From Climate to Kolmogorov - Simulations Spanning Upper Ocean Scales

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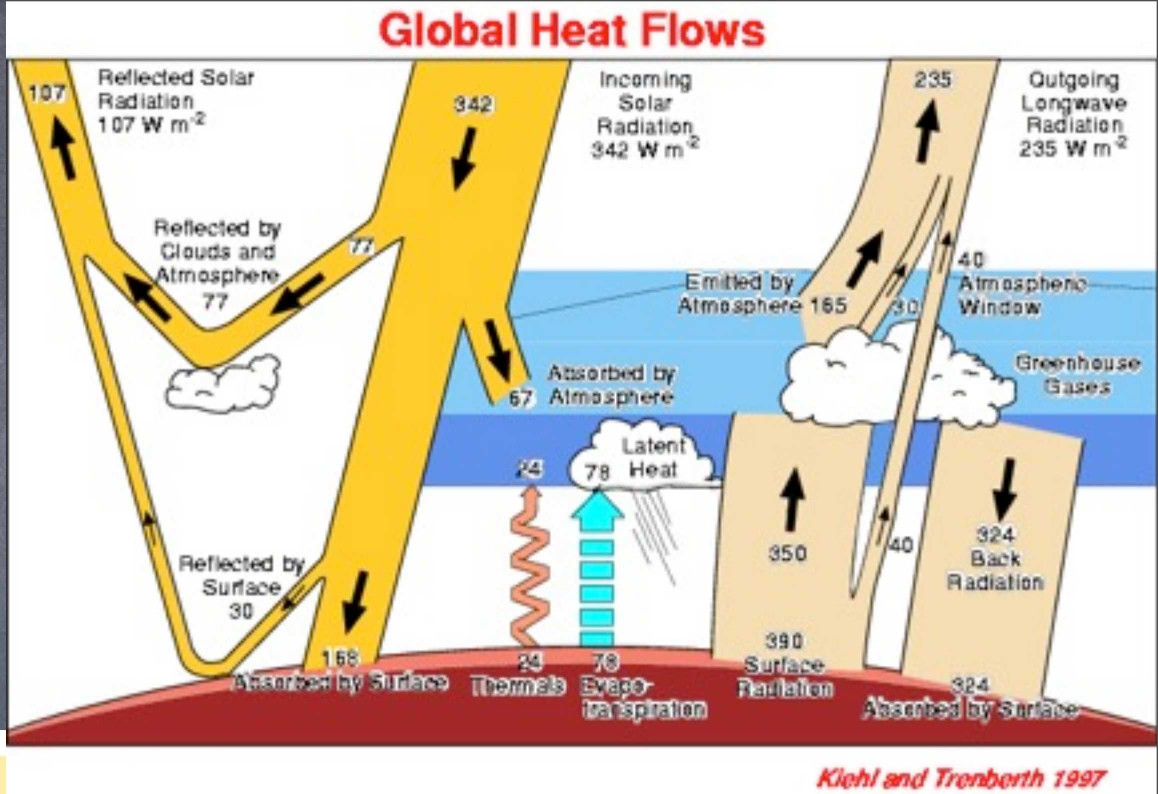
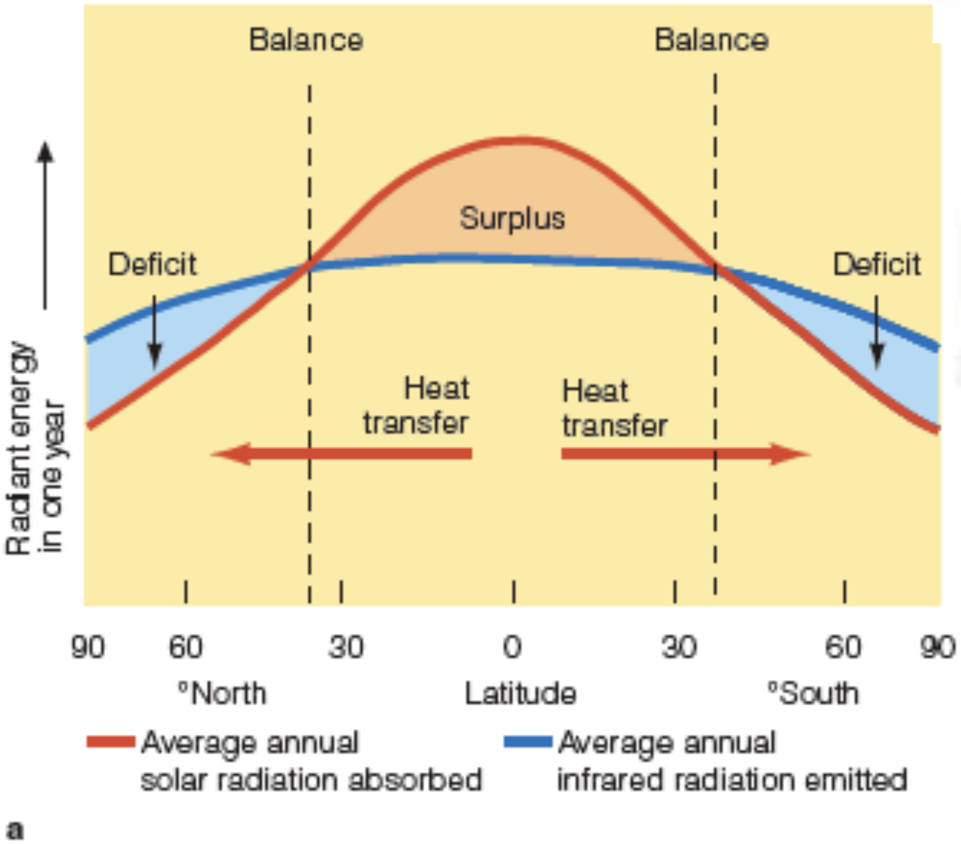
Keith Julien (CU-APPM),
Luke Van Roekel (Northland), Peter Sullivan (NCAR), Jim McWilliams (UCLA), Mark Hemer (CSIRO)

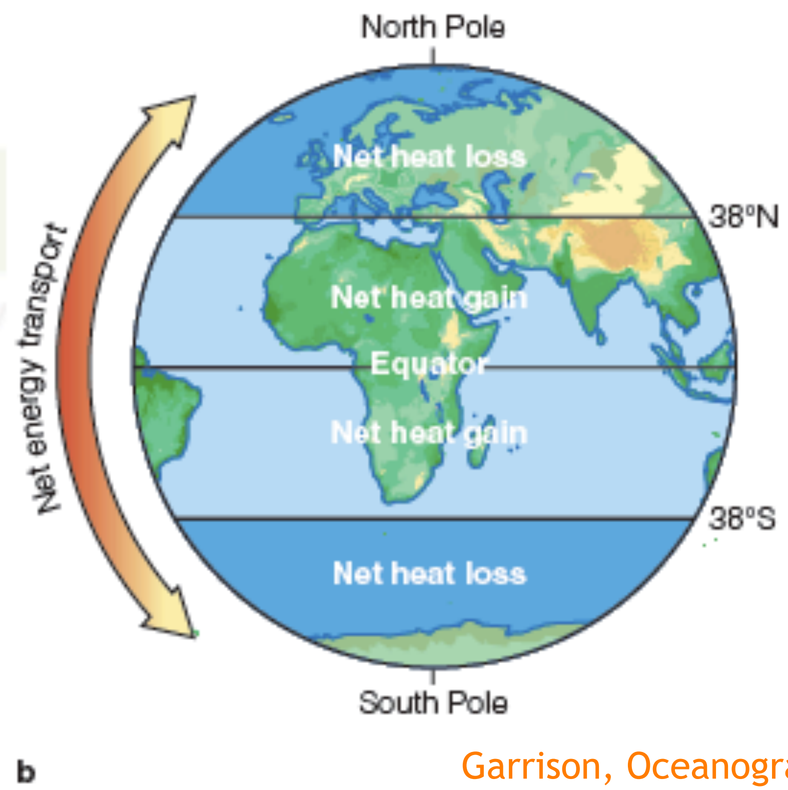
CU MCEN Seminar, 7/12/12

Sponsors: NSF 1245944, 0934737, 0825614, NASA NNX09AF38G

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







Garrison, Oceanography

Heat Transport by Oceans & Atmosphere, determines rebalancing of sun-outgoing radiation

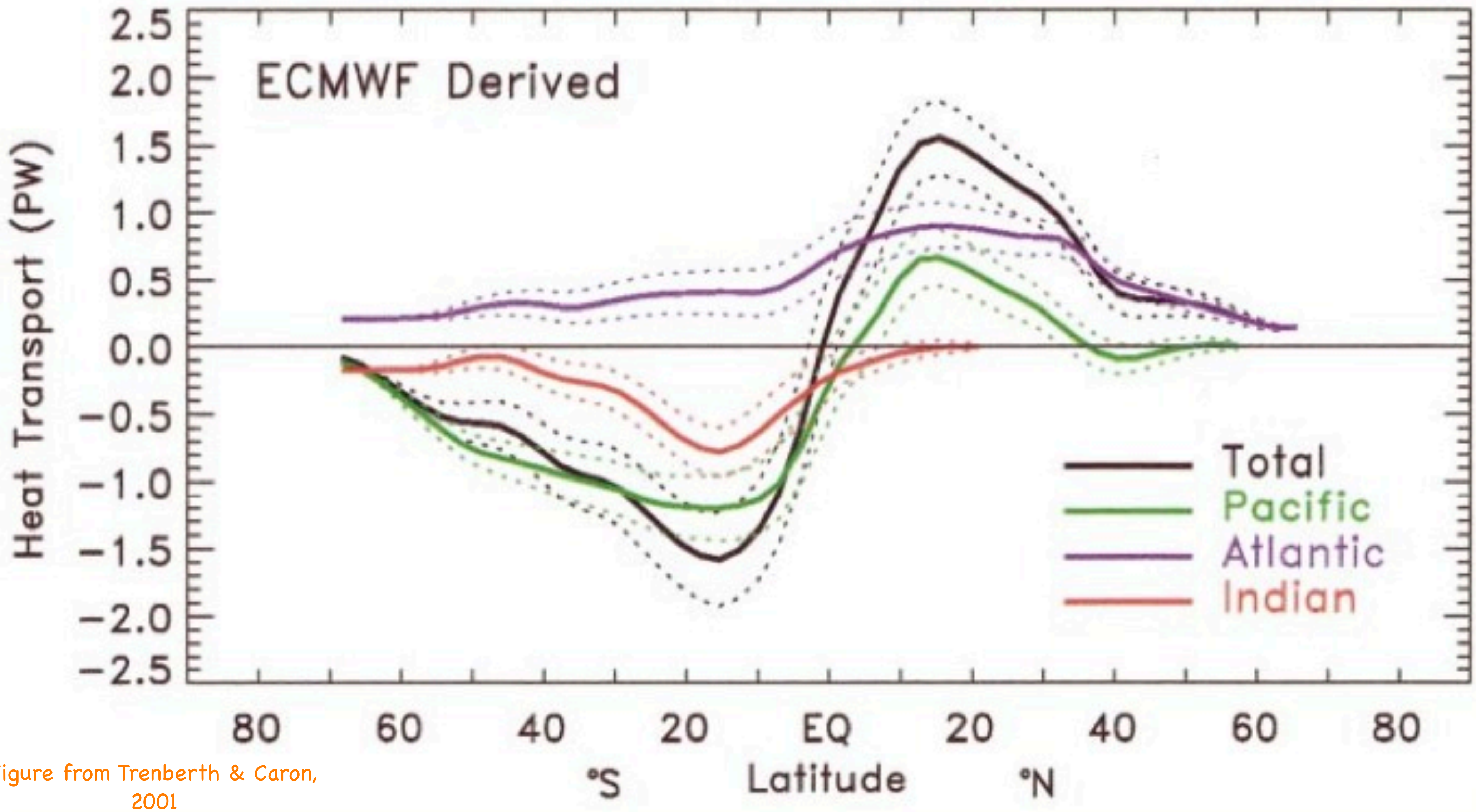
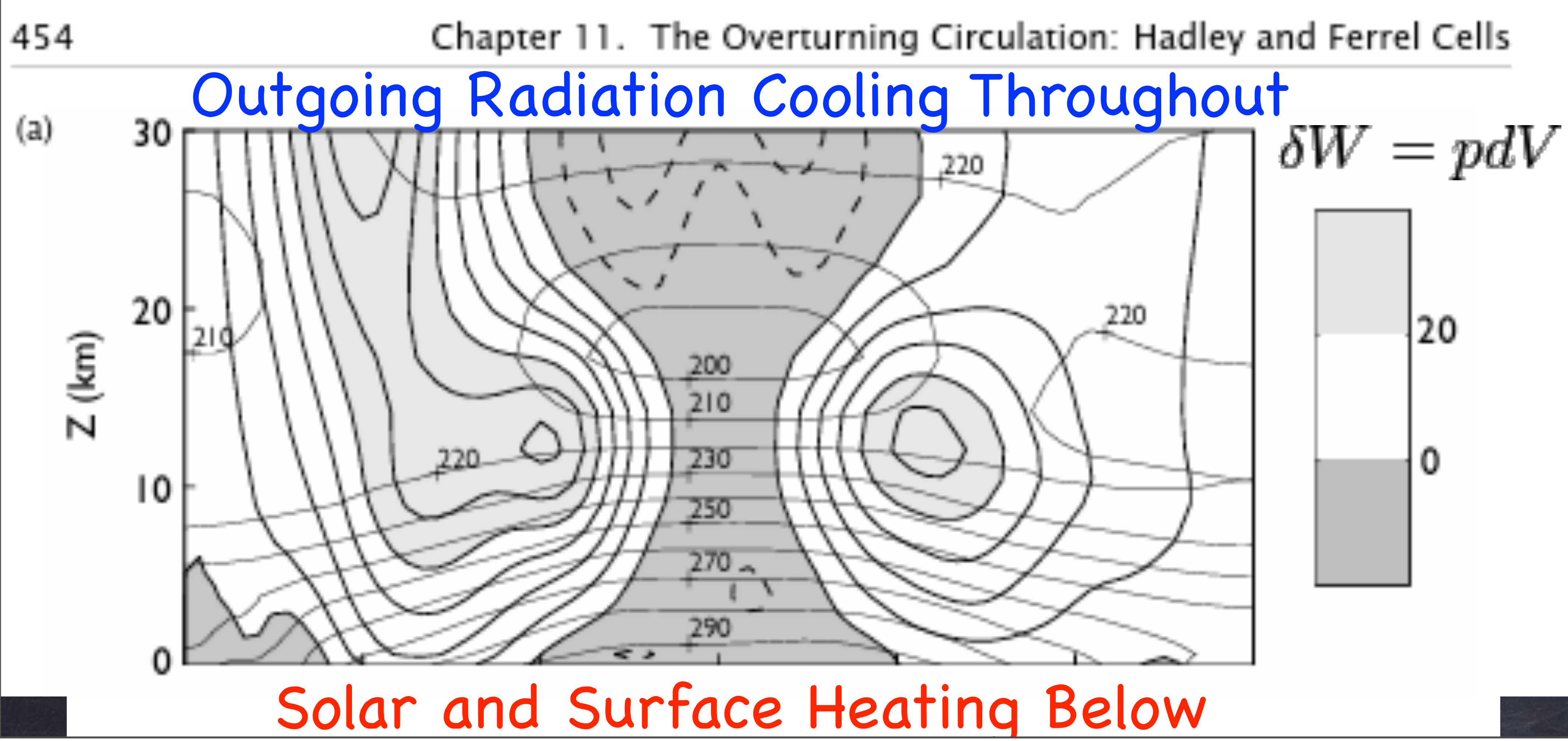


Figure from Trenberth & Caron, 2001

FIG. 5. Implied zonal annual mean ocean heat transports based upon the surface fluxes for Feb 1985–Apr 1989 for the total, Atlantic, Indian, and Pacific basins for NCEP and ECMWF atmospheric fields (PW). The 1 std err bars are indicated by the dashed curves.

Total Energy Budget of the Atmosphere

Conversion of radiation->mechanical energy via heating (expand) at hi pressure, cooling (compress) at lo:



Total Energy Budget of the Ocean

heat and cool at the same pressure! No net p dV.

Ocean energy from mechanical sources (winds!)

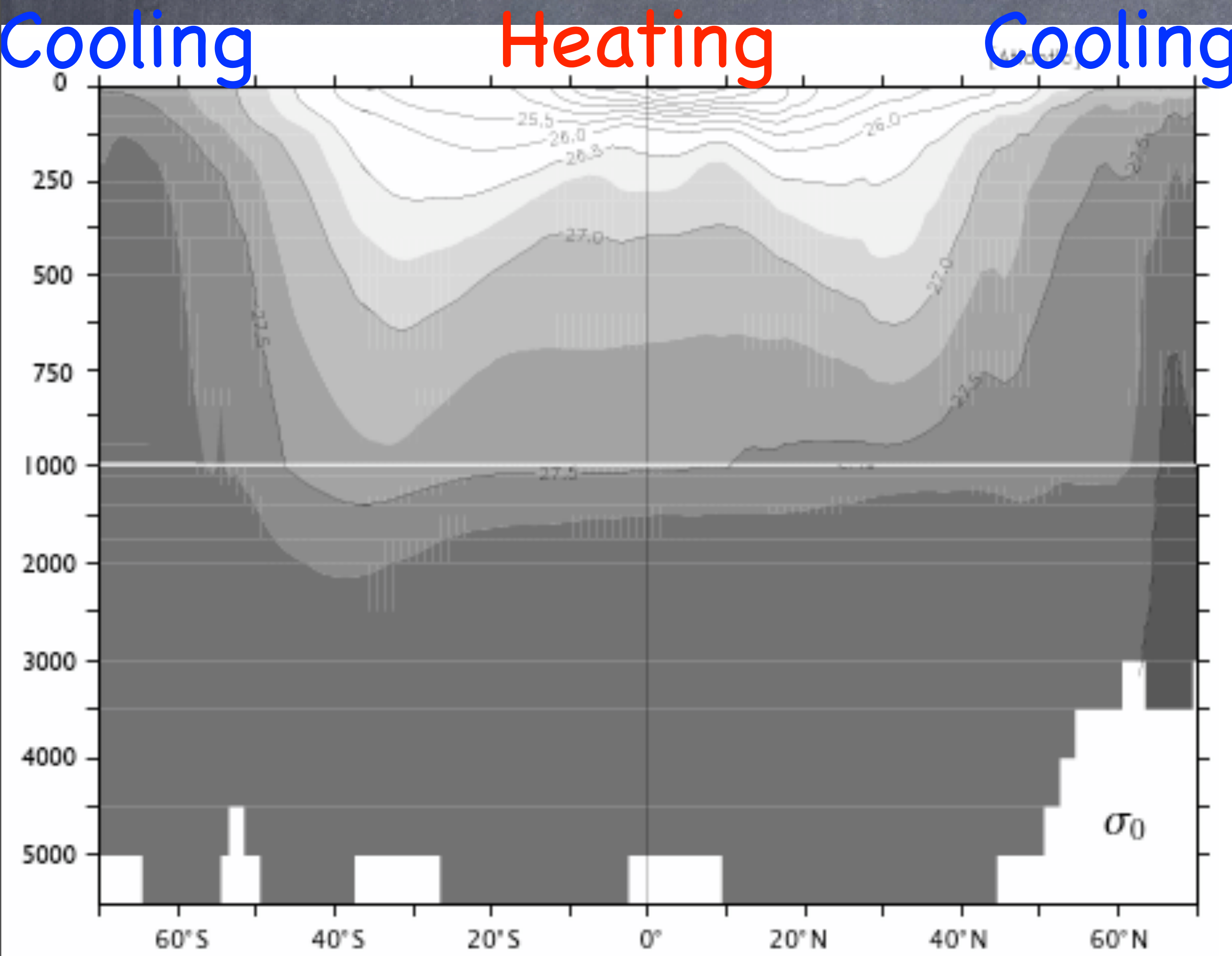
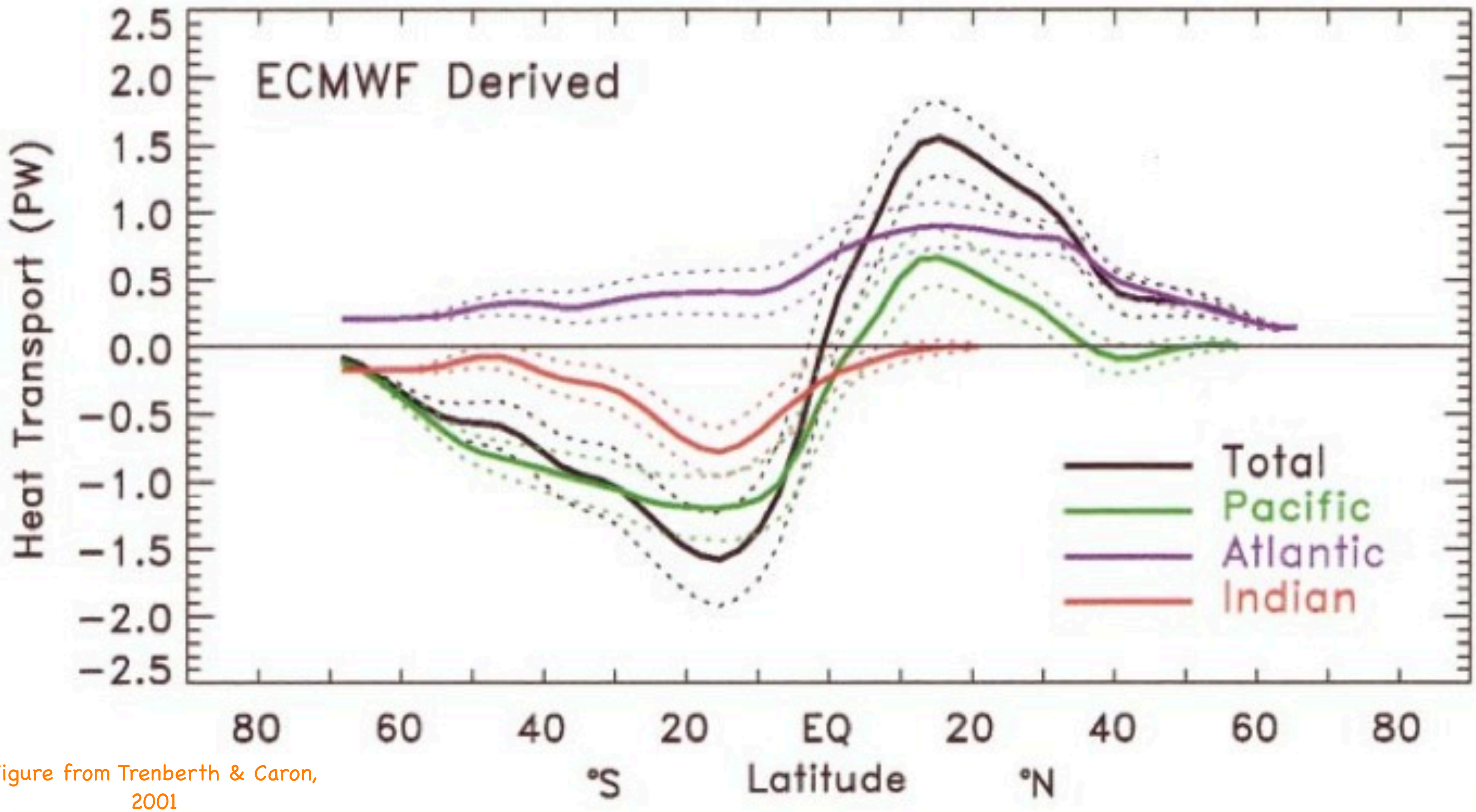


Fig. 15.2 The zonally averaged potential density (σ_θ) in the Atlantic ocean, as a function of depth (m) and latitude. Note the break in the vertical scale at 1000 m. The region of rapid change of density (and temperature) is concentrated in the upper kilometre, in the *main thermocline*, below which the ocean has a much more uniform density.[2]

Ocean receives lots of mechanical energy... where does it go?

Ocean stirs up cold & hot-- Circulation & heat transfer?

Heat Transport by Oceans & Atmosphere, determines rebalancing of sun-outgoing radiation



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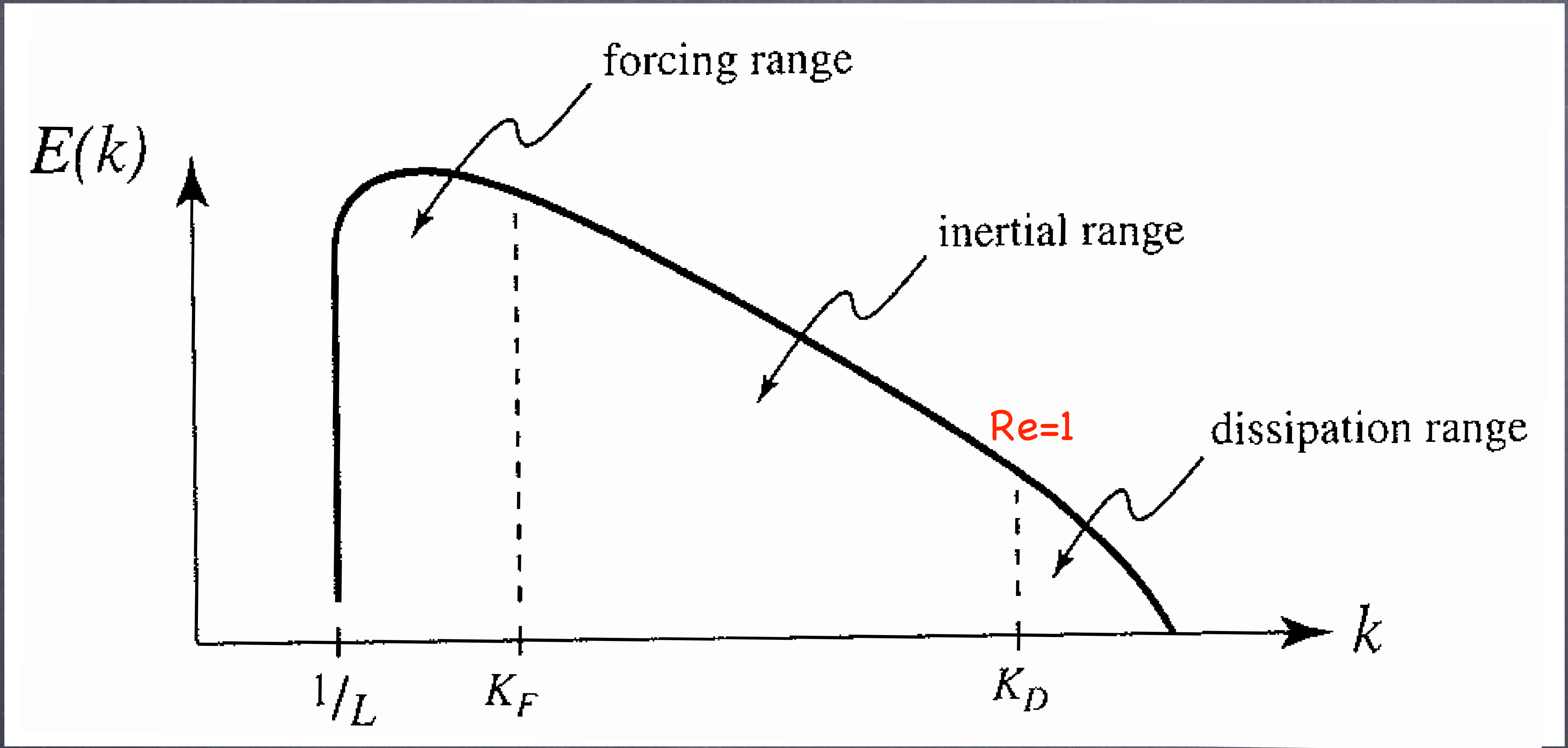
Fluids: Heat Circulation + Turbulence Cascades?



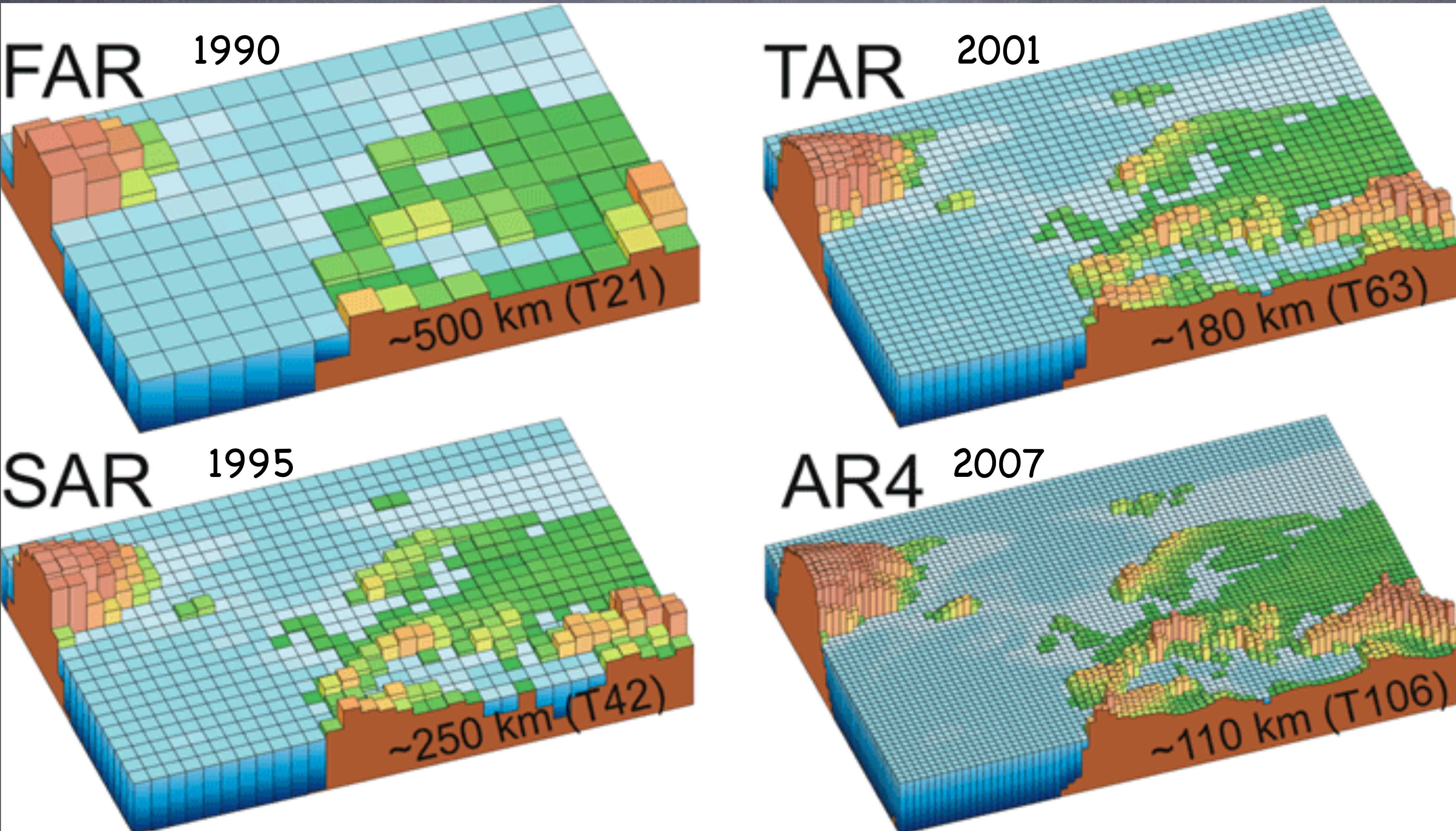
Power Spectrum:
Energy/Wavenumber

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

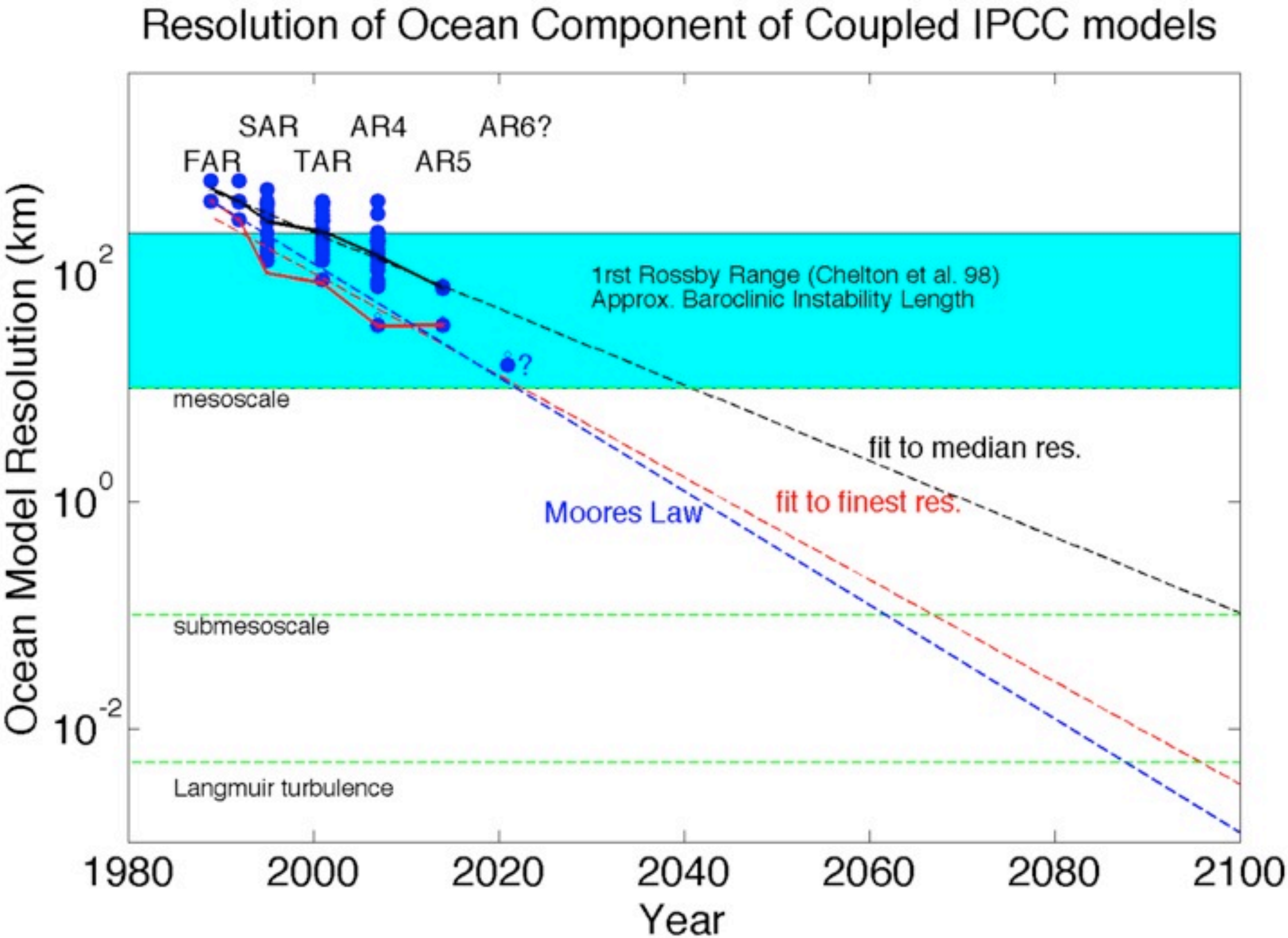
1941: Kolmogorov Envisions the Inertial Range

Image: ipcc.ch

Model resolution has been an issue...



and will be an issue for centuries to come!



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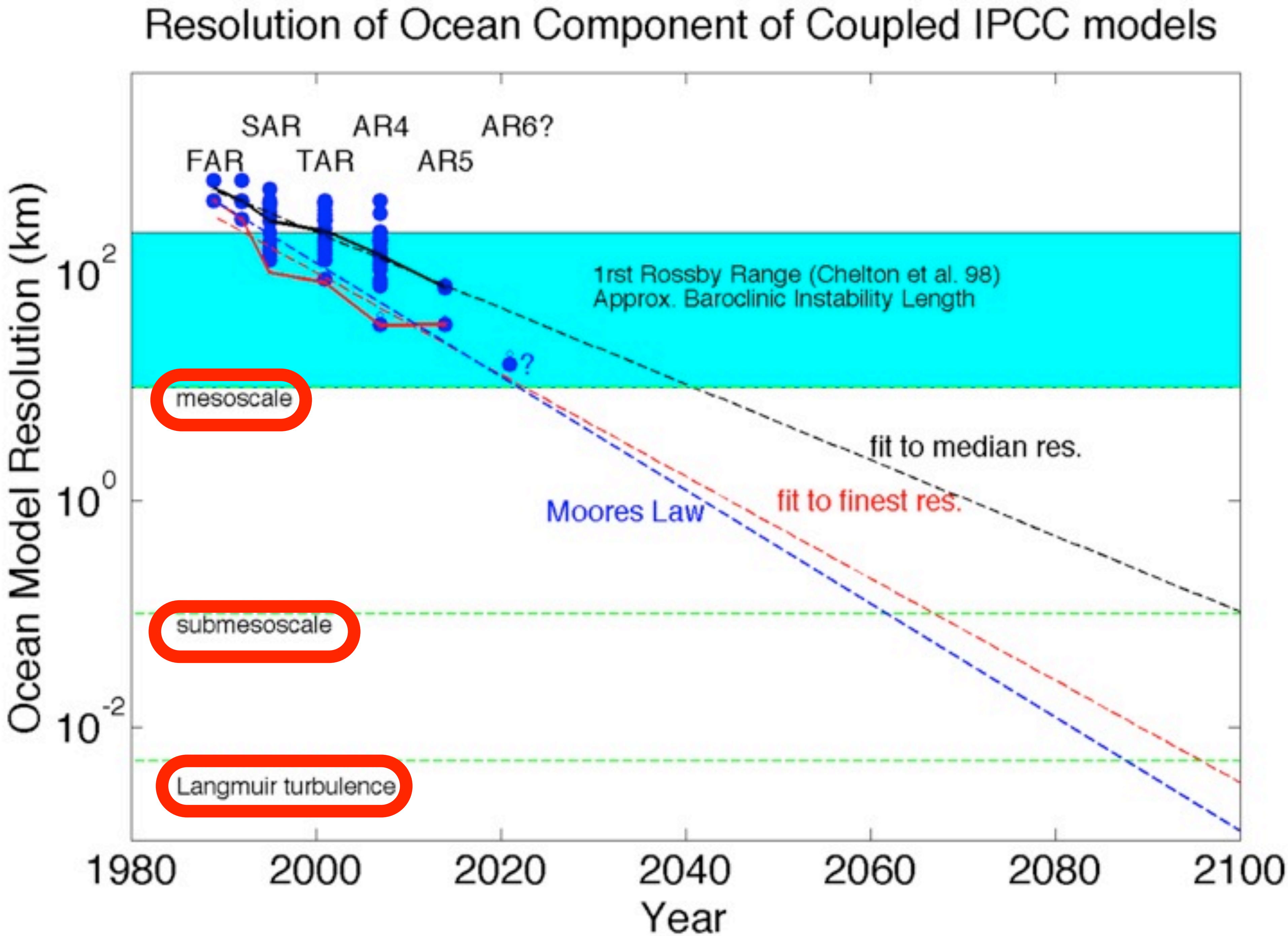
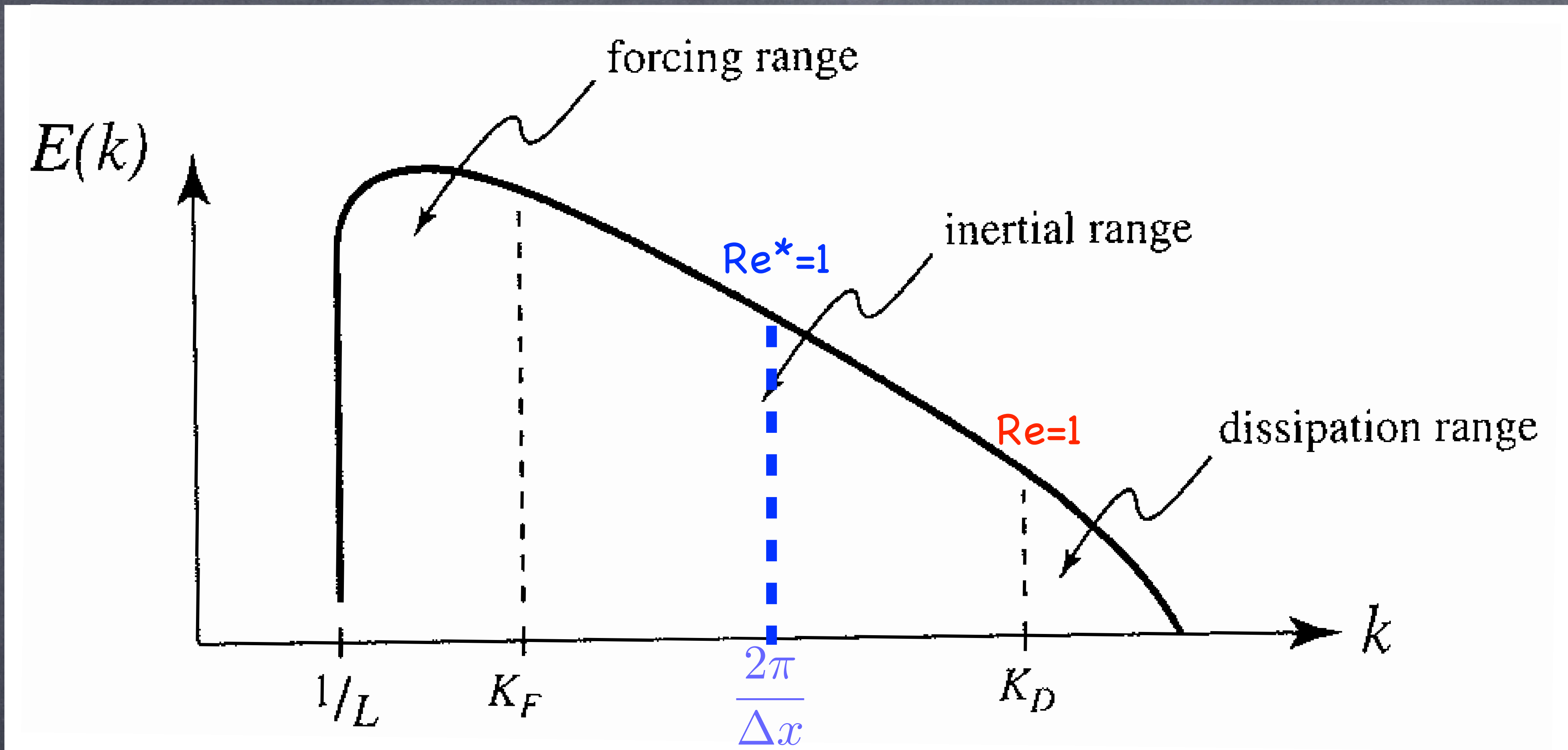


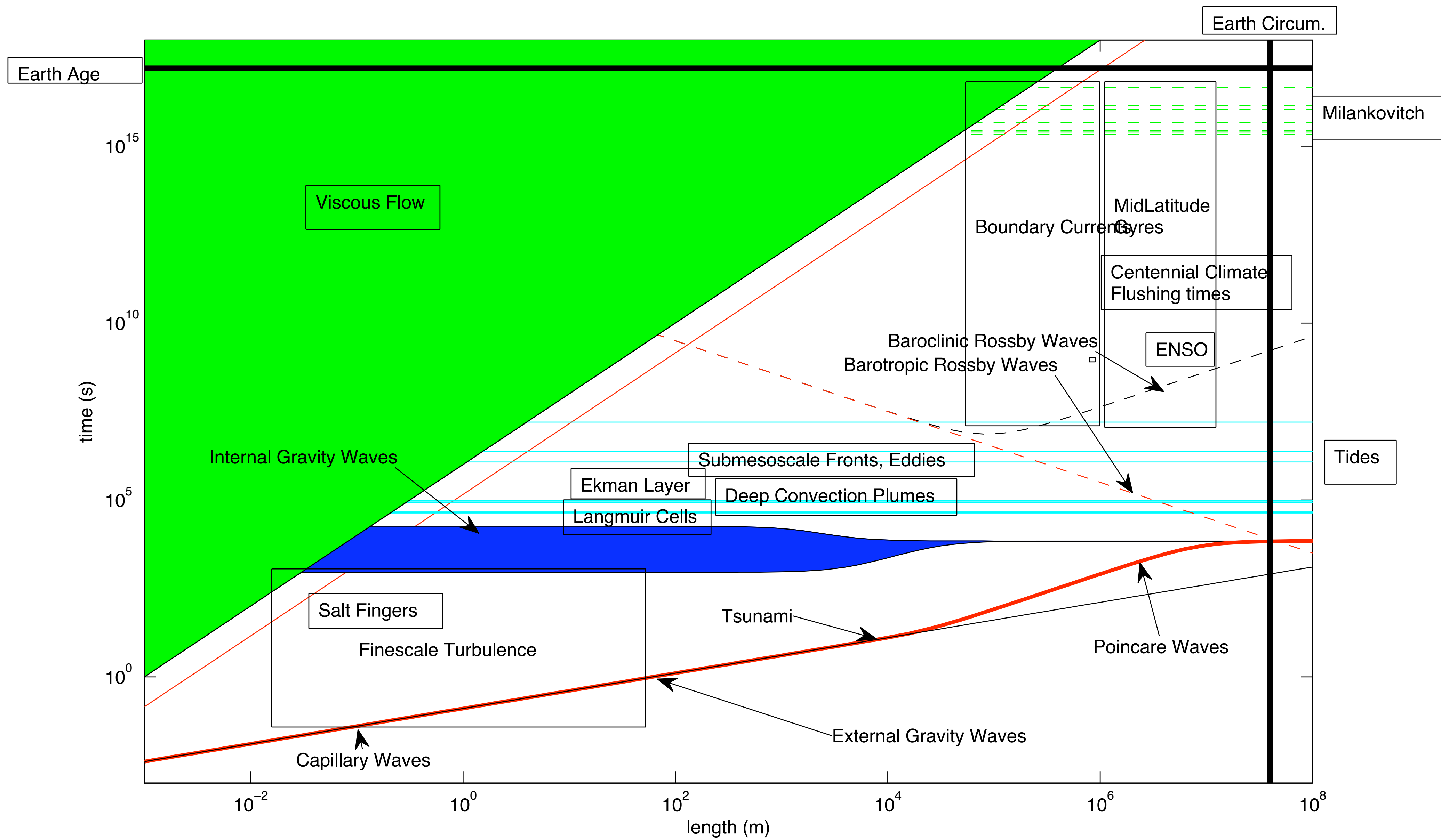
Truncation of Cascades in models



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 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: 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

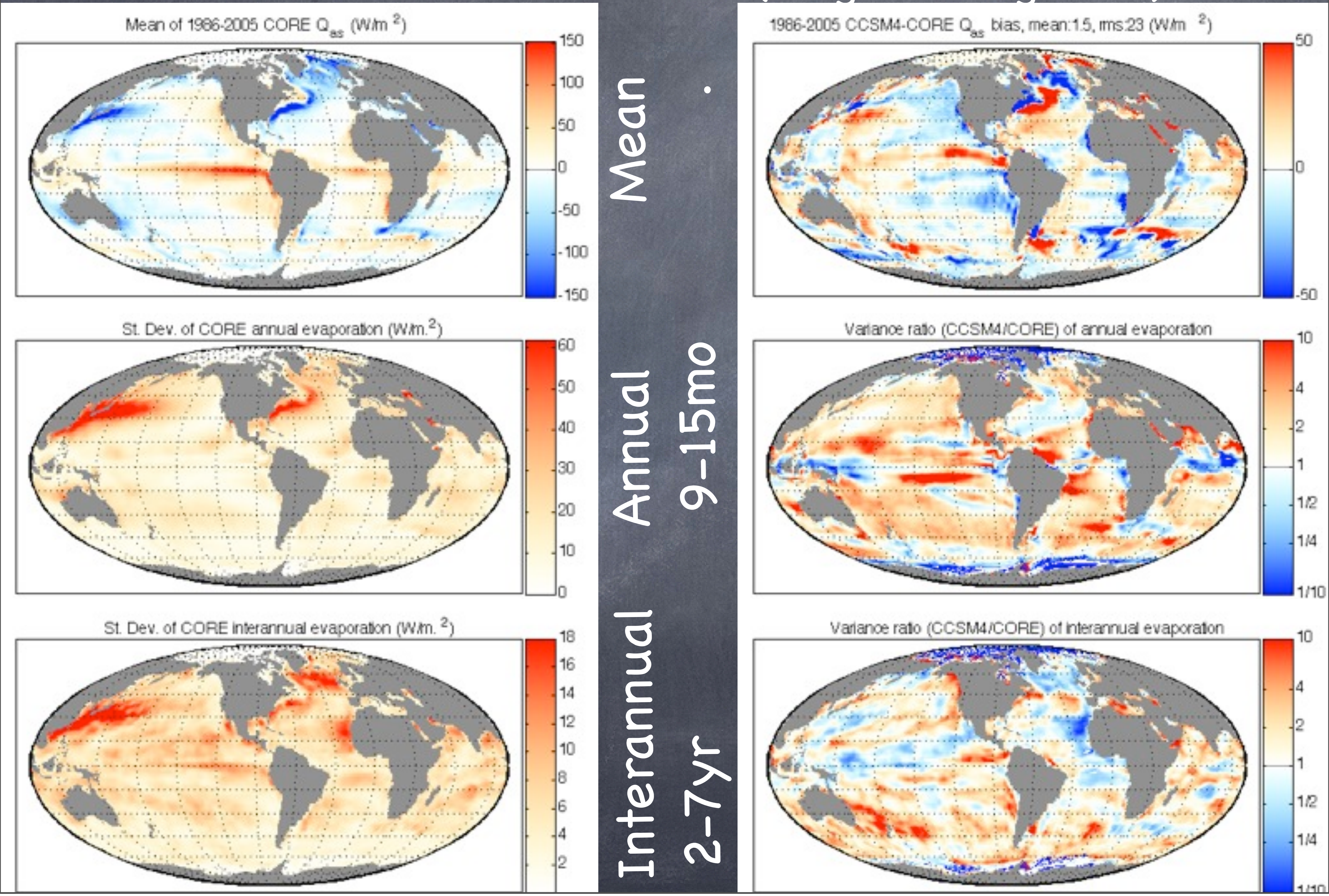
- And Couple different scales, small talks to large!

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!

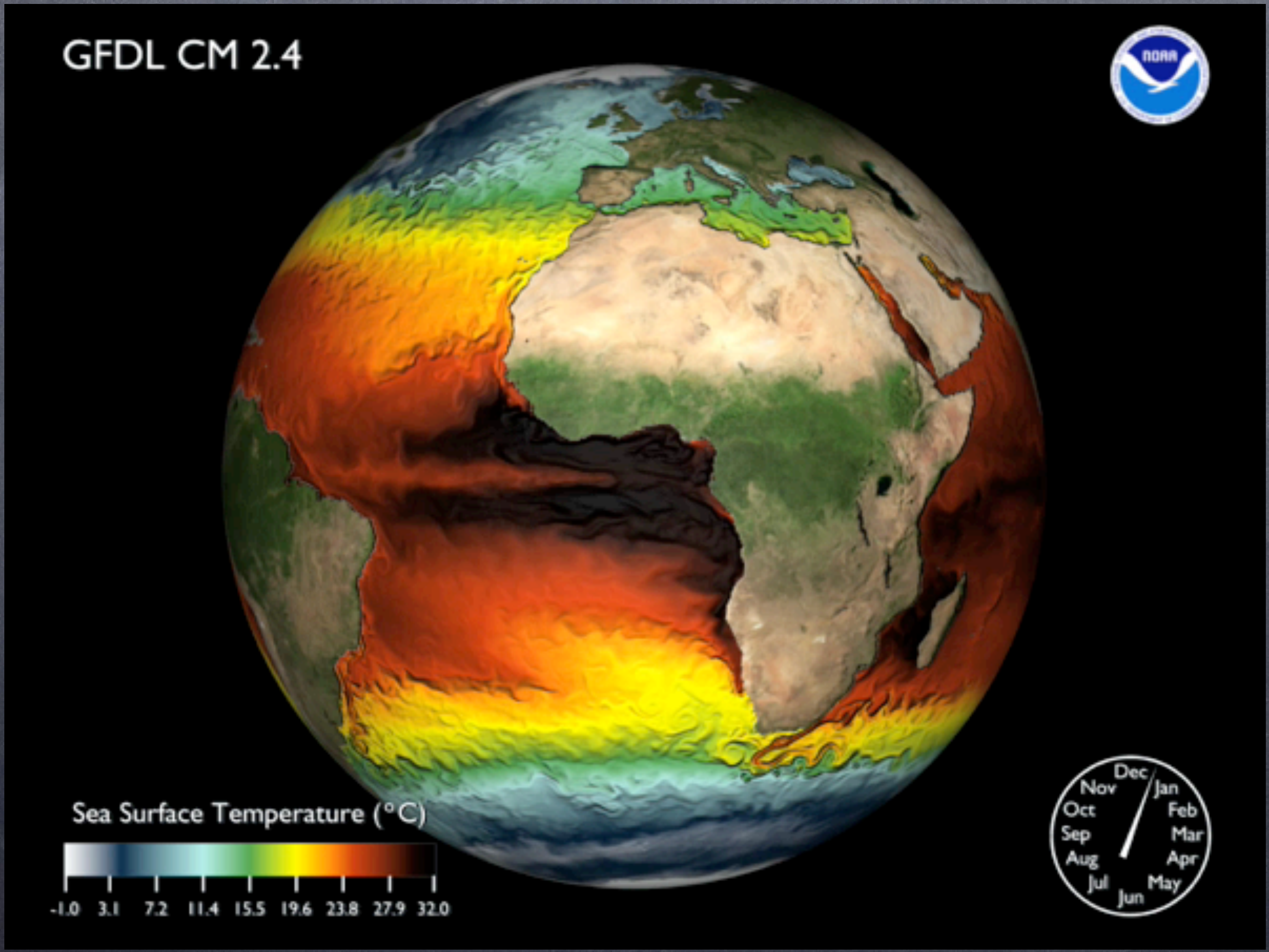
S. C. Bates, B. Fox-Kemper, S. R. Jayne, W. G. Large, S. Stevenson, and S. G. Yeager. Mean biases, variability, and trends in air-sea fluxes and SST in the CCSM4.Journal of Climate, 2012.

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



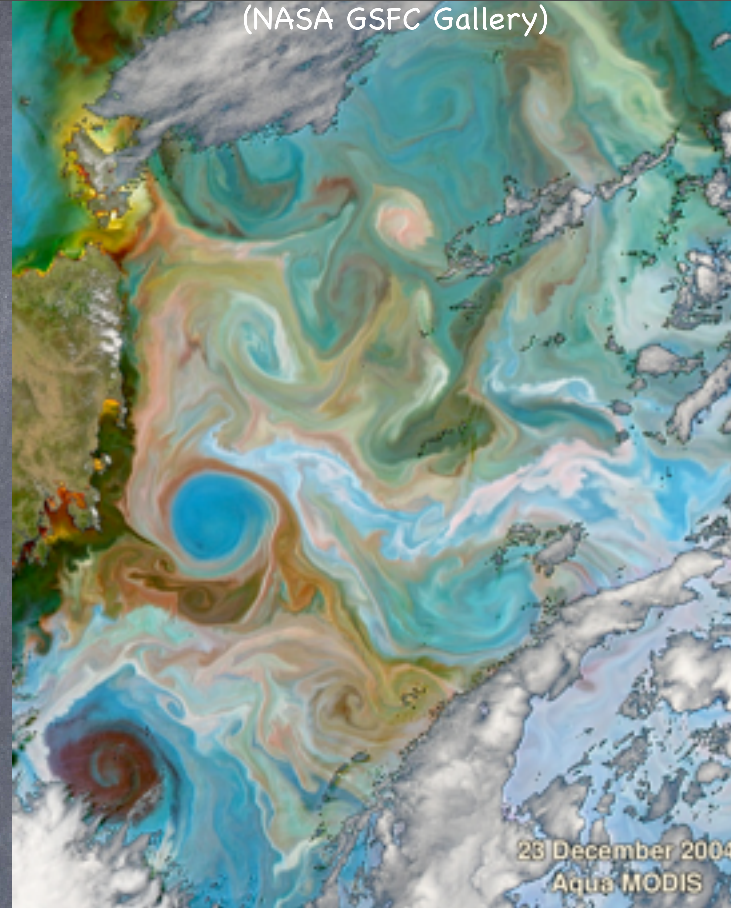
Monday, December 17, 12

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



The Character of the Mesoscale

100 km



(Capet et al., 2008)

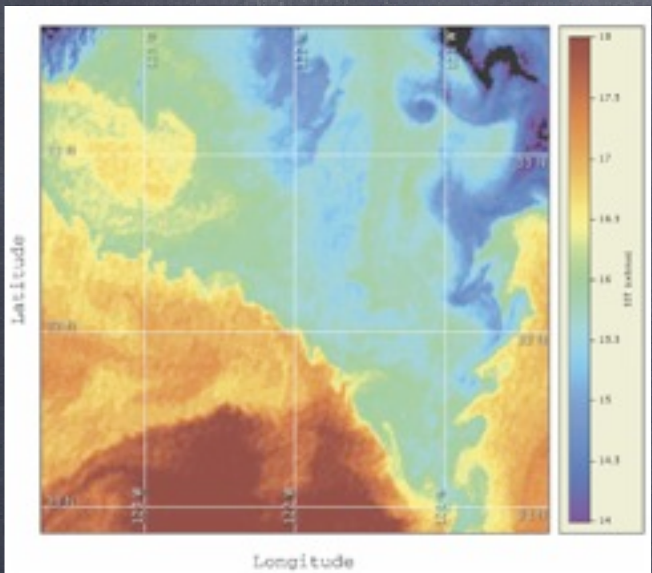
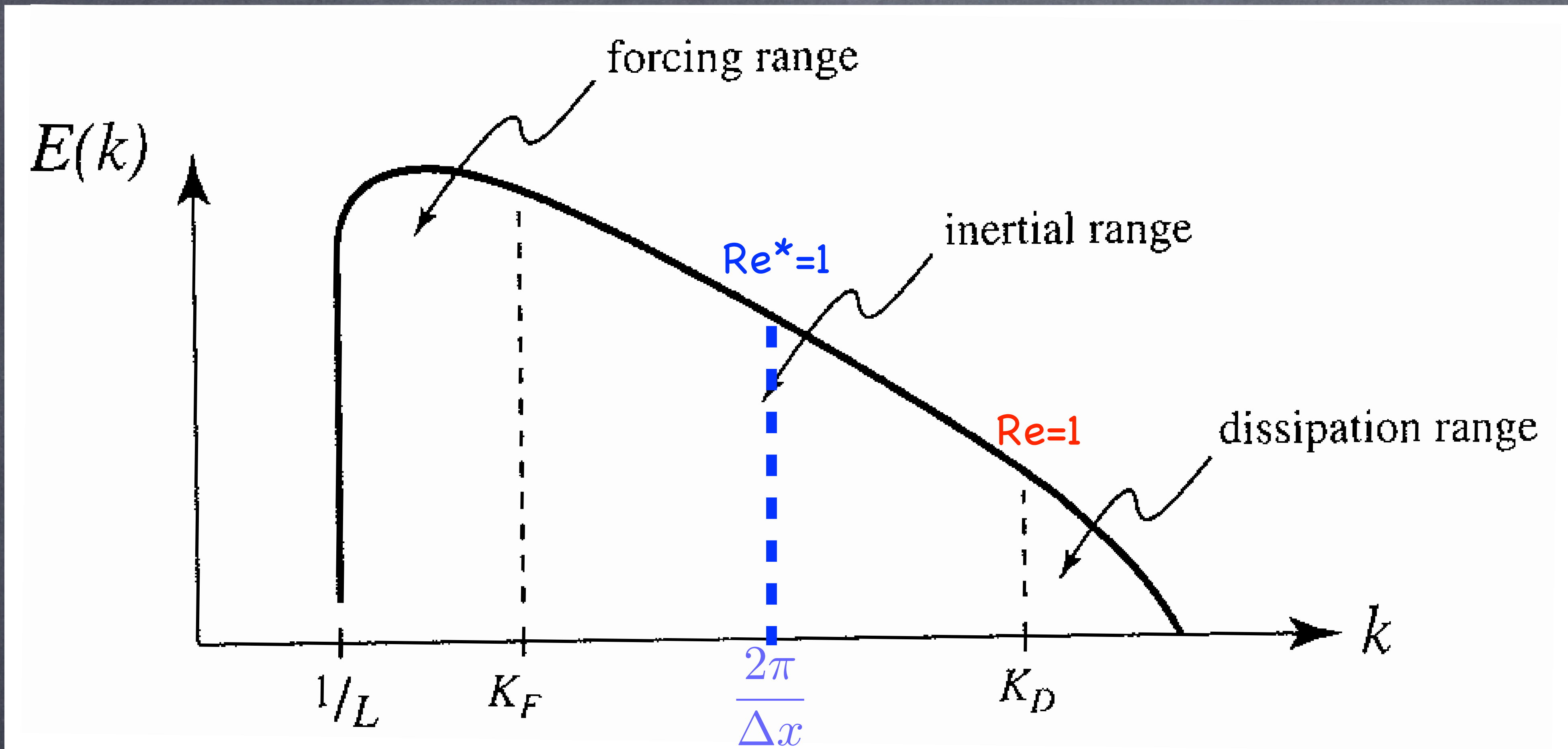


FIG. 16. Sea surface temperature measured at 1832 UTC 3 Jun 2006 off Point Conception in the California Current from CoastWatch (http://coastwatch.pfeg.noaa.gov). The fronts between recently upwelled water (i.e., 15°–16°C) and offshore water (≥17°C) show submesoscale instabilities with wavelengths around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

Truncation of Cascades



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

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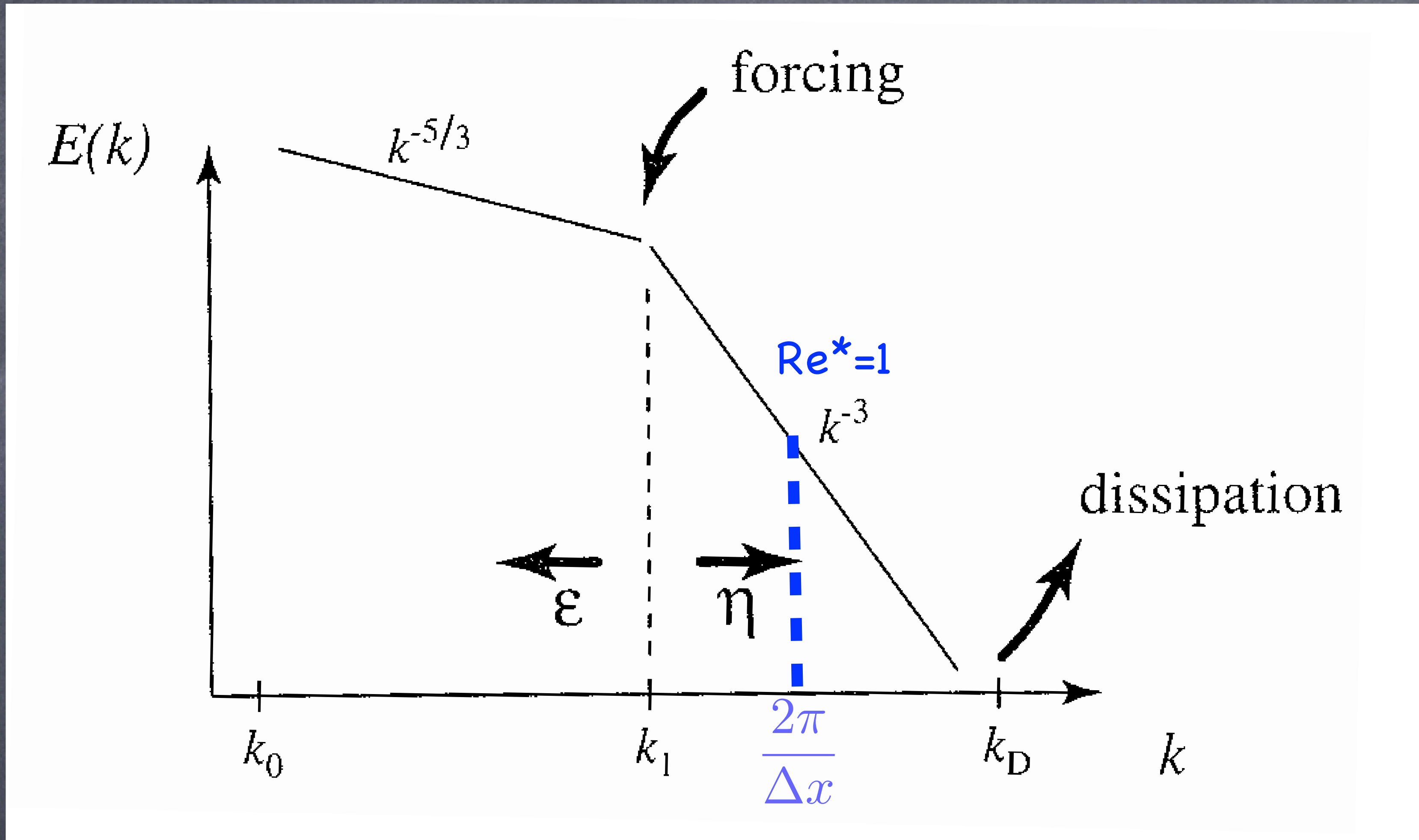
Except... Ocean Turbulence isn't 3d Turbulence at the mesoscale

- 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!

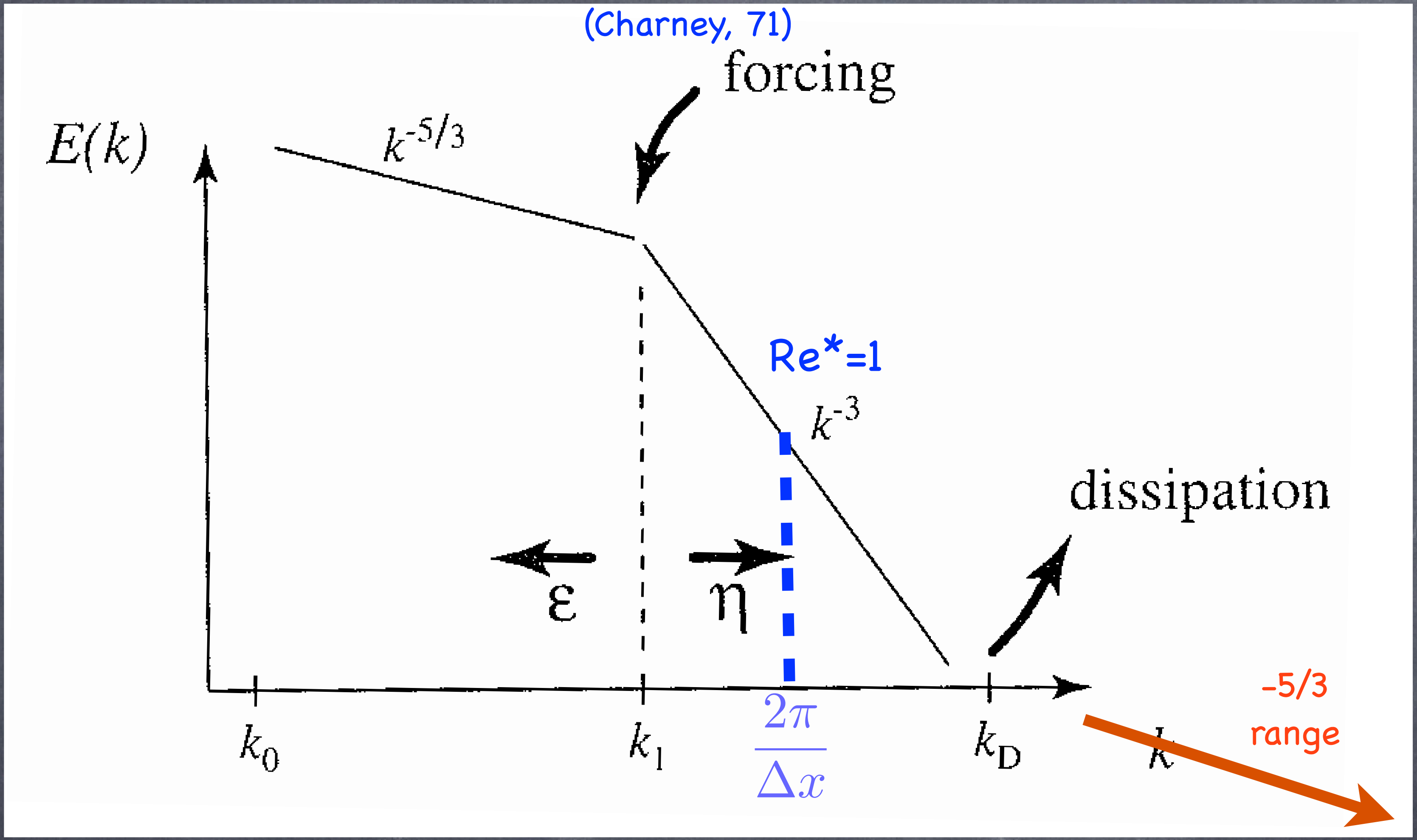
2d Turbulence Differs



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

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

MOLES Turbulence Like Pot'l Enstrophy cascade, but divergent

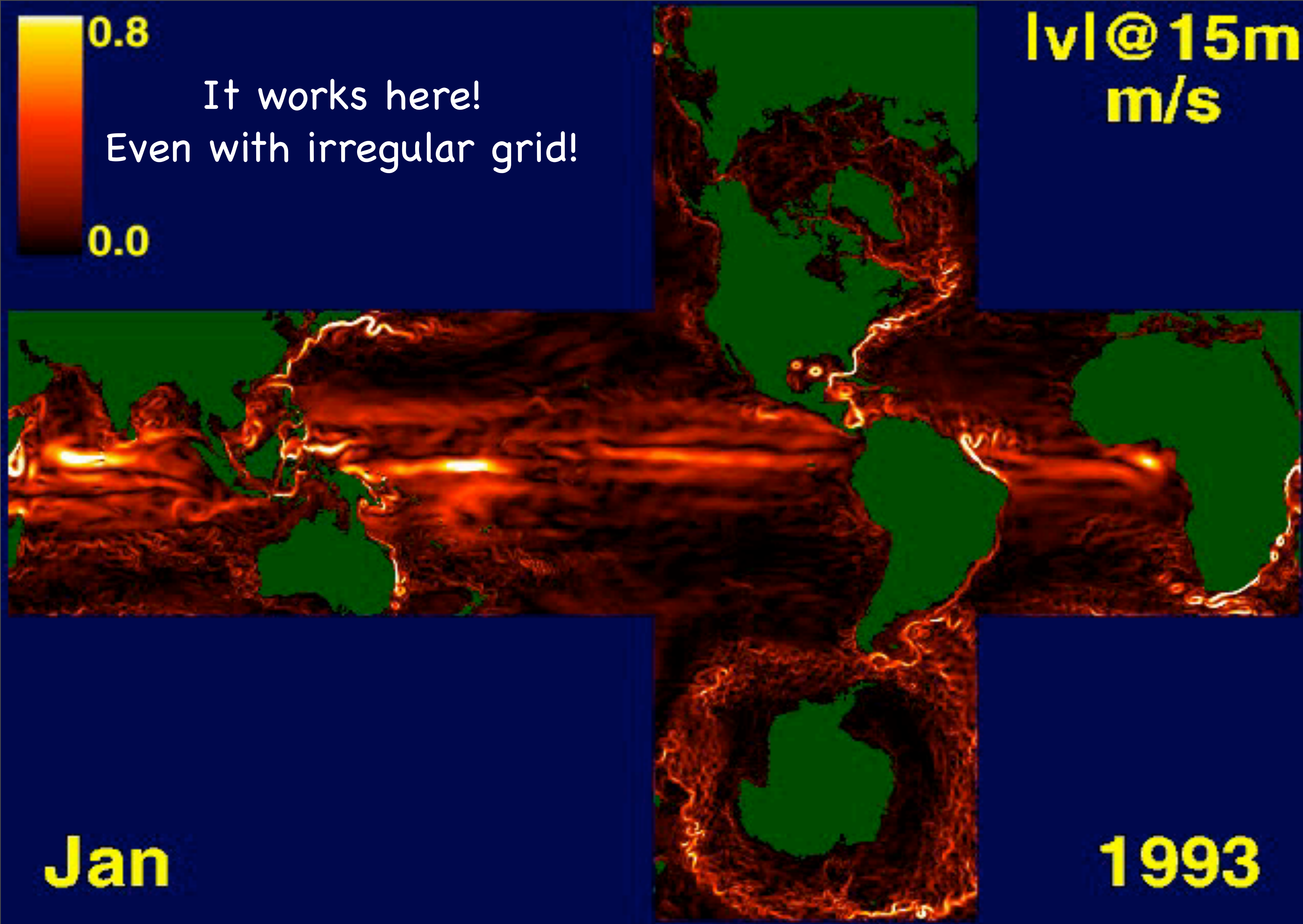


2008: F-K & Menemenlis Revise Leith Viscosity Scaling,
So that diverging, vorticity-free, modes are also damped

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

It works here!
Even with irregular grid!

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



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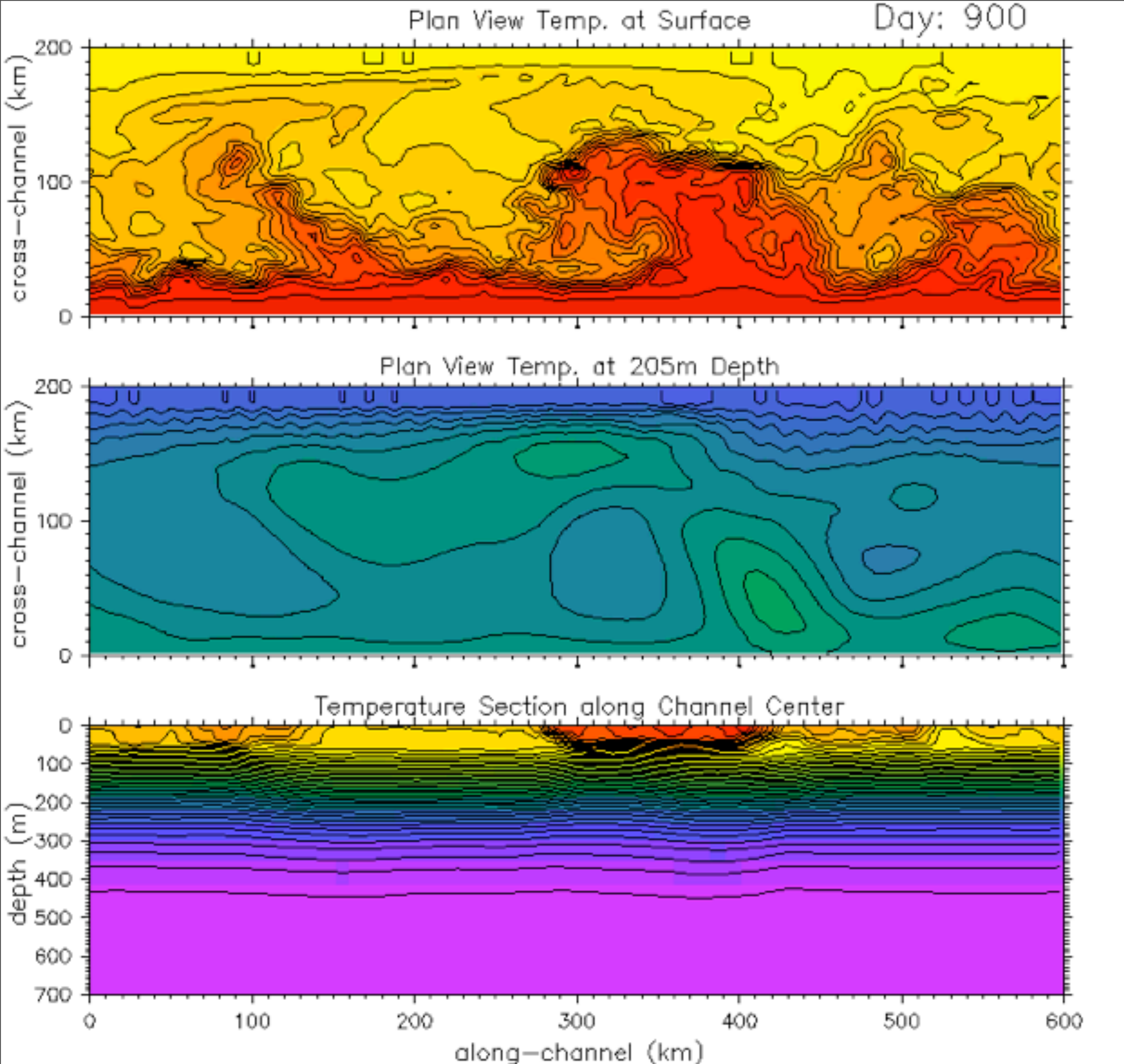


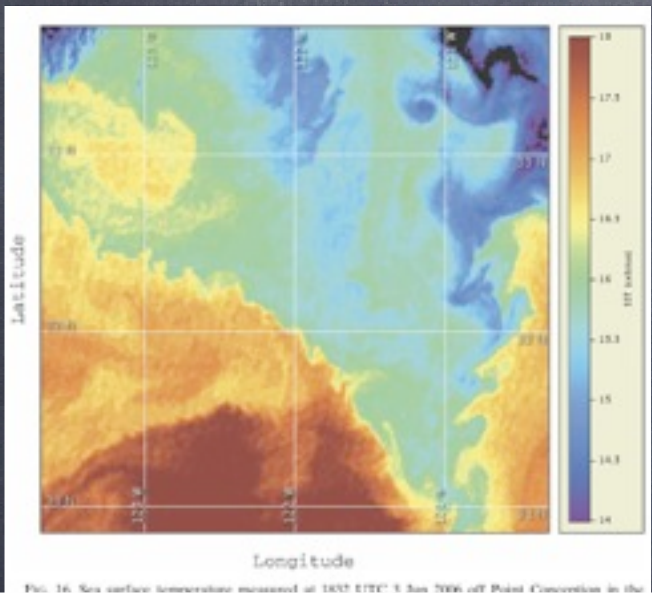
Big, Deep (meso)

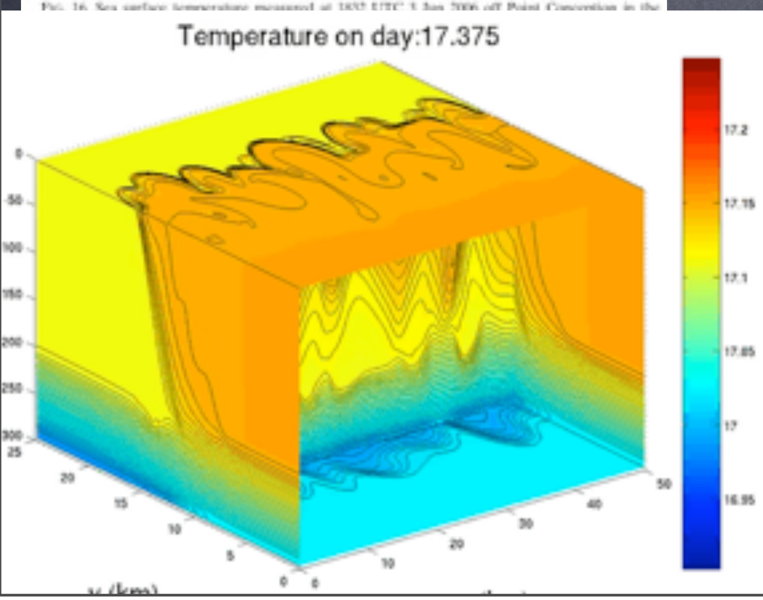
vs.

Little, Shallow (submeso)

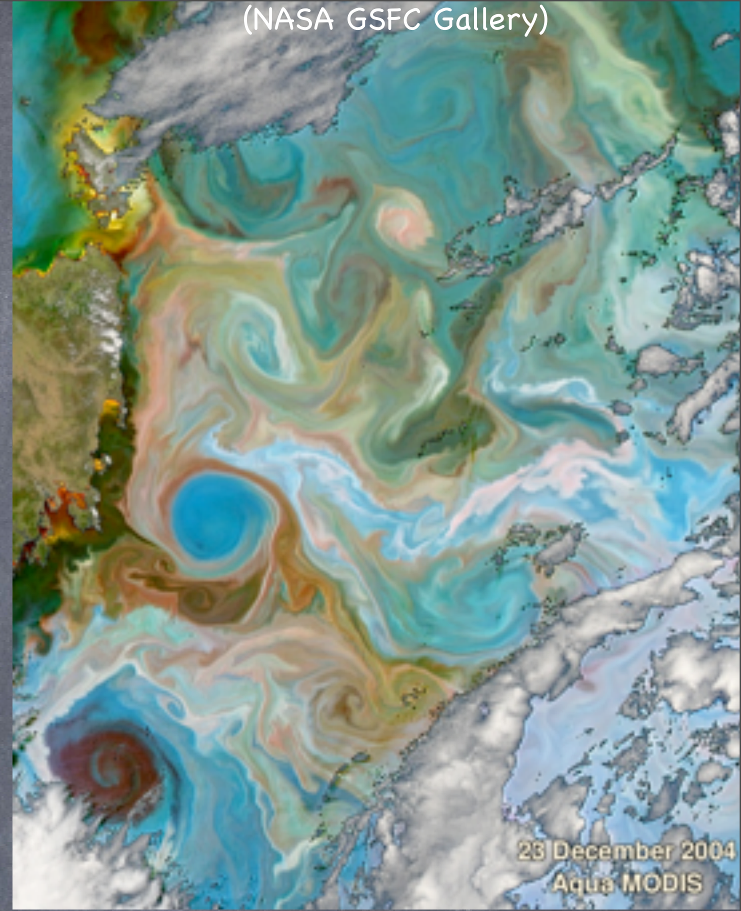
The Character of the Submesoscale

(Capet et al., 2008)





10 km



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

Eddy processes often baroclinic instability

Parameterizations of submesoscale baroclinic instability?

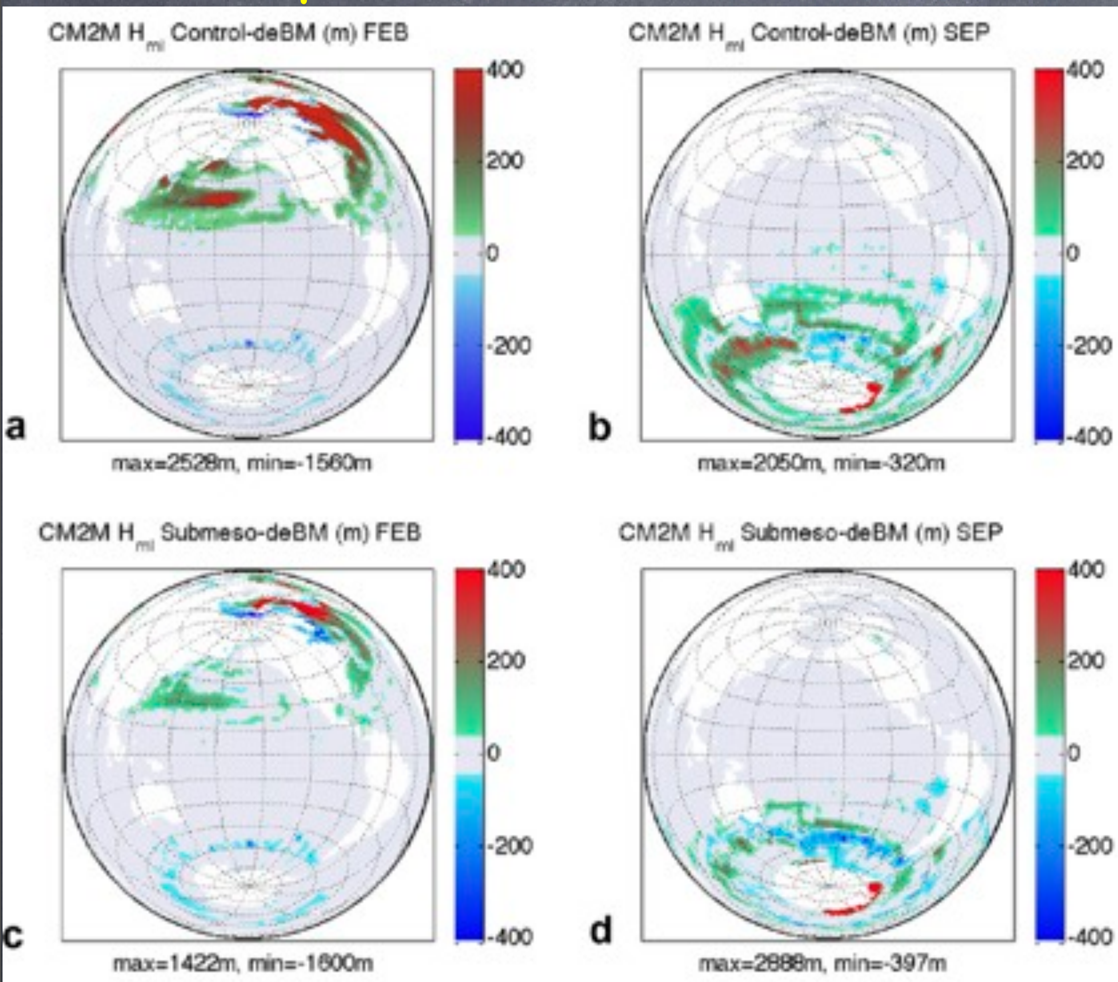
B. Fox-Kemper, R. Ferrari, and R. W. Hallberg. Parameterization of mixed layer eddies. Part I: Theory and diagnosis. Journal of Physical Oceanography,

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

Implemented in CCSM (NCAR), CM2M & CM2G (GFDL)



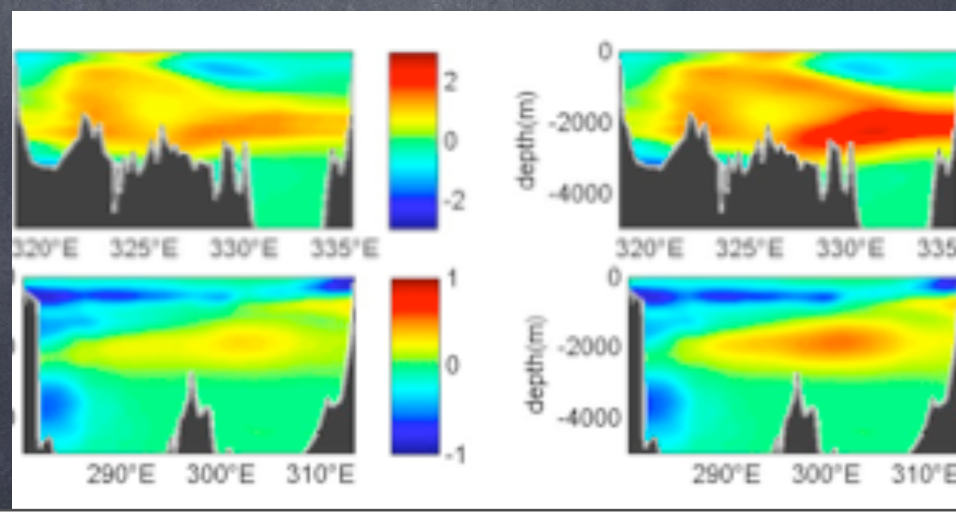
Bias w/o MLE

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.

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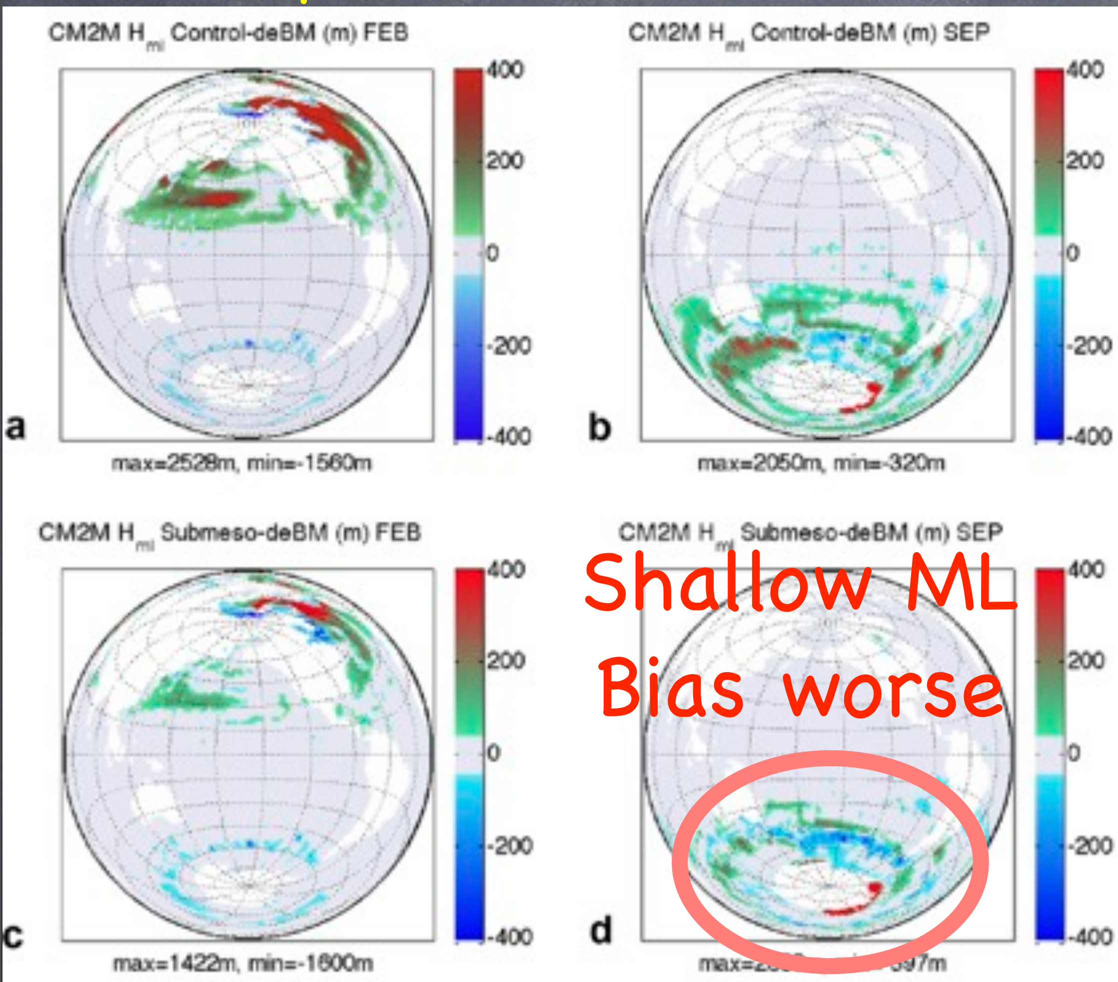

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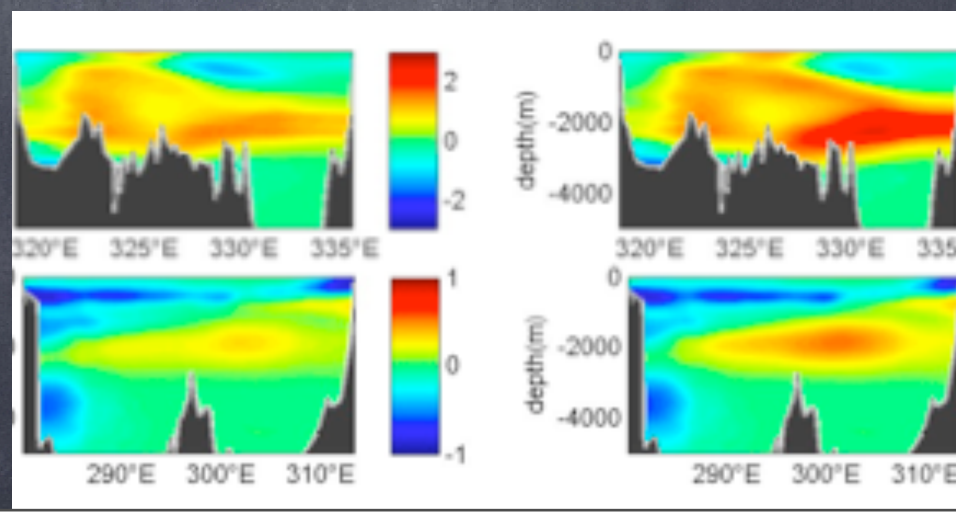

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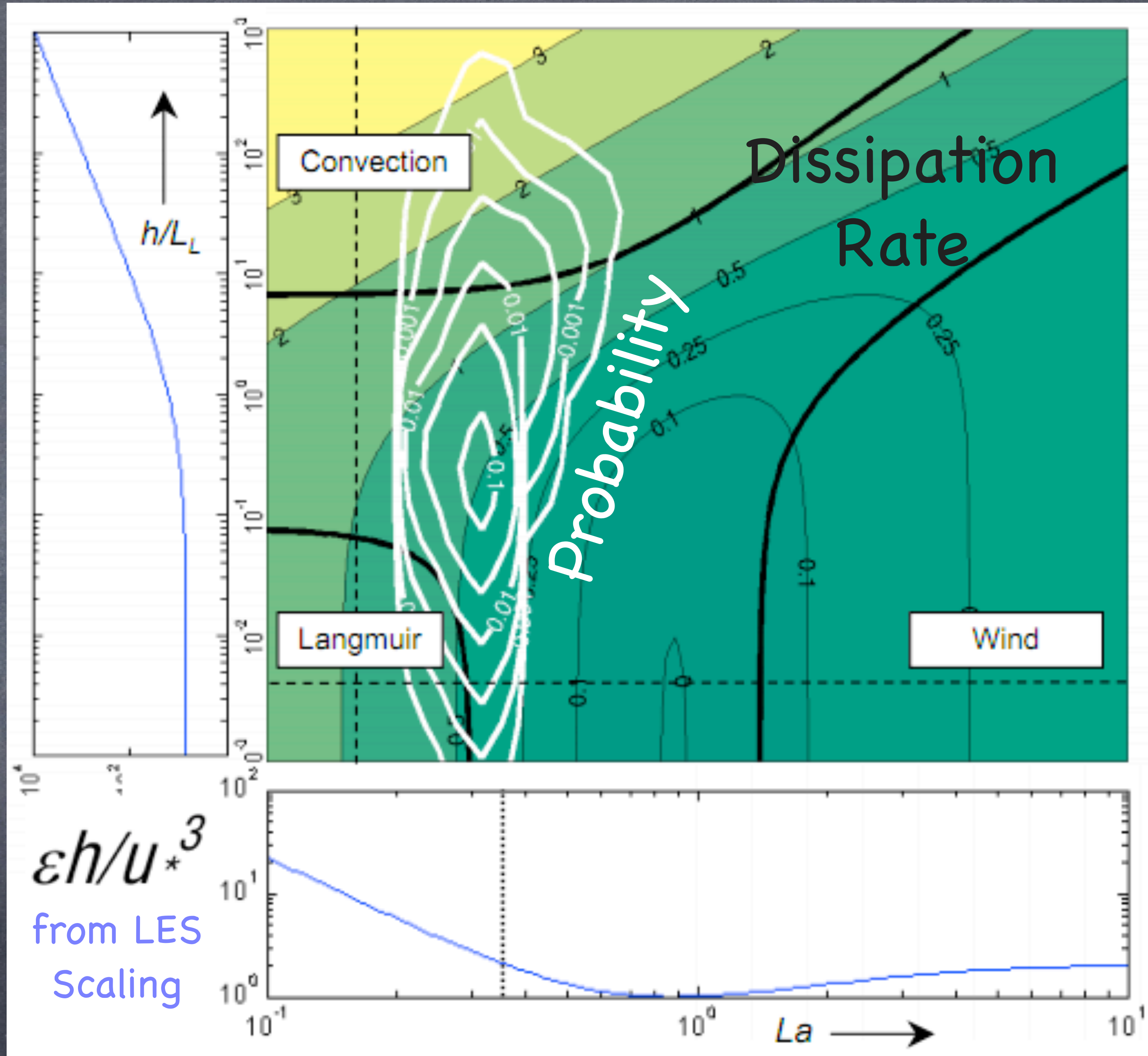
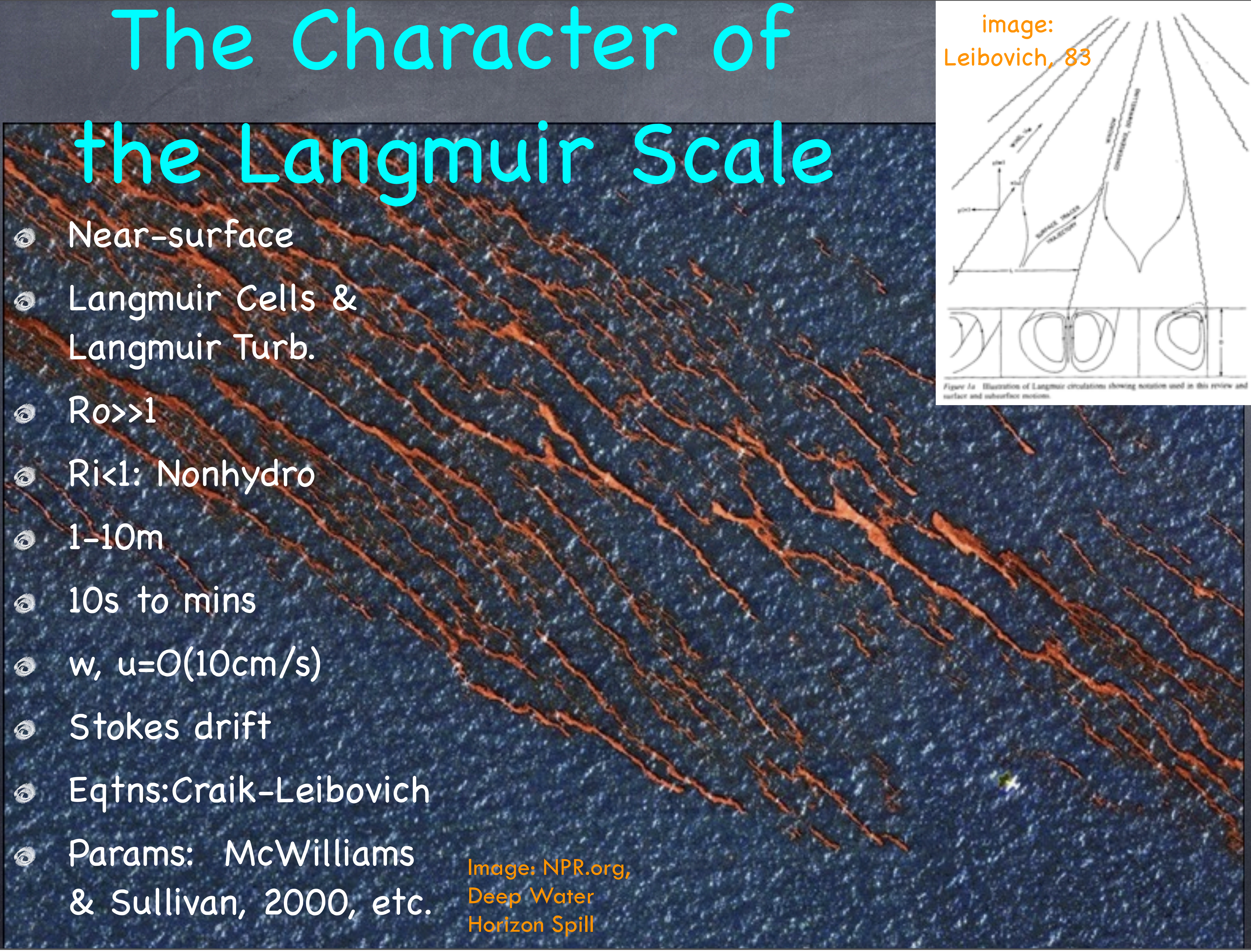
Data + LES, Southern Ocean mixing energy: Langmuir (Stokes-drift-driven) and Convective



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 mixing in the ocean surface boundary layer. *Geophysical Research Letters*, 2012.

The Character of the Langmuir Scale



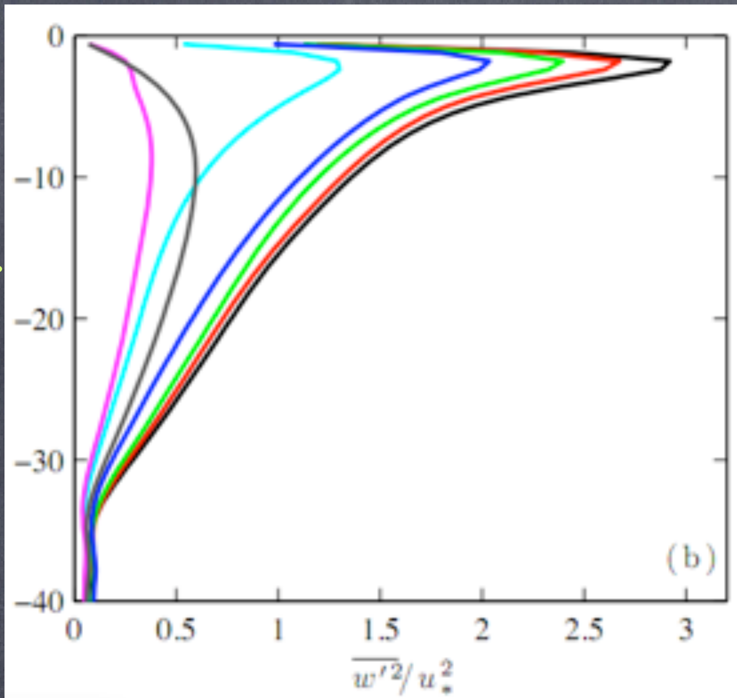
- Near-surface
- Langmuir Cells & Langmuir Turb.
- Ro>>1
- Ri<1: Nonhydro
- 1-10m
- 10s to mins
- w, u=O(10cm/s)
- Stokes drift
- Eqtns:Craik-Leibovich
- Params: McWilliams & Sullivan, 2000, etc.

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

<w²>



depth

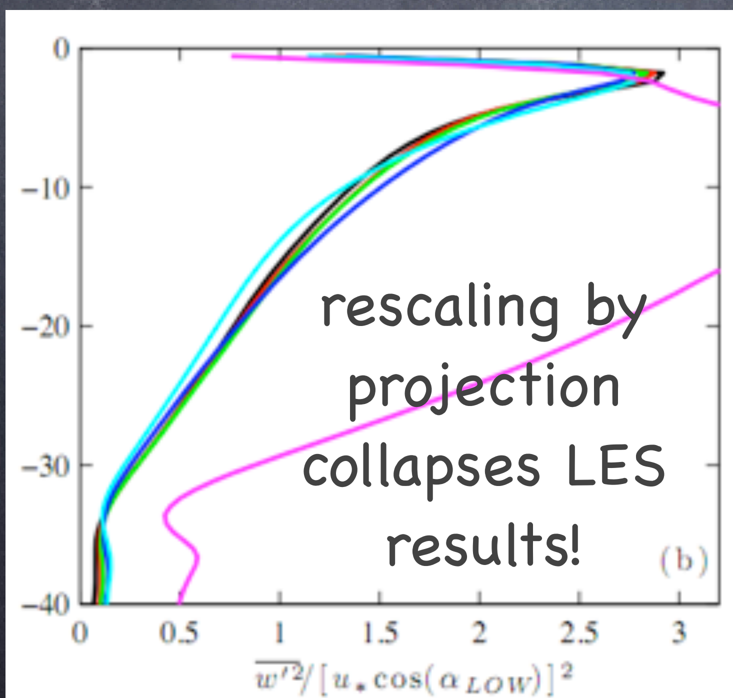
Generalized Turbulent Langmuir No., Projection of u*, u_s into Langmuir Direction

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

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

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

rescaled <w²>



depth

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.

Including Wave-driven Mixing Deepens the Mixed Layer!

Estimates by Hemer using Harcourt 2012 model similar to ours

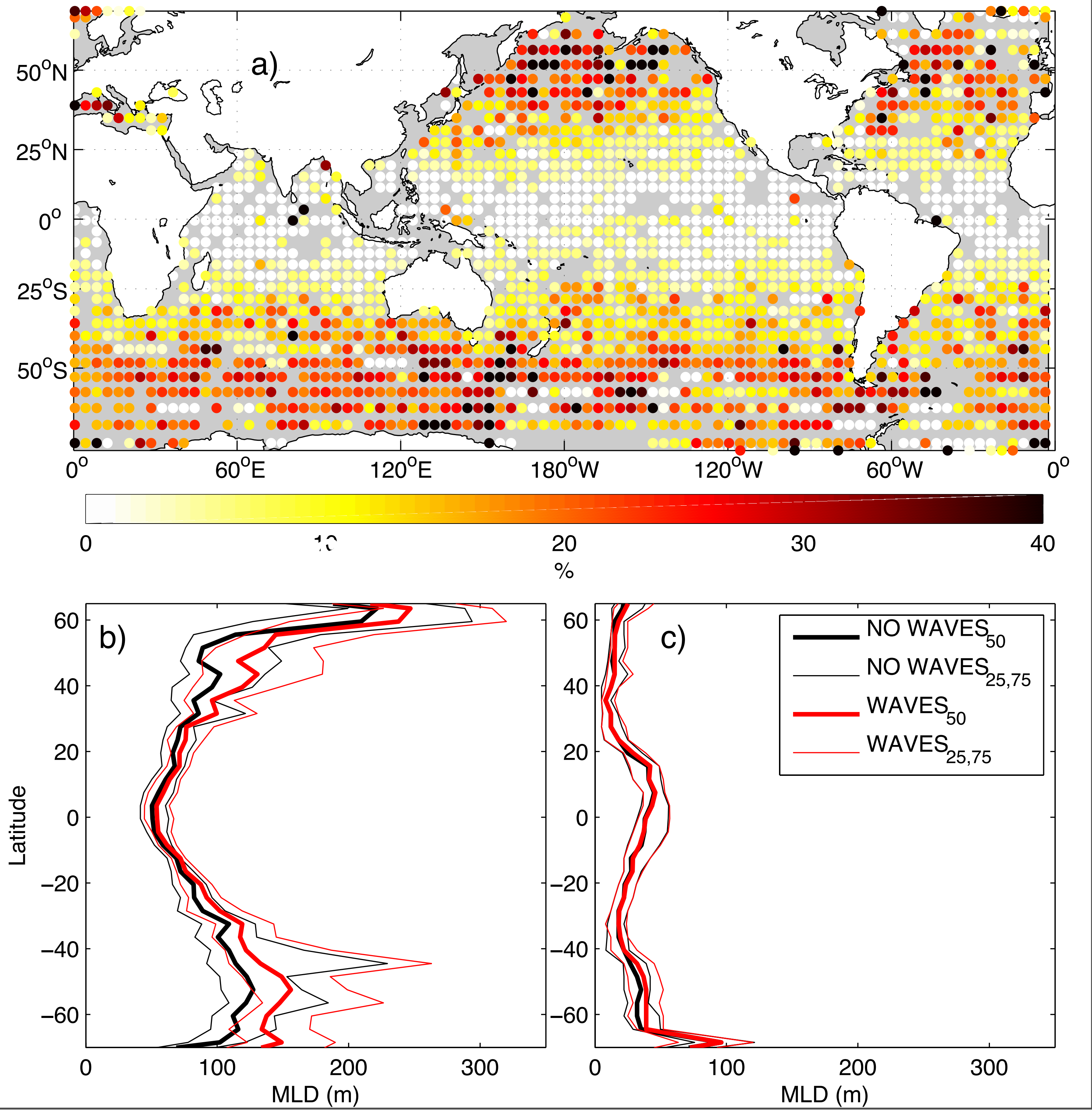


Fig: M. Hemer

Up to now: all small-scales acting on global scale

What about neighboring scale-to-scale?

Next Scale Down: Approaching 3d!

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

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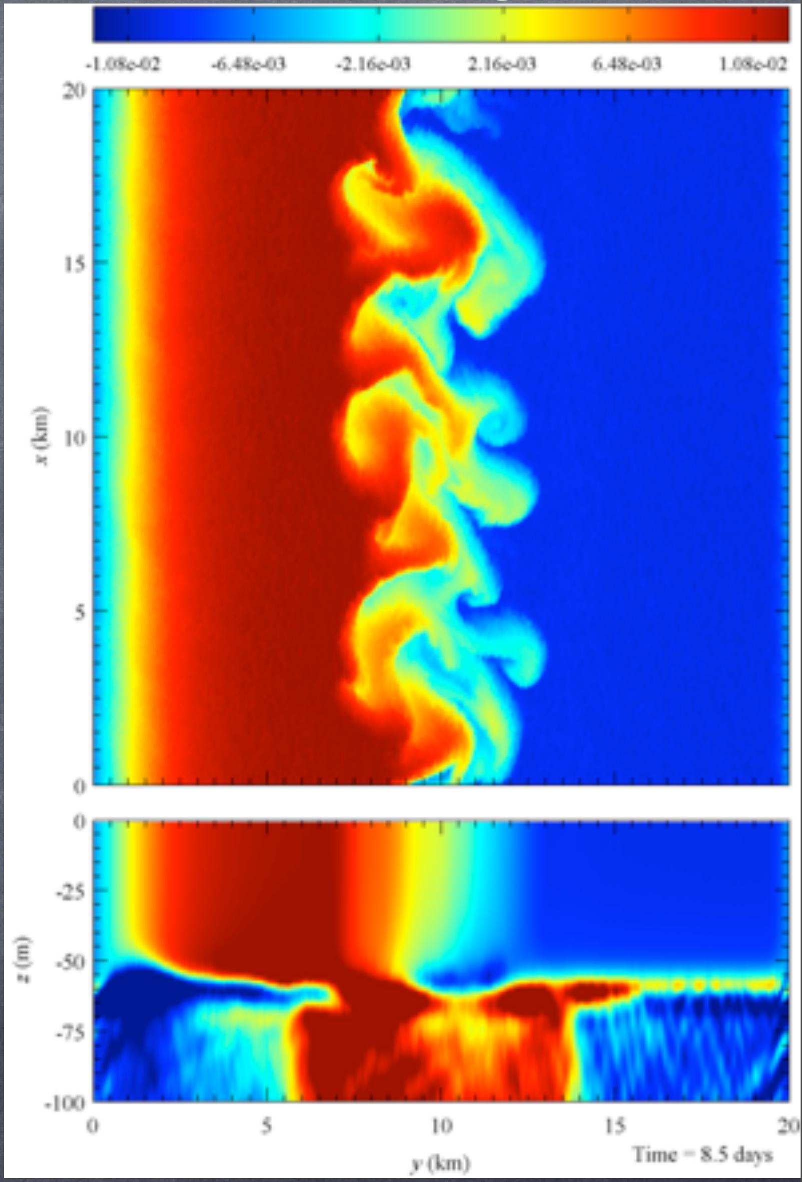

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Coupling between Langmuir and Submeso?

Wind Only

Stokes & Wind

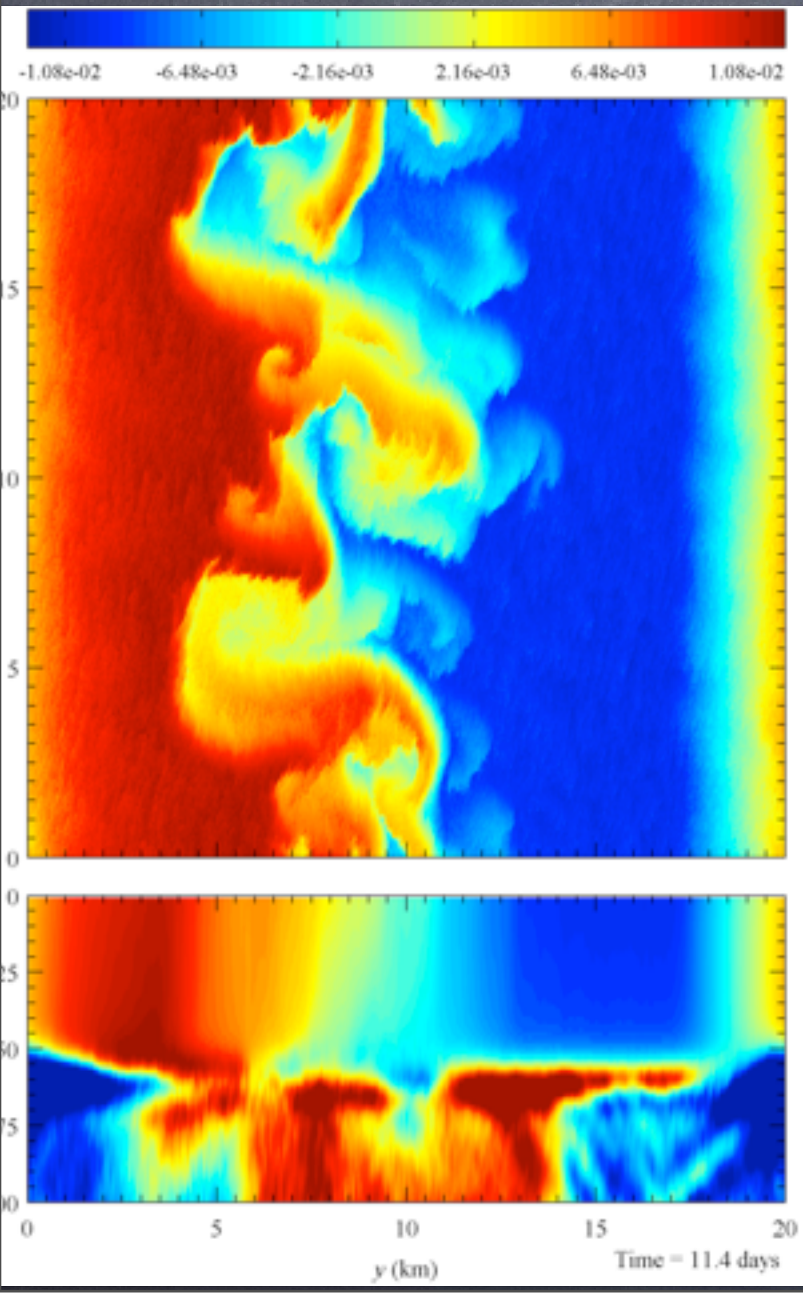
2 runs:
Both spindown of submesoscale filament

Right -->
Stokes & Wind

<-- Left
Wind Only

Coupling between Langmuir and Submeso?

Wind Only



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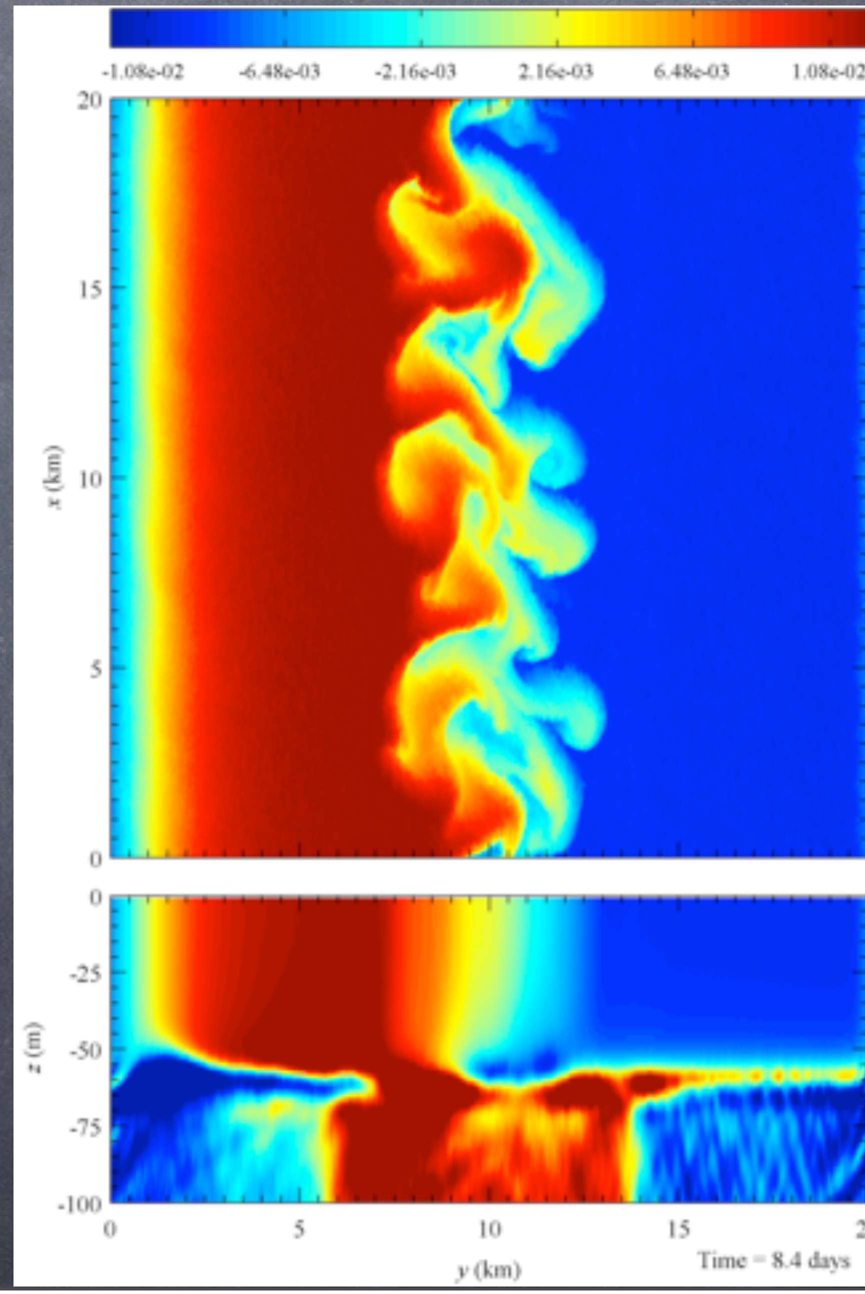
Both spindown of submesoscale filament

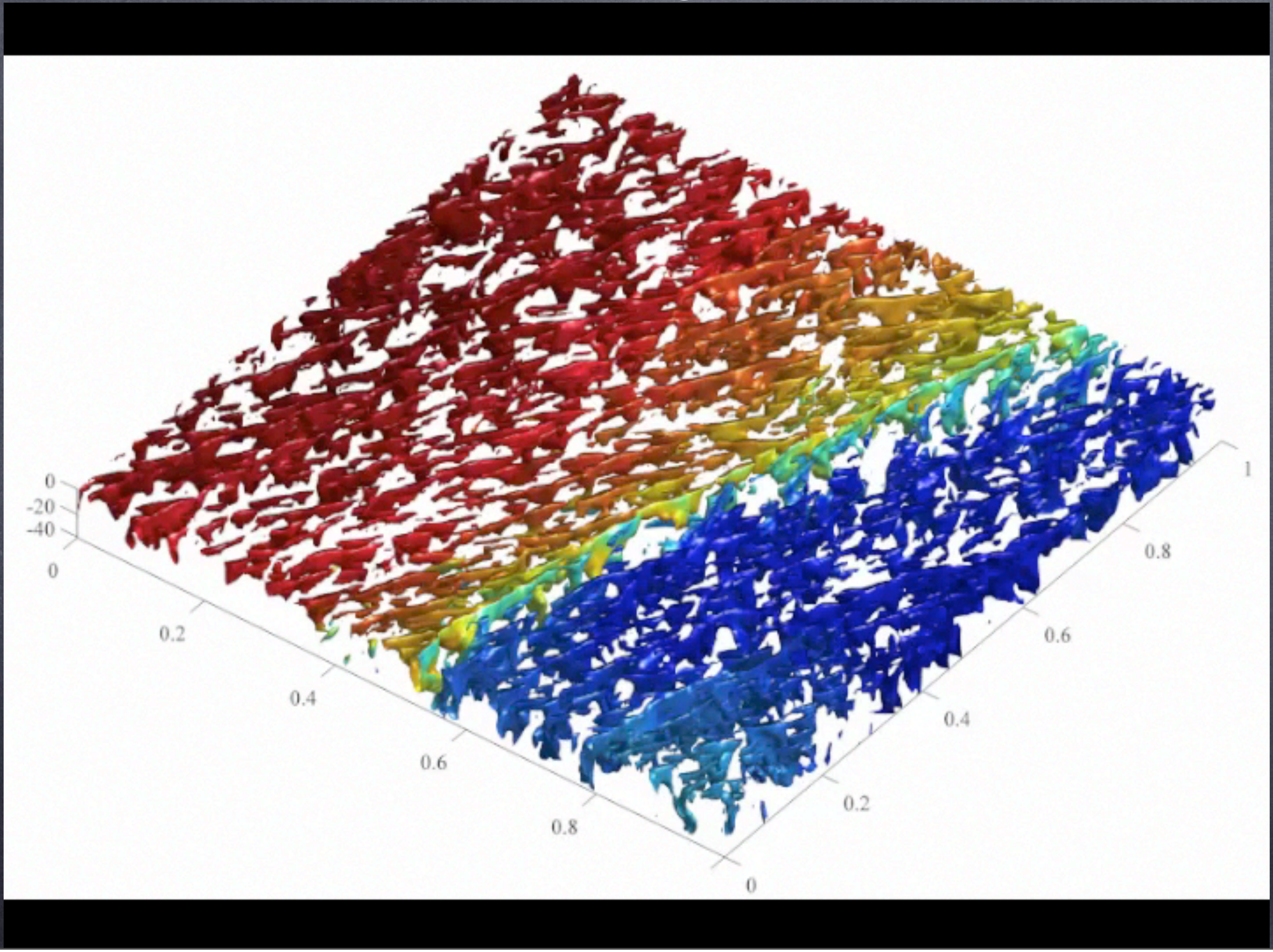
Right --> Stokes & Wind

<-- Left Wind Only

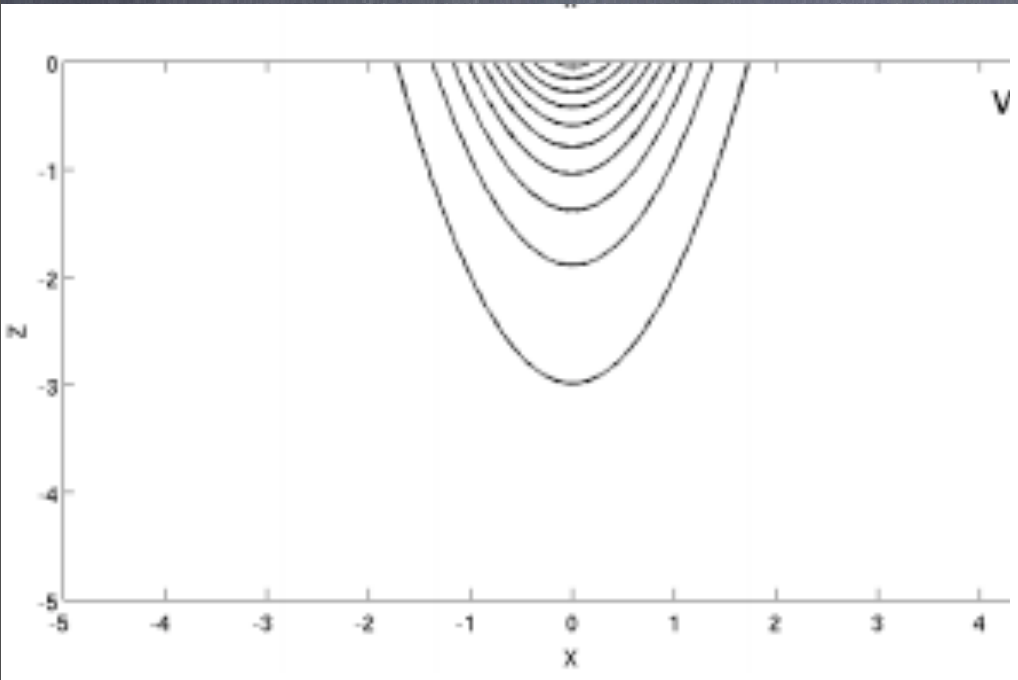
Stokes & Wind

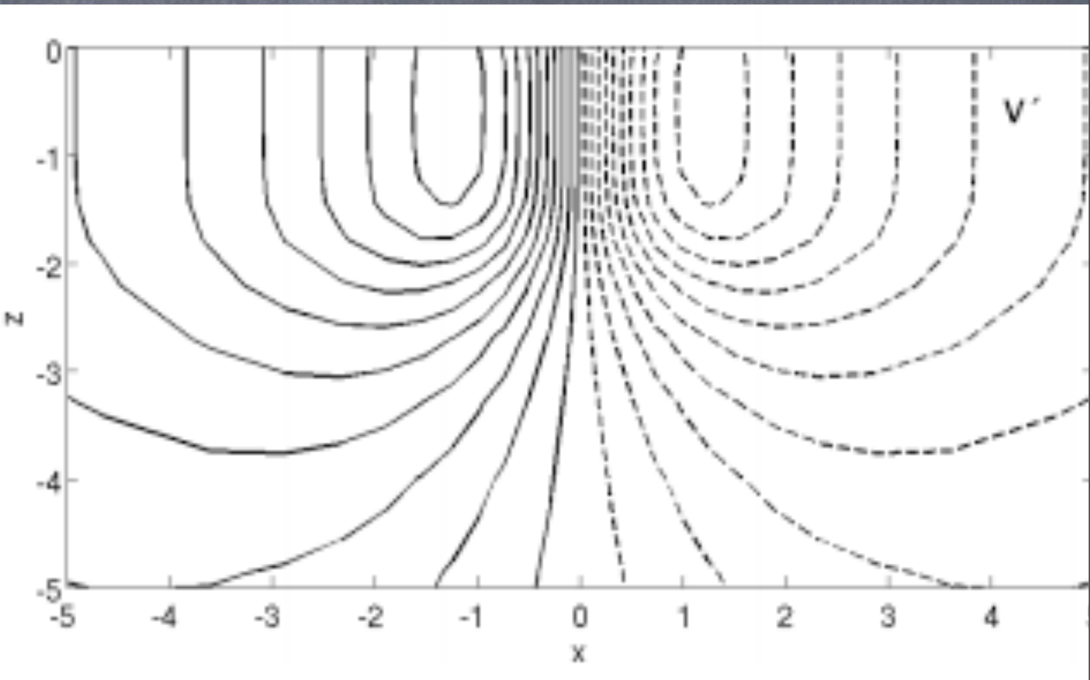


Zoom: Submeso-Langmuir Interaction!



Waves->Submeso, Meso





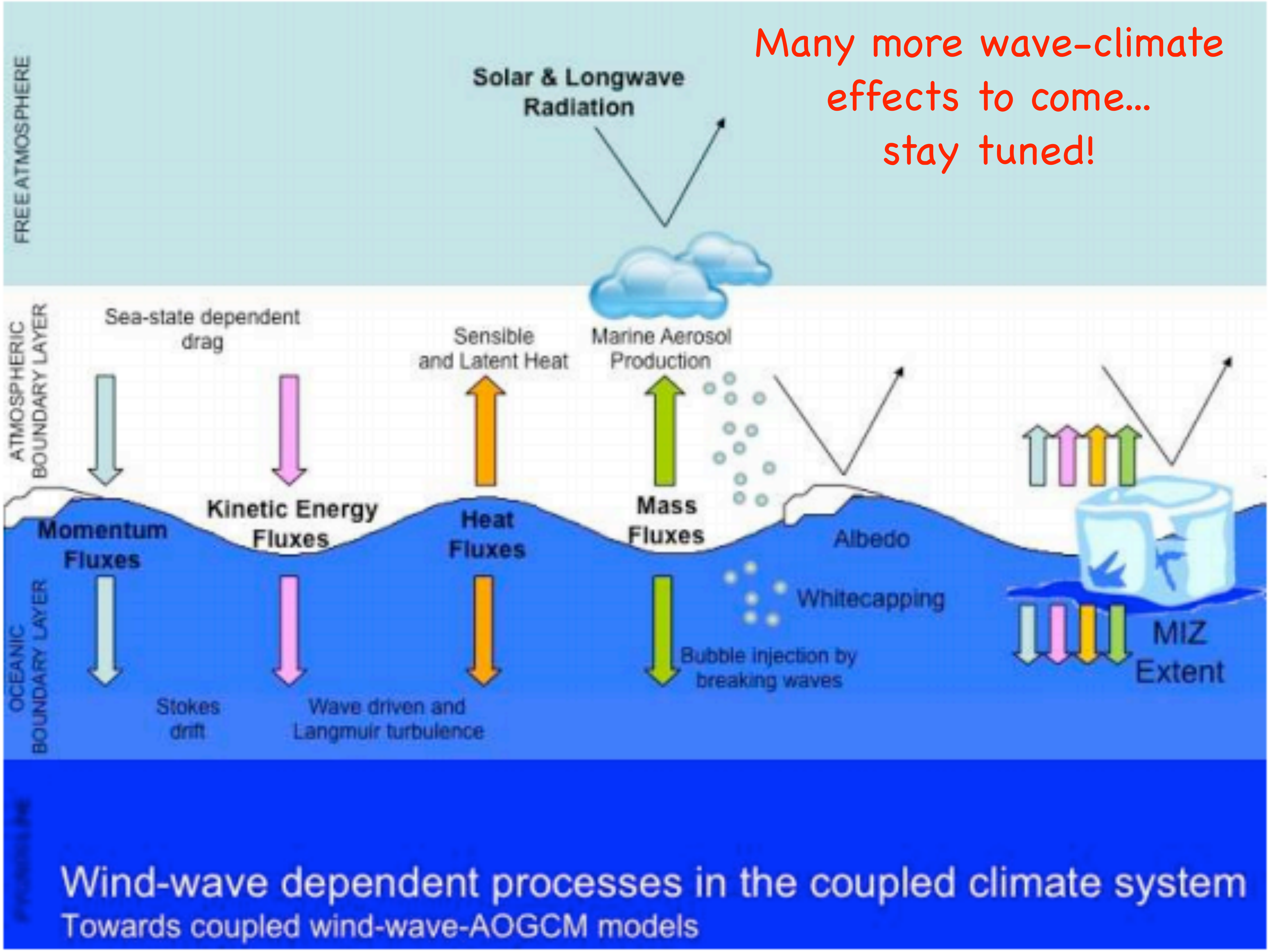
Initial Submeso flow

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.

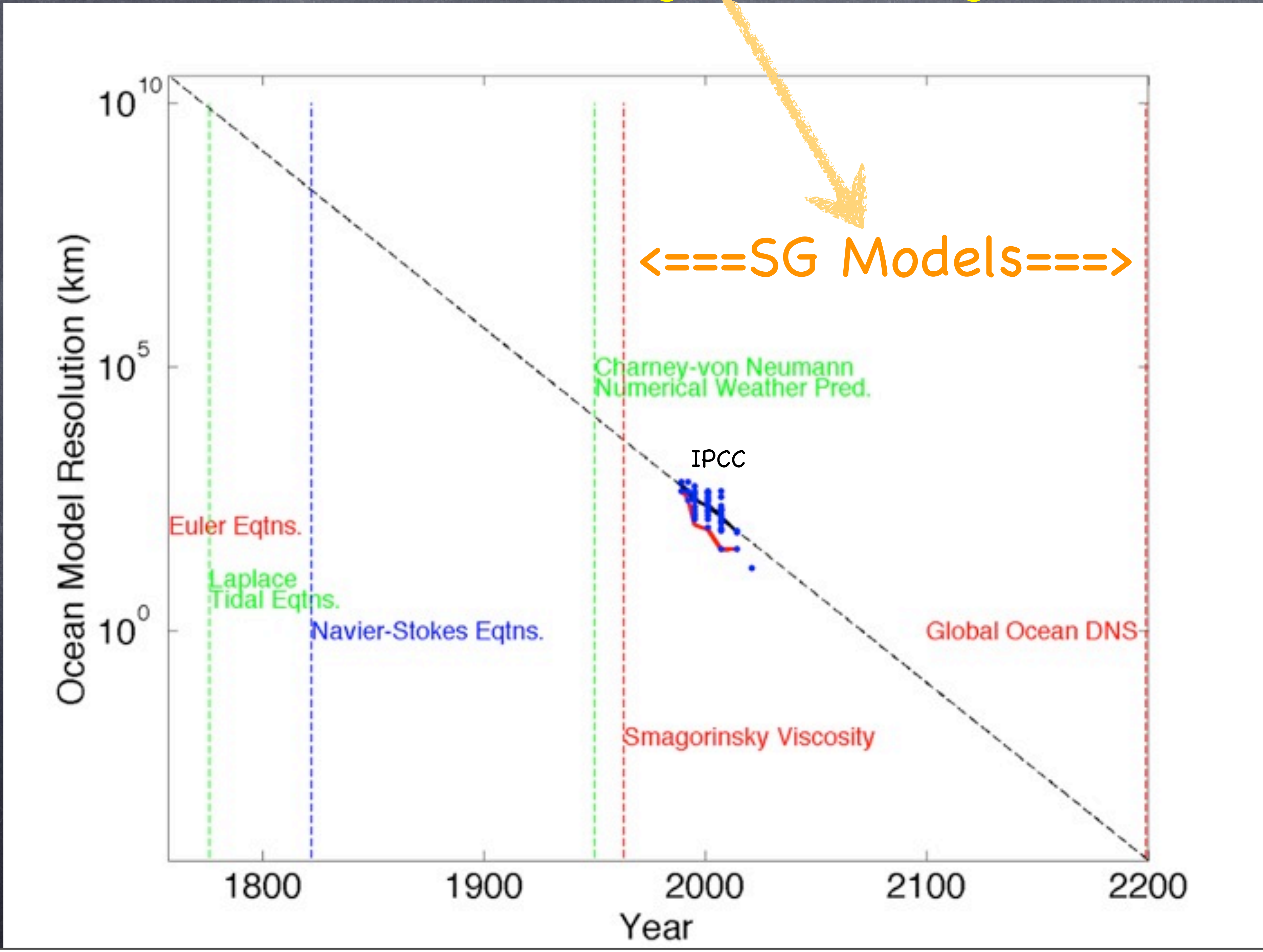


L. Cavaleri, B. Fox-Kemper, and M. Hemer. Wind waves in the coupled climate system. *Bulletin of the American Meteorological Society*, 2012.

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 contributed 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