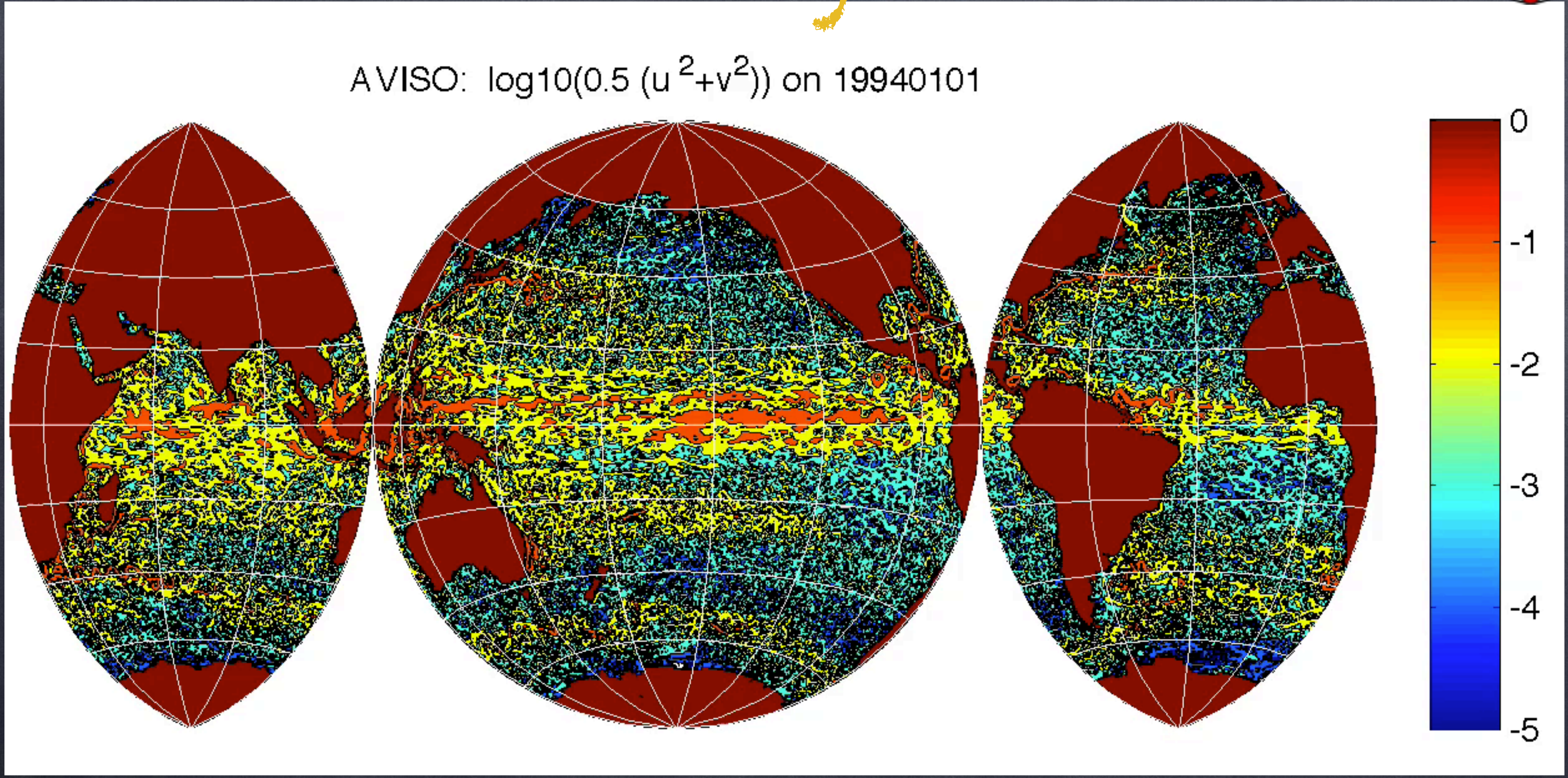
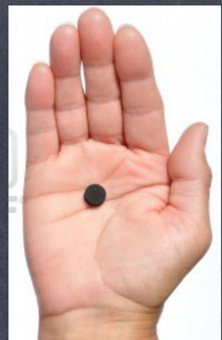
From Climate to Kolmogorov: Ocean Variability Across Scales



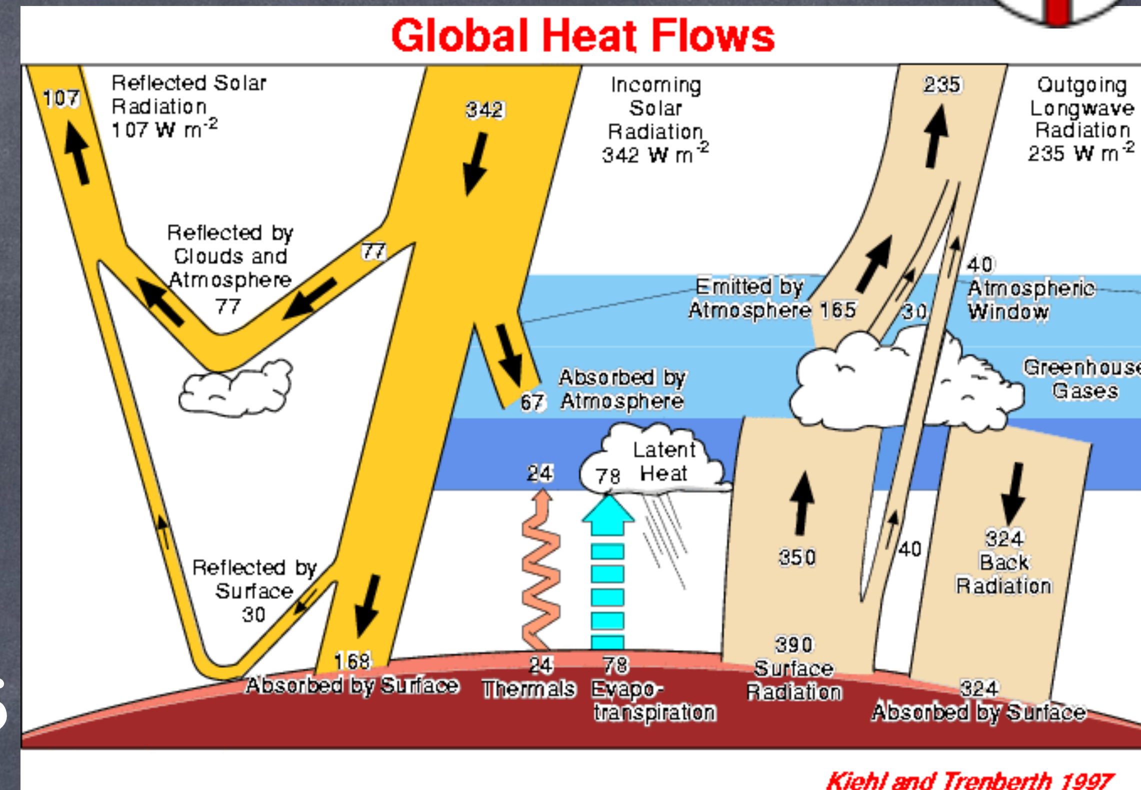
Baylor Fox-Kemper
Brown University
Dept. of Earth, Environmental, and Planetary Sciences

Support: NSF, ONR, GoMRI

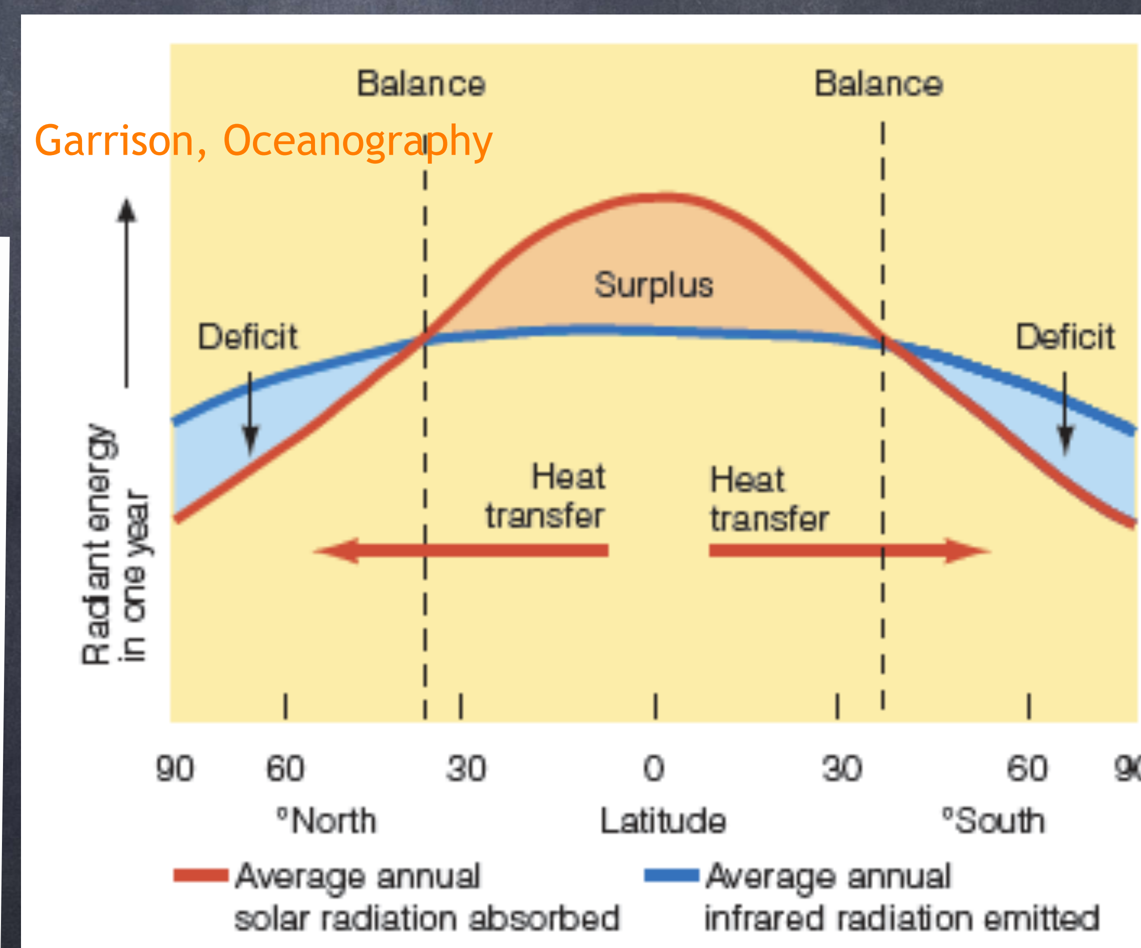


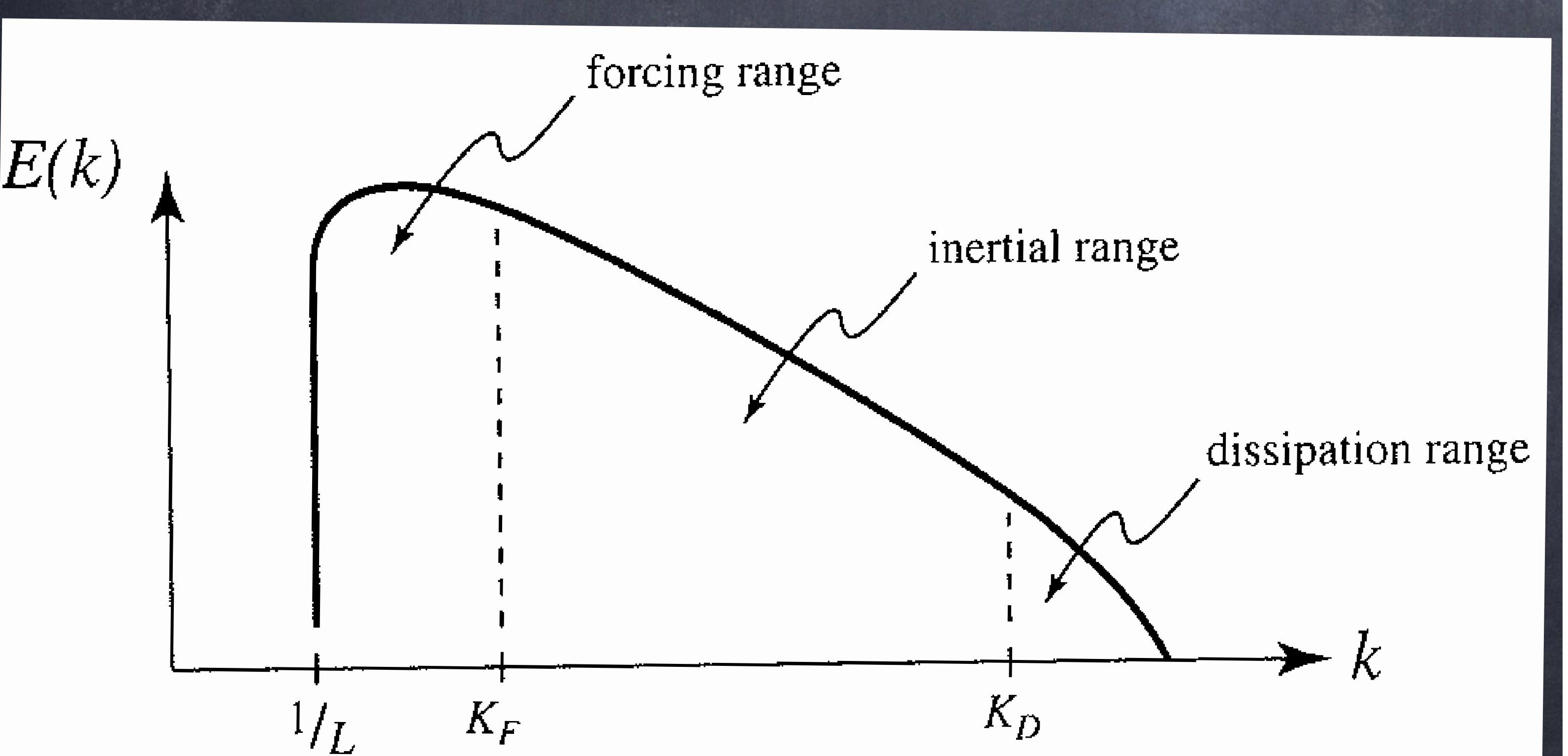
The Earth's Climate System is driven by the Sun's light
(minus outgoing infrared)
on a global scale

Energy dissipation concludes turbulence cascades to scales about a billion times smaller



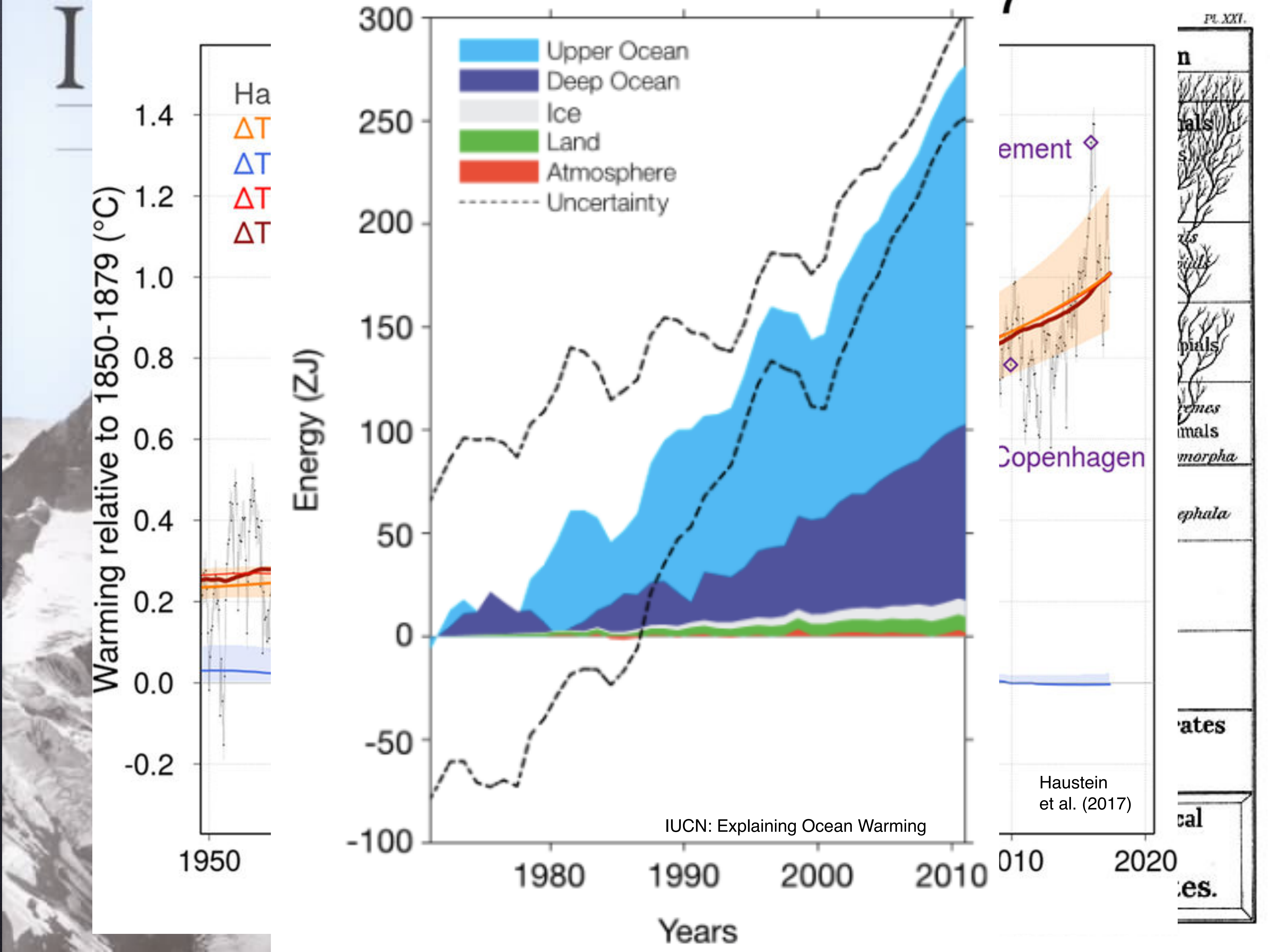
Garrison, Oceanography



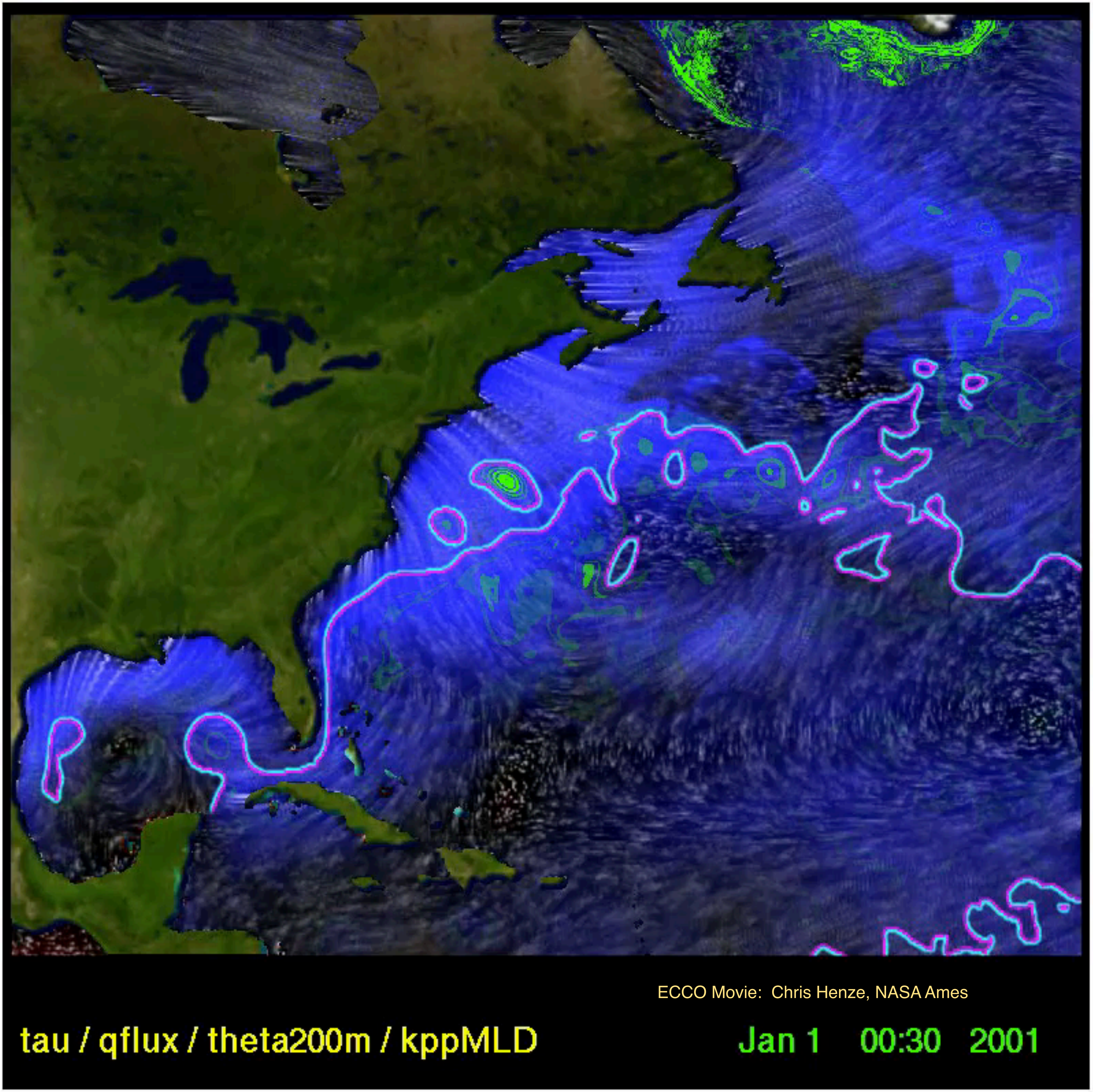


Earth is special;
Water is special

- Water has many properties that are intertwined with the Earth system and life on Earth
  - Water is the only substance in gas, liquid and solid form on earth
  - Water has enormous heat capacity
- Let's talk a bit about seawater's heat capacity



Upper Ocean
Deep Ocean
Ice
Land
Atmosphere
Uncertainty
Energy (ZJ)
Years
300
250
200
150
100
50
0
-50
-100
1980
1990
2000
2010
IUCN: Explaining Ocean Warming
Warming relative to 1850-1879 (°C)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
1950
2020
ement
Copenhagen
Haustein
et al. (2017)
Pl. XXI.

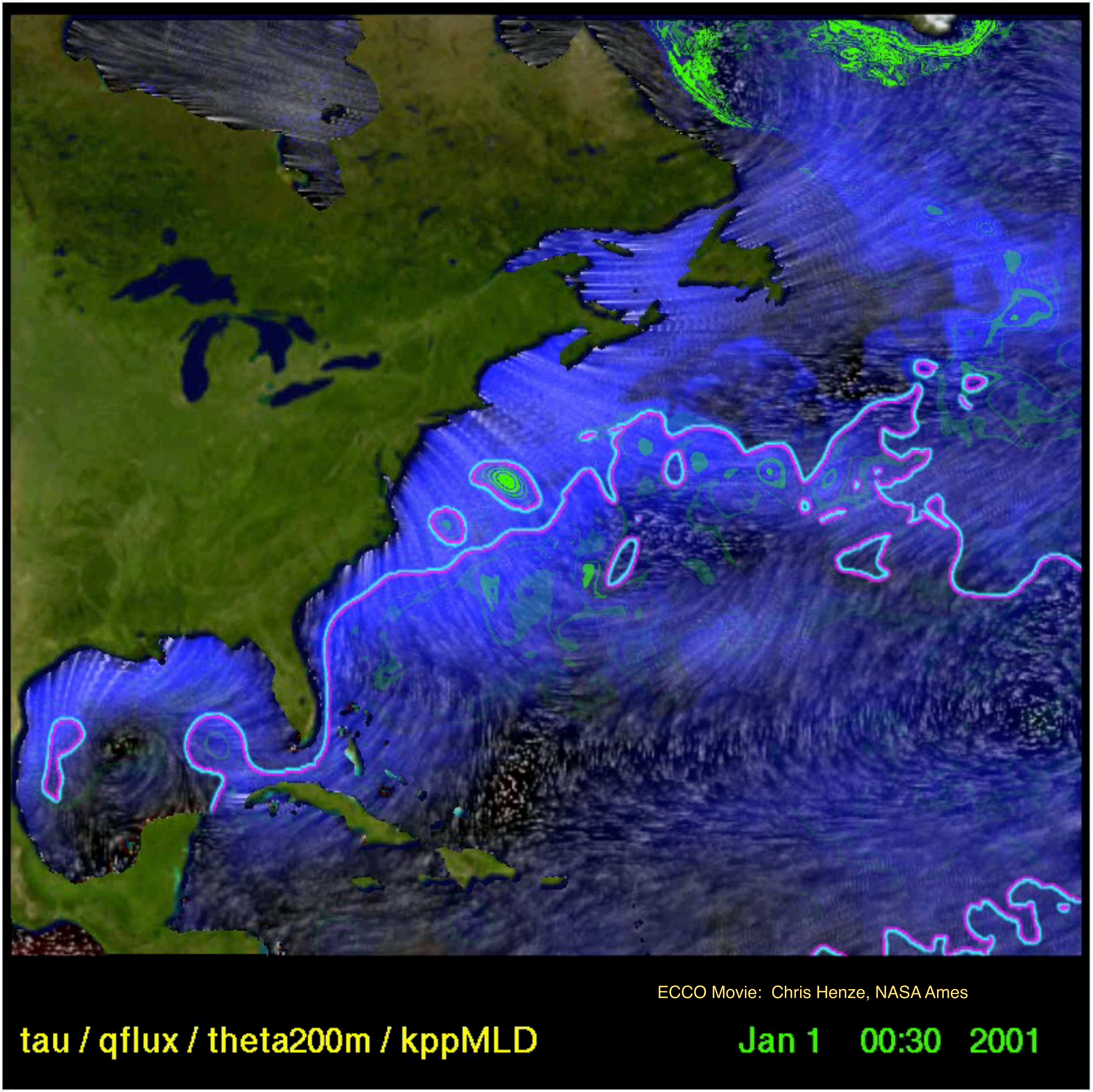


Weather, Atmosphere Fast

Ocean, Climate Slow

3.4m of ocean water has same heat capacity as the WHOLE atmosphere

Heat Capacity= Energy Storage per unit Temp Change



Weather,
Atmosphere
Fast

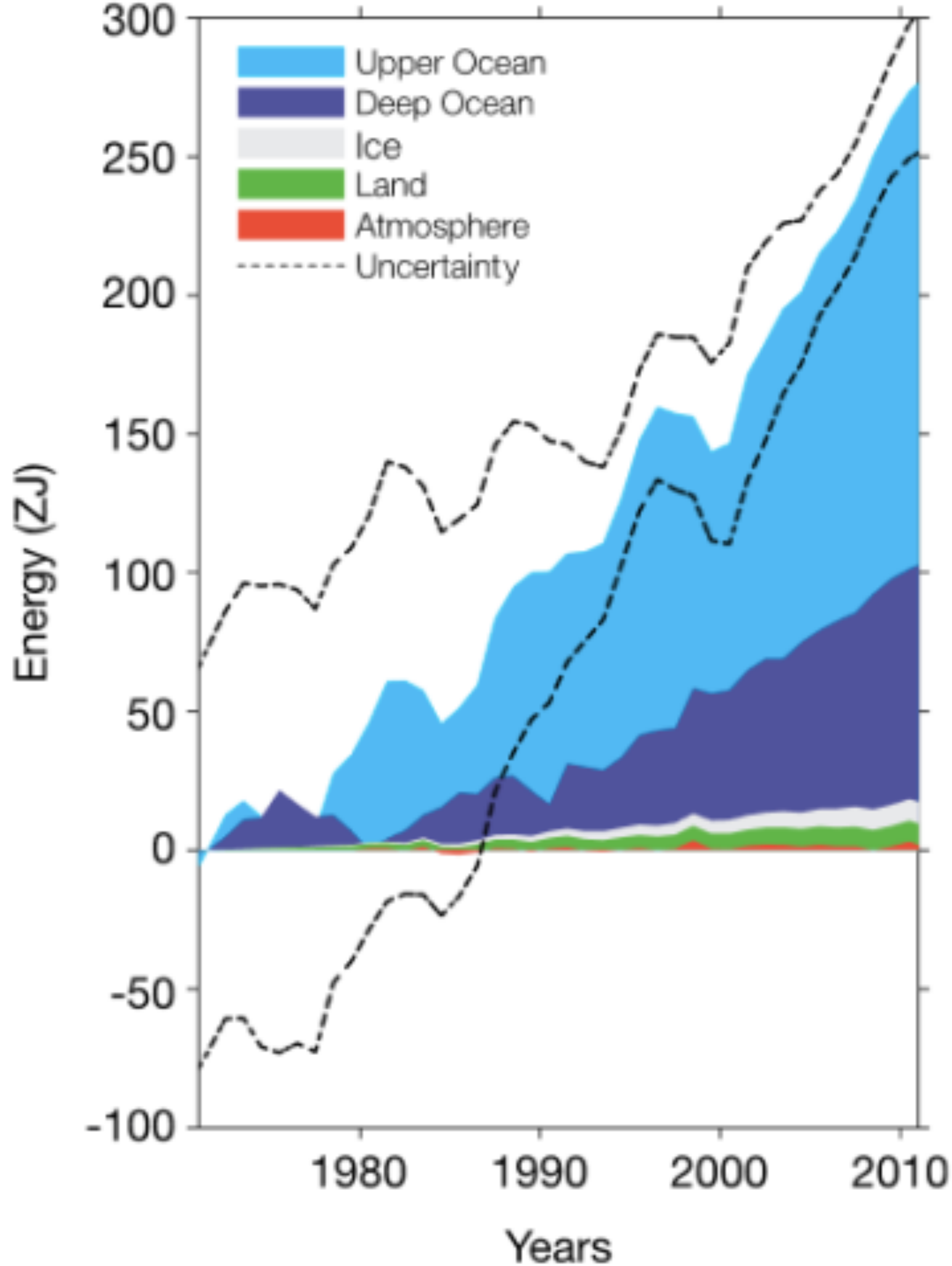
Ocean,
Climate
Slow

3.4m of ocean water has same heat capacity as the WHOLE atmosphere

Heat Capacity=
Energy Storage per unit Temp Change

Air-Sea Exchanges

- Ocean heat capacity, even just mixed layer, is vastly larger than the atmosphere
- Air-sea heat fluxes are sensitive to air-sea temperature differences (and wind—i.e. momentum differences)
- Thus heat anomalies end up in the ocean



Trends: What do hydrographic observations show?

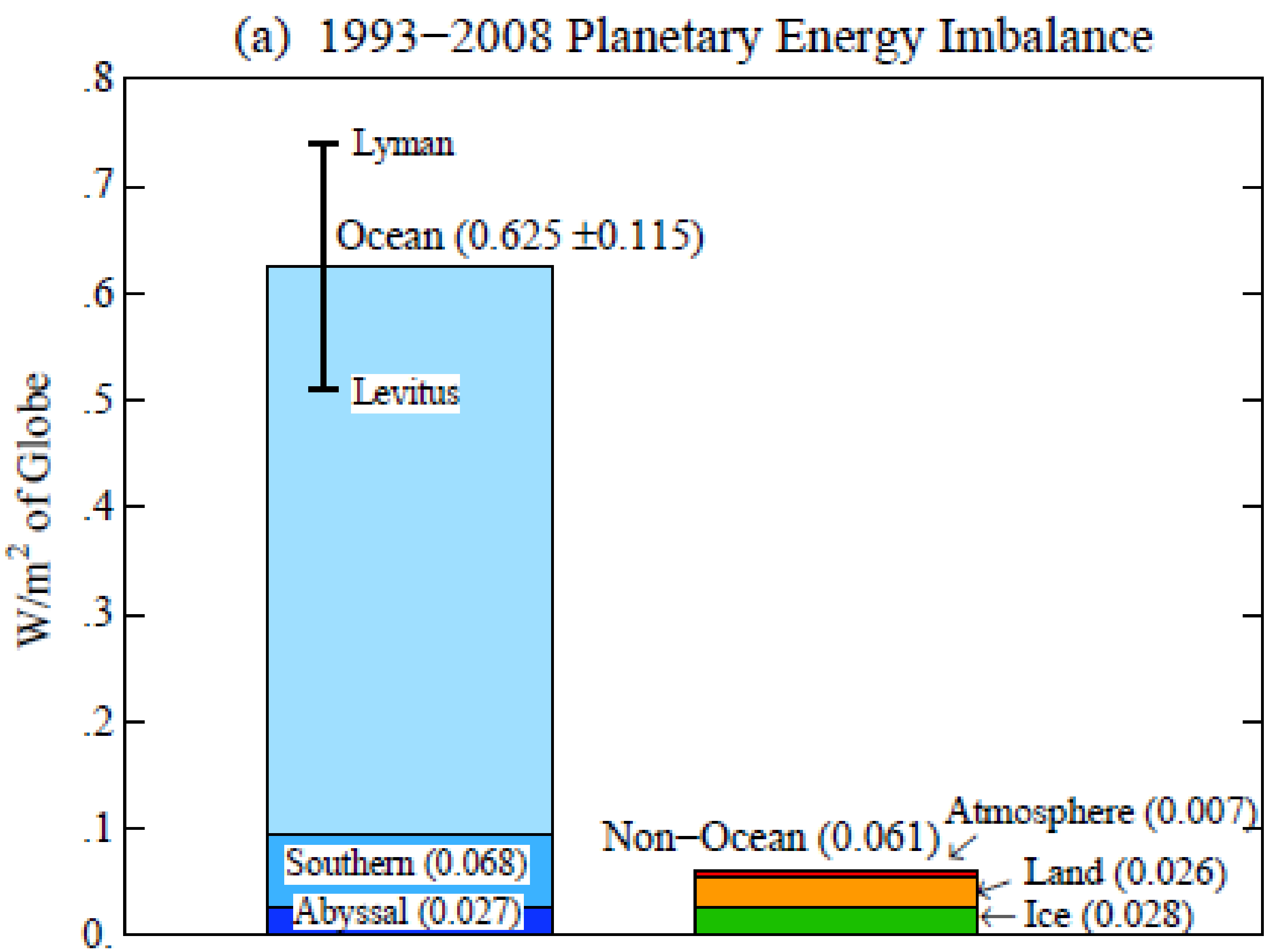
Ocean Heat Content not fixed!

28% of anthropogenic forcing equals the warming in the oceans and about 70% goes back to space.

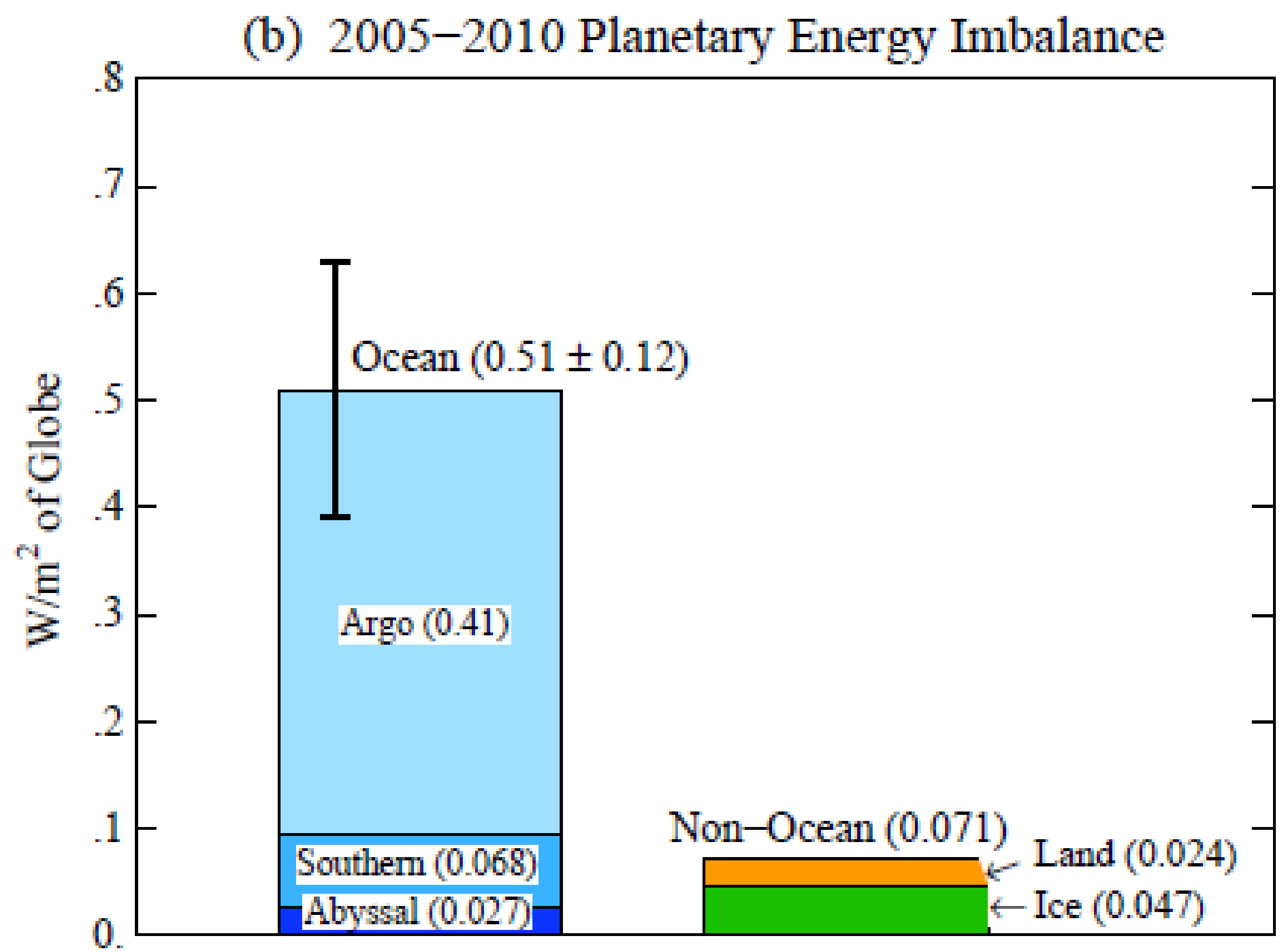
90% of anomalous warming is in the oceans.

0.7 W/m² to atmosphere only is about 1.5K/yr

Trad. Hydrography



From the Argo Era

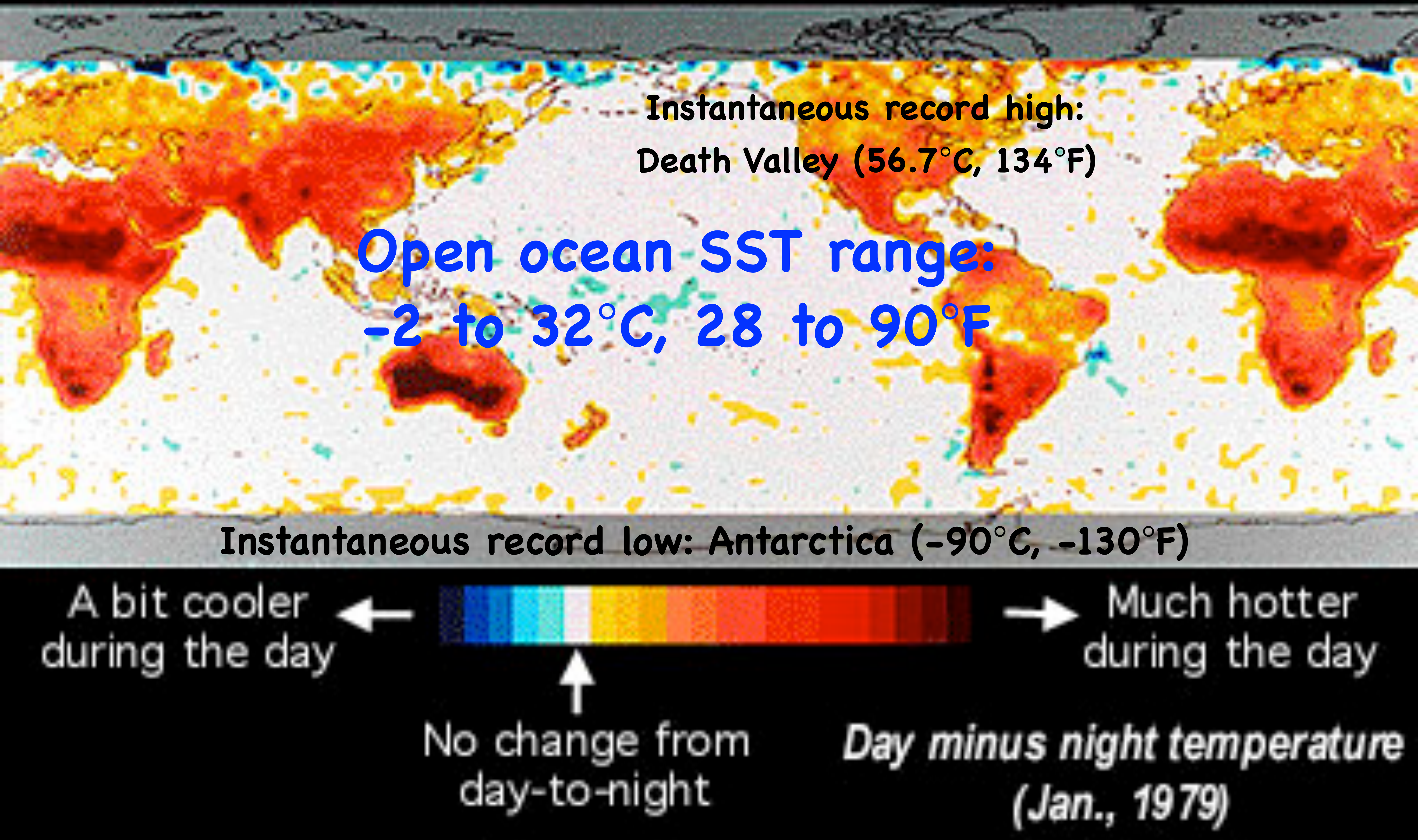


Hansen et al. (2011)

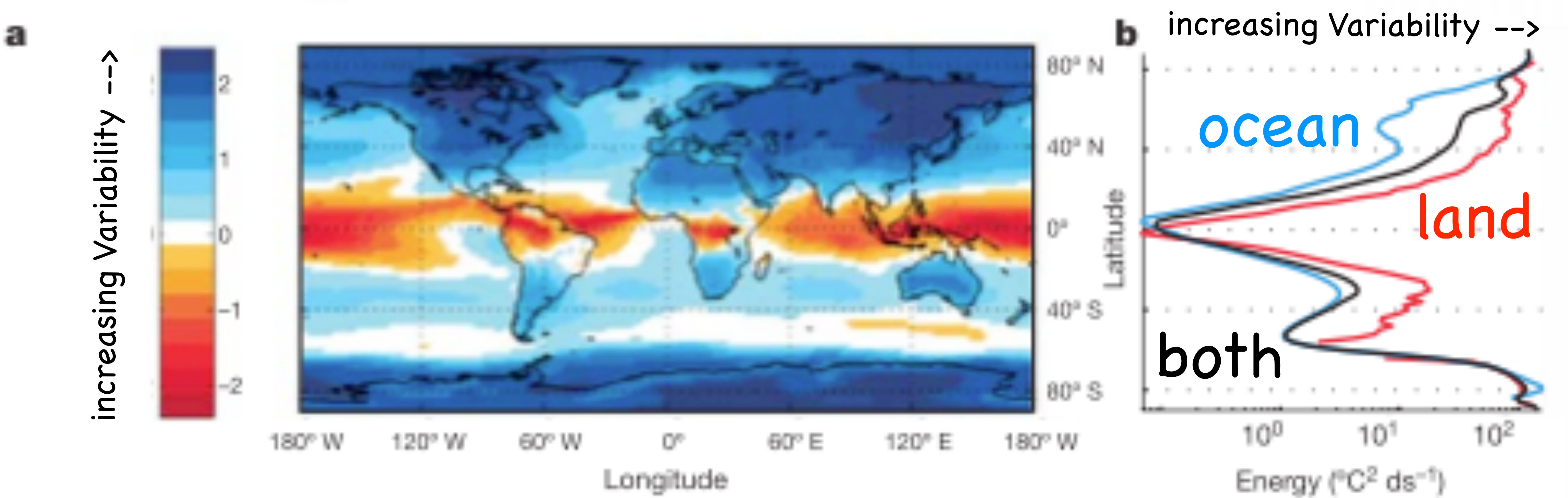
Continental Vs. Maritime:

Day - night air temperature change

Land: up to 30°C Ocean: ~1°C



Seasonal Temperature Variability



- Similar patterns show the degree of Summer to Winter Temperature difference. (Huybers & Curry, 2006)

Melting ice—Latent Heat

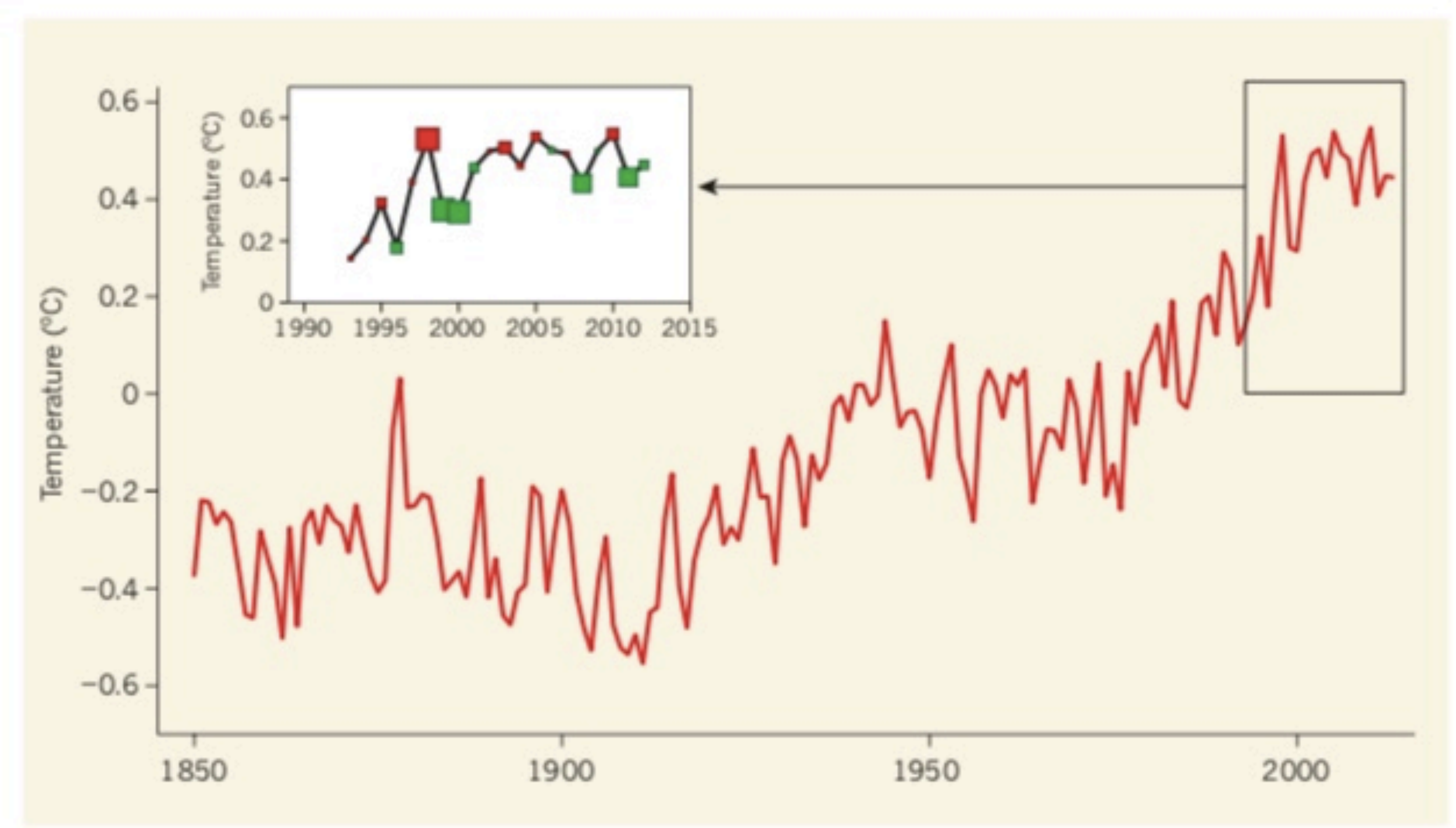
- ice first warms to the melting point (0.5 cal/g/°C)
- latent heat of fusion (80 cal/g) goes into melting (higher than almost any other substance)

Vaporization and Evaporation—Latent Heat

- Water requires enough energy to warm to the boiling point (1.0 cal/g/°C)
- latent heat of vaporization is 540 cal/g (higher than almost any other substance)

A Revealing Example: The "Hiatus"

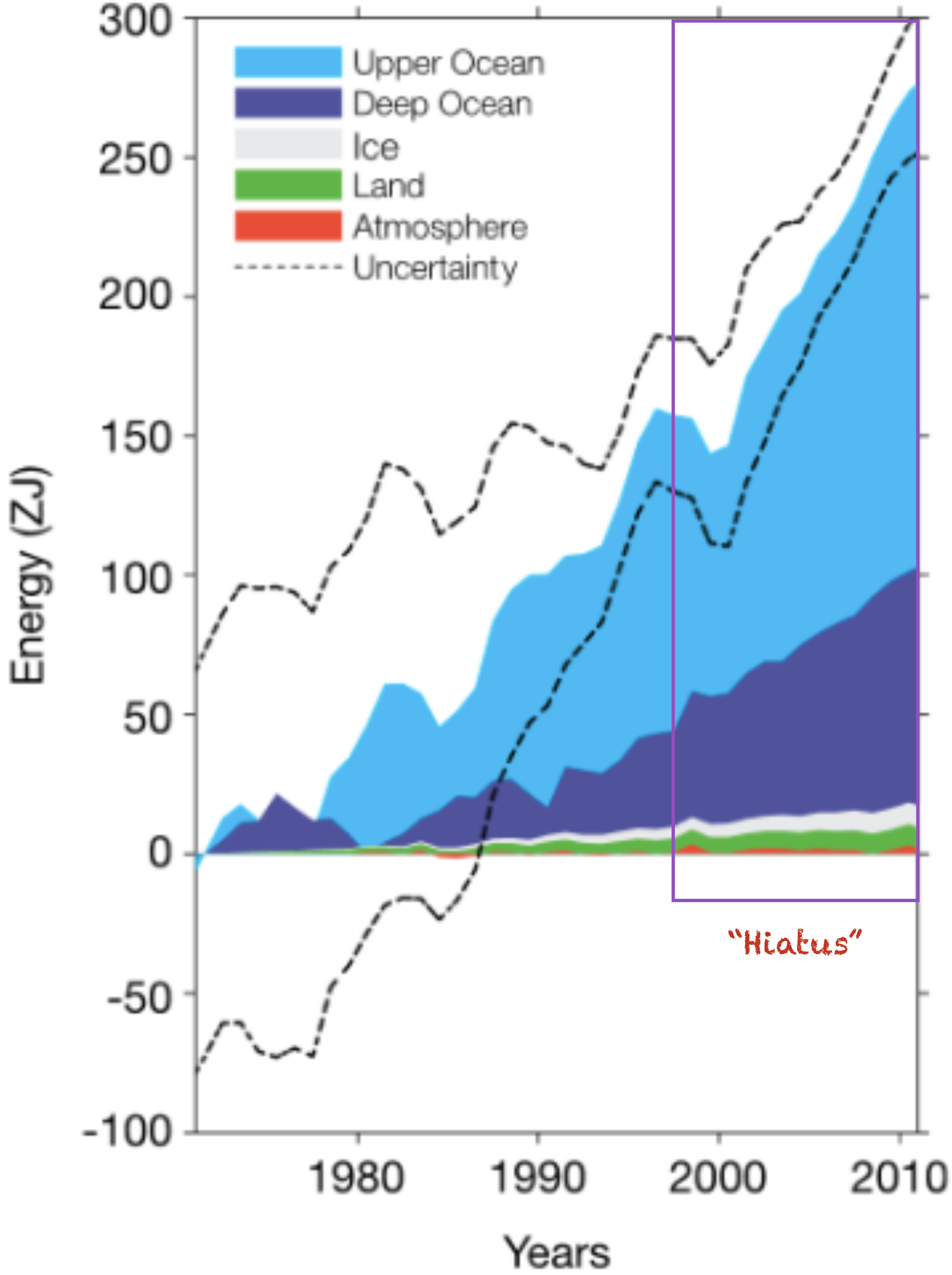
Global Mean Surface Temperature = GMST



Held, I.M., 2013. Climate science: The cause of the pause. *Nature*, *501*(7467), p.318.

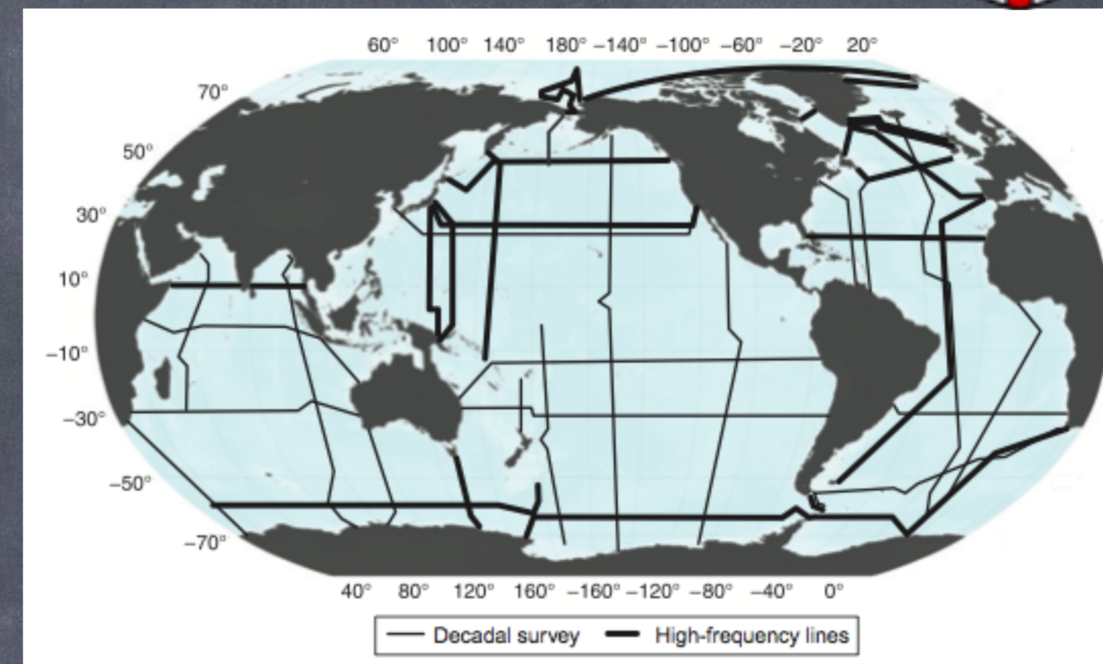
No Pause in Ocean Heat Content

- Ocean heat capacity, even just mixed layer, is vastly larger than the atmosphere
- Remember—heat anomalies end up in the ocean
- Global Mean Surface Temperature is a tiny fraction of energy.



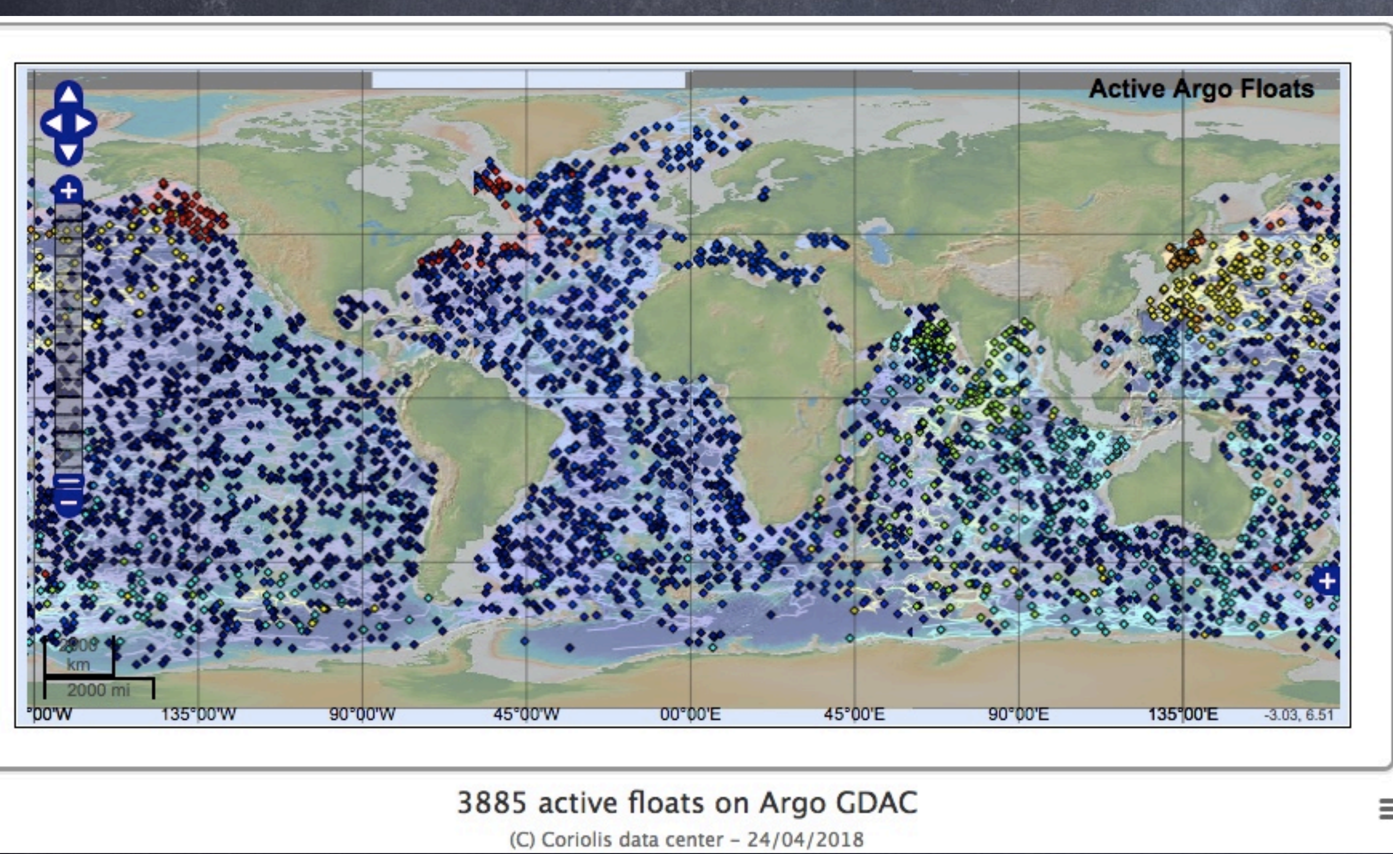
How do we know OHC?

Traditional Hydrography (http://www.ukosnap.org/)

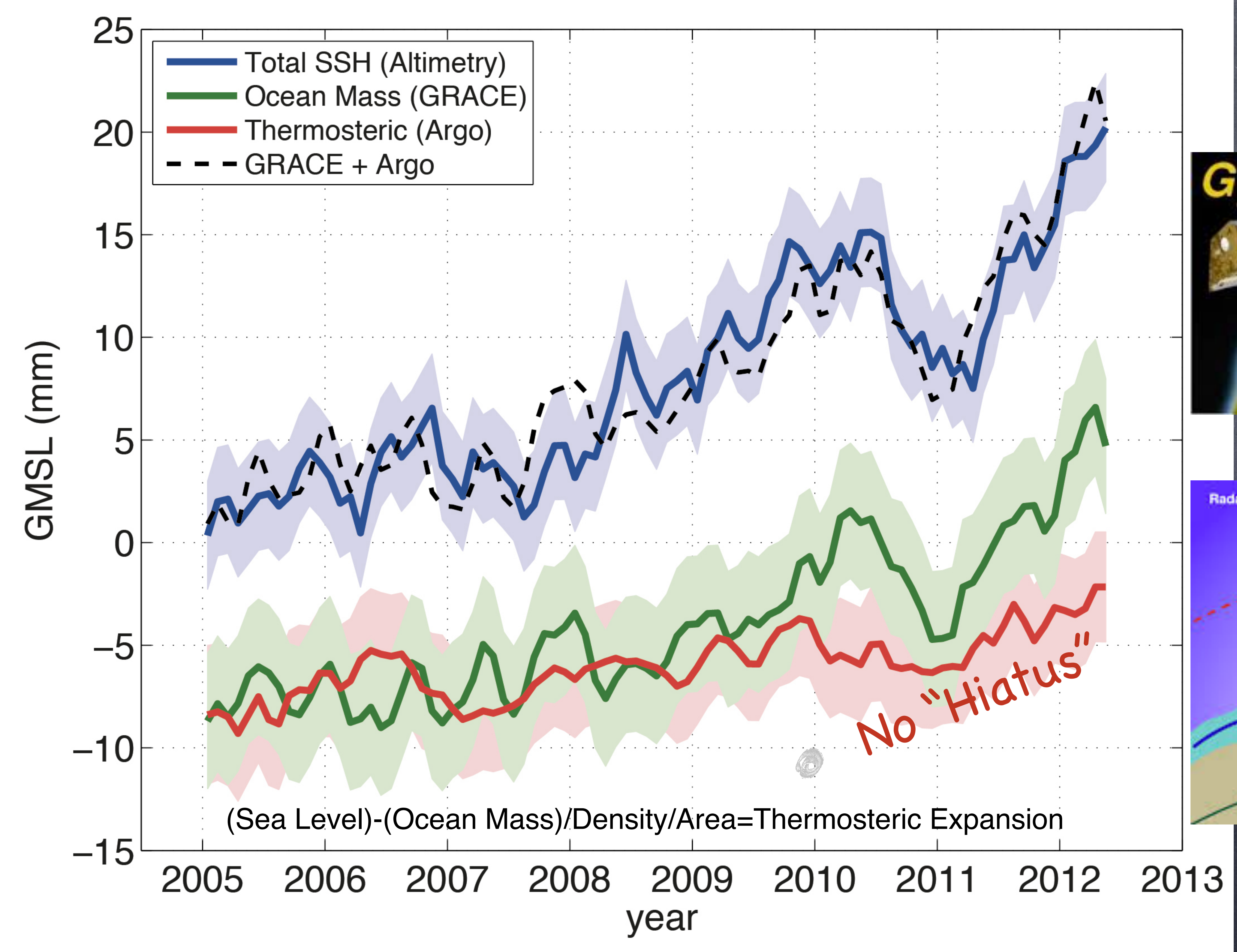


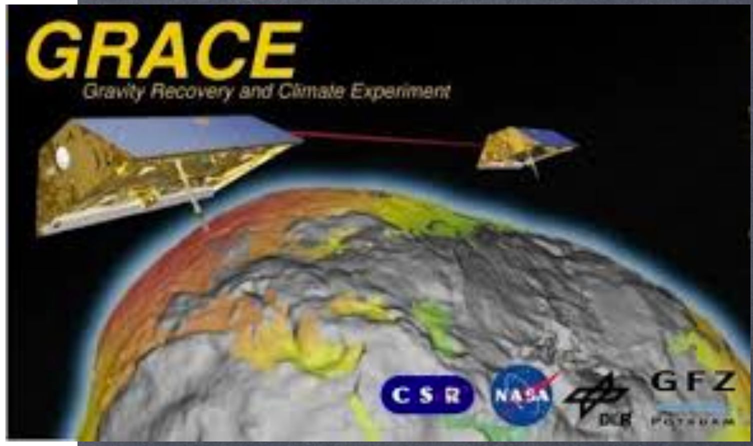
GO-SHIP repeat sections: Siedler et al. 2013

Autonomous: e.g., Argo and Satellites.
http://www.argo.ucsd.edu/

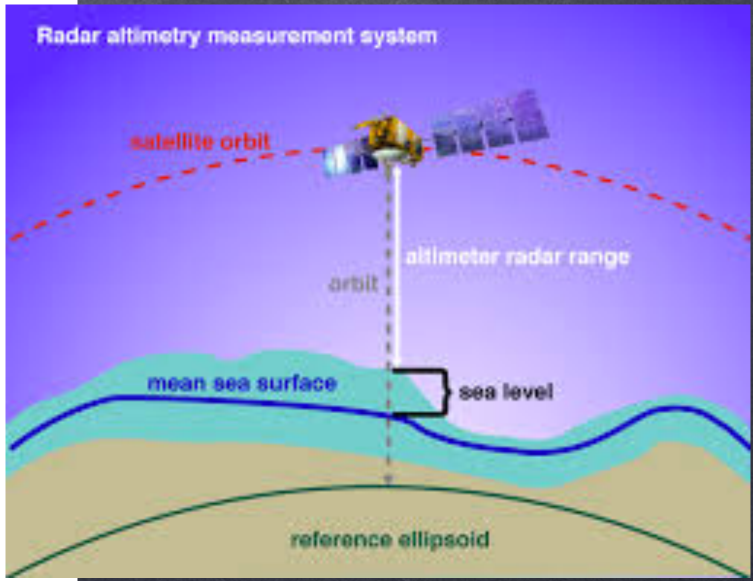


Another reason to care about ocean warming— and to observe it (by inference): Sea Level Rise





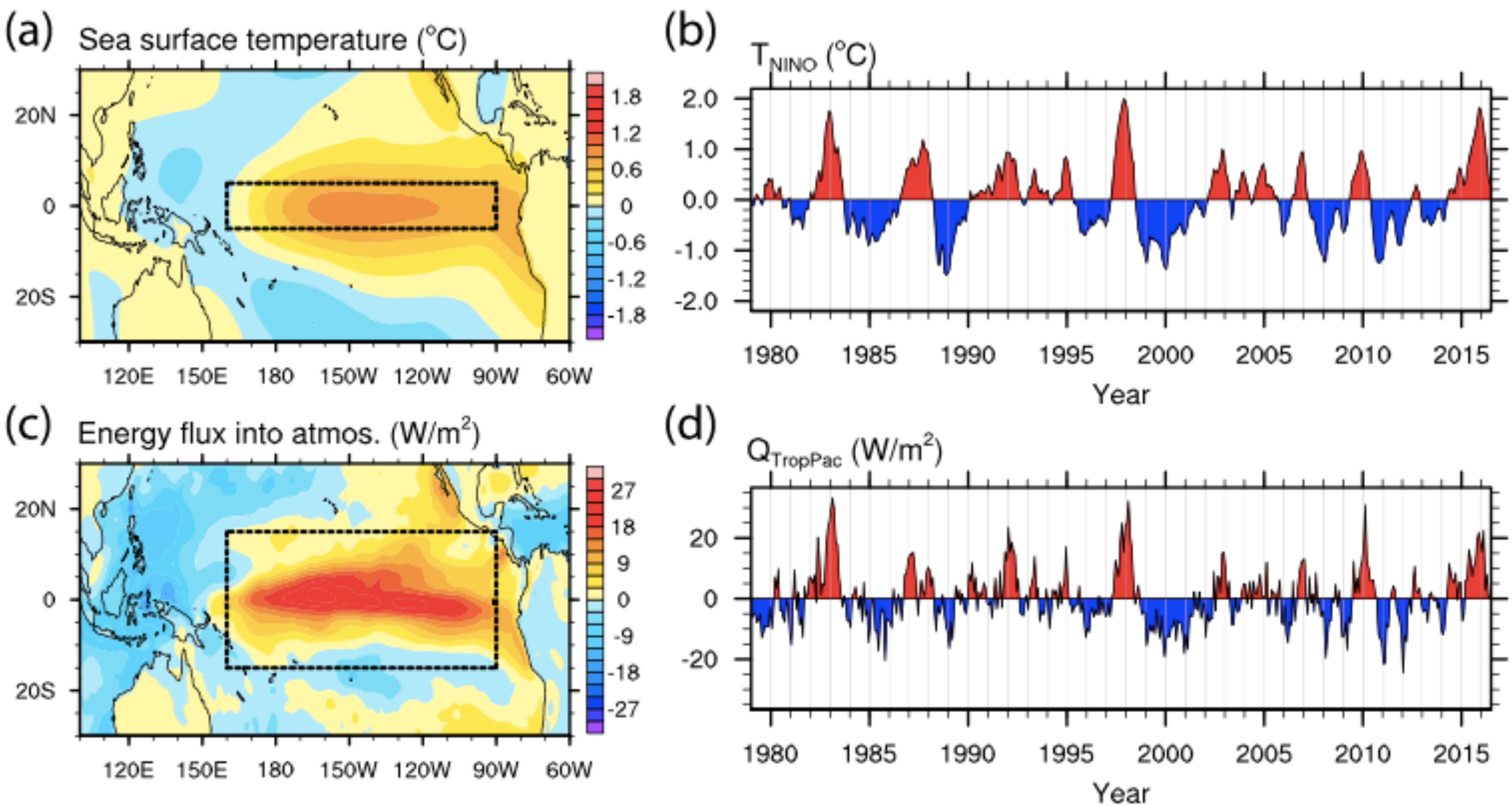
podaac.jpl.nasa.gov



nesdis.noaa.gov

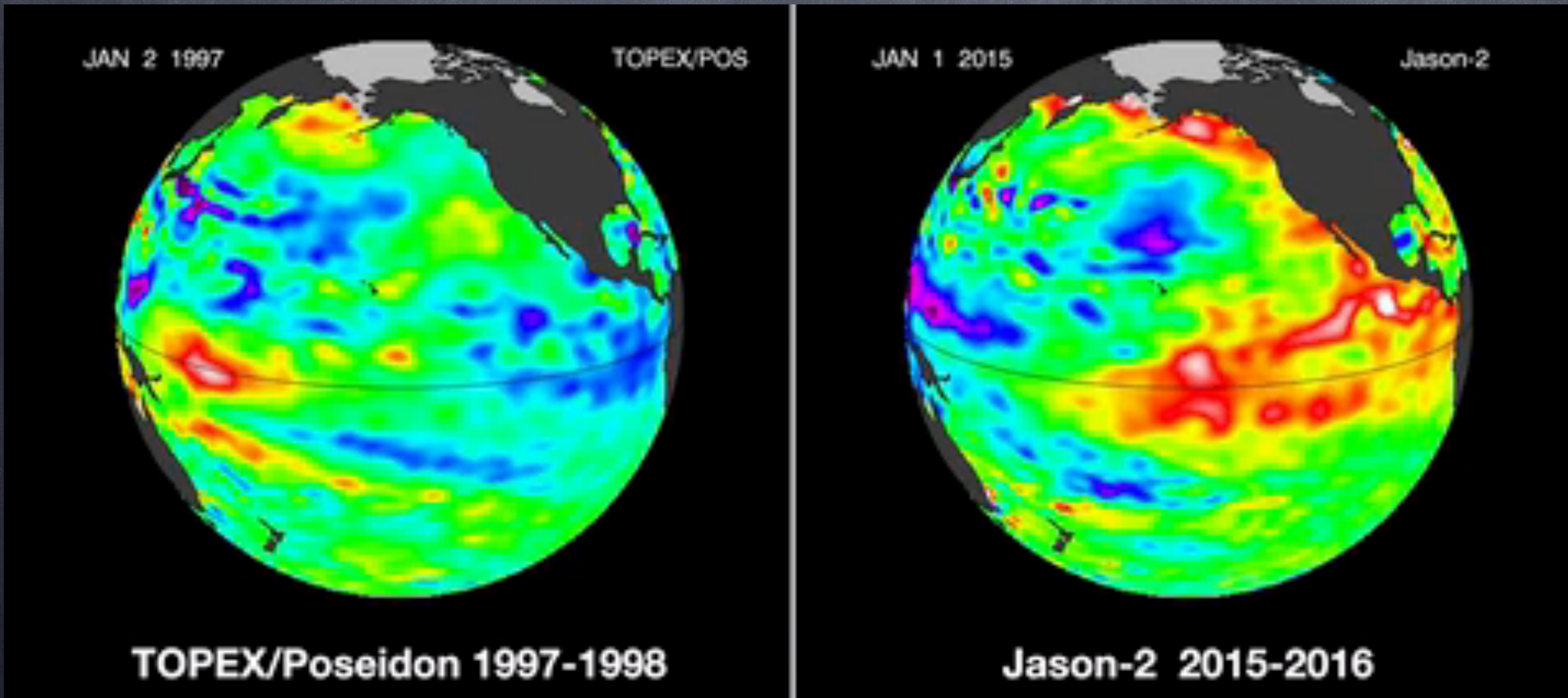
IPCC AR5, 2013

Effect of Climate Modes & Aerosols: Hu & Fedorov (2017)



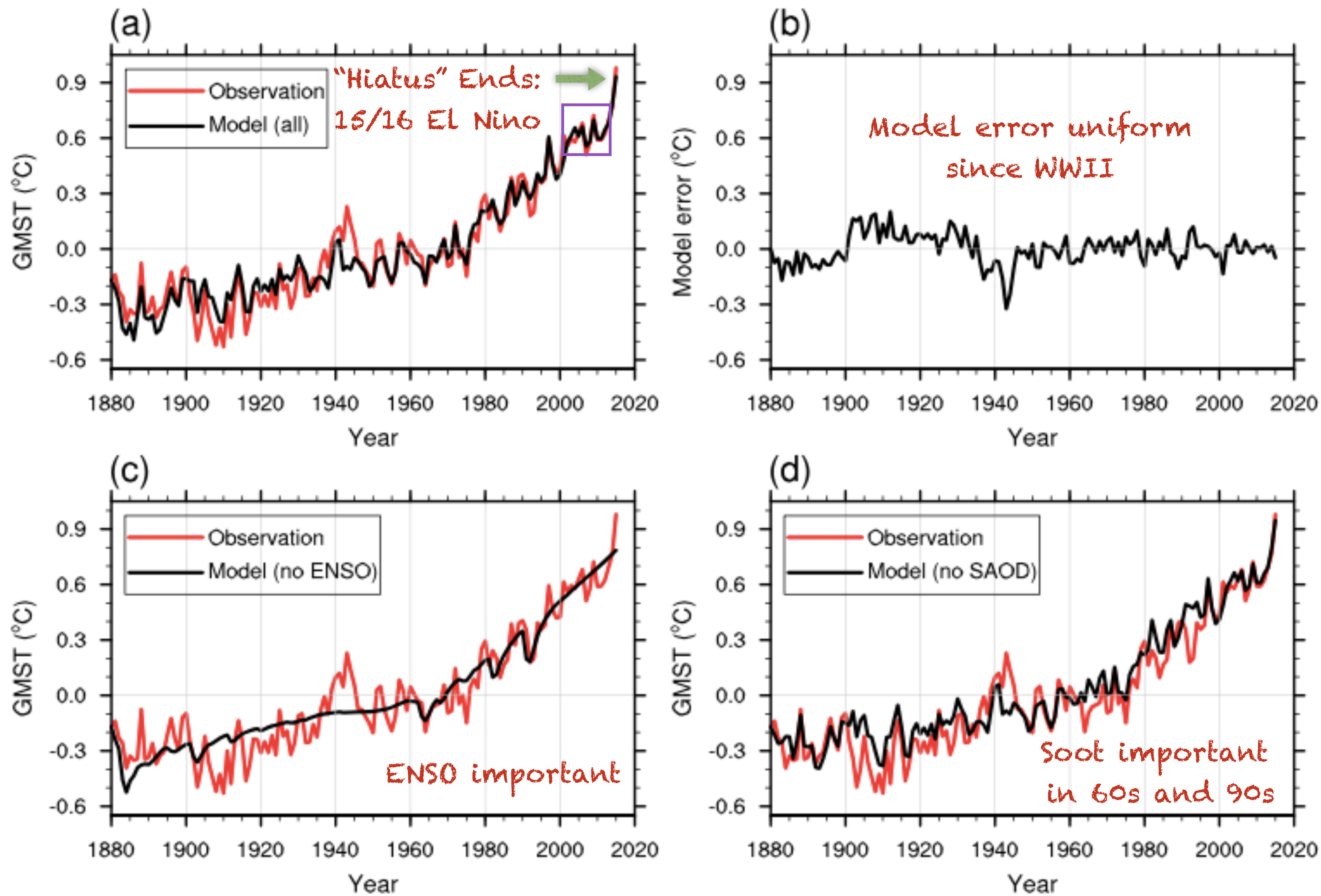
$$\frac{dT_g}{dt} = -\frac{T_g}{\tau} + a \cdot \log(CO_2/CO_{2,\mathrm{ref}}) + b \cdot T_{\mathrm{NINO}} + c \cdot \mathrm{SAOD} + d,$$

El Nino: 1998 vs 2015



- SSH Movie Credit: NASA JPL

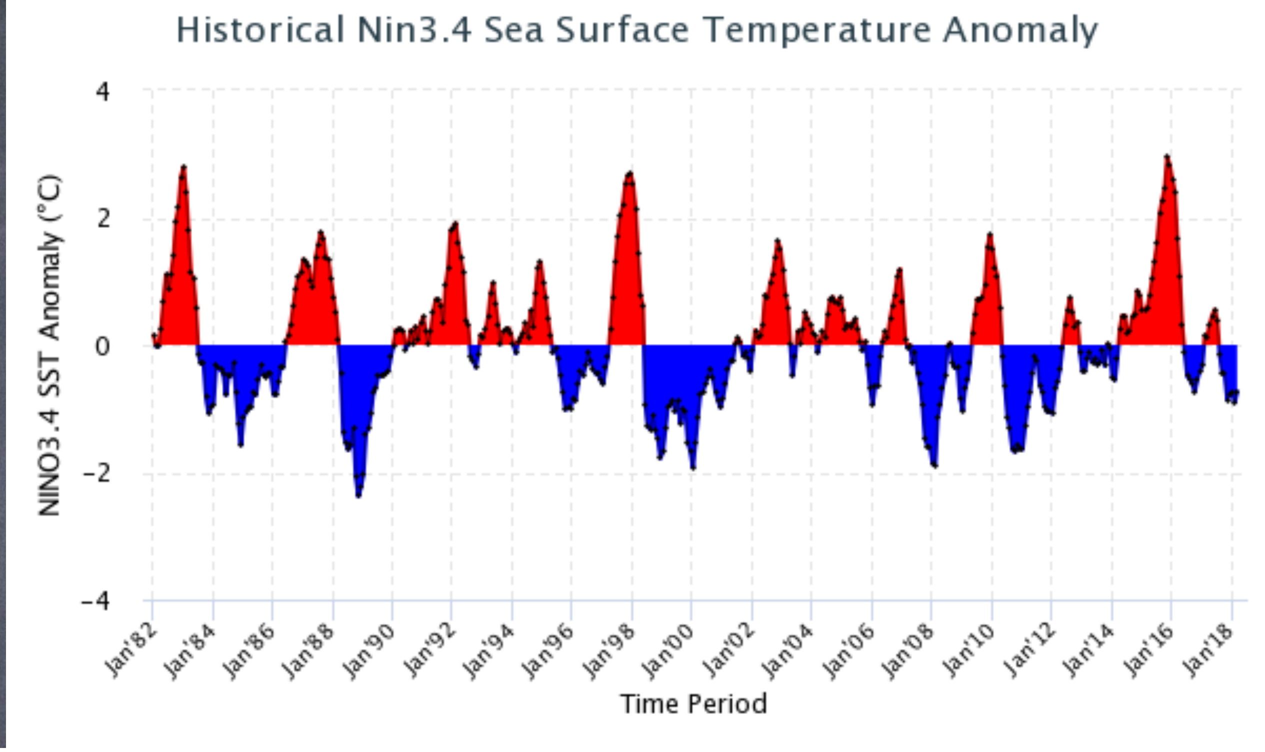
Effect of Climate Modes & Aerosols: Hu & Fedorov (2017)

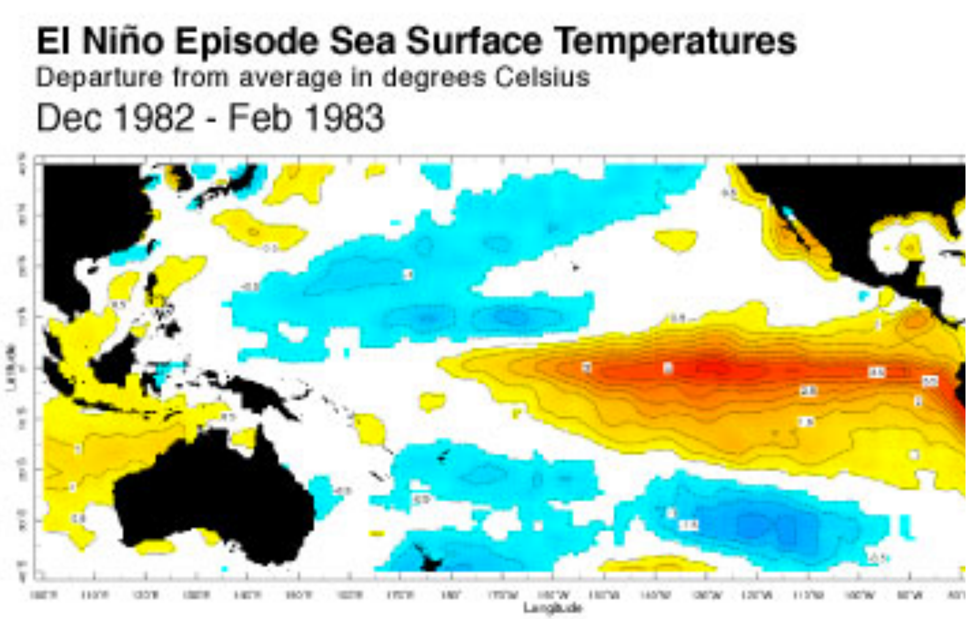


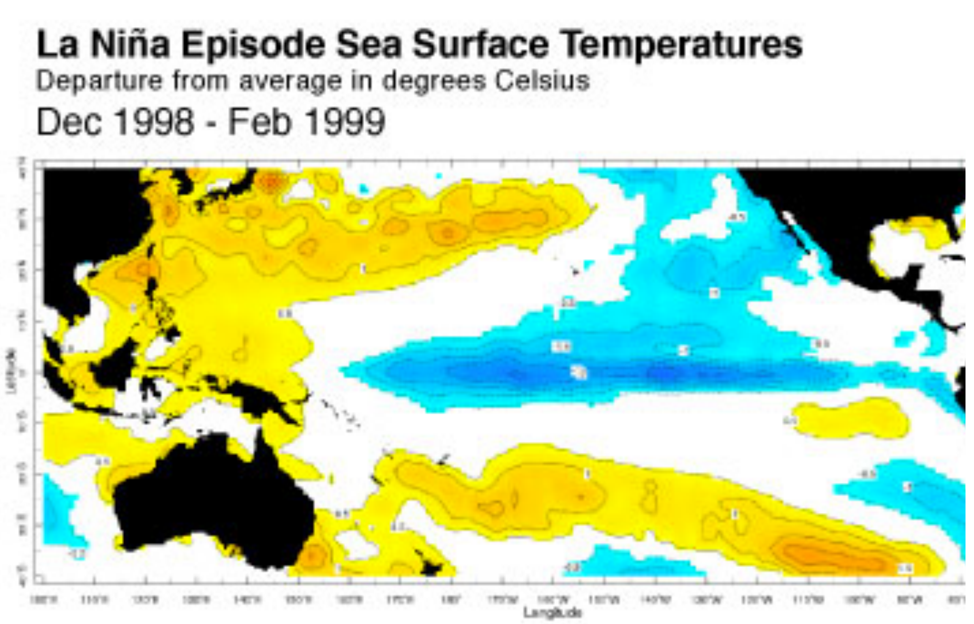
Prediction of ENSO

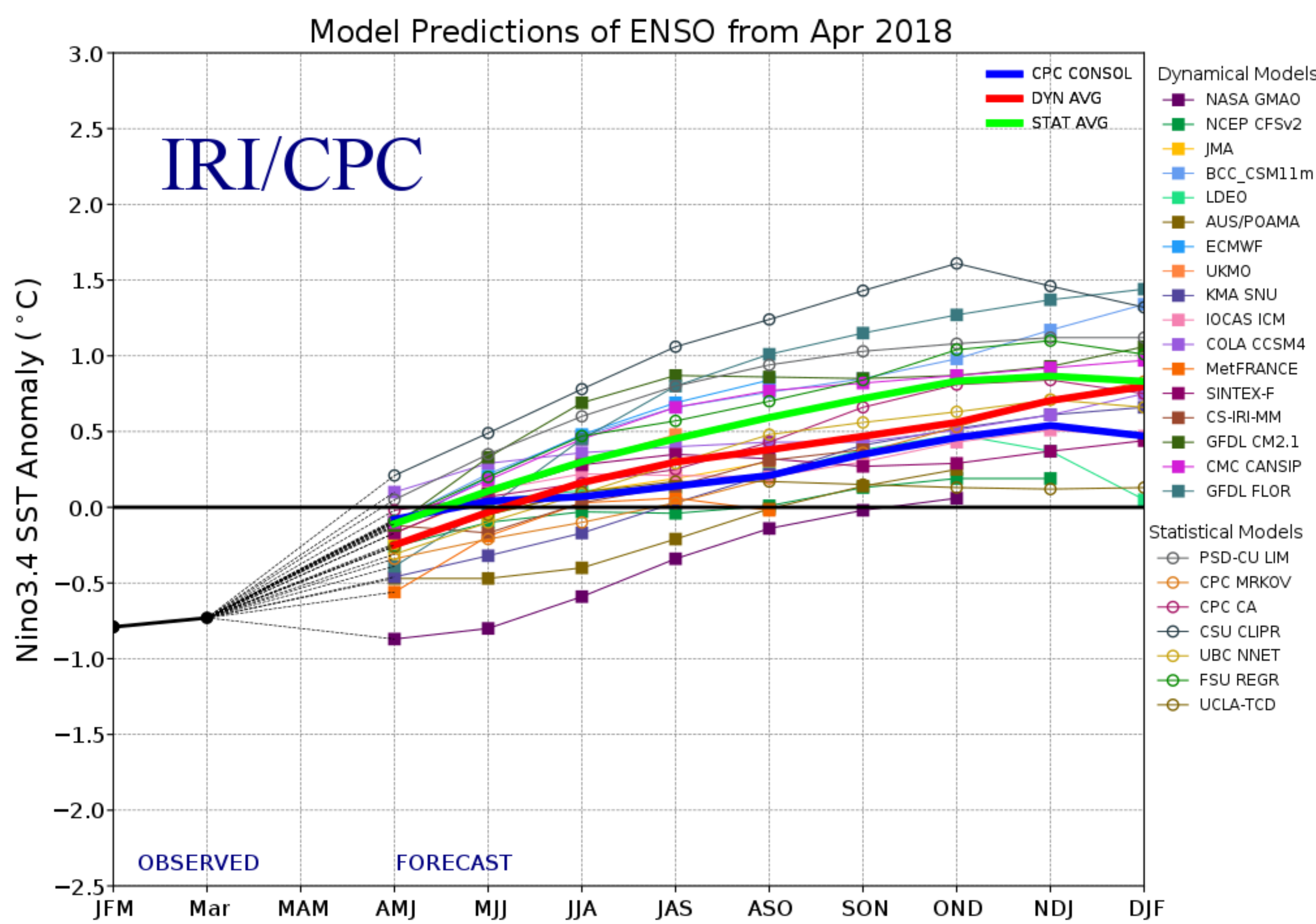
Predictability of ENSO events limited to < 1.5yr

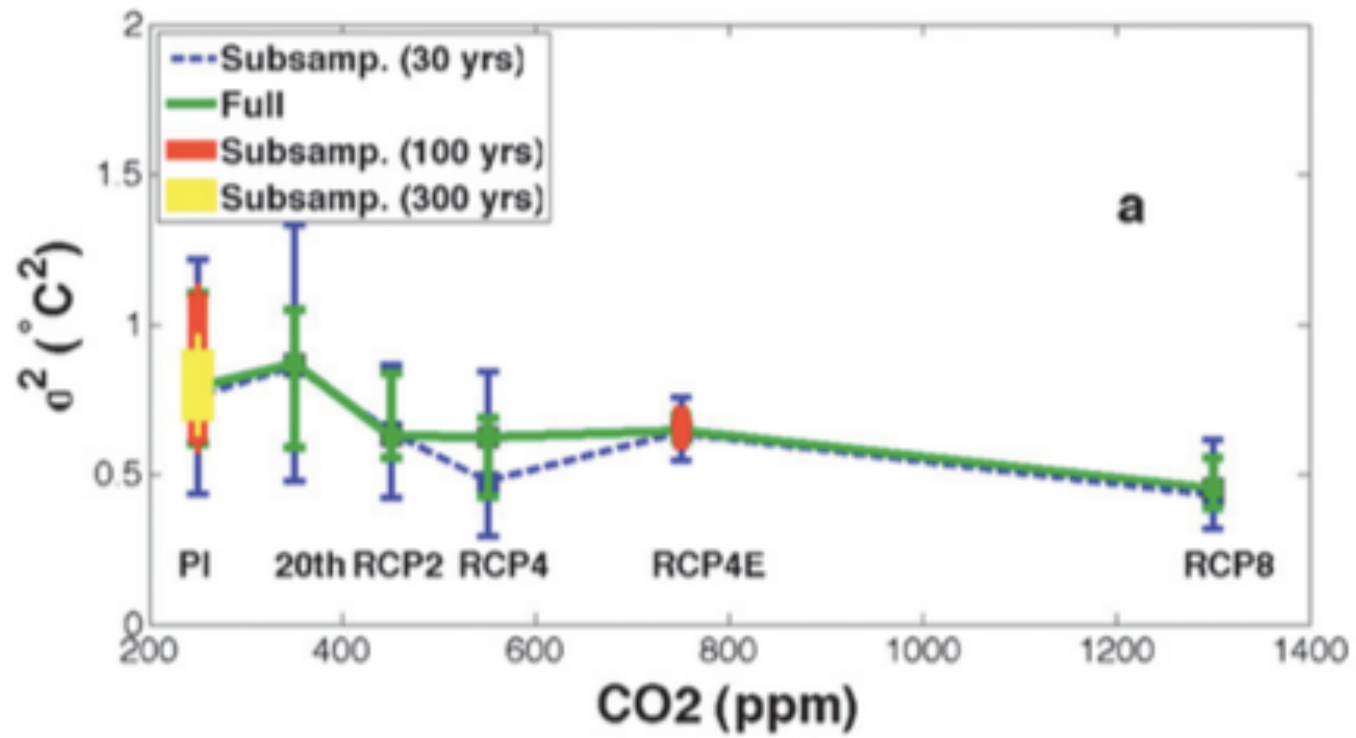
ENSO statistics more predictable?











Does ENSO variability change with climate?...

(>200 yr to detect)

Almost no GHG change to ENSO

Big GHG-induced change to ENSO impacts!

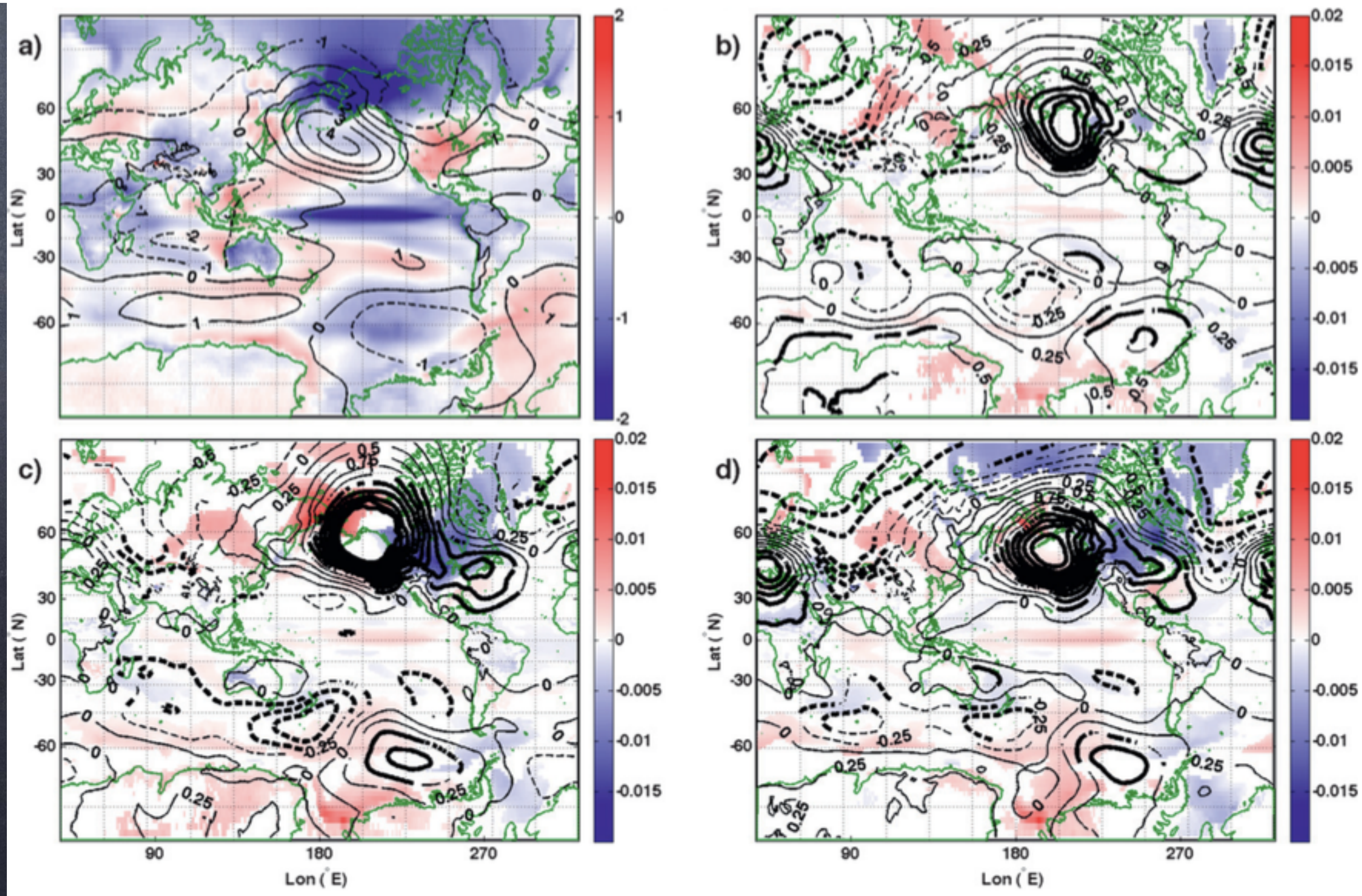


FIG. 6. As in Fig. 5 but for La Niña DJF

S. Stevenson, BFK, M. Jochum, R. Neale, C. Deser, and G. Meehl. Will there be a significant change to El Nino in the 21st century? Journal of Climate, 25(6):2129-2145, March 2012.

Decadal Predictions

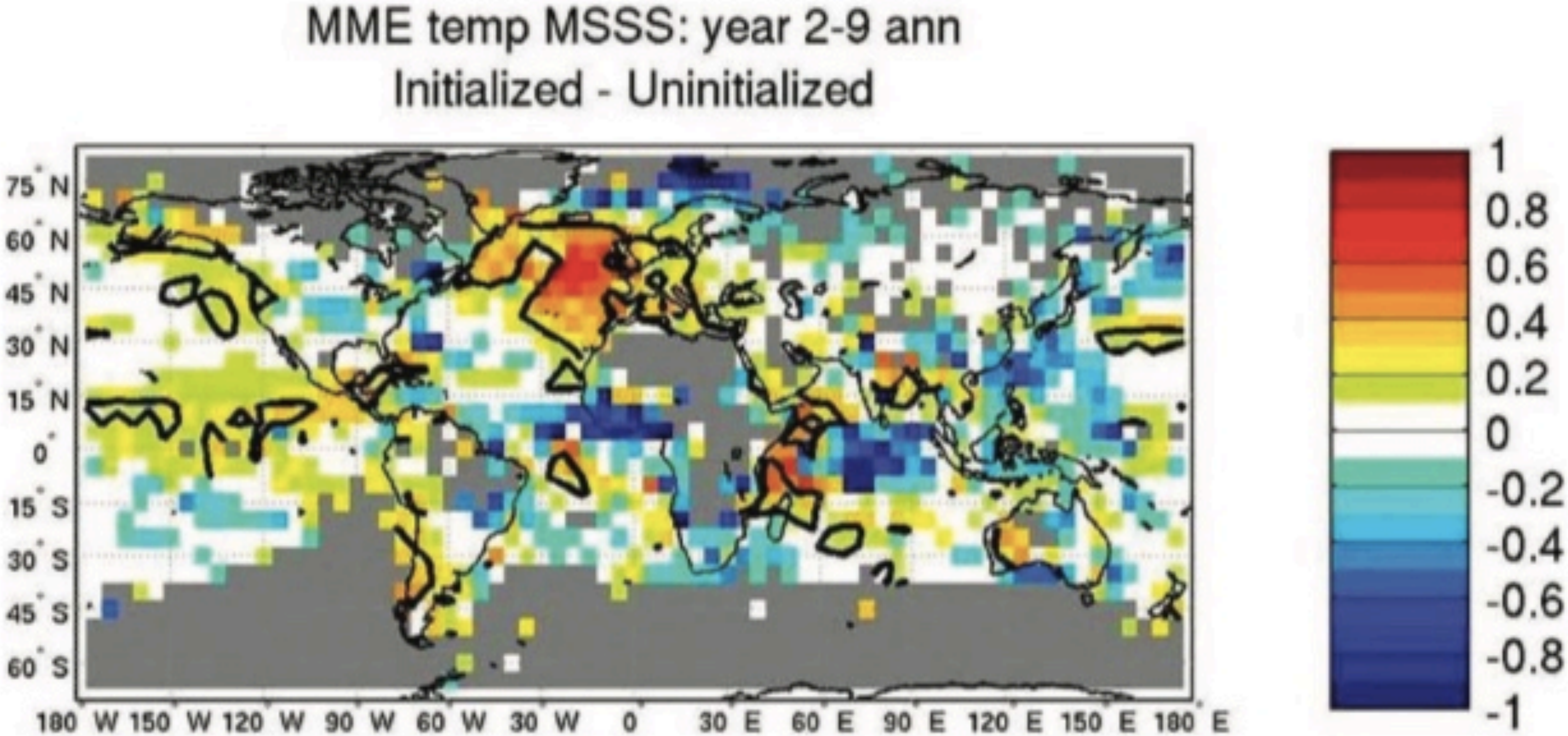
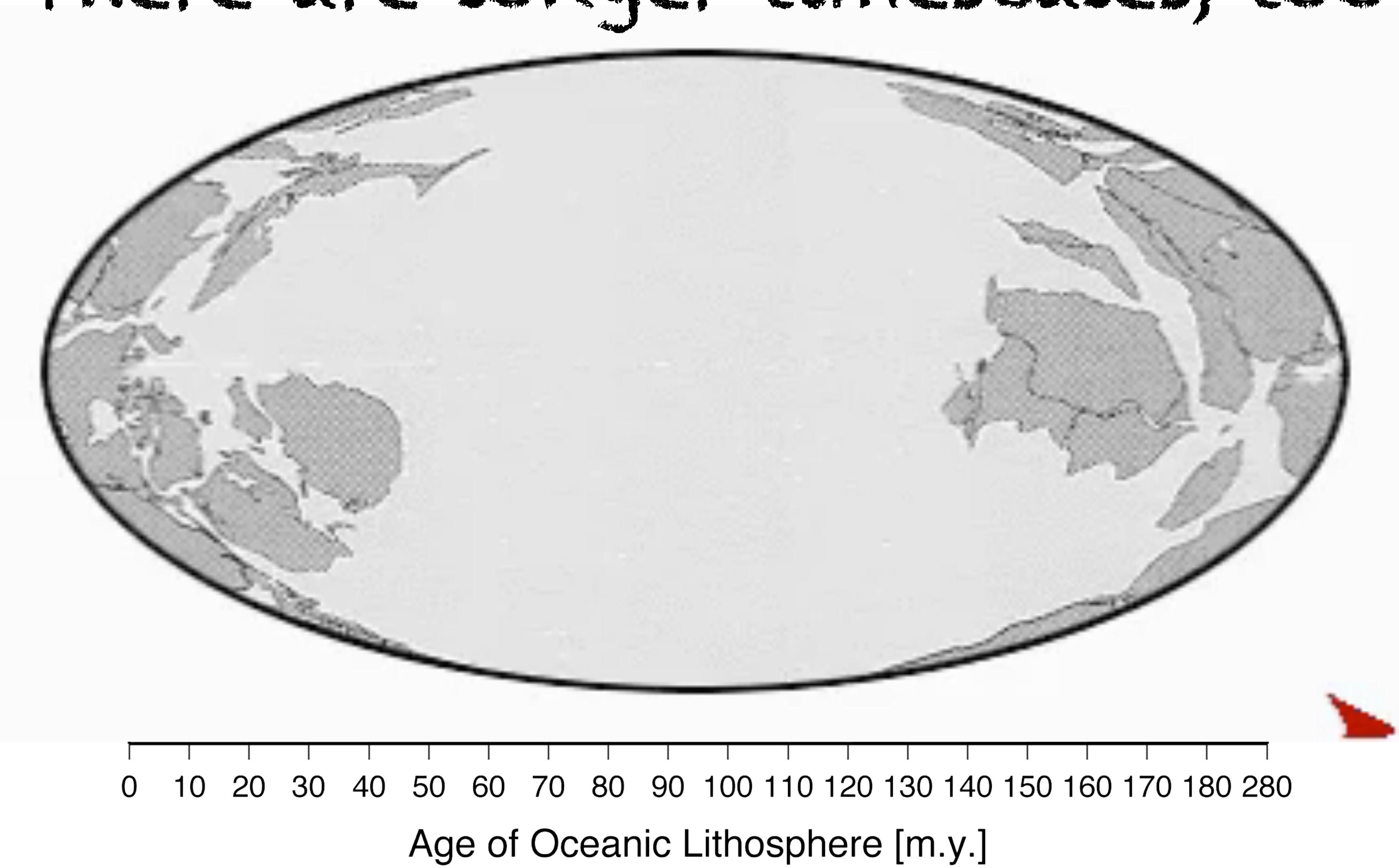


Fig. 3. Mean squared skill score (MSSS) differences for decadal temperature hindcasts from a 12-member multimodel ensemble from CMIP5, for the initialized hindcasts ("forecasts") minus the uninitialized hindcasts ("reference") as predictions of the observed climate. The forecast target is years 2–9 following

A Bright Spot—in some regions, long timescales of the ocean memory yield predictive skill!

Meehl et al. 2014: Decadal Climate Prediction: An Update from the Trenches

There are longer timescales, too

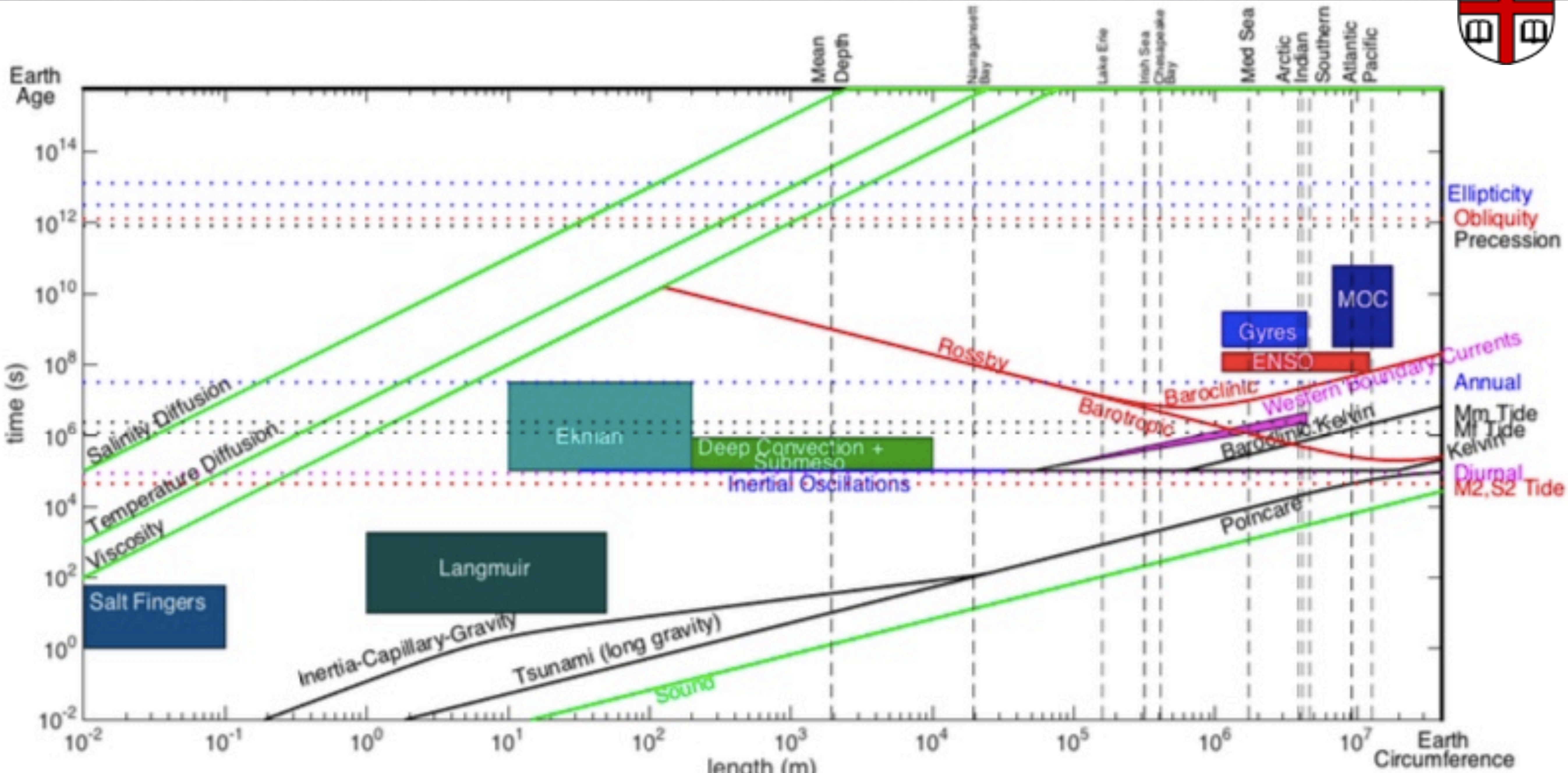


http://www.ucmp.berkeley.edu/geology/tectonics.html

Sea floor age (millions of years). Black lines indicate tectonic plate boundaries.
Source: From Müller, Sdrolias, Gaina, and Roest (2008).

TALLEY

The Ocean is Vast & Diverse

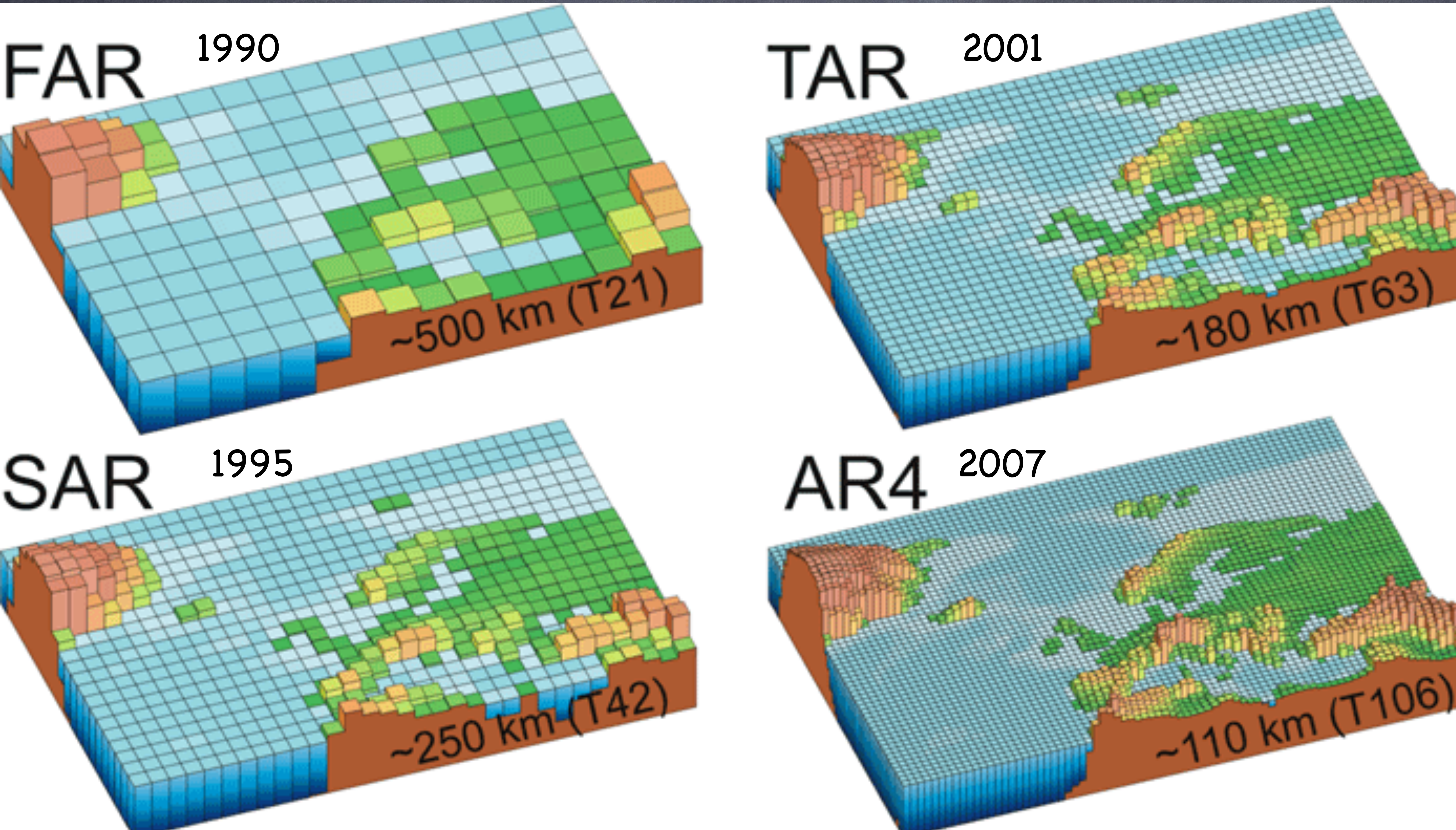


The climate also depends on atmosphere, cryosphere, biosphere, pedosphere, lithosphere & coupled modes!— We need models to integrate and explore.

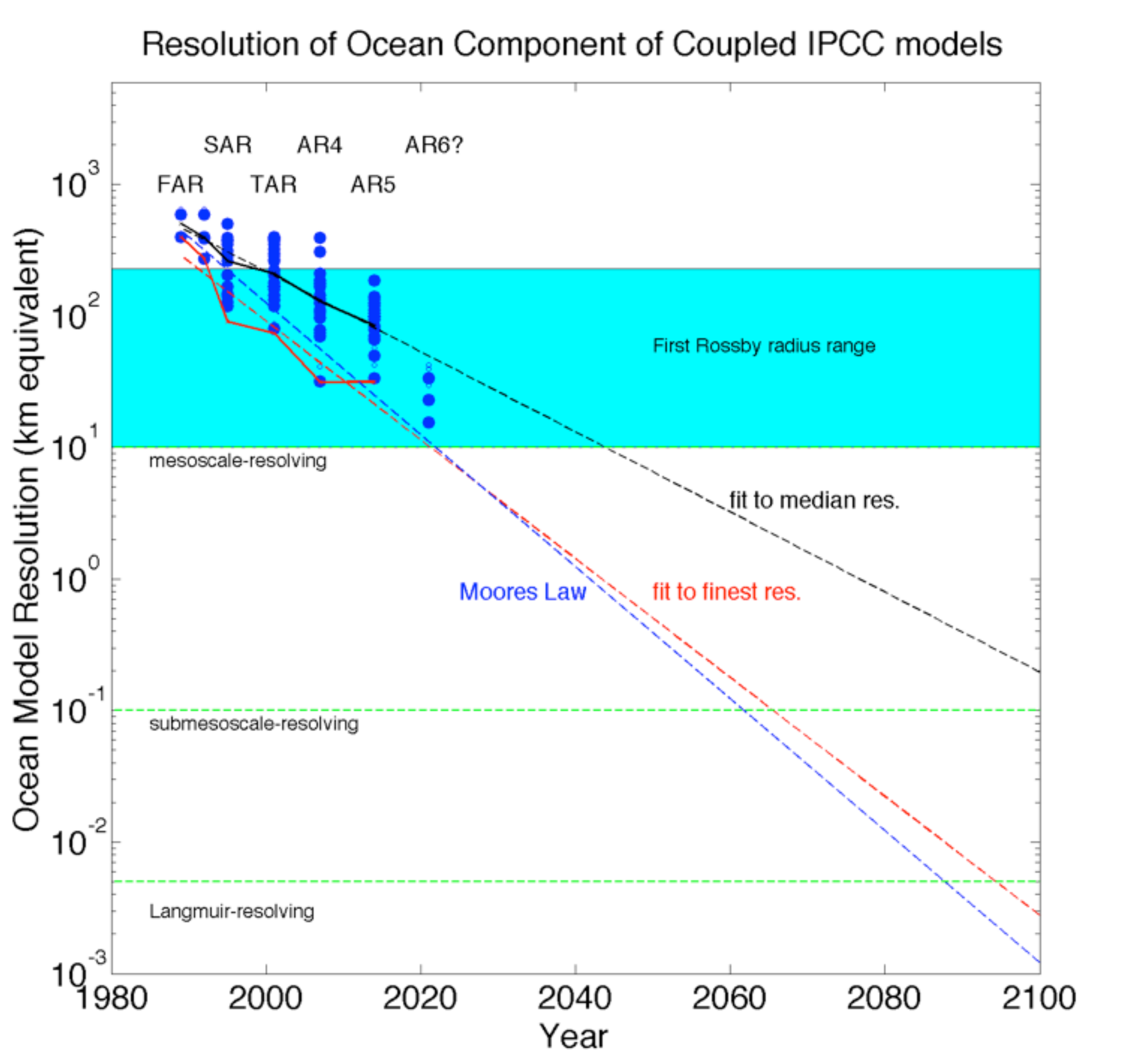
D. B. Haidvogel, E. N. Curchitser, S. Danilov, and BFK. Numerical modelling in a multi-scale ocean (invited). In The Sea: The Science of Ocean Prediction, special issue. Journal of Marine Research, December 2017. In press.

Climate model resolution introduces a scale...

Image: ipcc.ch



We are modeling important processes in climate models, right?
Don't we have big enough computers?



Here are the collection of IPCC models...

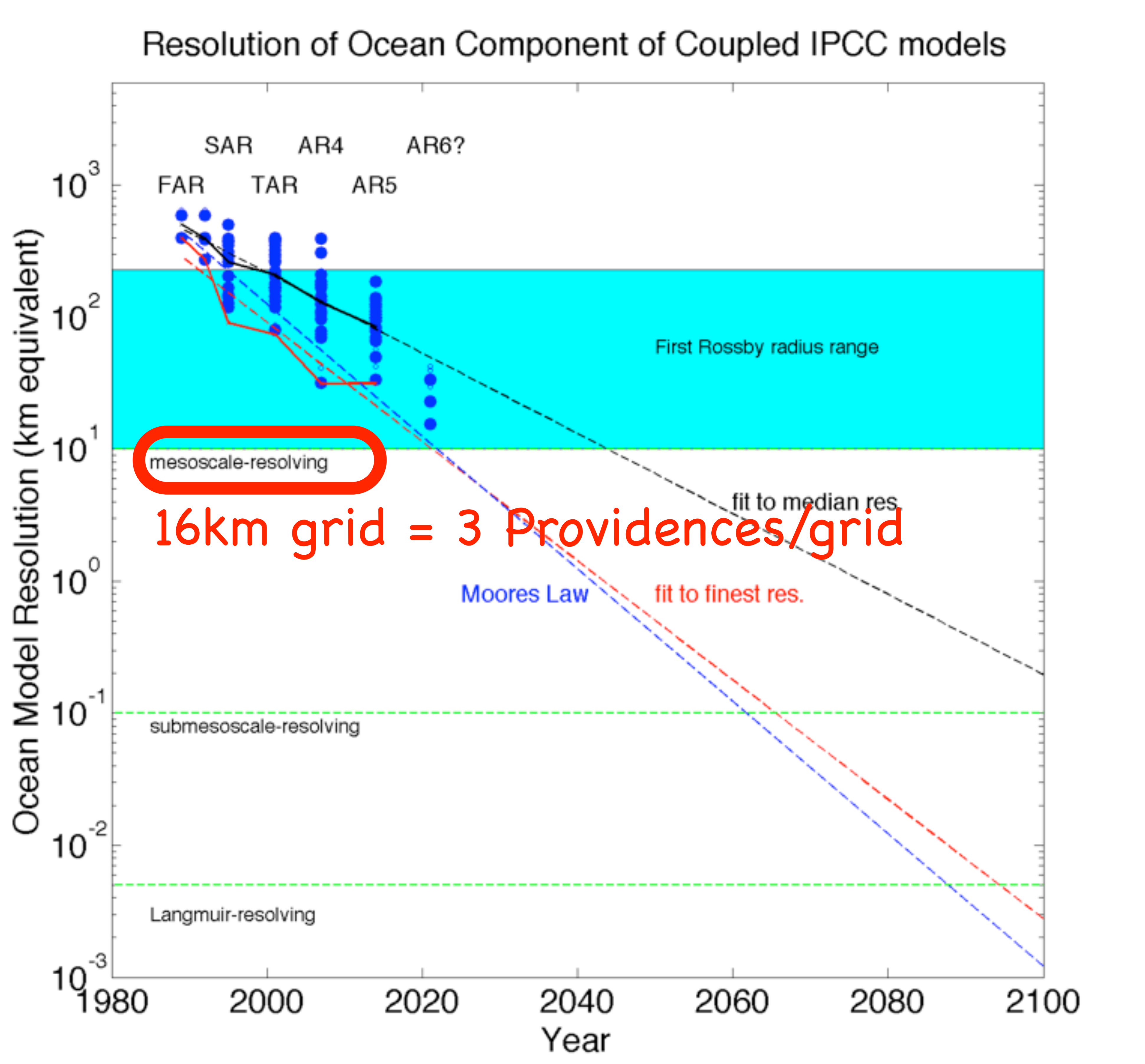
If we can't resolve a process, we need to develop a parameterization (educated guess) of its effect

BFK, 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.

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.

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

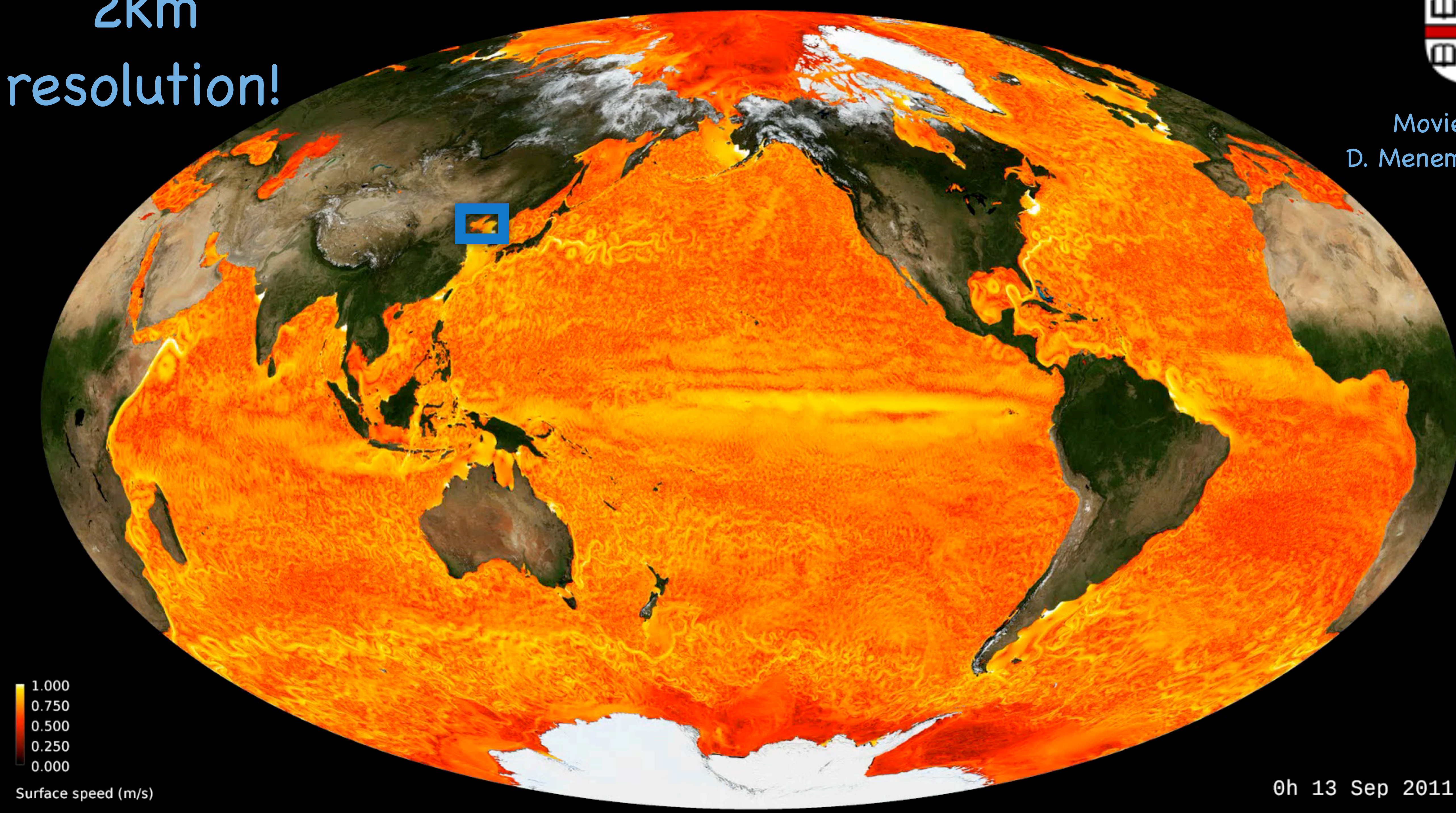
BFK, S. Bachman, B. Pearson, and S. Reckinger. Principles and advances in subgrid modeling for eddy-rich simulations. CLIVAR Exchanges, 19(2):42-46, July 2014.

Estimating the Circulation & Climate of the Ocean

LLC4320 Model

2km resolution!

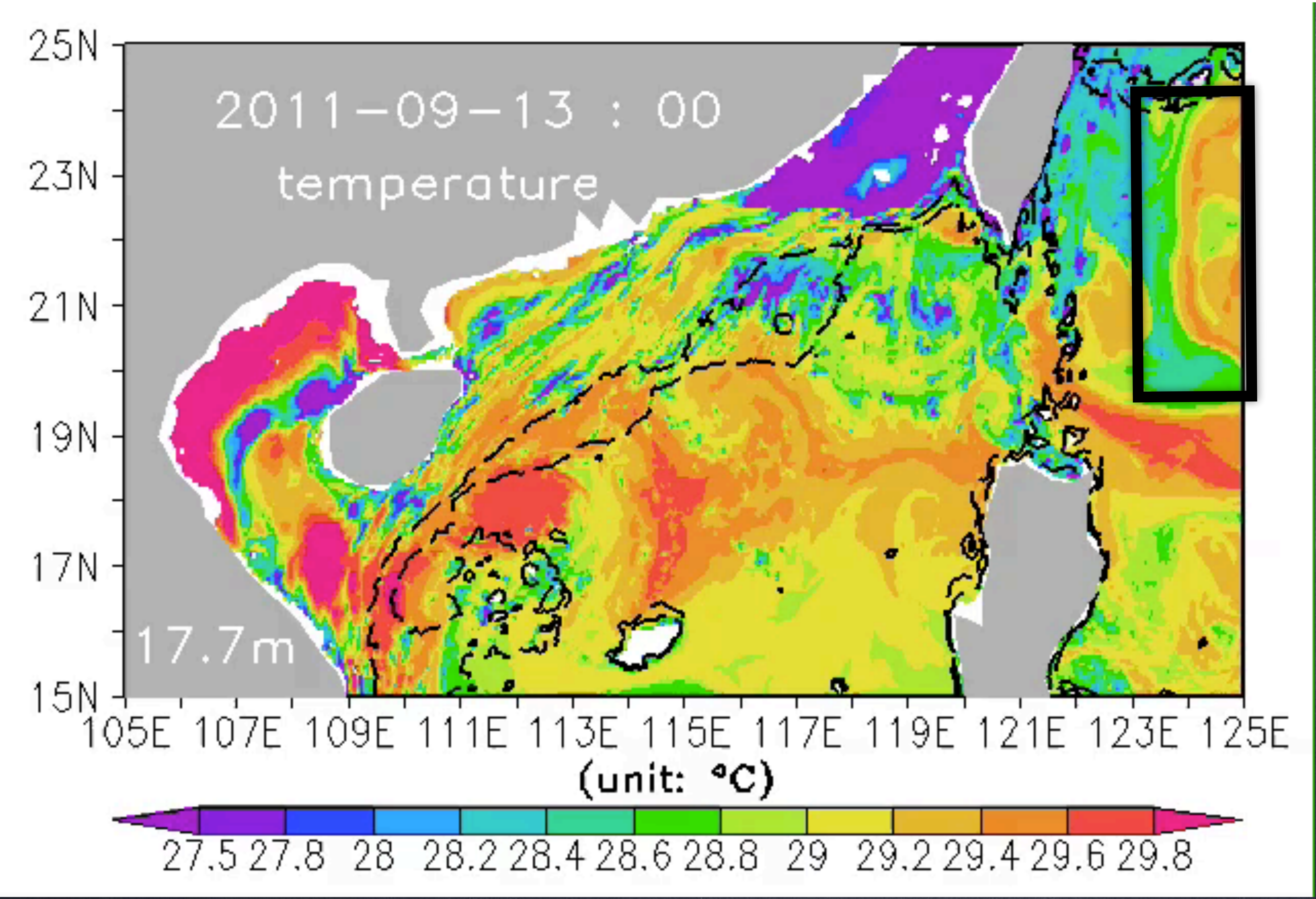
Movie: D. Menemenlis



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

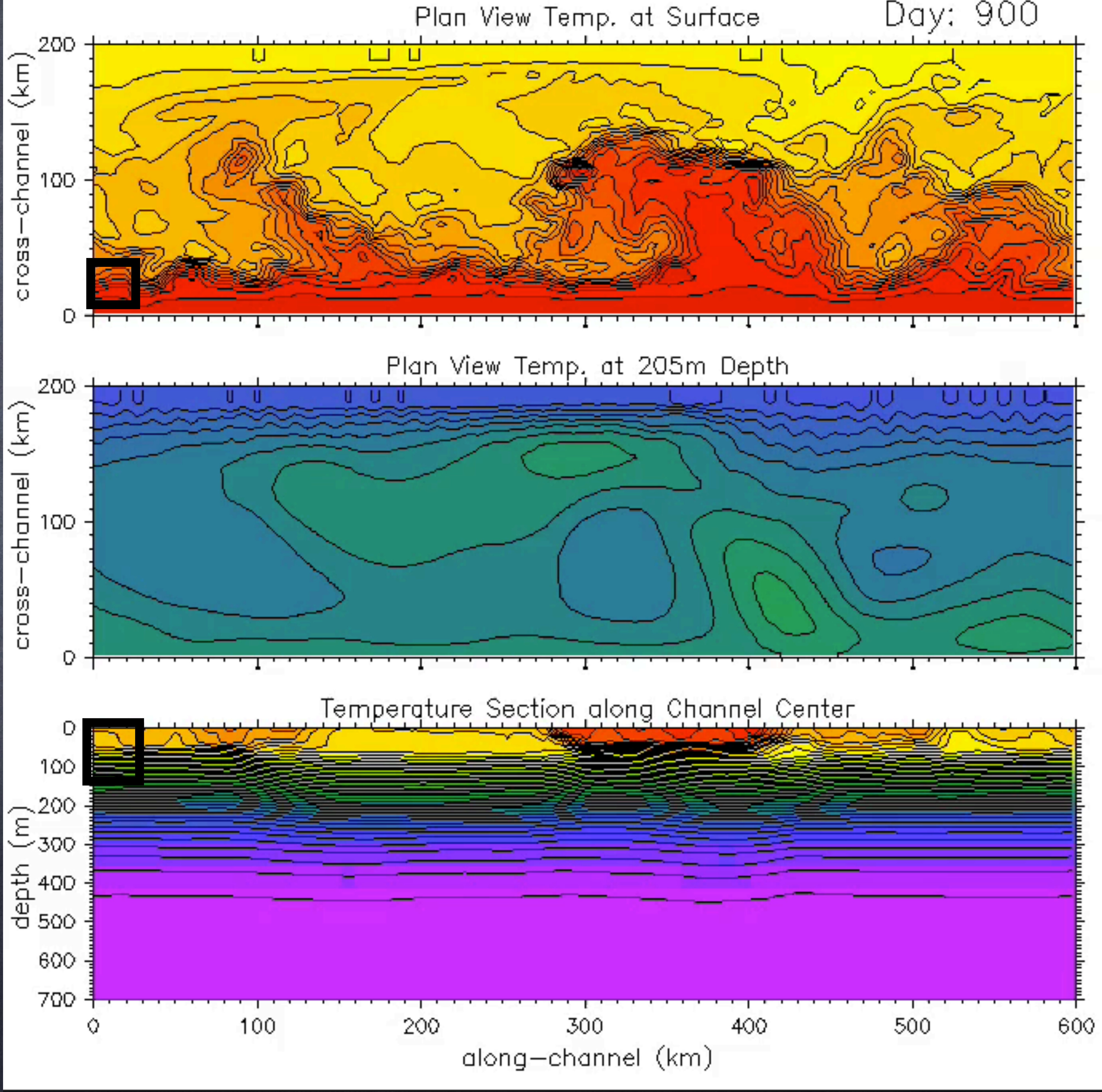


Movie:
Z. Jing

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, 121:1914-1930, April 2016.

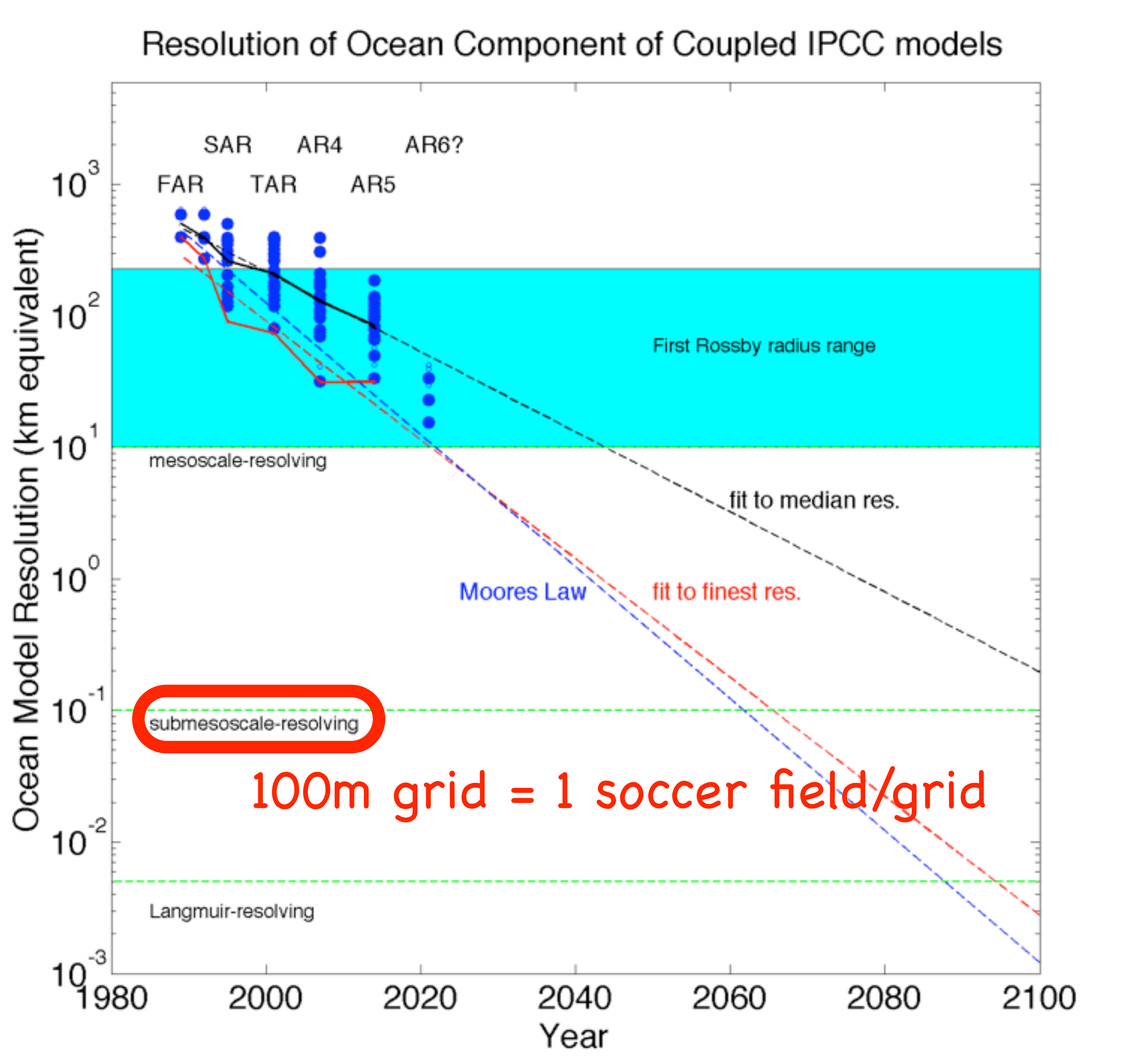
200km x 600km x 700m domain

1000 Day Simulation



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?



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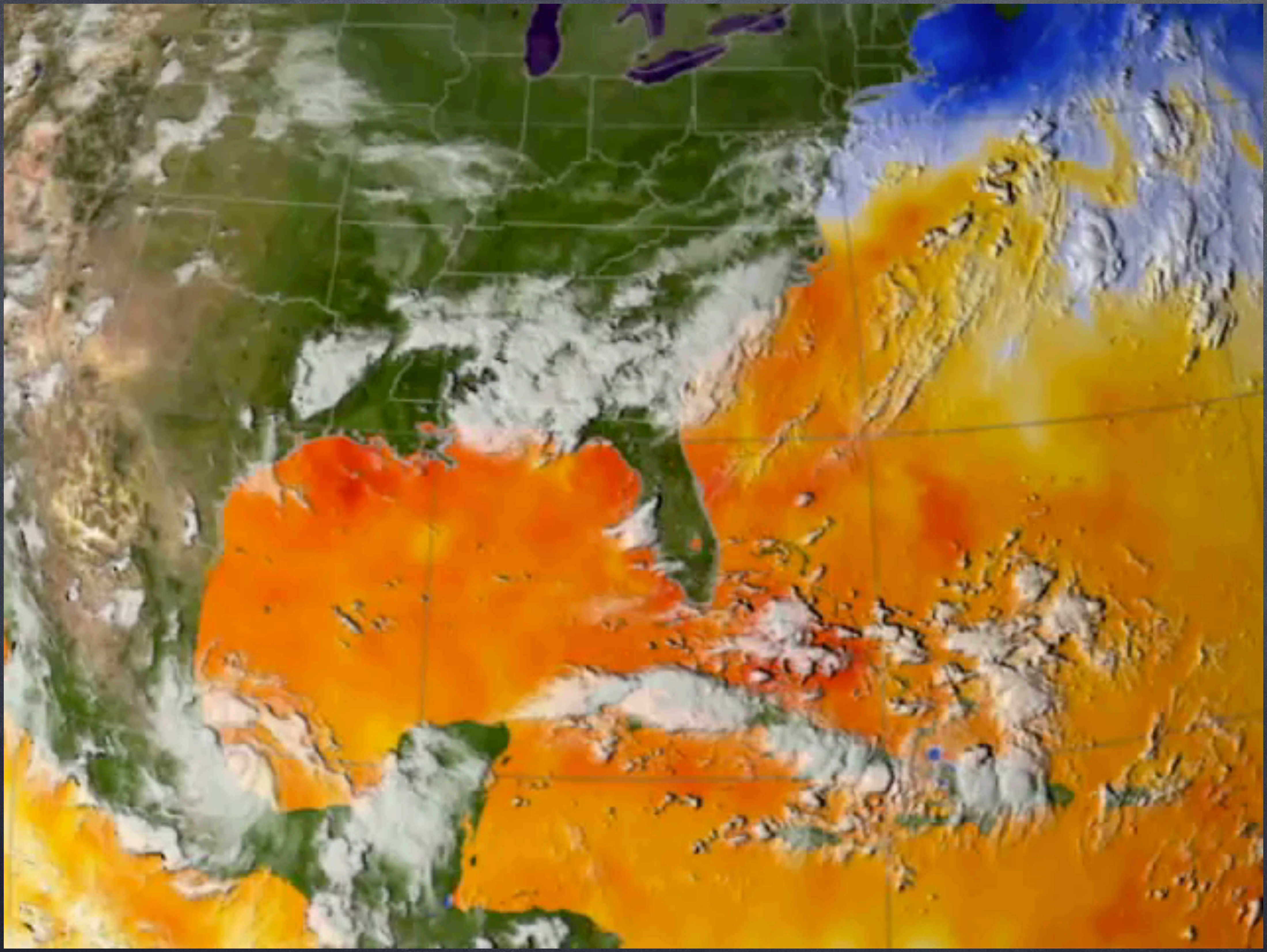
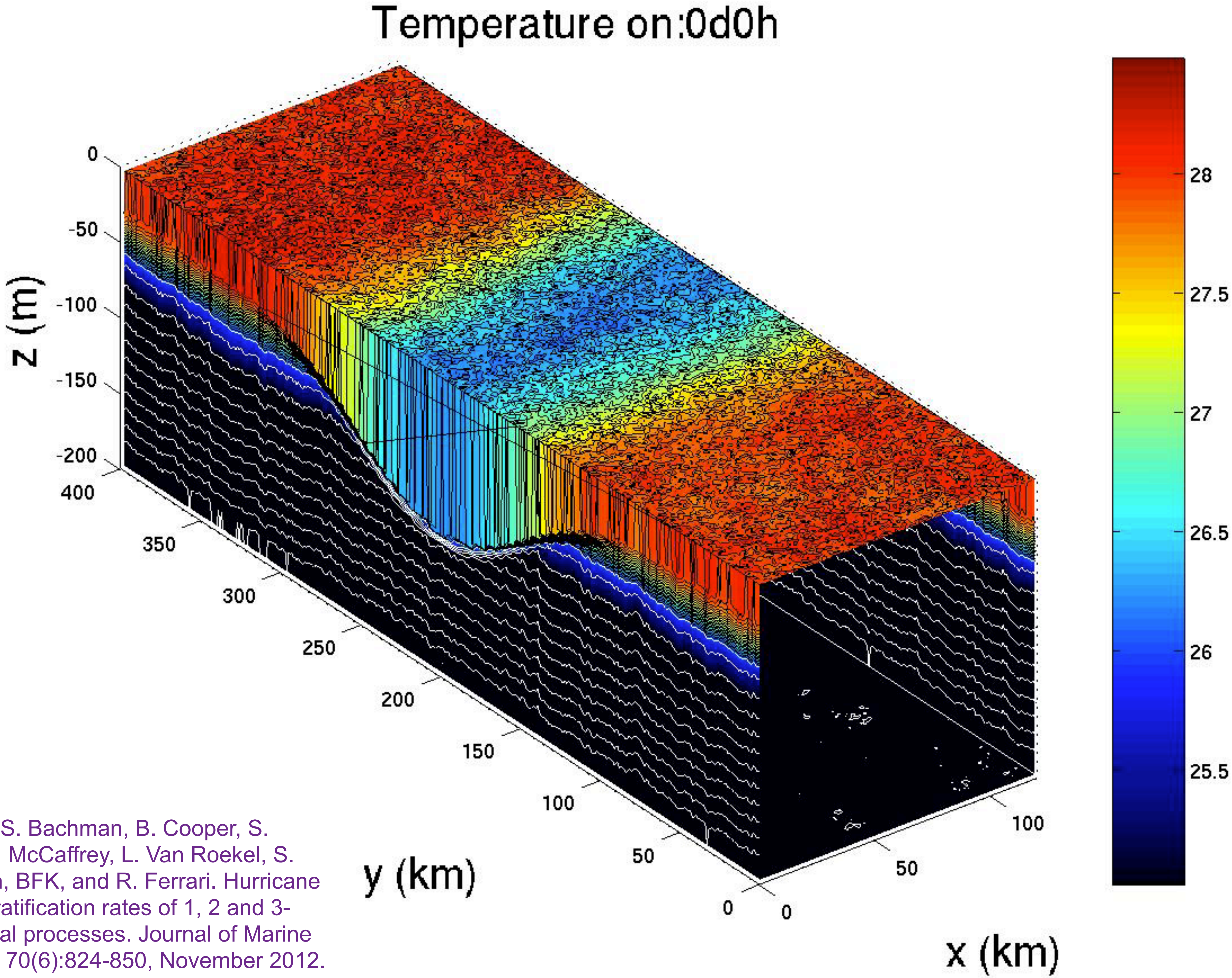
BFK, S. Bachman, B. Pearson, and S. Reckinger. Principles and advances in subgrid modeling for eddy-rich simulations. CLIVAR Exchanges, 19(2):42-46, July 2014.

Hurricane Katrina hits an eddy, strengthens, & digs a wake



That's Air-Sea Interaction!

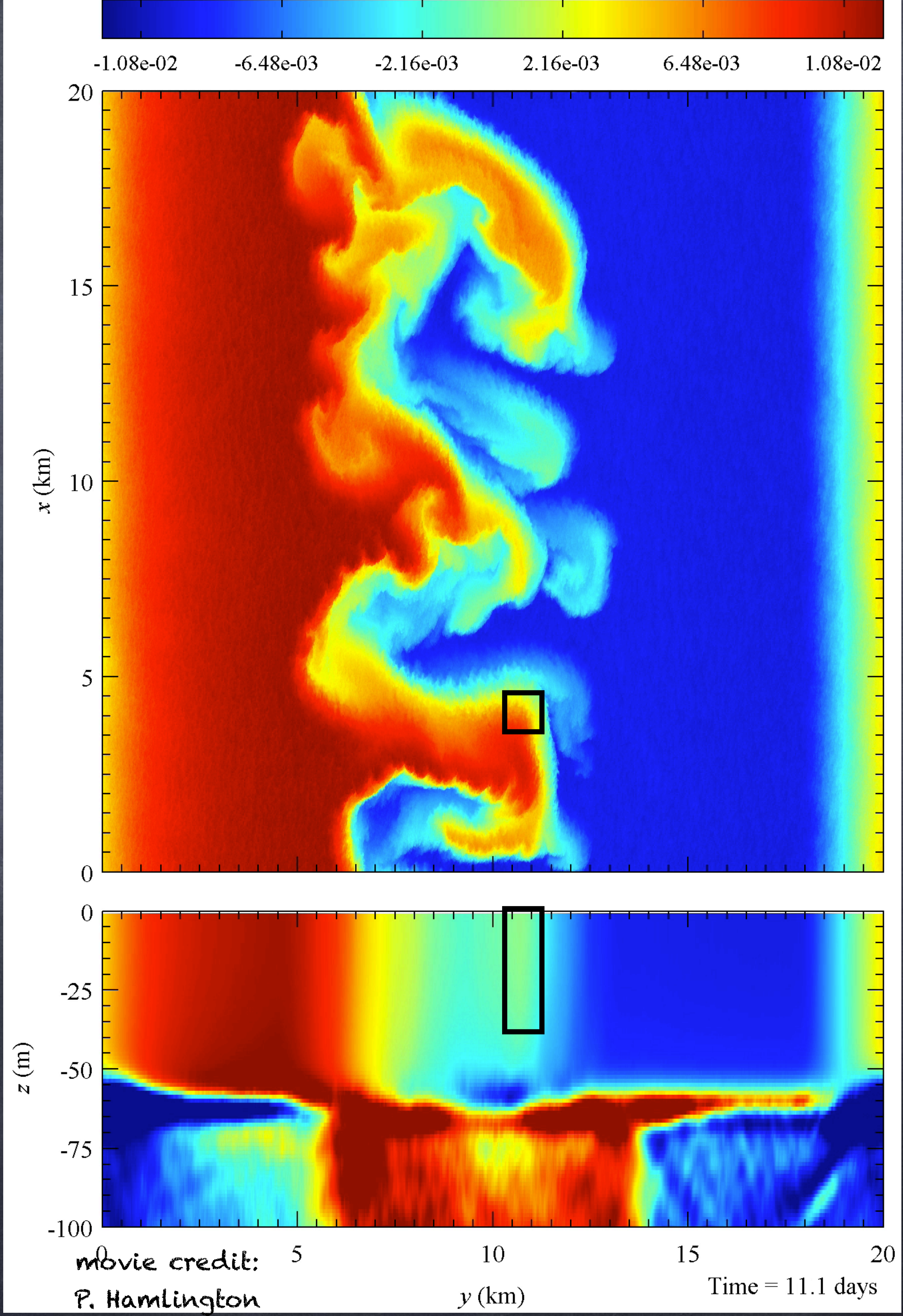
http://svs.gsfc.nasa.gov



S. Haney, S. Bachman, B. Cooper, S. Kupper, K. McCaffrey, L. Van Roekel, S. Stevenson, BFK, and R. Ferrari. Hurricane wake restratification rates of 1, 2 and 3-dimensional processes. Journal of Marine Research, 70(6):824-850, November 2012.

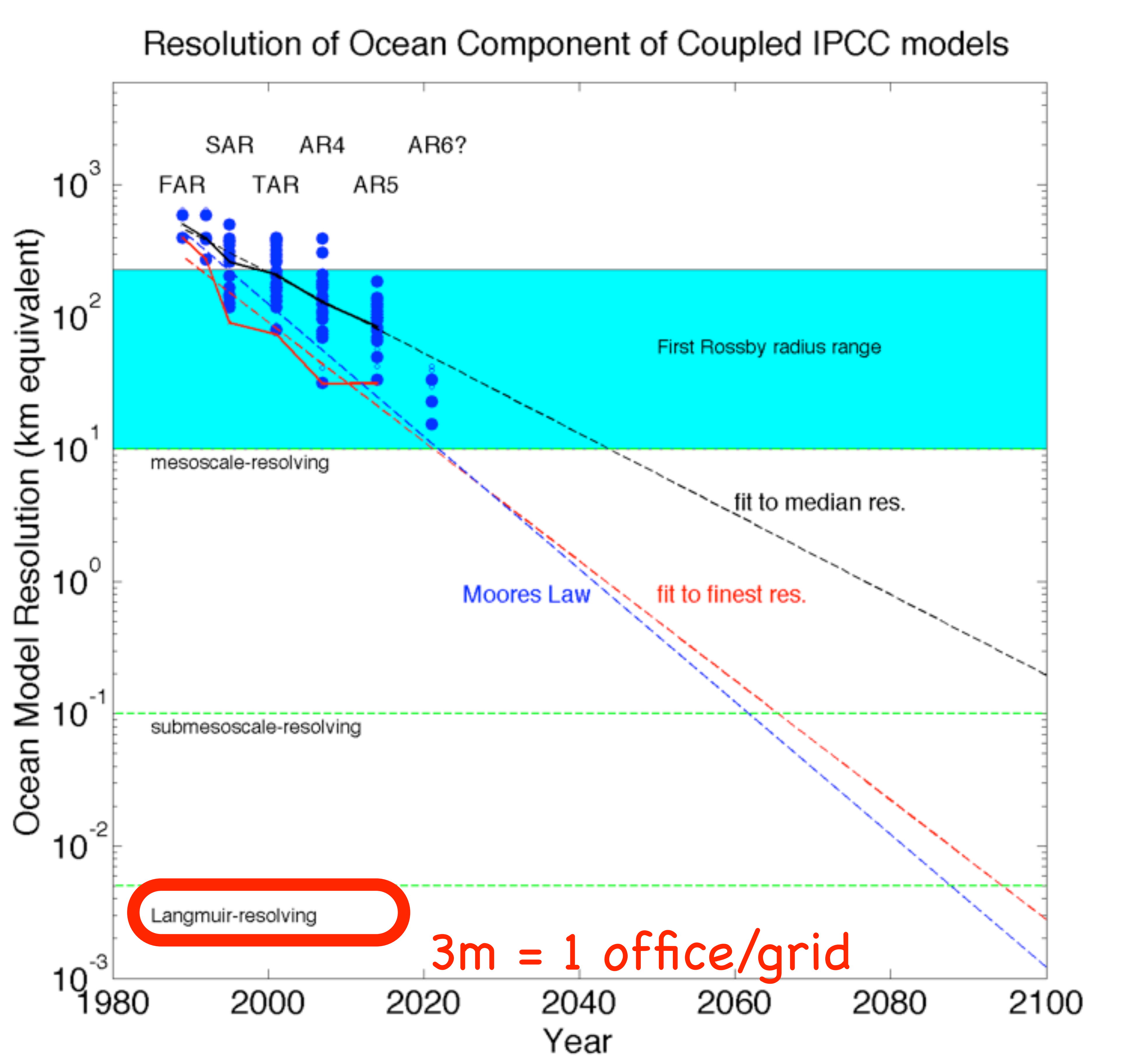
20km x 20km x 150m domain

10 Day Simulation



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!



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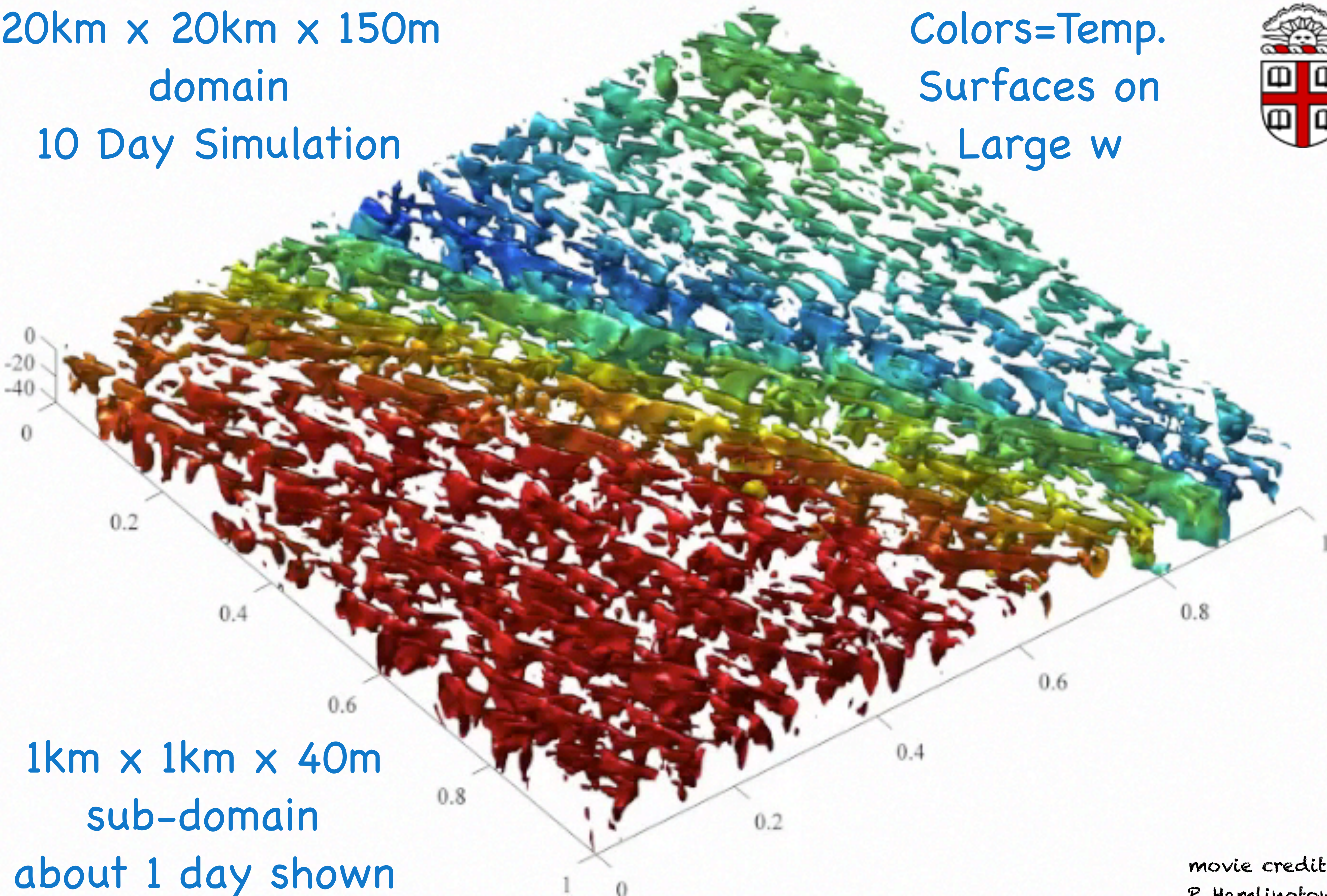
BFK, S. Bachman, B. Pearson, and S. Reckinger. Principles and advances in subgrid modeling for eddy-rich simulations. CLIVAR Exchanges, 19(2):42-46, July 2014.

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.

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}

Process Models & Satellites to Explore

Climate Models, observations, & Reconstructions to integrate...

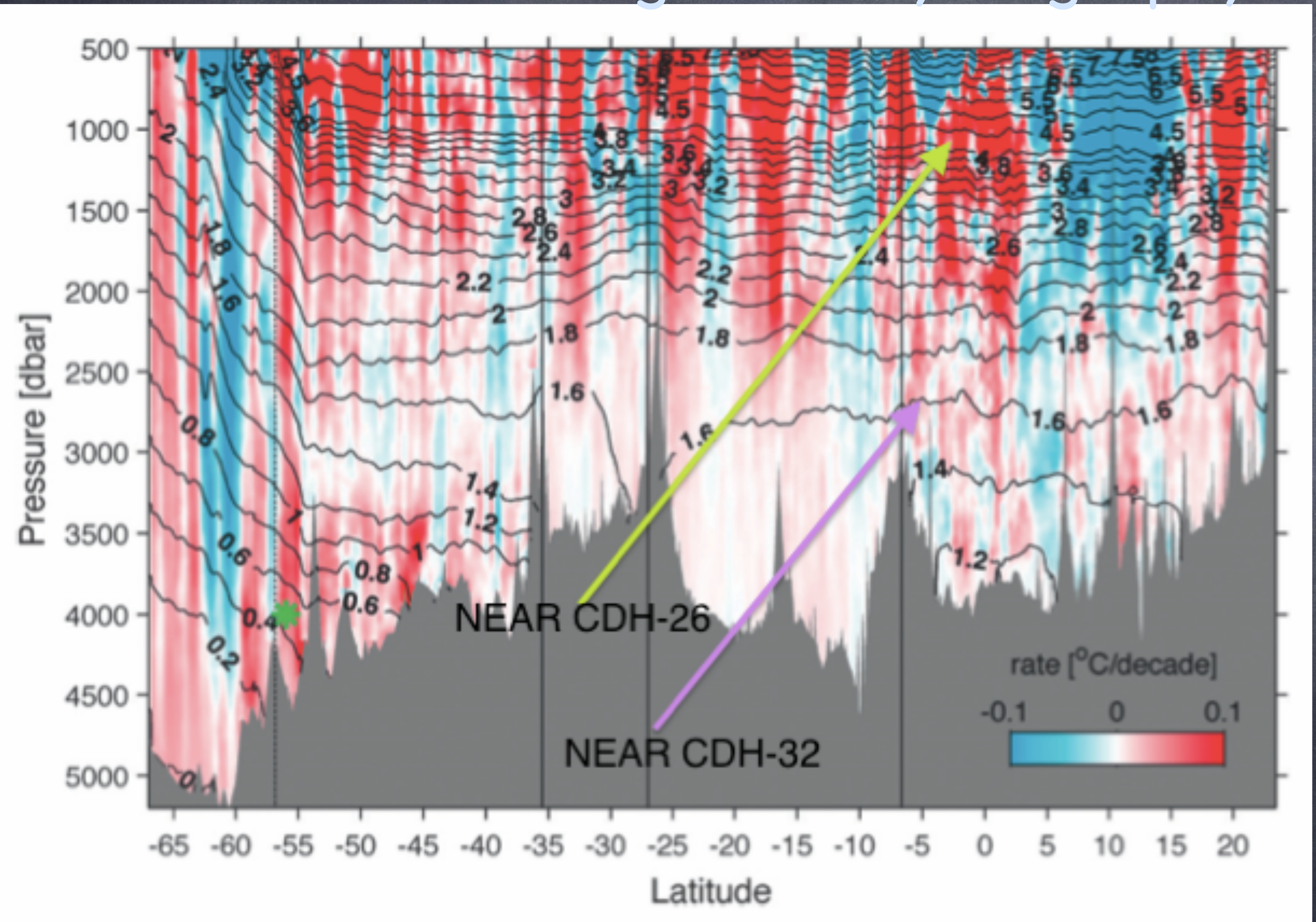
- What else is there?
- Are the parts of the ocean & climate variability we dont know about?
- Almost surely...
- Two examples:

Zissou: the Explorer

Understanding of past variability

Even with Argo, it will be a while until we have long timescale variability. What to do?

Pattern of Warming from Hydrography



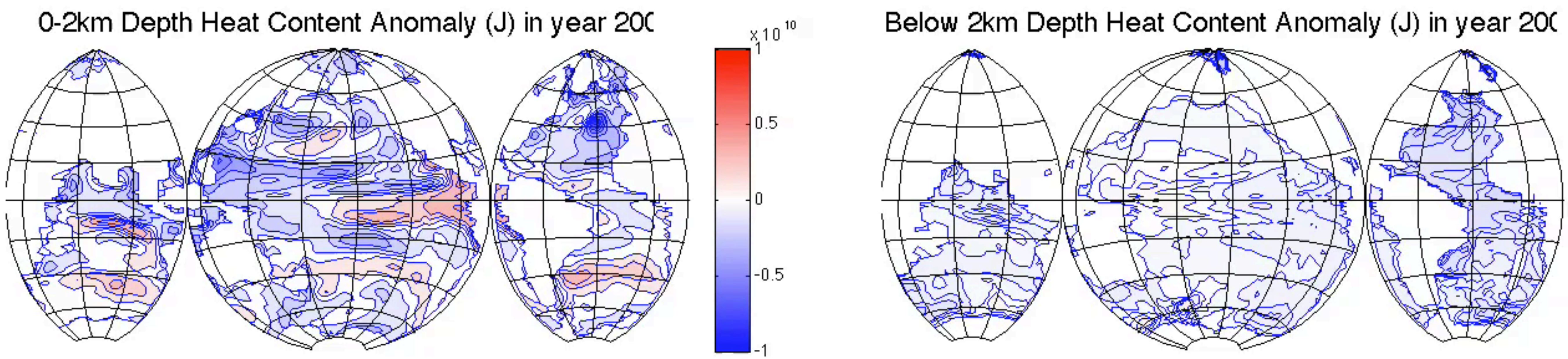
Purkey & Johnson, 2010

Examine CDH-26 sediment core from the Holocene indicated

now Rutgers

What does a climate model—WITHOUT WARMING—look like in Ocean Heat Content Variability?

Doesn't even include mesoscale eddies



Contours = 4 units

Contours = 1 unit

From the >1000yr steady forcing CCSM3.5

S. Stevenson, BFK, and M. Jochum, 2012: Understanding the ENSO-CO_2 link using stabilized climate simulations. Journal of Climate, 25(22):7917–7936.

CU, now UCSB

Understanding of past variability

Assessing variability using individual benthic foraminifera

$$\delta^{18}O = \left(\frac{\left(\frac{^{18}O}{^{16}O}\right)_{sample}}{\left(\frac{^{18}O}{^{16}O}\right)_{standard}} - 1 \right) * 1000\ ‰$$

- Benthic foraminiferal $\delta^{18}O$ values record temperature and salinity properties of ambient seawater

$$T\ (°C) = 21.6 - 5.50 \times (\delta^{18}O_c - \delta^{18}O_{sw})$$

Bemis et al. 2002

$$\delta^{18}O_{sw} = -14.38 + 0.42 * salinity$$

Conroy et al. 2014

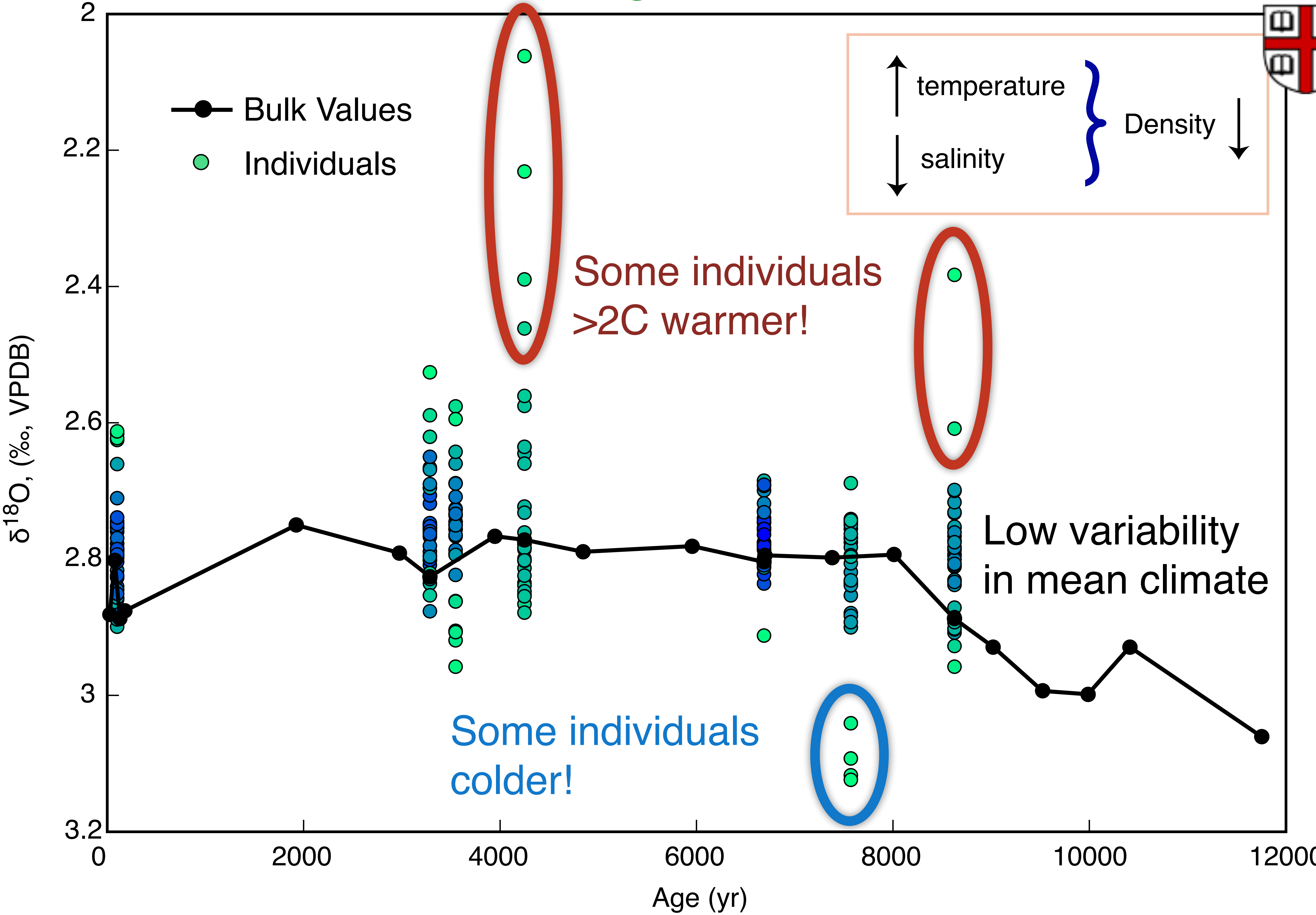
- Individual foraminifera provide 2-3 week snapshots of seawater properties

- We analyze 30-40 individuals within 200 year windows to assess the mean and variance of foraminiferal $\delta^{18}O$ values On roughly decadal timescales

Uvigerina spp.

S. Bova, T. D. Herbert, and BFK. Rapid variations in deep ocean temperature detected in the holocene. Geophysical Research Letters, 43, December 2016.

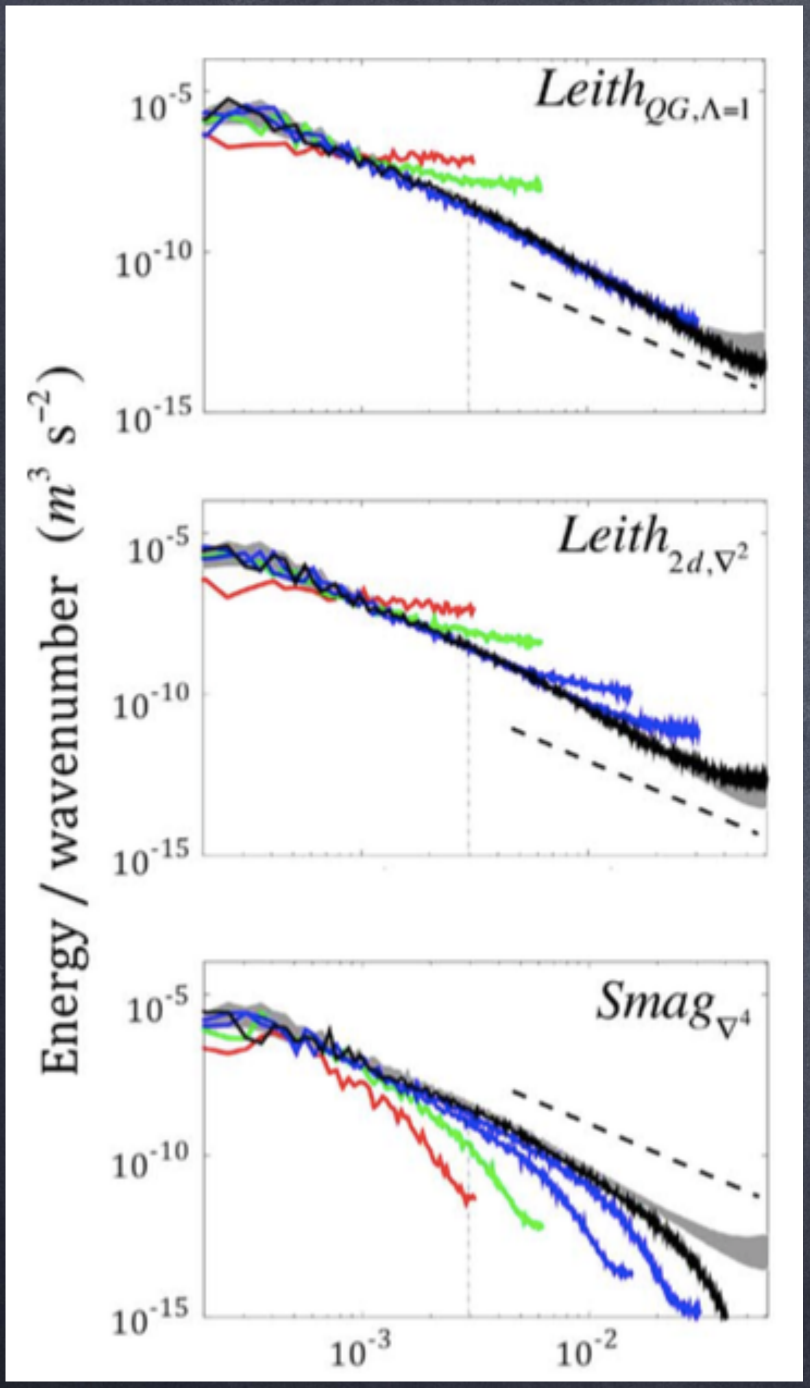
Understanding of past variability



S. Bova, T. D. Herbert, and BFK. Rapid variations in deep ocean temperature detected in the Holocene. Geophysical Research Letters, 43, December 2016.

Where does ocean energy go?

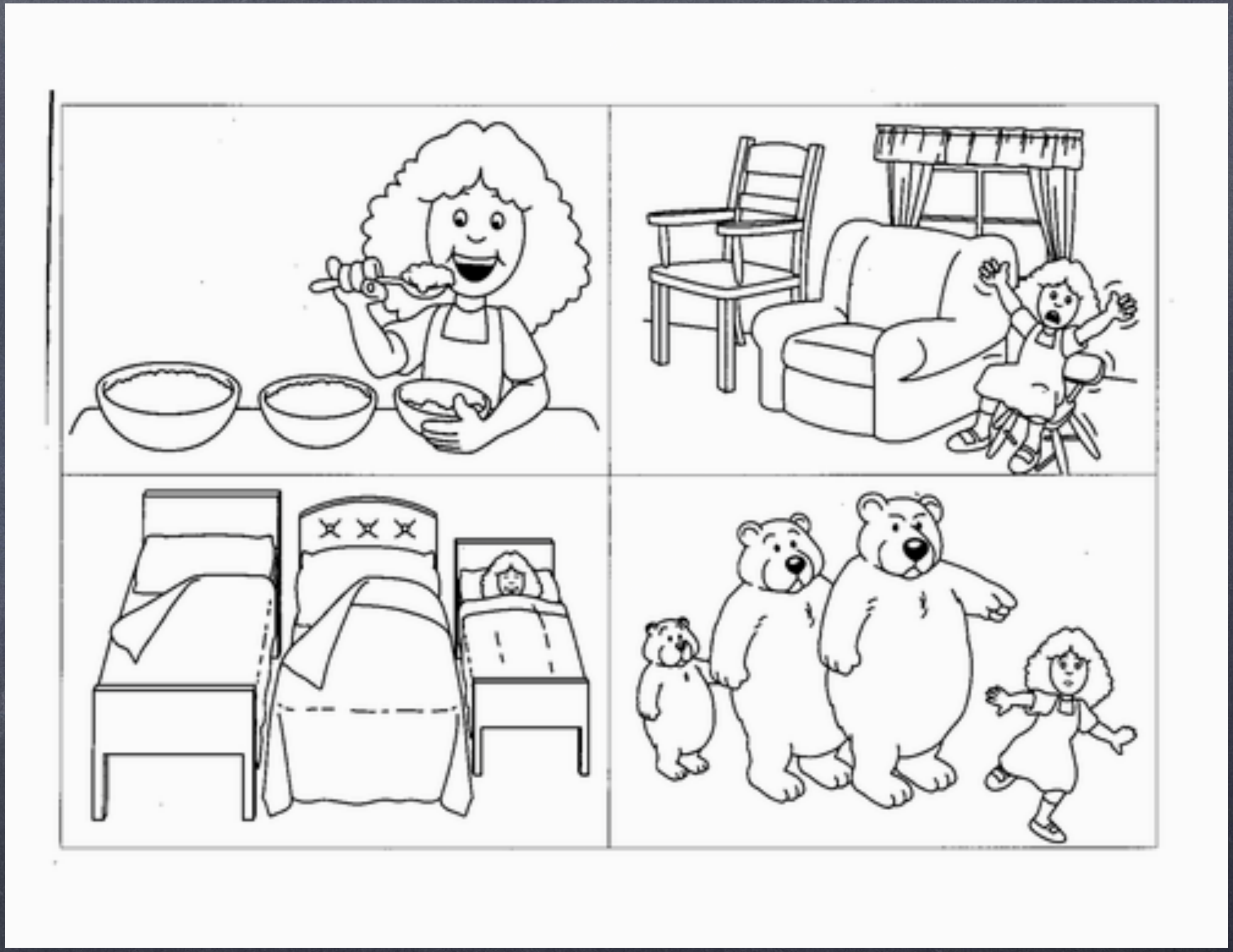
Spectrally speaking



QGLeith: Just Right!

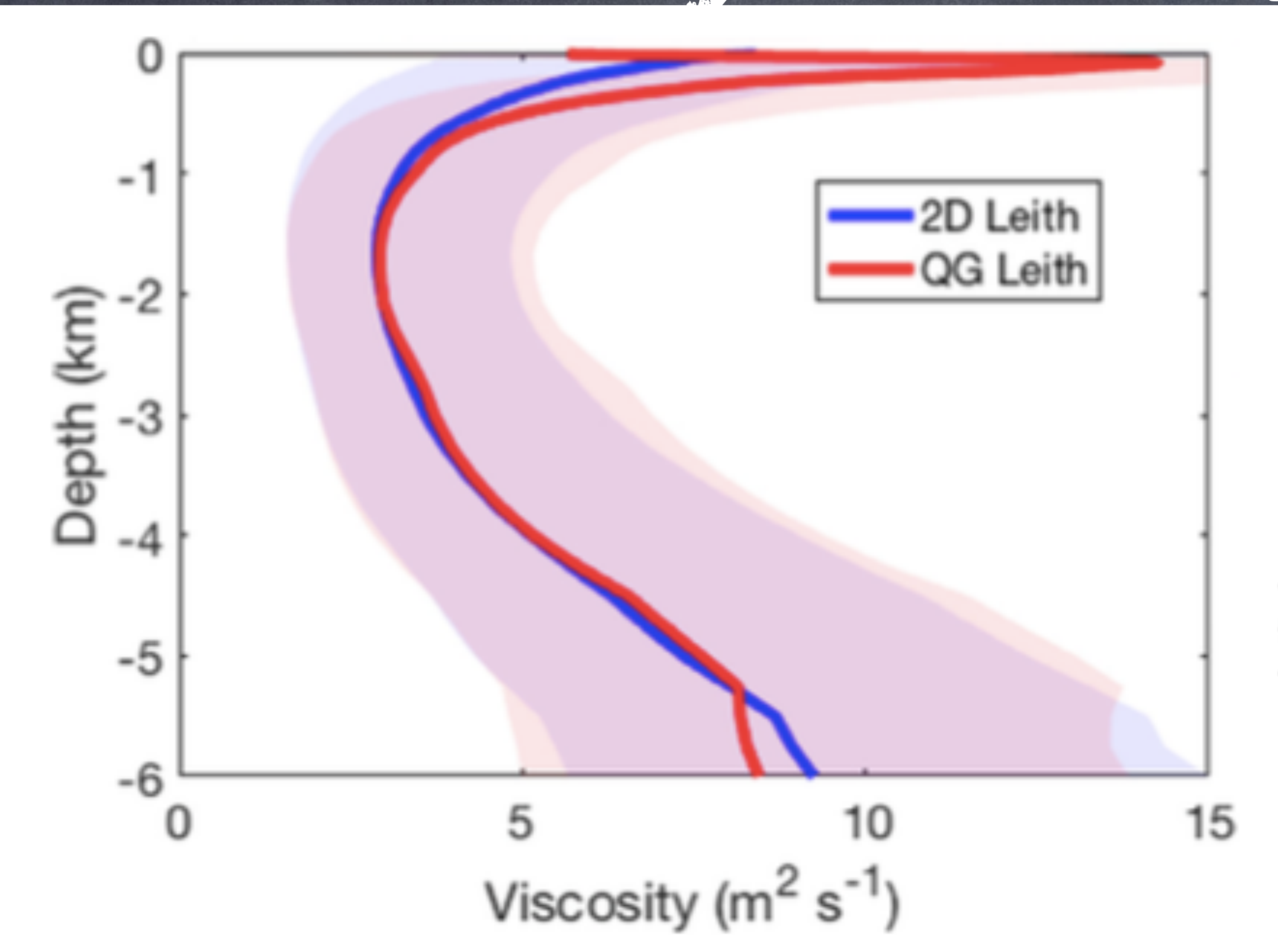
2DLeith: Too Noisy

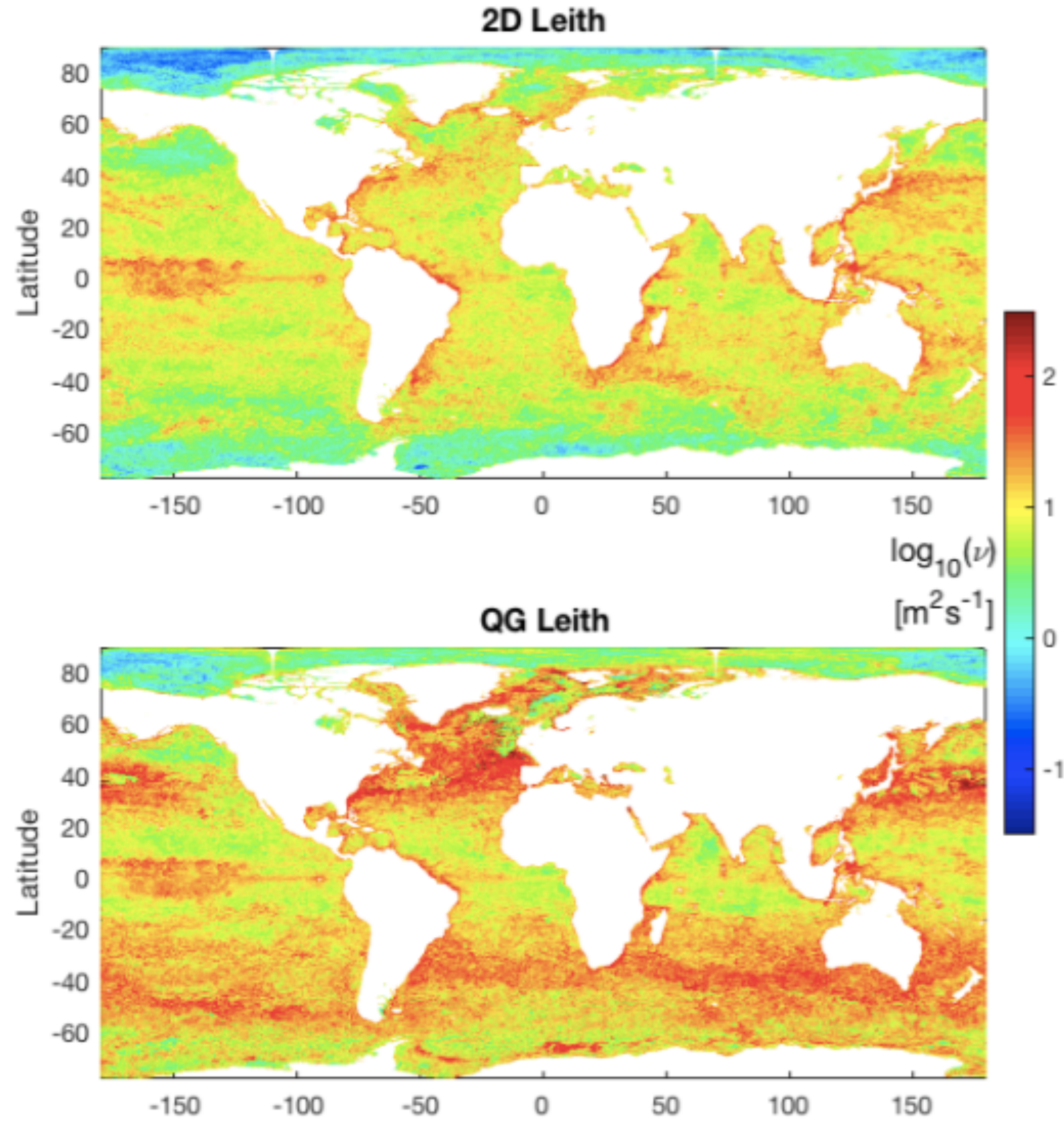
Smagorinsky: Too Smooth



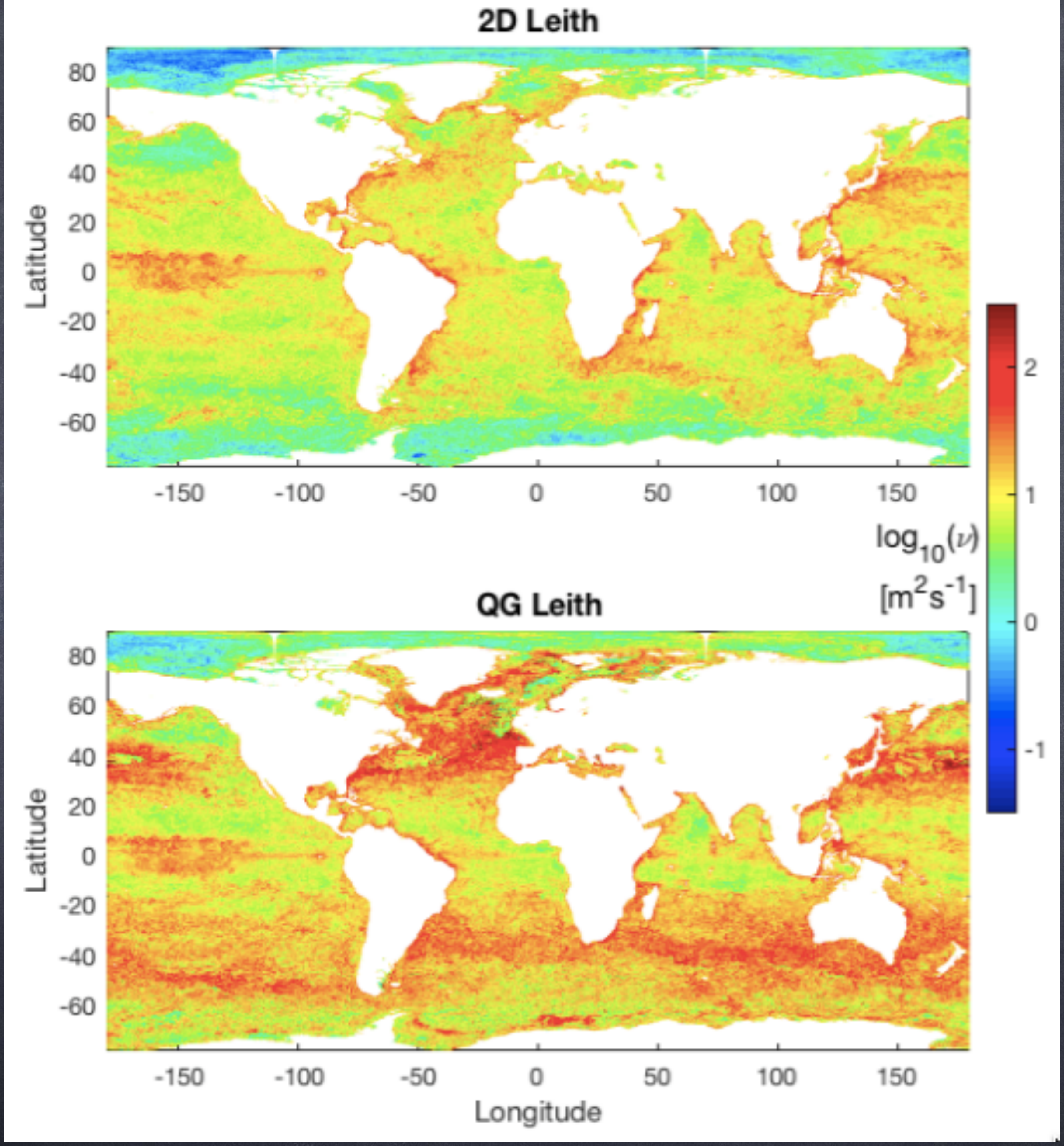
S. D. Bachman, BFK, and B. Pearson. A scale-aware subgrid model for quasigeostrophic turbulence. Journal of Geophysical Research-Oceans, 122:1529-1554, March 2017.

QGLeith: Let's try it in a global model!

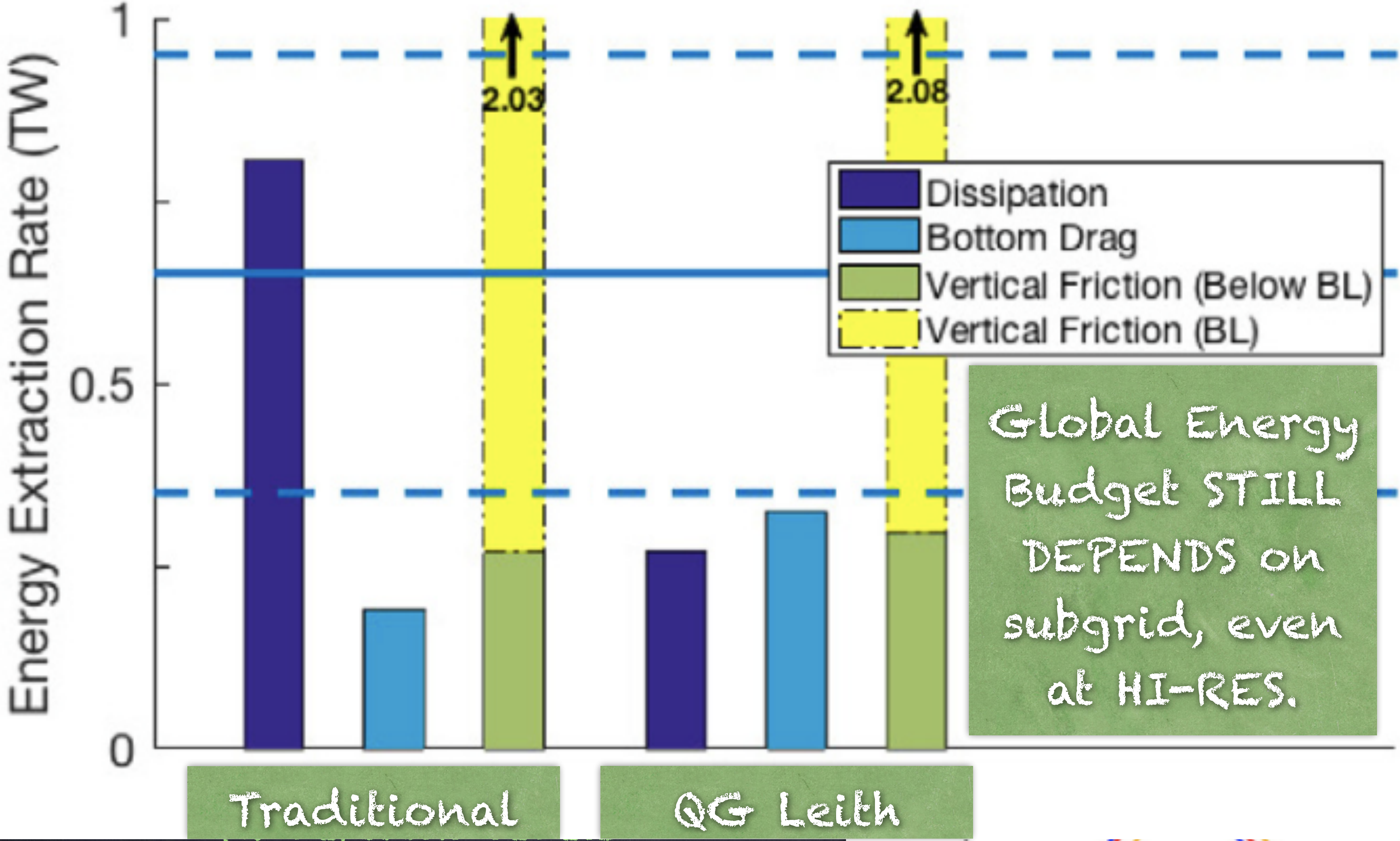




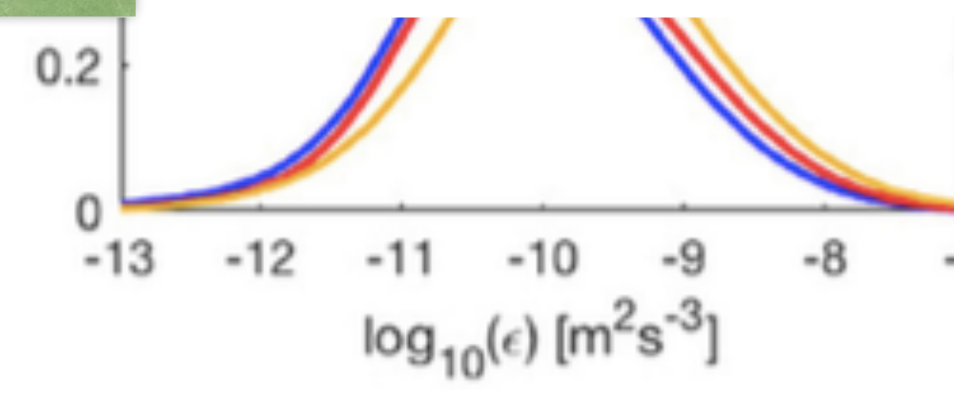
B. Pearson, BFK, S. D. Bachman, and F. O. Bryan, 2017: Evaluation of scale-aware subgrid mesoscale eddy models in a global eddy-rich model. Ocean Modelling, 115:42–58.



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.



(most in upper 200m)



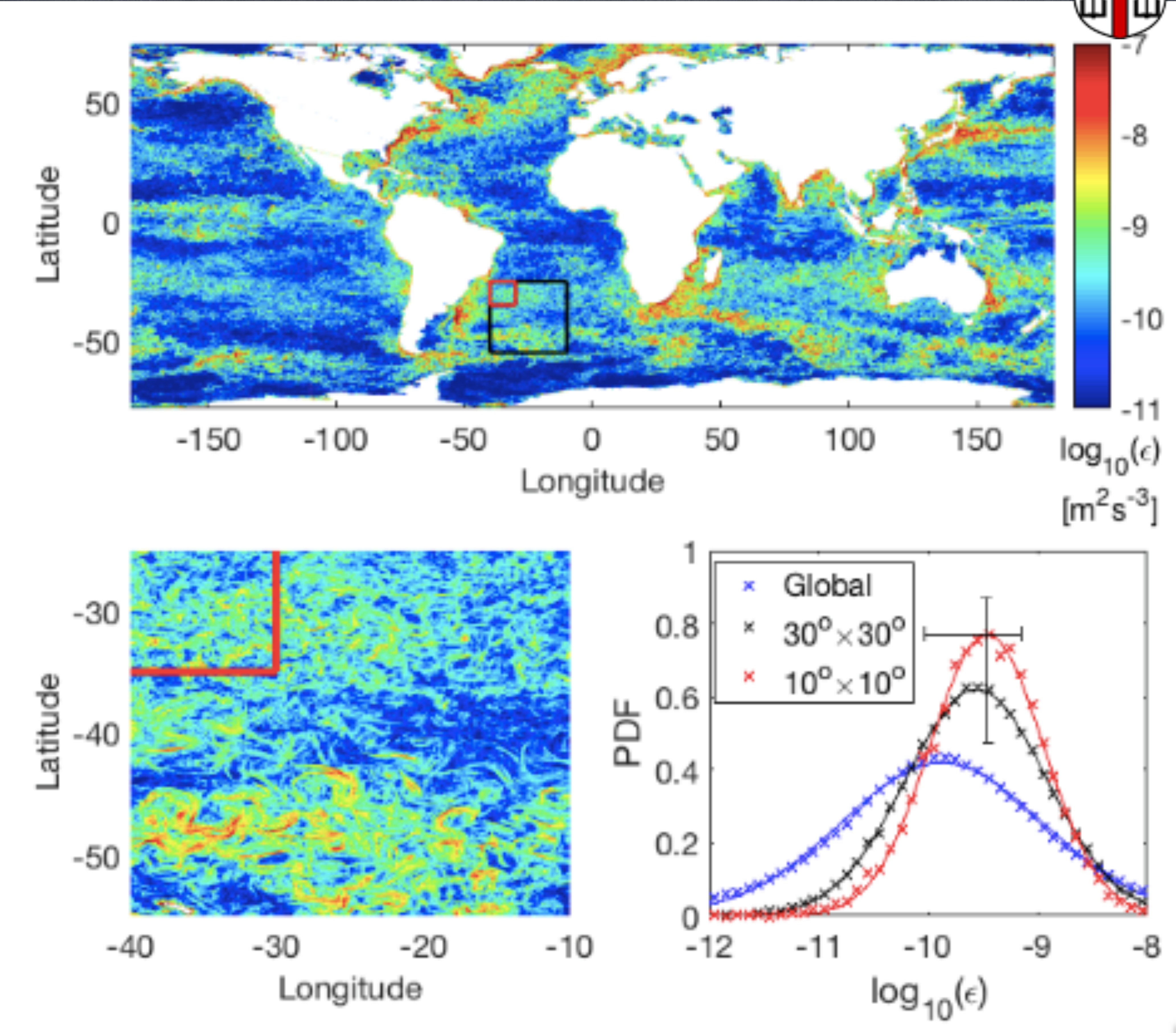
B. Pearson, BFK, S. D. Bachman, and F. O. Bryan, 2017: Evaluation of scale-aware subgrid mesoscale eddy models in a global eddy-rich model. Ocean Modelling, 115:42–58.

MOLES: Log-Normal Dissipation Intermittency

A (weak) dissipation of energy with pot'l enstrophy cascade ... that's lognormally distributed (super-Yaglom '66)

90% of KE dissipation in 10% of ocean

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



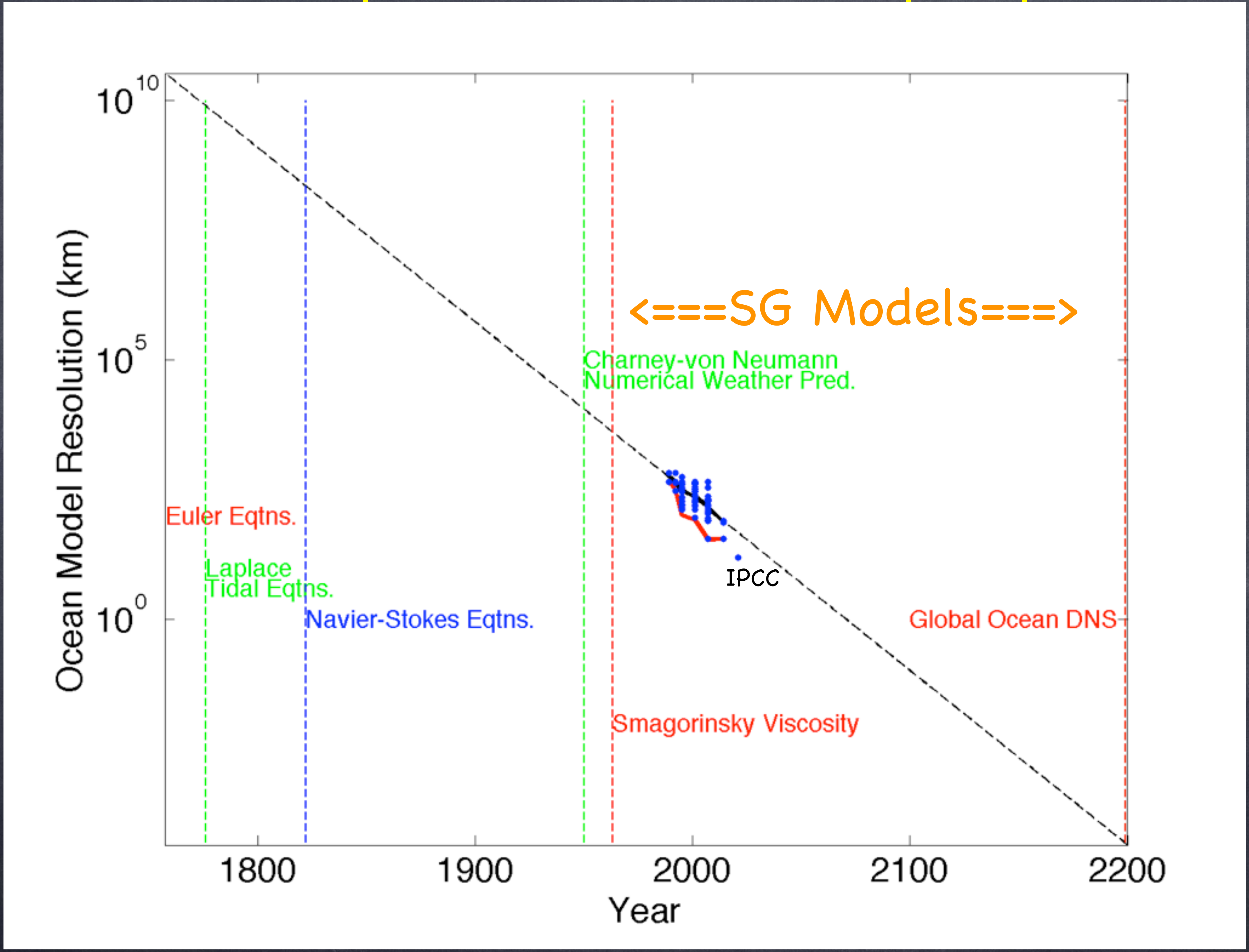
Atmosphere, Cryosphere, Biosphere, Pedosphere Responses

- The ocean is only one component of the earth system with slow response time, others:
  - Clouds
  - Glaciers
  - Ecosystem Shifts & Species Extinction
  - Melting permafrost

Climate to Kolmogorov: What is important?

- The equations to directly solve for fluid motion are known for 200 years, but we can't resolve all the way, so new equations for the coarse-grained statistics are needed
- Need atmospheric, biological, & geological chemistry (greenhouse gasses) & clouds for absorption & reemission
- Need atmospheric & oceanic motions to redistribute
- Oceans are the relevant thermal energy reservoir
- Oceans lend longer timescale predictabiliy, and ocean heat content is a useful measure of global warming
- Exploration of too small or fast to observe can be made with models—will discuss techniques on that tomorrow
- We will one day be able to resolve all of the ocean processes, but for now:

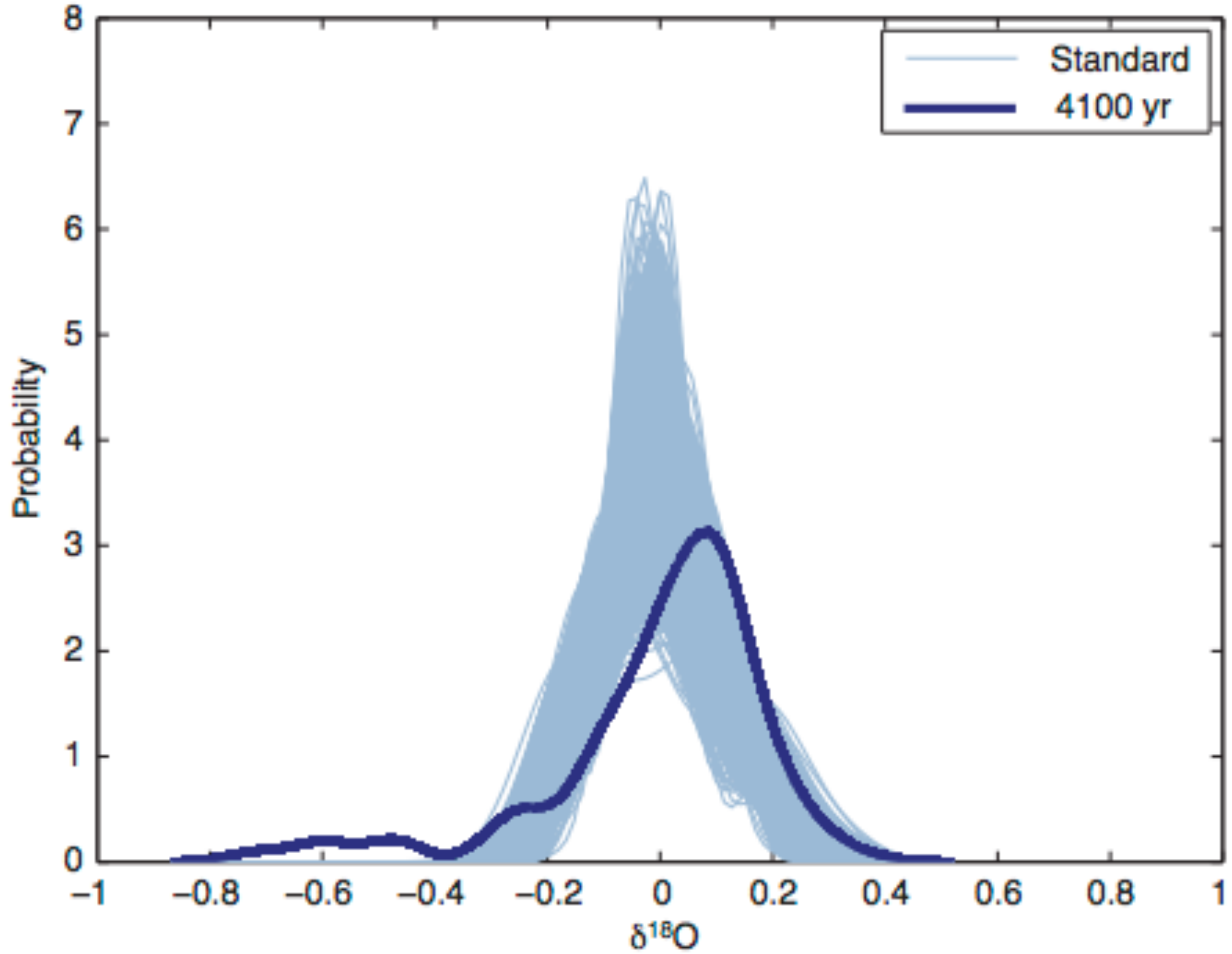
Fun to extrapolate for historical perspective!



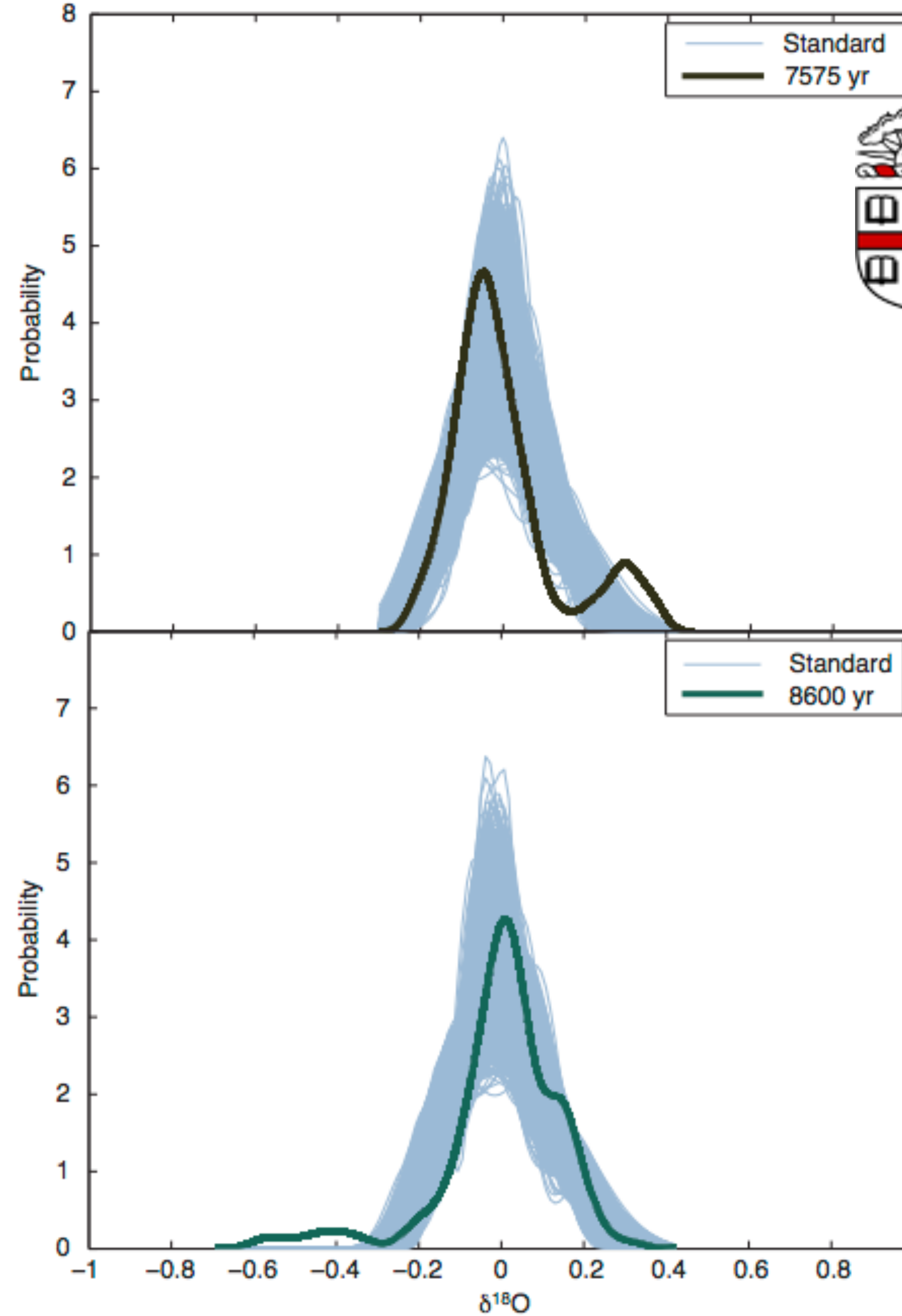
200 years since the fluid equations were discovered,

200 years to go until we can directly solve them!

p<0.01



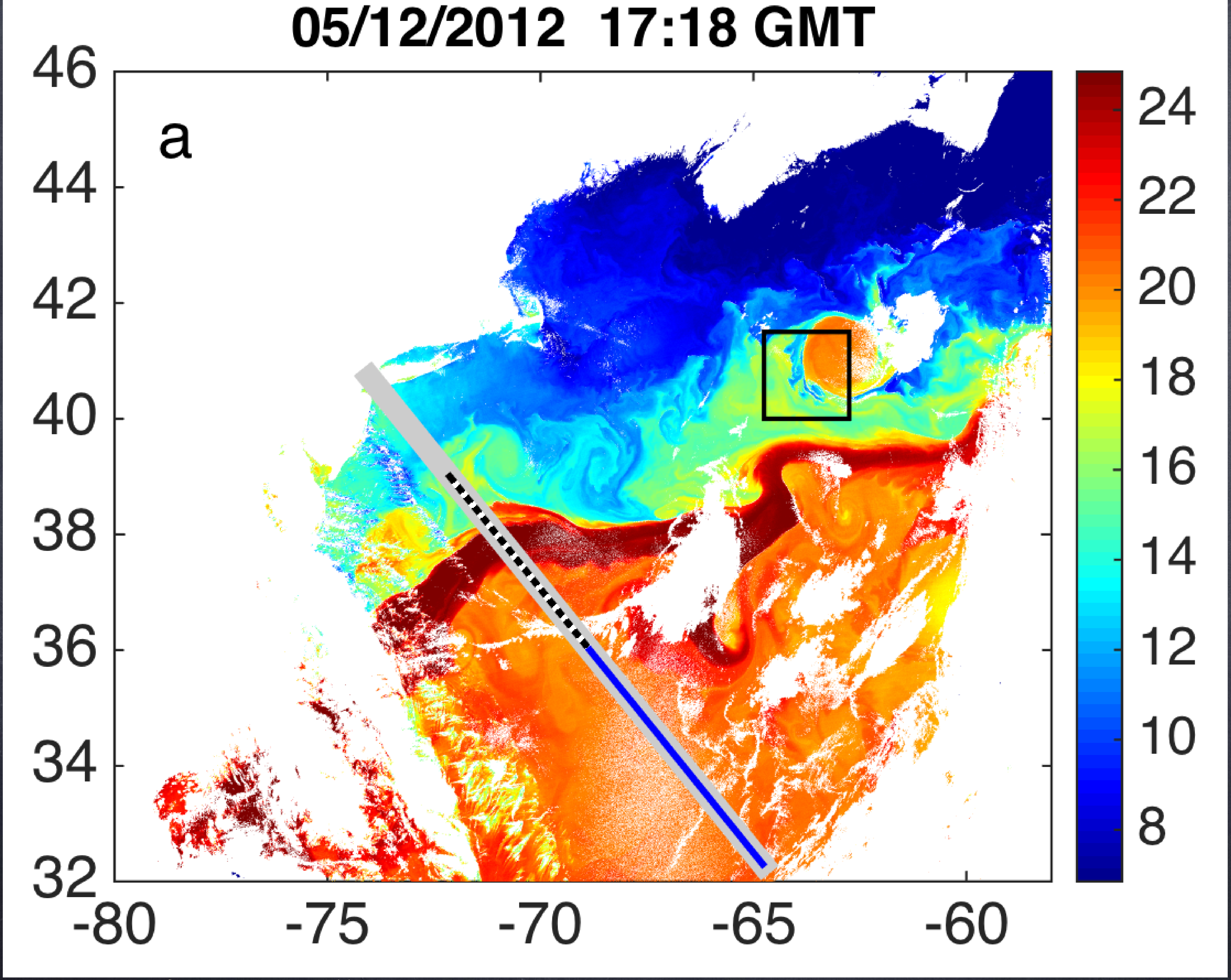
p<0.10



At these three time intervals, the spread of individual values exceeds a size-matched spread of instrumental standards.

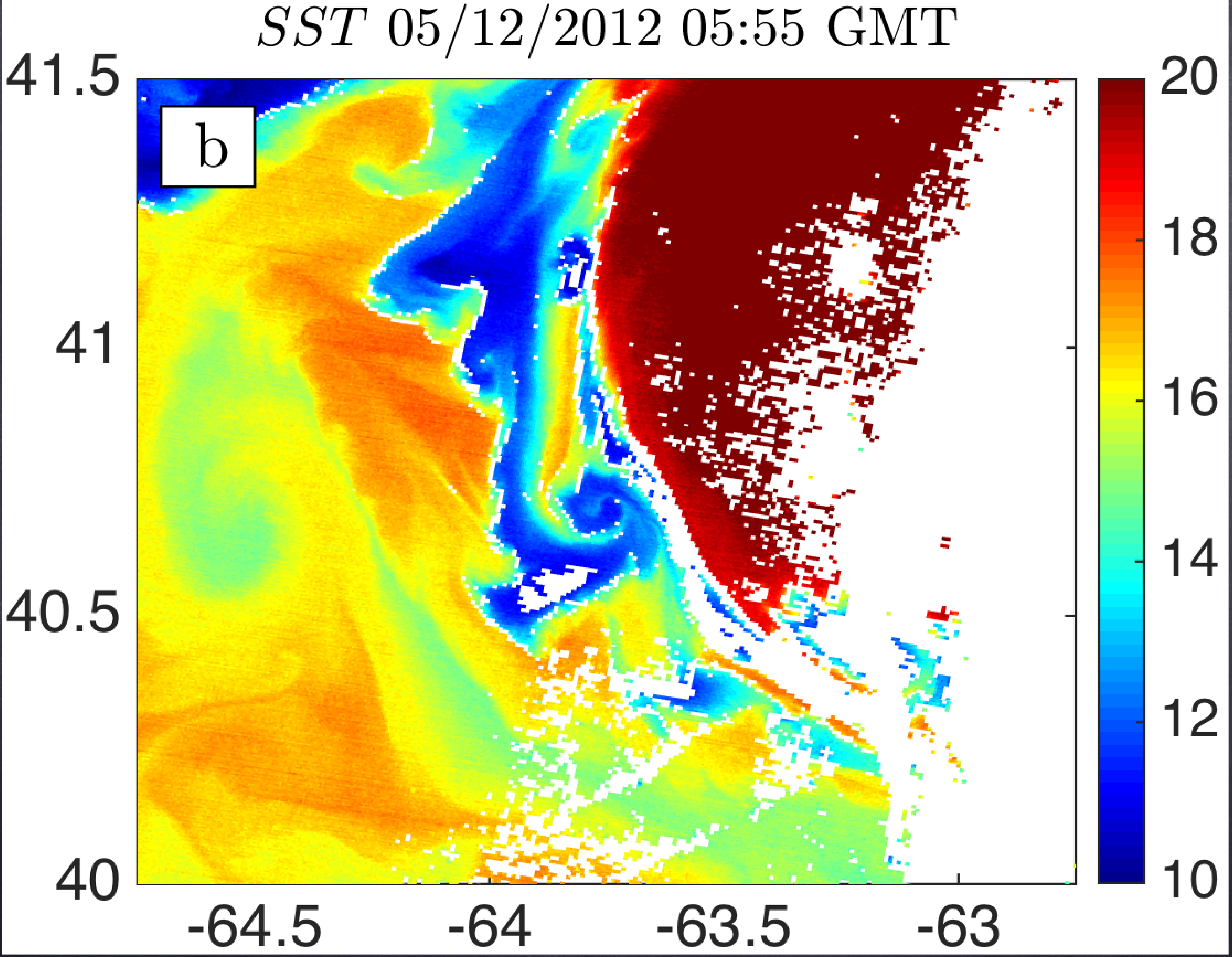
The statistical significance of this deviation is given by the p-values of a Kolmogorov-Smirnov test comparing the distributions.

According to these forams—deep water variability is **unexpectedly important, intermittently** through the past!



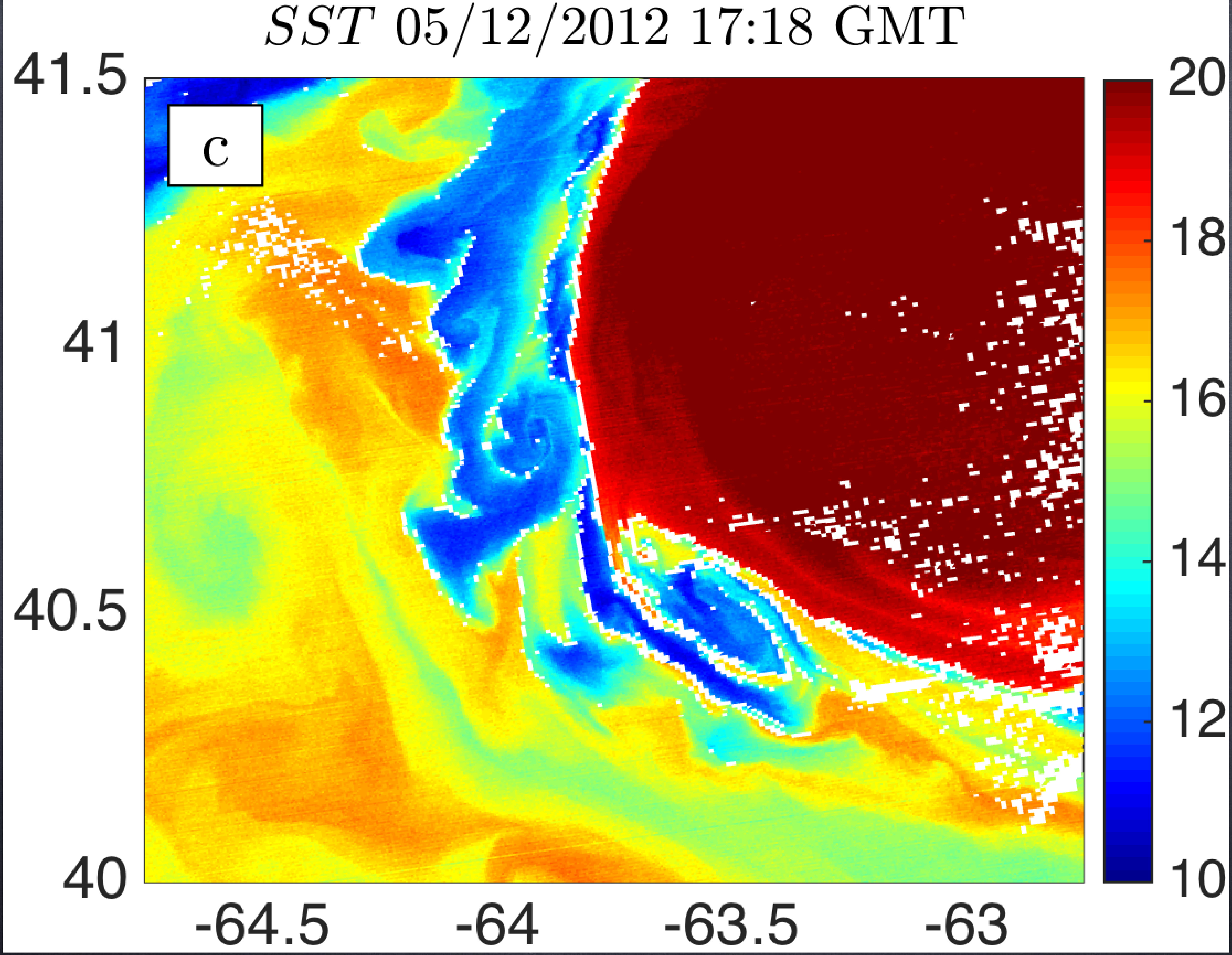
VIIRS image, courtesy P. Cornillon
Roughly 1km Resolution

Satellite SST, NW Atlantic



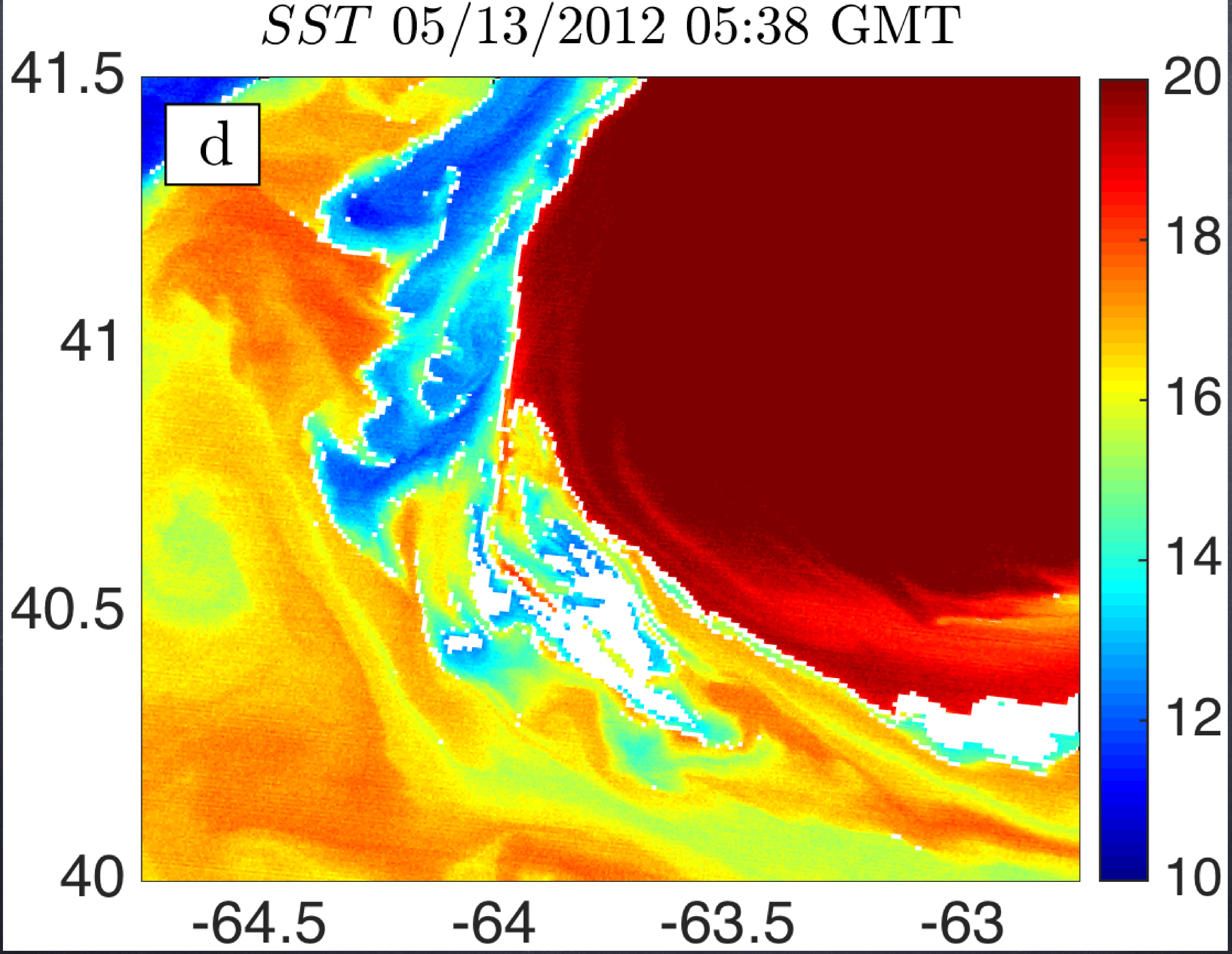
VIIRS image, courtesy P. Cornillon

Observations of MLEs NW Atlantic



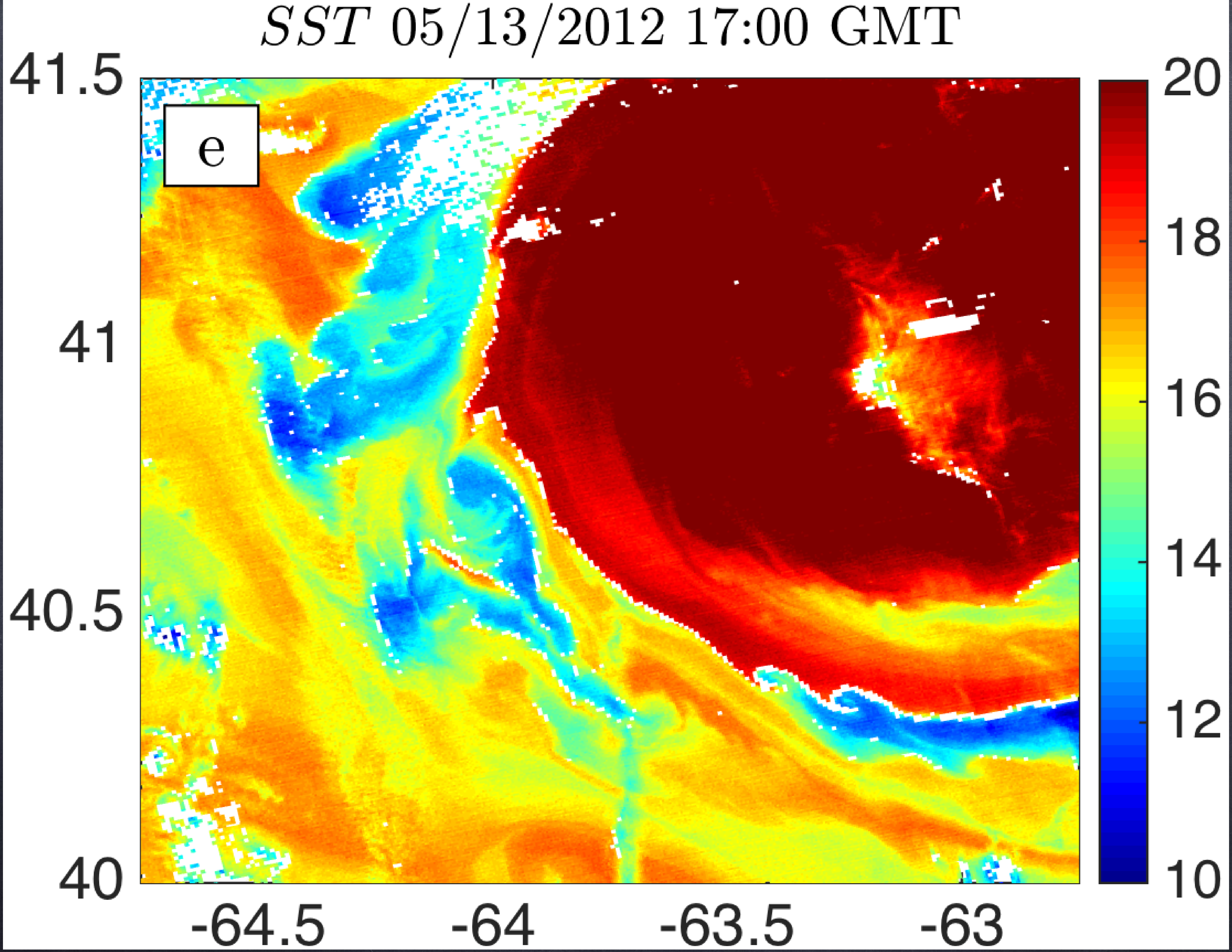
VIIRS image, courtesy P. Cornillon

Observations of MLEs NW Atlantic

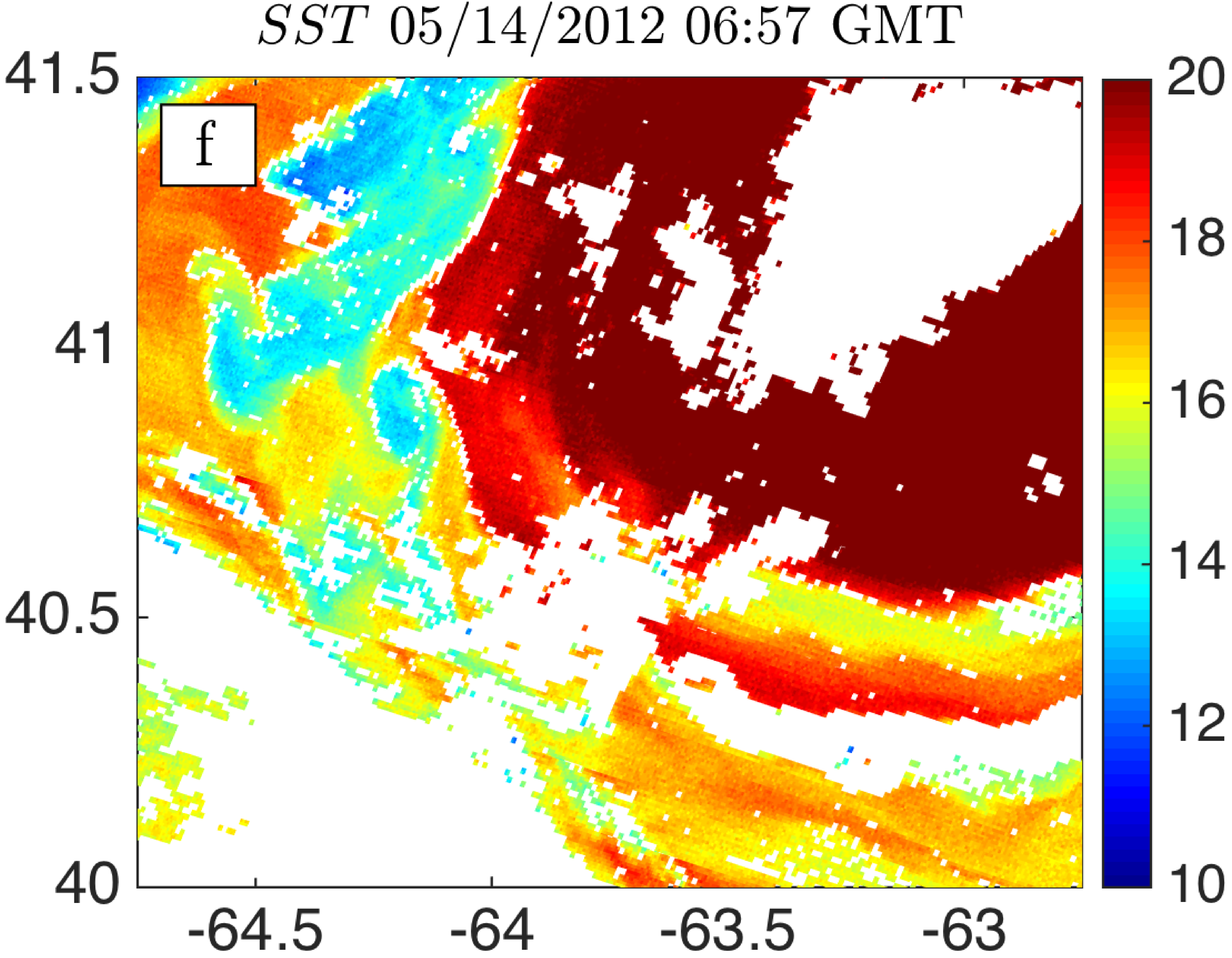


VIIRS image, courtesy P. Cornillon

Observations of MLEs NW Atlantic



VIIRS image, courtesy P. Cornillon



VIIRS image, courtesy P. Cornillon

Observations of MLEs NW Atlantic