# From Climate to Kolmogorov - Simulations Spanning Upper Ocean Scales

Baylor Fox-Kemper (CU-Boulder & CIRES)
with Peter Hamlington (CU),
Sean Haney (ATOC), Adrean Webb (APPM), Scott Bachman (ATOC), Katie McCaffrey (ATOC)
Keith Julien (CU-APPM),
Luke Van Roekel (Northland), Peter Sullivan (NCAR), Jim McWilliams (UCLA), Mark Hemer (CSIRO)

Frontiers in Computation

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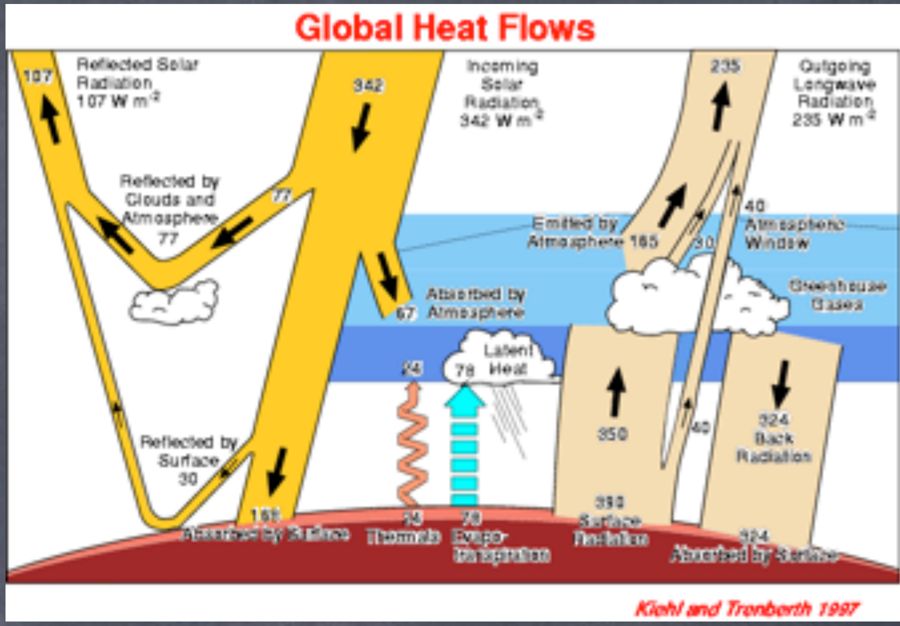
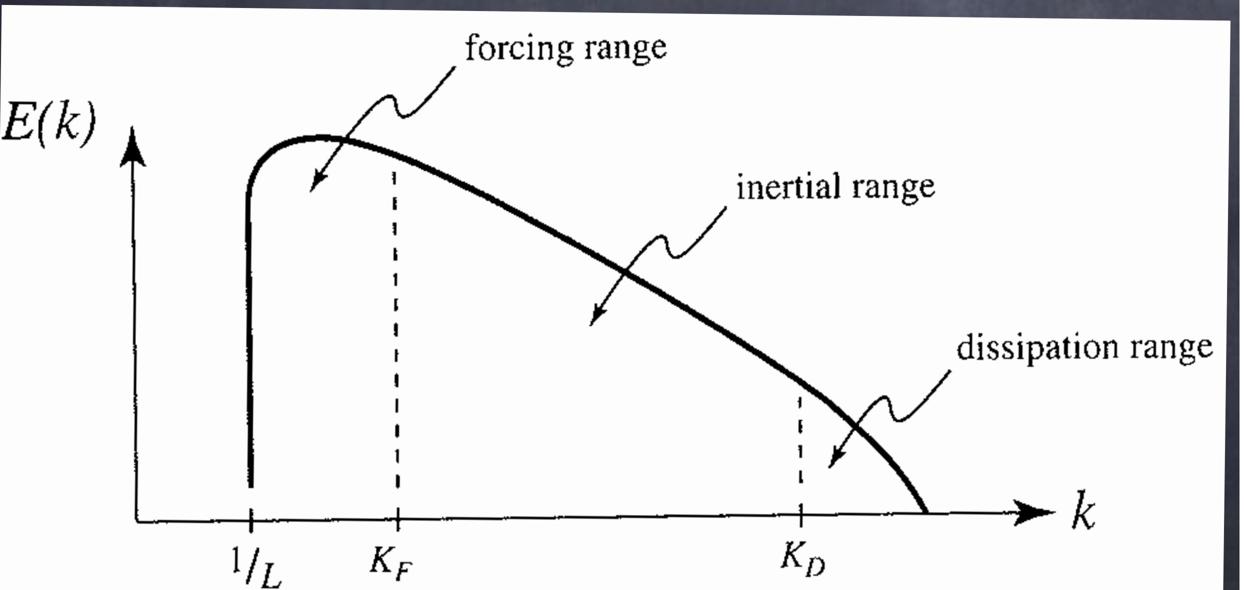
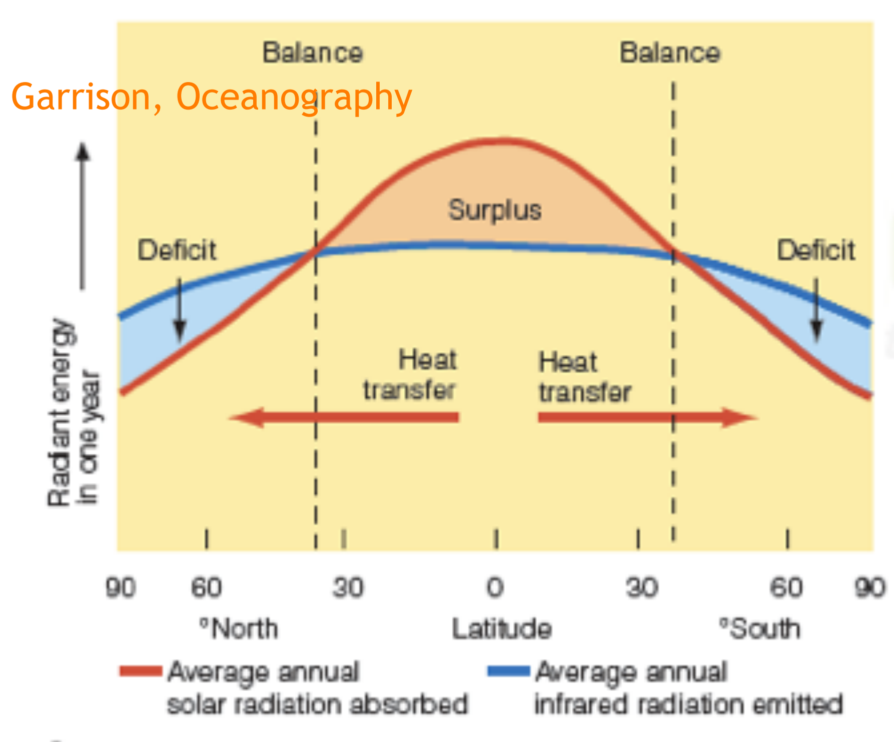
The Earth's Climate System is driven by the Sun's light (minus outgoing infrared) on a global scale



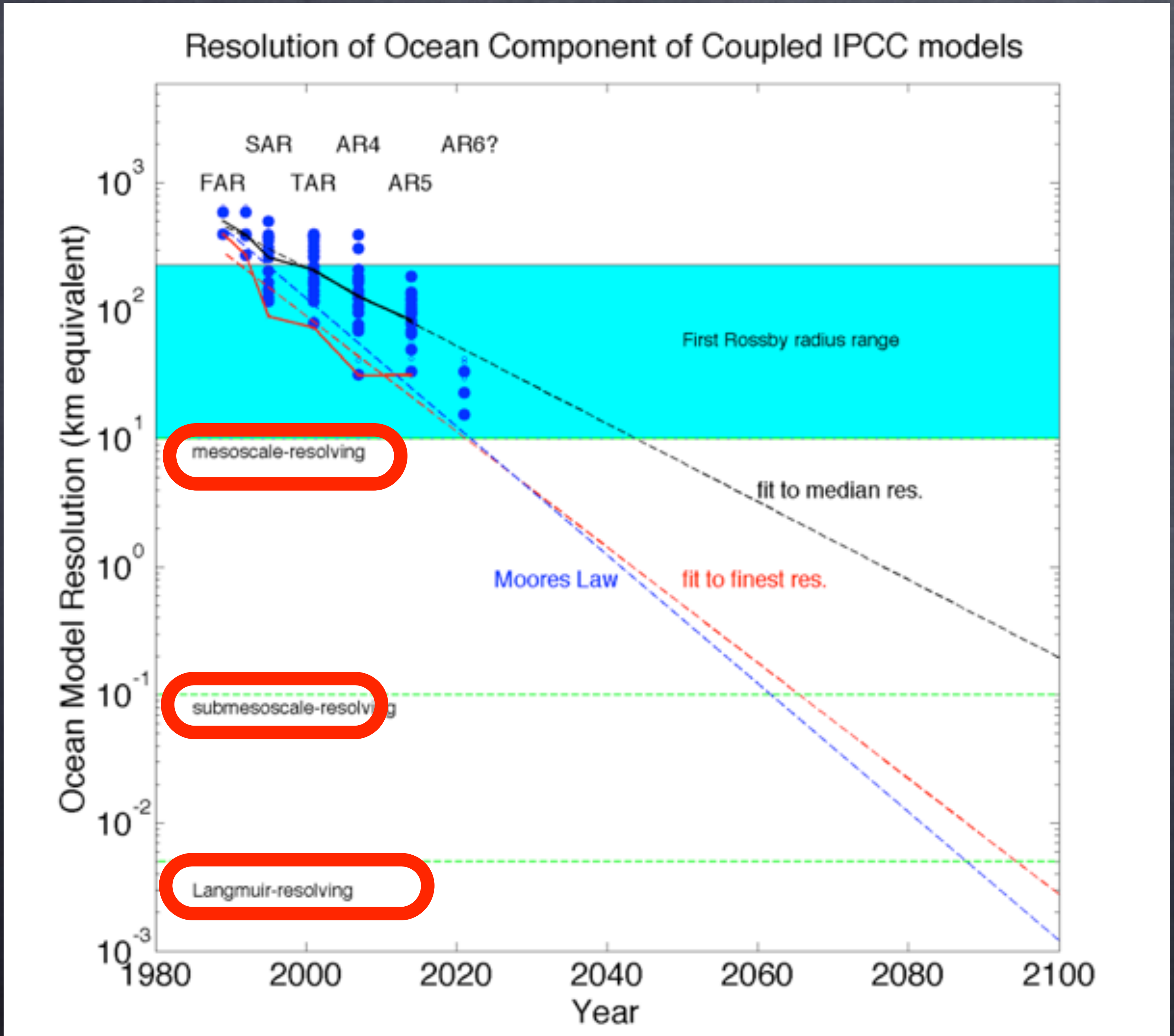

Dissipation concludes turbulence cascades on scales about a billion times smaller



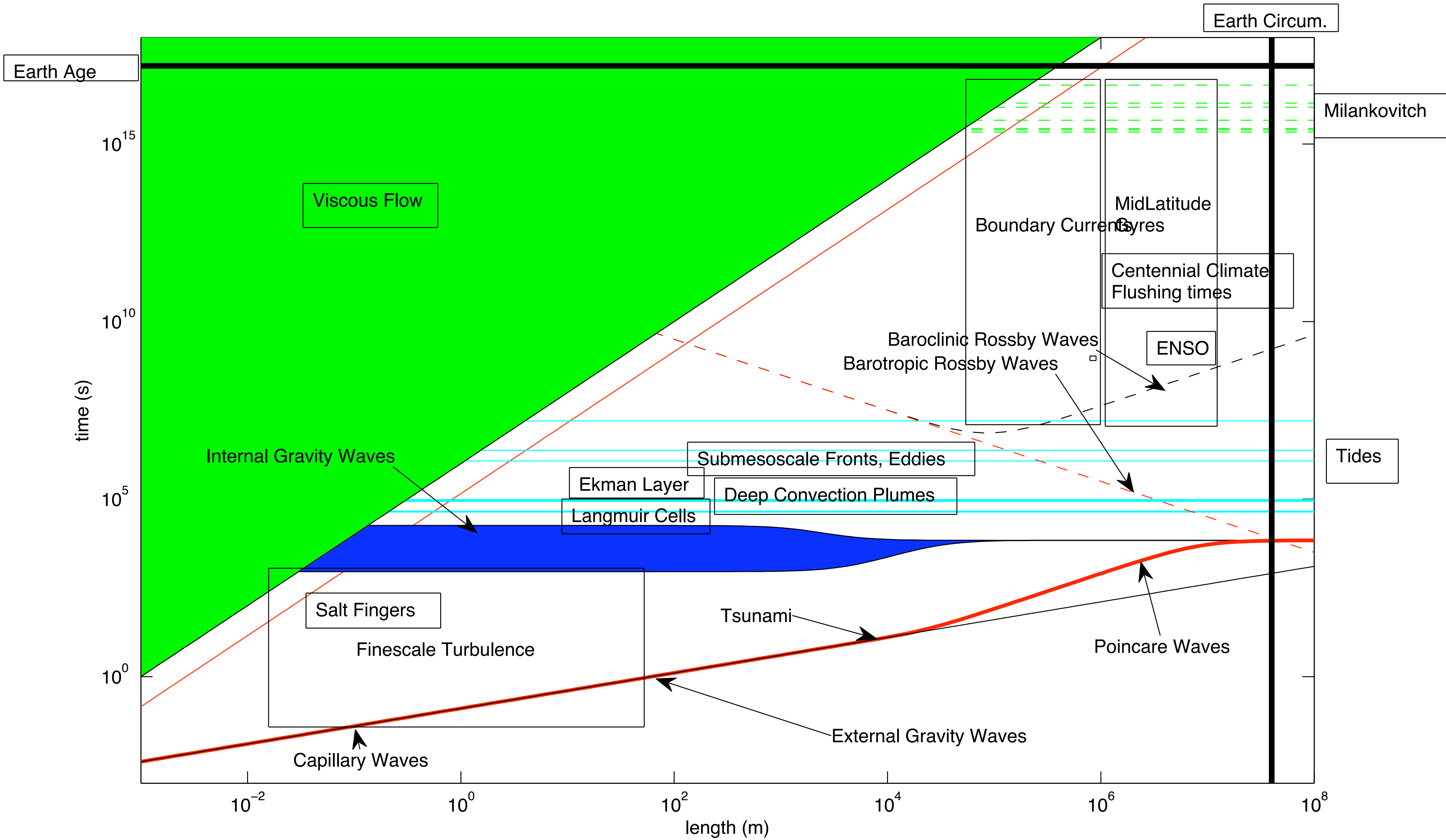

Garrison, Oceanography



# Resolution will be an issue for centuries to come!

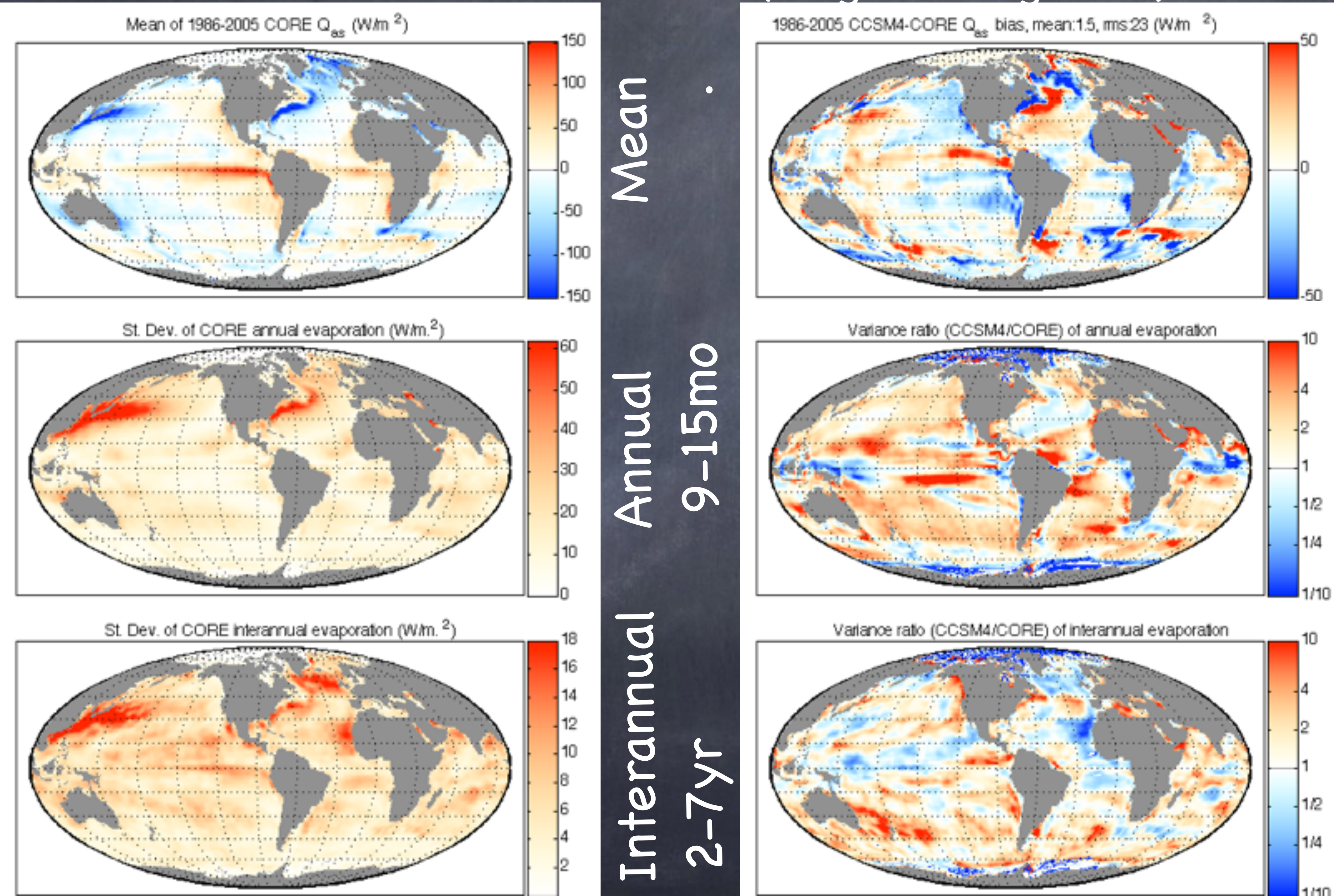


# The Ocean is Vast & Diverse: just one spectral cascade?

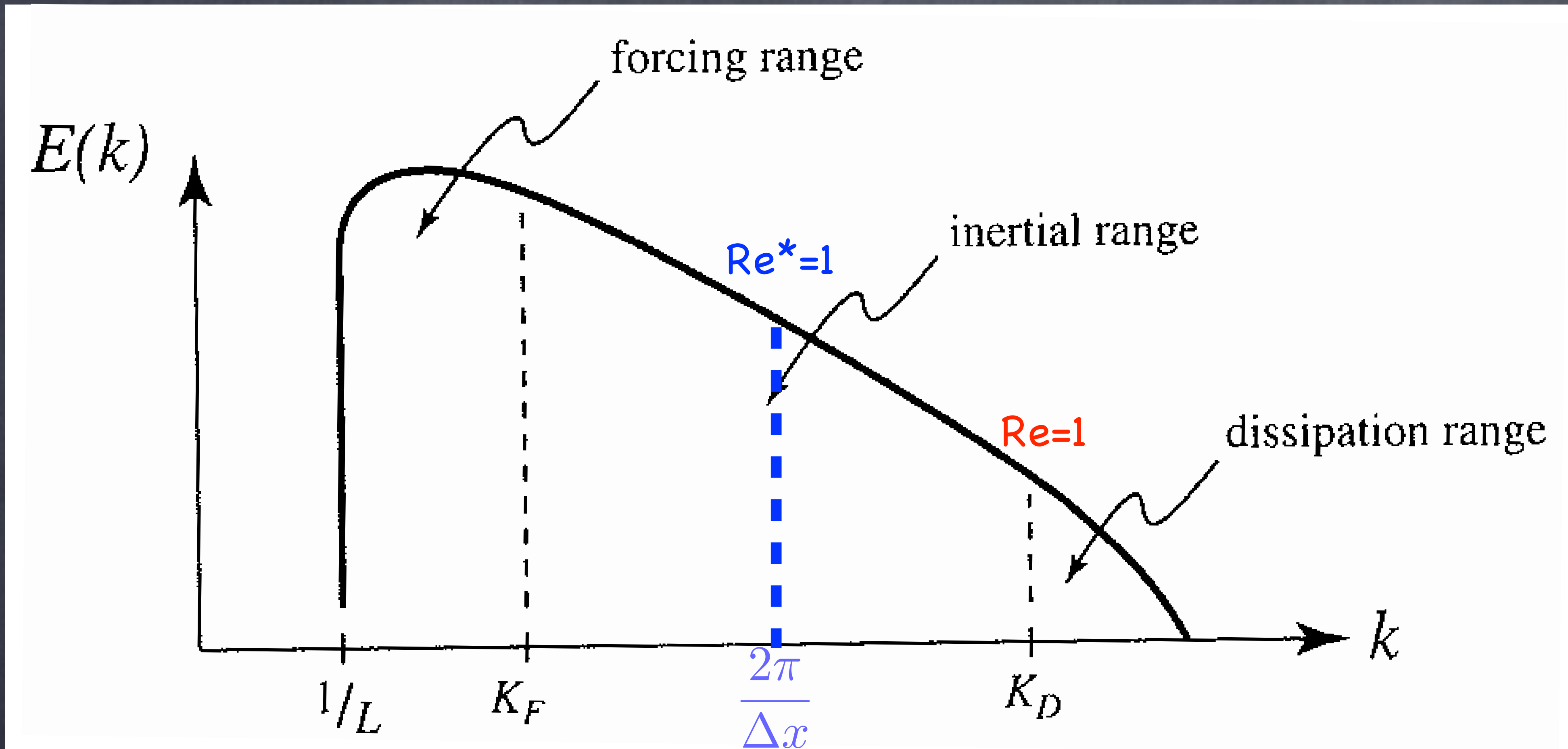


S. C. Bates, B. Fox-Kemper, S. R. Jayne, W. G. Large, S. Stevenson, and S. G. Yeager. Mean biases, variability, and trends in air-sea fluxes and SST in the CCSM4.Journal of Climate, 25(22):7781-7801, 2012.

# Air-Sea Flux Errors vs. Data (Large & Yeager 09)



# Truncation of Cascades



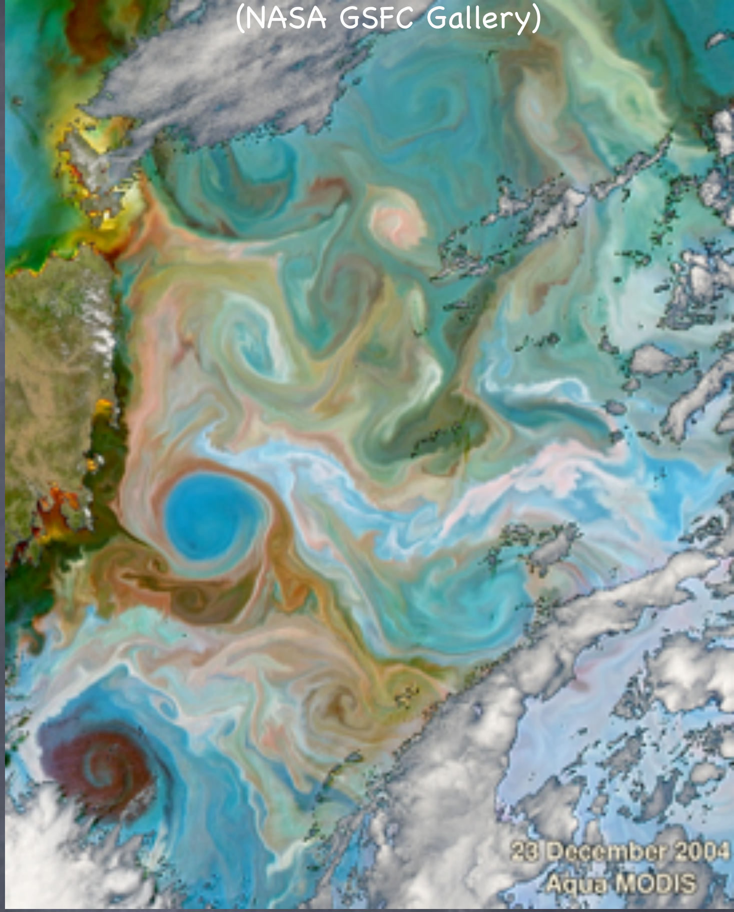

1963: Smagorinsky Devises Viscosity Scaling,
So that the Energy Flow is Preserved,
but order-1 gridscale Reynolds #: $Re^* = UL/\nu_*$

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

# The Character of the Mesoscale

100 km

(NASA GSFC Gallery)




(Capet et al., 2008)

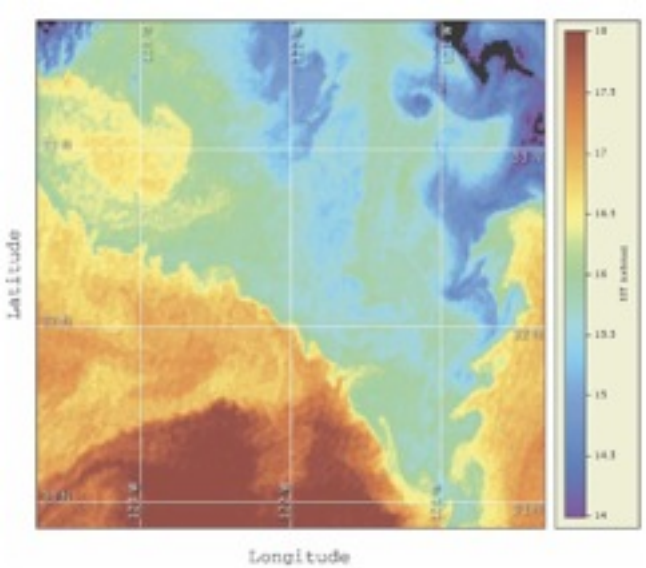
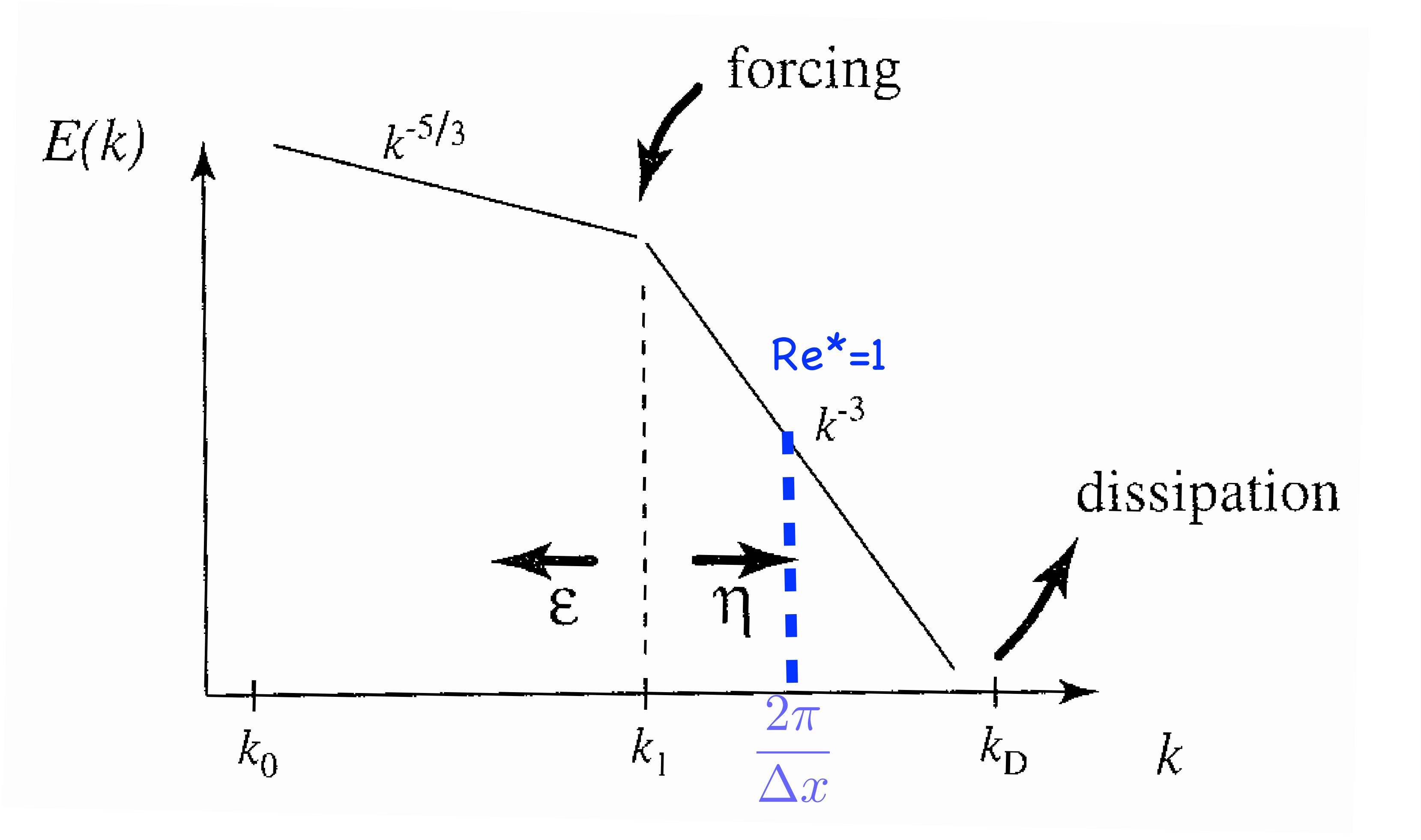



FIG. 16. Sea surface temperature measured at 1832 UTC 3 Jun 2006 off Point Conception in the California Current from CoastWatch (http://coastwatch.pfeg.noaa.gov). The fronts between recently upwelled water (i.e., 15°–16°C) and offshore water (≥17°C) show submesoscale instabilities with wavelengths around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

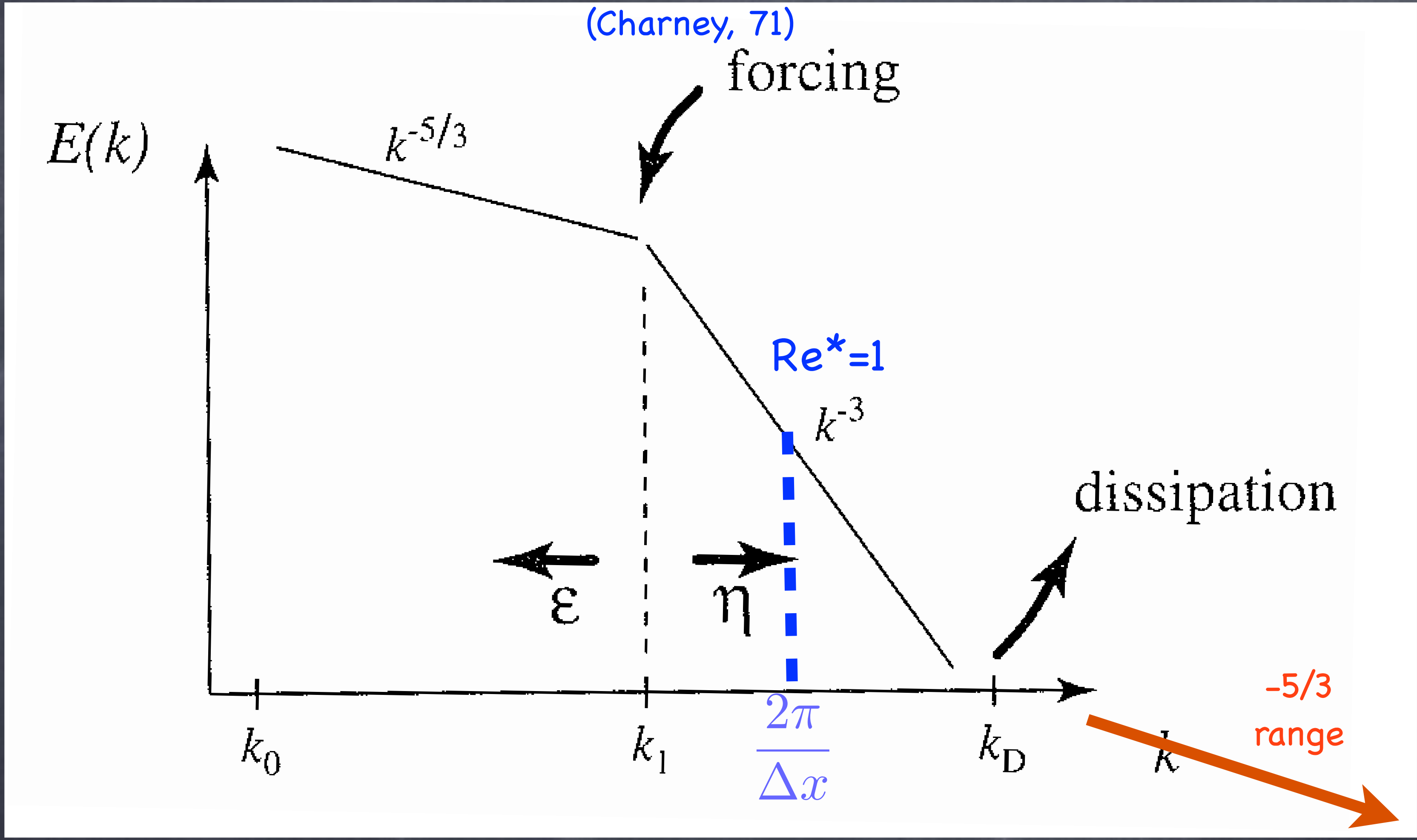
# 2d Turbulence Differs




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

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

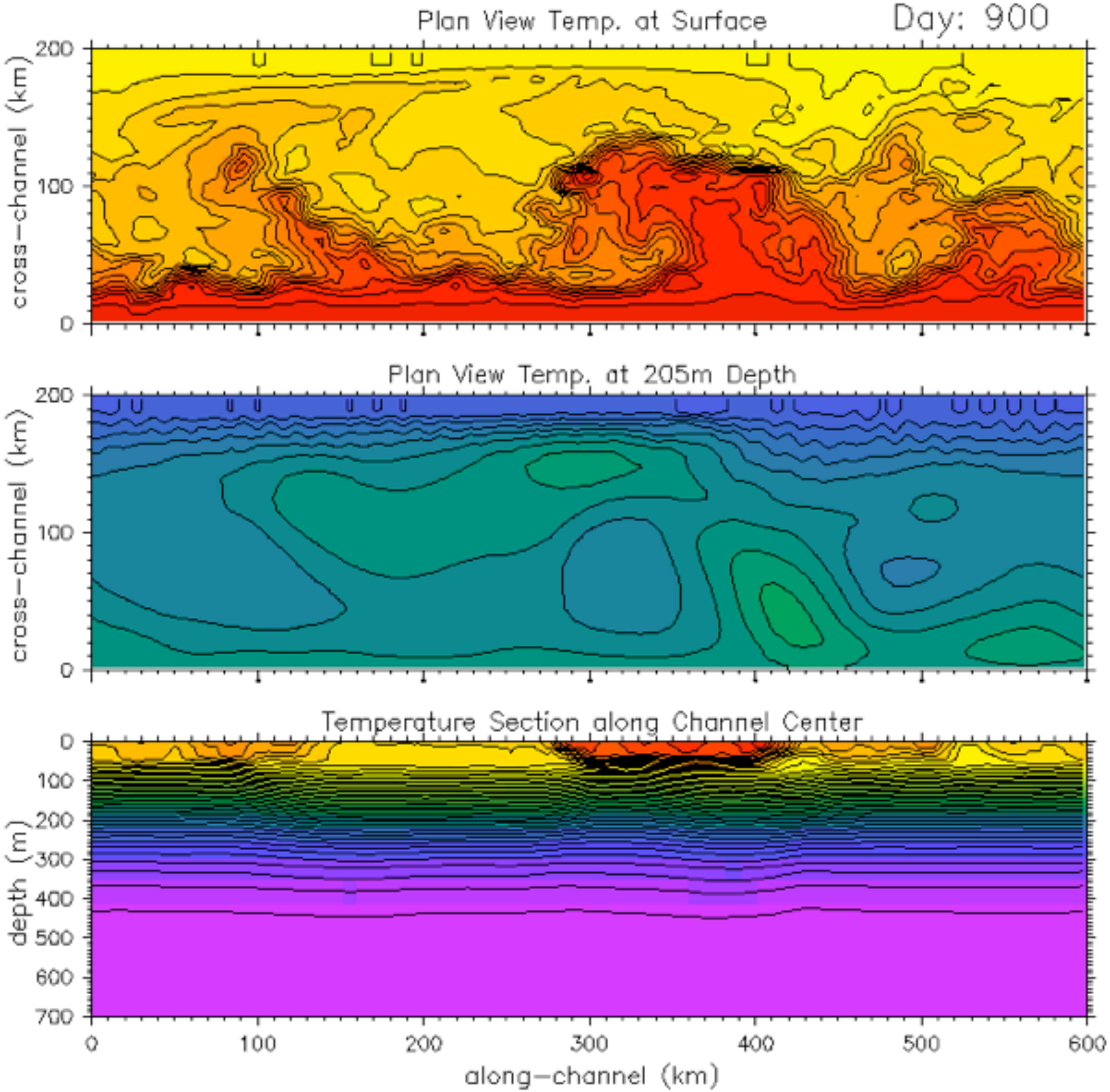
# MOLES Turbulence Like Pot'l Enstrophy cascade, but divergent




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

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

B. Fox-Kemper and D. Menemenlis. Can large eddy simulation techniques improve mesoscale-rich ocean models? In M. Hecht and H. Hasumi, editors, Ocean Modeling in an Eddying Regime, volume 177, pages 319-338. AGU Geophysical Monograph Series, 2008.




Big, Deep (meso)

interact with

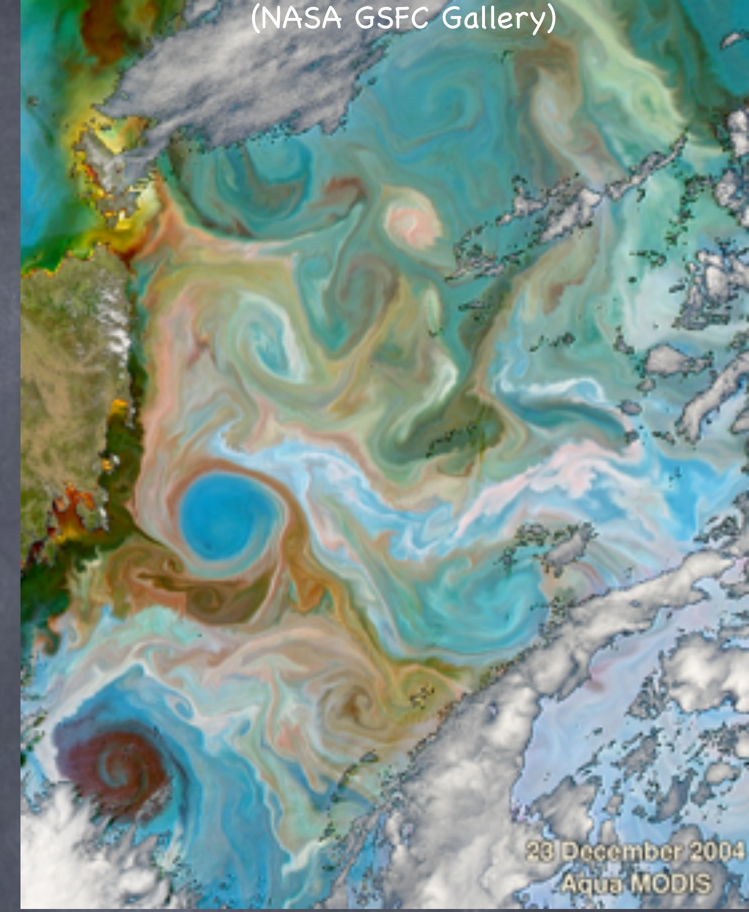
Little, Shallow (submeso)

B. Fox-Kemper, R. Ferrari, and R. W. Hallberg. Parameterization of mixed layer eddies. Part I: Theory and diagnosis. Journal of Physical Oceanography, 38(6):1145-1165, 2008.

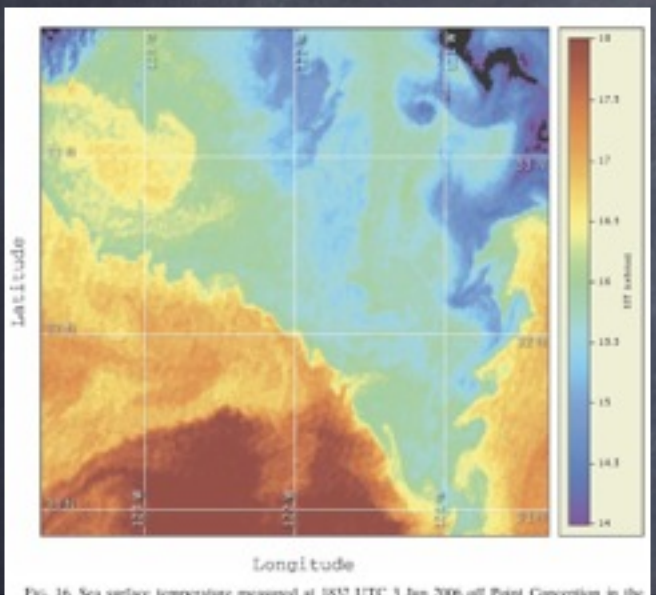
# The Character of the Submesoscale

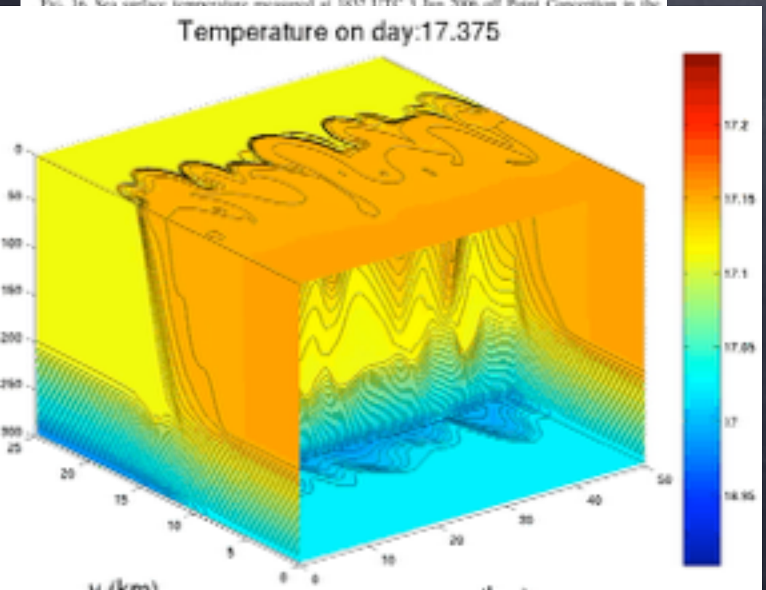
10 km

(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

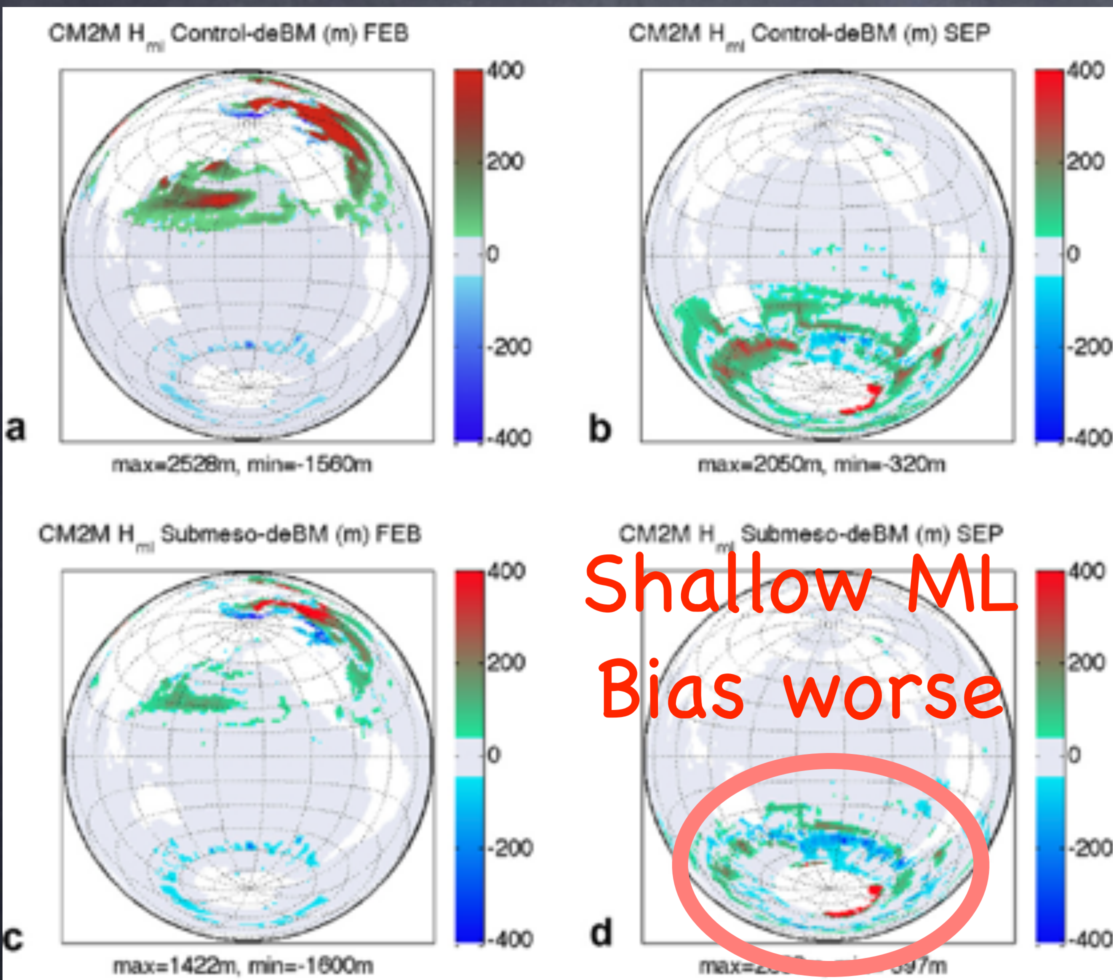
Parameterizations of submesoscale baroclinic instability?


B. Fox-Kemper, R. Ferrari, and R. W. Hallberg. Parameterization of mixed layer eddies. Part I: Theory and diagnosis. Journal of Physical Oceanography,

S. Bachman and B. Fox-Kemper. Eddy parameterization challenge suite. I: Eady spindown. Ocean Modelling, 2013. In press.

# Physical Sensitivity of Ocean Climate to MLE:

## Mixed Layer Eddy Restratification

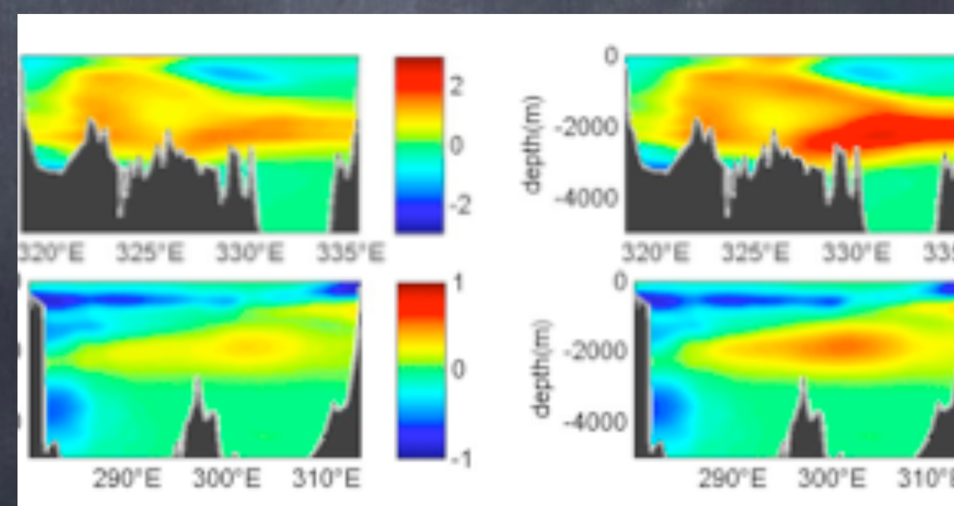



Bias w/o MLE

Improves CFCs (water masses)

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.

# The Character of the Langmuir Scale

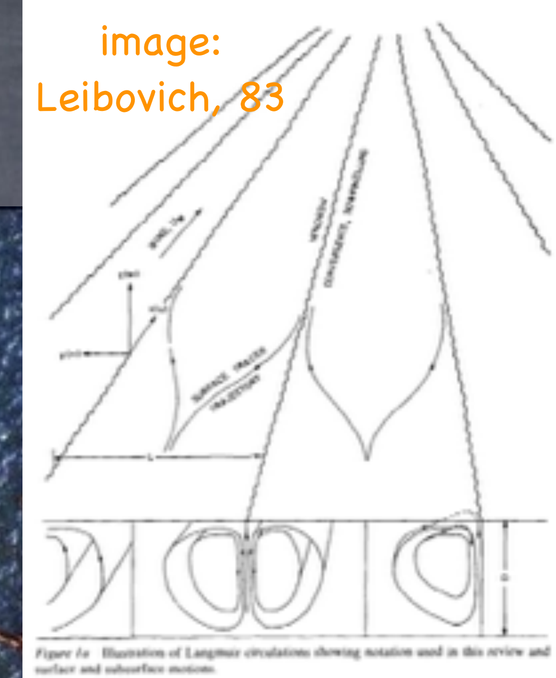
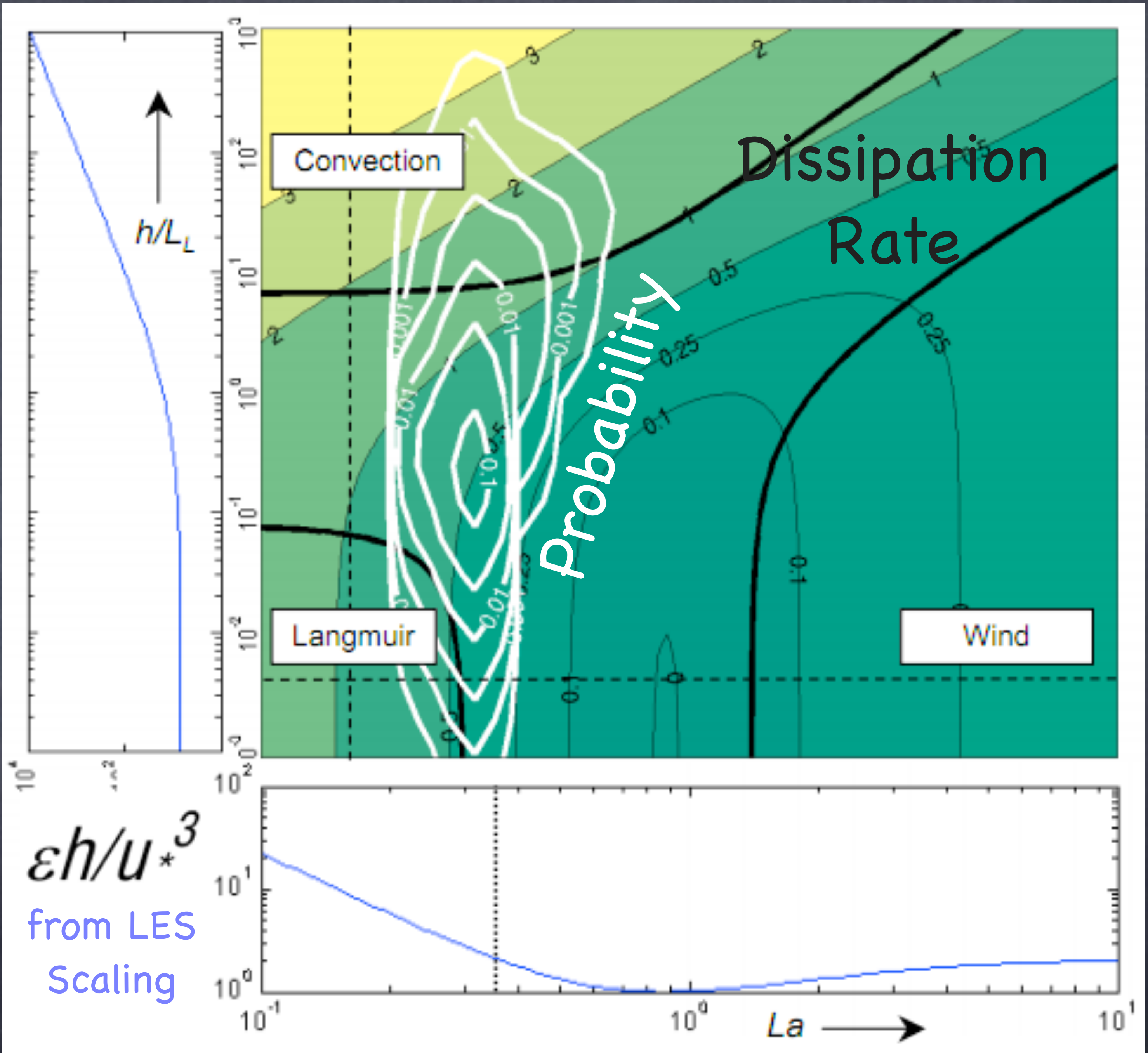


image: Leibovich, 83

- Near-surface
- Langmuir Cells & Langmuir Turb.
- Ro>>1
- Ri<1: Nonhydro
- 1-10m
- 10s to mins
- w, u=O(10cm/s)
- Stokes drift
- Eqtns:Craik-Leibovich
- Params: McWilliams & Sullivan, 2000, etc.

Image: NPR.org, Deep Water Horizon Spill

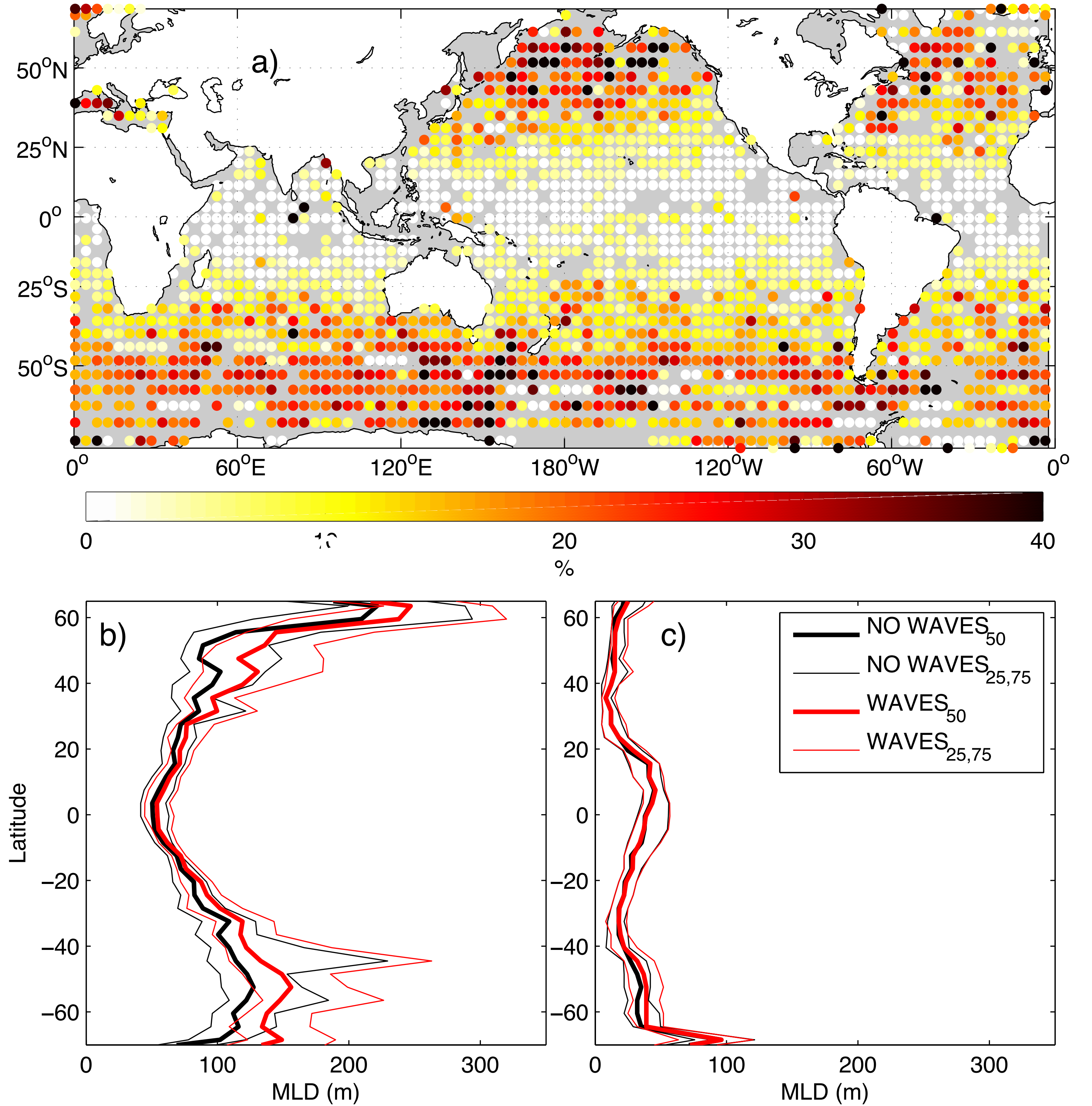
# Data + LES, Southern Ocean mixing energy: Langmuir (Stokes-drift-driven) and Convective




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 Langmuir turbulence in the ocean surface boundary layer. Geophysical Research Letters, 39(18):L18605, 9pp, 2012.

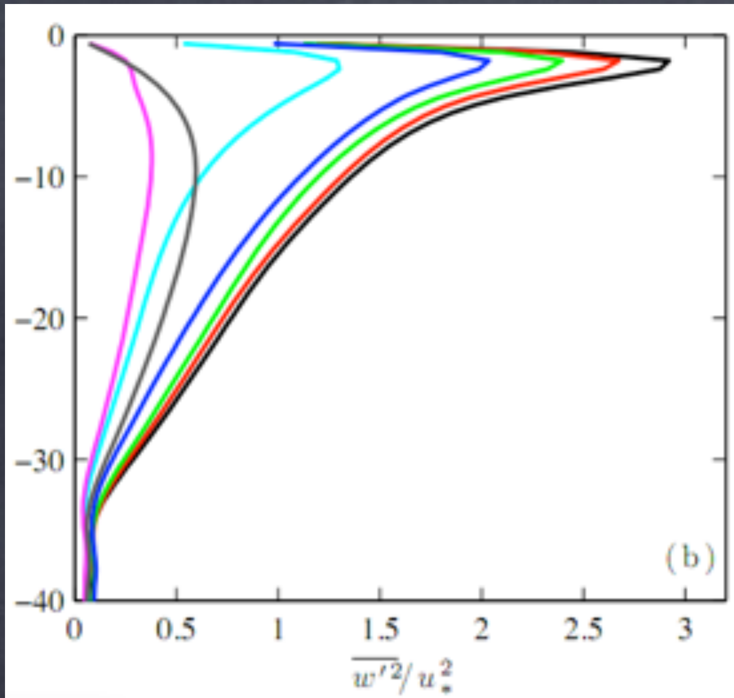
# Including Wave-driven Mixing Deepens the Mixed Layer!

Fig: M. Hemer

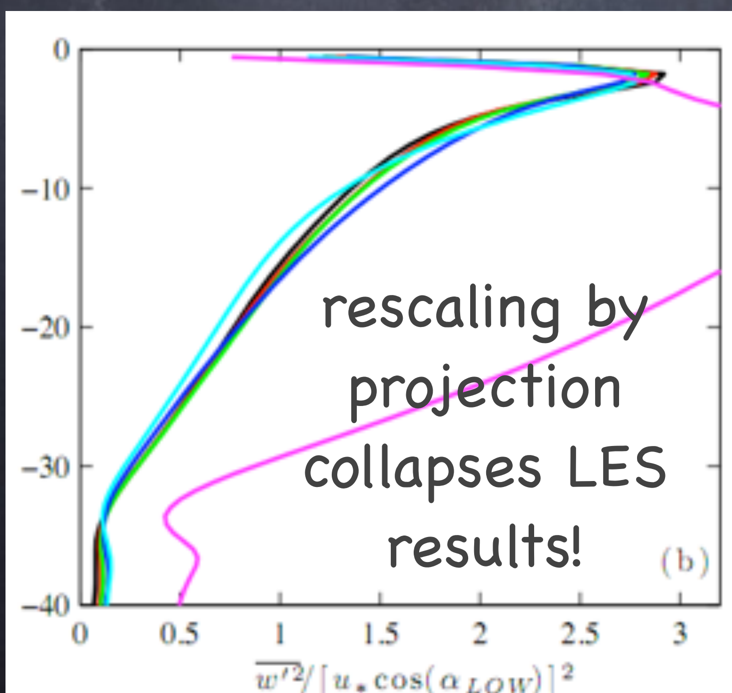



M. A. Hemer, B. Fox-Kemper, & R. R. Harcourt. Quantifying the effects of wind waves the the coupled climate system, in prep. 2012.

<w$^2$>




rescaled <w$^2$>




# Generalized Turbulent Langmuir No., Projection of u*, $u_s$ into Langmuir Direction

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

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

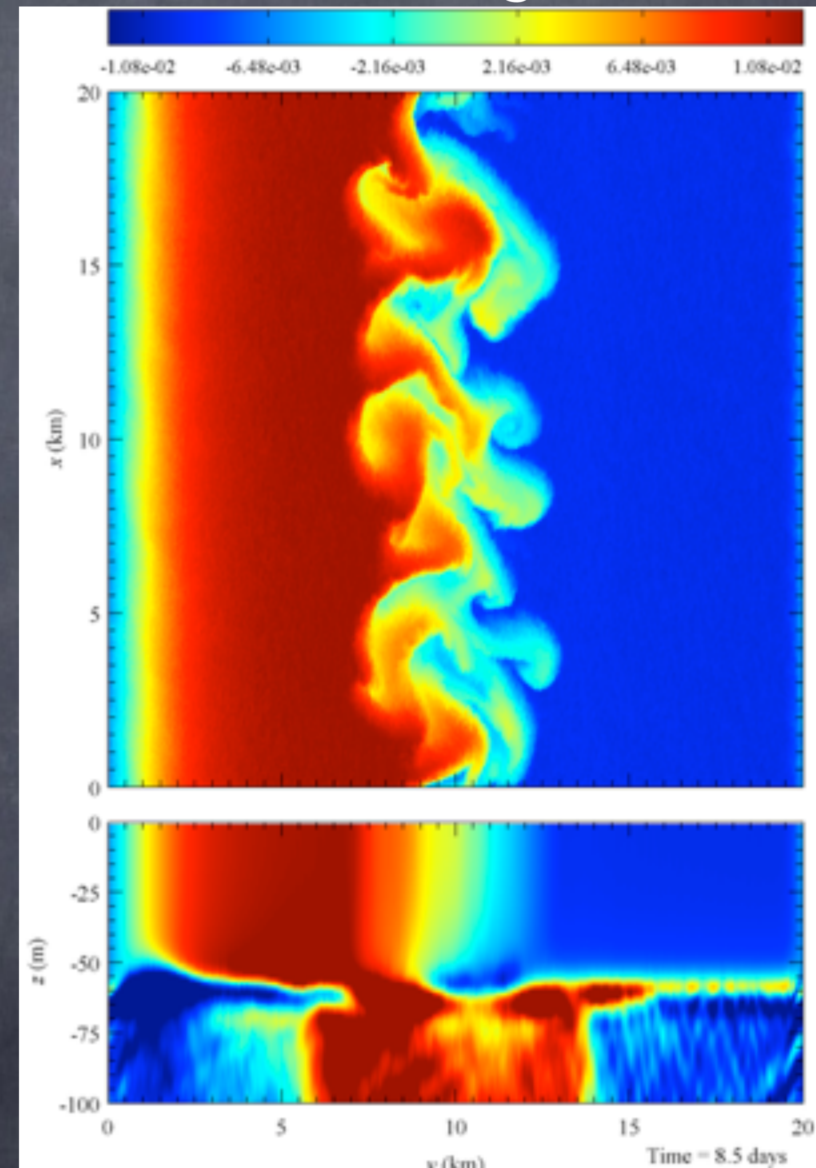
$$\alpha_{LOW} \approx \tan^{-1}\left(\frac{\sin(\theta_{ww})}{\frac{u_*}{u_s(0)\kappa}\ln\left(\left|\frac{H_{ML}}{z_1}\right|\right) + \cos(\theta_{ww})}\right)$$

## A scaling for LC strength & direction!


L. P. 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, 117:C05001, 22pp, 2012.

# What about Langmuir-Submeso Interactions?

Movie: P. Hamlington




Perform large eddy simulations (LES) of Langmuir turbulence with a submesoscale temperature front

Use NCAR LES model to solve Craik-Leibovich equations (Moeng, 1984, McWilliams et al, 1997)

$$\frac{\partial \rho}{\partial t} + \mathbf{u}_L \cdot \nabla \rho = \mathrm{SGS} \qquad \nabla \cdot \mathbf{u} = 0$$

$$\frac{\partial \mathbf{u}}{\partial t} + (\boldsymbol{\omega} + f\hat{\mathbf{z}}) \times \mathbf{u}_L = -\nabla \pi - \frac{g\rho\hat{\mathbf{z}}}{\rho_0} + \mathrm{SGS}$$

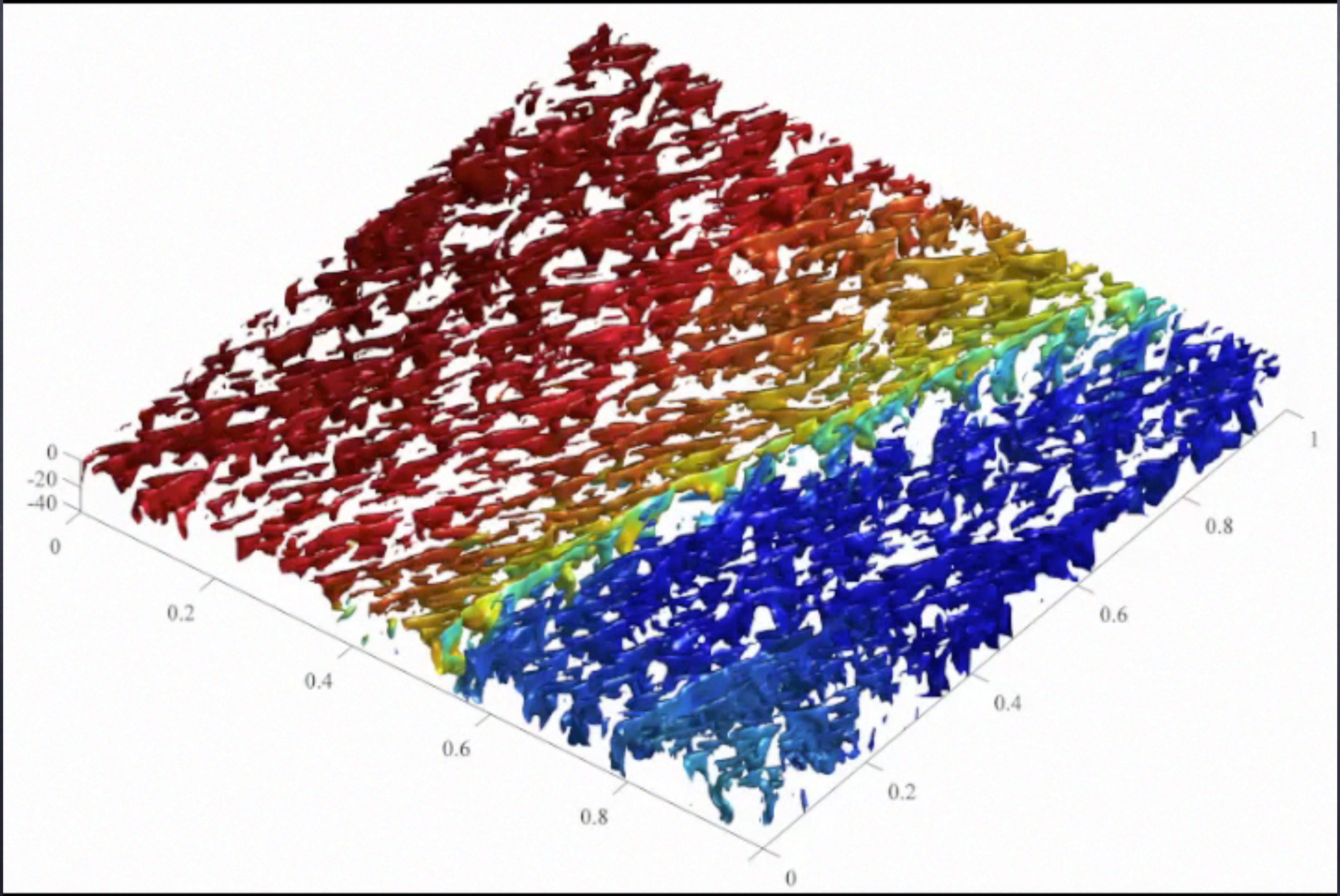
Computational parameters:

Domain size: 20km x 20km x -160m

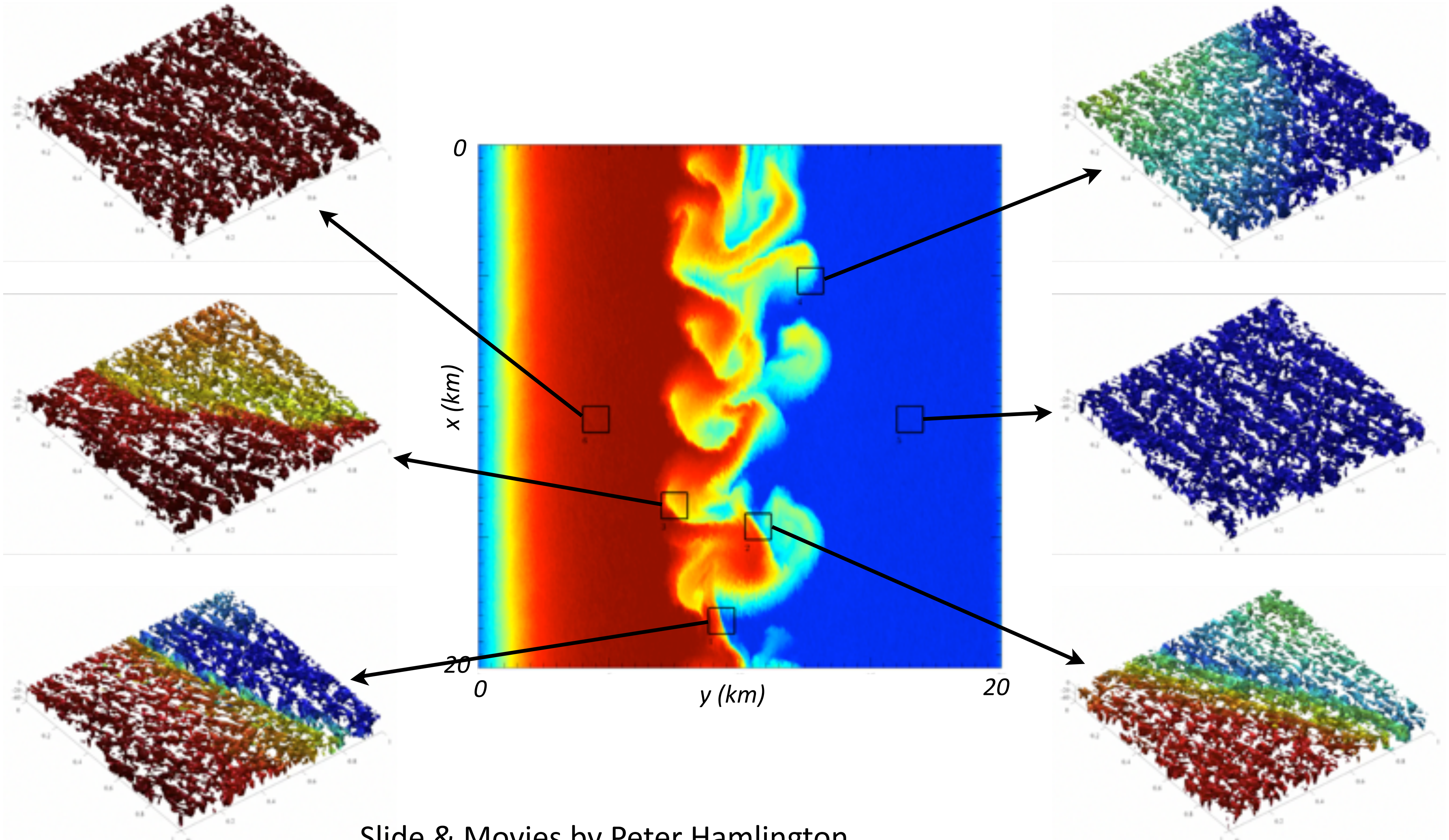
Grid points: 4096 x 4096 x 128

Resolution: 5m x 5m x -1.25m

# Zoom: Submeso-Langmuir Interaction!



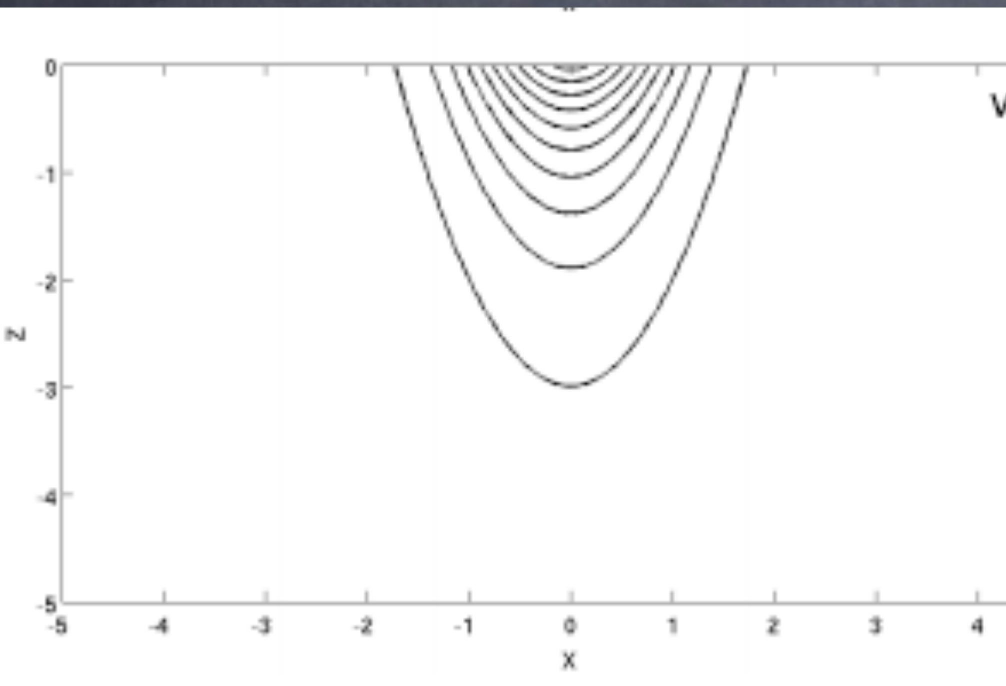
# Diverse types of interaction

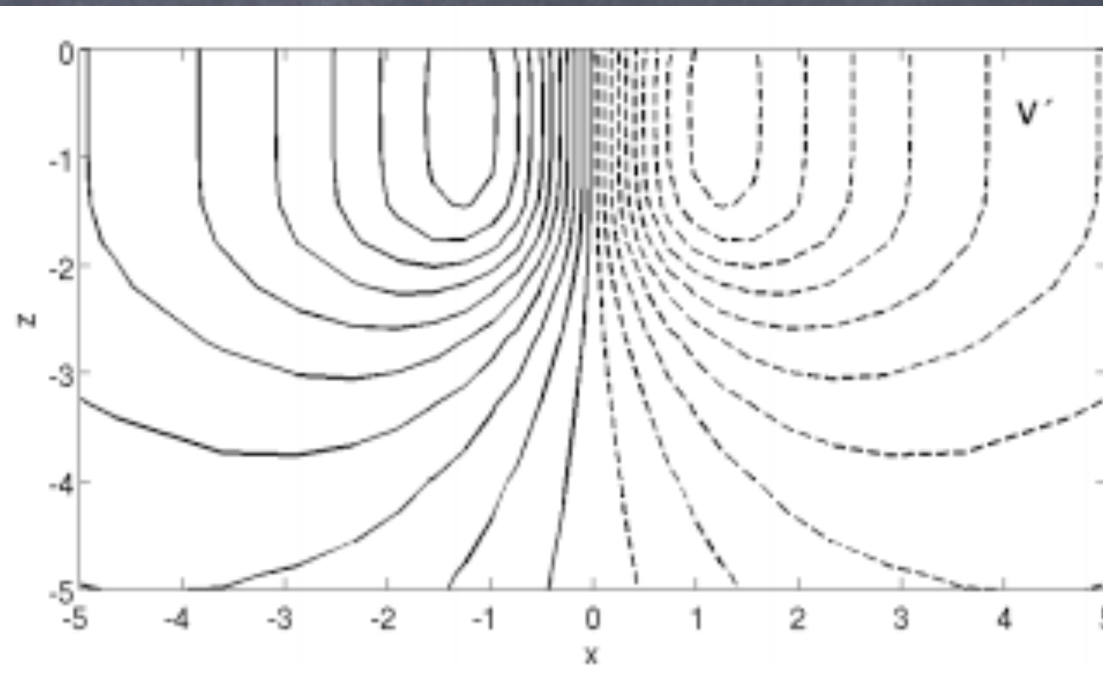



Slide & Movies by Peter Hamlington

P. E. Hamlington, L. P. Van Roekel, B. Fox-Kemper, K. Julien, and G. P. Chini. Langmuir-submesoscale interactions: Descriptive analysis of multiscale simulations. In preparation, 2012.

# Waves (Stokes Drift Vortex Force) -> Submeso, Meso




Initial Submeso flow

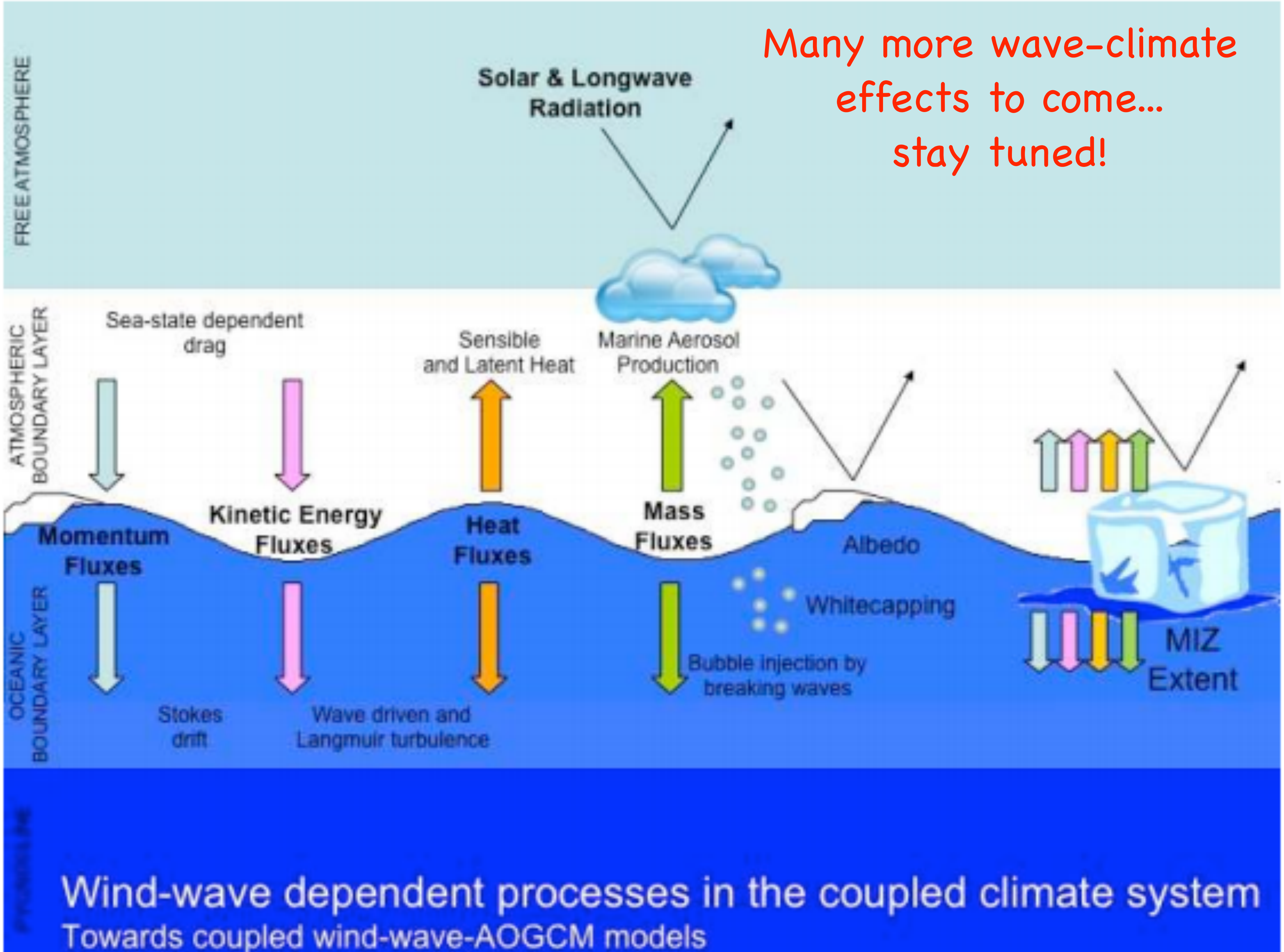
Contours: 0.1

Perturbation on that scale due to waves

Contours: 0.014

J. C. McWilliams and B. Fox-Kemper. Oceanic wave-balanced surface fronts and filaments. Journal of Fluid Mechanics, 2012. Submitted.

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

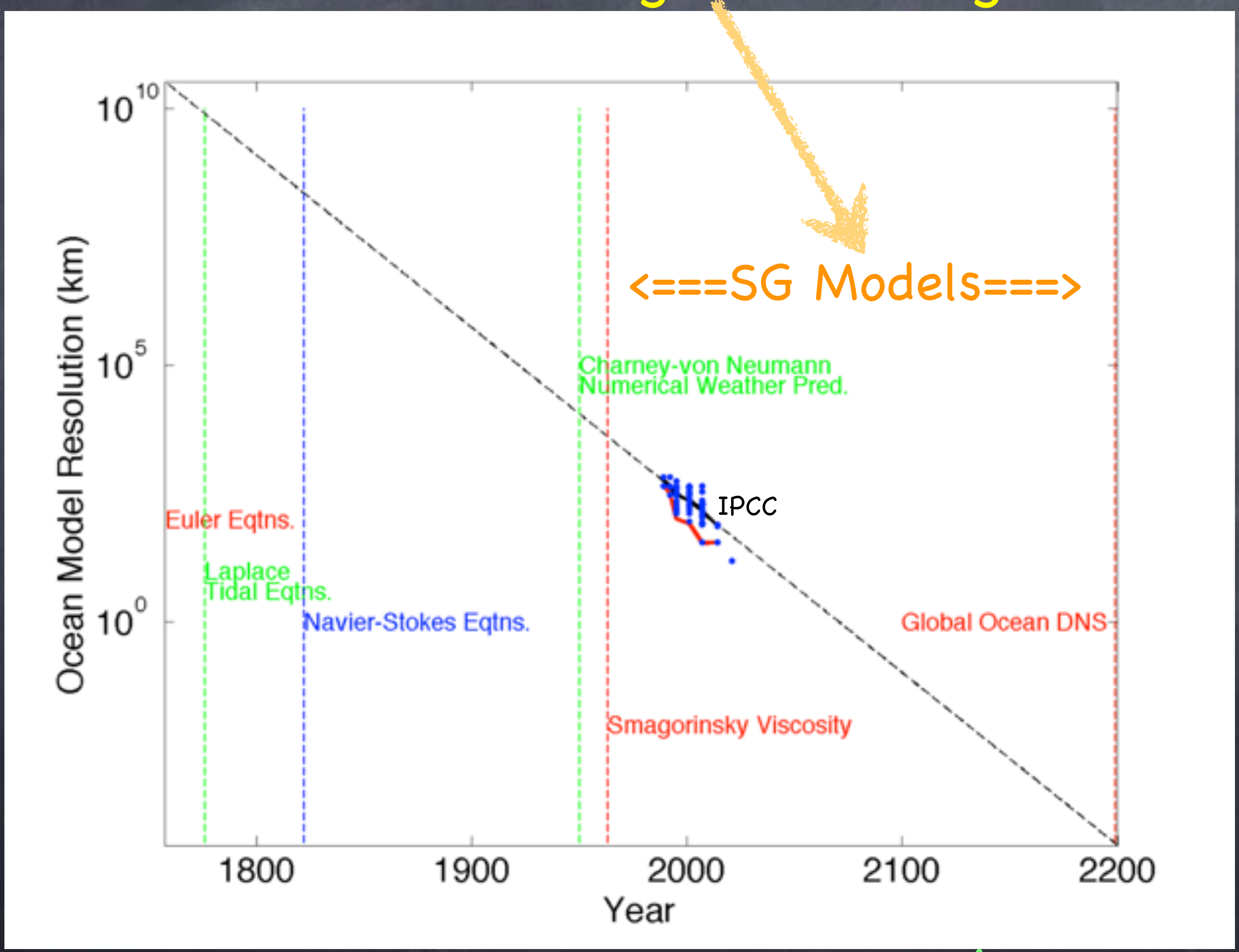



L. Cavaleri, B. Fox-Kemper, and M. Hemer. Wind waves in the coupled climate system. Bulletin of the American Meteorological Society, 93(11):1651-1661, 2012.

# Conclusions

- Climate modeling is challenging partly due to the vast and diverse scales of fluid motions
- In the upper ocean, horizontal scales as big as basins, and as small as meters contribute non-negligibly to the air-sea exchange
- Process models, especially those spanning a whole or multiple scales, are a powerful tool in studying these connections and improving subgrid models.

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




All papers at: fox-kemper.com/research