Getting Fundamentals Right: Lognormality and Reactions of Oceanic Turbulence

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CalTech: Atmosphere, Oceans, and Computational Infrastructure
Pasadena, 5/16/18

with Brodie Pearson, Jenna Palmer (Brown), Arin Nelson (U. Mich.), Jeff Weiss, Peter Hamlington (CU), Royce Zia (Va. Tech.), & Kat Smith (Cambridge)

Sponsors: NSF 1245944, 1258907, 1350795, ONR N00014-17-1-2963, GoMRI/CARTHE

If we wanted a new (ocean) climate model–

- Capability of refinement–in place and on-line with realistic forcing down to scales we "trust"–then ML or parameter adjust back to global scale

- Parameterization consequence tool. If I change a parameterization at one scale, what are global consequences?

- Regional modeling capability

News from Brown

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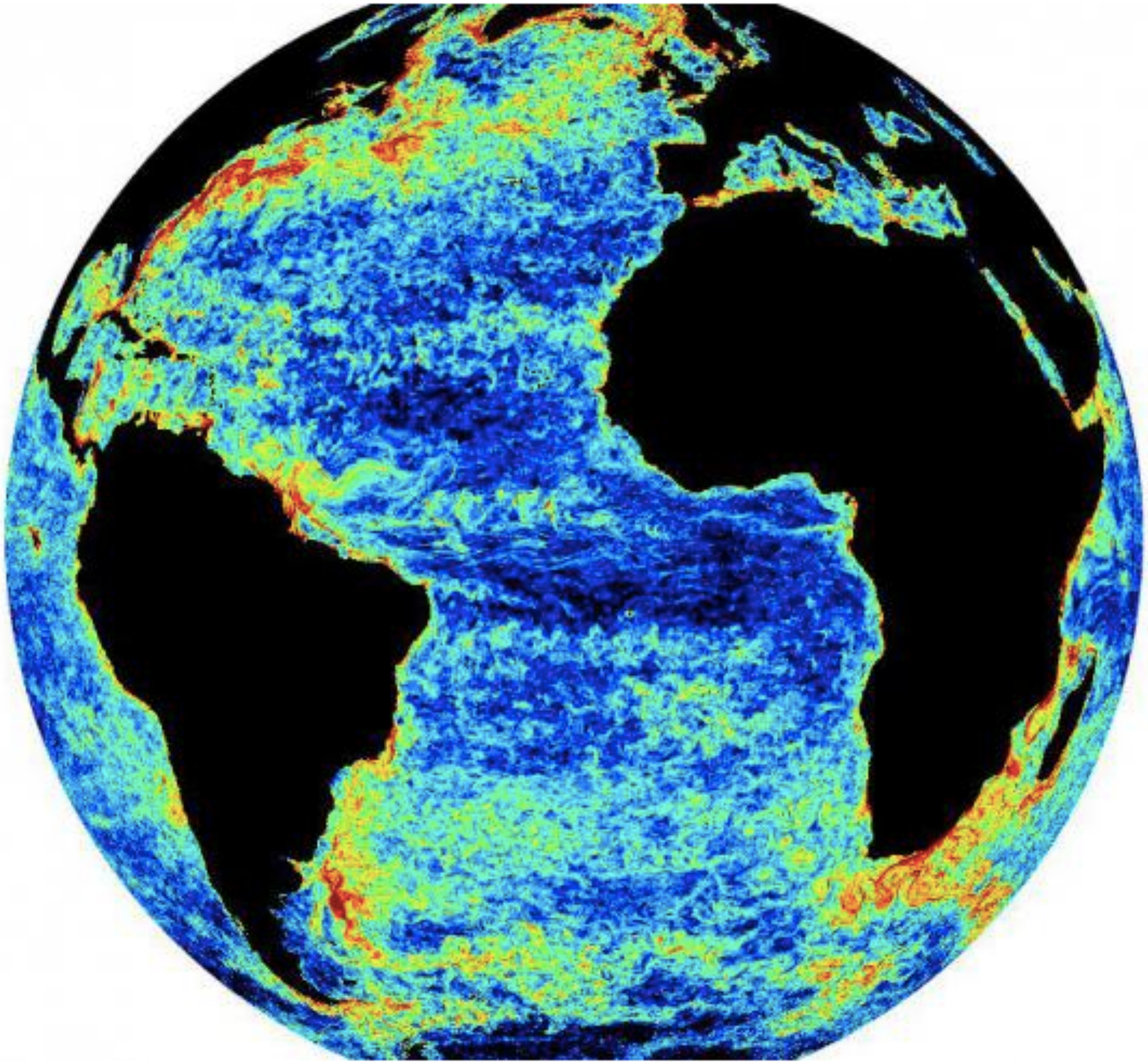


Hotspots
Brown University researchers have made a new

New understanding of ocean turbulence could improve climate models

February 26, 2018 Media contact: Kevin Stacey
401-863-3766

Researchers have developed a new statistical understanding of how turbulent flows called mesoscale eddies dissipate their energy, which could be helpful in creating better ocean and climate models.

PROVIDENCE, R.I. [Brown University] — Brown University researchers have made a key insight into how high-resolution ocean models simulate the dissipation of turbulence in the global ocean. Their research, published in Physical Review Letters, could be helpful in developing new climate models that better capture ocean dynamics.

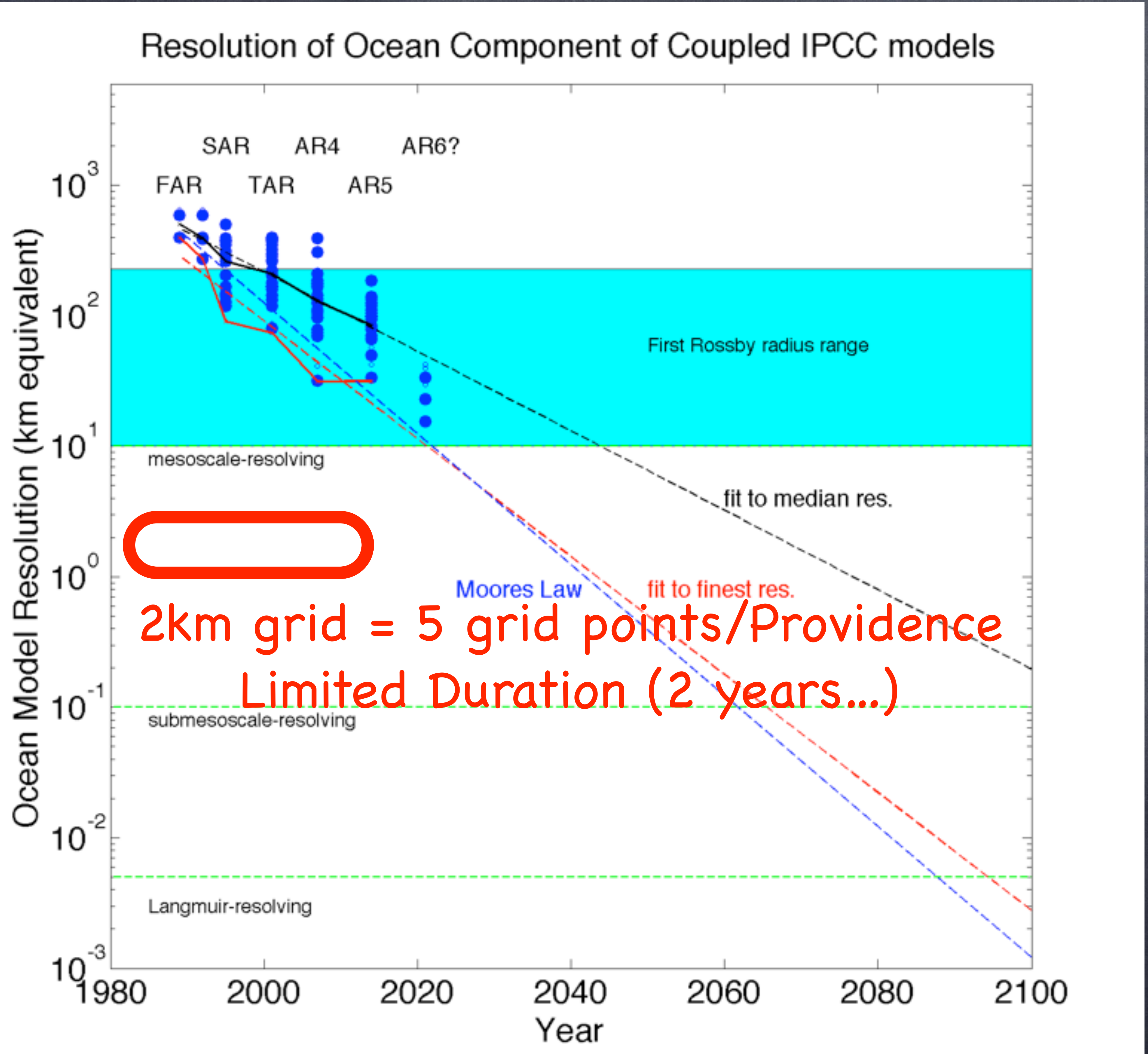
B. Pearson and BFK. Log-normal turbulence dissipation in global ocean models. Physical Review Letters, 120(9):094501, March 2018.

ECCO2 Model

Viscosity Scheme: BFK 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.

18km resolution

What about modeling important processes in climate models?
Don't we have big enough computers? or won't we soon?



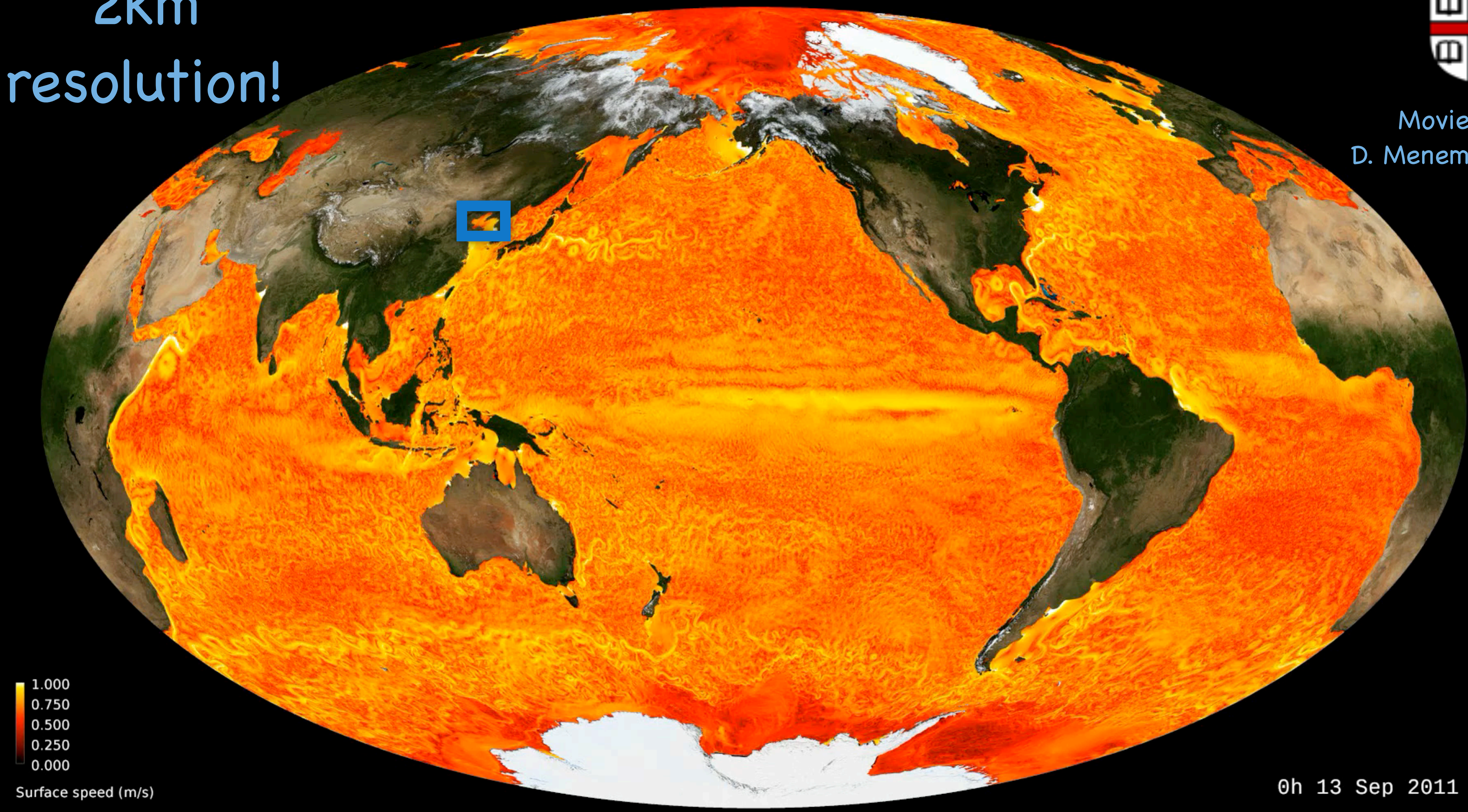
The observed IPCC resolution doubling rate is 6.9 years for basic atmosphere-ocean models and 10.2 years for complex ESMs

Estimating the Circulation & Climate of the Ocean

LLC4320 Model

2km resolution!

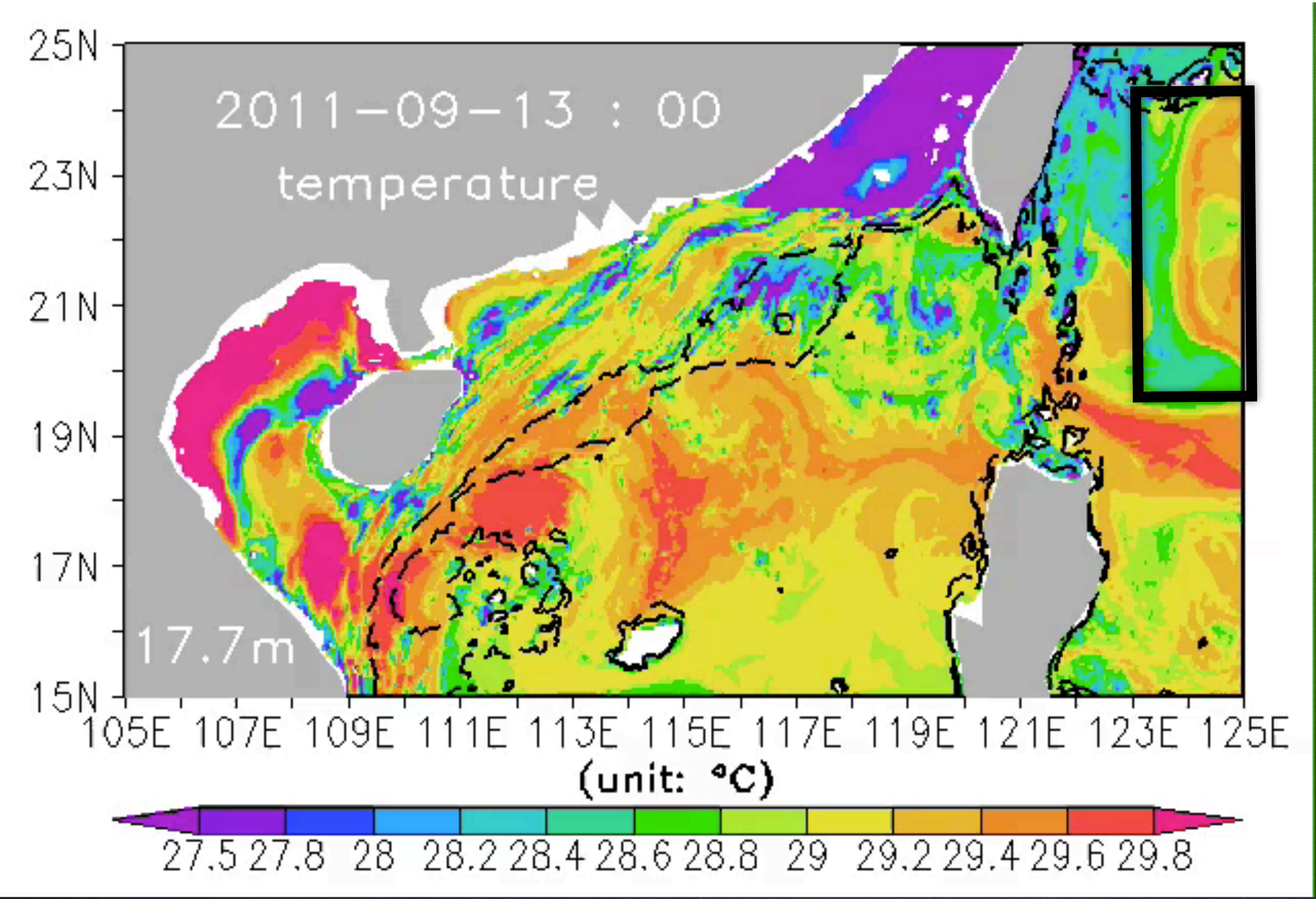
Movie: D. Menemenlis



B. Fox-Kemper, S. Bachman, B. Pearson, and S. Reckinger. Principles and advances in subgrid modeling for eddy-rich simulations. CLIVAR Exchanges, 19(2):42-46, July 2014.

Estimating the Circulation & Climate of the Ocean

LLC4320 Model



Movie:
Z. Jing

Local Analysis: Z. Jing, Y. Qi, B. Fox-Kemper, Y. Du, and S. Lian. Seasonal thermal fronts and their associations with monsoon forcing on the continental shelf of northern South China Sea: Satellite measurements and three repeated field surveys in winter, spring and summer. Journal of Geophysical Research-Oceans, 121:1914-1930, April 2016.

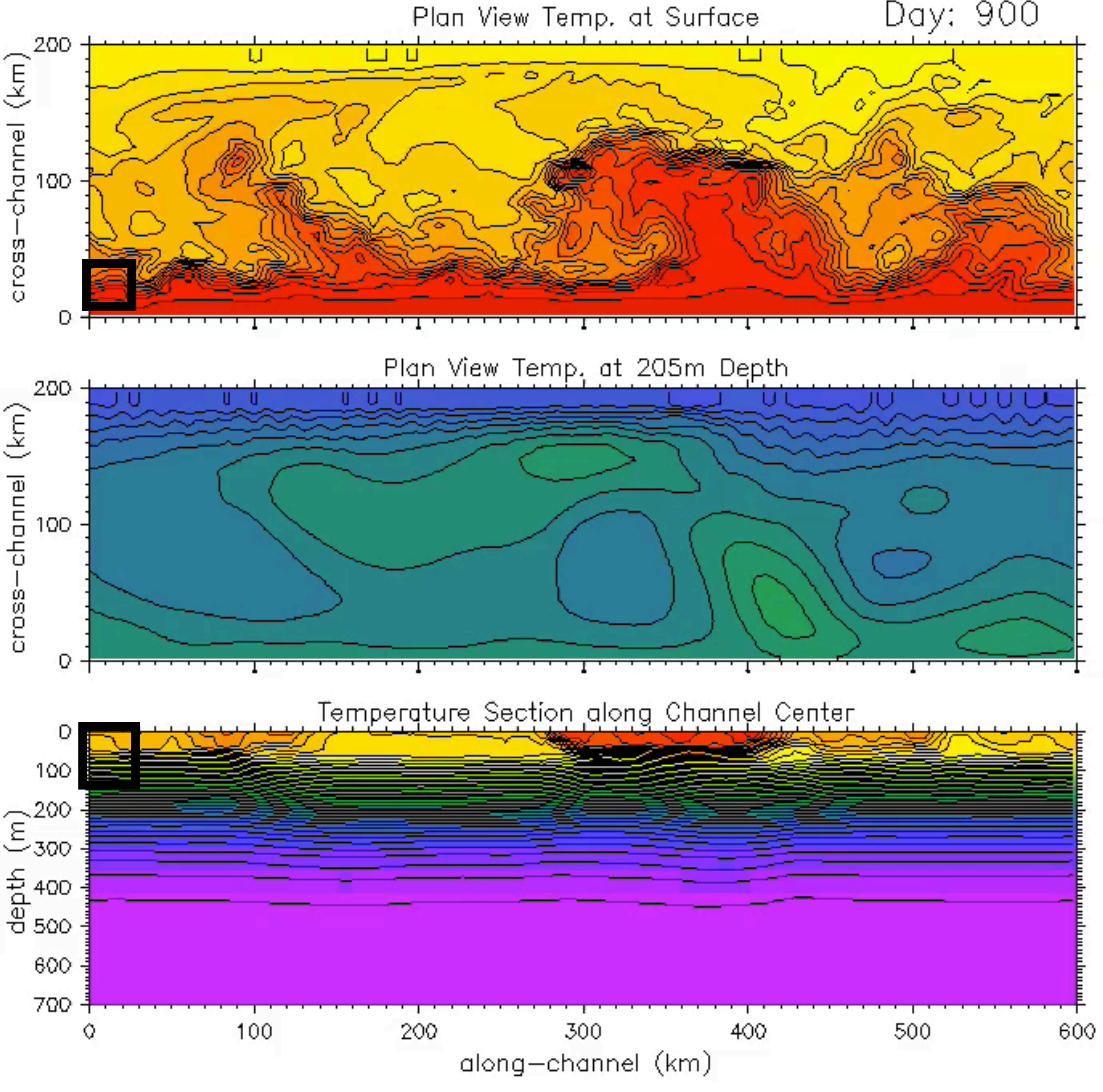
200km x 600km x 700m domain

1000 Day Simulation

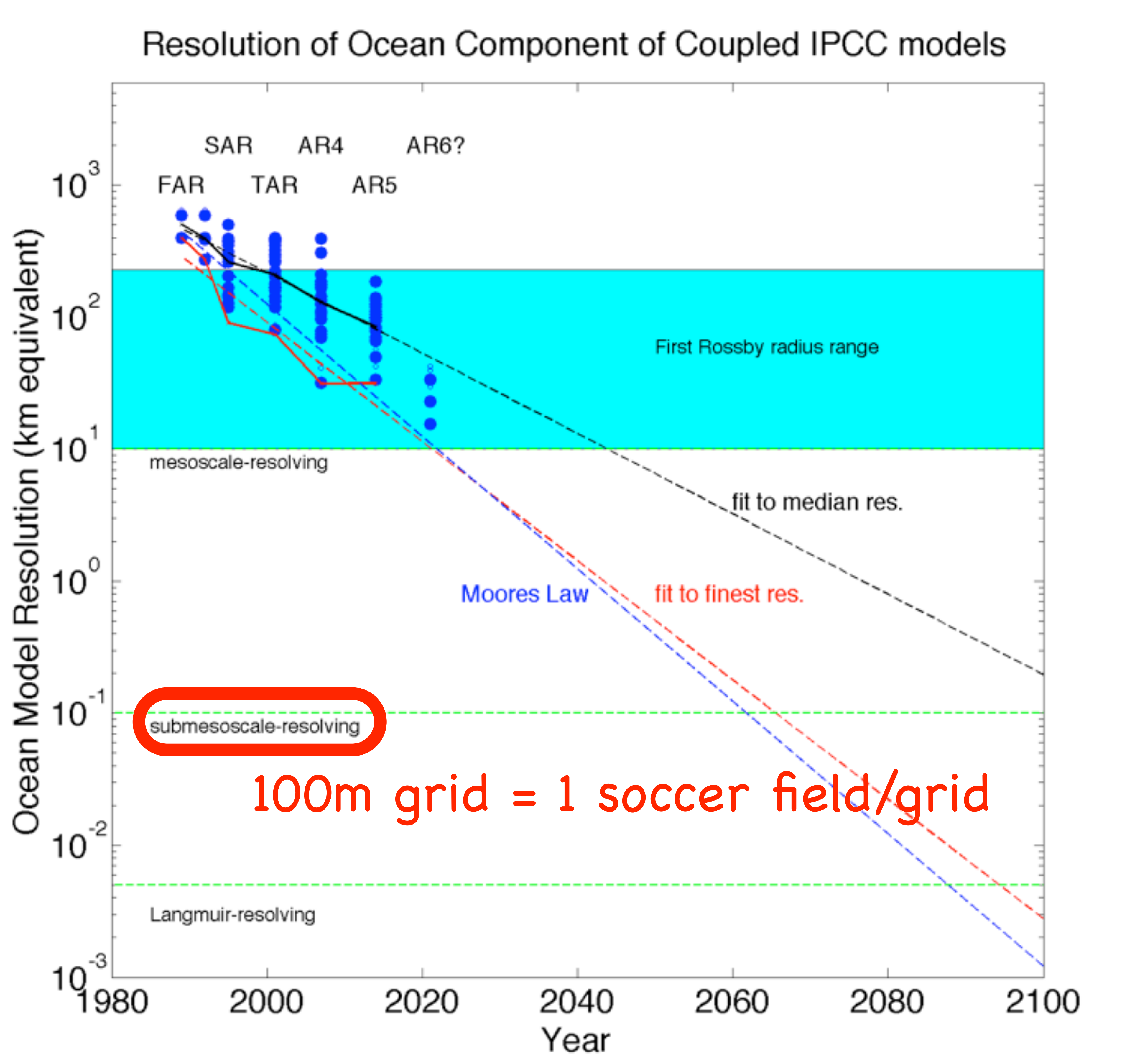
Limited Domain & Duration= Affordable

Cleverness required to capture 2 separate scales: meso & submeso

G. Boccaletti, R. Ferrari, and BFK. Mixed layer instabilities and restratification. Journal of Physical Oceanography, 37(9):2228-2250, 2007.



What about modeling important processes in climate models?
Don't we have big enough computers? or won't we soon?

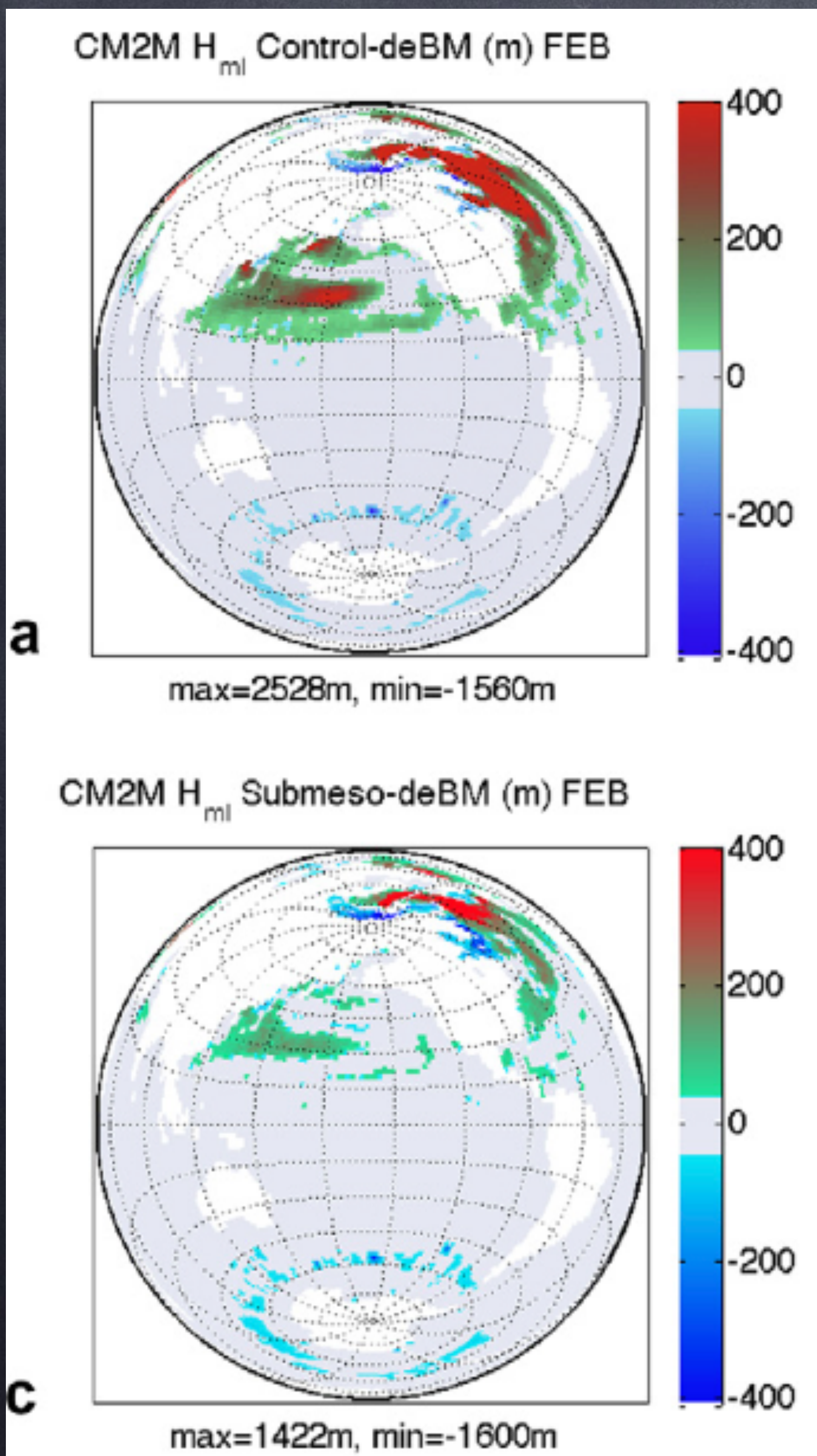


Here are the collection of IPCC models...

If we can't resolve a process, we need to develop a parameterization or subgrid model of its effect

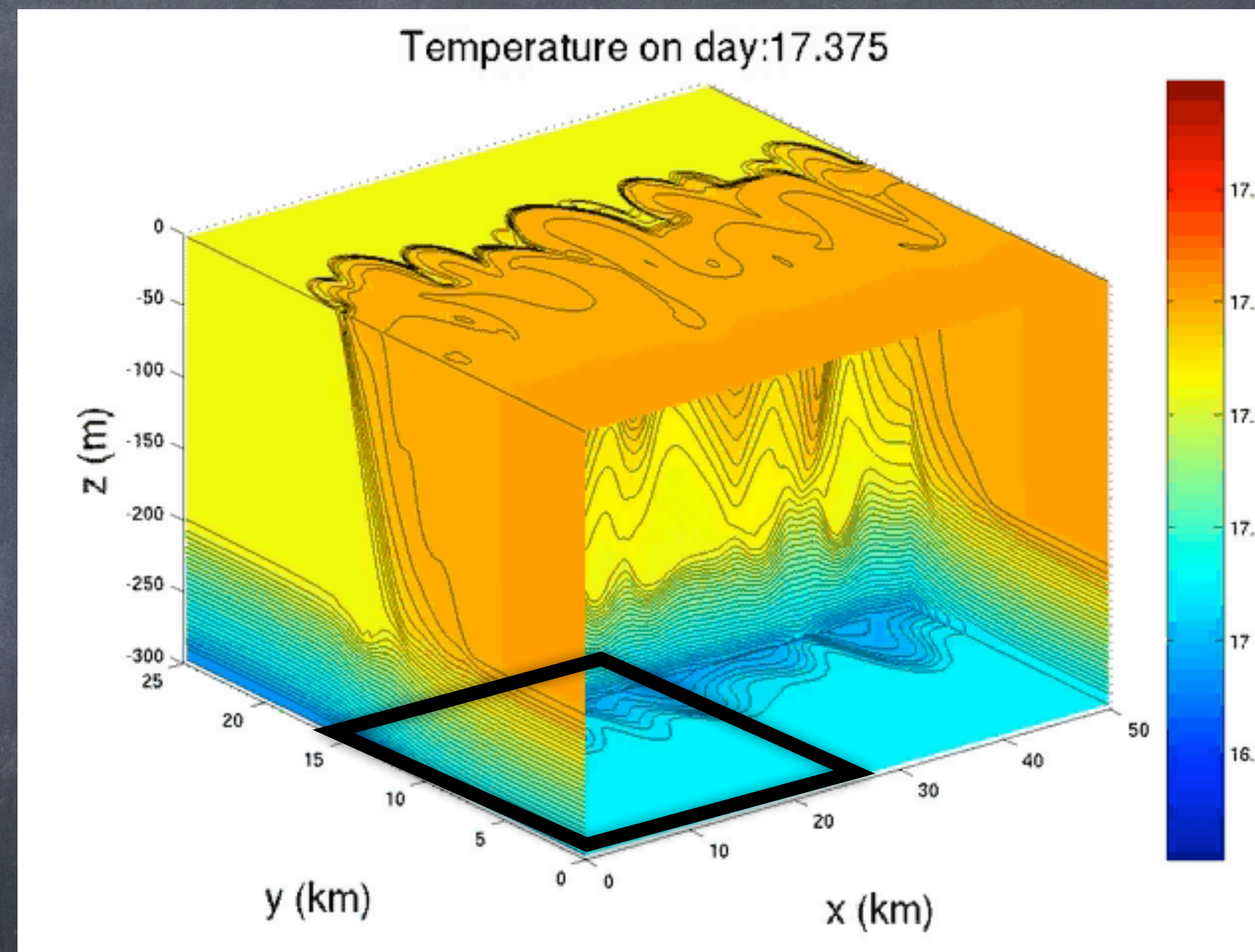
Global Ocean Climate is SENSITIVE to these Submesoscale Eddies! At least in parameterized form

Implemented in IPCC AR5 & 6: NCAR, GFDL, Hadley, NEMO,...



February Mixed layer depth Bias w/o MLE

February MLD Bias With MLE Parameterization



BFK, 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 eddie III: Implementation and impact in global ocean climate simulations. *Ocean Modelling*, 39:61-78, 2011.

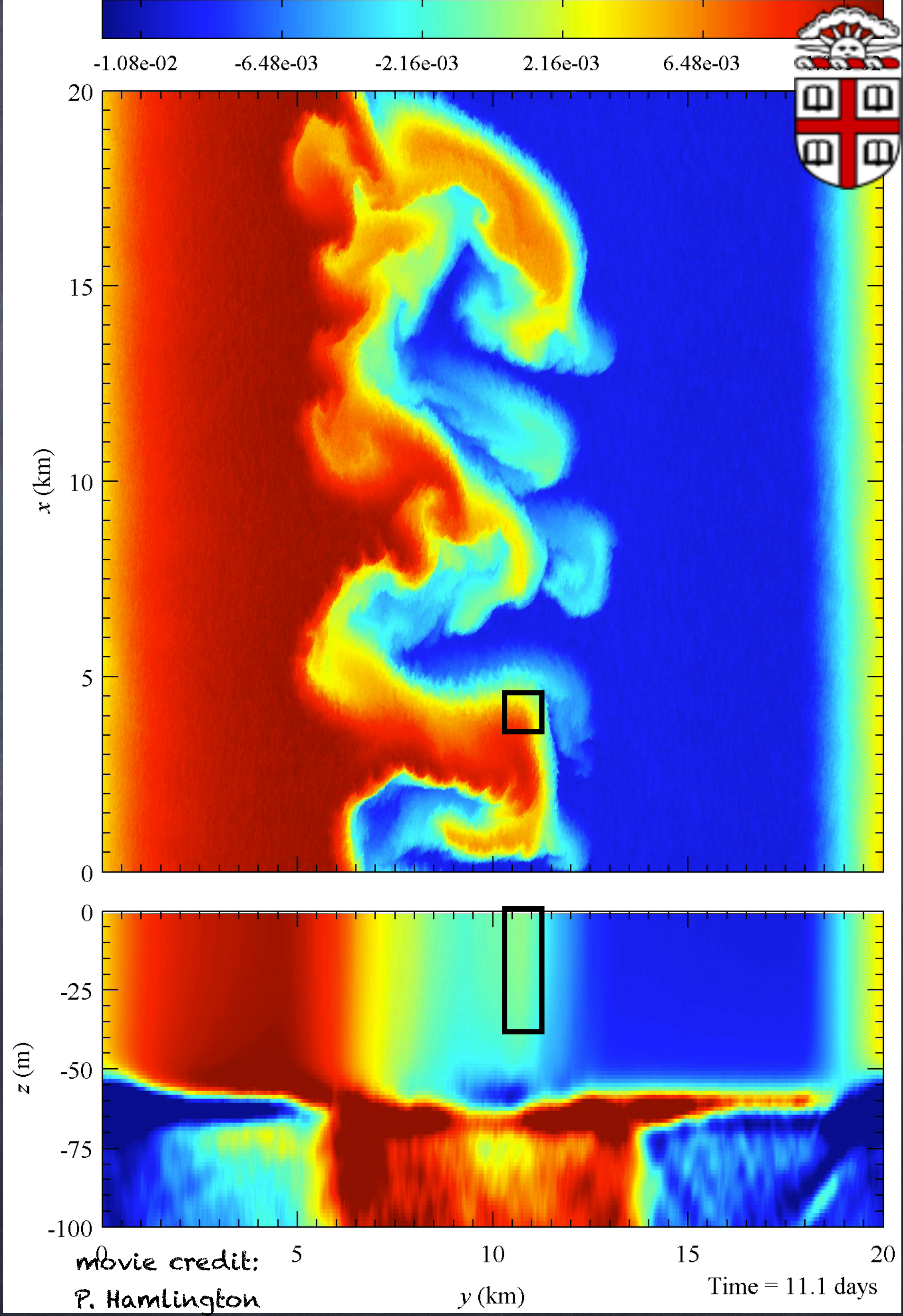
20km x 20km x 150m domain

15 Day Simulation

4m x 4m x 1m resolution

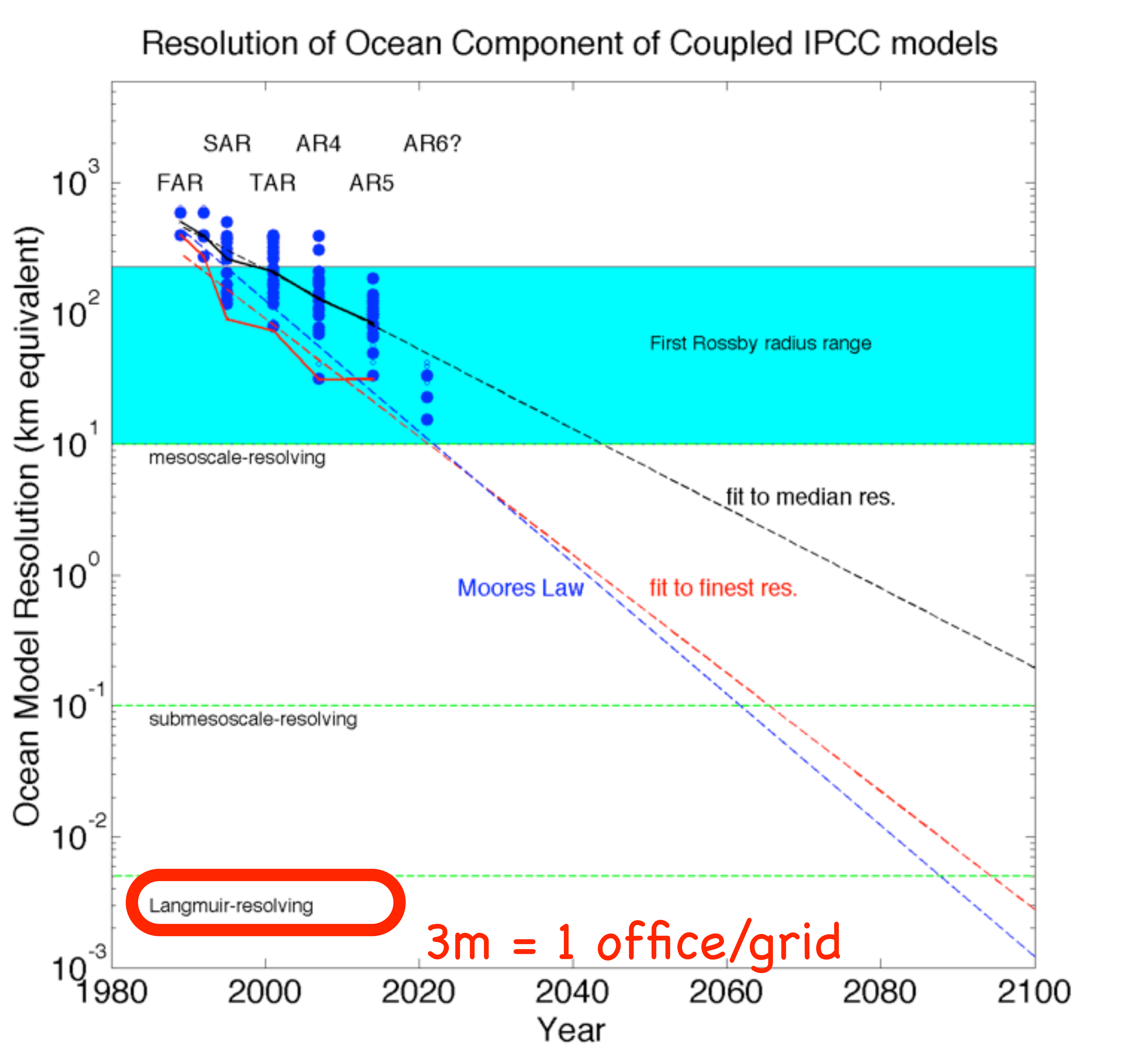
Limited Domain & Duration=
Still Very Expensive!!

Cleverness required to capture 2 separate scales:
submeso & boundary layer LES



P. E. Hamlington, L. P. Van Roekel, BFK, K. Julien, and G. P. Chini. Langmuir-submesoscale interactions: Descriptive analysis of multiscale frontal spin-down simulations. Journal of Physical Oceanography, 44(9):2249-2272, September 2014.

Climate Model Resolution: an issue for centuries to come!

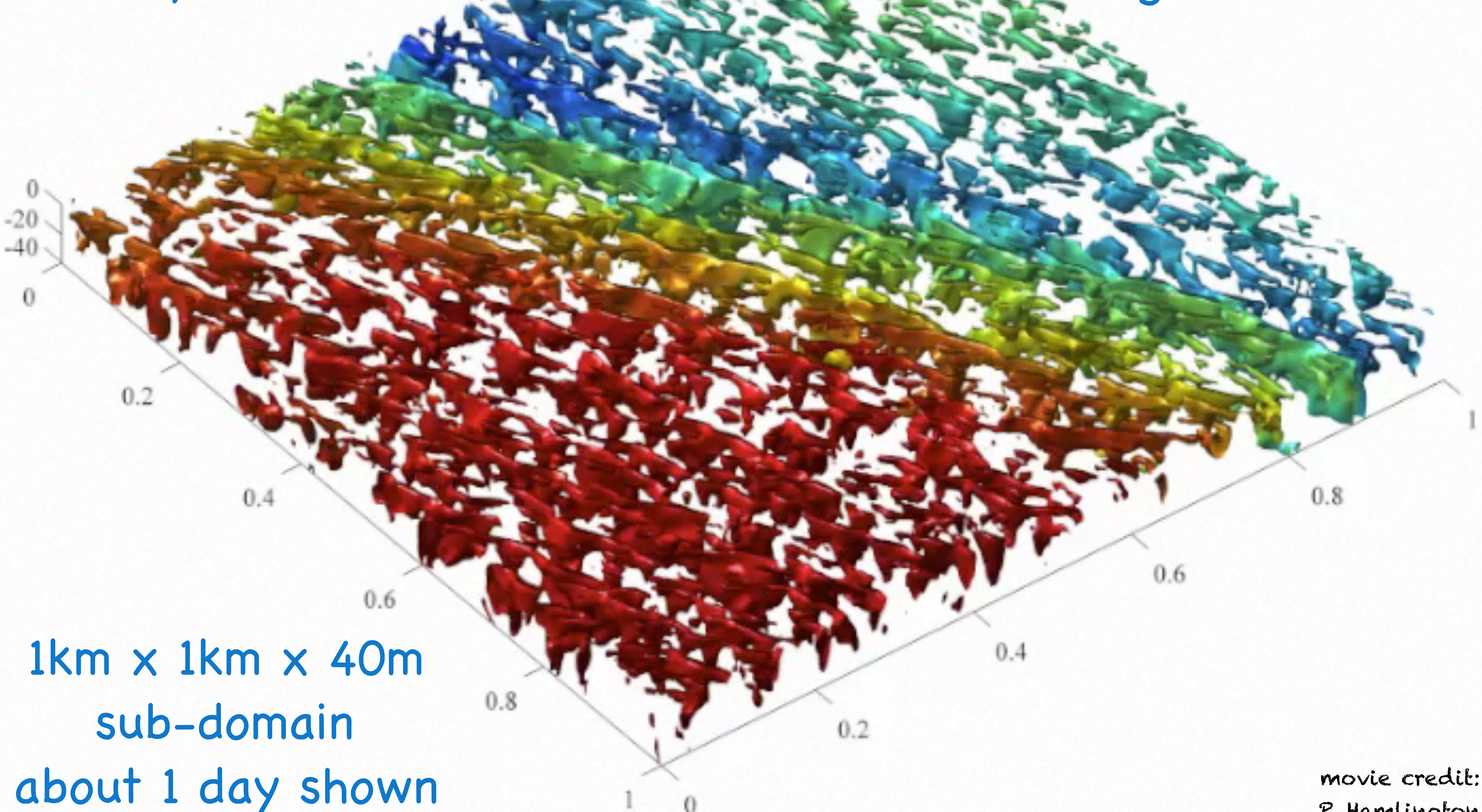


Here are the collection of IPCC models...

If we can't resolve a process, we need to develop a parameterization or subgrid model of its effect

20km x 20km x 150m
domain
10 Day Simulation

Colors=Temp.
Surfaces on
Large w

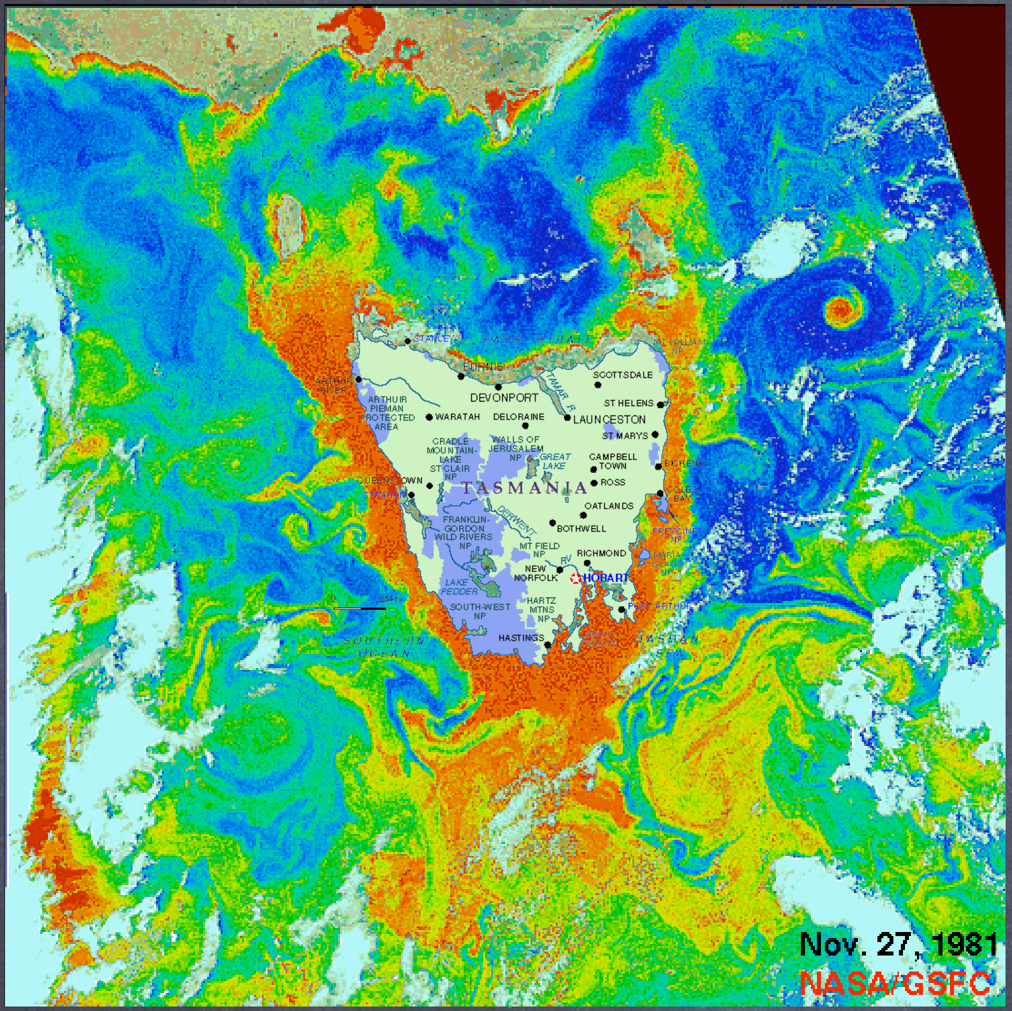


1km x 1km x 40m
sub-domain
about 1 day shown

movie credit:
P. Hamlington

P. E. Hamlington, L. P. Van Roekel, BFK, K. Julien, and G. P. Chini. Langmuir-submesoscale interactions: Descriptive analysis of multiscale frontal spin-down simulations. Journal of Physical Oceanography, 44(9):2249-2272, September 2014.

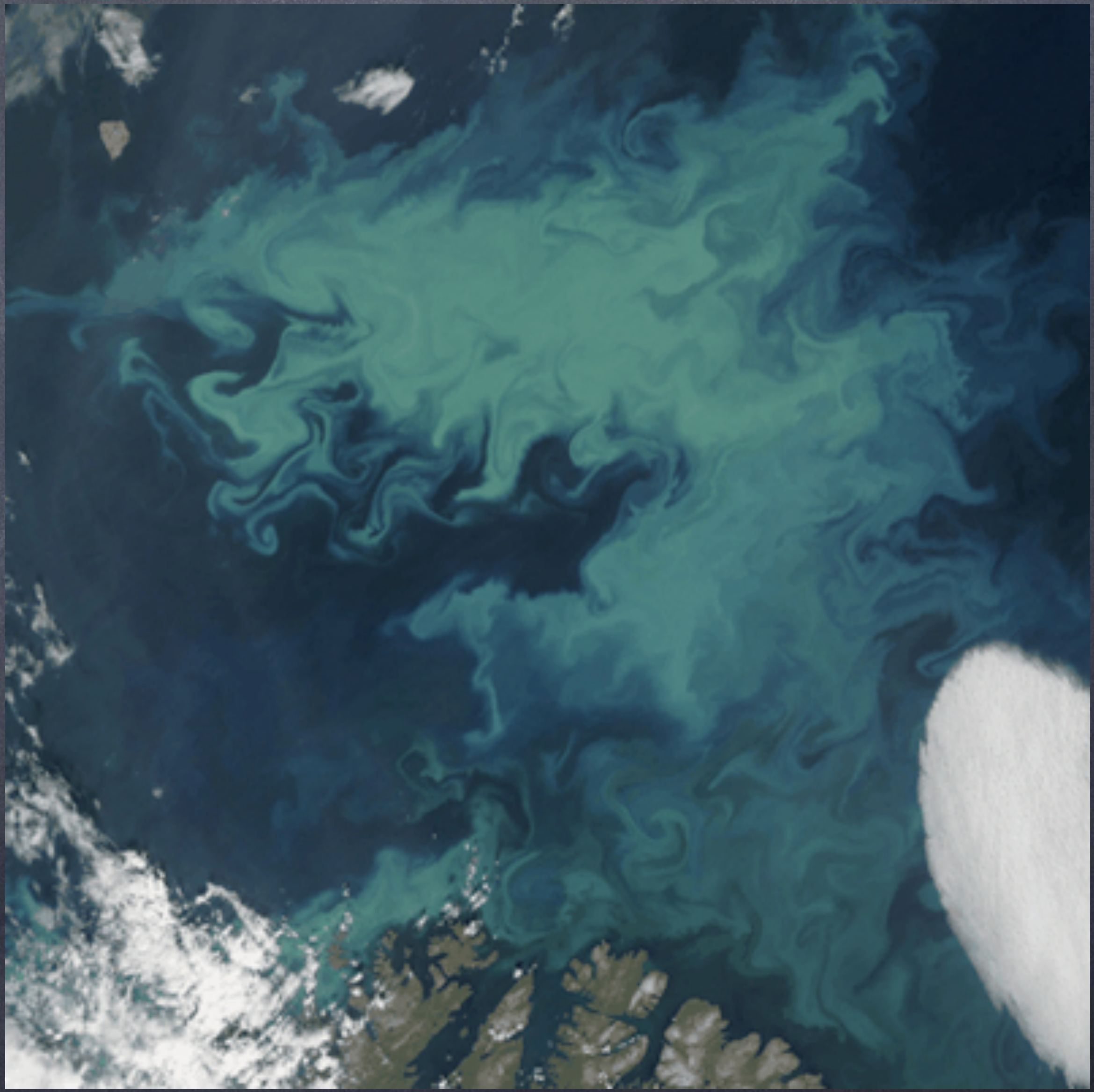
Biological Reactions?



Ocean color image showing submesoscale structure in chlorophyll concentration near Tasmania

100 km

A. Thompson, Caltech

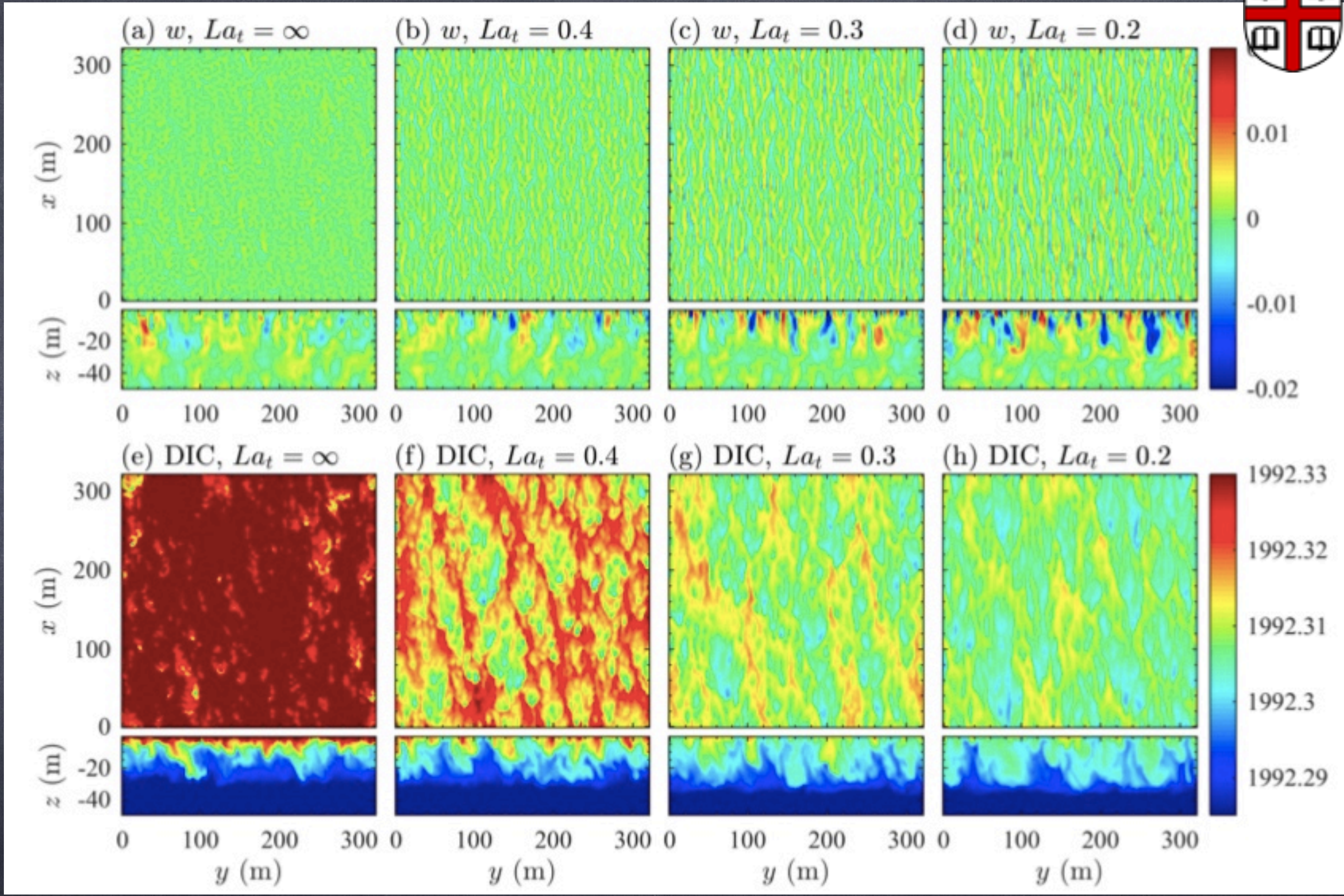


Vert. velocity of typical submesoscale eddies:
> 20 m/day

Submesoscale-Biology Damkoelher = 1

Chemical Reactions?

Vert. velocity of typical Langmuir: >30 m/hr



Boundary Layer-Chemistry Damkoelher near 1

K. M. Smith, P. E. Hamlington, K. E. Niemeyer, B. Fox-Kemper, and N. S. Lovenduski. Effects of Langmuir turbulence on upper ocean carbonate chemistry. Geophysical Research Letters, March 2018. Submitted.

Nesting/Overlapping

- Simulate global down to 3D LES in 4-5 single-scale nestings, each 1 teragrid (10^{12} space+time units)

- Subgrid schemes for these scales are optimized—avoiding grey zones. We have developed scale-aware versions across these scales (ILES is a start)

- If a simulation spans more than one scale, the simulations are much more expensive (but more meaningful, O(10-1000 teragrids)).

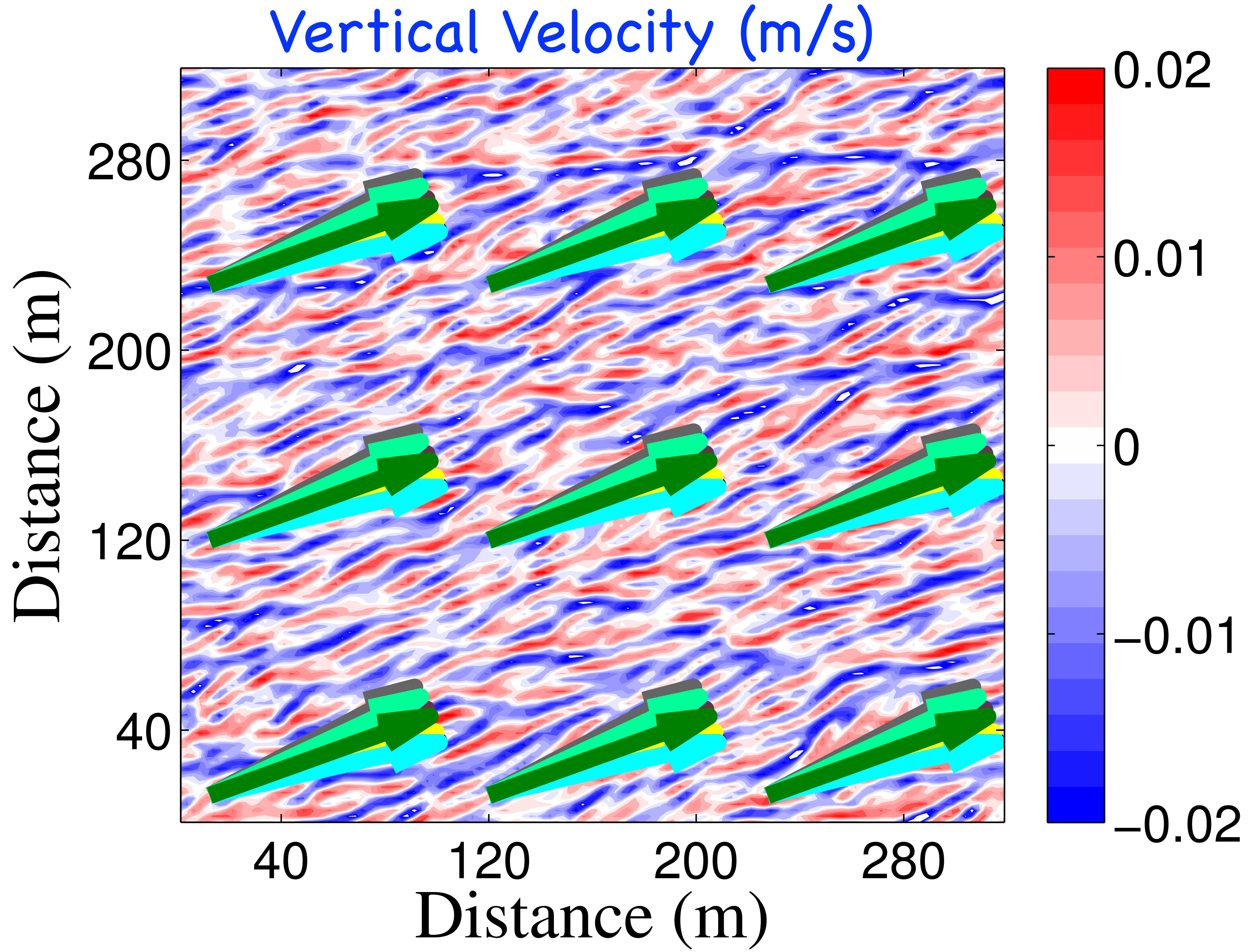
Realistic Forcing Helps Find Right Stuff...

- Examples of what we didn't see coming...
- But occurred naturally when considering realistic forcing.

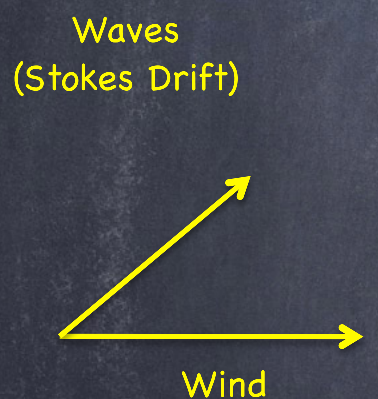
Discovered a new regime for LES, when trying to couple LES results into climate models: Misaligned Wind & Waves

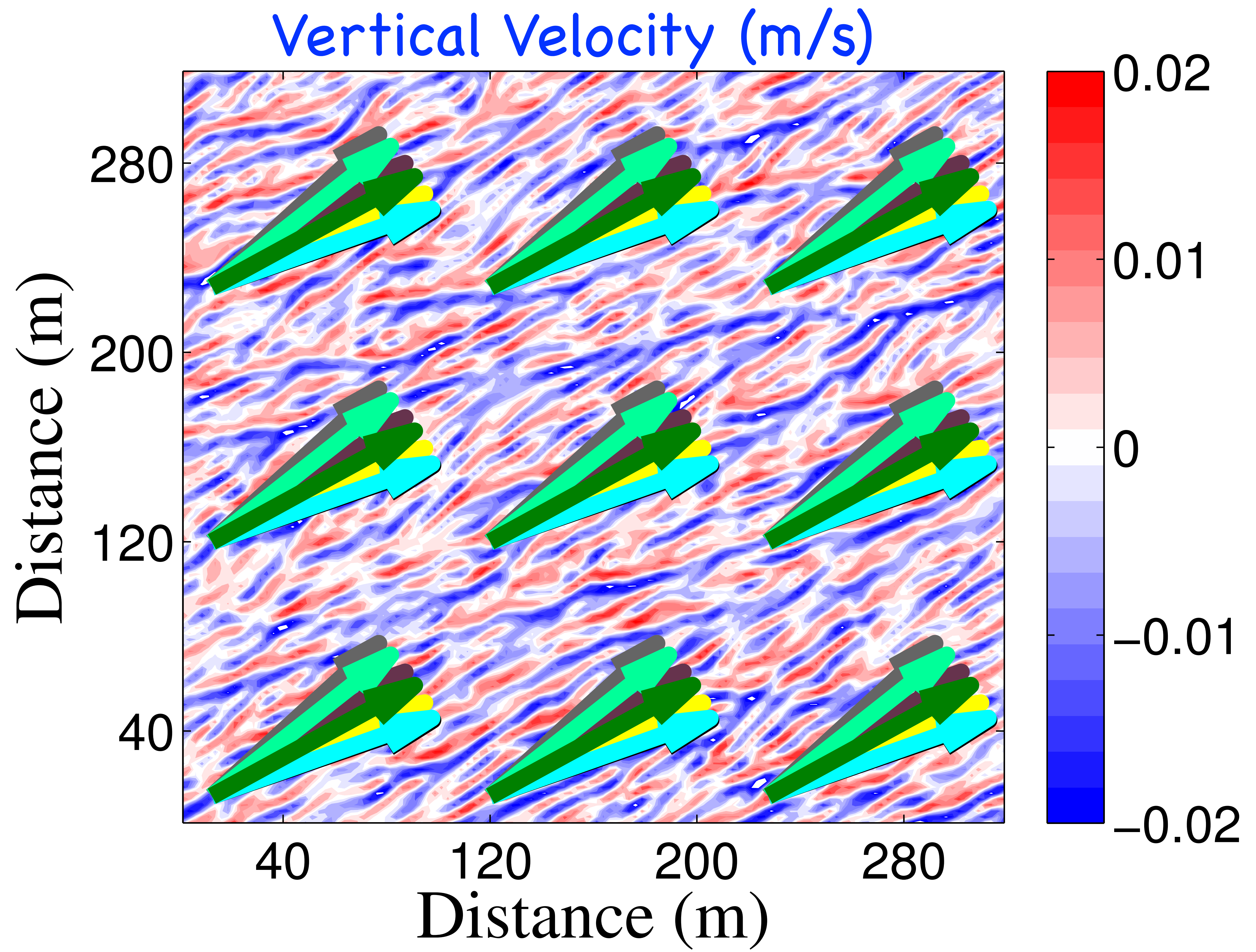
A. Webb and BFK. Impacts of wave spreading and multidirectional waves on estimating Stokes drift. Ocean Modelling, 96(1): 49-64, December 2015.

L. P. Van Roekel, BFK, 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, May 2012.



Tricky: Misaligned Wind & Waves





L. P. Van Roekel, BFK, 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, May 2012.

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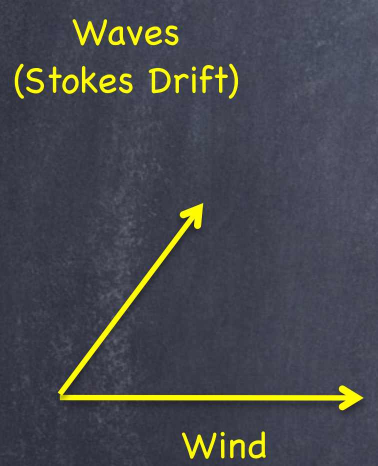

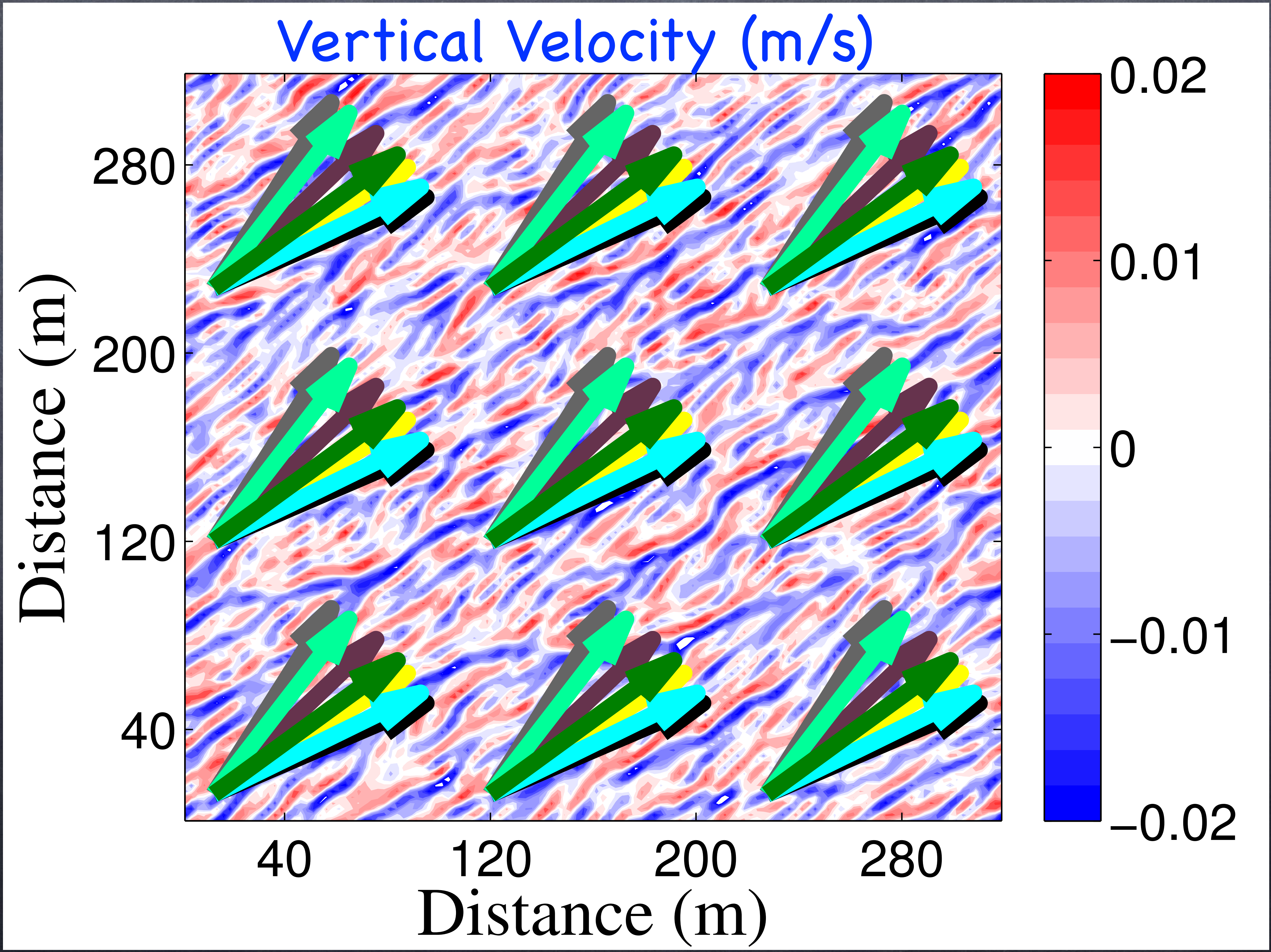

L. P. Van Roekel, BFK, P. P. Sullivan, P. E. Hamlington, and S. R. Haney. The form and orientation of Langmuir cells for misaligned winds and waves. Journal of Geophysical Research-Oceans, 117:C05001, 22pp, May 2012.

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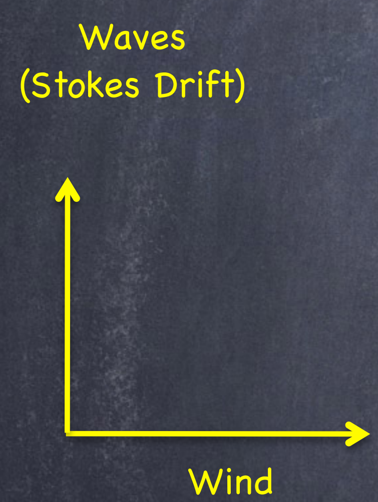
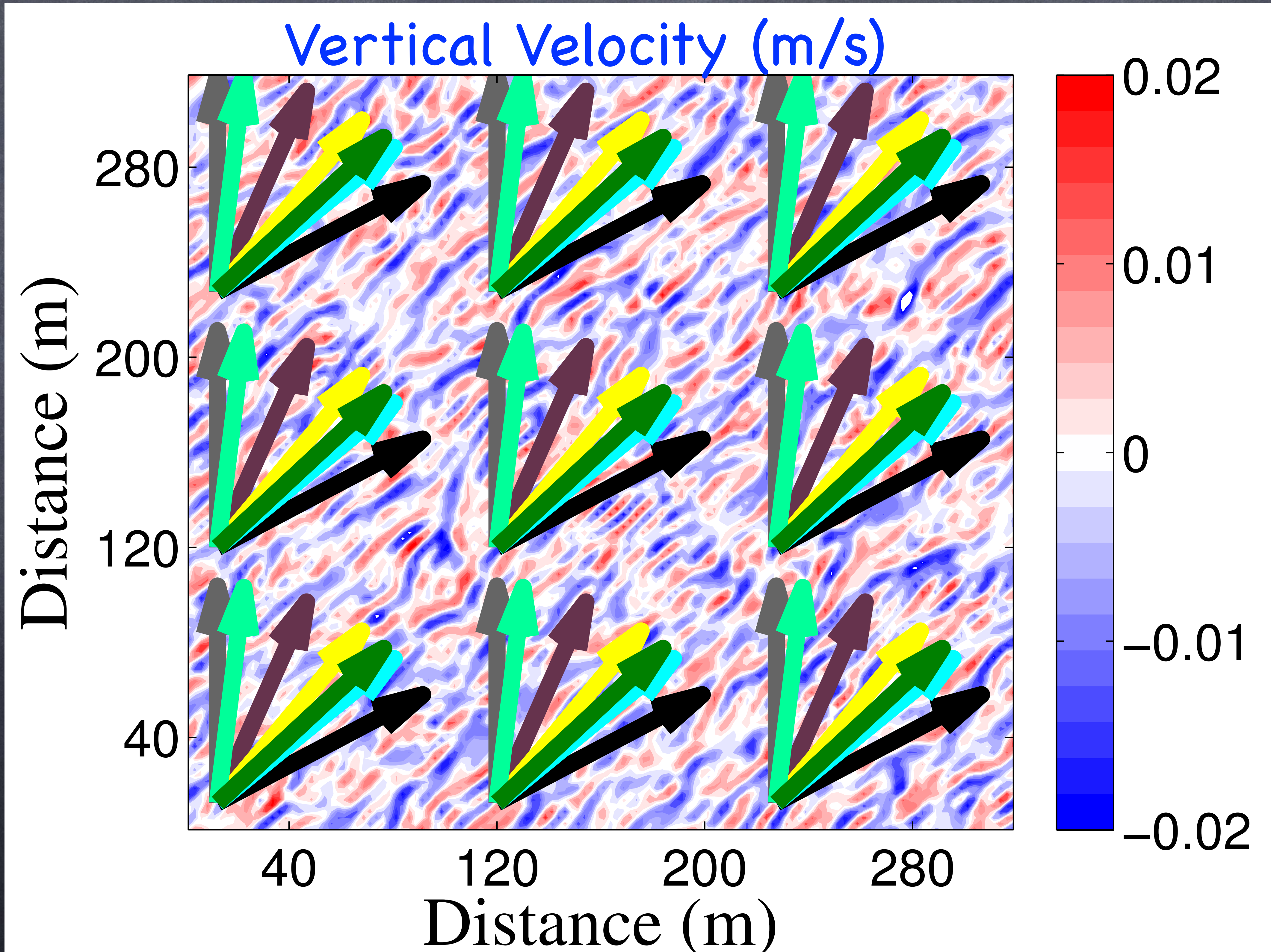
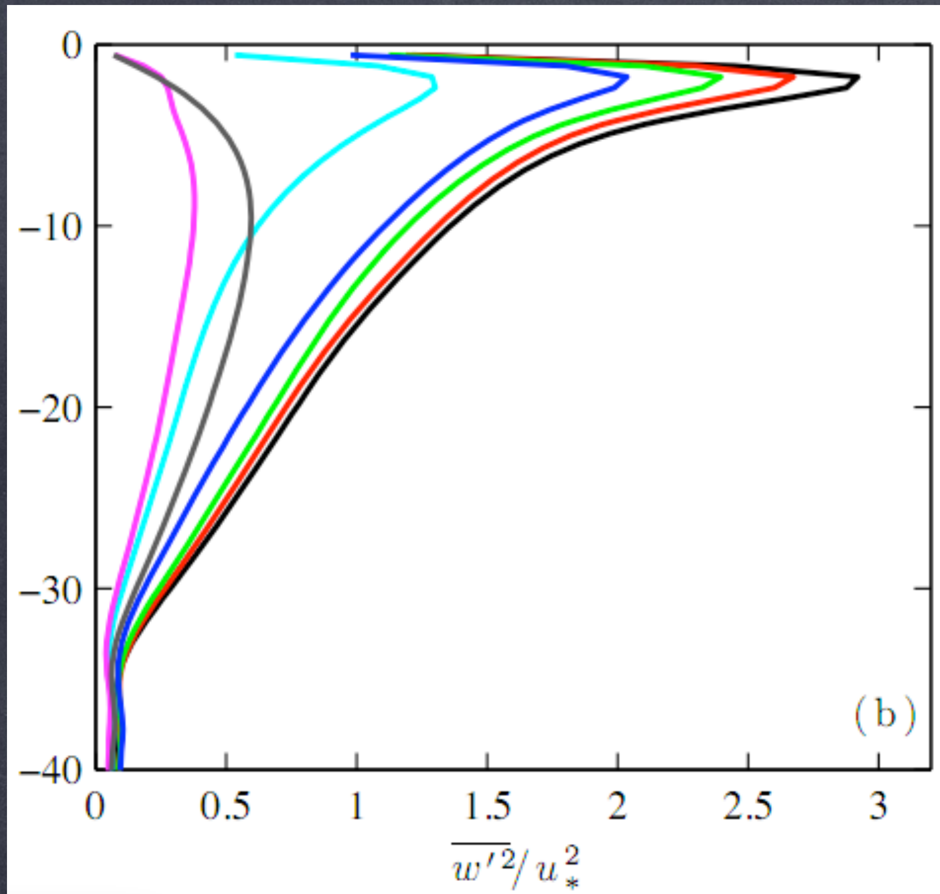




L. P. Van Roekel, BFK, P. P. Sullivan, P. E. Hamlington, and S. R. Haney. The form and orientation of Langmuir cells for misaligned winds and waves. Journal of Geophysical Research-Oceans, 117:C05001, 22pp, May 2012.

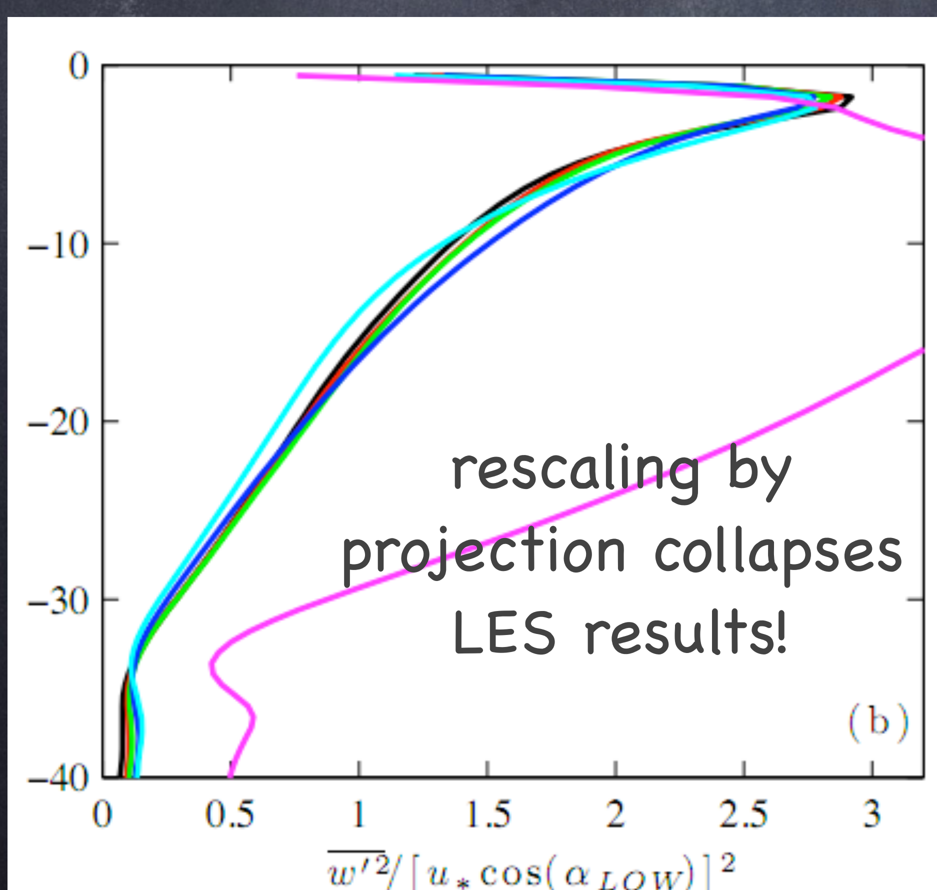
<w^2>

depth



rescaled <w^2>

depth



Generalized Turbulent Parameter (Langmuir Number)

Projection of u*, u_s into Langmuir Direction

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

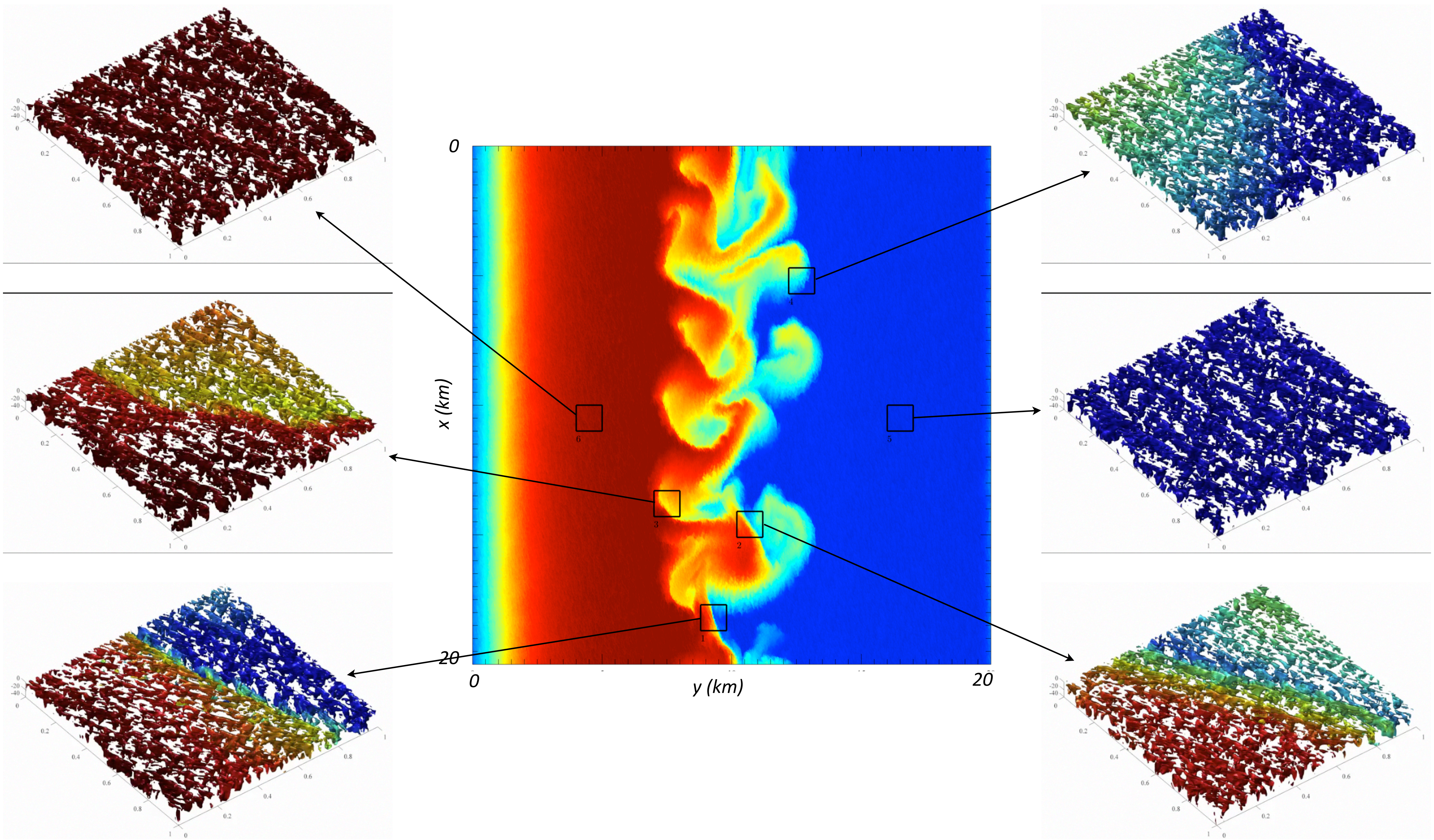
A scaling for LC strength & direction!
Enough for climate model application

L. P. Van Roekel, BFK, 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.

Discovery Territory…

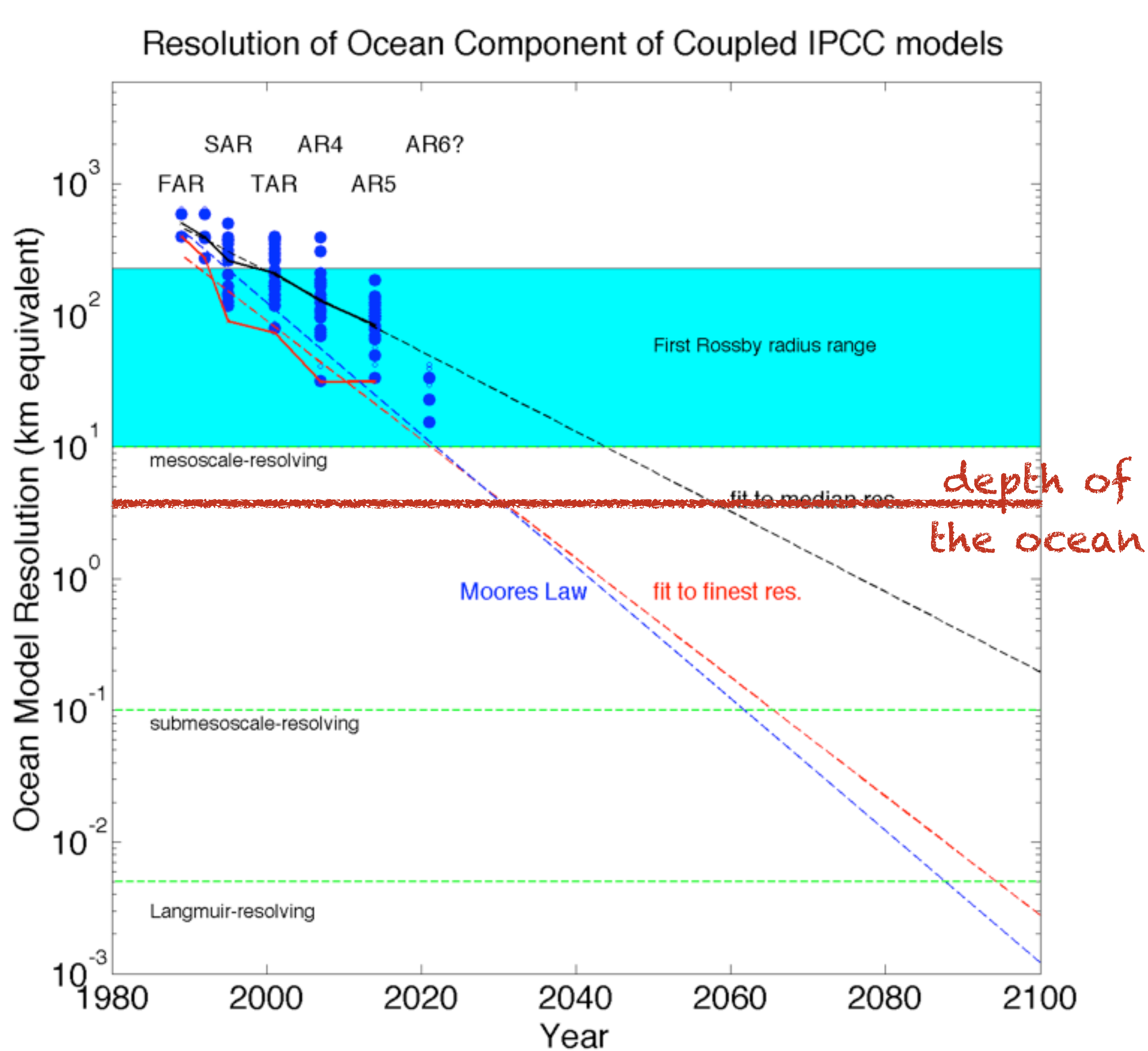
- Examples of what we didn’t see coming…
- But dominate in multi scale simulations.

Boundary Layer-Submeso Interactions, without parameterizing revealed nontrivial/ countergradient/novel interactions PLUS wave effects directly on submesoscale



P. E. Hamlington, L. P. Van Roekel, BFK, K. Julien, and G. P. Chini. Langmuir-submesoscale interactions: Descriptive analysis of multiscale frontal spin-down simulations. Journal of Physical Oceanography, 44(9): 2249-2272, September 2014.

Climate Model Resolution: an issue for centuries to come!

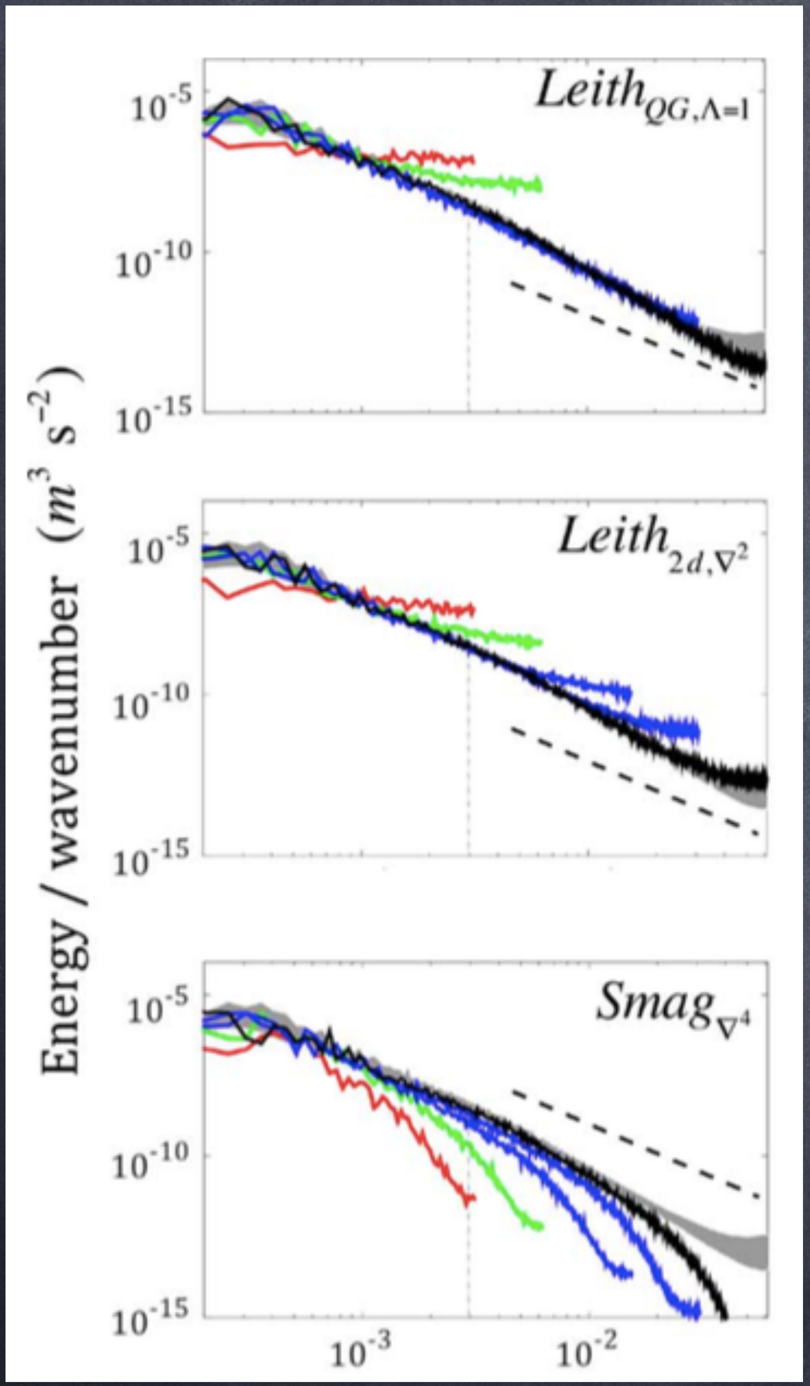


Here are the collection of IPCC models...

If we can't resolve a process, we need to develop a parameterization or subgrid model of its effect

Where does ocean energy go?

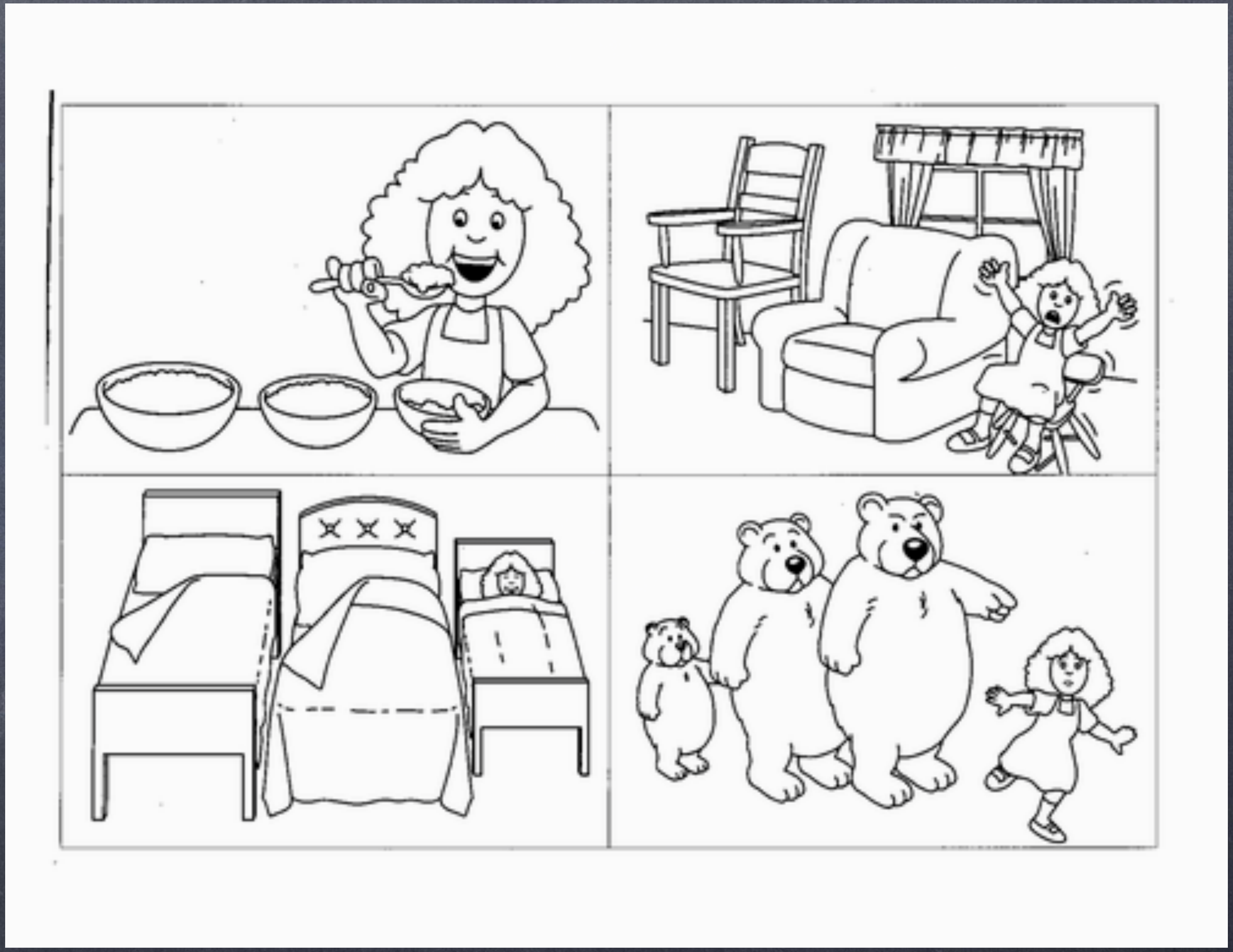
Spectrally speaking



QGLeith:
Just Right!

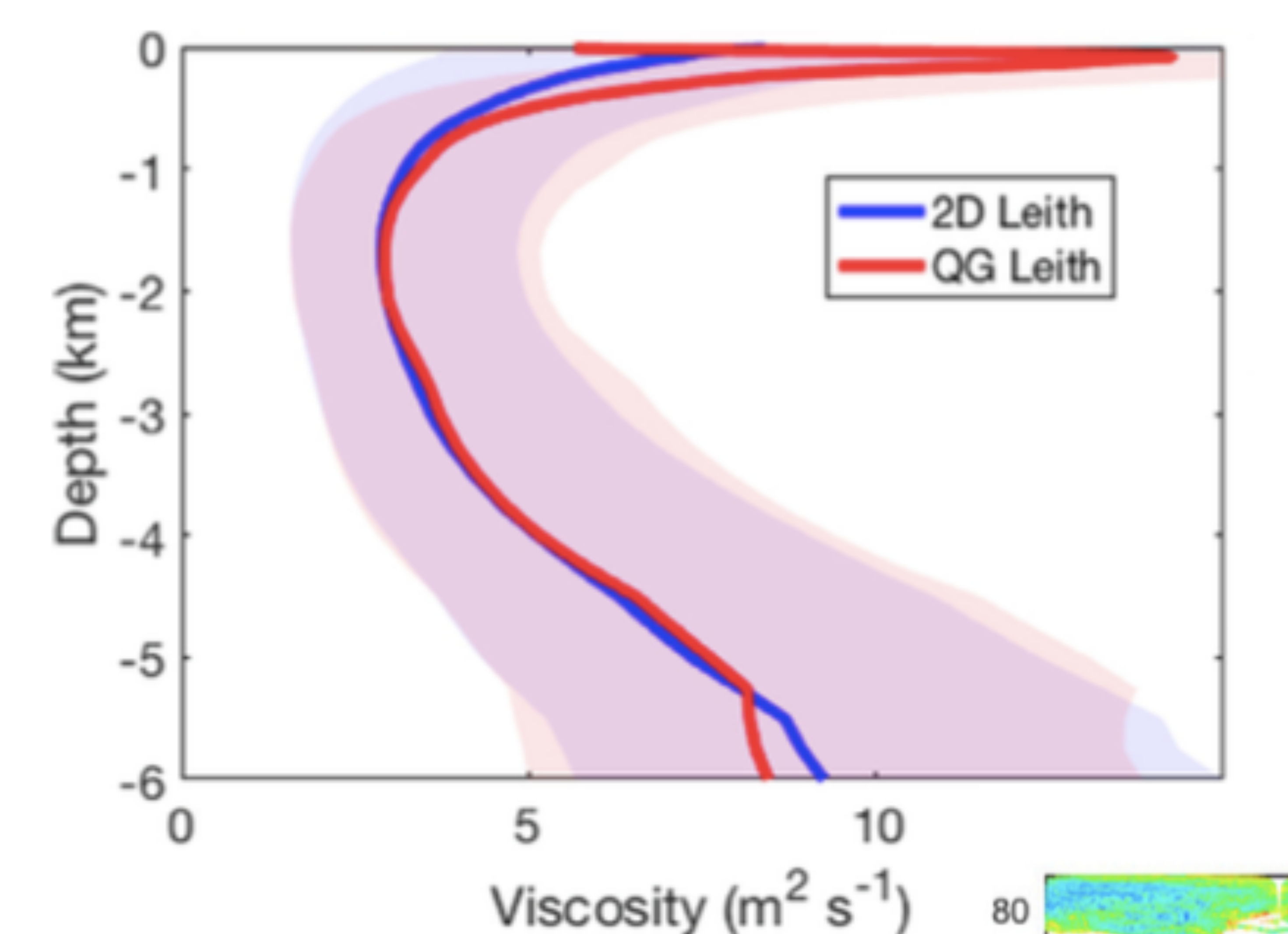
2DLeith:
Too Noisy

Smagorinsky
(3D):
Too Smooth

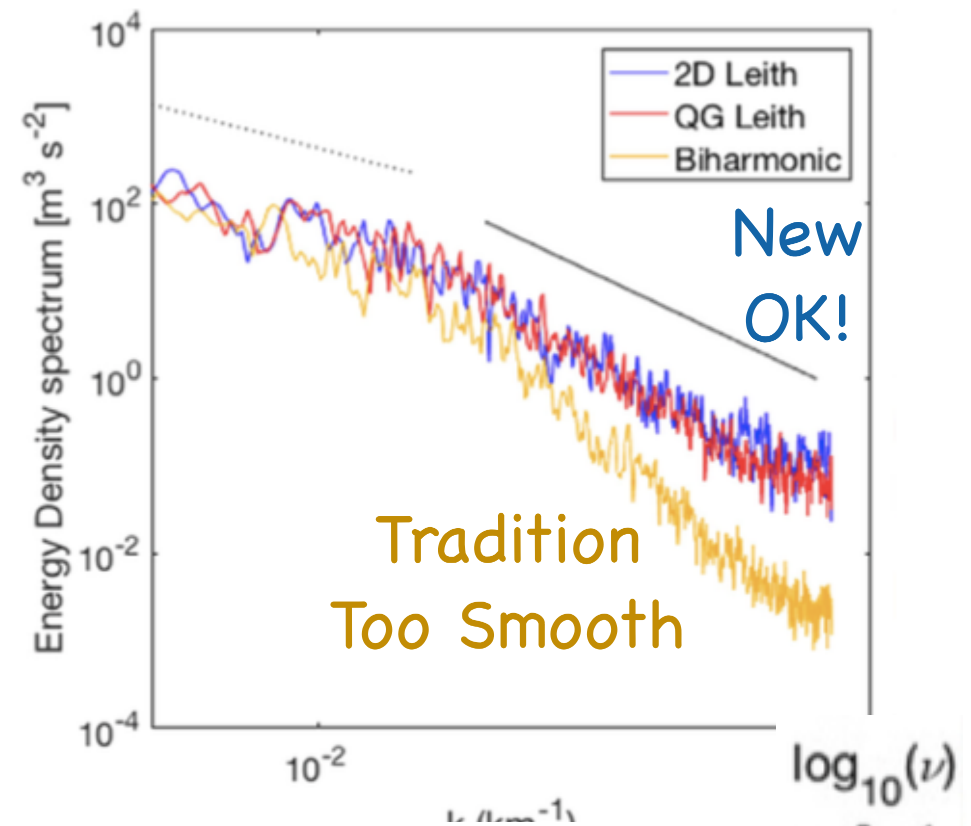


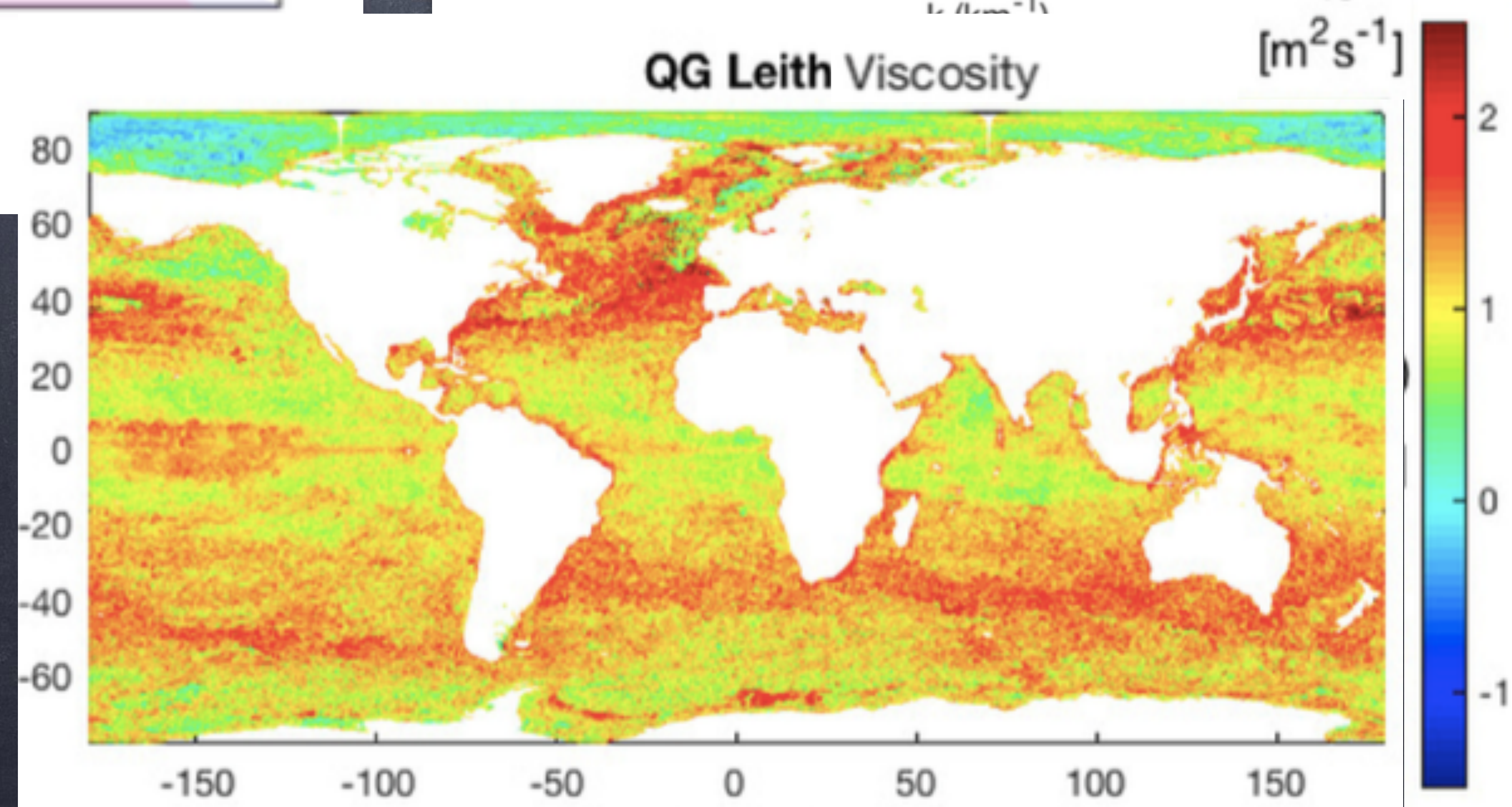
S. D. Bachman, B. Fox-Kemper, and B. Pearson, 2017: A scale-aware subgrid model for quasi- geostrophic turbulence. Journal of Geophysical Research–Oceans, 122:1529–1554. URL http: //dx.doi.org/10.1002/2016JC012265.

A QGLeith global model!



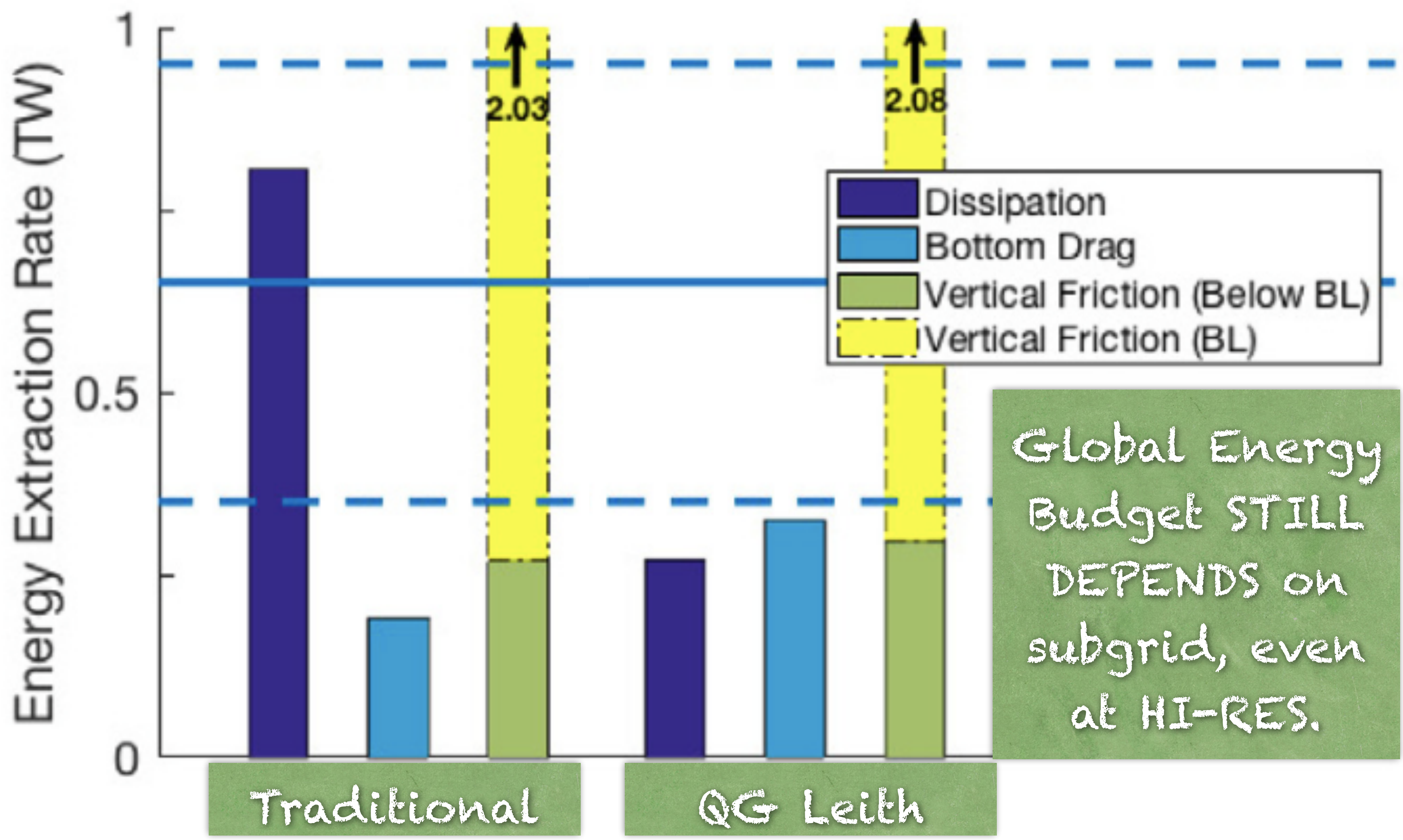
ACC in Global!





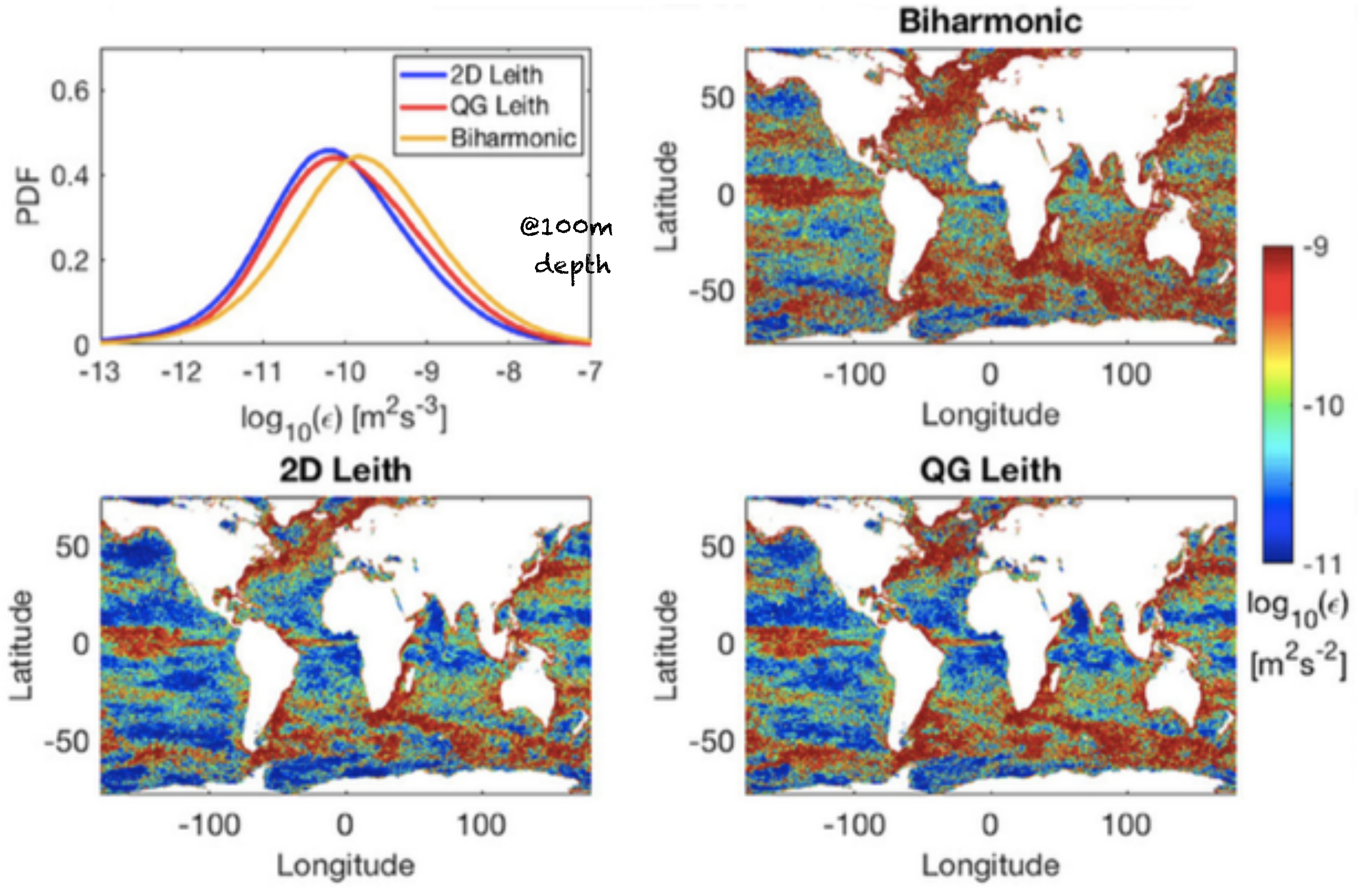
S. D. Bachman, BFK, and B. Pearson, 2017: A scale-aware subgrid model for quasi-geostrophic turbulence. Journal of Geophysical Research–Oceans, 122:1529–1554.

B. Pearson, BFK, S. D. Bachman, and F. O. Bryan, 2017: Evaluation of scale-aware subgrid mesoscale eddy models in a global eddy-rich model. Ocean Modelling, 115:42–58.



B. Pearson, BFK, S. D. Bachman, and F. O. Bryan, 2017: Evaluation of scale-aware subgrid mesoscale eddy models in a global eddy-rich model. Ocean Modelling, 115:42–58.

Lognormally distributed—AND knows where the Gulf Stream is!



MOLES: Log-Normal Dissipation Intermittency

Lognormally distributed

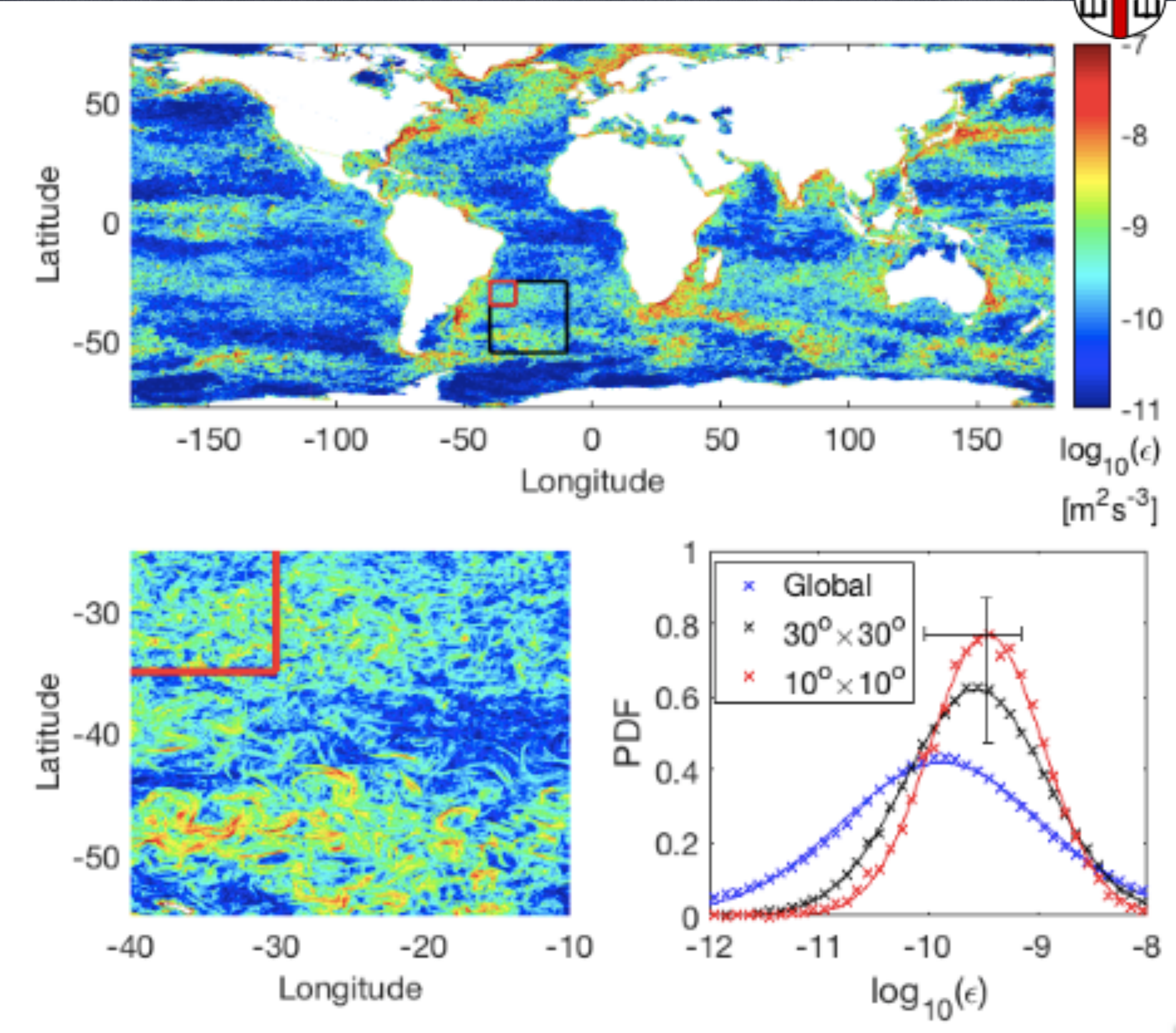
(super-Yaglom '66)

Hard to Observe:

90% of KE dissipation in 10% of ocean

Multiplicative rather than additive stochastics

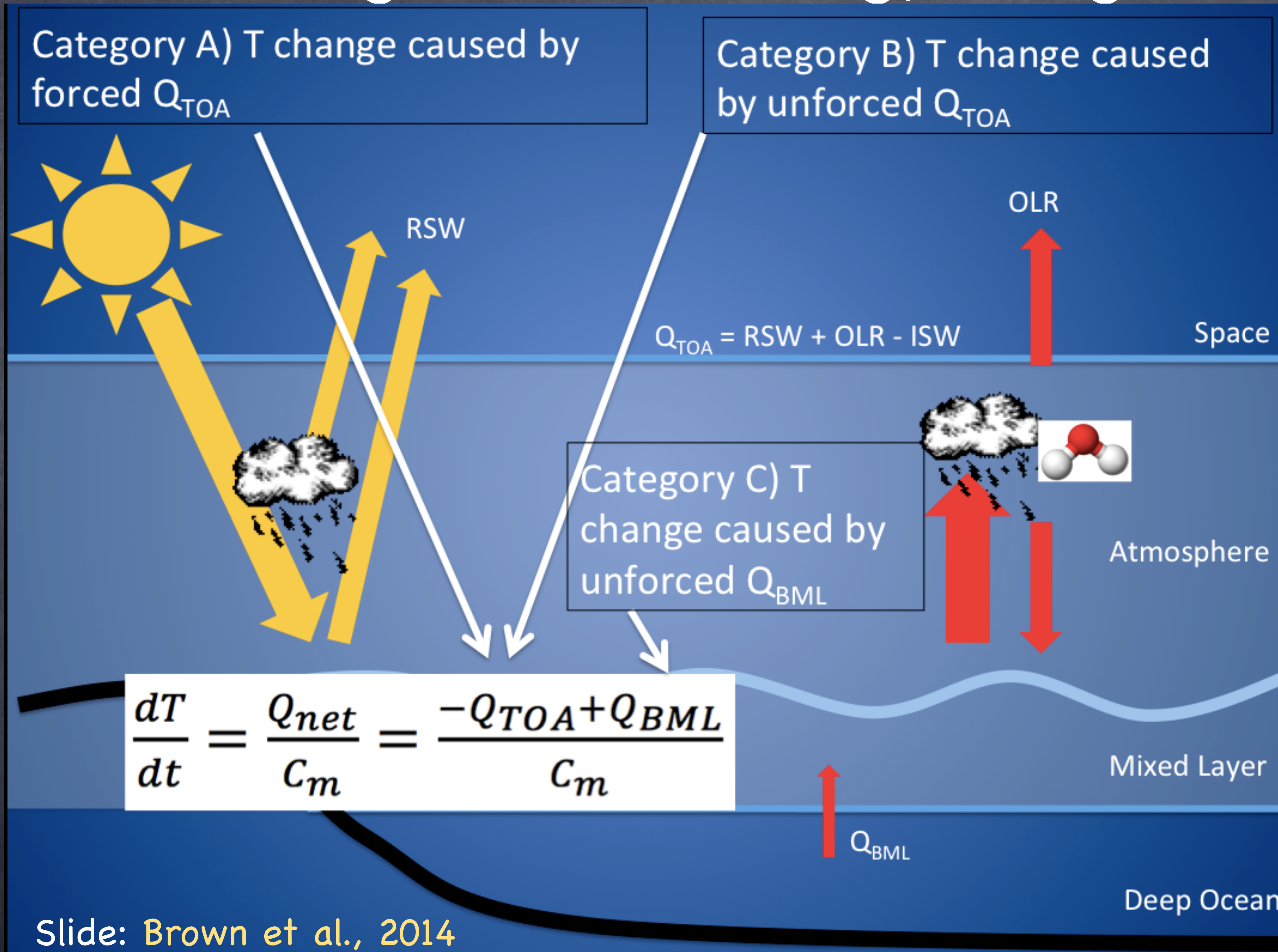
B. Pearson and BFK. Log-normal turbulence dissipation in global ocean models. Physical Review Letters, 120(9): 094501, March 2018.



Observations—check the statistics carefully!

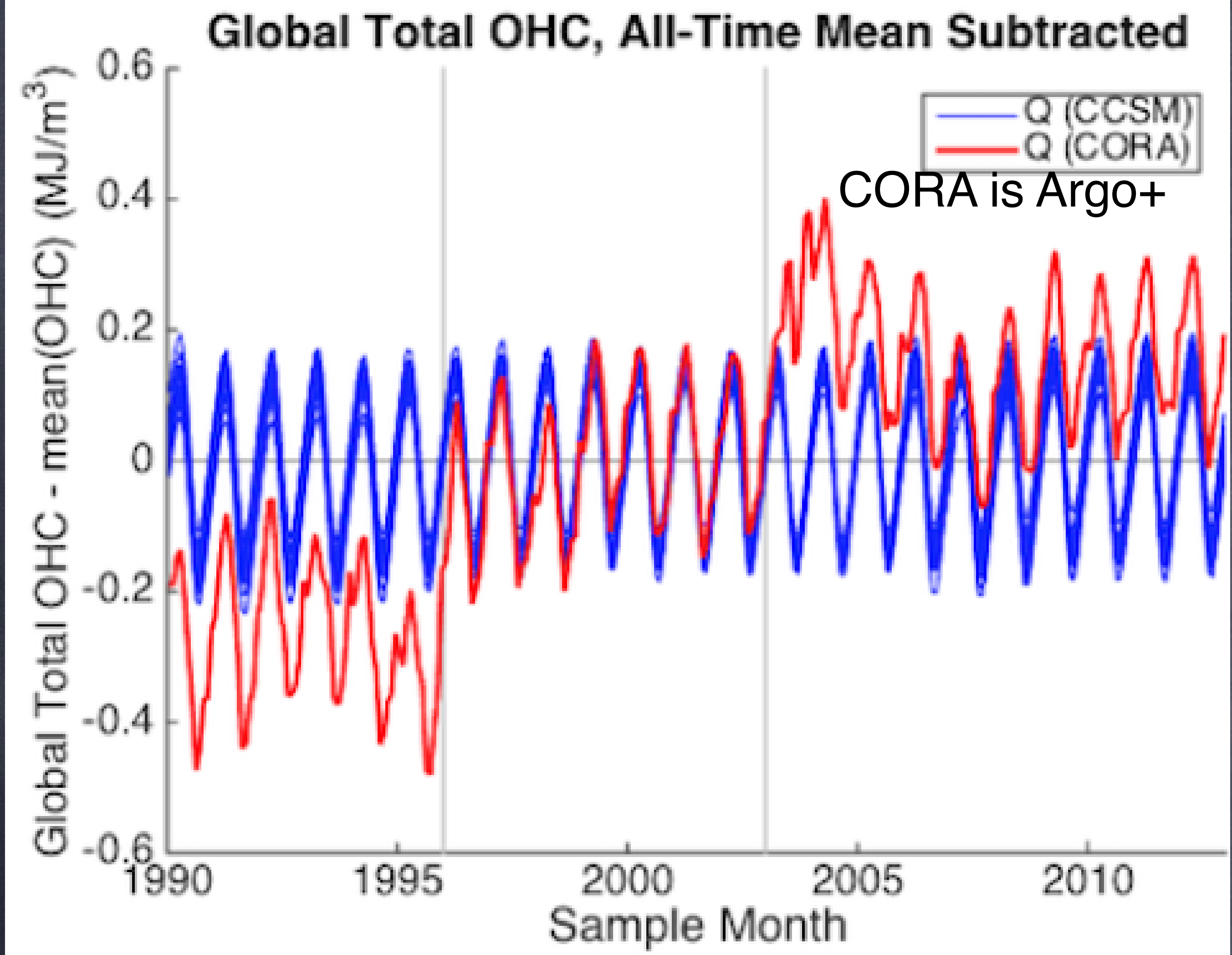
- Ocean observations are hard & expensive
- We rarely have enough info to make inferences without intervening or sophisticated models

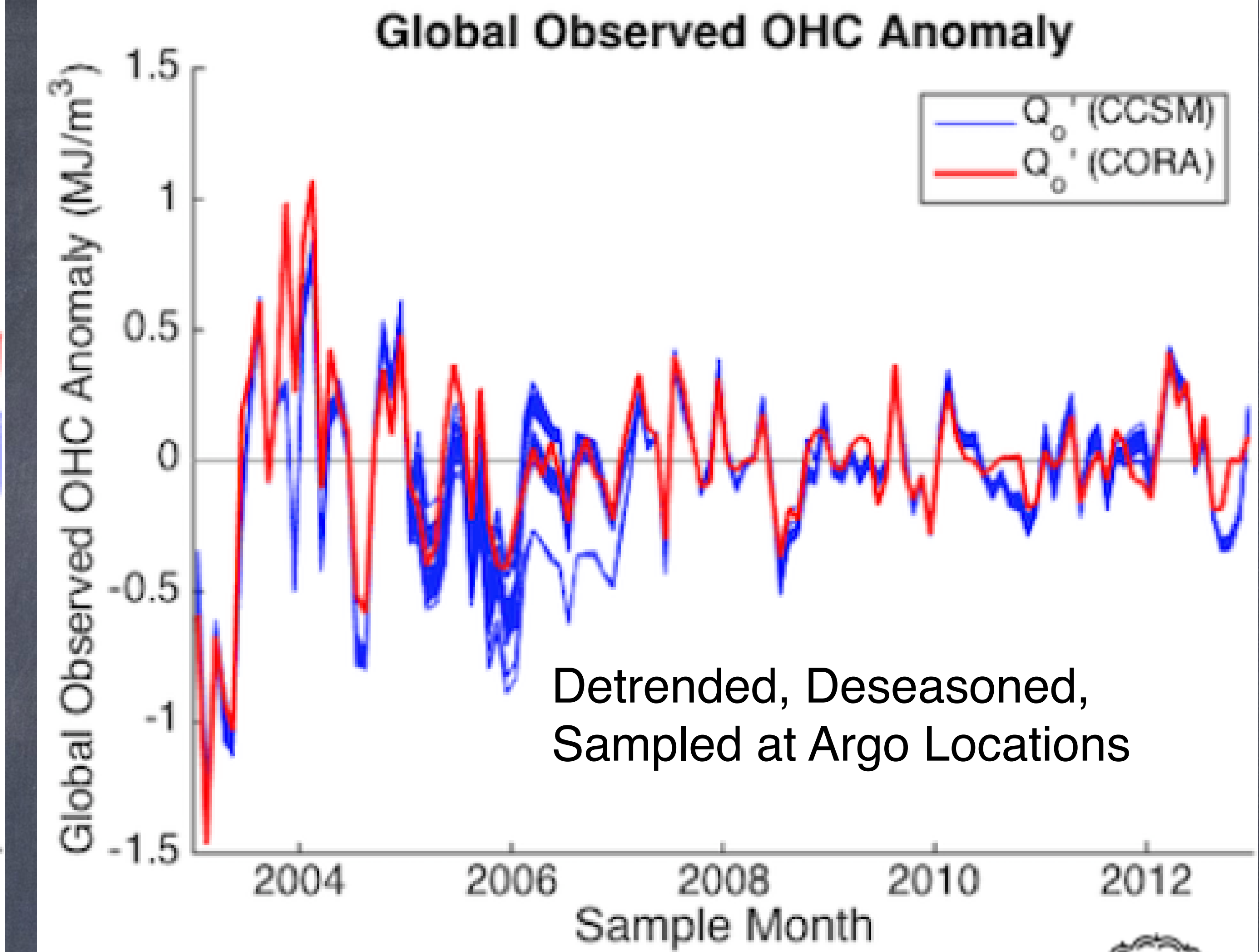
Observing Surface Energy Budget?



Slide: Brown et al., 2014

- O(2W/m²) change to Q_{BML} as important as GHG





Sophisticated analysis req'd to overcome Ship & Argo sampling problems—inherent uncertainty, O(0.2W/m²), on interannual timescales in global average.

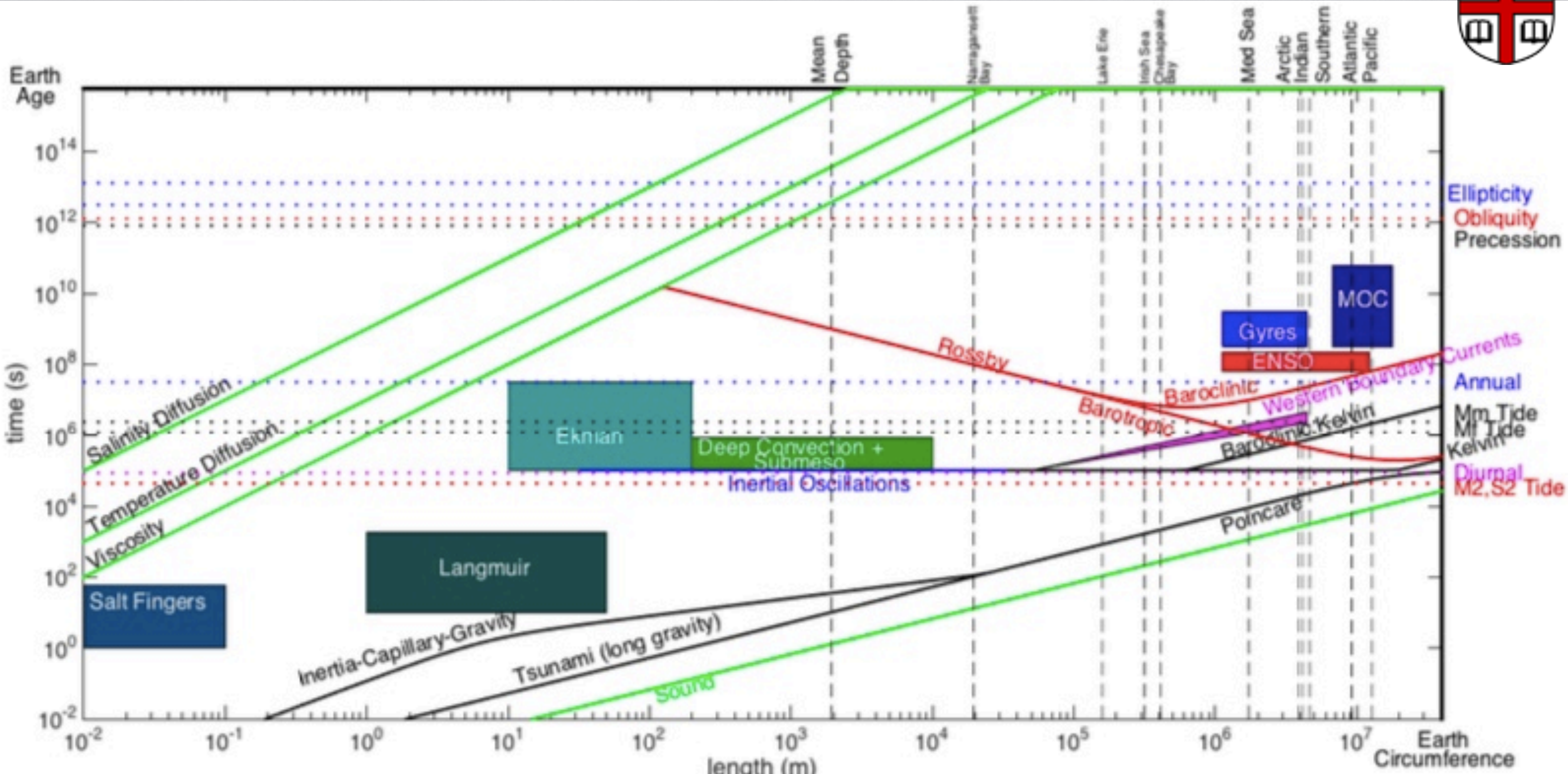
O(10W/m²) without sophisticated interpolation analysis.

Nelson, A. D., Weiss, J., BFK, B., Zia, R. K. P., and Gaillard, F.: An Ensemble Observing System Simulation Experiment of Global Ocean Heat Content Variability, Ocean Sci. Discuss., http://sci-hub.tw/10.5194/os-2016-105.

Thoughts

- Nesting/Refining is a powerful tool, but…
- Understanding & flexibility needed:
- We think we've got everything, but
  - Submesoscale unexpected—important globally
  - Langmuir observed, but not implemented—important globally
- It's still hard to discover automatically
  - Wave-front interaction unexpected—potentially important
  - Mesoscale lognormality unexpected—affects parameterizations, observations, energy budgets at leading order
- Realistic forcing helps point out oversights
  - Submesoscale-boundary interaction misunderstood & hard to model
  - Wave-wind misalignment unexpected—important globally
- Direct inference from observations probably not ready in subsurface oceans—sampling too sparse

The Ocean is Vast & Diverse



The climate also depends on atmosphere, cryosphere, biosphere, pedosphere, lithosphere & coupled modes!—

We need models to integrate and explore.

D. B. Haidvogel, E. N. Curchitser, S. Danilov, and BFK. Numerical modelling in a multi-scale ocean (invited). In The Sea: The Science of Ocean Prediction, special issue. Journal of Marine Research, December 2017. In press.

Useful Unit: a Teragrid (10^{12})

- 1024^4: 1024^3 3D spatial & 1024 time-steps
- 400 years of a 350km paleo model
- 5 years of a 100km climate model
- 32 days of a 10km ocean model
- 2 hours of a submesoscale & Langmuir LES

Direct Numerical Simulation at about 10^{35}