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

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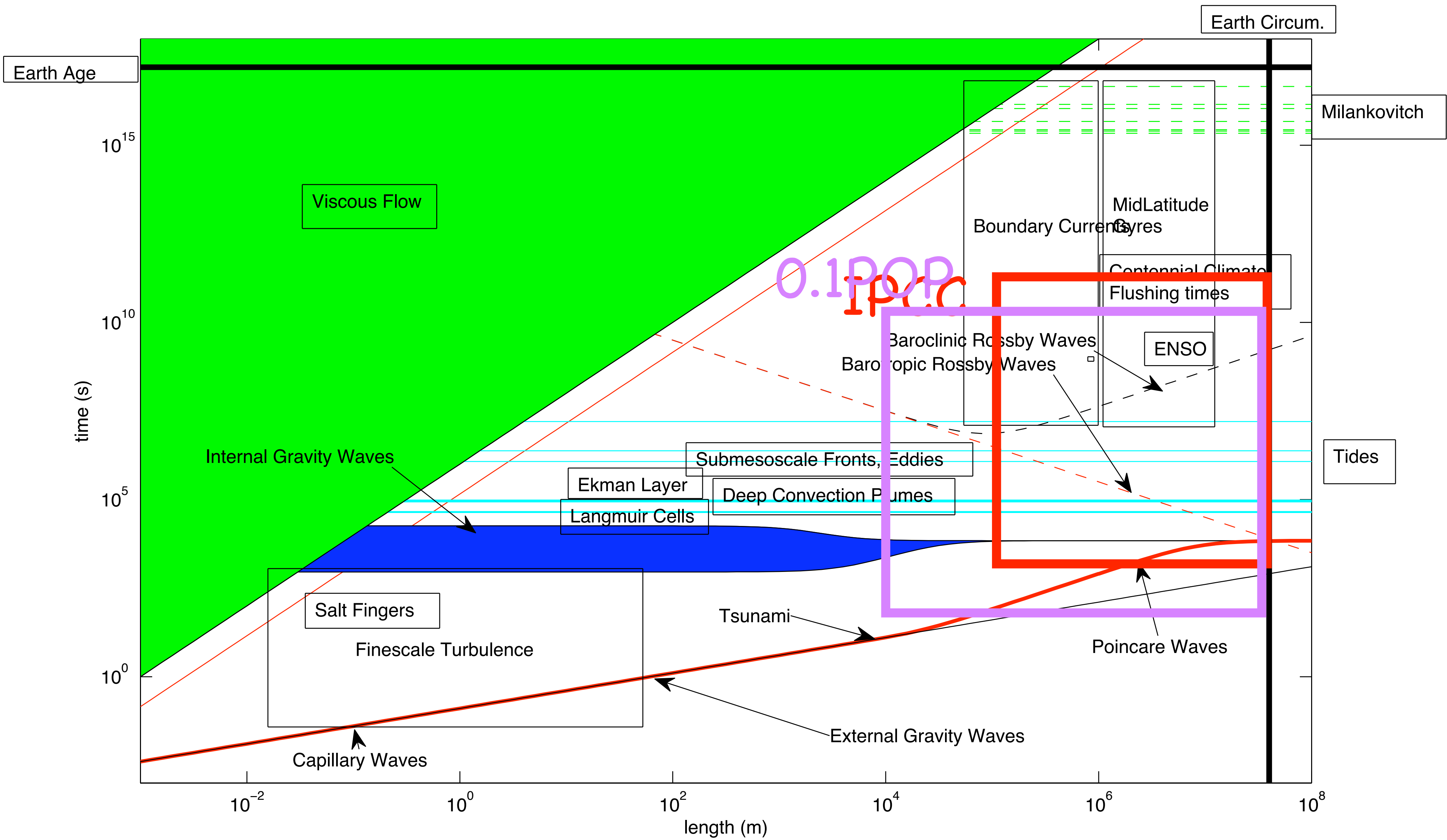
Keith Julien, Raf Ferrari, NCAR Oceanography Section, Peter Sullivan

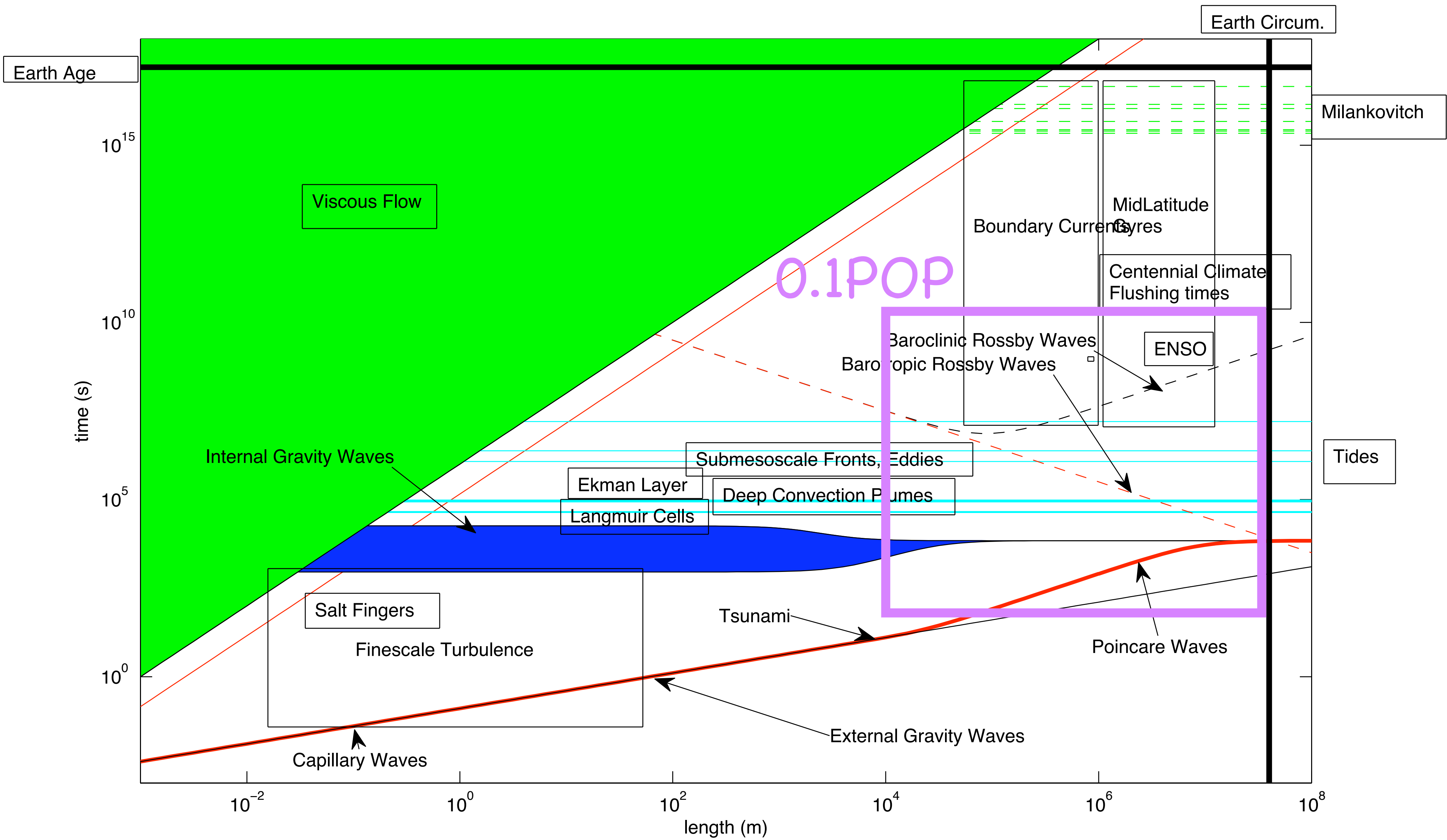
TOY, 5/16/12

Sponsors: NSF, NASA, CIRES, CU, UCAR

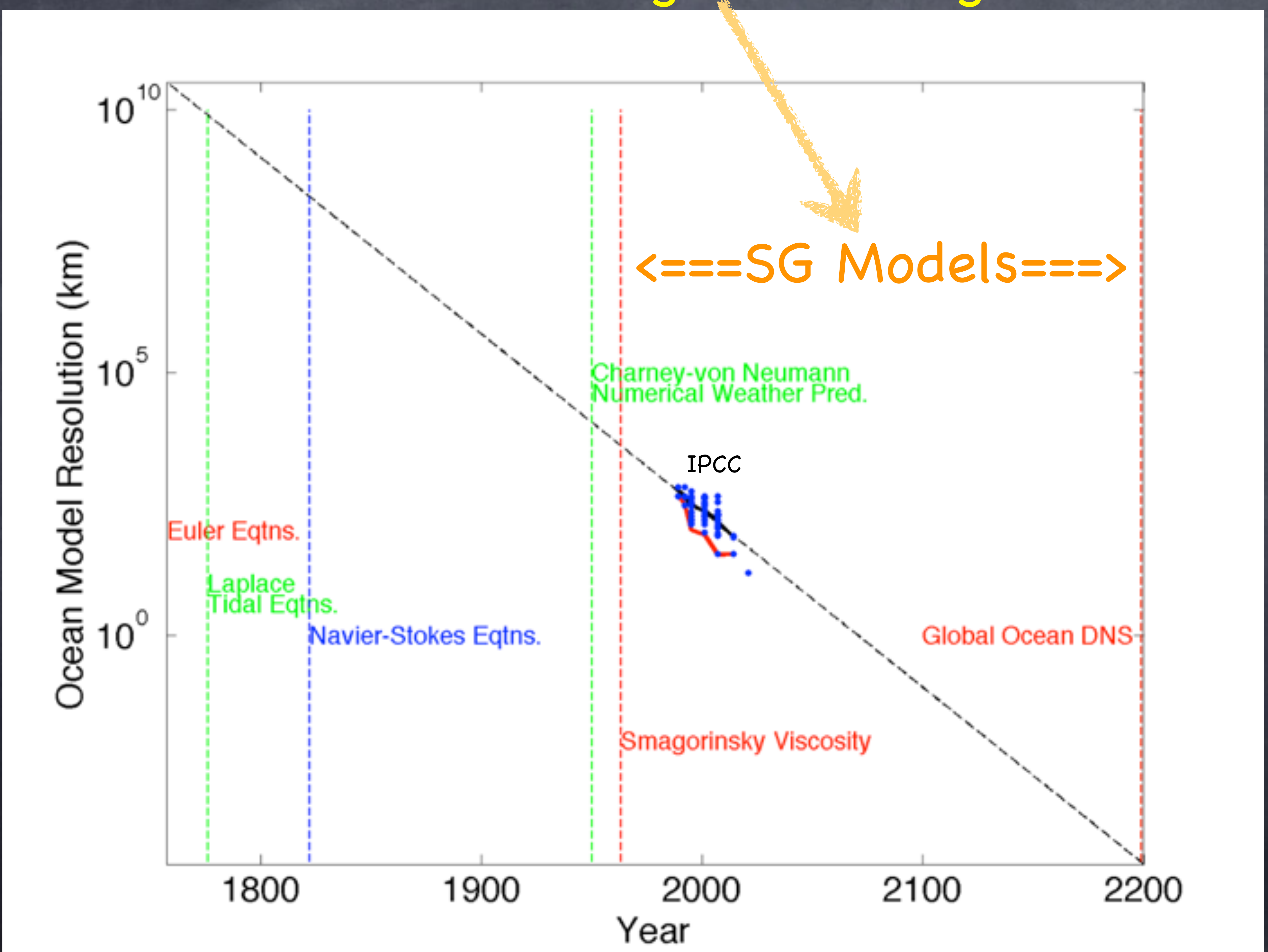
The Ocean is Vast and Diverse



The Ocean is Vast and Diverse



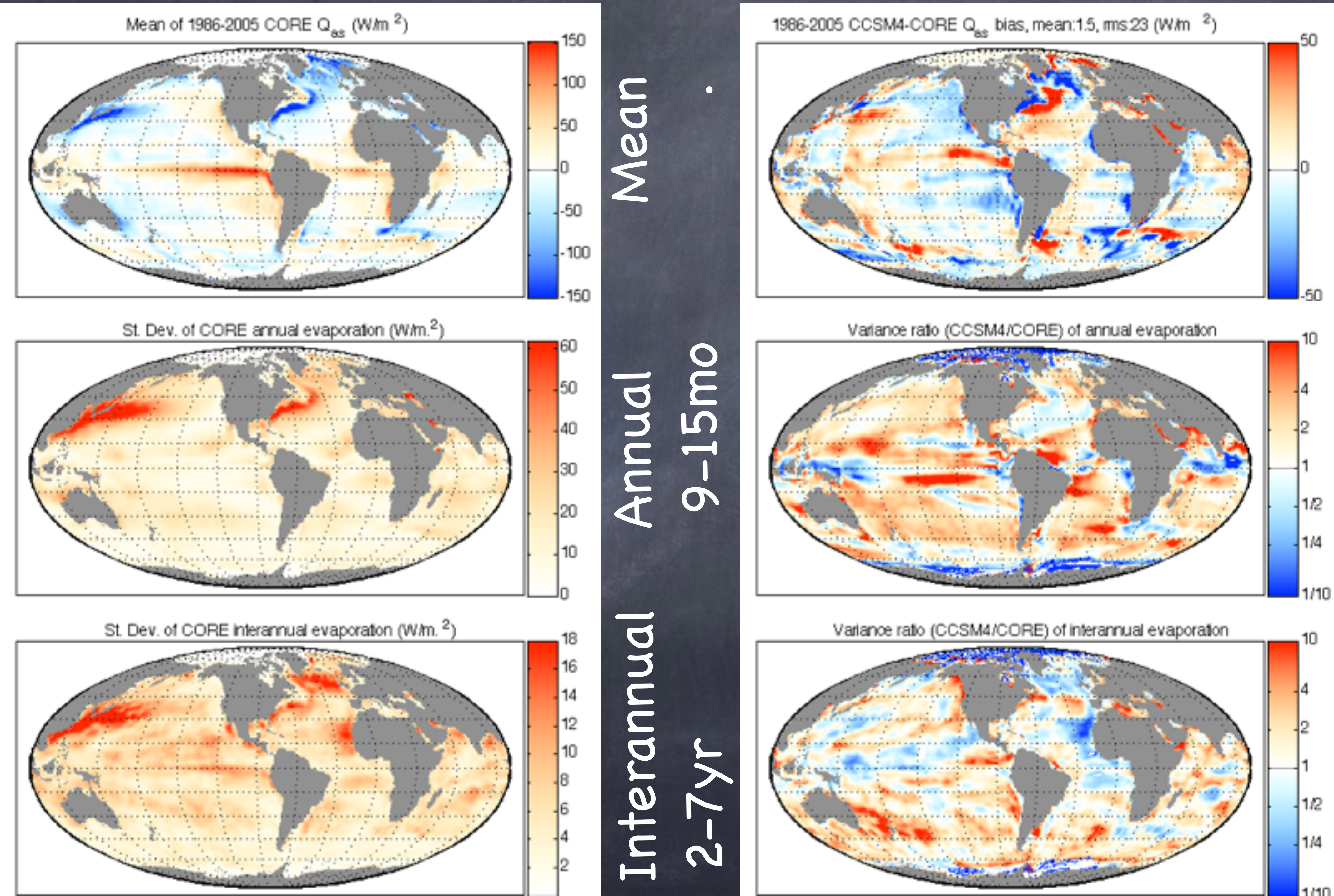
Extrapolate for historical perspective: The Golden Era of Subgrid Modeling is Now!



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. Data (Large & Yeager 09)



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.

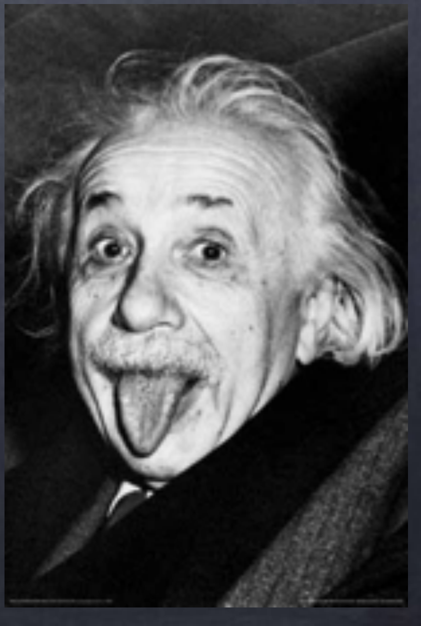
S. C. Bates, B. Fox-Kemper, S. R. Jayne, W. G. Large, S. Stevenson, and S. G. Yeager. Mean biases, variability, and trends in air-sea fluxes and SST in the CCSM4.Journal of Climate, 2012. Submitted.

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

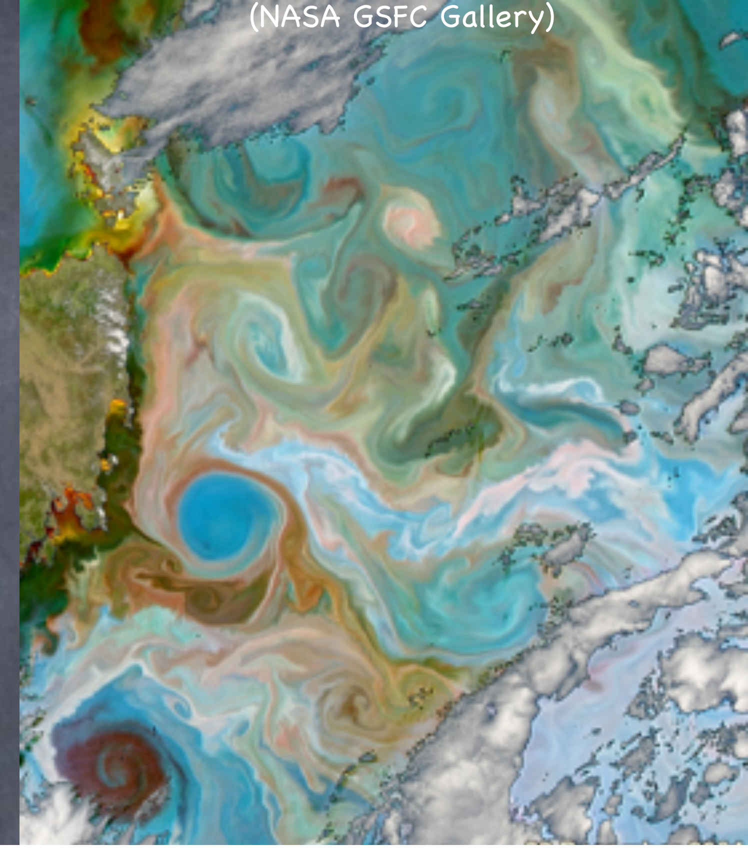
Parameterizations

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

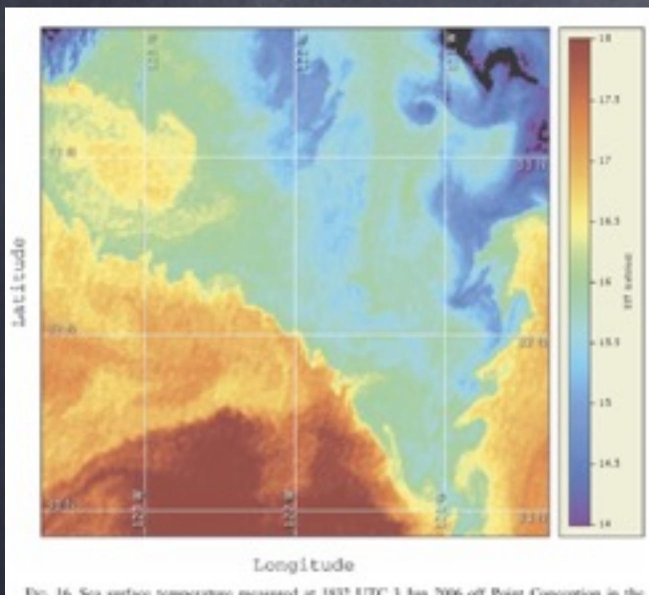


The Character of the Submesoscale

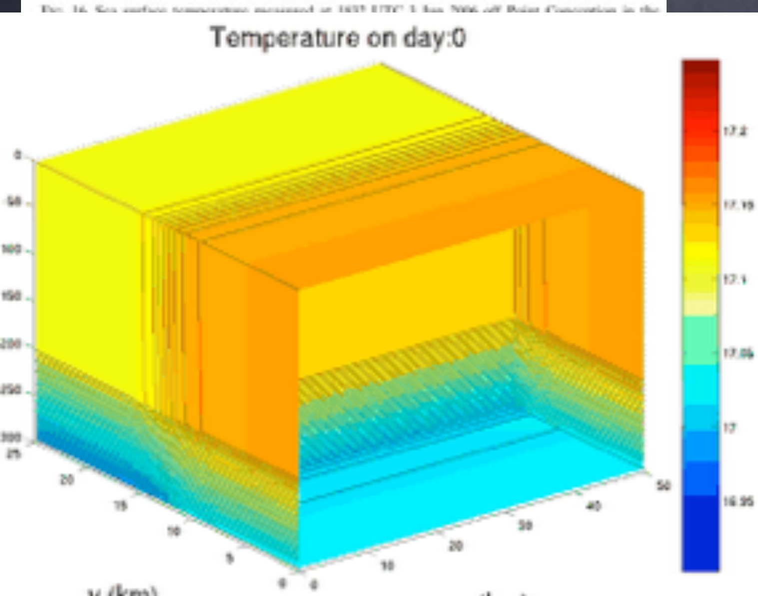
10 km



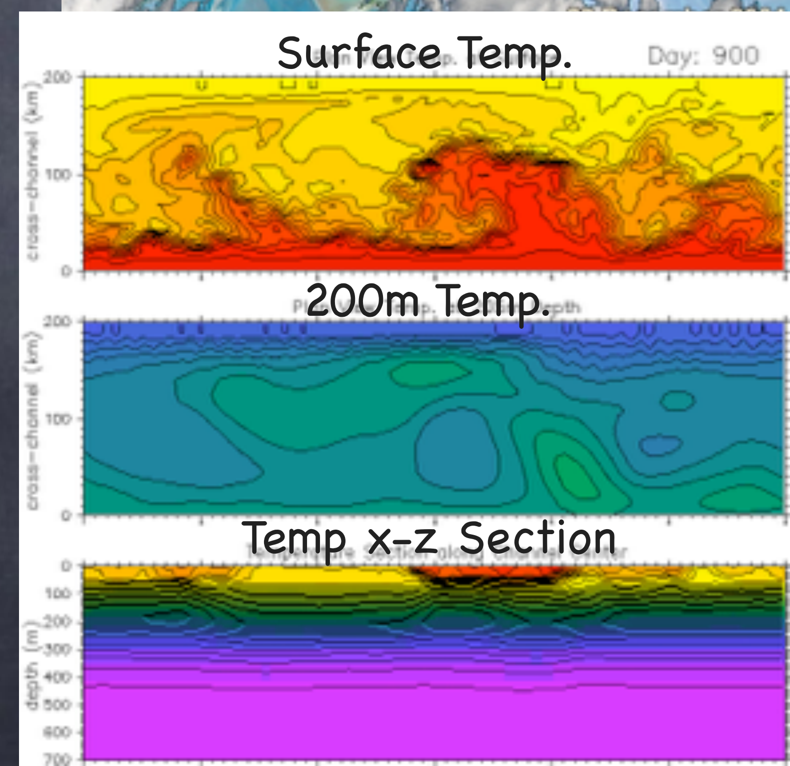
(Capet et al., 2008)



- 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:

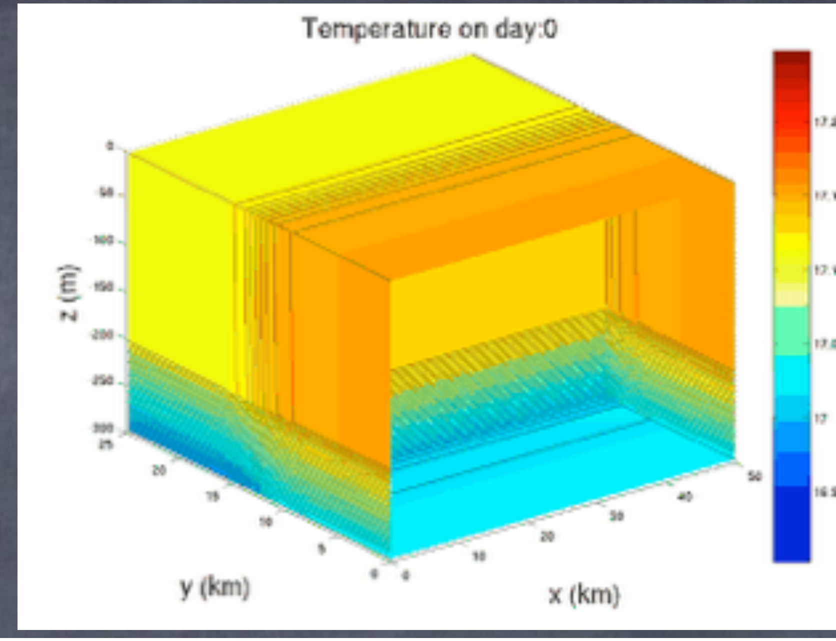
$$\mu(z) = 0 \text{ if } z < -H$$

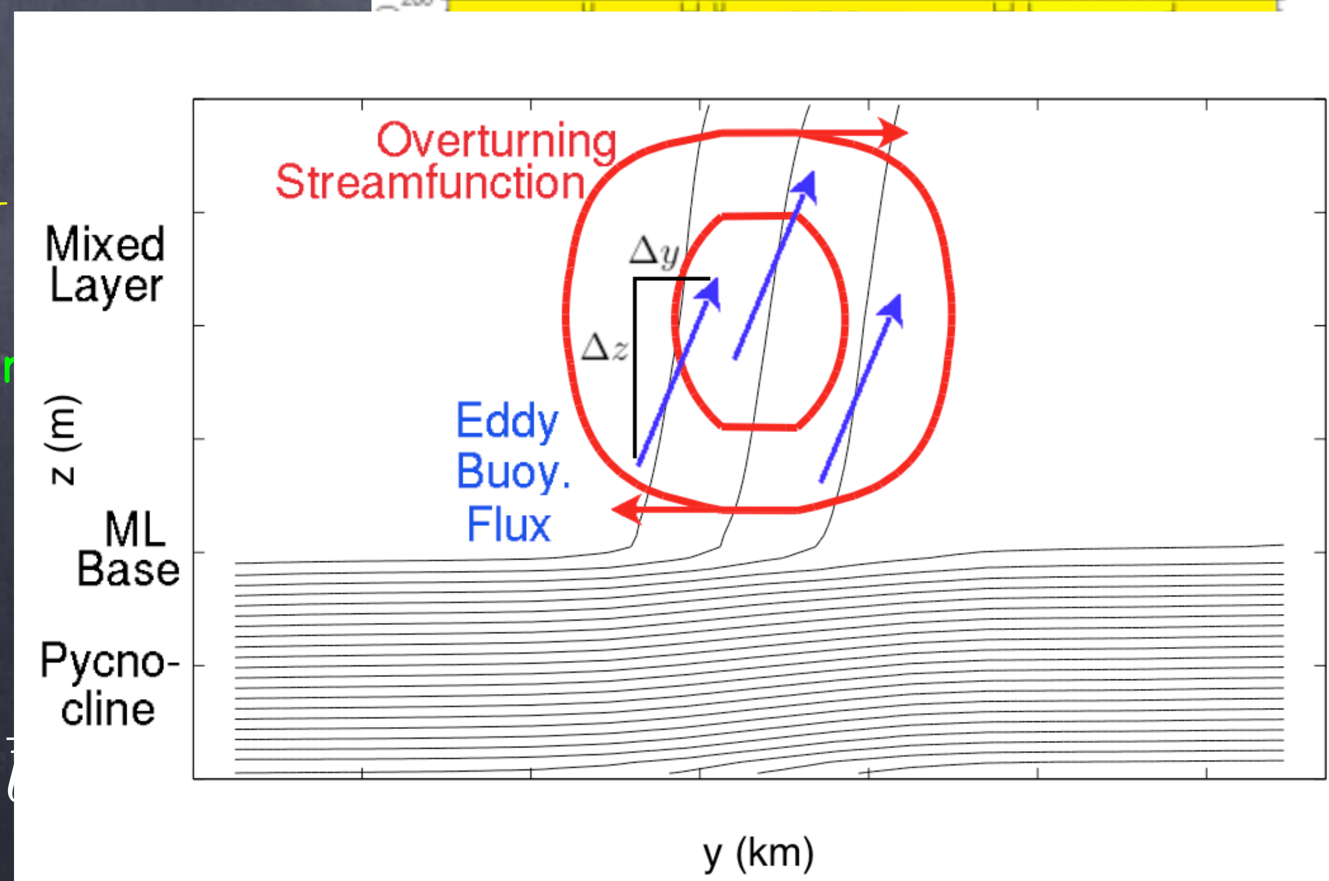
For a consistently restratifyi

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

and horizontally downgradient

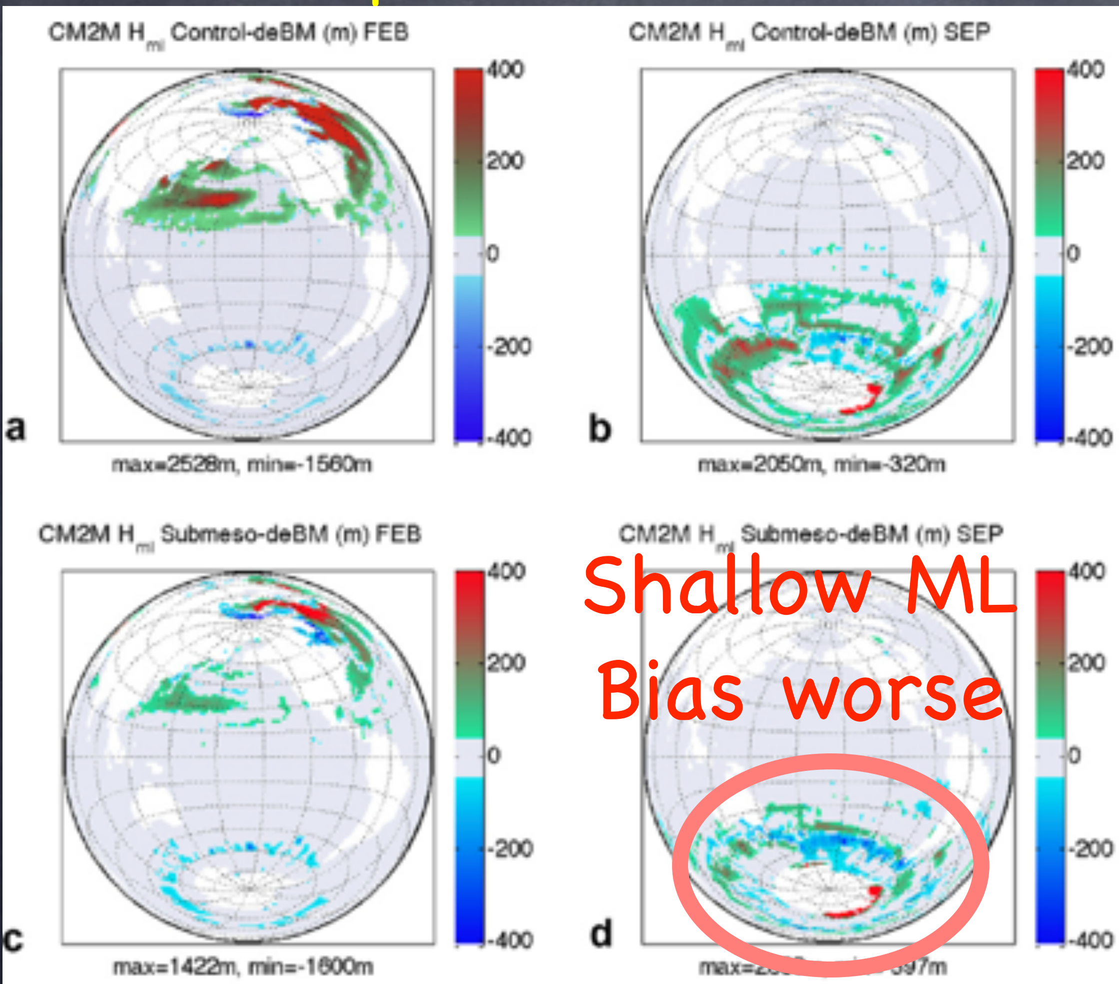
$$\overline{\mathbf{u}'_H b'} \propto \frac{-H^2 \frac{\partial \bar{b}}{\partial z}}{|f|} \nabla_H$$





Physical Sensitivity of Ocean Climate to Submesoscale Eddy Restratification:

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



Bias w/o MLE

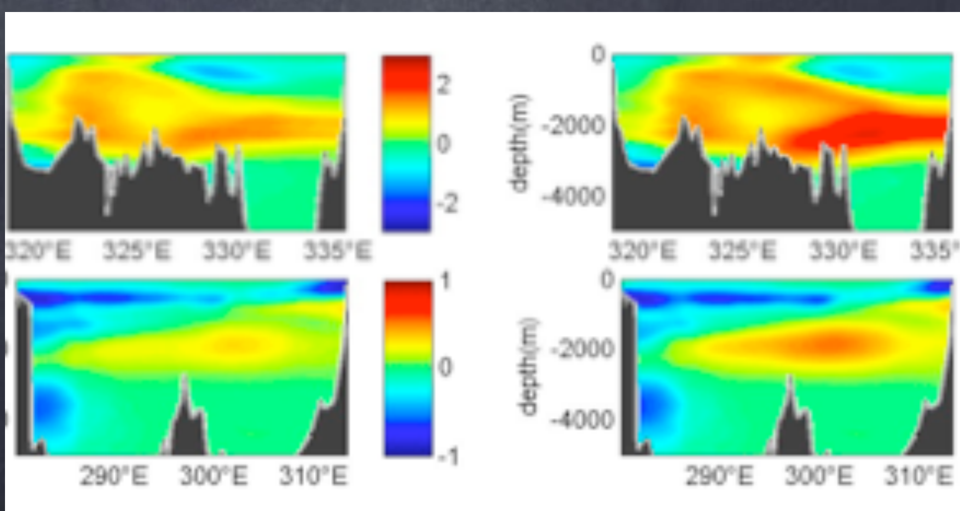
NO RETUNING NEEDED!!!

Improves CFCs (water masses)

Deep ML Bias reduced

Bias with MLE

Bias w/o MLE

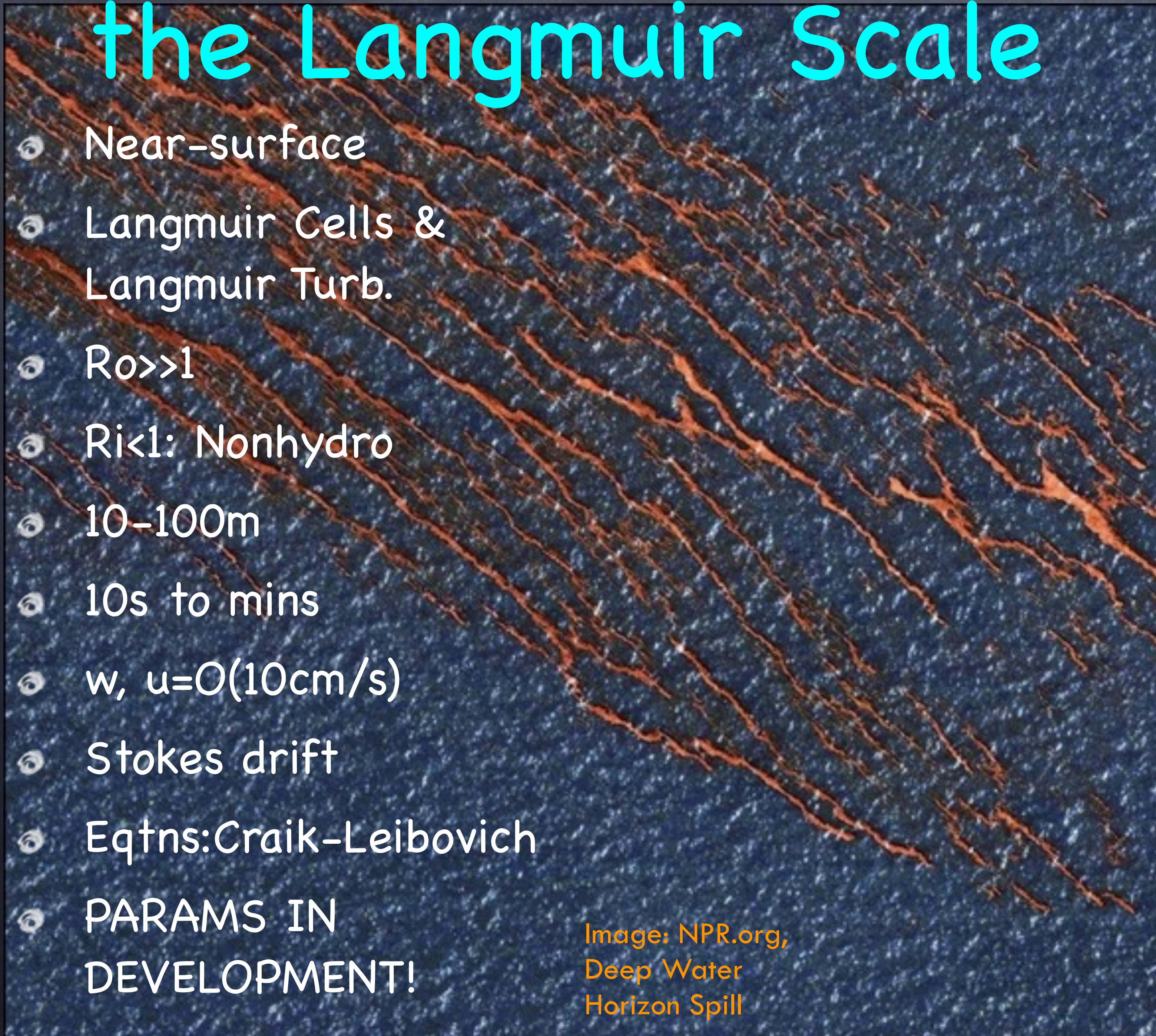


B. Fox-Kemper, G. Danabasoglu, R. Ferrari, S. M. Griffies, R. W. Hallberg, M. M. Holland, M. E. Maltrud, S. Peacock, and B. L. Samuels. Parameterization of mixed layer eddies. III: Implementation and impact in global ocean climate simulations. *Ocean Modelling*, 39:61-78, 2011.

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

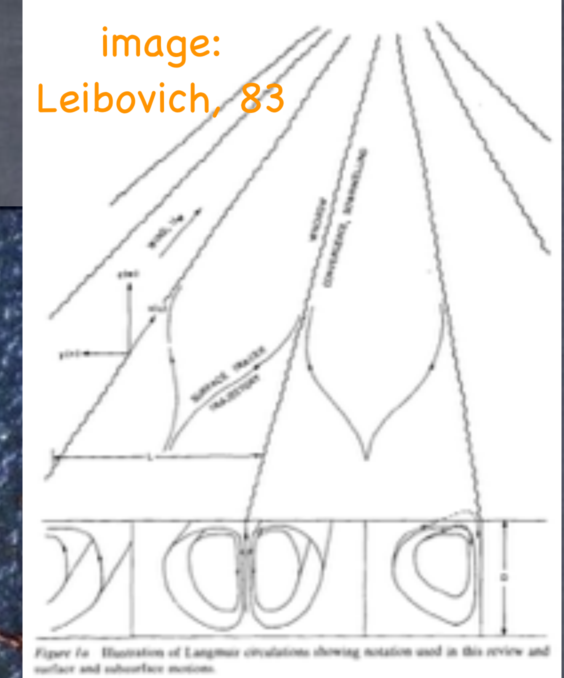
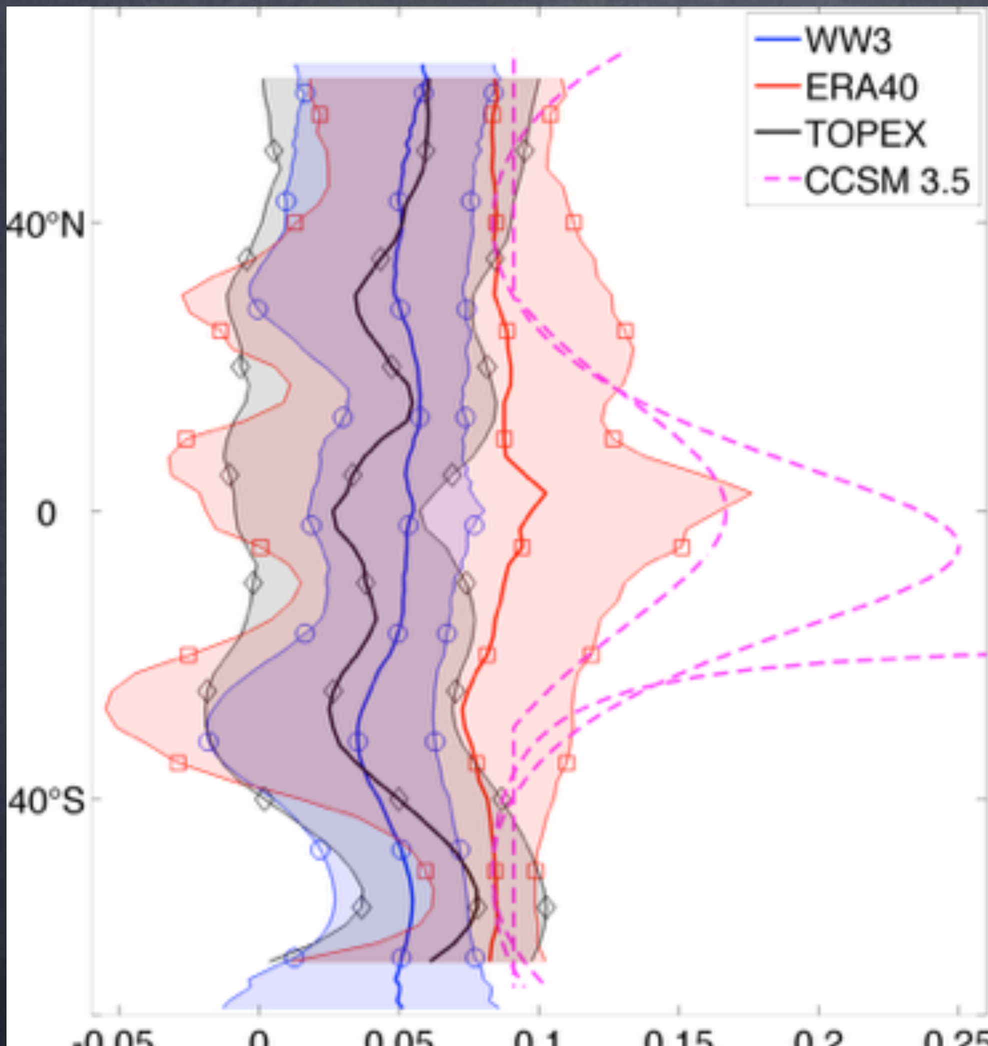


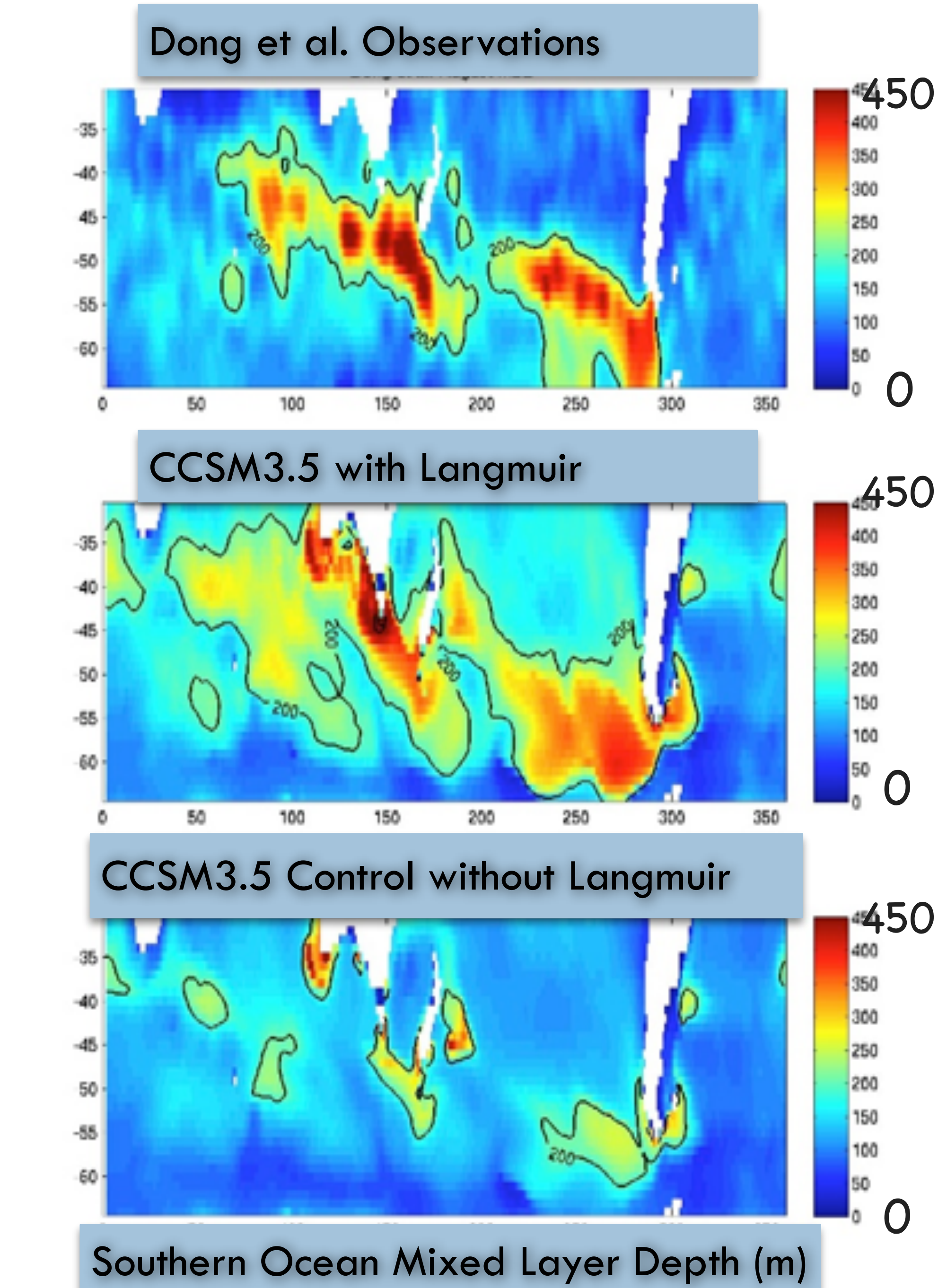
image: Leibovich, 83

Langmuir Mixing Estimate from Climatology (Wind->Wave)



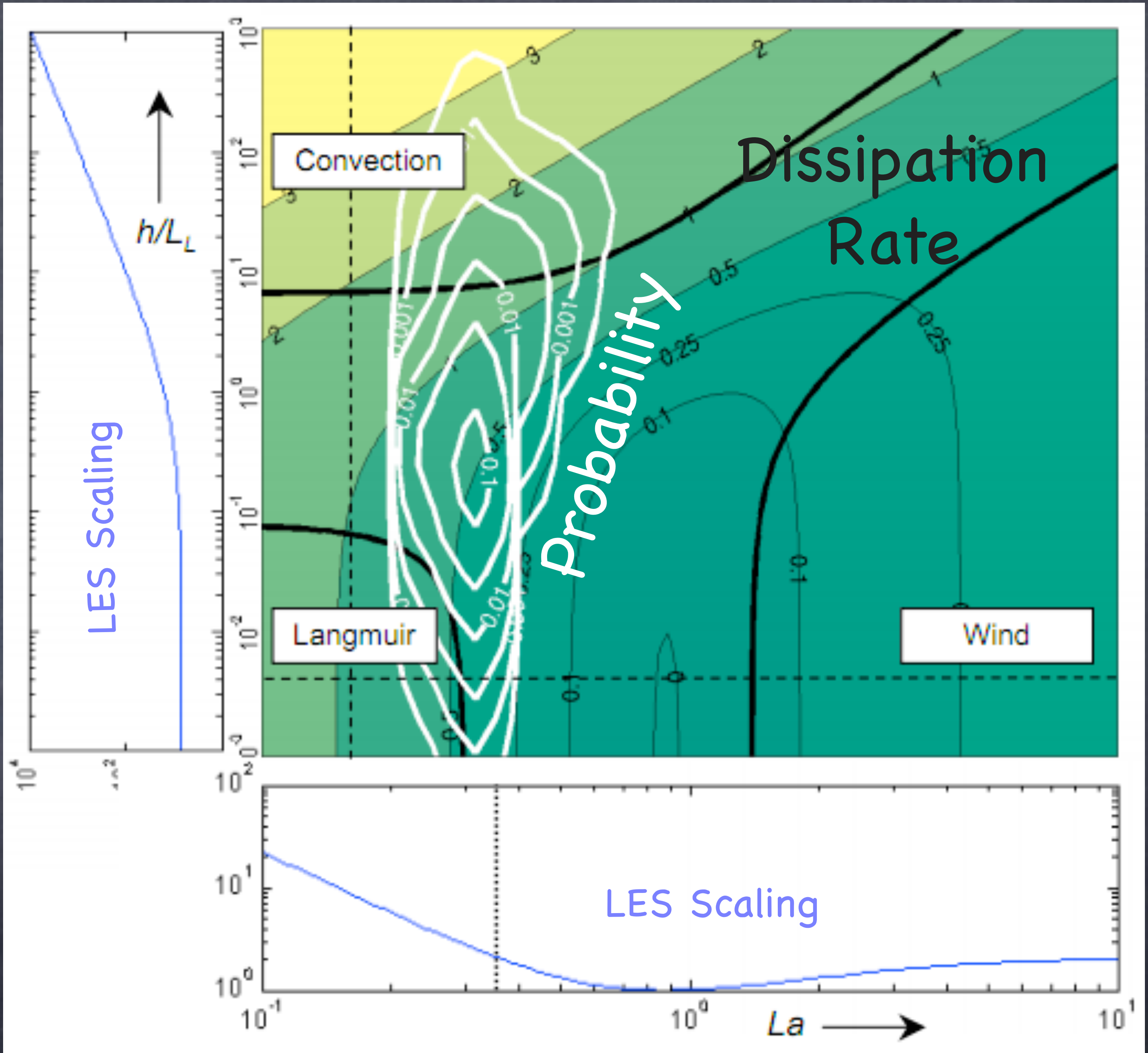
La²

UNDERESTIMATES WAVE IMPACT



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

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.

How well do we know Stokes Drift?

Reanalysis vs wave model

Altimetry vs wave model

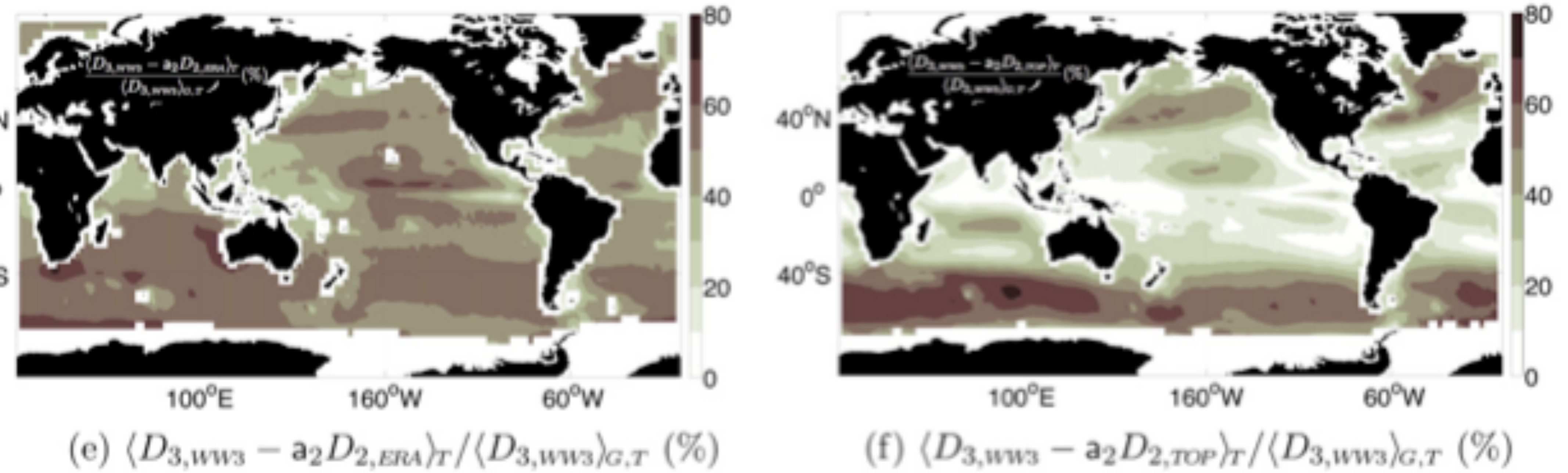


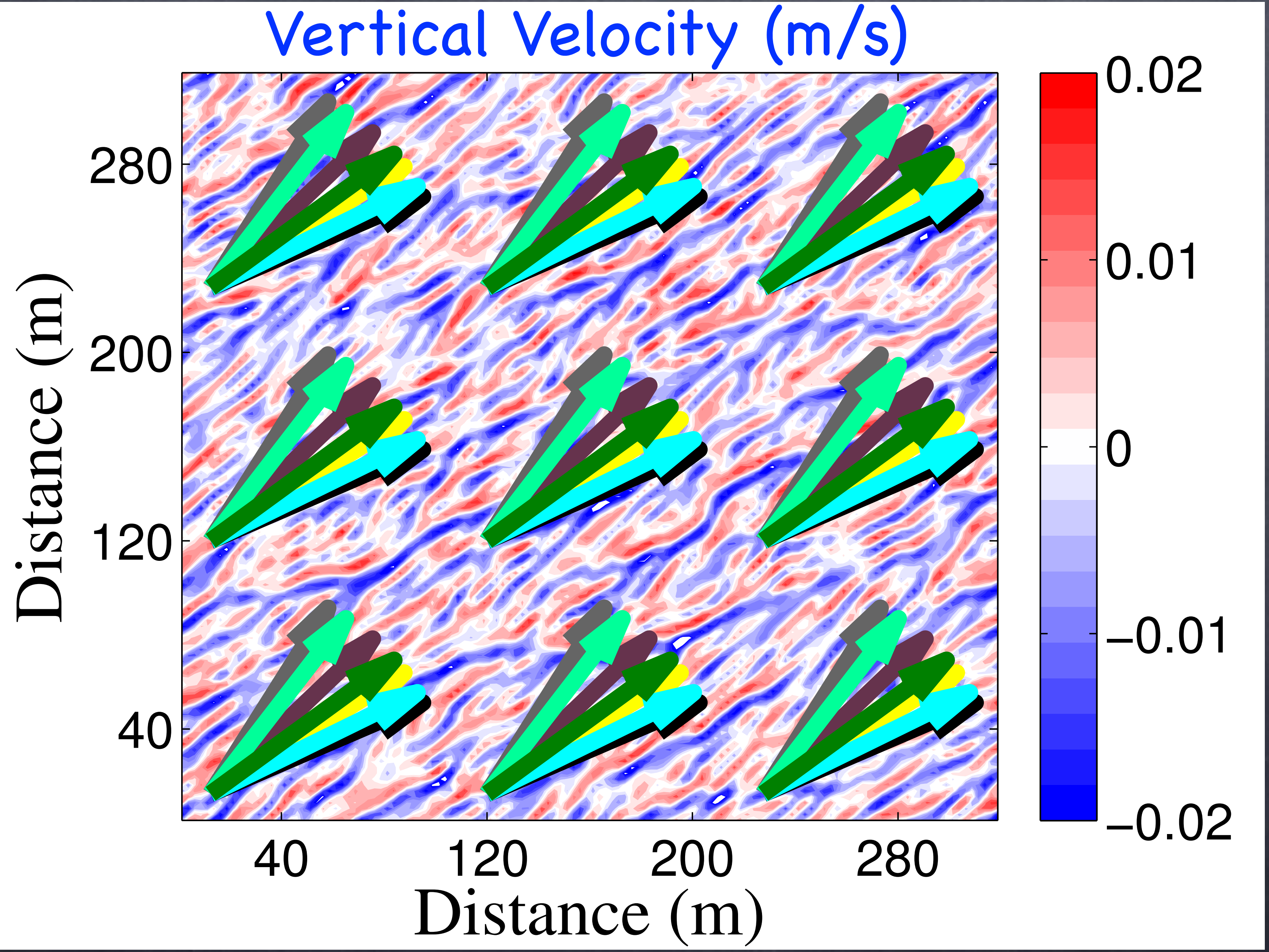
Fig. 4. D_2 Comparison of ERA40 reanalysis and TOPEX satellite data with WW3 using eight year means (1994–2001).

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



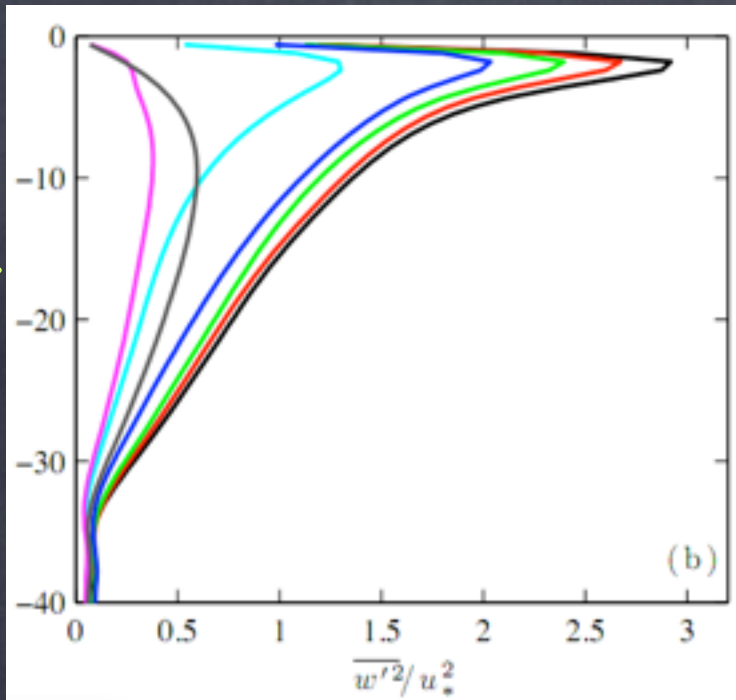
L. Van Roekel, B. Fox-Kemper, P. P. Sullivan, P. E. Hamlington, and S. R. Haney. The form and orientation of Langmuir cells for misaligned winds and waves. *Journal of Geophysical Research-Oceans*, 2012. In press.

Generalized Turbulent Langmuir No.,

Projection of u*, u_s into Langmuir Direction

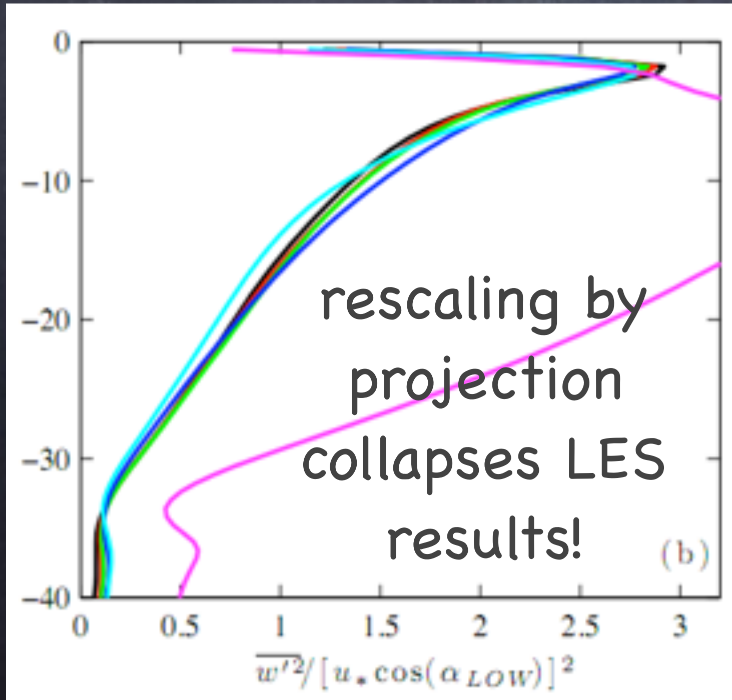
<w²>

depth



rescaled <w²>

depth



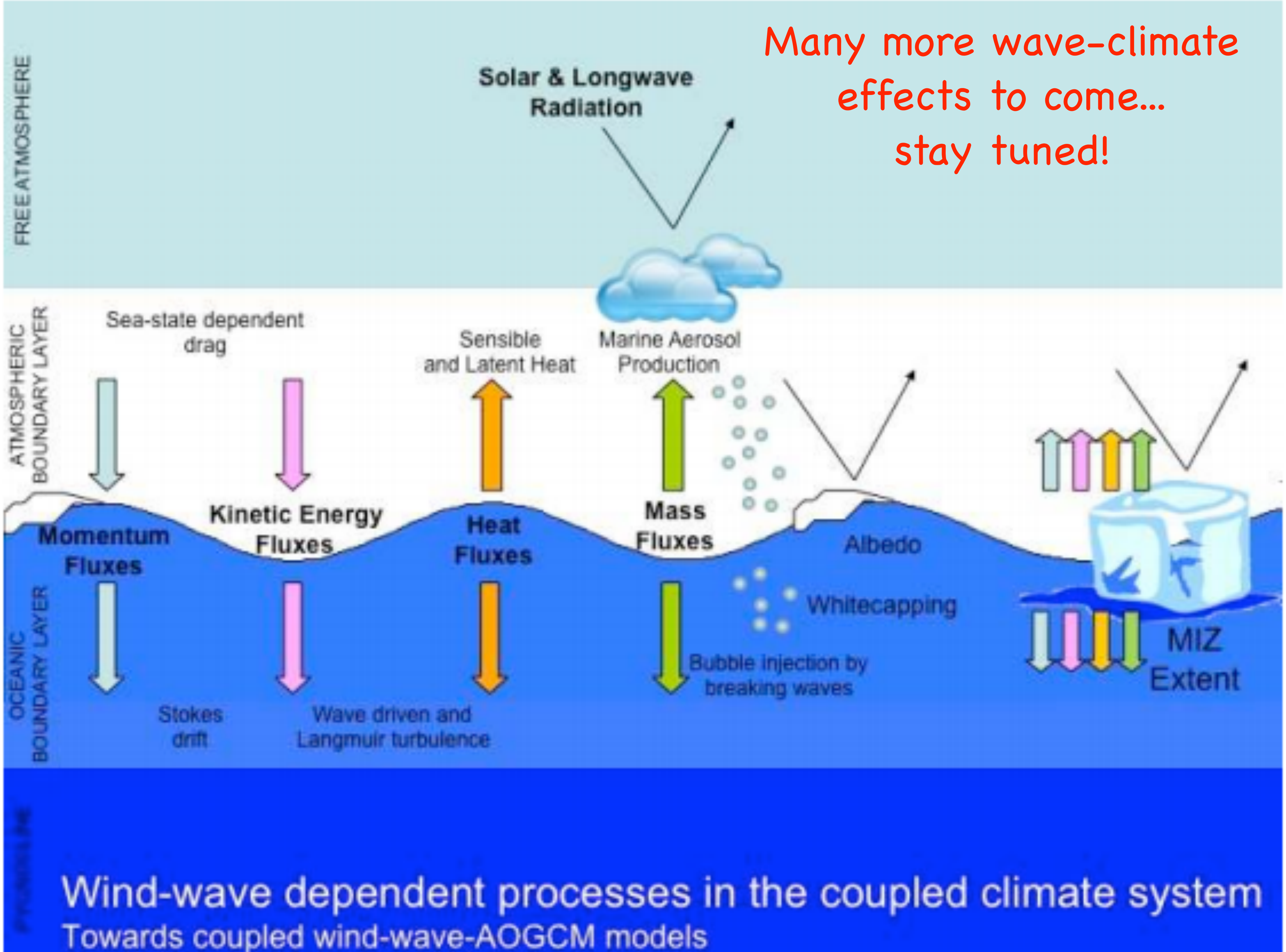
$$\frac{\left\langle \overline{w'^2} \right\rangle_{ML}}{u_*^2} = 0.6 \cos^2(\alpha_{LOW}) \left[1.0 + (3.1 La_{proj})^{-2} + (5.4 La_{proj})^{-4}\right],$$

$$La_{proj}^2 = \frac{|u_*| \cos(\alpha_{LOW})}{|u_s| \cos(\theta_{ww} - \alpha_{LOW})},$$

$$\alpha_{LOW} \approx \tan^{-1}\left(\frac{\sin(\theta_{ww})}{\frac{u_*}{u_s(0)\kappa} \ln\left(\left|\frac{H_{ML}}{z_1}\right|\right) + \cos(\theta_{ww})}\right)$$

A scaling for LC strength & direction!

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.



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?

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)

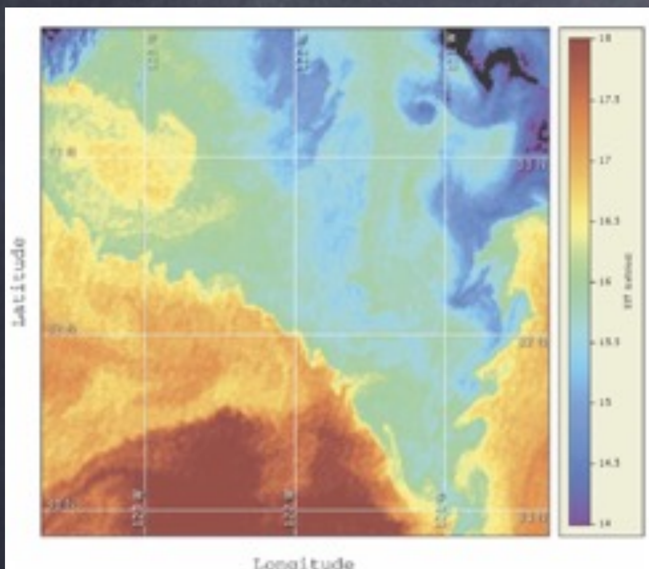
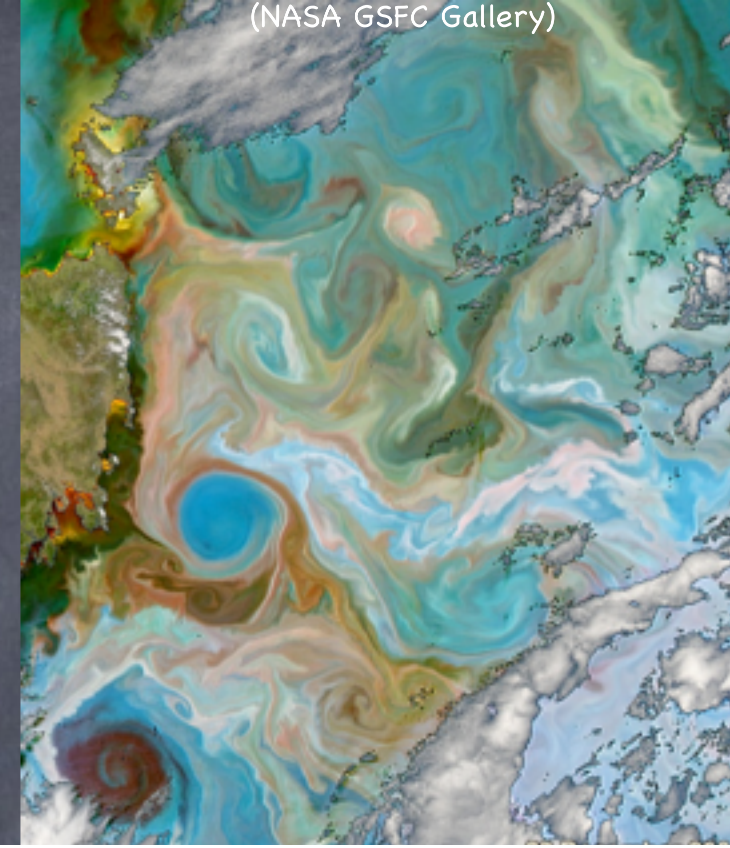
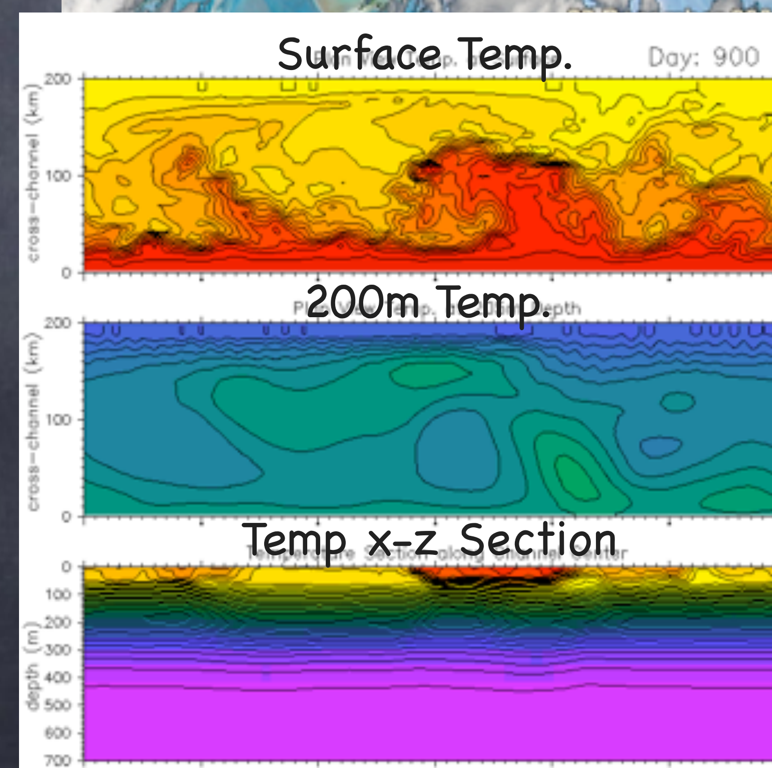


FIG. 16. Sea surface temperature measured at 1832 UTC 3 Jun 2006 off Point Conception in the California Current from CoastWatch (http://coastwatch.pfeg.noaa.gov). The fronts between recently upwelled water (i.e., 15°–16°C) and offshore water (>17°C) show submesoscale instabilities with wavelengths around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

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

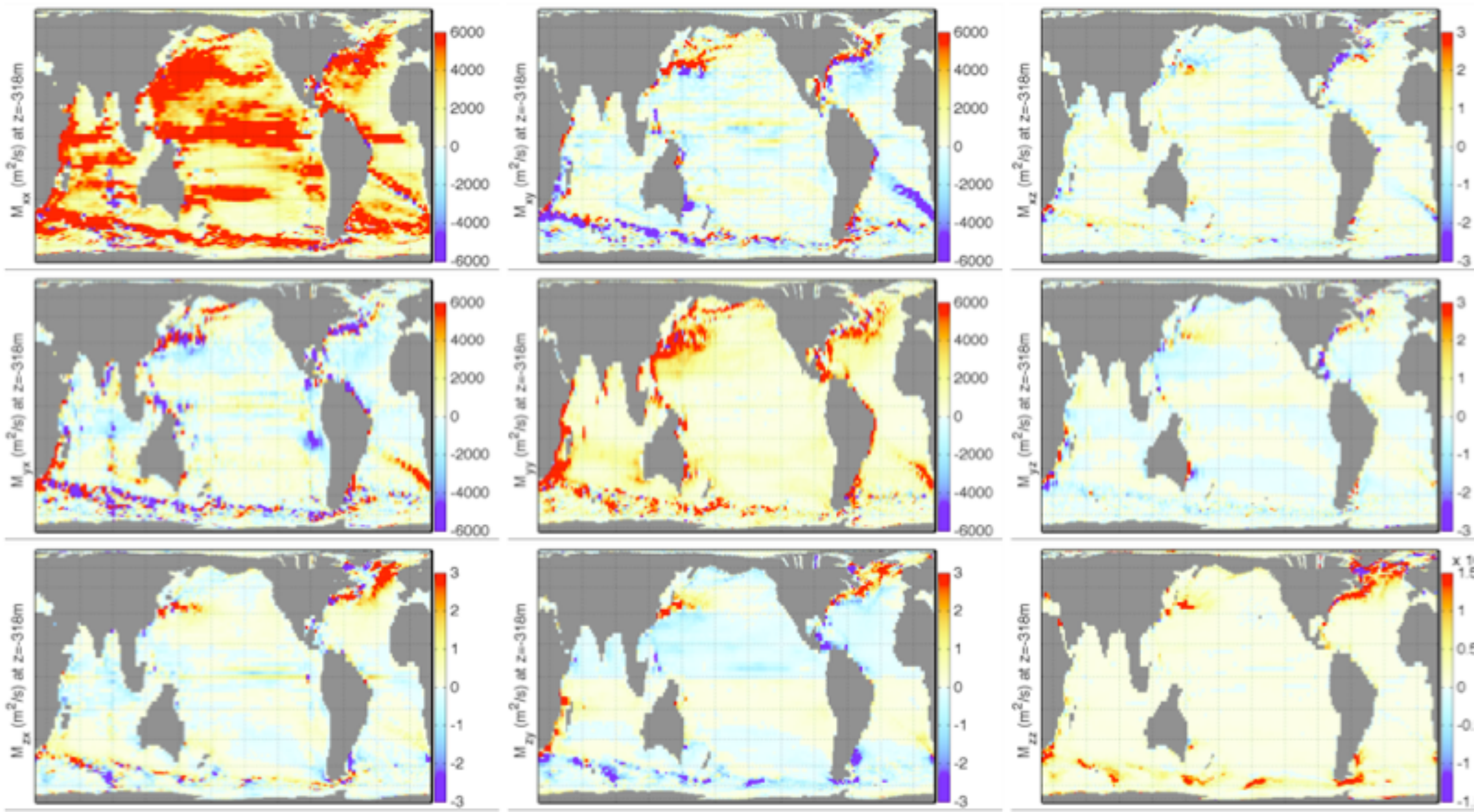
9 unknowns ($\mathbf{M}$ components)

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

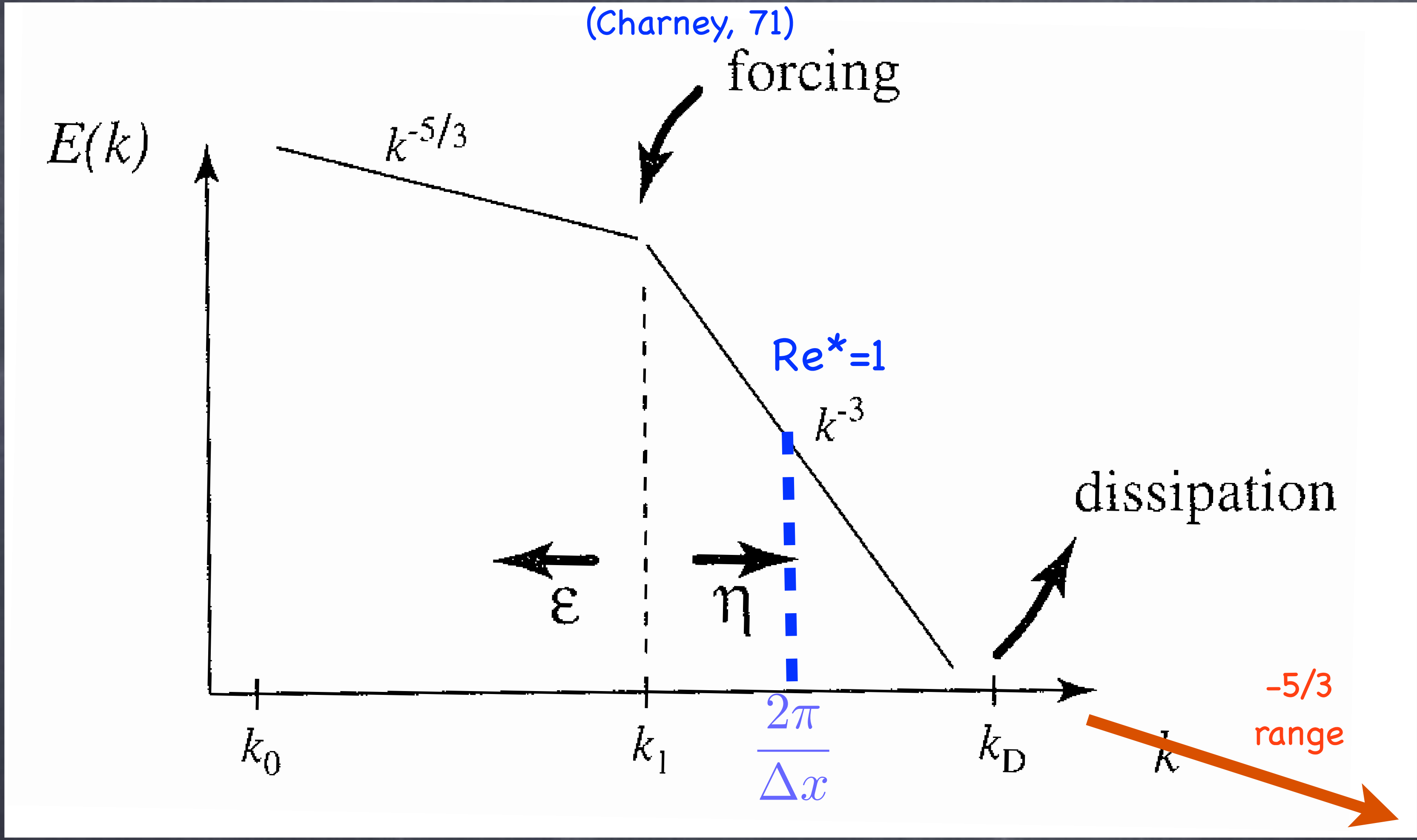
(a la Plumb & Mahlman '87, Bratseth '98)

No assumptions about symmetry required.

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

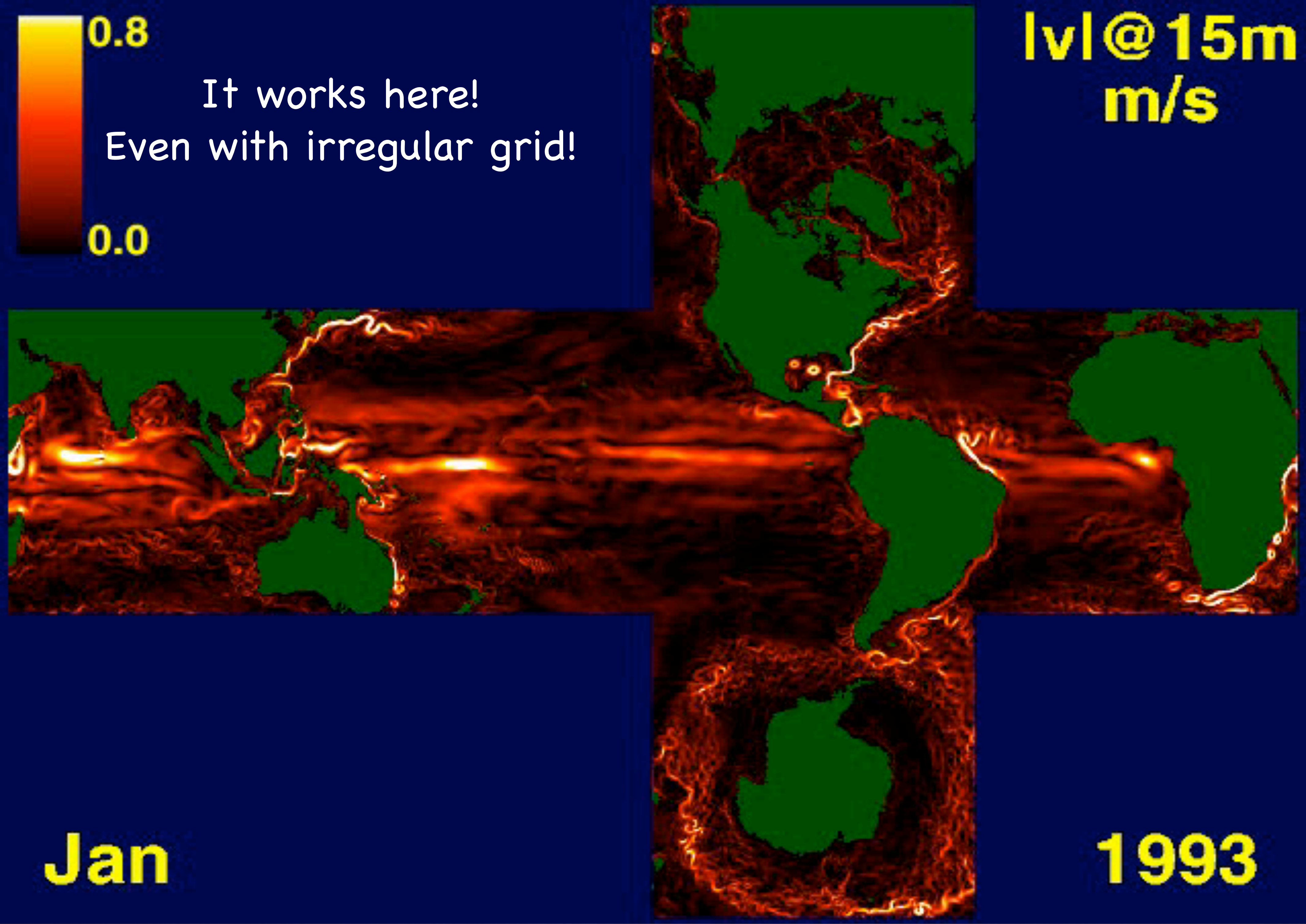


MOLES Turbulence Like Pot'l Enstrophy cascade, but divergent



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

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



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

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.

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