Mesoscale Ocean Large Eddy Simulations (MOLES)

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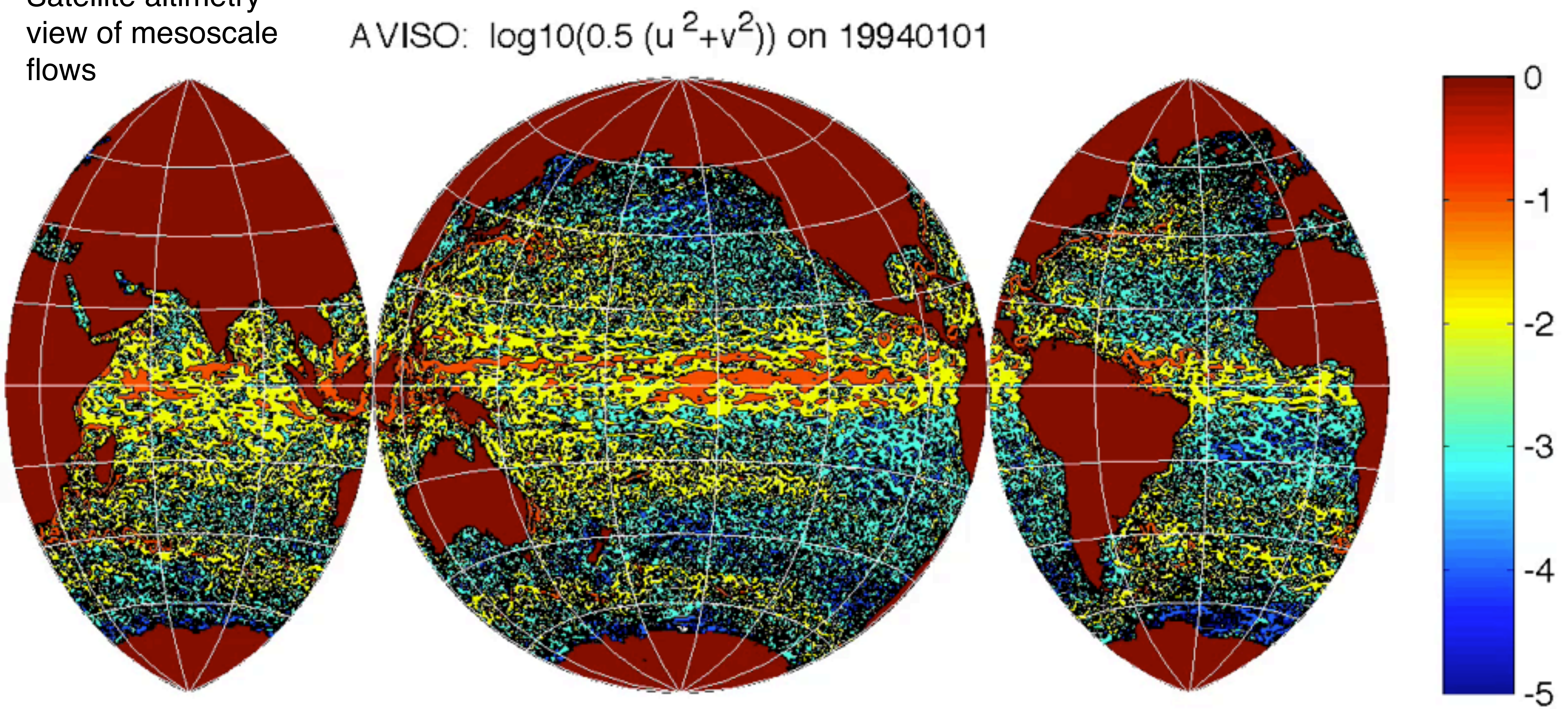
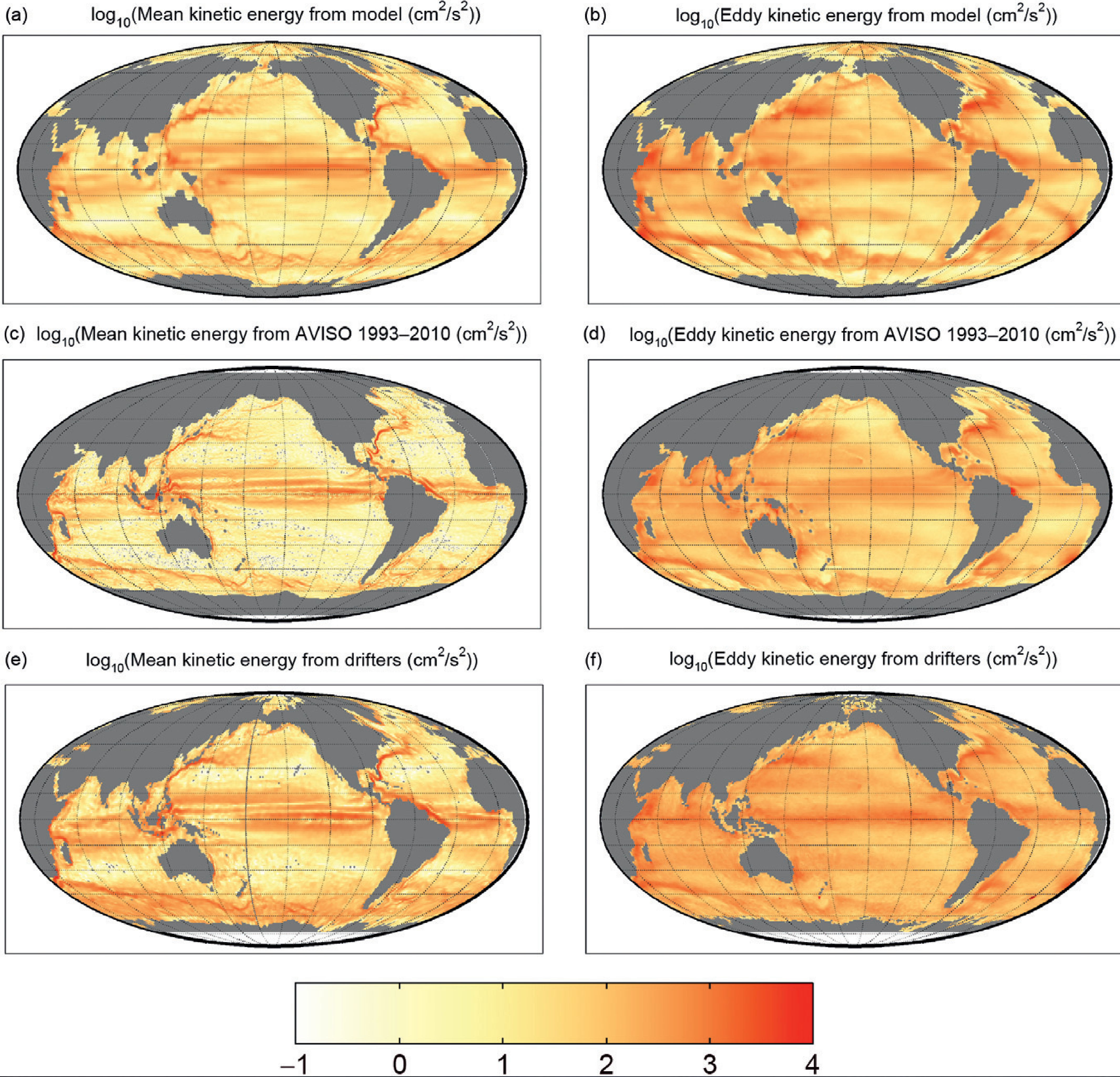
with Brodie Pearson (Brown), Frank O. Bryan (NCAR), and S. Bachman (DAMTP)

UKMO Hadley Centre 4/15/16, Sponsor: NSF 1350795

Satellite altimetry view of mesoscale flows





On cursory analysis, 0.1 degree models do well vs. Satellites and Drifters

B. Fox-Kemper, R. Lumpkin, and F. O. Bryan. Lateral transport in the ocean interior. In G. Siedler, S. M. Griffies, J. Gould, and J. A. Church, editors, Ocean Circulation and Climate: A 21st century perspective, volume 103 of International Geophysics Series, chapter 8, pages 185-209. Academic Press (Elsevier Online), 2013.

But, we know choices are made in models...

- Subgrid parameterizations
  - "Do no harm" vs. "approximate unresolved scales"
- Resolution
  - "Permitting", "Resolving", Etc.

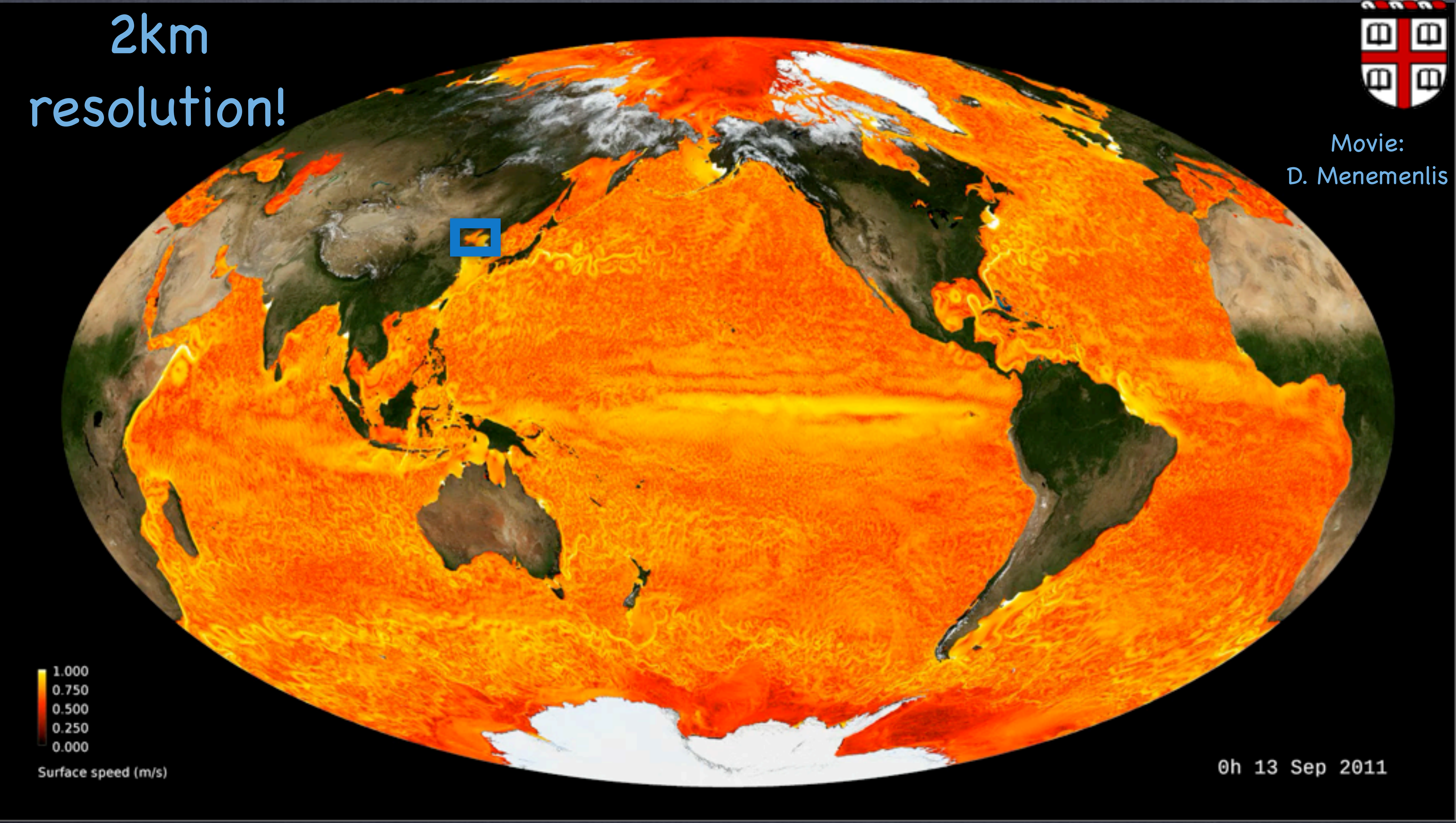
ECCO2 Model

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

LLC4320 Model

2km resolution!

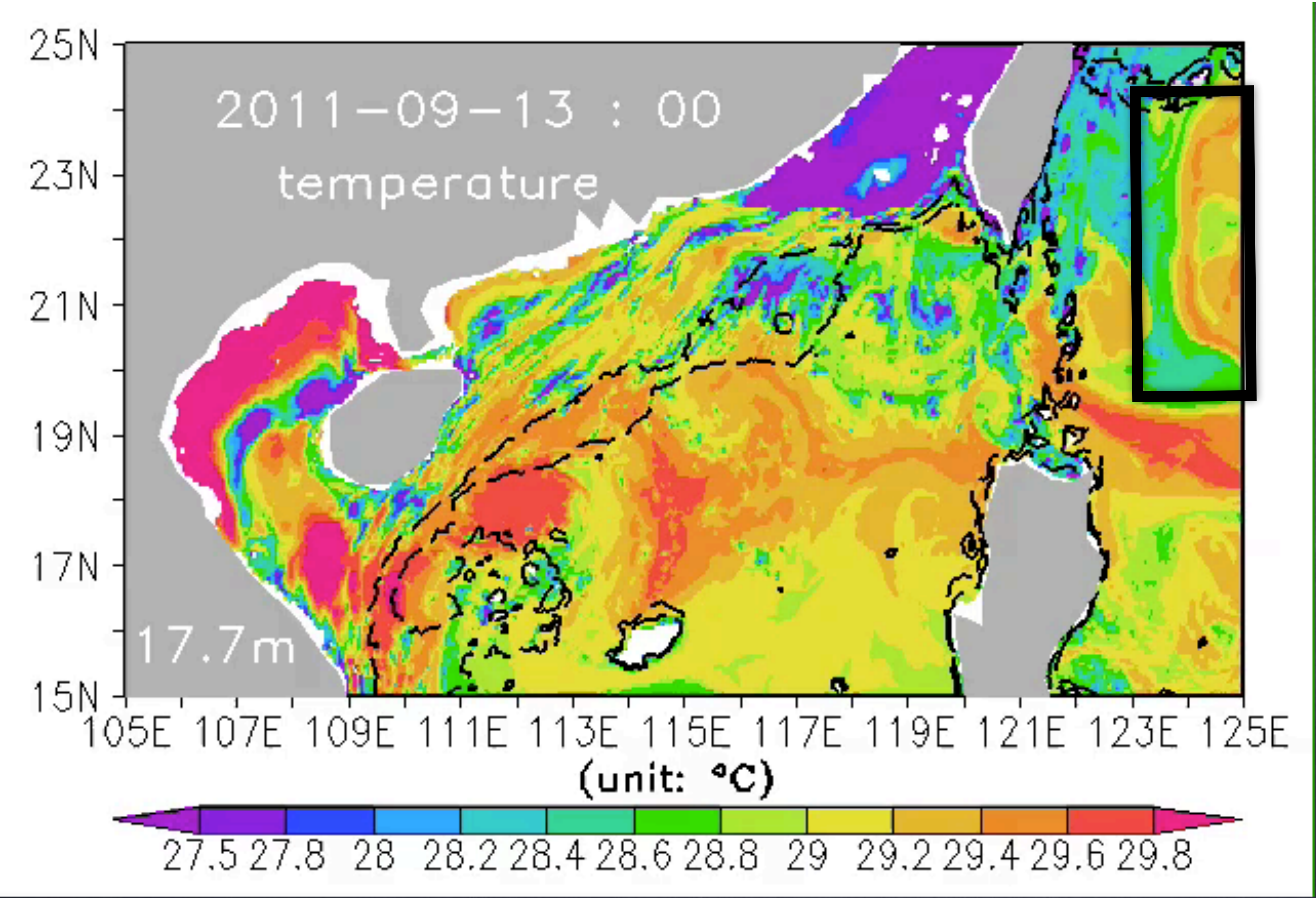


Movie:
D. Menemenlis

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



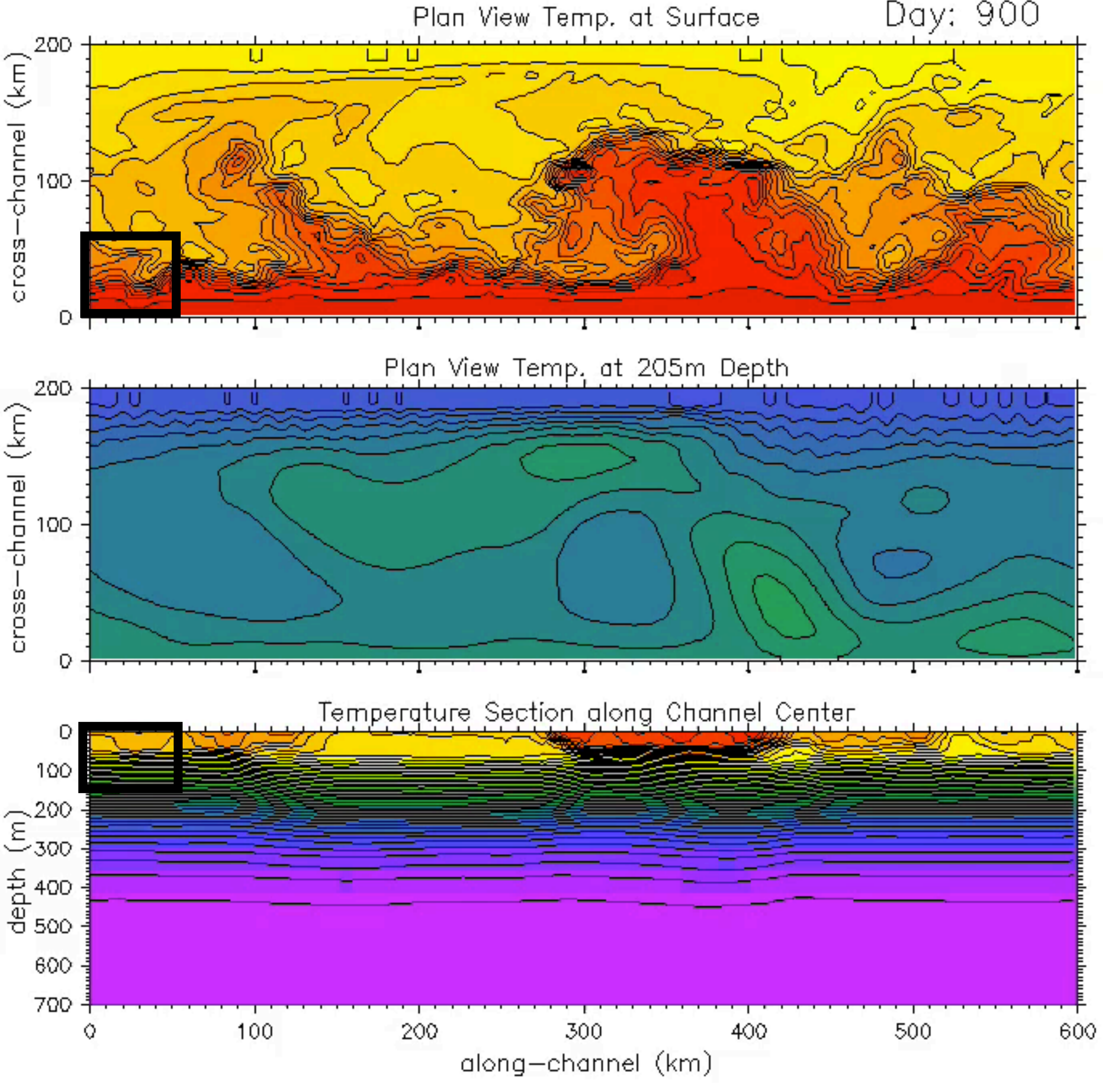
Movie:
Z. Jing

Brown Visitor from S. China Sea Institute of Ocean.

Local Analysis: Z. Jing, Y. Qi, BFK, 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, August 2015. In press.

200km x 600km x 700m domain

1000 Day Simulation



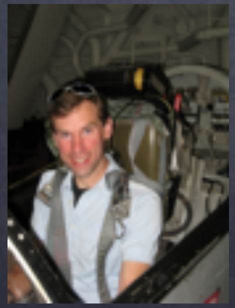
If we lose the globe, much higher resolution!

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

20km x 20km x 150m domain

10 Day Simulation

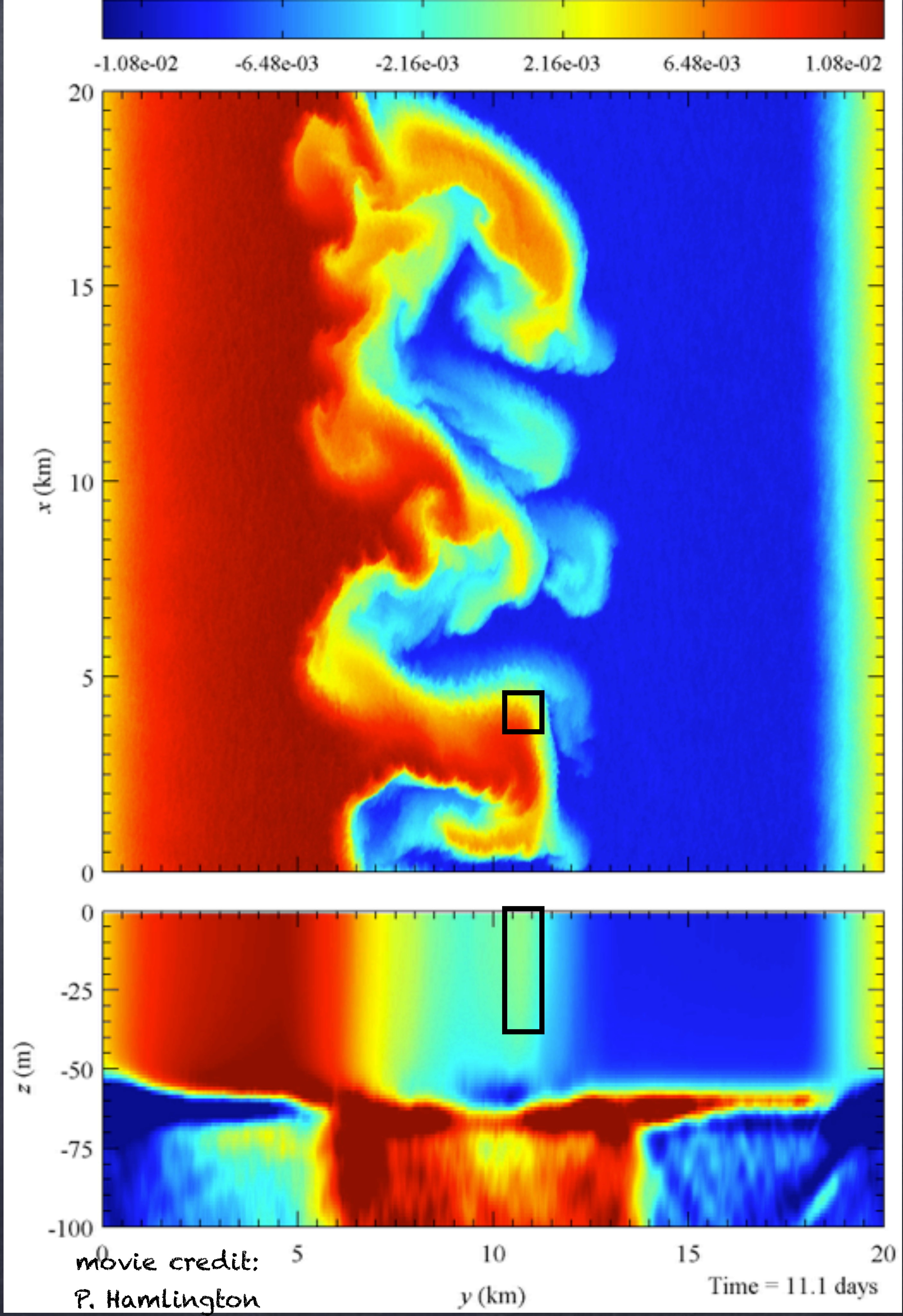
4m x 4m x 1m Resolution



CU, now CU

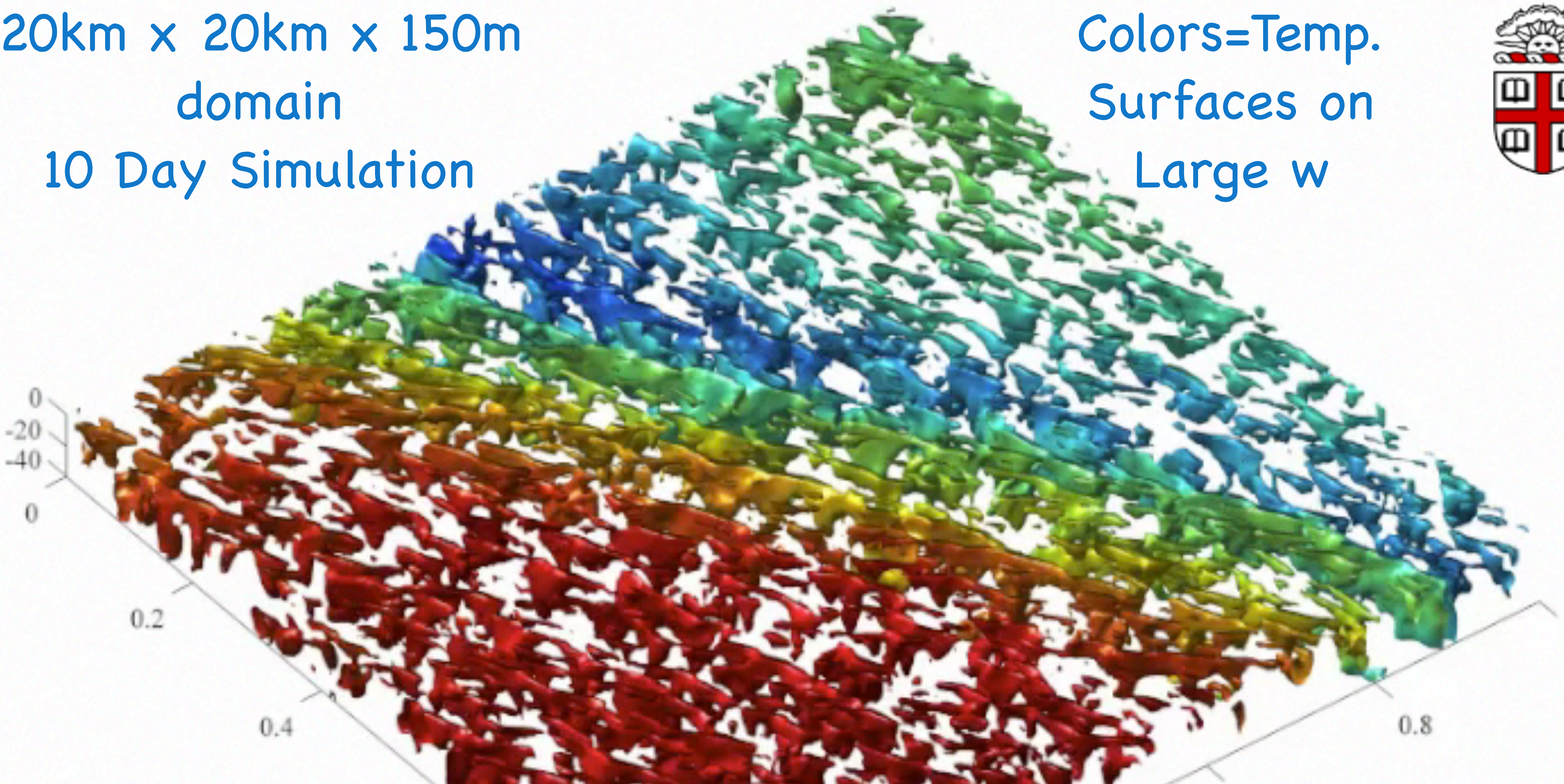
CU, now LANL

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.



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

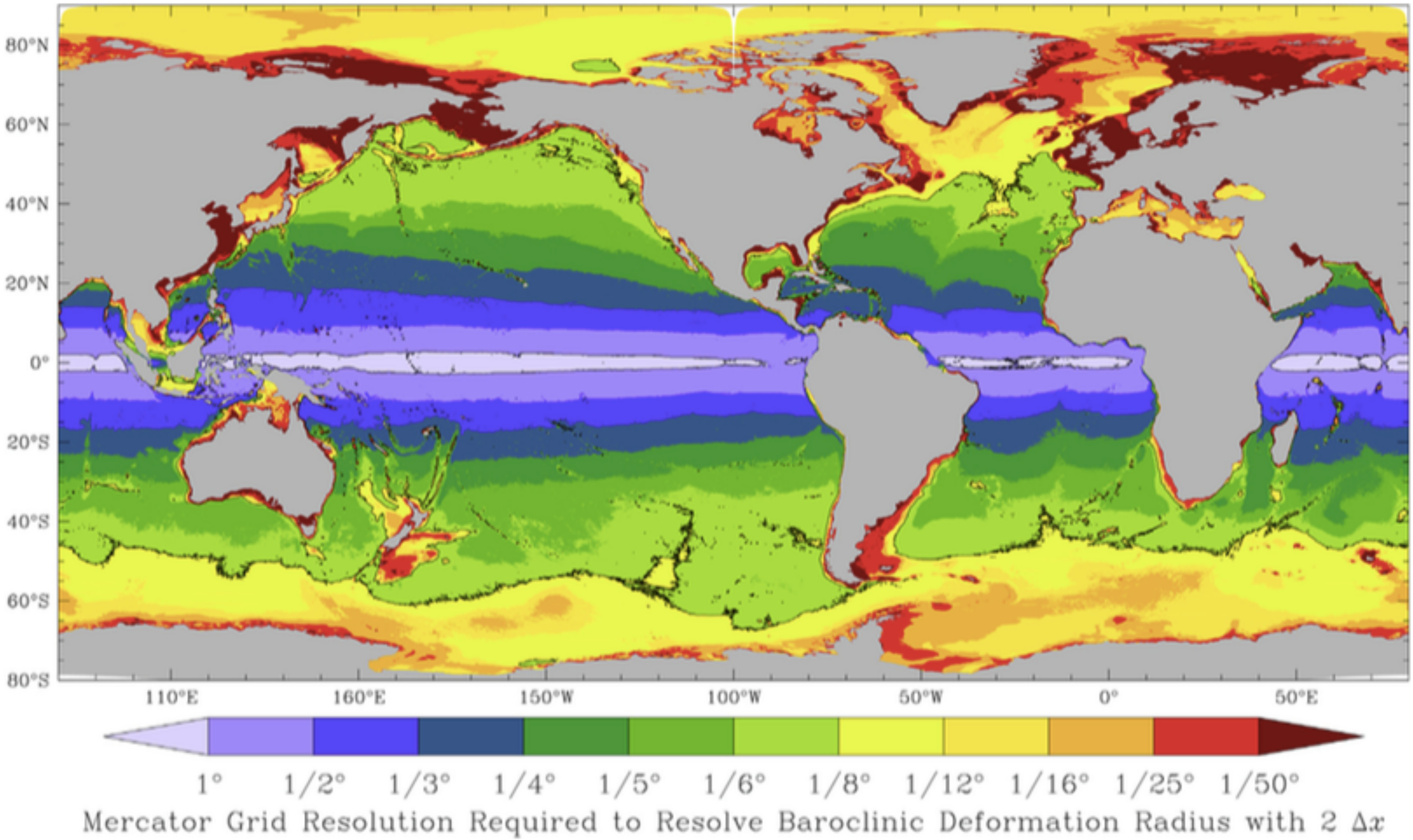
Brown

CU, now CU

CU, now LANL

movie credit:
P. Hamlington

N. Suzuki, BFK, P. E. Hamlington, L. P. Van Roekel. Surface waves affect frontogenesis. JGR-Oceans, 2016, submitted.



- In most places, 0.1 degree resolves the largest deformation radius, plus a bit: Mesoscale Ocean Large Eddy Simulation

Key Concept for

Mesoscale Ocean Large Eddy Simulations (MOLES):

Gridscale* Nondimensional Parameters

Gridscale Reynolds[1]:

$$Re^* = \frac{U^* \Delta x}{\nu^*}$$

Gridscale Péclet[1]:

$$Pe^* = \frac{U^* \Delta x}{\kappa^*}$$

Gridscale Rossby:

$$Ro^* = \frac{U^*}{f \Delta x}$$

Gridscale Richardson:

$$Ri^* = \frac{\Delta {b^*}^2 \Delta z}{\Delta {U^*}^2}$$

Gridscale Burger:

$$Bu^* = \frac{{N^*}^2 \Delta z^2}{f^2 \Delta x^2} \sim {Ro^*}^2 Ri^*$$

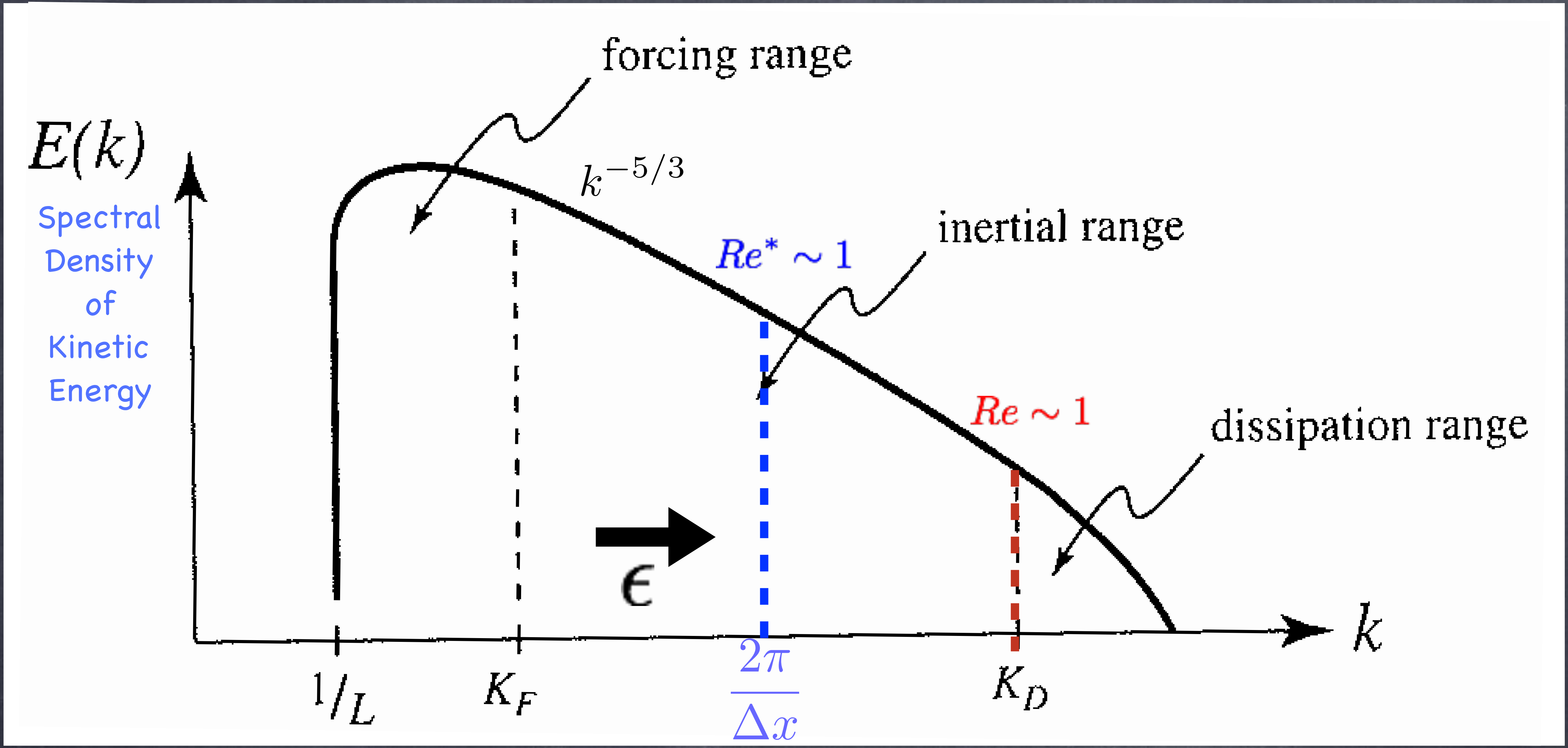
Asterisks denote *resolved* quantities, rather than true values

[1] Gridscale Reynolds and Péclet numbers MUST be O(1) for numerical stability

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.

3D Turbulence Cascade

Kolmogorov, 1941



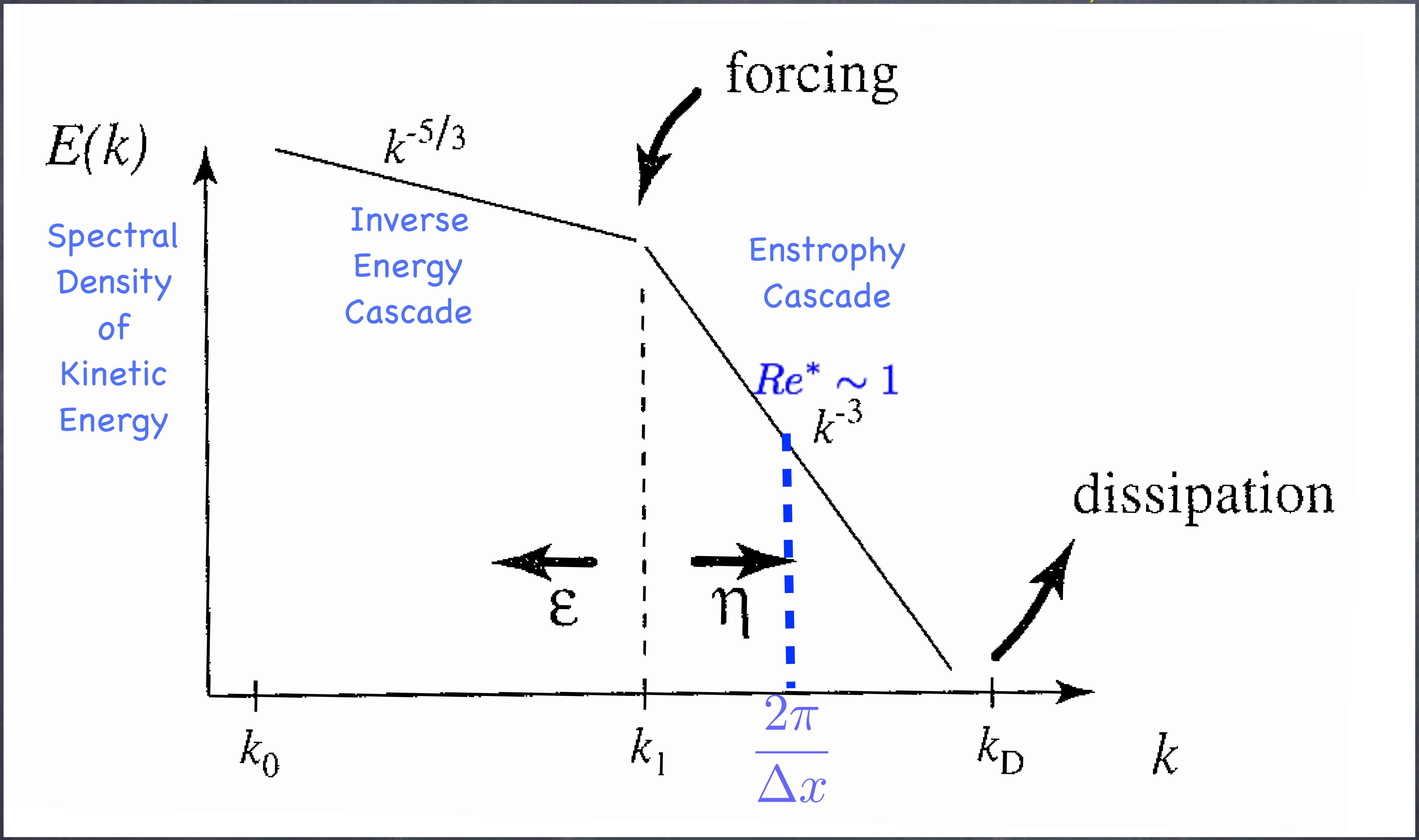
Smagorinsky (1963) Scale & Flow Aware Viscosity Scaling,
So the Energy Cascade is Preserved, and $Re^* = \frac{U^* \Delta x}{\nu^*} = O(1)$

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

$\Upsilon_h \approx 1$

2D Turbulence Differs

R. Kraichnan, 1967 JFM



Leith (1996) Devises Viscosity Scaling,

So that the Enstrophy Cascade is preserved, and $Re^* = \frac{U^* \Delta x}{\nu^*} = O(1)$

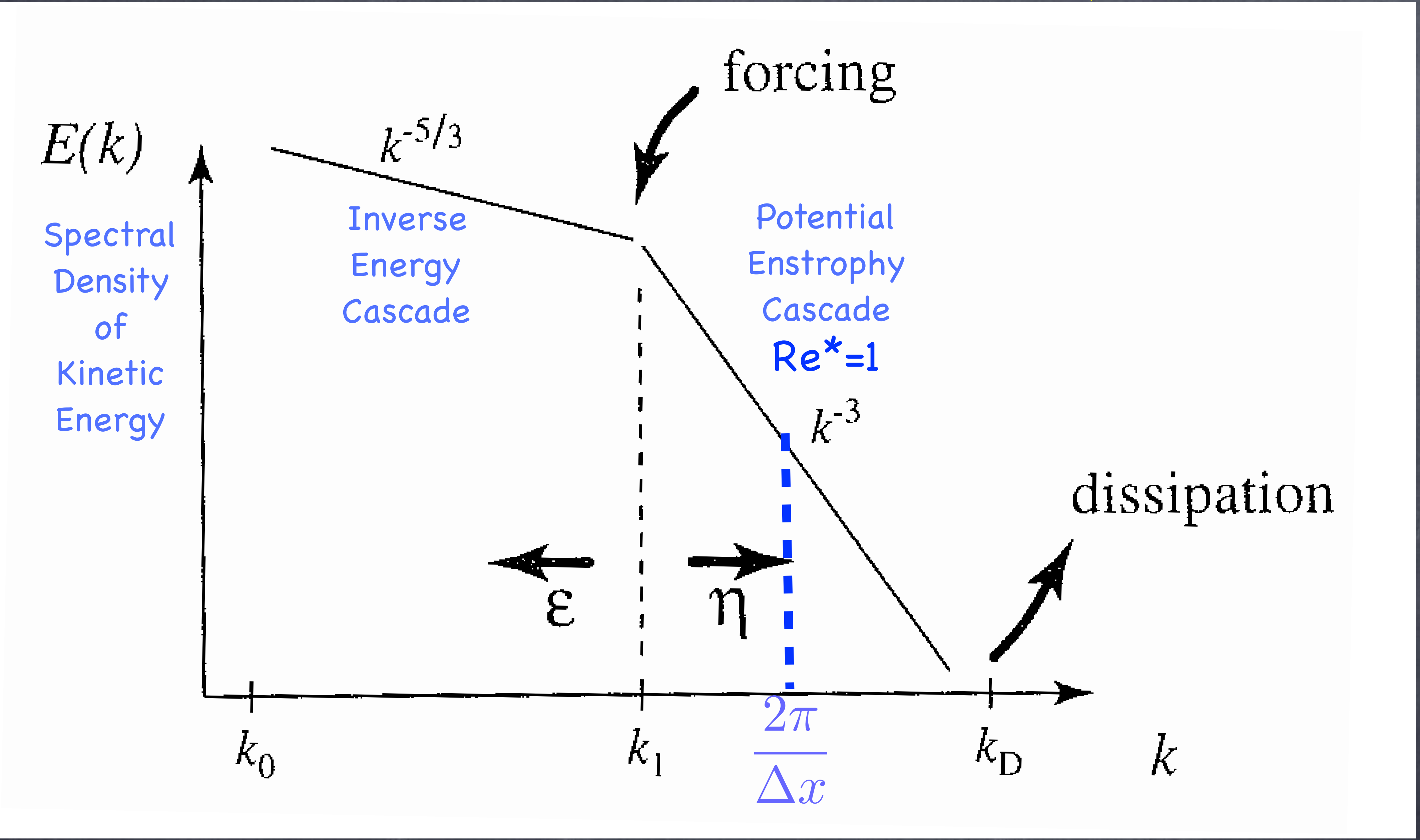
2D Leith:

$$\nu^*_{2d} = \left(\frac{\Lambda_{2d} \Delta x}{\pi} \right)^3 |\nabla_h q^*_{2d}|$$

$$q^*_{2d} = \frac{\partial u^*}{\partial y} - \frac{\partial v^*}{\partial x}$$

2D Turbulence: (enstrophy=vorticity^2)

R. Kraichnan, 1967 JFM



F-K & Menemenlis '08: 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.

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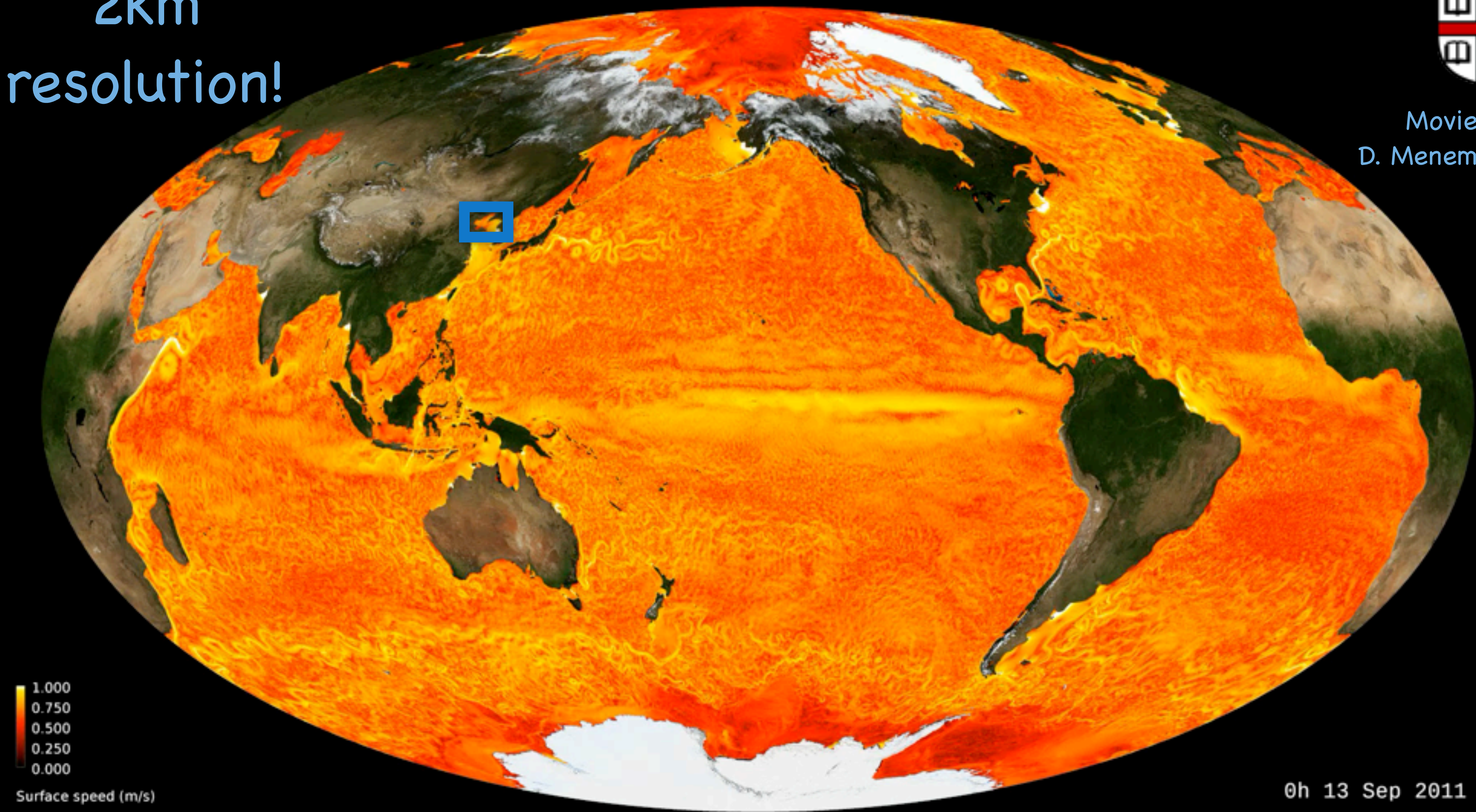
Viscosity Scheme: BFK and D. Menemenlis. Can large eddy simulation techniques improve mesoscale-rich ocean models? In M. Hecht and H. Hasumi, editors, Ocean Modeling in an Eddying Regime, volume 177, pages 319-338. AGU Geophysical Monograph Series, 2008.

18km resolution

LLC4320 Model

2km resolution!

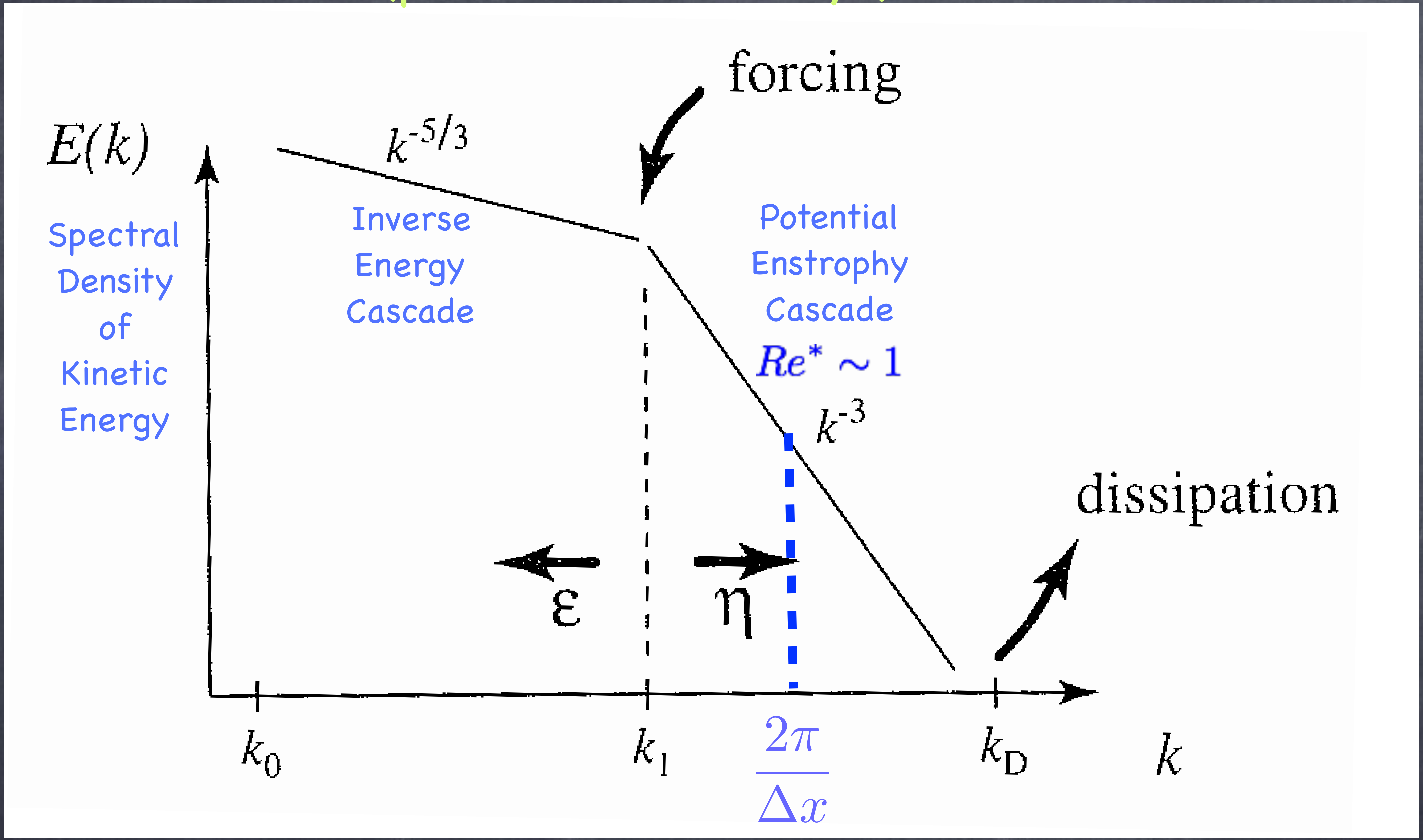
Movie: D. Menemenlis



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.

QG Turbulence: Pot'l Enstrophy cascade
(potential vorticity^2)

J. Charney, 1971 JAS



QG Leith:

$$\nu^*_{qg} = \left(\frac{\Lambda_{qg}\Delta x}{\pi}\right)^3 |\nabla q^*_{qg}|$$

$$q^*_{2d} = f + \hat{k} \cdot \nabla \times u^*$$

$$q^*_{qg} = f + \hat{k} \cdot \nabla \times u^* + \frac{\partial}{\partial z}\frac{f^2}{N^2}b^*$$

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.

QG vs. 2D

$$\nu^*_{qg} = \left(\frac{\Lambda_{qg}\Delta x}{\pi}\right)^3 |\nabla q^*_{qg}|$$

Different (Pot'l) Vorticity Gradients:

$$q^*_{2d} = f + \hat{k}\cdot\nabla\times u^*$$

$$q^*_{qg} = f + \hat{k}\cdot\nabla\times u^* + \frac{\partial}{\partial z}\frac{f^2}{N^2}b^*$$

Also, different implications, because relative vorticity, buoyancy, T, S dissipation now must be consistent with PV:

$$\frac{Dq^*_{qg}}{Dt} = -\nabla\cdot\overline{u'q'_{qg}} \approx \nabla\cdot\left[\nu^*\nabla q_{2d} + \kappa^*_{gm}\nabla\left(q_{qg} - q_{2d}\right)\right] \to \kappa^*_{gm} = \nu^* = \kappa^*_i$$

S. Bachman, BFK. A Scale-Aware Subgrid Model for Oceanic Quasigeostrophic Turbulence. In prep.

QG vs. 2D

$$\nu^*_{qg} = \left(\frac{\Lambda_{qg}\Delta x}{\pi}\right)^3 \left|\nabla q^*_{qg}\right|$$

Different Vorticity Gradients

$$q^*_{2d} = f + \hat{k} \cdot \nabla \times u^*$$

$$q^*_{qg} = f + \hat{k} \cdot \nabla \times u^* + \frac{\partial}{\partial z}\frac{f^2}{N^2} b^*$$

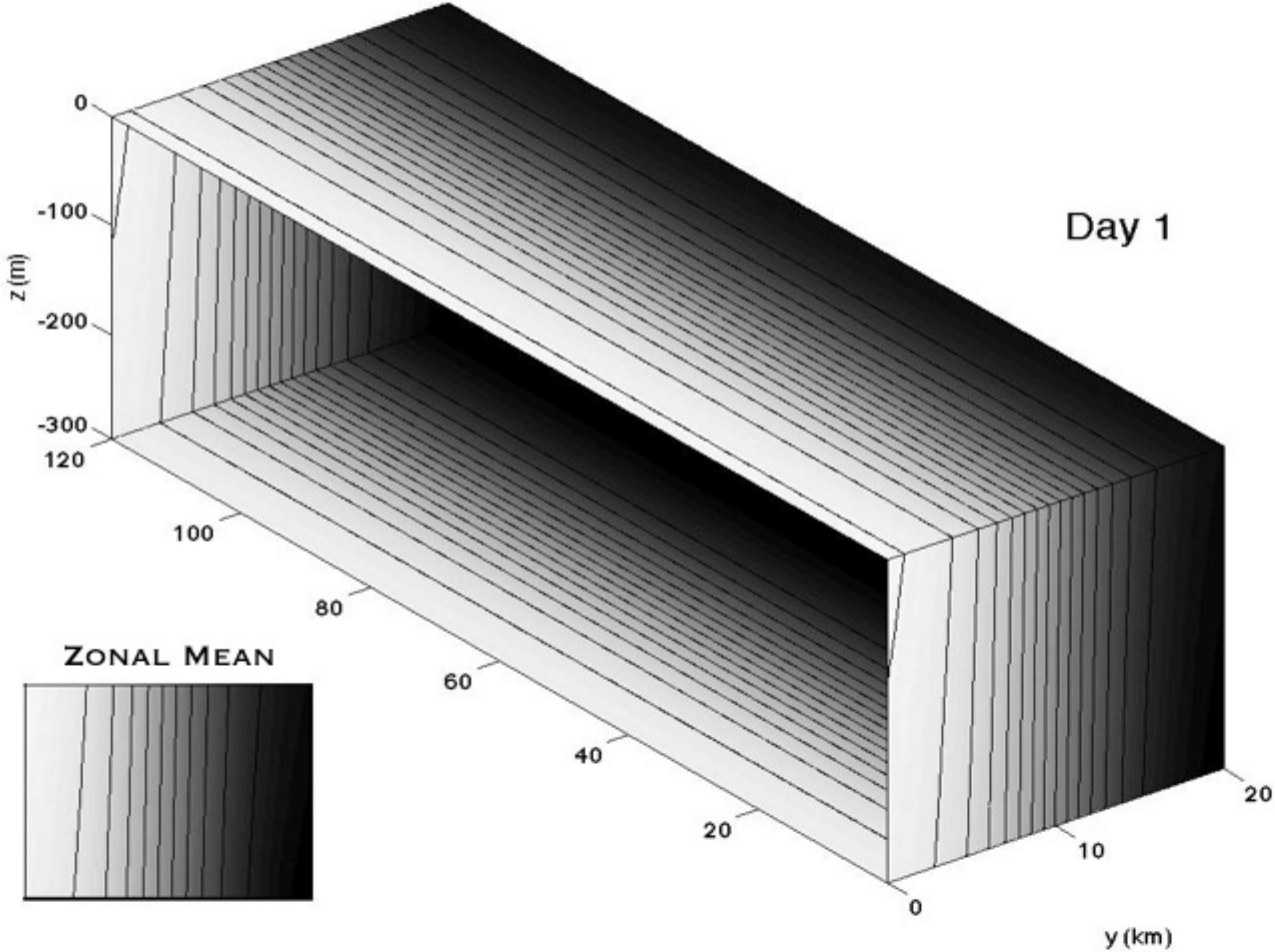
stretching needs "taming" where QG is a bad approx (equator, boundary layers, etc.)

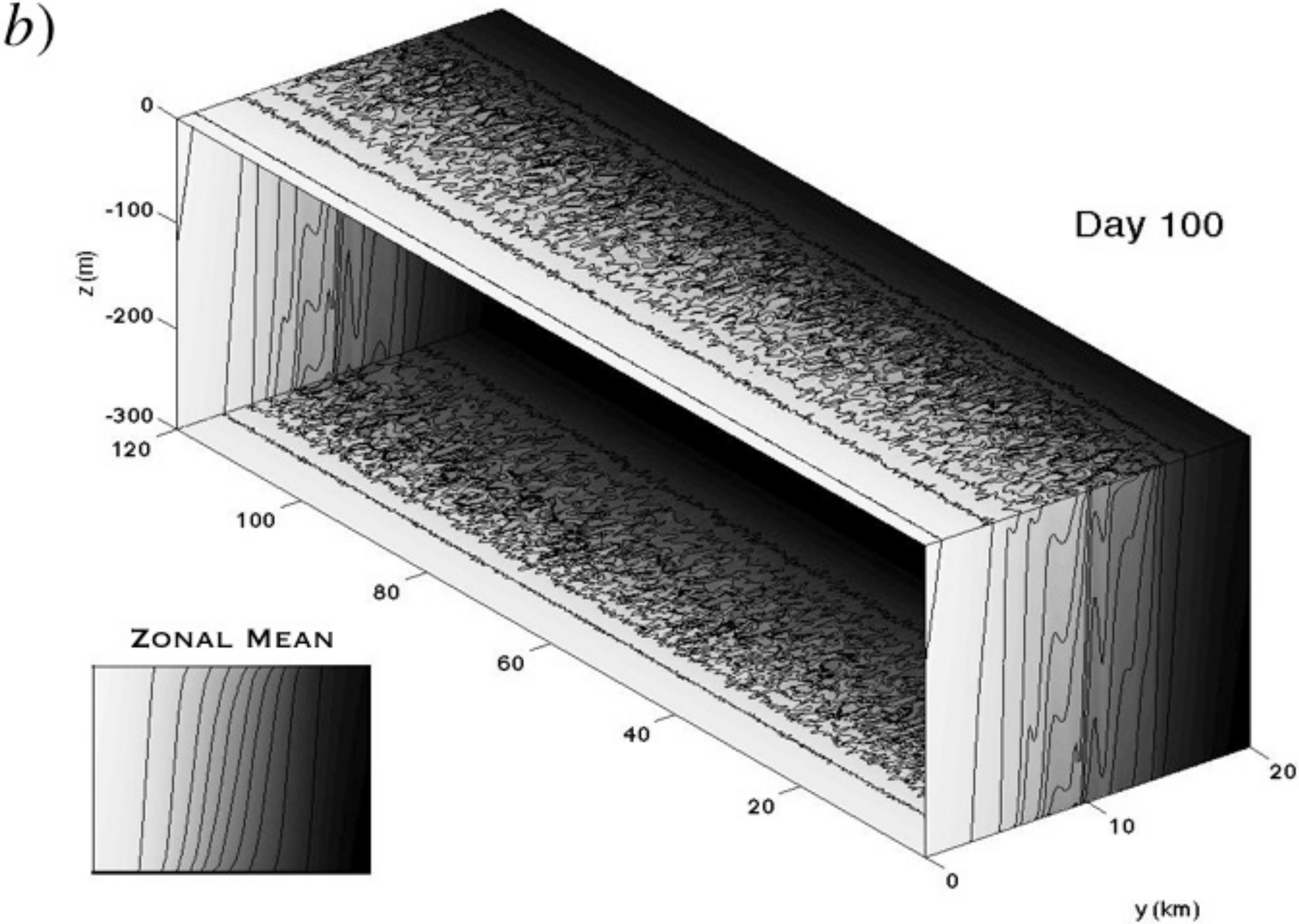
Use gridscale nondims to determine when on the fly

$$Ro^* = \frac{U^*}{f\Delta x} \quad Bu^* = \frac{{N^*}^2 \Delta z^2}{f^2 \Delta x^2} \sim {Ro^*}^2 Ri^*$$

B. Pearson, S. Bachman, BFK. Global Application of a Scale-Aware Subgrid Model for Oceanic Quasigeostrophic Turbulence. In prep.

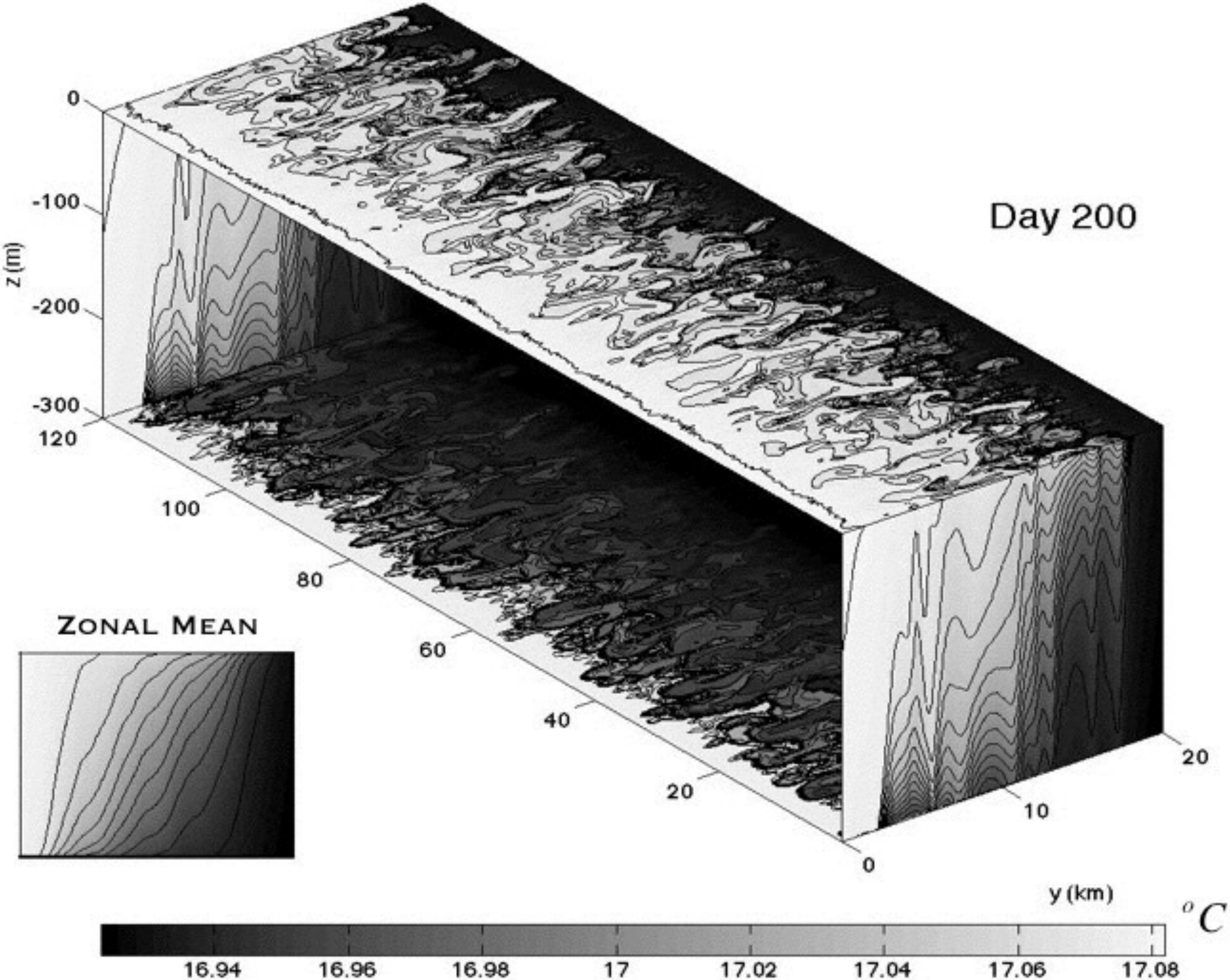
a)

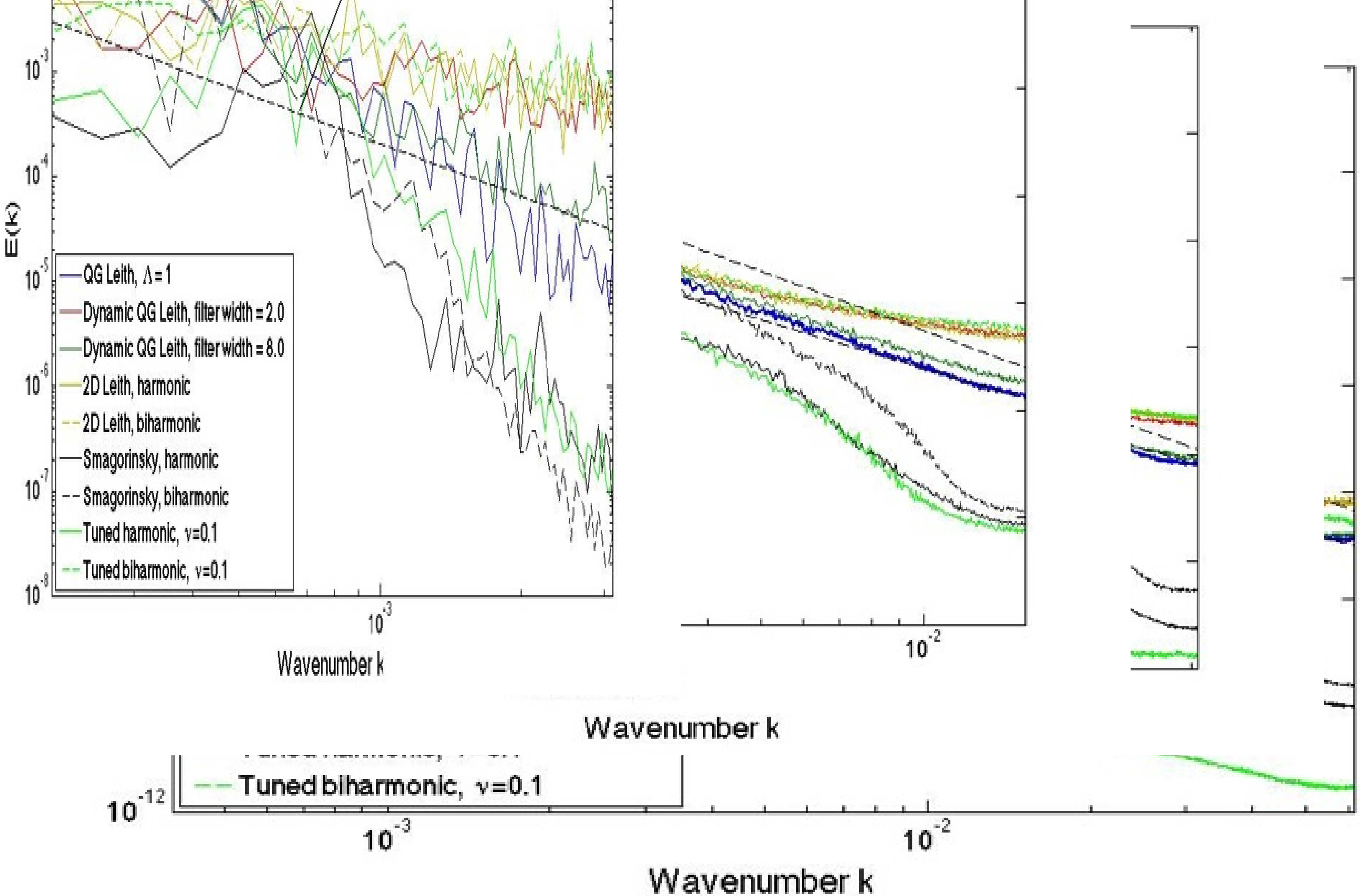




b)
Day 100
z (m)
0
-100
-200
-300
120
100
80
60
40
20
0
10
20
y (km)
Zonal Mean

c)


Day 200
0
-100
-200
-300
z (m)
120
100
80
60
40
20
0
10
20
y (km)
ZONAL MEAN
°C
16.94
16.96
16.98
17
17.02
17.04
17.06
17.08

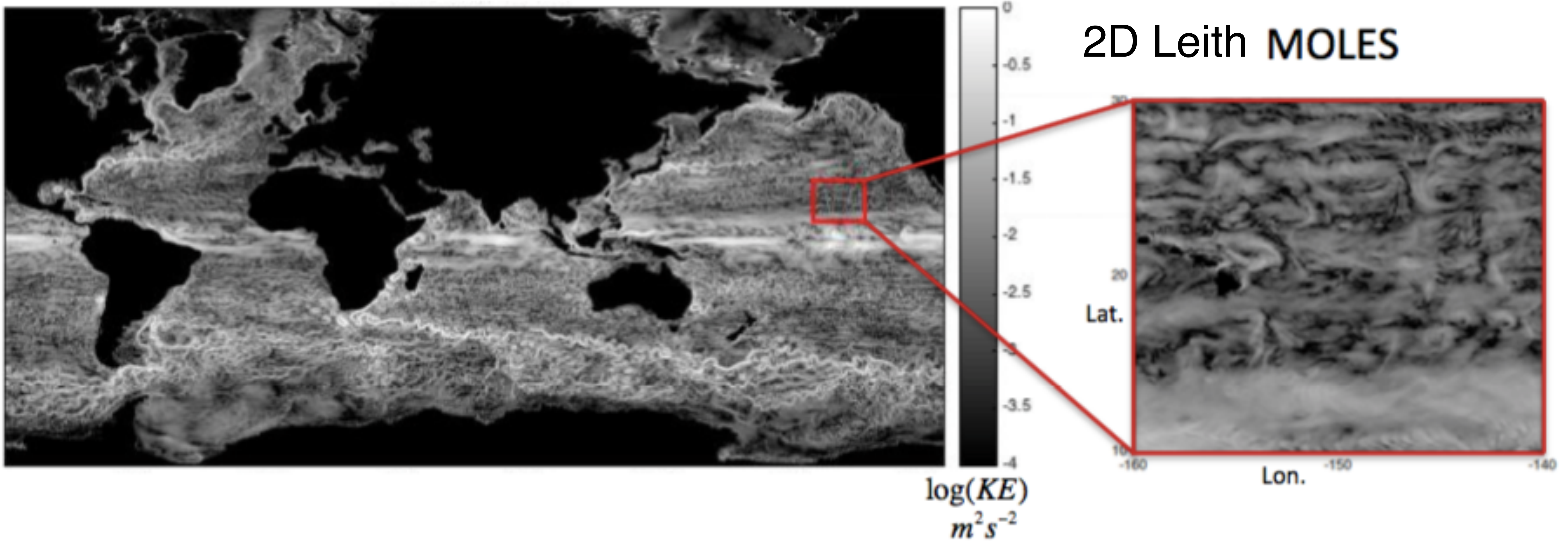


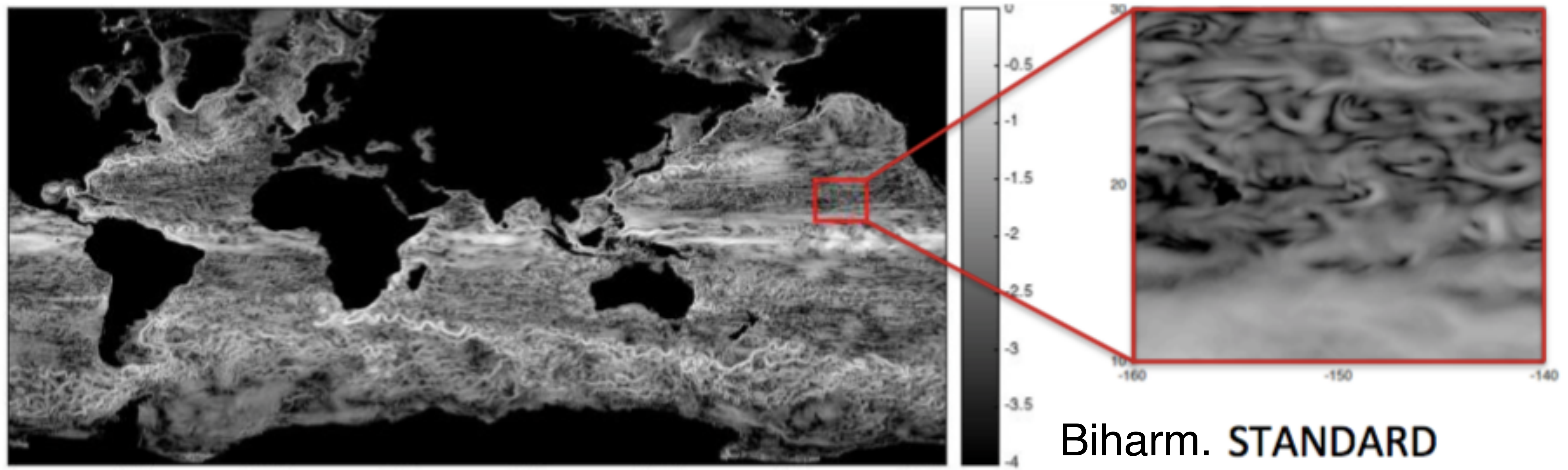
$L_d = 0.4\Delta x$ $1/4°$

$L_d = 2.5\Delta x$ $1/25°$

$L_d = 5\Delta x$ $1/50°$

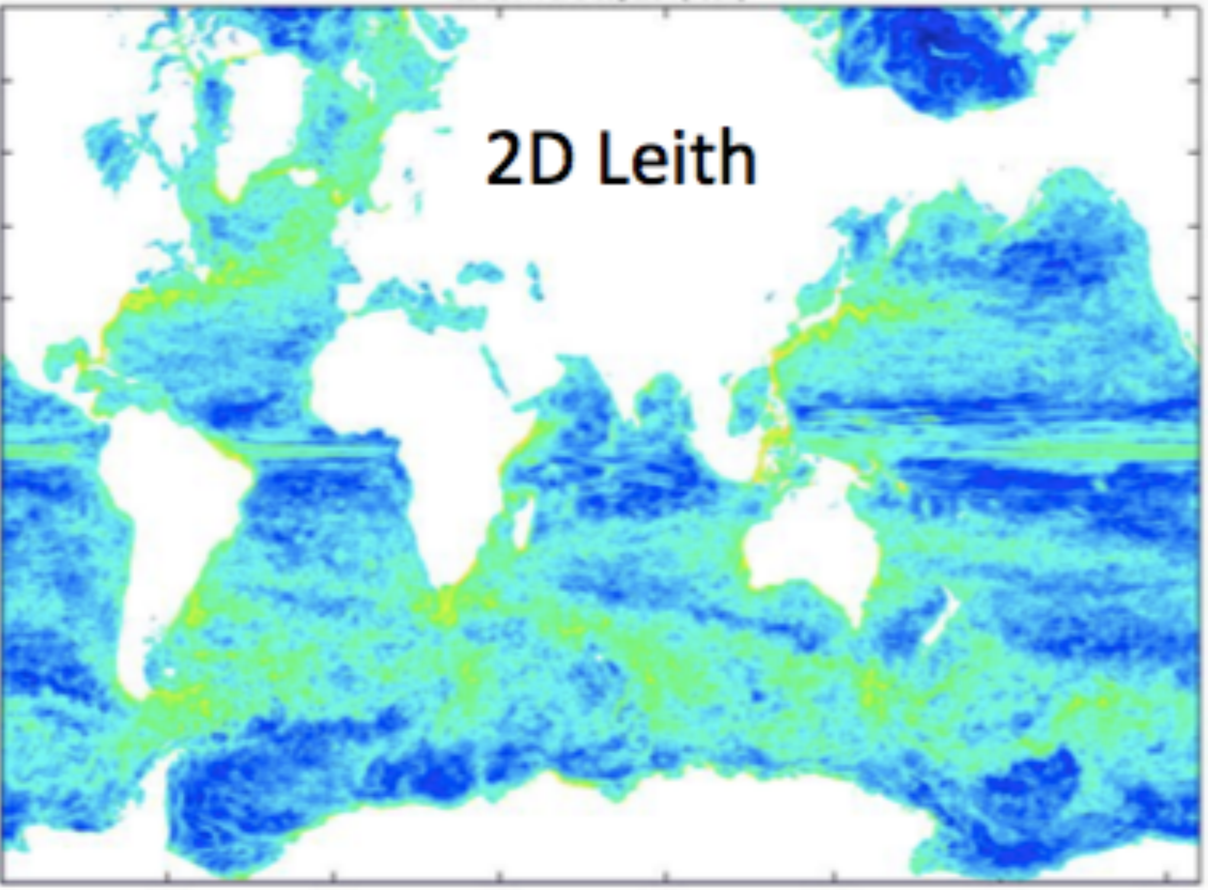
$L_d = 10\Delta x$ $1/100°$

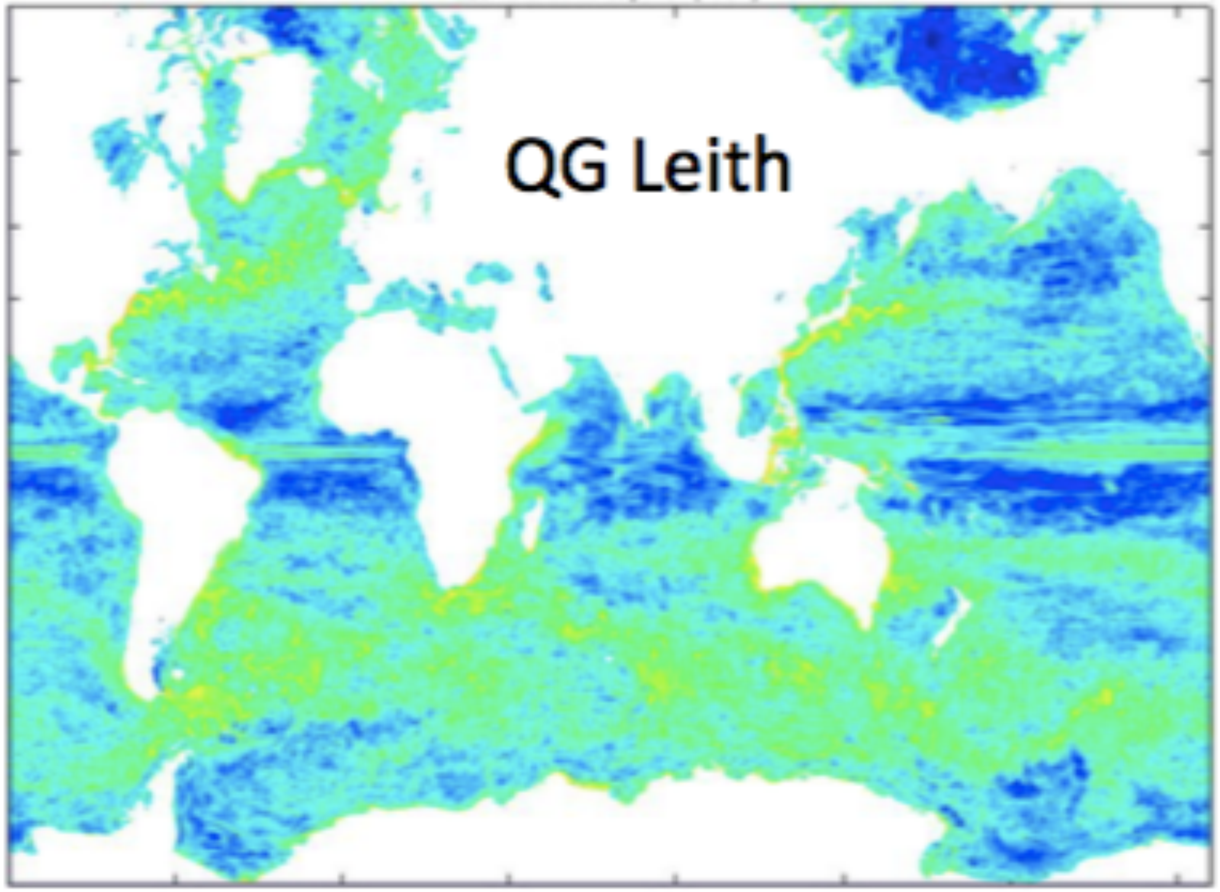


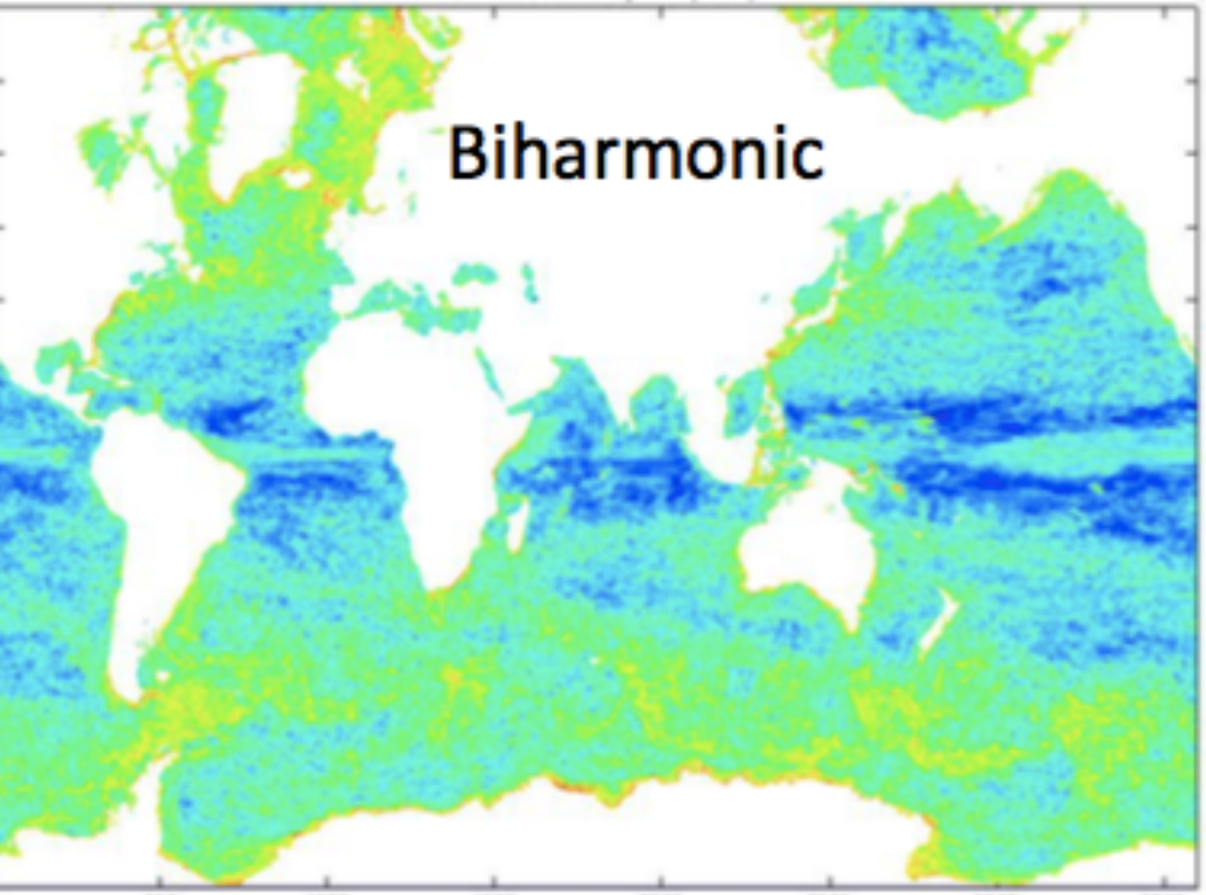


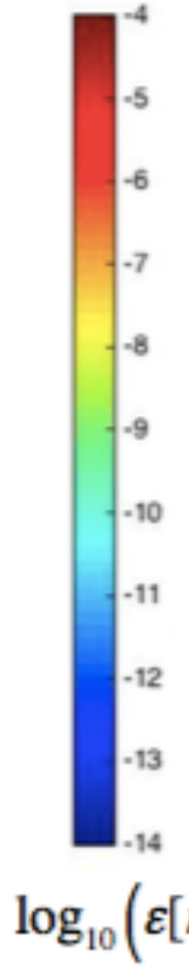
More EKE and Small Structures in MOLES

B. Pearson, S. Bachman, BFK. Global Application of a Scale-Aware Subgrid Model for Oceanic Quasigeostrophic Turbulence. In prep.









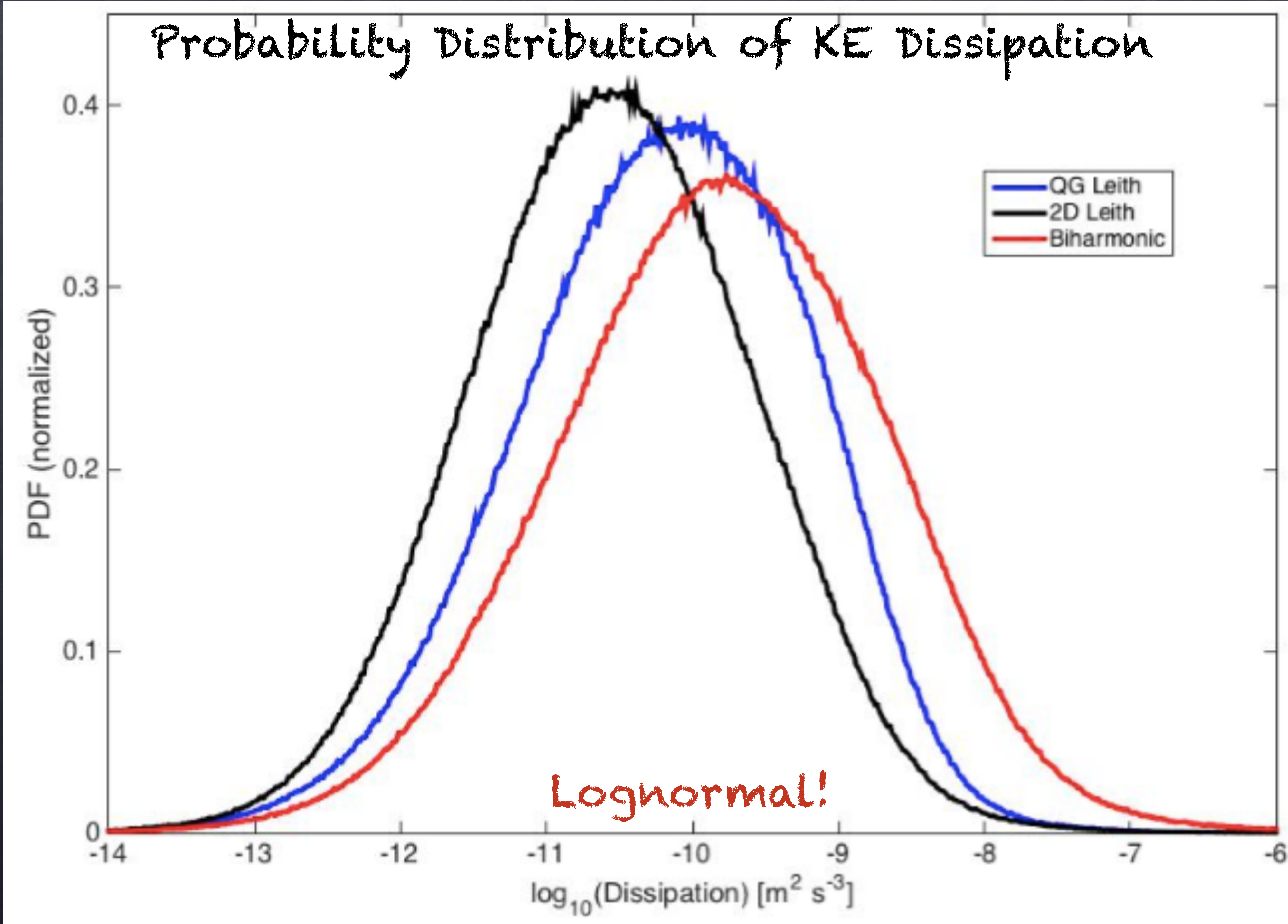
KE Dissipation

$$\epsilon_{2d} = \nu_{2d} \left(|\nabla_h u|^2 + |\nabla_h v|^2 \right)$$

$$\epsilon_{qg} = \nu_{qg} \left(|\nabla_h u|^2 + |\nabla_h v|^2 \right)$$

$$\epsilon_{bh} = \nu_{bh} \left(|\nabla_h^2 u|^2 + |\nabla_h^2 v|^2 \right)$$

B. Pearson, S. Bachman, BFK. Global Application of a Scale-Aware Subgrid Model for Oceanic Quasigeostrophic Turbulence. In prep.



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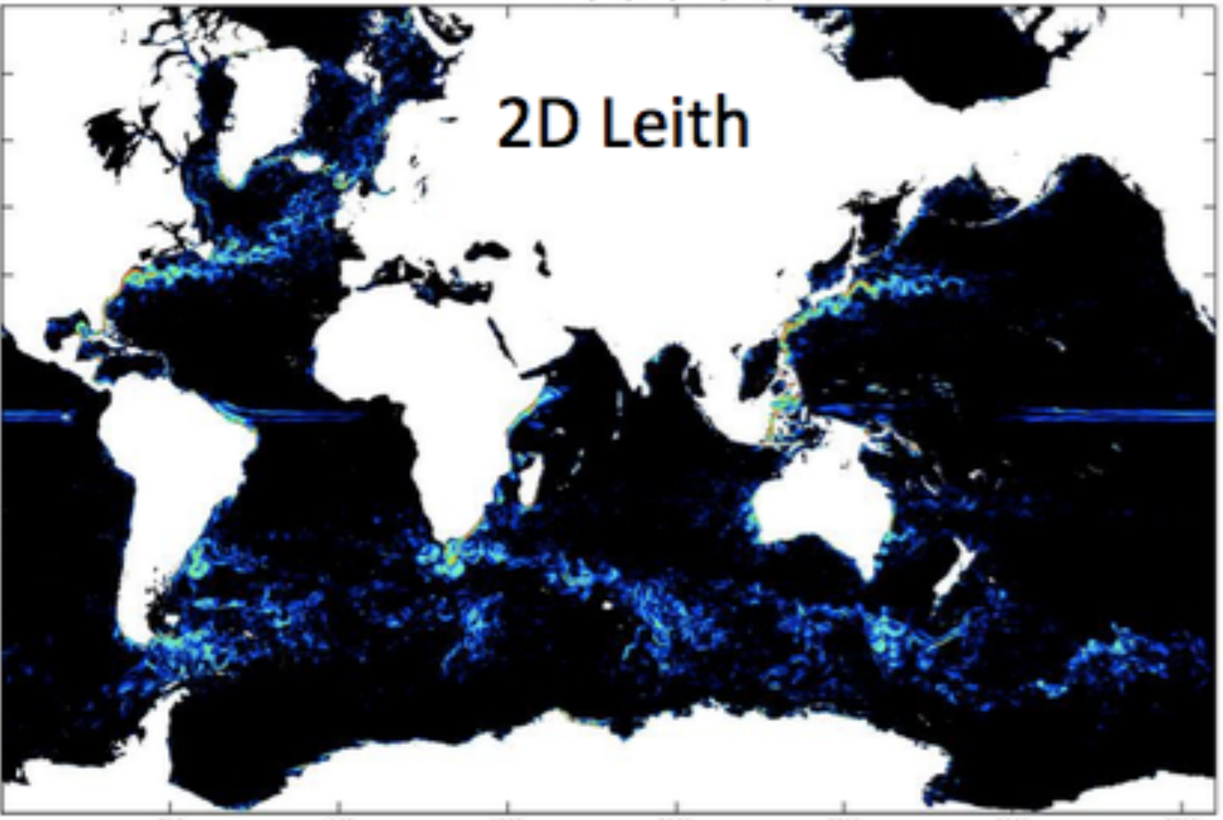
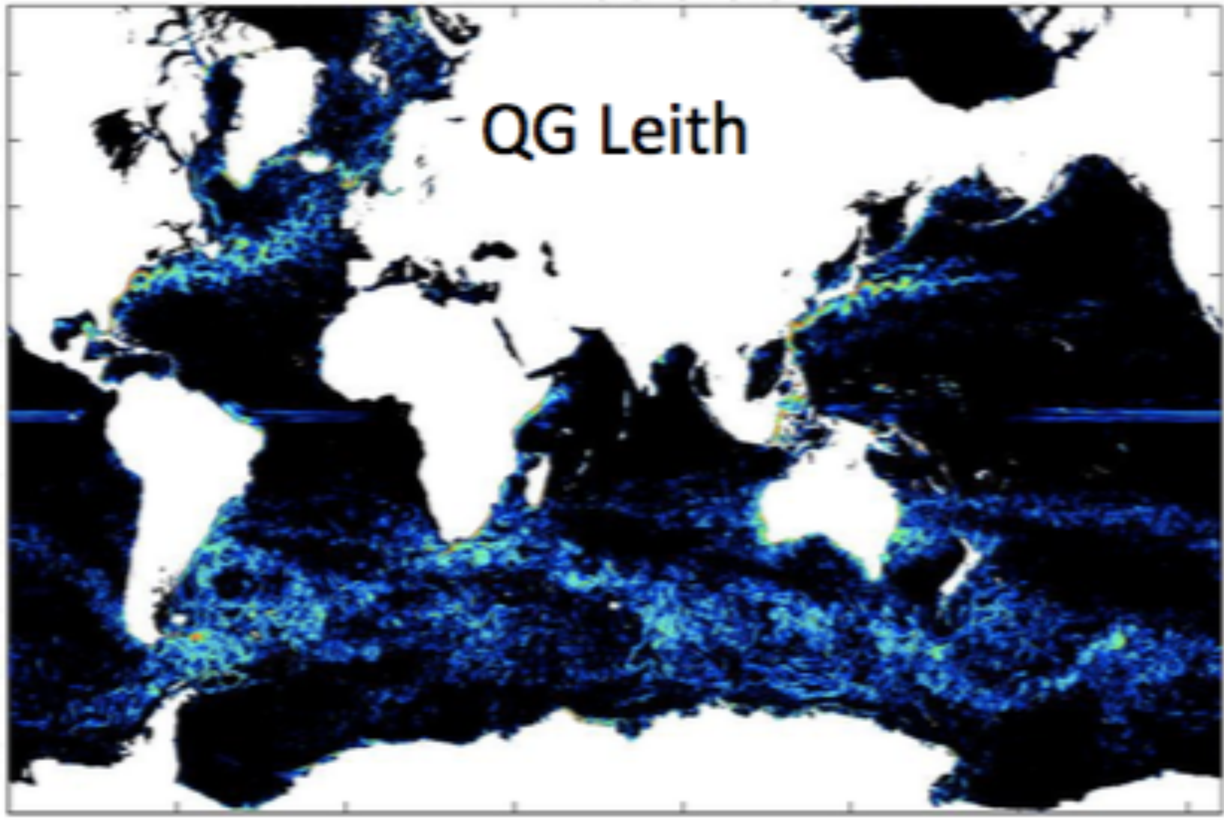
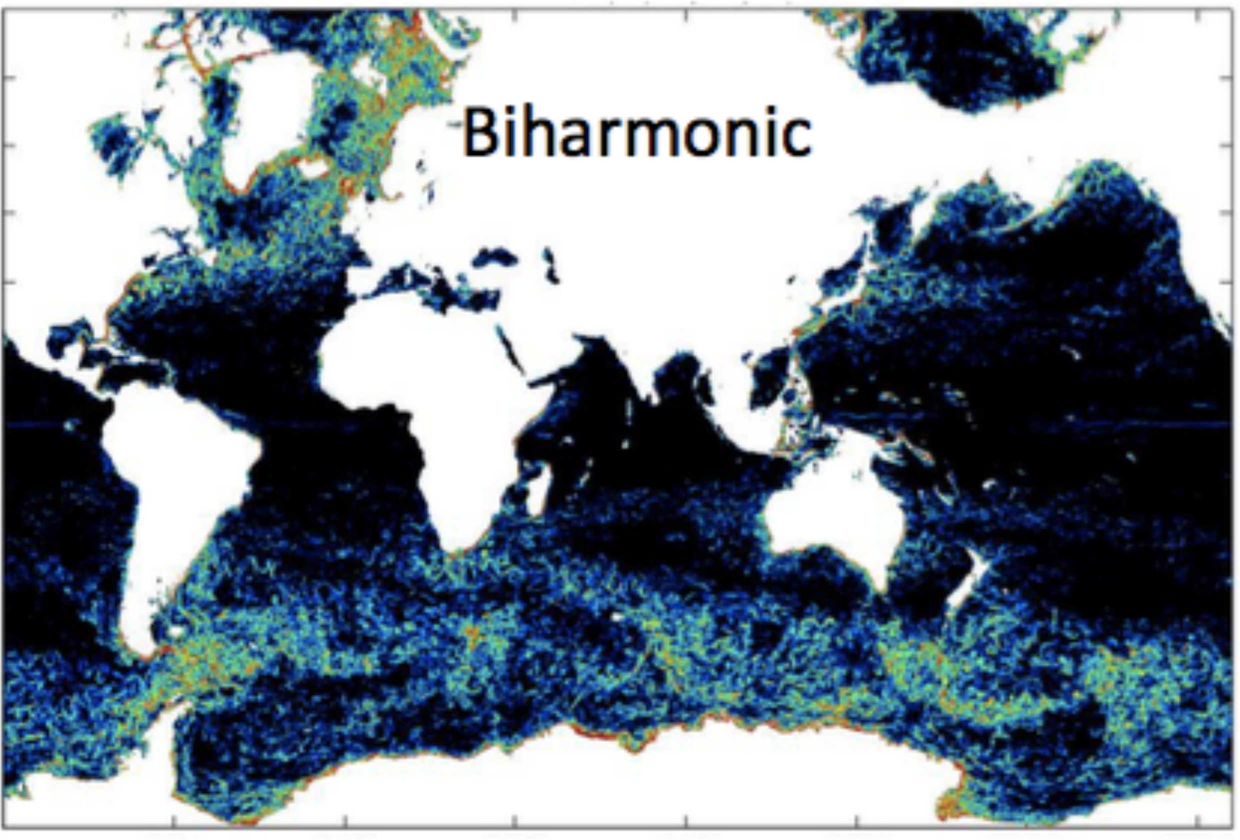
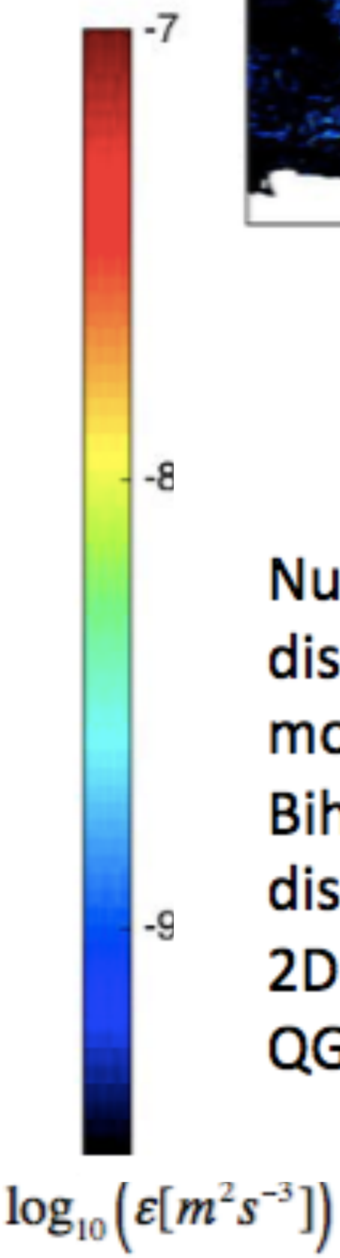








A Consequence of Lognormal Statistics—limited regions do most of the work!

Number of points providing 95% of dissipation at 100 m varies between models:

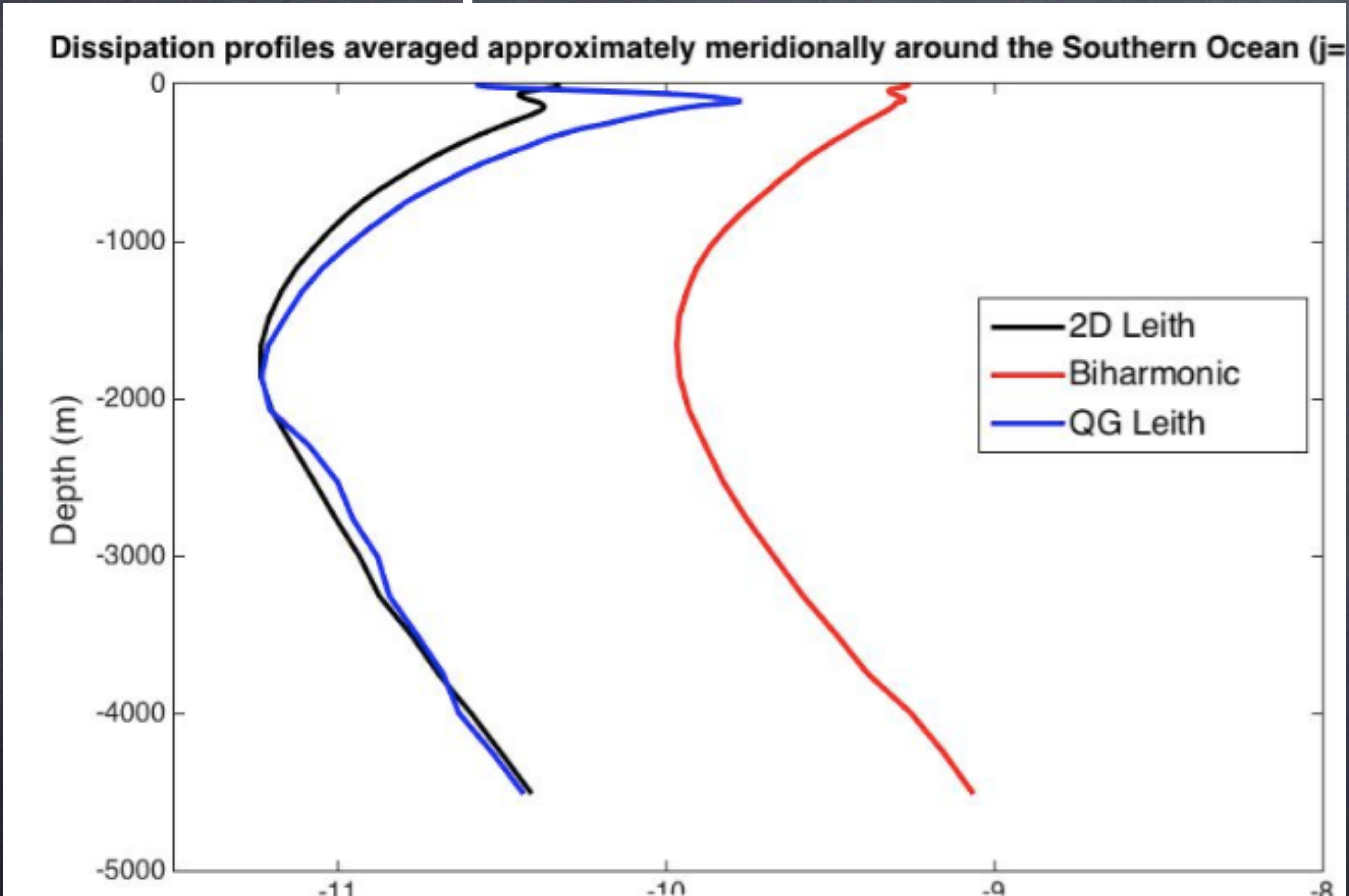
Biharmonic (13% of data points for 95% of dissipation),

2D Leith (23%)

QG Leith (31%)

B. Pearson, S. Bachman, BFK. Global Application of a Scale-Aware Subgrid Model for Oceanic Quasigeostrophic Turbulence. In prep.

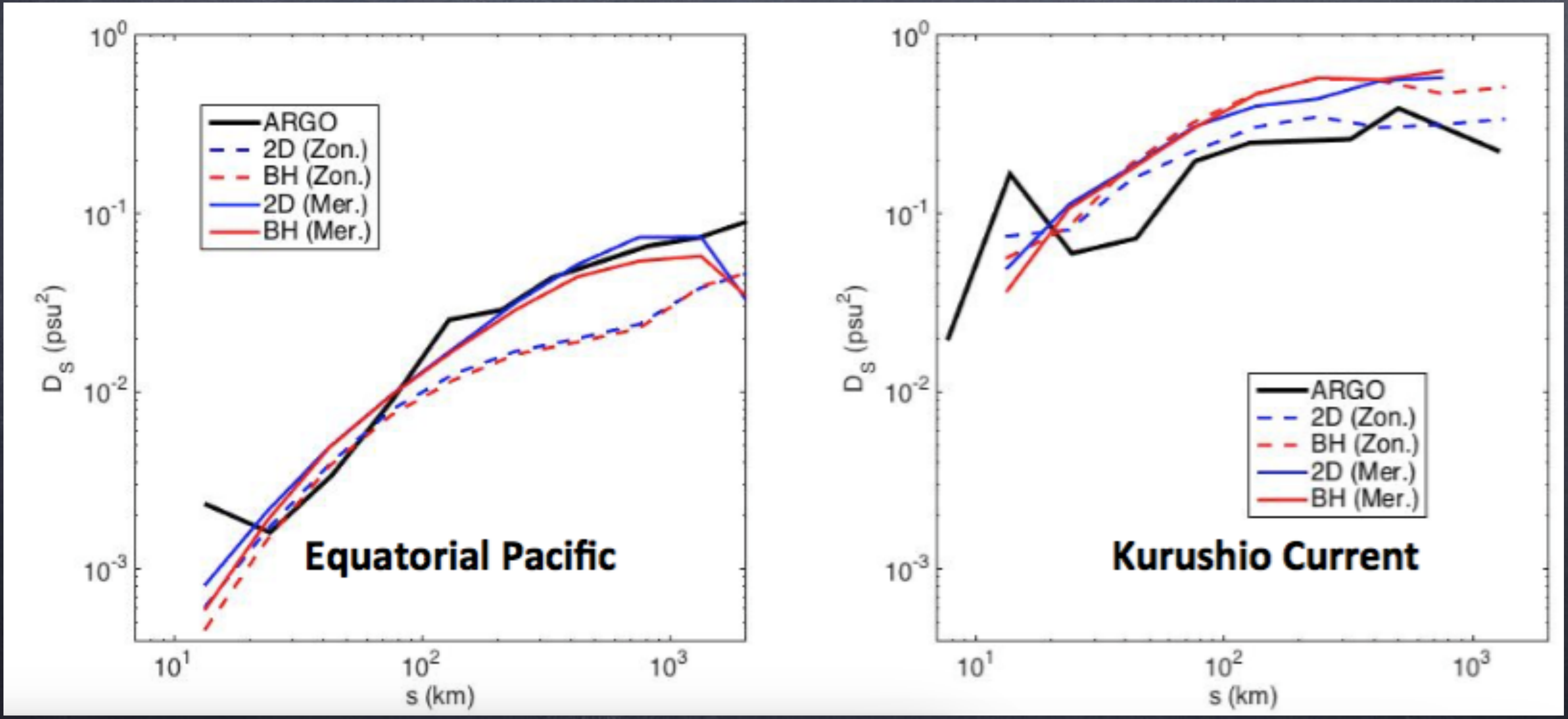
KE Dissipation in Vertical



$$\log_{10}\left(\varepsilon[m^2 s^{-3}]\right)$$

New Benchmark: Structure Functions

$$D_S(s) = \overline{\overline{[S'(x) - S'(x+s)]^2}},$$

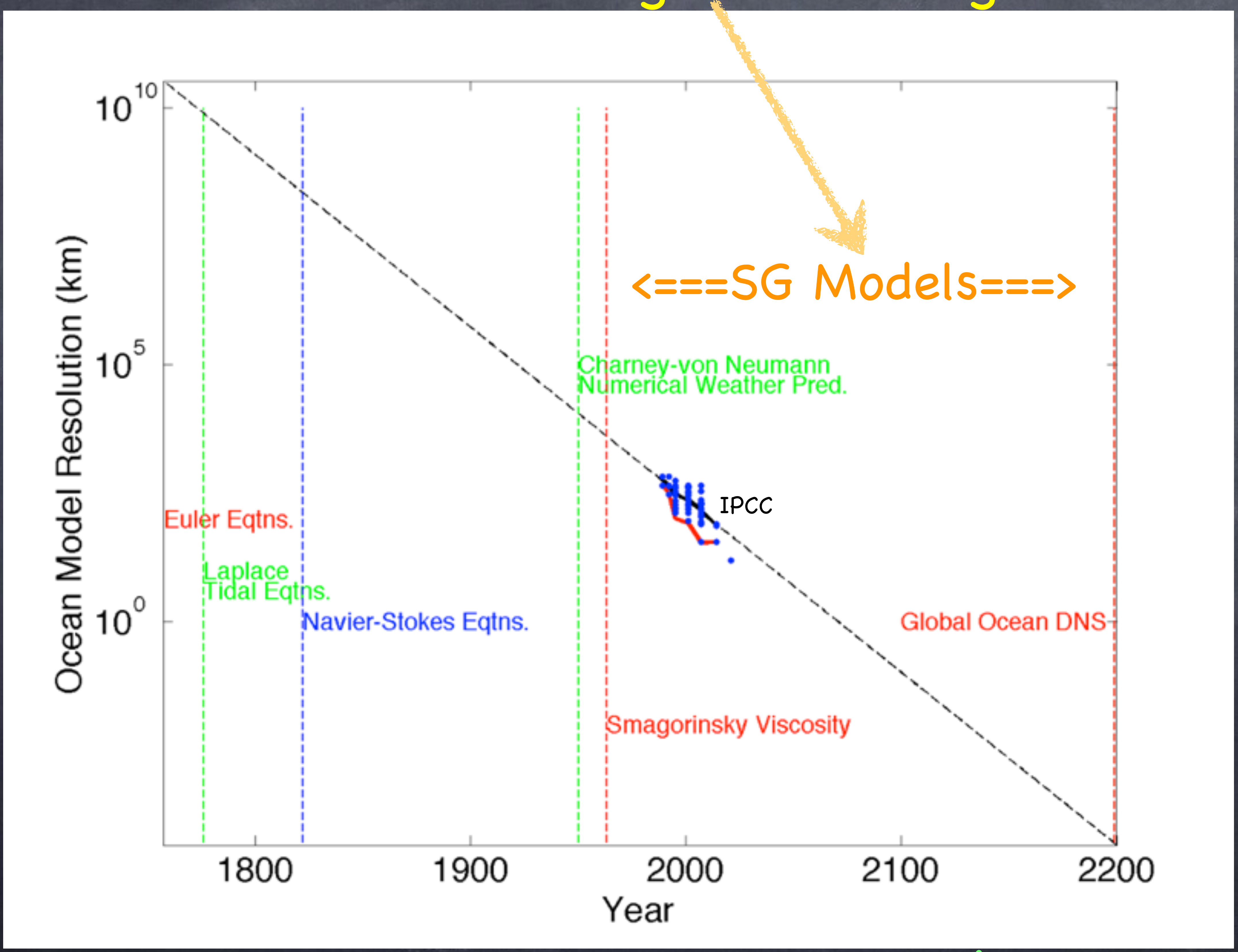


K. McCaffrey, B. Fox-Kemper, and G. Forget. Estimates of ocean macro-turbulence: Structure function and spectral slope from Argo profiling floats. Journal of Physical Oceanography, 45(7):1773-1793, July 2015.

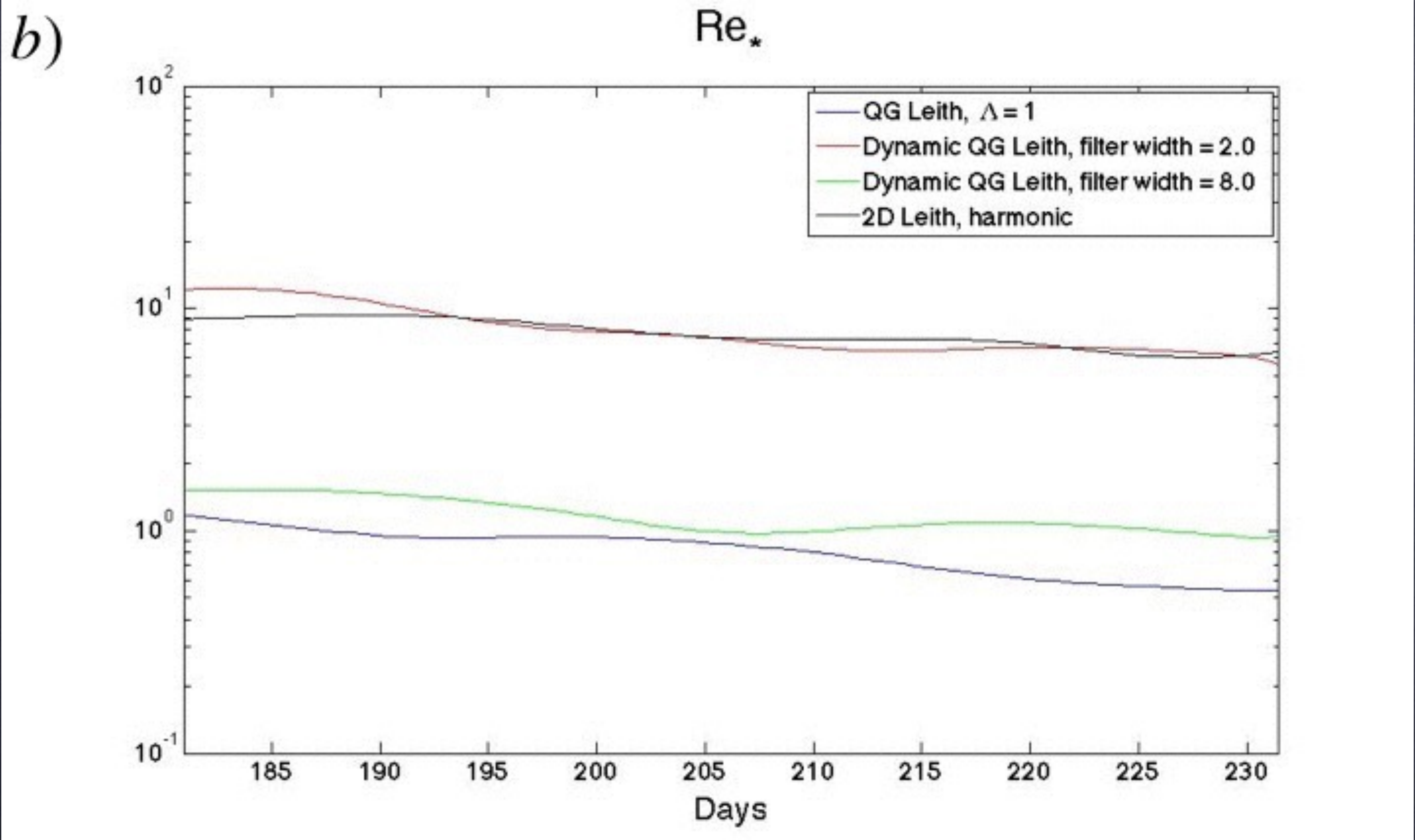
Conclusions

- It is best to think of high-res simulations as “large eddy simulations”.
- Then, take advantage of resolved flow and scaling for physically-based subgrid schemes.
- QG theory has provided such a scheme for mesoscale-permitting to resolving simulations.
- 10x less dissipative than biharmonic viscosity and dissipates where theory suggests it should do.
- Small scales are more energetic, salinity variance can be doubled, even at O(1000km scales).
- Dynamic version more expensive, no better

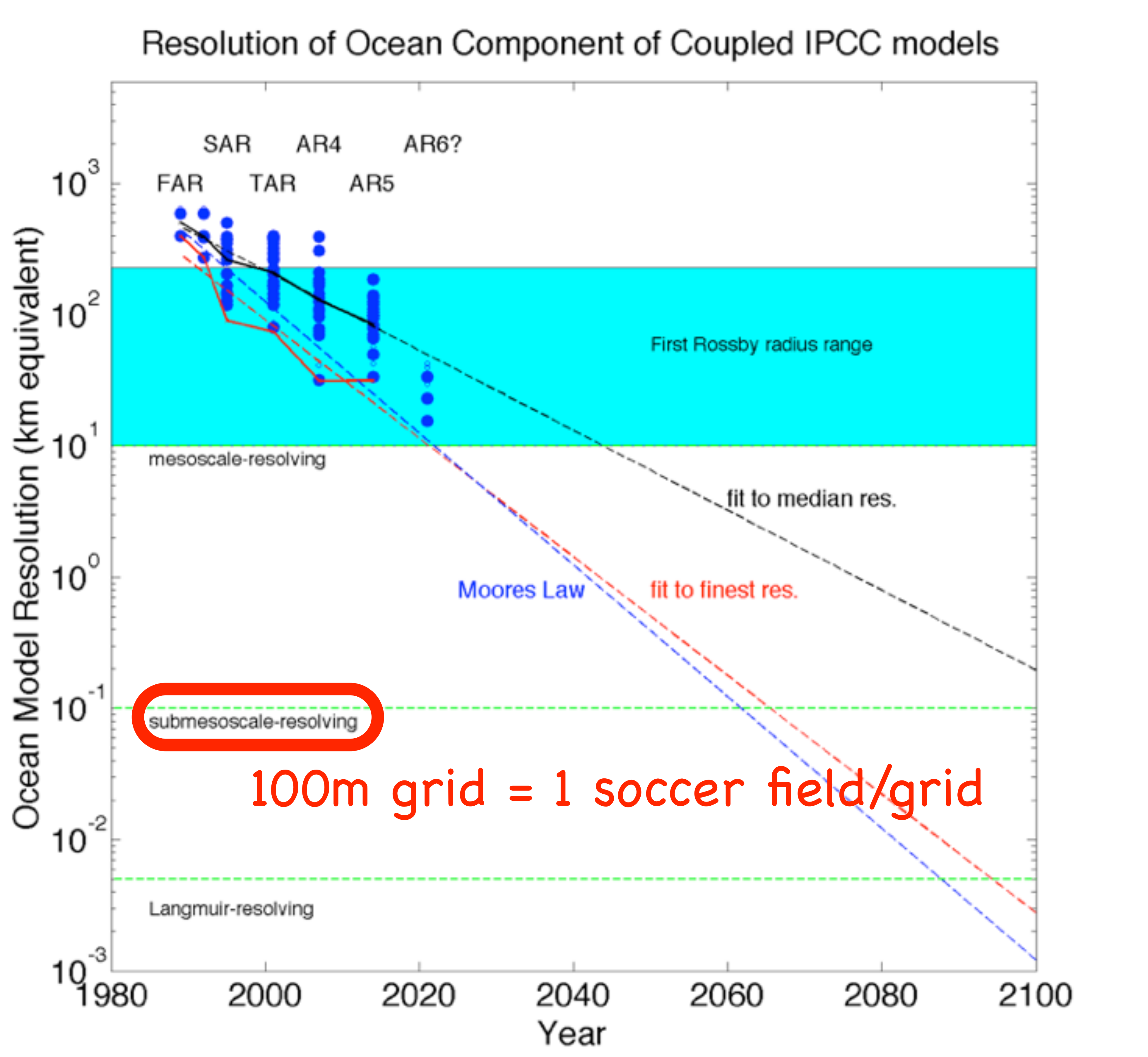
Extrapolate for historical perspective:
The Golden Era of Subgrid Modeling is Now!



All papers at: fox-kemper.com/research


b)
Re*
QG Leith, Λ = 1
Dynamic QG Leith, filter width = 2.0
Dynamic QG Leith, filter width = 8.0
2D Leith, harmonic
10^2
10^1
10^0
10^-1
185
190
195
200
205
210
215
220
225
230
Days

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