Ocean physics from 4m to 400km: Parameterizations and biases

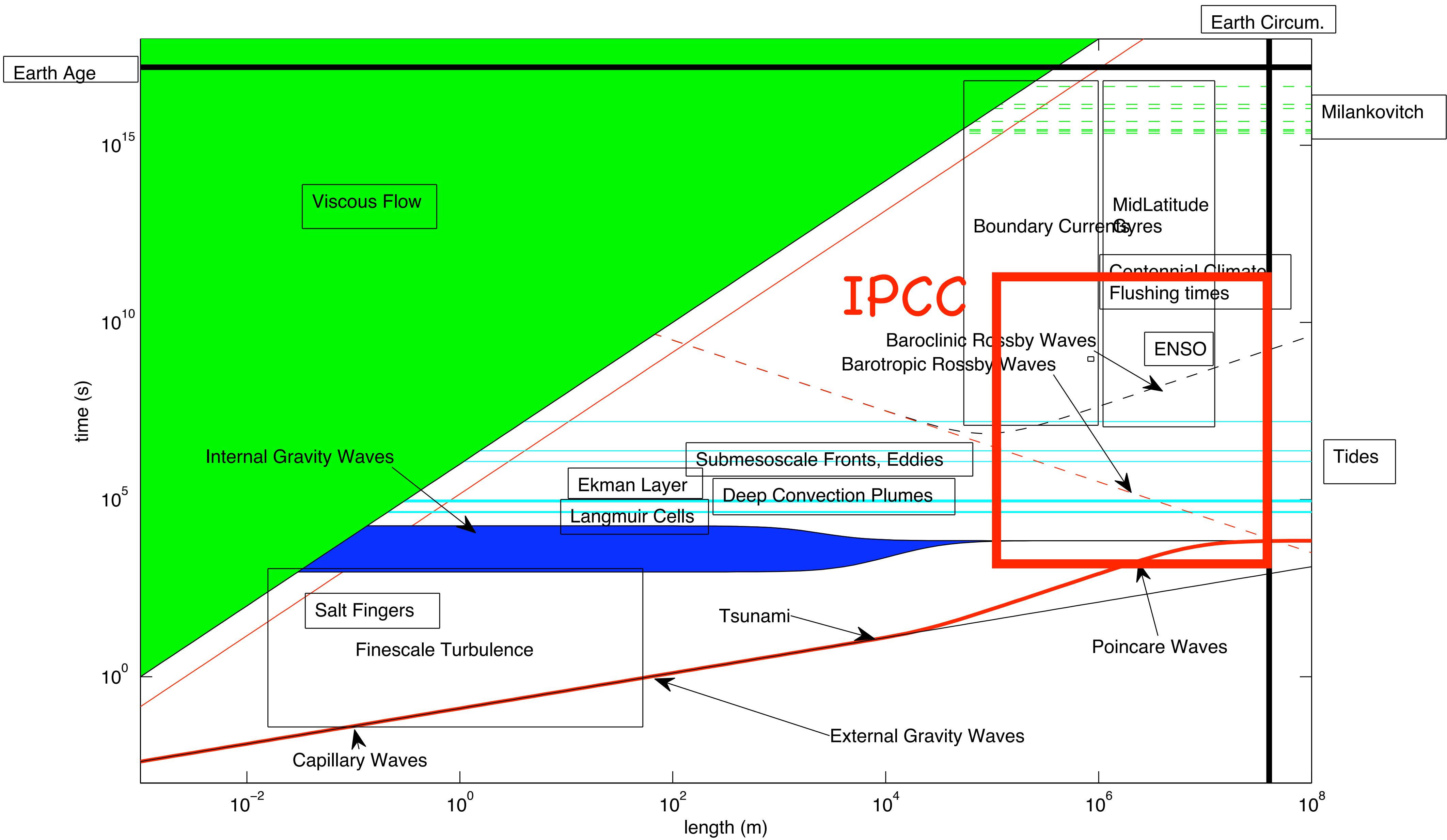
Baylor Fox-Kemper (CU-Boulder & CIRES)

with Luke Van Roekel (CIRES), Peter Hamlington (CU),
Scott Bachman (CIRES/ATOC), Sean Haney (CIRES/ATOC), Katie McCaffrey (CIRES/ATOC),
Adrean Webb (CIRES/APPM), Andrew Margolin (CU/CHEM), Ian Grooms (CU/APPM), Sam Stevenson (IPRC)
Keith Julien, Raf Ferrari, NCAR Oceanography Section, Peter Sullivan

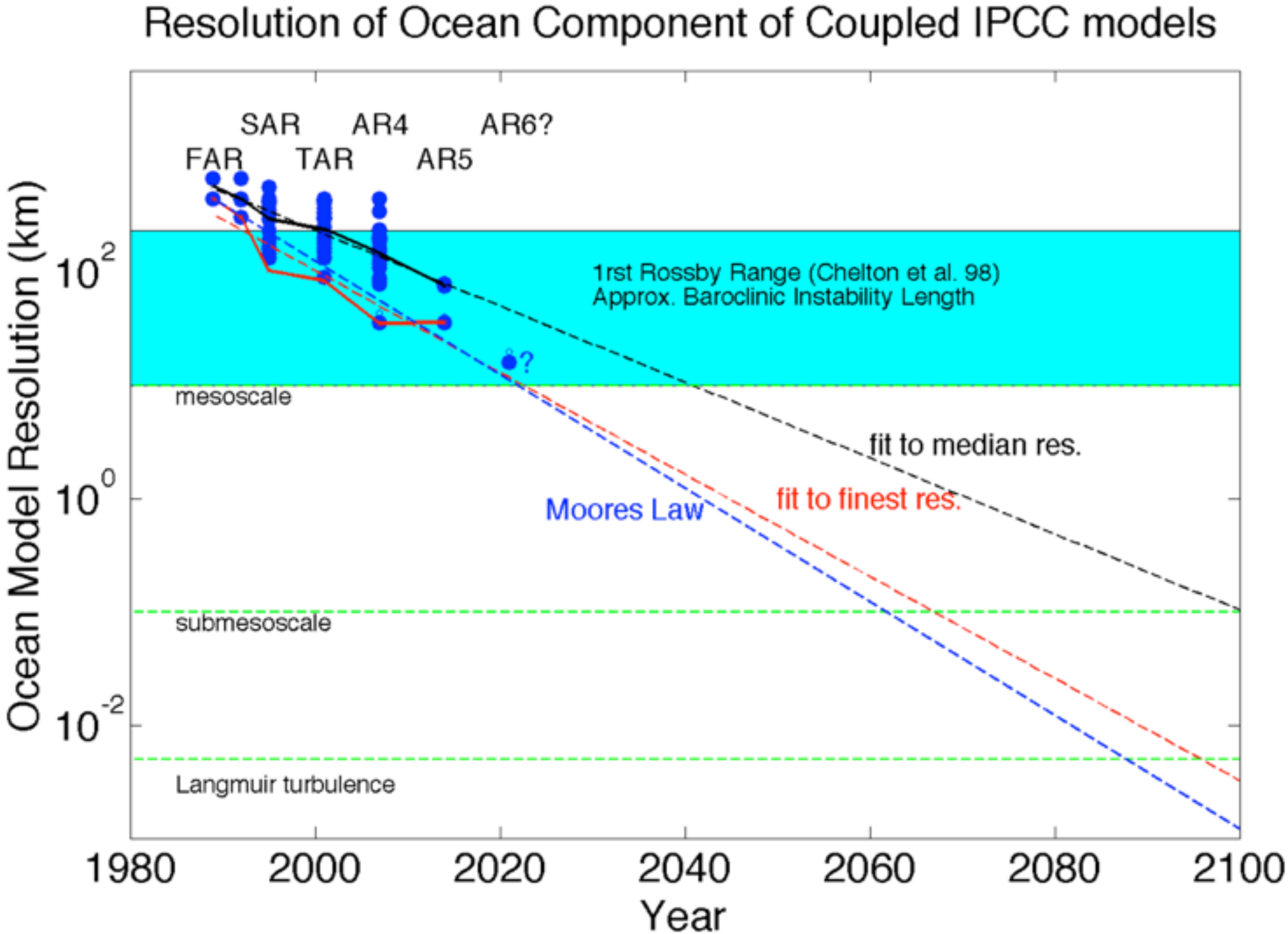
Stanford Fluid Mechanics Seminar, 4/24/12, 16:15-17:15

Sponsors: NSF, NASA, CIRES, CU, UCAR

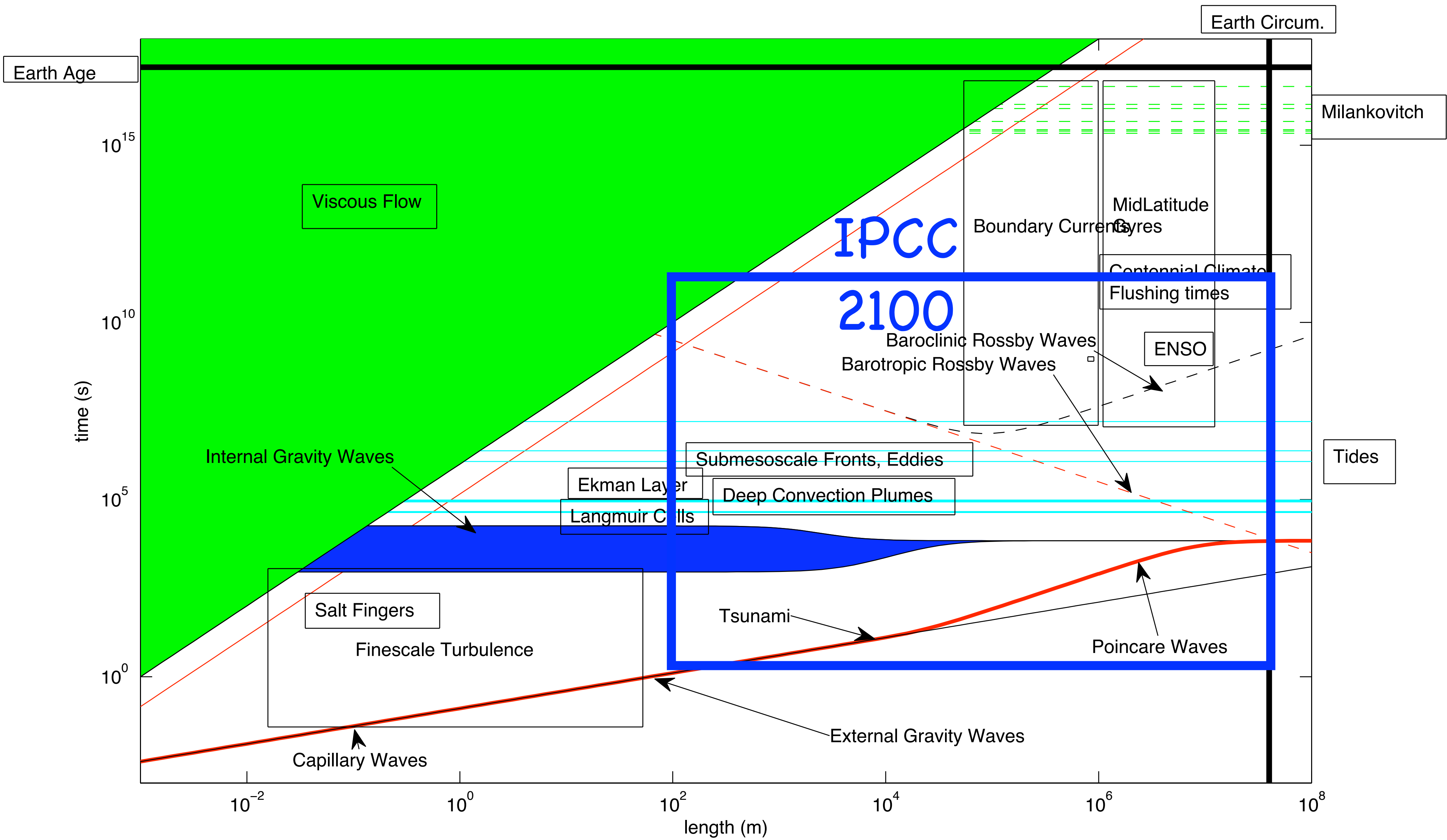
The Ocean is Vast and Diverse



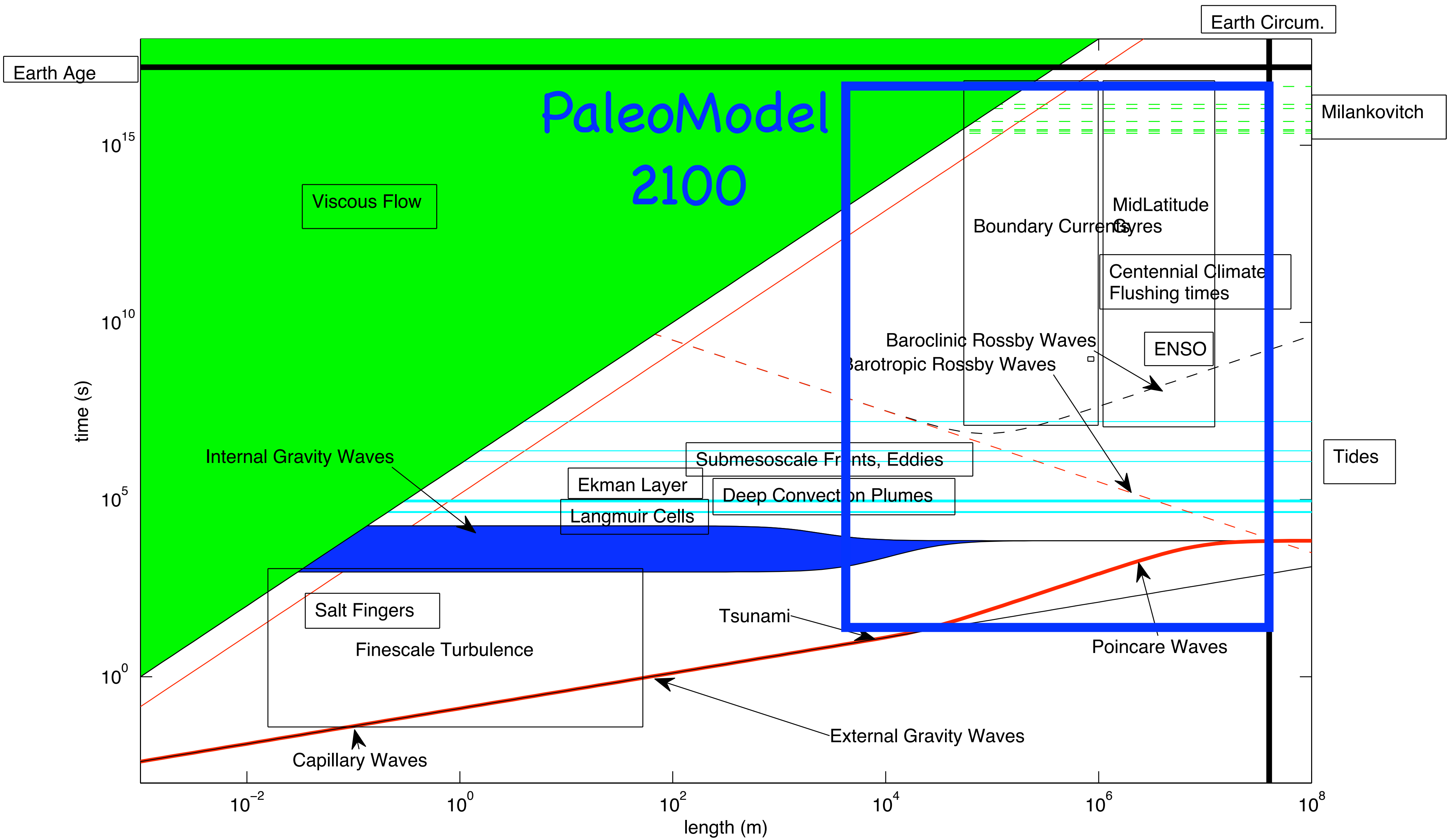
Forecast--Where to go?



The Ocean is Vast and Diverse



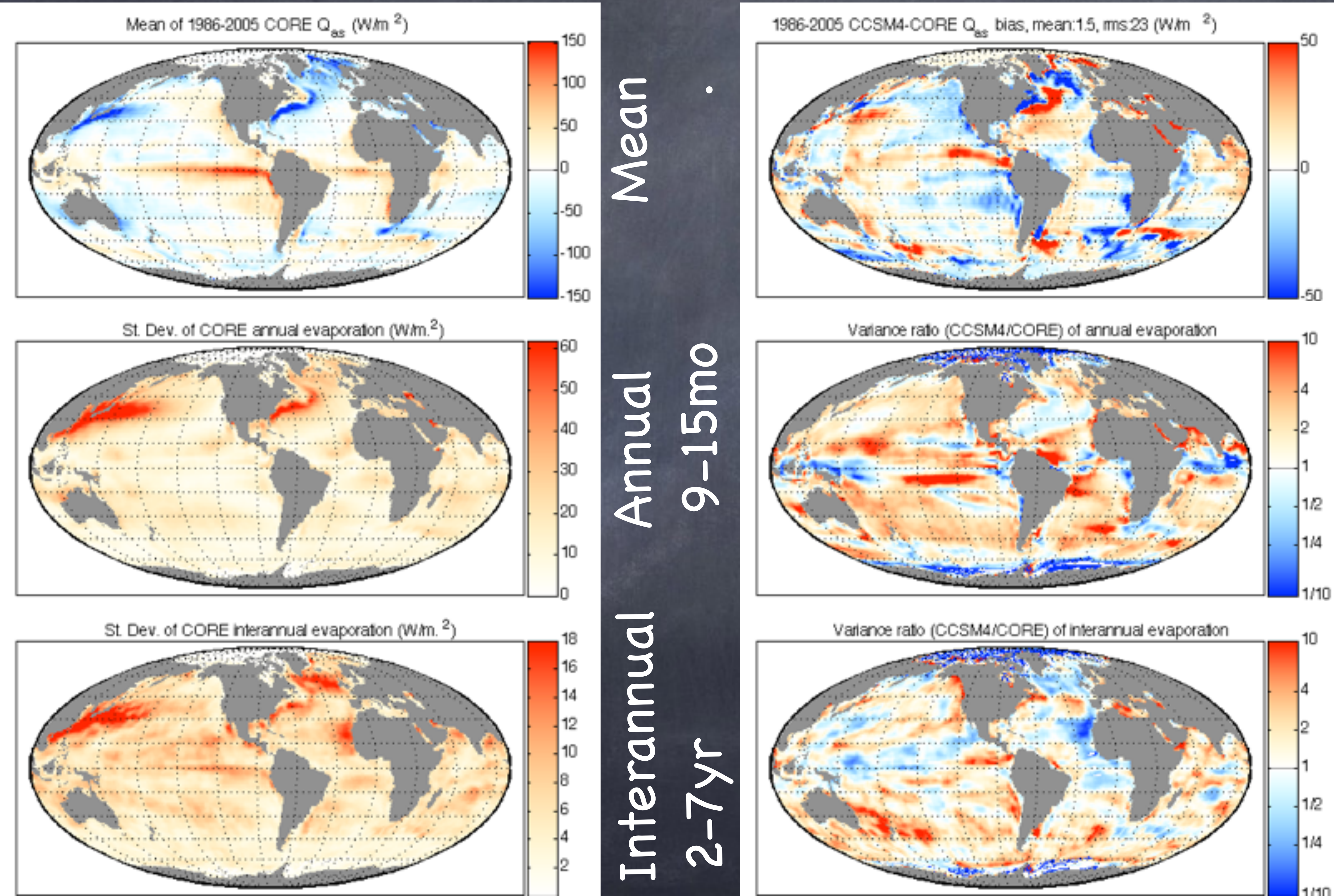
The Ocean is Vast and Diverse



So, resolution isn't a quick fix...

- What biased regions/scales matter for climate?
- What do observations constrain?
- What biased timescales matter for climate?
- What do we know how to parameterize/ nest?

Not abstract--Air-Sea Errors vs. Large & Yeager (09, Data)



Biases and Variance Errors

- Mean Biases are familiar: WBC, Upwelling, Deep Convection, ITCZ
- Annual errors are *larger & more significant* than interannual
- Annual=Fast=Mixed Layer; Global extent!
- Continental vs. Maritime, Monsoon, Seasonal Clouds, etc.

S. Stevenson, B. Fox − Kemper, M. Jochum, B. Rajagopalan, and S. G. Yeager, 2010: ENSO model validation using wavelet probability analysis. Journal of Climate, 23:5540–5547.

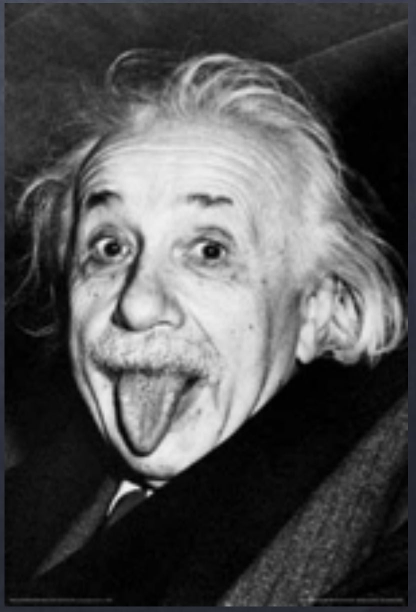
S. C. Bates, B. Fox-Kemper, S. R. Jayne, W. G. Large, S. Stevenson, and S. G. Yeager. Mean biases, variability, and trends in air-sea fluxes and SST in the CCSM4.Journal of Climate, 2012. Submitted.

Results

- Errors in climate model on annual to interannual timescales can be attributed (partly) to
  - Submesoscale mixed layer eddy restratification
  - Langmuir turbulence mixing
  - Mesoscale eddy mixing
- We have been improving parameterizations
- But much work remains--long-term observational and paleo data validation is still crucial, but not yet accurate or sufficient...
- Hypothesis: Improving Seasonality will Improve

Parameterizations

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



Different Uses, Different Needs

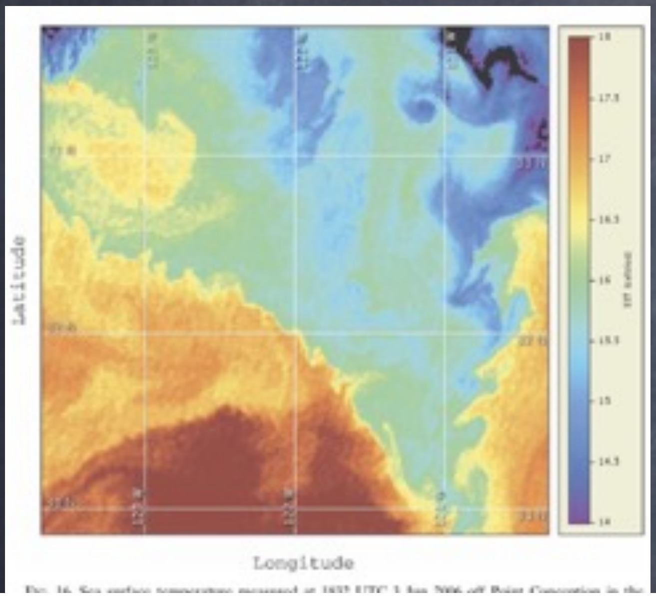
- MORANS (e.g., CESM; >50km)
- Mesoscale Ocean Reynolds-Averaged Navier-Stokes
- No small-scale instabilities resolved, all instabilities to be parameterized
- MOLES = SMORANS (e.g., grid 5-50km)
- Mesoscale Ocean Large Eddy Simulation
- Submesoscale Ocean Reynolds-Averaged Navier-Stokes
- Same Resolution, Different Parameterizations!
- SMOLES = BLORANS (e.g., grid 100m-1km)
- Submesoscale Ocean Reynolds-Averaged Navier-Stokes
- Boundary Layer Ocean Reynolds-Averaged Navier-Stokes
- BLOLES (e.g., grid 1-5m)
- Boundary Layer Ocean Large Eddy Simulation

The Character of the Submesoscale

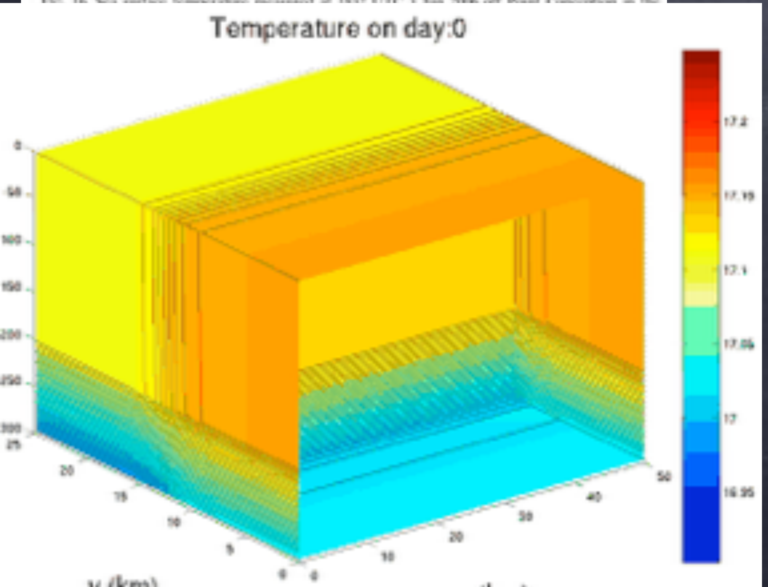
10 km

(NASA GSFC Gallery)

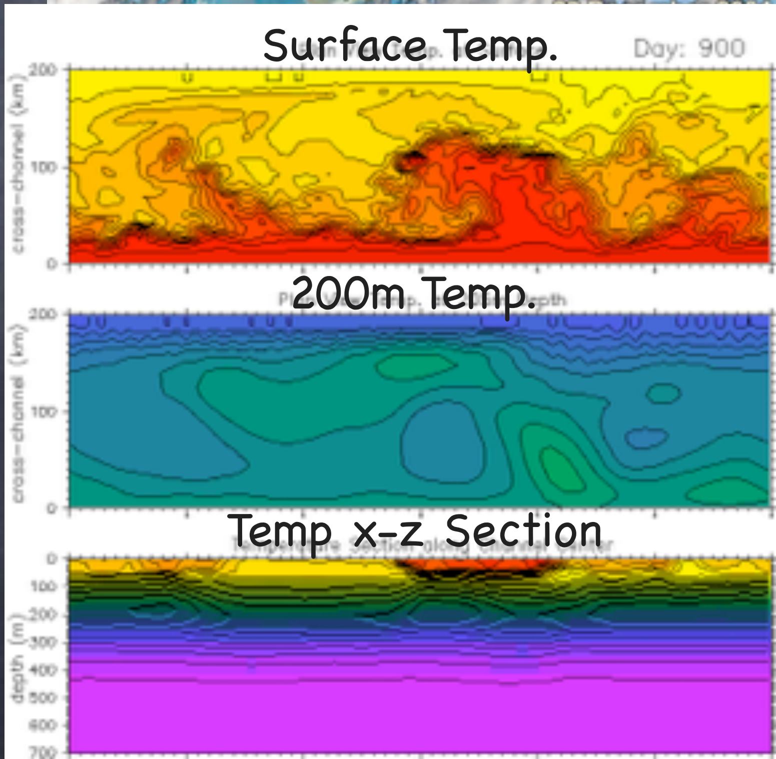
(Capet et al., 2008)



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



Eddy processes often baroclinic instability (Boccaletti et al '07, Haine & Marshall '98).



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:

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

in ML only:

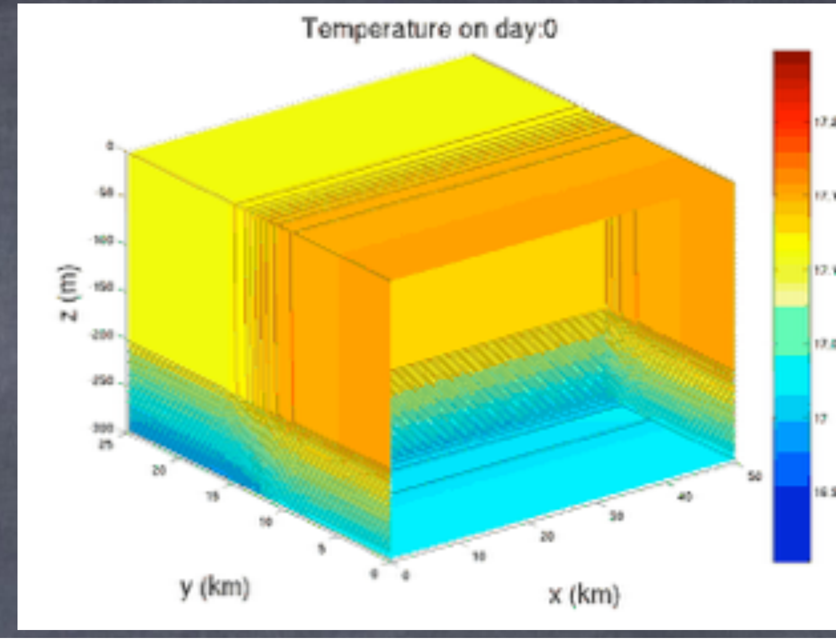
$$\mu(z) = 0 \text{ if } z < -H$$

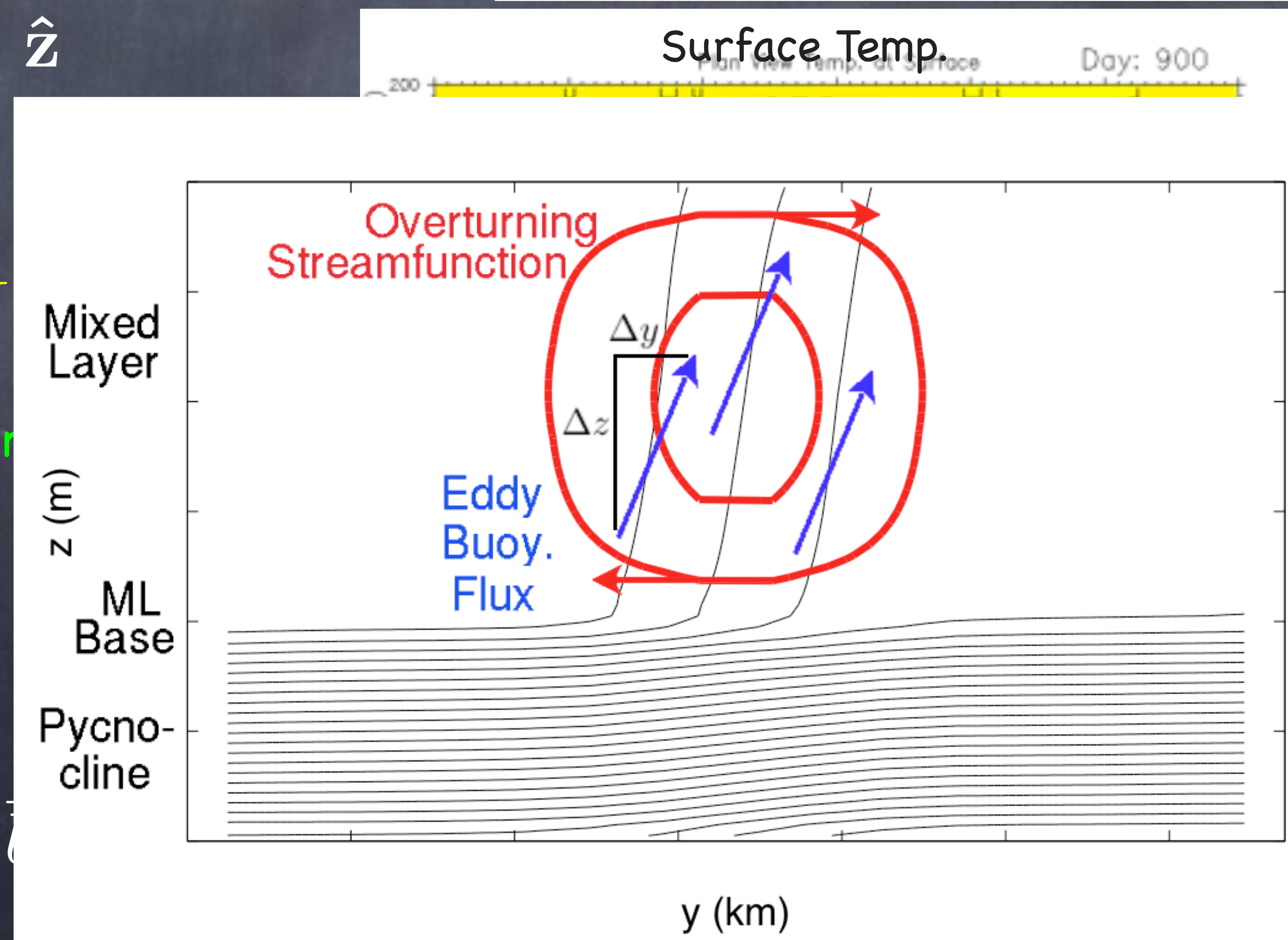
For a consistently restratifyi

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

and horizontally downgradient

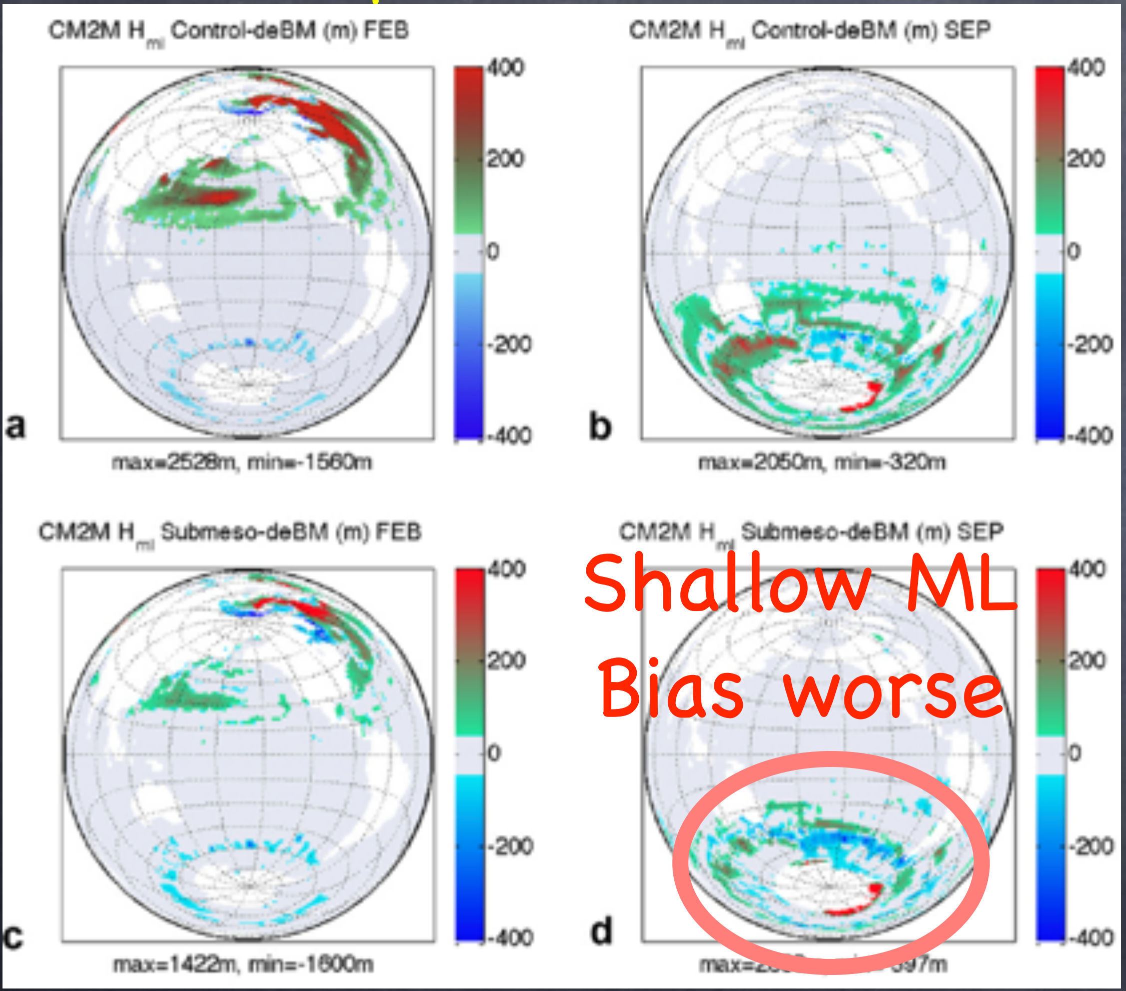
$$\overline{\mathbf{u}'_H b'} \propto \frac{-H^2 \frac{\partial \bar{b}}{\partial z}}{|f|} \nabla_H$$





Physical Sensitivity of Ocean Climate to Submesoscale Eddy Restratification:

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



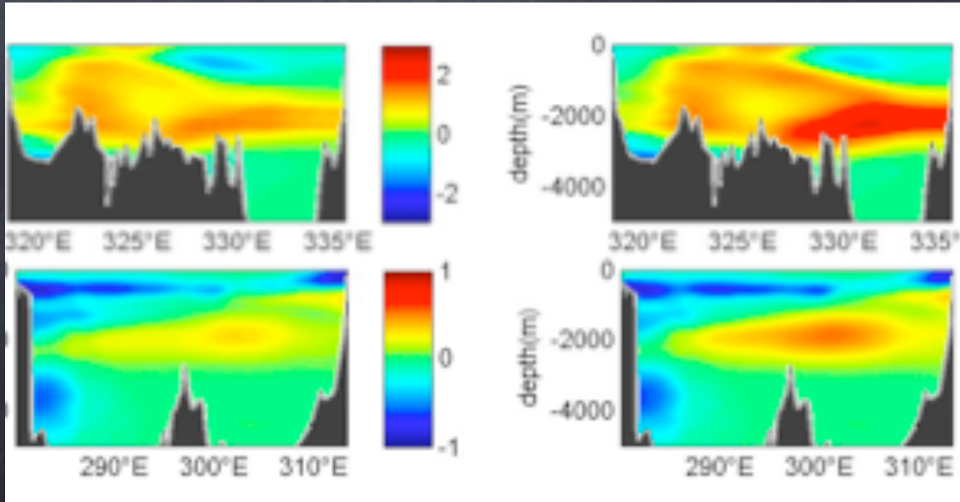
Bias w/o MLE

NO RETUNING NEEDED!!!

Improves CFCs (water masses)

Bias with MLE

Bias w/o MLE



Deep ML Bias reduced

B. Fox-Kemper, G. Danabasoglu, R. Ferrari, S. M. Griffies, R. W. Hallberg, M. M. Holland, M. E. Maltrud, S. Peacock, and B. L. Samuels. Parameterization of mixed layer eddies. III: Implementation and impact in global ocean climate simulations. *Ocean Modelling*, 39:61-78, 2011.

Sensitivity of Climate to Submeso: AMOC & Cryosphere Impacts

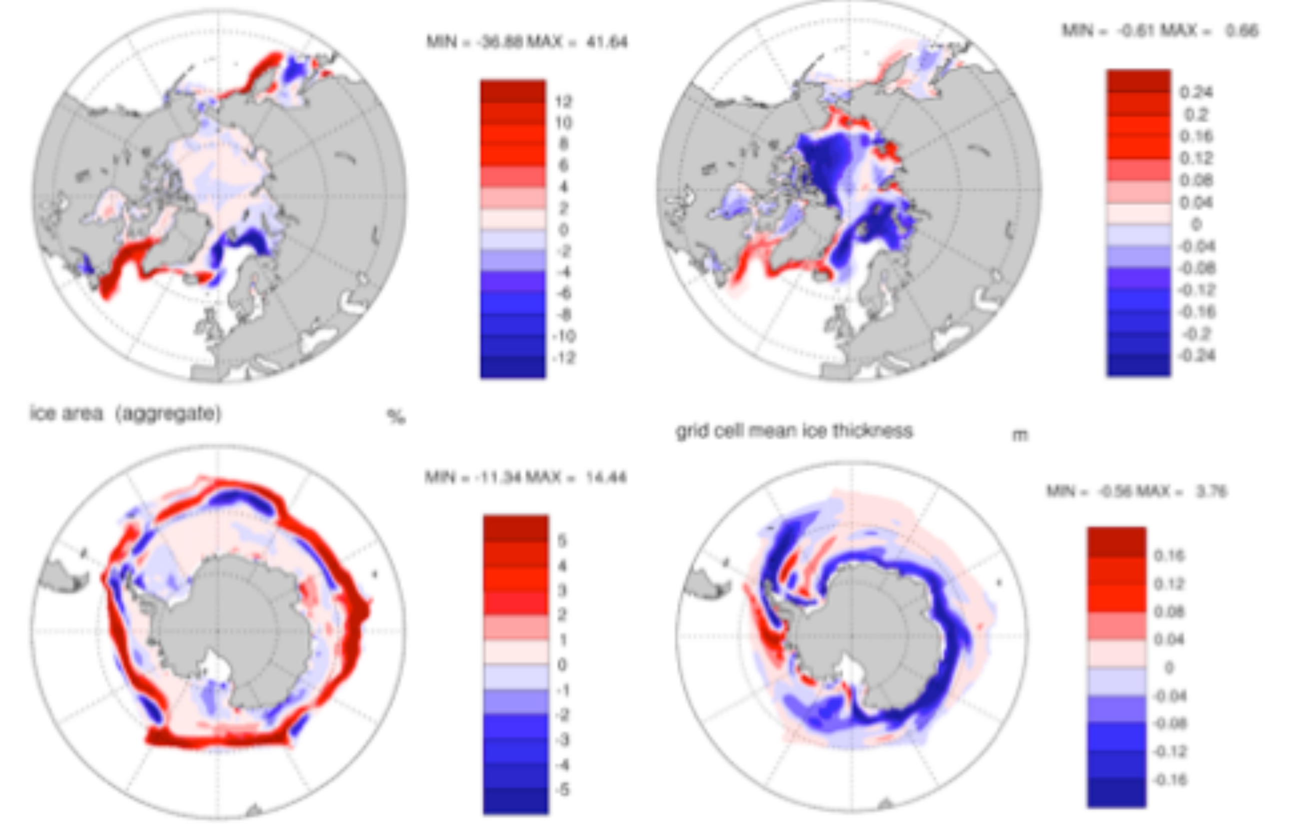
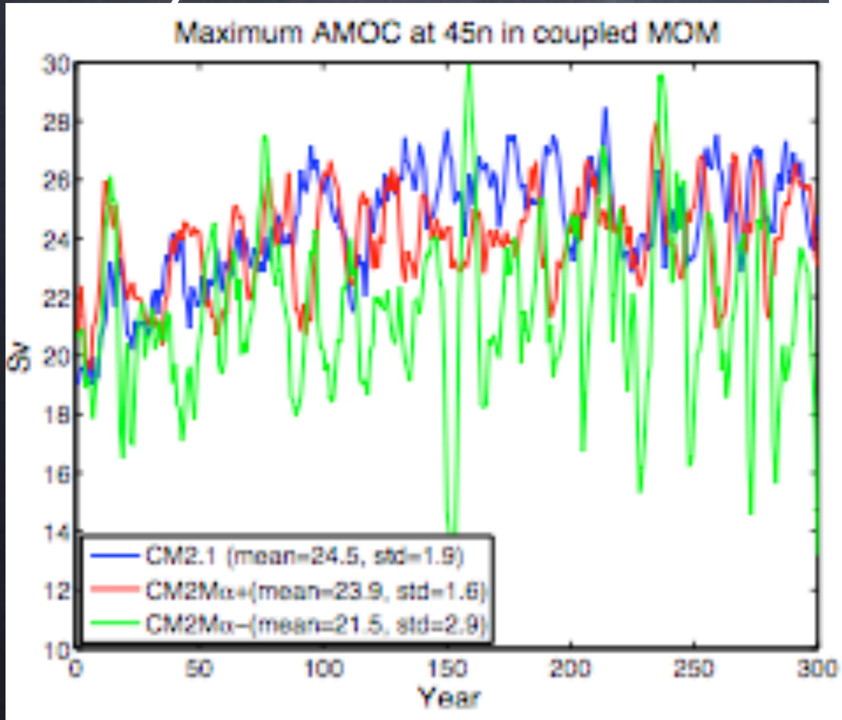


Figure 10: Wintertime sea ice sensitivity to introduction of MLE parameterization ($CCSM^{+}$ minus $CCSM^{-}$): January to March Northern Hemisphere a) ice area and b) thickness and July to September Southern Hemisphere c) ice area and d) thickness.

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
- 10s to mins
- w, u=O(10cm/s)
- Stokes drift
- Eqtns:Craik-Leibovich
- PARAMS IN DEVELOPMENT!

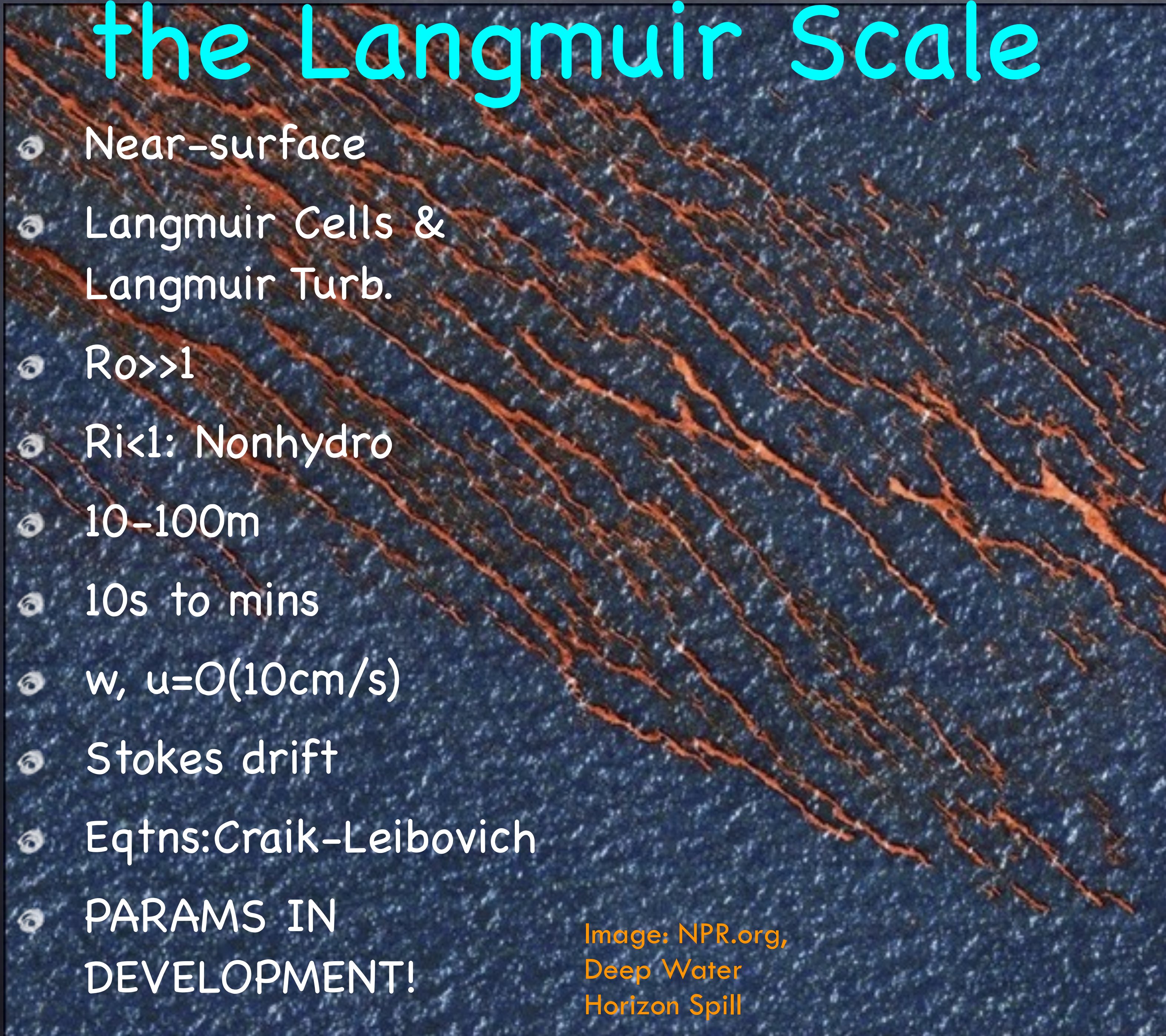
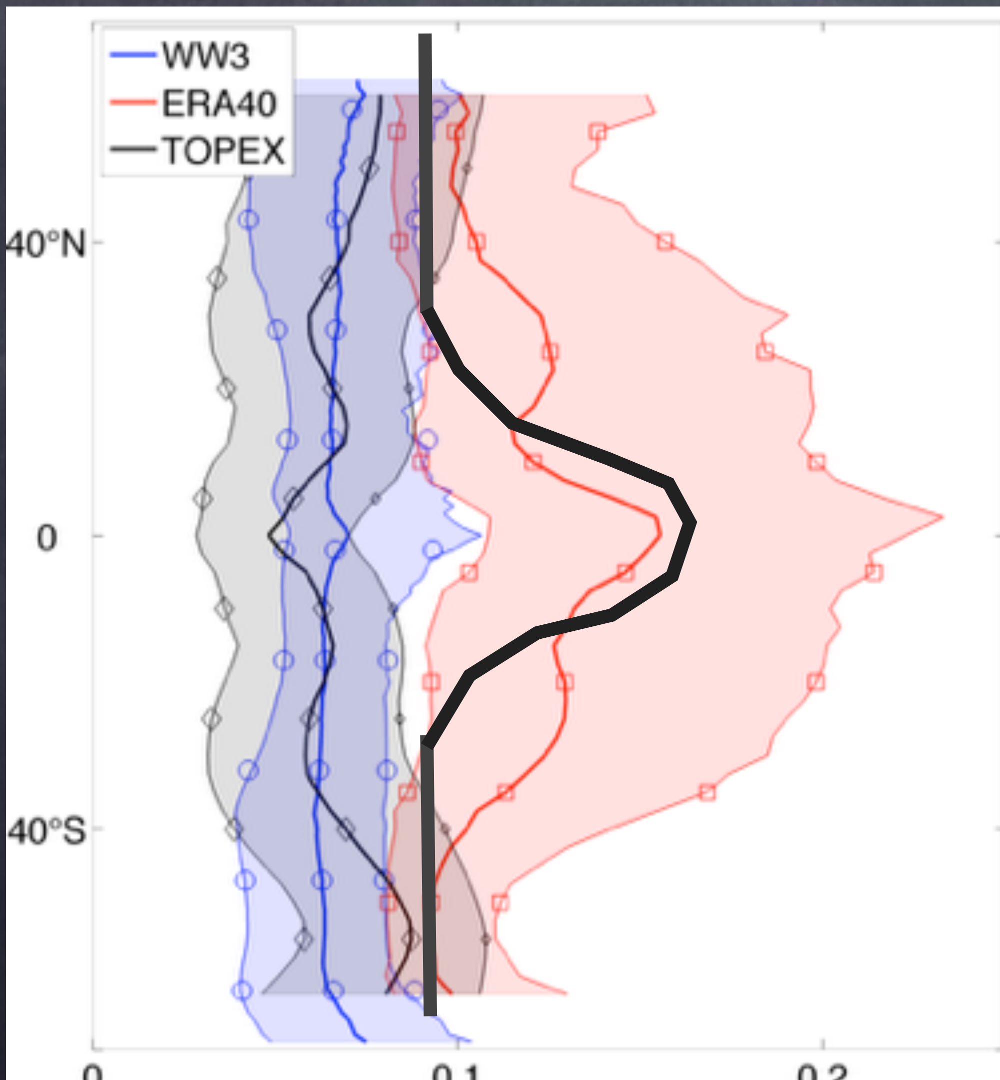


Image: NPR.org, Deep Water Horizon Spill

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

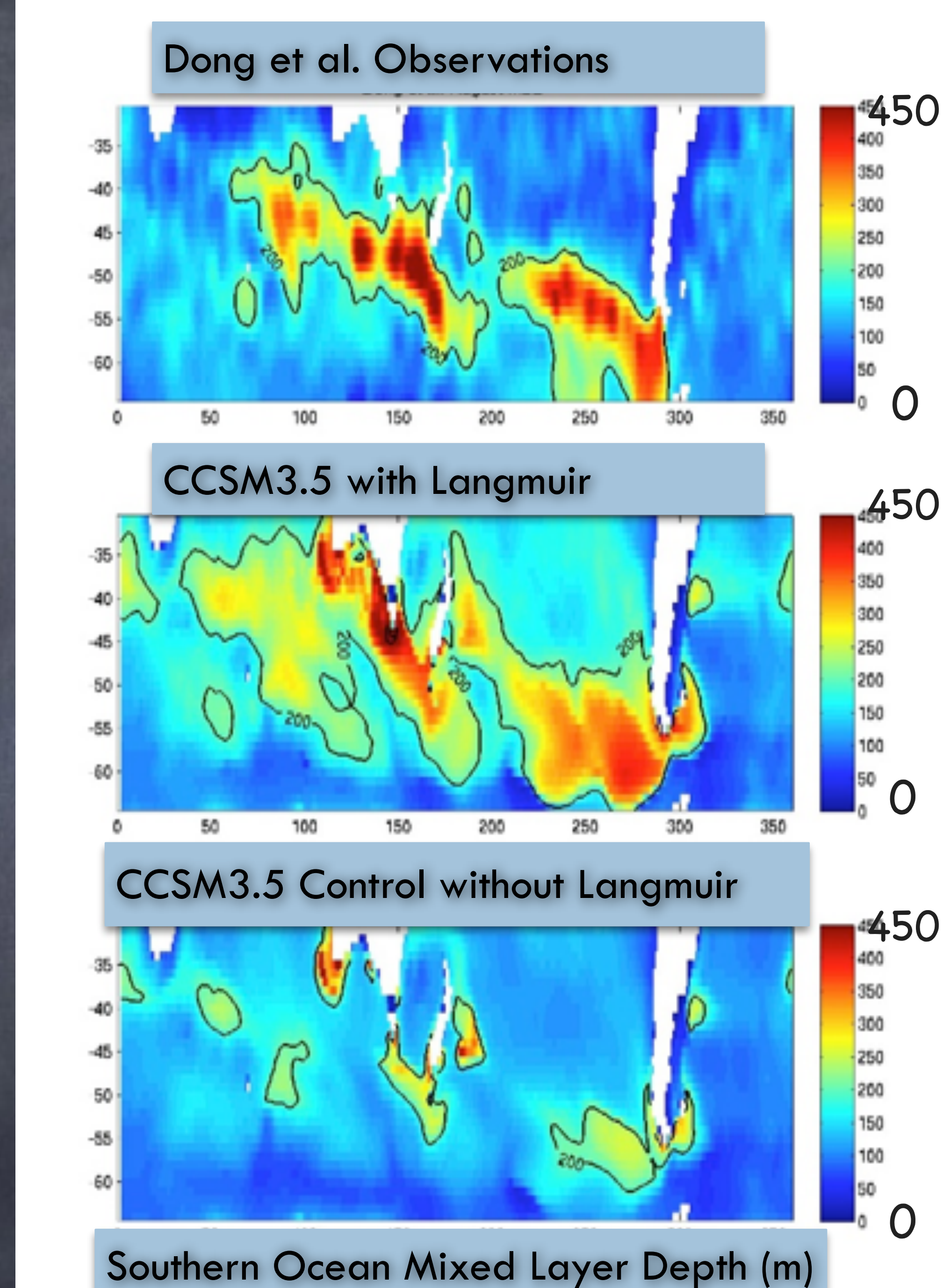
image: Leibovich, 83

Langmuir Mixing Estimate from Climatology (Wind->Wave)



La^2

UNDERESTIMATES WAVE IMPACT



Crude estimate of the effect of Langmuir mixing in a forward ESM on MLD (m)

How well do we know Stokes Drift?

Reanalysis vs wave model | Altimetry vs wave model

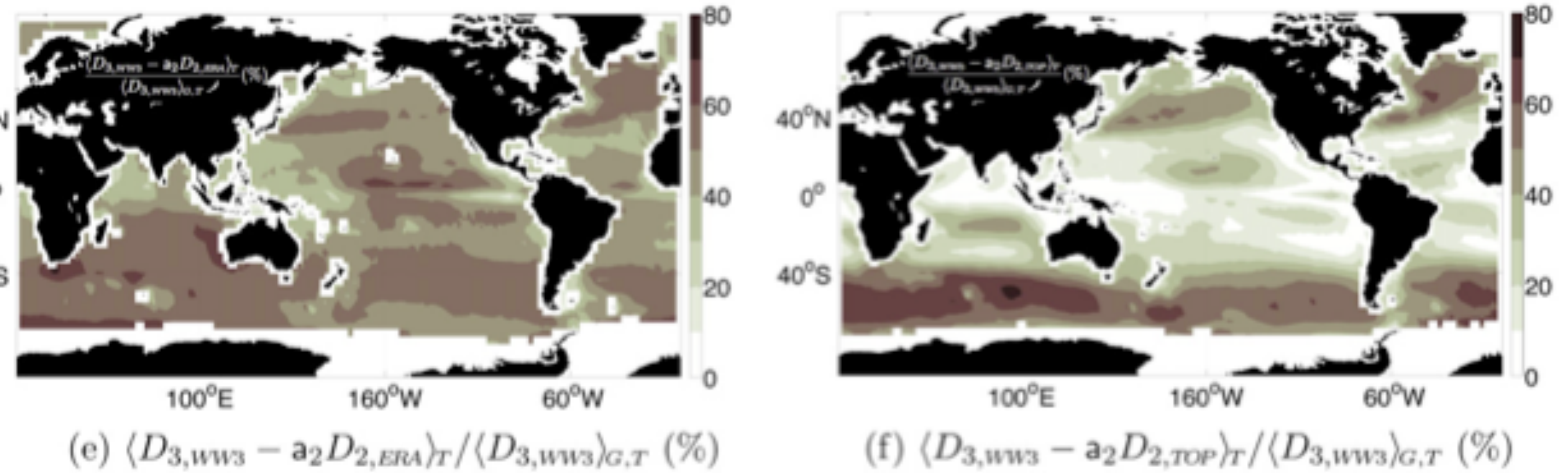


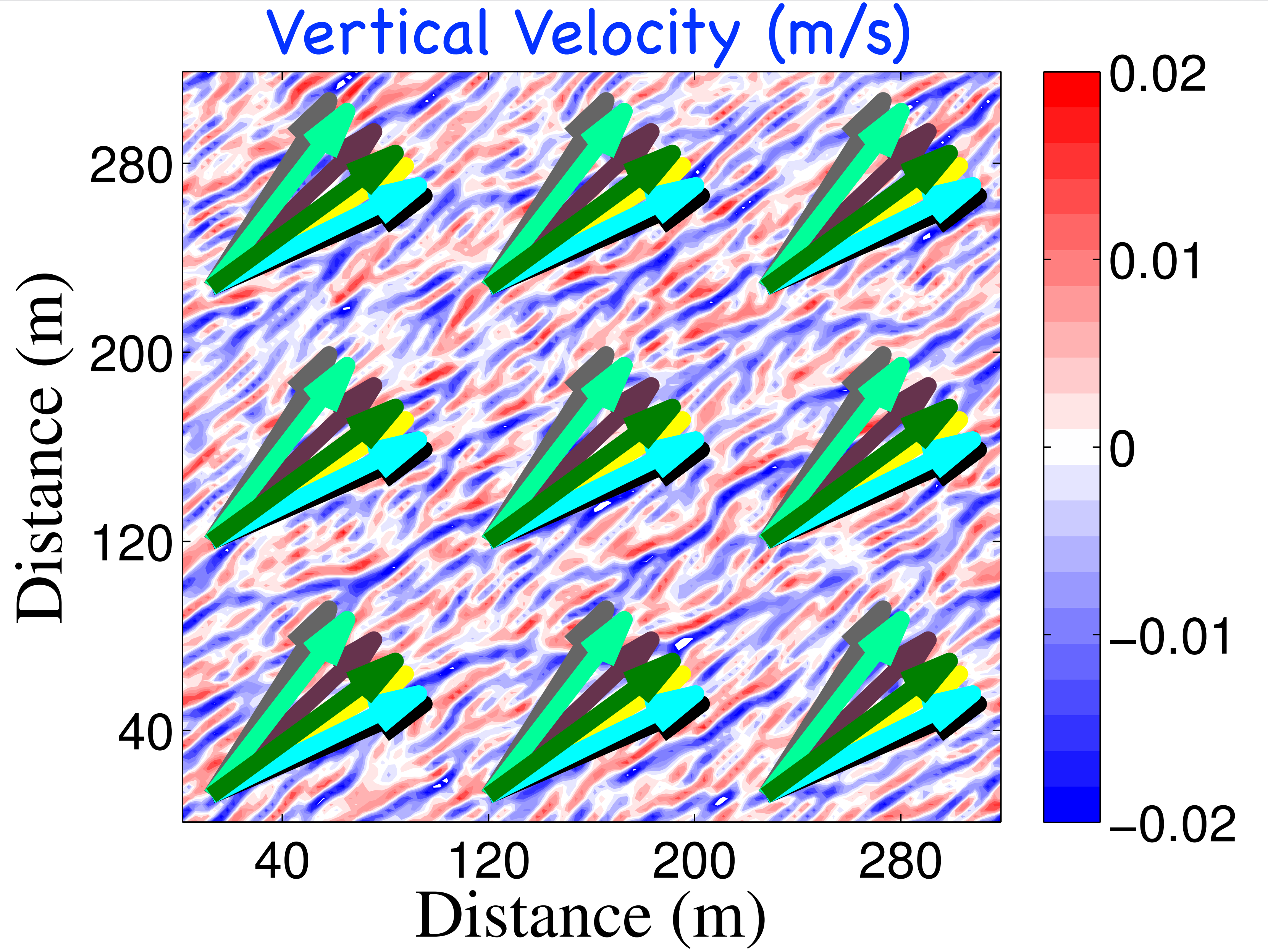
Fig. 4. D_2 Comparison of ERA40 reanalysis and TOPEX satellite data with WW3 using eight year means (1994–2001).

Within a factor of 2.

Assuming full-development (e.g., McWilliams & Restrepo, 1999) is worse

A. Webb and B. Fox-Kemper. Wave spectral moments and Stokes drift estimation. *Ocean Modelling*, 40(3-4): 273-288, 2011

Real World Forcing: Misaligned Wind & Waves

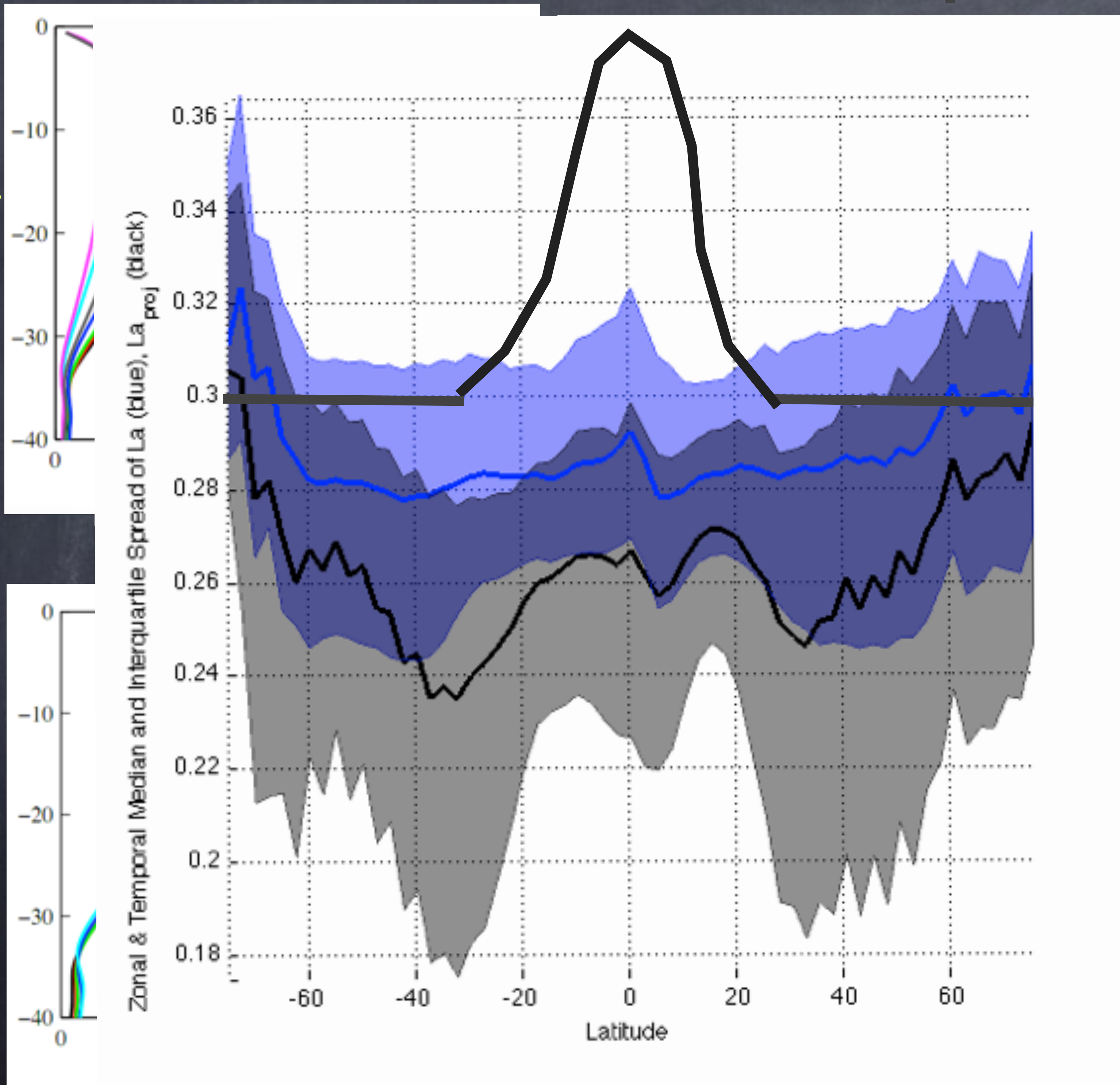


L. Van Roekel, B. Fox-Kemper, P. P. Sullivan, P. E. Hamlington, and S. R. Haney. The form and orientation of Langmuir cells for misaligned winds and waves. *Journal of Geophysical Research-Oceans*, 2012. In press.

<w^2>

depth

depth



Langmuir No.,

angmuir Direction

$.0 + (3.1 La_{proj})^{-2}$

$\sin(\theta_{ww})$

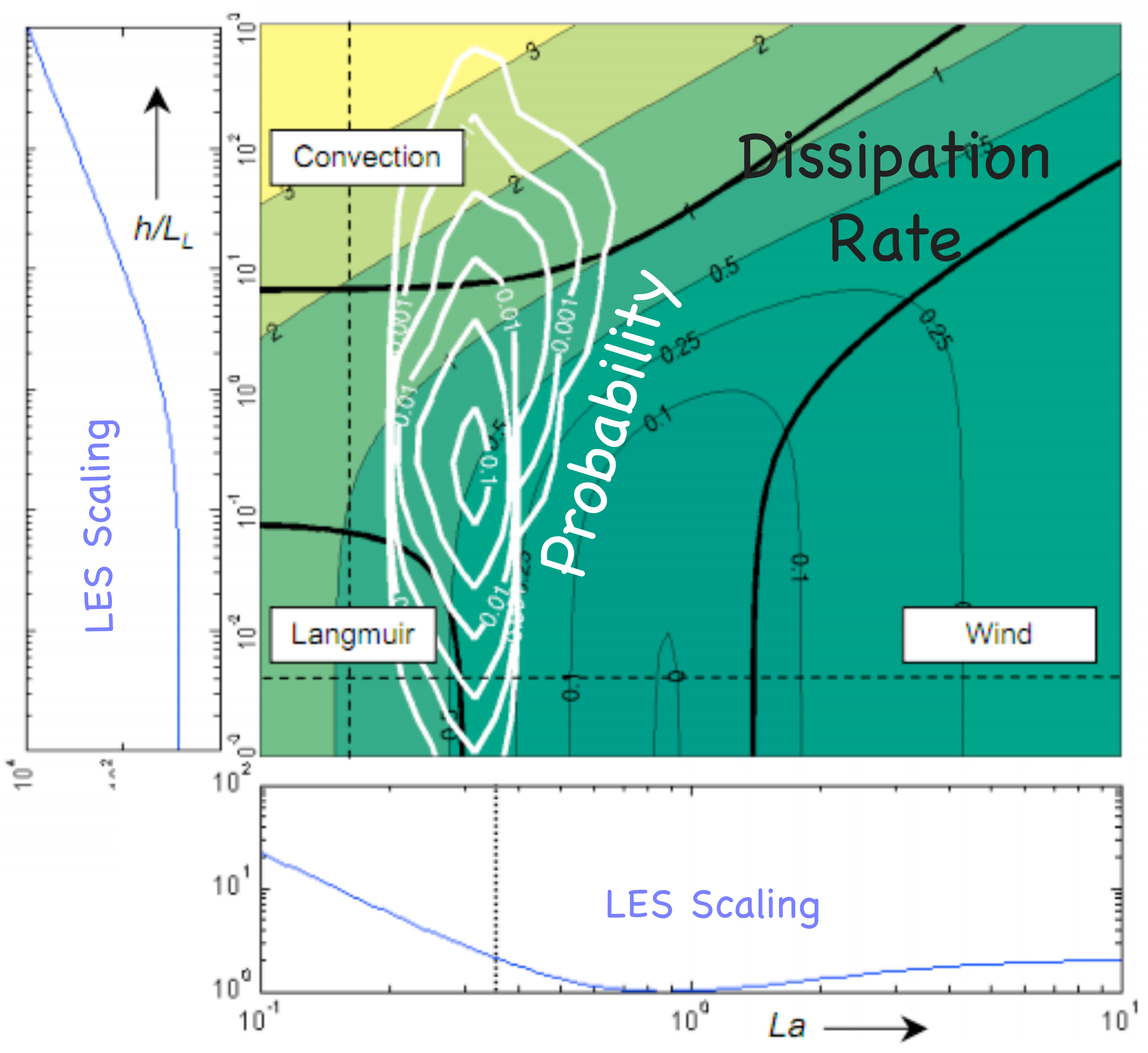
$\left|\frac{H_{ML}}{z_1}\right|) + \cos(\theta_{ww})$

or LC

irection!

an, P. E. Hamlington, and
Langmuir cells for
Geophysical Research-

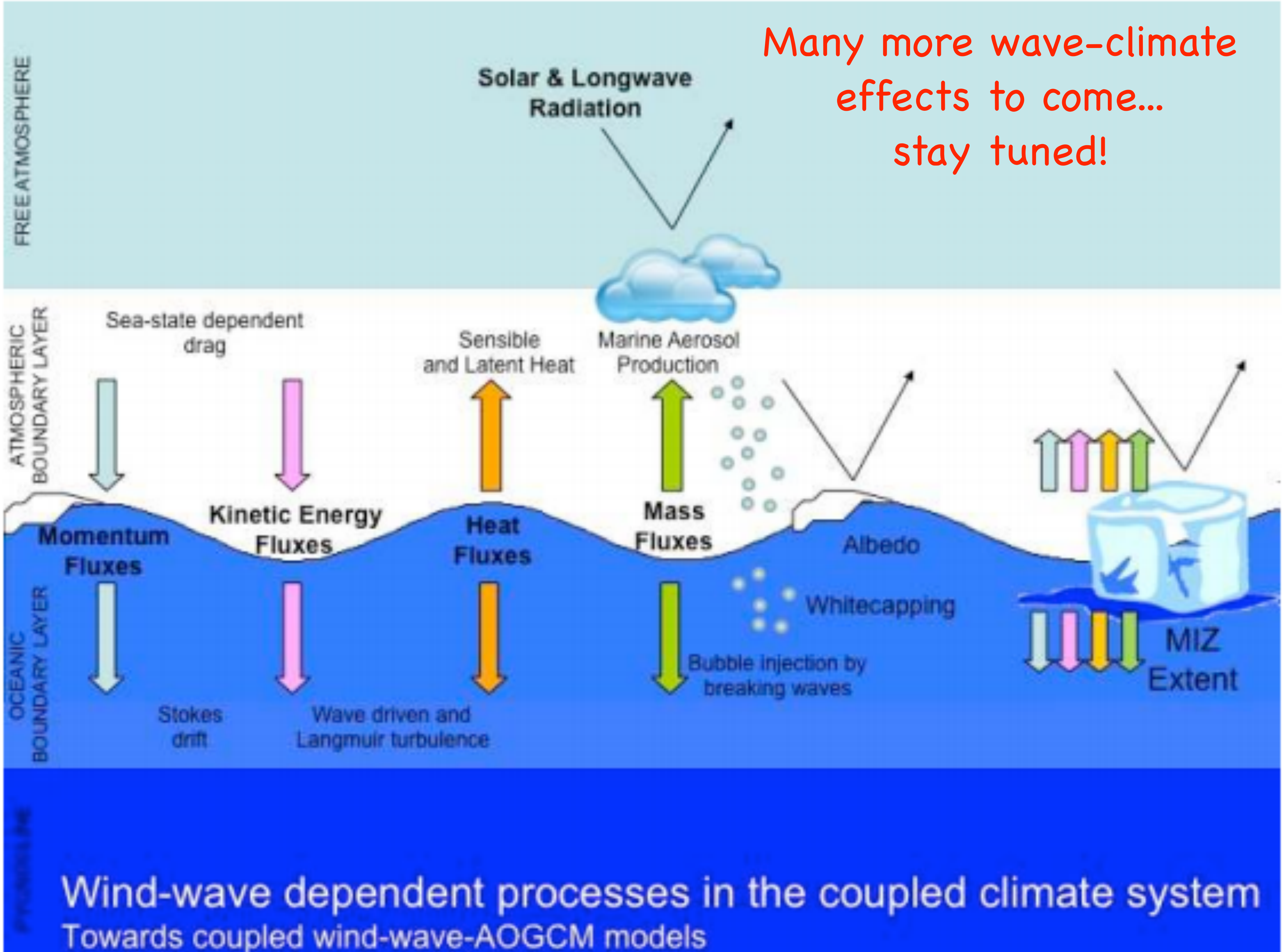
Data + LES, Southern Ocean mixing energy: Langmuir (Stokes-drift-driven) and Convective



But, how well do we know Stokes drift?
(Turb. Lang. #=La $= u^*/u_s$)

S.E. Belcher, A.A.L.M. Grant, K.E. Hanley, B. Fox-Kemper, L. Van Roekel, P.P. Sullivan, W.G. Large, A. Brown, A. Hines, D. Calvert, A. Rutgersson, H. Petterson, J. Bidlot, P.A.E.M. Janssen, and J.A. Polton. A global perspective on mixing in the ocean surface boundary layer. *Geophysical Research Letters*, 2011. In revision.

Many more wave-climate effects to come… stay tuned!



L. Cavaleri, B. Fox-Kemper, and M. Hemer. Wind waves in the coupled climate system. *Bulletin of the American Meteorological Society*, 2012. In press.

Coupling between Langmuir and Submeso?

- Together?

- Separate?

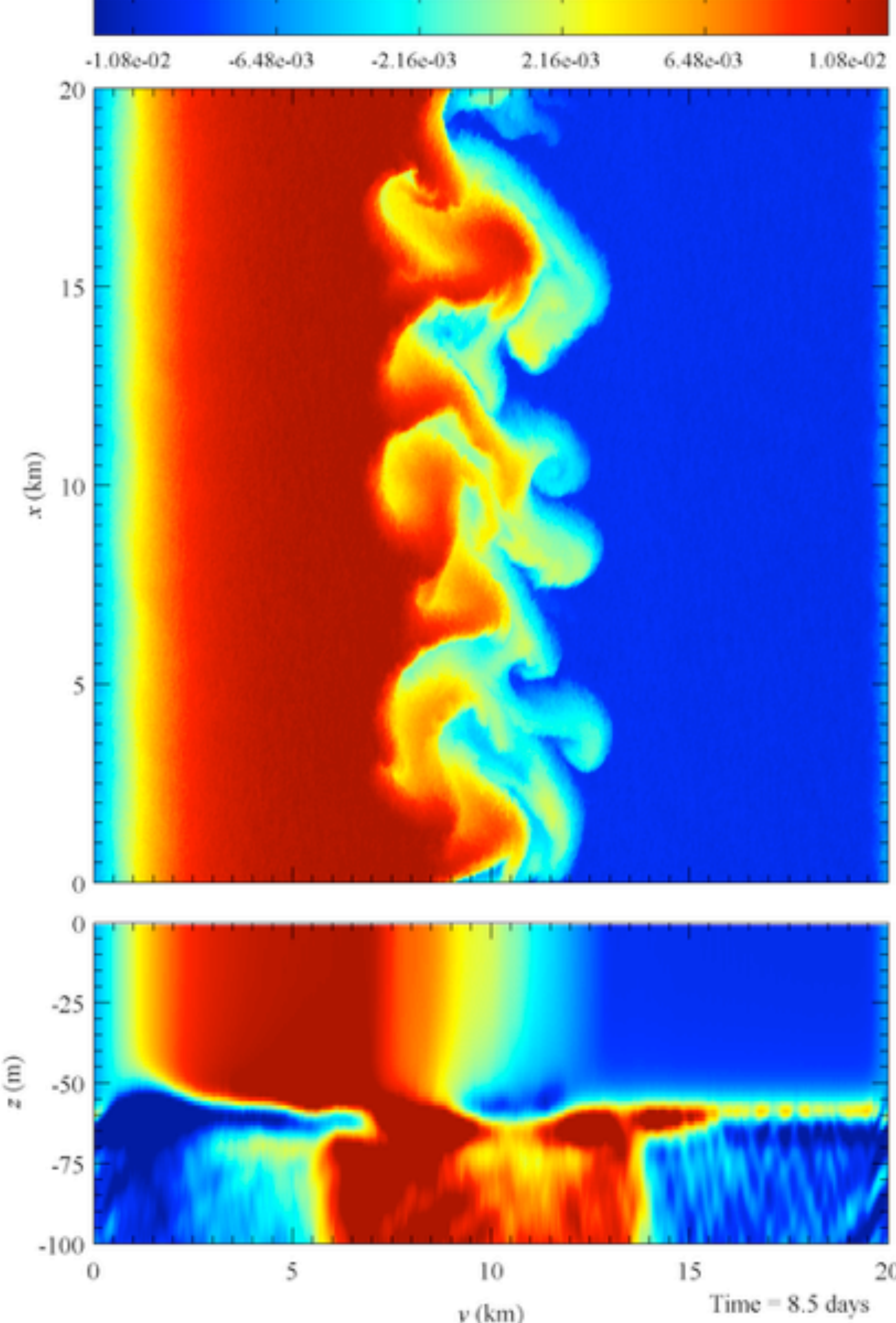
Wind and wave forced, dying submeso filament

$$\overline{Ro} \approx 0.1$$

$$\overline{Ri} < 1$$

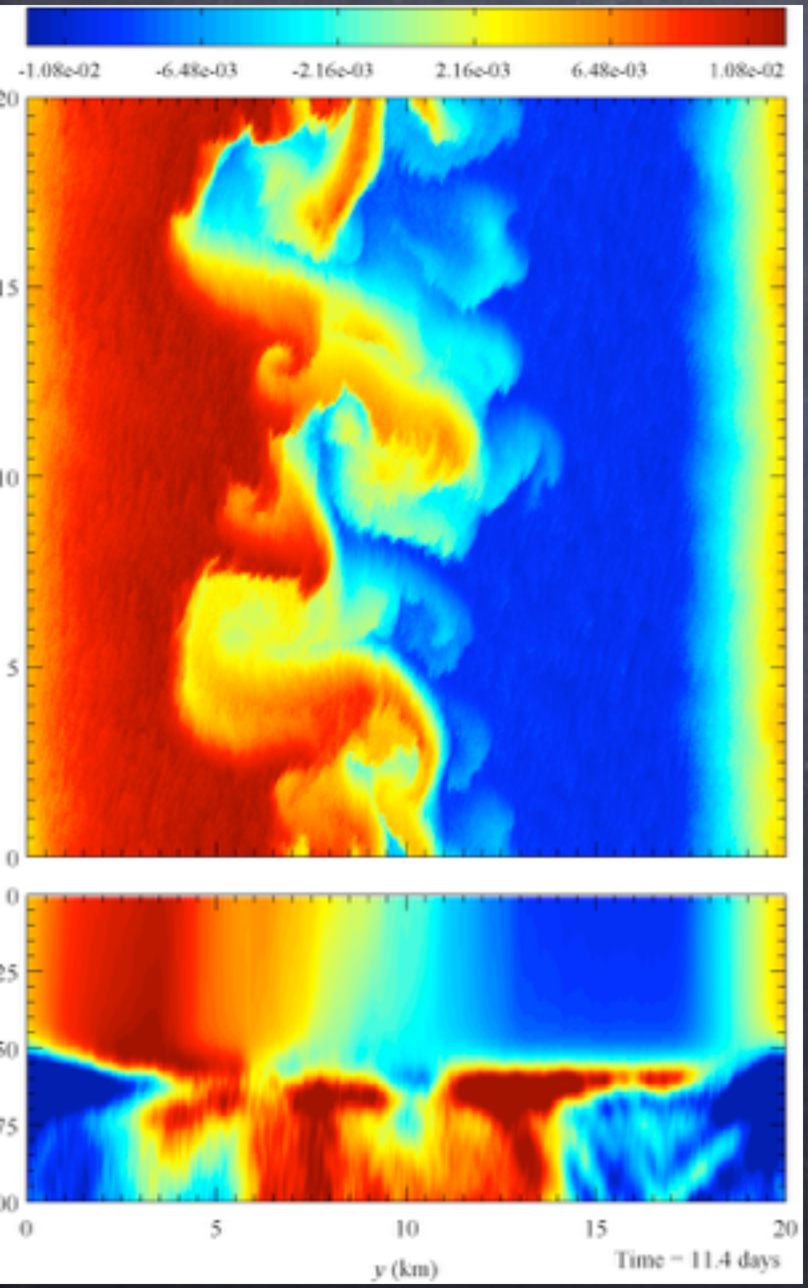
$$La_t \approx 0.3$$

Computational parameters:
Domain size: 20km x 20km x -160m
Grid points: 4096 x 4096 x 128
Resolution: 5m x 5m x -1.25m



Coupling between Langmuir and Submeso?

Wind Only

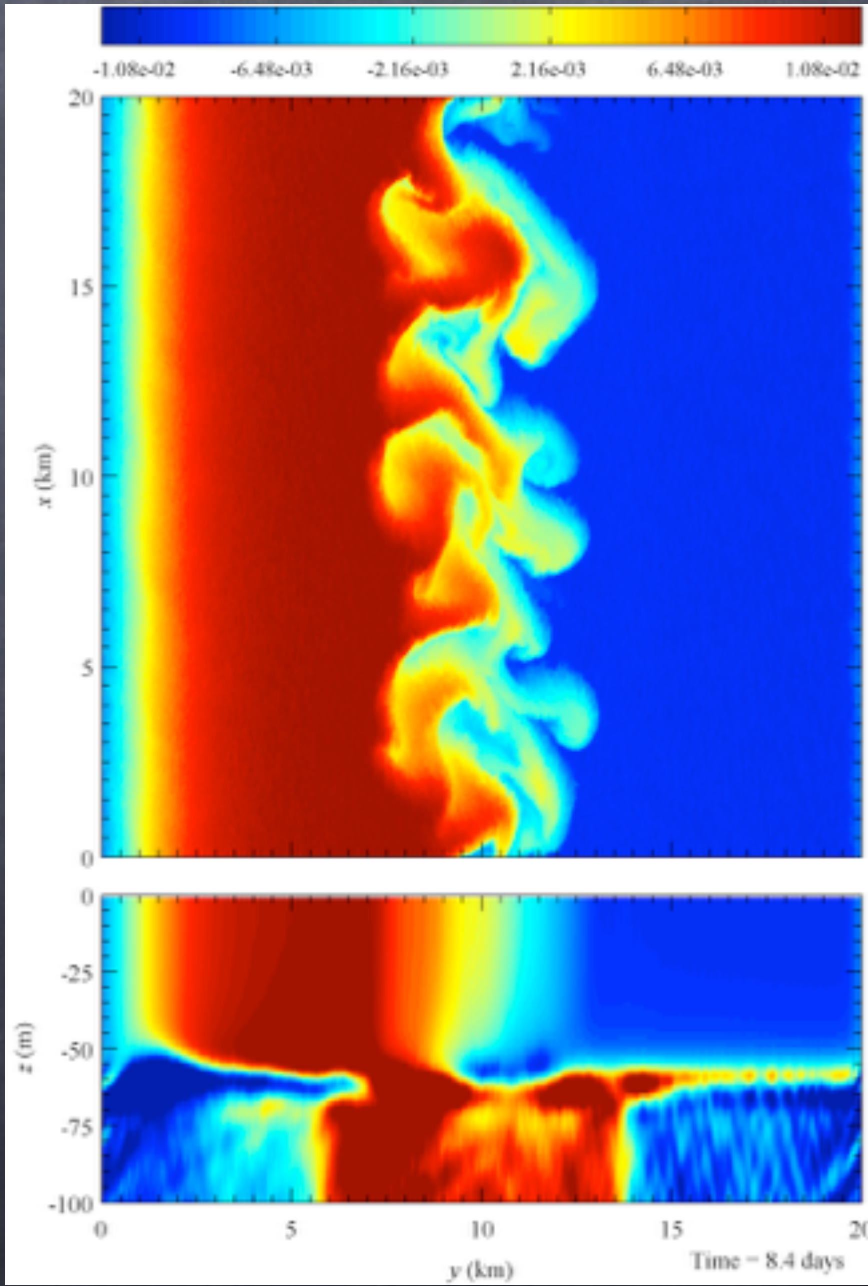


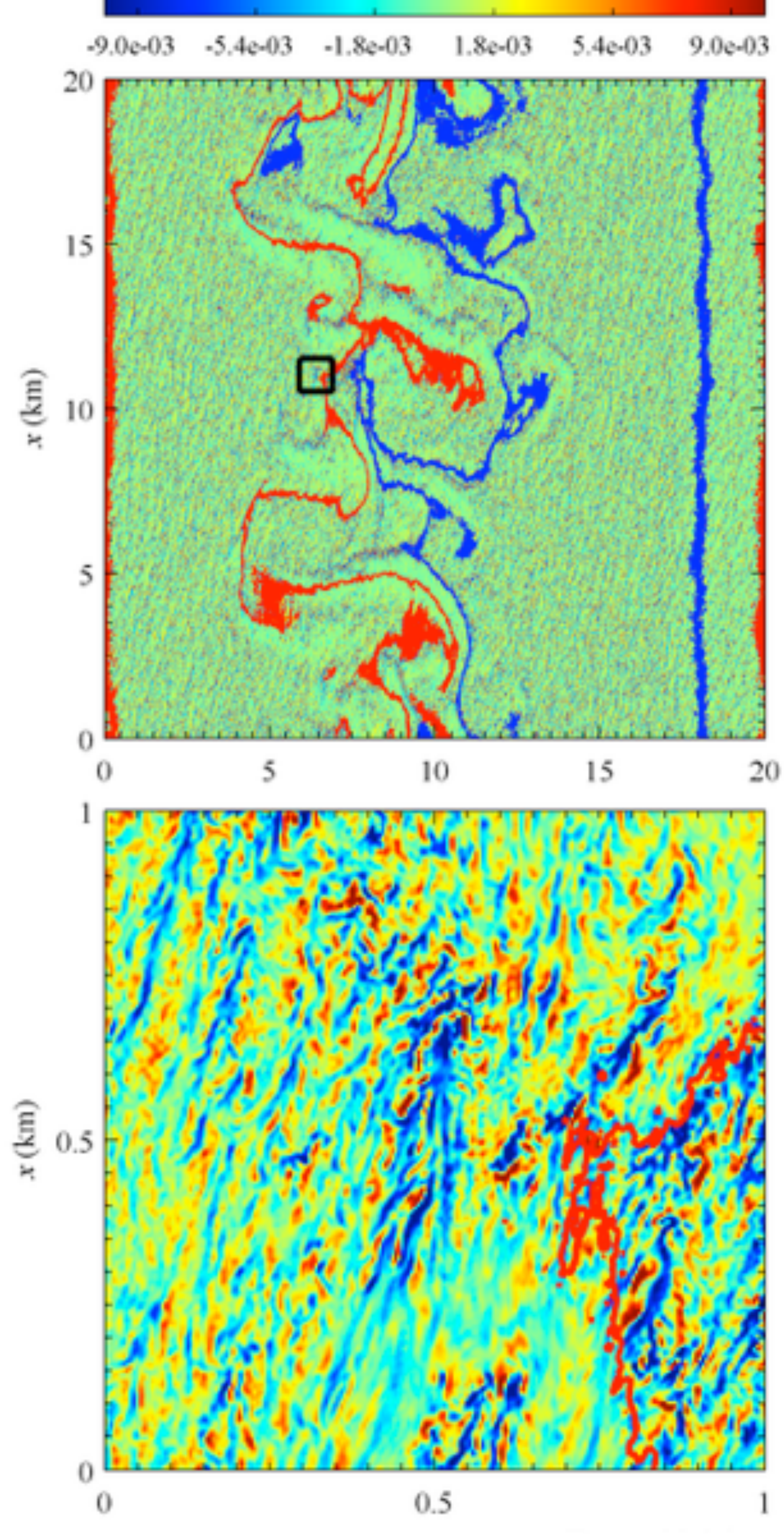
2 runs:
Both spindown of submesoscale filament

Right --> Stokes & Wind

<-- Left Wind Only

Stokes & Wind



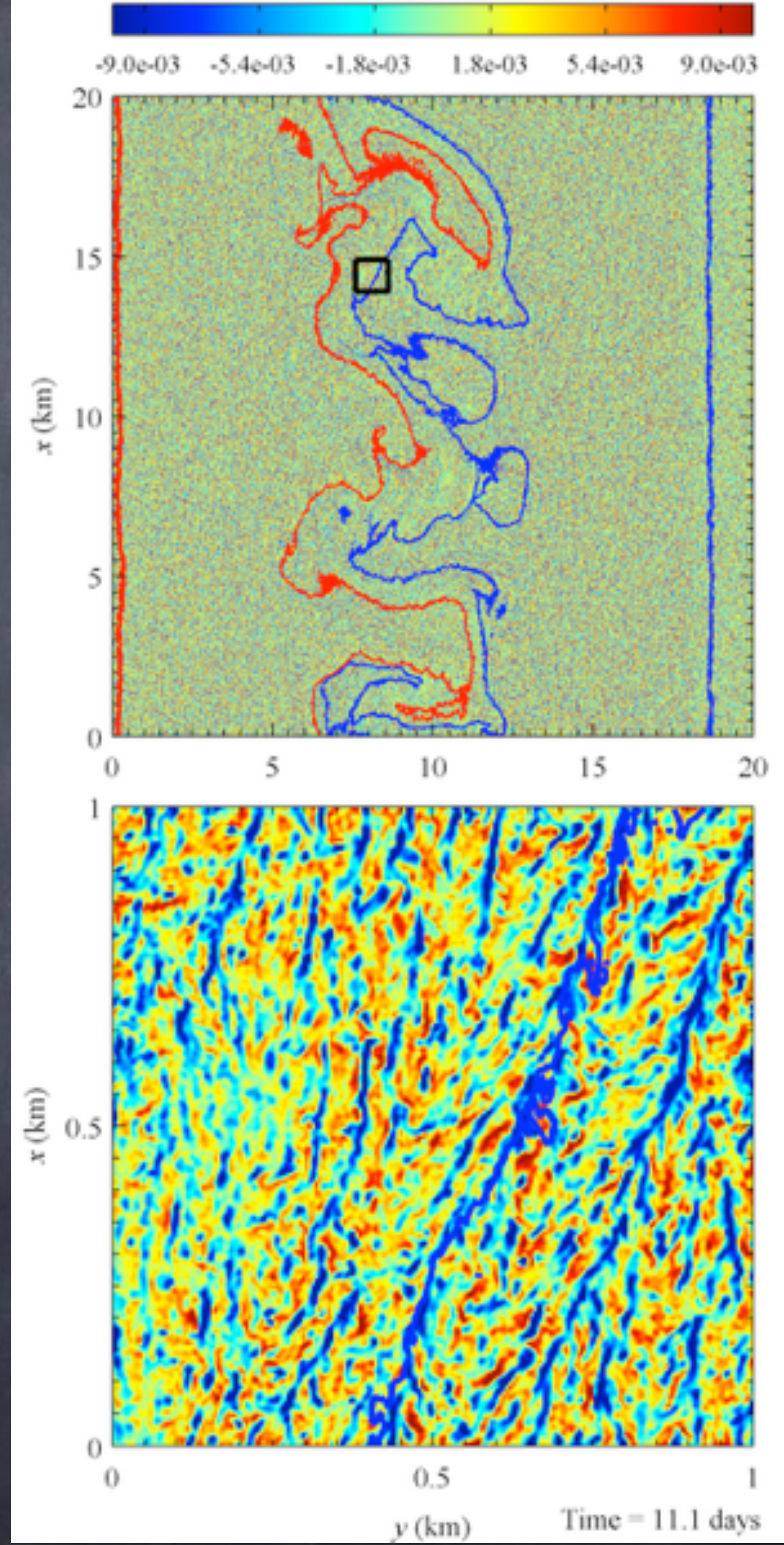


Coupling between Langmuir and Submeso?

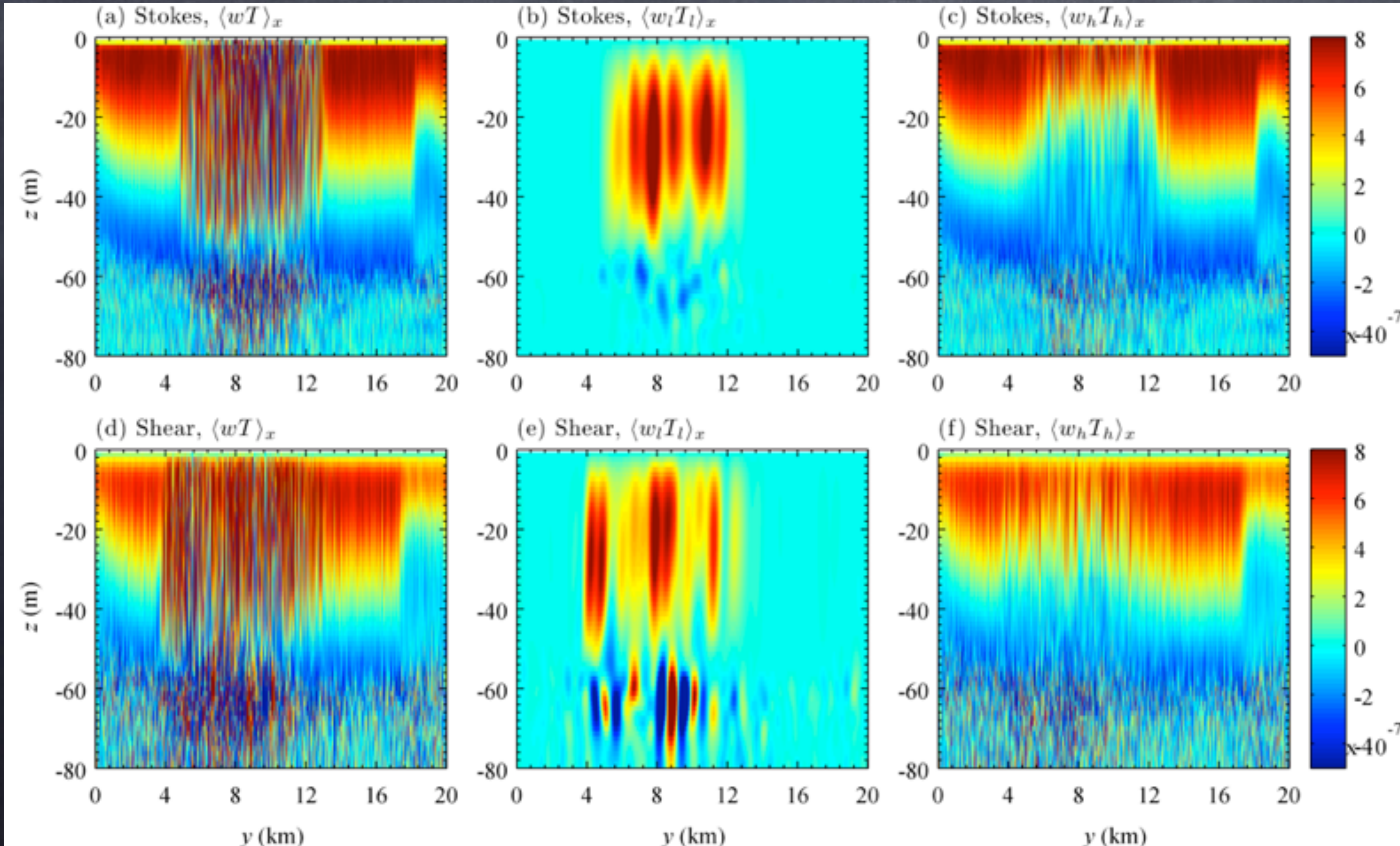
2 runs:
Both spindown of submesoscale filament

Right -->
Stokes & Wind

<-- Left
Wind Only

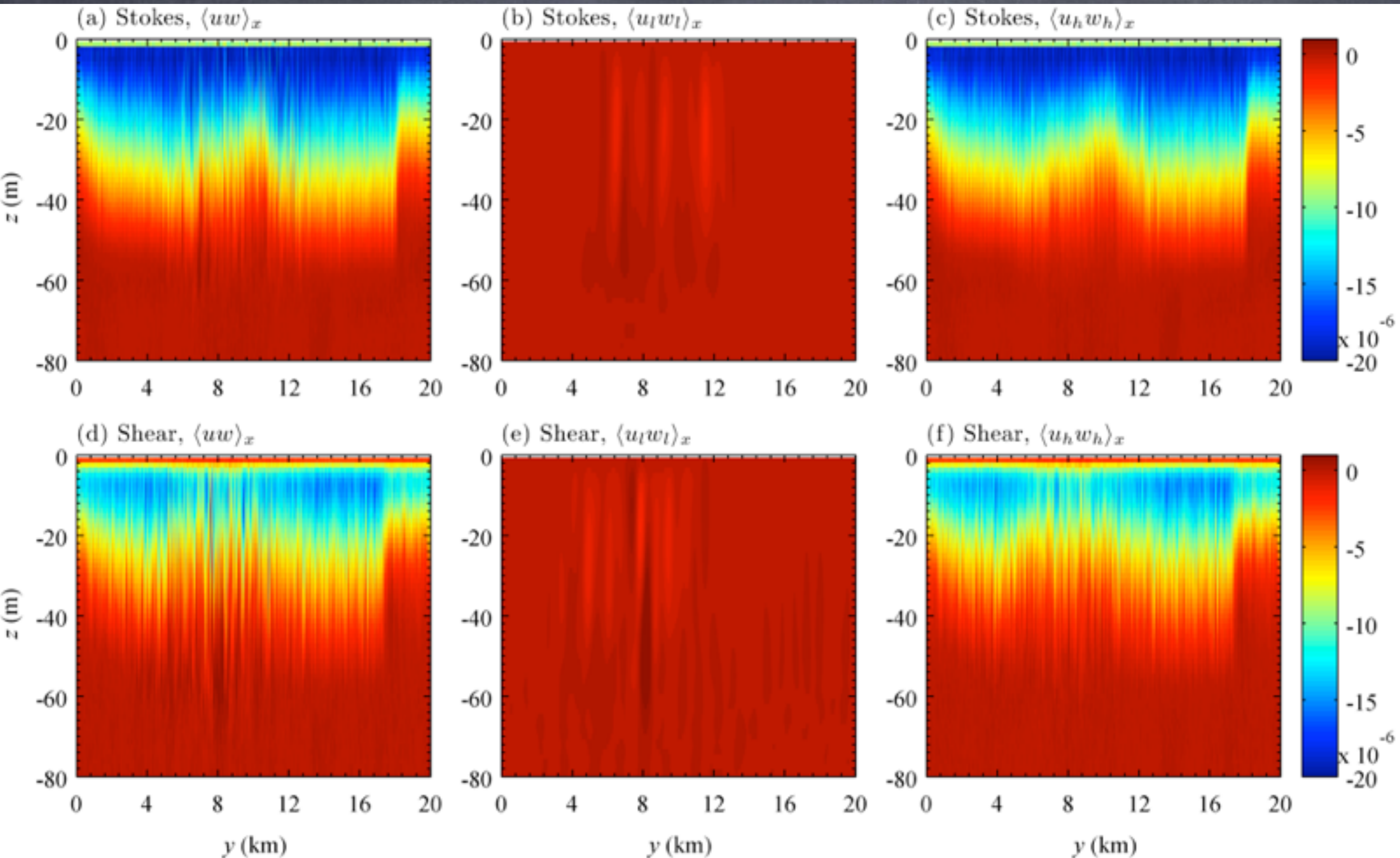


Heat Flux <wT>.

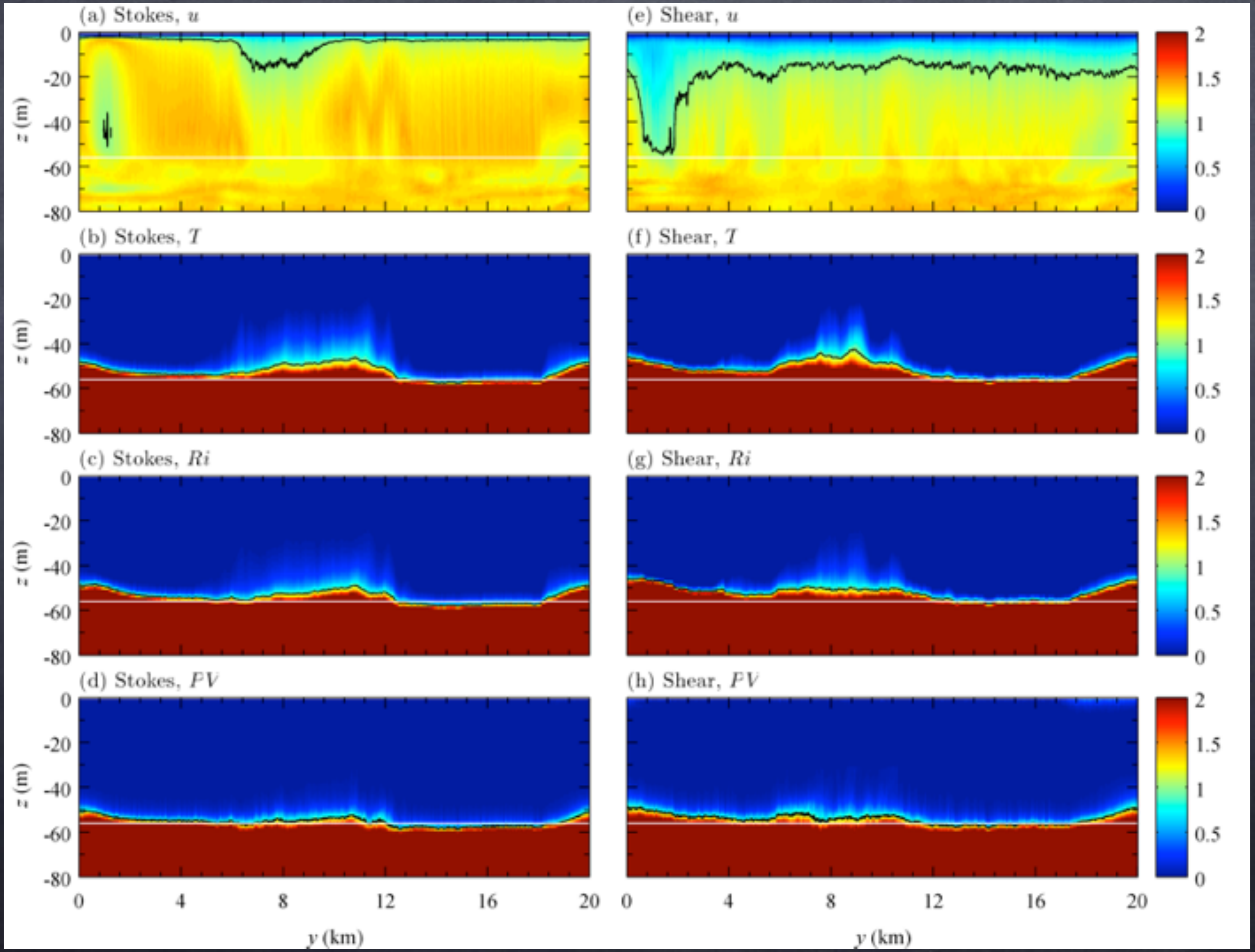


(a) Stokes, $\langle wT \rangle_x$
(b) Stokes, $\langle w_l T_l \rangle_x$
(c) Stokes, $\langle w_h T_h \rangle_x$
(d) Shear, $\langle wT \rangle_x$
(e) Shear, $\langle w_l T_l \rangle_x$
(f) Shear, $\langle w_h T_h \rangle_x$
z (m)
y (km)
0
-20
-40
-60
-80
0 4 8 12 16 20
8 6 4 2 0 -2
x10^-7

Momentum Flux: <uw>.



Mixed Layers Differ by Variable.



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

(Capet et al., 2008)

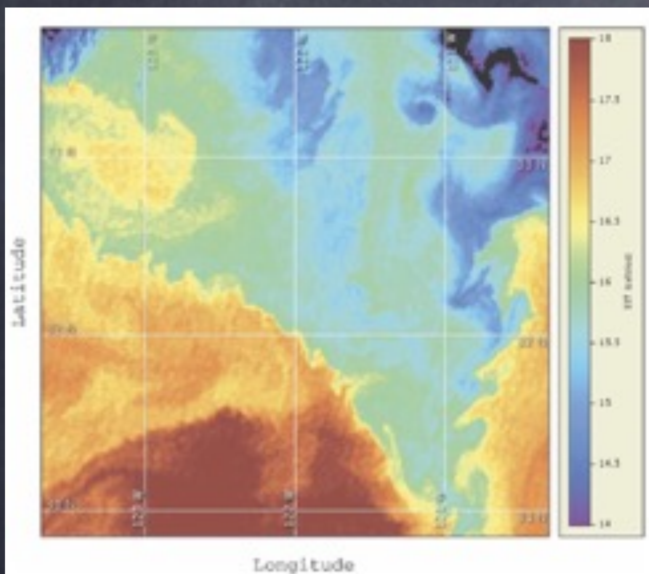
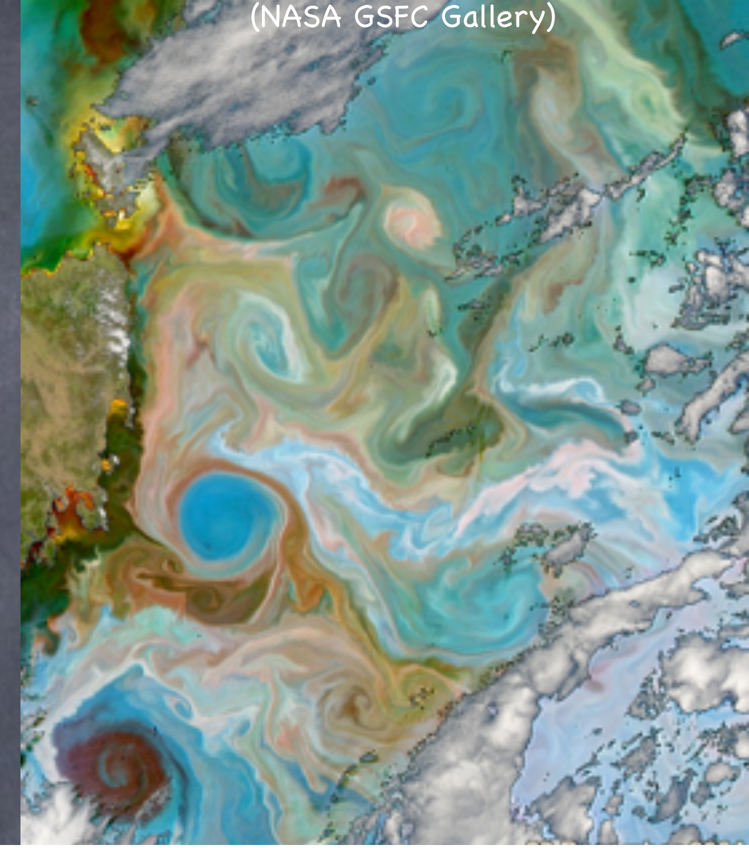
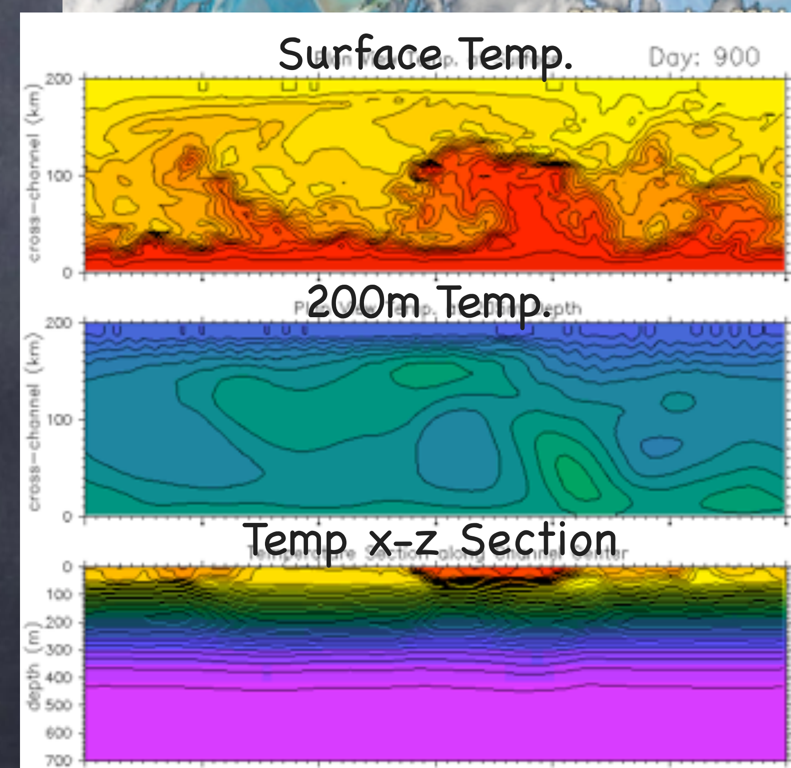


FIG. 16. Sea surface temperature measured at 1832 UTC 3 Jan 2006 off Point Conception in the California Current from CoastWatch (http://coastwatch.pfeg.noaa.gov). The fronts between recently upwelled water (i.e., 15°–16°C) and offshore water (>17°C) show submesoscale instabilities with wavelengths around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

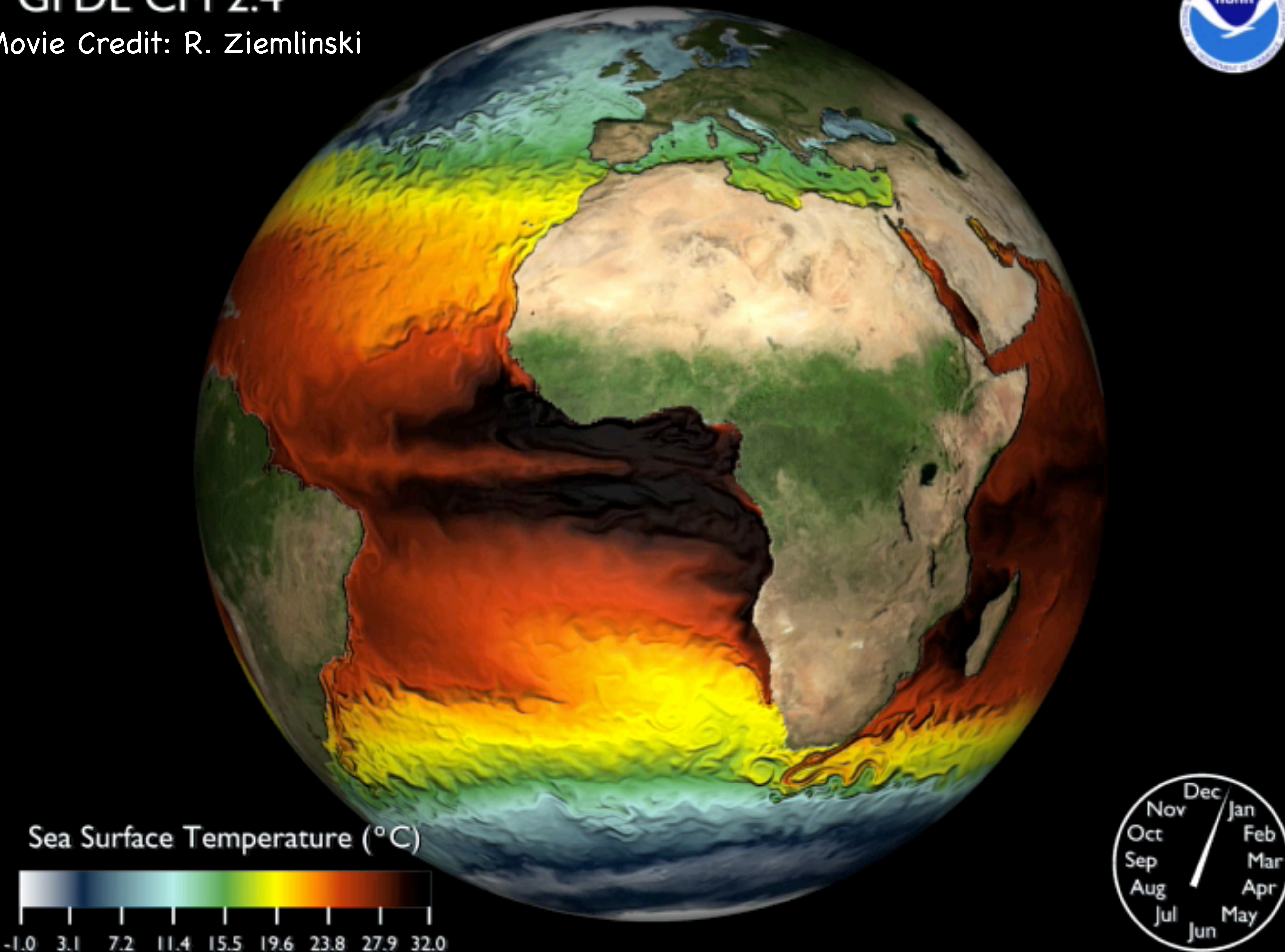
Eddy processes mainly baroclinic & barotropic instability. Parameterizations of baroclinic instability (GM, Visbeck...).





GFDL CM 2.4

Movie Credit: R. Ziemlinski



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.

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

Sym Part=Anisotropic* Redi

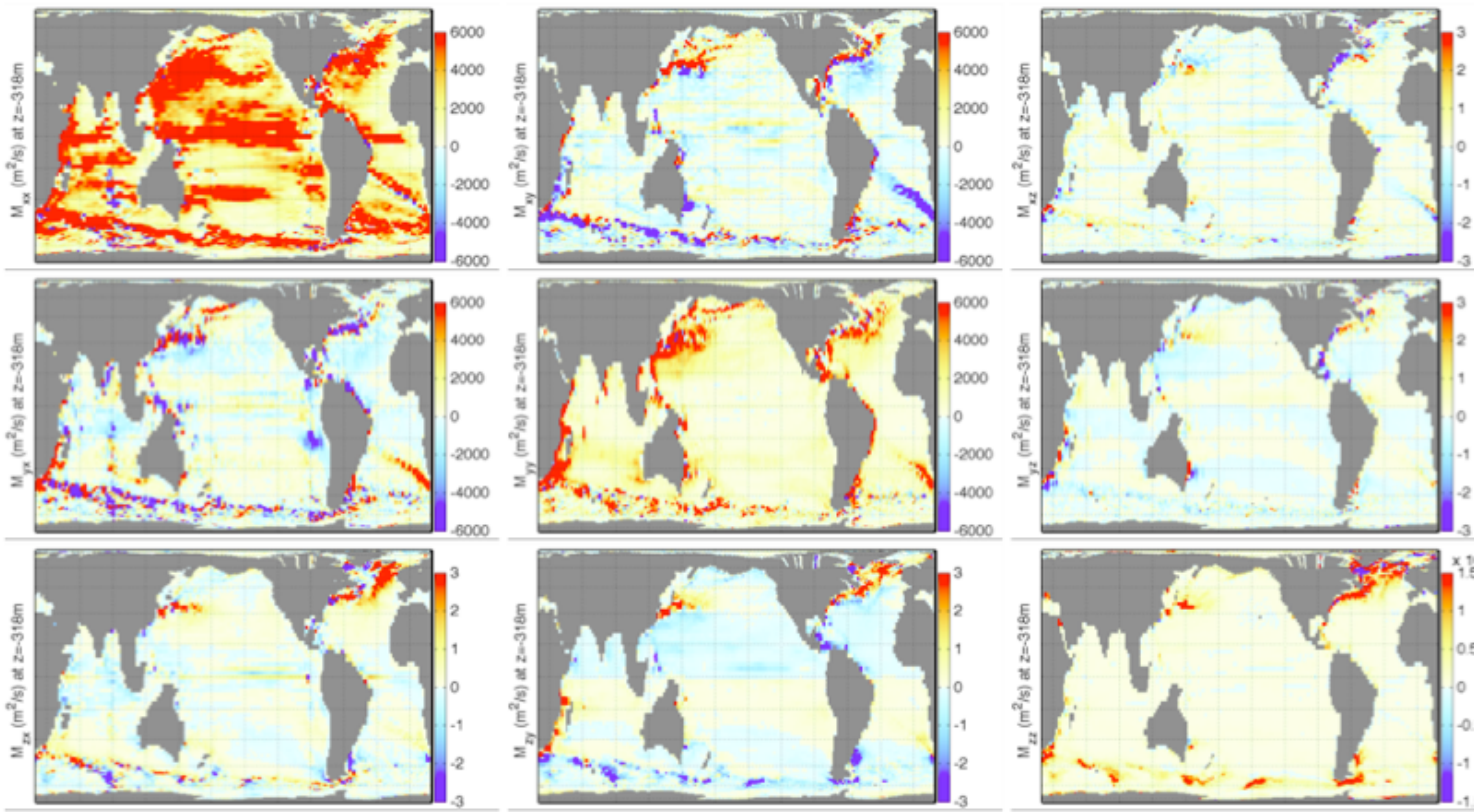
$$\begin{bmatrix} \overline{u'\tau'} \\ \overline{v'\tau'} \\ \overline{w'\tau'} \end{bmatrix} = -\begin{bmatrix} K_{xx} & K_{xy} & \hat{\mathbf{x}}\cdot\mathbf{K}\cdot\tilde{\nabla}\mathbf{z} \\ K_{yx} & K_{yy} & \hat{\mathbf{y}}\cdot\mathbf{K}\cdot\tilde{\nabla}\mathbf{z} \\ \hat{\mathbf{x}}\cdot\mathbf{K}\cdot\tilde{\nabla}\mathbf{z}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

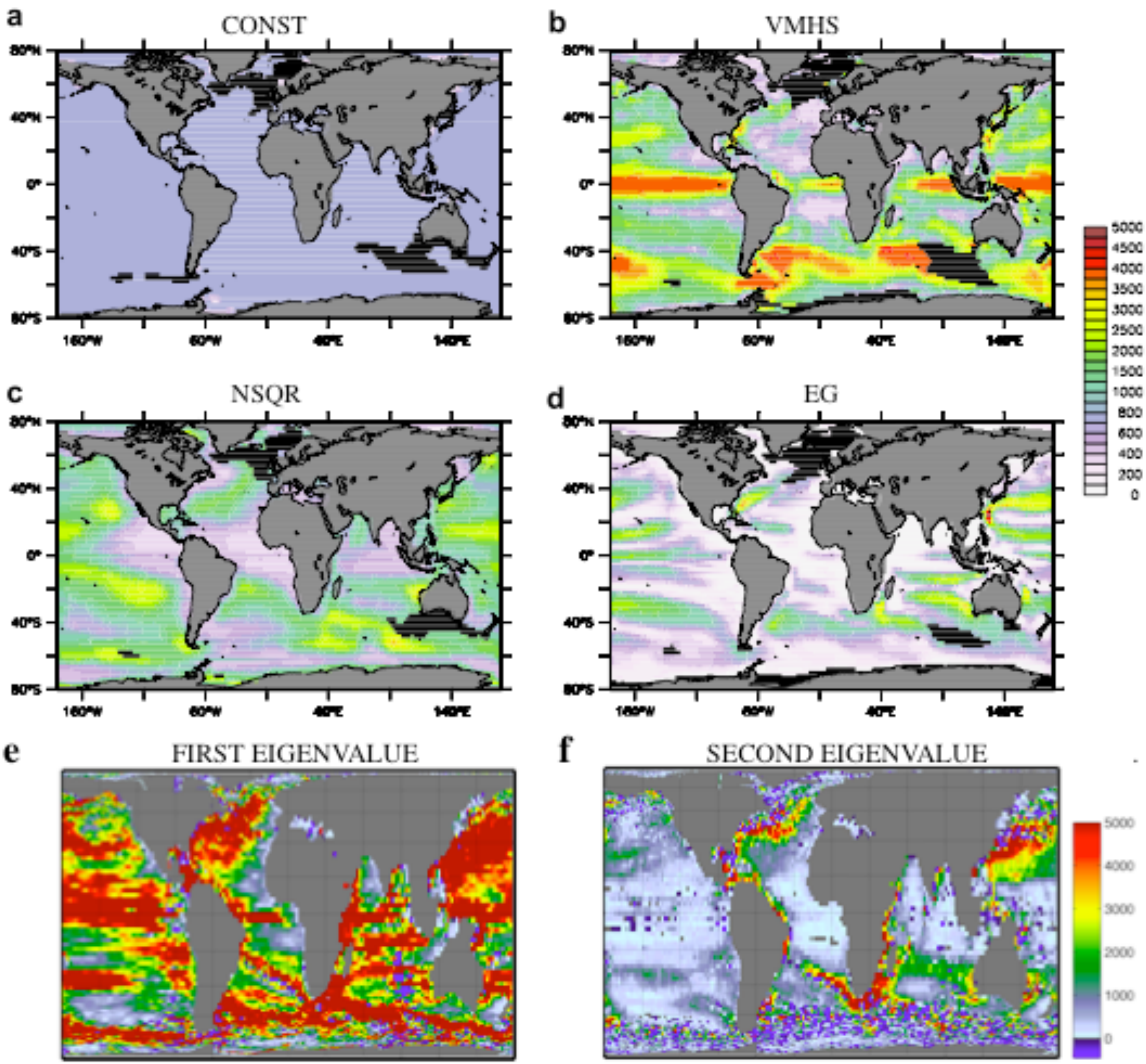
AntiSym Part=Anisotropic* GM

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

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

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





State of the art parameterizations don't do very well!

Do better in idealized setting (Eady):

Bachman & F-K, OSM

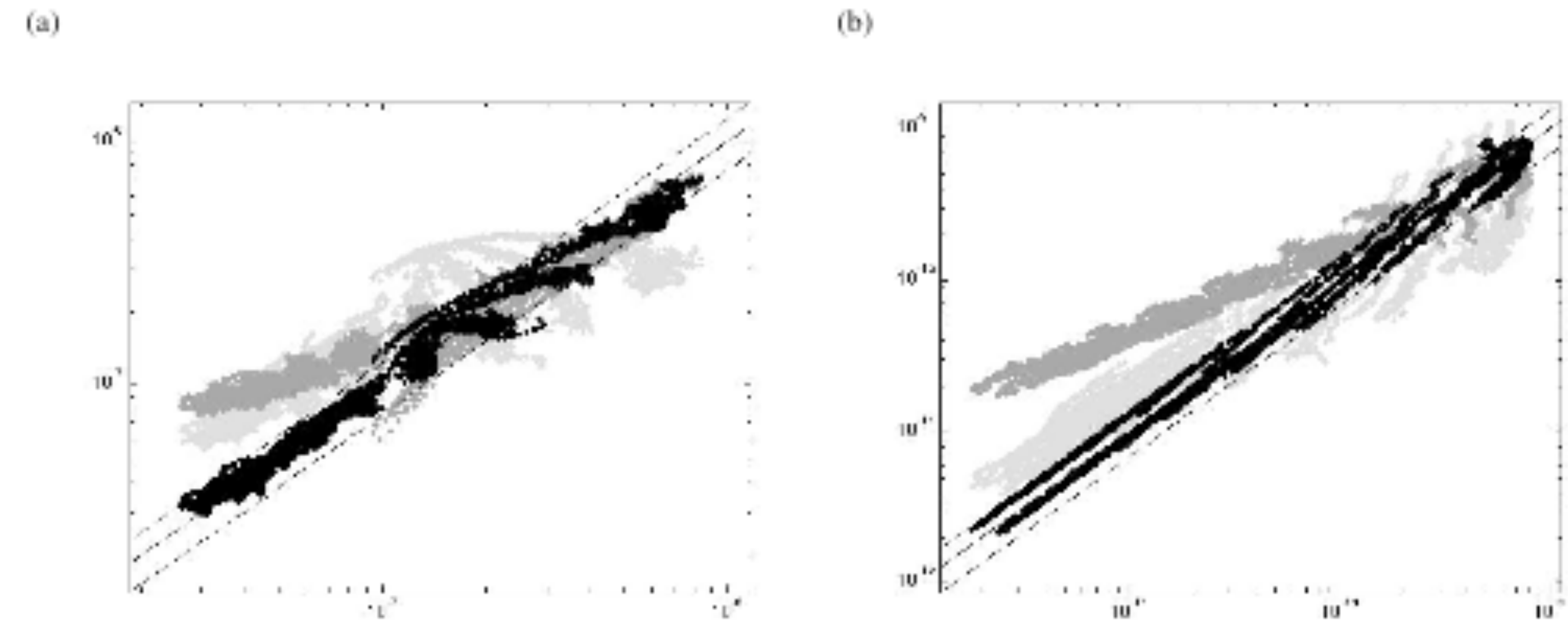


Figure 5: Above scalings:

a) $\overline{v'b'}_z = (0.25 \pm 0.06)\ Ri^{-0.25\pm0.06}\ \frac{N^2 H}{M^2}\left(\sqrt{\overline{v'^2}}M^2 + \sqrt{\overline{w'^2}}N^2\right)$

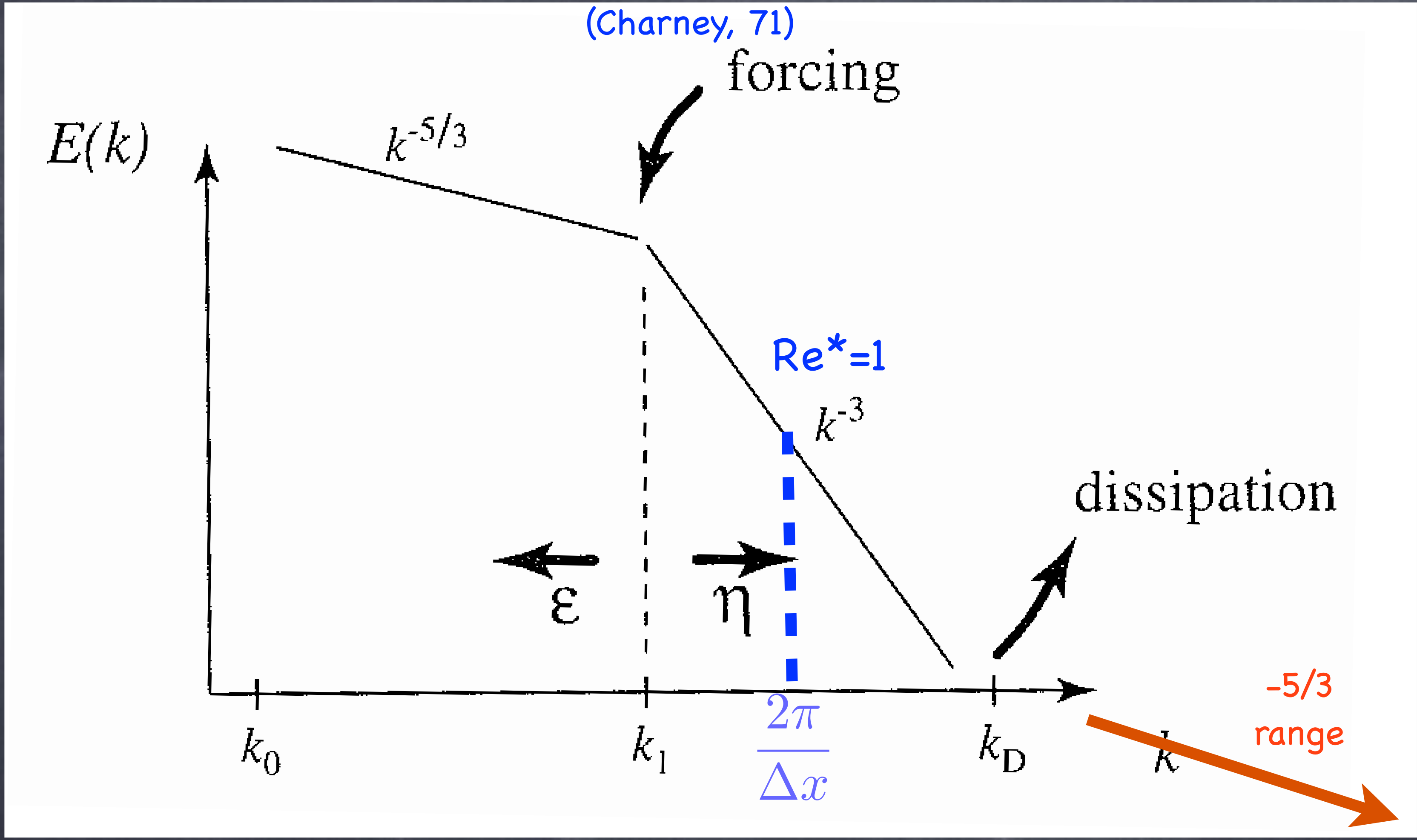
b) $\overline{w'b'}_z = (0.54 \pm 0.17)\ Ri^{-0.49\pm0.15}\ \frac{N^2 H}{M^2}\frac{\sqrt{\overline{w'^2}}}{\sqrt{\overline{v'^2}}}\left(\sqrt{\overline{v'^2}}M^2 + \sqrt{\overline{w'^2}}N^2\right)$

Eddy buoyancy fluxes scaled to within few %

GM k=Redi k to within few %

All advective and diffusive scaling behaviors known

MOLES Turbulence Like Pot'l Enstrophy cascade, but divergent



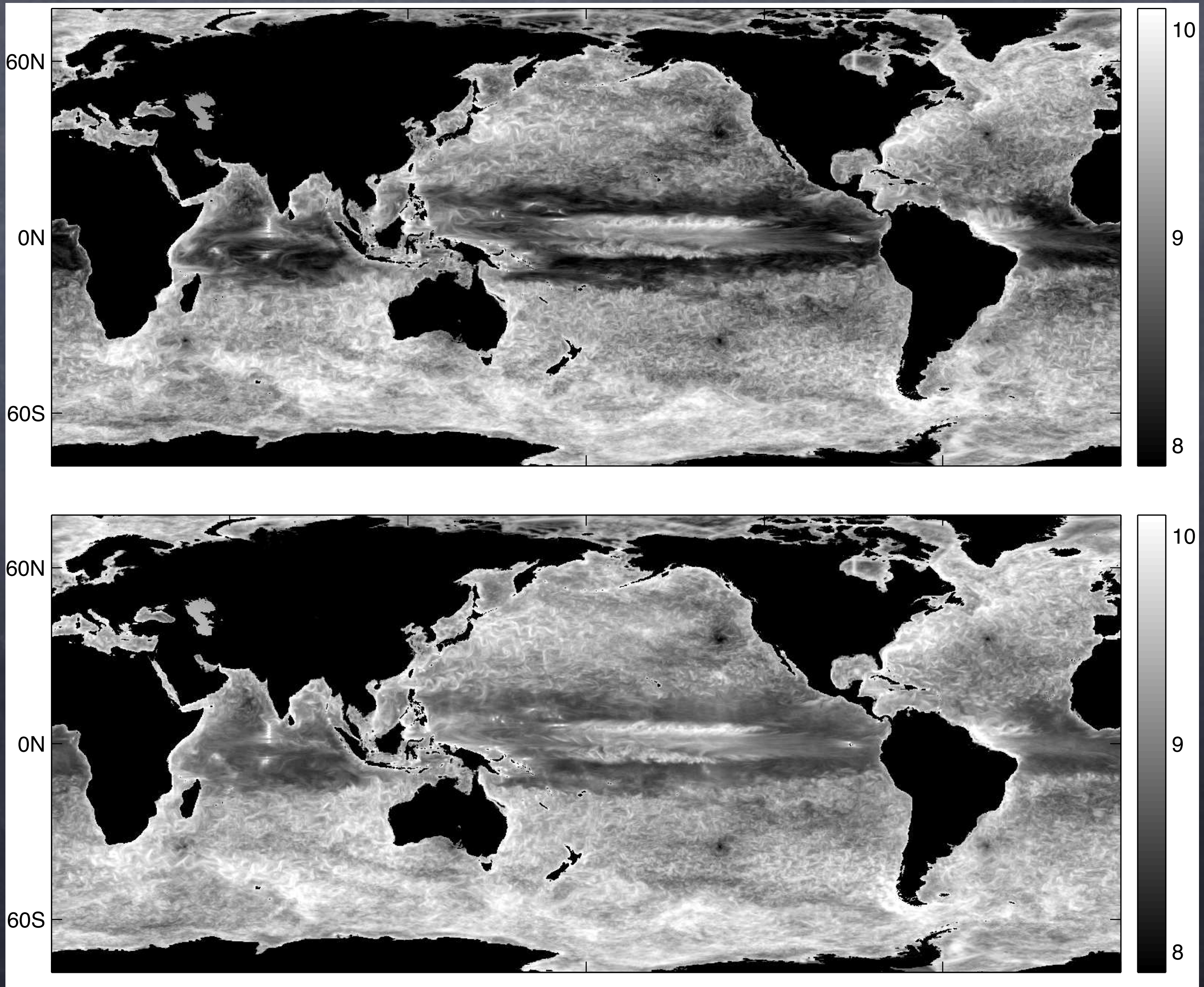
2008: F-K & Menemenlis Revise Leith Viscosity Scaling, So that diverging, vorticity-free, modes are also damped

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

Makes viscosity a bit bigger, especially near Eq.

Leith

F-K&M



But matters a lot for stability!

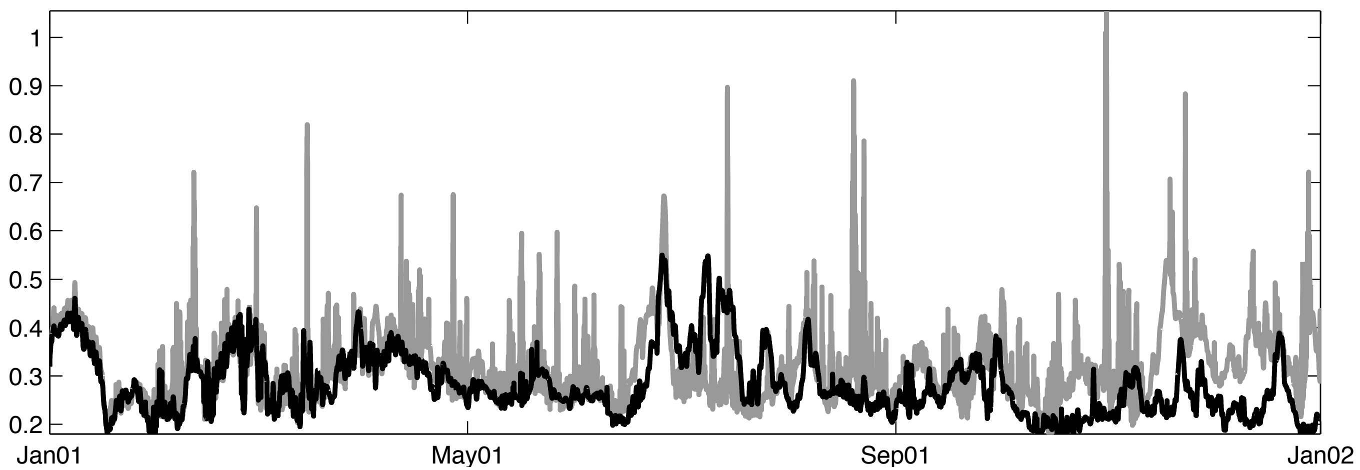
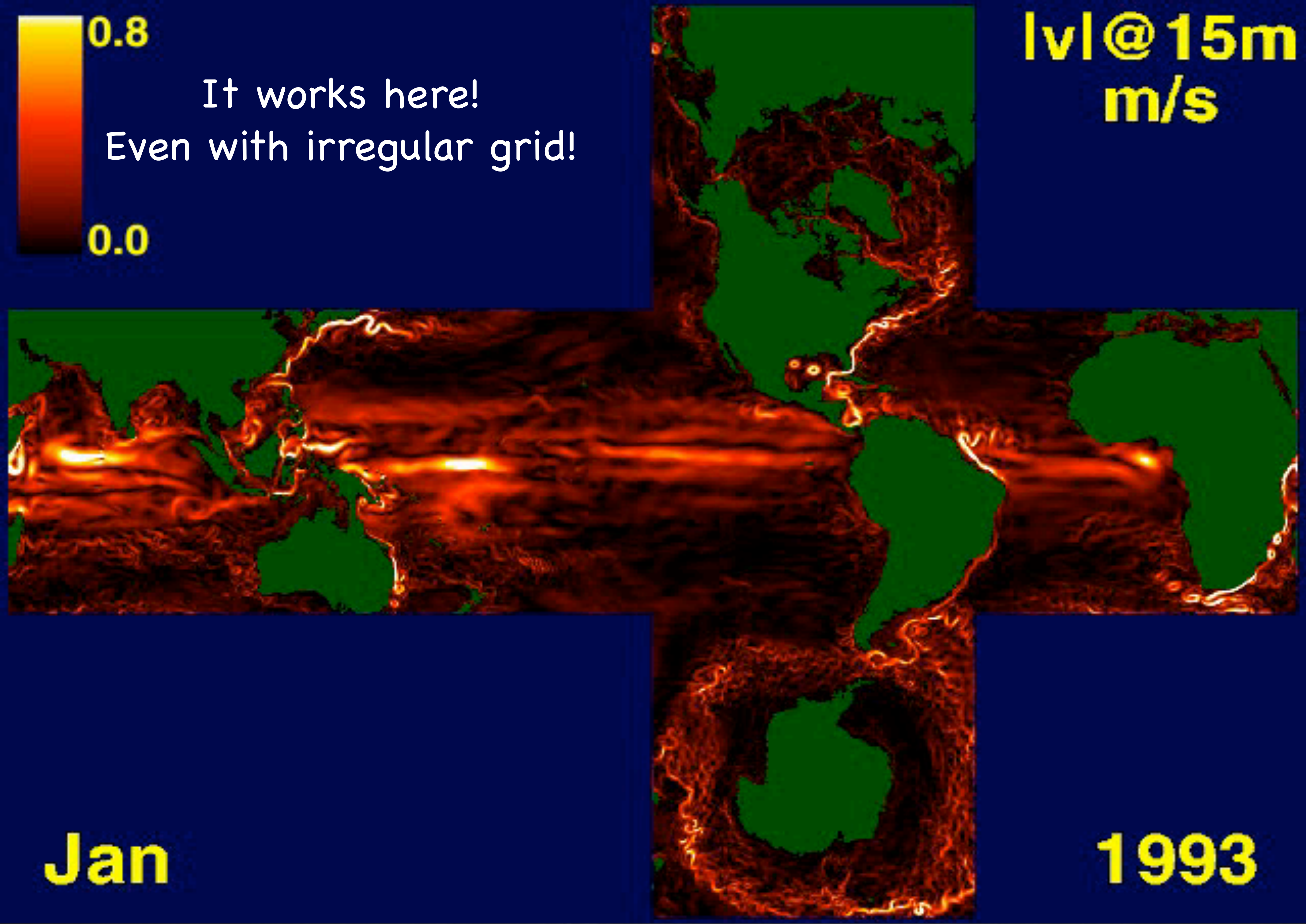


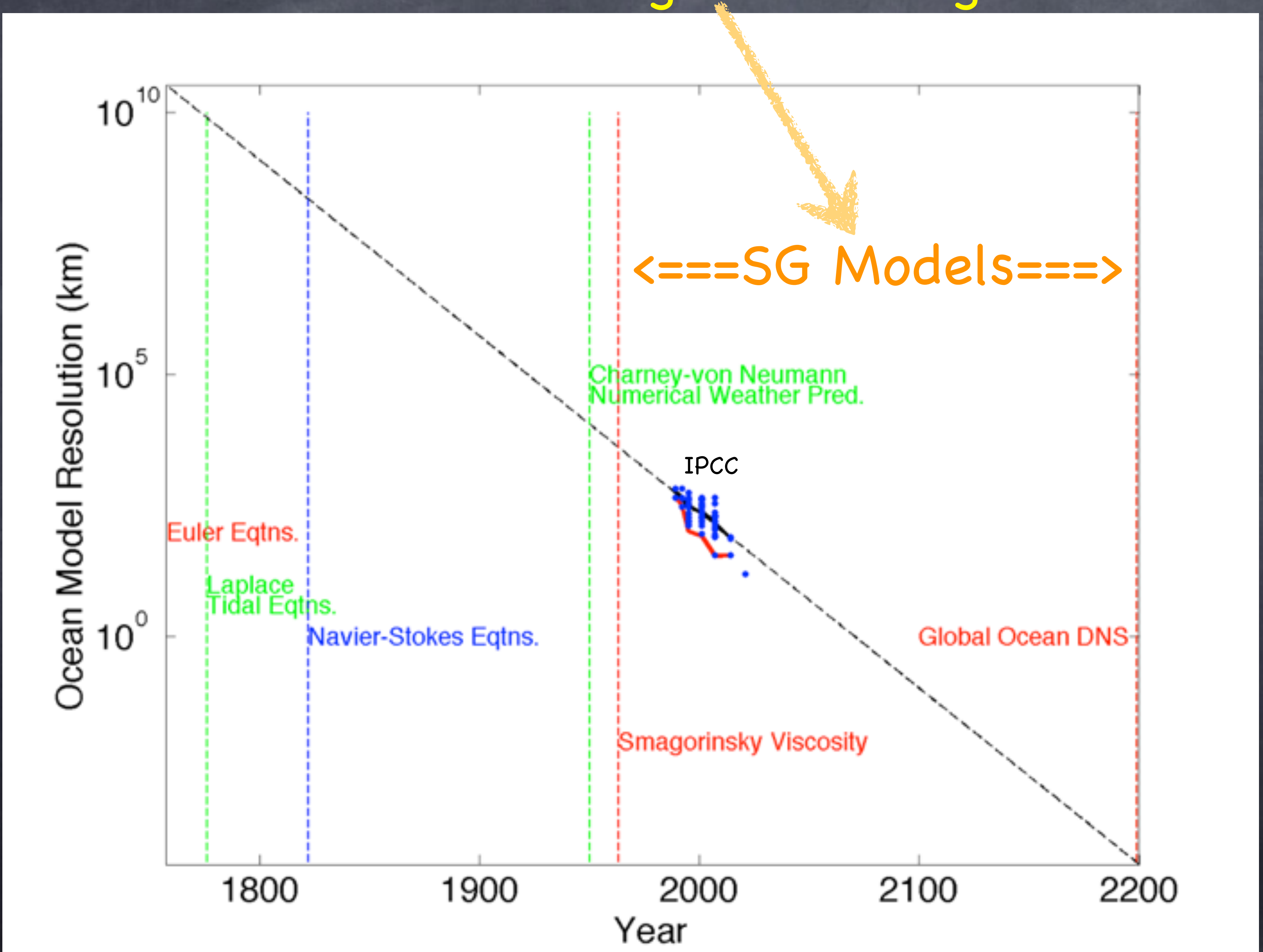
Figure 4. Maximum Courant number, $w\Delta t/\Delta z$, for vertical advection. Gray line is from the *LeithOnly* integration and black line is from the *LeithPlus* integration.

Fox-Kemper & Menemenlis, 2008



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

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



Results

- Biases in climate model on annual to interannual timescales can be attributed (partly) to
  - Submesoscale mixed layer eddy restratification
  - Langmuir turbulence mixing
  - Mesoscale eddy tracer transport
- We have been improving parameterizations
- But much work remains--observational and paleo data validation is still crucial, and insufficient...

All papers at: fox-kemper.com/research

B. Fox-Kemper, R. Lumpkin, and F. O. Bryan. Lateral Transport in the Ocean Interior. Siedler, Church, Gould, & Griffies, ed. *Ocean Circulation and Climate*, 2012, submitted.

B. Fox-Kemper, G. Danabasoglu, R. Ferrari, S. M. Griffies, R. W. Hallberg, M. M. Holland, M. E. Maltrud, S. Peacock, and B. L. Samuels. Parameterization of mixed layer eddies. III: Implementation and impact in global ocean climate simulations. *Ocean Modelling*, 39:61-78, 2011.

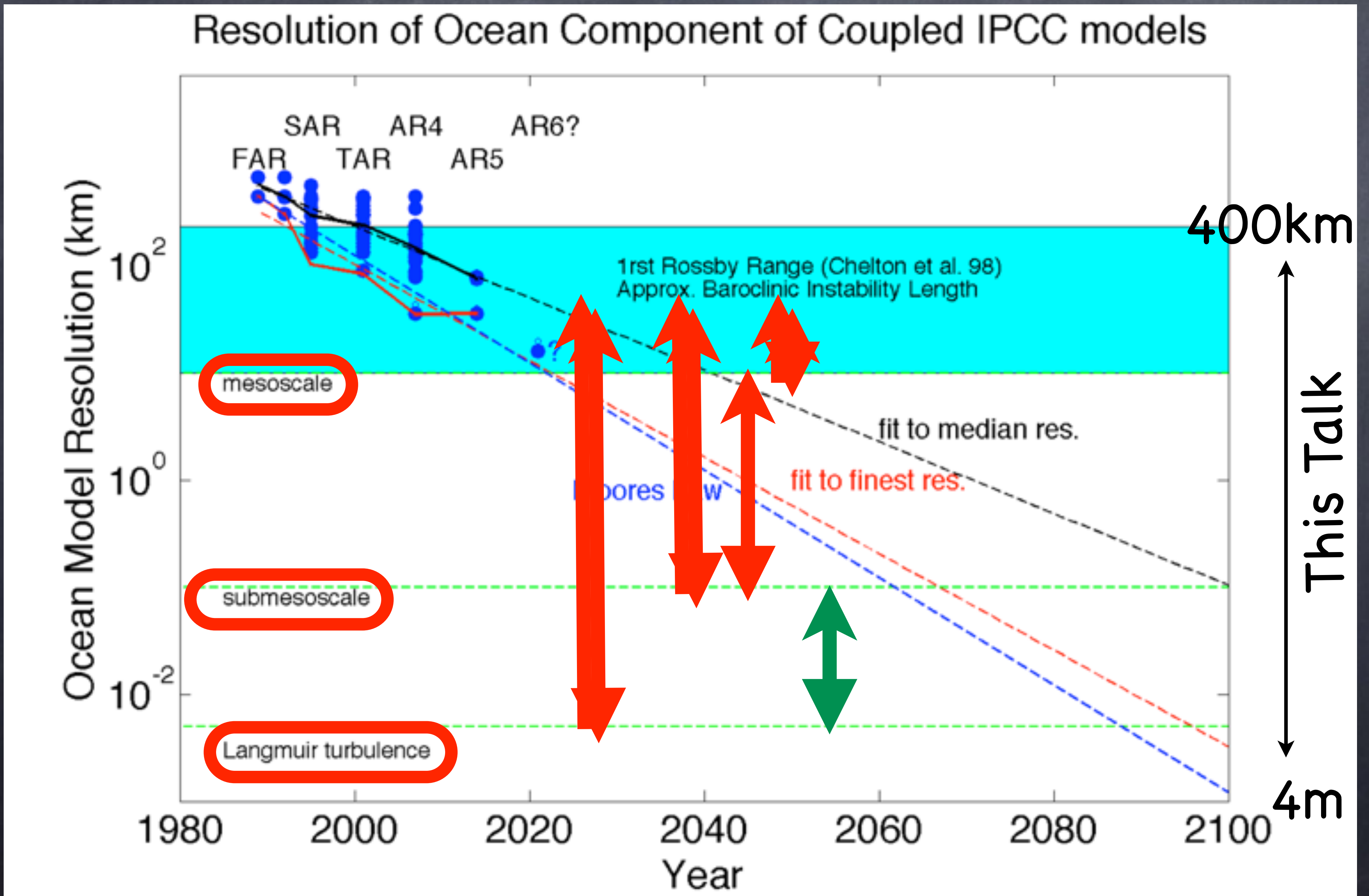
A. Webb and B. Fox-Kemper. Wave spectral moments and Stokes drift estimation. *Ocean Modelling*, 40(3-4):273-288, 2011

L. Van Roekel, B. Fox-Kemper, P. P. Sullivan, P. E. Hamlington, and S. R. Haney. The form and orientation of Langmuir cells for misaligned winds and waves. *Journal of Geophysical Research-Oceans*, 2012. In press.

S. C. Bates, B. Fox-Kemper, S. R. Jayne, W. G. Large, S. Stevenson, and S. G. Yeager. Mean biases, variability, and trends in air-sea fluxes and SST in the CCSM4.Journal of Climate, 2012. Submitted.

L. Cavaleri, B. Fox-Kemper, and M. Hemer. Wind waves in the coupled climate system. *Bulletin of the American Meteorological Society*, 2012. In press.

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



But, do cascades exist in the ocean?

McCaffrey & F-K, OSM

Structure Function Results

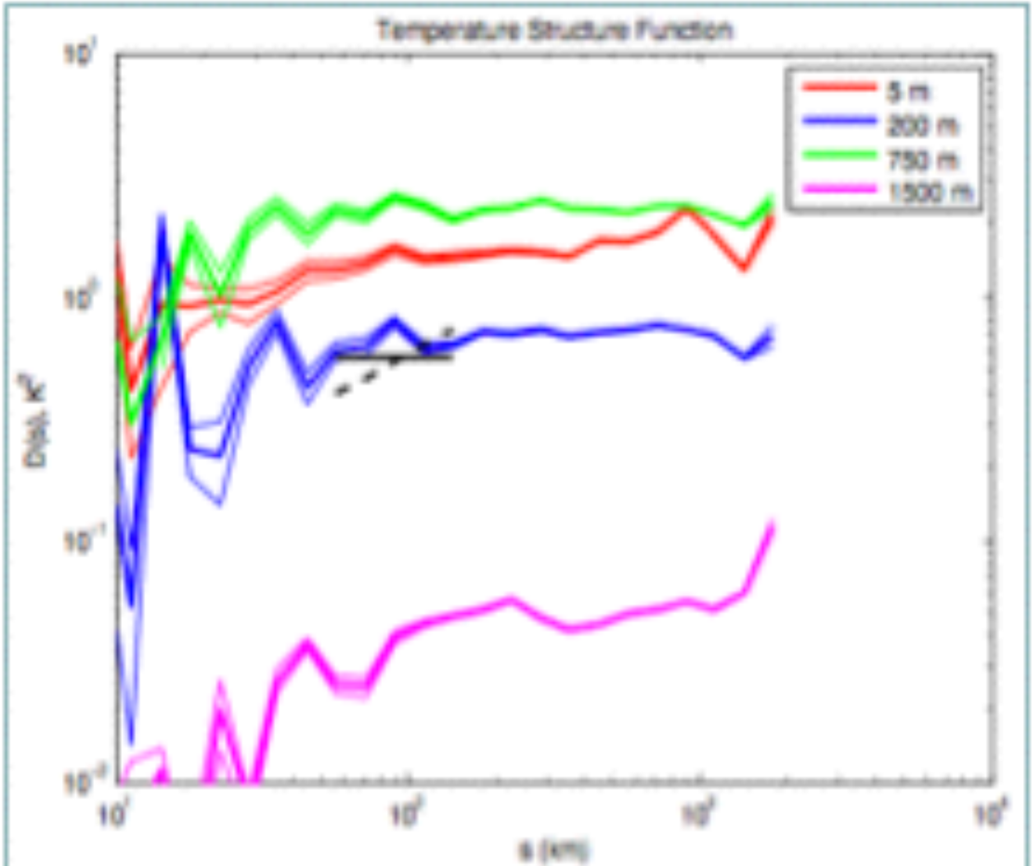


Figure 3: Structure function in south central Atlantic for 5, 200, 750, and 1500m. Also included are two black lines showing spectral slopes of 2/3 (dashed) and 0 (solid).

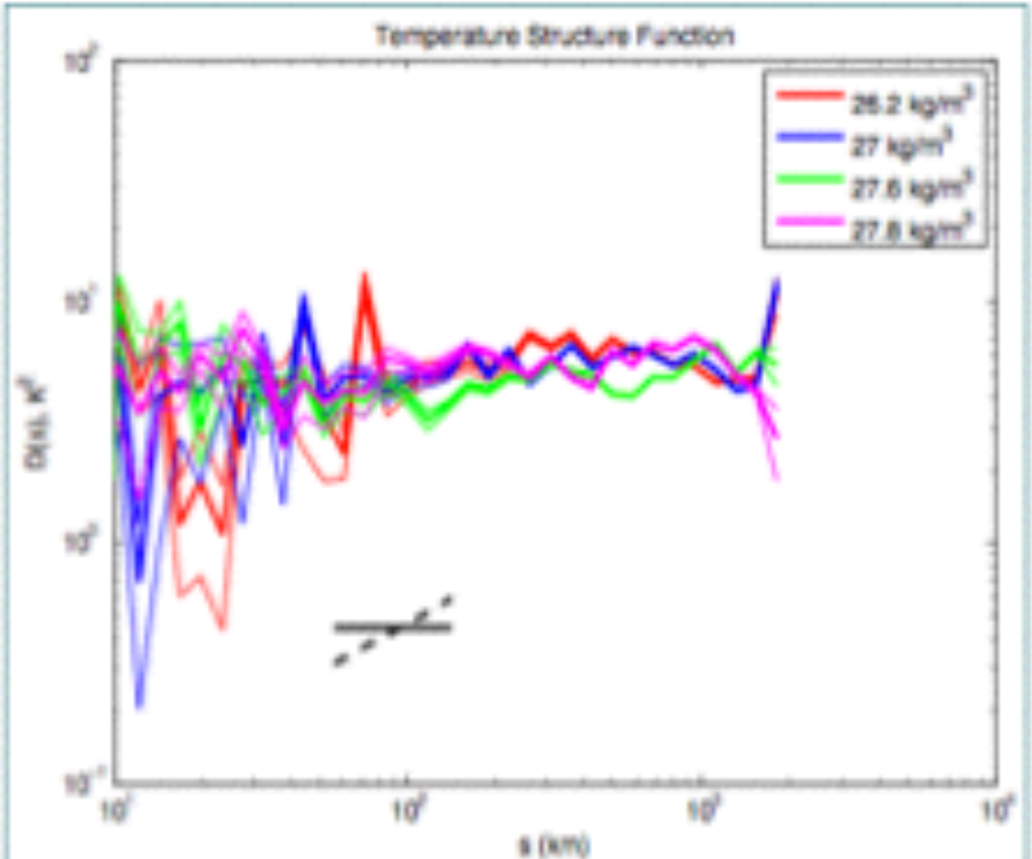


Figure 4: Structure function in the south central Atlantic for 26.2, 27, 27.6 and 27.8 kg/m³. Also included are two black lines showing spectral slopes of 2/3 (dashed) and 0 (solid).