From Climate to Kolmogorov - Simulations Spanning Upper Ocean Scales

Baylor Fox-Kemper

with

Sean Haney (ATOC), Adrean Webb (APPM), Scott Bachman (ATOC), Katie McCaffrey (ATOC) Keith Julien (CU-Boulder), Peter Hamlington (CU-Boulder), Luke Van Roekel (Northland College), Peter Sullivan (NCAR), Ramsey Harcourt (UW), Eric D'Asaro (UW), Jim McWilliams (UCLA), Mark Hemer (CSIRO)

URI GSO Physical Oceanography Seminar

Sponsors: NSF 1245944, 0934737, 0825614, NASA NNX09AF38G

Now with Rhode Island Ingredients!

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Brown University

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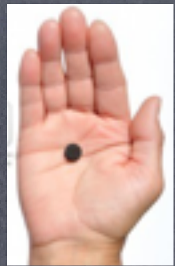
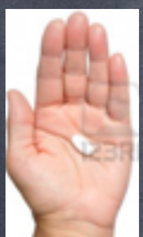
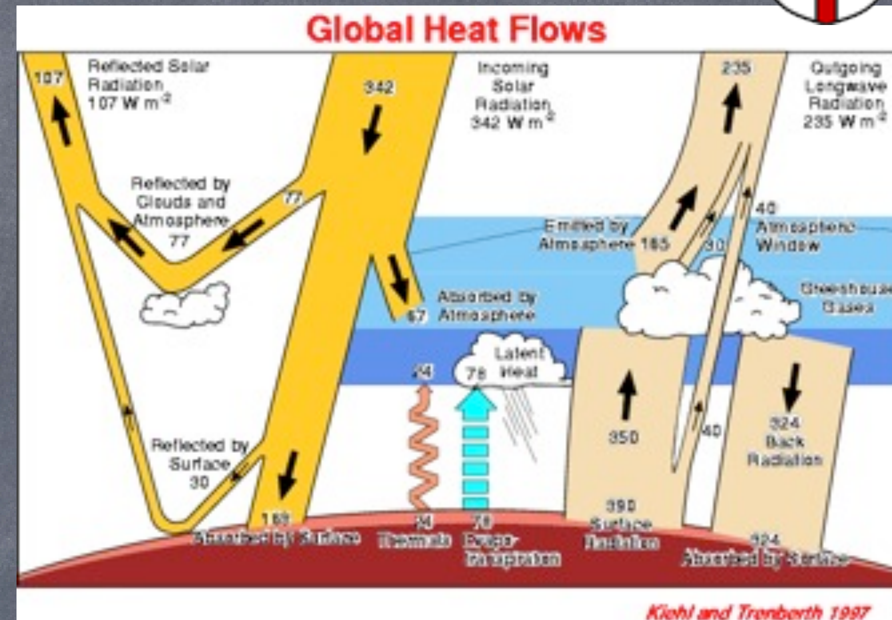
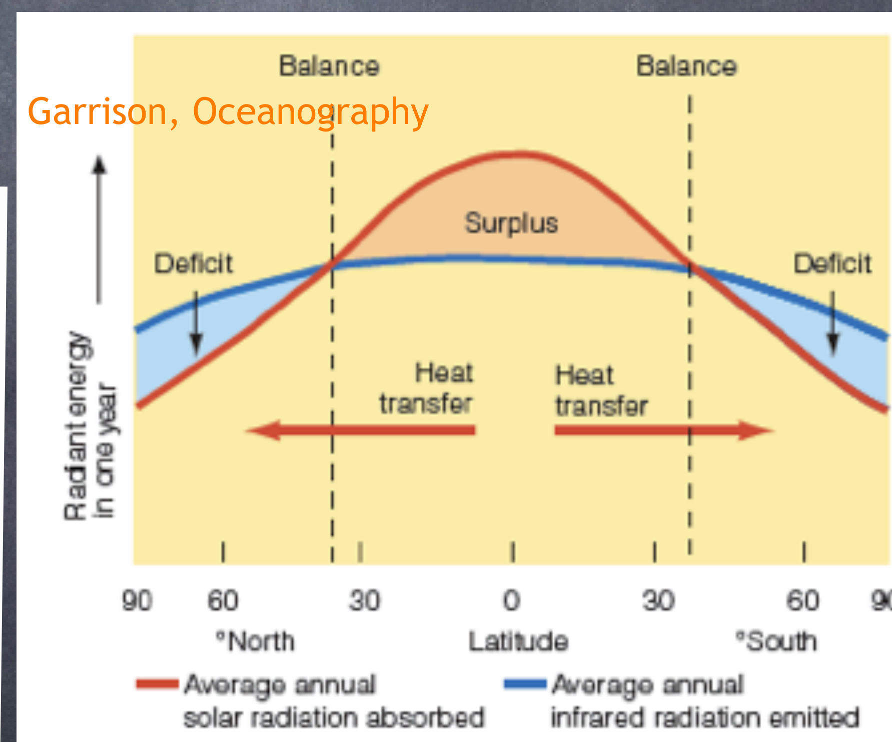


The Earth's Climate System is driven by the Sun's light (minus outgoing infrared) on a global scale



Dissipation concludes turbulence cascades to scales about a billion times smaller





Garrison, Oceanography

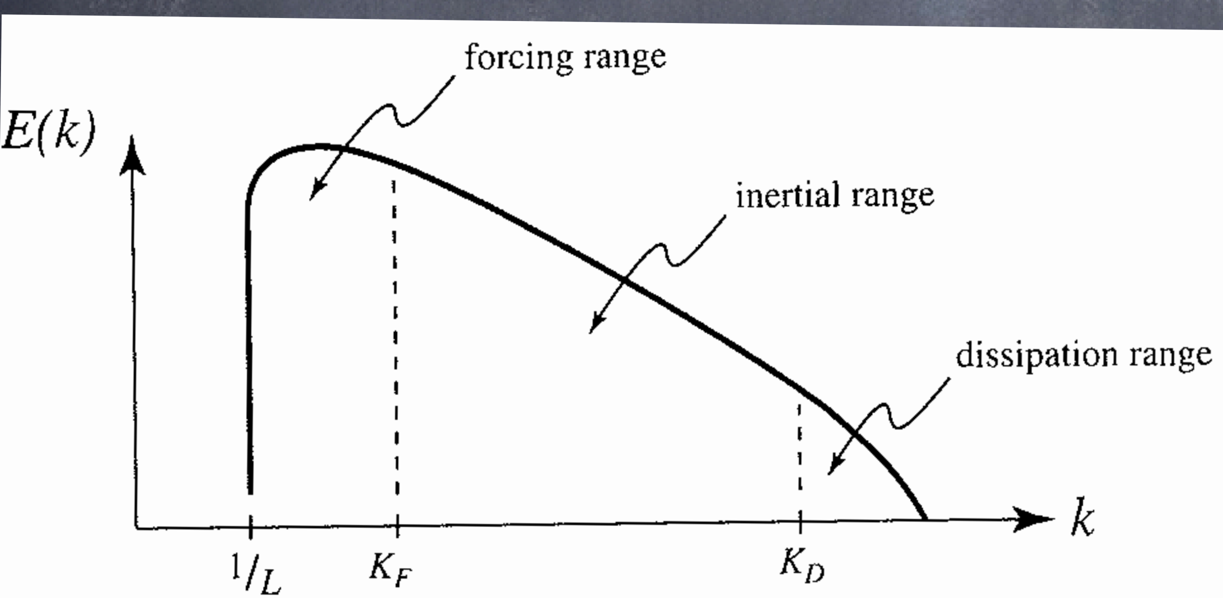
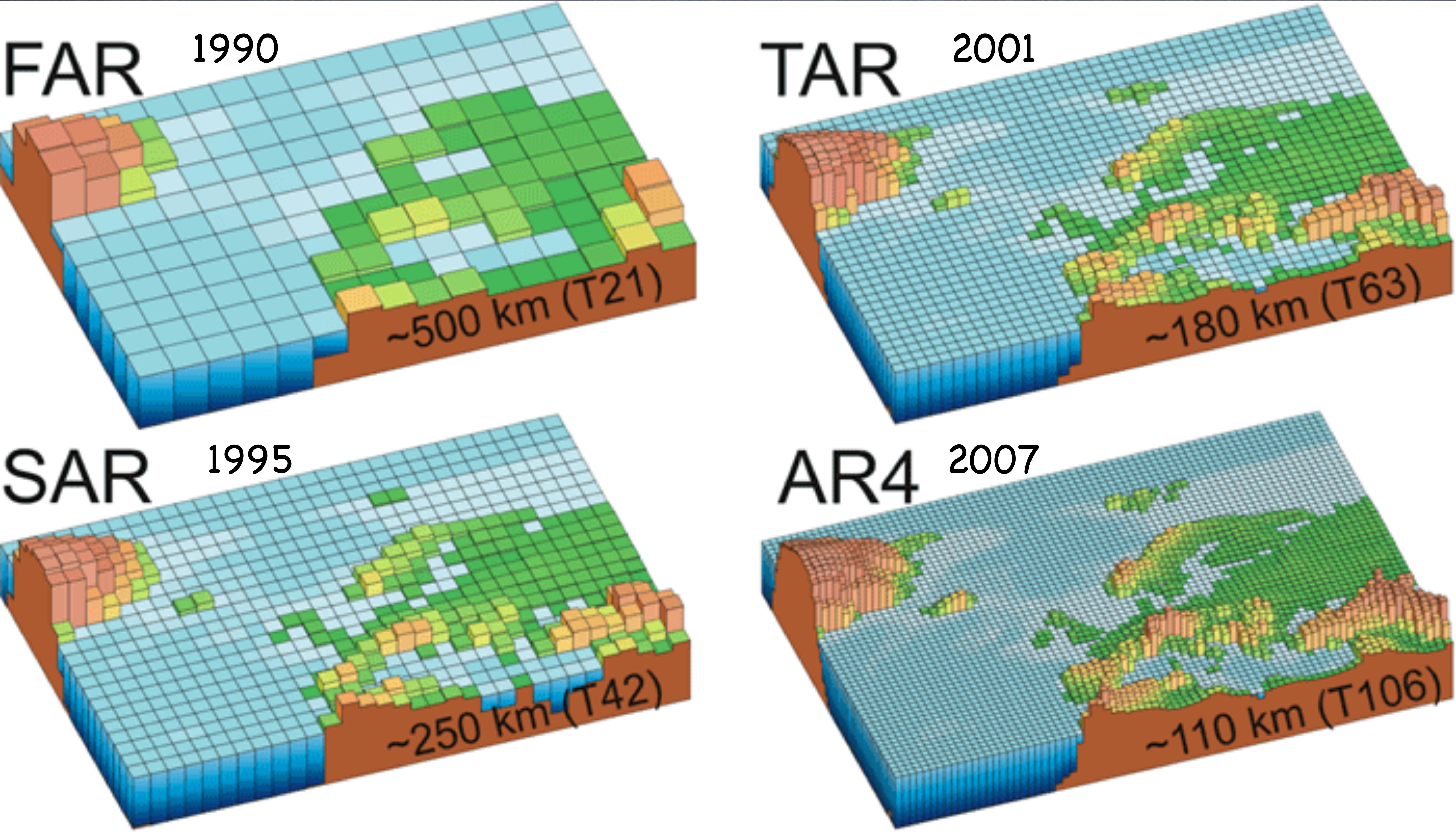
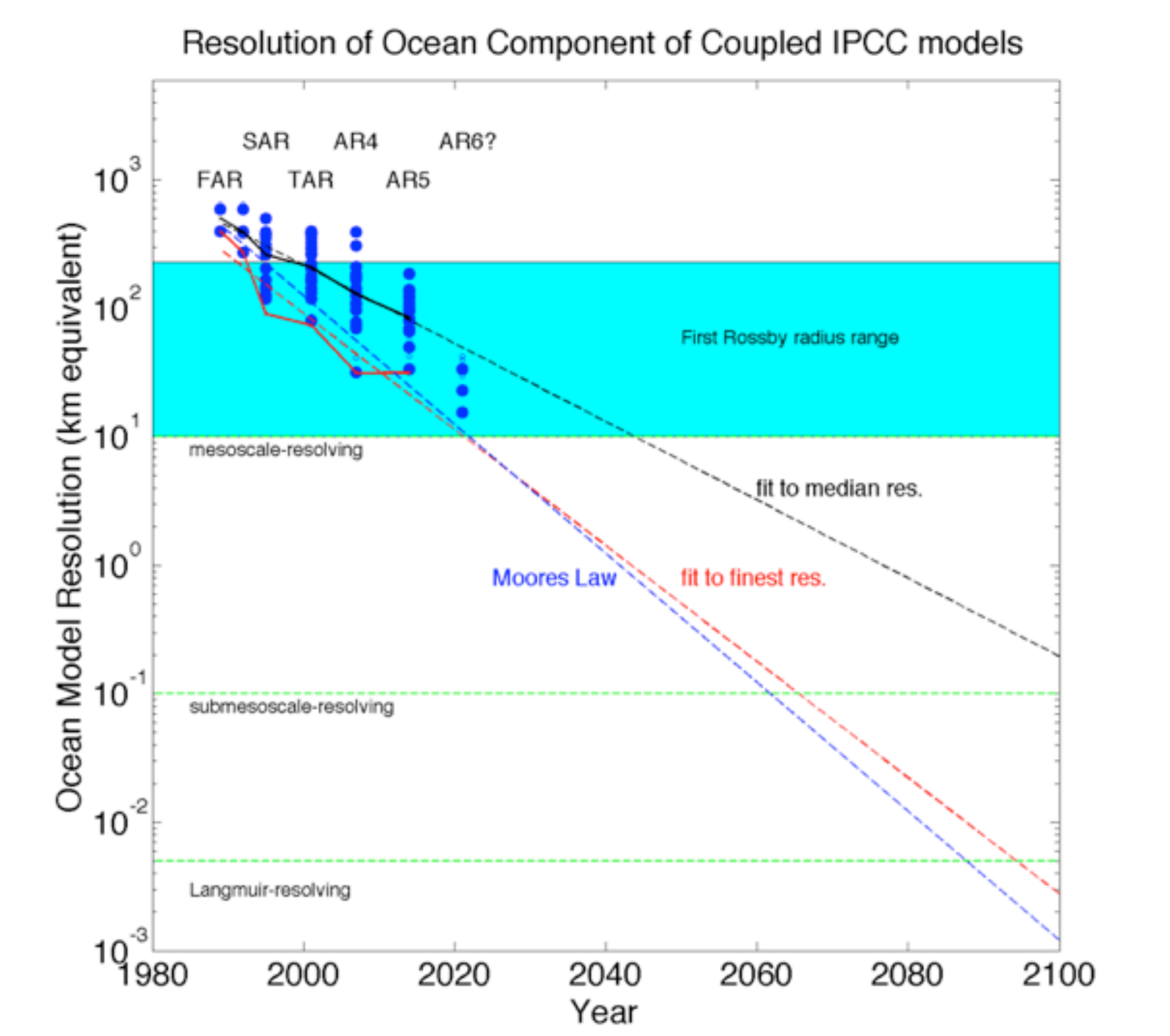


Image: ipcc.ch

Climate model resolution has been an issue...



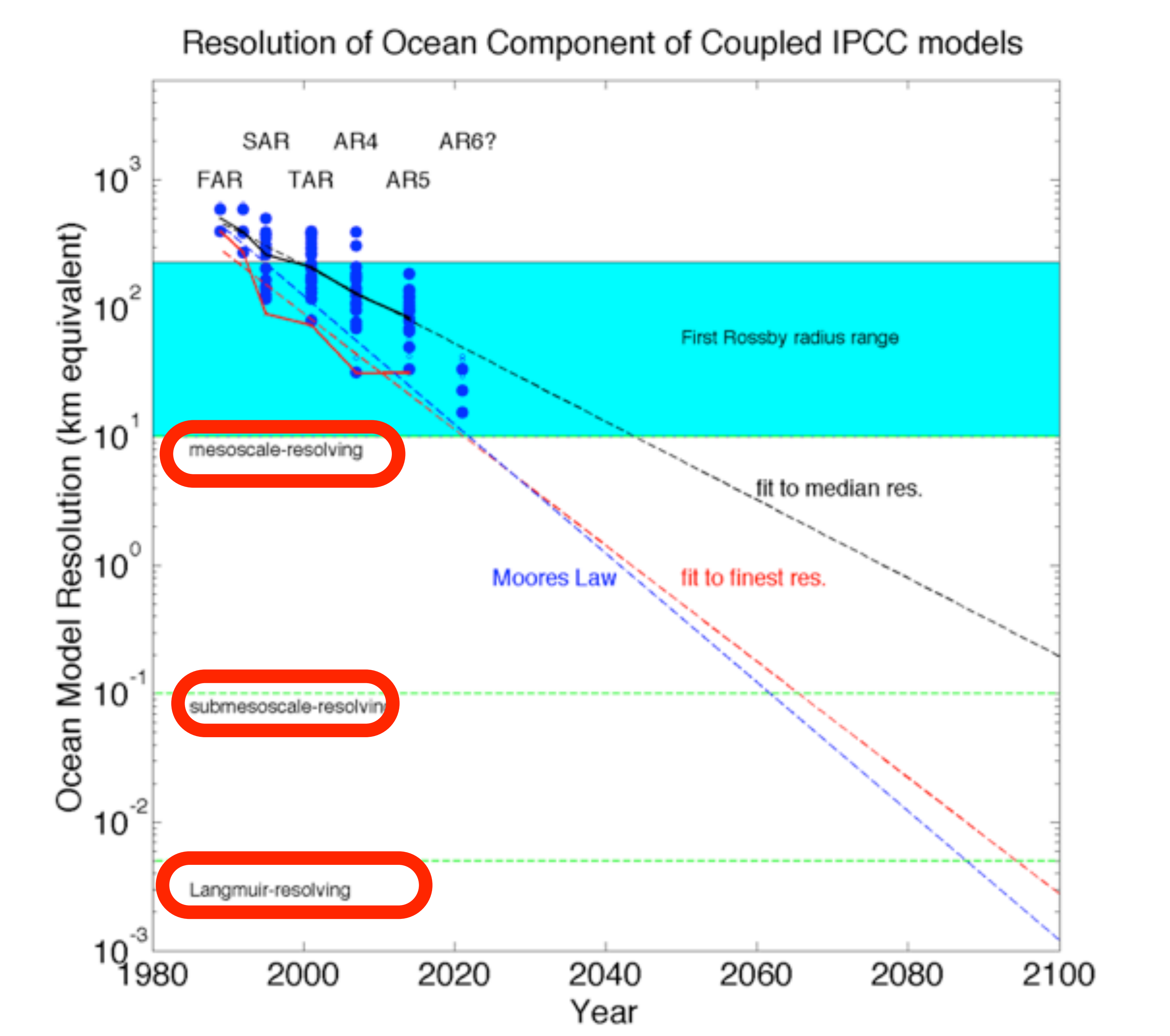
And will be an issue for centuries to come!



What are the processes capable of spanning scales?

What unresolved physics should we worry about?

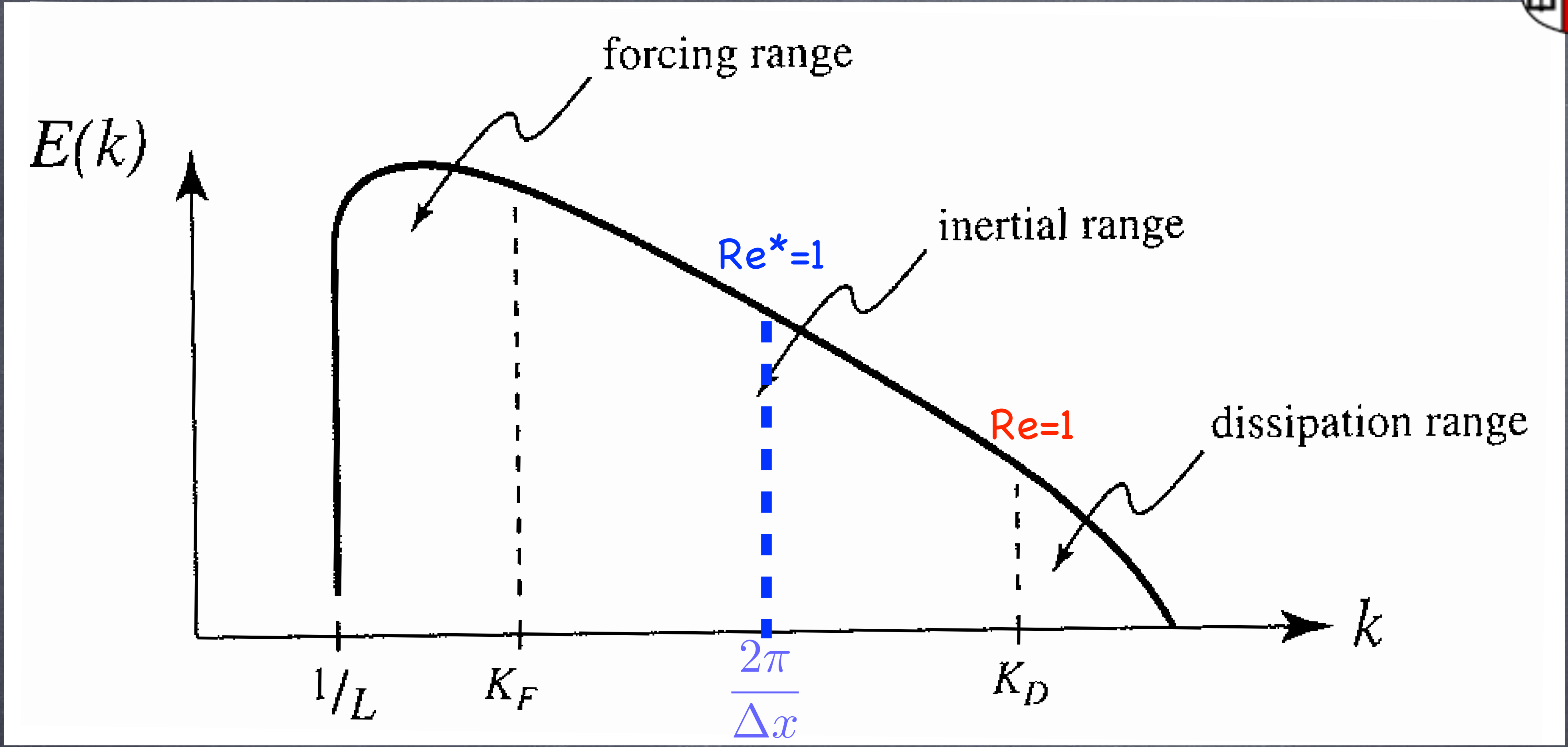
And will be an issue for centuries to come!



What are the processes capable of spanning scales?

What unresolved physics should we worry about?

Truncation of Cascades in models

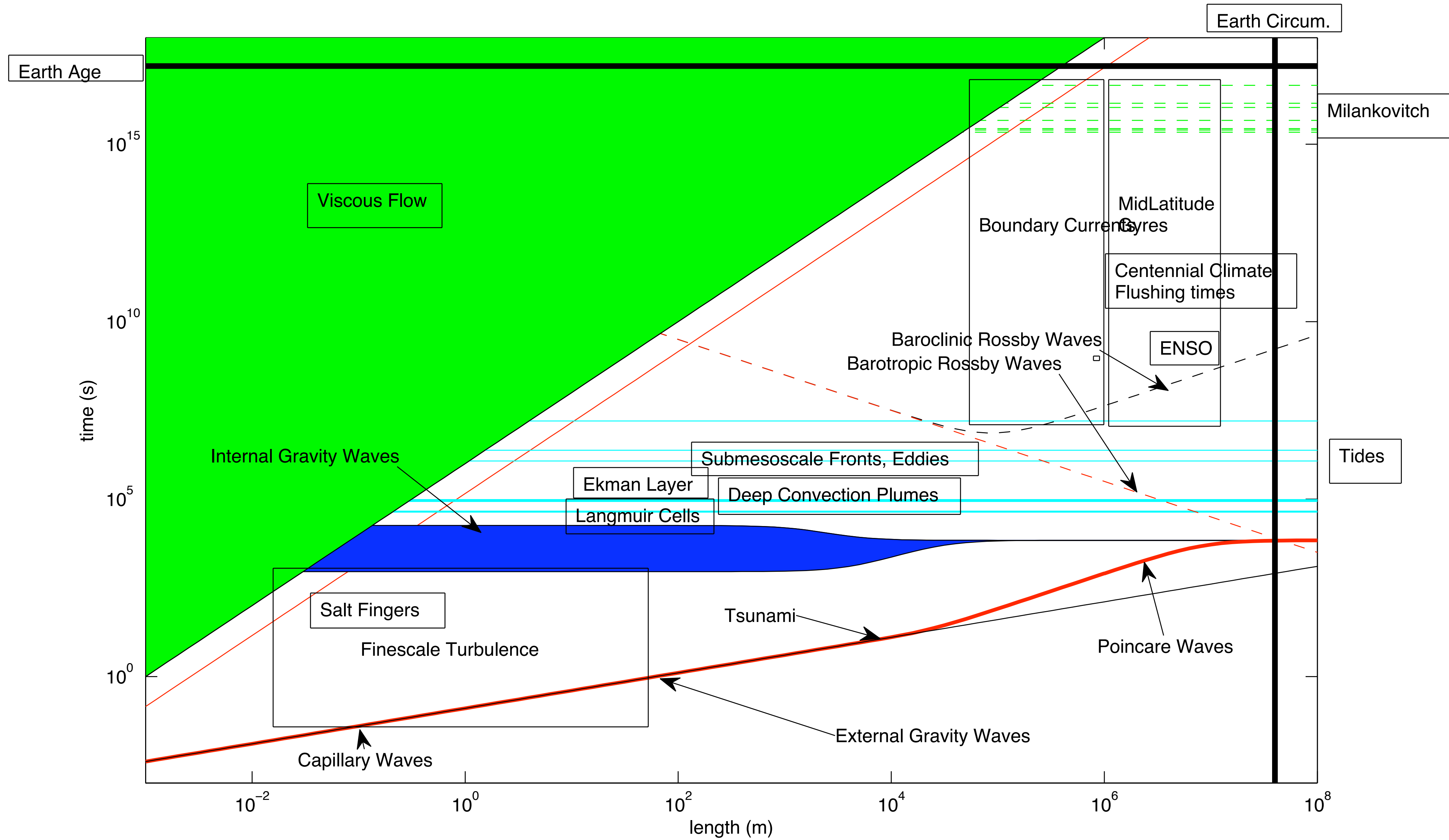


1963: Smagorinsky Devises Viscosity Scaling,
Energy Flow is Preserved,
but order-1 gridscale Reynolds #: $Re^* = UL/\nu_*$

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

Gridscale-dependent

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



So, what to do?

- Climate modelling requires that we truncate the model grid at coarse resolution (albeit improving slowly)
- Whatever resolution we can afford will leave some physics unresolved or partially-resolved, so we need subgrid closures!
- The vast & diverse scales of motion in the ocean suggest that we cannot use a one-size-fits-all approach, e.g., a turbulent cascade of 3d turbulence
- So, we have to invent new subgrid closures repeatedly, parameterizing processes important at each gridscale

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

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

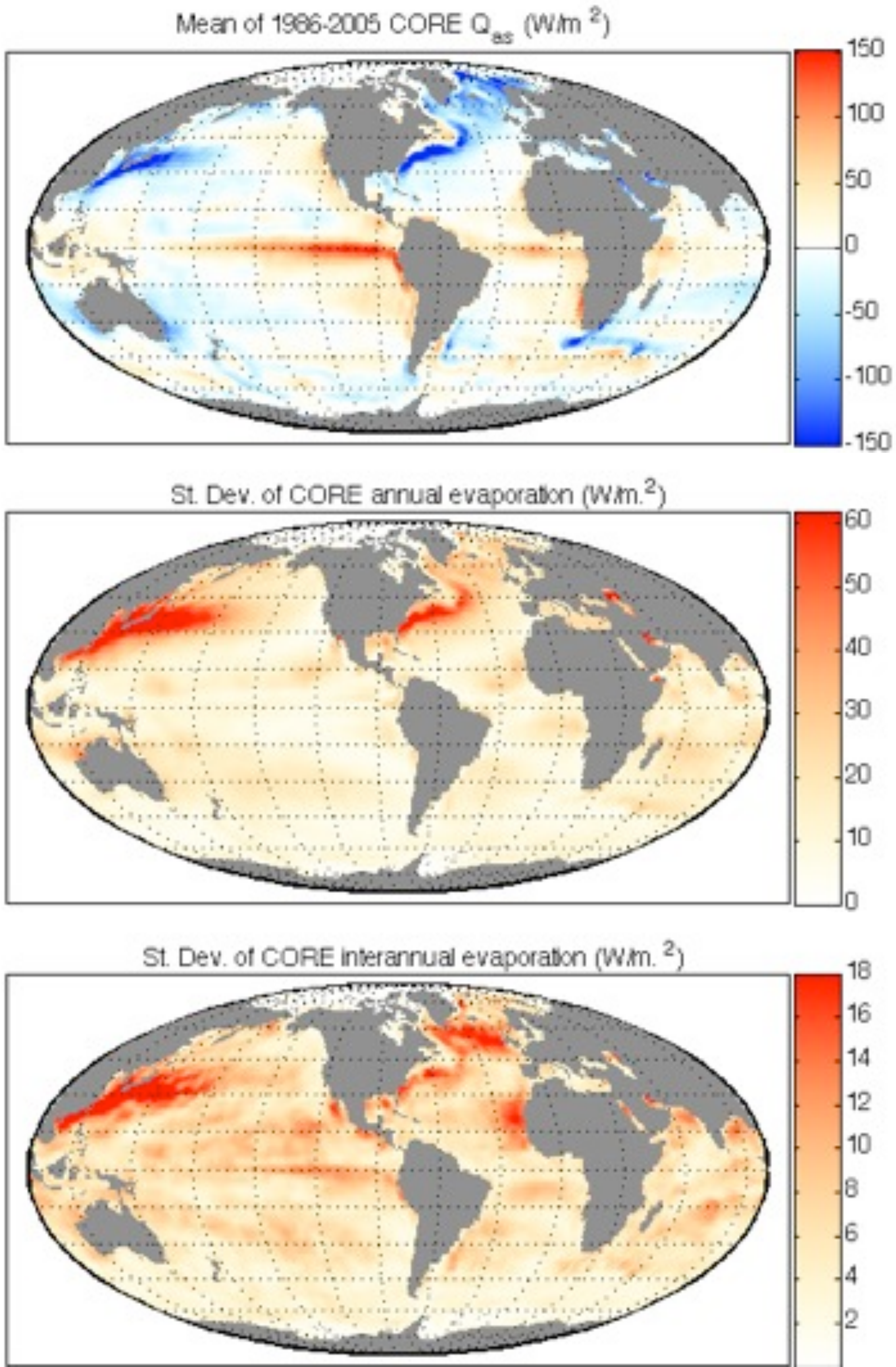
- Note that nonlinear terms require special treatment
- These couple different scales, small talks to large

Climate: What is important?

- To approximate absorption, reemission, and redistribution of the Sun's energy across the globe
- Need atmospheric chemistry (greenhouse gasses) & clouds for absorption & reemission
- Need ocean (surface) as it exchanges
  - sensible heat
  - latent heat (evaporation, freezing, precipitation)
  - gasses
  - momentum
- Plus, ocean transports heat itself!

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.

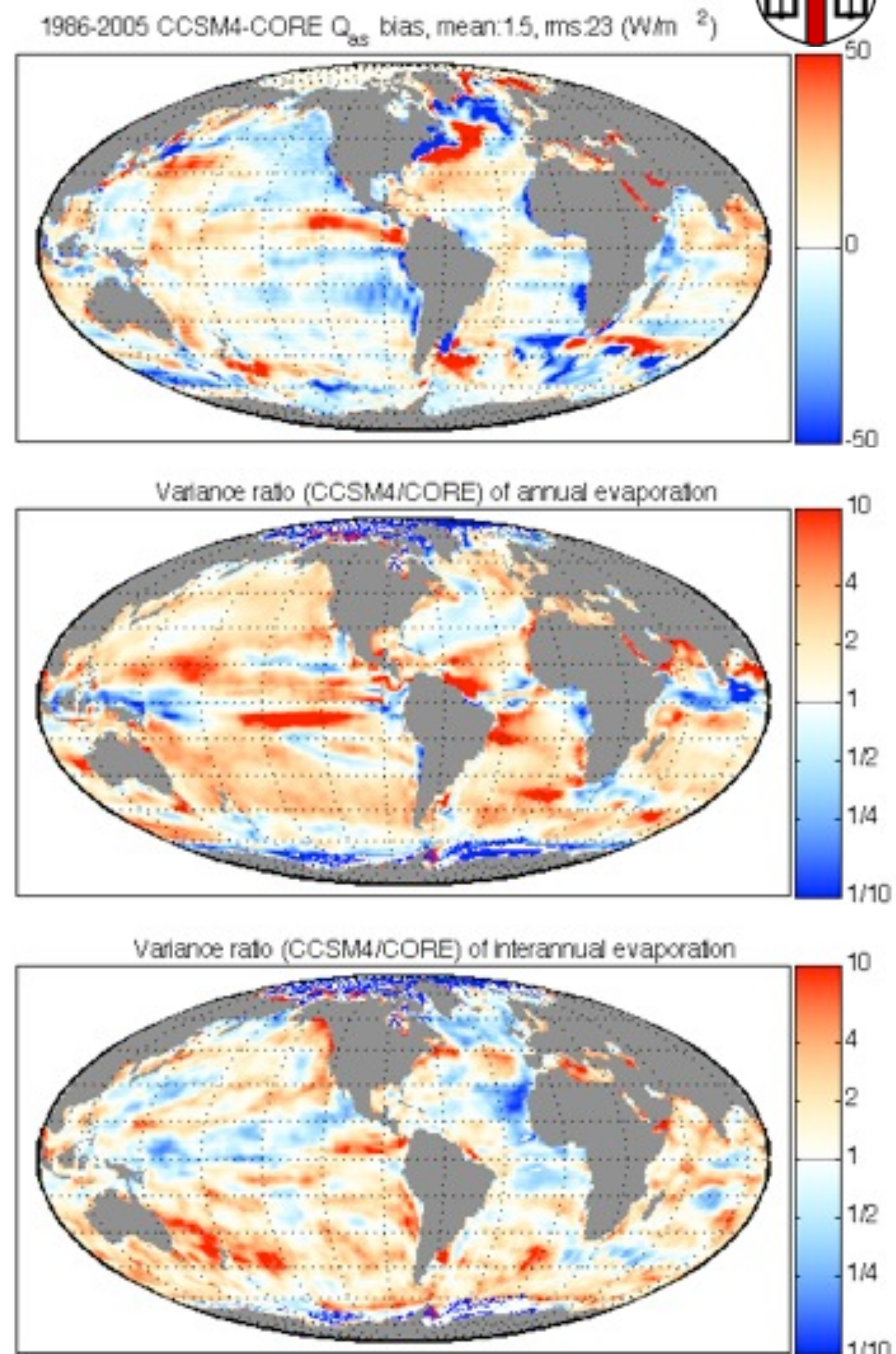
CCSM4 Air-Sea Flux Errors vs. Data (Large & Yeager 09)



Mean

Annual
9-15mo

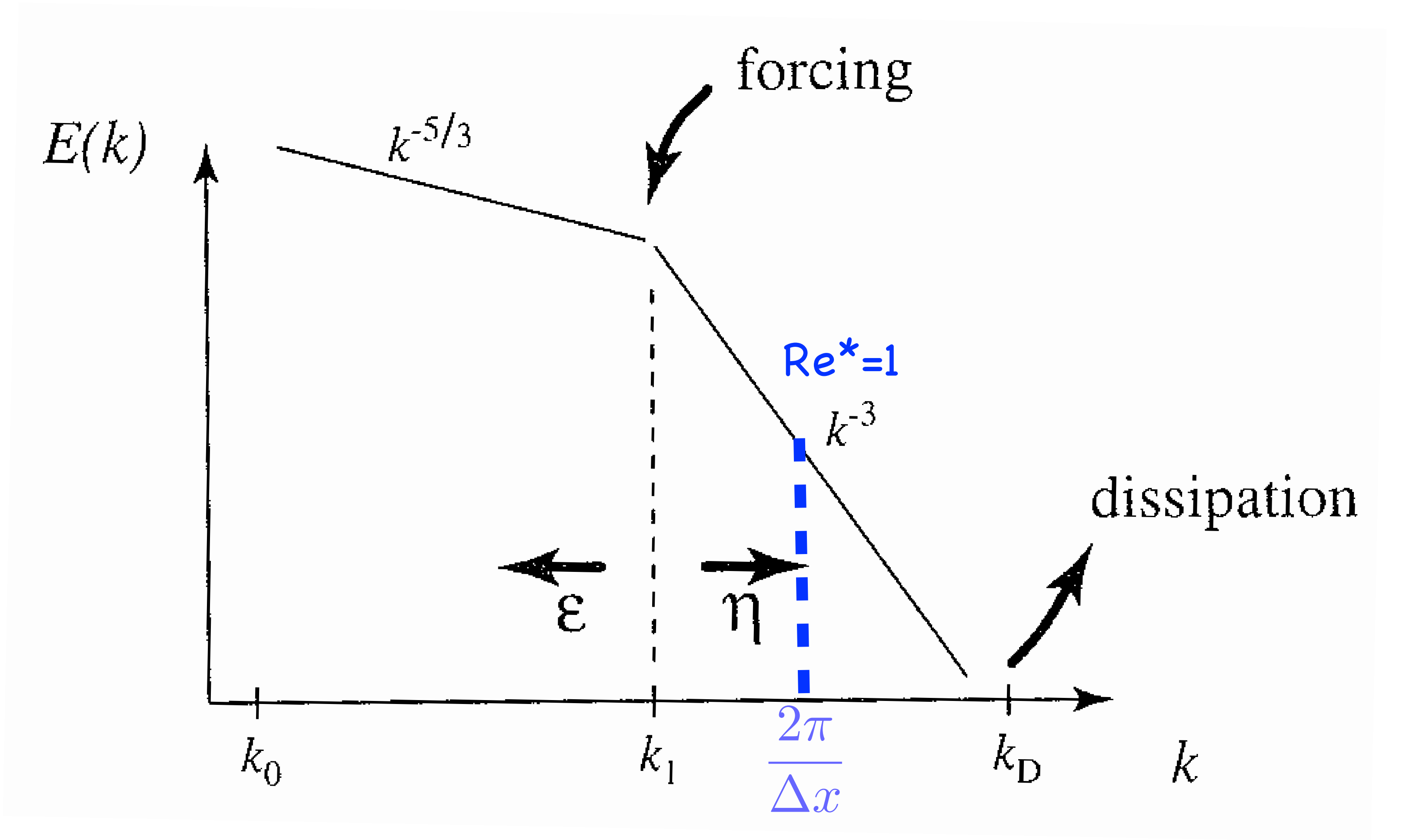
Interannual
2-7yr



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

- The ocean is wide (10,000km)
- But not deep (4km)
  - Motions in upper 1km
- Motions are largely 2d
- The layer of blue paint on a globe has roughly the right aspect ratio!

2d Turbulence Differs



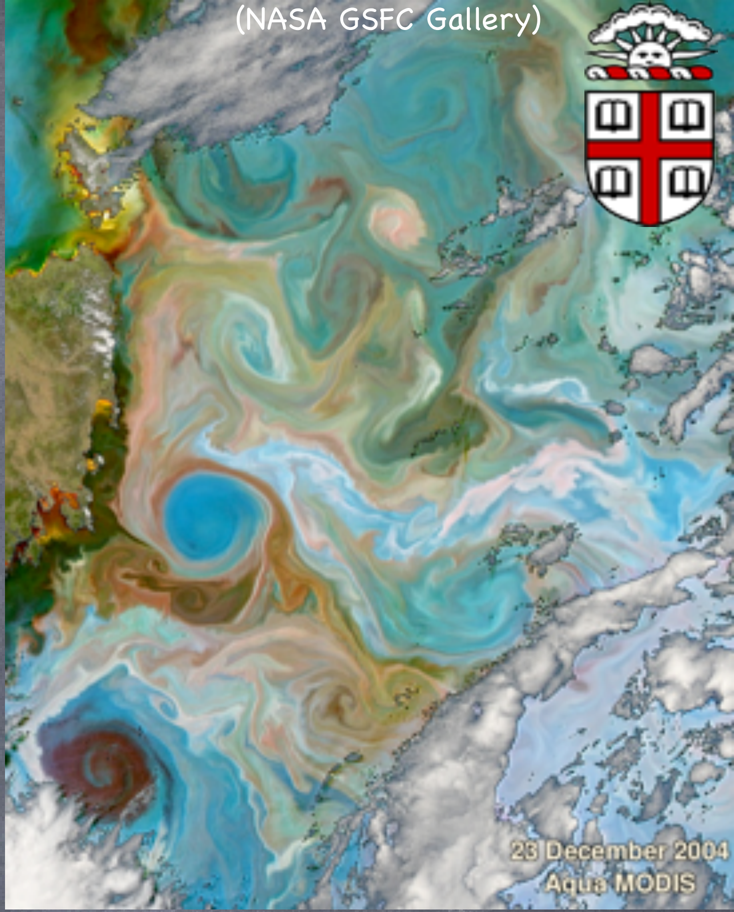
1996: Leith Devises Viscosity Scaling,
So that the Enstrophy Flow is Preserved

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

The Character of the Mesoscale

100 km

(NASA GSFC Gallery)



(Capet et al., 2008)

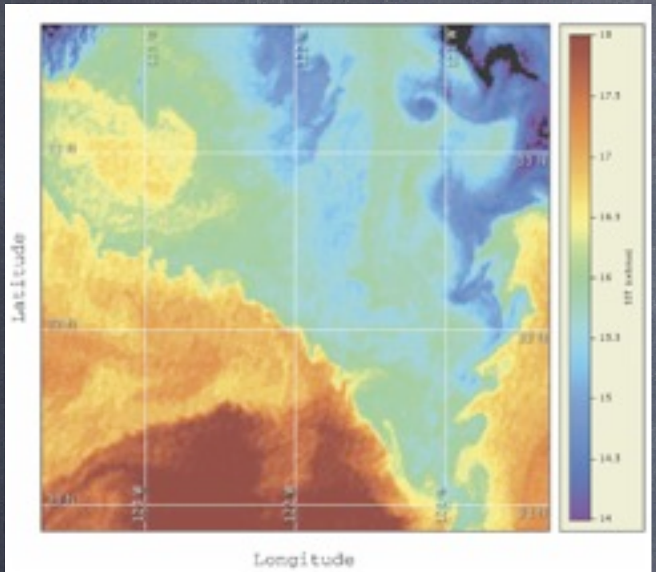
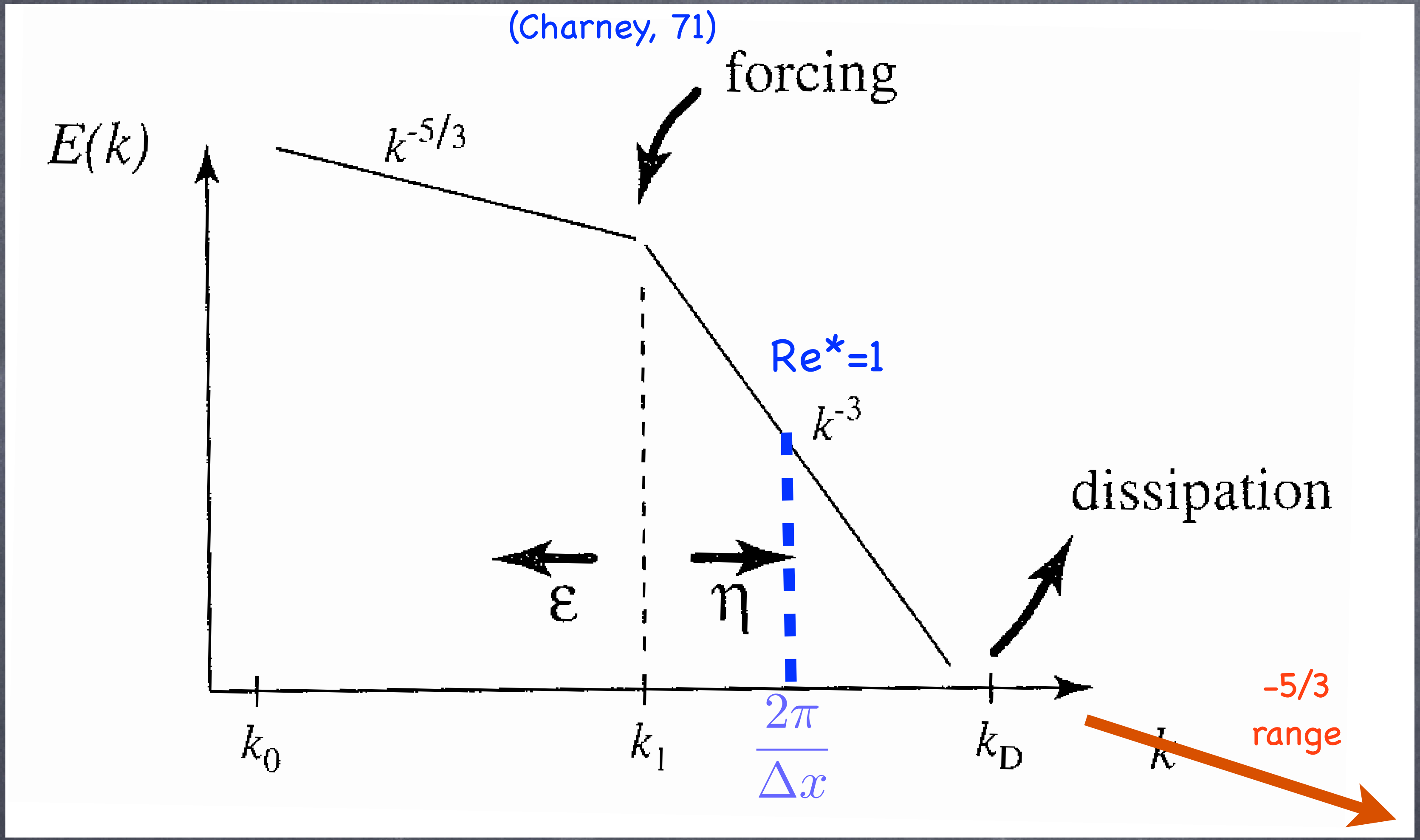


FIG. 16. Sea surface temperature measured at 1832 UTC 3 Jun 2006 off Point Conception in the California Current from CoastWatch (http://coastwatch.pfeg.noaa.gov). The fronts between recently upwelled water (i.e., 15°–16°C) and offshore water (≥17°C) show submesoscale instabilities with wavelengths around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

Mesoscale Turb. has Pot'l Enstrophy cascade, but divergent



F-K & Menemenlis Revise Leith Viscosity Scaling,

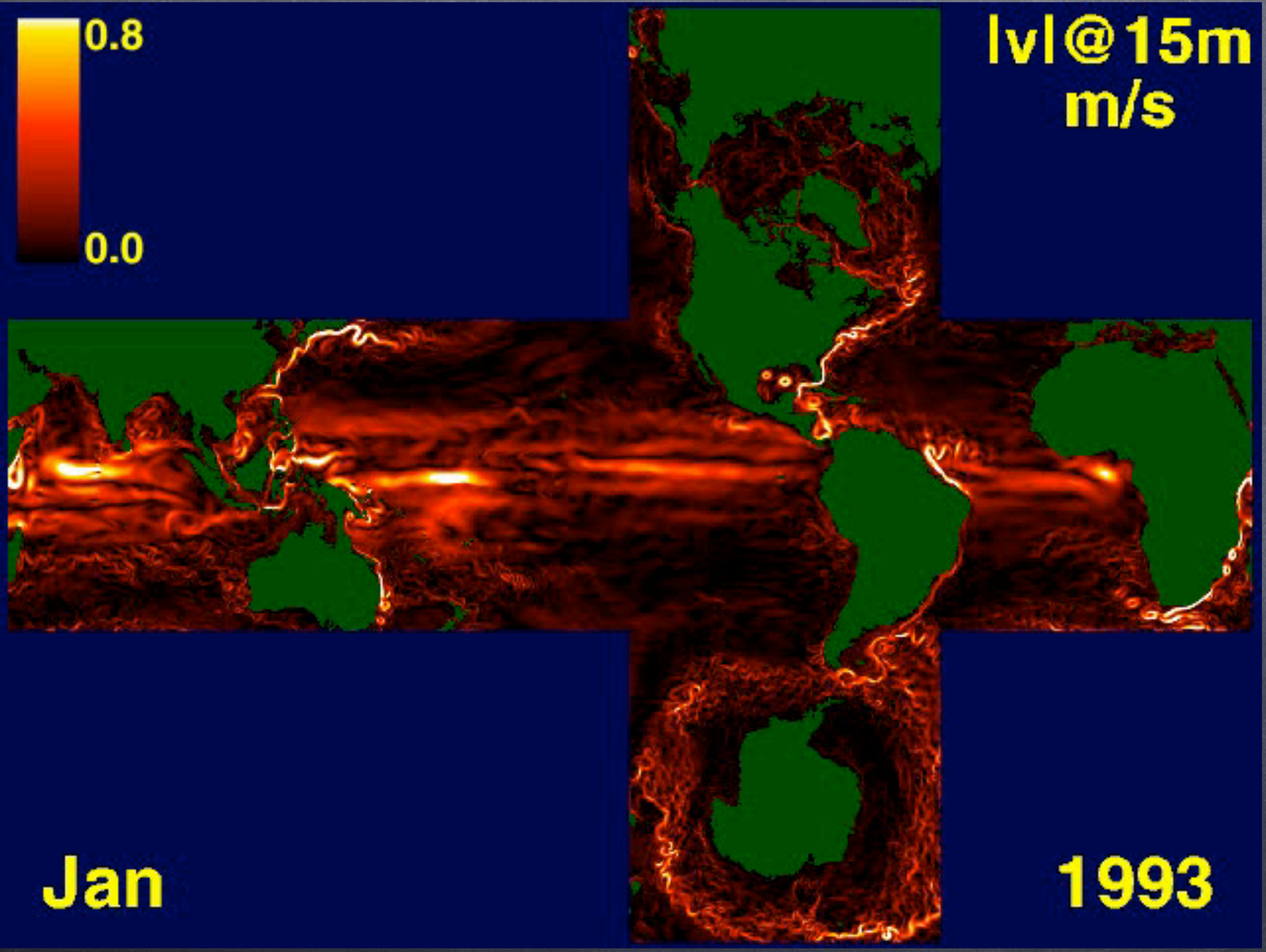
So that diverging, vorticity-free, modes are also damped

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

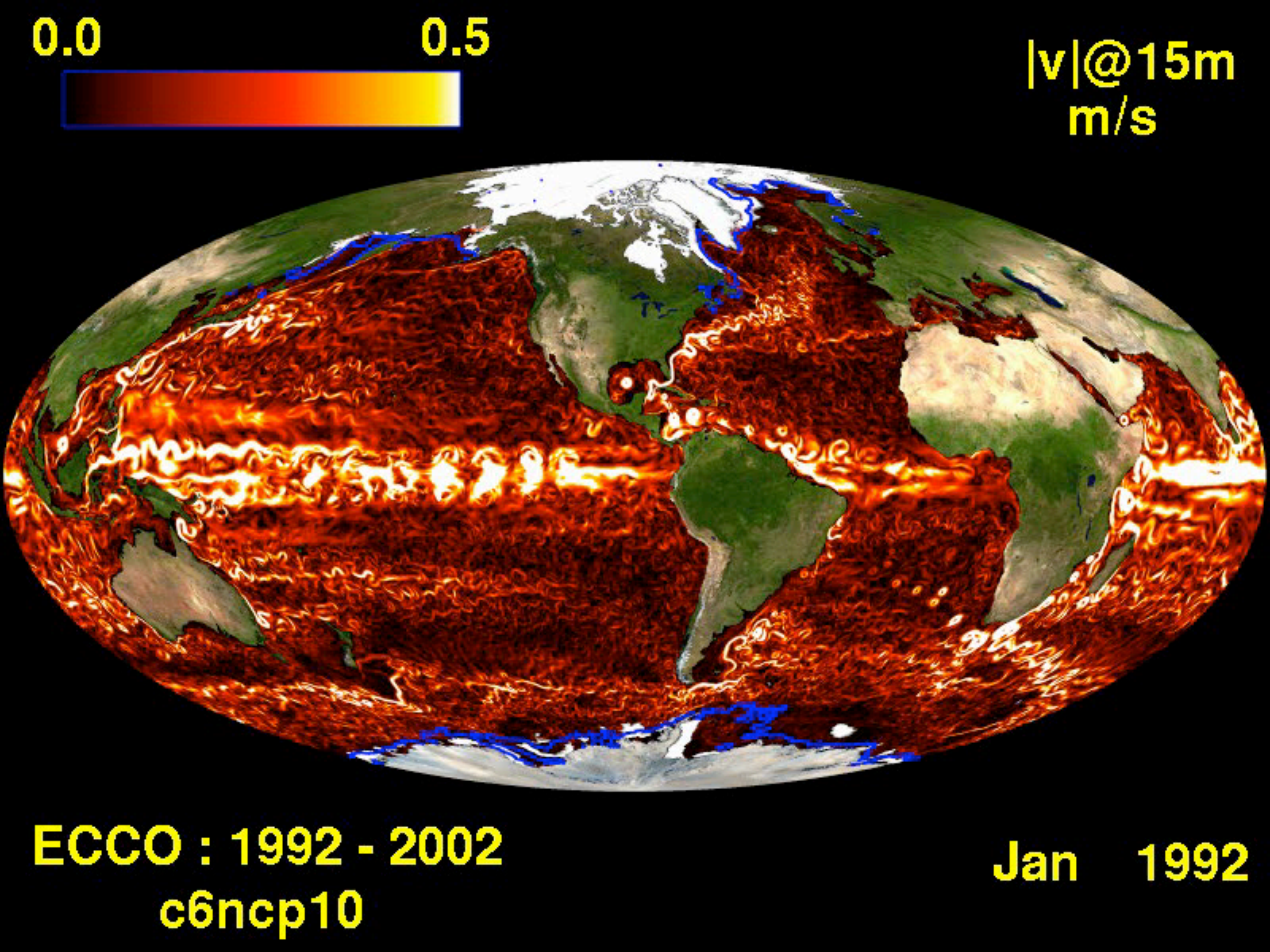
B. Fox-Kemper and D. Menemenlis. Can large eddy simulation techniques improve mesoscale-rich ocean models? In M. Hecht and H. Hasumi, editors, Ocean Modeling in an Eddying Regime, volume 177, pages 319-338. AGU Geophysical Monograph Series, 2008.

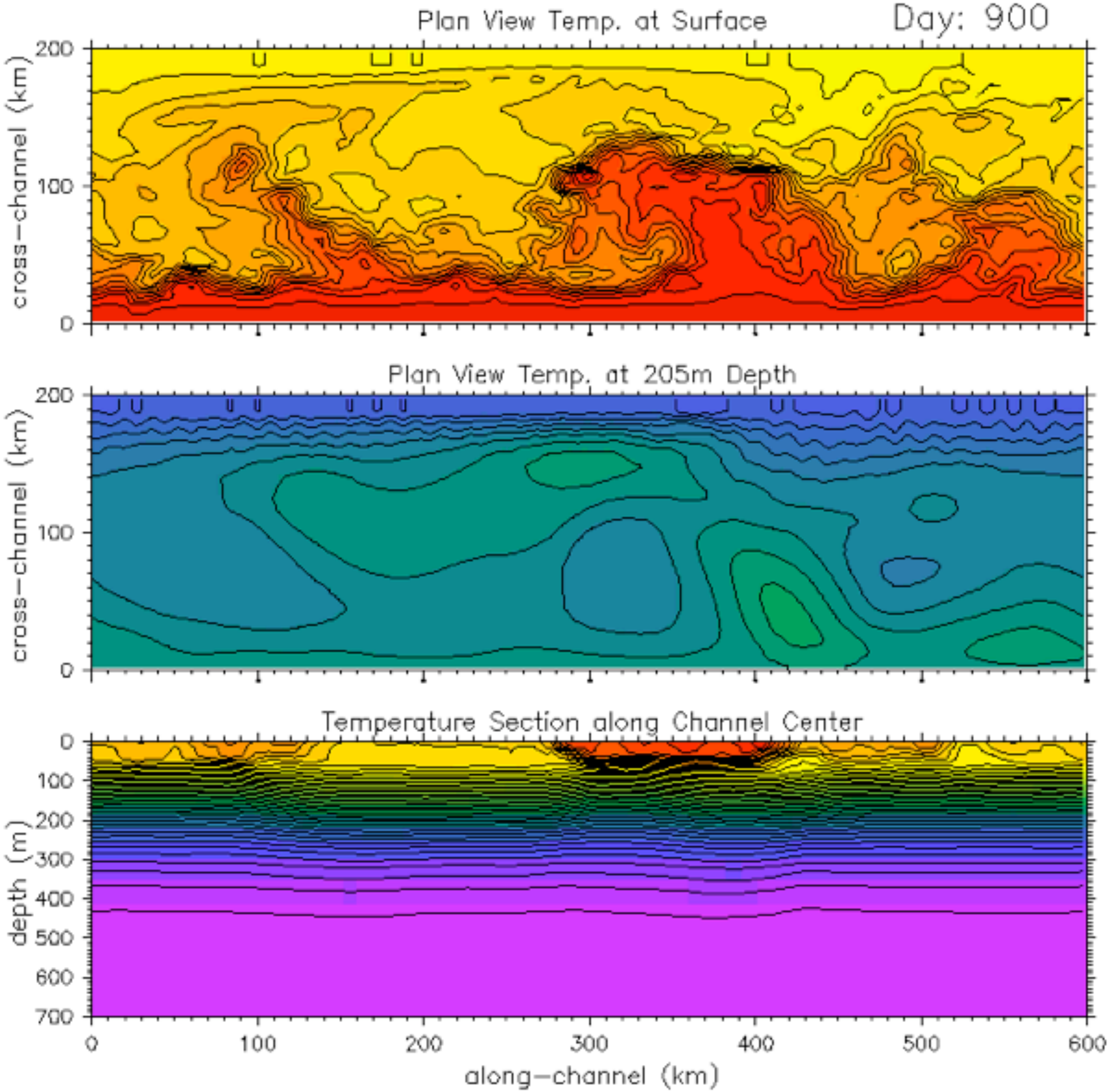
ECCO2: Estimating the Current Climate of the Ocean

Phase II uses this viscosity scaling.



Note how no obvious artifacts occur at the grid joints, despite variations in grid scale, etc.


0.0
0.5
|v|@15m
m/s
ECCO : 1992 - 2002
c6ncp10
Jan 1992



Big, Deep (meso)

interact with

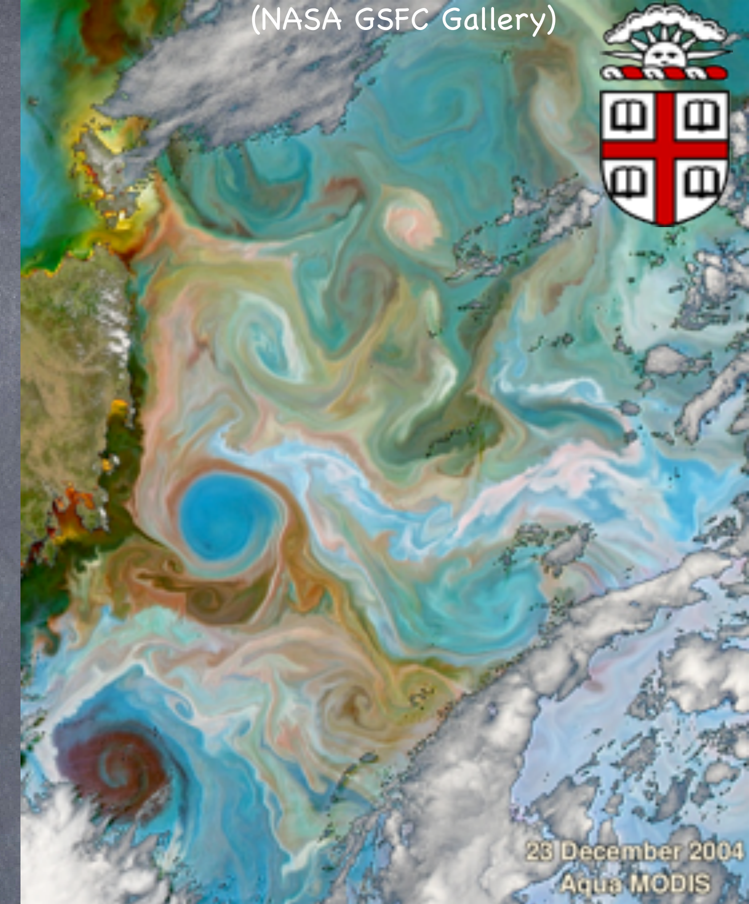
Little, Shallow (submeso)

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.

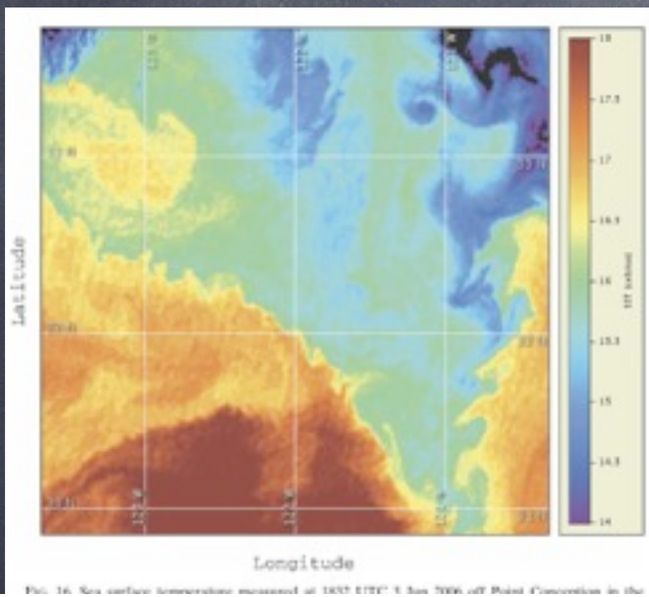
The Character of the Submesoscale

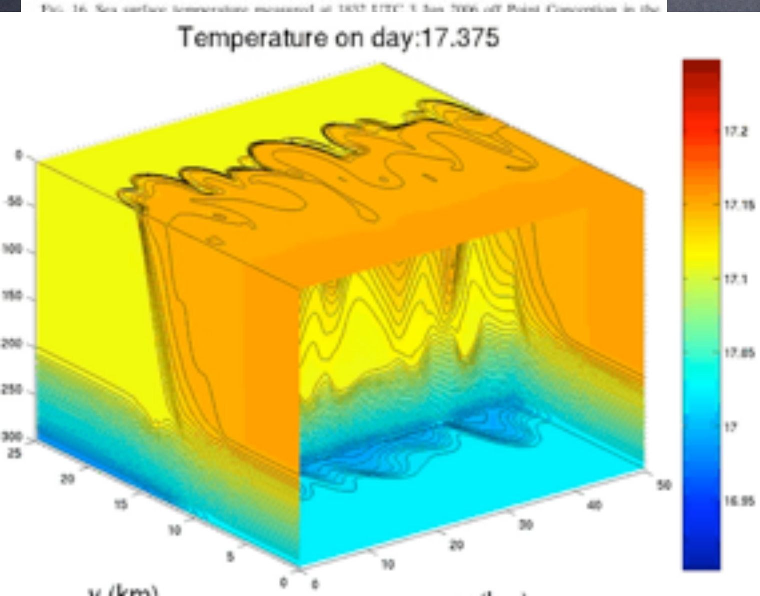
10 km

(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

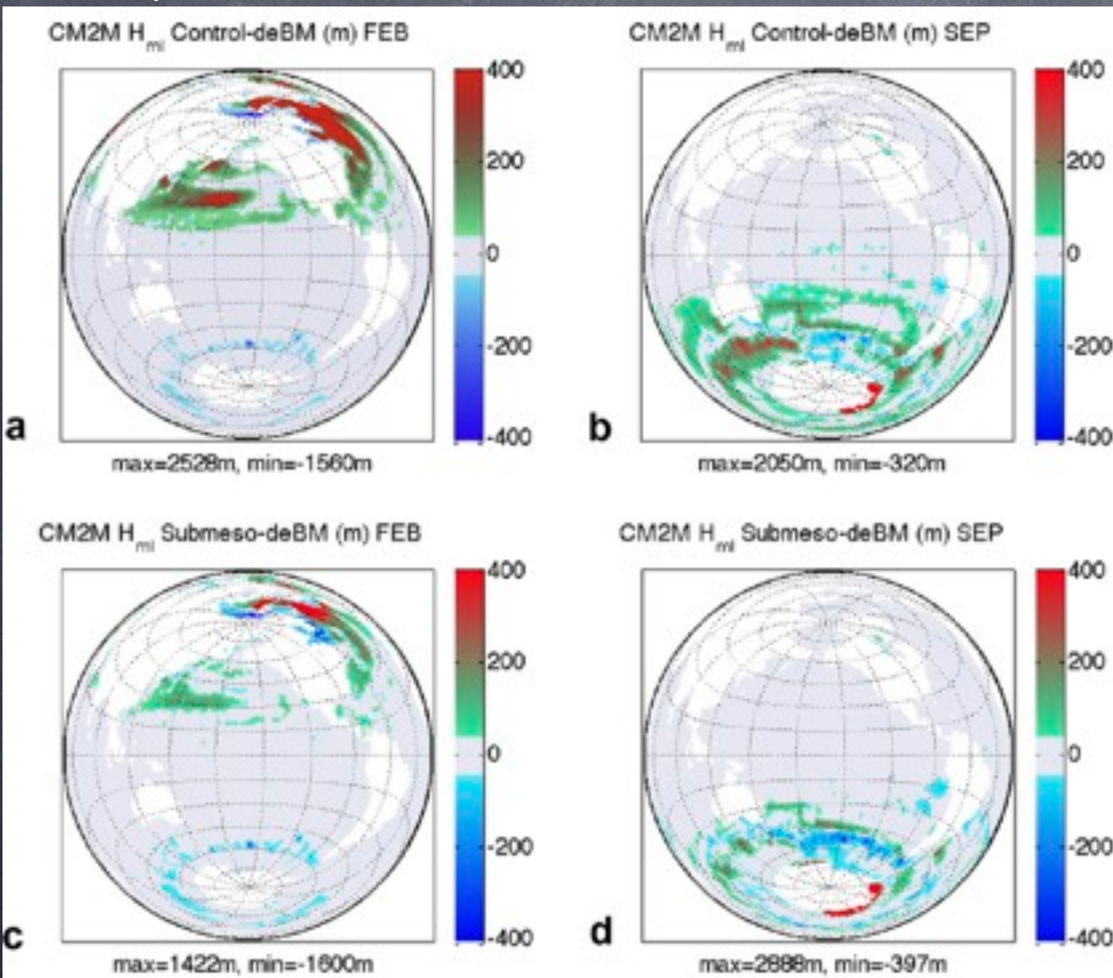
Parameterizations of submesoscale baroclinic instability?

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

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

Improves Mixed Layers

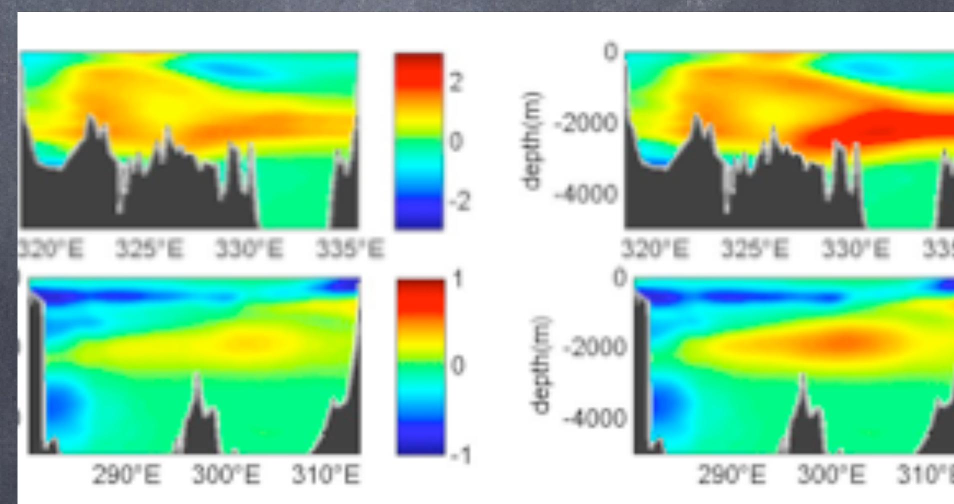


Bias w/o MLE

Improves CFCs (water masses)

Bias with MLE

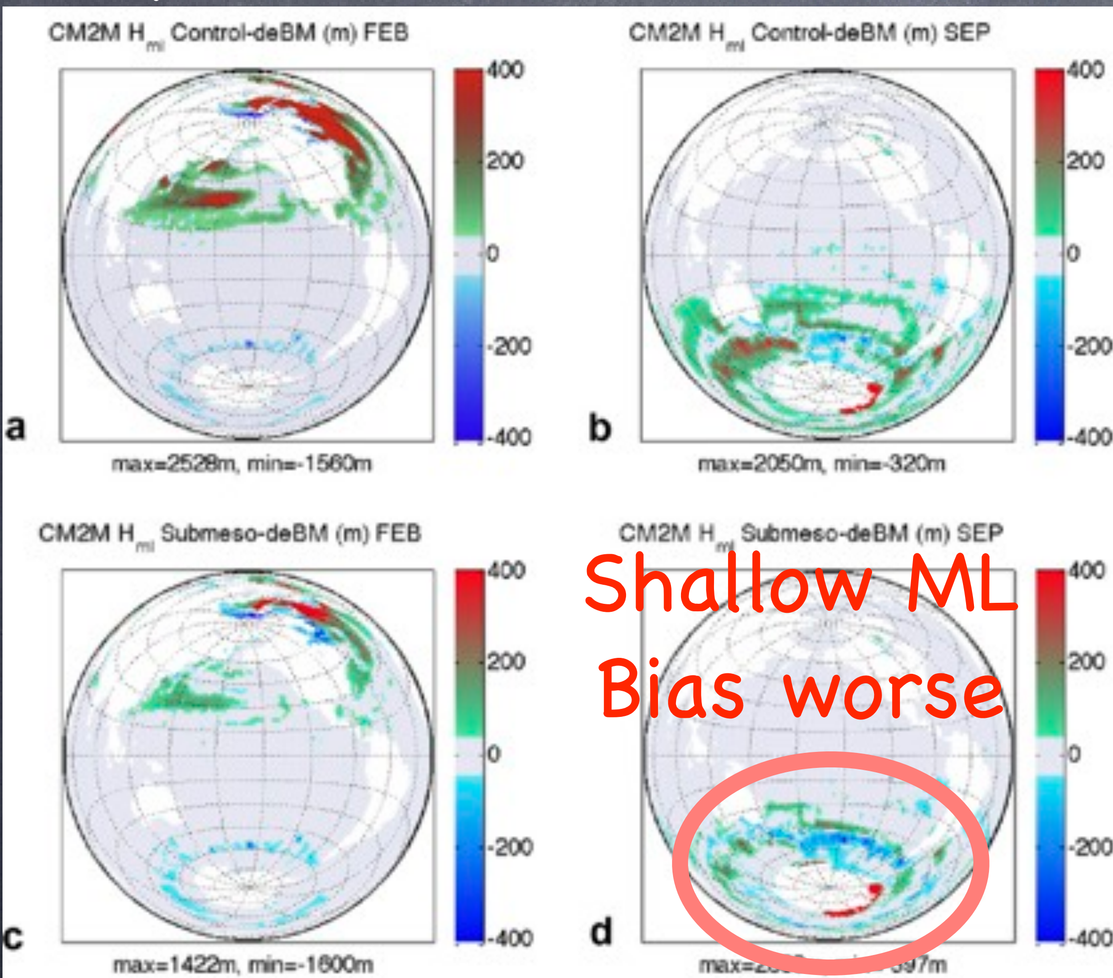
Bias w/o MLE



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.

Physical Sensitivity of Ocean Climate to MLE: Mixed Layer Eddy Restratification

Improves Mixed Layers



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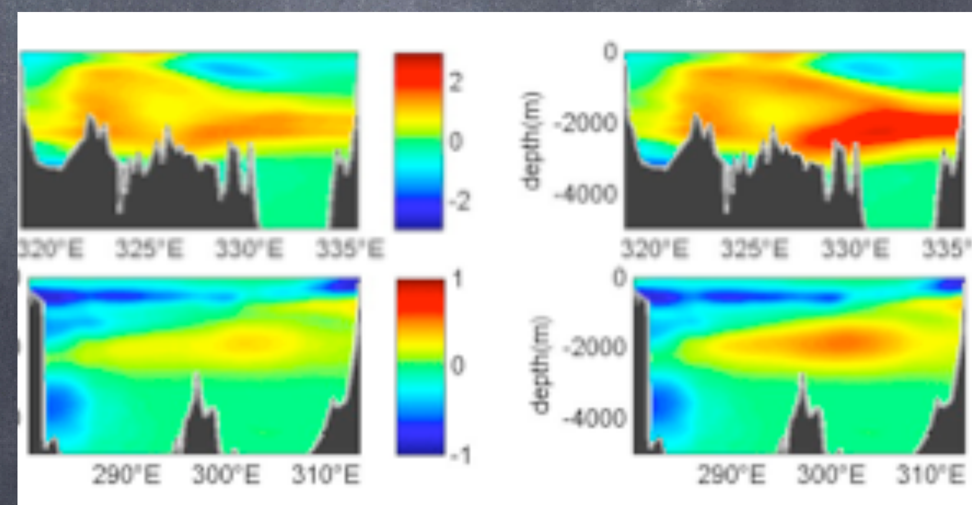

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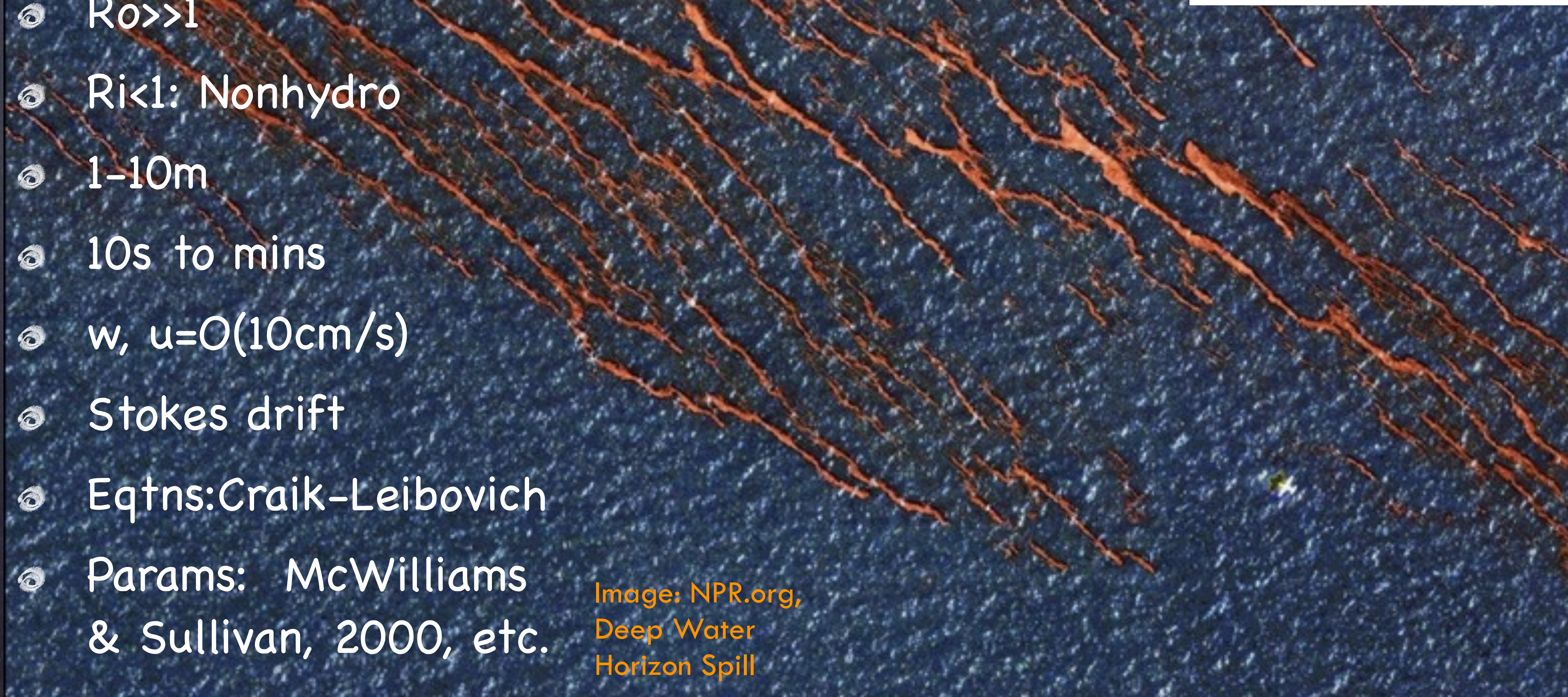
The Character of the Langmuir Scale



- 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

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

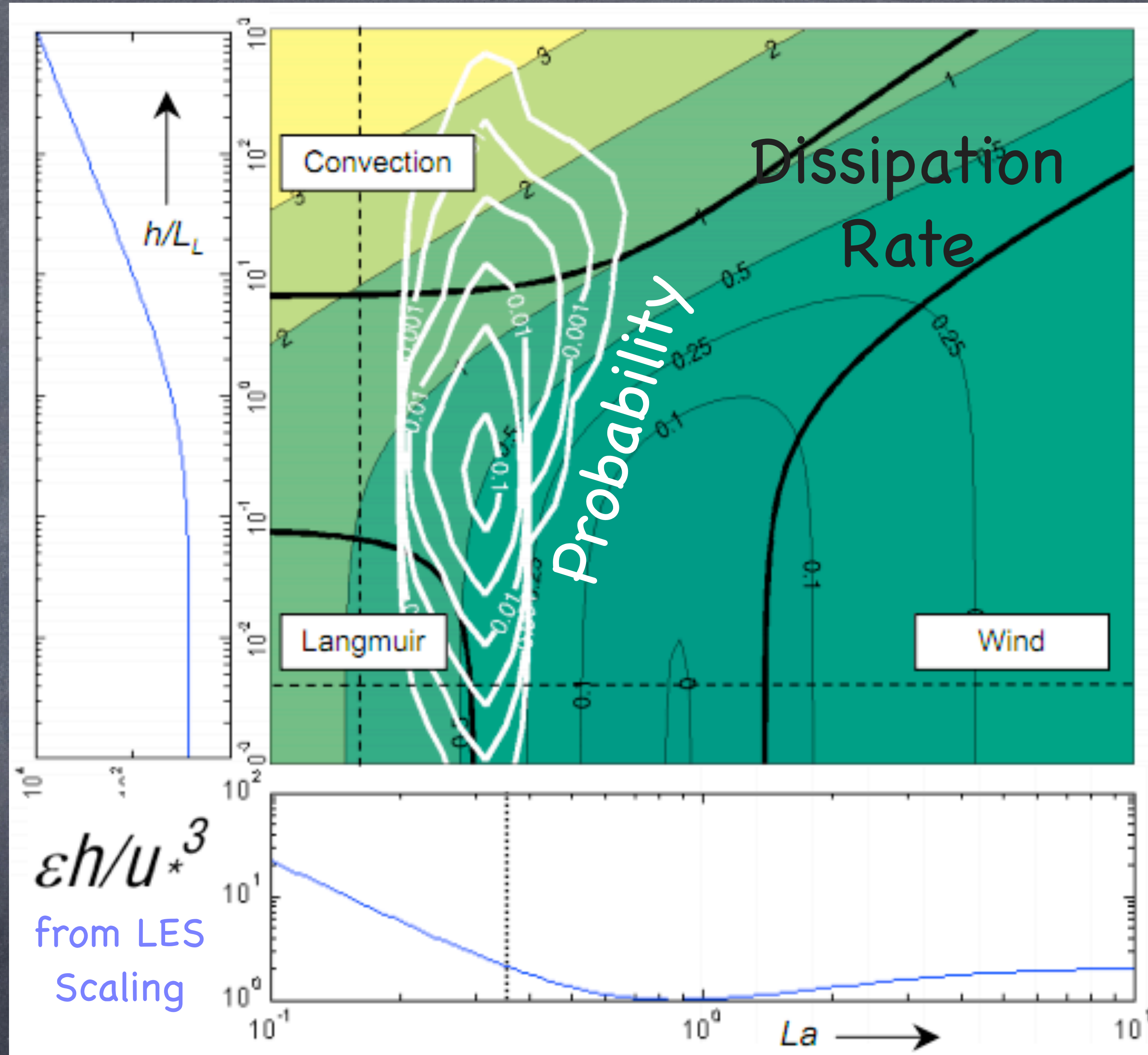
image: Leibovich, 83

Combining Data w/ LES scalings:

Where does energy for Southern Ocean mixing come from?

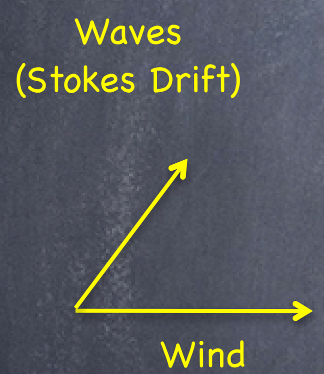
Langmuir (wave-driven) and Convective

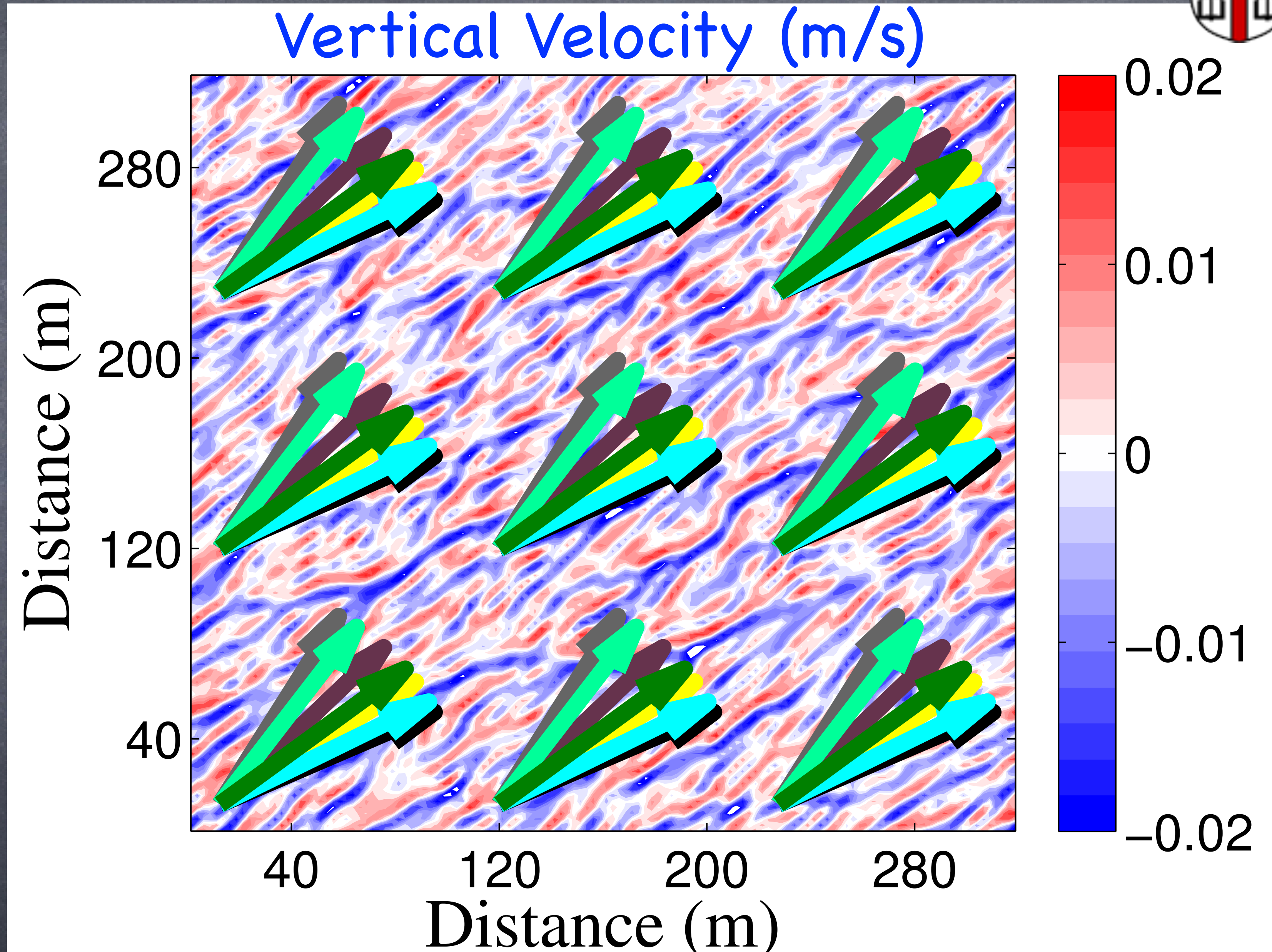
But, we don't have wave-driven mixing in climate models!!!



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.

Real World Forcing: Misaligned Wind & Waves

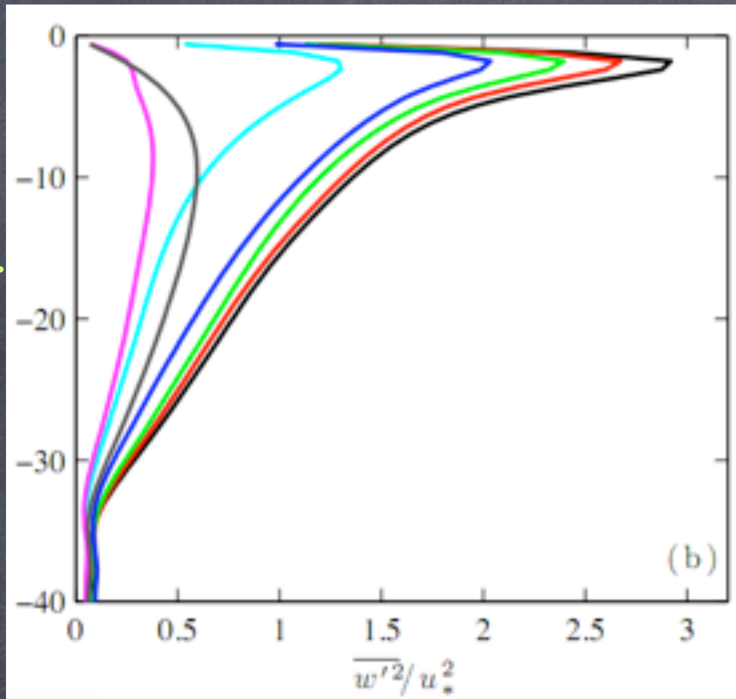




L. Van Roekel, B. Fox-Kemper, P. P. Sullivan, P. E. Hamlington, and S. R. Haney. The form and orientation of Langmuir cells for misaligned winds and waves. *Journal of Geophysical Research-Oceans*, 2012. In press.

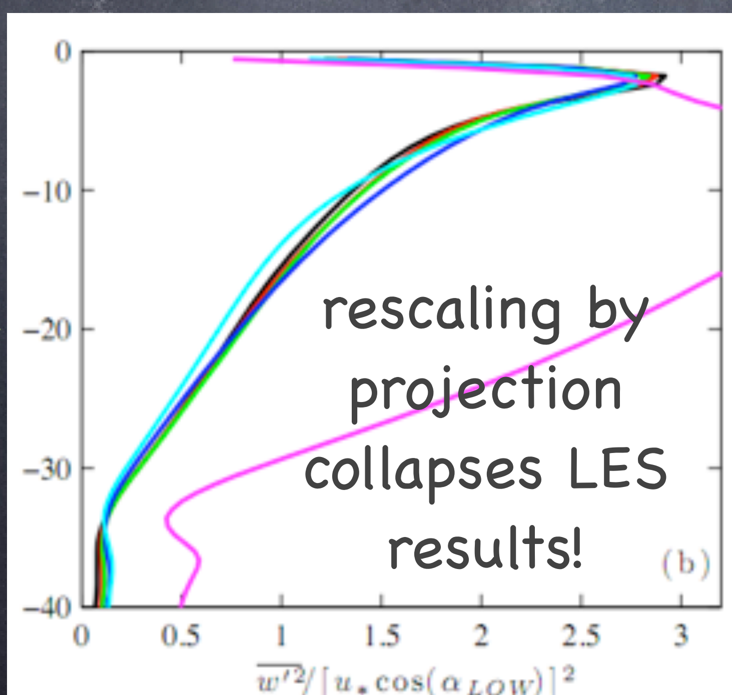
$\langle w^2 \rangle$

depth



rescaled $\langle w^2 \rangle$

depth



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.

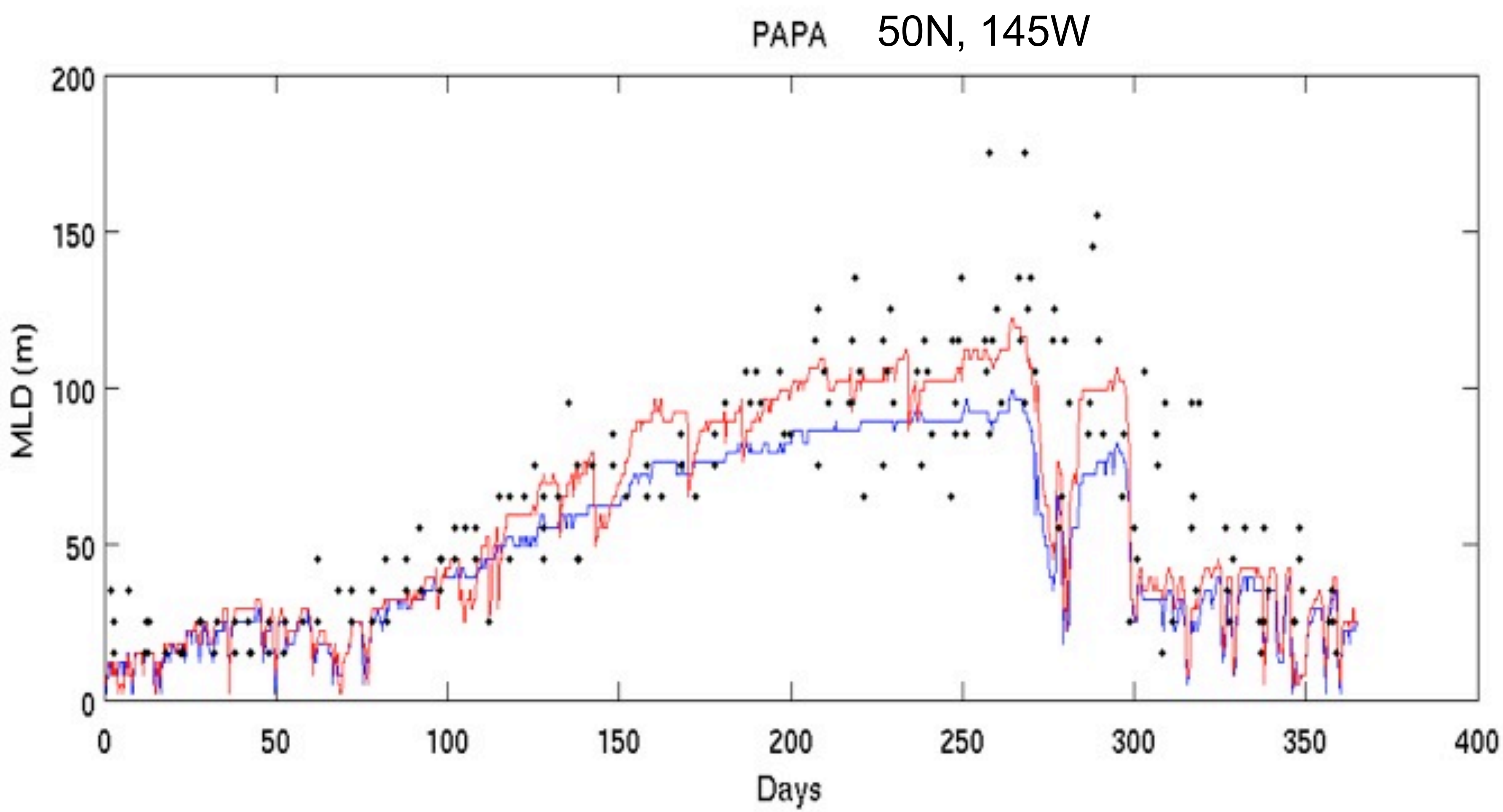
Estimated Mixing with Harcourt Second Moment Closure Model:

- Expands on implementation of Langmuir mixing of Kantha & Clayson (and Mellor-Yamada, etc).
- Allows waves to affect diffusivity and vertical momentum flux as well as energy sources...
- Consistent treatment of wave-wind misalignment
- Was run for 1-year, using Large & Yeager (2004) "Normal Year" and matching WaveWatch-III-simulated waves.
- ARGO profiles near summer solstice initial condition.
- Pure 1D mixing vs. solar & fluxes only -- No ocean circulation or eddy restratification, etc.

R. R. Harcourt. A second moment closure model of Langmuir turbulence. Journal of Physical Oceanography, 2013, in press.

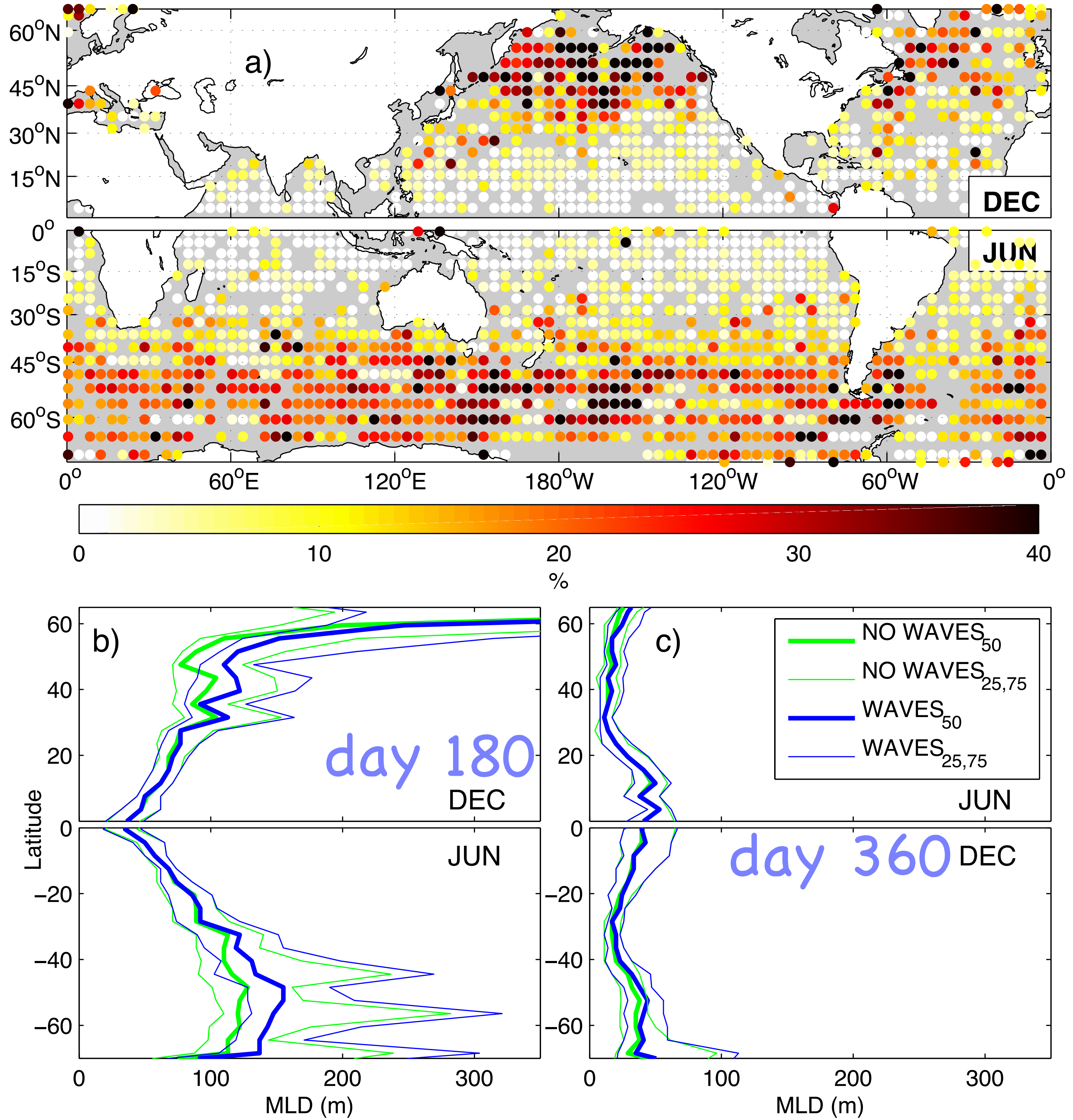
Harcourt--Evolving Mixed Layer Depth Results
(Simulated by M. Hemer, CSIRO)

Potential for improvement! (not all look so good...)



NO WAVES WAVES Nearby ARGO PROFILES (dots)

Including Wave-driven Mixing Deepens the Wintertime and S. Ocean Mixed Layer!



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

Well that was fun...

Lots of small turbulence affects the upper ocean on seasonal timescales!

But, why stop now?

How do these small processes affect each other?

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

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, 2013.

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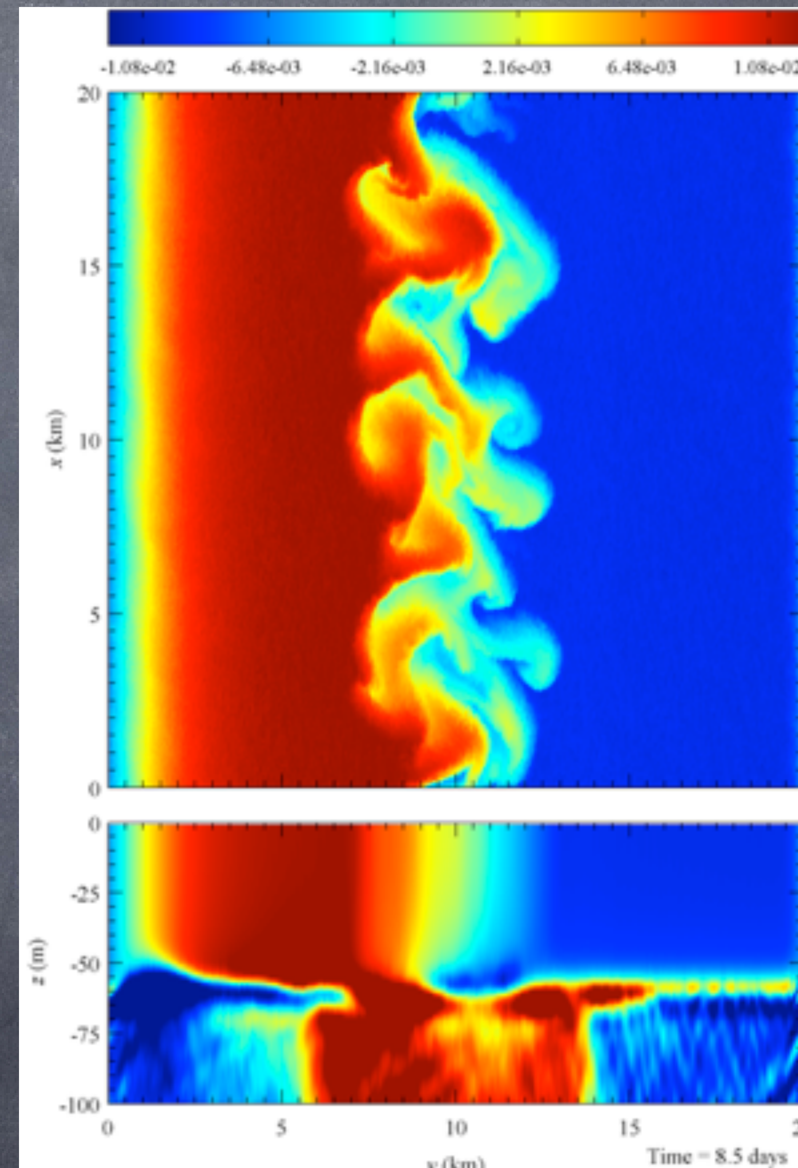
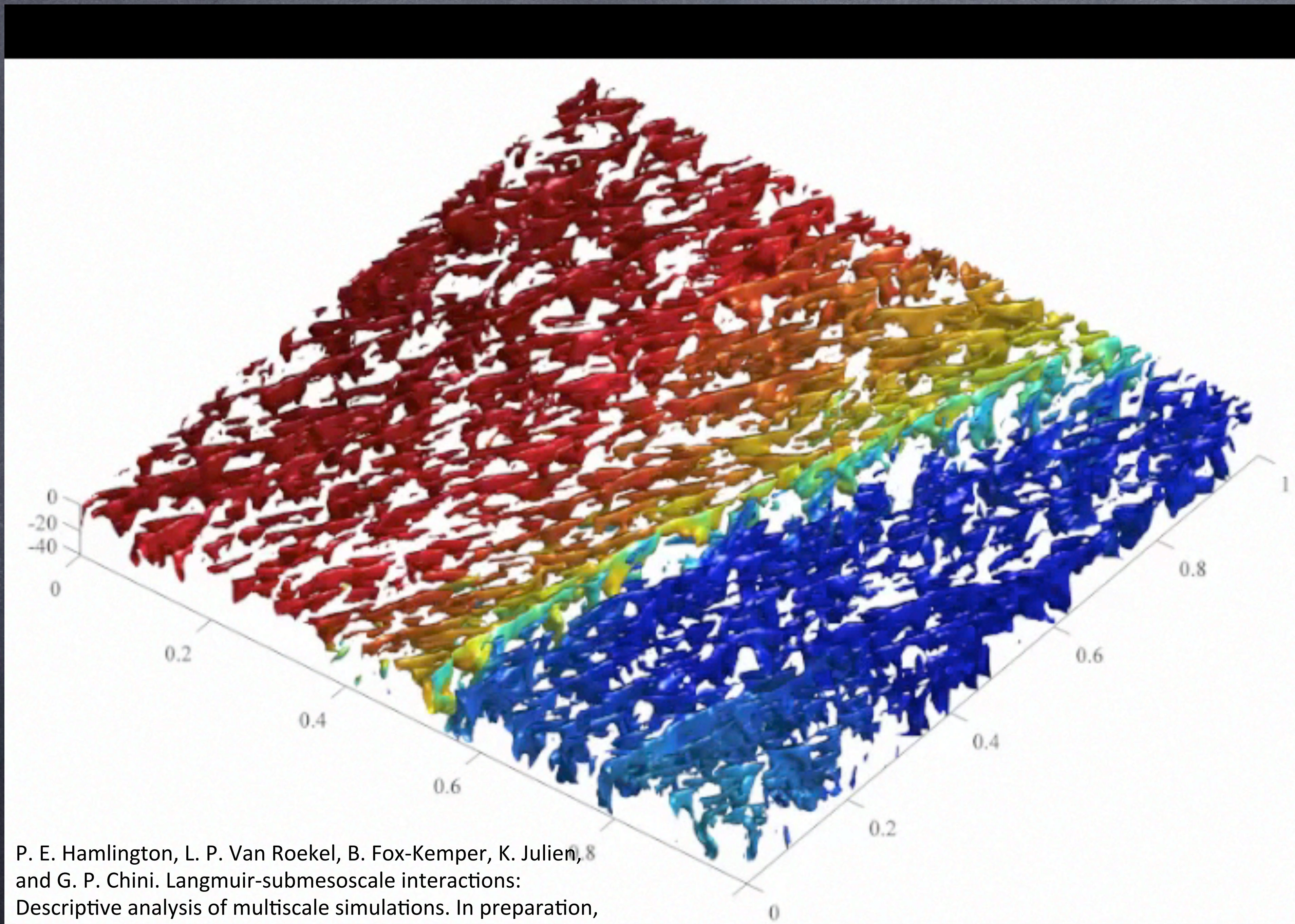


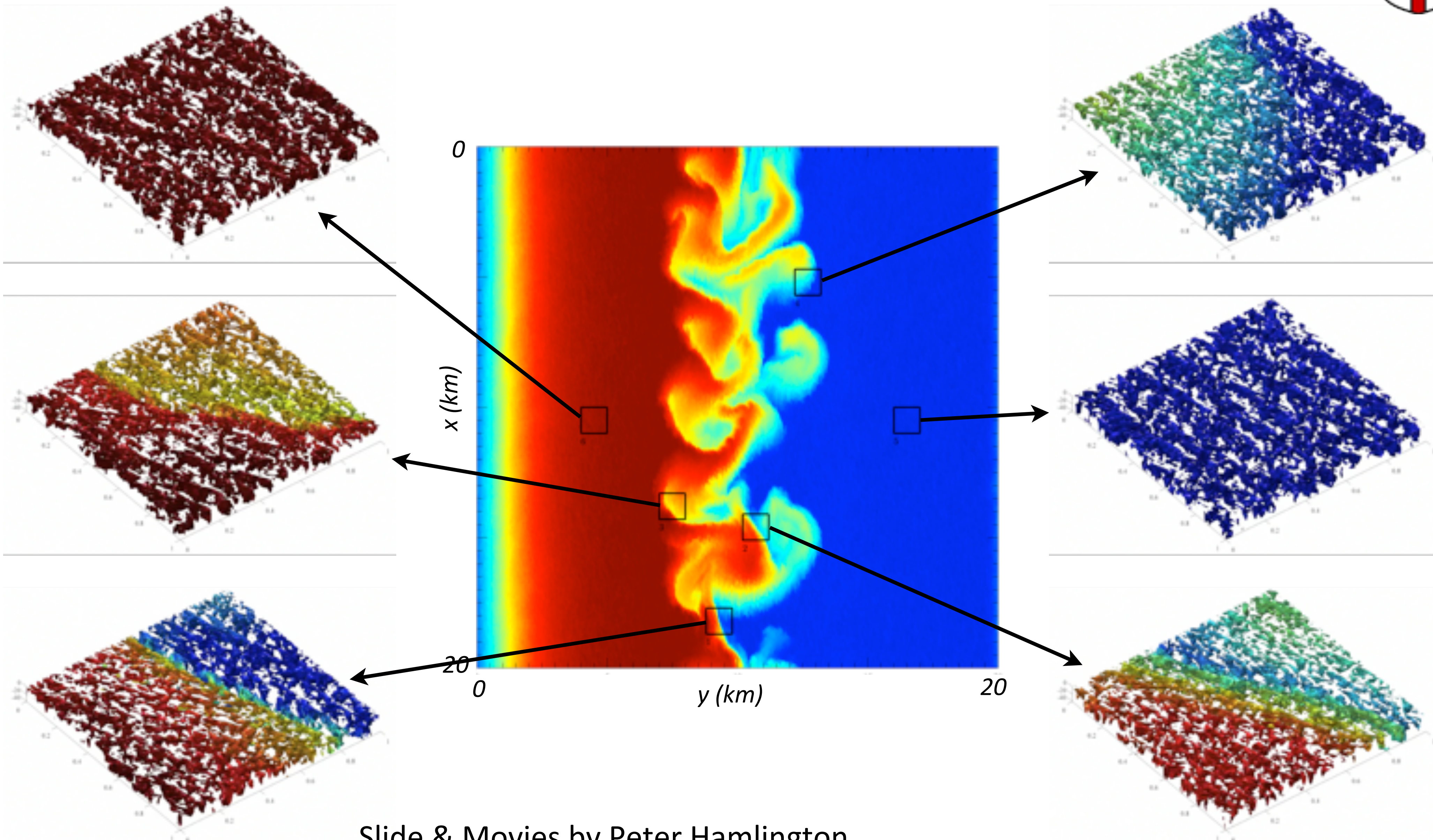
P. E. Hamlington, L. P. Van Roekel, B. Fox-Kemper, K. Julien, and G. P. Chini. Langmuir-submesoscale interactions: Descriptive analysis of multiscale simulations. In preparation, 2013.

Zoom: Submeso-Langmuir Interaction!



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,

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, 2013.

But, why stop now?

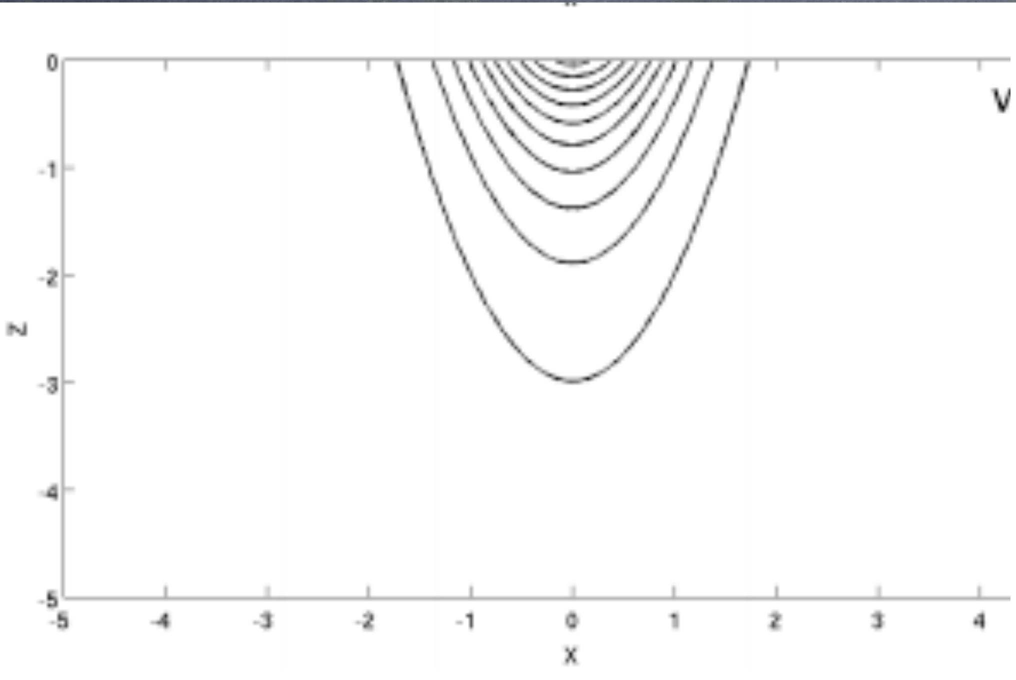
How do these small processes affect each other?

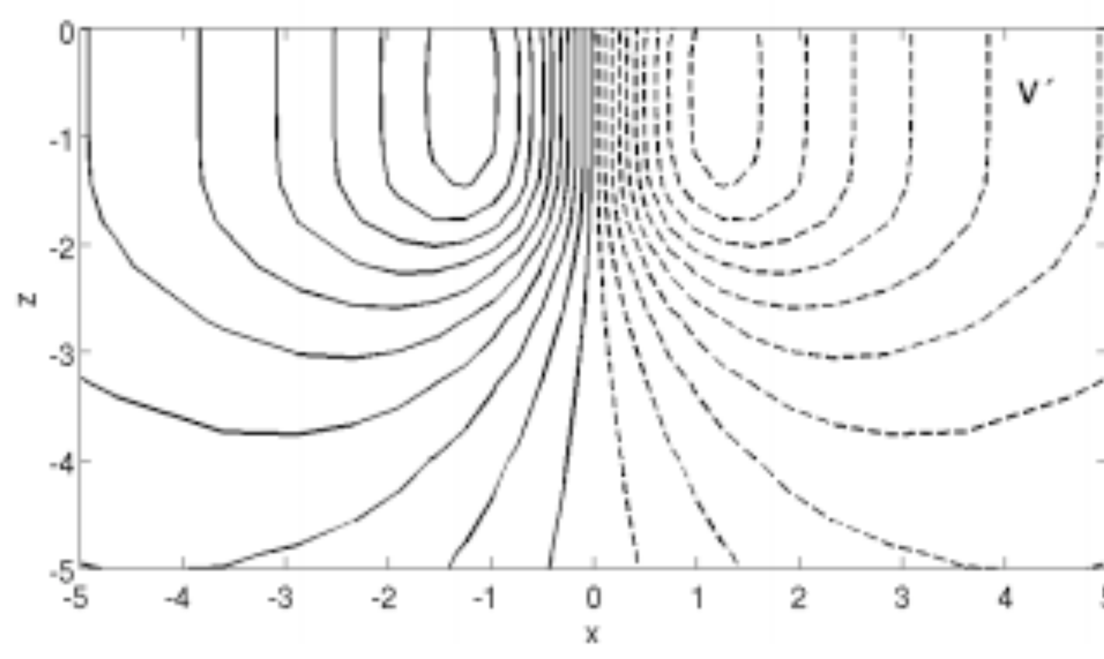
Weakly, except near strong fronts... stay tuned...

OK, Langmuir Turbulence can interact with larger scales...

What about the surface waves themselves, do they interact?

Waves (Stokes Drift Vortex Force) -> Submeso, Meso Balanced Flows Change!





Initial Submeso Front

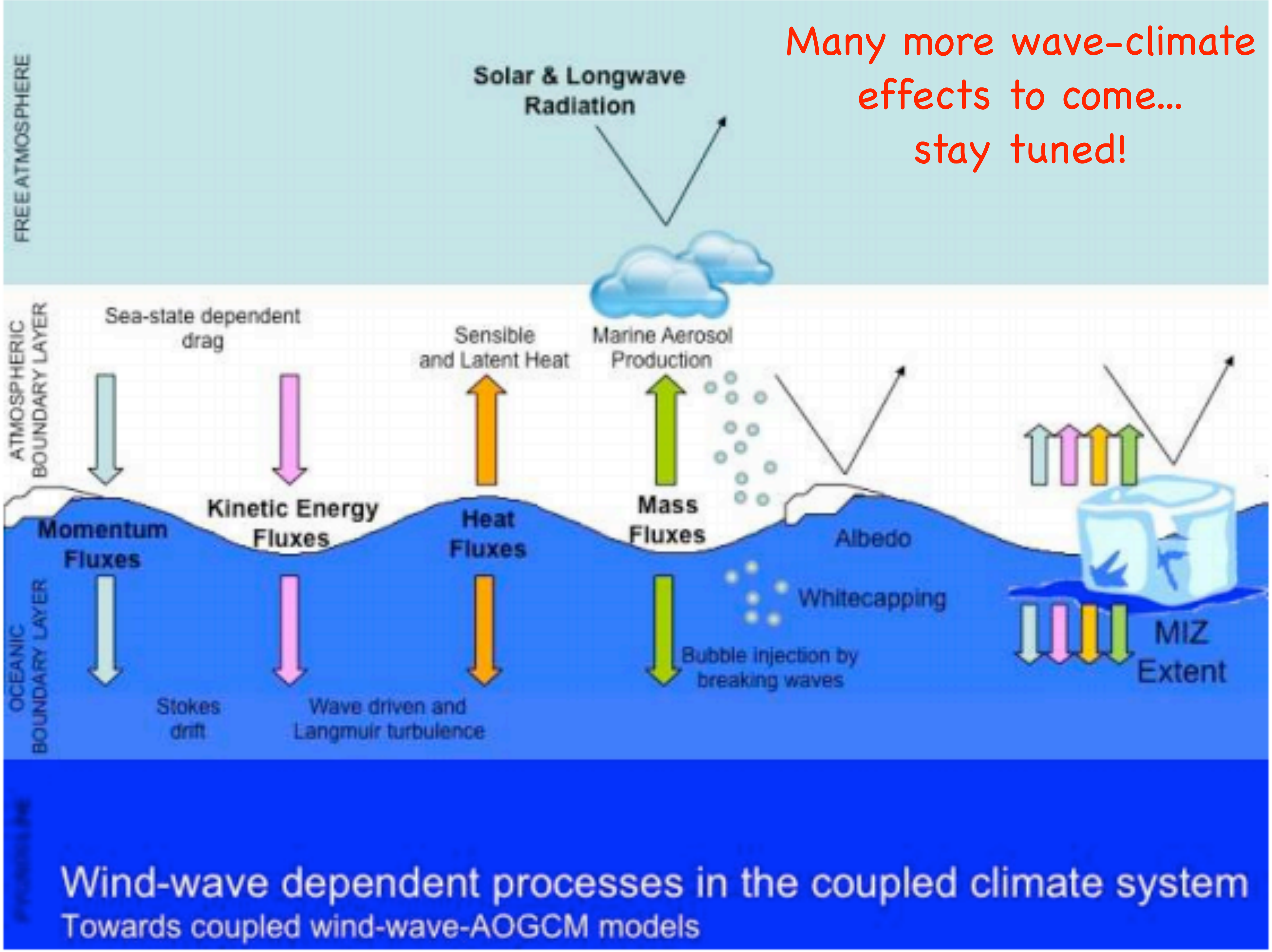
Contours: 0.1

Perturbation on that scale due to waves (Stokes Force)

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!

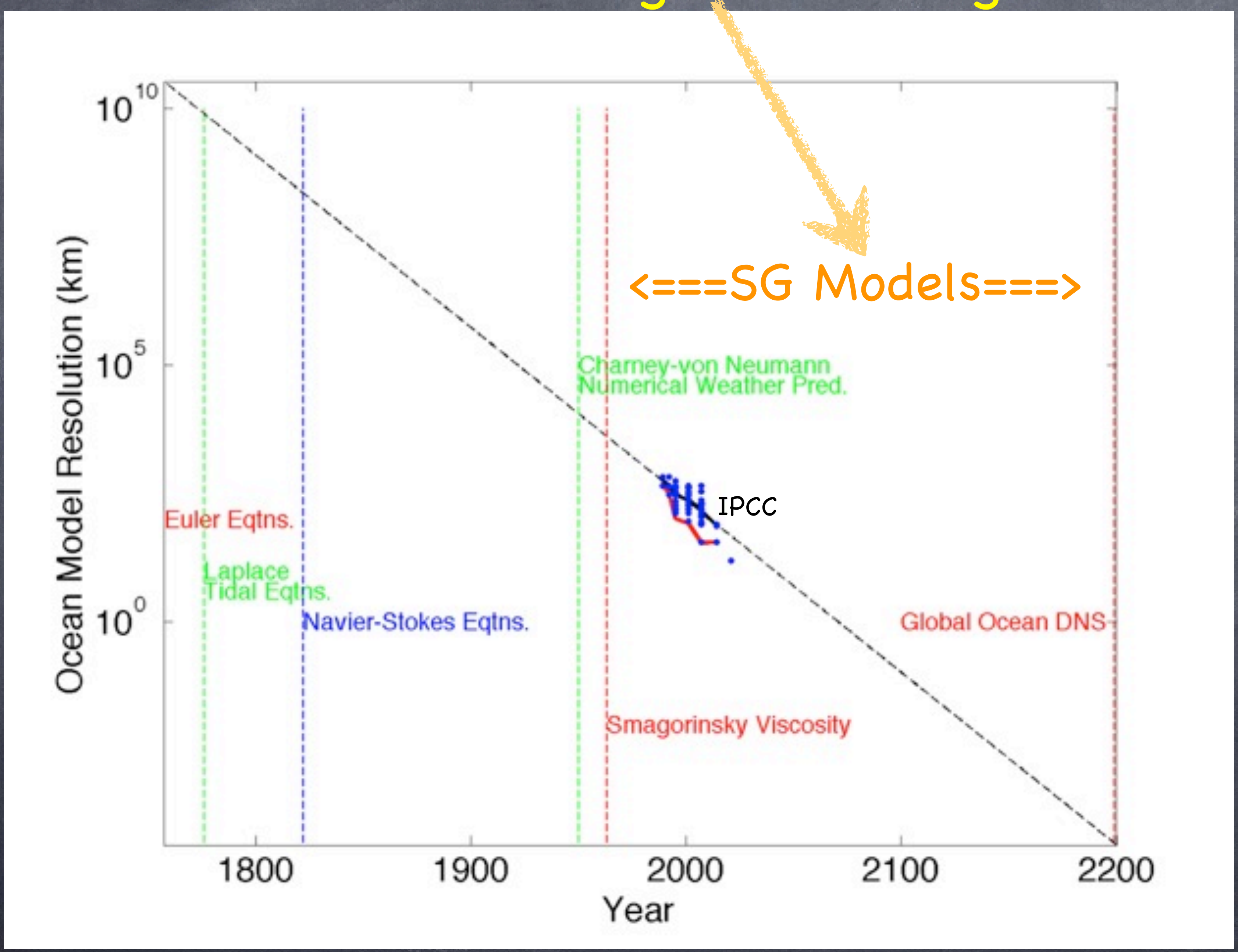


L. Cavaleri, B. Fox-Kemper, and M. Hemer. Wind waves in the coupled climate system. Bulletin of the American Meteorological Society, 93(11):1651-1661, 2012.

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.
- Based on present rates of increase of computing power, we will need these subgrid models for at least another century!

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



All papers at: fox-kemper.com/research