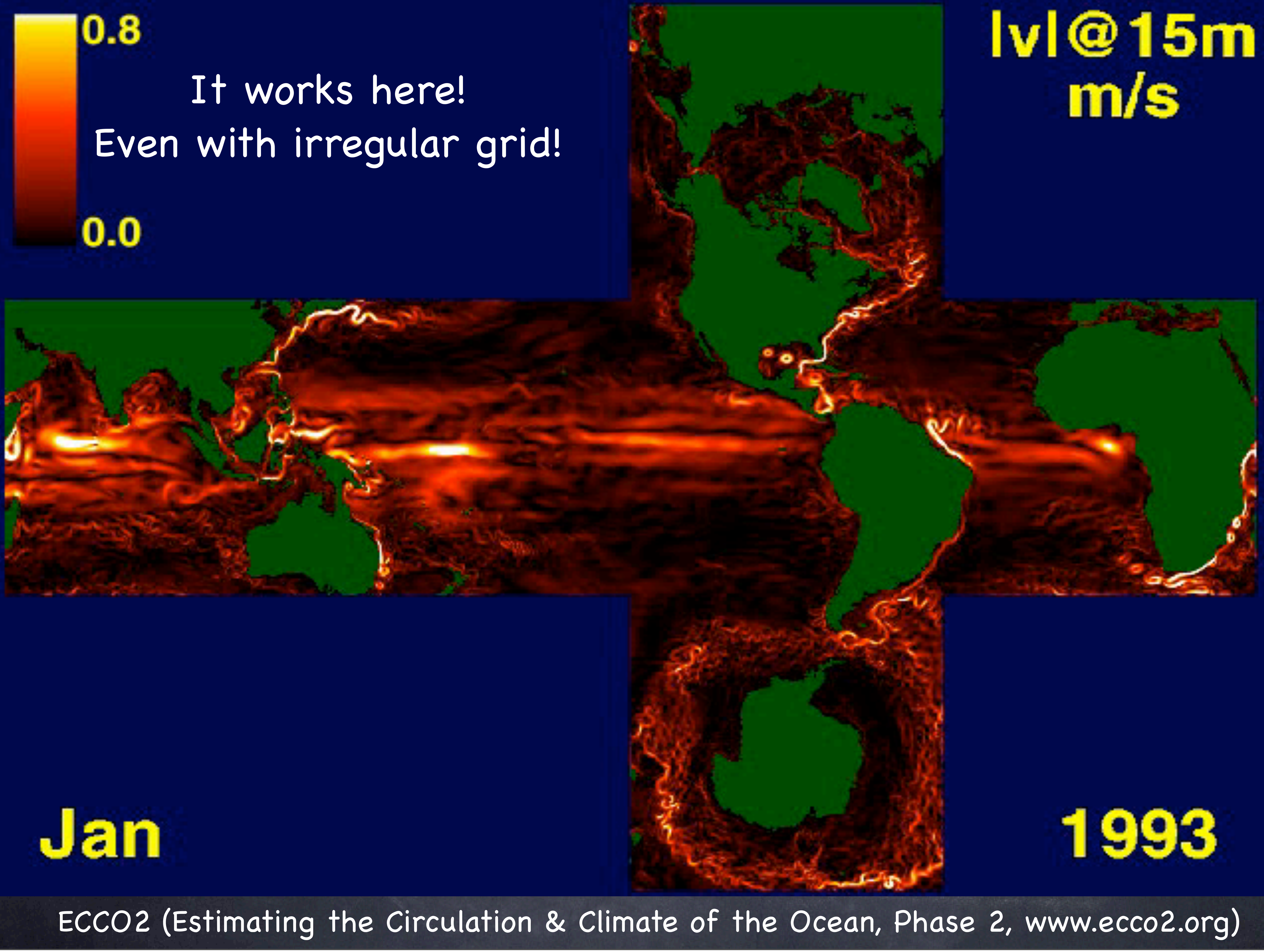
Figure 4. Maximum Courant number, $w\Delta t/\Delta z$, for vertical advection. Gray line is from the *LeithOnly* integration and black line is from the *LeithPlus* integration.

Fox-Kemper & Menemenlis, 2008

It works here!
Even with irregular grid!

ECCO2 (Estimating the Circulation & Climate of the Ocean, Phase 2, www.ecco2.org)

It works here!
Even with irregular grid!



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Spectra & Viscosity are good for MOLES, but... Asymptotics tell us to worry about scalar transport, not momentum for MORANS!

Equations for Large Scale Ocean Dynamics:

$$
\begin{aligned}
(f_0 + \beta Y)\hat{\mathbf{z}} \times \overline{\mathbf{u}} &= -\overline{\nabla}_h \overline{p}, \\
\partial_z \overline{p} &= \overline{b}, \\
\overline{\nabla}_h \cdot \overline{\mathbf{u}} + \partial_z \overline{w} &= 0, \\
\partial_\tau \overline{b} + \overline{\mathbf{u}} \cdot \overline{\nabla}_h \cdot \overline{b} + \overline{w}\partial_z \overline{b} + \overline{\nabla}_h \cdot \boxed{\left(\overline{\mathbf{u}'b'}\right)} + \partial_z \boxed{\left(\overline{w'b'}\right)} &= \kappa_v \partial_z^2 \overline{b}
\end{aligned}
$$

No more momentum fluxes!, i.e., $\cancel{\overline{\nabla}_h \boxed{\left(\overline{\mathbf{u}'\mathbf{u}'}\right)}}$

Grooms, Julien, & F-K, 2011

TESTING MORANS Closures:

Validation & Spatial variations of Gent-McWilliams & Redi

Idea: Study the fluxes of passive tracers and reconstruct the flux-gradient relationship

Relies on:

Unique Lagrangian Transport Operator for All Tracers

Mesoscale Eddy Parameterizations all have the form:

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

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

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

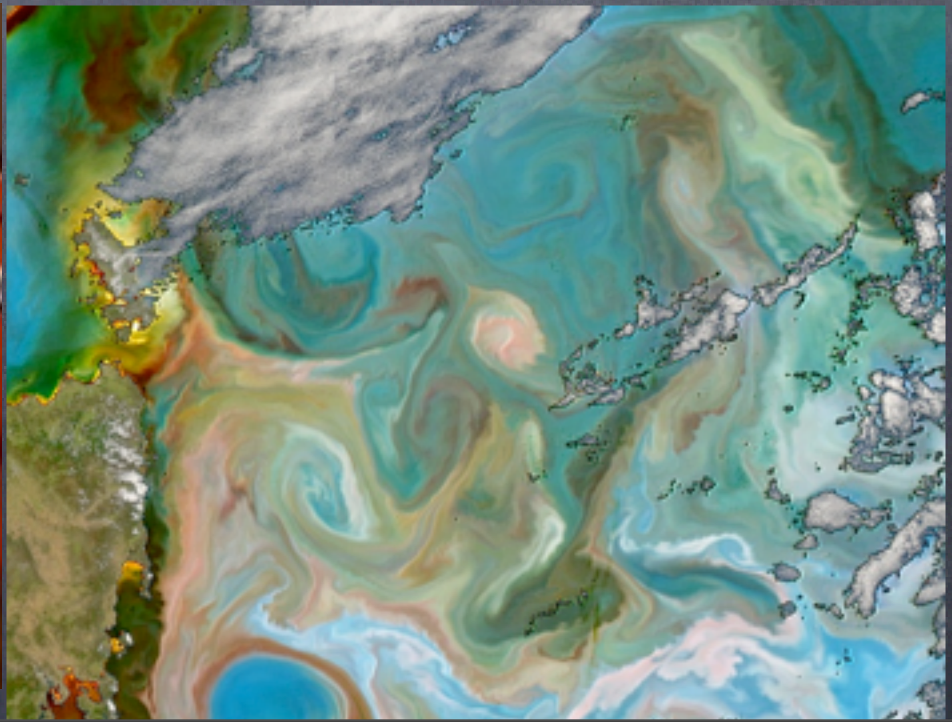
Added 9 Passive tracers--restored x,y,z @ 3 rates

Kept all the eddy fluxes for passive & active

Coarse-grained to 2°, transient eddies, tracers to $\mathbf{M}$

Does this cover all the degrees of freedom?

- More tracers does provide a just-determined or overdetermined (Moore-Penrose/least squares) problem for M with a unique answer, but...
- Different tracers will have different fluxes as they feel the subgrid 'nooks and crannies' of the mesoscale eddies!



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

Sym Part=Anisotropic* Redi

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

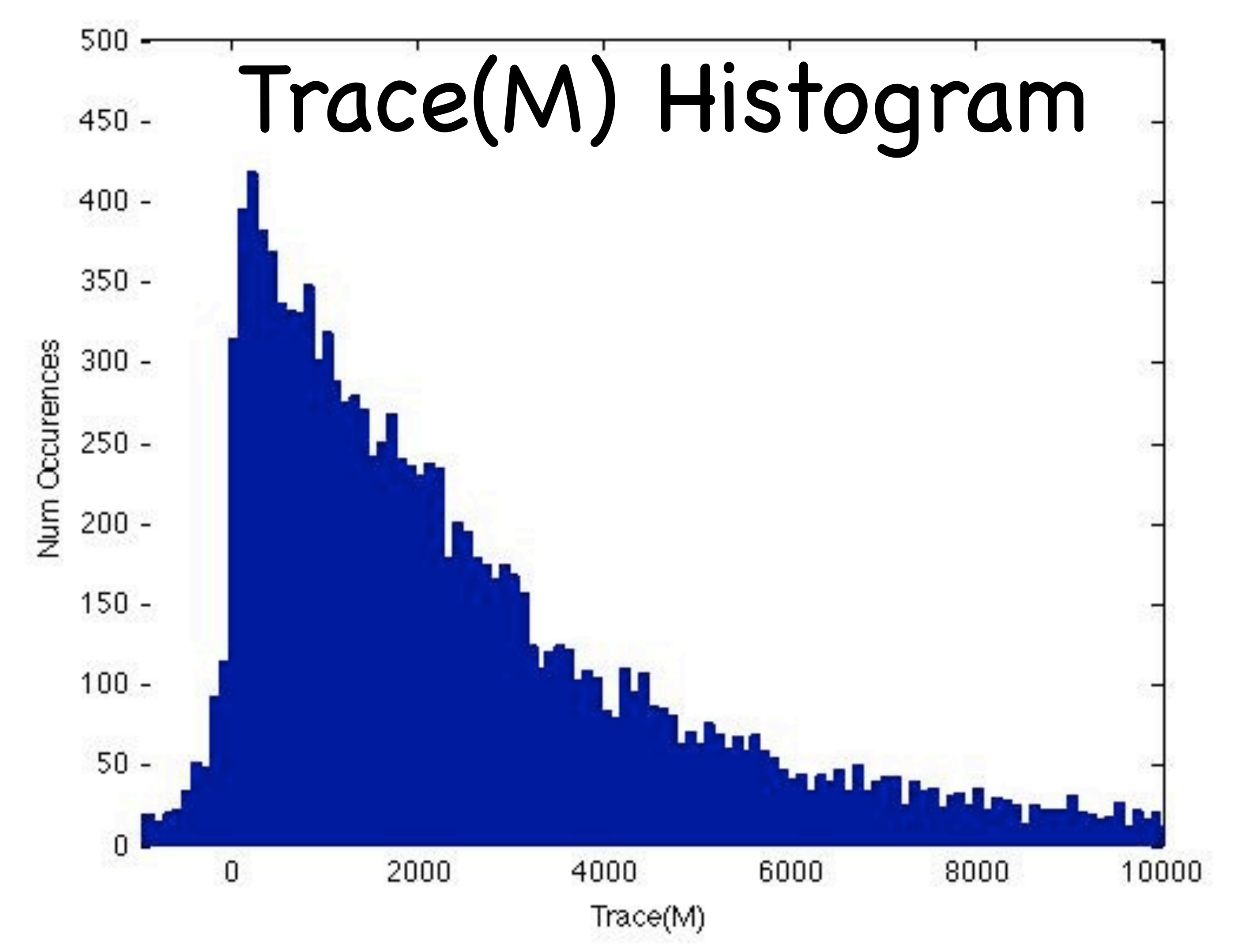
AntiSym Part=Anisotropic* GM

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

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

Are Diffusivity Values Resonable?

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

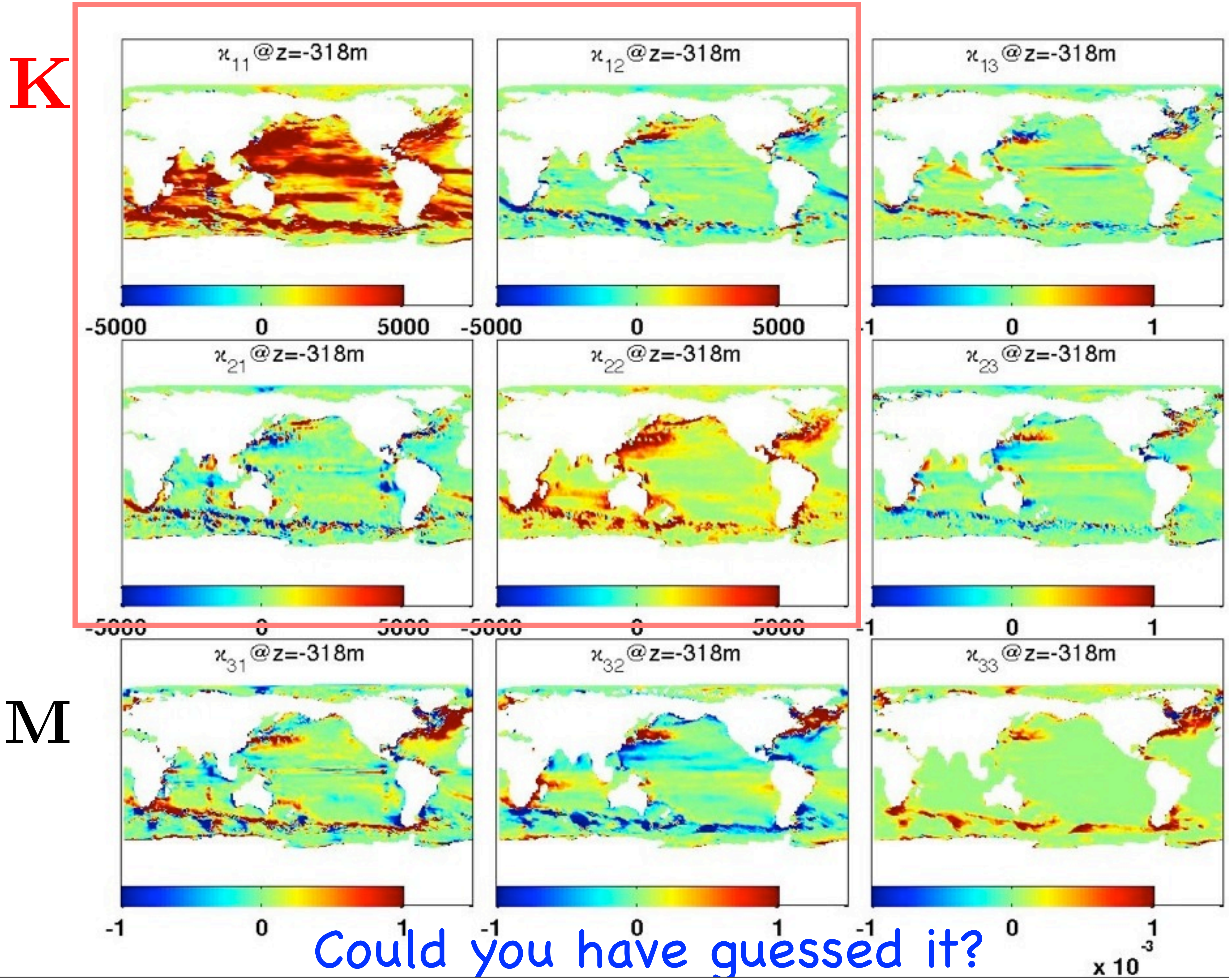


Hor. Diffusivity is roughly Trace(M)/2

Peak of Diffusivity near 250 m^2/s

Median Diffusivity near 1000m^2/s

<6% negative



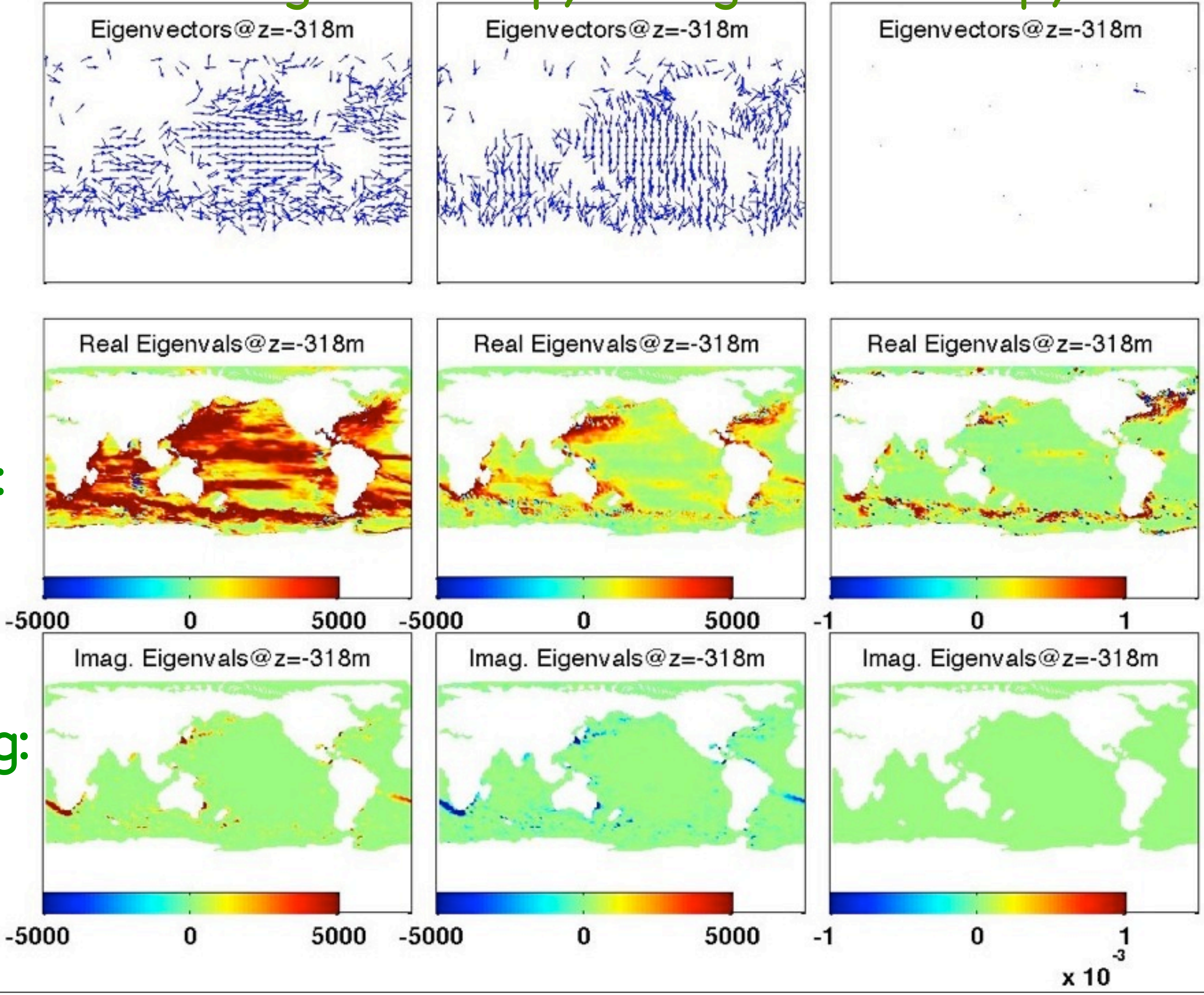
Could you have guessed it?

Result: Strong Anisotropy Along/Across Isopycnals

Mixing direction

Mixing:

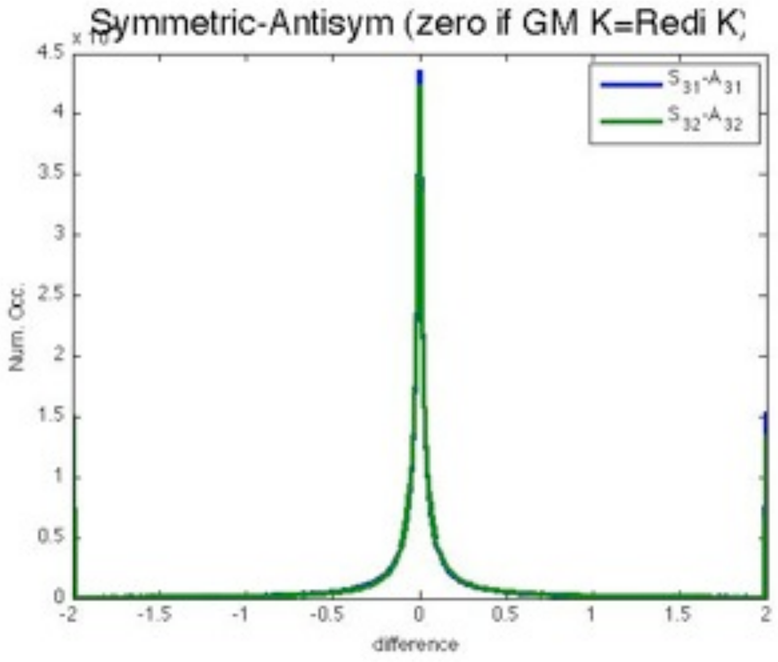
Stirring:

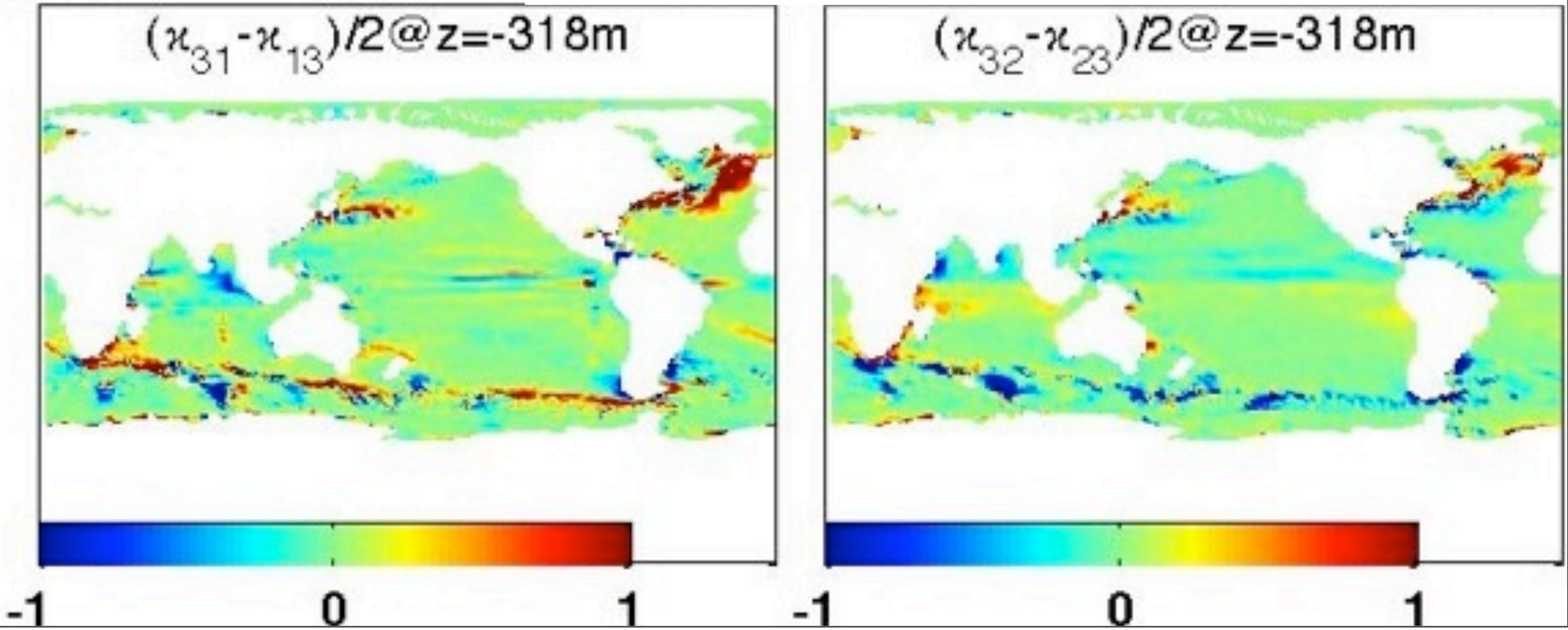


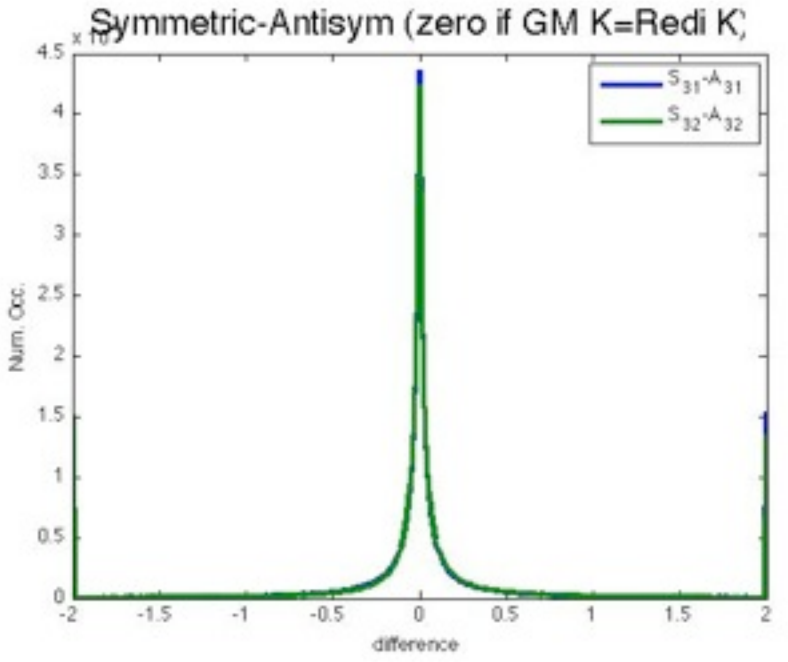
Result:

Redi K=GM K(mostly)

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







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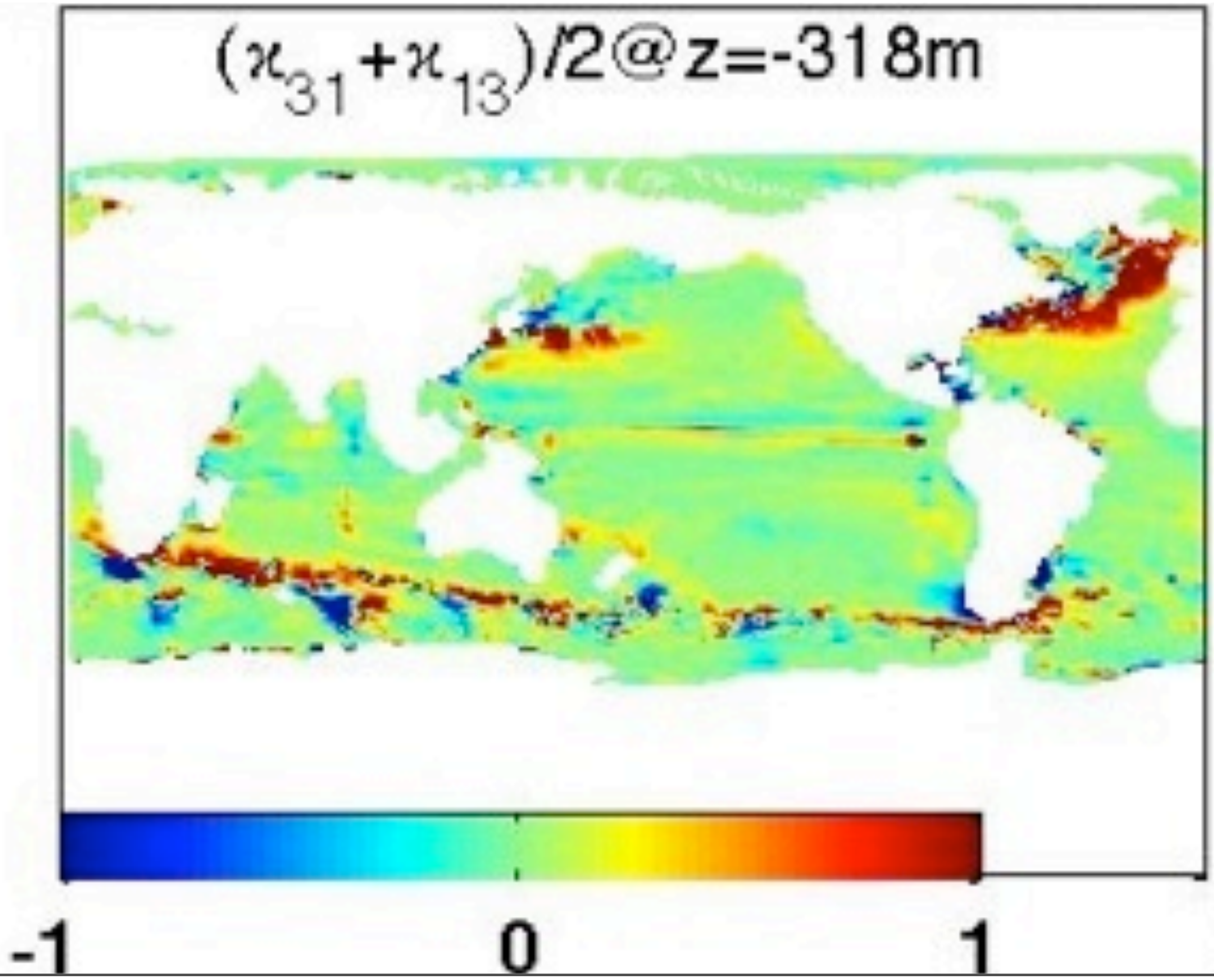
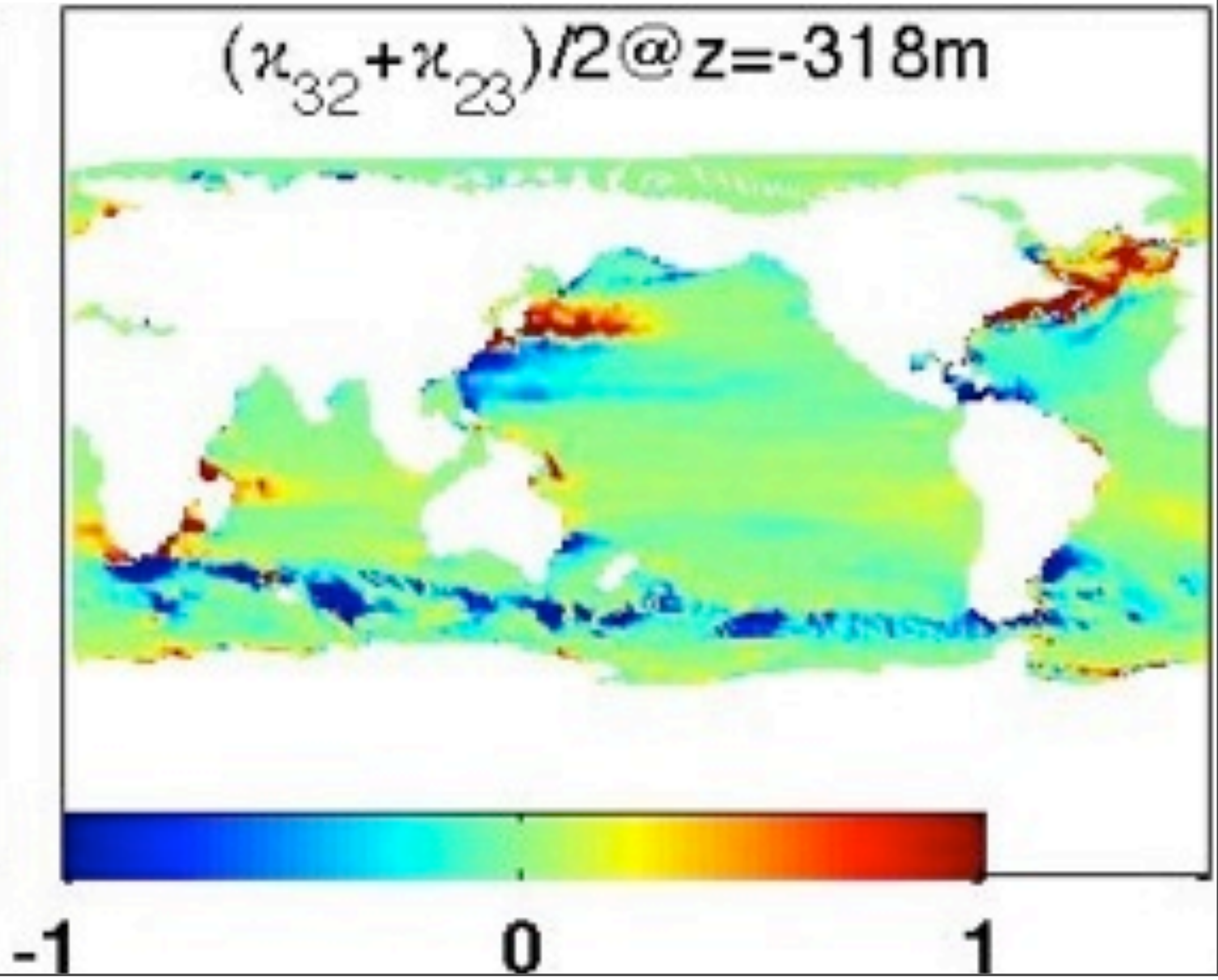


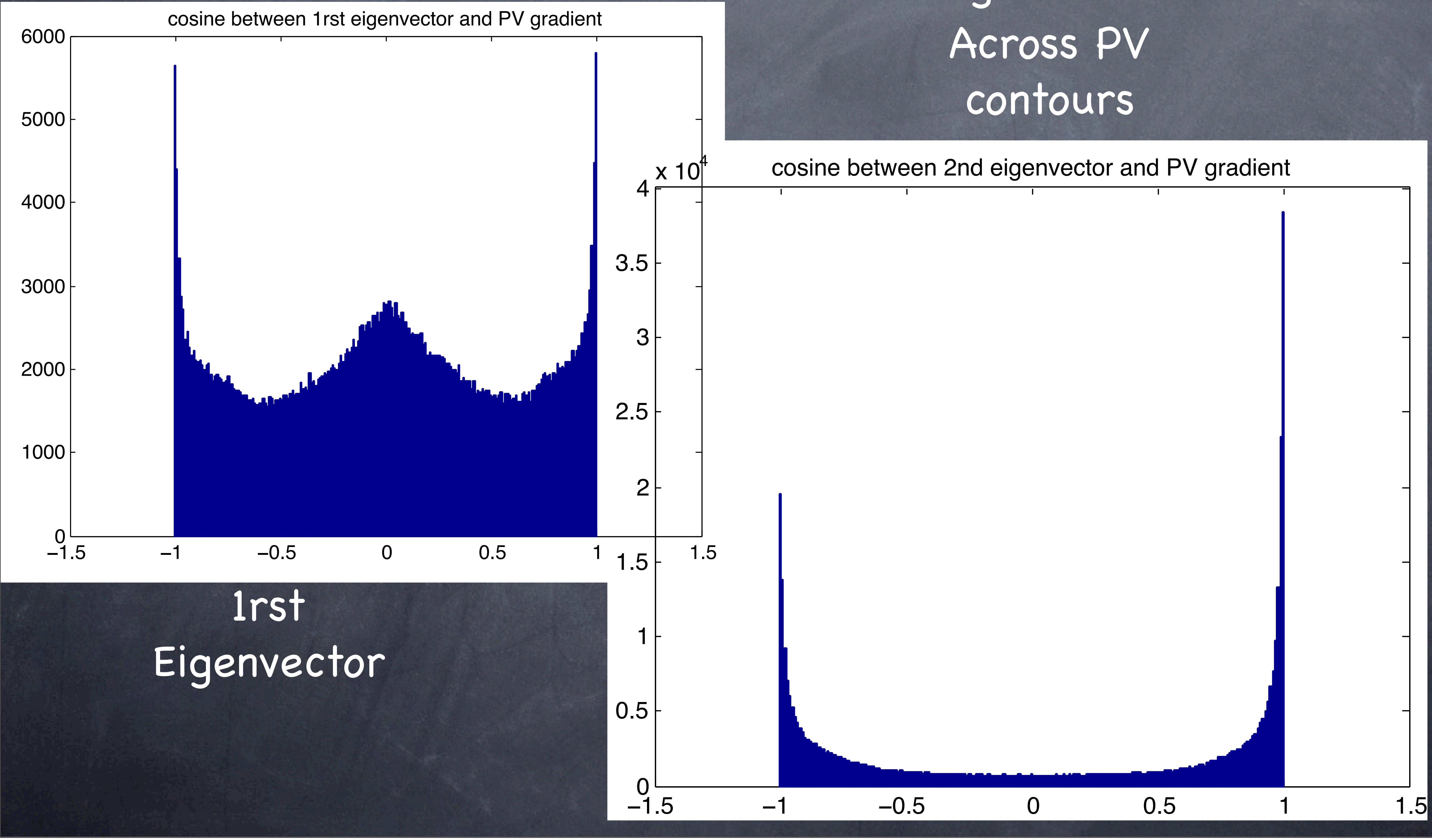


Result: Strong Anisotropy Along/Across PV Grads.

Mixing direction

Either along PV contours or across

2nd Eigenvector Across PV contours

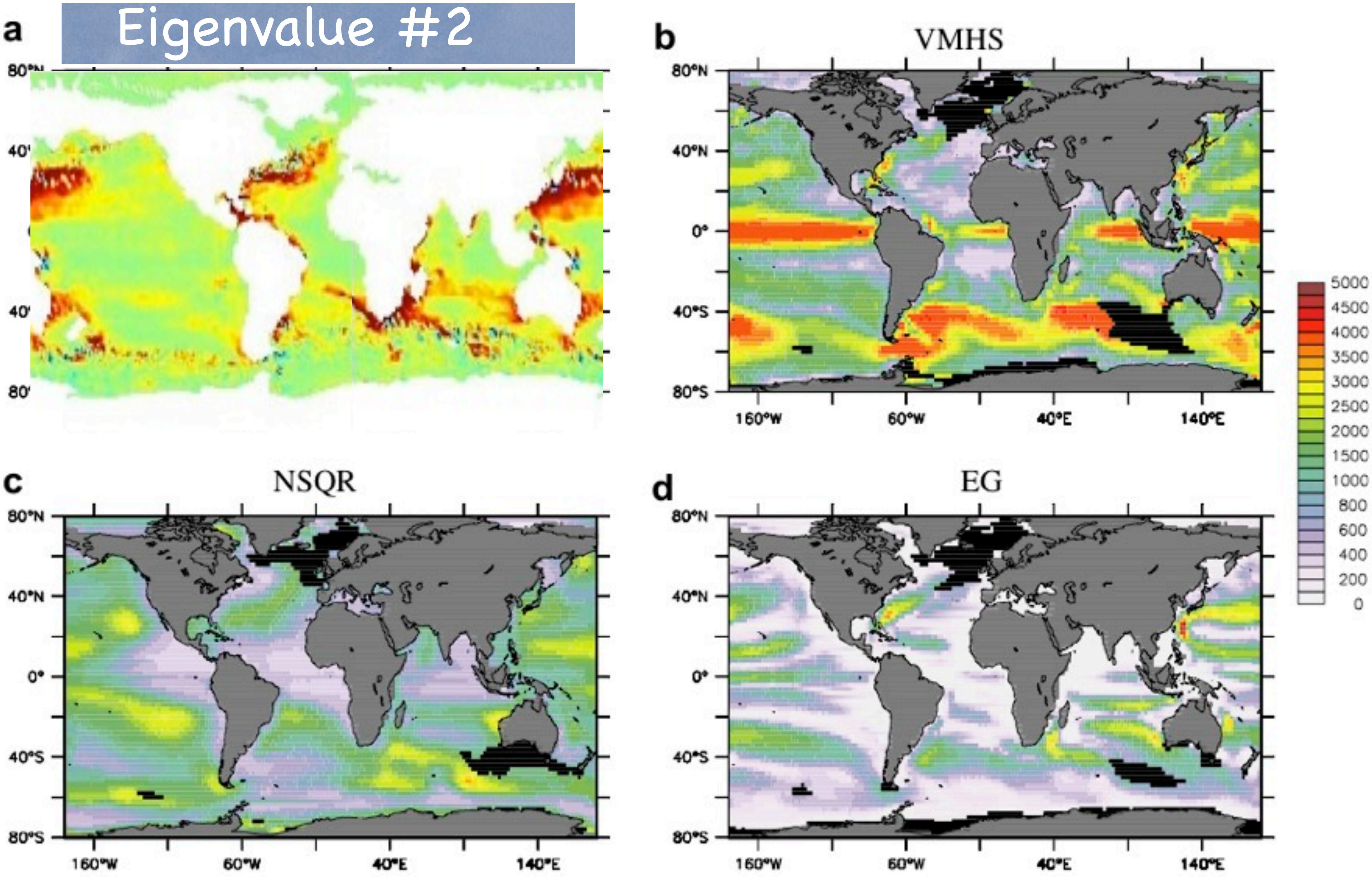


cosine between 1rst eigenvector and PV gradient

cosine between 2nd eigenvector and PV gradient

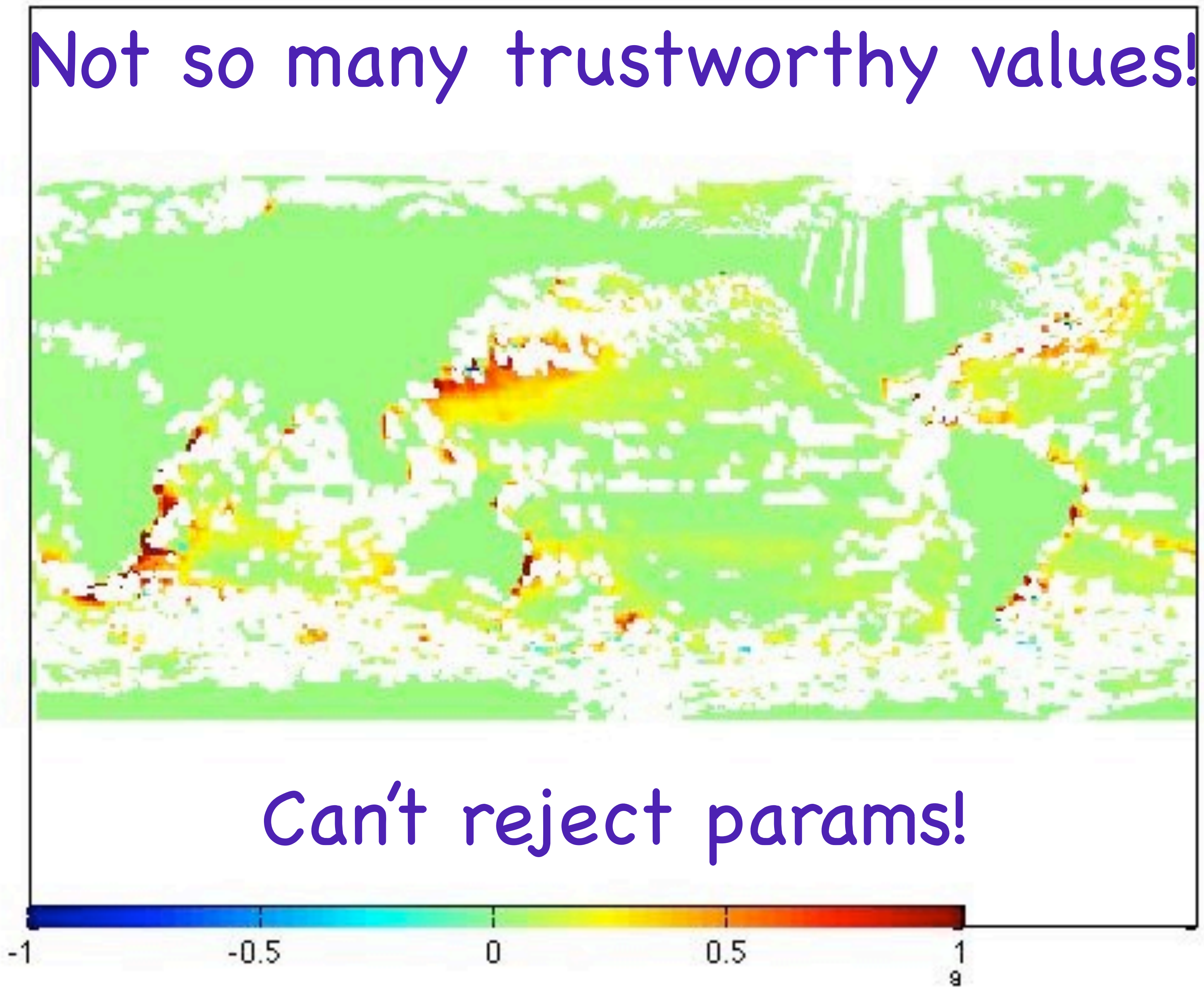
1rst Eigenvector

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.

But, how well does it work? Suppose we only plot values where different tracer sets agree...

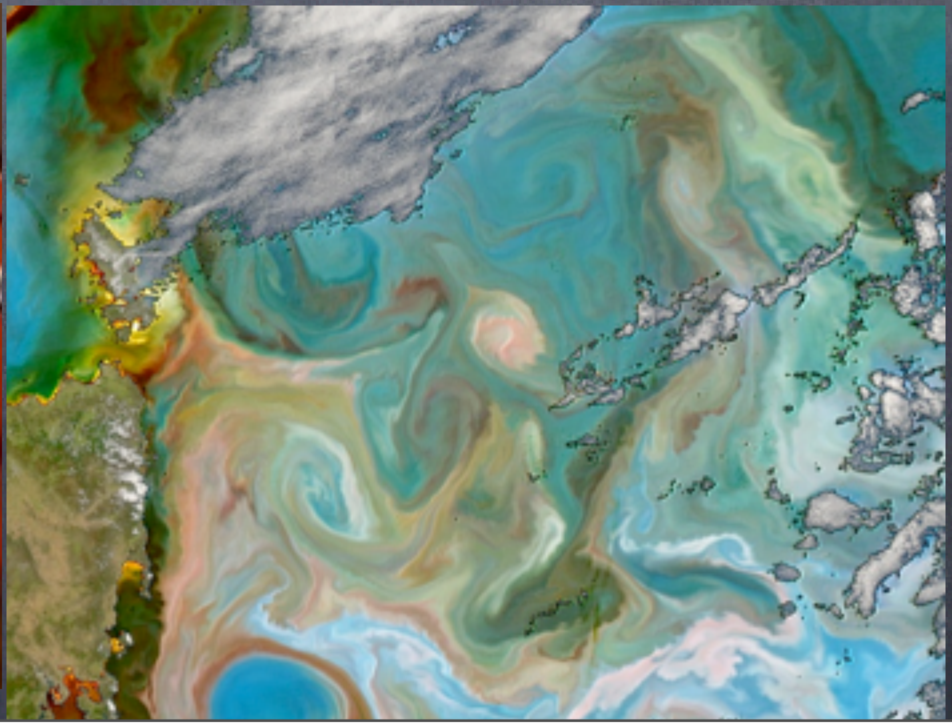

Not so many trustworthy values!

Can't reject params!

Does this cover all the degrees of freedom?

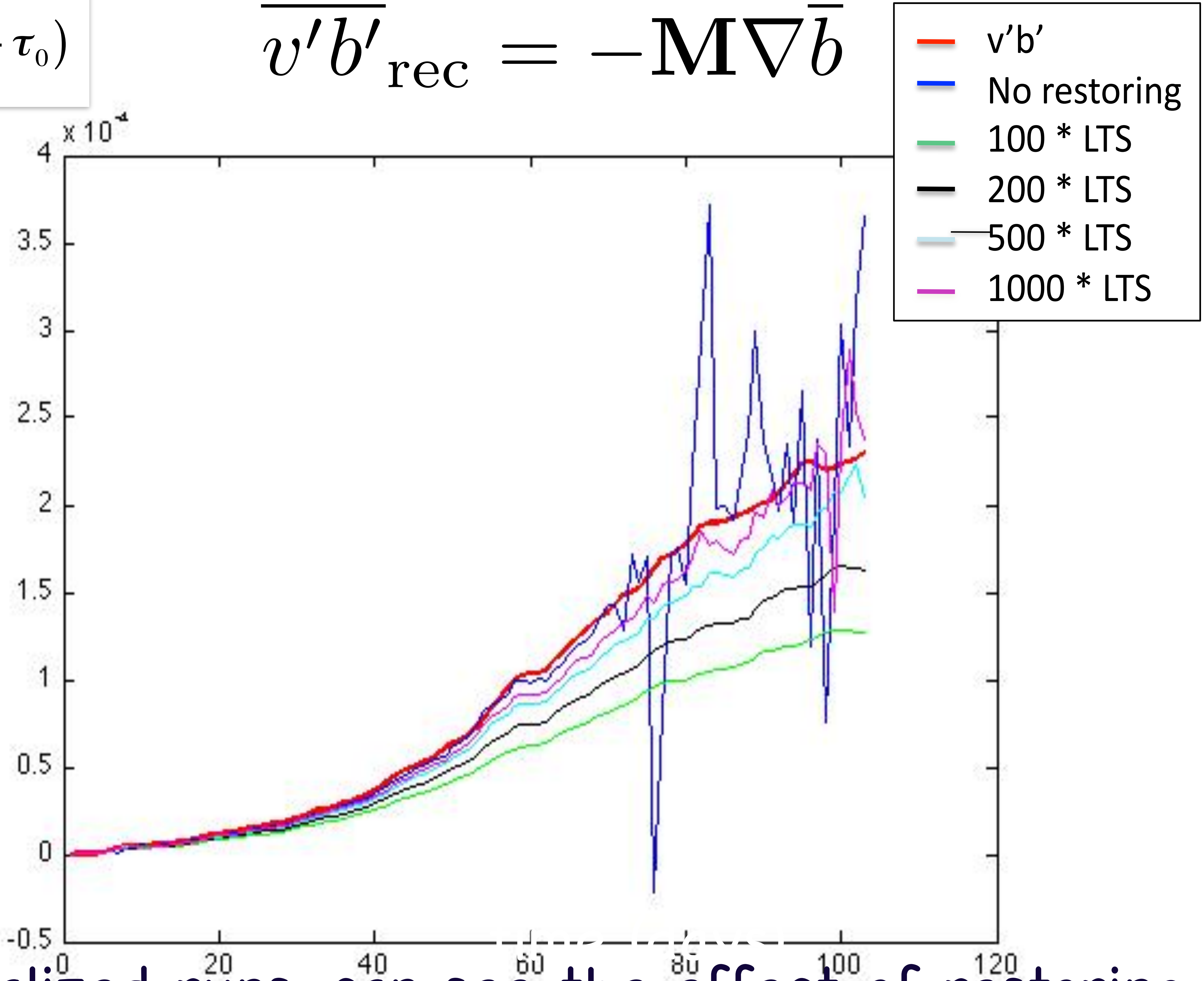
- More tracers does provide a just-determined or overdetermined (Moore-Penrose/least squares) problem for M with a unique answer, but...

- Different tracers will have different fluxes as they feel the subgrid 'nooks and crannies' of the mesoscale eddies!



$$\frac{d\tau}{dt} = -\lambda(\tau - \tau_0)$$

$$\overline{v'b'}_{\mathrm{rec}} = -\mathbf{M}\nabla\overline{b}$$

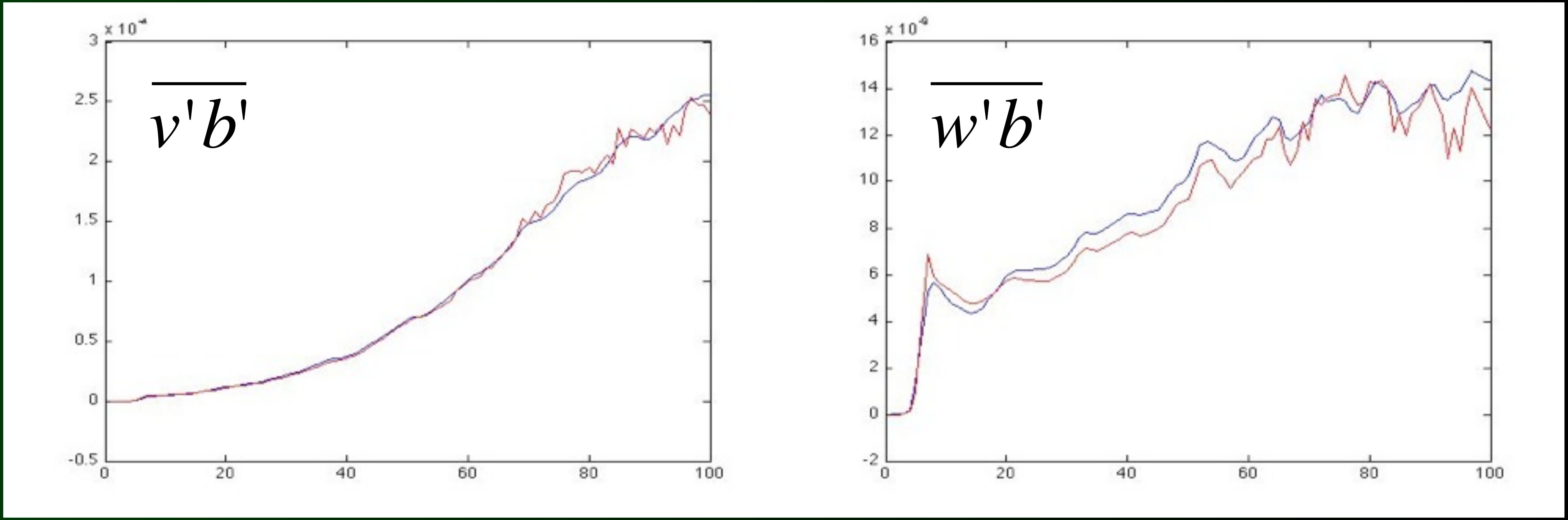


In idealized runs, can see the effect of restoring.

Whatever we do, we need to get buoyancy right!

In idealized setting, can do better

Reconstruction of eddy buoyancy fluxes



Using specially-tailored non-restored tracers improves estimate (error is now < 10%)… but not feasible in realistic diagnosis.

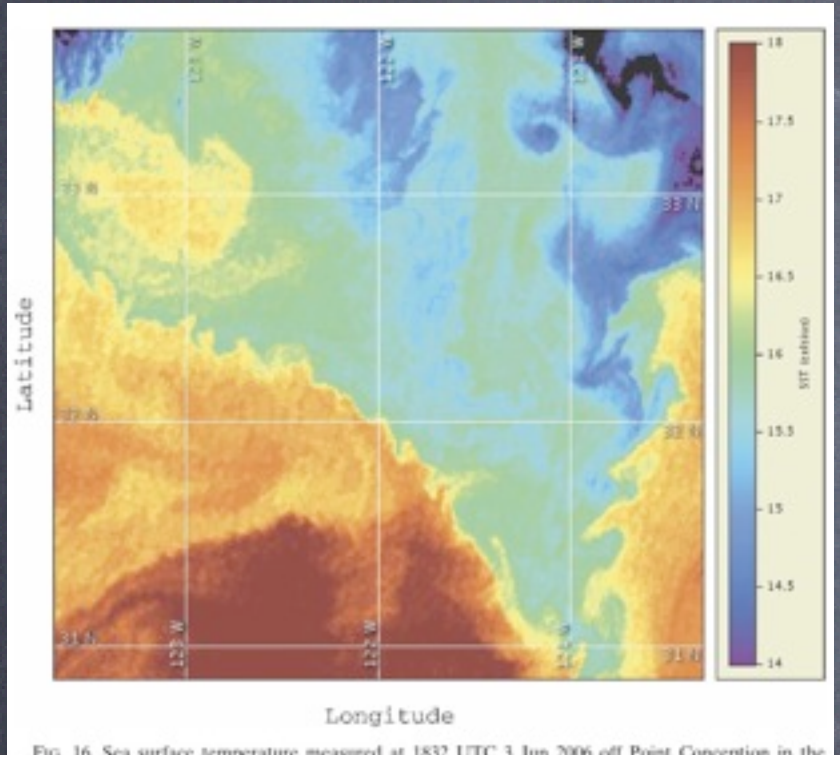
In realistic diagnosis, we can improve the estimate a bit by approximating restoring effect

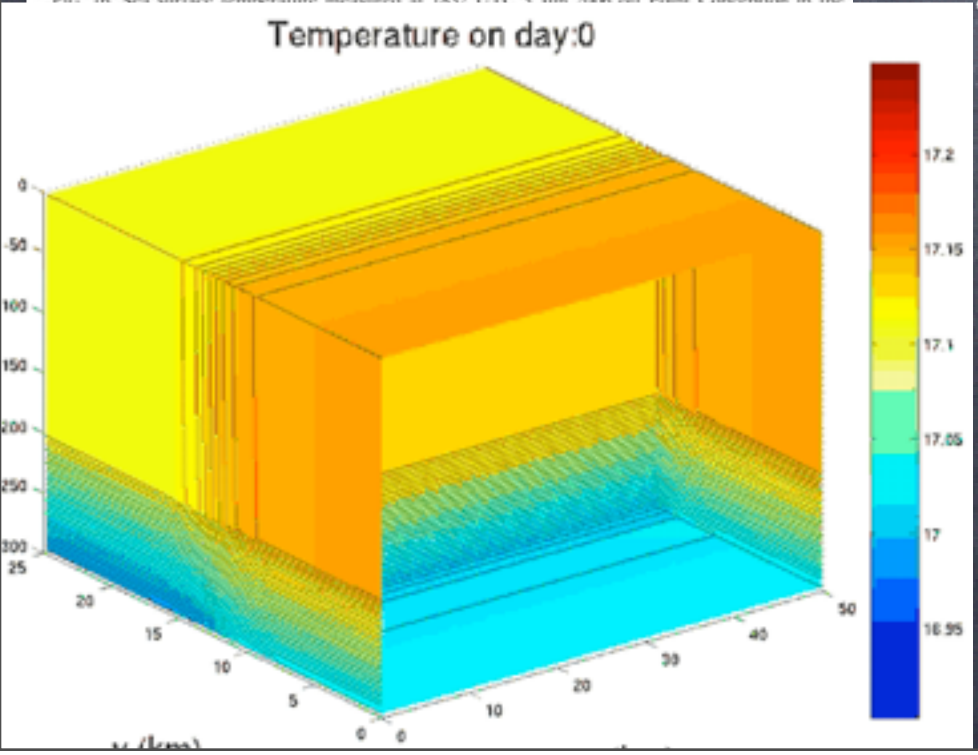
Sub-Mesoscale Parameterizations

- Anyone who doesn't take truth seriously in small matters cannot be trusted in large ones either.
  - --Albert Einstein

The Character of the Submesoscale

(Capet et al., 2008)

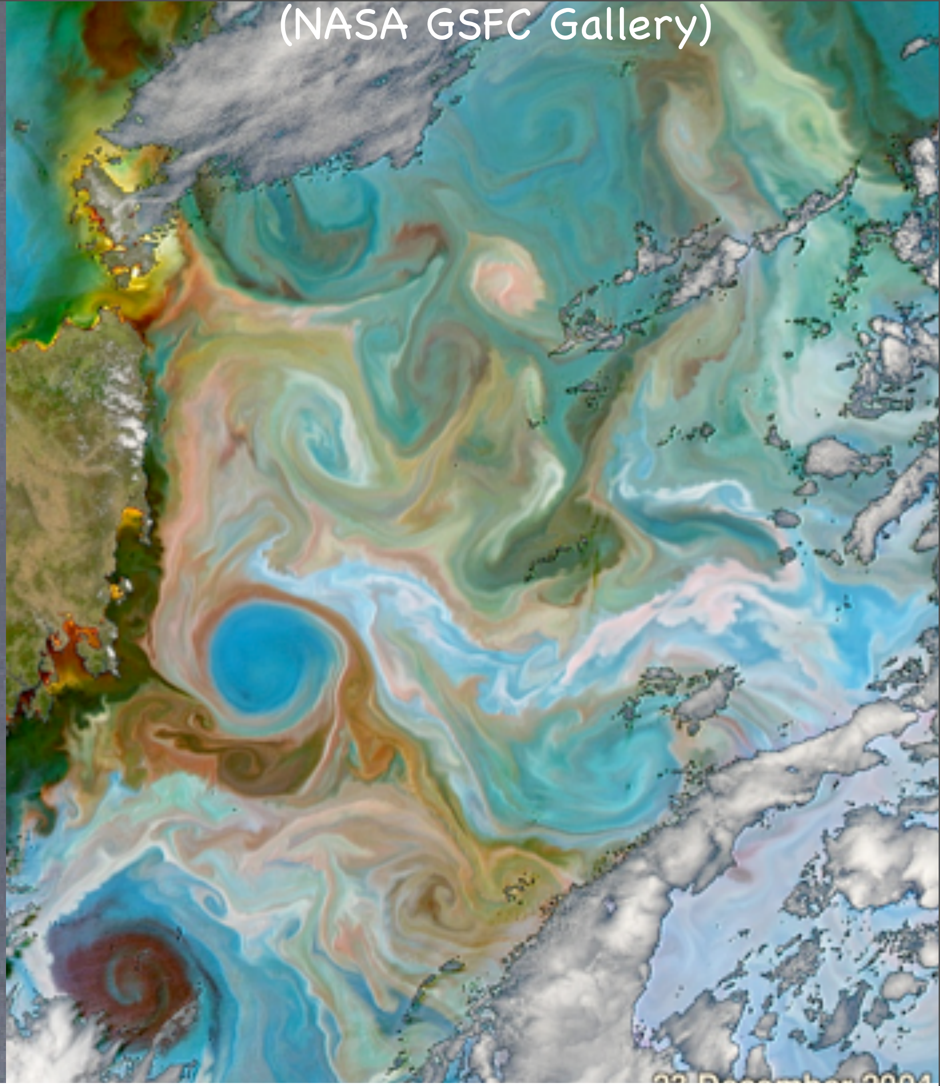


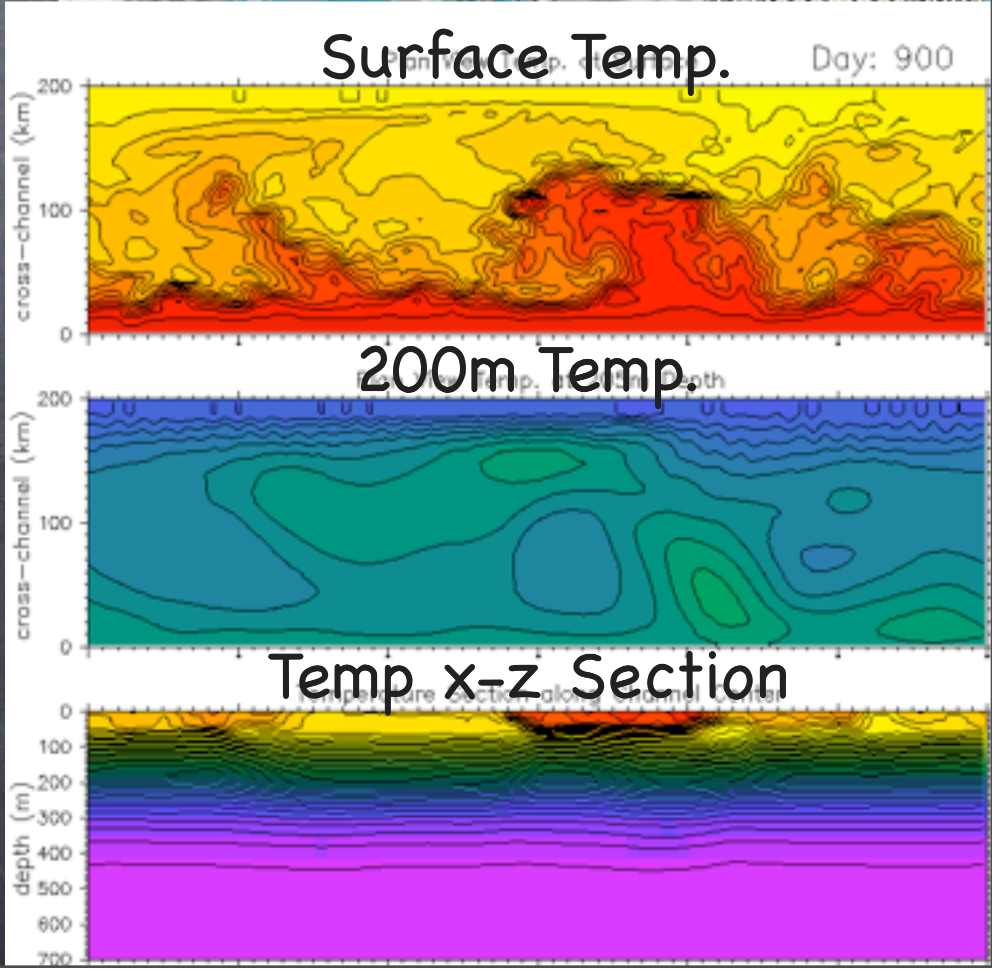


- Fronts
- Eddies
- Ro=O(1)
- Ri=O(1)
- near-surface
- 1-10km, days

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

10
km


(NASA GSFC Gallery)


Surface Temp.

200m Temp.

Temp x-z Section

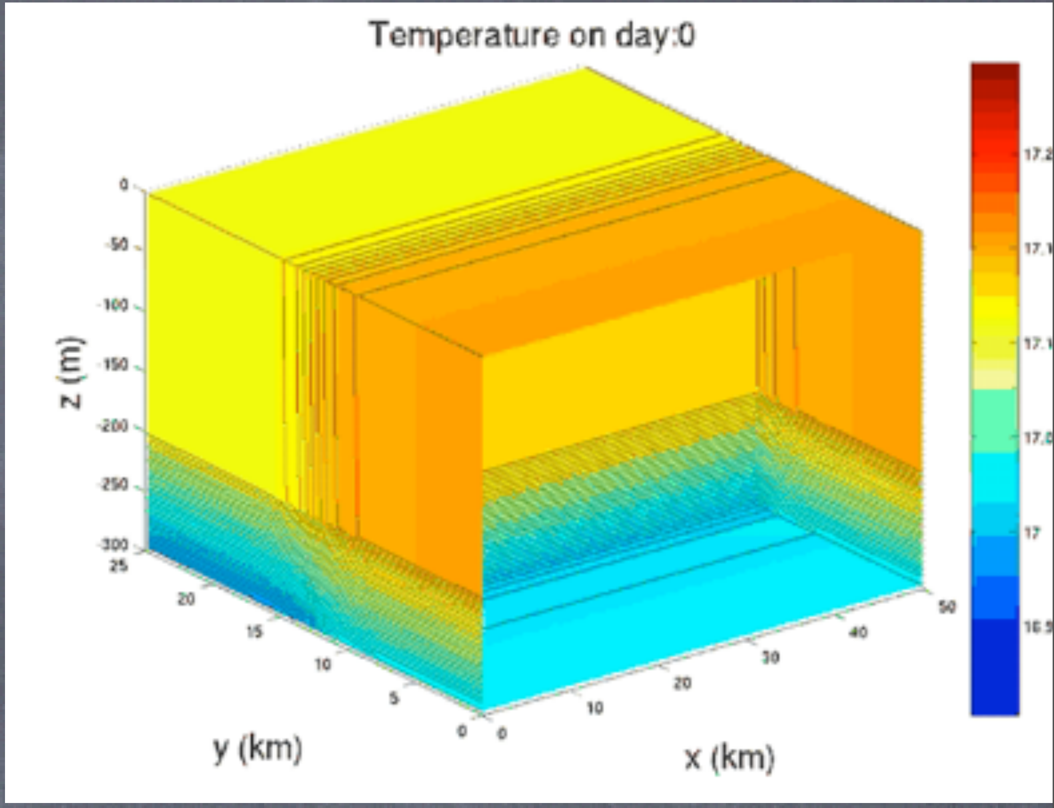
Mixed Layer Eddy Restratification

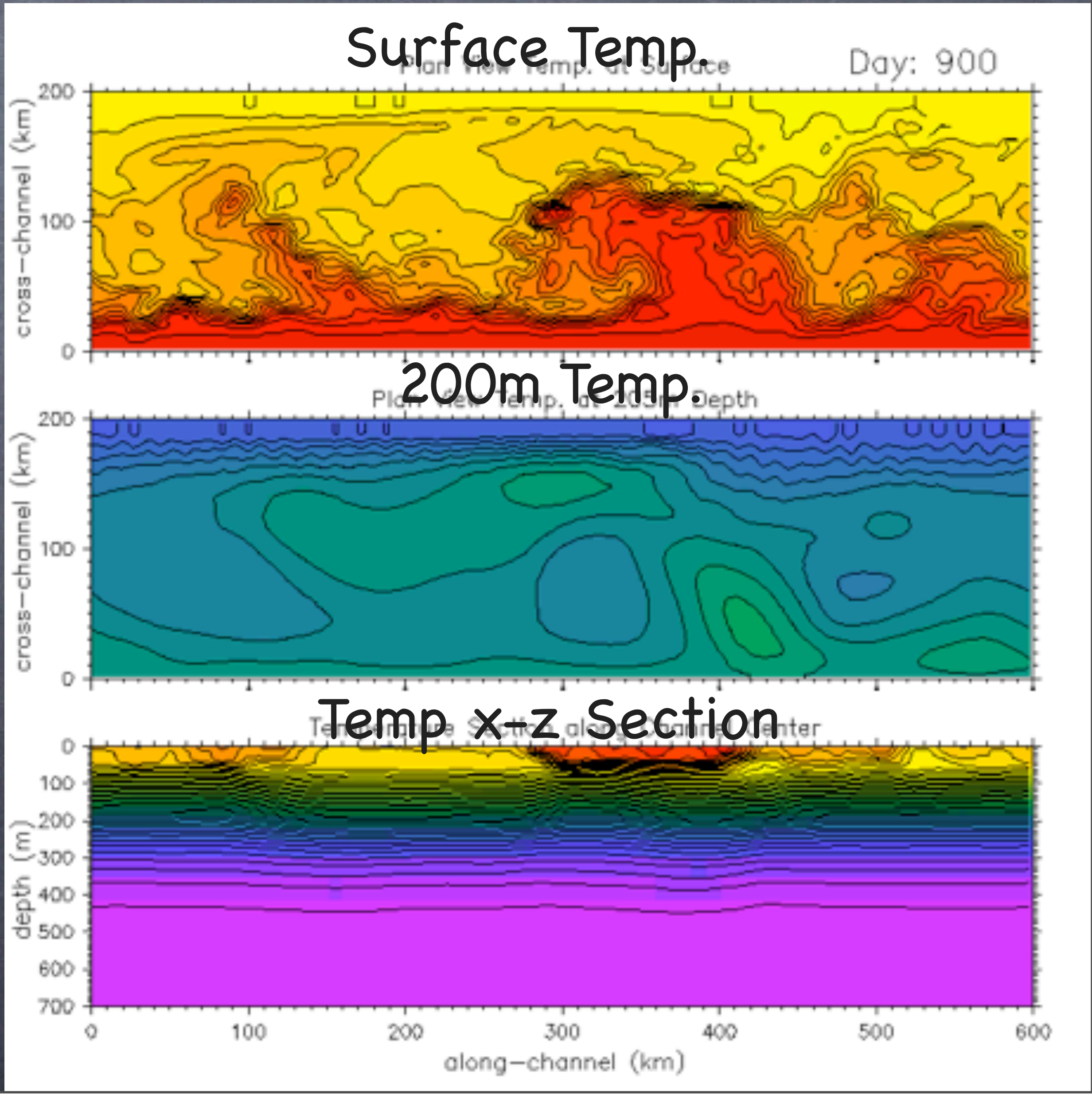
Estimating eddy buoyancy/density fluxes:

$$\overline{\mathbf{u}'b'} \equiv \mathbf{\Psi} \times \nabla\bar{b}$$

A submeso eddy-induced overturning:

$$\mathbf{\Psi} = \frac{C_e H^2 \mu(z)}{|f|} \nabla\bar{b} \times \hat{\mathbf{z}}$$





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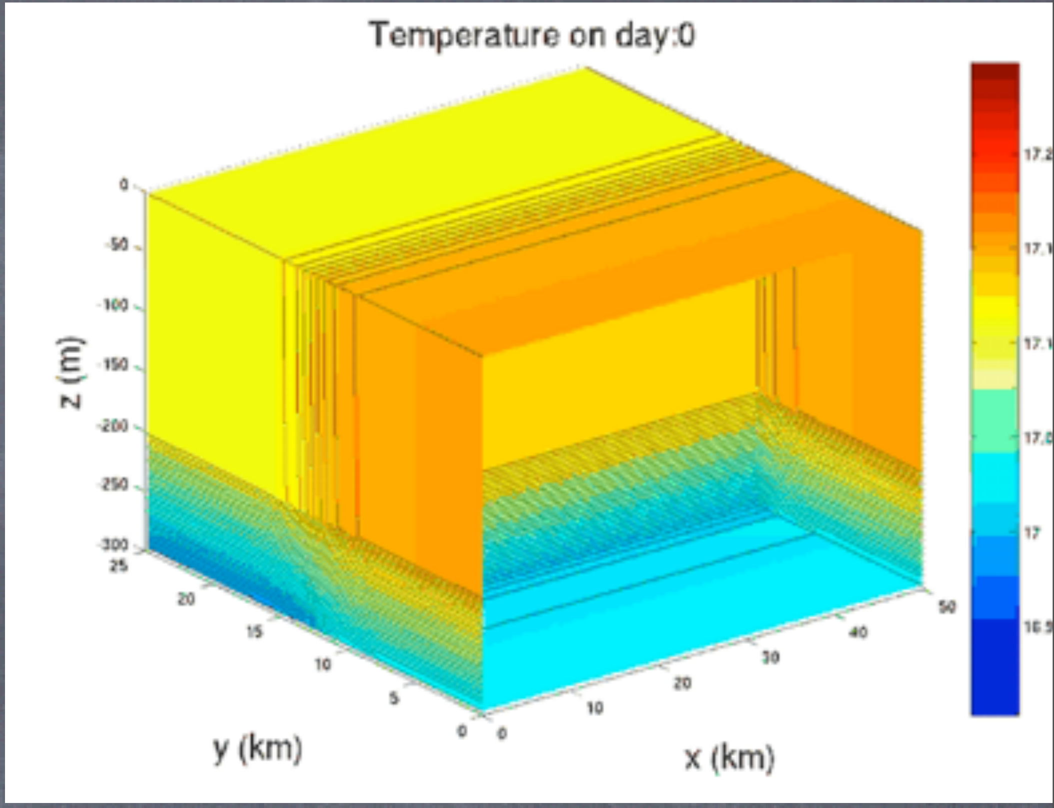
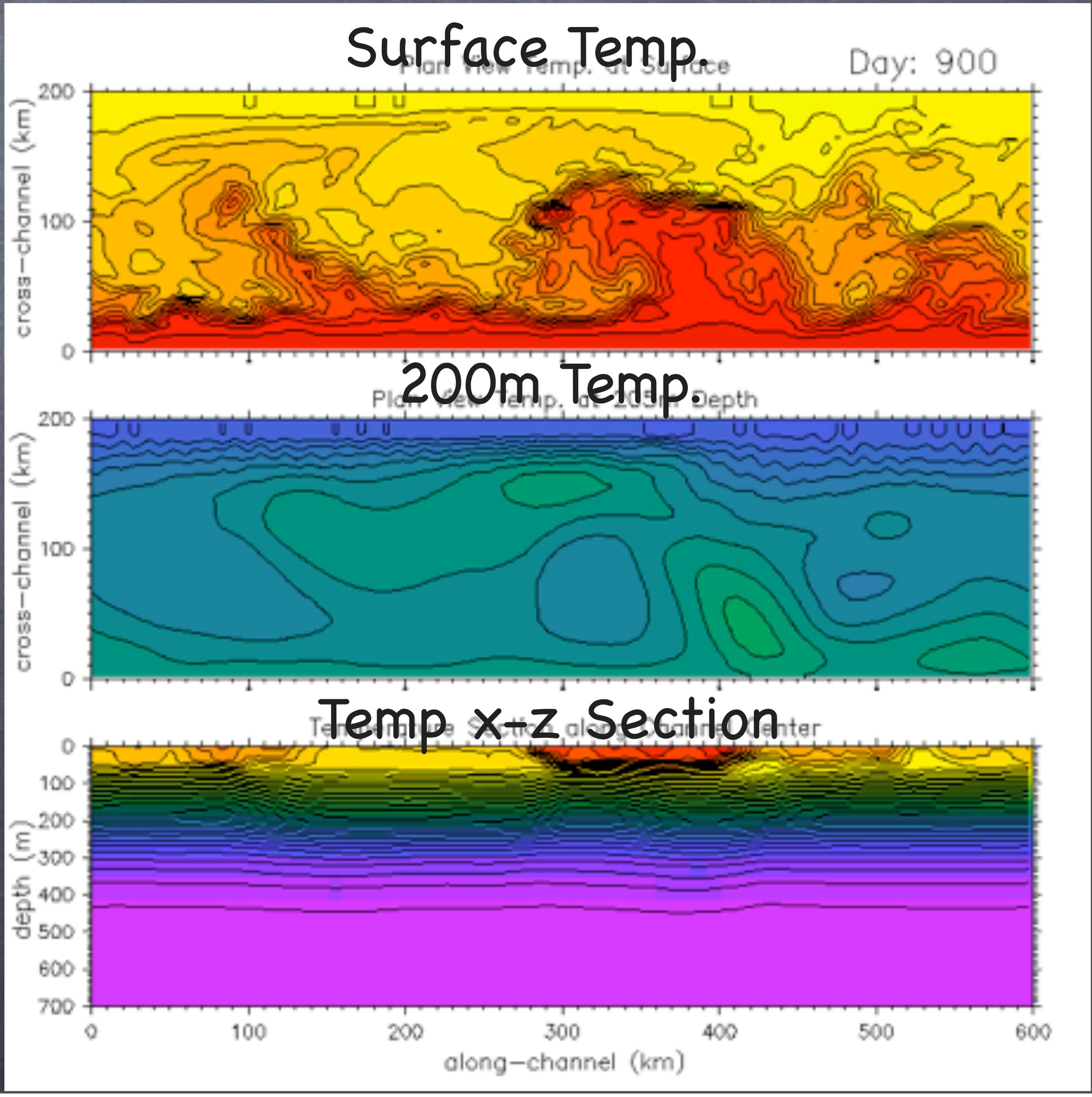
in ML only:

$$\mu(z) = 0 \text{ if } z < -H$$





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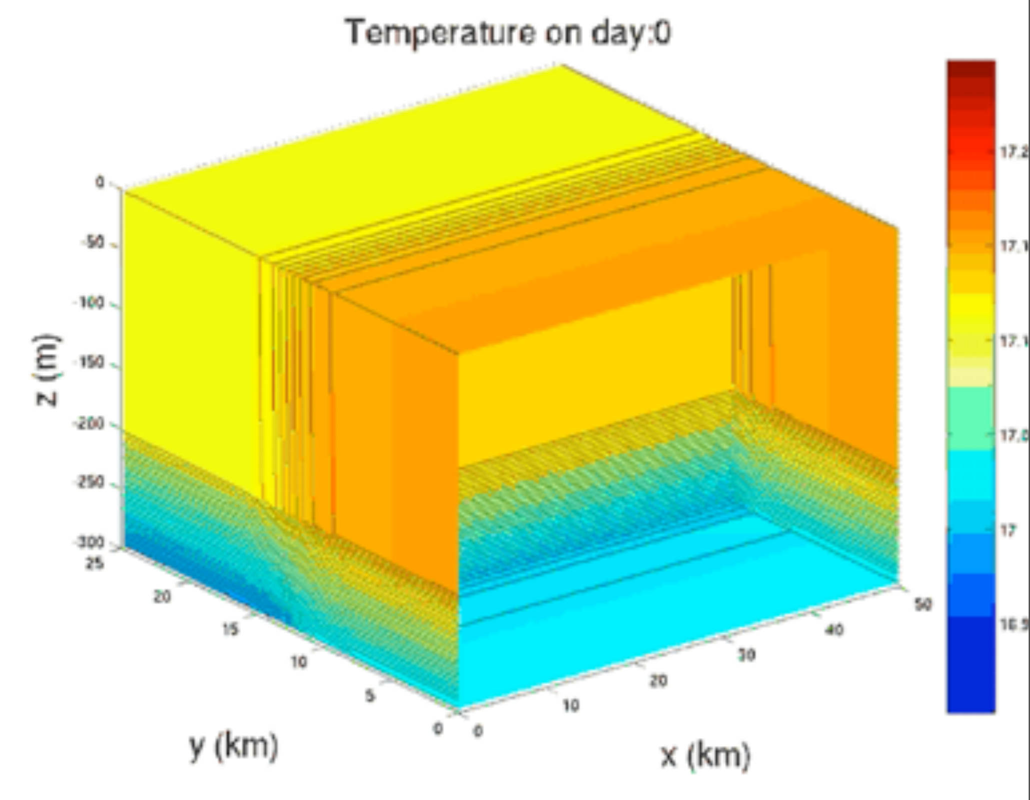

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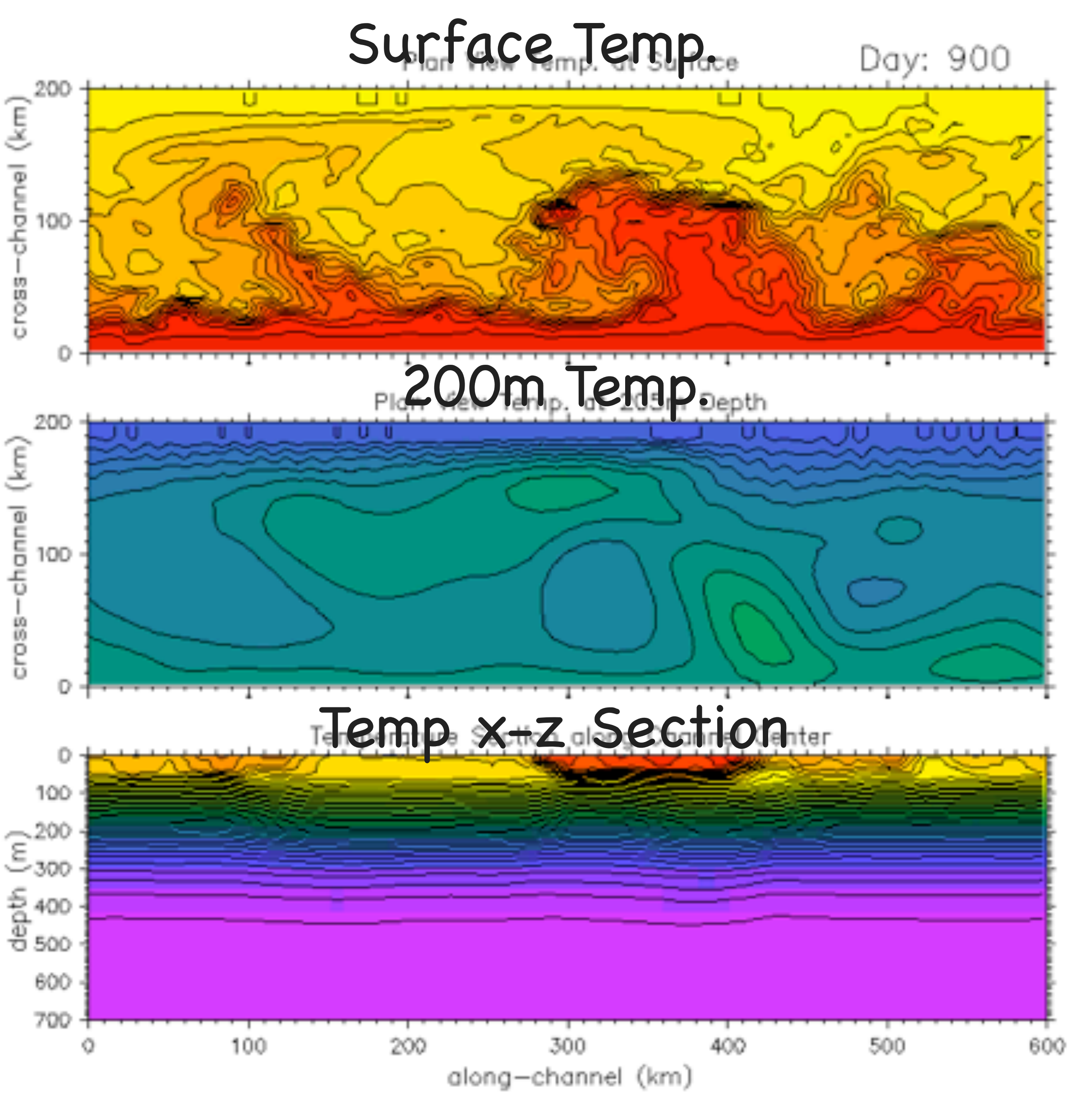
For a consistently restratifying,

$$\overline{w'b'} \propto \frac{H^2}{|f|} \left|\nabla_H \bar{b}\right|^2$$



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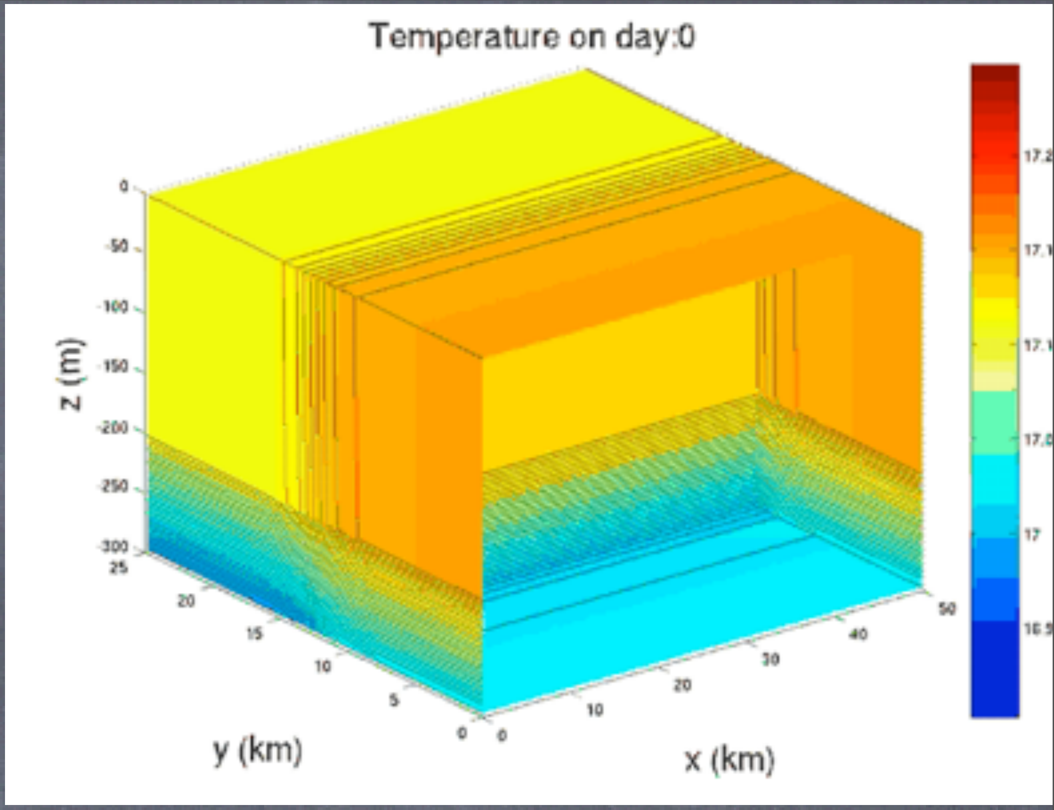
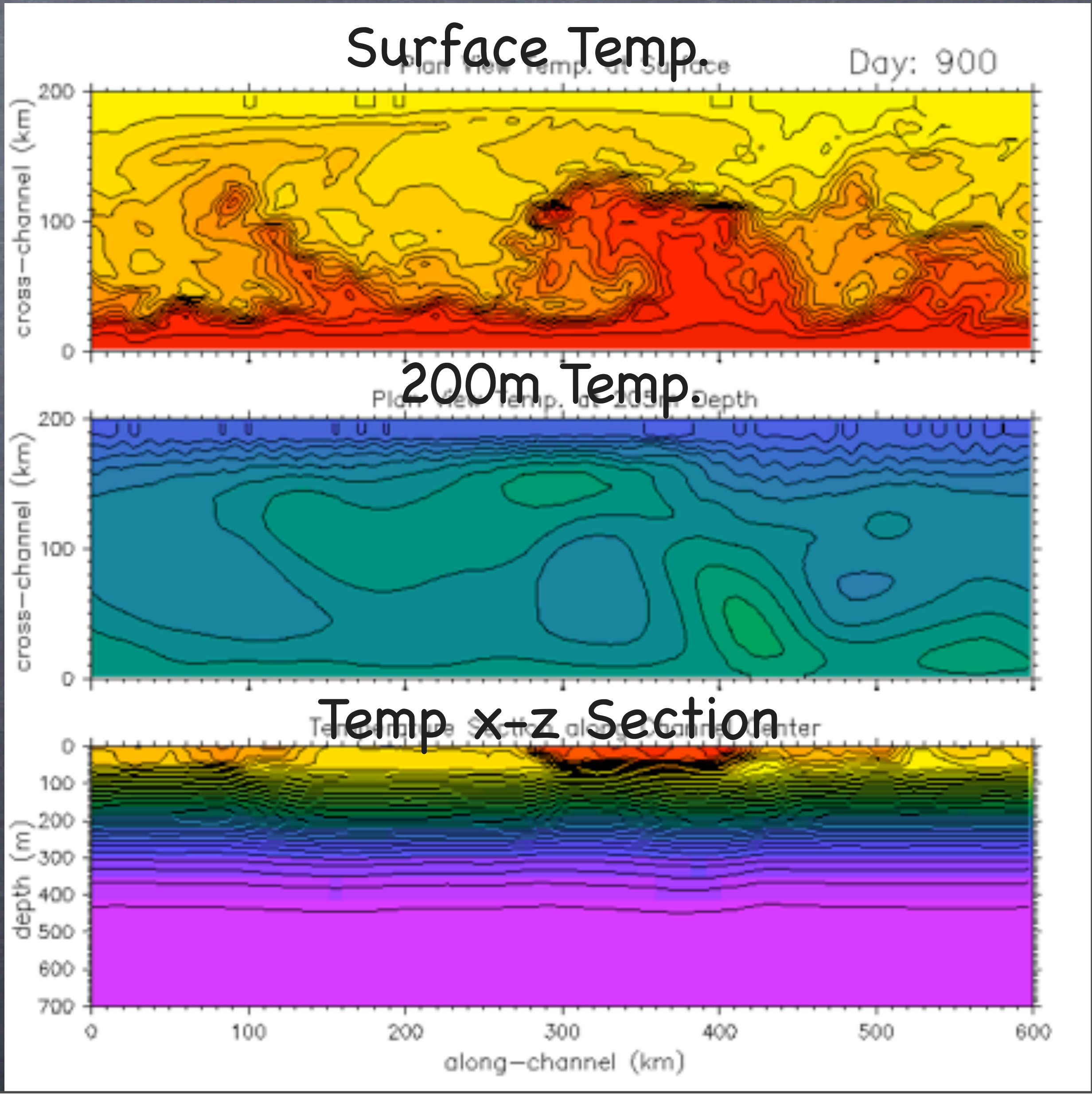
For a consistently restratifying,

$$\overline{w'b'} \propto \frac{H^2}{|f|} \left|\nabla_H \bar{b}\right|^2$$

and horizontally downgradient flux.

$$\overline{\mathbf{u}'_H b'} \propto \frac{-H^2 \frac{\partial \bar{b}}{\partial z}}{|f|} \nabla_H \bar{b}$$





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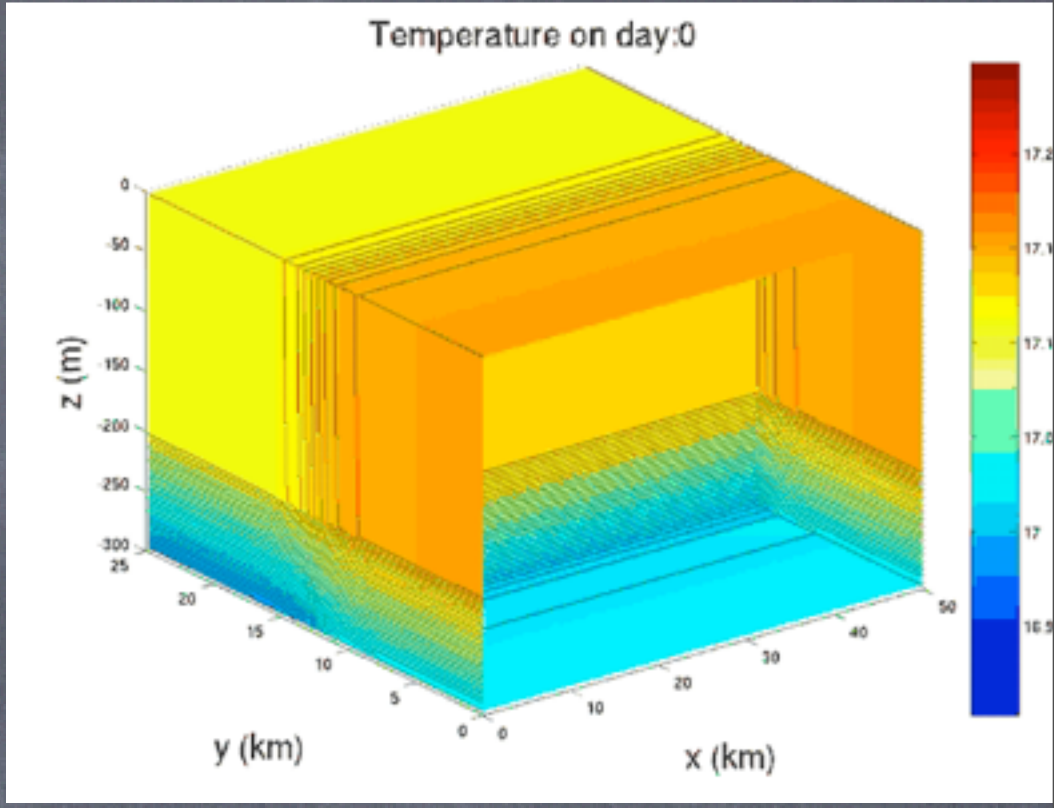
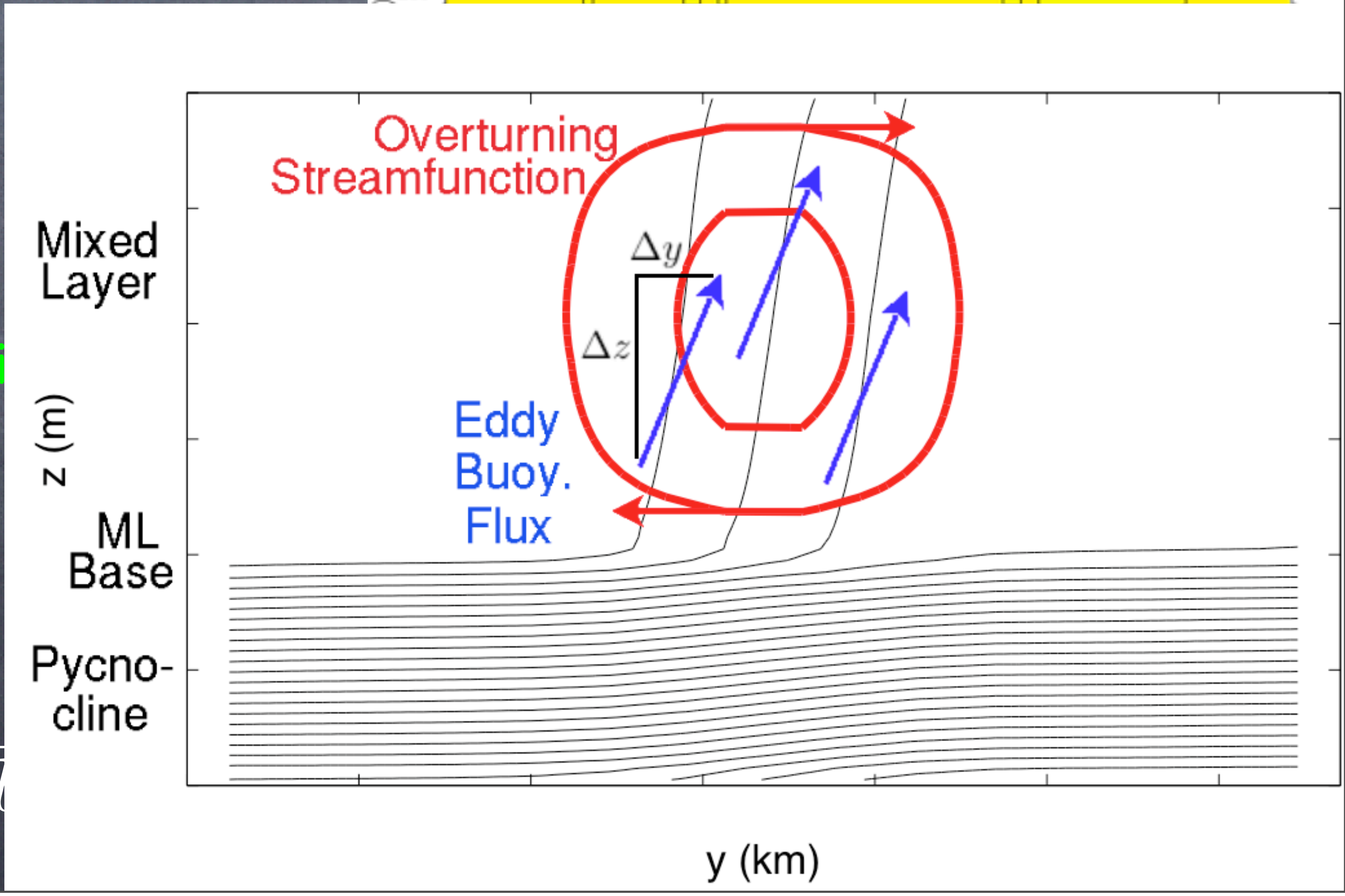
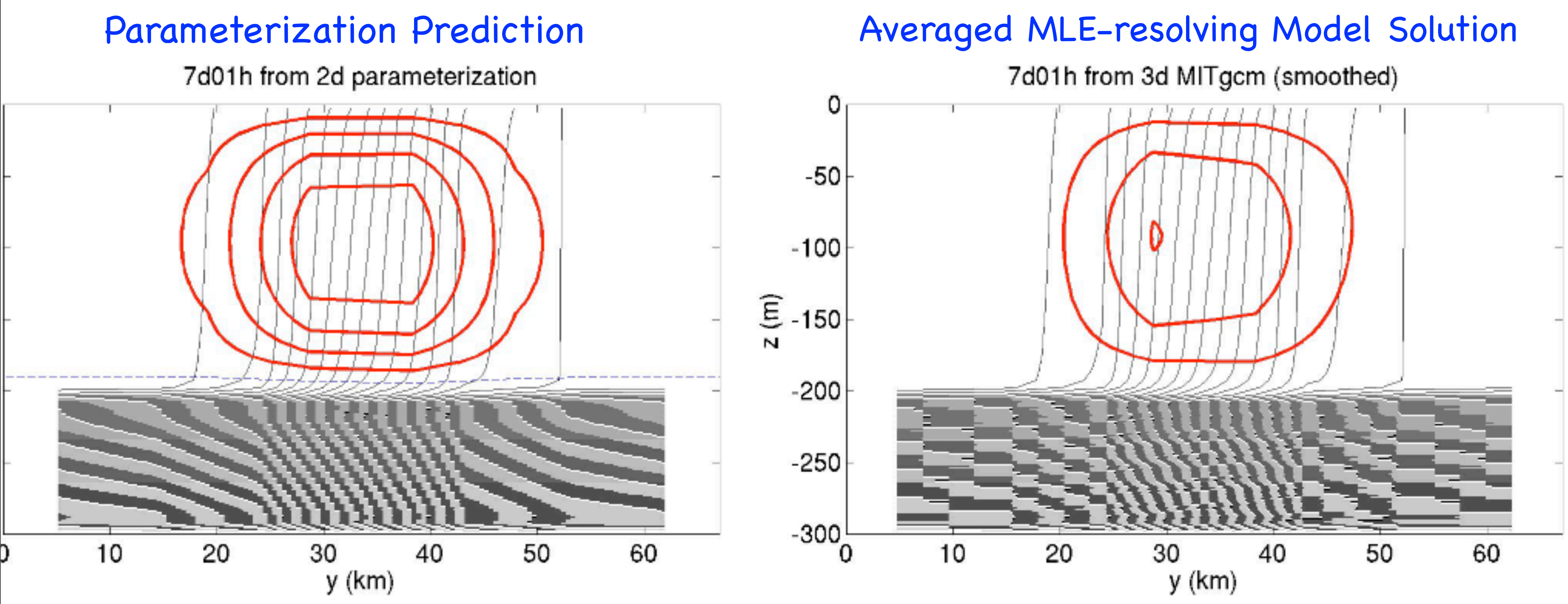




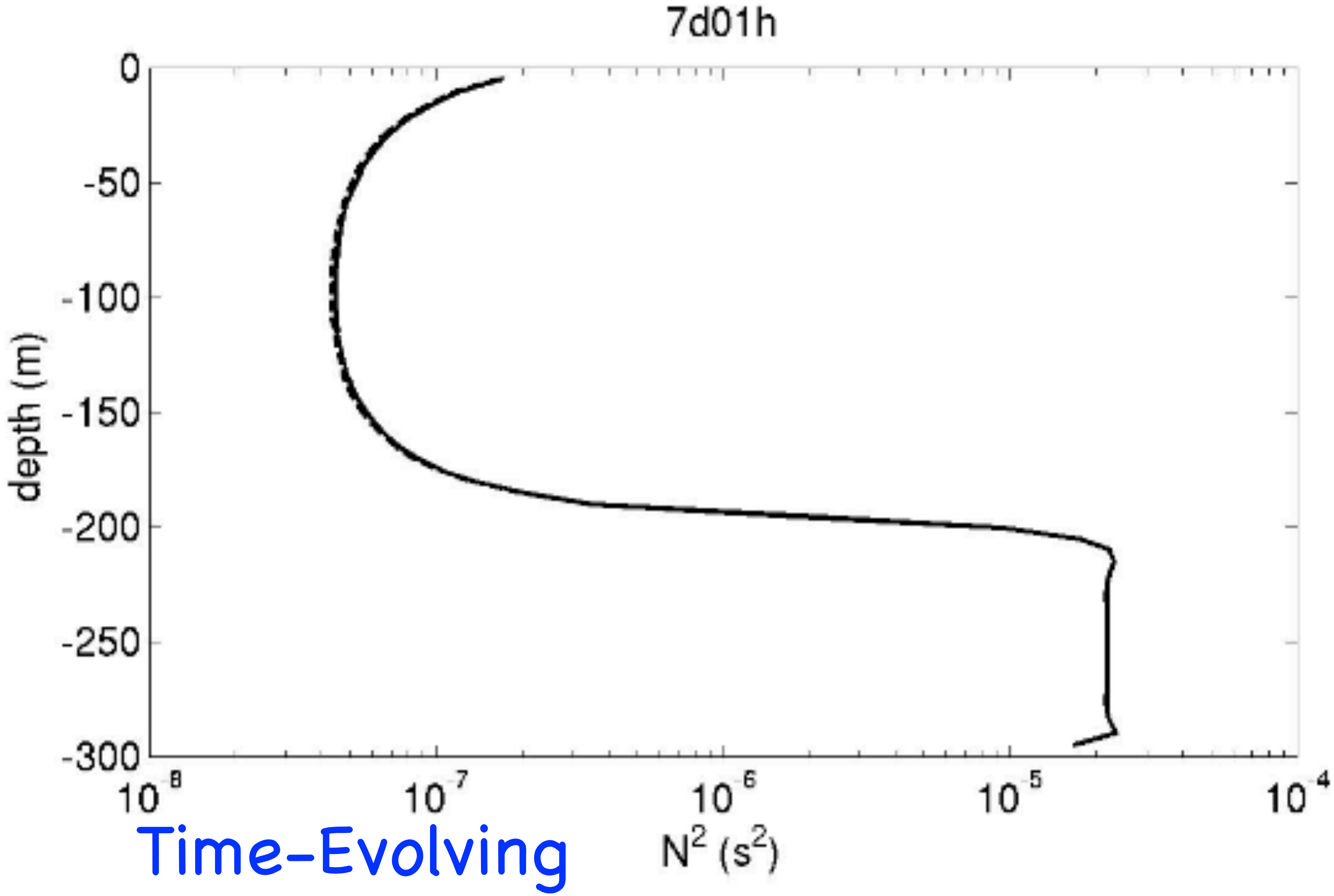
What does eddy restratification look like?



red=streamfunction

black=mean density

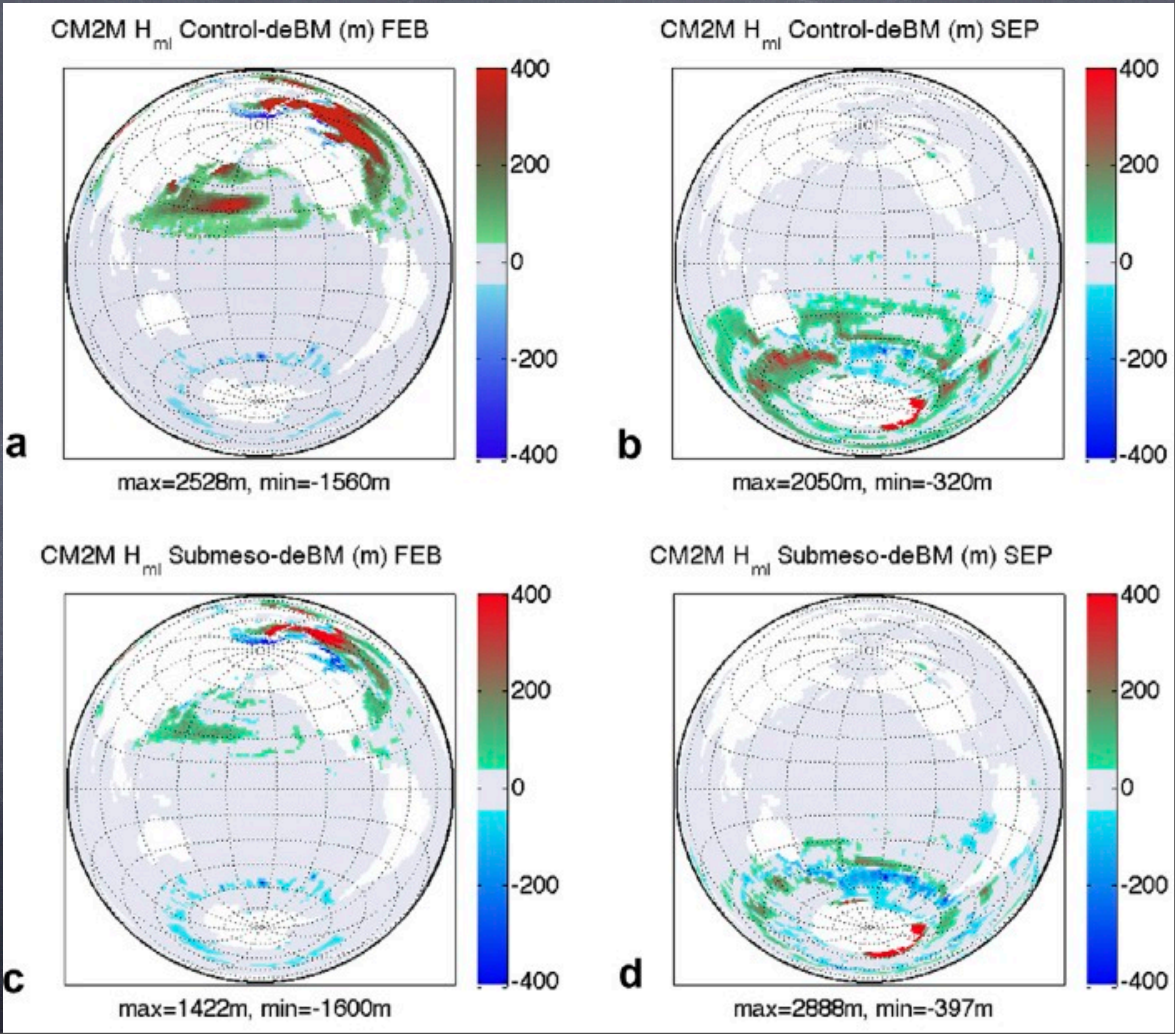
What does eddy restratification look like?



Time-Evolving Stratification (N^2)

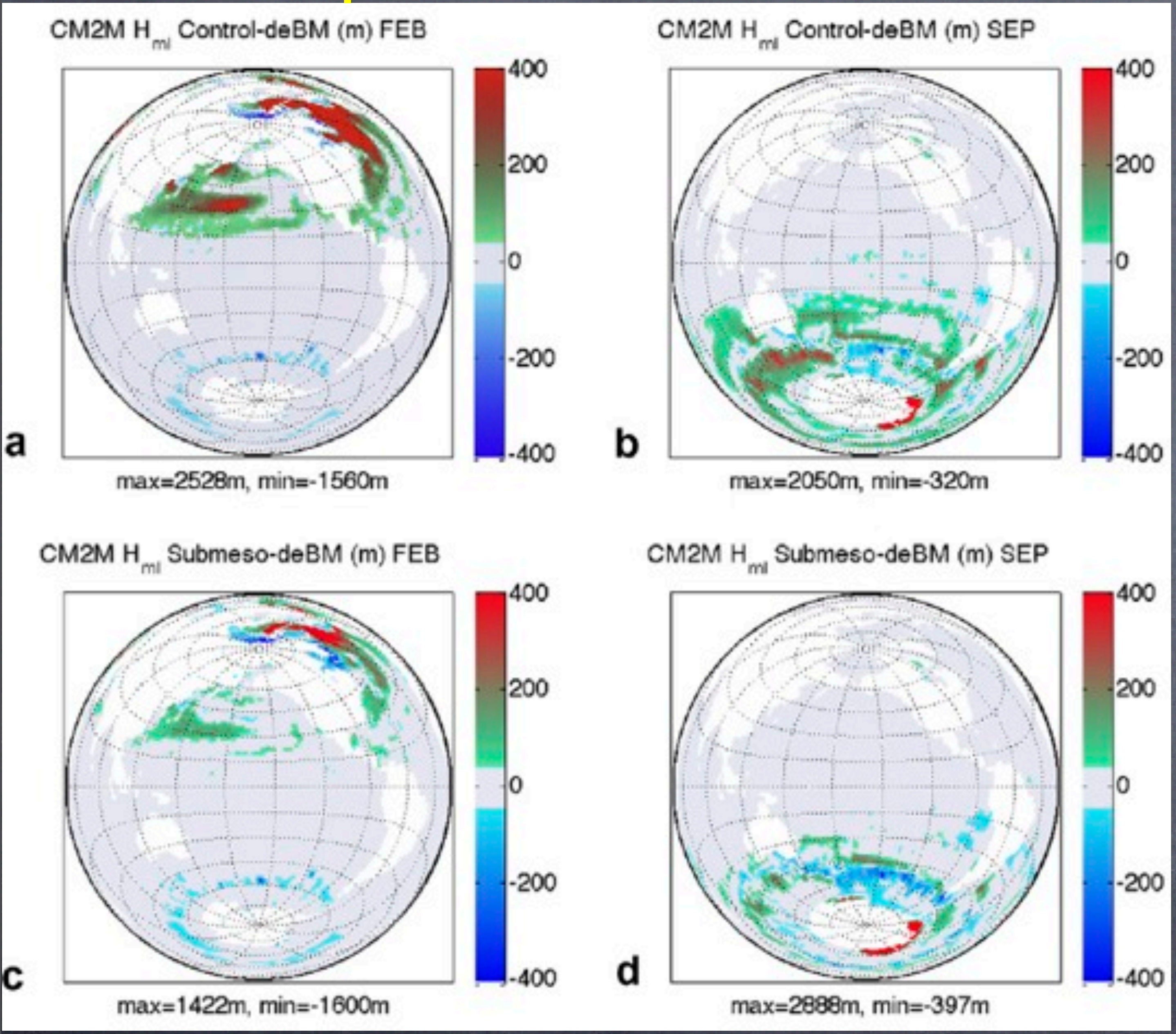
Mixed Layer Depth Bias Versus Observations (No MLE, Control)

Mixed Layer Depth Bias Versus Observations (With MLE)



Physical Sensitivity of Ocean Climate to Submesoscale Eddy Restratification:

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



Deep ML Bias reduced

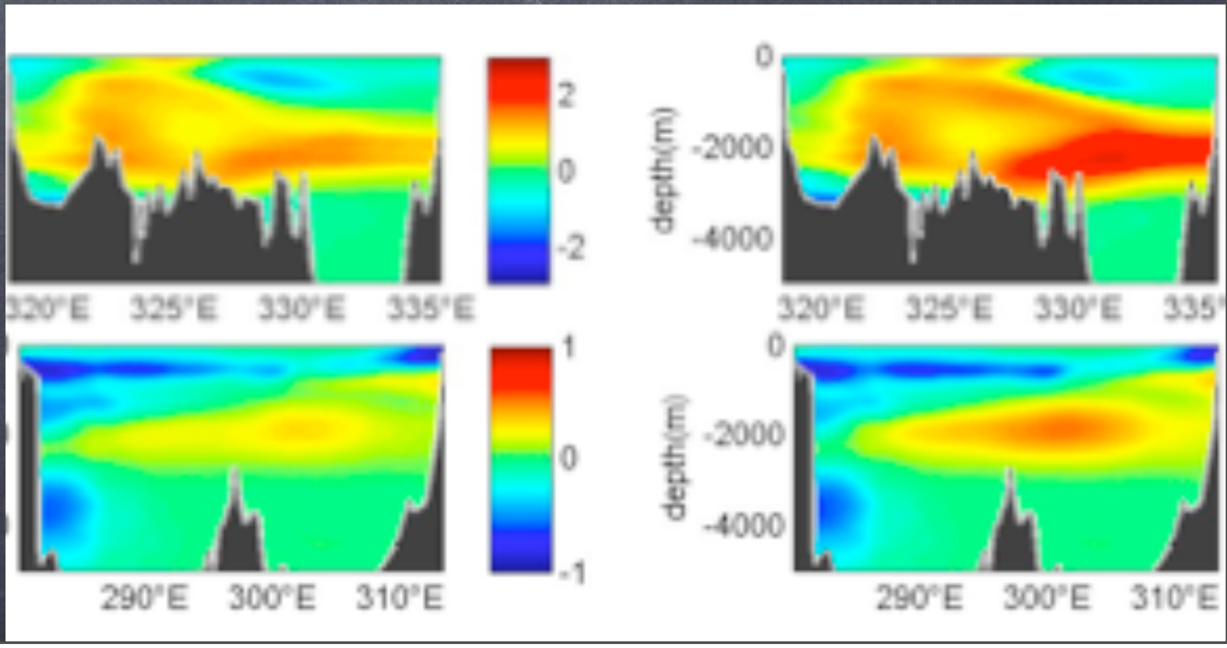
From Fox-Kemper et al., 2011

NO RETUNING NEEDED!!!

Improves CFCs Passive tracer

Bias with MLE

Bias w/o MLE



Sensitivity of Climate to Submeso: AMOC & Cryosphere Impacts

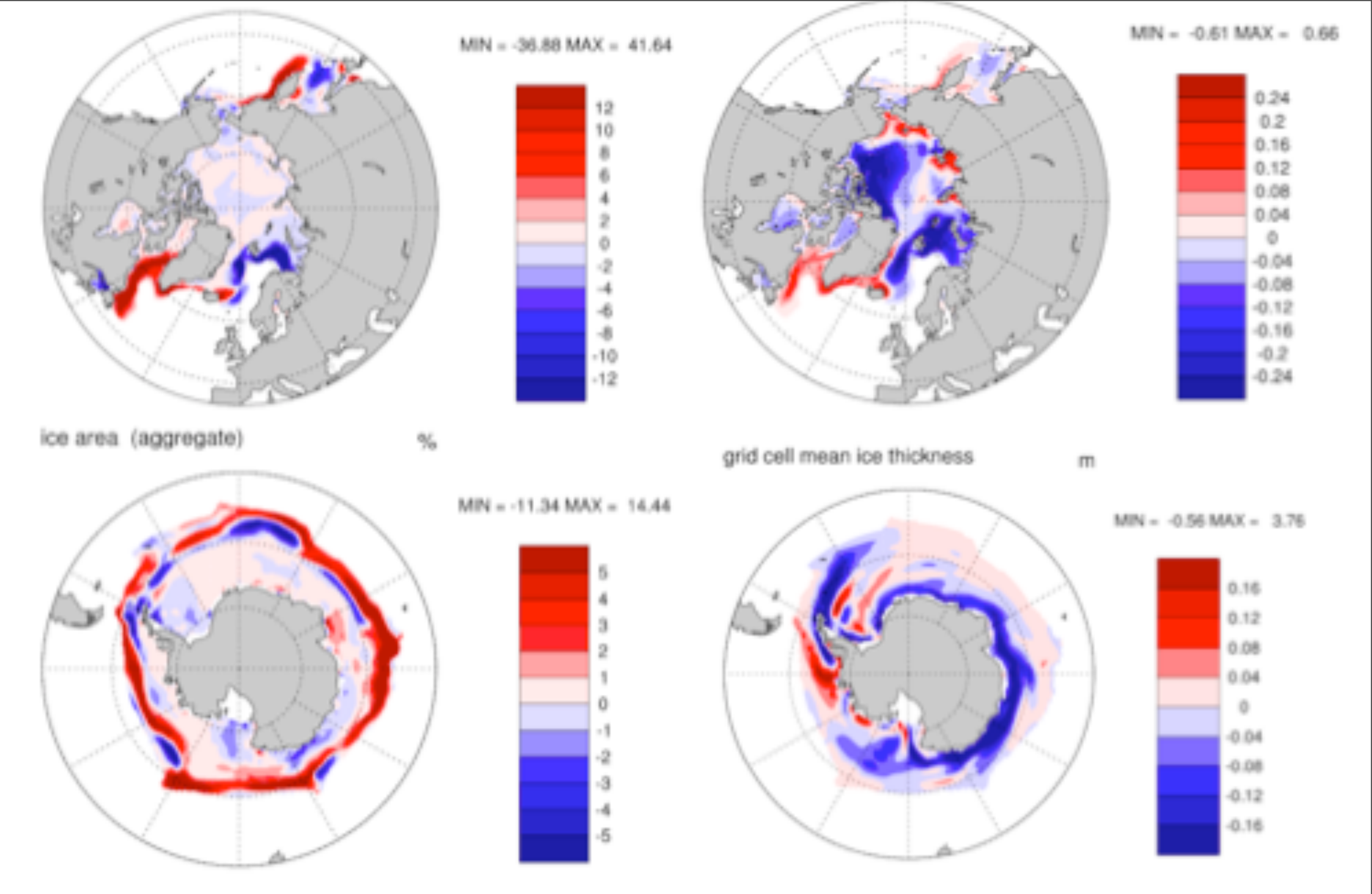
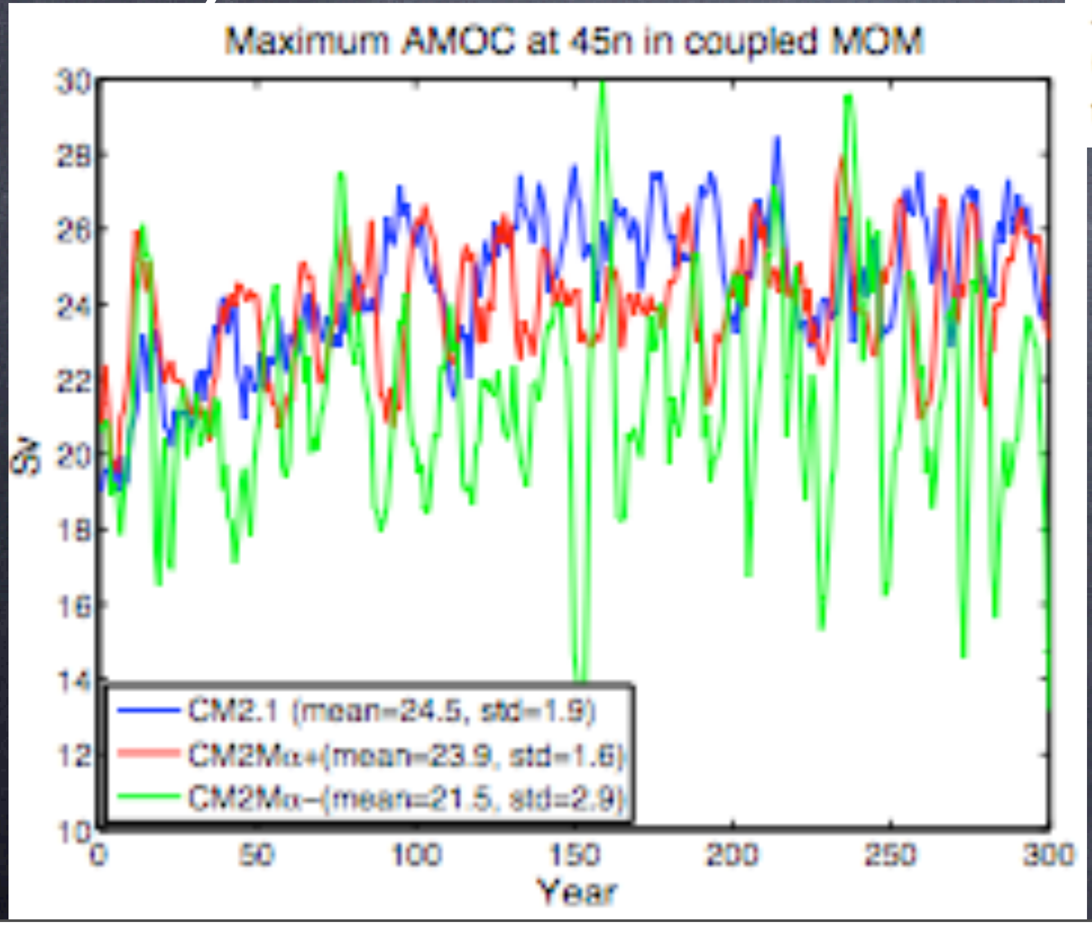


Figure 10: Wintertime sea ice sensitivity to introduction of MLE parameterization (CCSM$^+$ minus CCSM$^-$): January to March Northern Hemisphere a) ice area and b) thickness and July to September Southern Hemisphere c) ice area and d) thickness.

May Stabilize AMOC



Affects sea ice

NO RETUNING NEEDED!!!

These are impacts:
bias change unknown

Langmuir Turbulence Parameterizations

- On a list of the 50 most important things to fix in the ocean model, Langmuir is number 51.

  - --Bill Large

The Character of the 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

image: Leibovich, 83

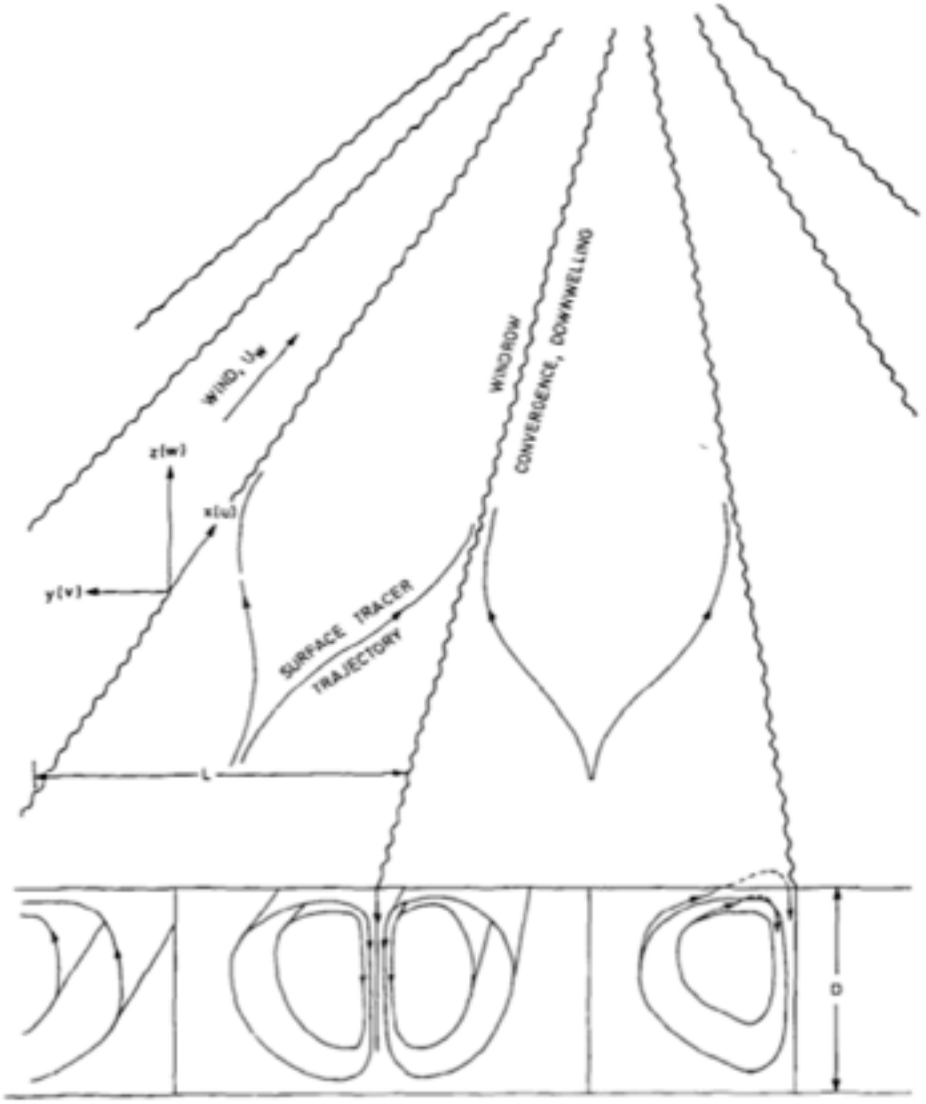


Figure 1a Illustration of Langmuir circulations showing notation used in this review and surface and subsurface motions.

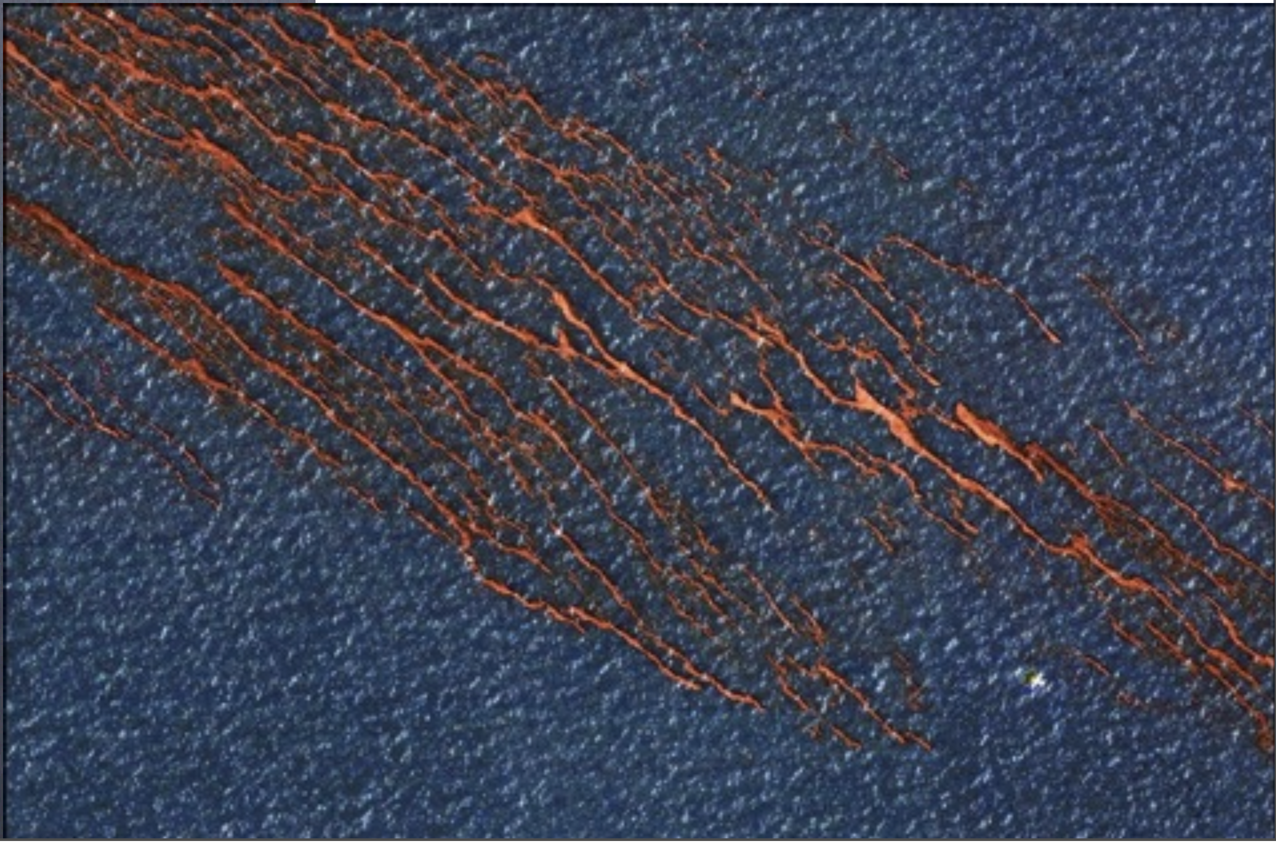
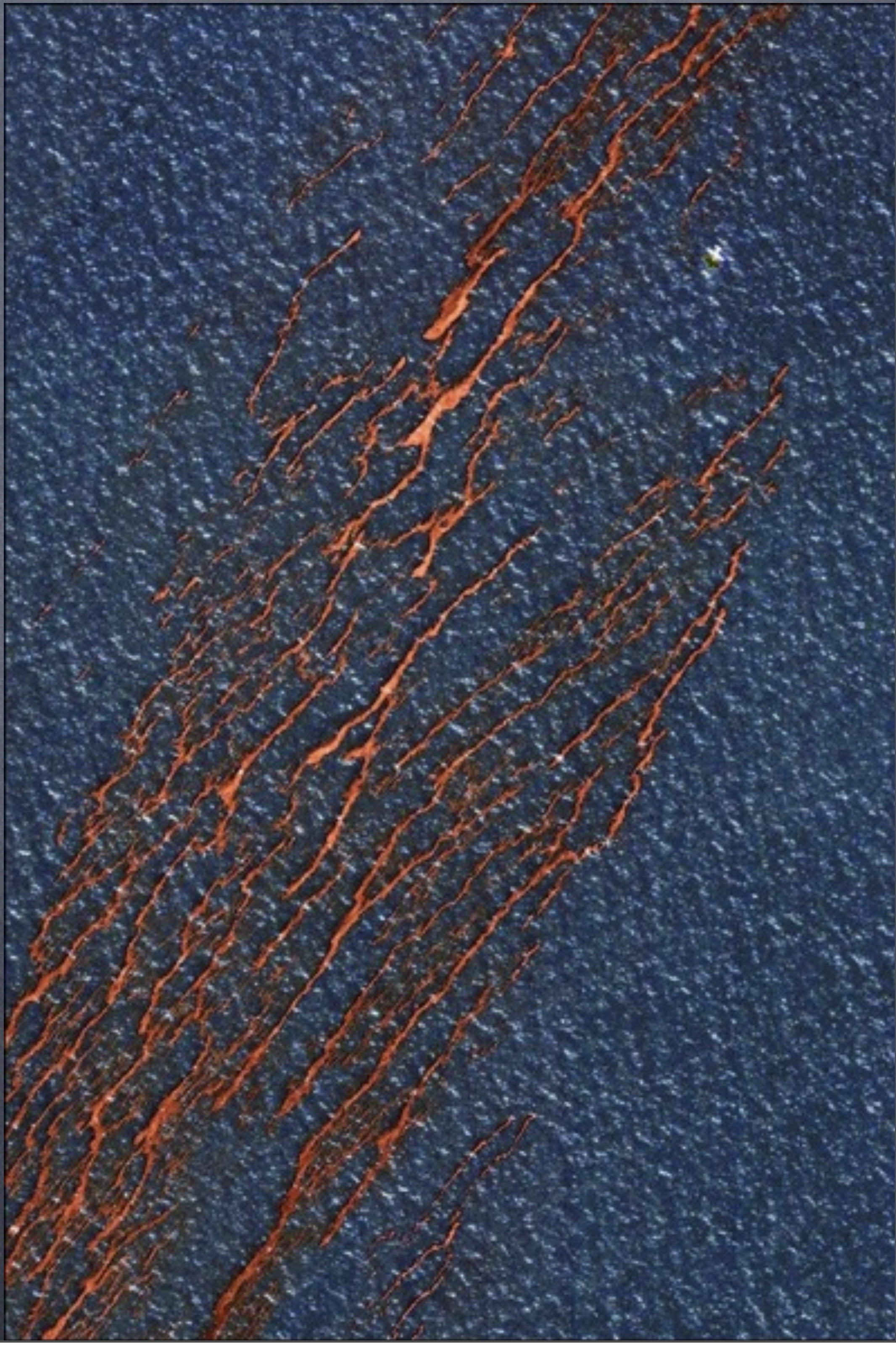


Image: NPR.org, Deep Water Horizon Spill

Shuga Ice
Image: aspect.aq

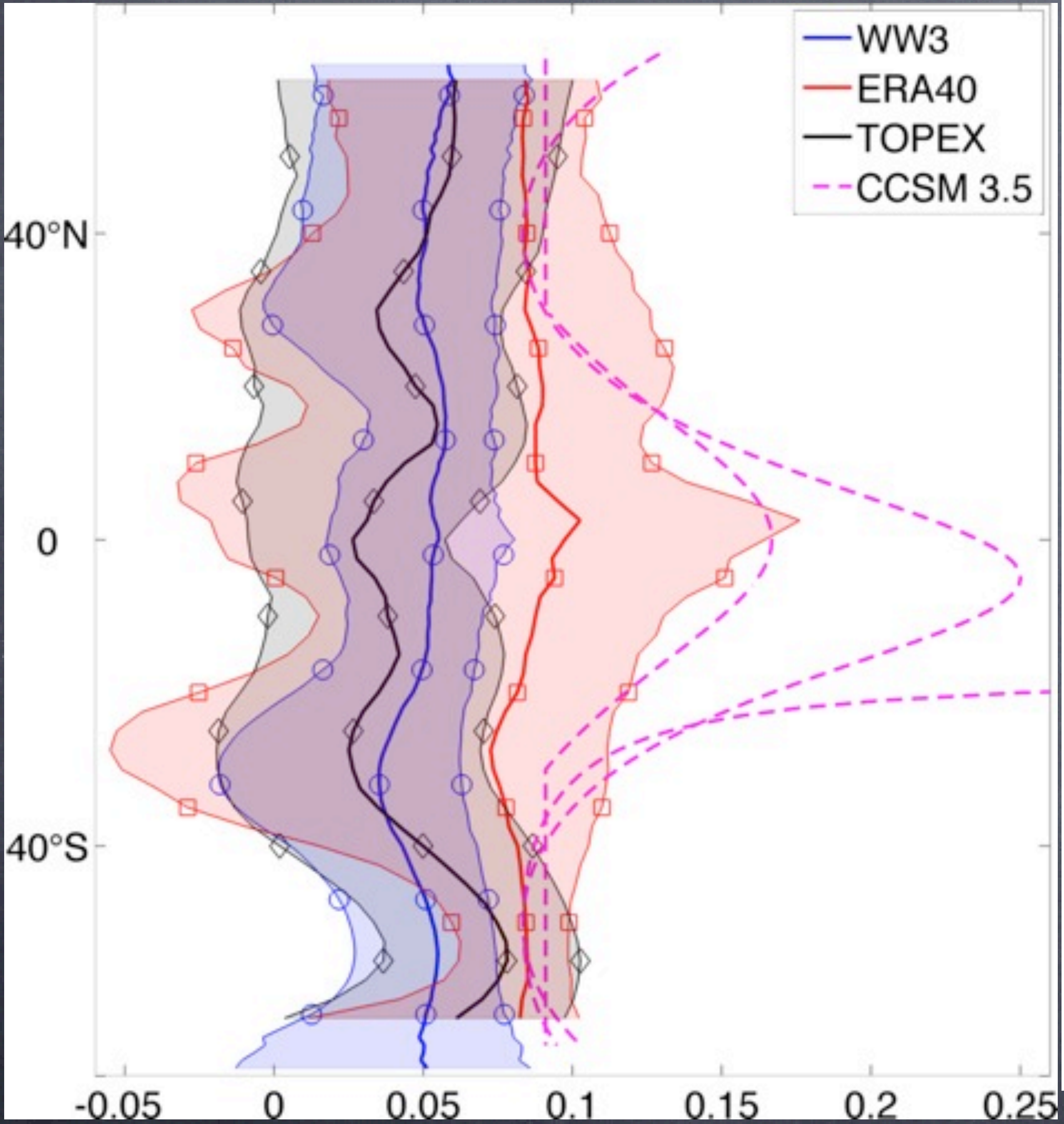
An Immature Improvement to Air-Sea BL

Image: NPR.org, Deep Water Horizon Spill

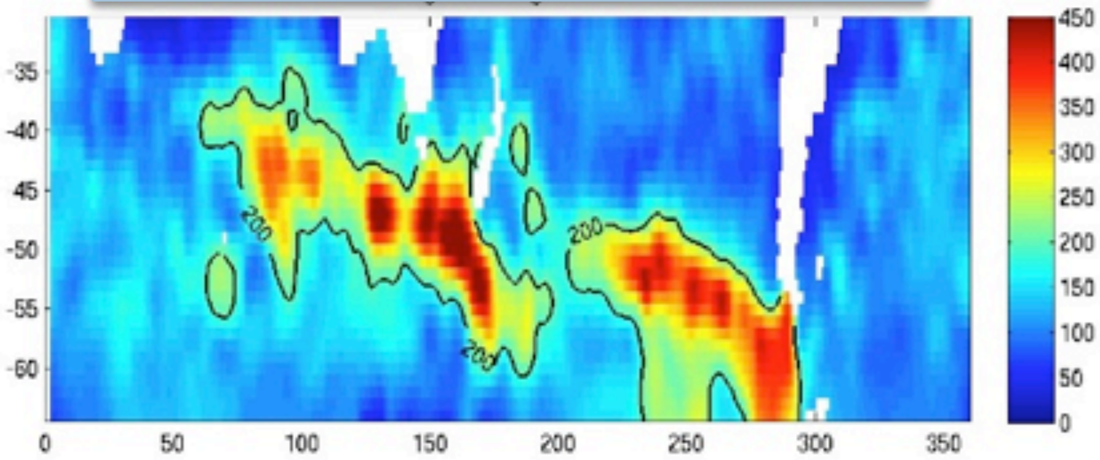


- Mixing by Langmuir Turbulence
  - Forced by wind and waves
    - i.e., Stokes drift & Eulerian Shear
  - Scalings from LES, Observations disagree
- We used a 2-part approximation
  - 1) McWilliams & Sullivan (01) additional OBL mixing (within mixed layer)
  - 2) Li & Garrett (98) Langmuir mixing depth (entrainment)
  - Roughly comparable to other schemes, but crude & incompletely validated
  - Needs only u^*, u_s to work

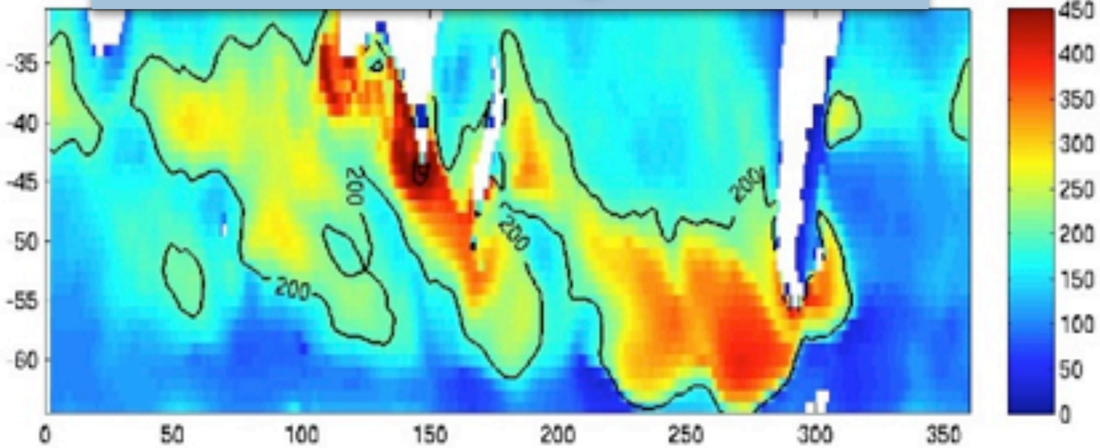
Langmuir Mixing Forced by Climatology



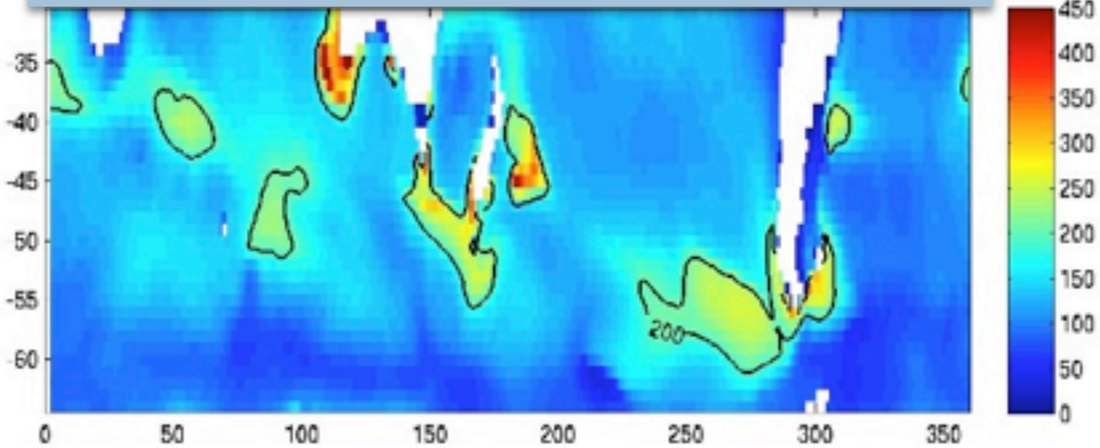
Dong et al. Observations



CCSM3.5 with Langmuir



CCSM3.5 Control without Langmuir

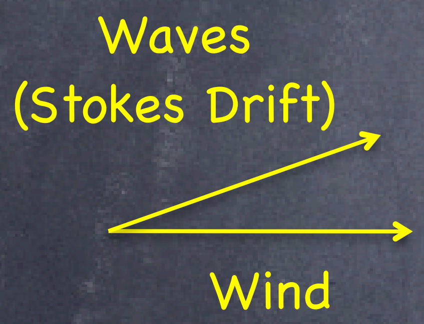


(Generalized Turbulent Langmuir)^2

Projection of u*, u_s into Langmuir Direction

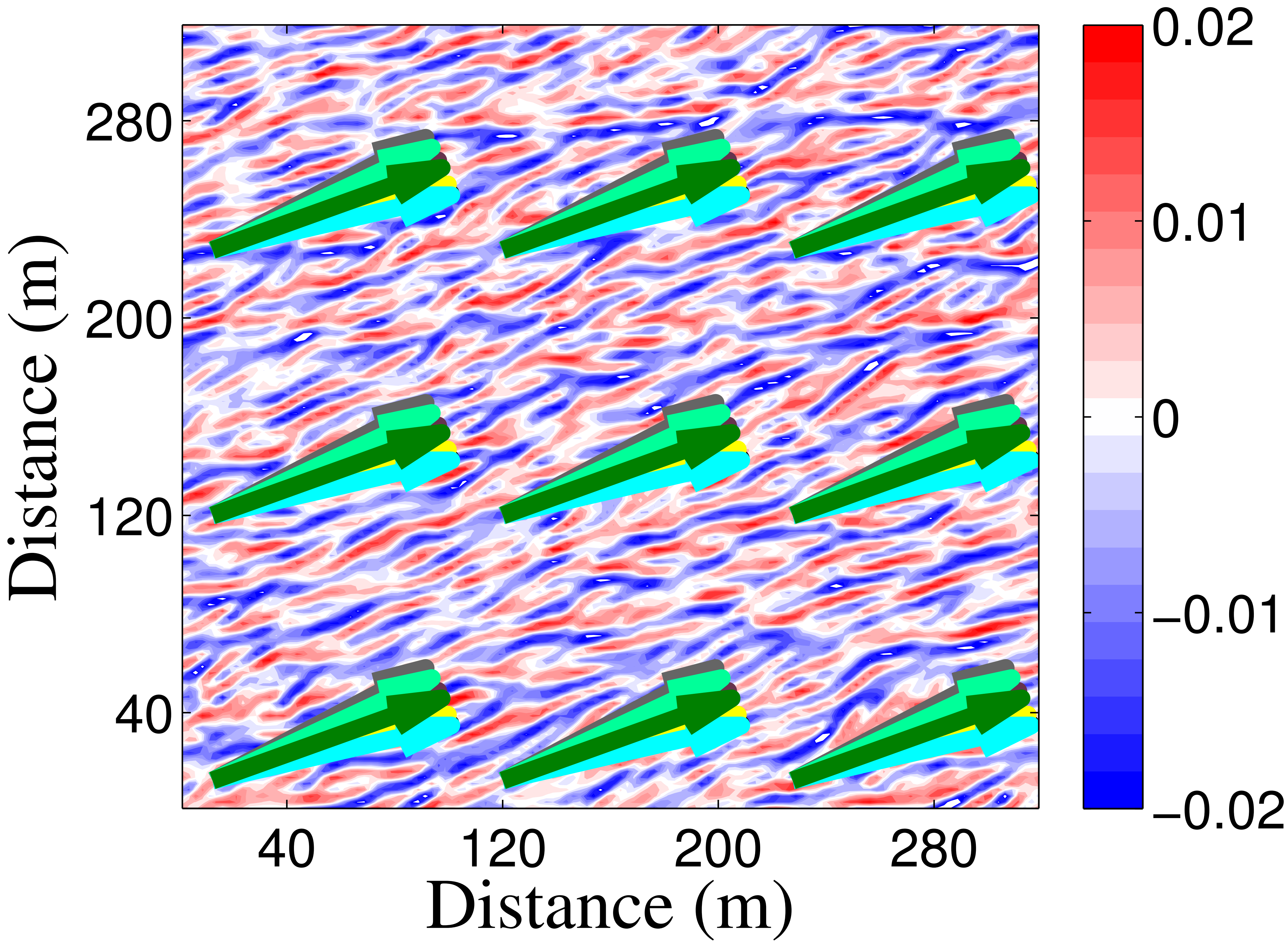
$$La_t^2 = \frac{|u^*|}{|u_s|}\left[\frac{|u^*|+|u_s|\cos\theta}{|u_s|+|u^*|\cos\theta}\right]$$

Tricky: Misaligned Wind & Waves



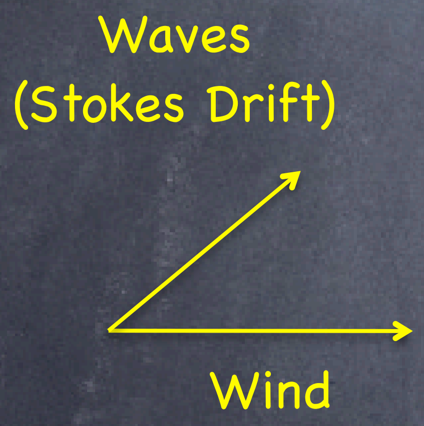
Waves
(Stokes Drift)

Wind



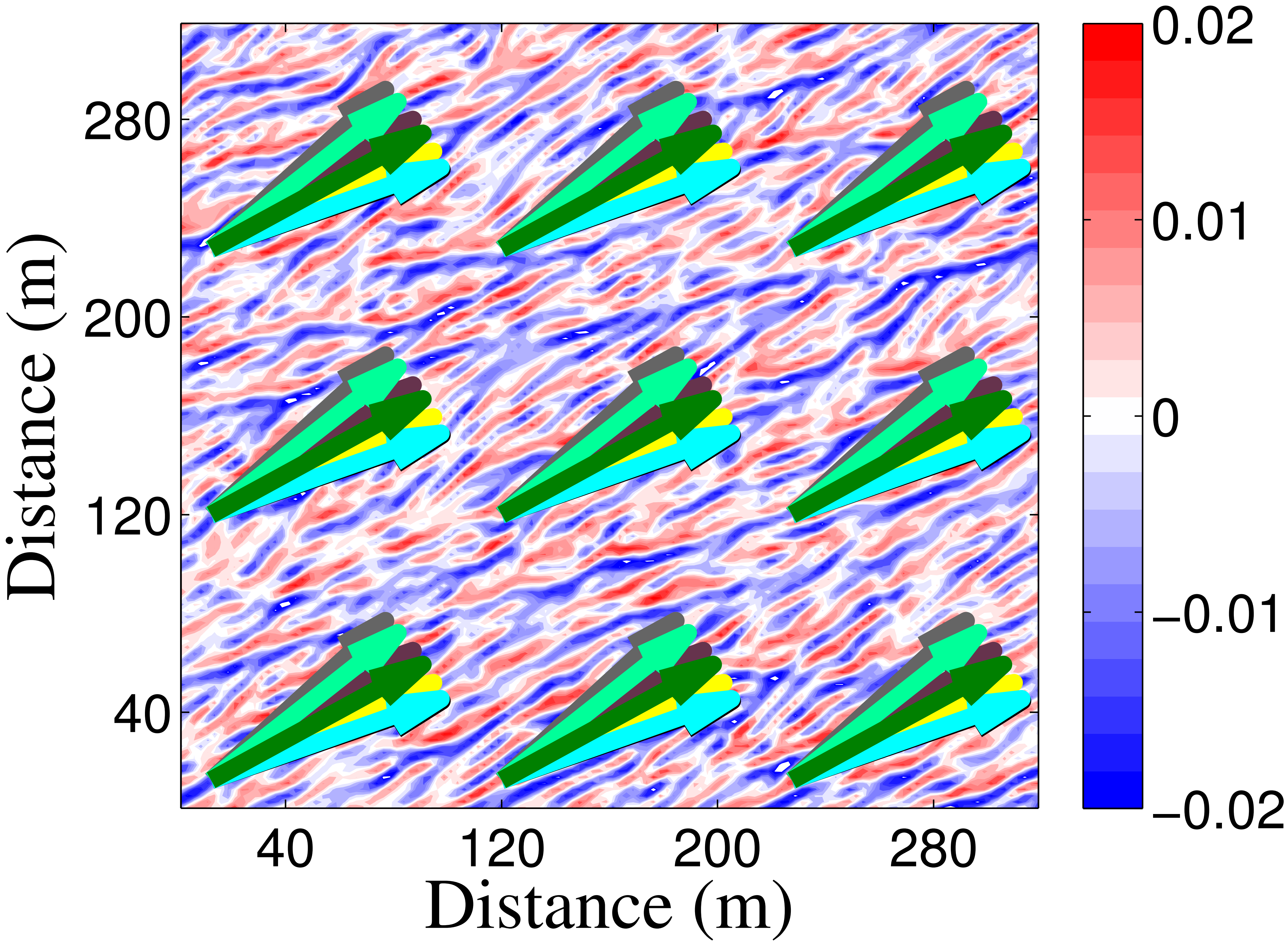
Van Roekel et al. 2011
(in prep)

Tricky: Misaligned Wind & Waves



Waves
(Stokes Drift)

Wind



Van Roekel et al. 2011
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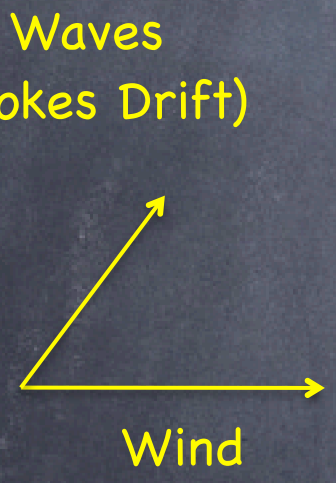

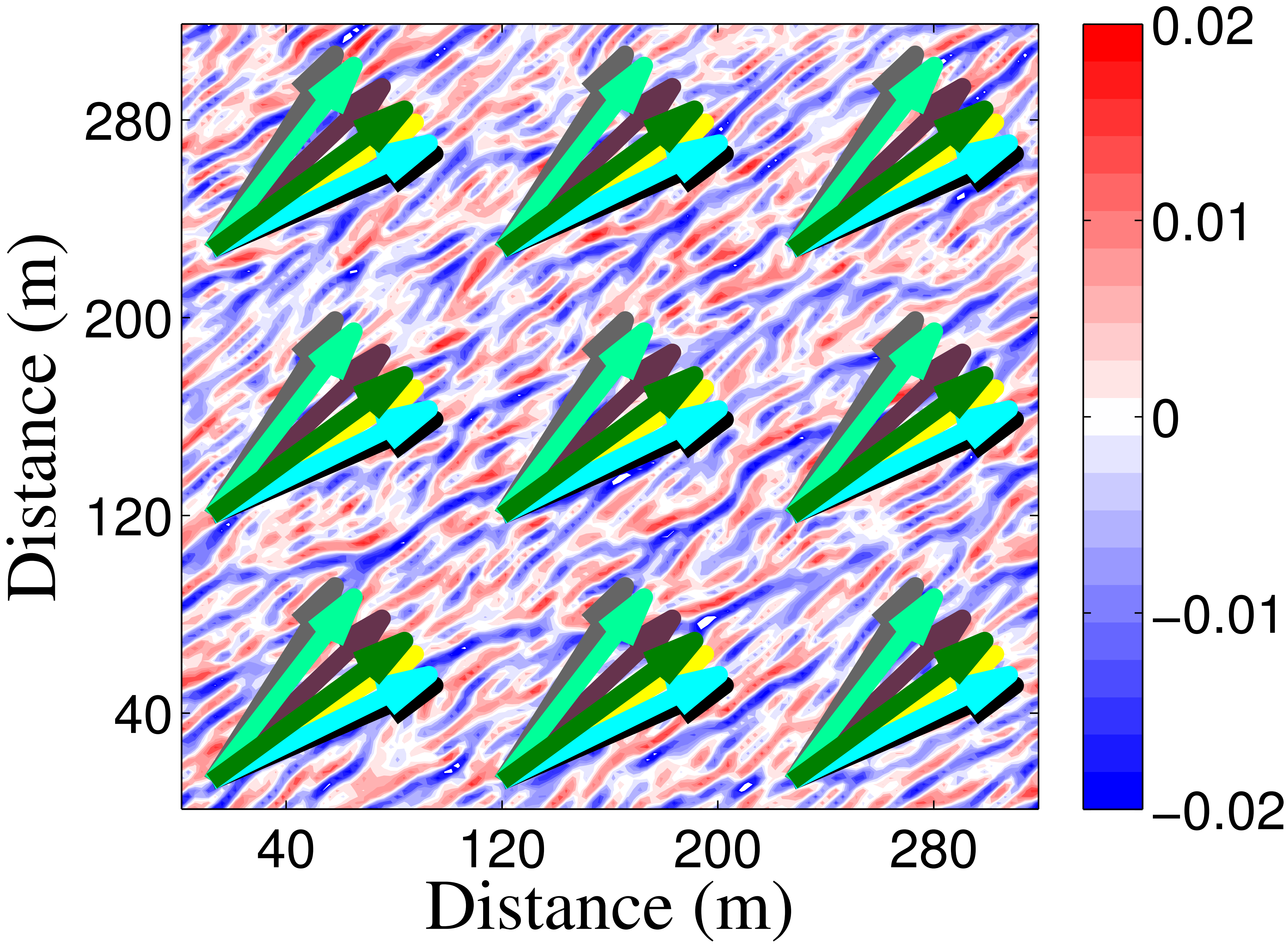

Van Roekel et al. 2011
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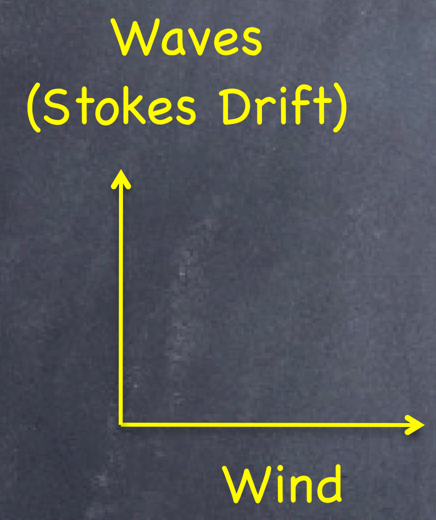
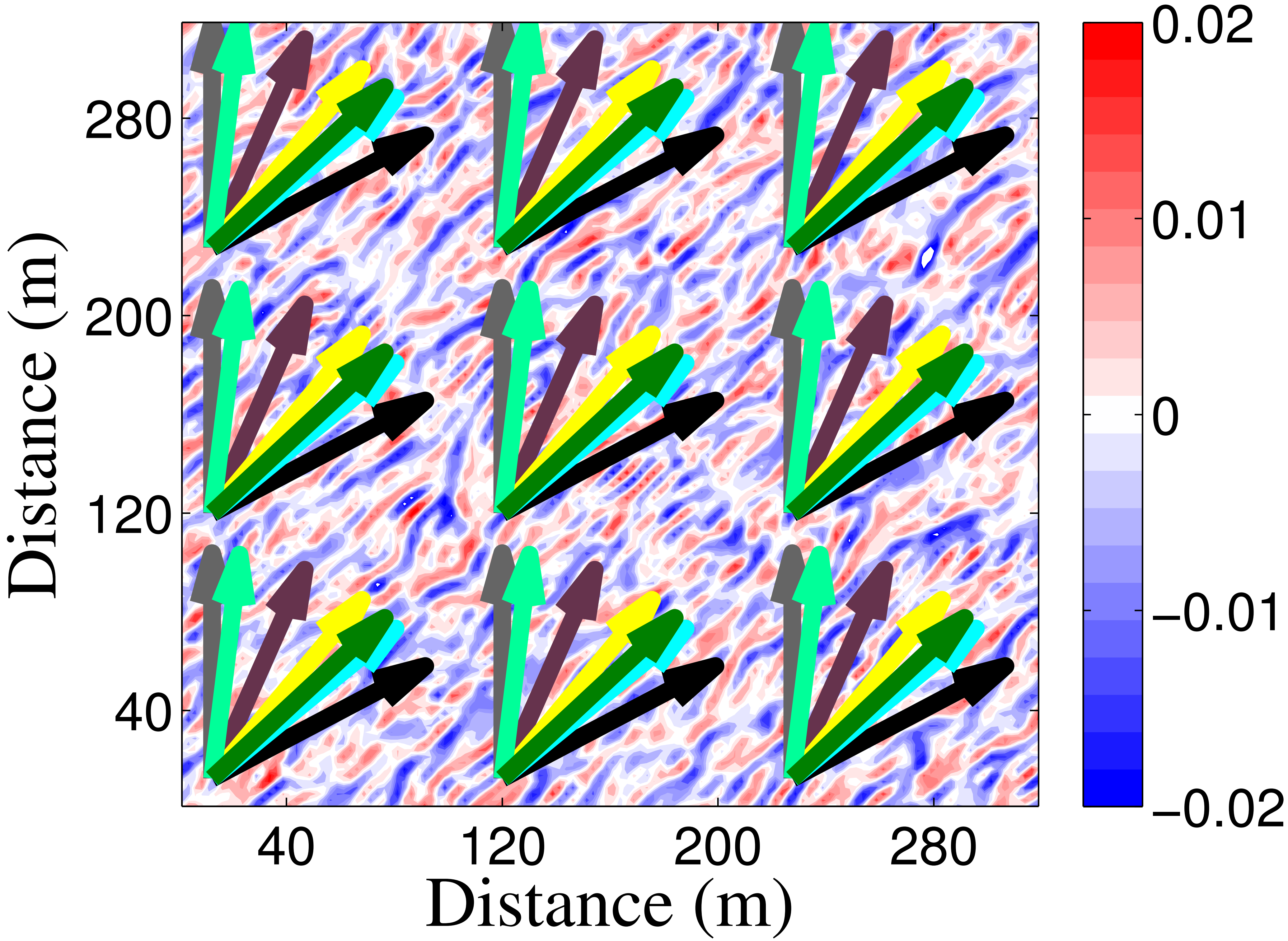




Van Roekel et al. 2011
(in prep)

Coupling between Langmuir and Submeso?

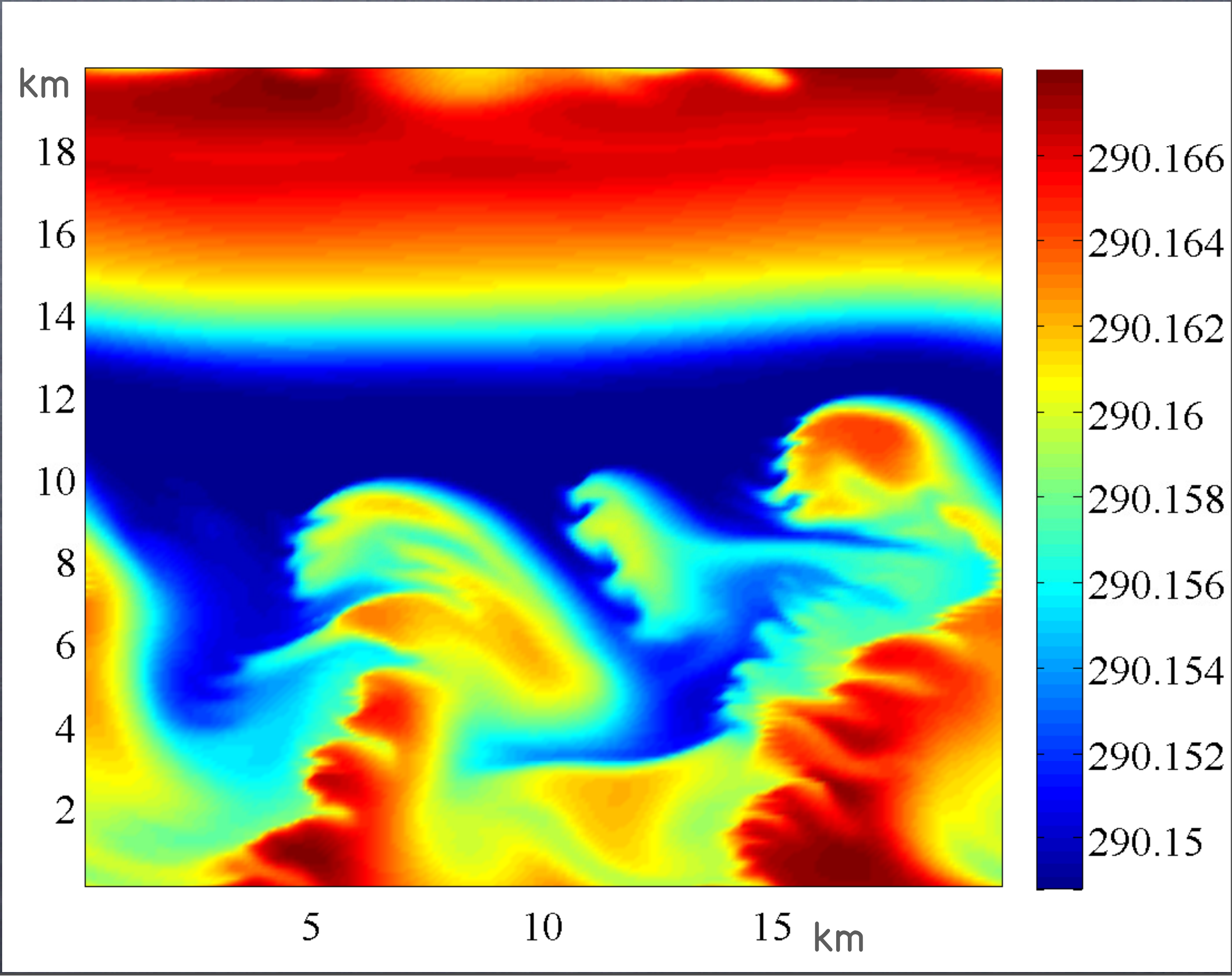
- Together?

- Separate?

The Game

- Spin up a submeso-resolving, but not Langmuir resolving model
    - 20kmx20kmx0.1km
    - Grid 384x384x20
    - 52m resolution
- Interpolate down to Langmuir resolving LES
    - 20kmx20kmx0.3km
    - Grid 4096x4096x128
    - 5m resolution
- Run for 2 more days, then...

Day 6.5 of a Submeso Resolving run
Near Surf. Temp



km

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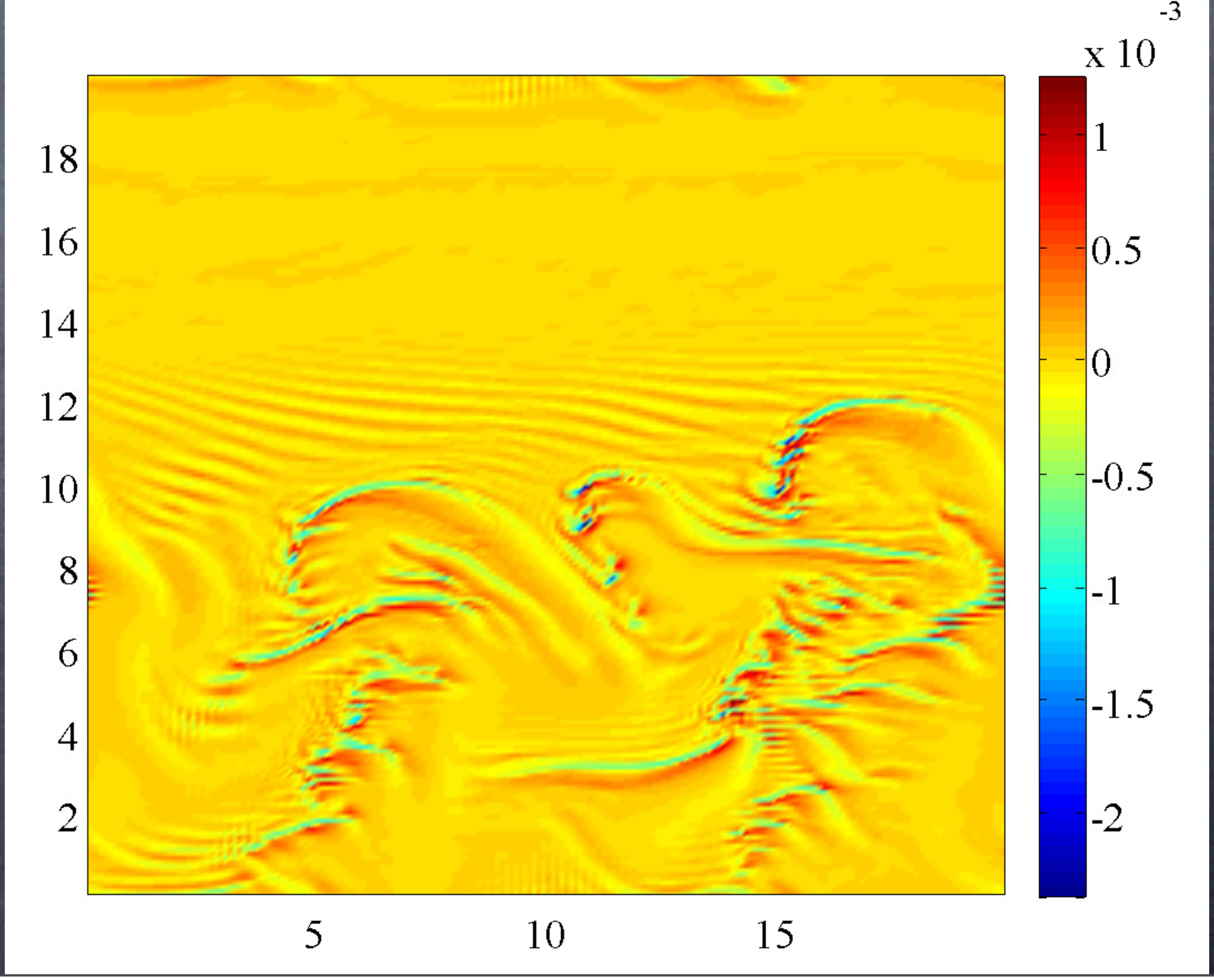
km

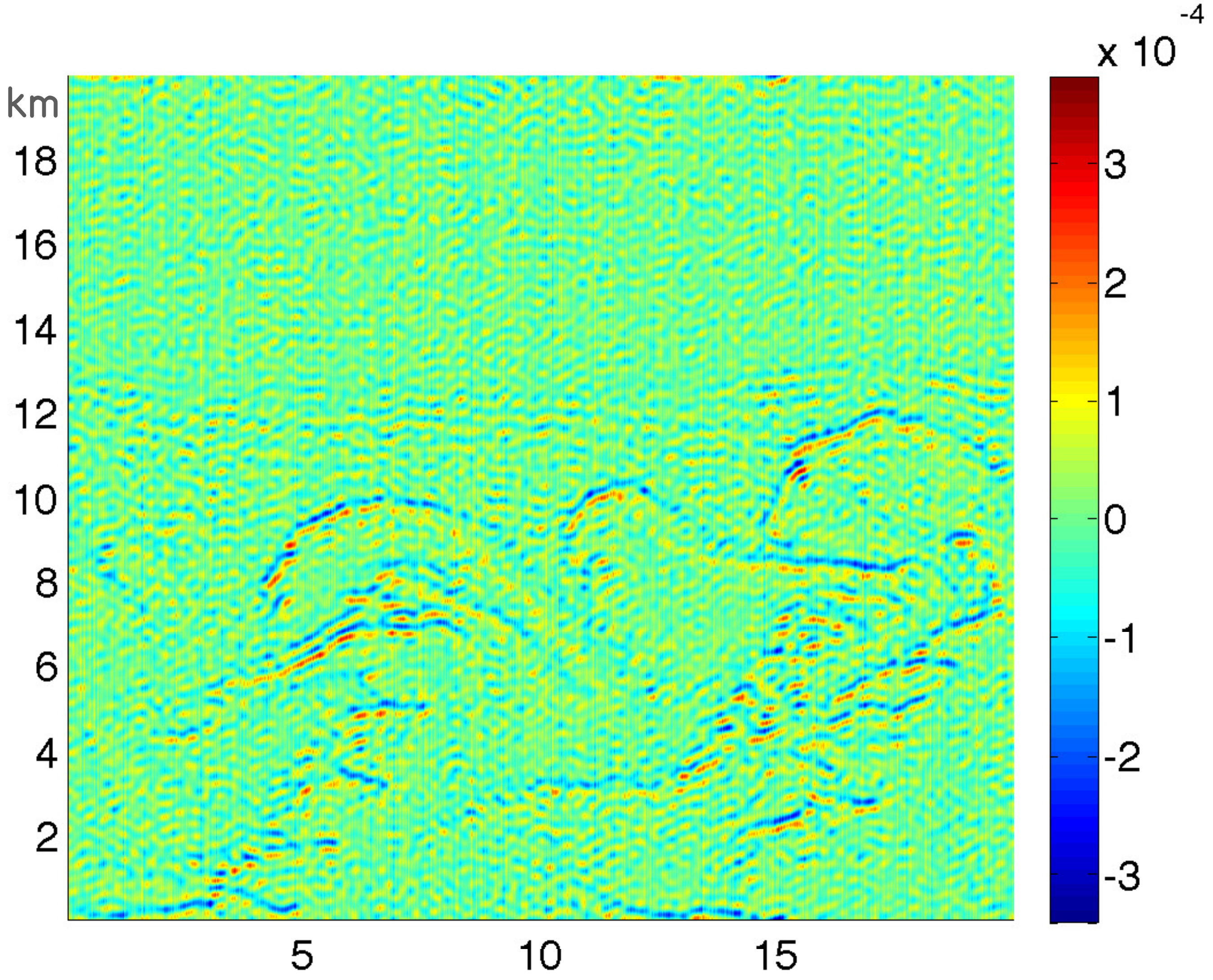
Day 6.5 of a Submeso Resolving run Vert. Velocity

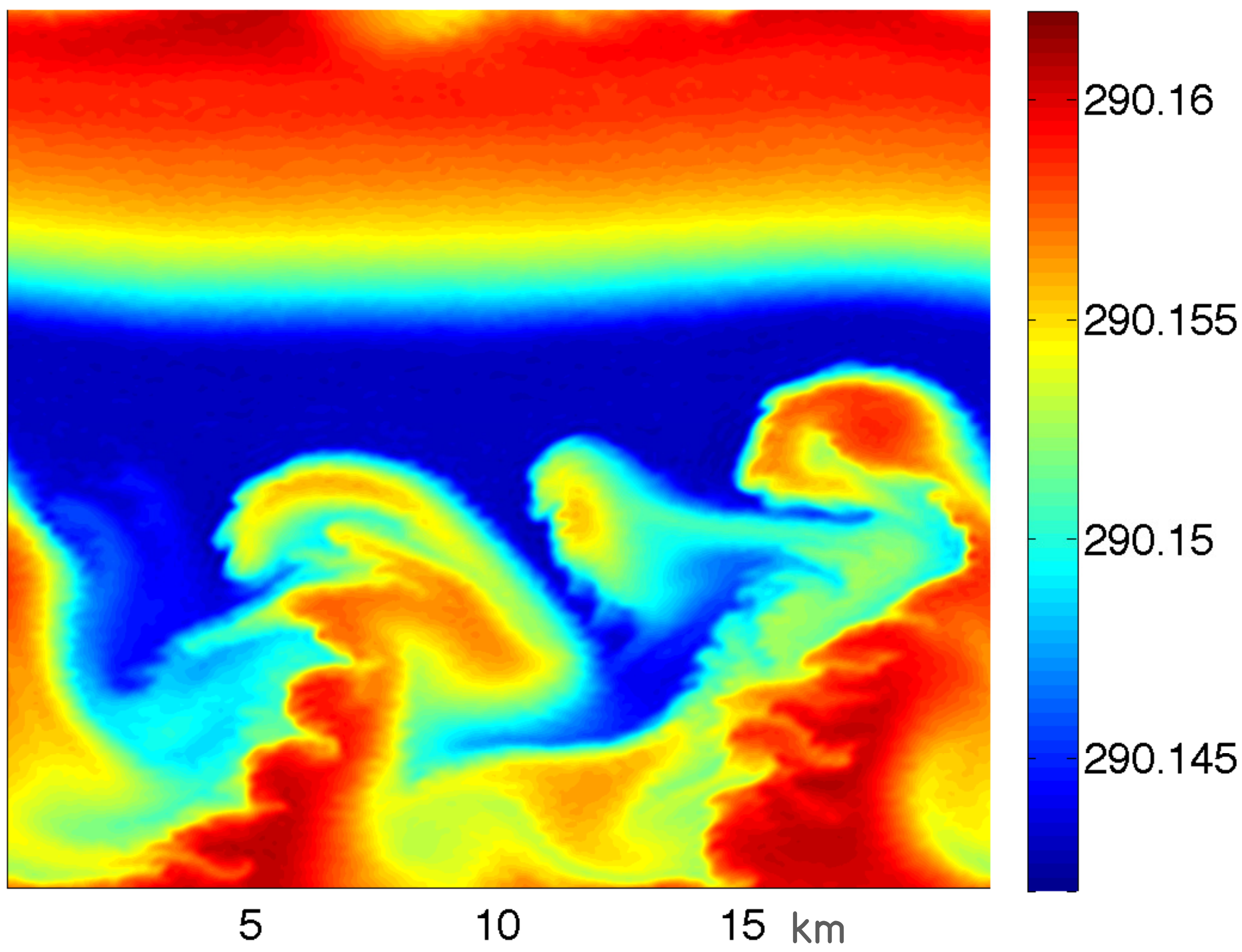


Coupling Langmuir to Submesoscale?

Near-Surf Vert. Vel.
With Stokes Drift

Near-Surf Temp.
With Stokes Drift

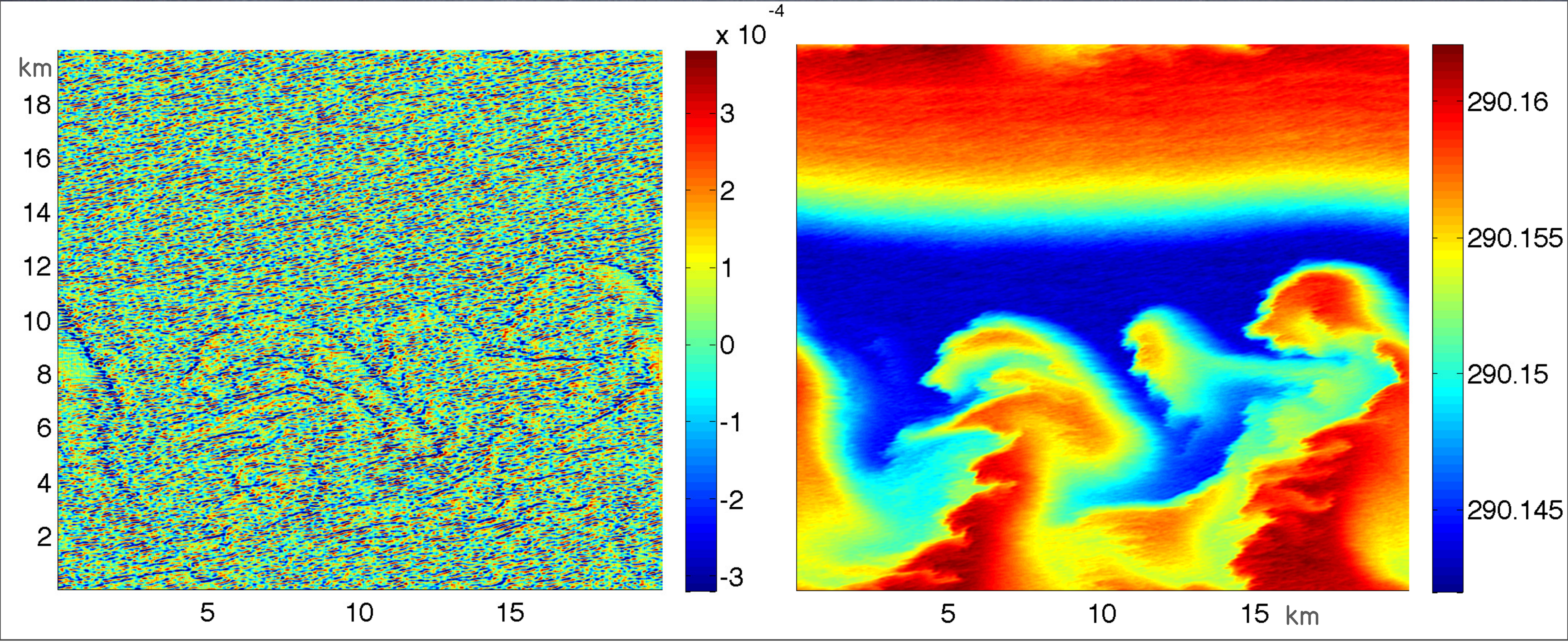




Coupling Langmuir to Submesoscale?

Vertical Velocity
No Stokes Drift

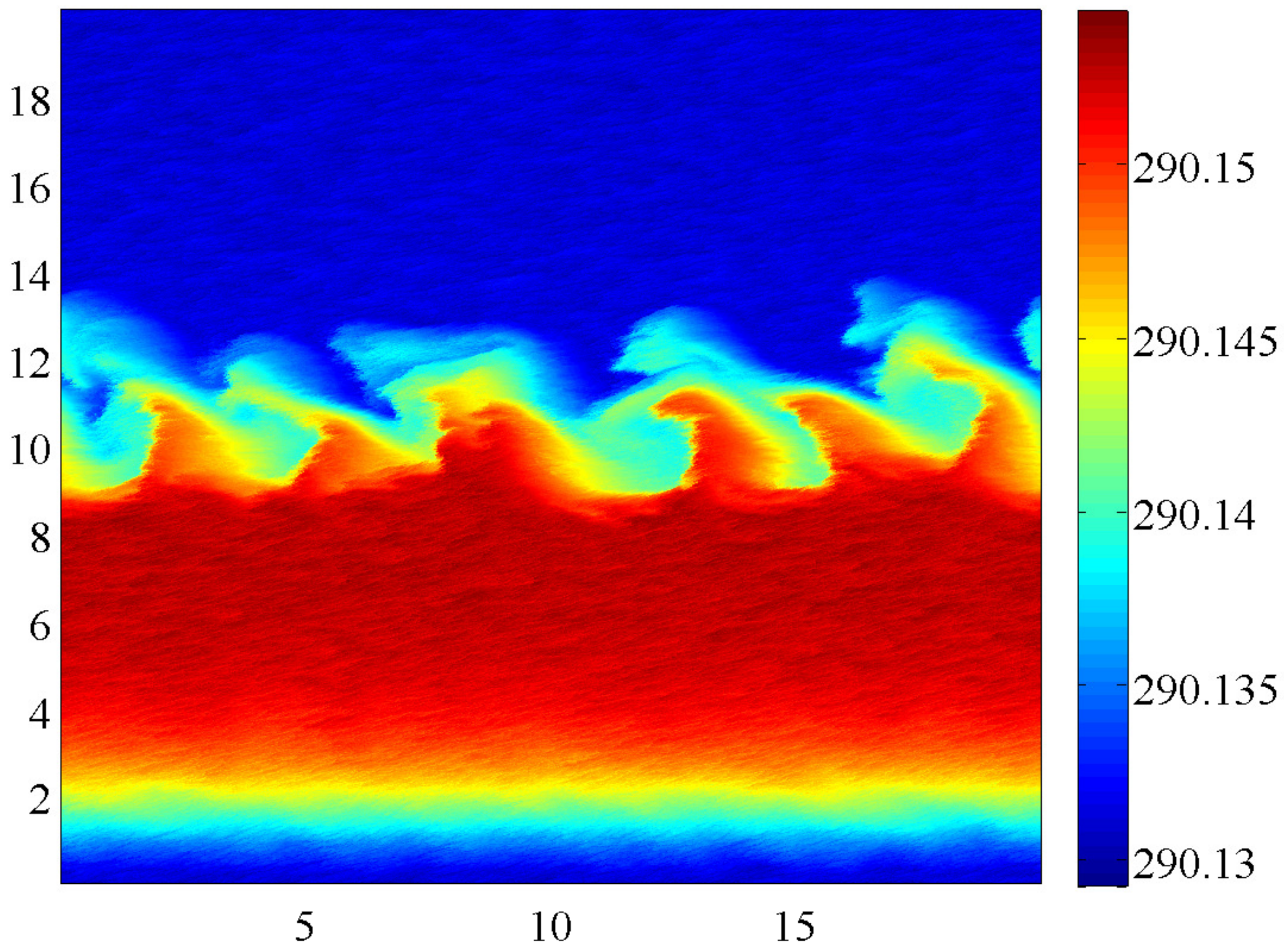
Near-Surf. Temp.
No Stokes Drift



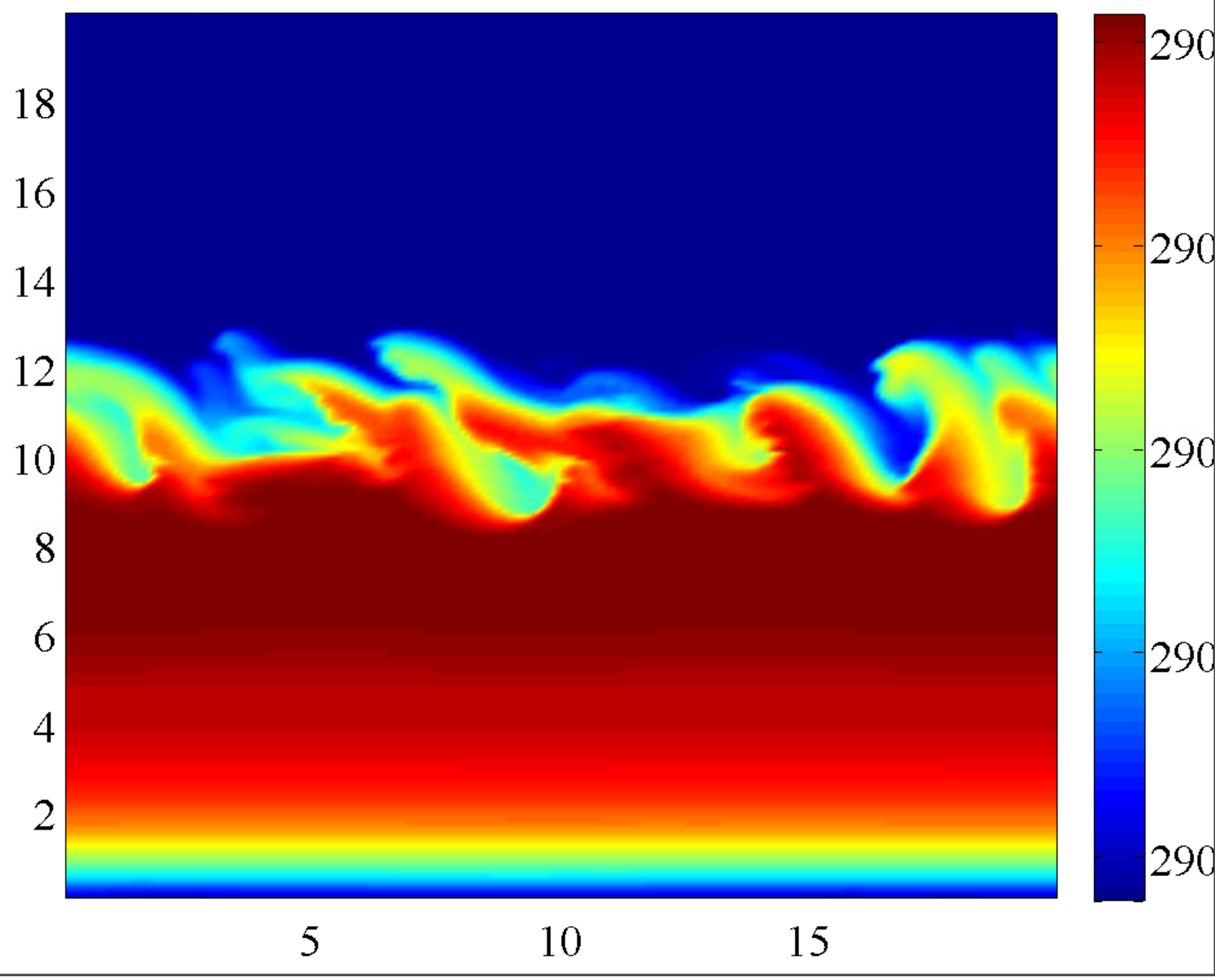
Coupling Langmuir to Submesoscale?

From Scratch... No interpolation!

Near-Surf. Temp.
No Stokes Drift



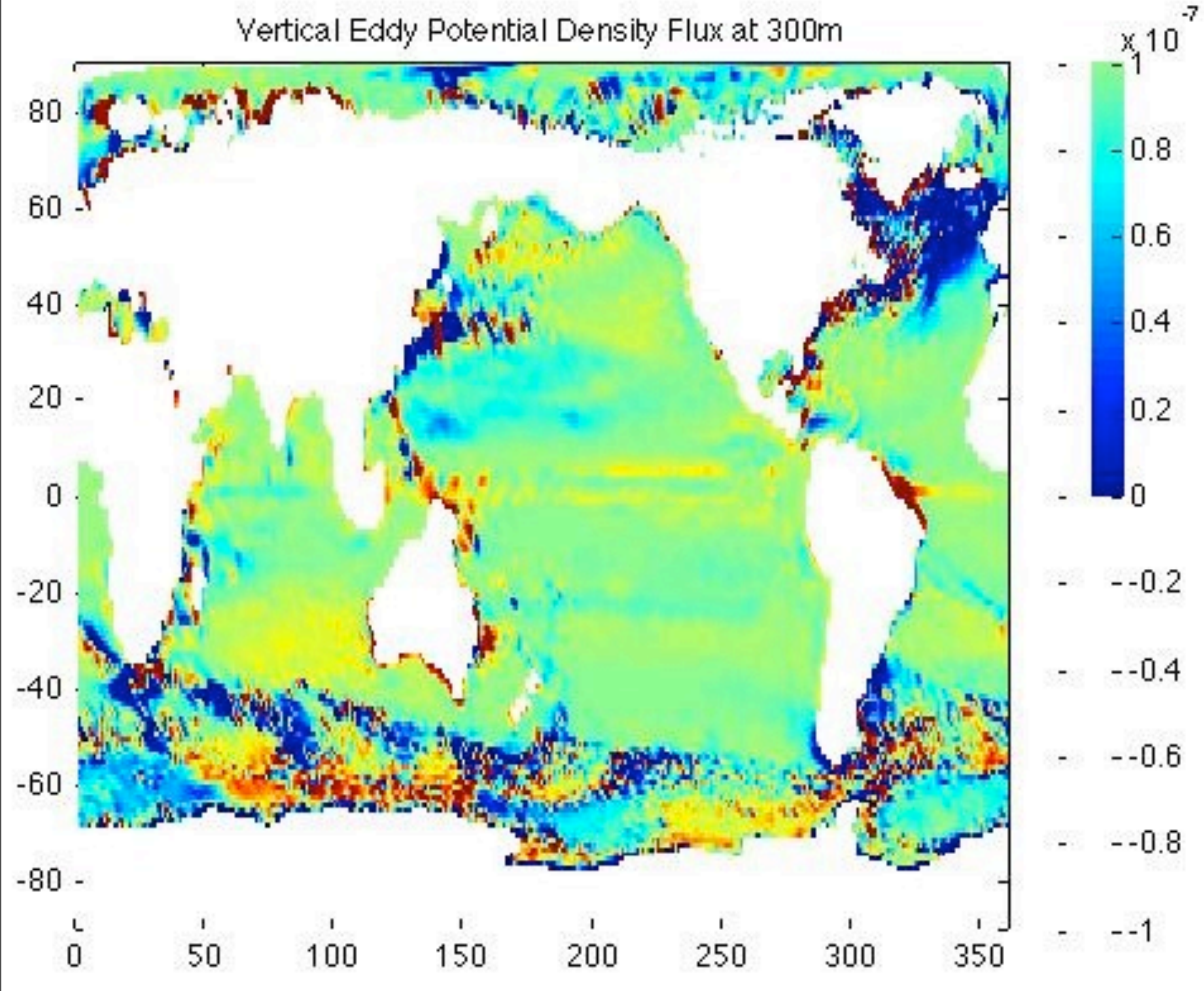
Near-Surf. Temp.
Submeso-Only Res.



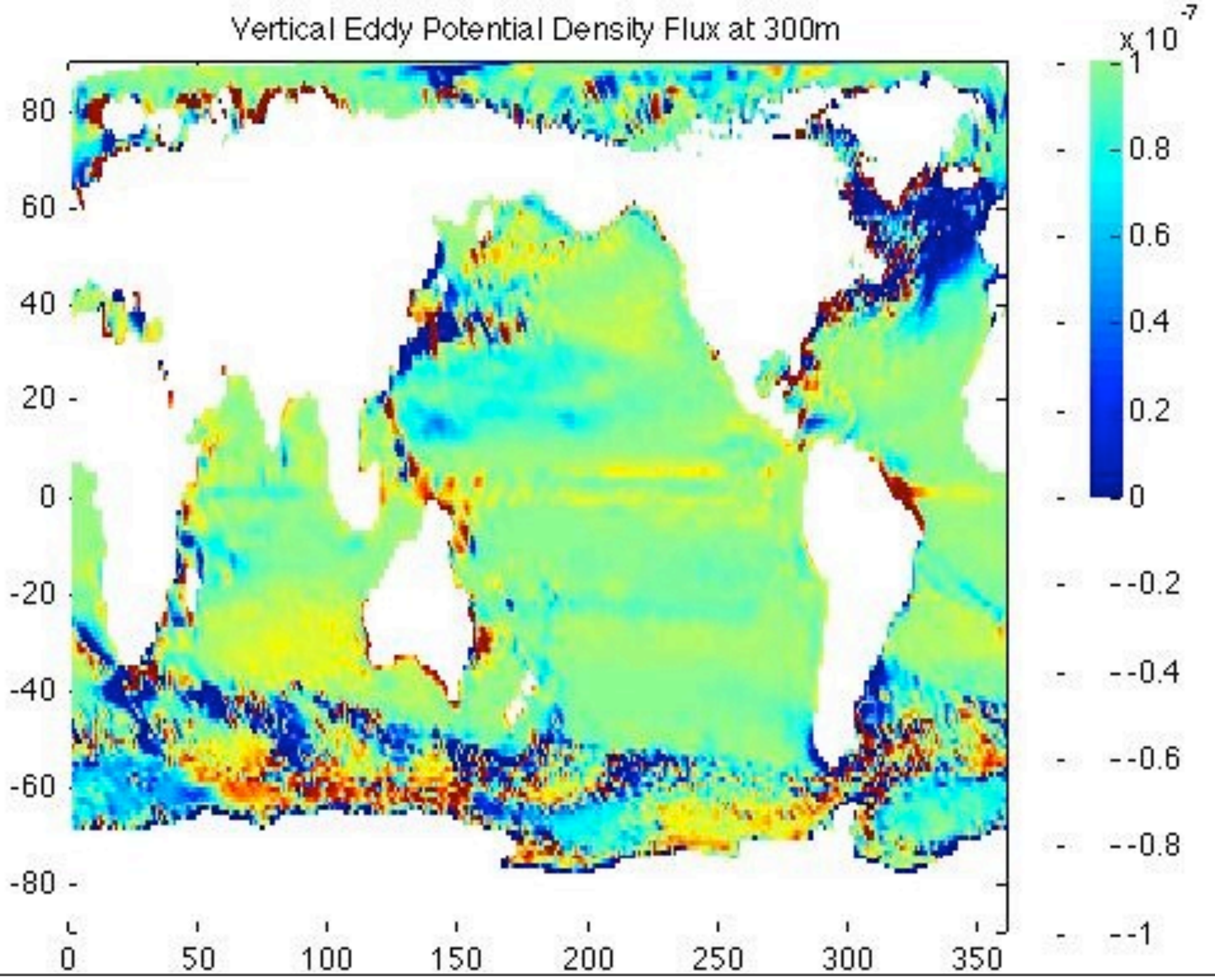
Conclusions

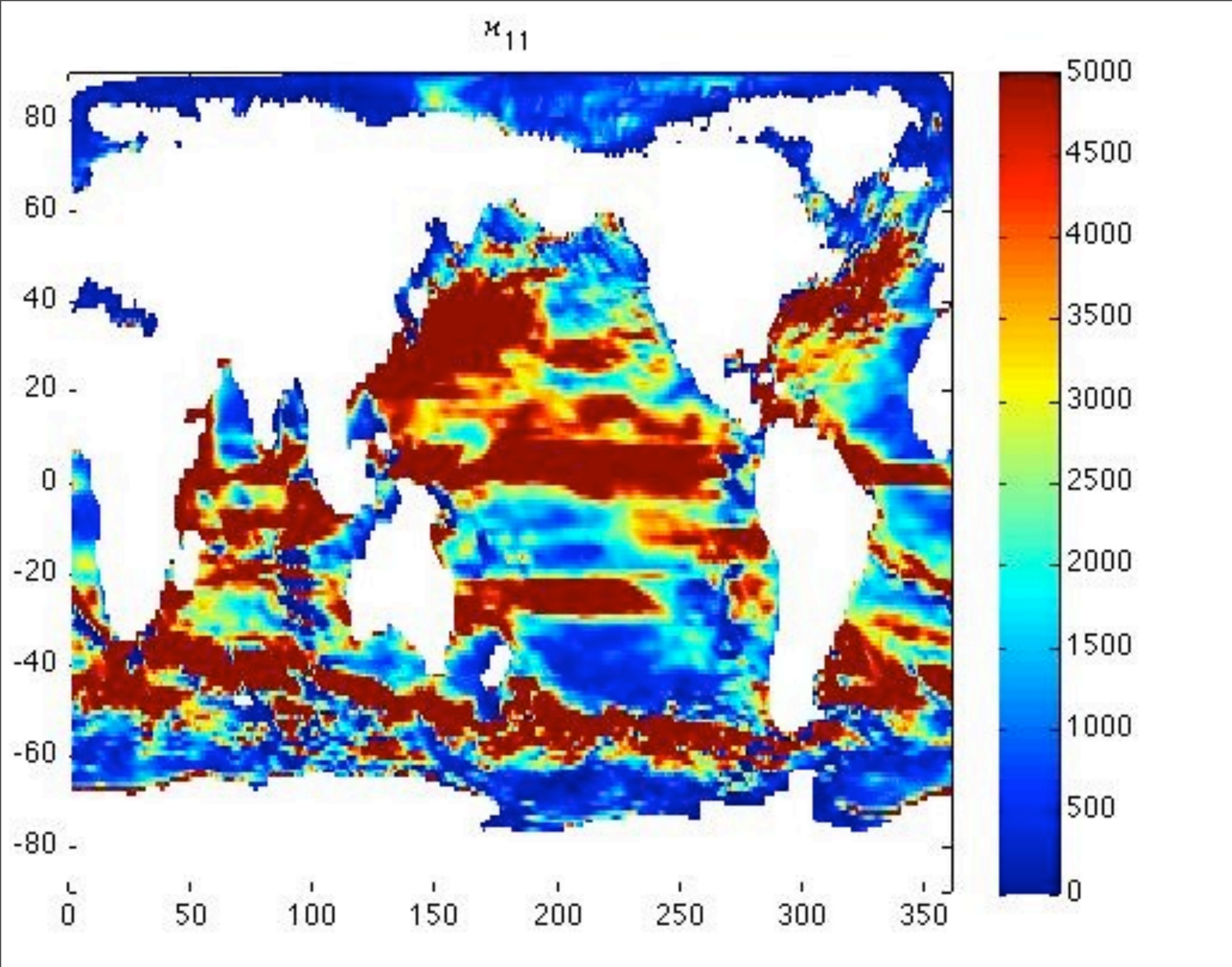
- Mesoscale, Submesoscale, and Langmuir scale phenomena all have a nontrivial affect on the global climate, thus need accurate parameterizations
- Parameterizations are developed by comparison to higher-resolution models, with careful diagnosis of interesting terms
- These high resolution models reveal primary balances and spatiotemporal dependence that should be approximated by the parameterizations.

Compare to vertical eddy density flux (PE Extraction)



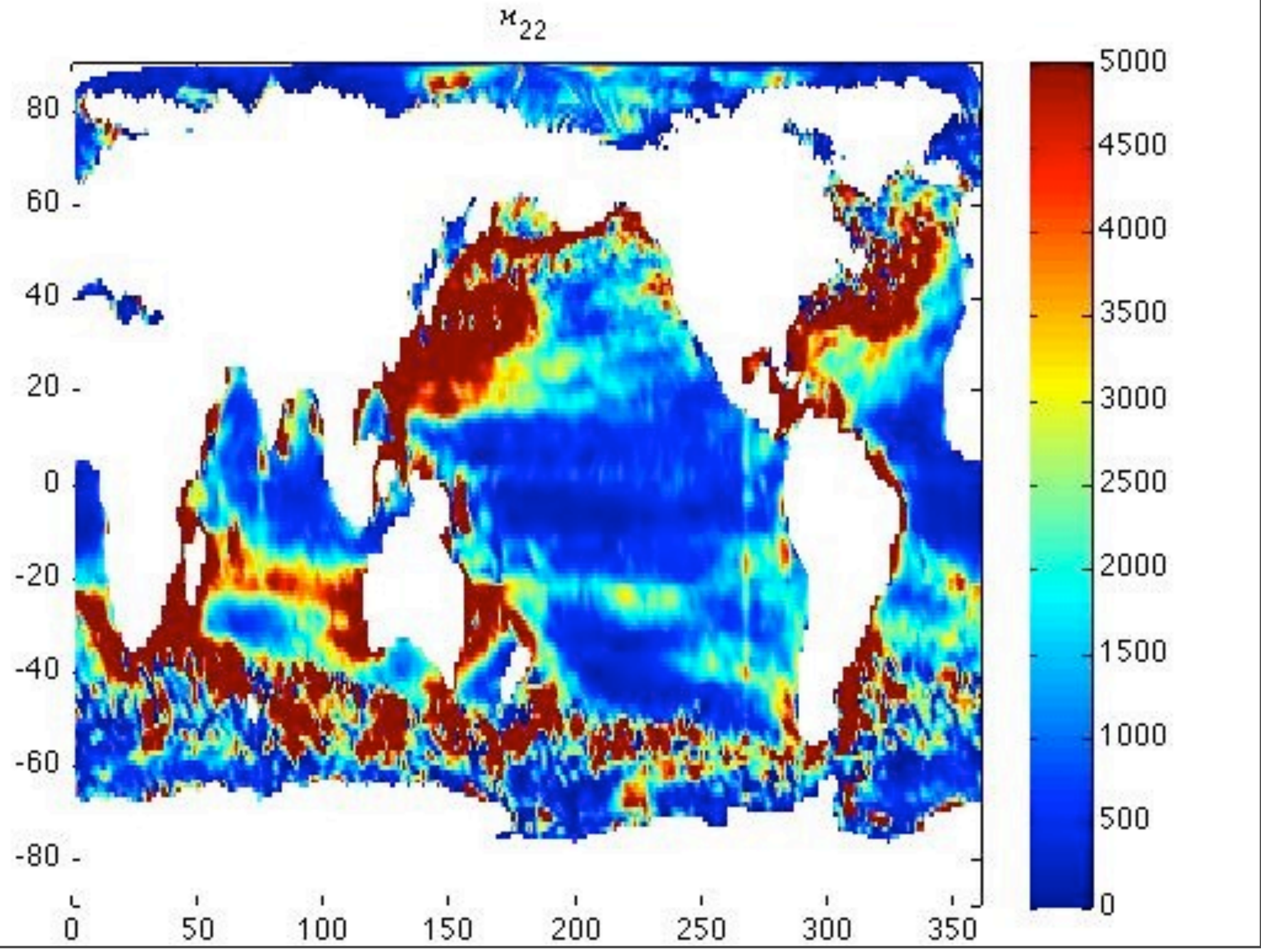
- Eden&Greatbatch (+others) propose that baroclinic instability's production of EKE from PE should guide M magnitude





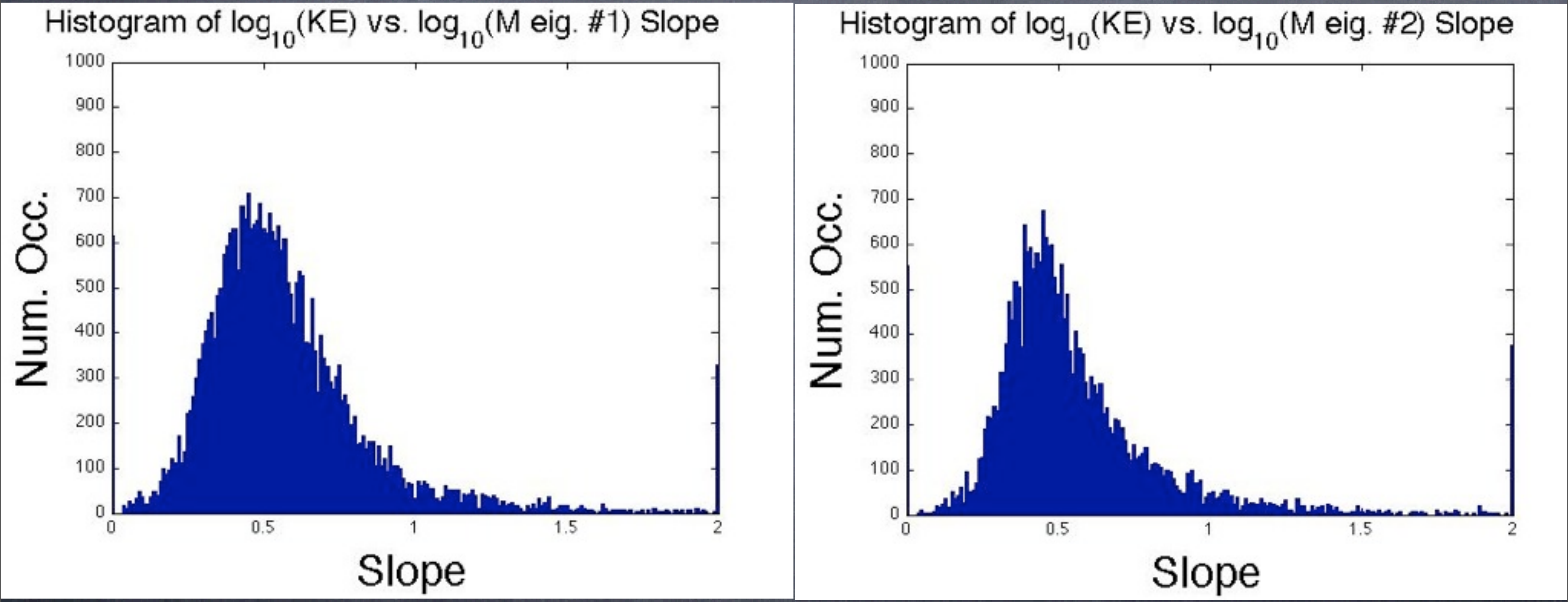
Locations of PE extraction are

Locations of large eigs of $\mathbf{K}$



Result:
coarse KE-> vertical structure of Mixing

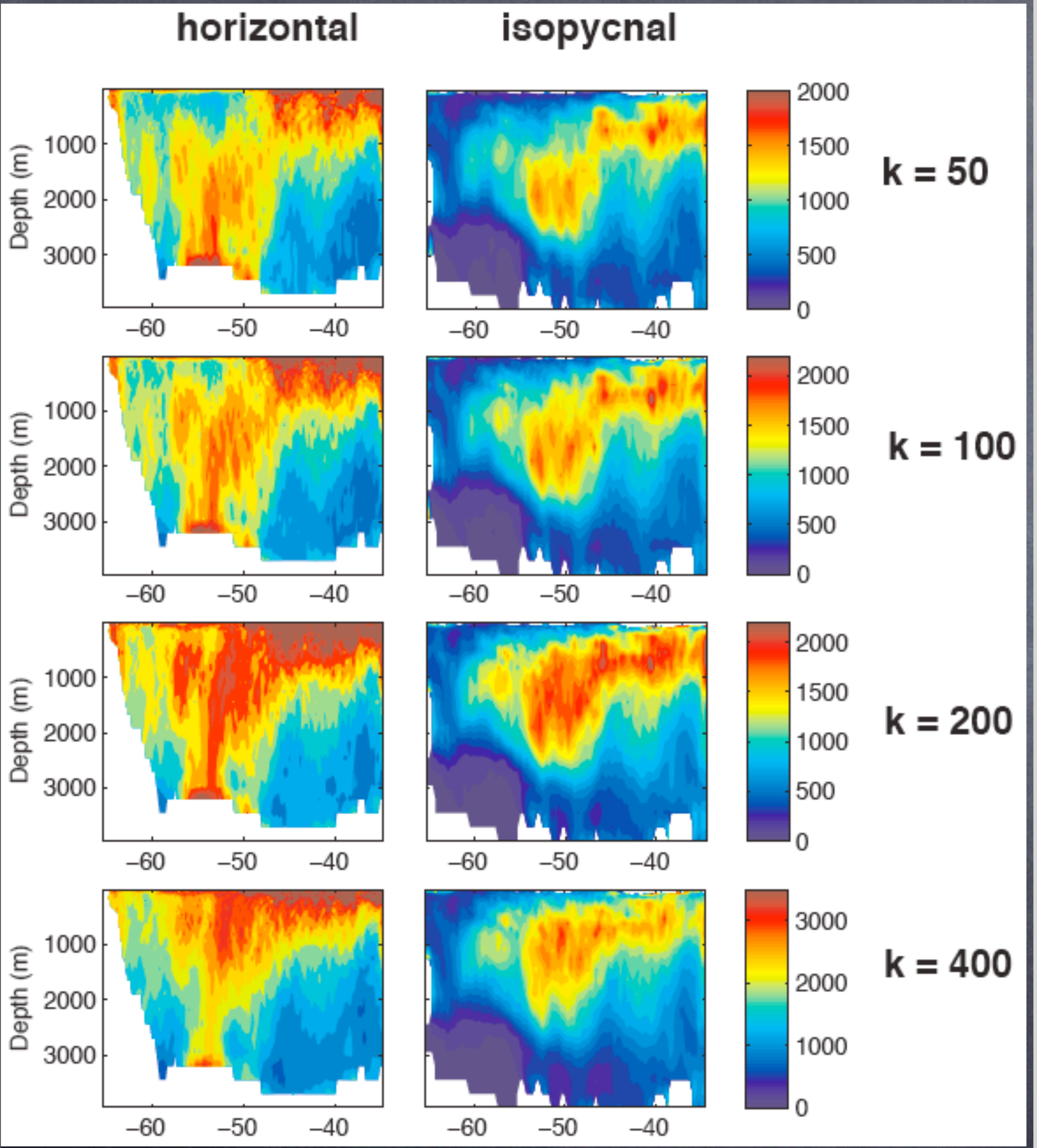
$$\mathbf{K} \propto \sqrt{\langle \mathbf{KE} \rangle}$$



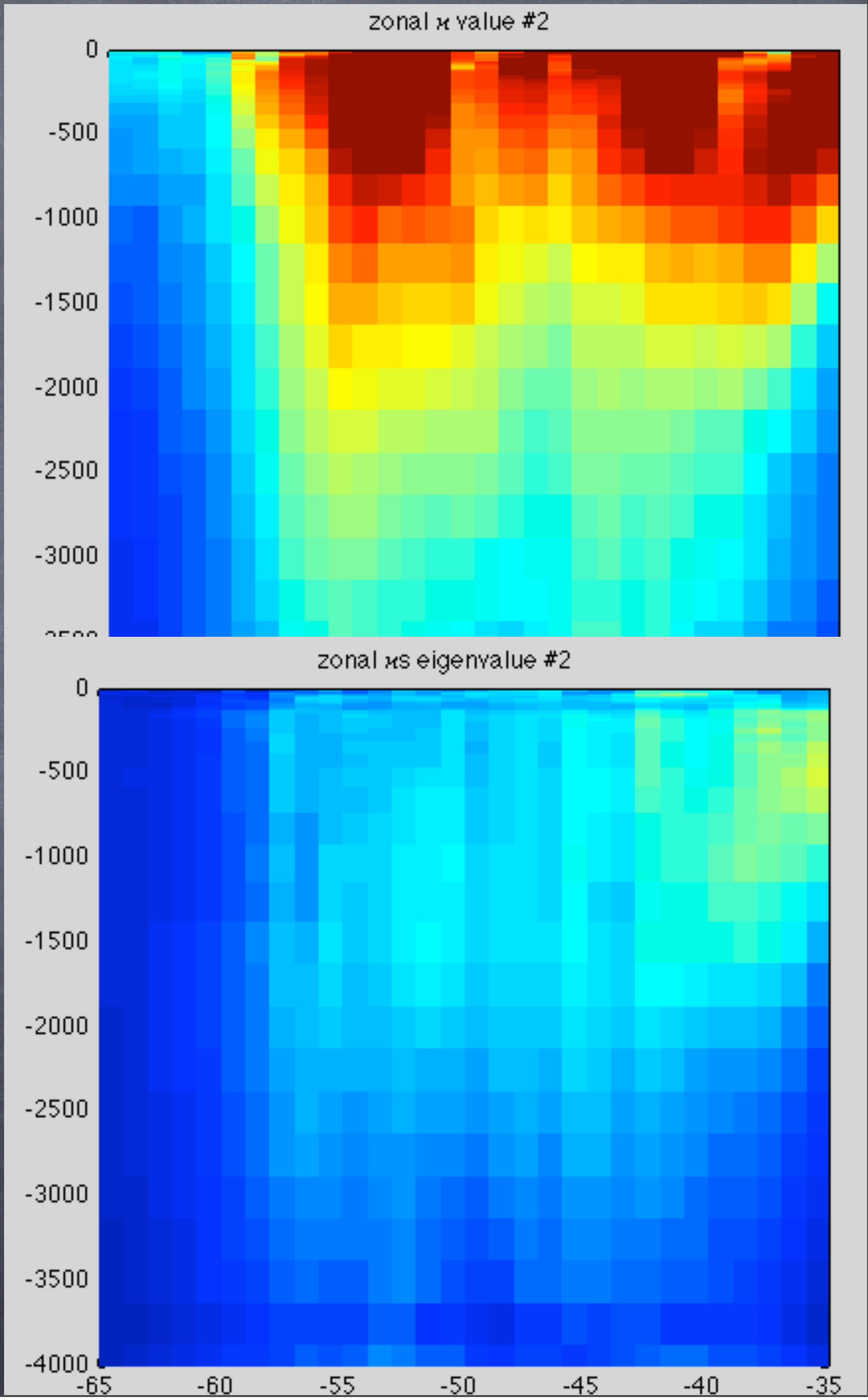
Even better with EKE!

Note--barotropic mode is in there!

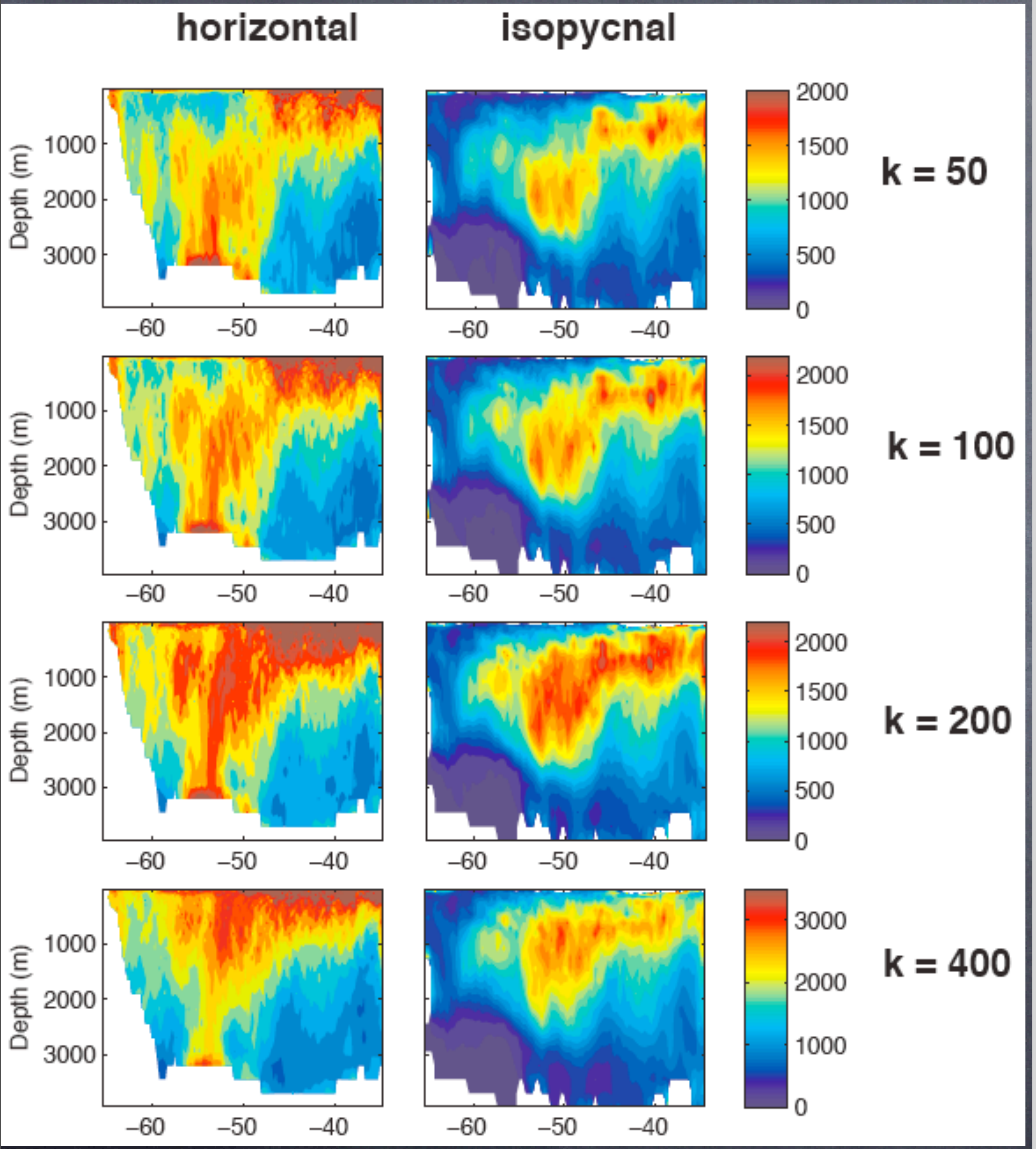
Comparisons with Marshall et al.



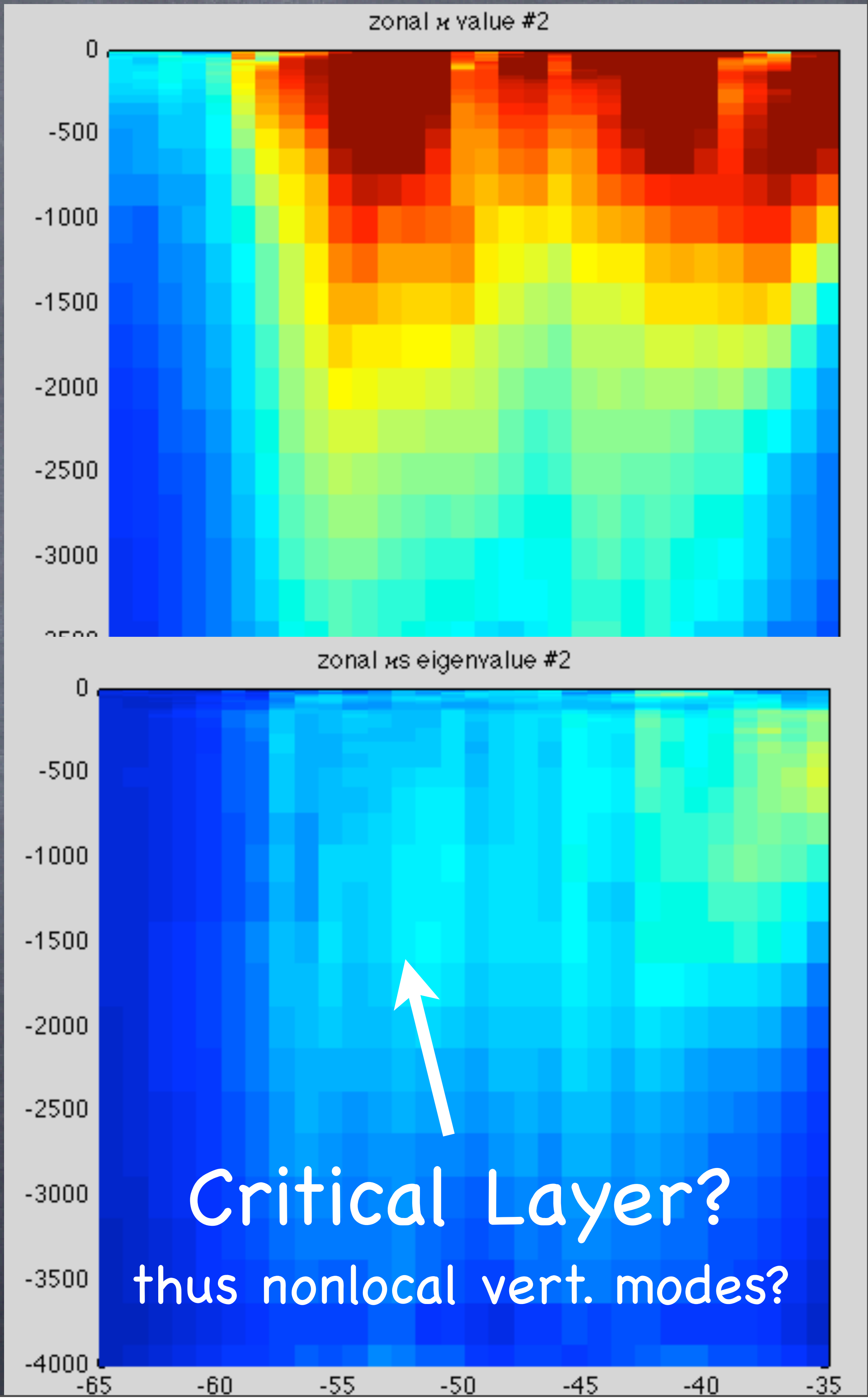
Abernathy et al 09



Comparisons with Marshall et al.

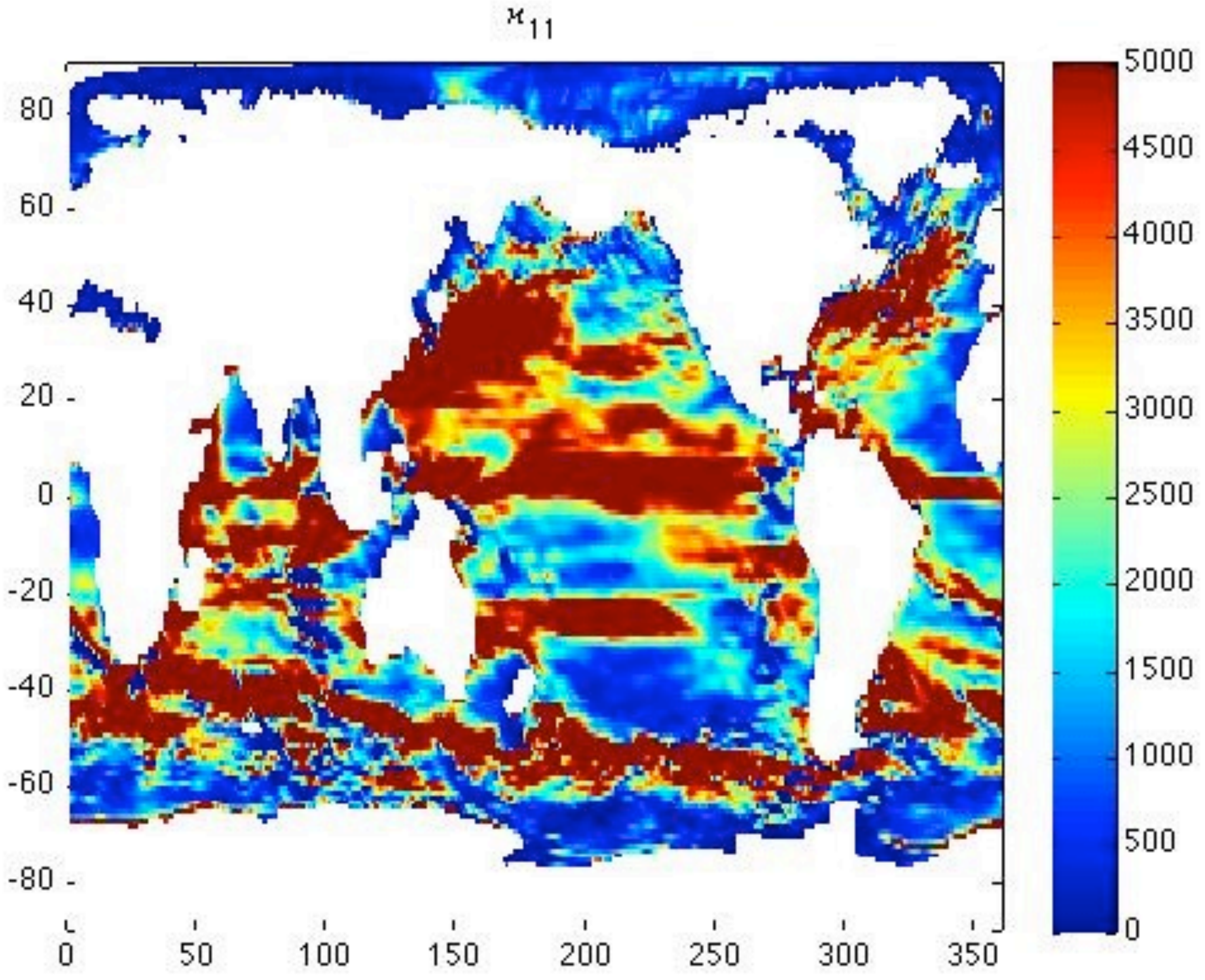


Abernathy et al 09



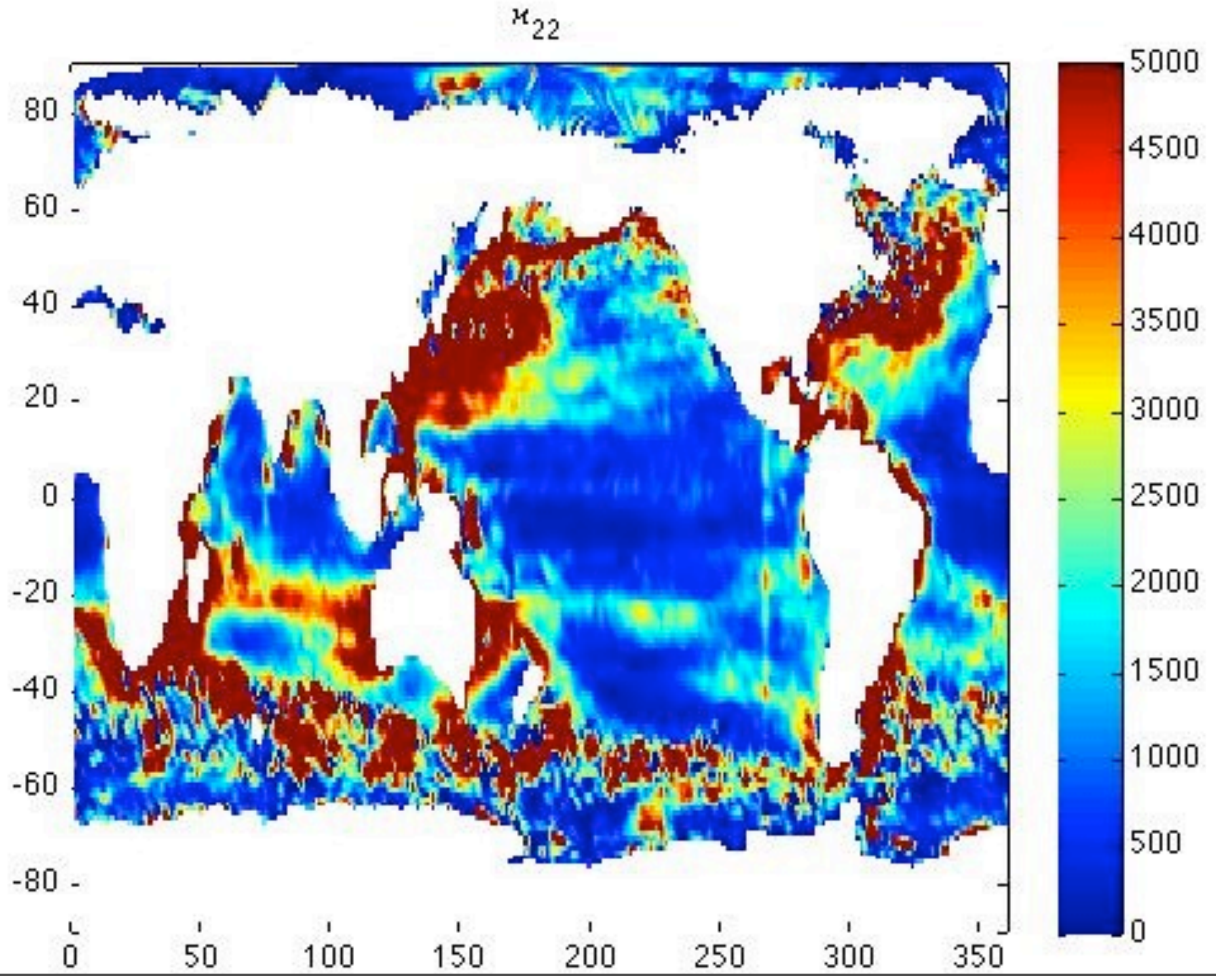
Critical Layer?

thus nonlocal vert. modes?



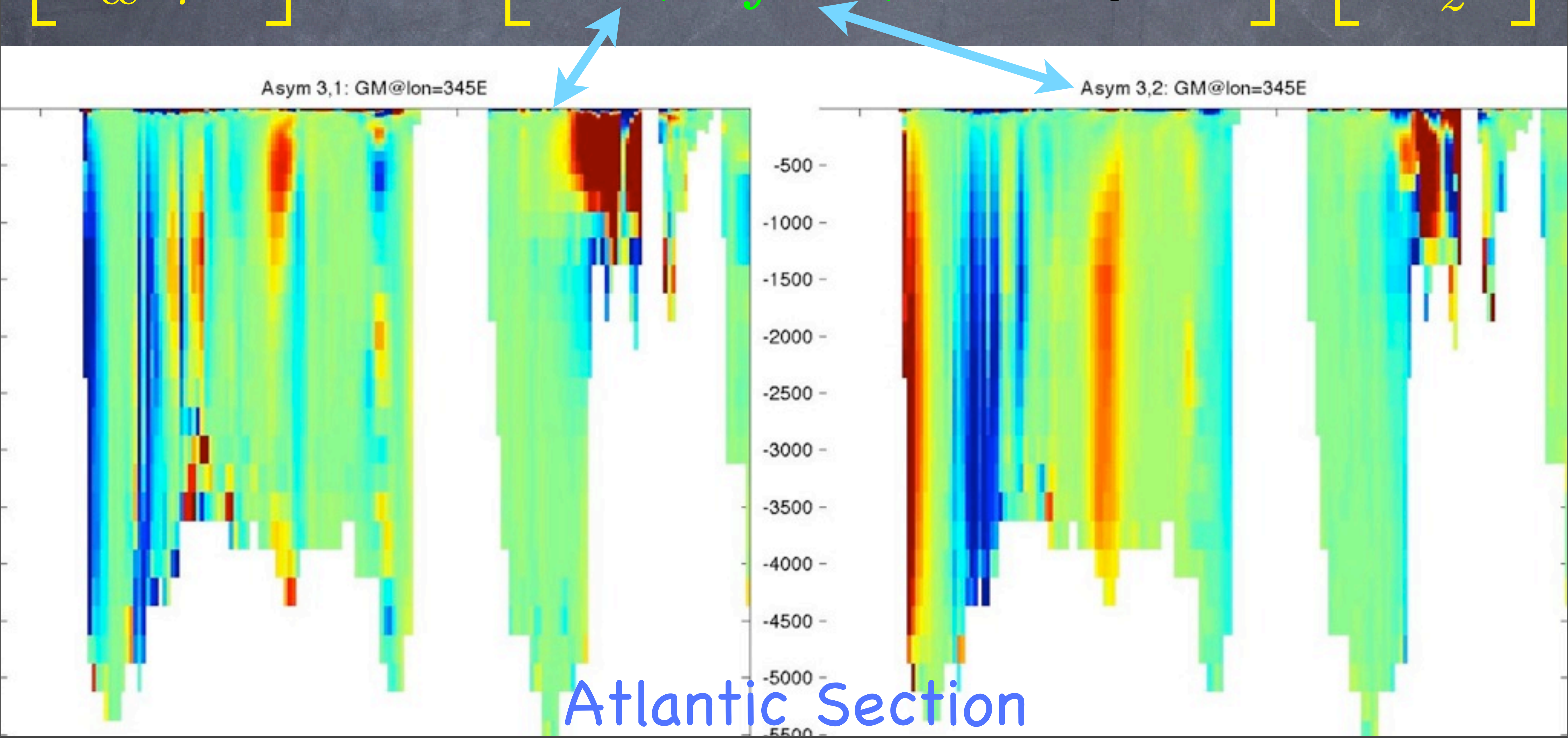
Locations of PE extraction are

Locations of large eigs of $\mathbf{K}$



Use a Natural, Mesoscale Eddy Environment to Test Out:

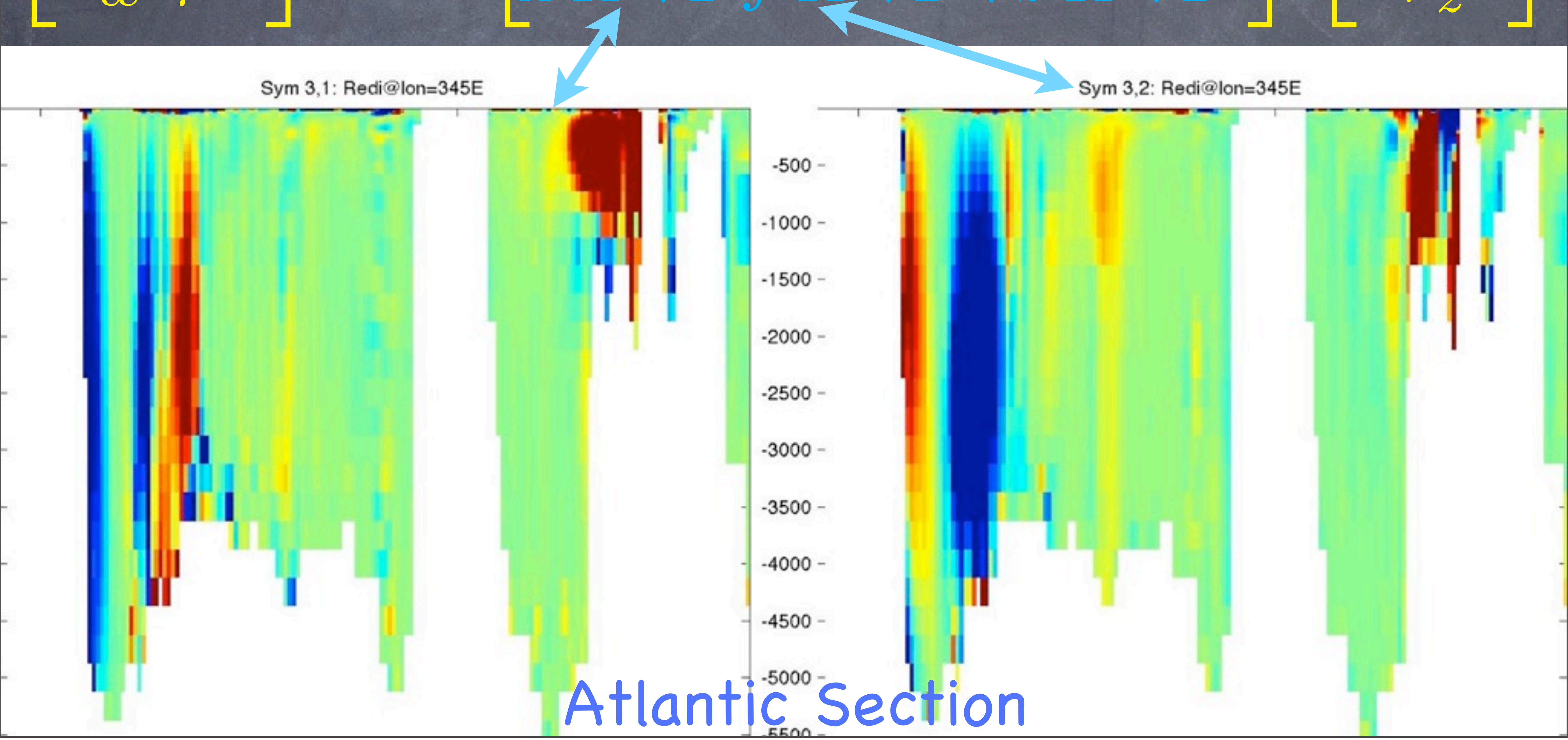
$$\begin{bmatrix}\overline{u'\tau'}\\ \overline{v'\tau'}\\ \overline{w'\tau'}\end{bmatrix} = -\begin{bmatrix} 0 & 0 & -\hat{\mathbf{x}}\cdot\mathbf{K}\cdot\tilde{\nabla}\mathbf{z}\\ 0 & 0 & -\hat{\mathbf{y}}\cdot\mathbf{K}\cdot\tilde{\nabla}\mathbf{z}\\ \hat{\mathbf{x}}\cdot\mathbf{K}\cdot\tilde{\nabla}\mathbf{z}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



Atlantic Section

Use a Natural, Mesoscale Eddy Environment to Test Out:

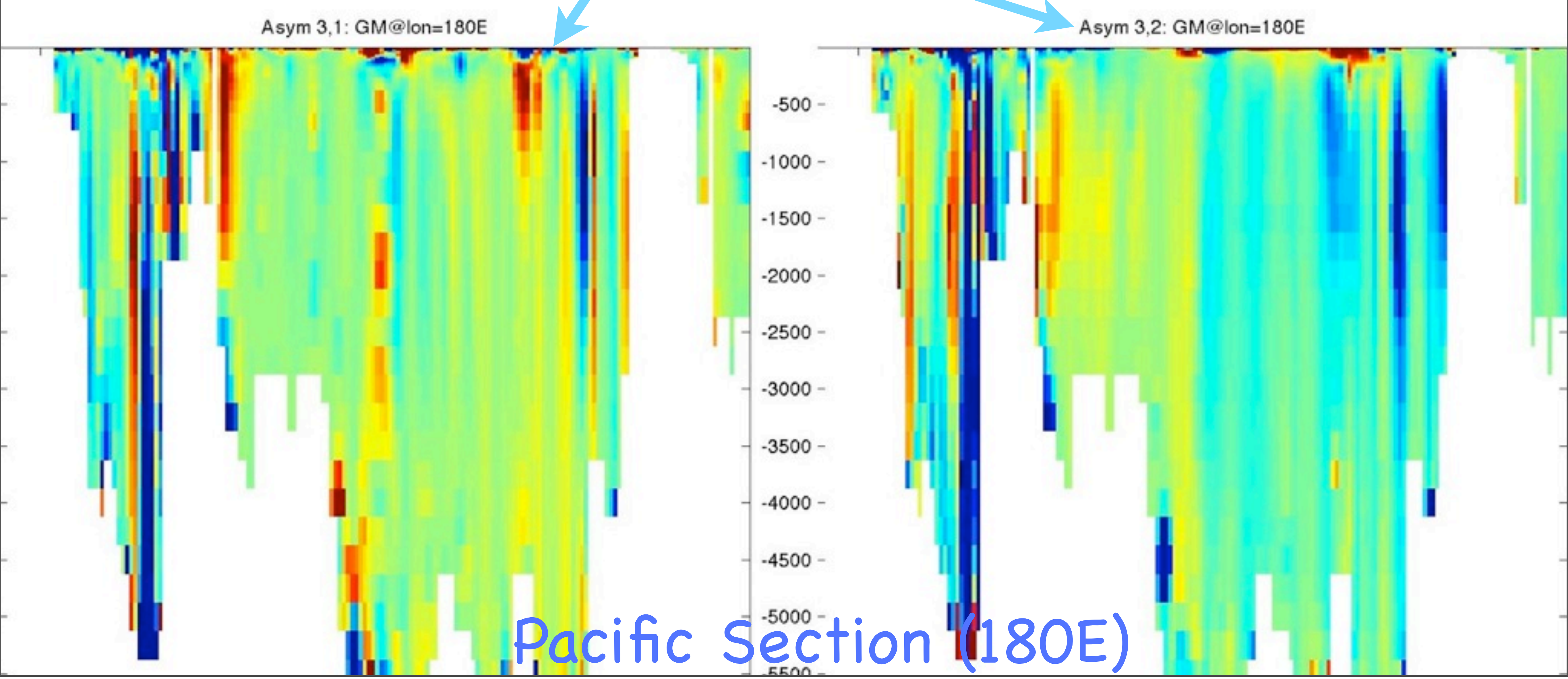
$$\begin{bmatrix}\overline{u'\tau'}\\ \overline{v'\tau'}\\ \overline{w'\tau'}\end{bmatrix} = -\begin{bmatrix} K_{xx} & K_{xy} & \hat{\mathbf{x}}\cdot\mathbf{K}\cdot\tilde{\nabla}\mathbf{z} \\ K_{yx} & K_{yy} & \hat{\mathbf{y}}\cdot\mathbf{K}\cdot\tilde{\nabla}\mathbf{z} \\ \hat{\mathbf{x}}\cdot\mathbf{K}\cdot\tilde{\nabla}\mathbf{z}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



Atlantic Section

Use a Natural, Mesoscale Eddy Environment to Test Out:

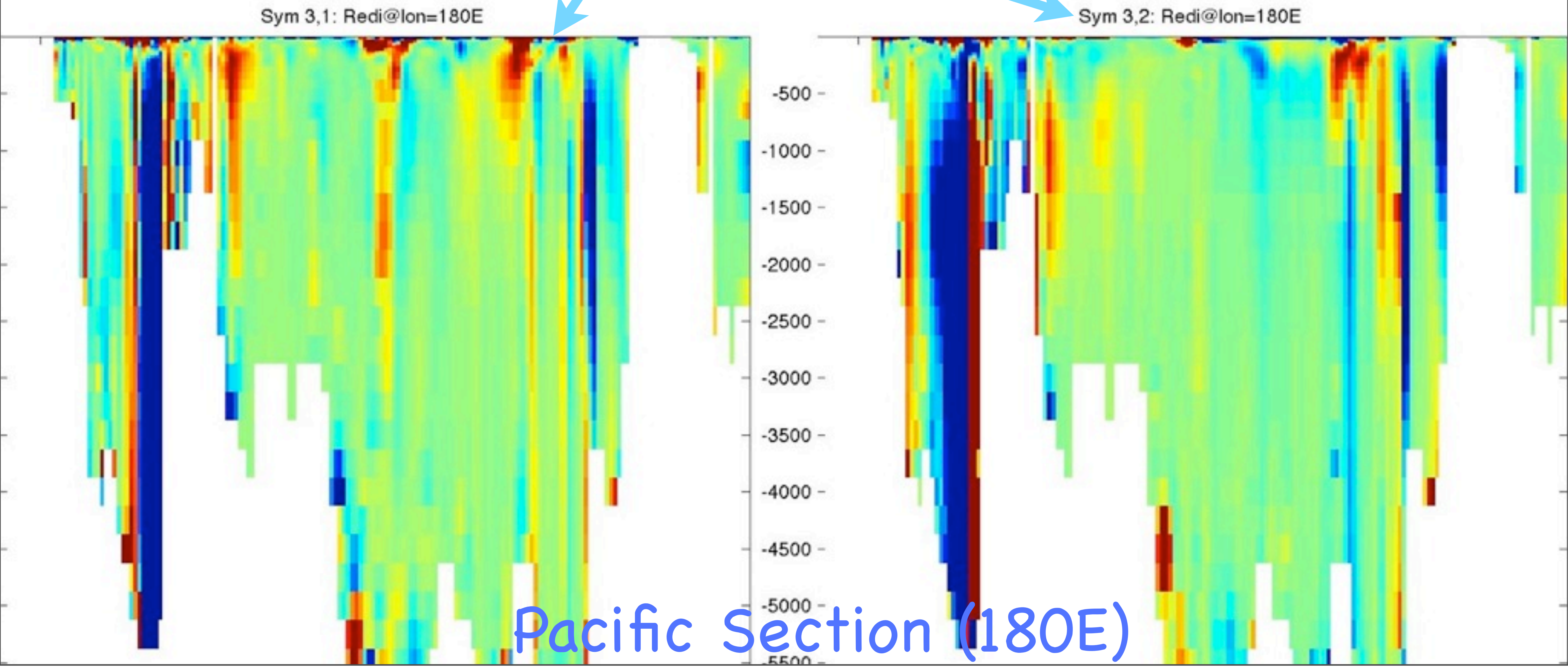
$$\begin{bmatrix}\overline{u'\tau'}\\ \overline{v'\tau'}\\ \overline{w'\tau'}\end{bmatrix} = -\begin{bmatrix}0 & 0 & -\hat{\mathbf{x}}\cdot\mathbf{K}\cdot\tilde{\nabla}\mathbf{z}\\ 0 & 0 & -\hat{\mathbf{y}}\cdot\mathbf{K}\cdot\tilde{\nabla}\mathbf{z}\\ \hat{\mathbf{x}}\cdot\mathbf{K}\cdot\tilde{\nabla}\mathbf{z}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



Pacific Section (180E)

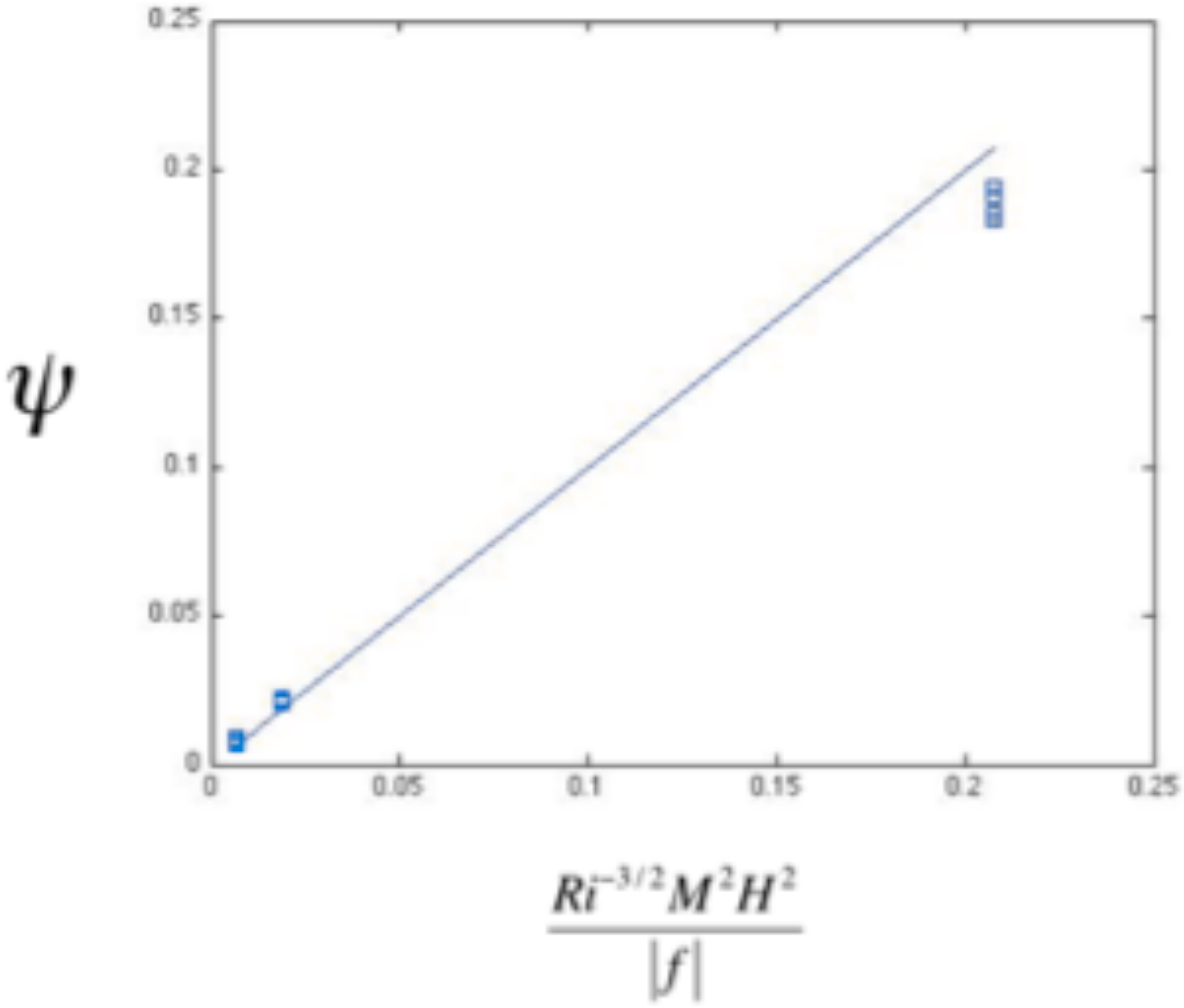
Use a Natural, Mesoscale Eddy Environment to Test Out:

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

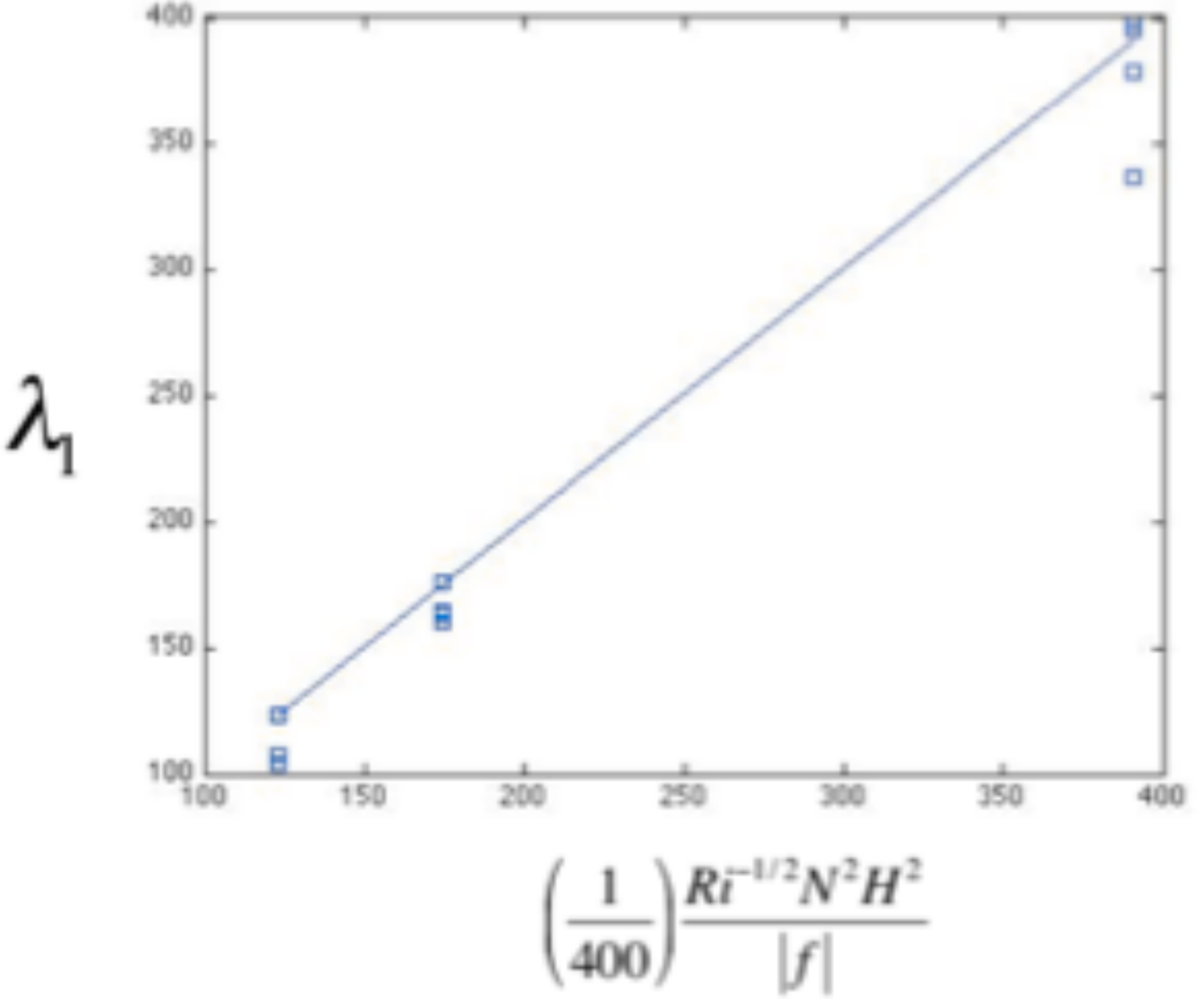


Pacific Section (180E)

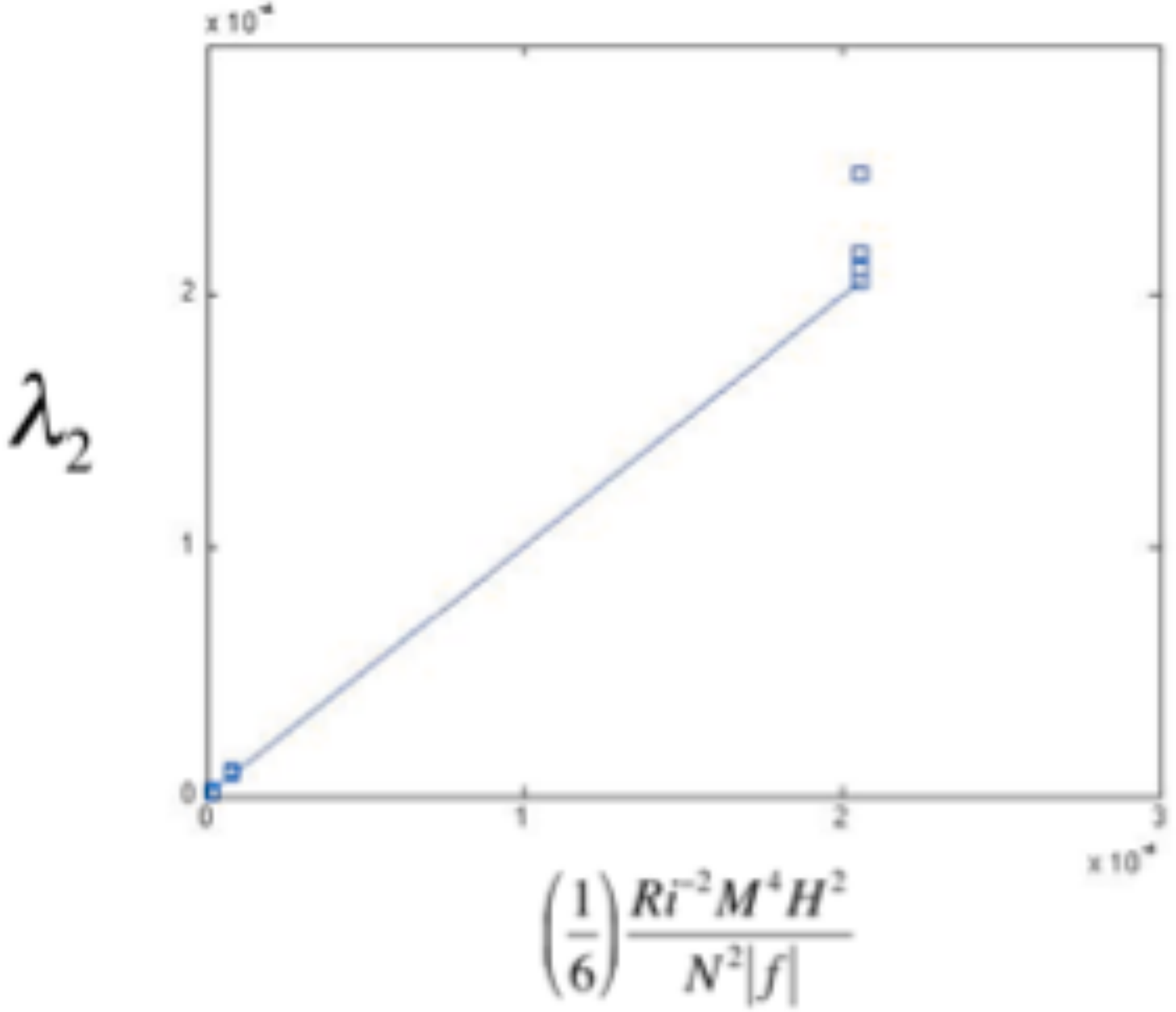
Scaling: Antisymmetric part



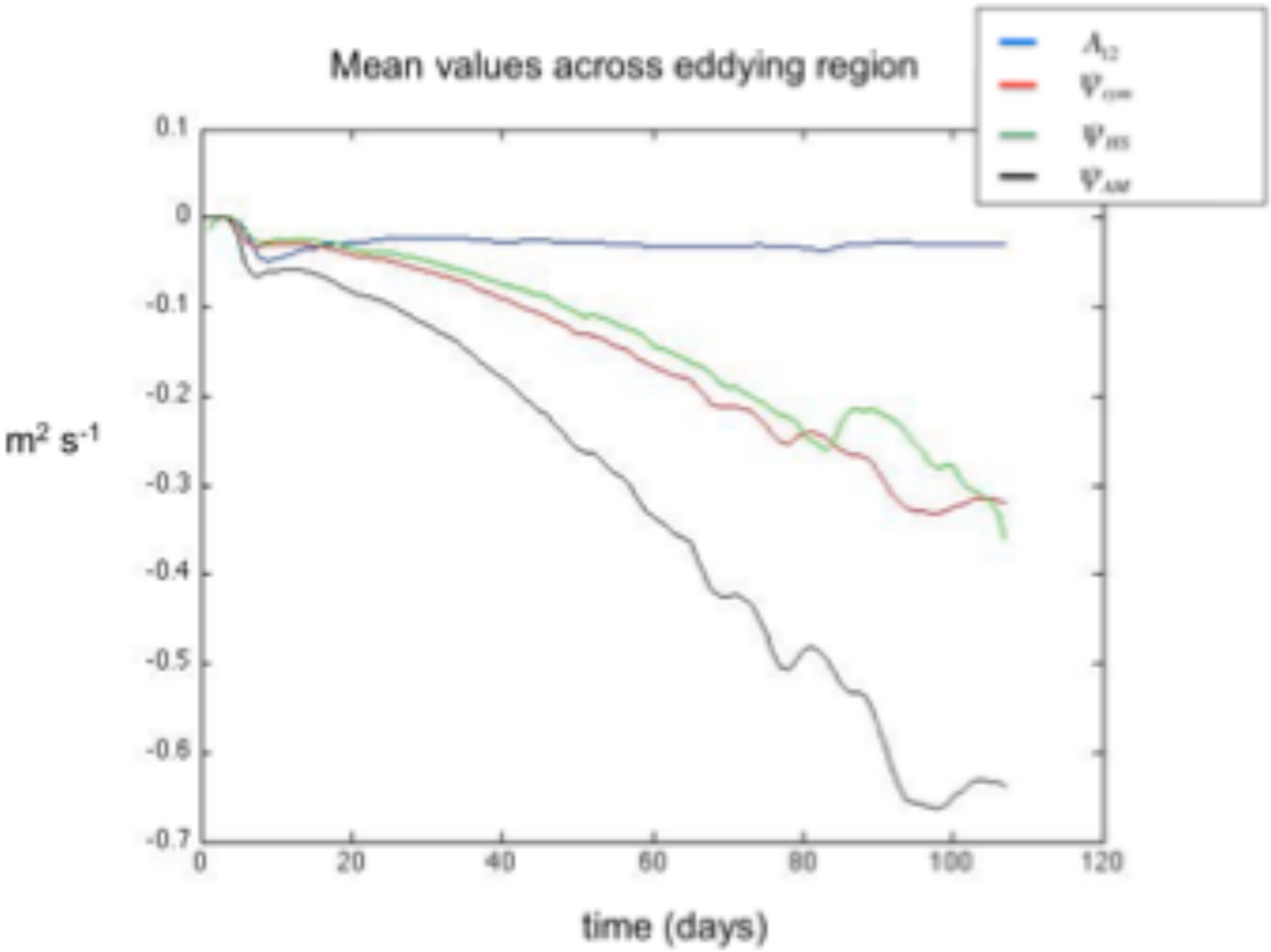
Scaling: Larger symmetric eigenvalue



Scaling: Smaller symmetric eigenvalue

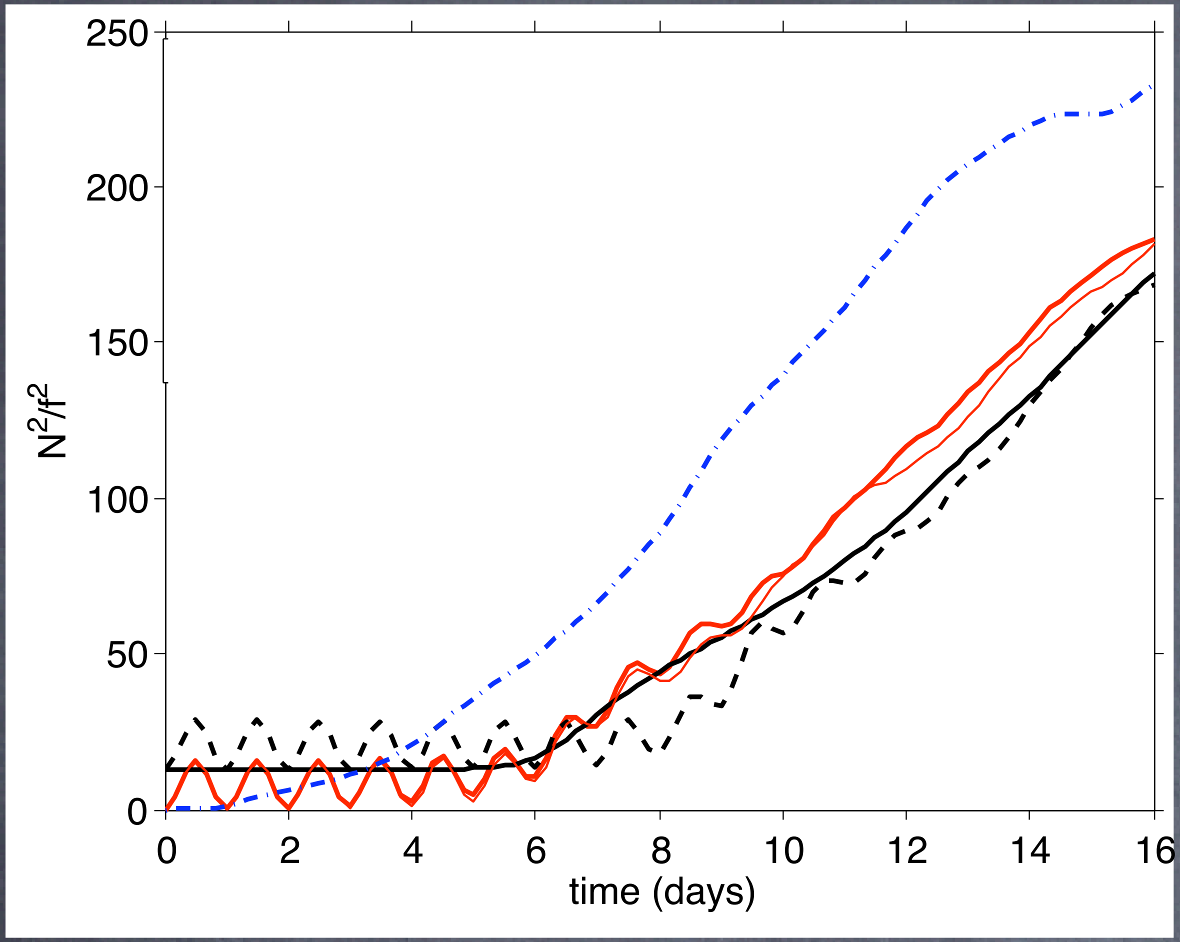


TEM..? Overdetermined vs. Underdetermined:

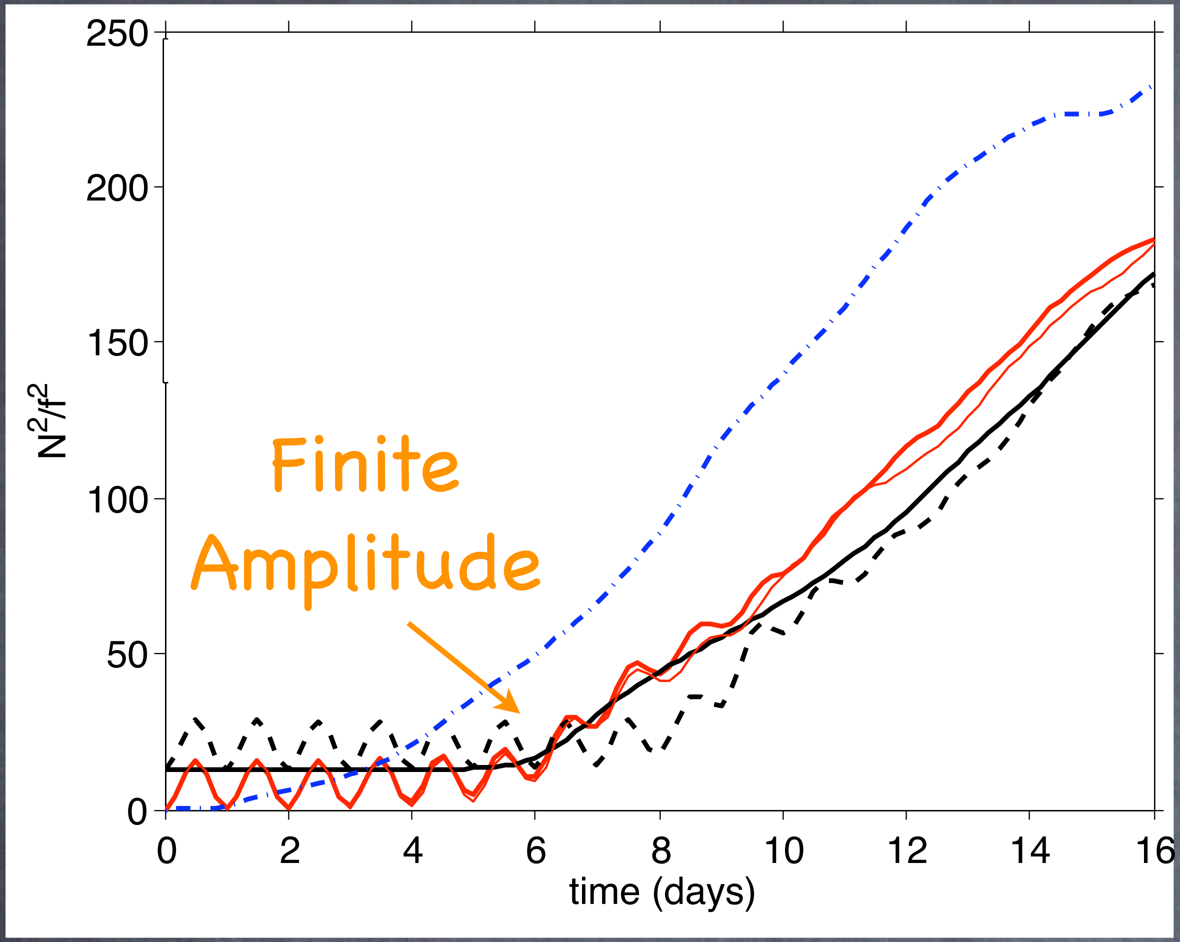


A_{12} and ψ_{sym} are mathematically equivalent!

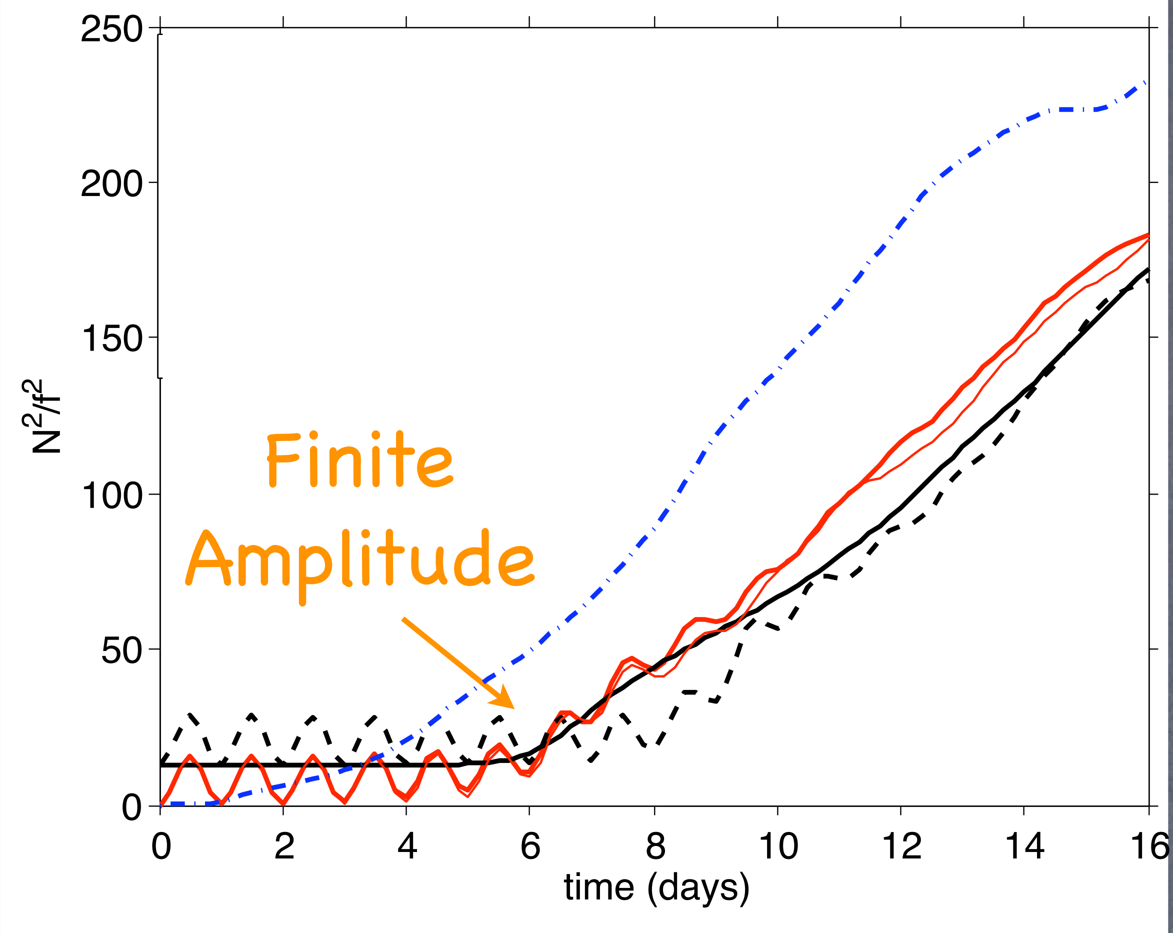
Parameterization of Finite Amp. Eddies: Ingredients

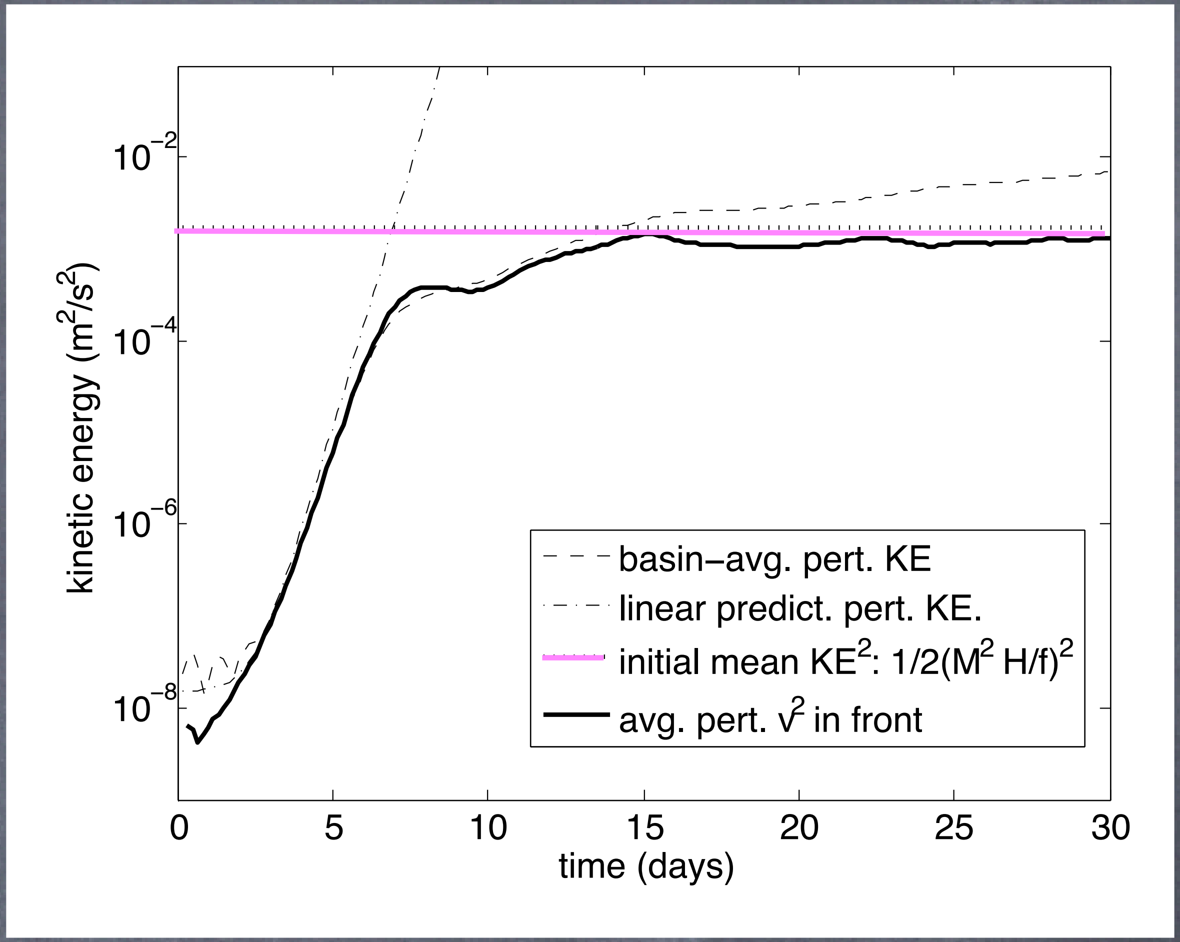


Parameterization of Finite Amp. Eddies: Ingredients

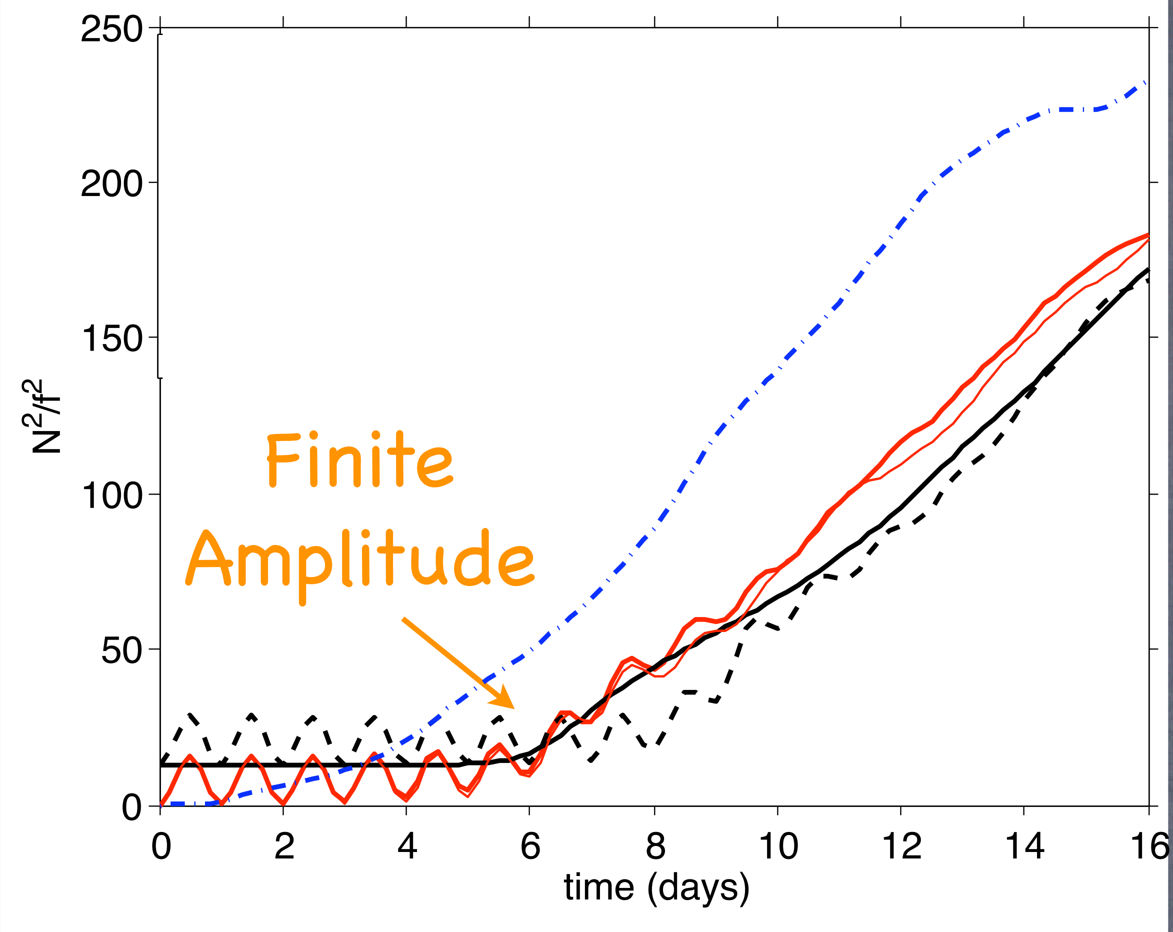


Parameterization of Finite Amp. Eddies: Ingredients

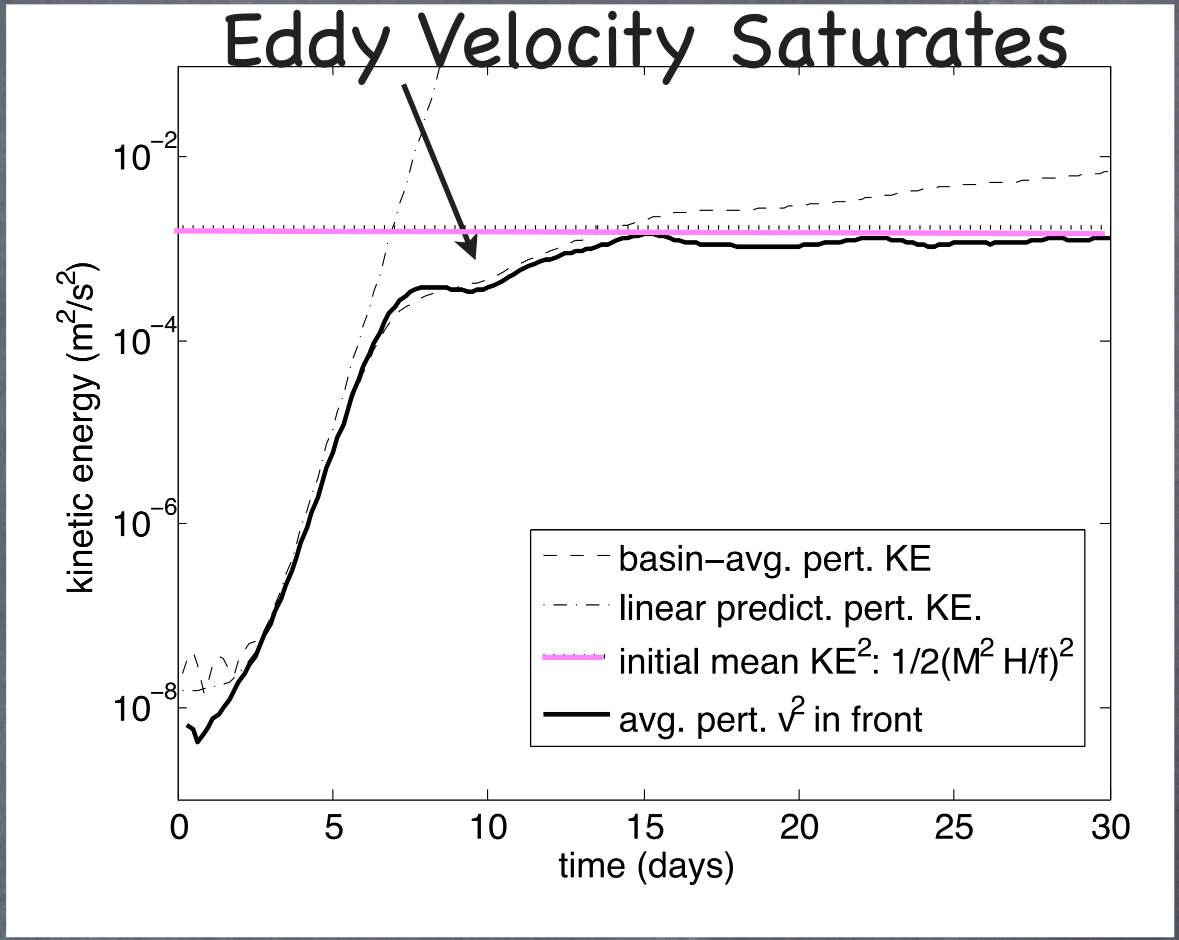




Parameterization of Finite Amp. Eddies: Ingredients

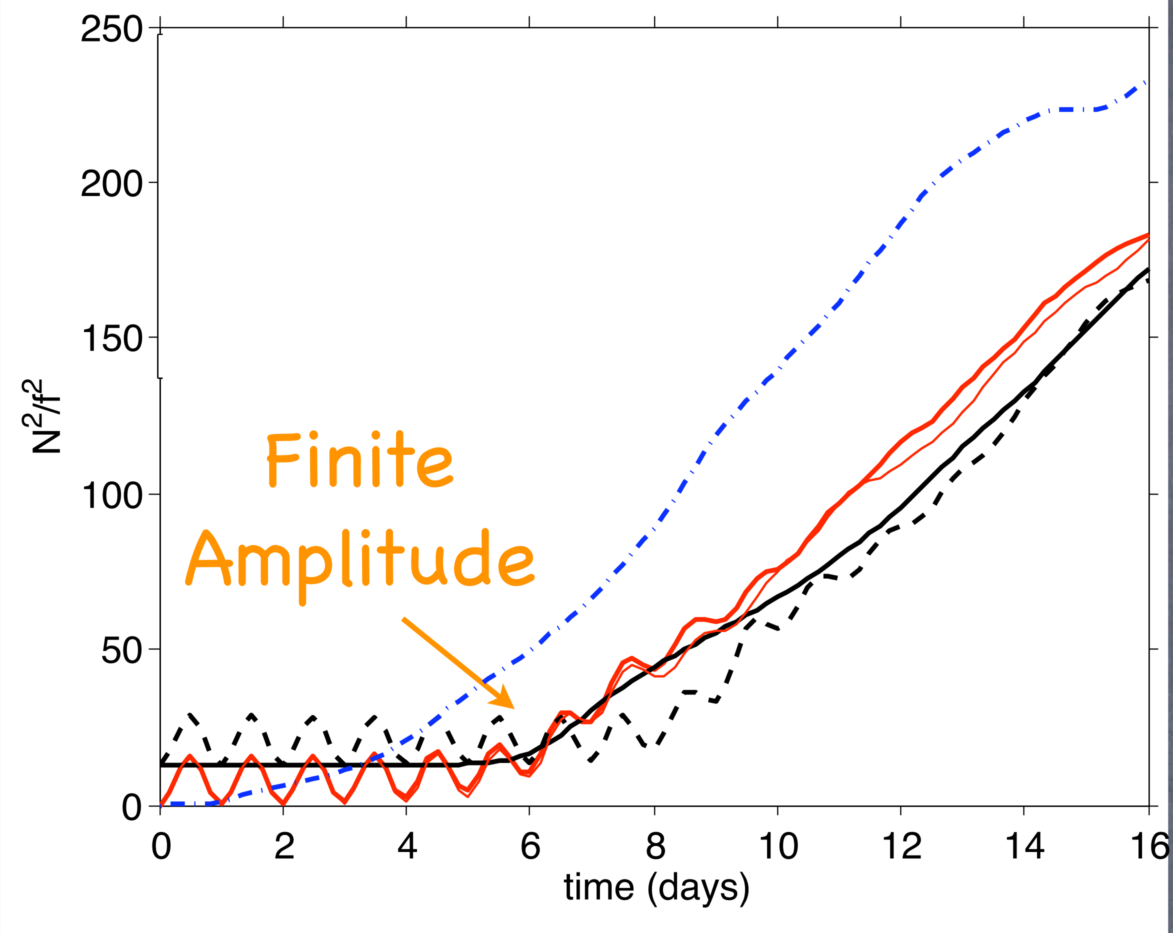


Finite Amplitude

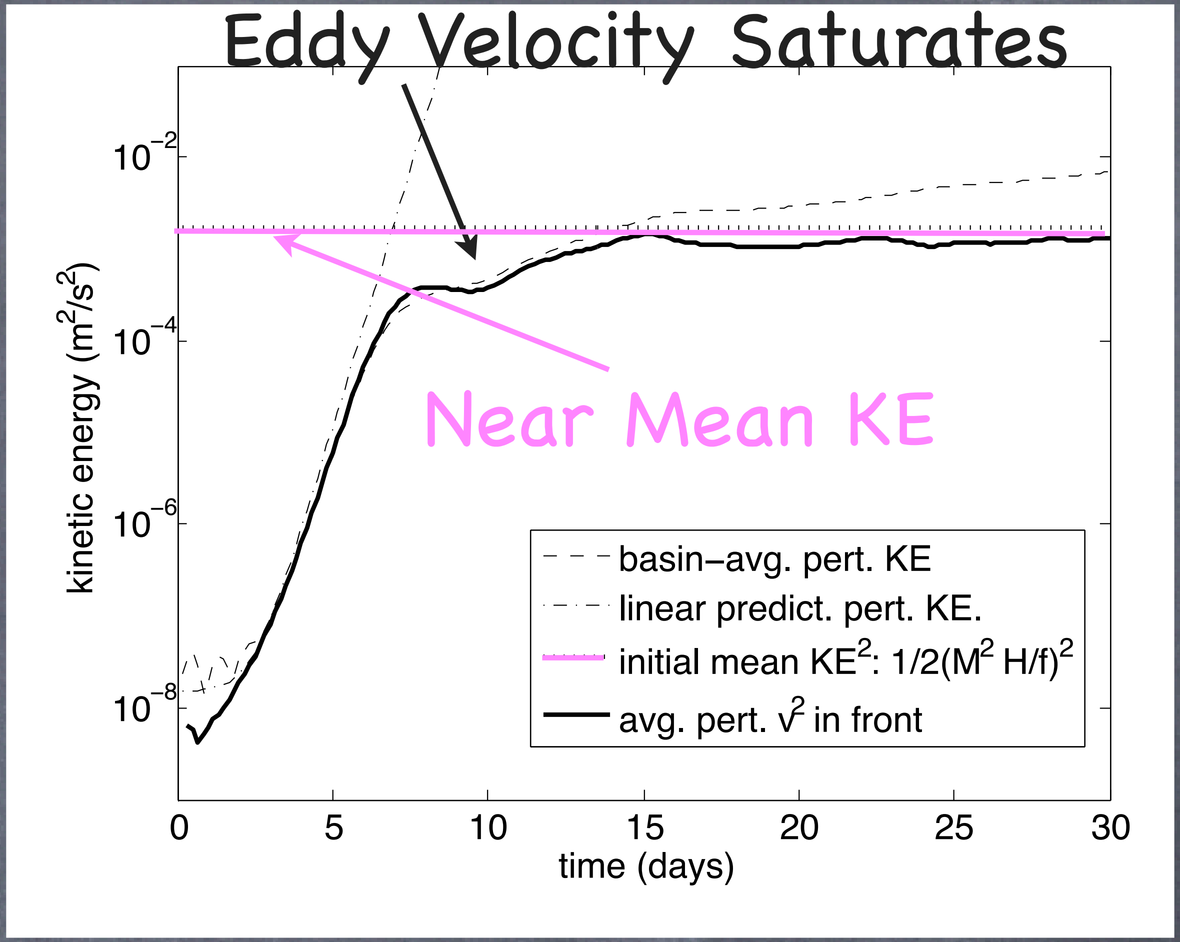


Eddy Velocity Saturates

Parameterization of Finite Amp. Eddies: Ingredients



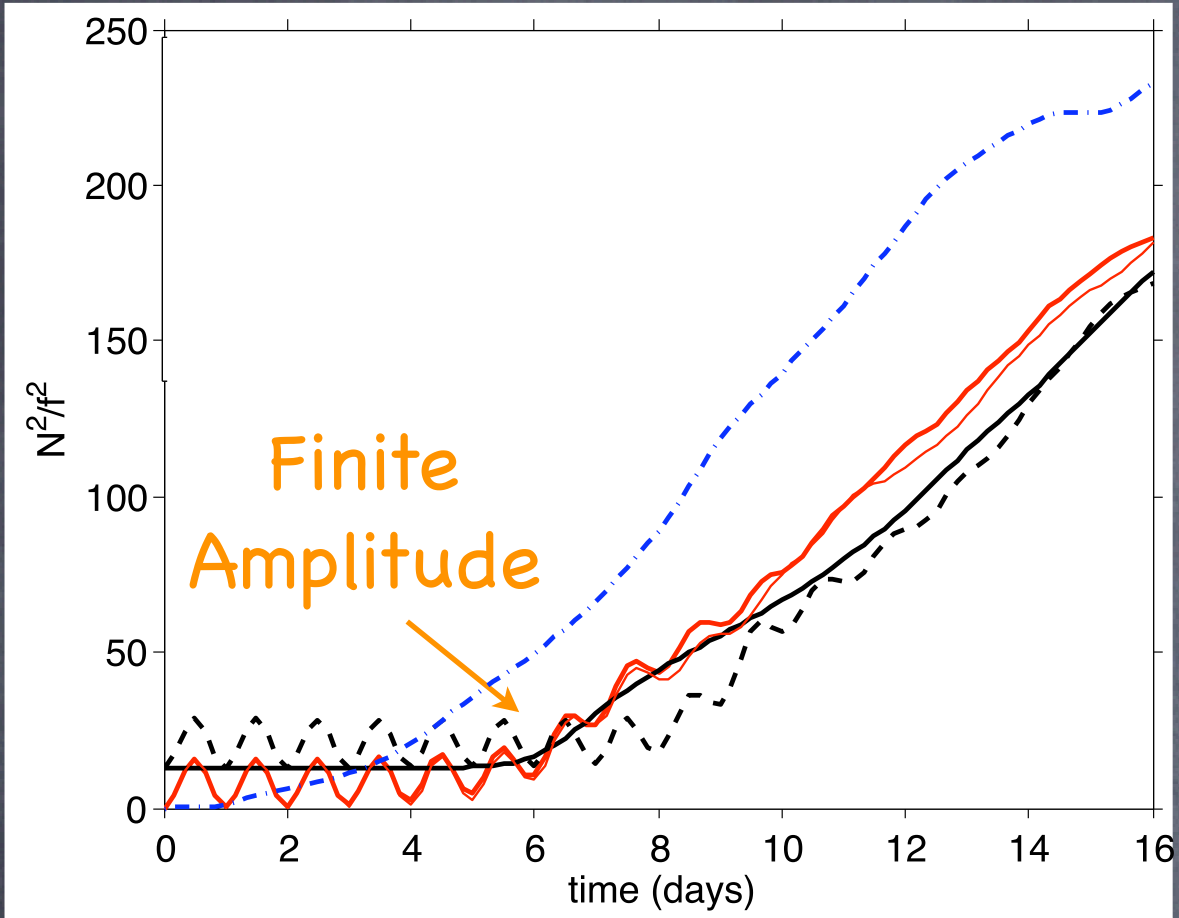
Finite Amplitude



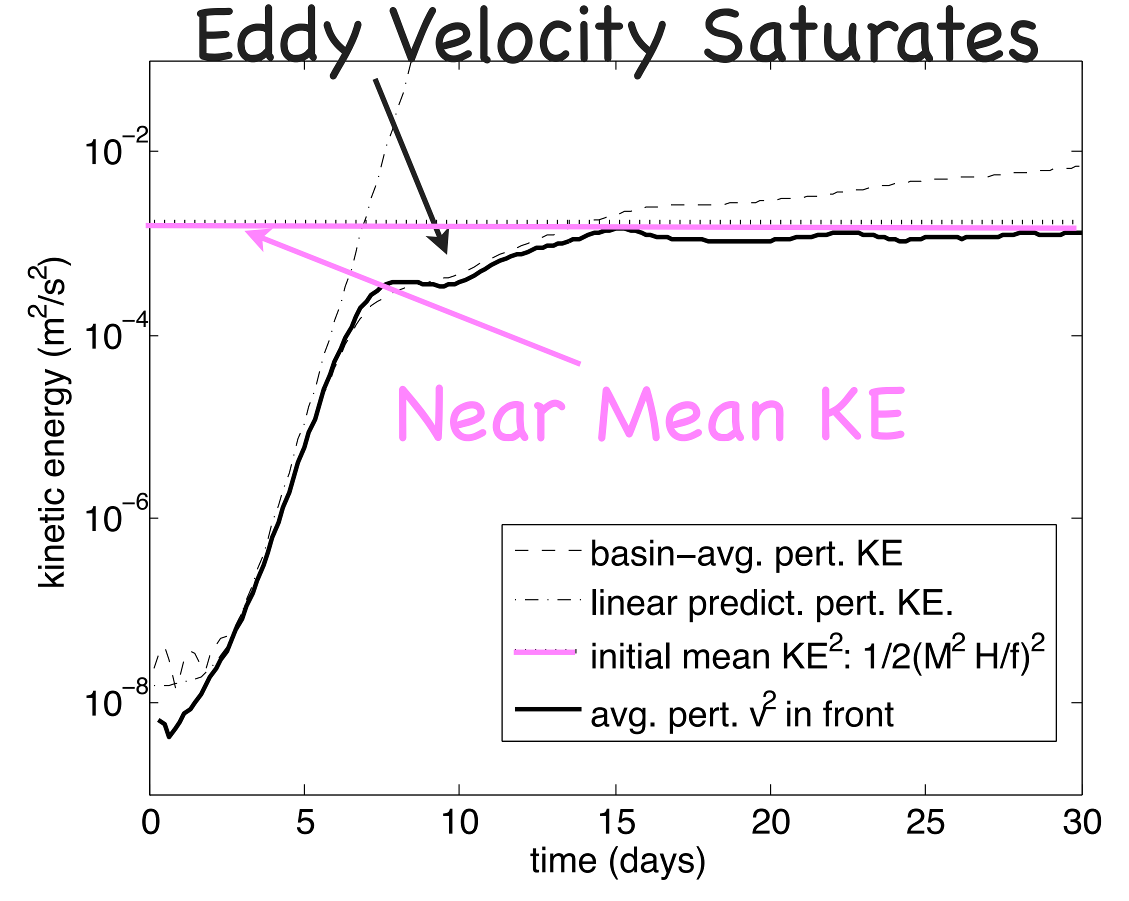
Eddy Velocity Saturates

Near Mean KE

Parameterization of Finite Amp. Eddies: Ingredients

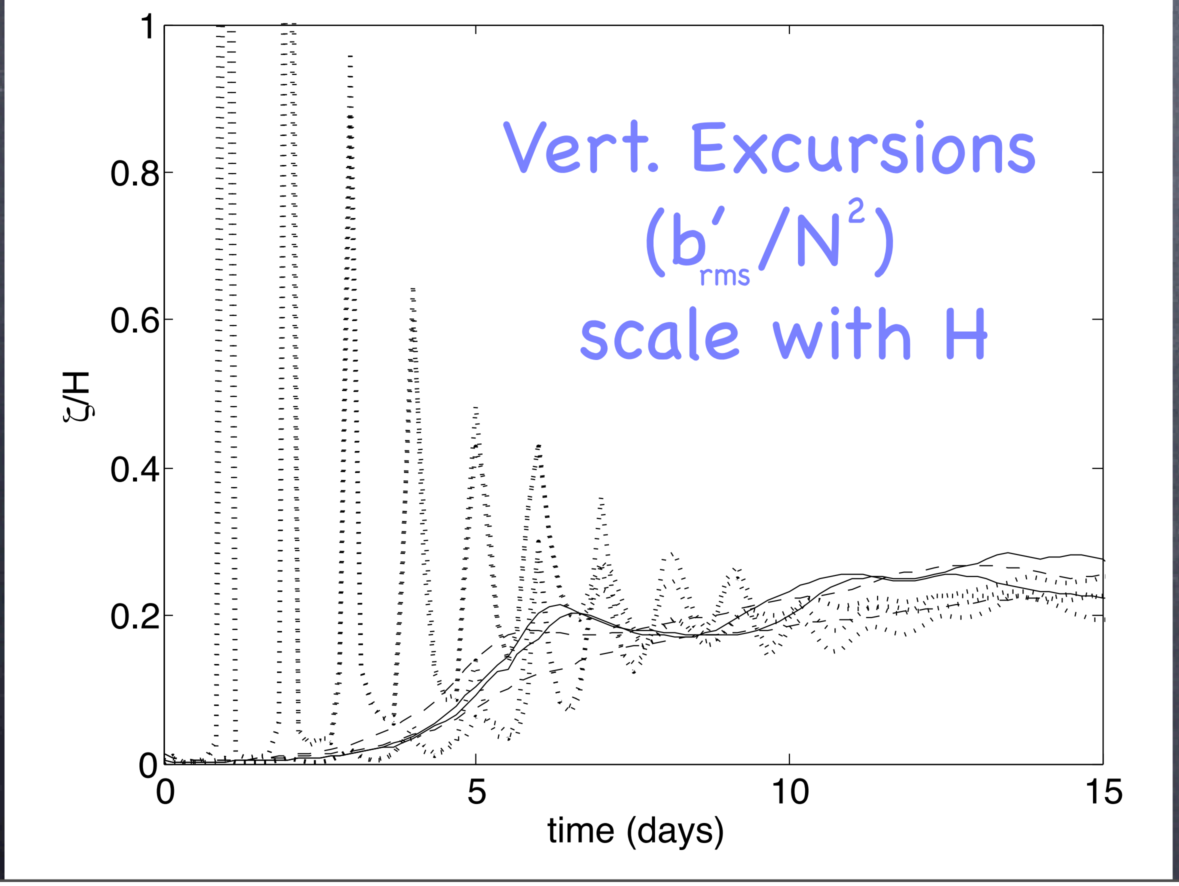


Finite Amplitude



Eddy Velocity Saturates

Near Mean KE

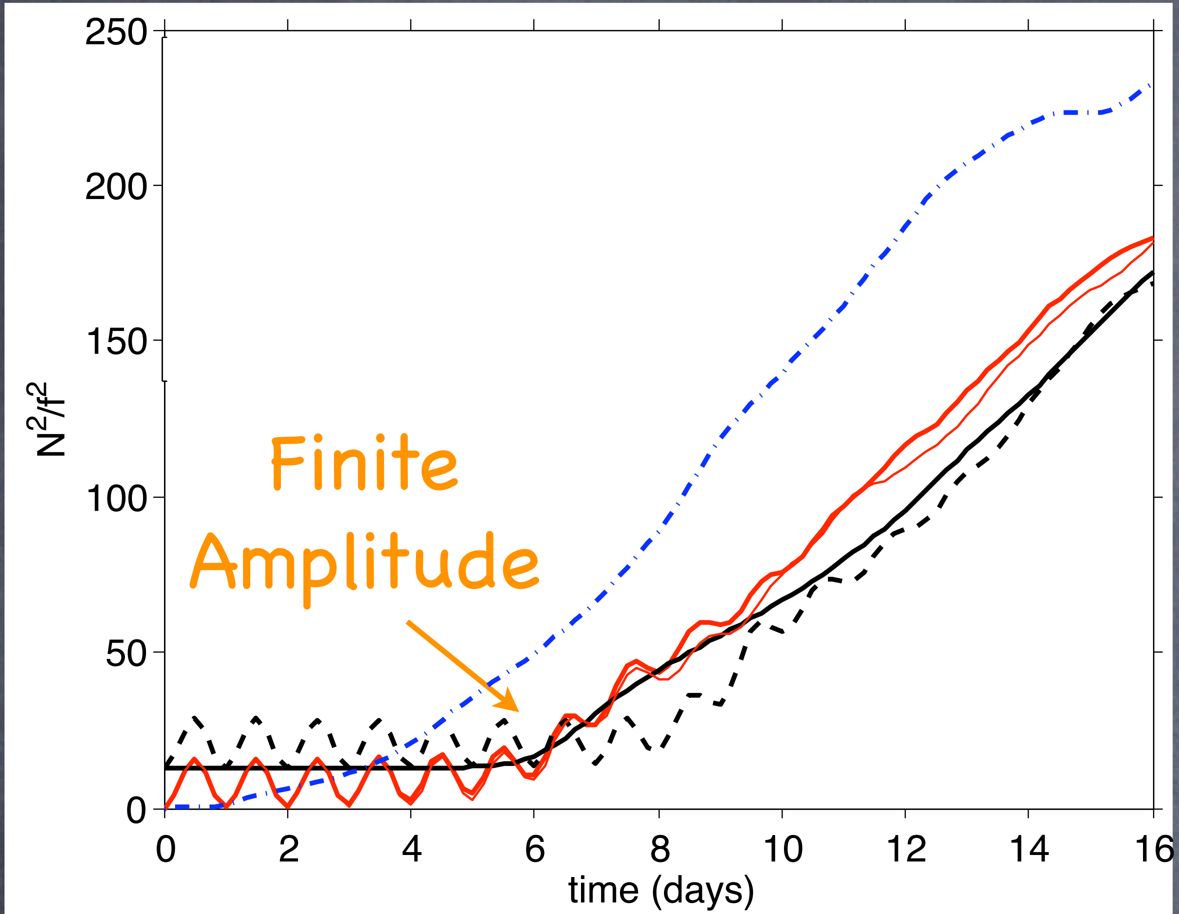


Vert. Excursions

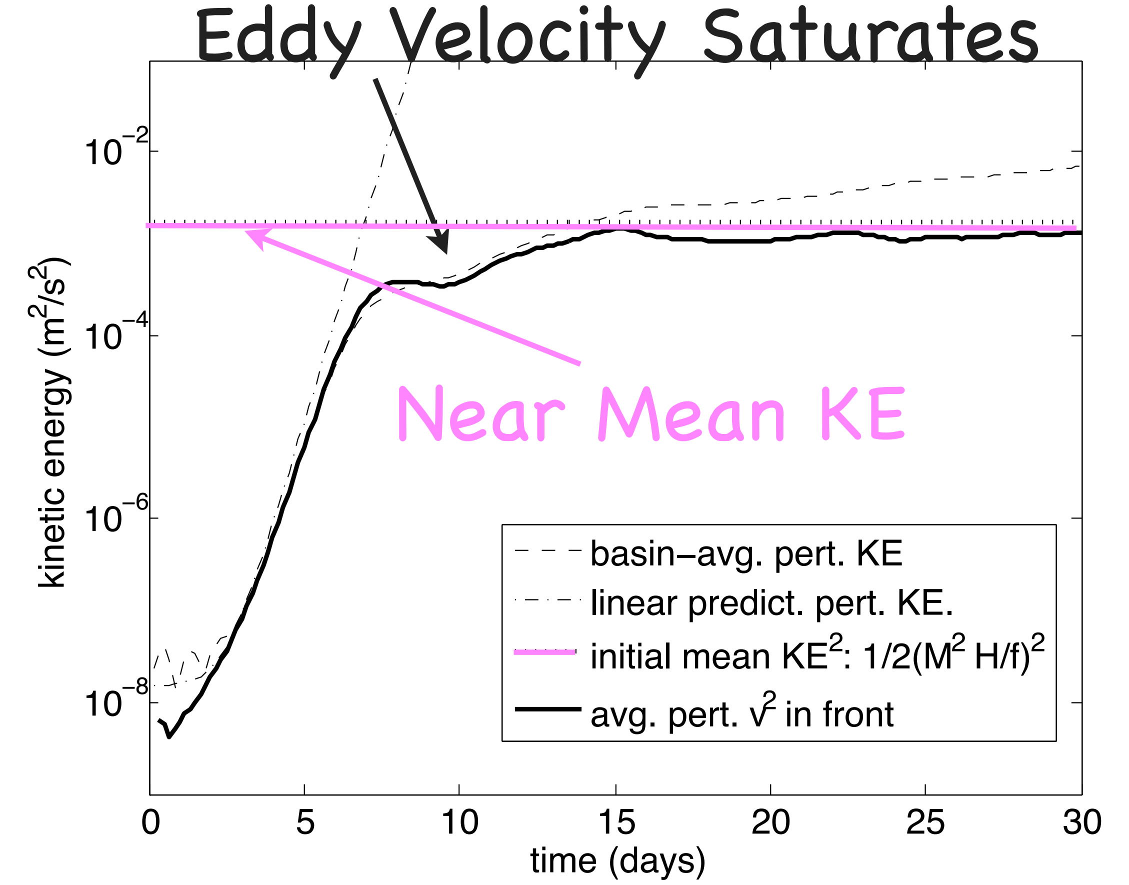
(b'_{rms}/N^2)

scale with H

Parameterization of Finite Amp. Eddies: Ingredients

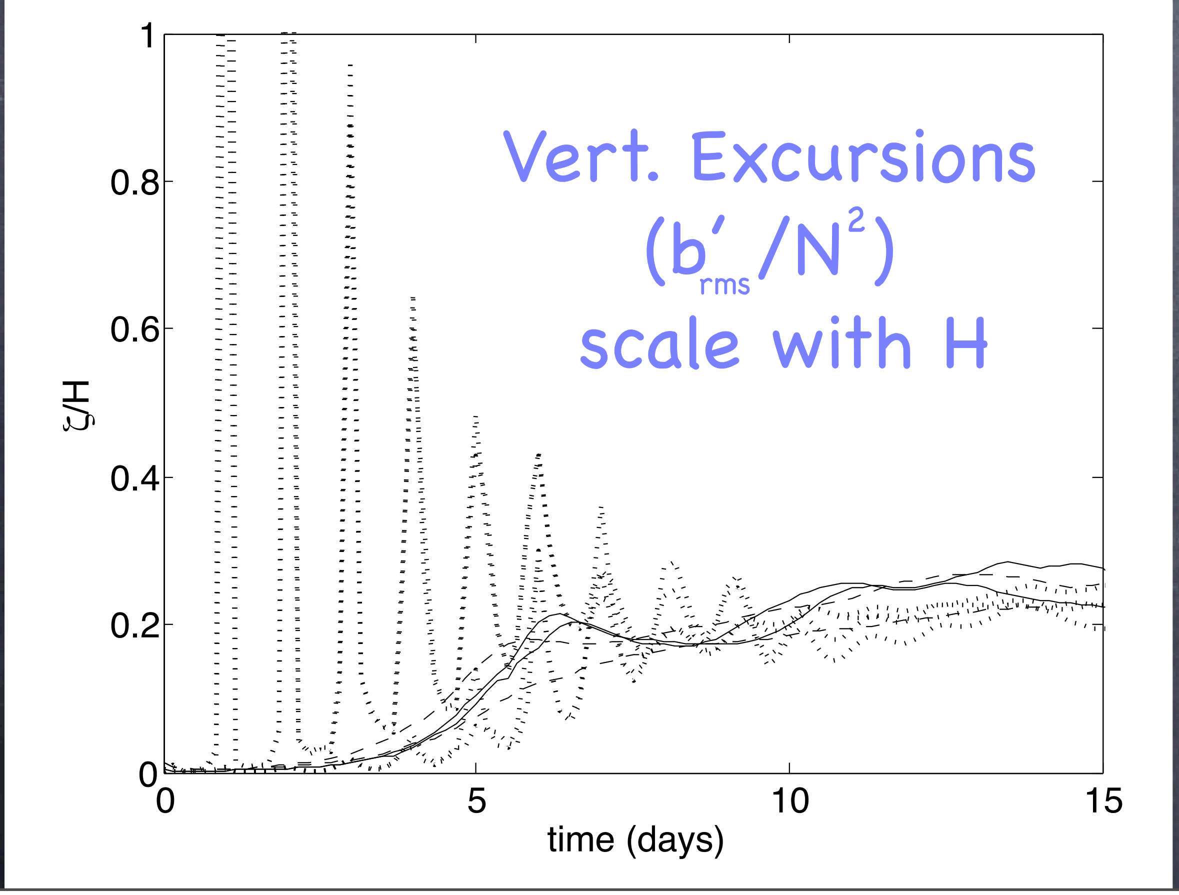


Finite Amplitude

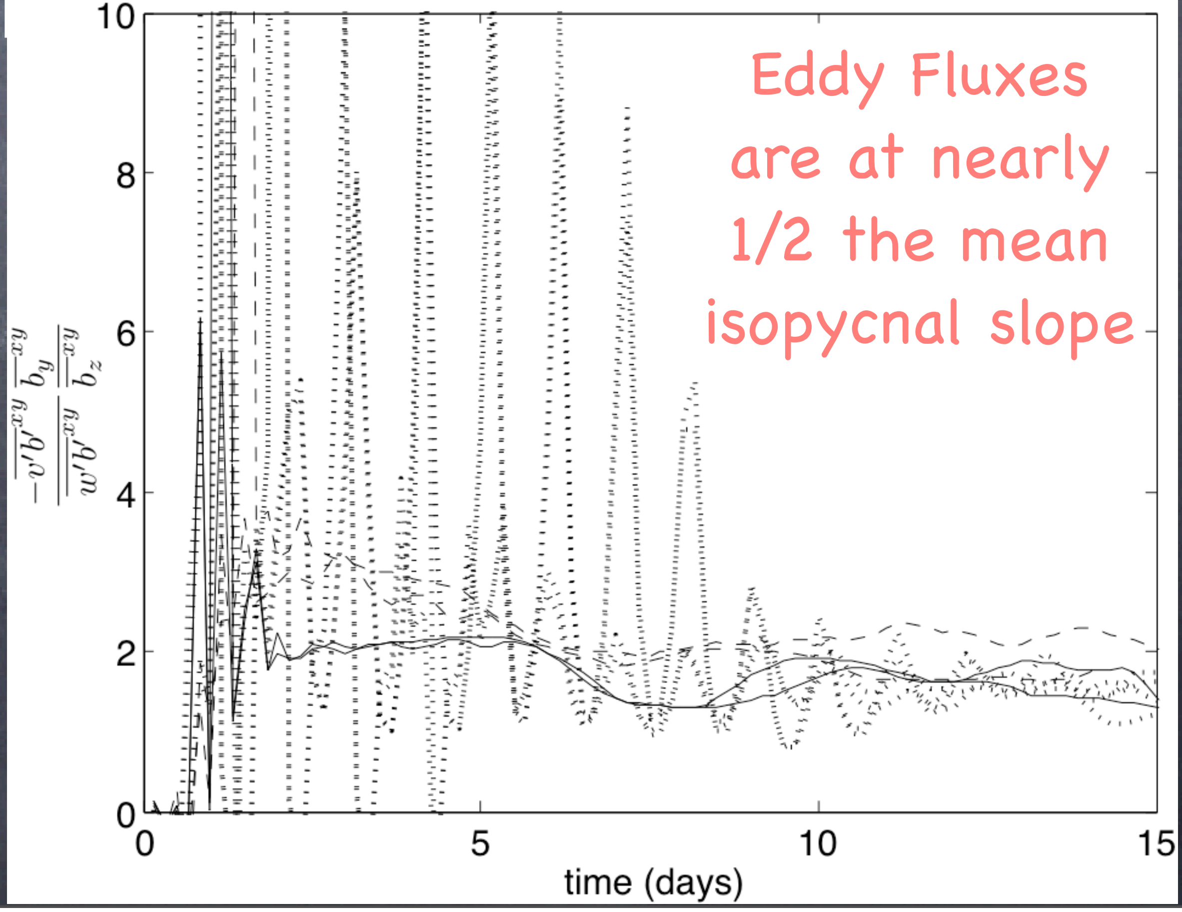


Eddy Velocity Saturates

Near Mean KE

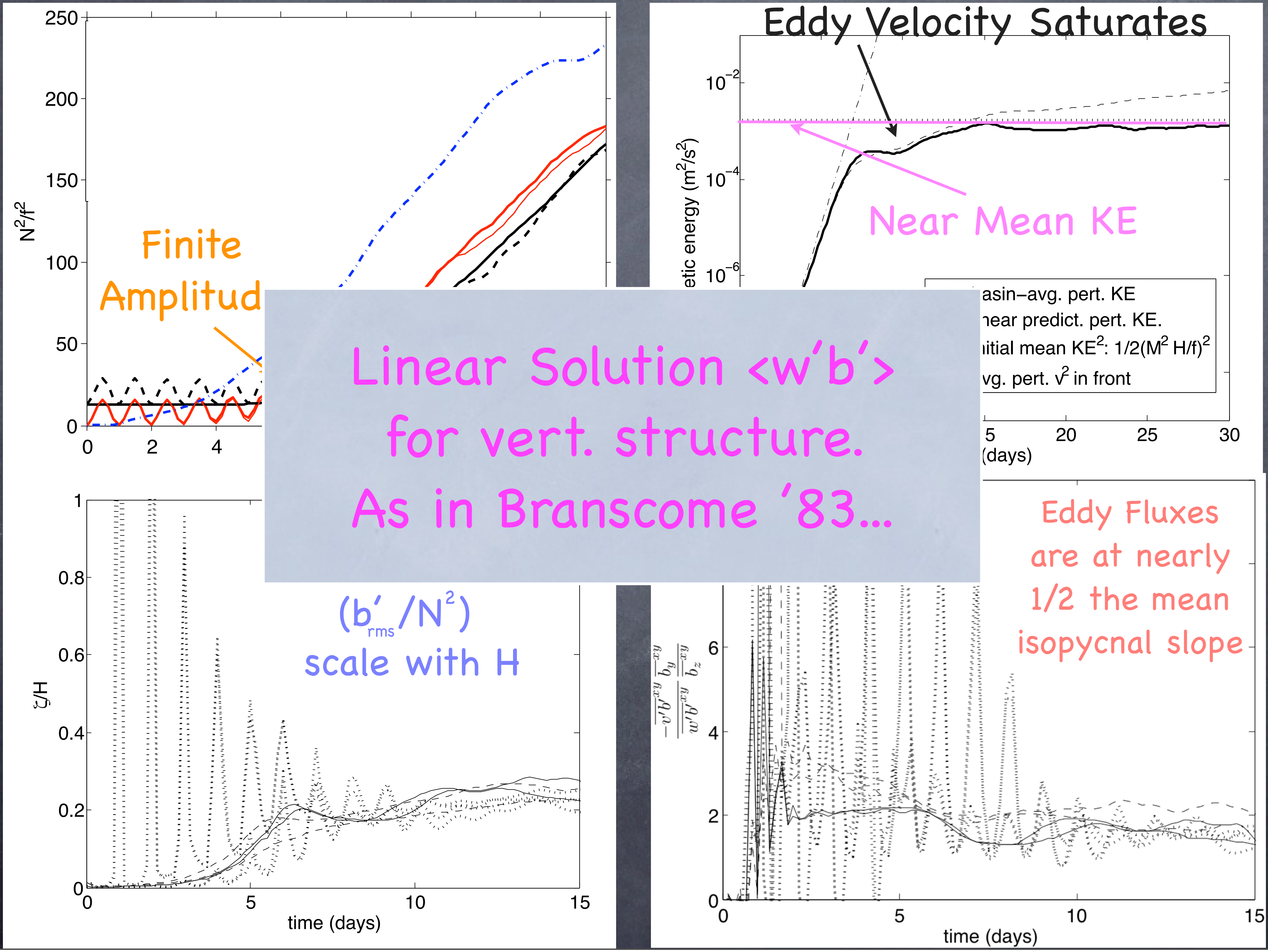


Vert. Excursions (b'_{rms}/N^2) scale with H



Eddy Fluxes are at nearly 1/2 the mean isopycnal slope

Parameterization of Finite Amp. Eddies: Ingredients



Finite Amplitud

Eddy Velocity Saturates

Near Mean KE

Linear Solution <w’b’> for vert. structure. As in Branscome ’83...

(b'_{rms}/N^2) scale with H

Eddy Fluxes are at nearly 1/2 the mean isopycnal slope