Ocean Variability from the Surface to the Abyss

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Arin Nelson & Jeff Weiss (CU-ATOC), Scott Reckinger (Montana State)
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School for Marine Science and Technology Seminar.
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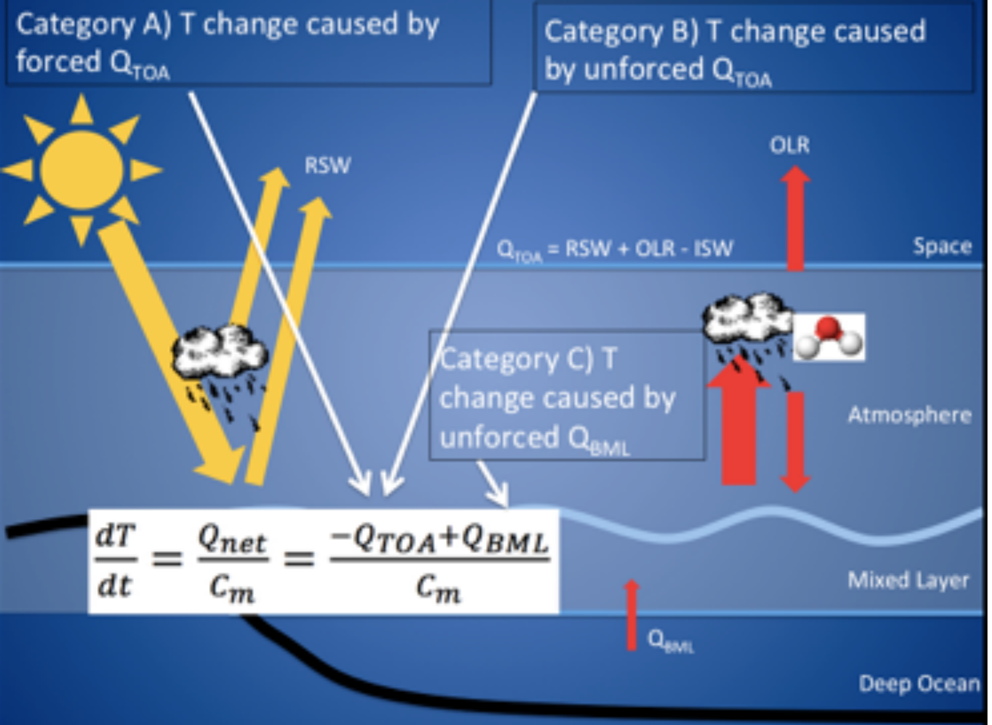
706 Rodney French Blvd, New Bedford, MA 9/30/15

Sponsors: NSF 1245944, 1258907, 1350795, GoMRI, and Institute at Brown for Environment and Society (IBES)

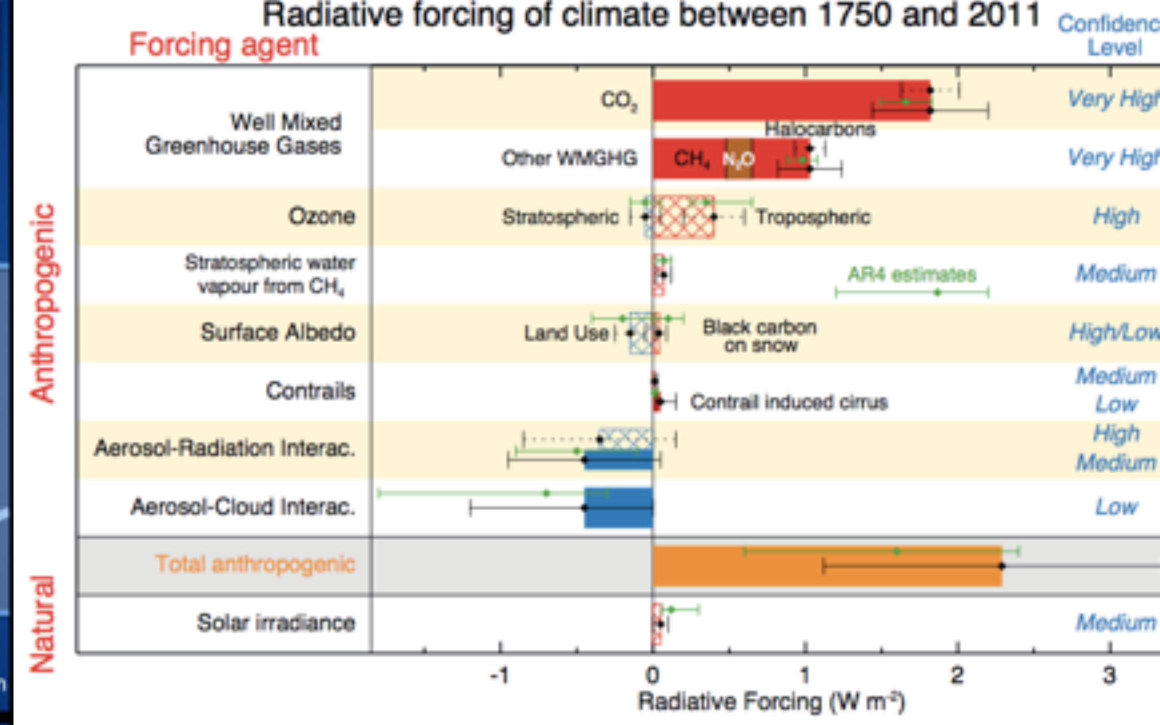
To understand air-sea effects on variability, and observations of the consequences, is important to distinguish:

- **Presence** of observable variability
- **Understanding** of past variability
- **Modeling** of variability
- **Prediction** of variability

Focus: diurnal to centennial variability



Brown et al., 2014



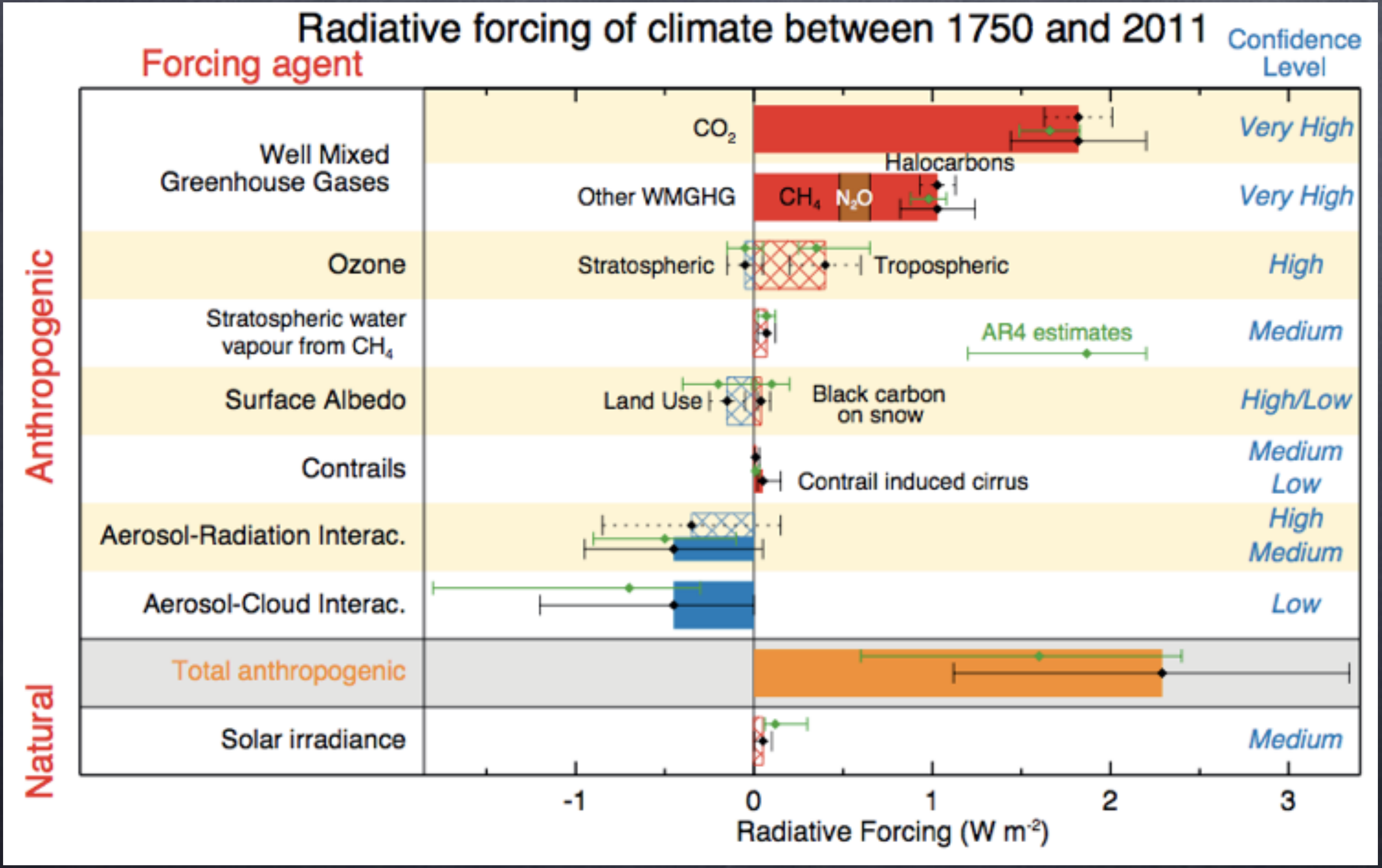
IPCC AR5, 2013

- **Presence** of observable variability

In practice, it is easier to observe the integrated ocean effects (ocean heat content (OHC), salinity) rather than the fluxes themselves. Sea Surface Temperature (SST) may approximate OHC.

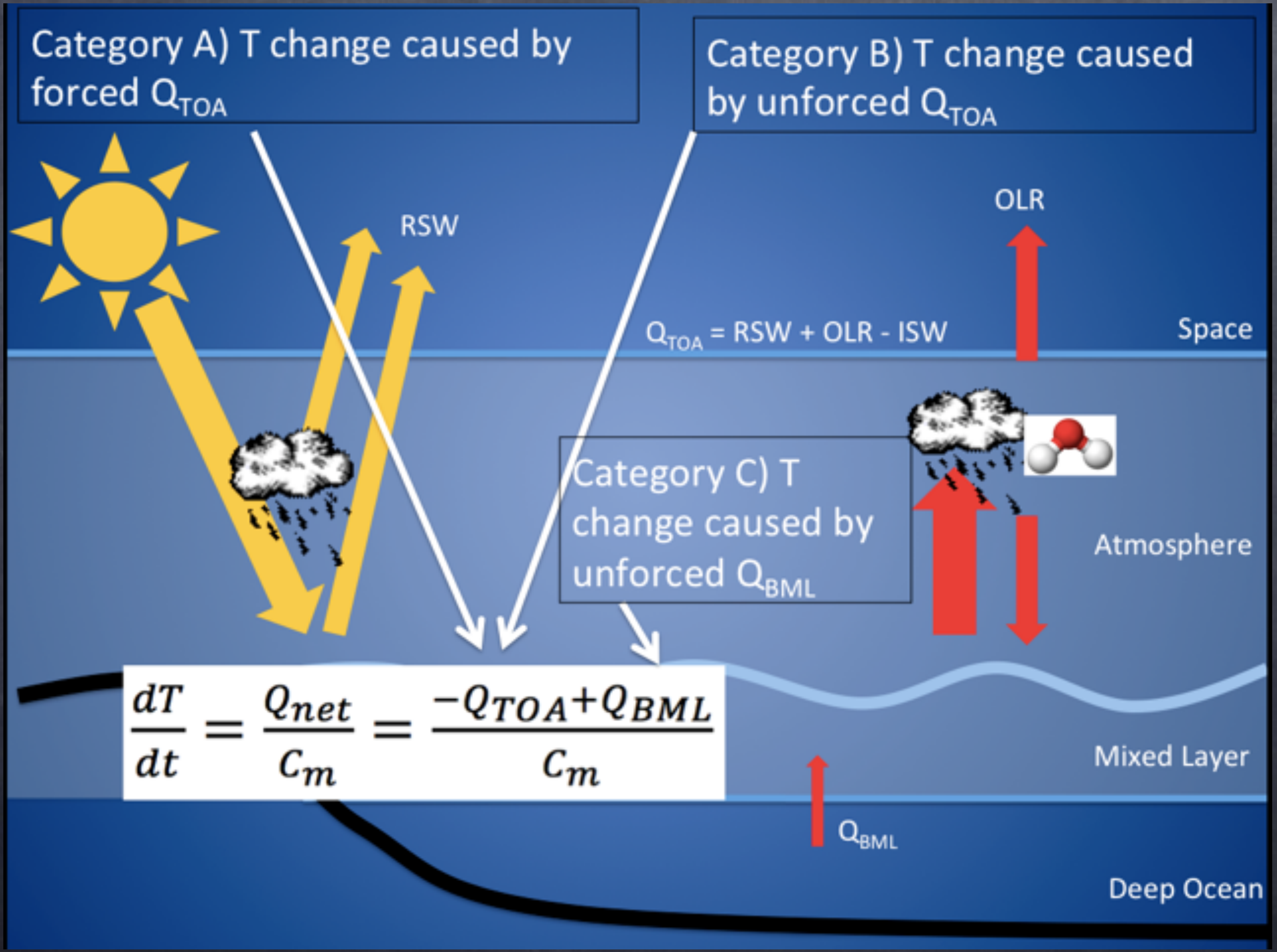
However, problematic **prediction** and **attribution**

Anthropogenic Forcing



IPCC AR5, 2013

Atmosphere & Surface Energy Budget



Brown et al., 2014

What does hydrography show?

Ocean Heat Content and Fluxes are not fixed!

About 1/3 of forcing ends up warming the oceans e.g., Hansen et al. (2011).

90% anomalous (anthropogenic?) warming ends up in the oceans.

0.7 W/m^2 to atmosphere only is about 1.5K/yr

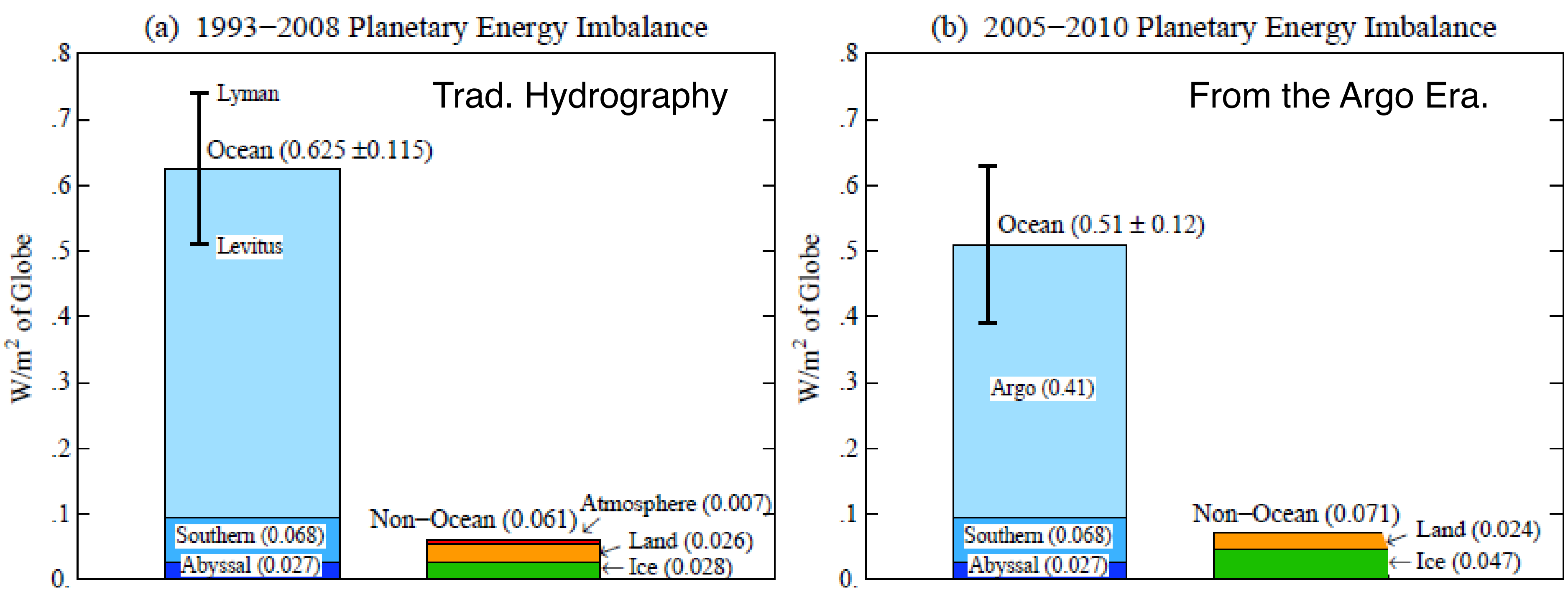
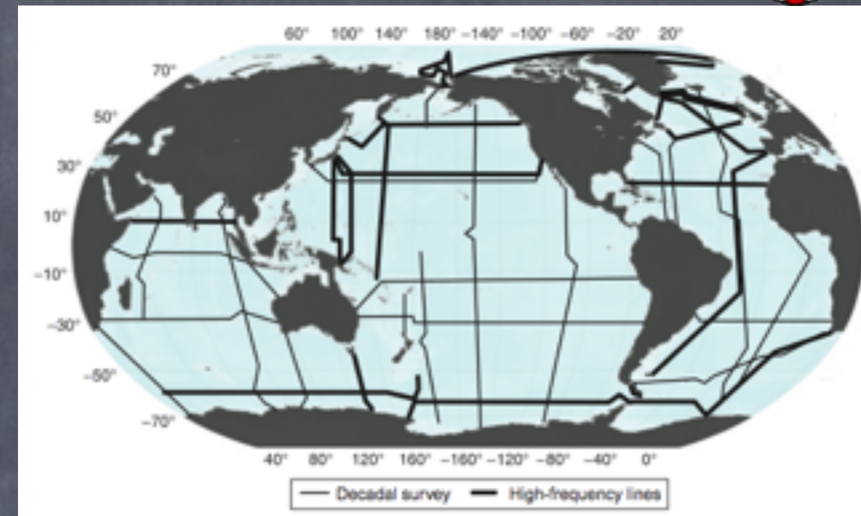


Fig. 10. (a) Estimated contributions to planetary energy imbalance in 1993–2008, and **(b)** in 2005–2010. Except for heat gain in the abyssal ocean and Southern Ocean, ocean heat change beneath the upper ocean (top 700 m for period 1993–2008, top 2000 m in period 2005–2010) is assumed to be small and is not included. Data sources are the same as for Figs. 8 and 9. Vertical whisker in **(a)** is not an error bar, but rather shows the range between the Lyman et al. (2010) and Levitus et al. (2009) estimates. Error bar in **(b)** combines estimated errors of von Schuckmann and Le Traon (2011) and Purkey and Johnson (2010).

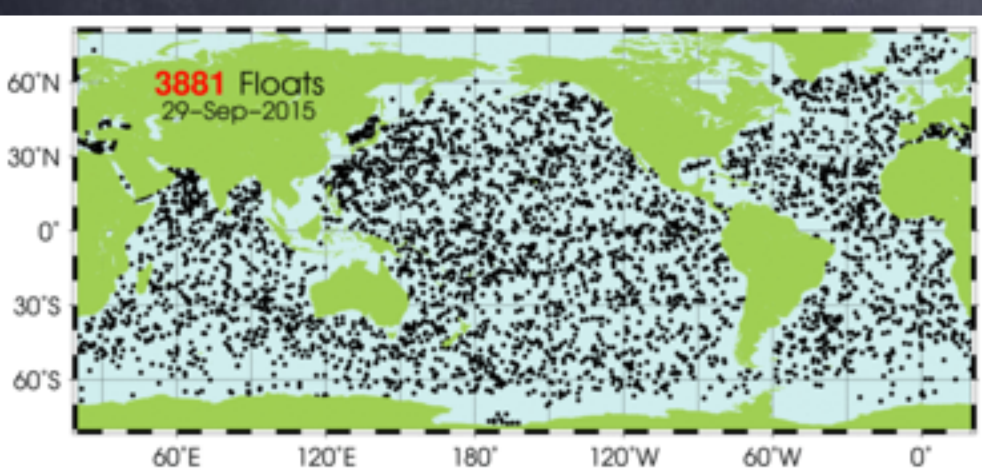
How do we know OHC?

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



GO-SHIP repeat sections: Siedler et al. 2013

Autonomous: e.g., Argo and Satellite Sea Levels. http://www.argo.ucsd.edu/



Argo floats presently active

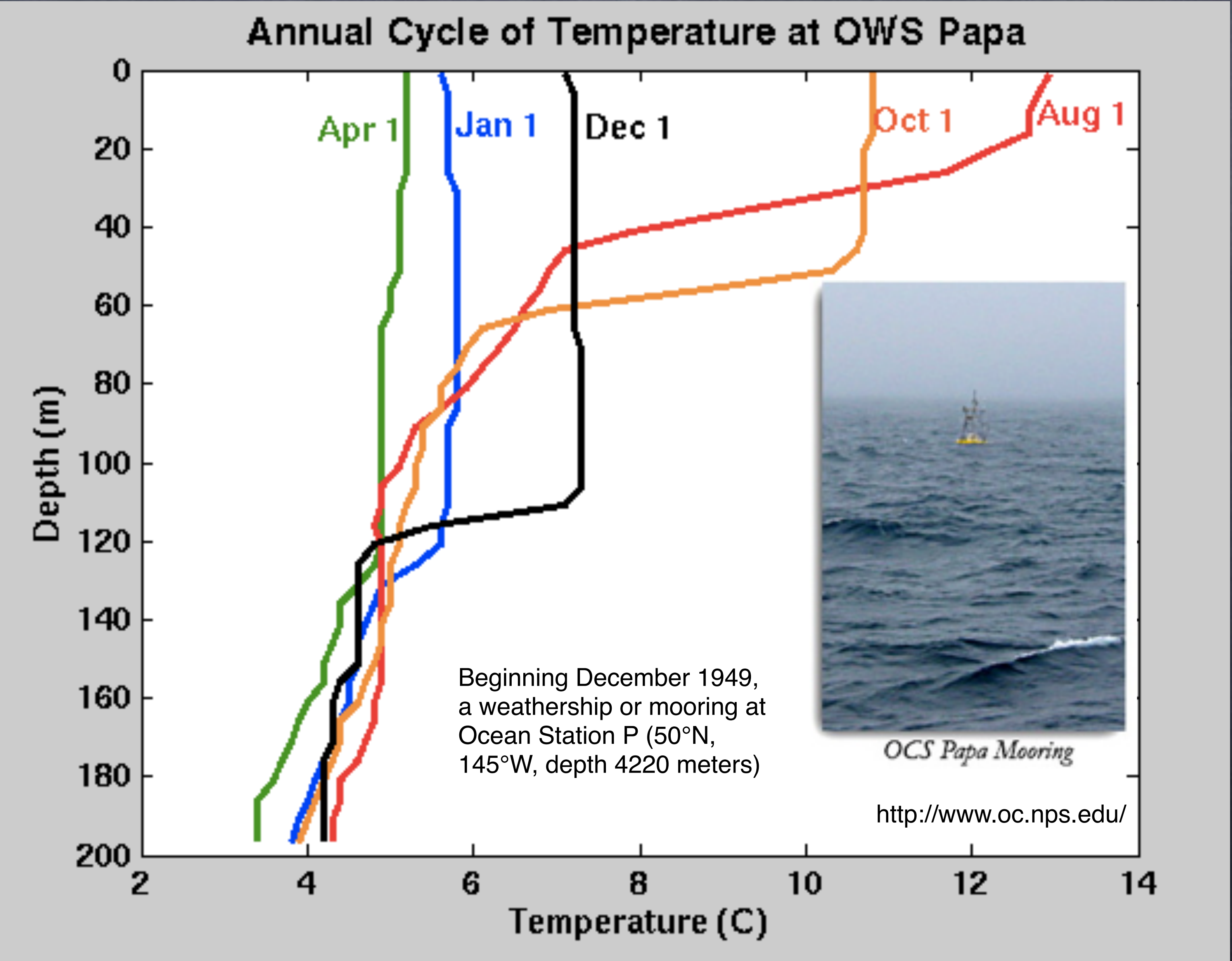
Which Temp?

GMST vs. SST vs. MLT vs. OHC

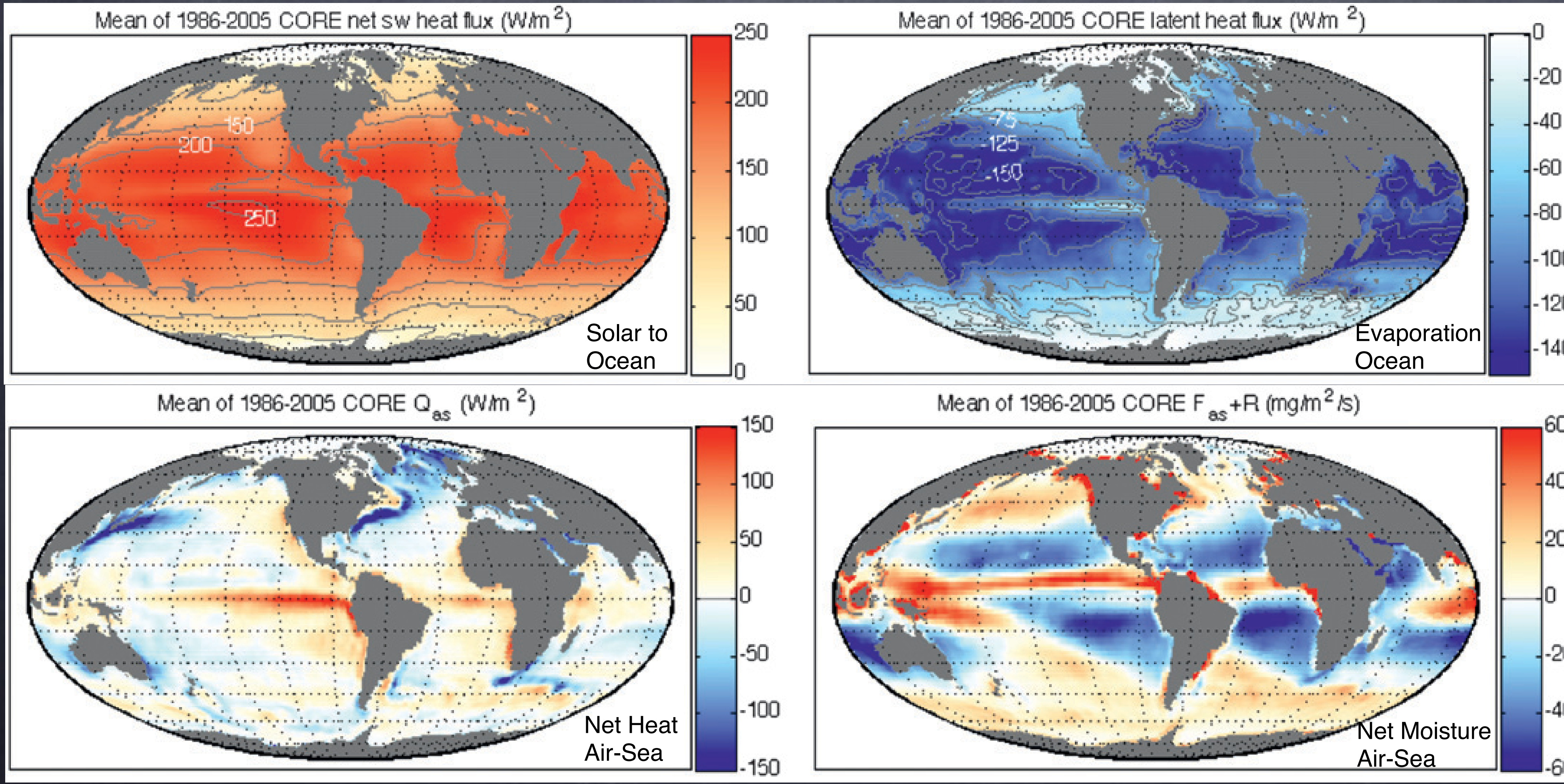
Warming:
0.7 W/m^2

Atmosphere:
1.5K/yr
=
3.4m Ocean:
1.5K/yr
=
34m Ocean:
0.15K/yr

1% of
mixed layer
seasonality



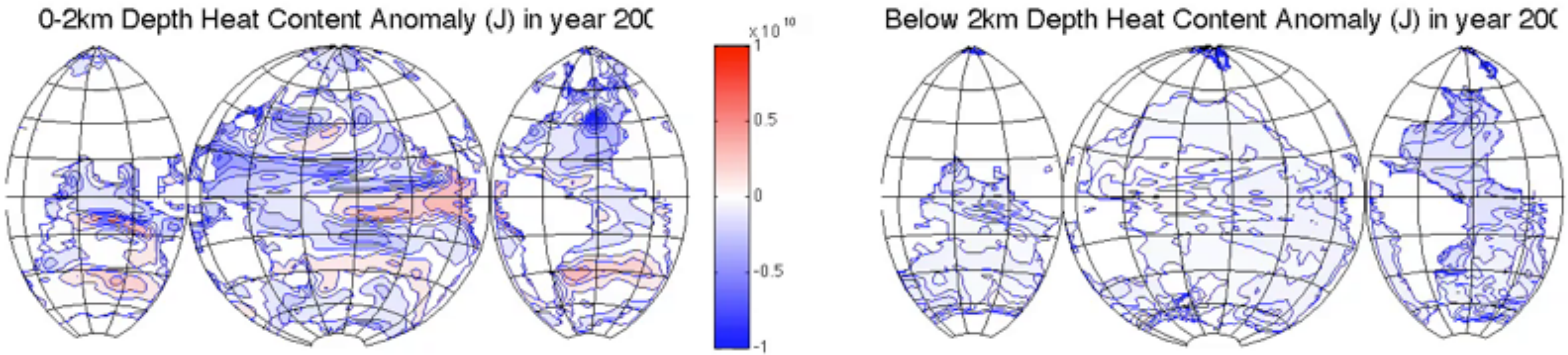
The net Air-Sea Flux is also about 1% of different flux components and about 1% of their spatial variation



S. C. Bates, BFK, 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, November 2012.

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

Doesn't even include mesoscale eddies



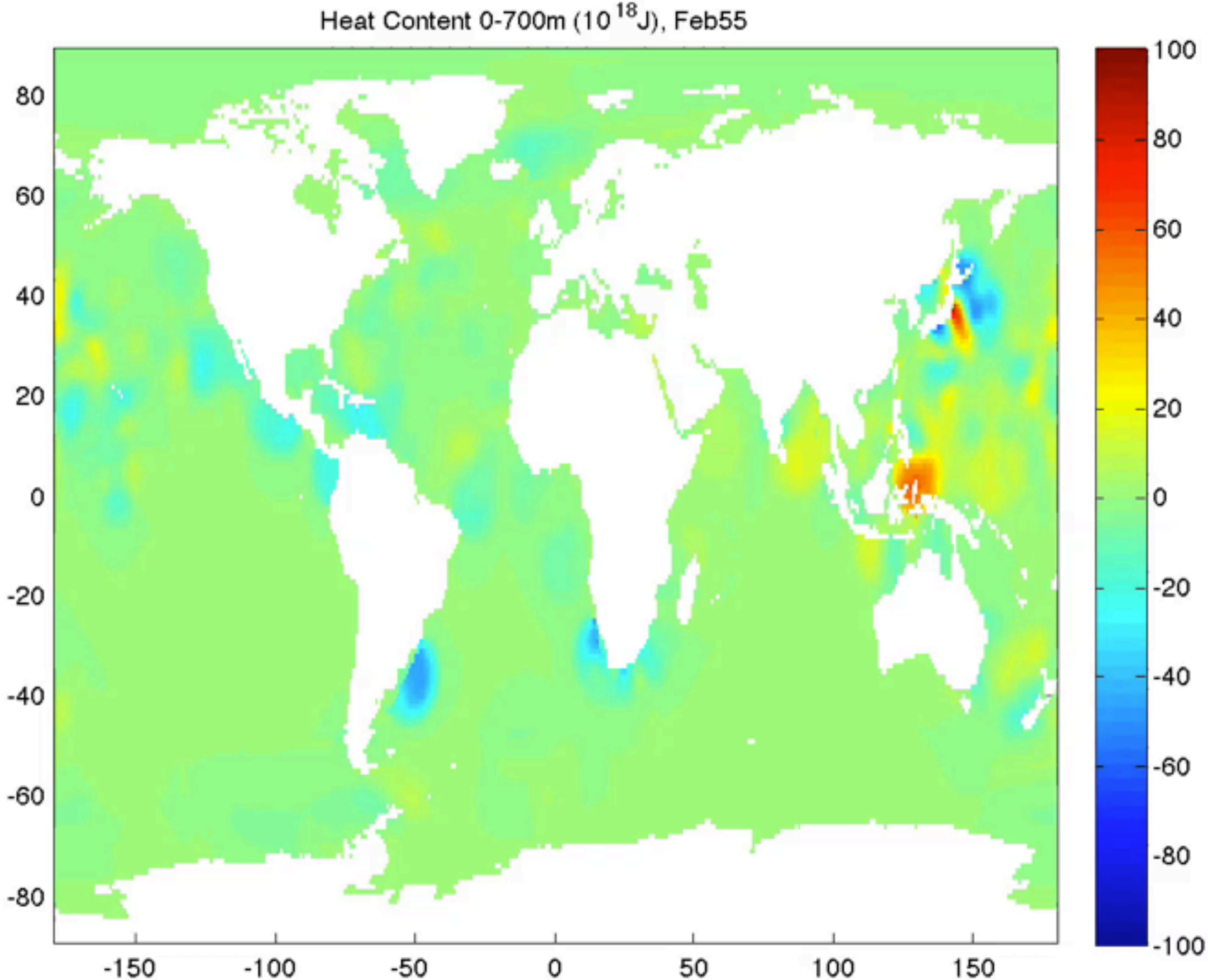
Contours = 4 units

Contours = 1 unit

From the >1000yr steady forcing CCSM3.5 runs of Stevenson et al. 2012

S. Stevenson, BFK, and M. Jochum, 2012: Understanding the ENSO-CO2 link using stabilized climate simulations. Journal of Climate, 25(22):7917–7936.

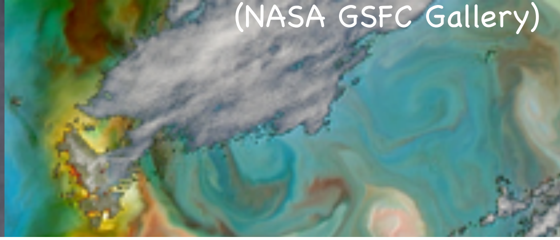
Compare to Observational Product



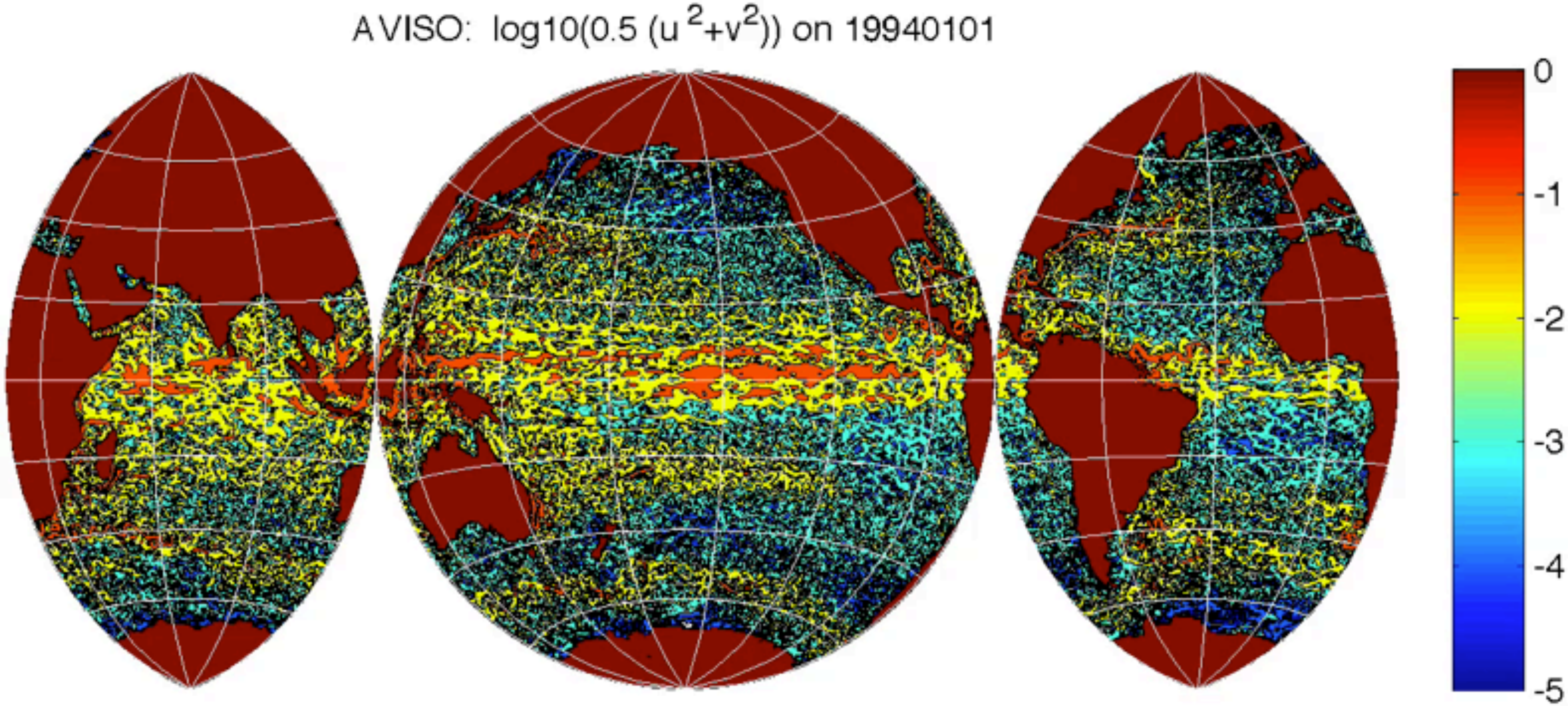
Levitus, S., J. I. Antonov, T. P. Boyer, O. K. Baranova, H. E. Garcia, R. A. Locarnini, A.V. Mishonov, J. R. Reagan, D. Seidov, E. S. Yarosh, M. M. Zweng, 2012: World Ocean heat content and thermosteric sea level change (0-2000 m) 1955-2010. Geophys. Res. Lett. , 39, L10603, doi: 10.1029/2012GL051106"

The Character of Mesoscale Eddies

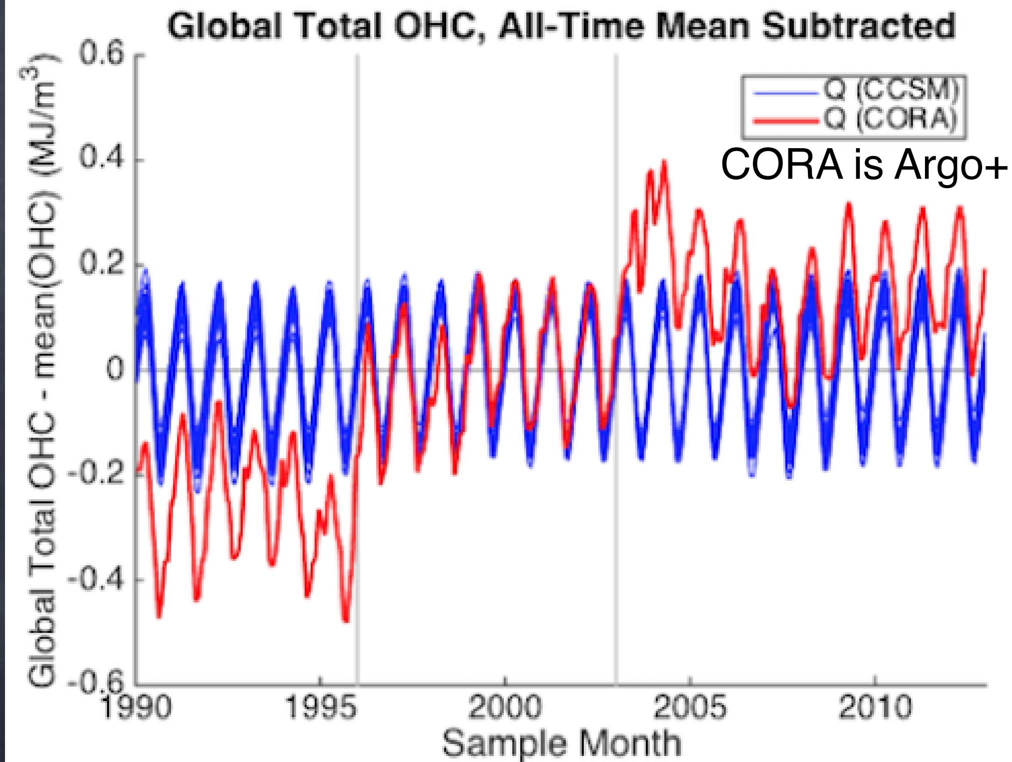
100 km

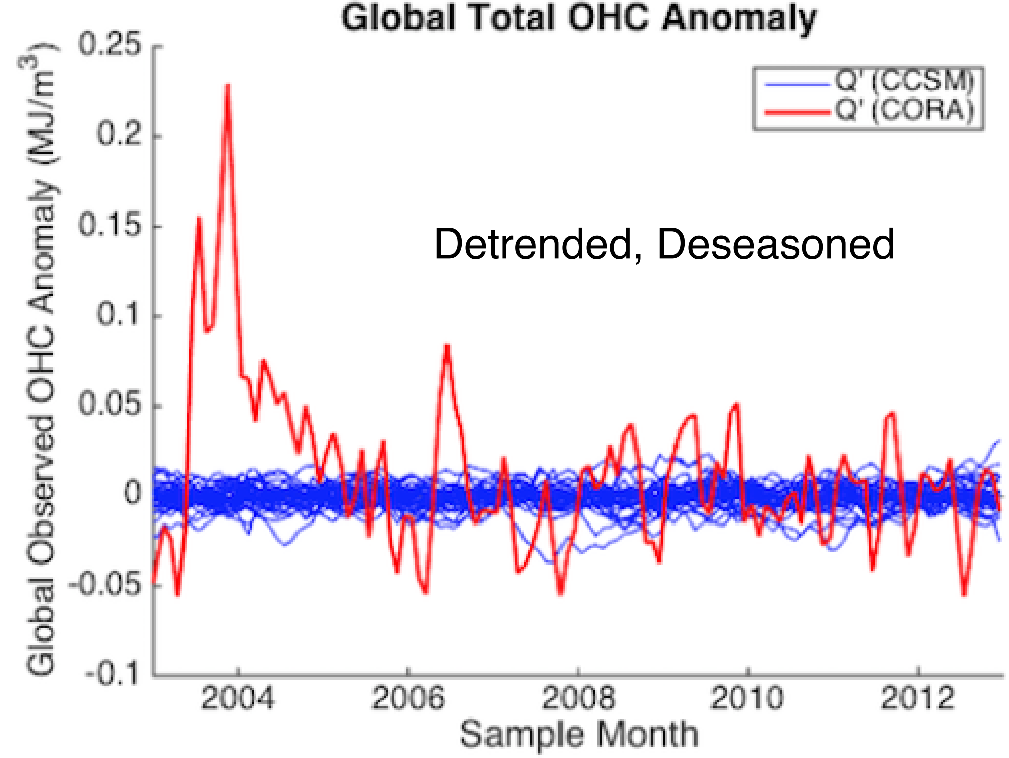


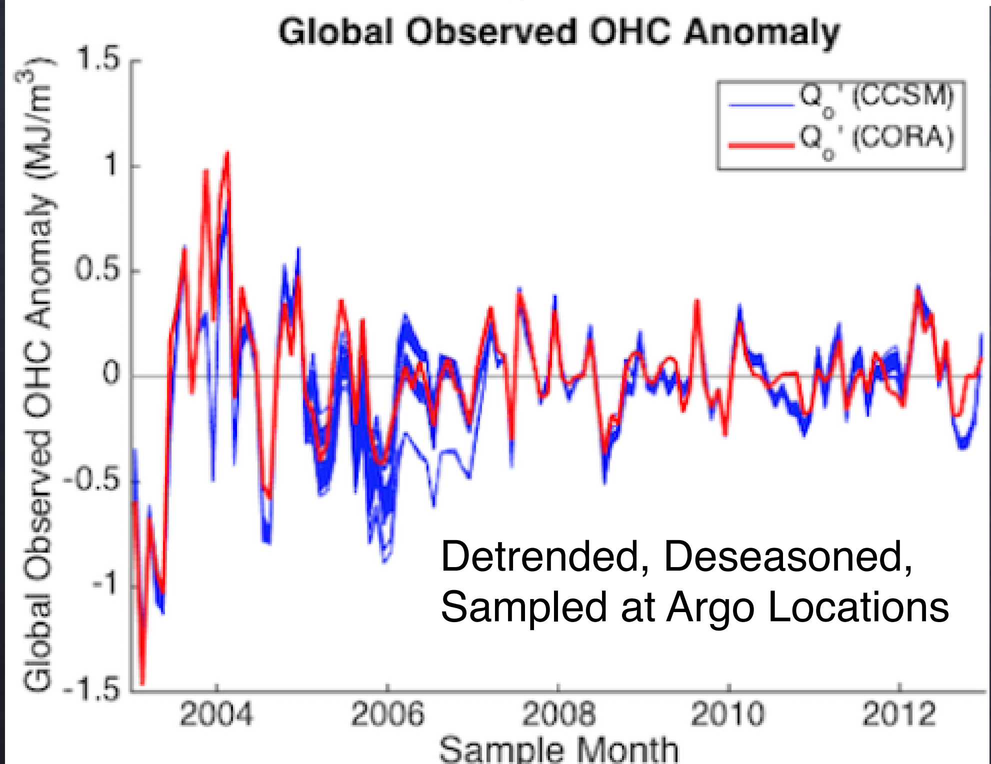
(NASA GSFC Gallery)



Mesoscale Eddies will be routinely resolved in climate models in 2040—some on this later!



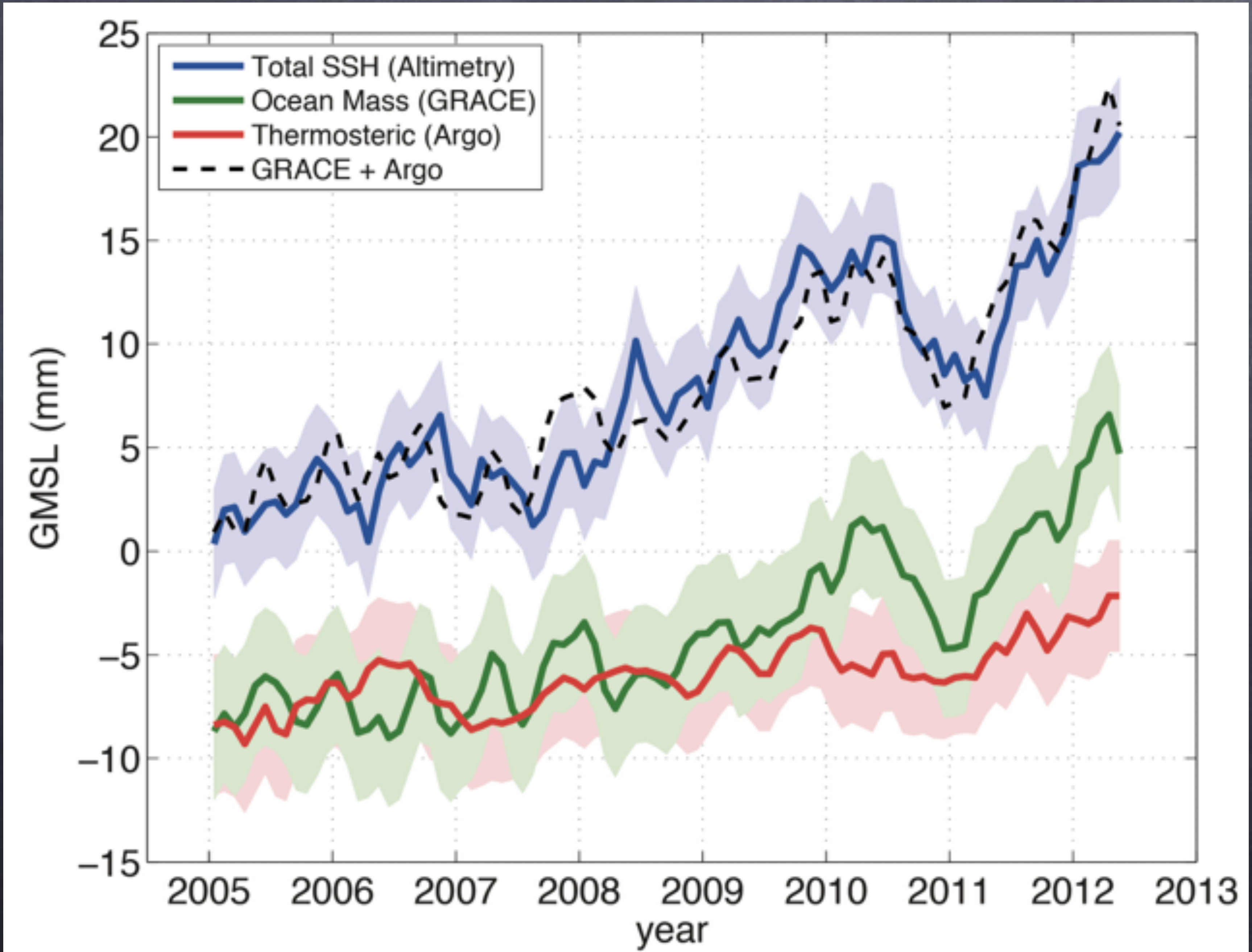




Sophisticated analysis to overcome Ship & Argo sampling problems—inherent uncertainty, O(0.2W/m^2), on interannual to decadal timescales in global average. O(10W/m^2) without analysis.

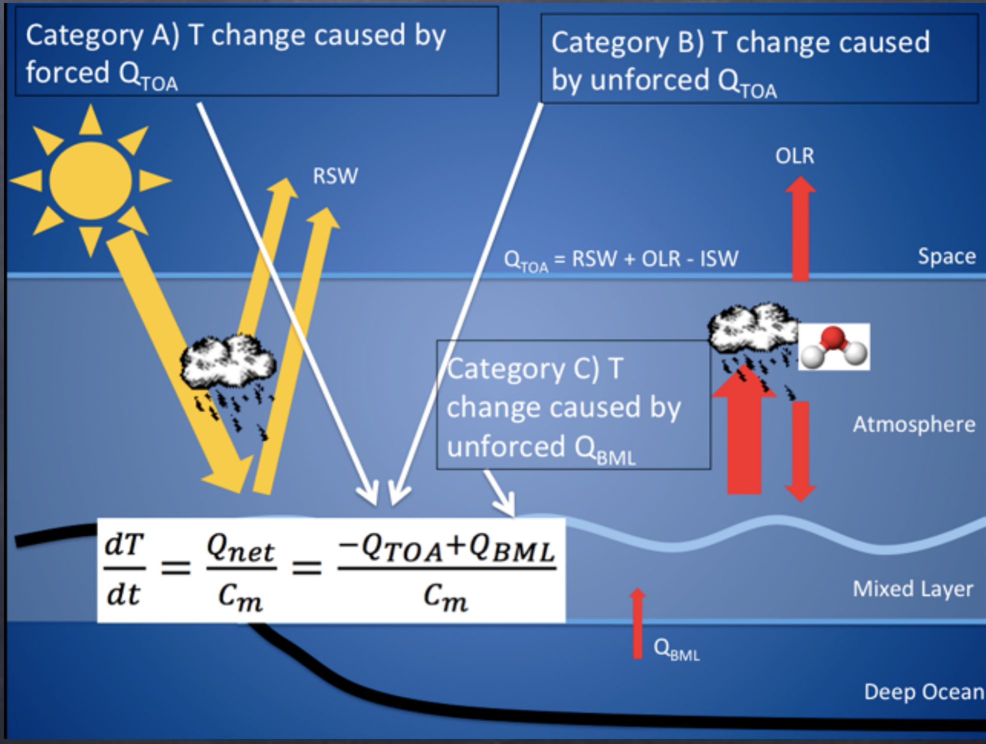
A. D. Nelson, J. B. Weiss, B. Fox-Kemper, 2015: Reconciling observations and models of ocean heat content variability. In preparation.

Another reason to care about ocean warming: Sea Level Rise



Presence of observable variability

- There is observable (autonomous & ship) ocean heat content variability.
- The near surface seasonal cycle, regional variations, and individual flux components are O(100 W/m^2)
- Global top of atmosphere net imbalance Q_{TOA} and net mixed layer entrainment Q_{BML} is more like O(1 W/m^2)
- Nonetheless this warming
- is about half of the
- observed sea level rise



Understanding of past variability

- Monday Morning Quarterbacking abounds in variability analyses, e.g.:
  - You can't use 1998 as a start year—it was the biggest ENSO event of the past 100yr...
  - Phase of the IPO/PDO explains the hiatus, but we don't know what causes the IPO/PDO...
- May be explanations and tests of understanding, but little predictive power.

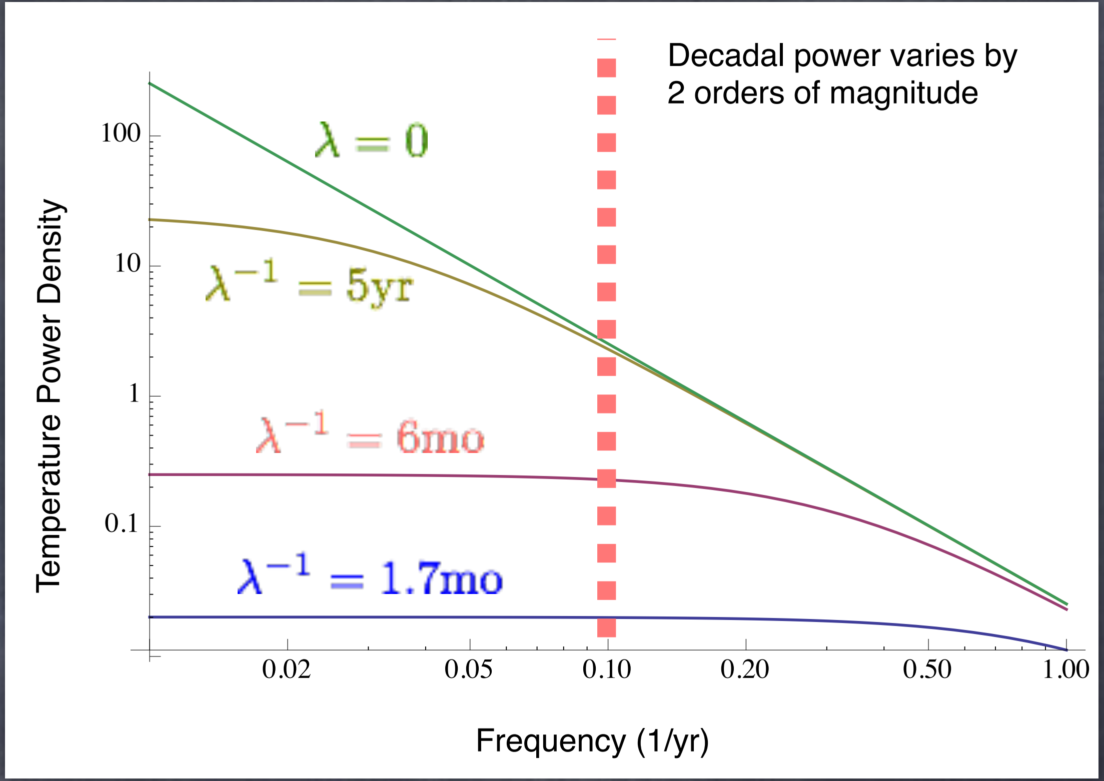
Modeling of variability

Stochastic, Unpredictable (beyond persistence) Model:
Frankignoul & Hasselmann (77)

$$\frac{dT}{dt} = \frac{f_1'}{h} - \lambda T$$

$$\lambda = \rho^a C_p^a (\rho^w C_p^w)^{-1} C_H (1 + B) \langle |\mathrm{U}| \rangle h^{-1}$$

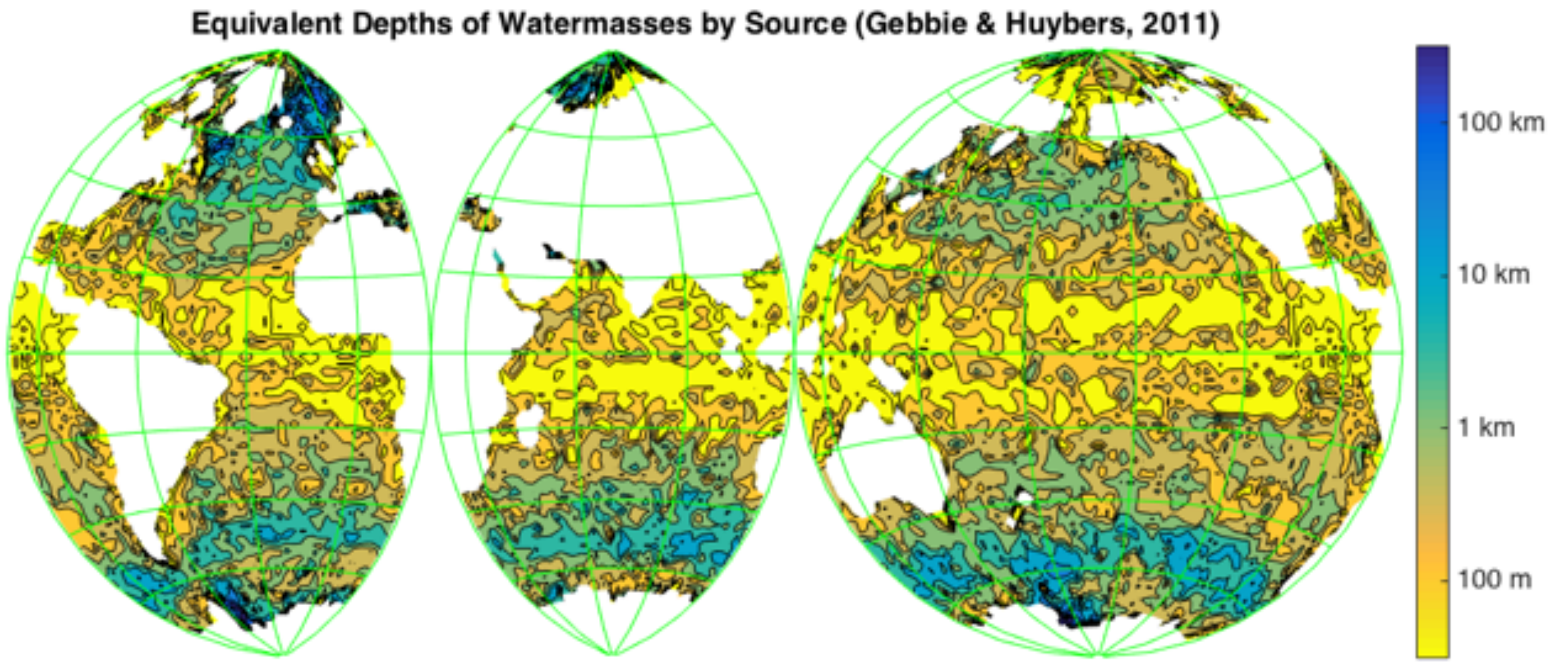
$$= (1.7 \text{ month})^{-1}$$

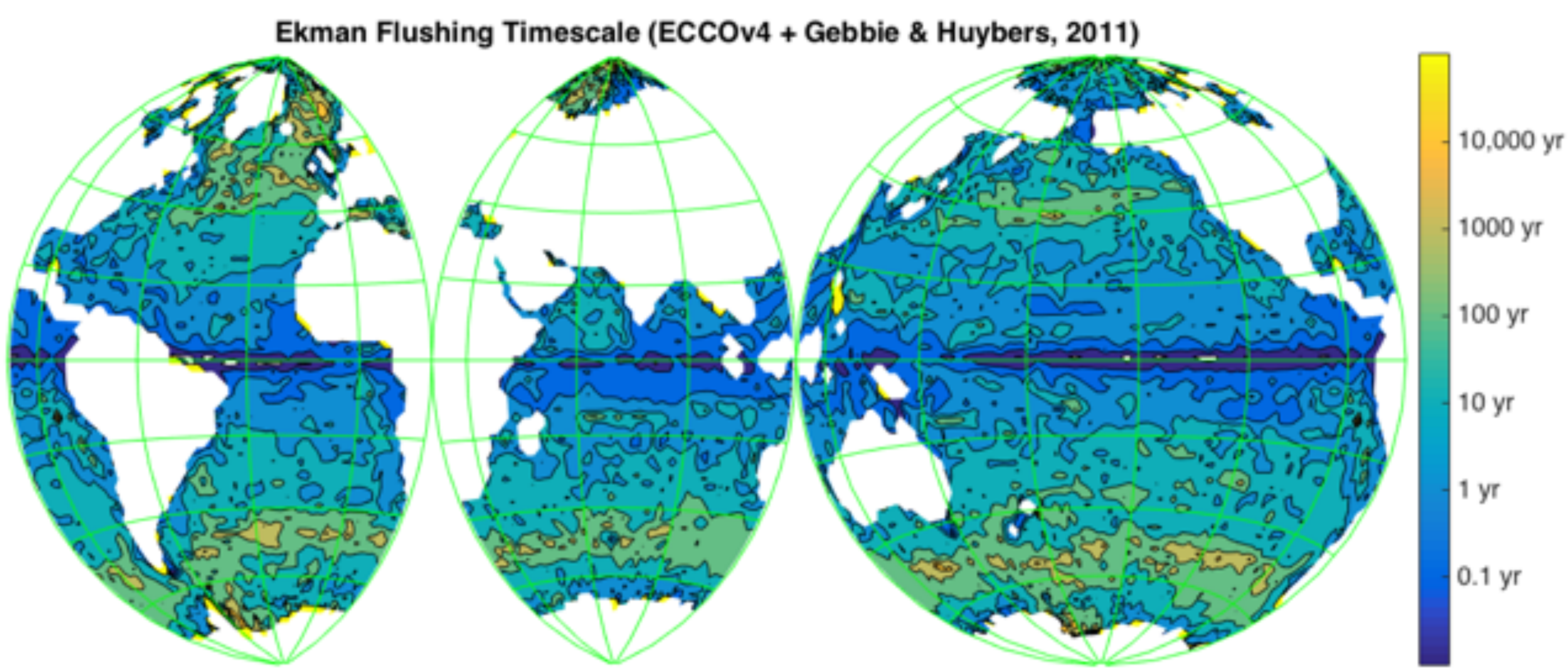


- Air: 1000 J/kg/K, Water: 4186 J/kg/K
- Density: Weight Atmosphere=10m Ocean
- Area: 71% of Surface => Weight Atmo=14m ocean
- Heat Cap: 3.4m Ocean=Whole Atmo
- Ocean = 1000x Atmo. in Heat Capacity

Consider 1D Oceans: one per watermass

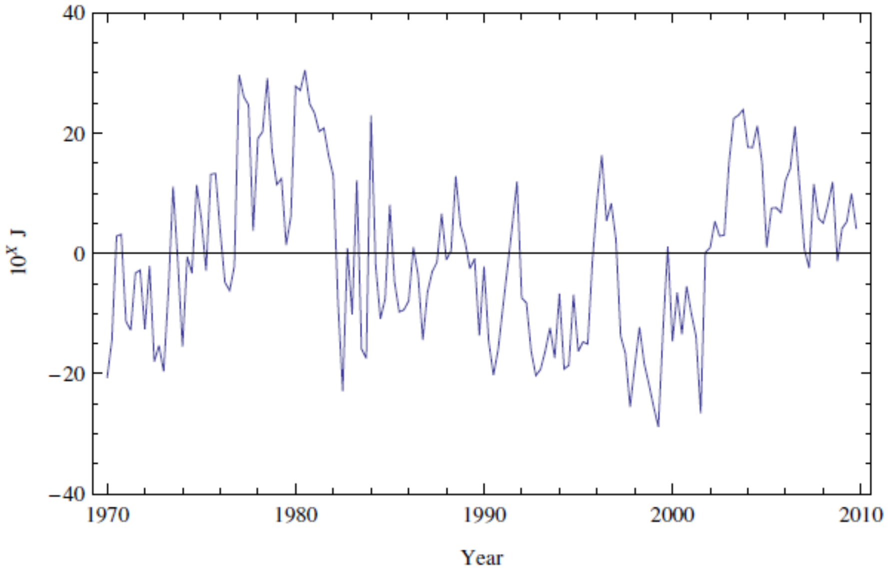
Wind-Driven (Ekman) flushing gives upper limit to λ^{-1} damping timescale



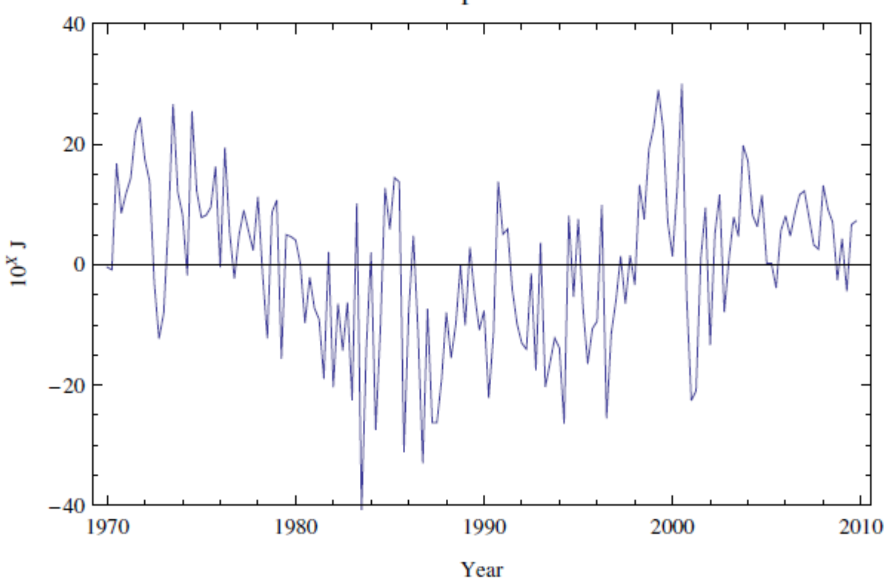


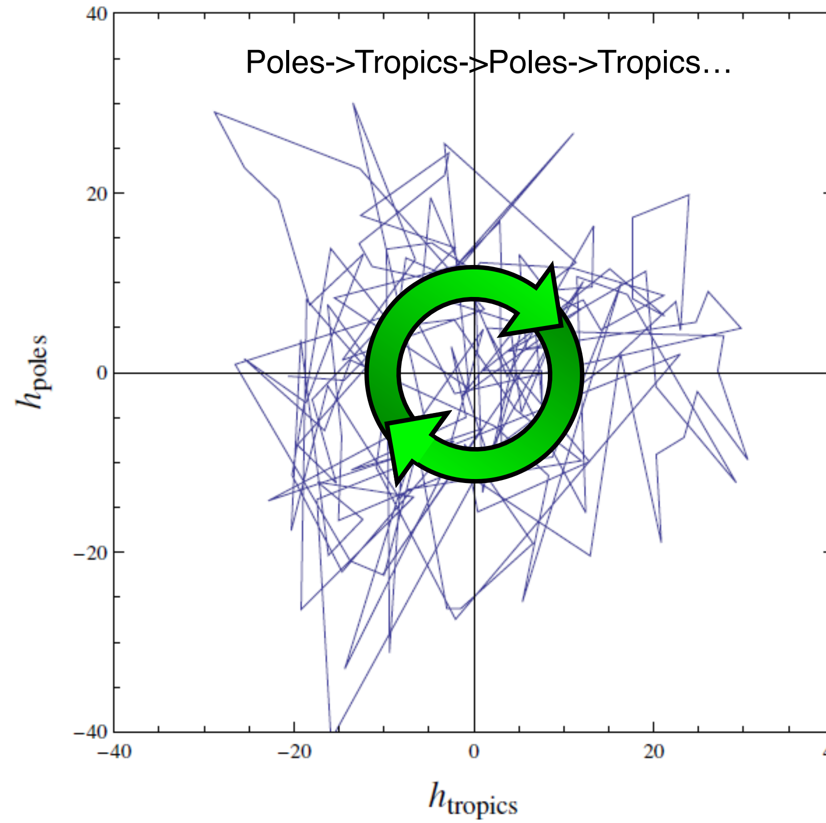
If Connections Occur Between Regions—Predictability Arises, Even in Stochastic Systems (Nonequilibrium Stat. Mechanics).

Tropical Ocean Heat Content h_{tropics}



Polar Ocean Heat Content h_{poles}



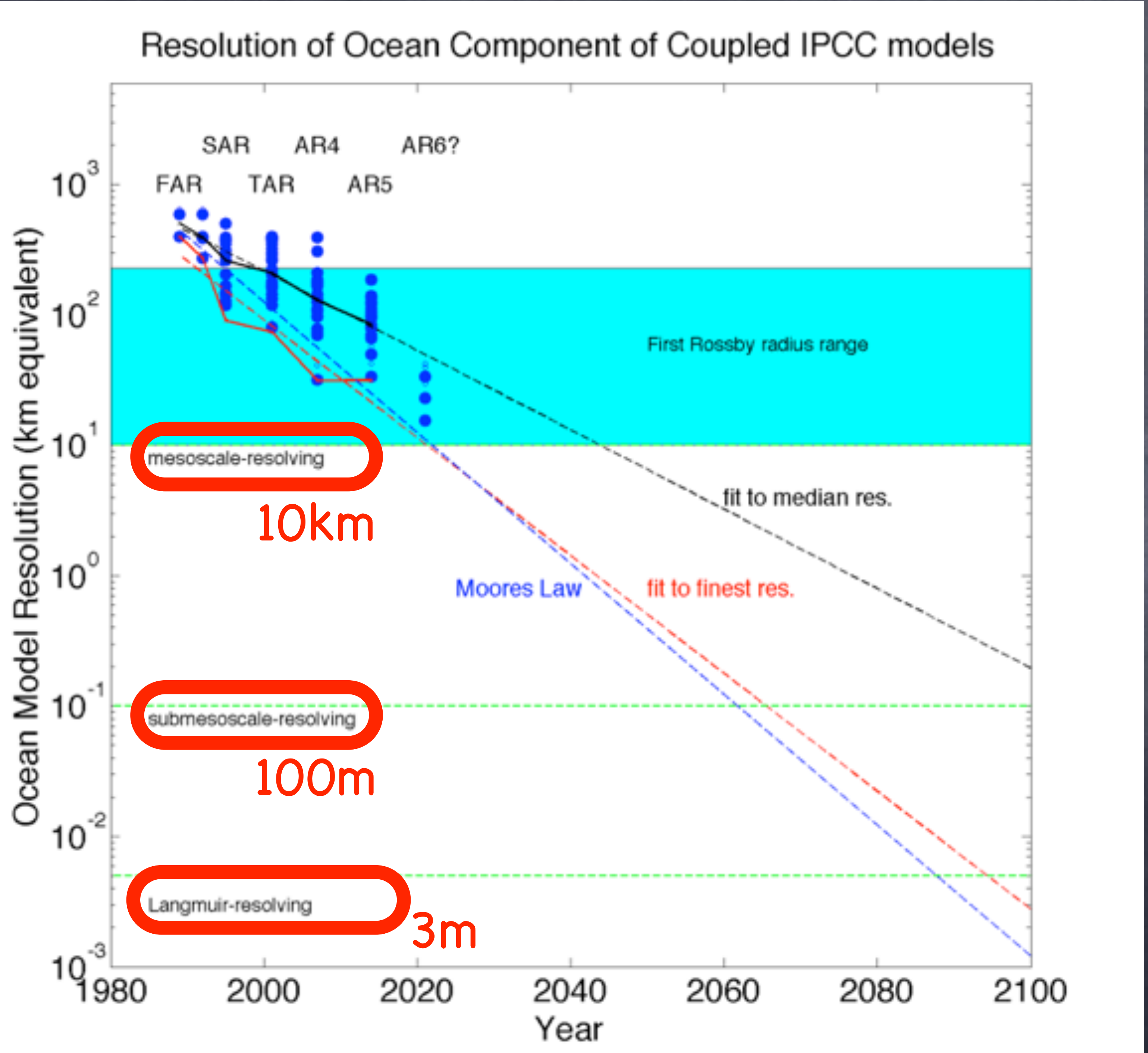


This is the root cause of most stochastic model predictability beyond persistence

Jeffrey B Weiss, Baylor Fox-Kemper, Dibyendu Mandal and Royce K P Zia, 2015: Fluctuation cycles of ocean heat content. New Journal of Physics, in prep.

What about modeling every important process 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

Yes, climate models do pretty well at matching heat fluxes.

Statistically significant differences in only a few timescales & regions from observation uncertainty

Models get better every generation due to improved resolution and parameterizations

What does it take to make these improvements?

S. C. Bates, BFK, 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, November 2012.

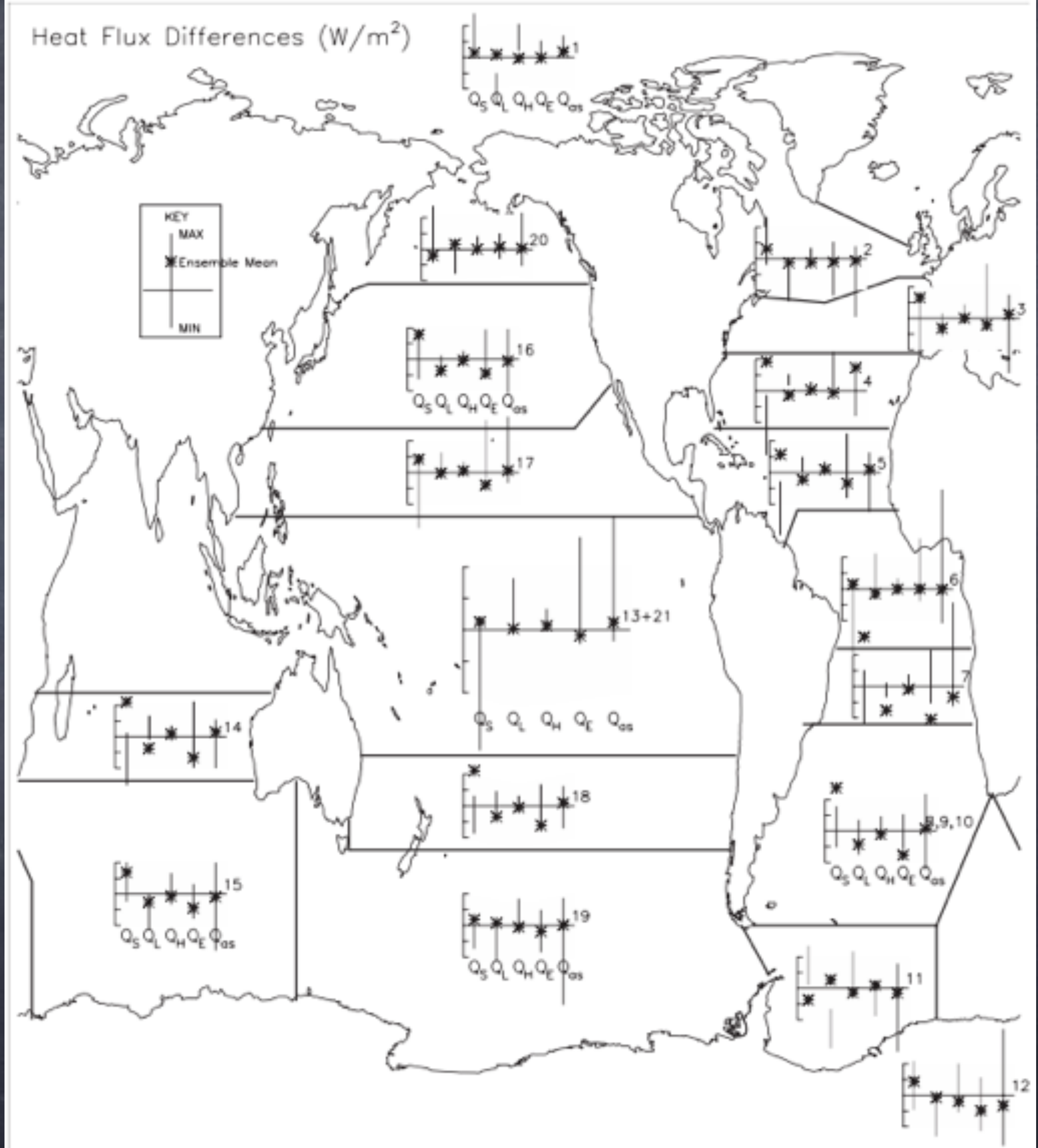
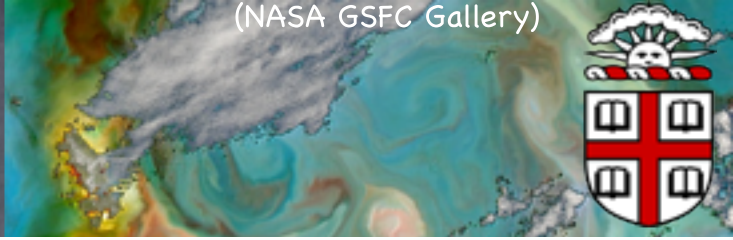
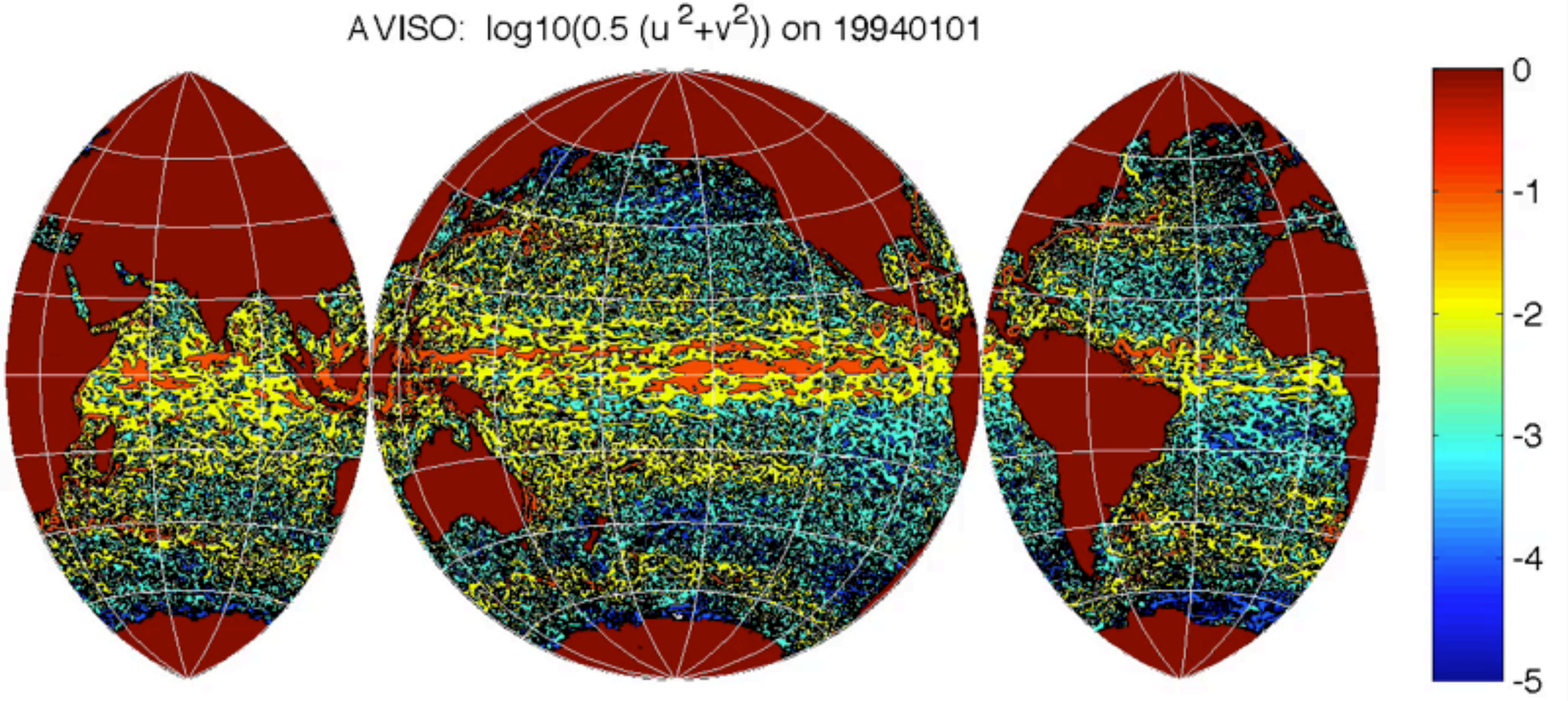


FIG. 4. Regional averages of the CCSM4 20C ensemble mean heat flux components differenced with the CORE

Recall: Mesoscale Eddies

100 km





Mesoscale Eddies will be routinely resolved in climate models in 2040!

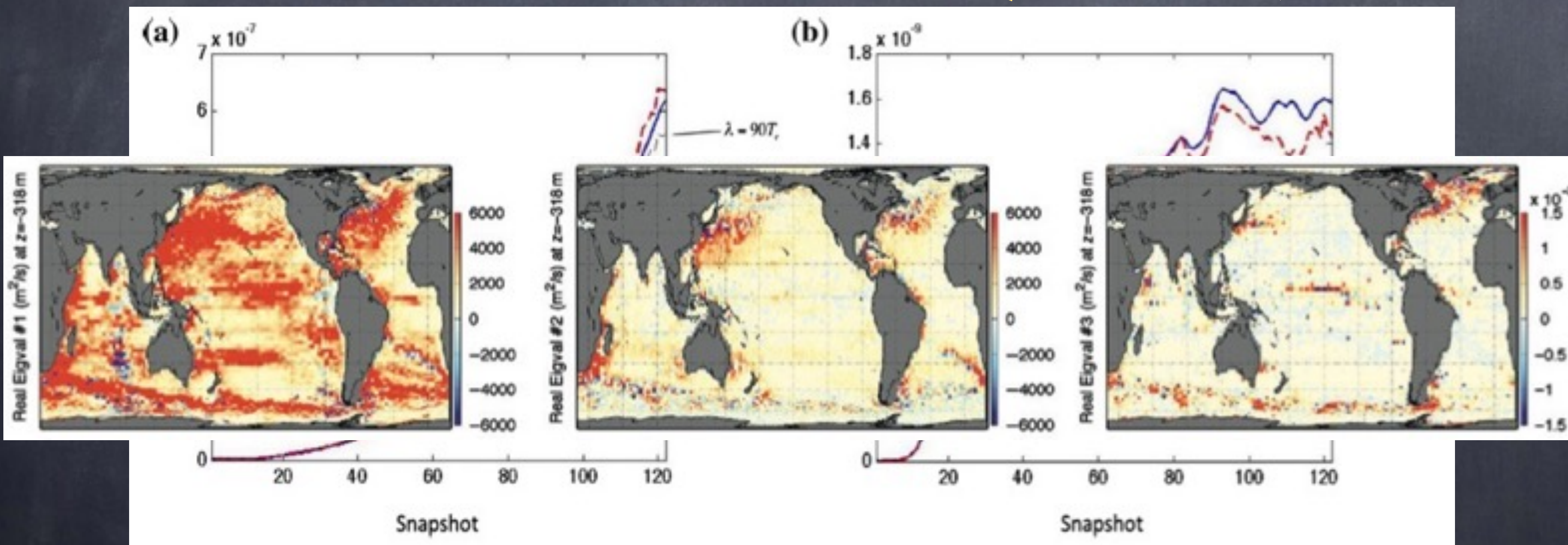
Mesoscale Eddy Advective & Diffusive Transport

$$\overline{u'_j \tau'_\pi} = -R_{ji} \nabla_i \bar{\tau}_\pi,$$

Flux-Gradient (Anisotropic)

Symmetric=Diff.

Antisymmetric=Adv.



BFK, 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.

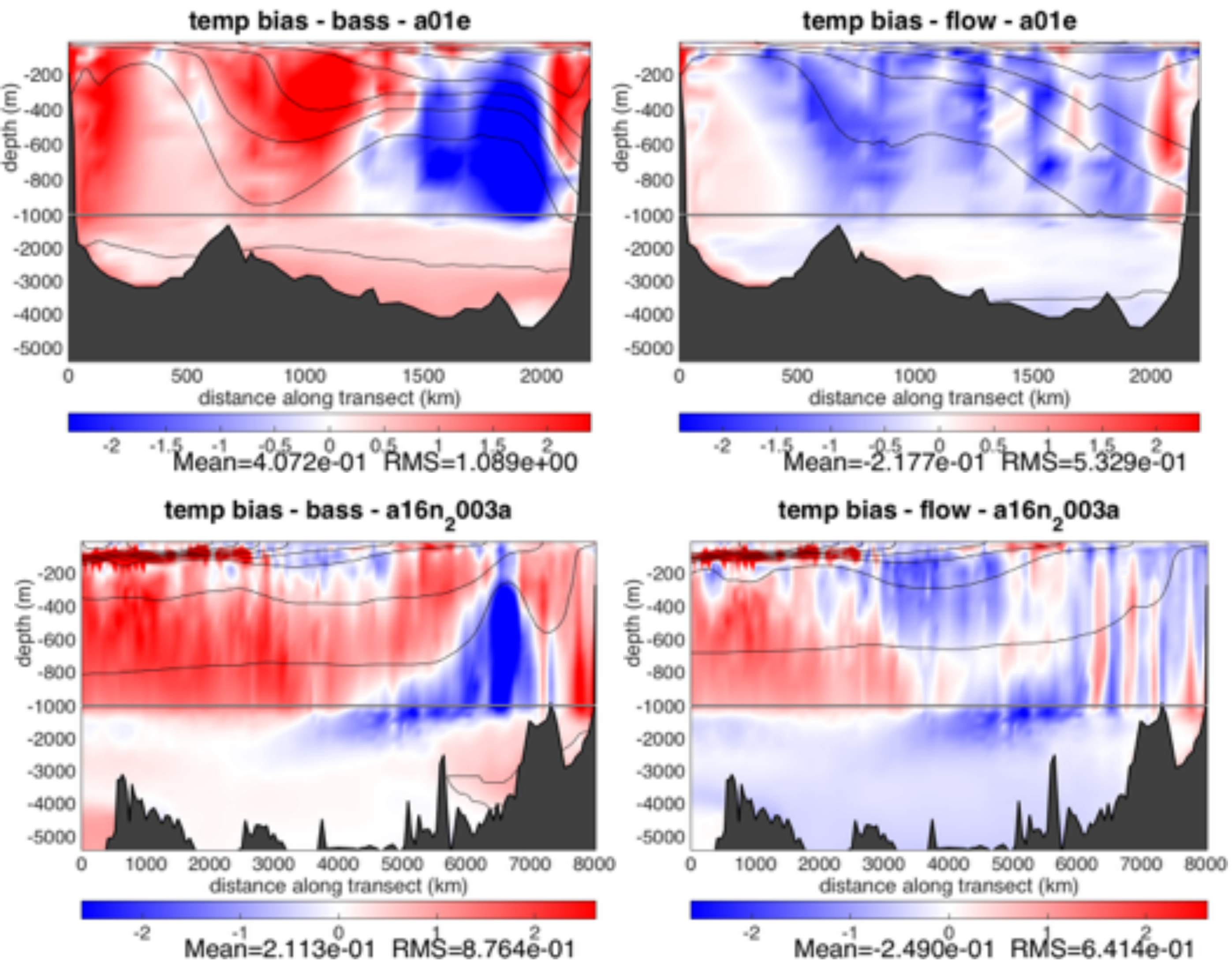
S. Bachman and BFK. Eddy parameterization challenge suite. I: Eady spindown. Ocean Modelling, 64:12-28, 2013

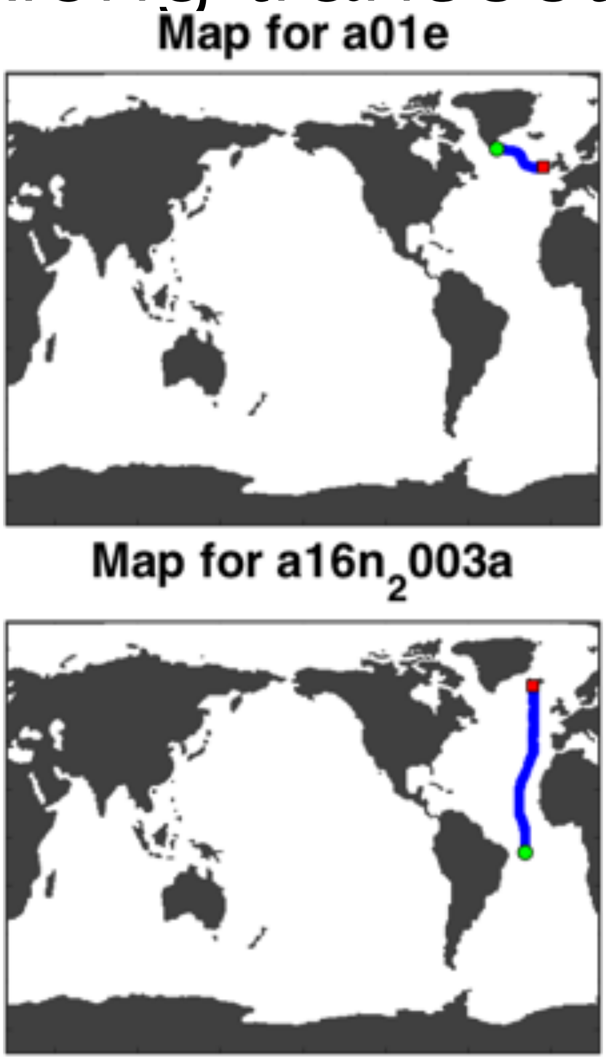
S. Bachman, BFK, and F. O. Bryan. A tracer-based inversion method for diagnosing eddy-induced diffusivity and advection. Ocean Modelling, 86:1-14, February 2015.

Control: Isotropic

Anisotropic

Along transects



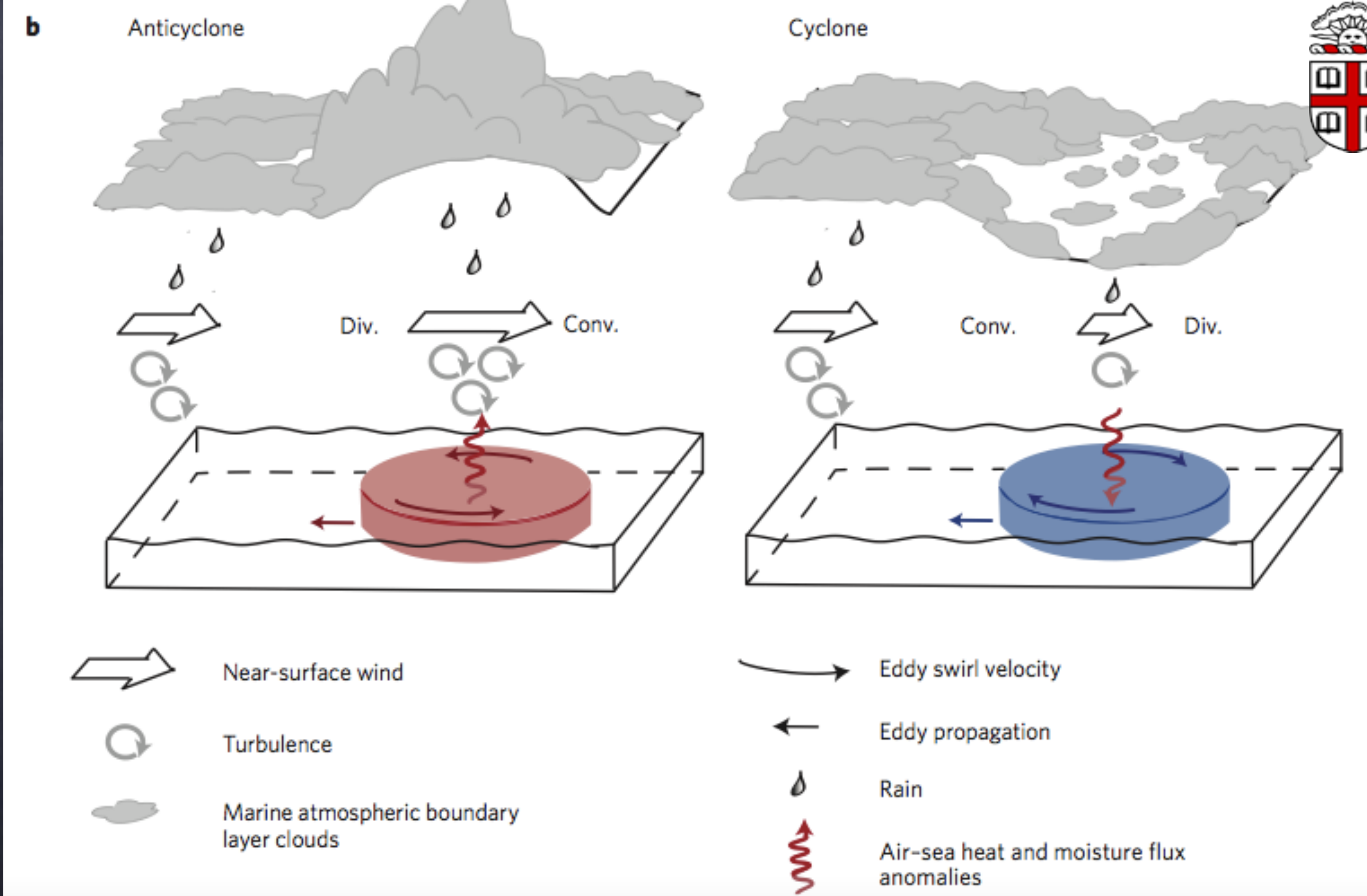


Anisotropy often reduces biases:

pCFC by up to 24%

Temp by up to 48%

Salinity by up to 63%



Mesoscale Eddy Air-Sea Feedbacks? Resolve the eddies!

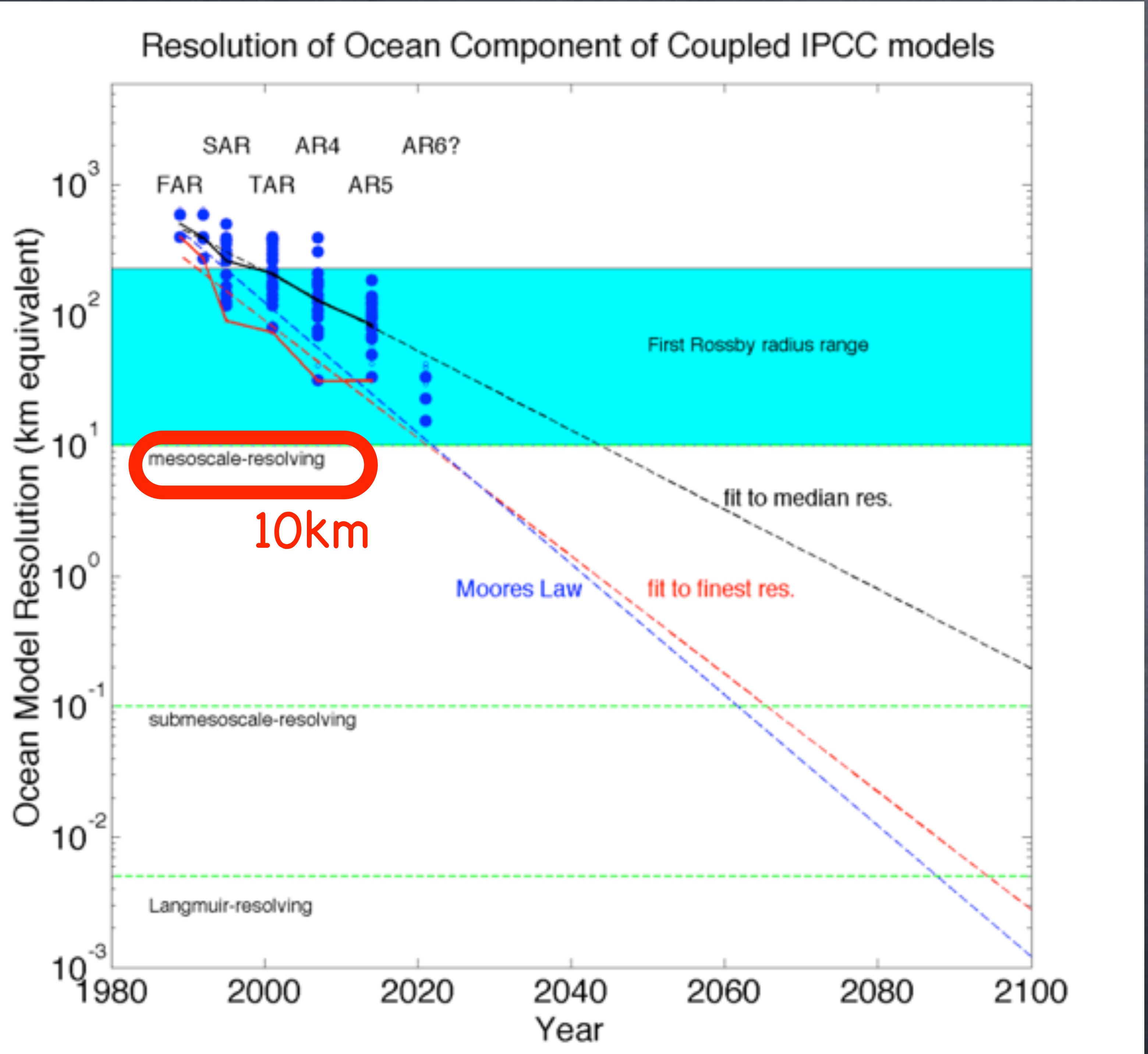
Effect on net air-sea fluxes observed statistically, not parameterized.

Bryan et al. 2010, Frenger et al. 2013

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.

Climate Model Resolution: an issue for centuries to come!

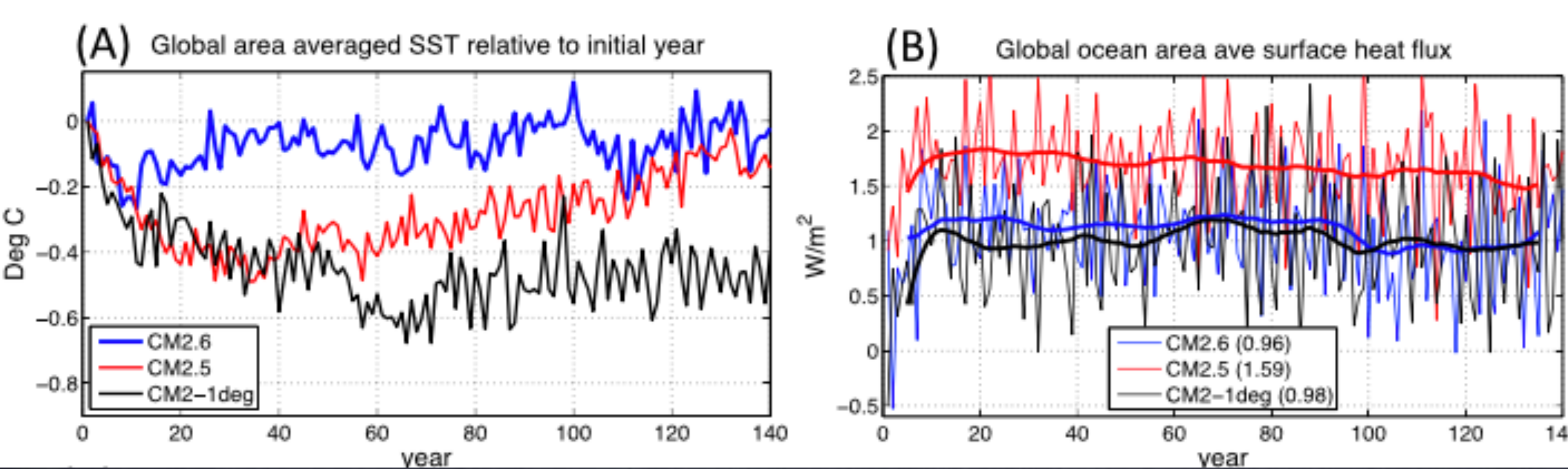


Here are the collection of IPCC models...

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

By comparing resolved mesoscale eddies to parameterized ones (with same 50km atmosphere), we get another entry in the pile!

O(0.7 W/m²) and O(0.4 K/century), i.e., significant warming to upper 1500m of ocean.



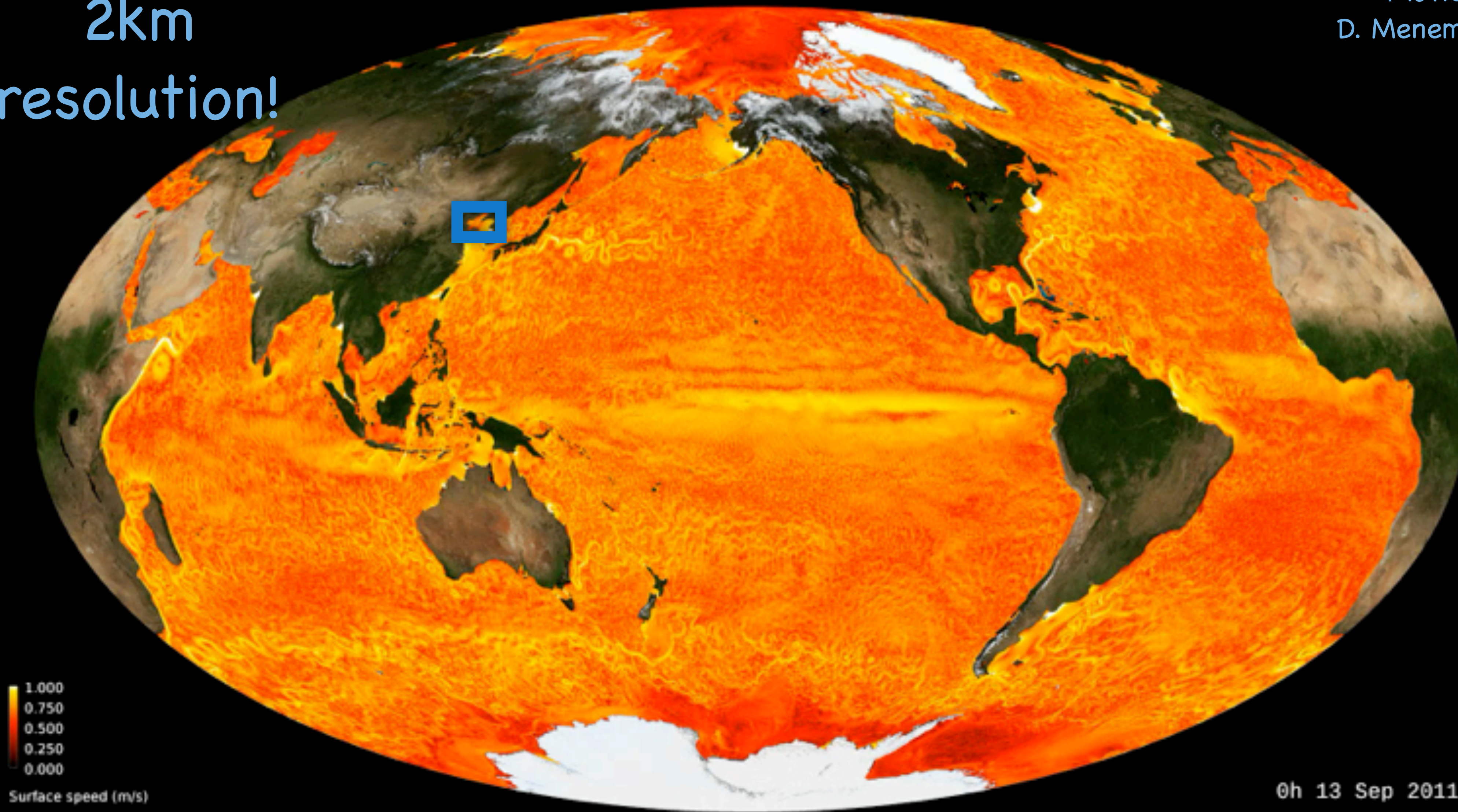
Stephen M. Griffies, Michael Winton, Whit G. Anderson, Rusty Benson, Thomas L. Delworth, Carolina O. Dufour, John P. Dunne, Paul Goddard, Adele K. Morrison, Anthony Rosati, Andrew T. Wittenberg, Jianjun Yin, and Rong Zhang, 2015: Impacts on Ocean Heat from Transient Mesoscale Eddies in a Hierarchy of Climate Models. J. Climate, 28, 952–977.

Estimating the Circulation & Climate of the Ocean

LLC4320 Model

2km resolution!

Movie:
D. Menemenlis



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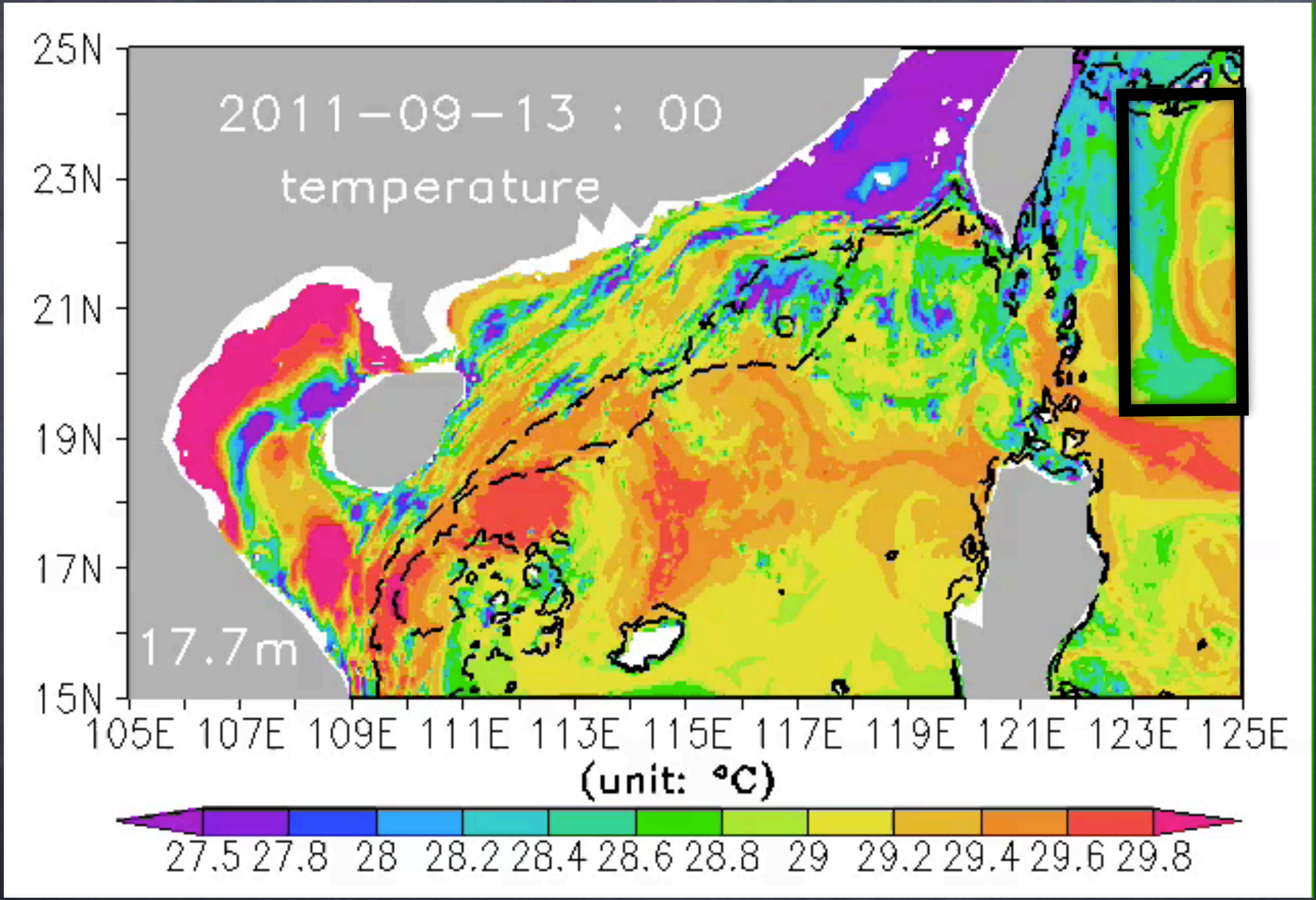
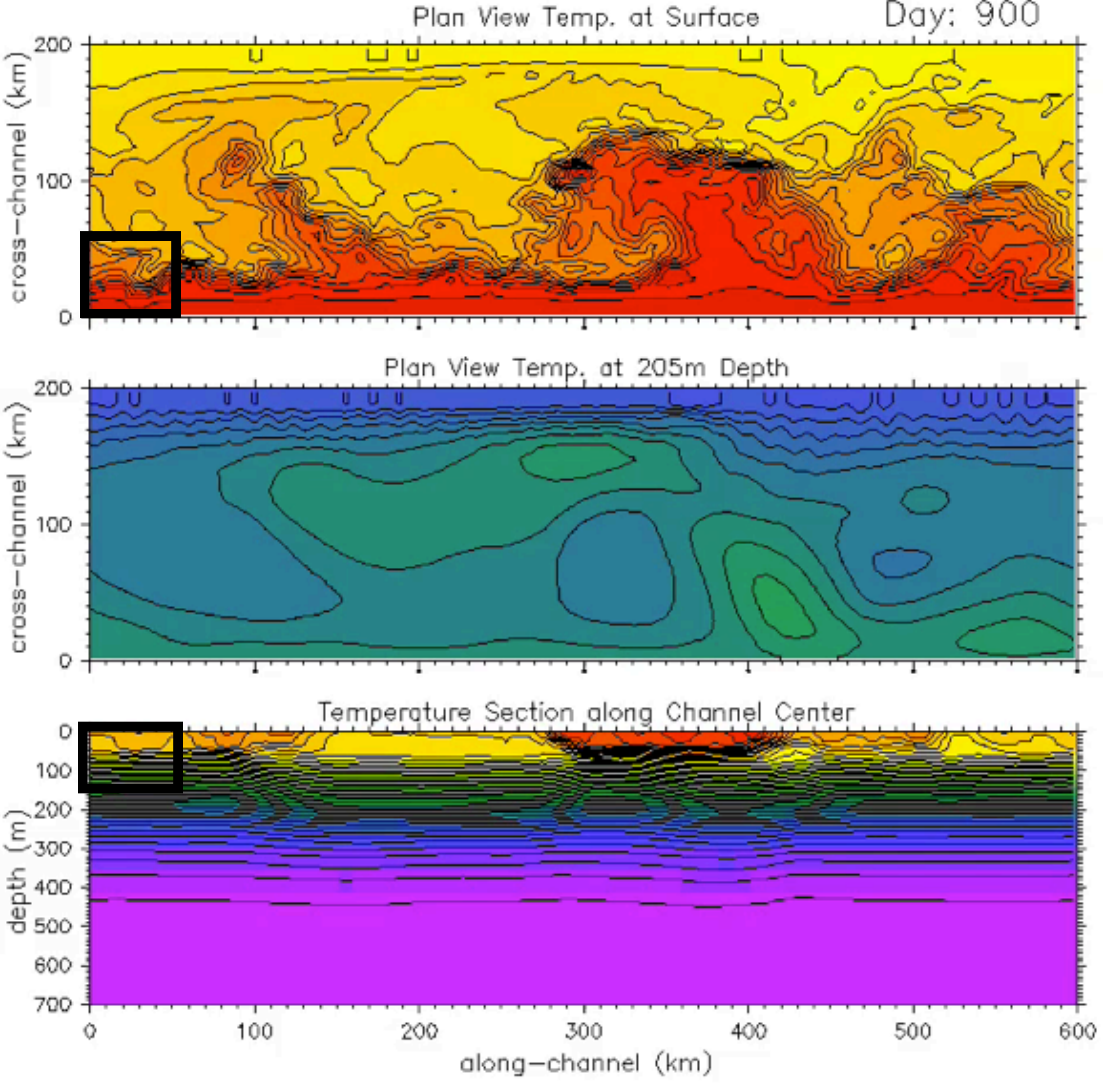
LLC4320 Model



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. Submitted.

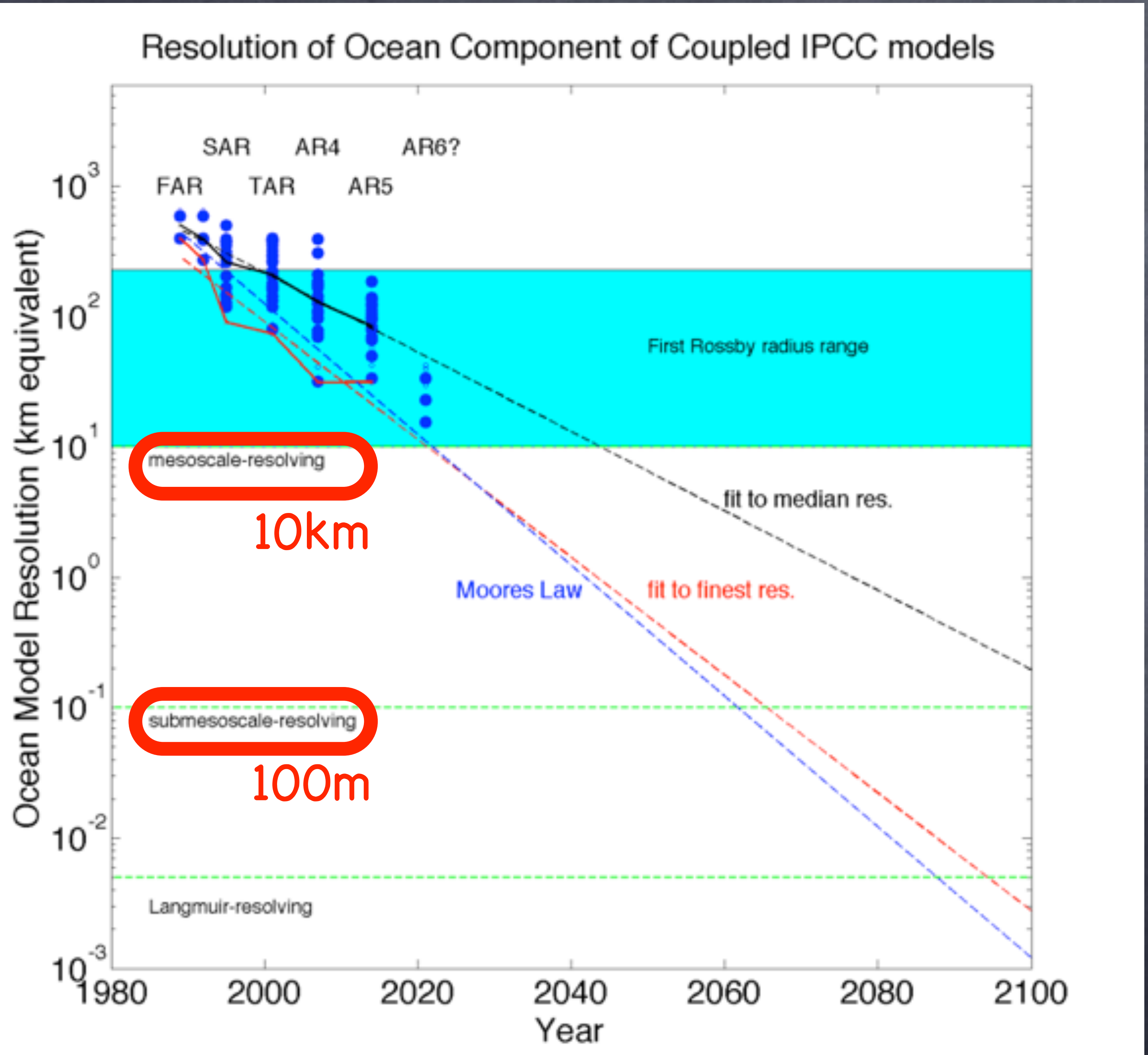
200km x 600km x 700m domain

1000 Day Simulation



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

Climate Model Resolution: an issue for centuries to come!



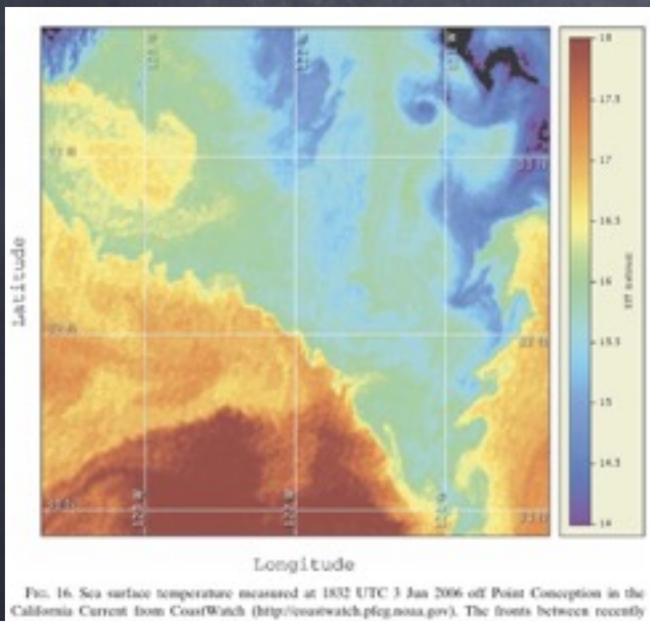
Here are the collection of IPCC models...

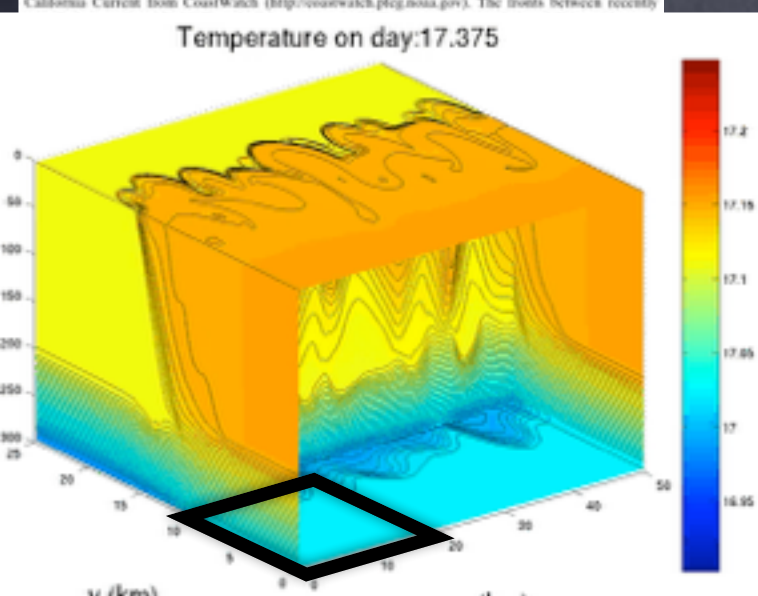
If we can't resolve a process, we need to develop a parameterization or subgrid model of its effect

The Character of the Submesoscale

← 10 km

(Capet et al., 2008)



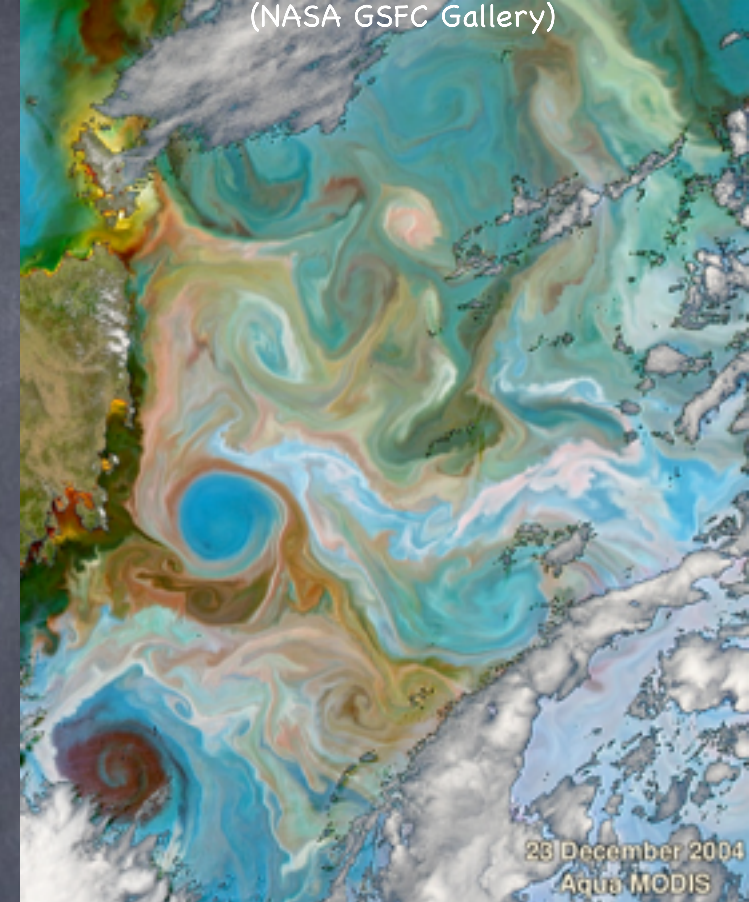


- Fronts
- Eddies
- Ro=O(1)
- Ri=O(1)
- near-surface (H=100m)
- 1-10km, days

Eddy processes often baroclinic instability

Parameterizations = BFK et al (08-11).

(NASA GSFC Gallery)



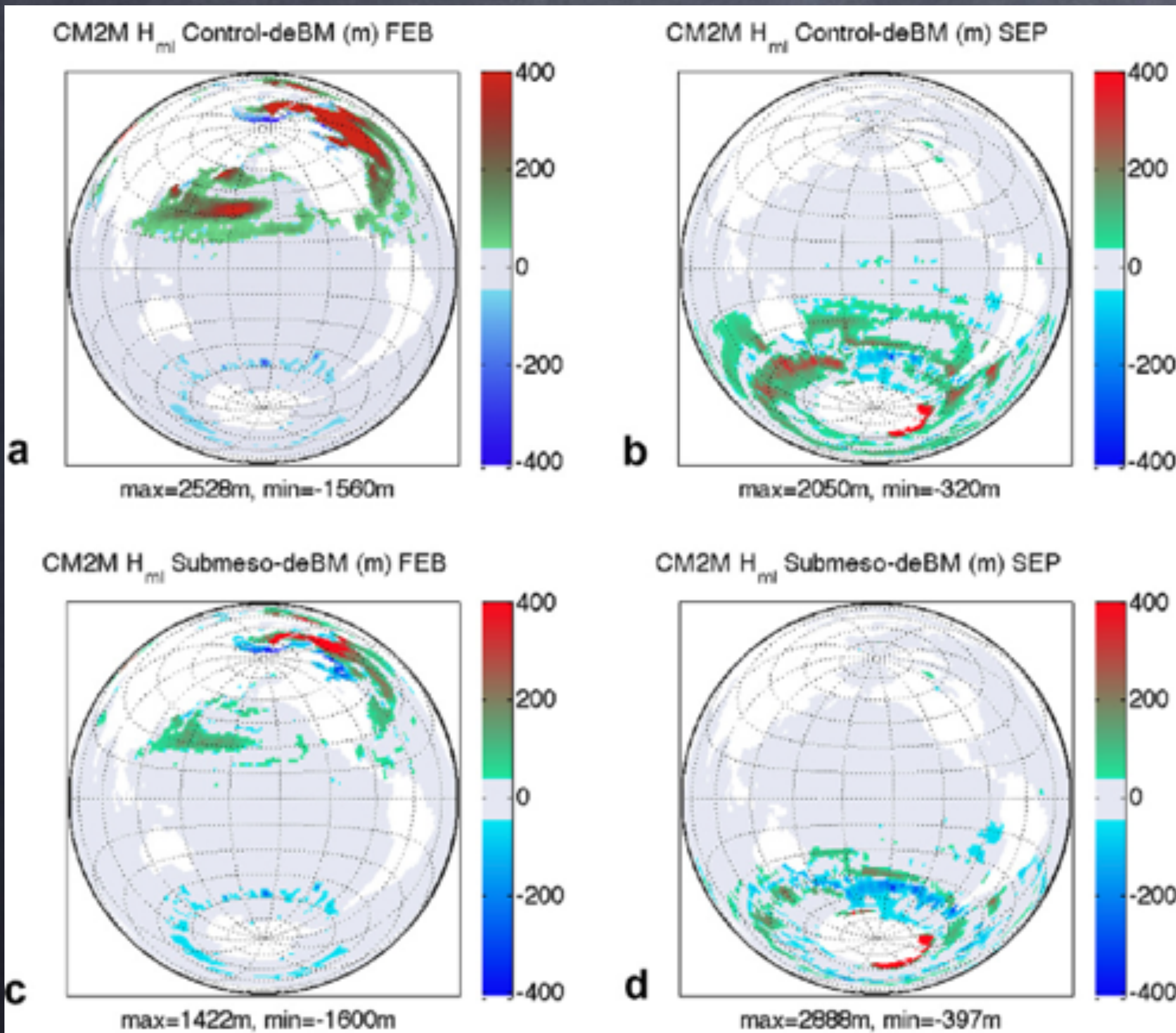
BFK, R. Ferrari, and R. W. Hallberg. Parameterization of mixed layer eddies. Part I: Theory and diagnosis. Journal of Physical Oceanography, 38(6):1145-1165, 2008

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

S. Bachman and BFK. Eddy parameterization challenge suite. I: Eady spindown. Ocean Modelling, 64:12-28, 2013

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

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

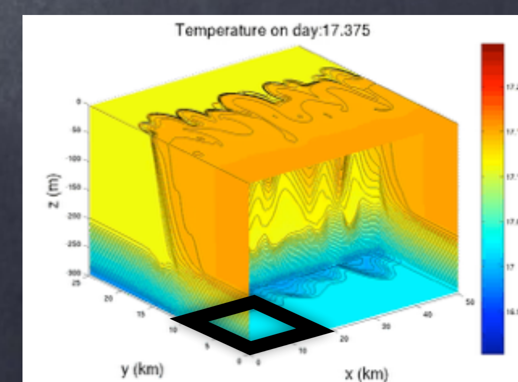


Deep Mixed Layer Bias reduced

Mixed layer depth Bias w/o MLE

O(0.1 W/m^2) change to global mean net fluxes, Regional: 5 to 50 W/m^2

MLD Bias With MLE Parameterization



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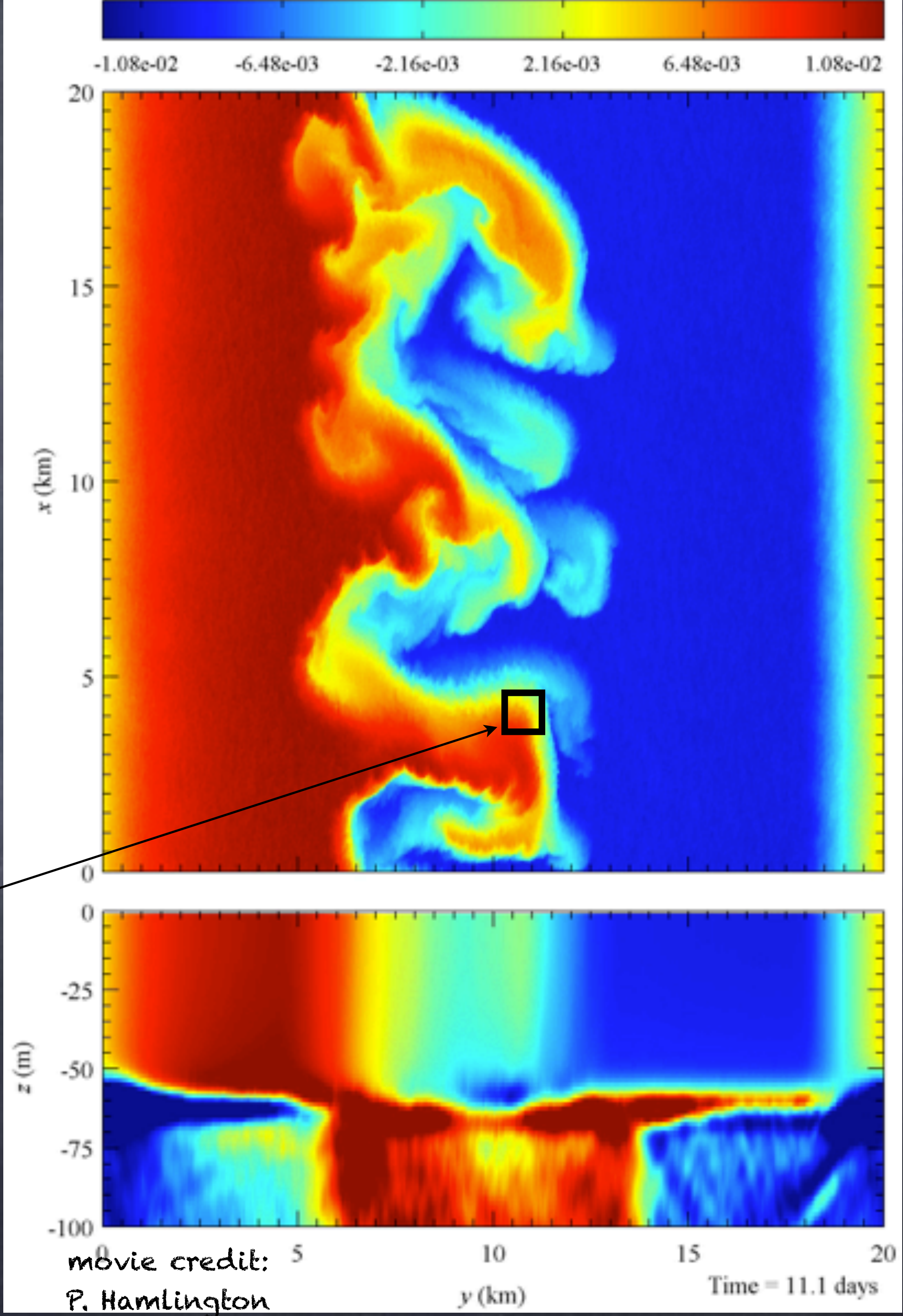
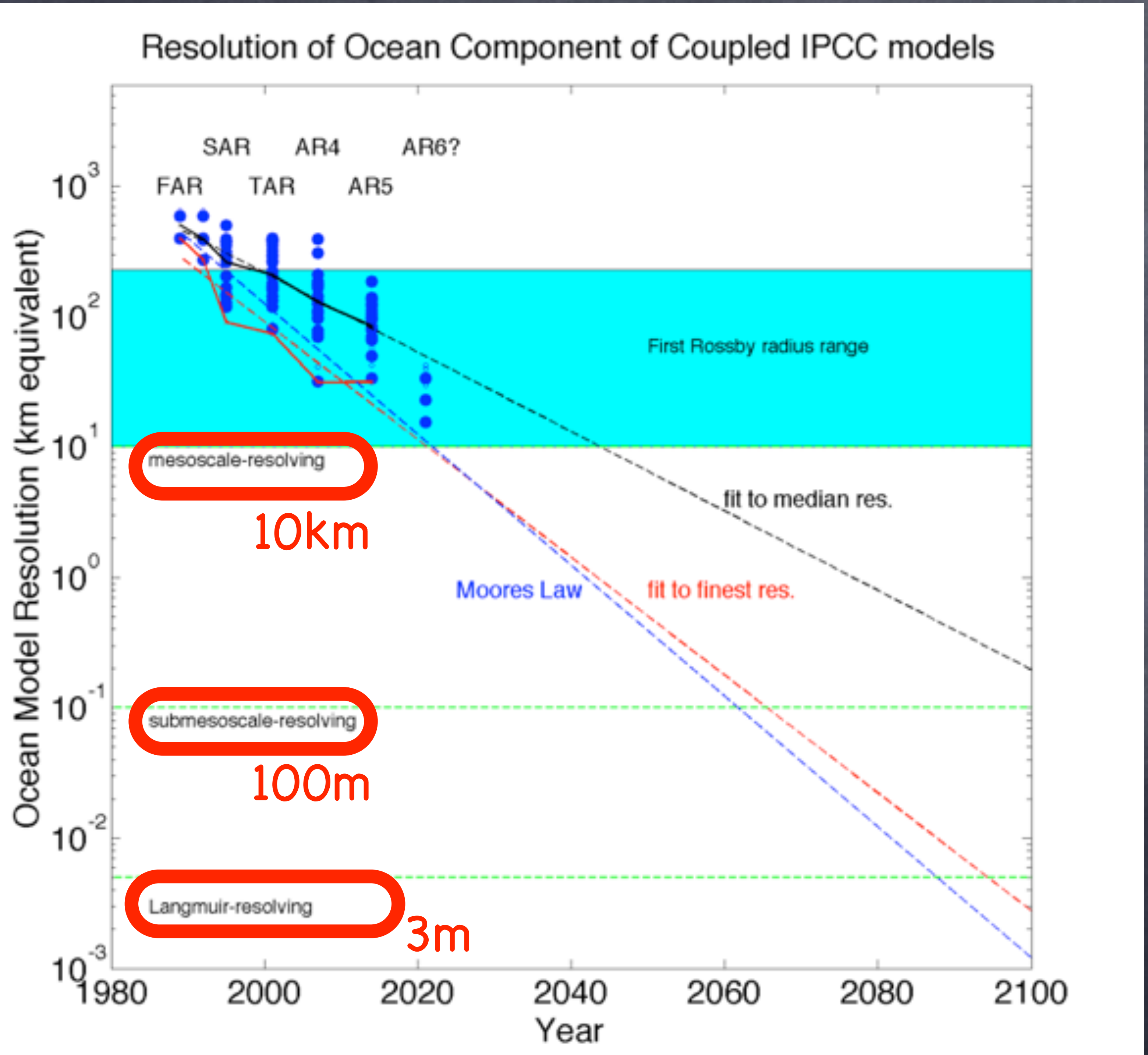
20km x 20km x 150m domain

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!

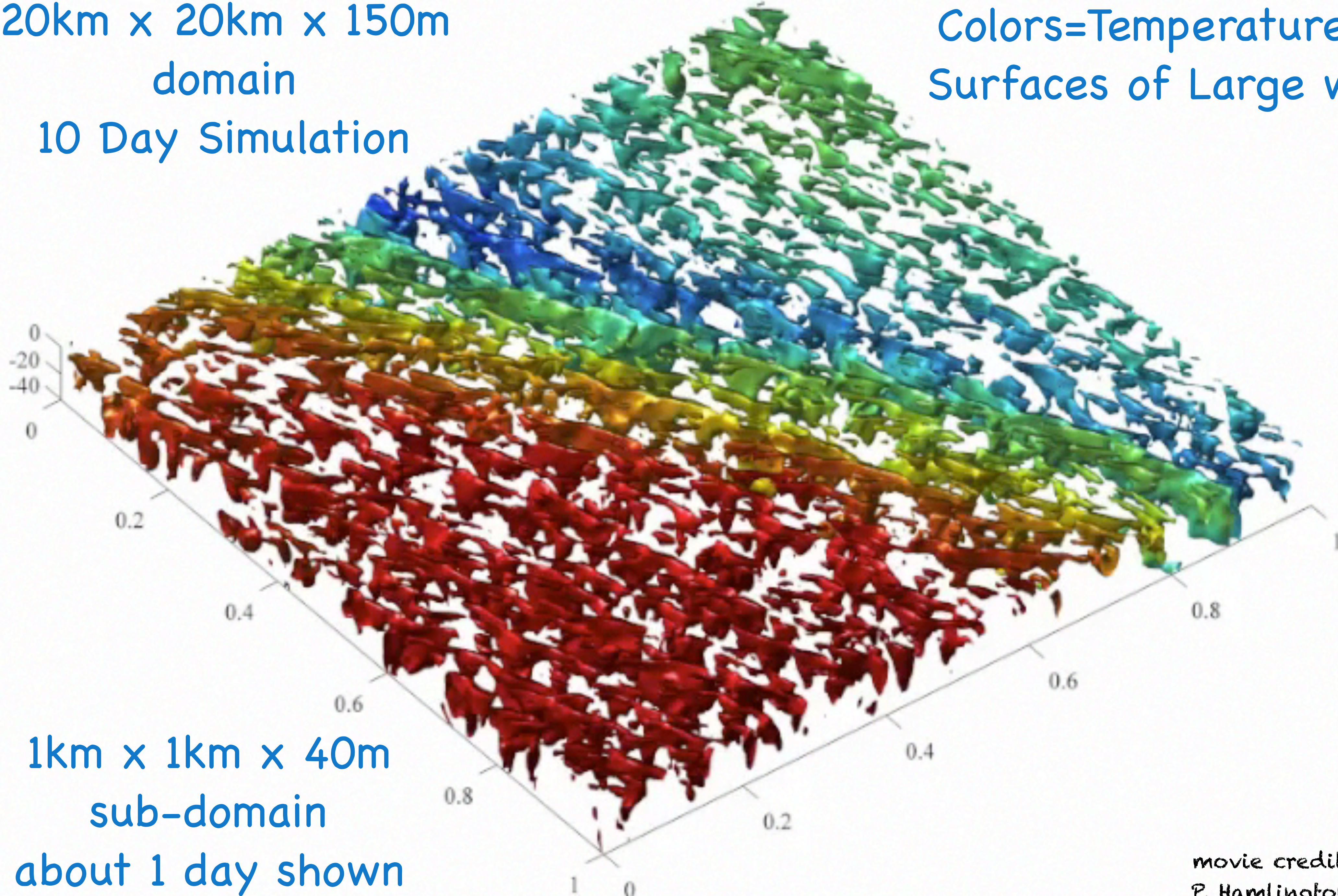


Here are the collection of IPCC models...

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=Temperature
Surfaces of 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.

The Character of the Langmuir Scale

image:
Thorpe, 04

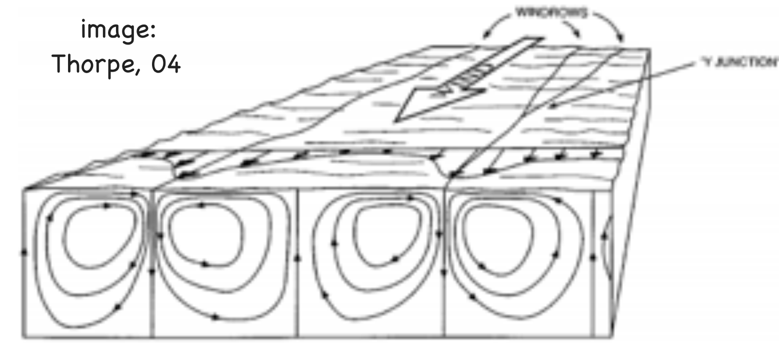
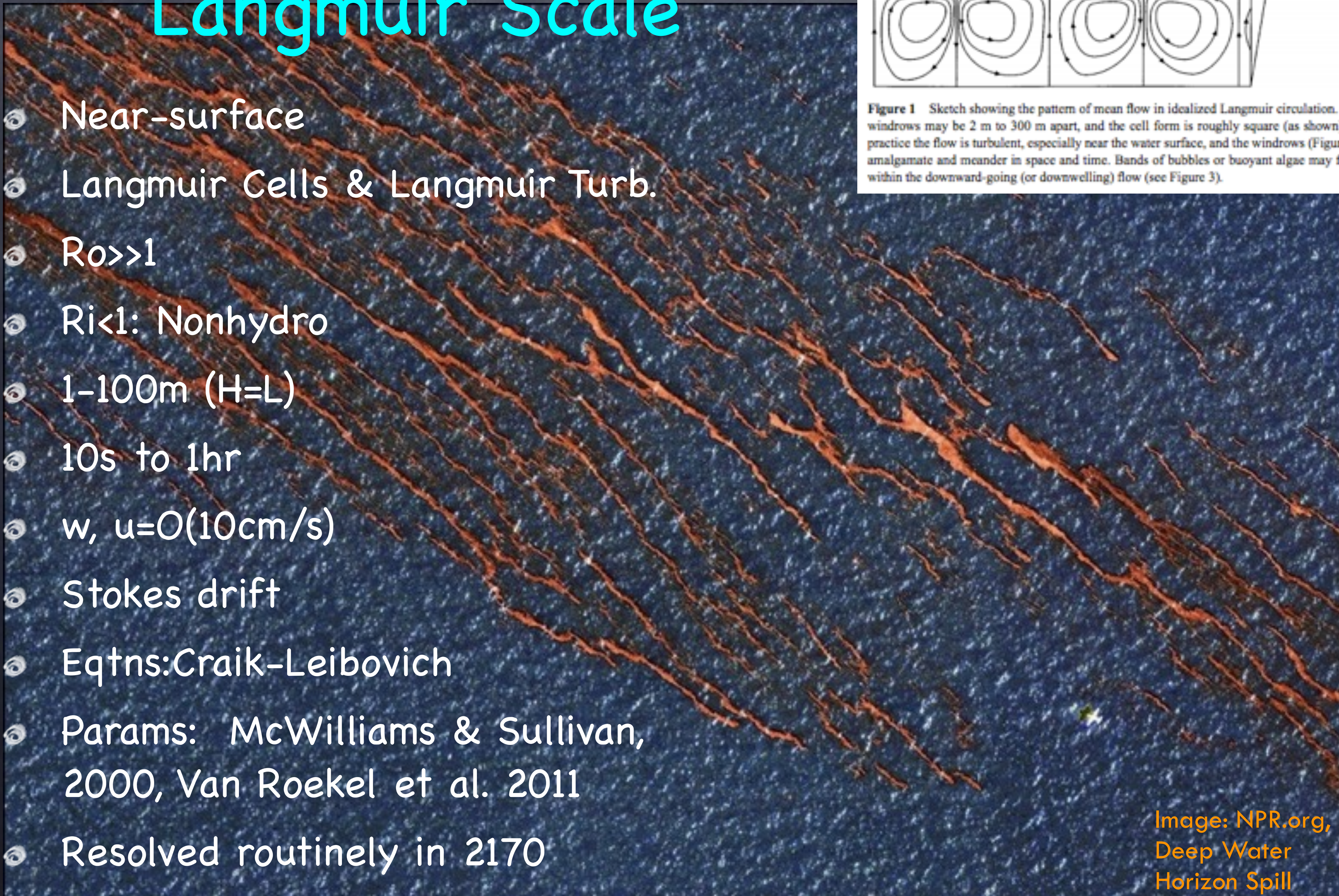


Figure 1 Sketch showing the pattern of mean flow in idealized Langmuir circulation. The windrows may be 2 m to 300 m apart, and the cell form is roughly square (as shown). In practice the flow is turbulent, especially near the water surface, and the windrows (Figure 2) amalgamate and meander in space and time. Bands of bubbles or buoyant algae may form within the downward-going (or downwelling) flow (see Figure 3).



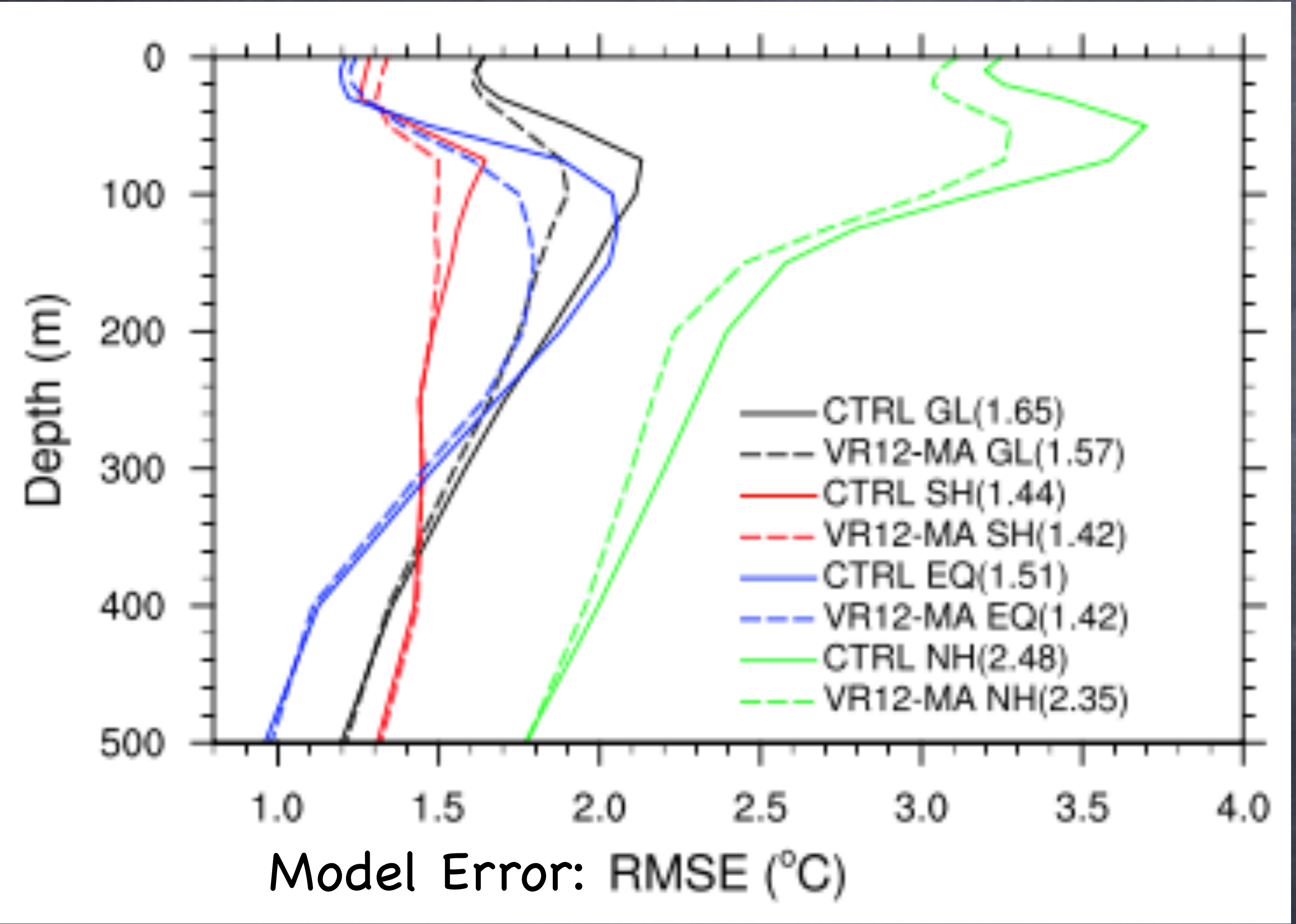
- Near-surface
- Langmuir Cells & Langmuir Turb.
- Ro>>1
- Ri<1: Nonhydro
- 1-100m (H=L)
- 10s to 1hr
- w, u=O(10cm/s)
- Stokes drift
- Eqtns:Craik-Leibovich
- Params: McWilliams & Sullivan, 2000, Van Roekel et al. 2011
- Resolved routinely in 2170

Image: NPR.org, Deep Water Horizon Spill

Modeling of variability

First-Principle Process & GCM Modeling: Predictions and Biases

How much do Langmuir mixing affect Global OHC?

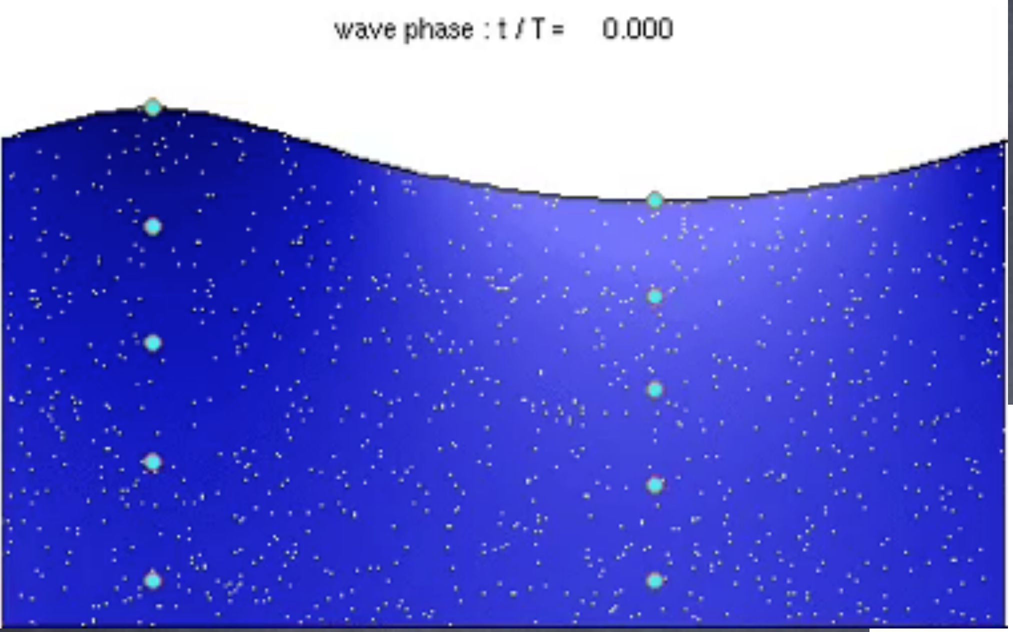


Global Air-sea flux changes by 0.26 W/m^2 when Langmuir mixing is introduced

Regions, e.g. Lab Sea: 10-15 W/m^2

Dashed lines include wave mixing

Q. Li, A. Webb, B. Fox-Kemper, A. Craig, G. Danabasoglu, W. G. Large, and M. Vertenstein. Langmuir mixing effects on global climate: WAVEWATCH III in CESM. Ocean Modelling, August 2015. in press.

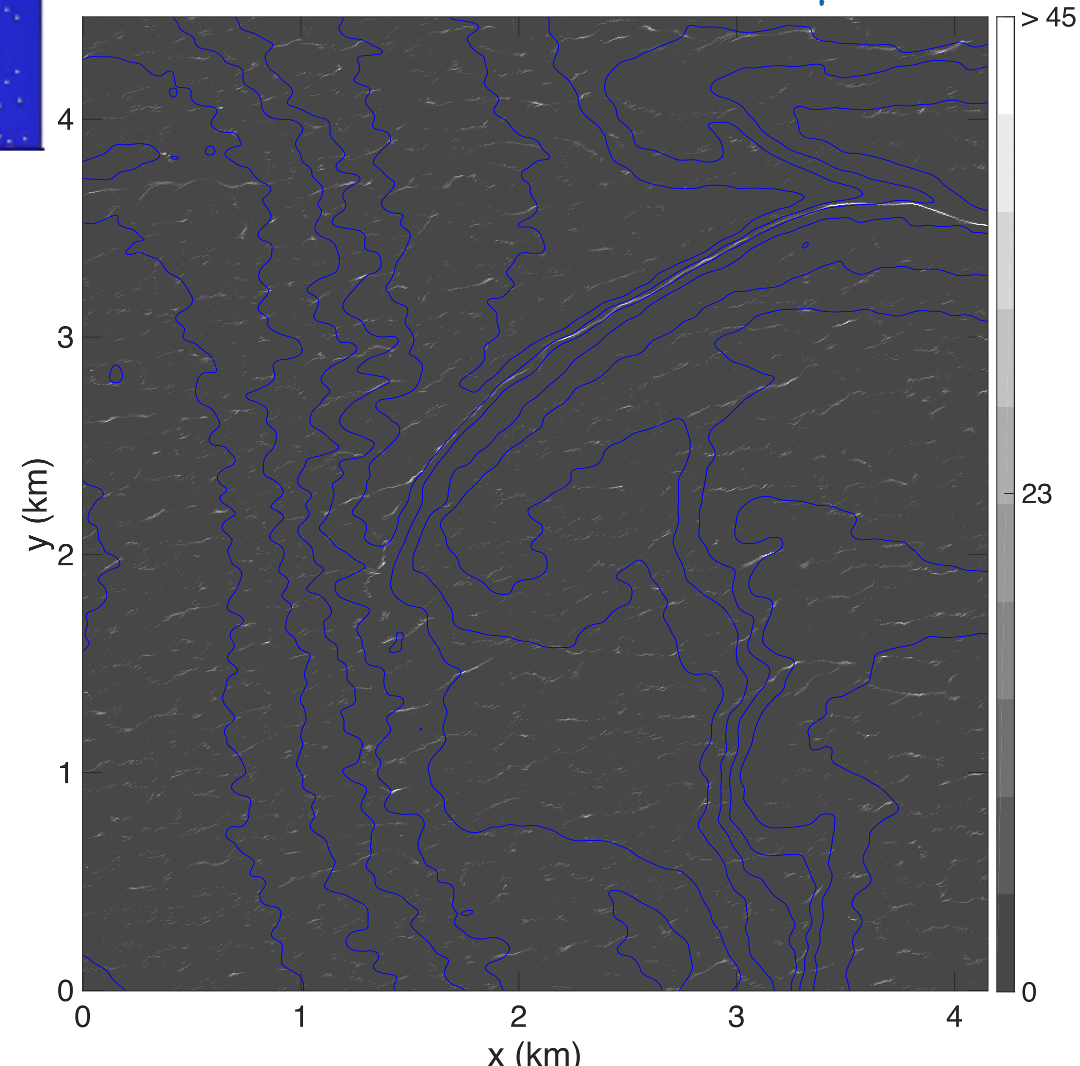


Stokes drift does more than wave mixing!

Making our way to new parameterizations

Movie: Creative Commons

There are 851796 drifters in the picture



After 80 Min

N. Suzuki and BFK. Understanding Stokes Forces in the Wave-Averaged Equations, JGR, in prep, 2015.

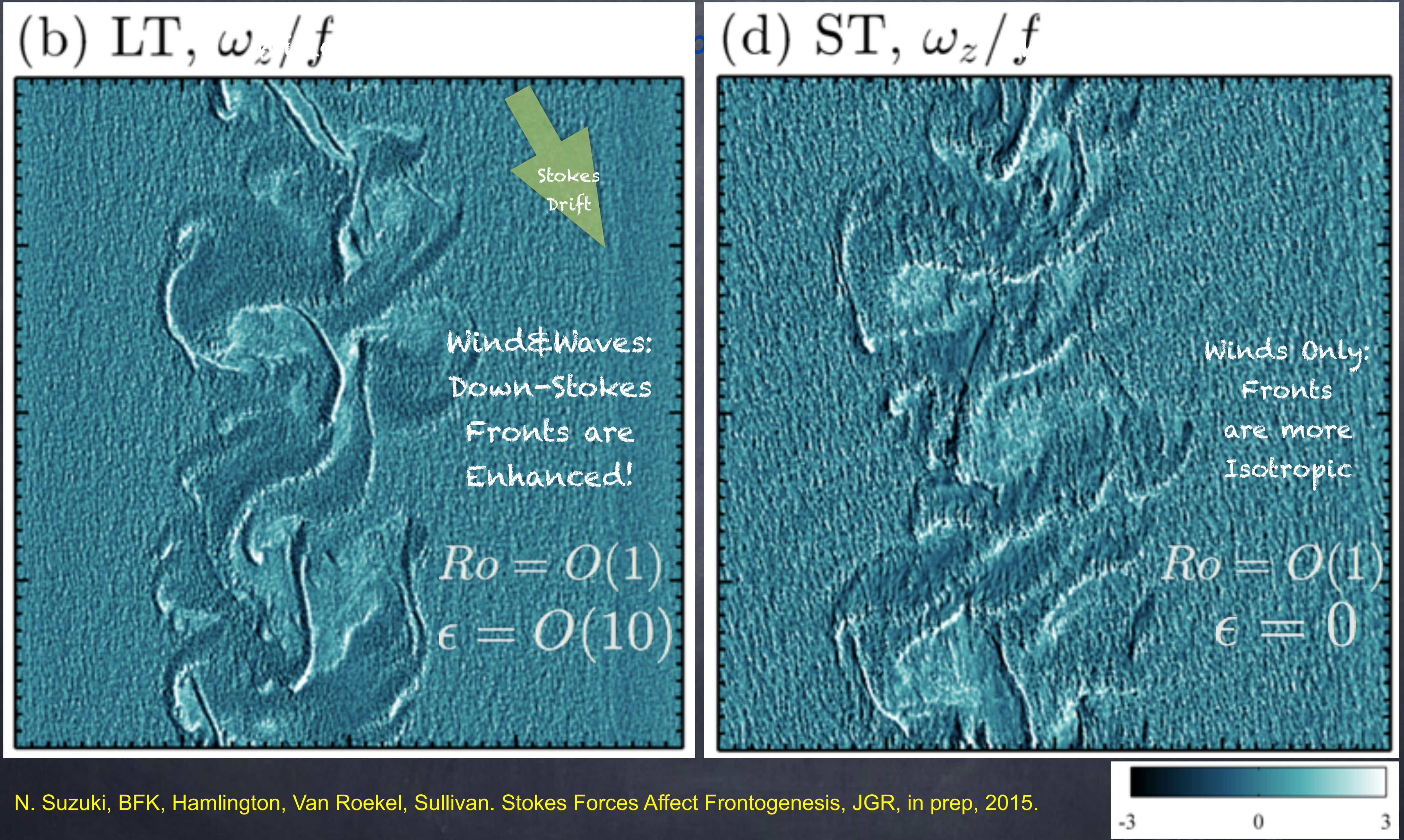
S. Haney, B. Fox-Kemper, K. Julien, and A. Webb. Symmetric and geostrophic instabilities in the wave-forced ocean mixed layer. Journal of Physical Oceanography, September 2015. In press.

A. Webb and B. Fox-Kemper. Impacts of wave spreading and multidirectional waves on estimating Stokes drift. Ocean Modelling, January 2015. In press

A. Webb and B. Fox-Kemper. Wave spectral moments and Stokes drift estimation. Ocean Modelling, 40(3-4): 273-288, 2011.

Are Fronts and Filaments different with Stokes shear force?

$$\frac{\alpha^2}{Ri}\left[w_{,t} + v_j^L w_{,j} + \frac{M_{Ro}}{RoRi} w w_{,z}\right] = -\pi_{,z} + b - \varepsilon v_j^L v^s_{j,z} + \frac{\alpha^2}{ReRi} w_{,jj}$$



N. Suzuki, BFK, Hamlington, Van Roekel, Sullivan. Stokes Forces Affect Frontogenesis, JGR, in prep, 2015.

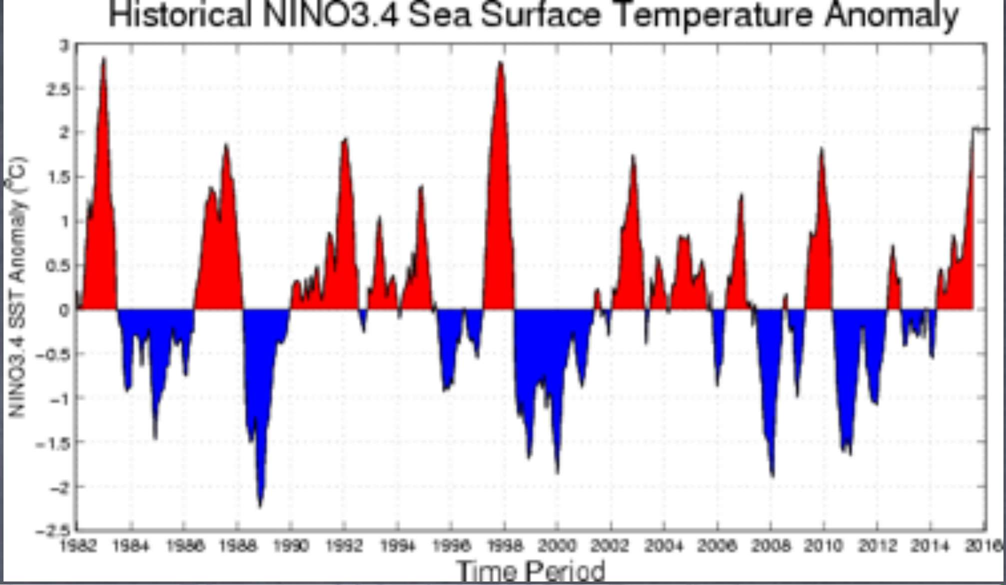
J. C. McWilliams and BFK. Oceanic wave-balanced surface fronts and filaments. Journal of Fluid Mechanics, 730:464-490, 2013.

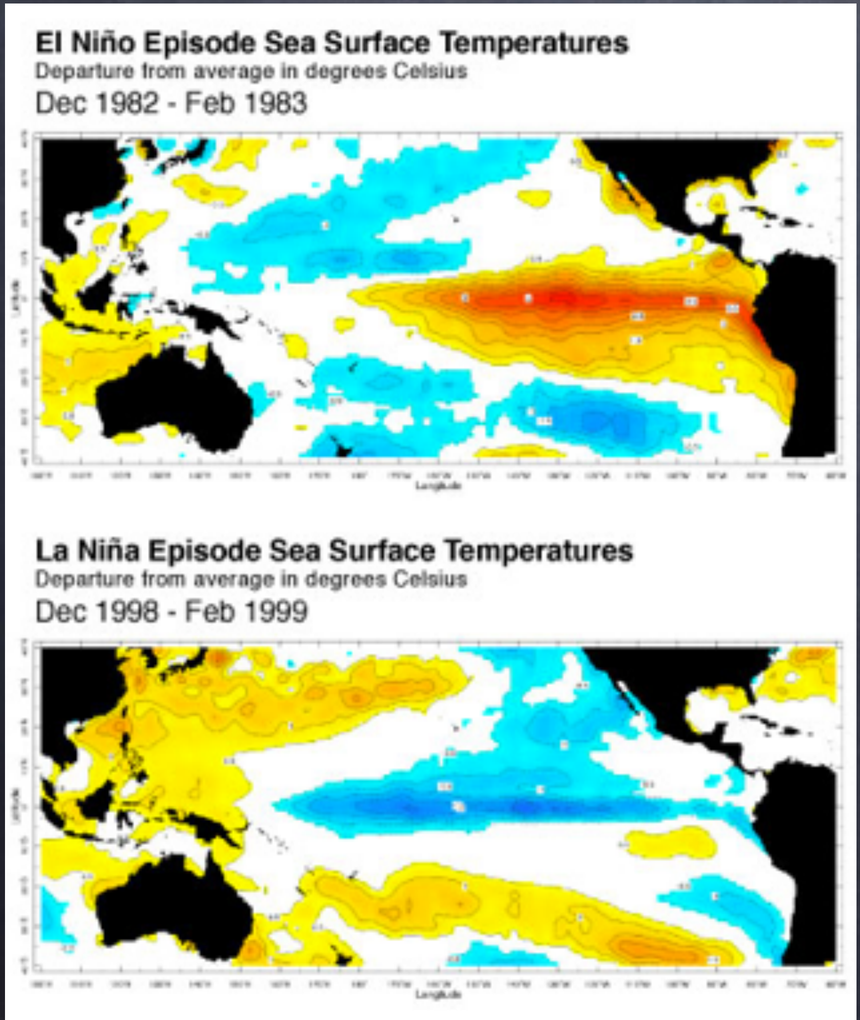
P. E. Hamlington, L. P. Van Roekel, B. Fox-Kemper, K. Julien, and G. P. Chini. Langmuir-submesoscale interactions: Descriptive analysis of multiscale frontal spin-down simulations. Journal of Physical Oceanography, 44(9):2249-2272, September 2014.

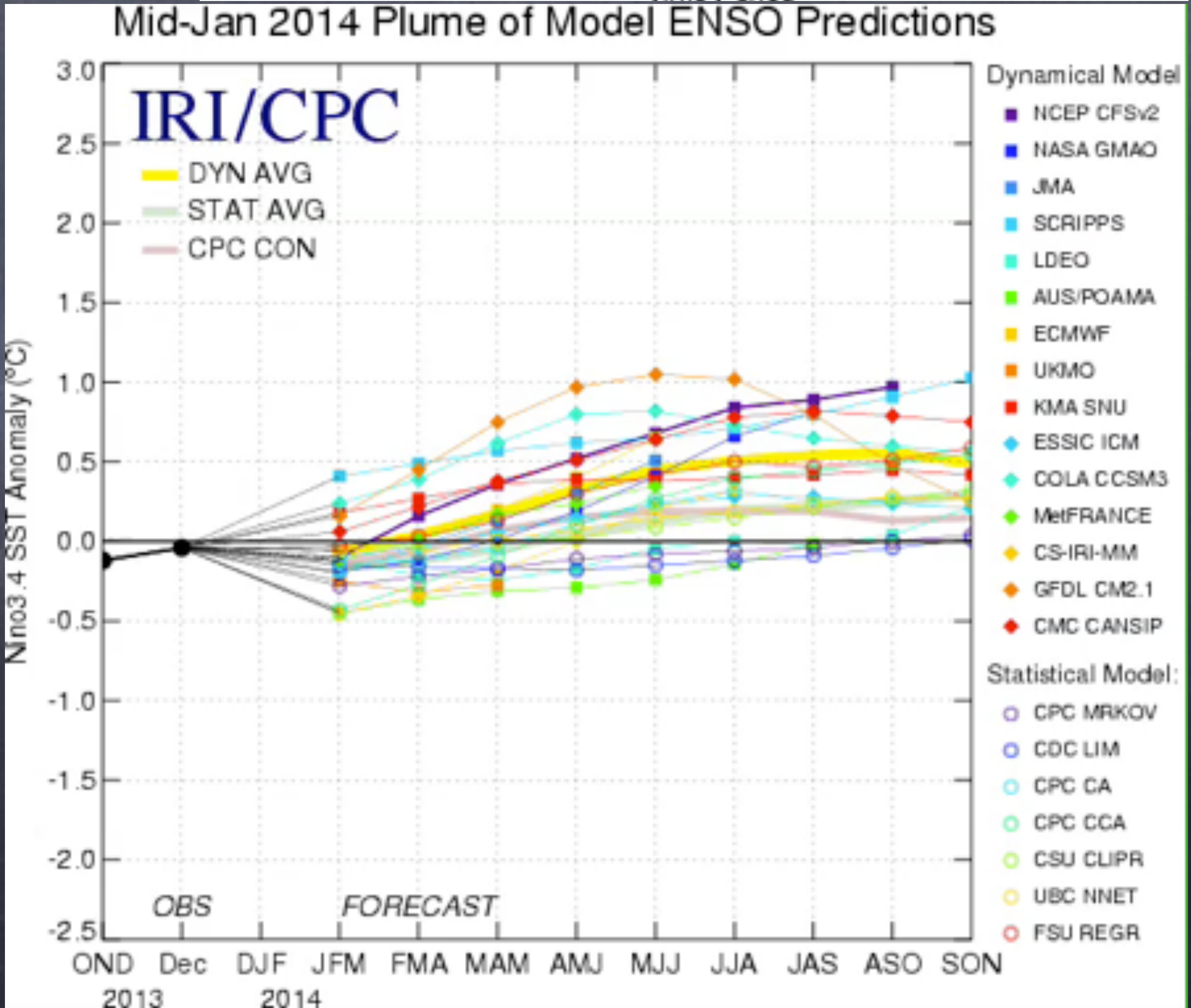
Prediction of variability

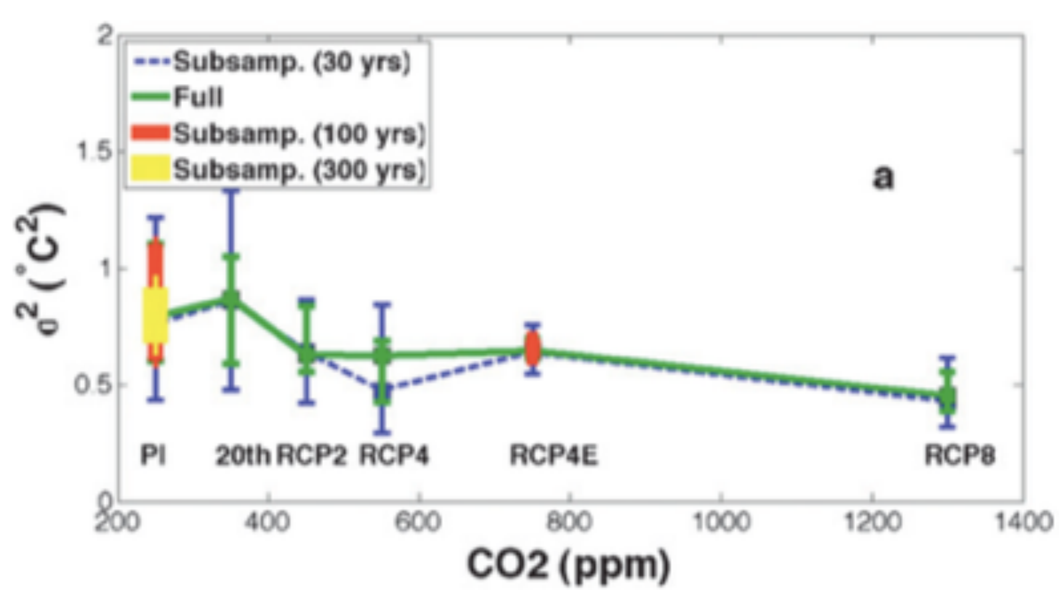
Predictability of ENSO events limited to < 1yr

ENSO statistics more predictable?









Almost no change to ENSO variability with GHG... (>200 yr to detect)

Big GHG Change to ENSO impacts!

REMOTE PROXY RECONSTRUCTION IMPOSSIBLE!!!

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.

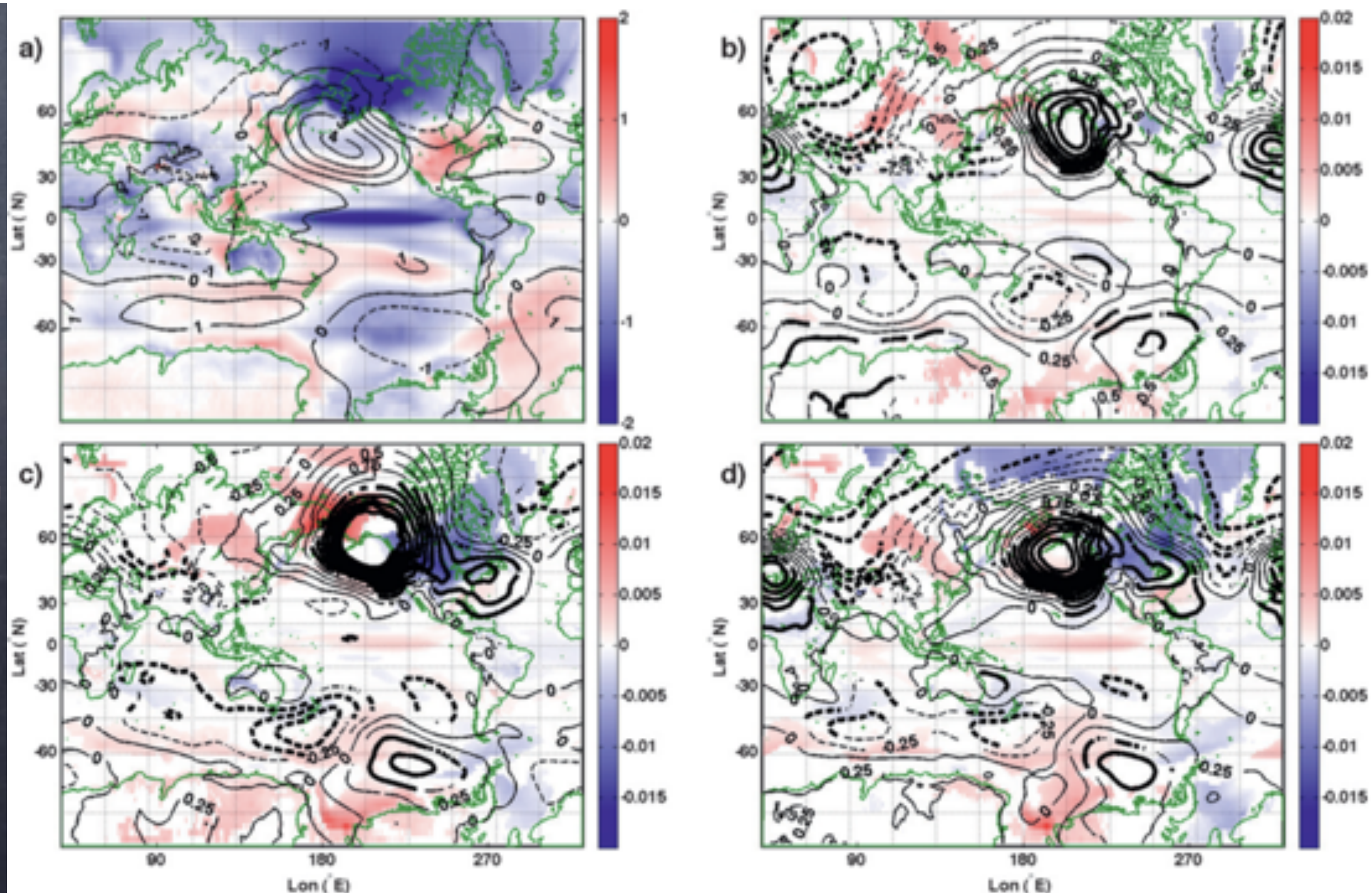
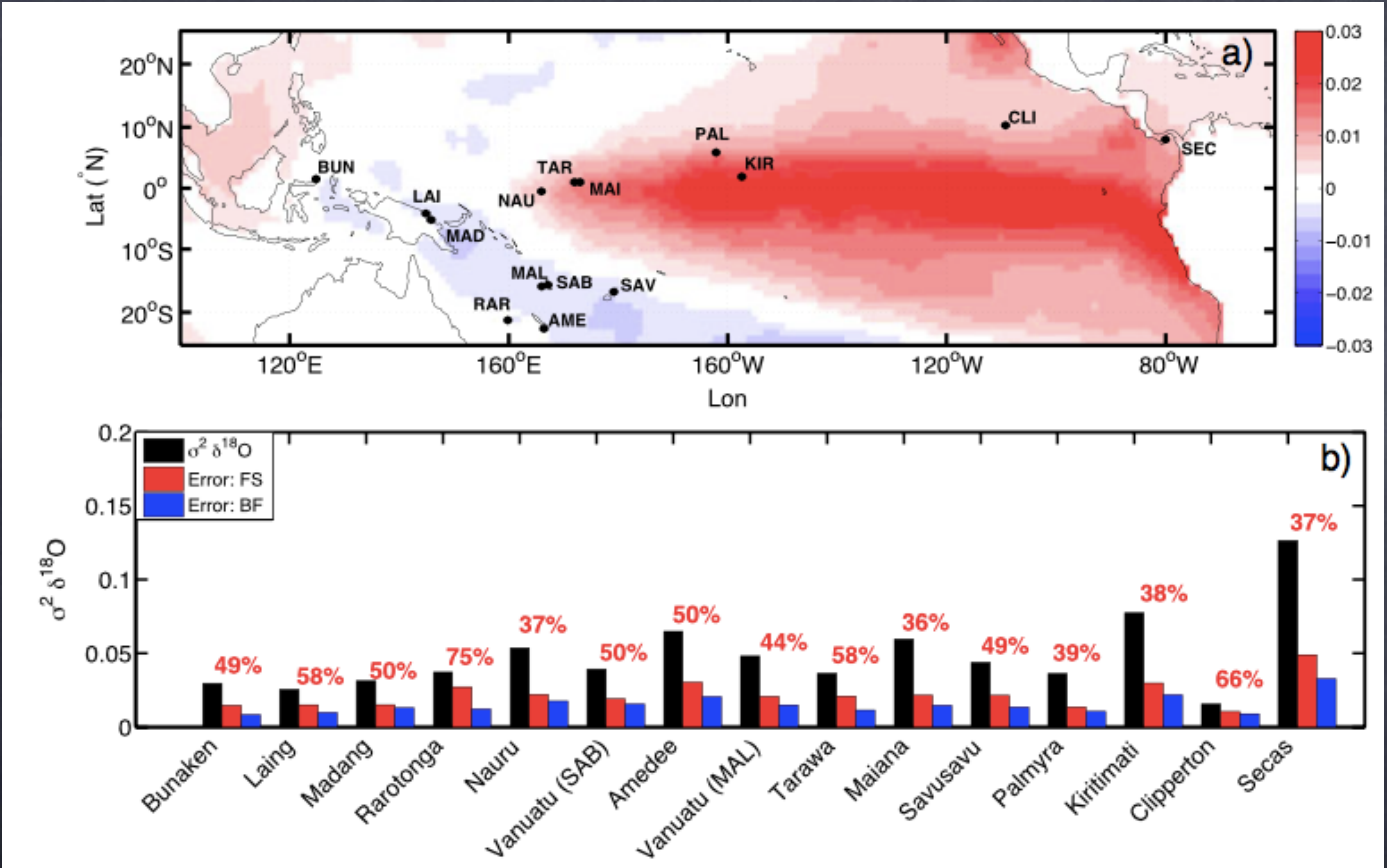


FIG. 6. As in Fig. 5 but for La Niña DJF



S. Stevenson, H. V. McGregor, S. J. Phipps, and B. Fox-Kemper. Quantifying errors in coral-based ENSO estimates: Towards improved forward modeling of δ18O. Paleoceanography, 28(4):633-649, December 2013.

Abyssal Variability is the HARDEST!

- Stochastic damping very slow!
  - huge heat capacity (biggest watermasses on Earth)!
- Timescales may be very long!
  - Watermasses O(1500yr) old
- Lengthscales may be very short!
  - (weak stratification implies a Rossby radius of O(2km) for modes trapped in AABW only)
- Water "formed" in very small areas!
  - Very small-scale atmospheric & oceanic phenomena will be disproportionately important
- Difficult to observe, IMPOSSIBLE TO MODEL = FUN!

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

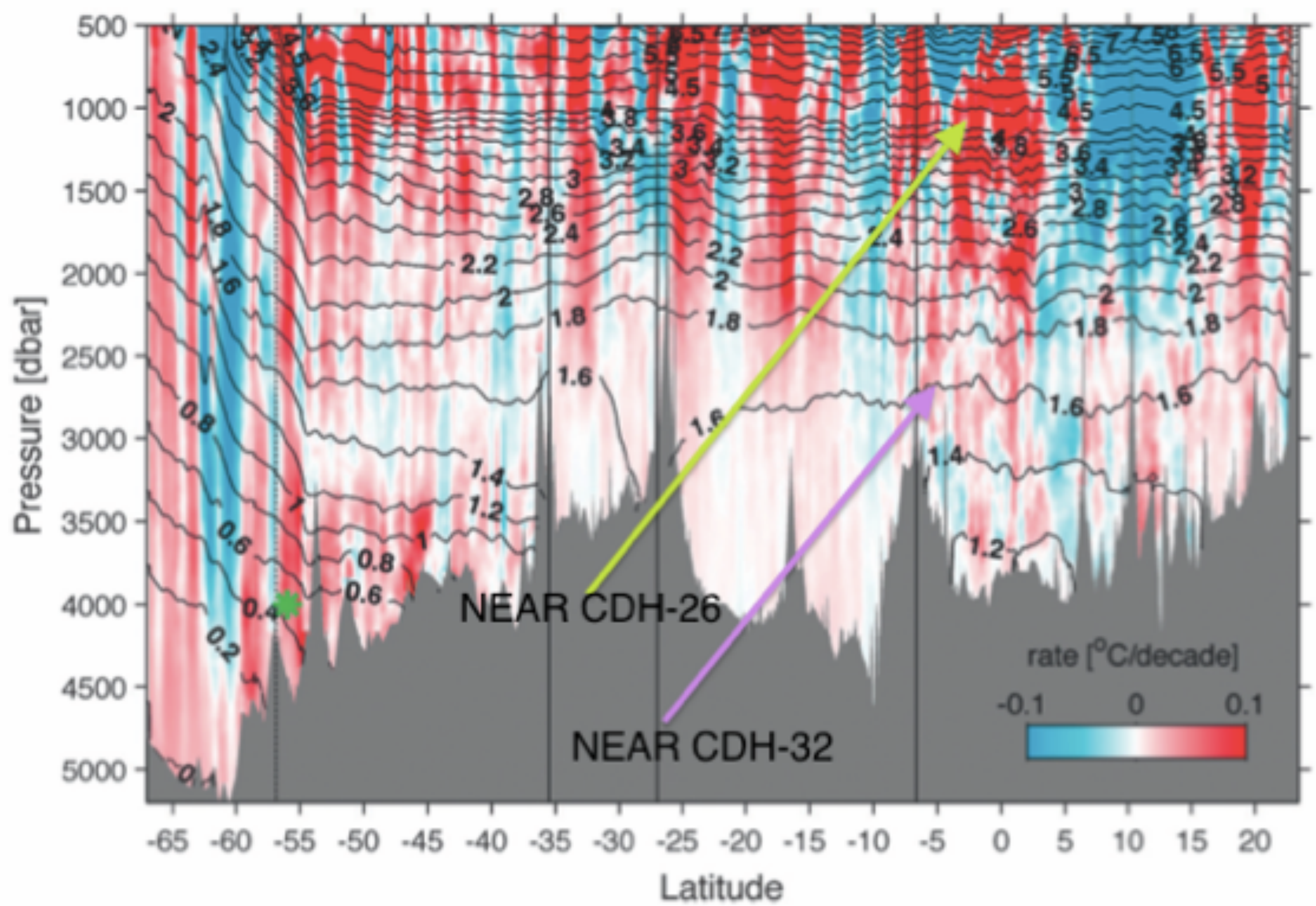


FIG. 4. Time rate of change of potential temperature $d\theta/dt$ (color bar), along the trackline of P18 (see Fig. 1 for location). Areas of warming are shaded in red, and regions of cooling are shaded in blue with intensity scaled by the magnitude of the change. Mean θ values over all occupations are contoured (black lines). This trackline is grouped into four basins for analysis (boundaries shown by vertical black lines), and the area south of the SAF (vertical dotted–dashed line) is also analyzed separately. The basins from south to north are the Amundsen–Bellinghausen Basin, Chile Basin, Peru Basin, and central Pacific Basin. Green asterisk denotes location of data used in Fig. 3.

Two locations of well-dated sediment cores from the mid-Holocene indicated

Purkey & Johnson, 2010

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.

Slide: Sam Bova

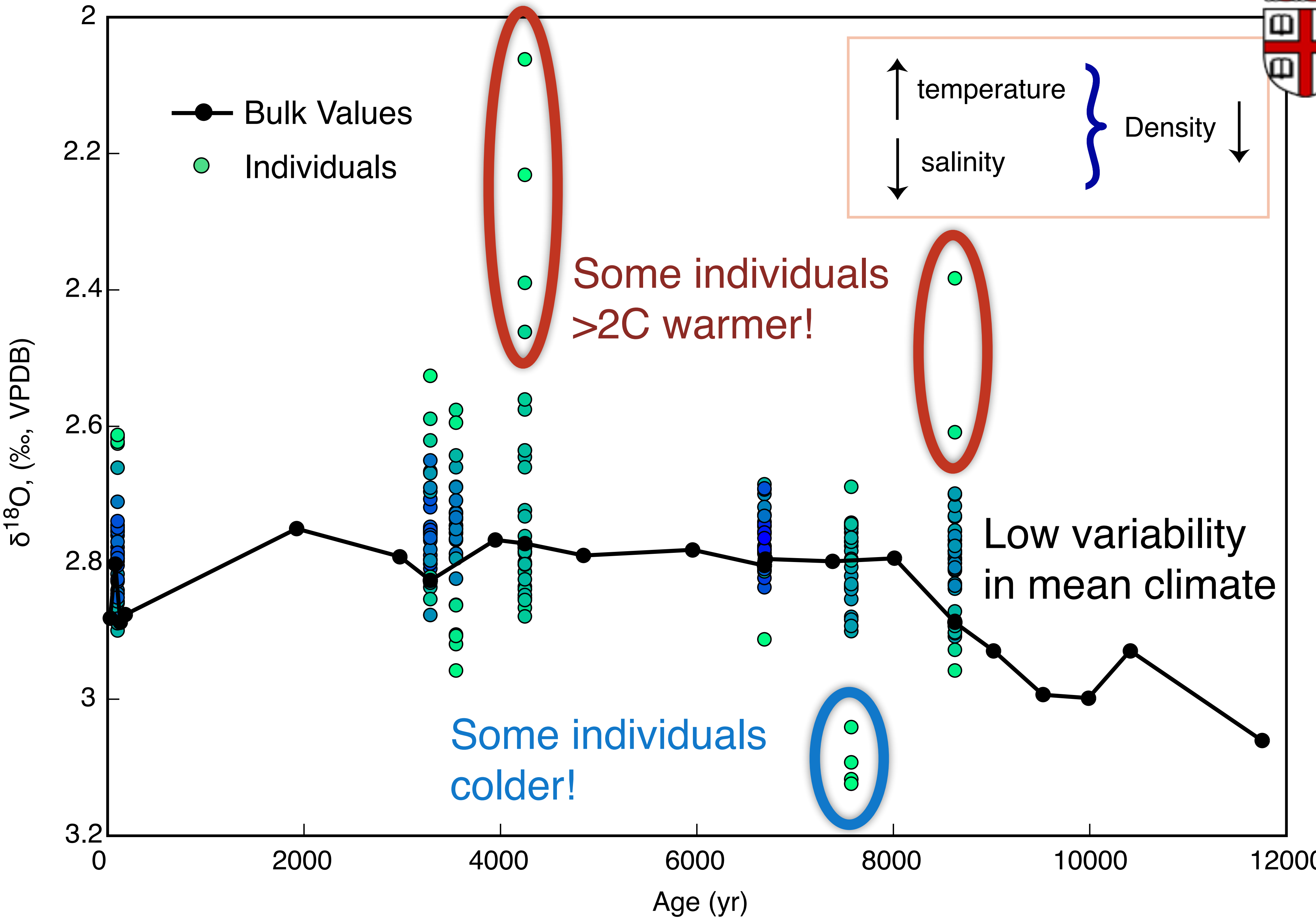
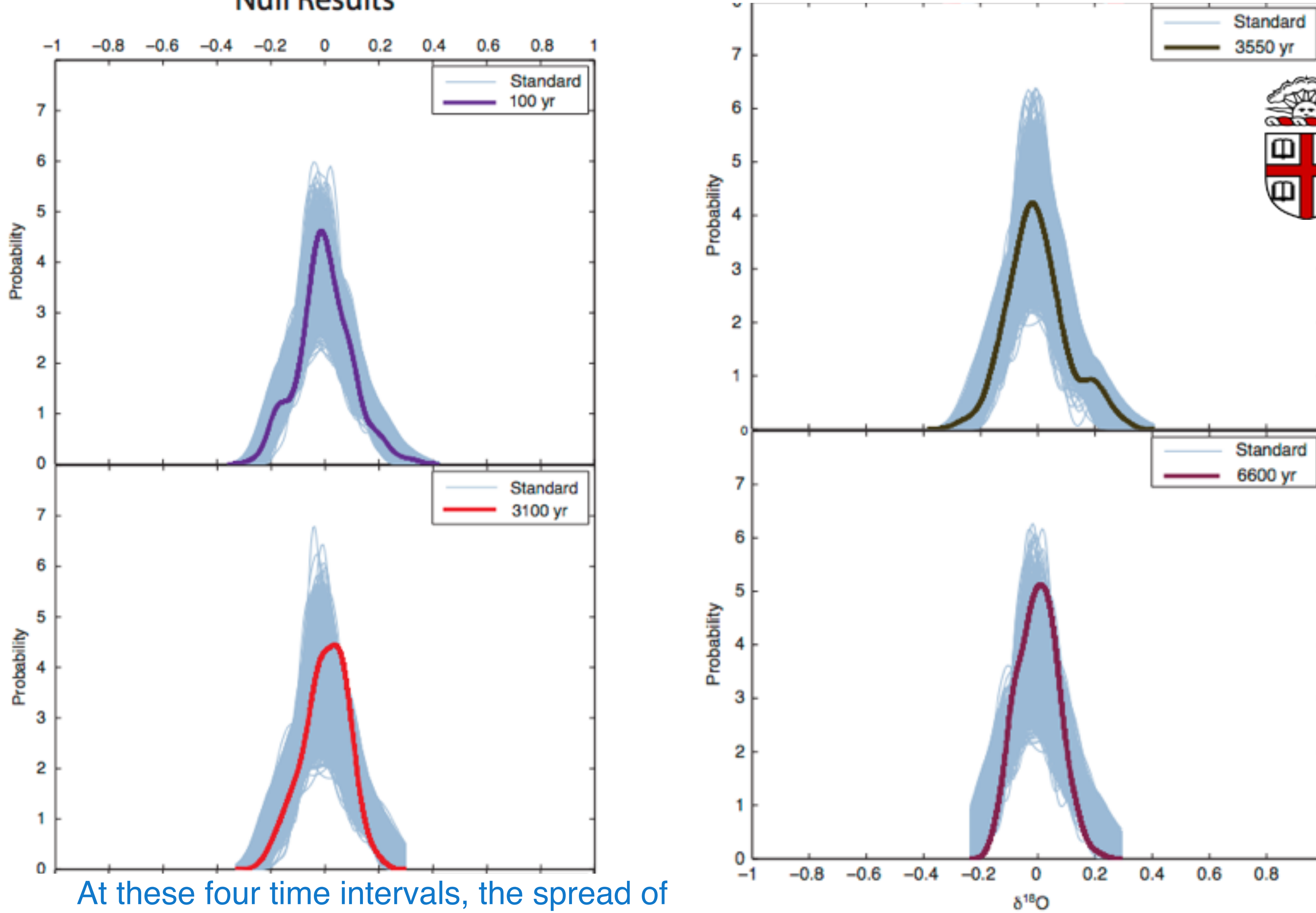


Figure Credit: Sam Bova

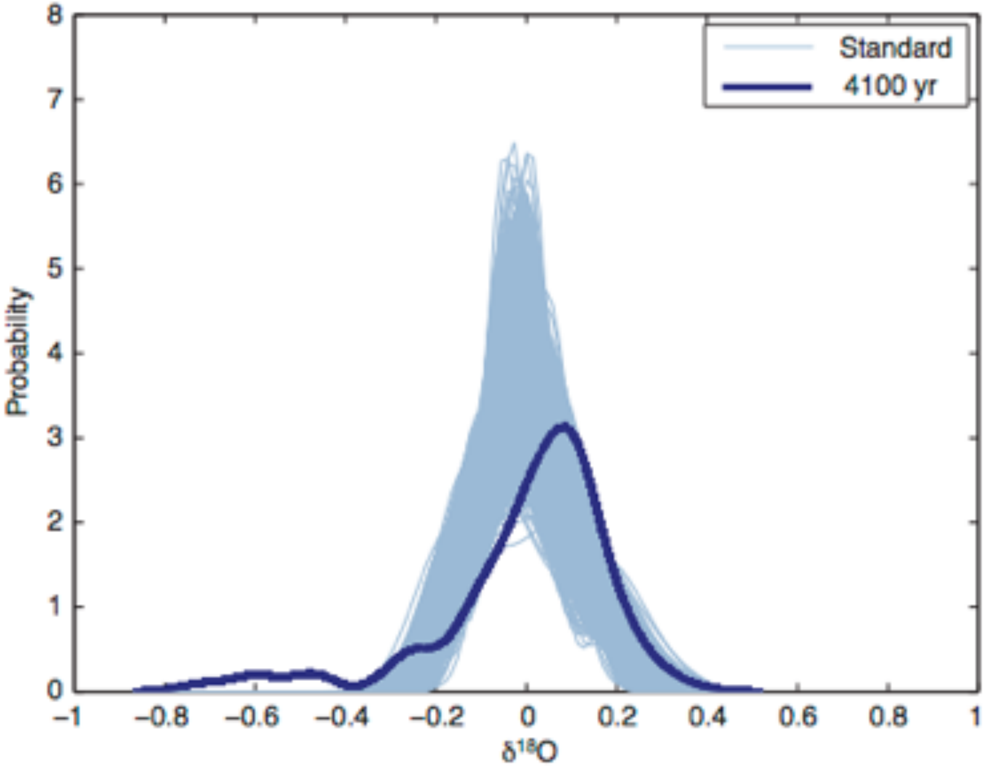
Null Results



At these four time intervals, the spread of individual values fits within a size-matched spread of instrumental standards.

Figure Credit: Sam Bova

p<0.01

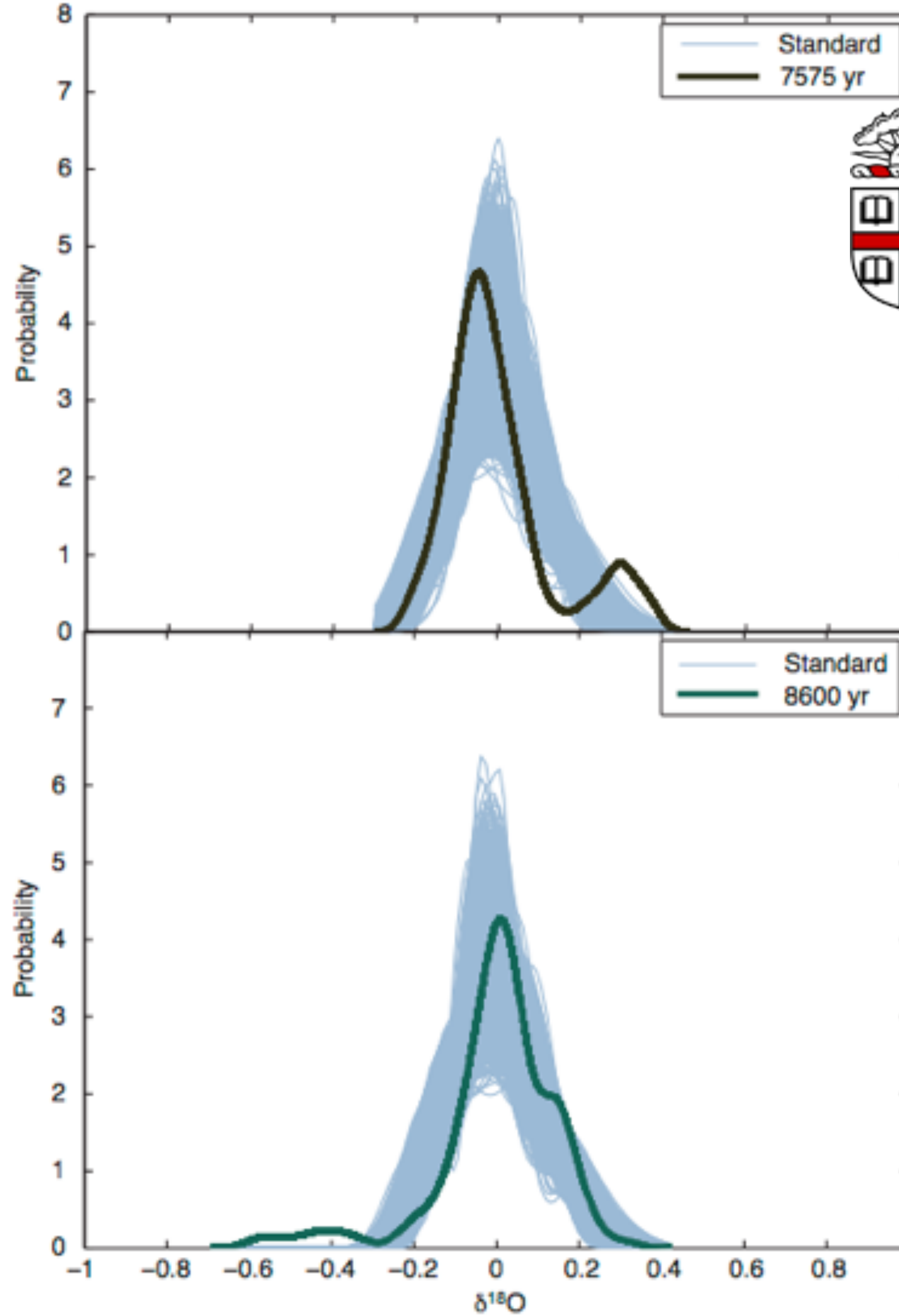


At these three time intervals, the spread of individual values exceeds a size-matched spread of instrumental standards.

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

If this is right—abyssal variability may have an unexpectedly important role!

p<0.10



Conclusions

- **Presence** of observable variability
  - Difficult due to sampling, obs. duration
  - Interesting problems require paleothermometry!
- **Understanding** of past variability
  - Possible, but not always a path to progress.
- **Modeling** of variability
  - Stochastic models work-not always predictive
  - Deterministic models: discrepancies in tuning, params, resolution.
- **Prediction** of variability
  - Possible in regions, but global budget requires an order-of-magnitude improvement in process-level understanding and modeling.