Turbulence and Variability in the Ocean

Baylor Fox-Kemper (Brown DEEP Sciences)

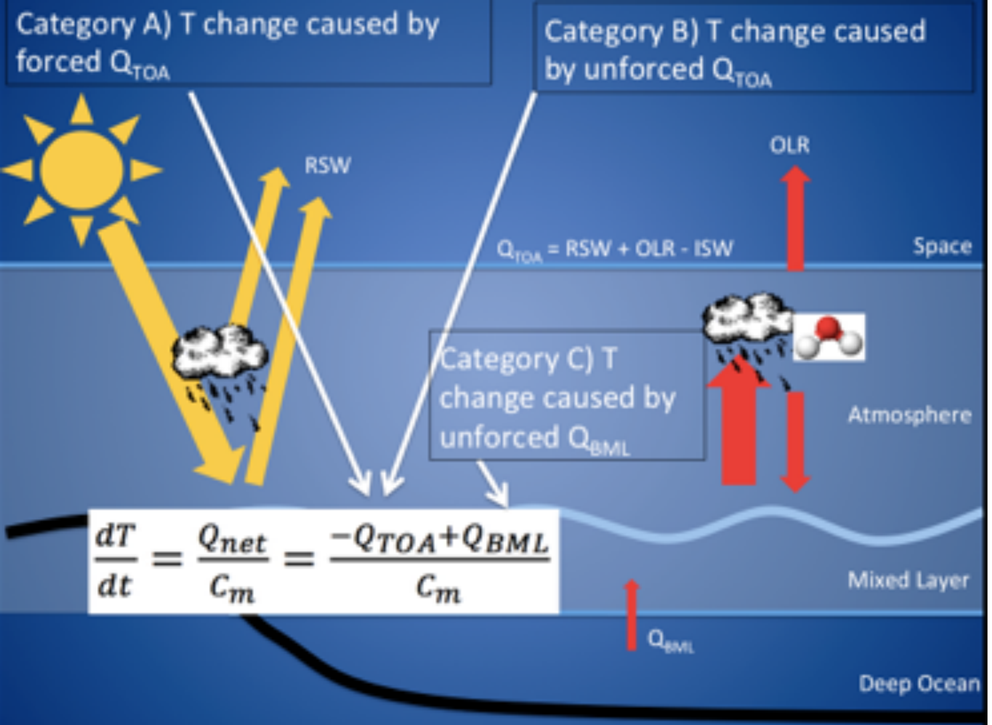
with Samantha Bova & Tim Herbert (Brown),
Dibyendu Mandal (UC-Berkley), Arin Nelson & Jeff Weiss (CU-ATOC),
Royce Zia (Va. Tech.)

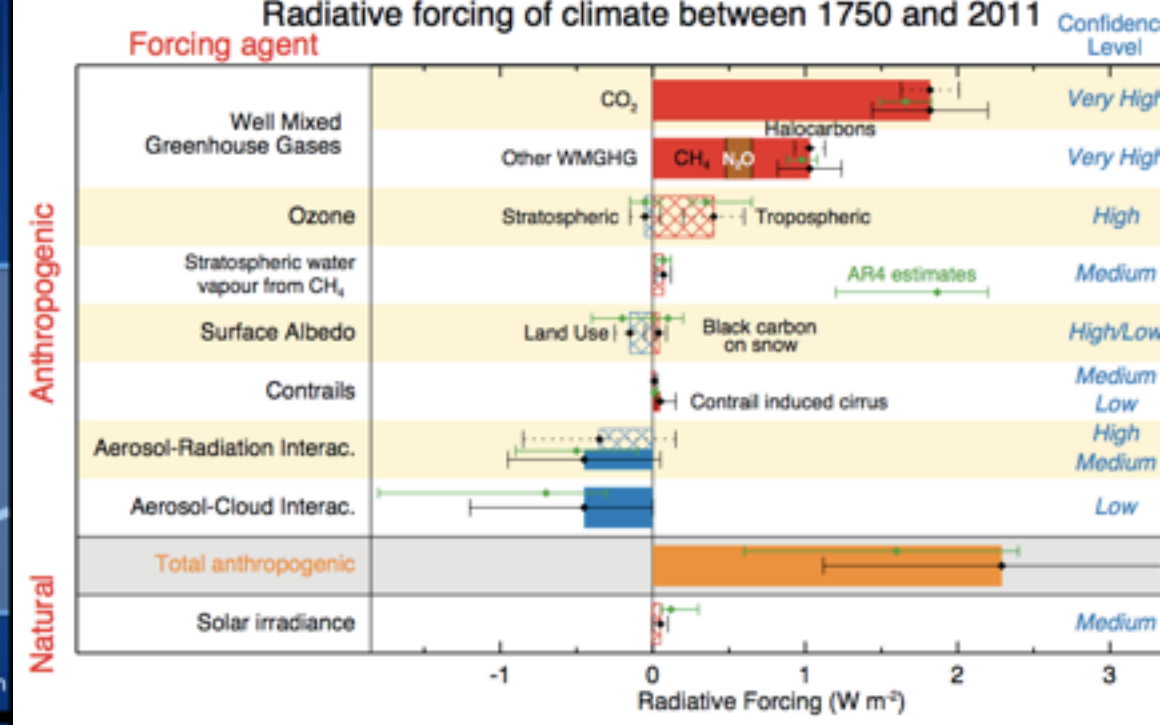
GAFD Seminar
University of Exeter 25/4/16

Sponsors: NSF 1245944 and Institute at Brown for Environment and Society (IBES)

To understand ocean & climate variability, it is important to distinguish:

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





Brown et al., 2014

IPCC AR5, 2013

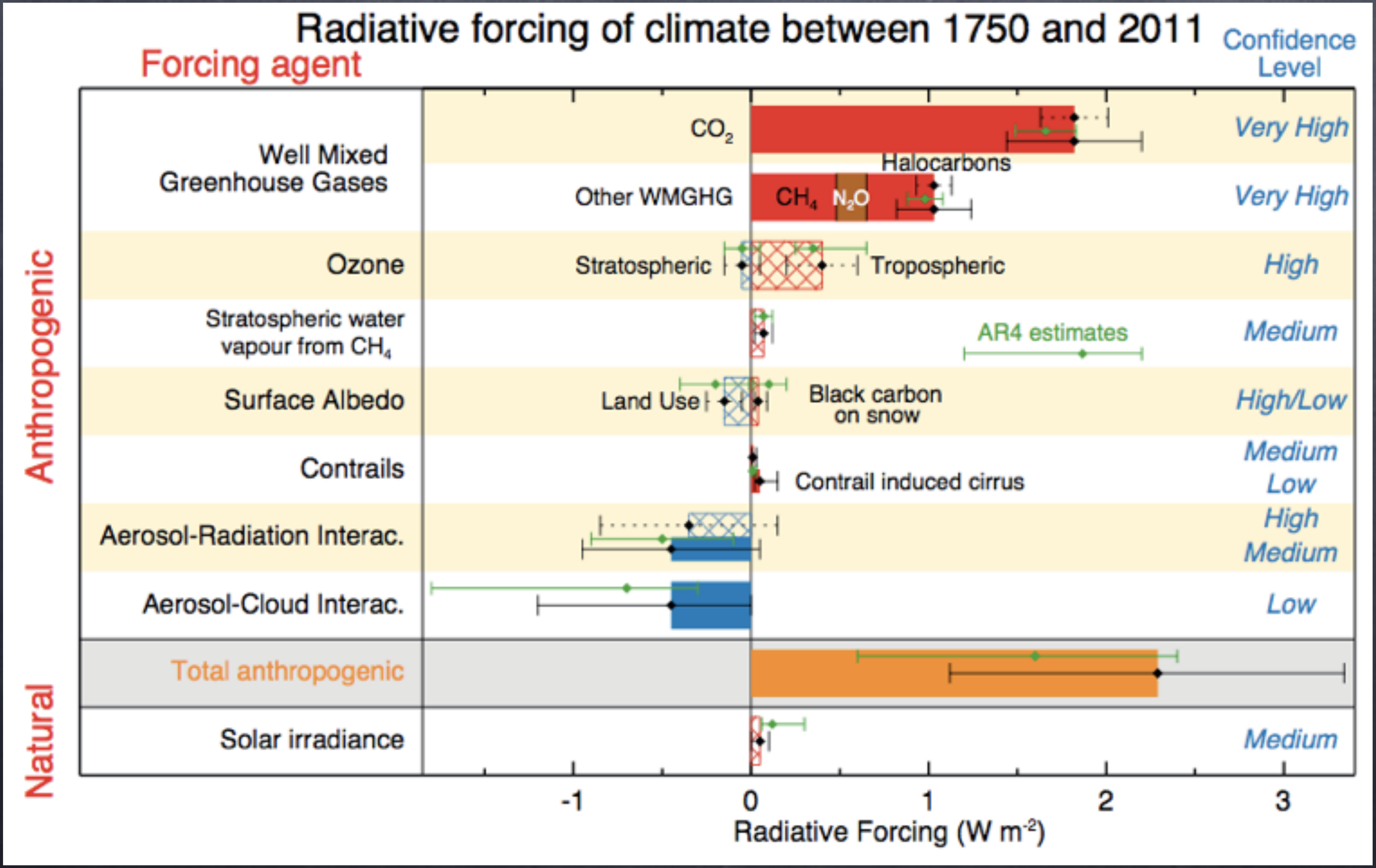
- **Presence** of observable variability

It is easier to observe the ocean consequences of air-sea exchange (ocean heat content (OHC), salinity) rather than exchanges (fluxes) themselves.

However, insufficient for **prediction** and **attribution**

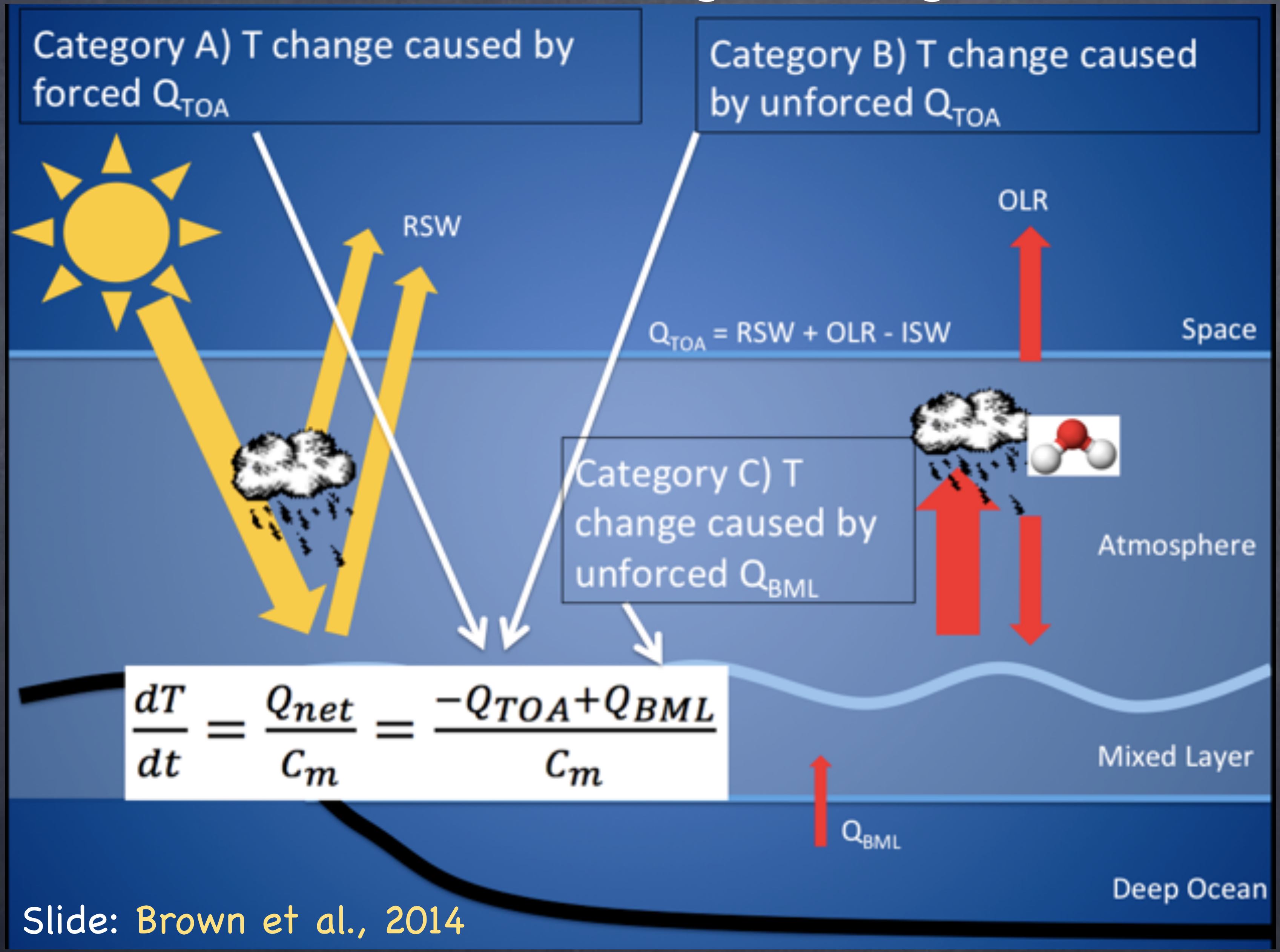
Prediction & Attribution Goal:

Effects of Anthropogenic Forcing



IPCC AR5, 2013

Surface Energy Budget



- O(2W/m^2) change to Q_{BML} as important as GHG
- Slight oversimplification—sensitivity + budget

What do hydrographic observations show?

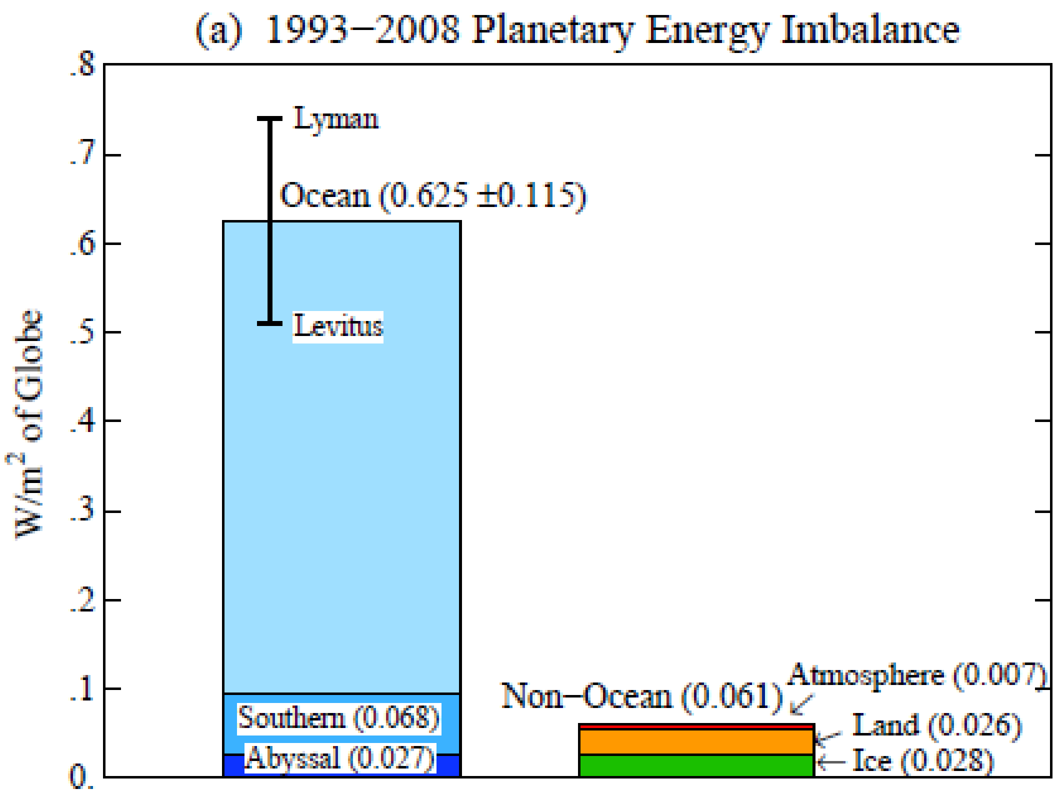
Ocean Heat Content not fixed: Q_{BML} not zero (and varies)!

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

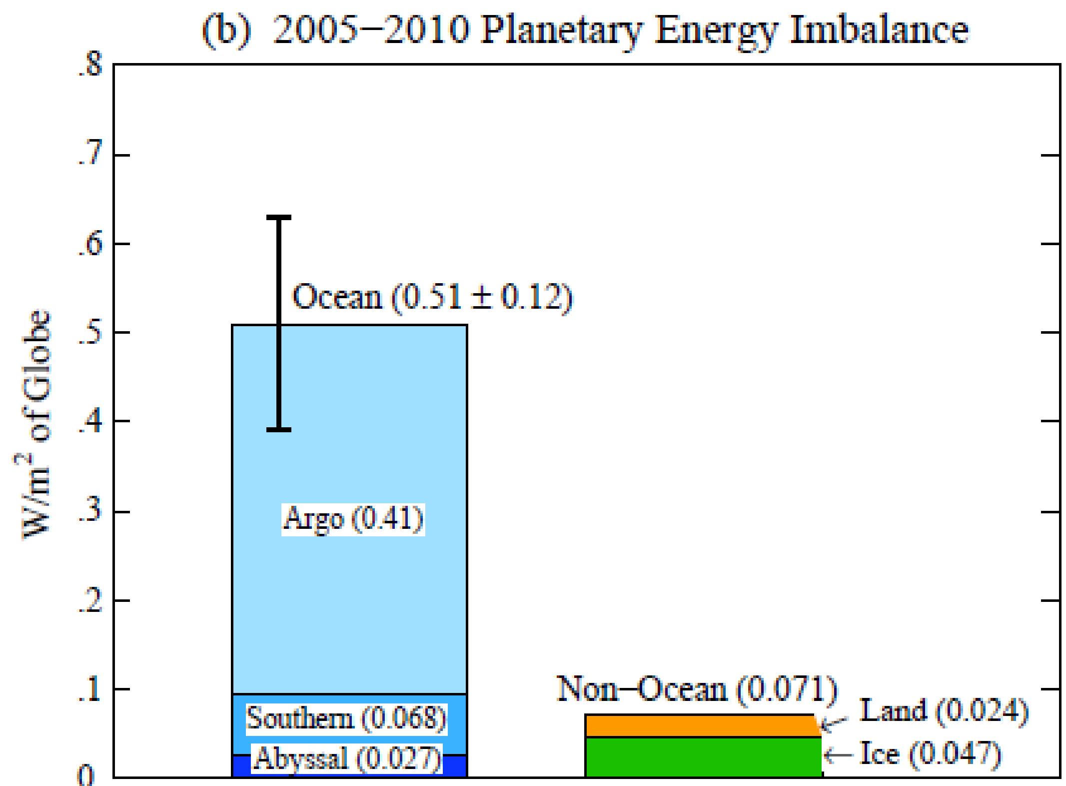
90% of anomalous warming is in the oceans.

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

Trad. Hydrography



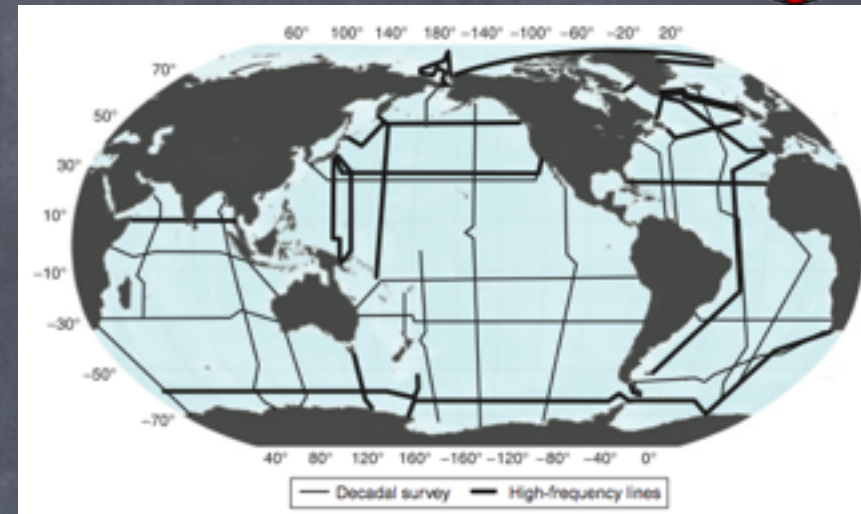
From the Argo Era



Hansen et al. (2011)

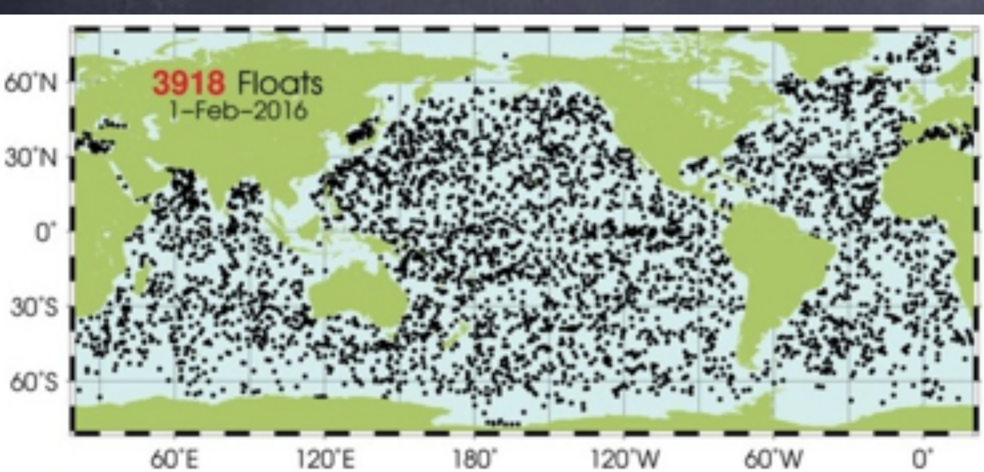
How do we know OHC?

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/



Argo floats presently active

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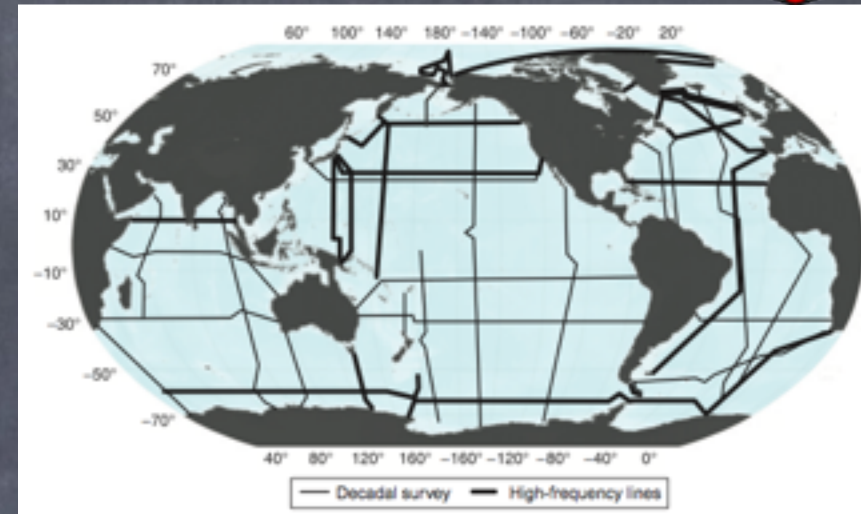

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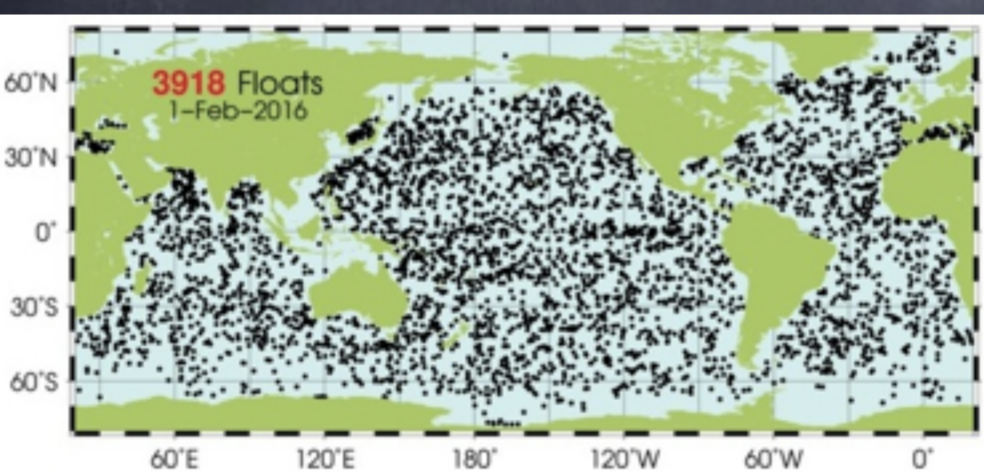
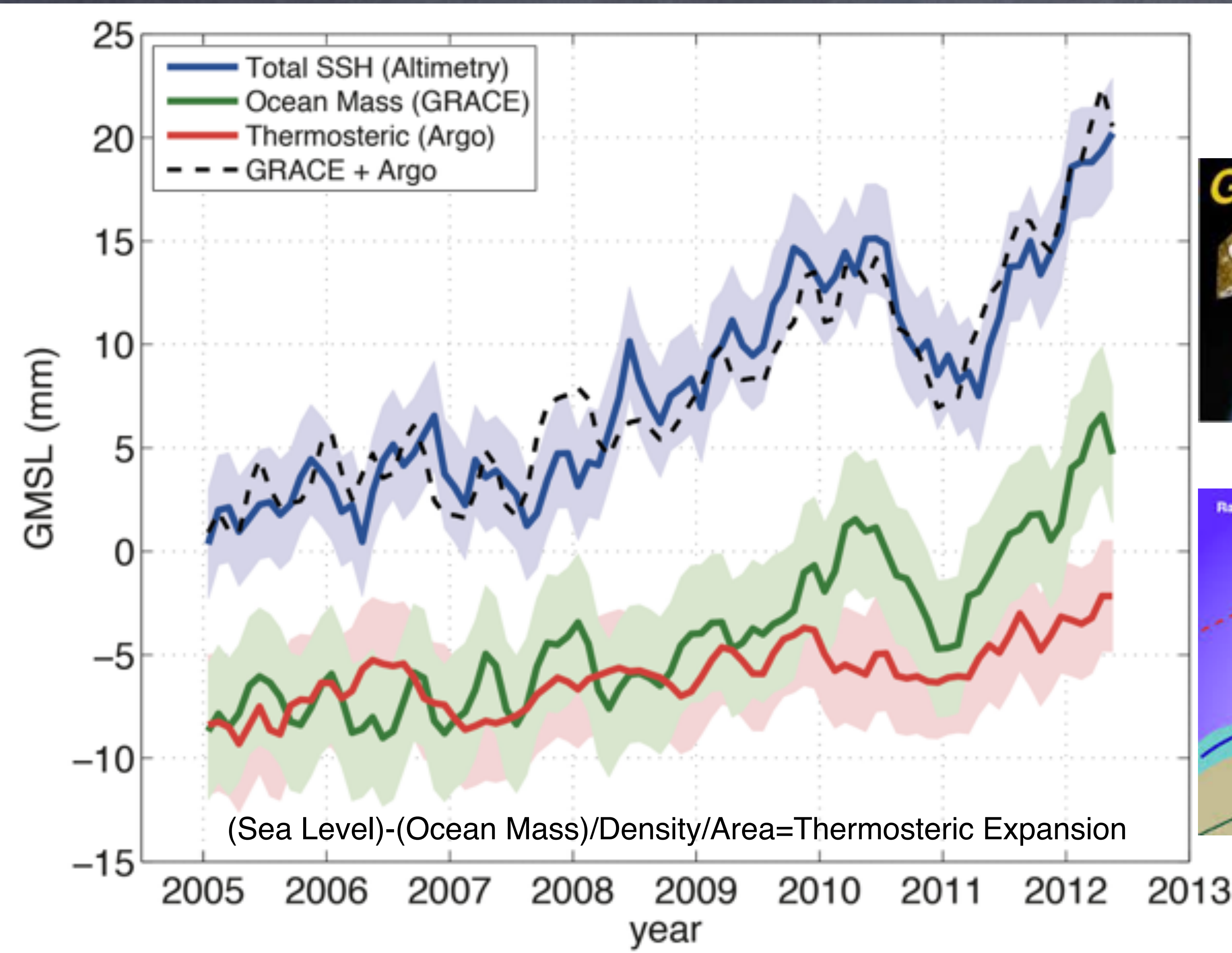
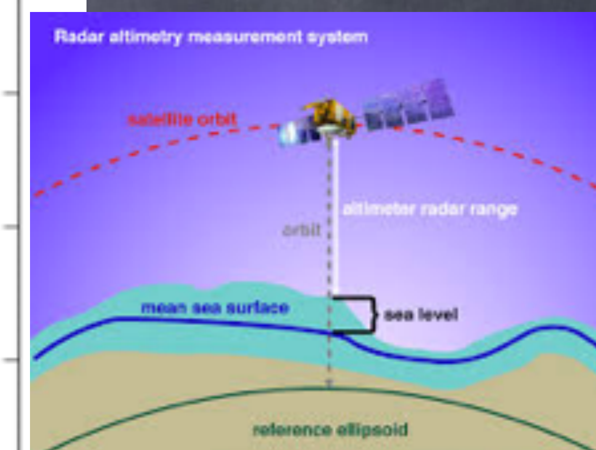


Argo floats presently active

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



podaac.jpl.nasa.gov



nesdis.noaa.gov

IPCC AR5, 2013

Surface, Mixed Layer, Seasons?

0.7 W/m^2

=

Atmosphere: 1.5K/yr

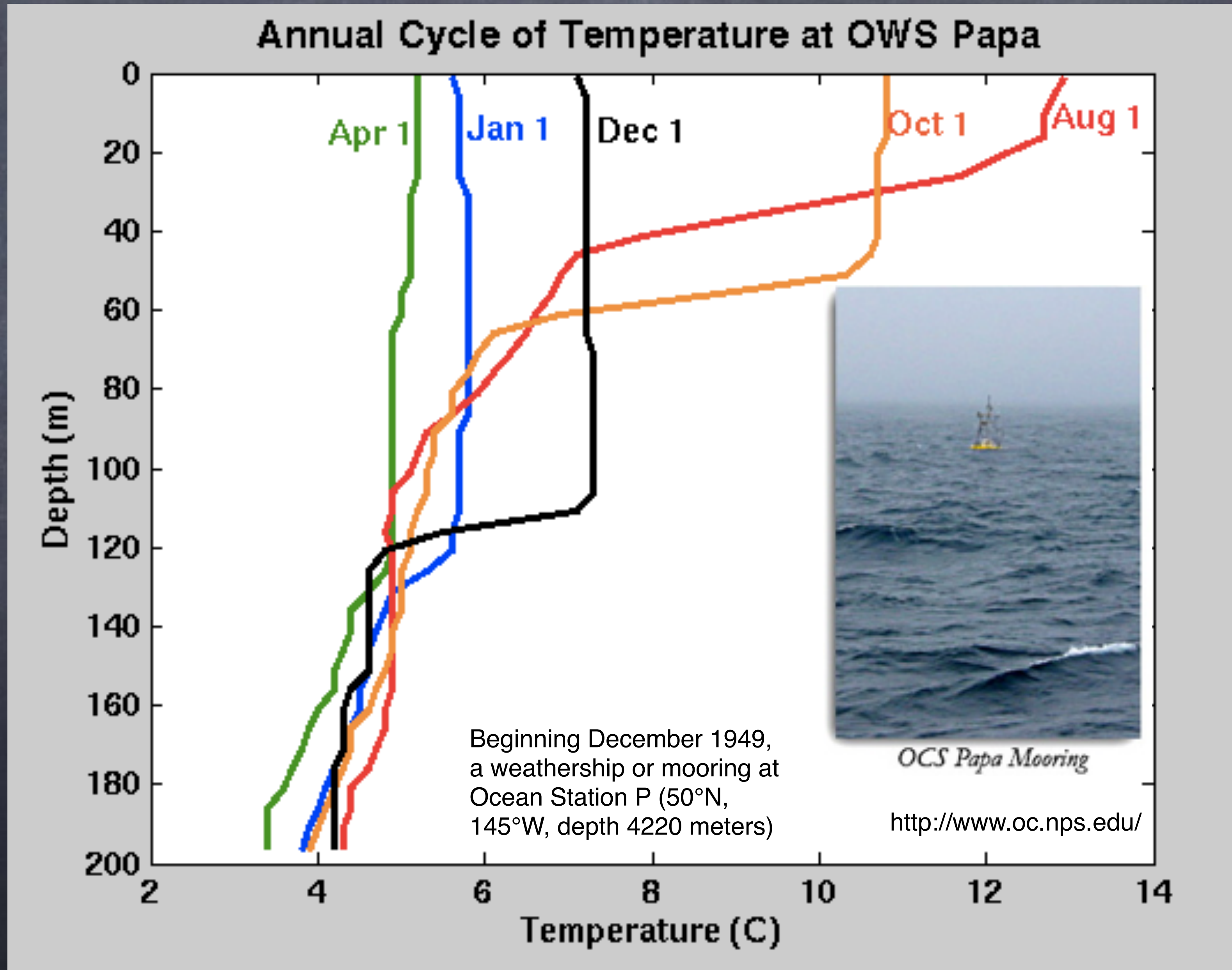
=

3.4m Ocean: 1.5K/yr

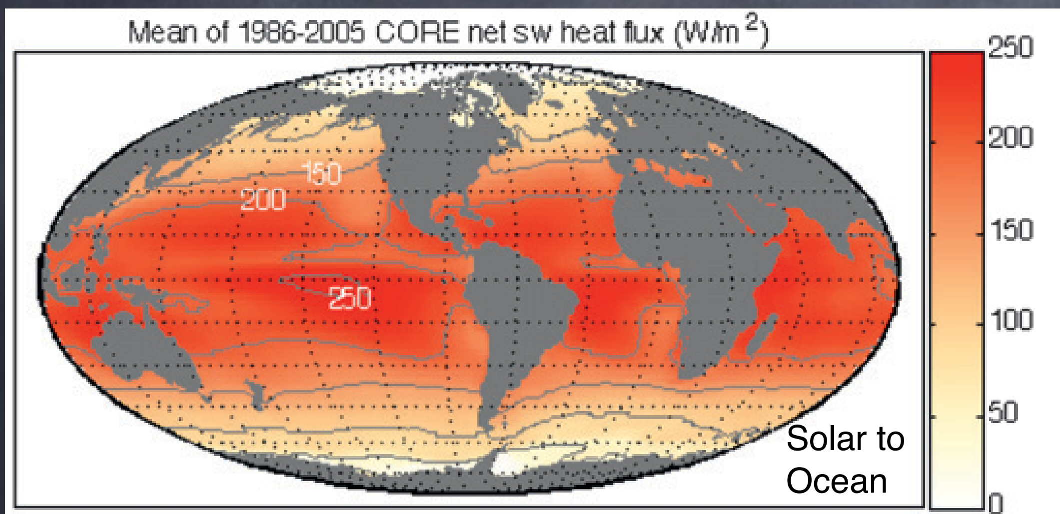
=

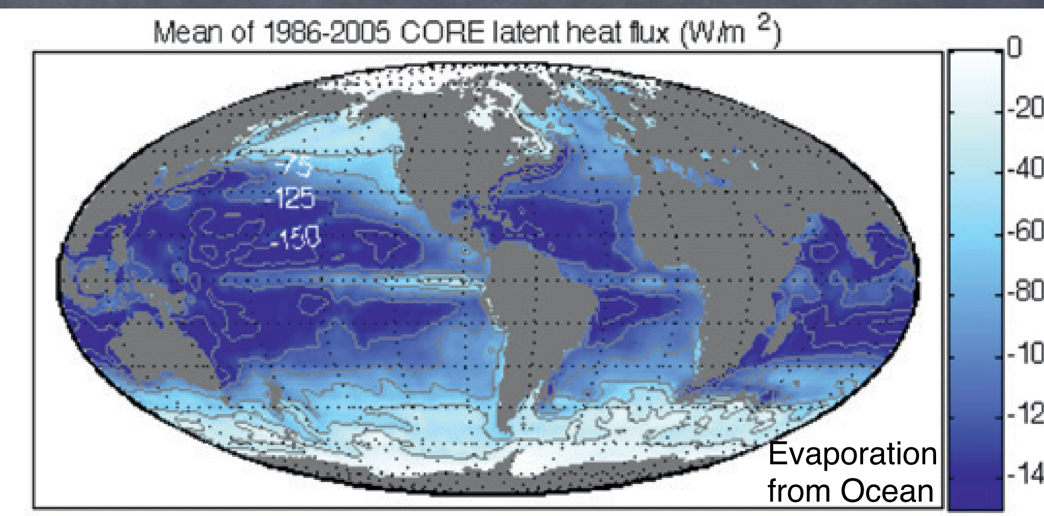
34m Ocean: 0.15K/yr

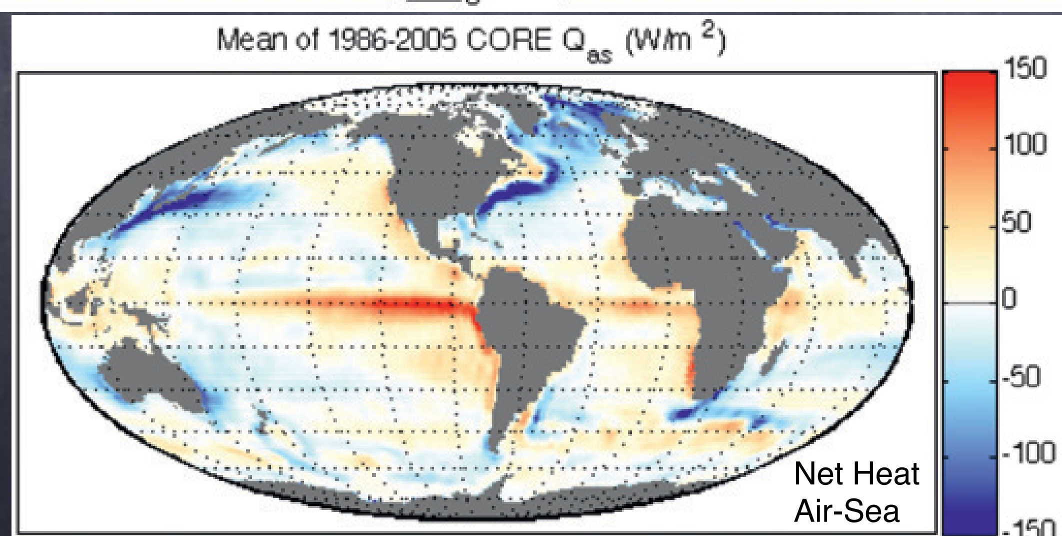
=1% of mixed layer seasonality



The net Q_{BML} is also about 1% of different flux components and about 1% of net spatial extremes





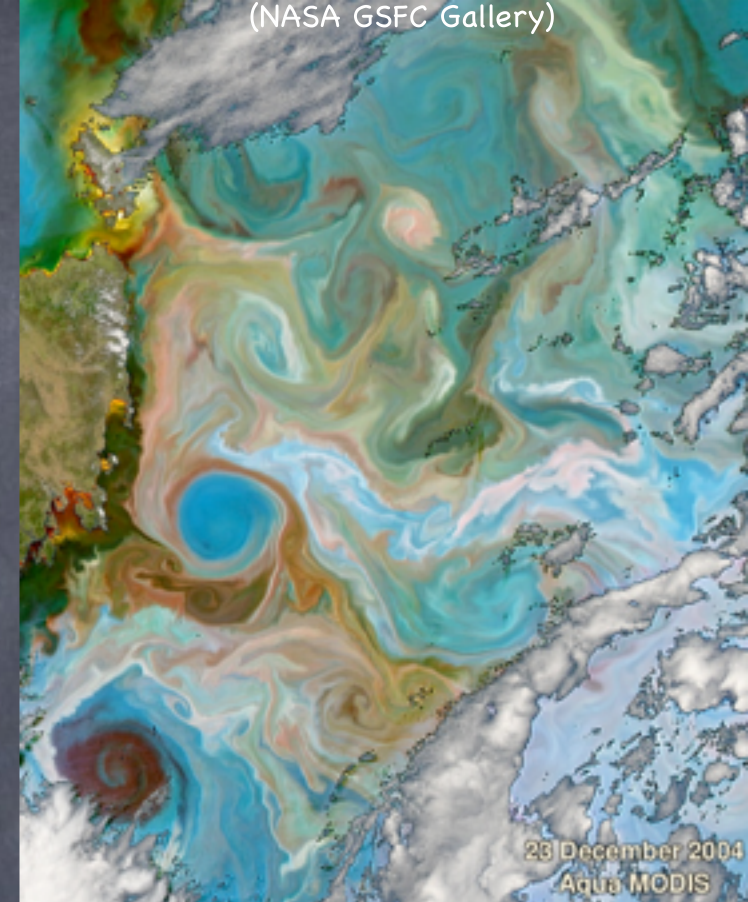


S. C. Bates, BFK, S. R. Jayne, W. G. Large, S. Stevenson, and S. G. Yeager. Mean biases, variability, and trends in air-sea fluxes and SST in the CCSM4. Journal of Climate, 25(22):7781-7801, November 2012.

The Mesoscale

← 100 km

(NASA GSFC Gallery)



- Boundary Currents
- Eddies
- 100km, months
- Full Depth (4km)
- Eddy Pot'l Energy: 13EJ vs. 20EJ in Mean Circulation
- Eddy Kinetic Power: About equal to mean circ. 2-3TW
- (Wunsch & Ferrari, 2004)

(Capet et al., 2008)

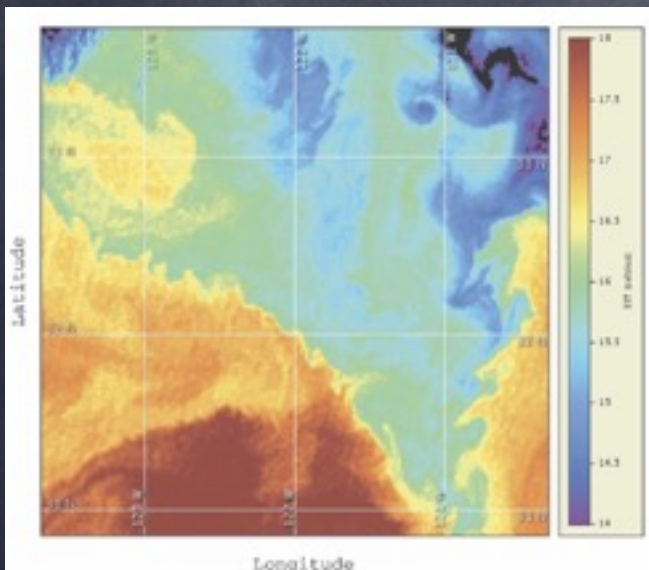
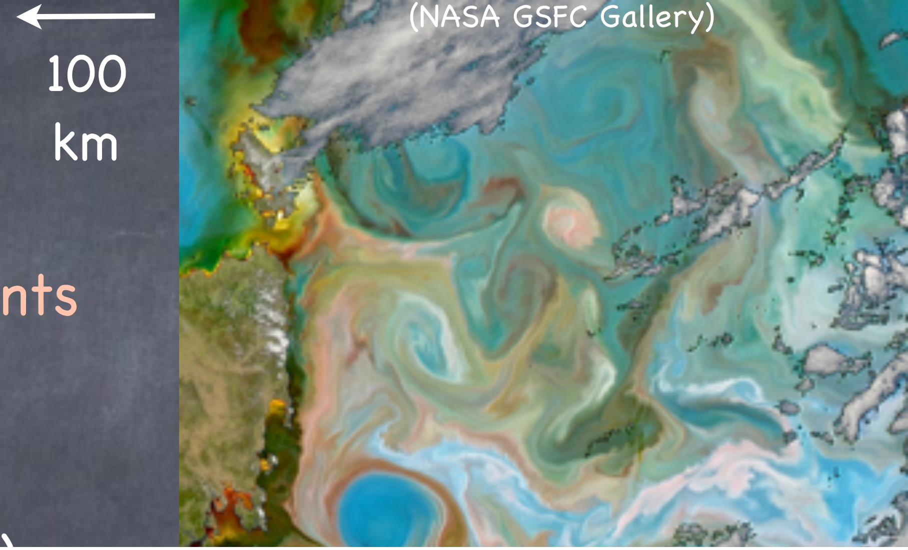


FIG. 16. Sea surface temperature measured at 1832 UTC 3 Jun 2006 off Point Conception in the California Current from CoastWatch (http://coastwatch.pfeg.noaa.gov). The fronts between recently upwelled water (i.e., 15°–16°C) and offshore water (≥17°C) show submesoscale instabilities with wavelengths around 30 km (right front) or 15 km (left front). Images for 1 day earlier and 4 days later show persistence of the instability events.

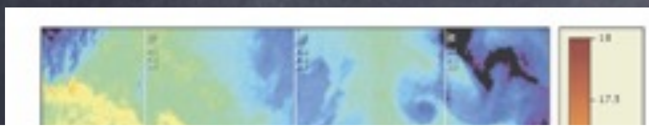
Mesoscale Eddies: How to represent in climate models?

The Mesoscale

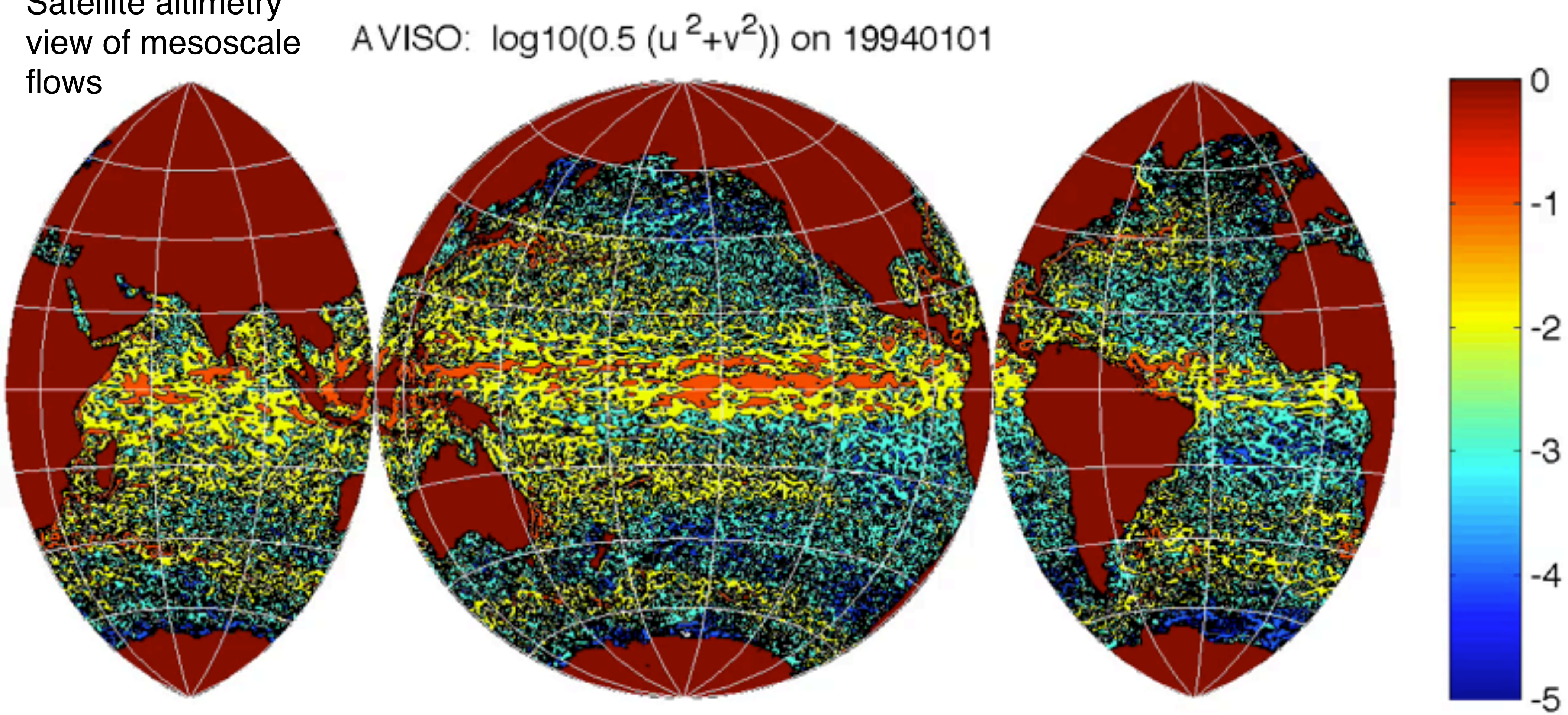


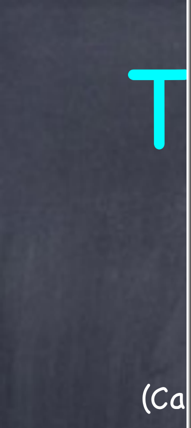
- Boundary Currents
- Eddies
- 100km, months

(Capet et al., 2008)



Satellite altimetry view of mesoscale flows





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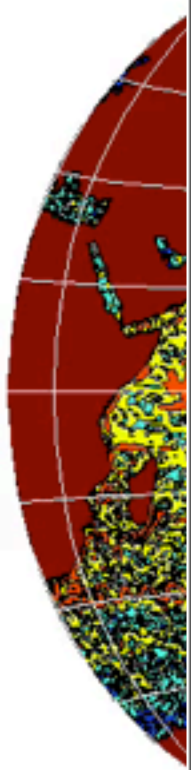
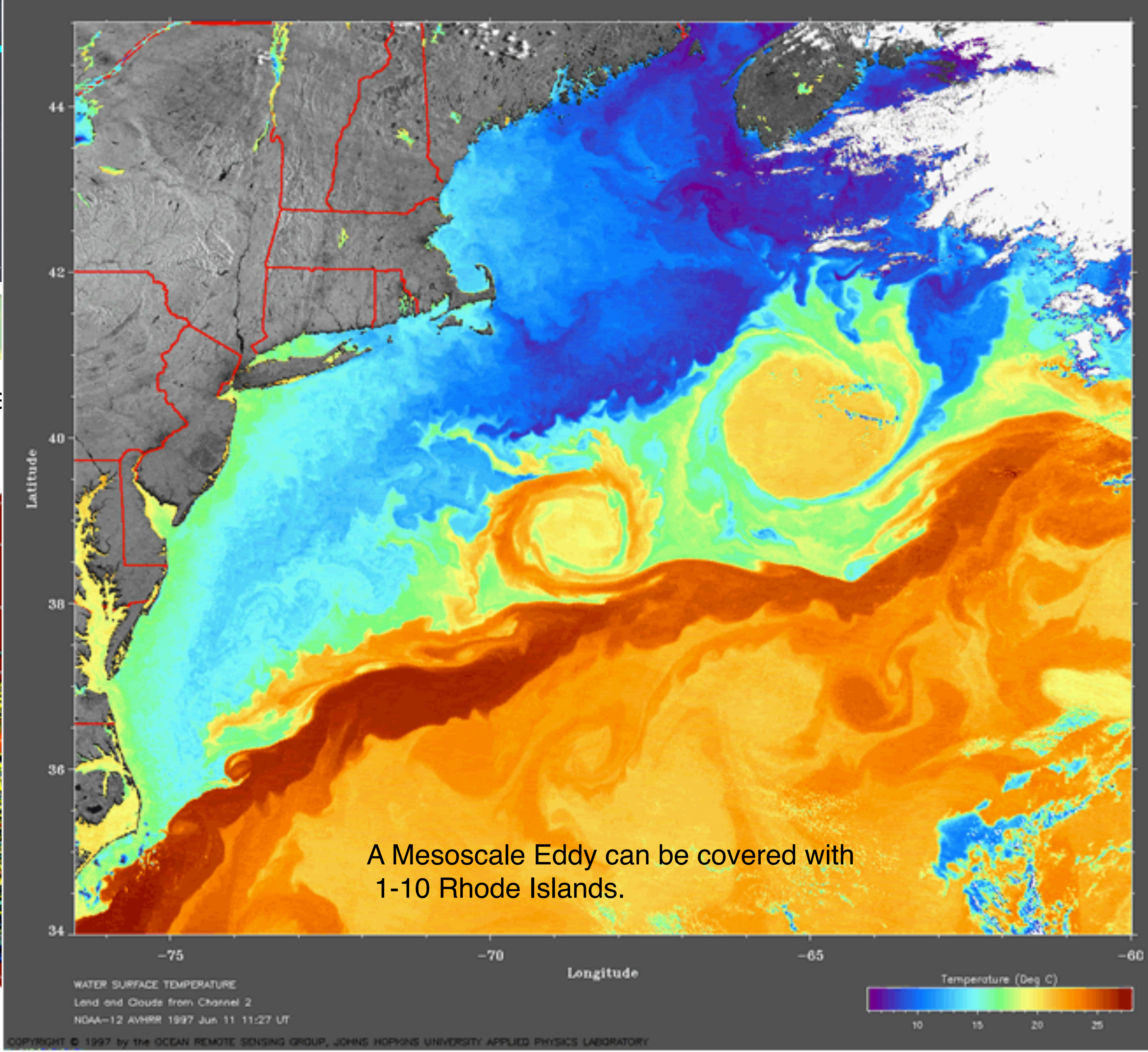
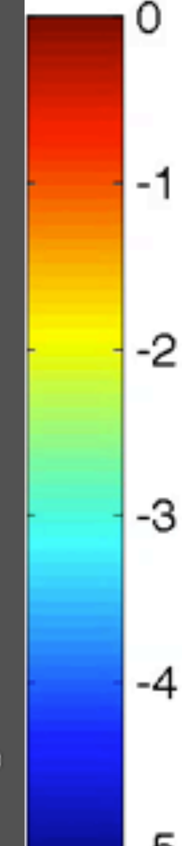
Satellite
view of
flows







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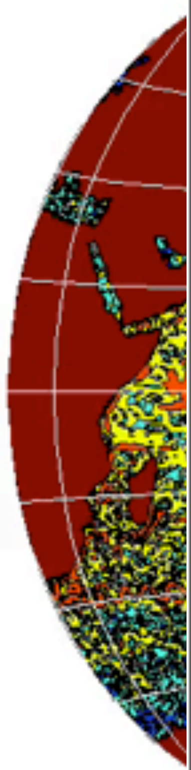
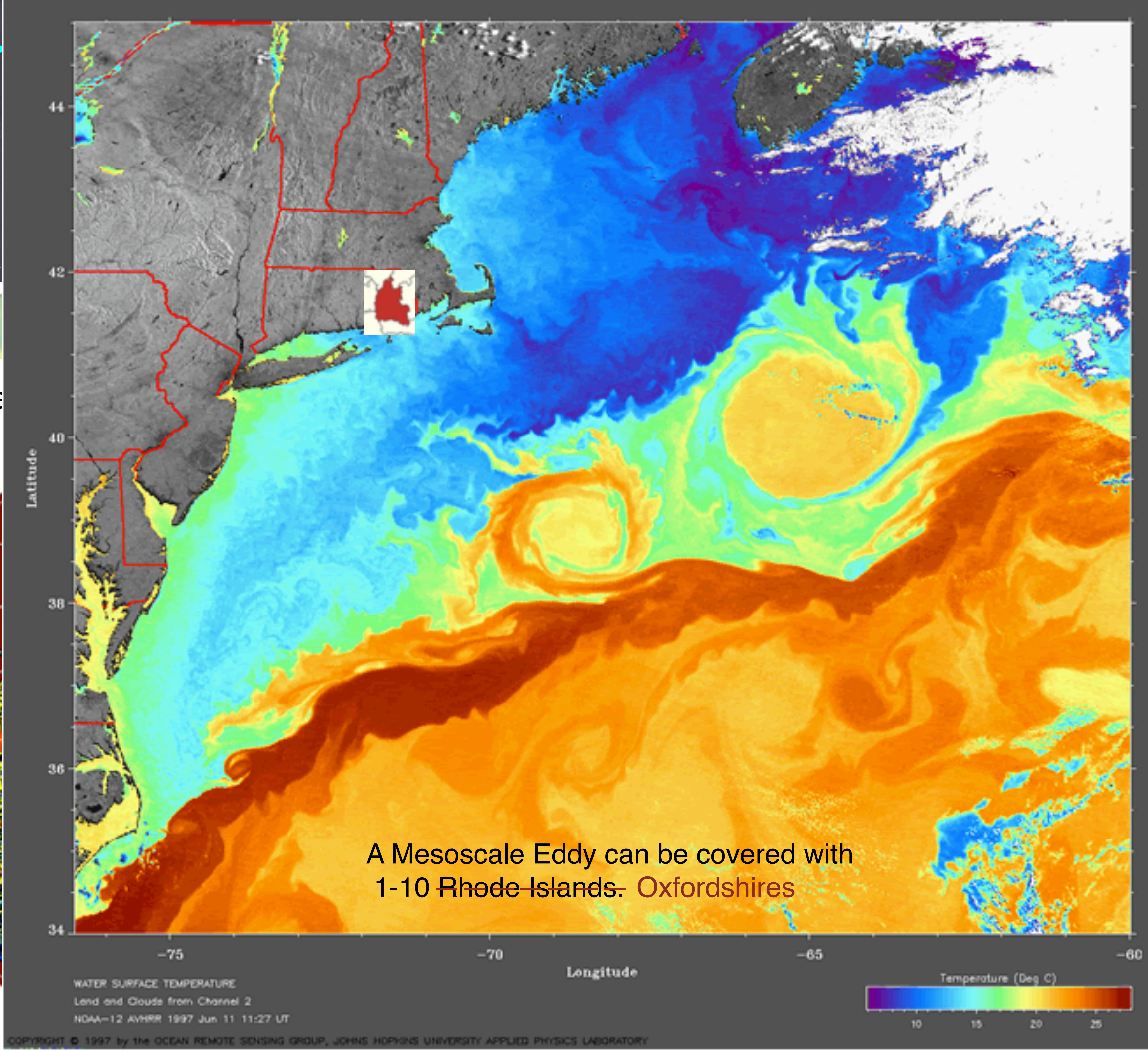
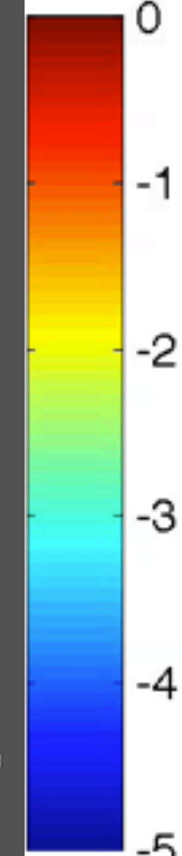
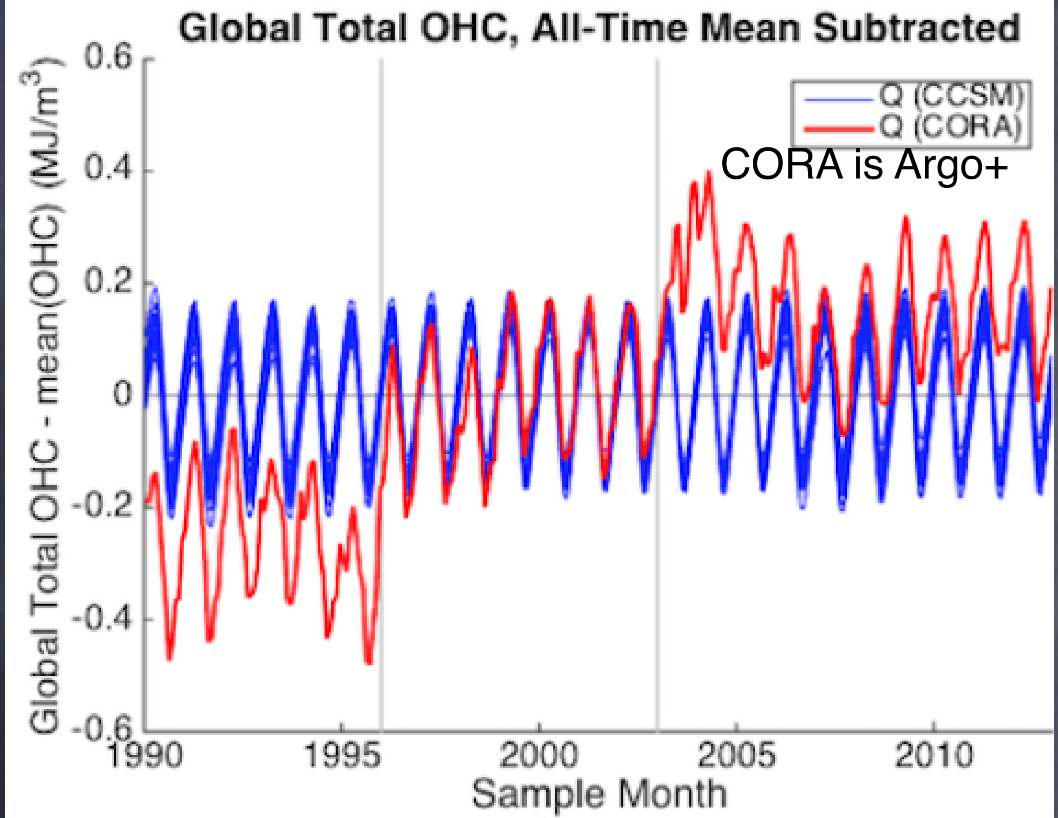
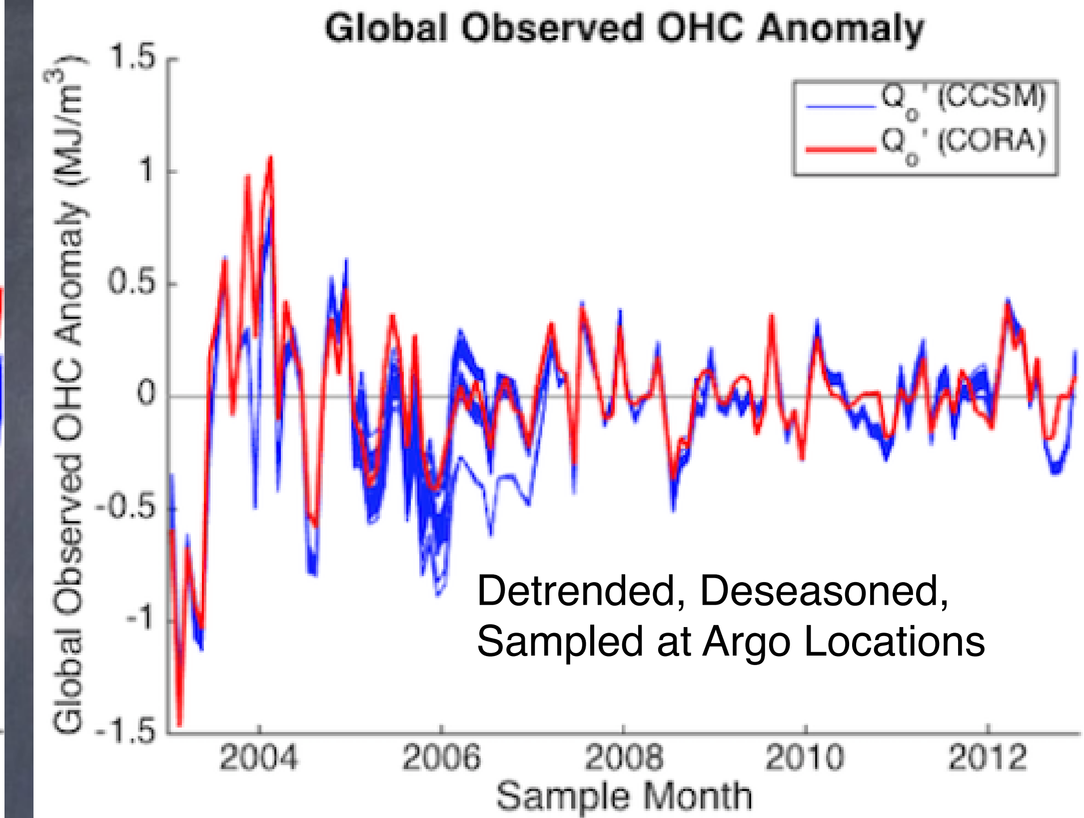










Sophisticated analysis to overcome Ship & Argo sampling problems—inherent uncertainty, $O(0.2W/m^2)$, on interannual to decadal timescales in global average.

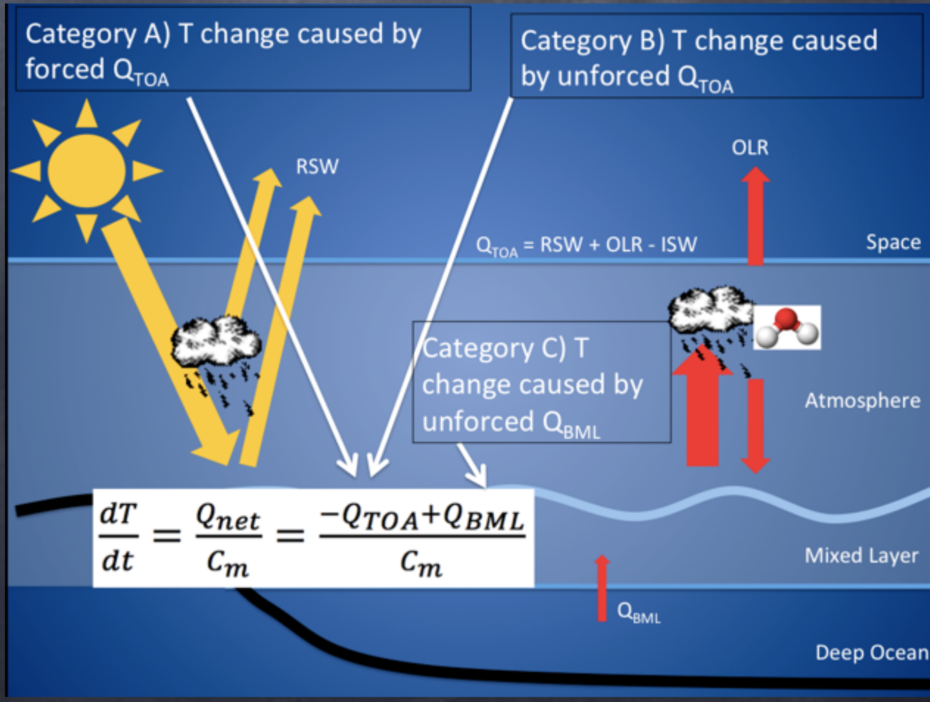
$O(10W/m^2)$ without analysis.

CU, soon Brown

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

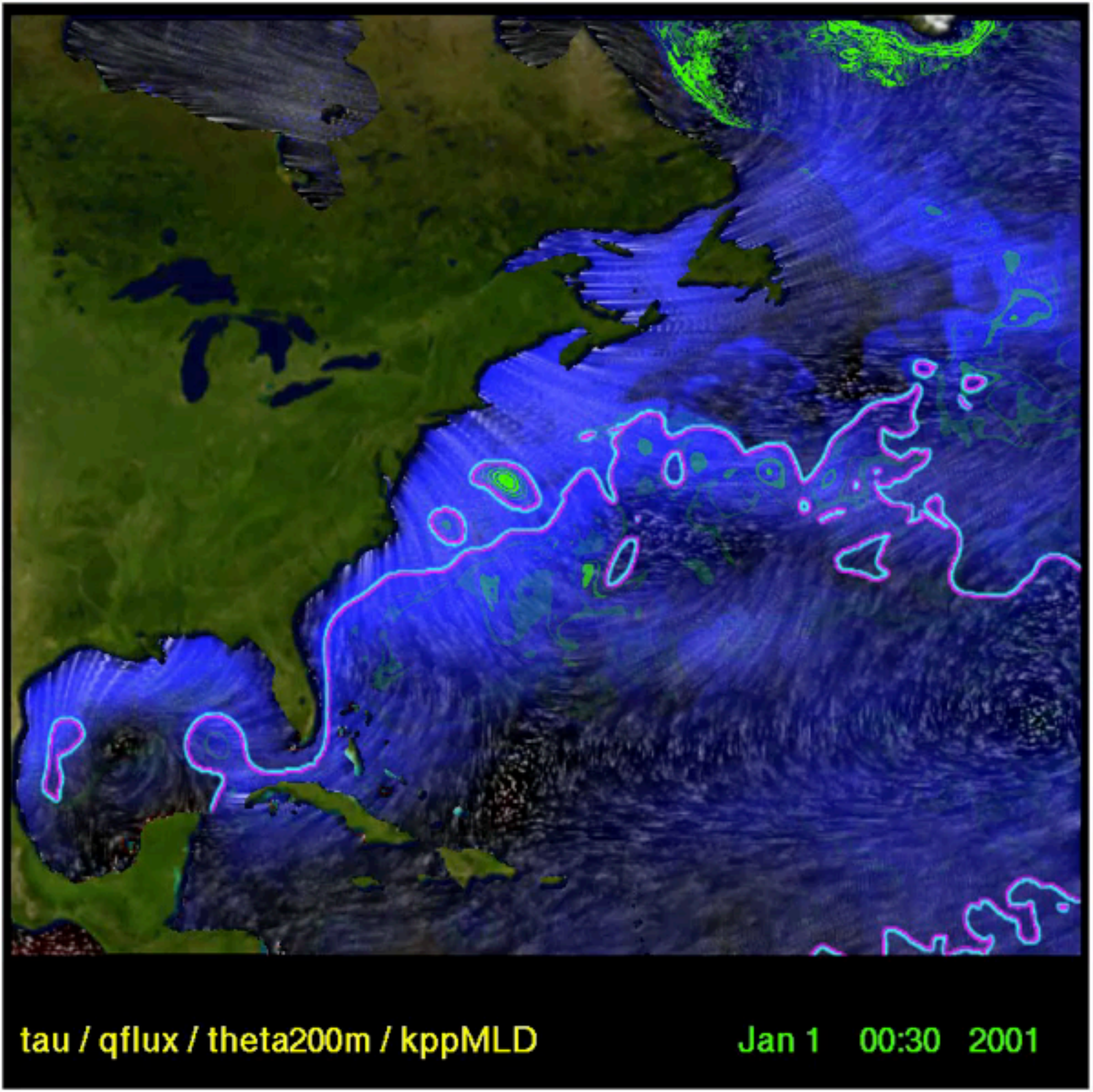
Presence of observable variability

- There is observable (autonomous, satellite & ship) ocean heat content variability.
- The near surface seasonal cycle, regional variations, and individual flux components are $O(100\ W/m^2)$
- Imbalance of Q_{TOA} and net mixed layer entrainment Q_{BML} are $O(1\ W/m^2)$



- In Situ & SSH agree.

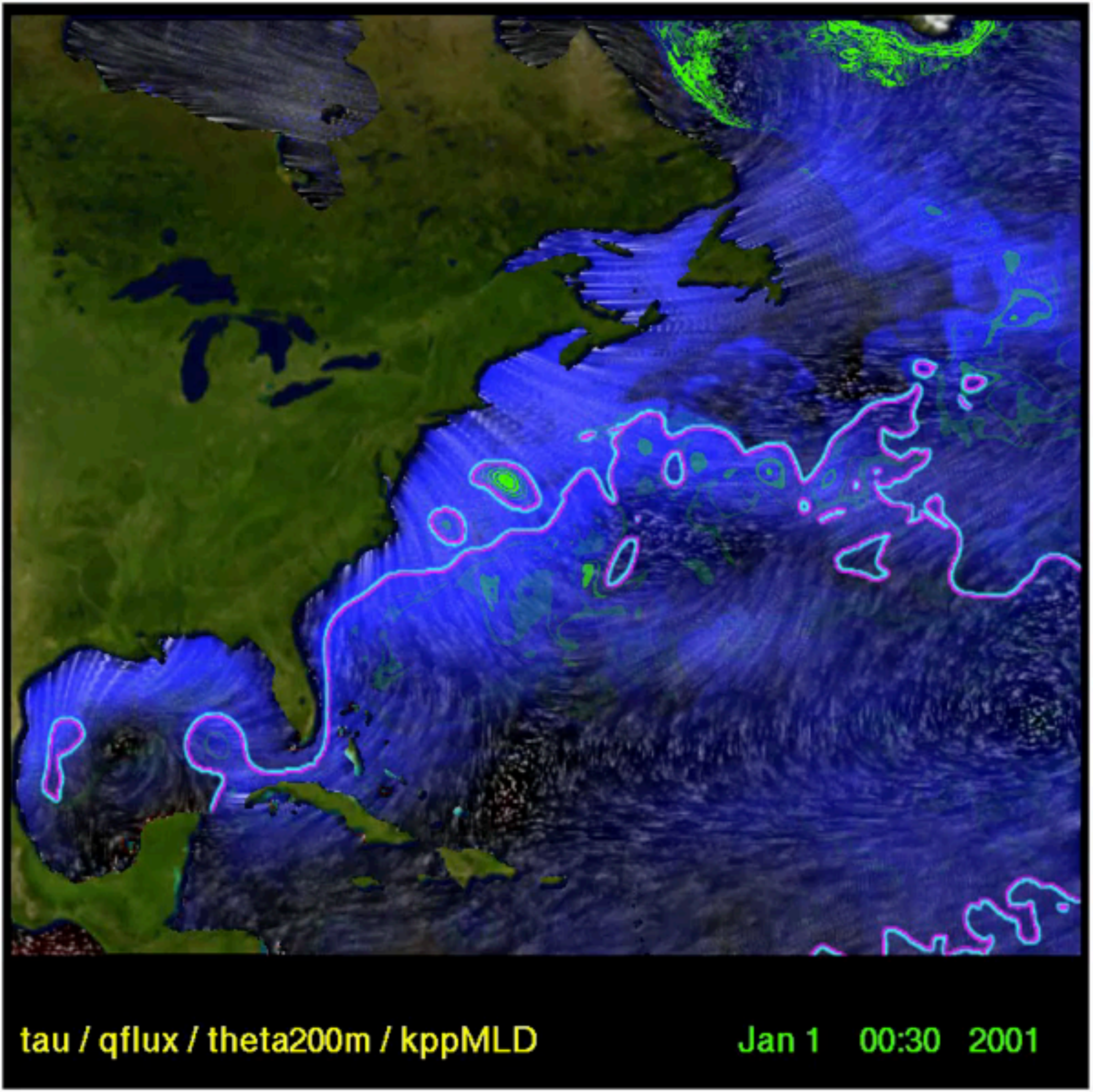
- **Understanding** of past variability
  - Monday Morning Quarterbacking abounds in variability analyses, e.g.:
    - You can't use 1998 as a start year for climate change—it was the biggest ENSO event of the past 100yr...
    - Phase of the PDO explains the recent warming hiatus, but we don't know what PDO is...
  - May explain and test our understanding, but it has little predictive power.



Weather,
Atmosphere
Fast

Ocean,
Climate
Slow

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



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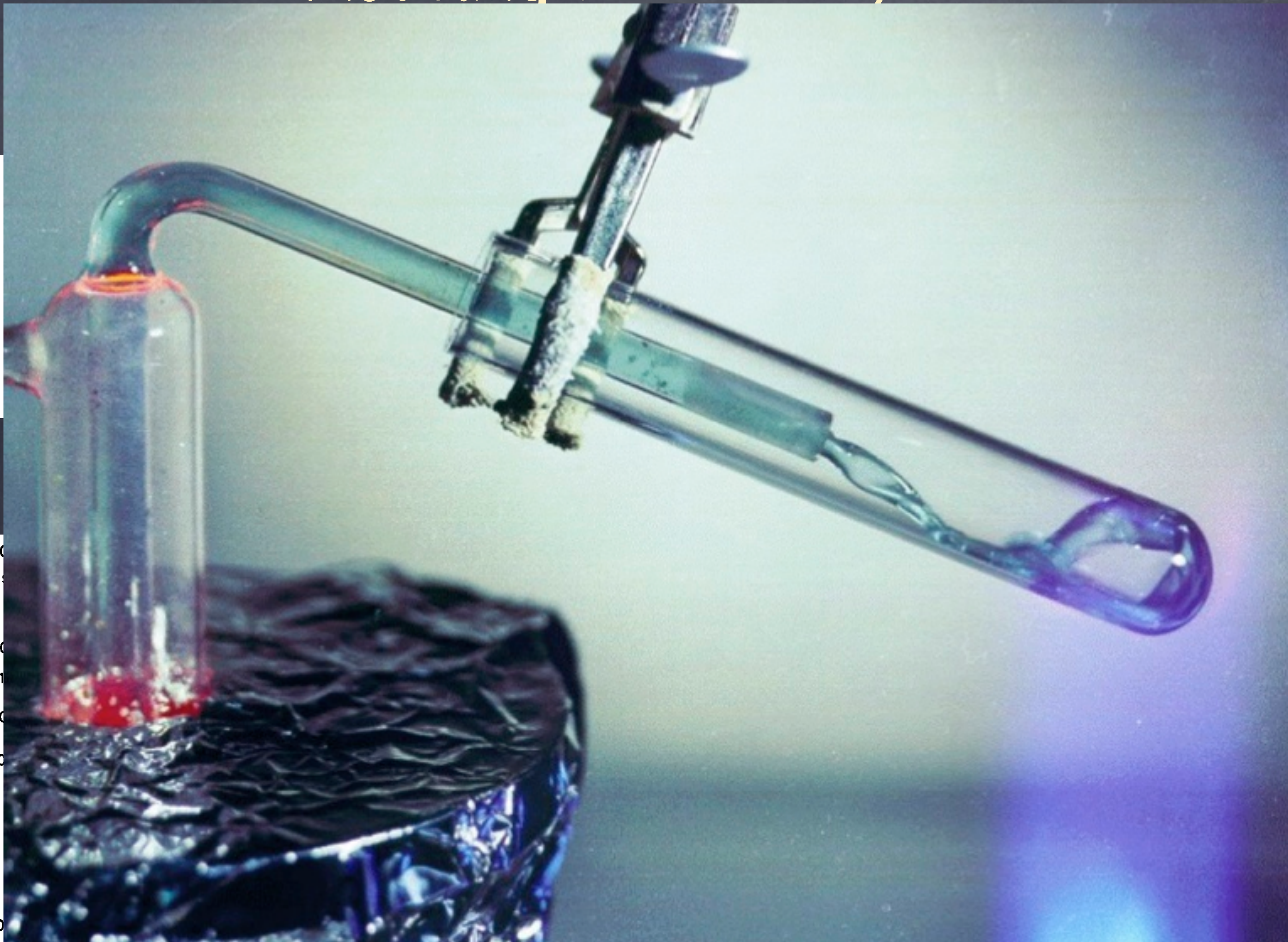
Modeling of variability

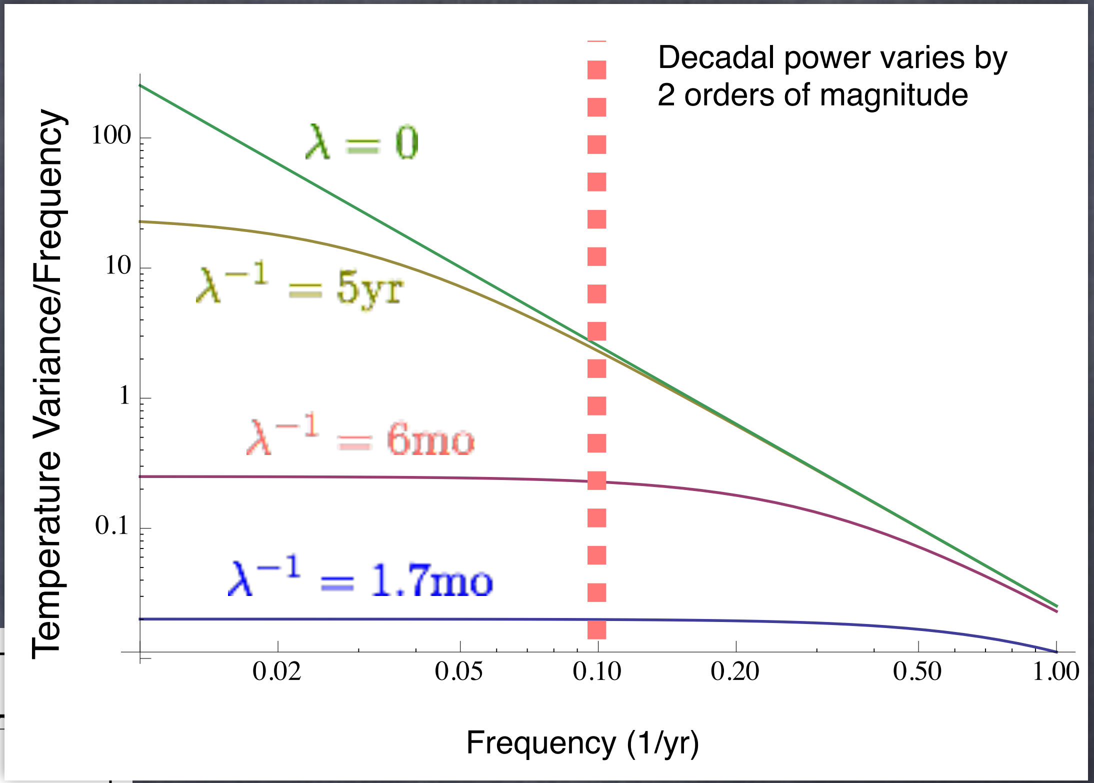


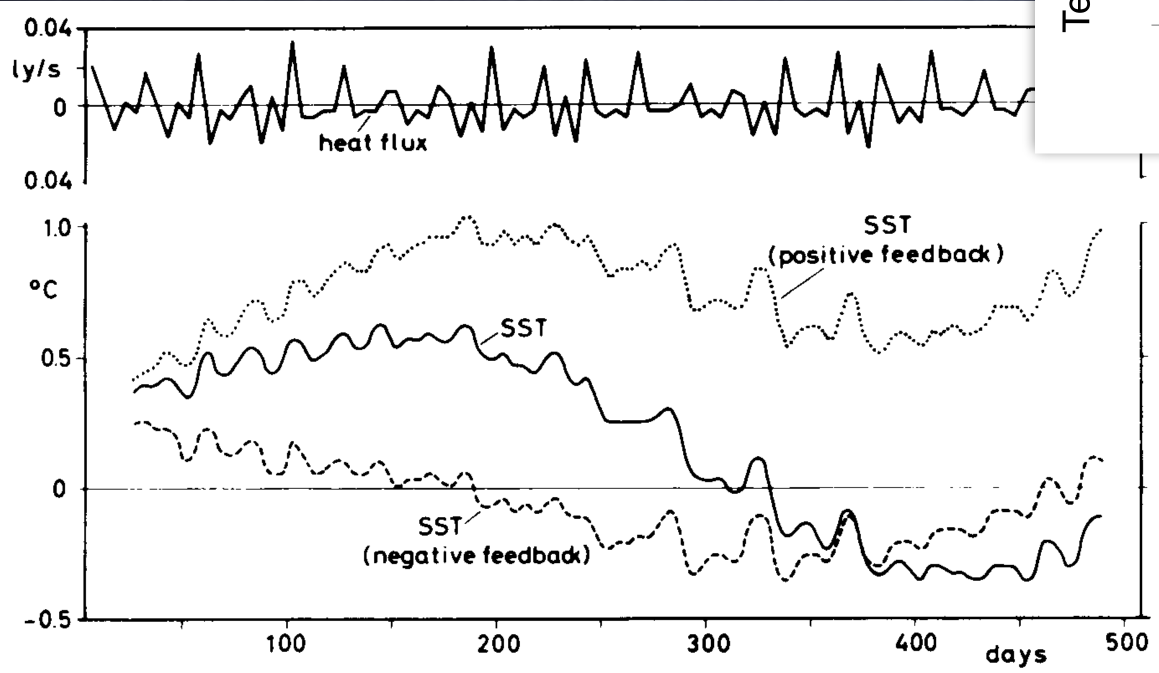
Modeling of variability

A stochastic, predictable persistence model:
Frankignoul & Hasselmann (77)

Temp Change, Random Atmosphere, Restoring, Mixed Layer

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

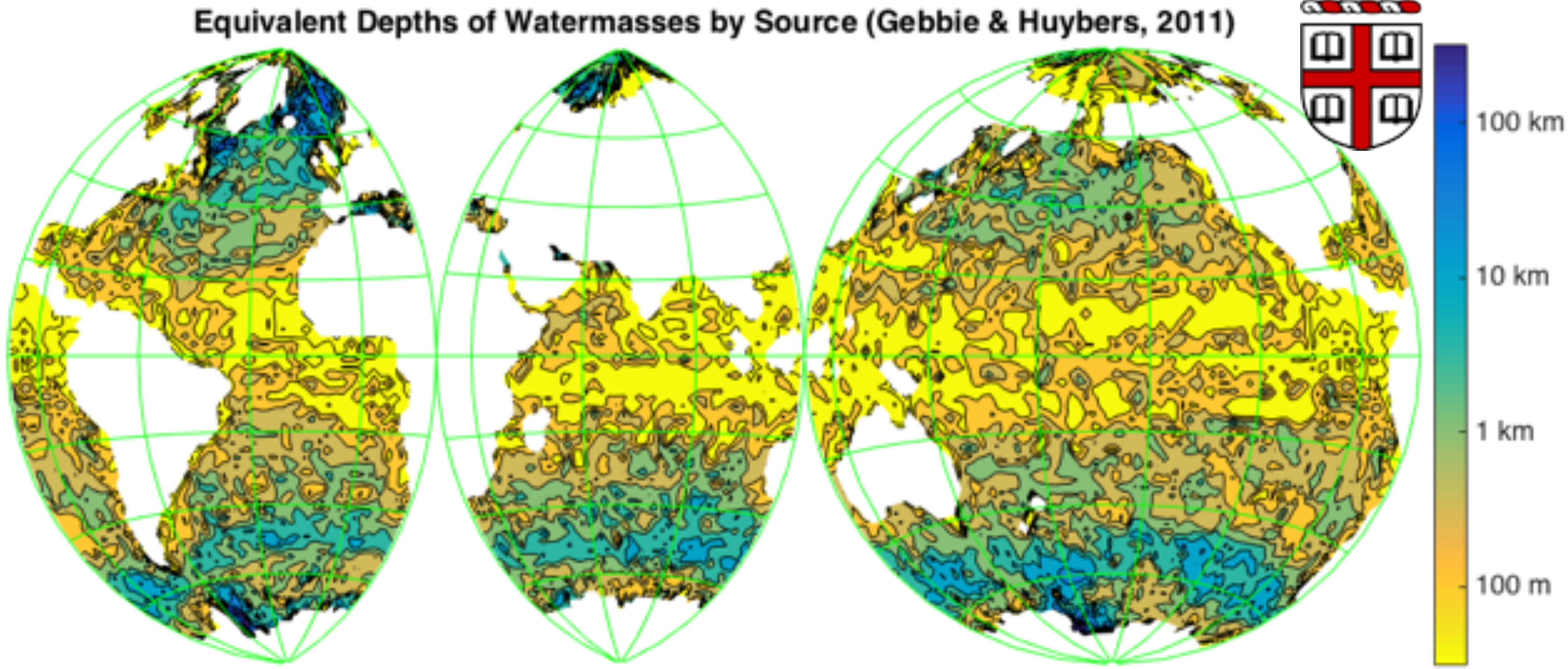




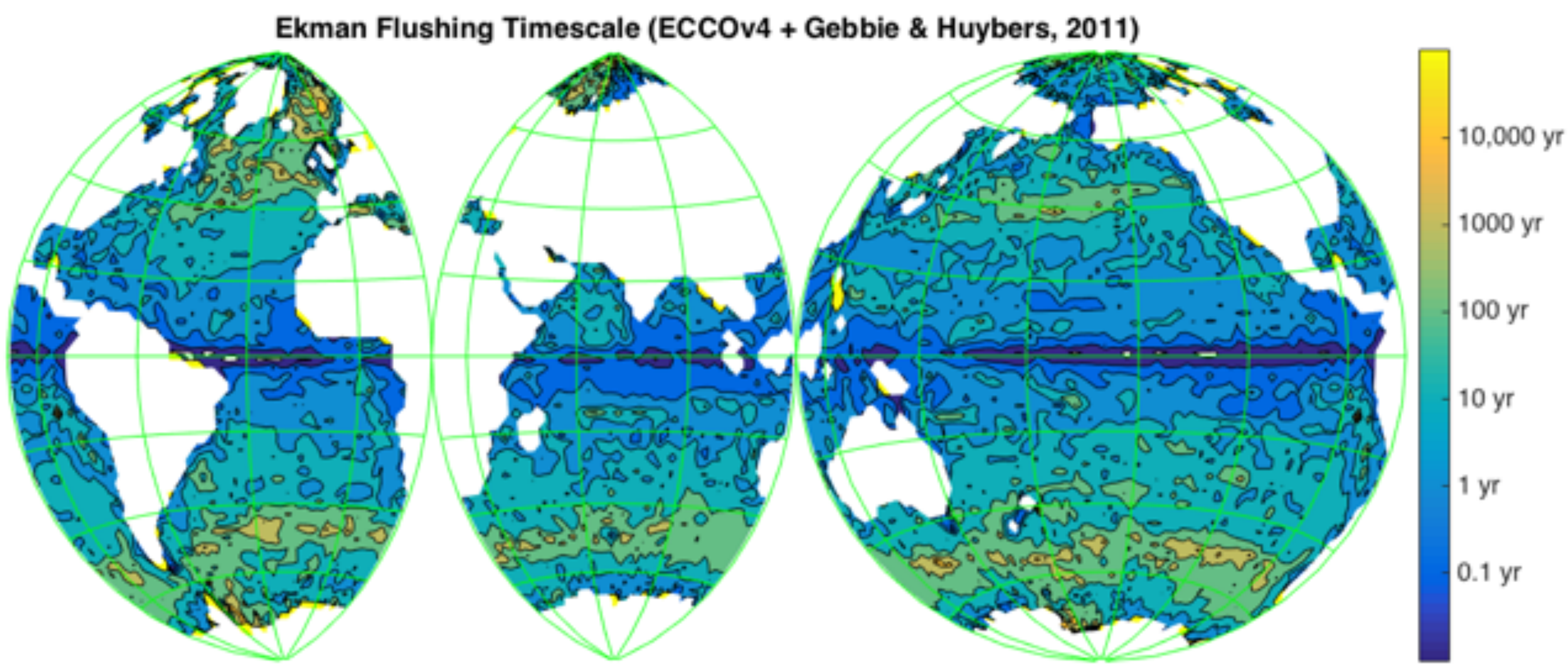
$$\lambda = \rho^a C_p^a (\rho^w C_p^w)^{-1} C_H (1 + B) \langle |\mathrm{U}| \rangle h^{-1}$$

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

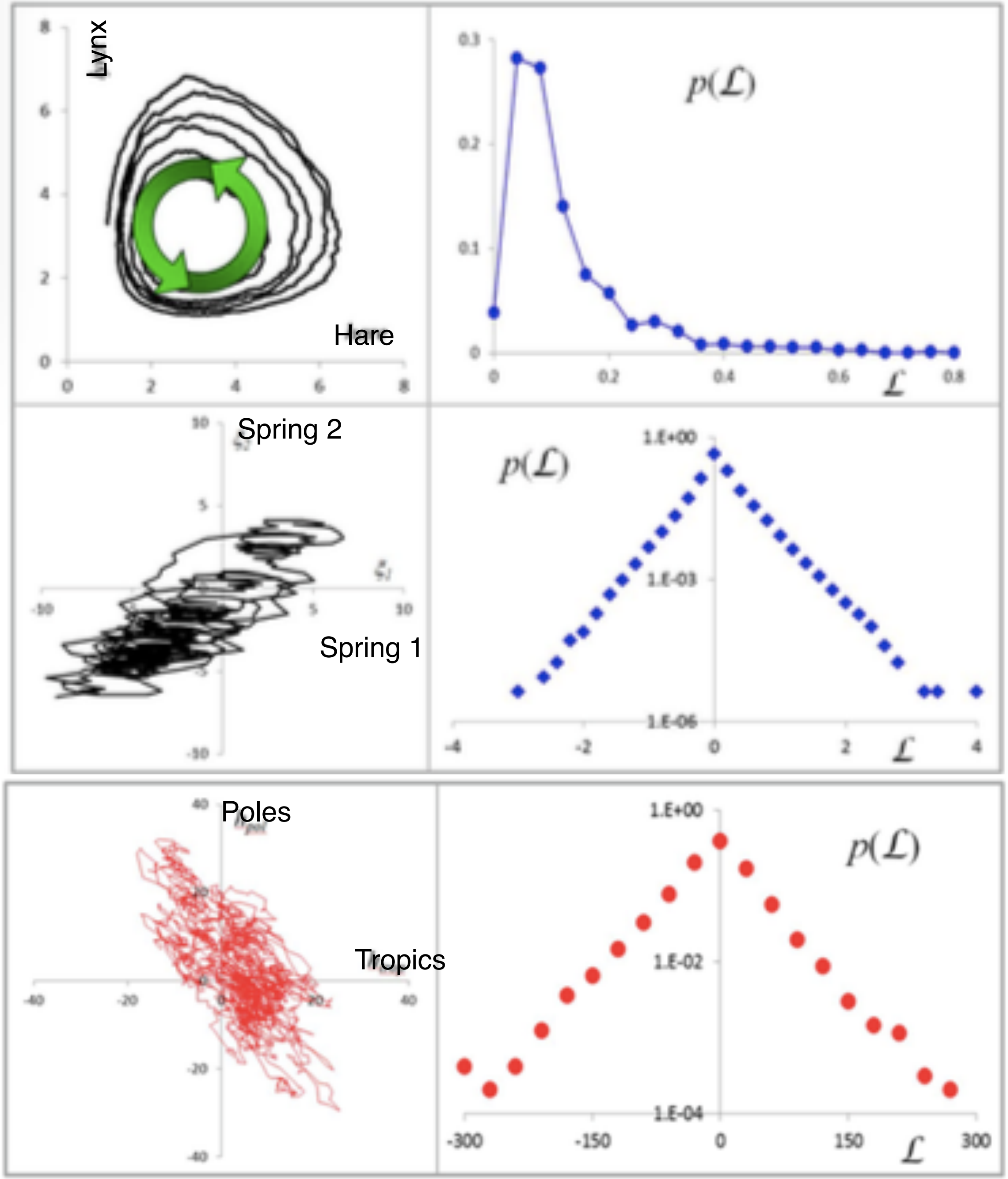
Consider lots of 1D Oceans: one per watermass



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



If Connections Occur Between Regions—
Predictability Can Arise, Even in Stochastic Systems.



Stochastic Predator-Prey Model (Lotka-Volterra)

Two springs connected to each other and to thermal baths at different temperatures

Earth System Model, averaged ocean heat content over tropics (>28S to <28N) or poles (>28N or <28S)

The root cause of most stochastic predictability beyond persistence

R.K.P. Zia, Jeffrey B Weiss, Dibyendu Mandal, & Baylor Fox-Kemper, 2016: Manifest and Subtle Cyclic Behavior in Nonequilibrium Steady States.

Global climate models do pretty well at matching heat fluxes and watermasses.

Statistically significant differences in a few timescales & regions from obs. (Ticks=10 W/m²)

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.

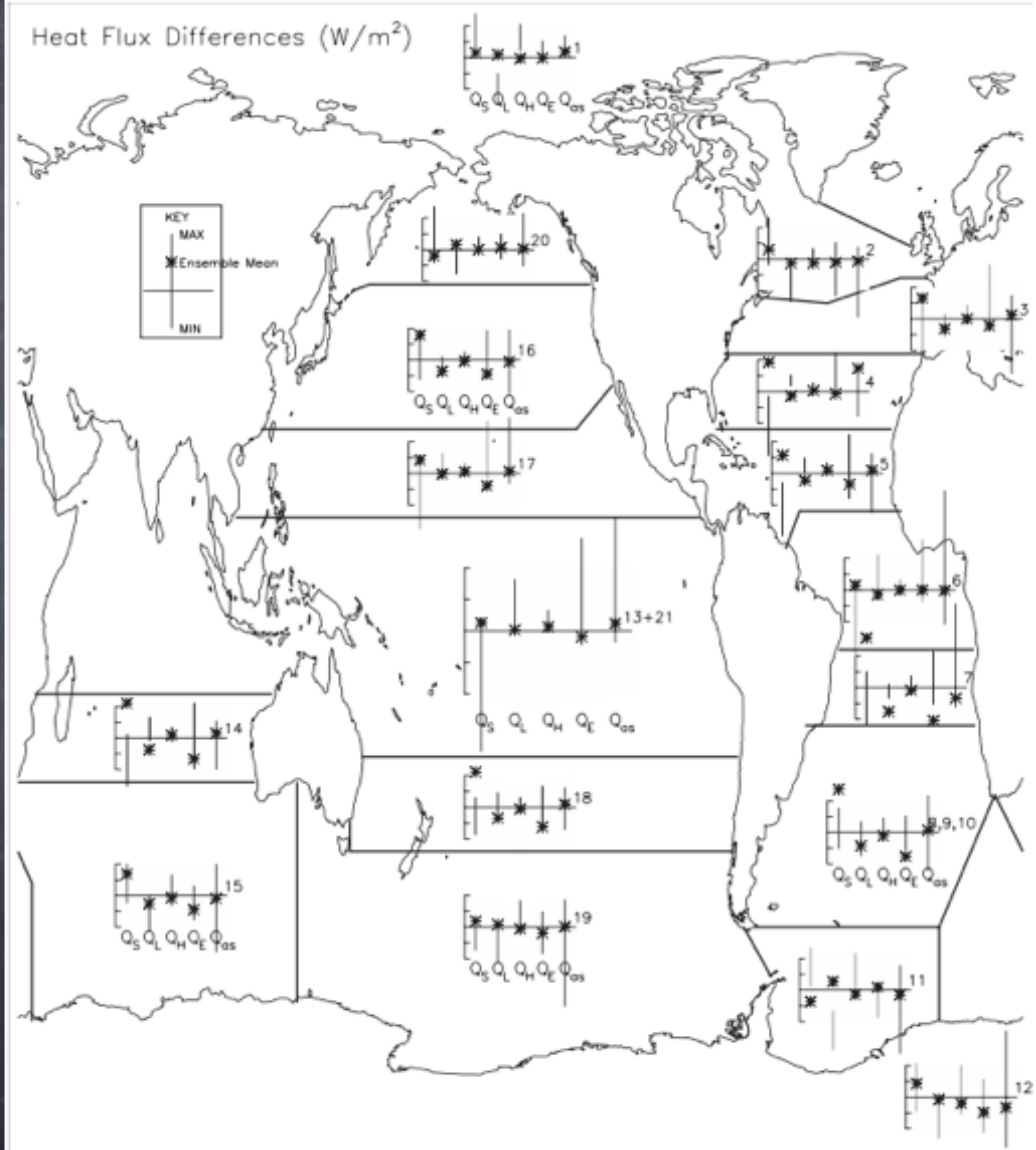
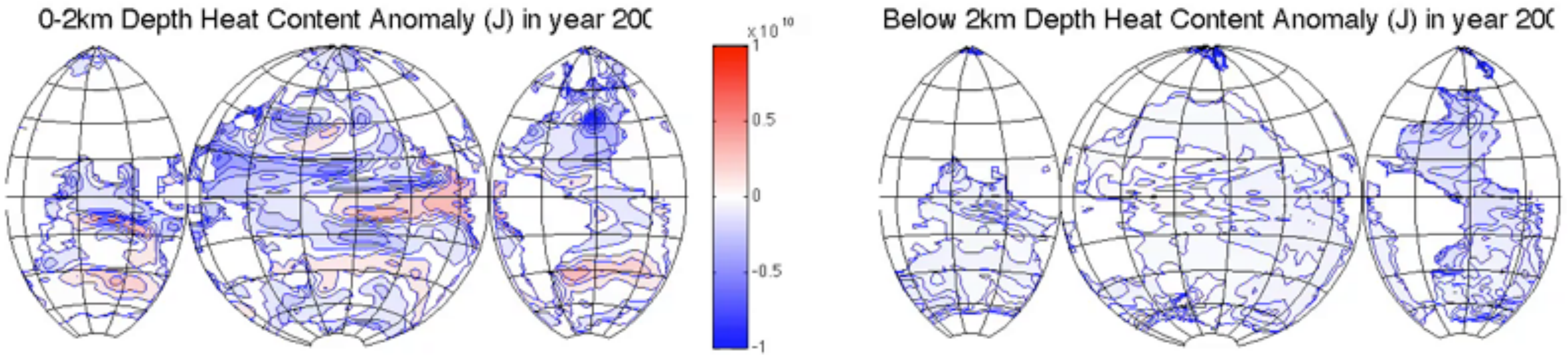


FIG. 4. Regional averages of the CCSM4 20C ensemble mean heat flux components differenced with the CORE

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.

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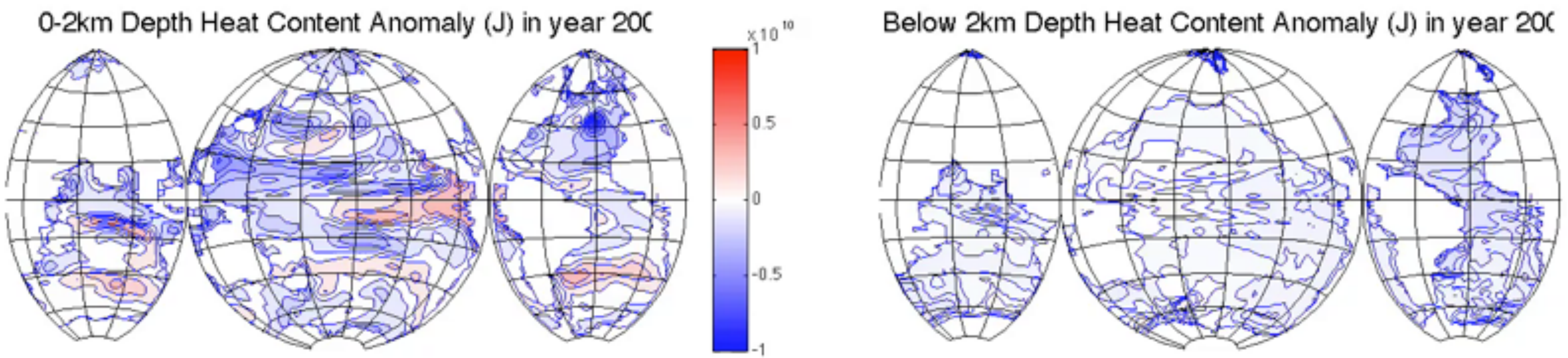

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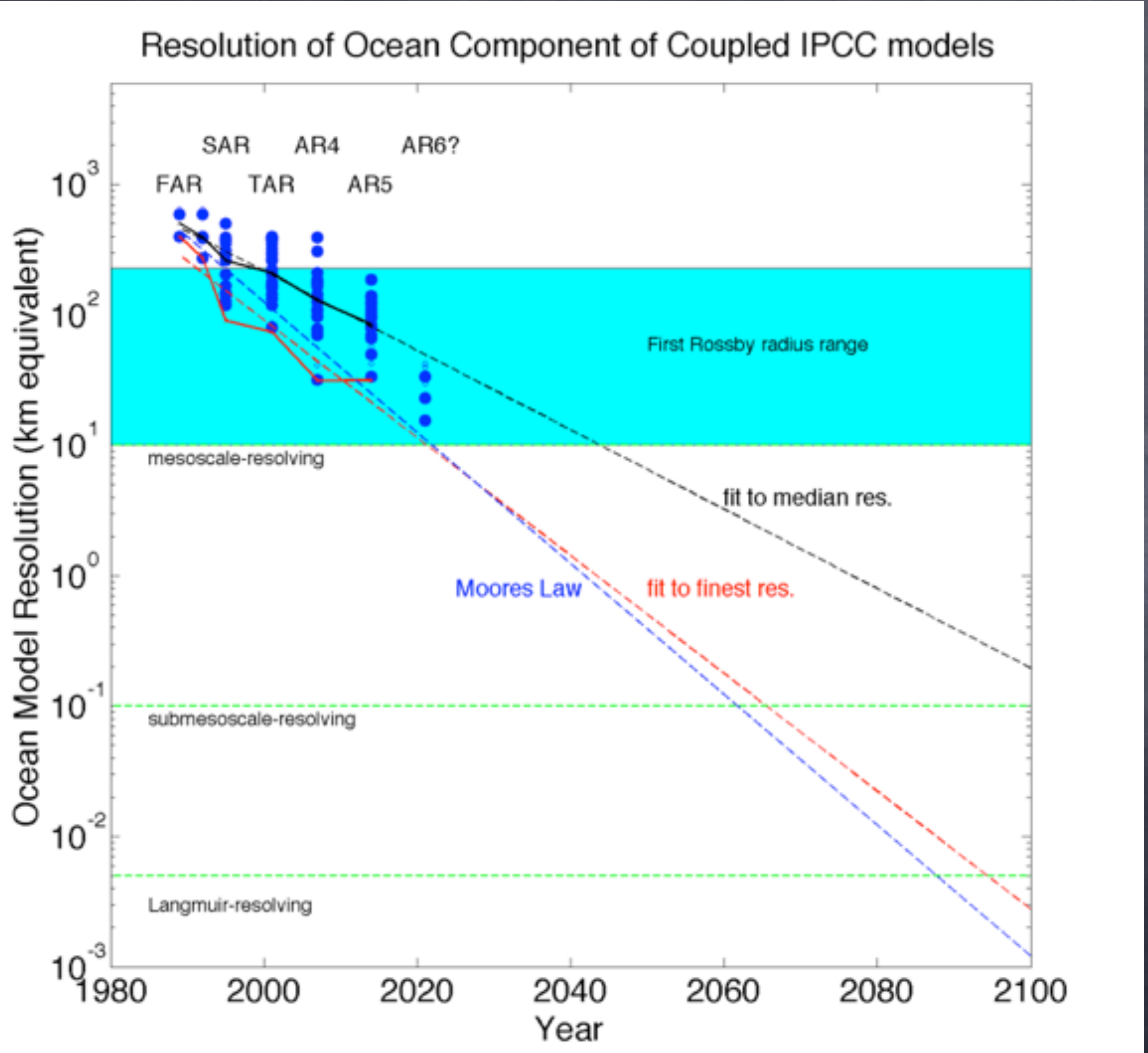
Too Simple: What about directly modeling processes in climate models? Don't we have big enough computers? or won't we soon?



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

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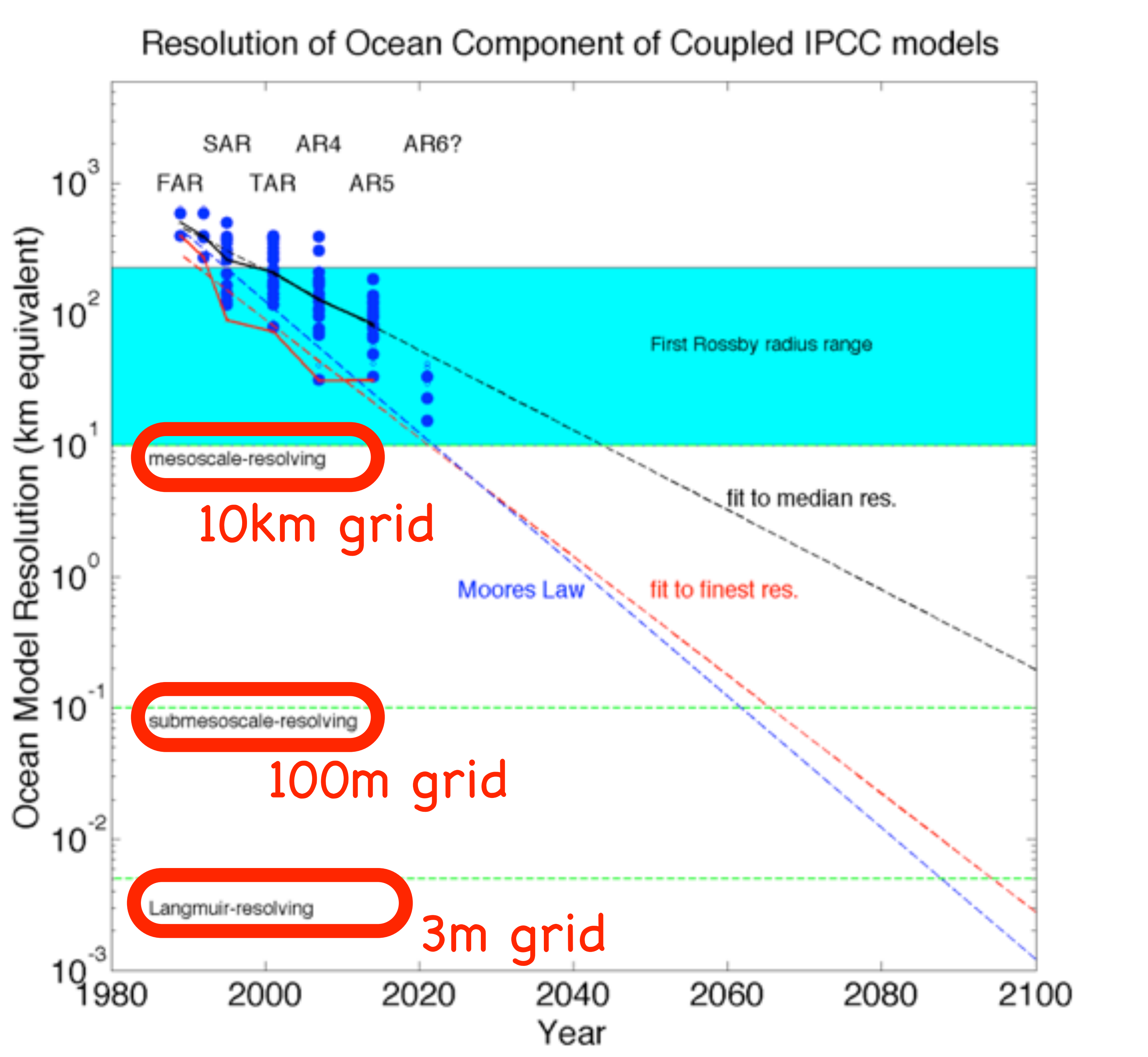

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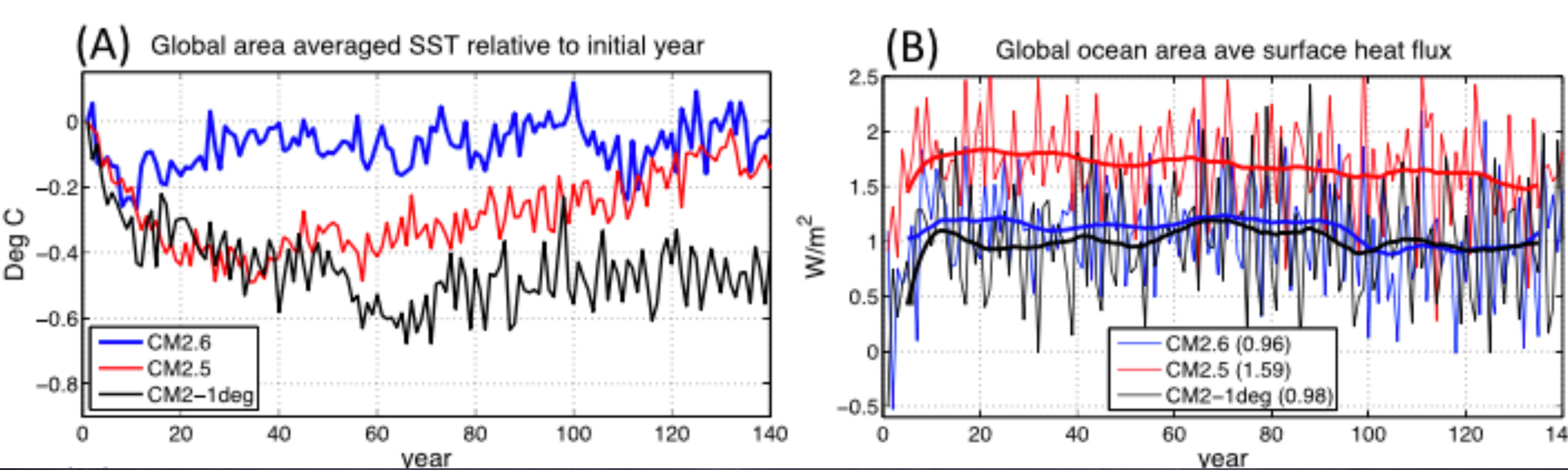
By comparing resolved mesoscale eddies to parameterized ones (with same 50km atmosphere), we get another entry in the pile!

O(0.7 W/m^2) persistent and O(0.4 K/century), i.e., significant warming to upper 1500m of ocean.



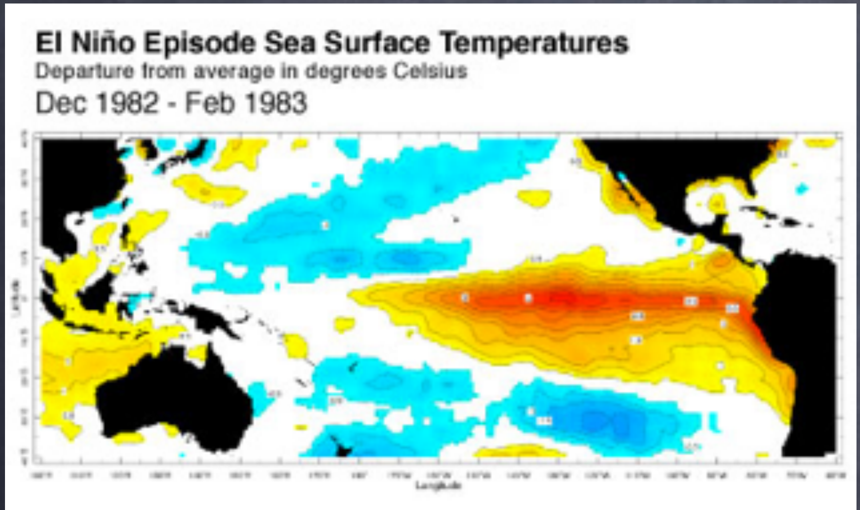
Stephen M. Griffies, Michael Winton, Whit G. Anderson, Rusty Benson, Thomas L. Delworth, Carolina O. Dufour, John P. Dunne, Paul Goddard, Adele K. Morrison, Anthony Rosati, Andrew T. Wittenberg, Jianjun Yin, and Rong Zhang, 2015: Impacts on Ocean Heat from Transient Mesoscale Eddies in a Hierarchy of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

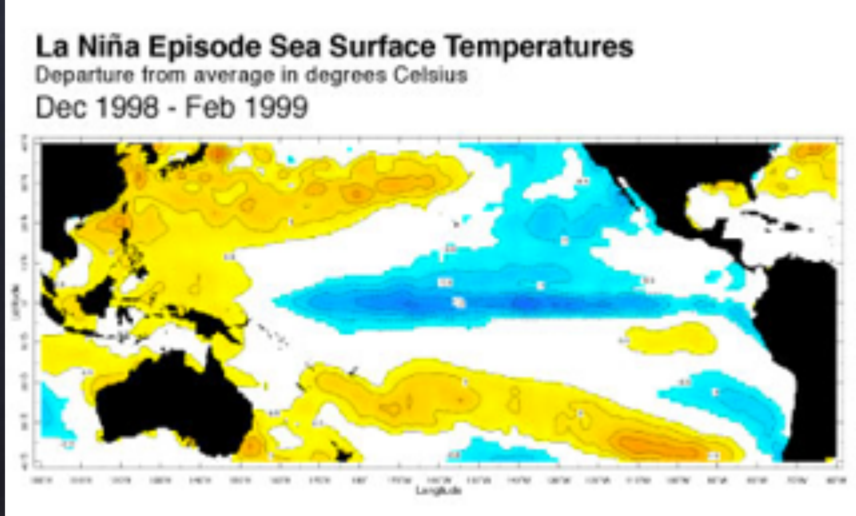
In global models, even with sophisticated parameterizations, numerics, and/or eddy-resolving, the overall heating of the abyss is *tunable* by choice among reasonable parameter values.

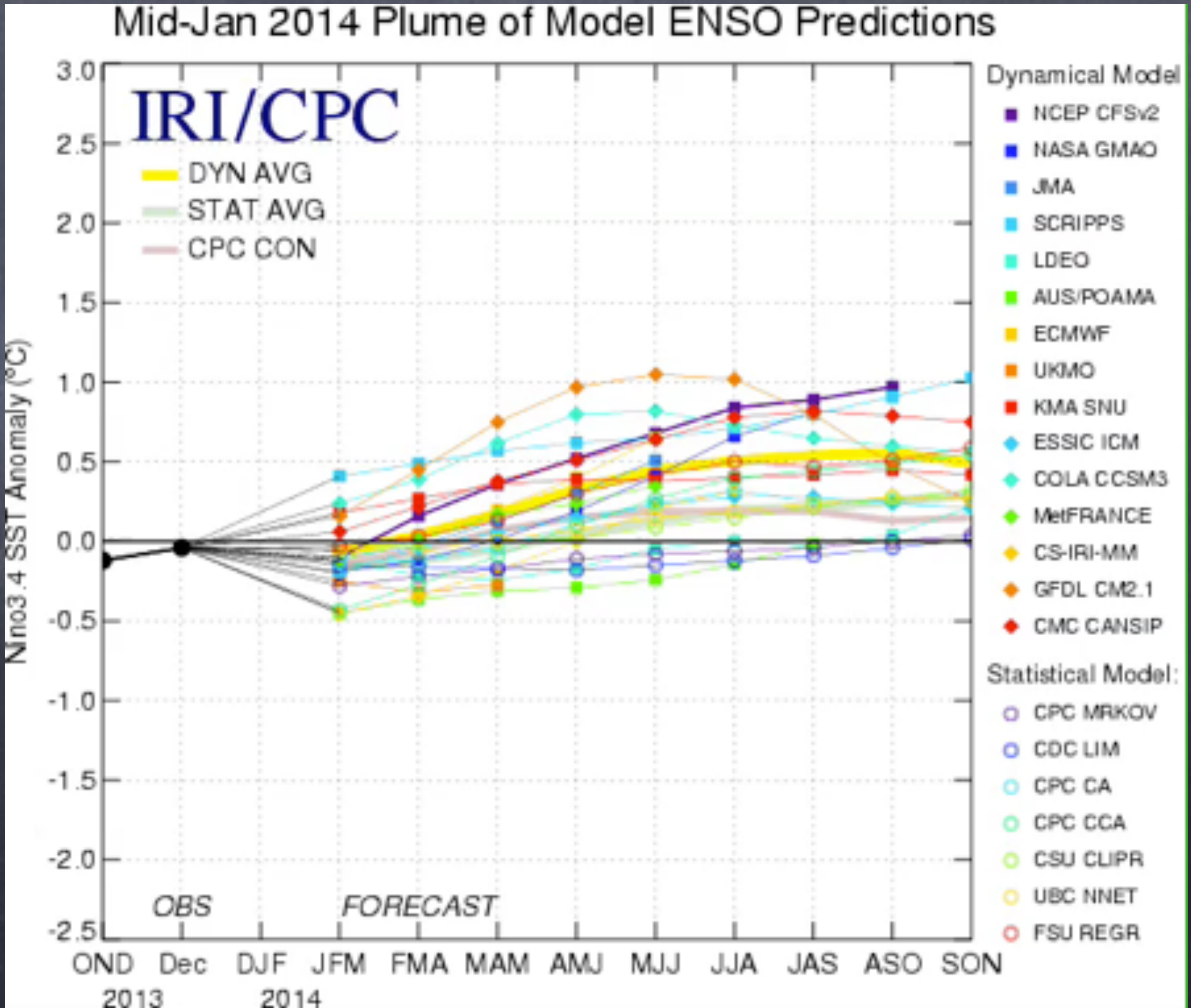
Prediction of variability

Predictability of ENSO events limited to < 1yr

ENSO statistics more predictable?







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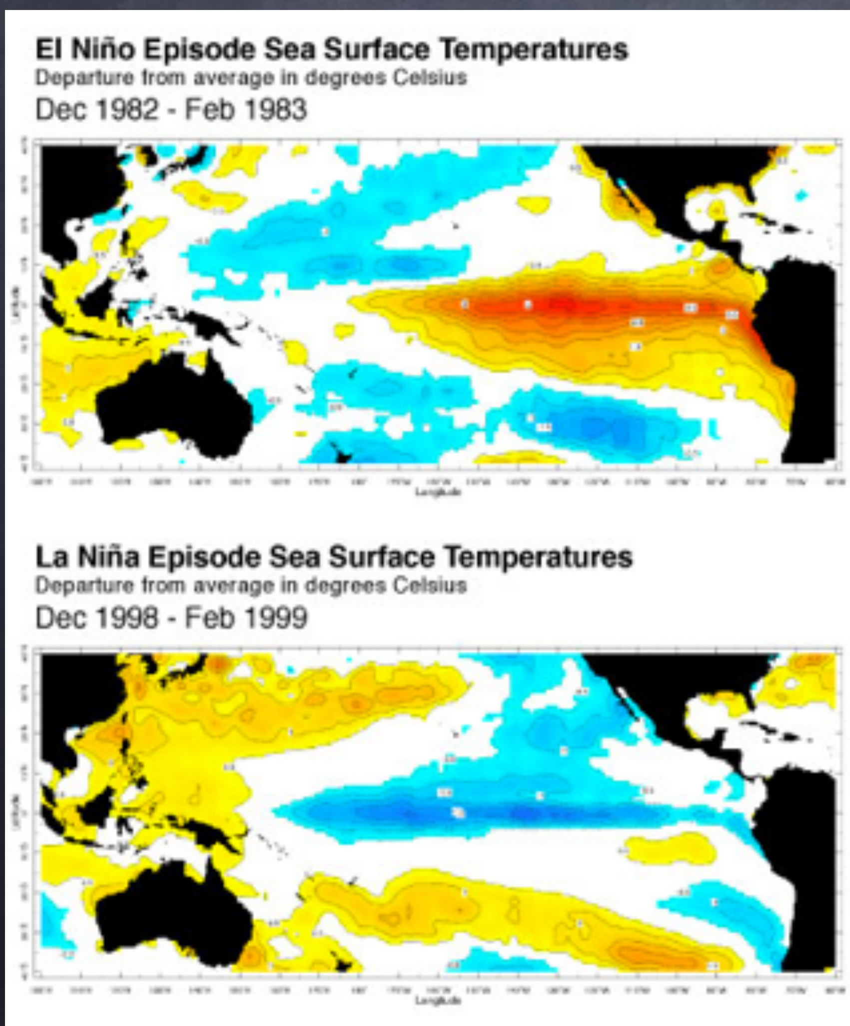
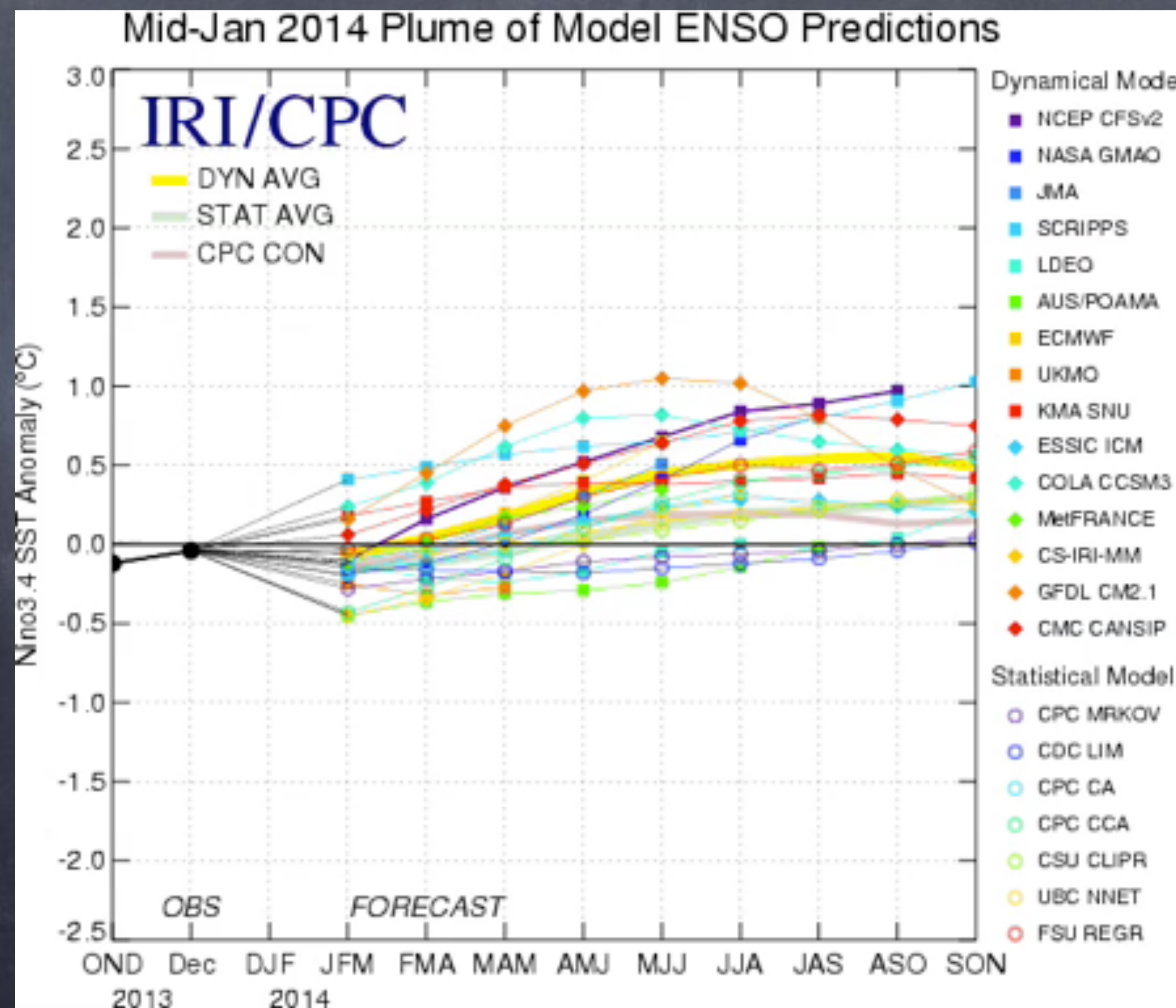
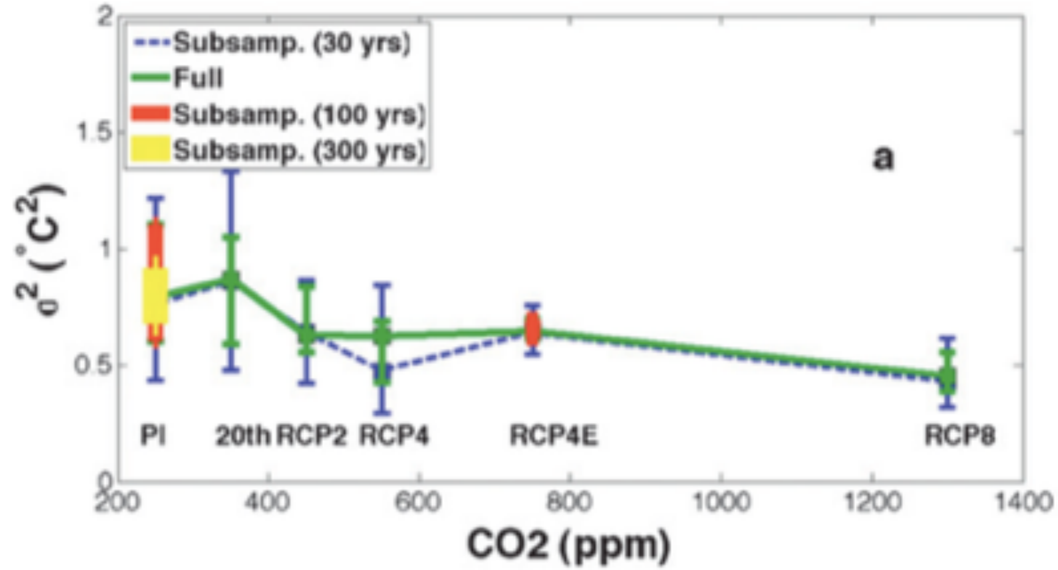






Almost no change to Direct ENSO variability with GHG...

(>200 yr to detect)

Stevenson

Big GHG Change to ENSO impacts!

INDIRECT Proxy Reconstructions won't work!!!

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.

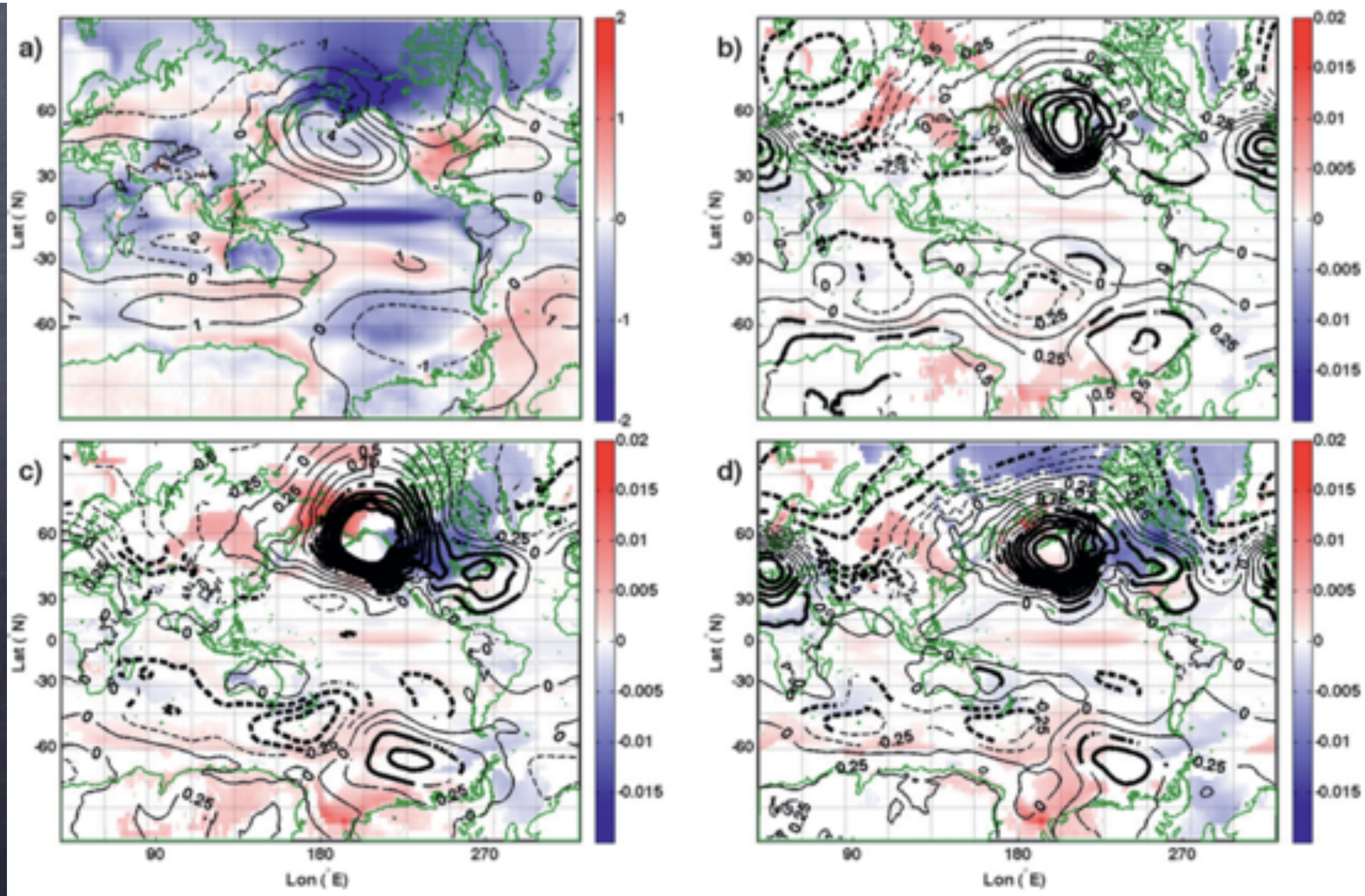
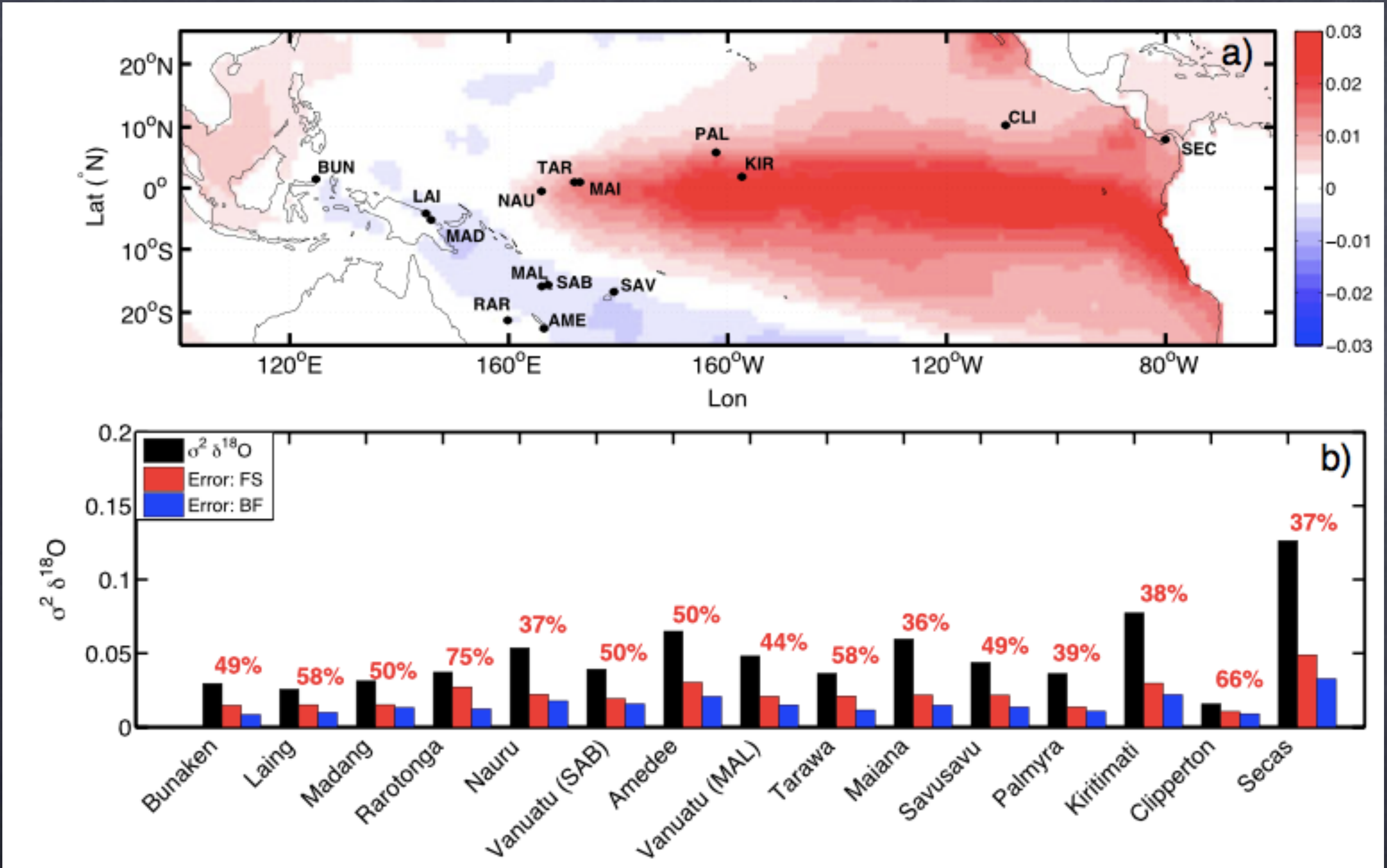


FIG. 6. As in Fig. 5, but for La Niña DJF



CU, now NCAR

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.

- **Understanding** of past variability

New: Abyssal Variability is the HARDEST!

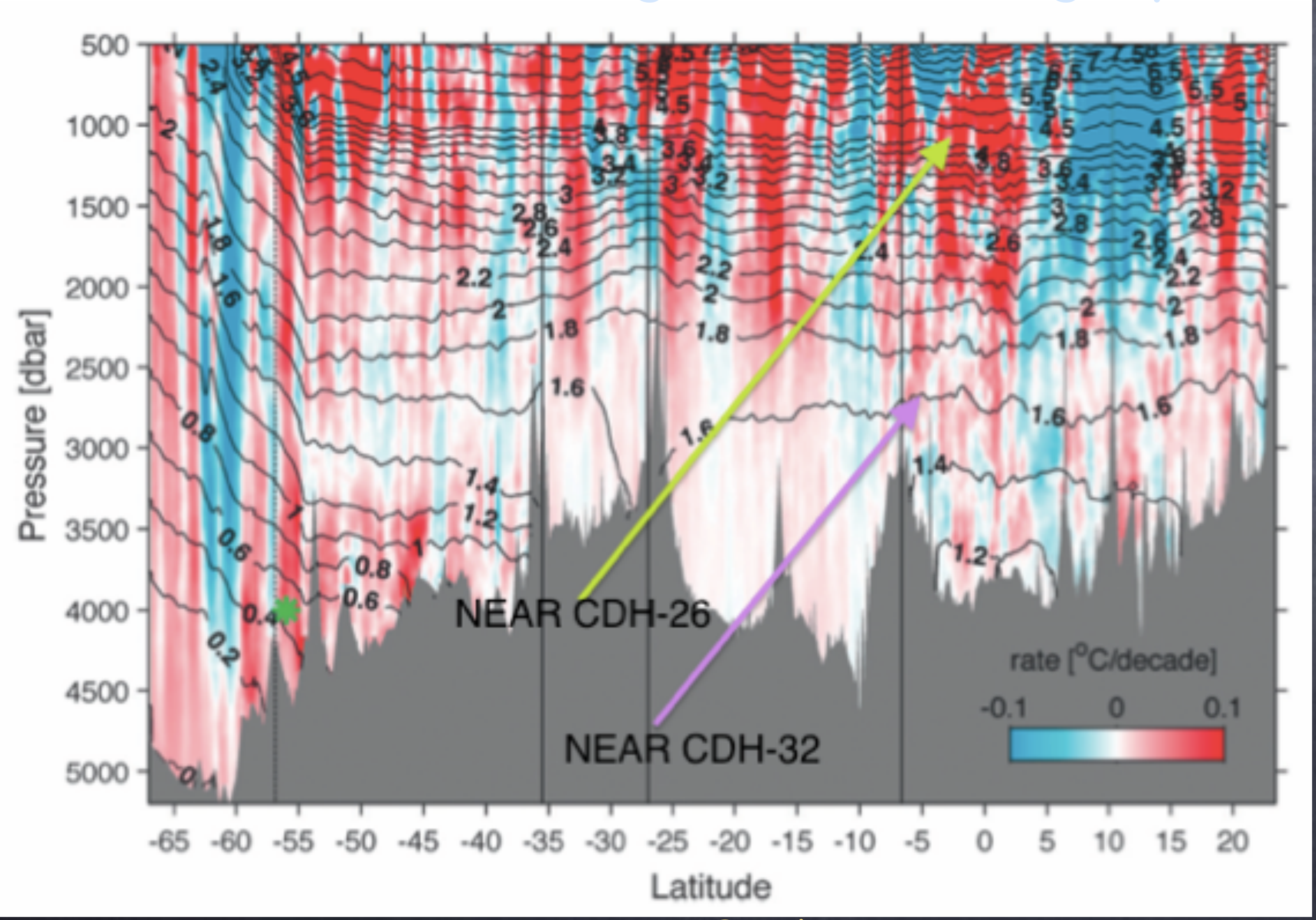
- Stochastic damping very slow!
  - huge heat capacity (biggest watermasses on Earth)!
- Timescales may be very long!
  - Watermasses O(1500yr) old by radiocarbon
- Lengthscales may be very short!
  - (weak stratification implies a Rossby radius of O(2km) for modes trapped in AABW only)
- Water "formed" in very small areas!
  - Small-scale atmospheric & oceanic phenomena will be disproportionately important on air-sea effects

- Difficult to observe, IMPOSSIBLE TO MODEL = FUN!

Understanding of past variability

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

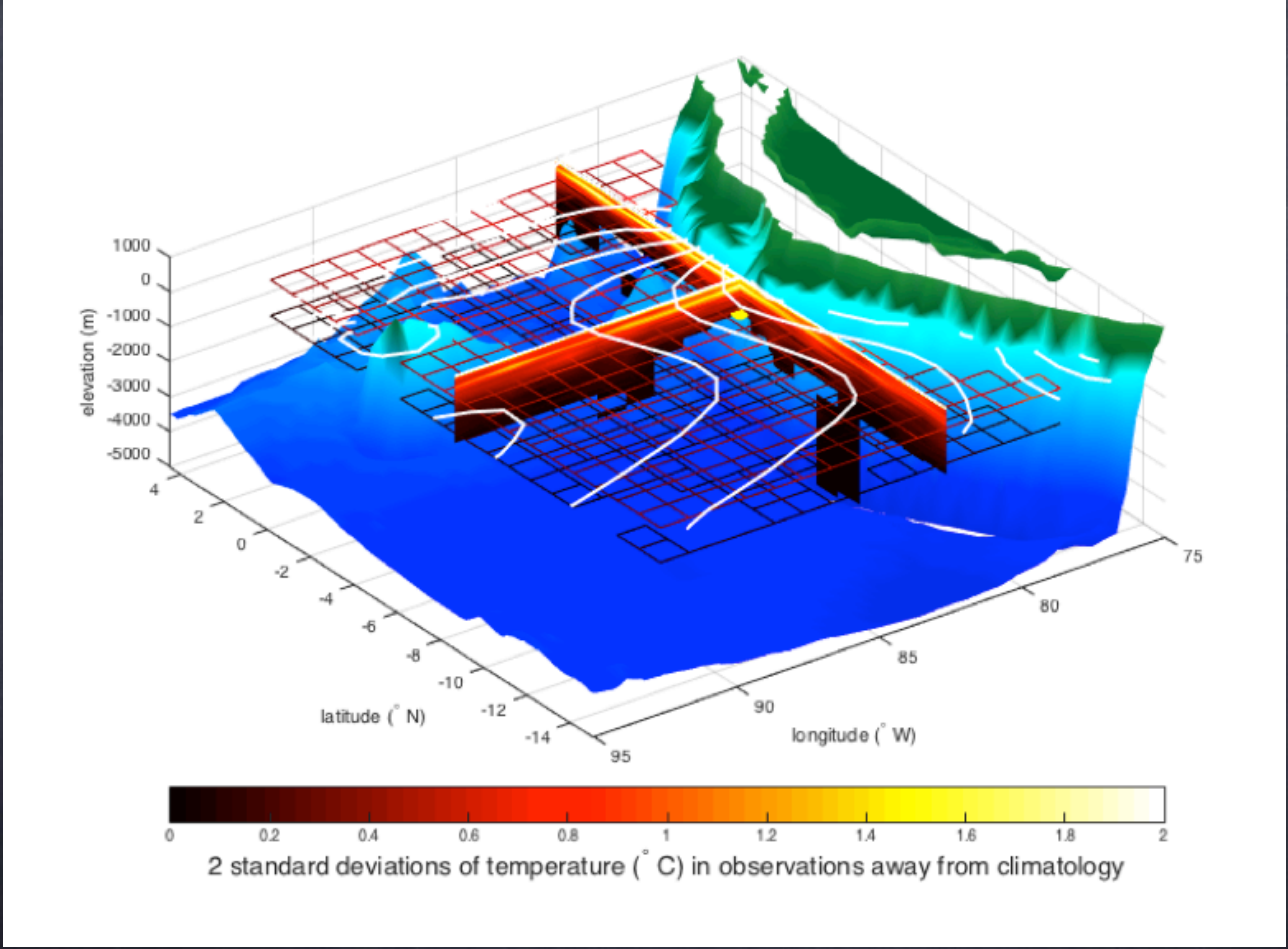
Pattern of Warming from Hydrography



Purkey & Johnson, 2010

Examine CDH-26 sediment core from the Holocene indicated

Brown



S. Bova, T. D. Herbert, and B. Fox-Kemper. Deep ocean variability detected with individual benthic foraminifera. 2016. In preparation.

Understanding of past variability

Assessing variability using individual benthic foraminifera

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

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

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

  Bemis et al. 2002

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

  Conroy et al. 2014

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

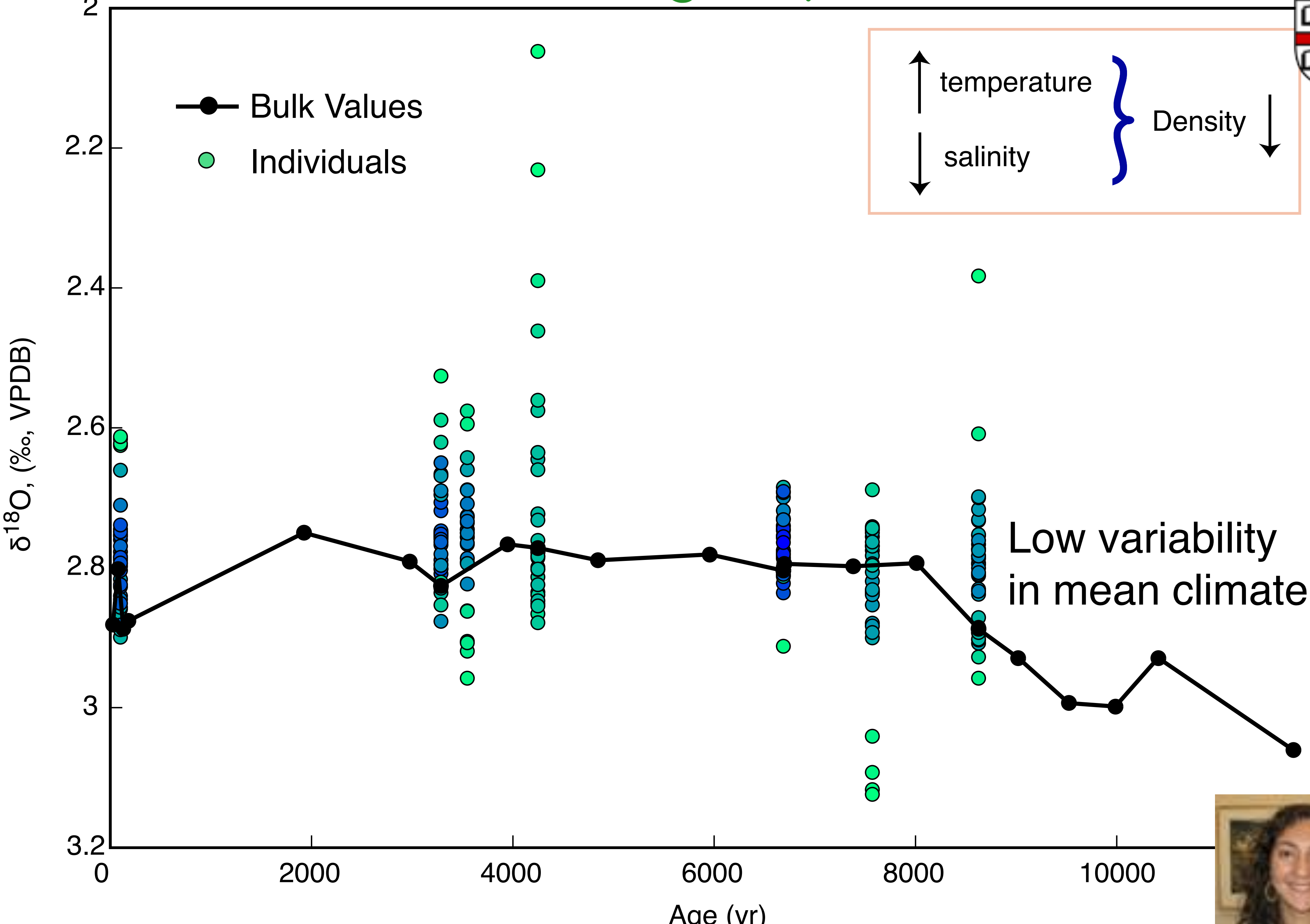
- We analyze 30-40 individuals within 200 year windows to assess the mean and variance of foraminiferal $\delta^{18}O$ values On roughly decadal timescales

Uvigerina spp.

Brown

S. Bova, T. D. Herbert, and B. Fox-Kemper. Deep ocean variability detected with individual benthic foraminifera. 2016. In preparation.

Understanding of past variability



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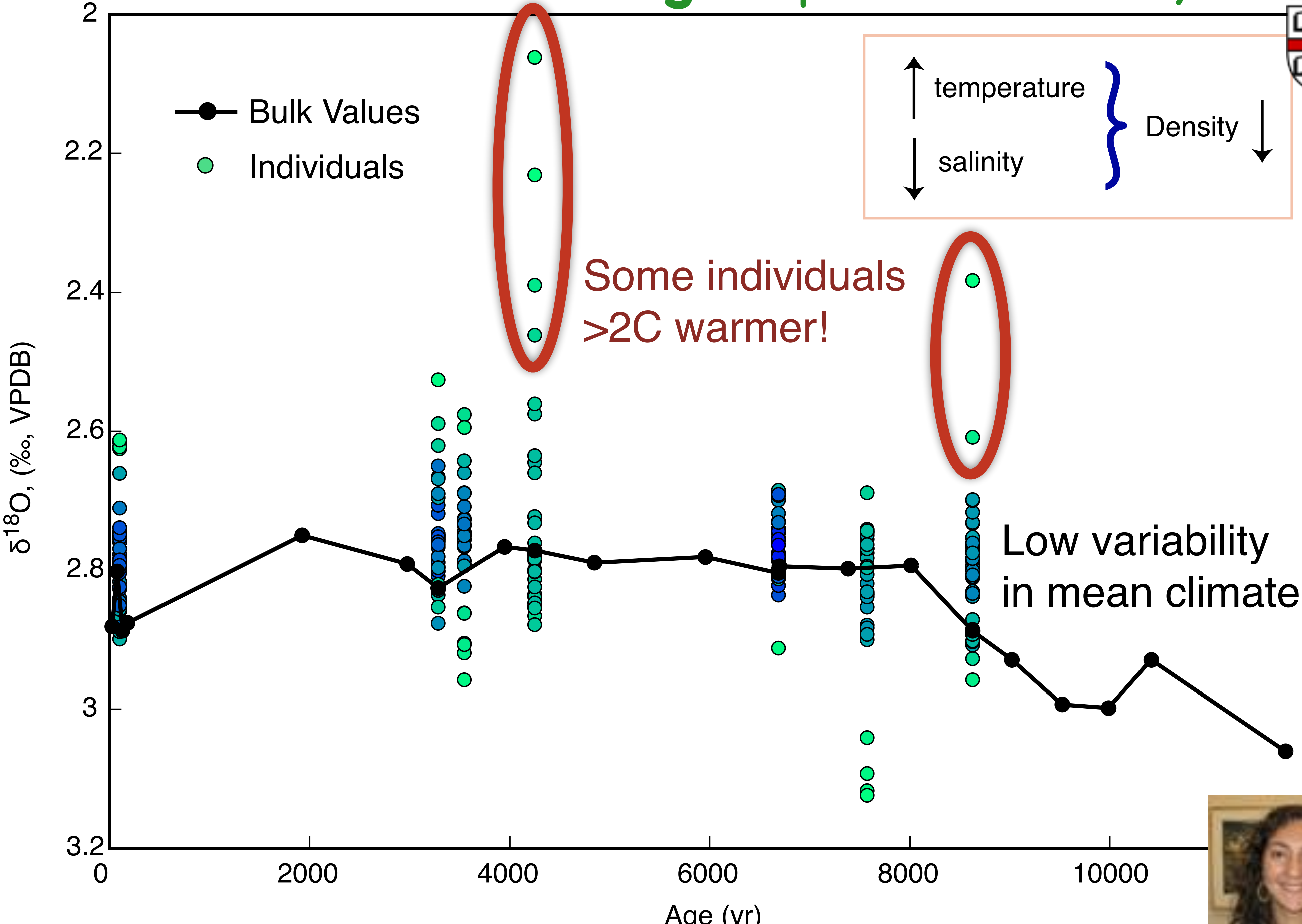
Understanding of past variability



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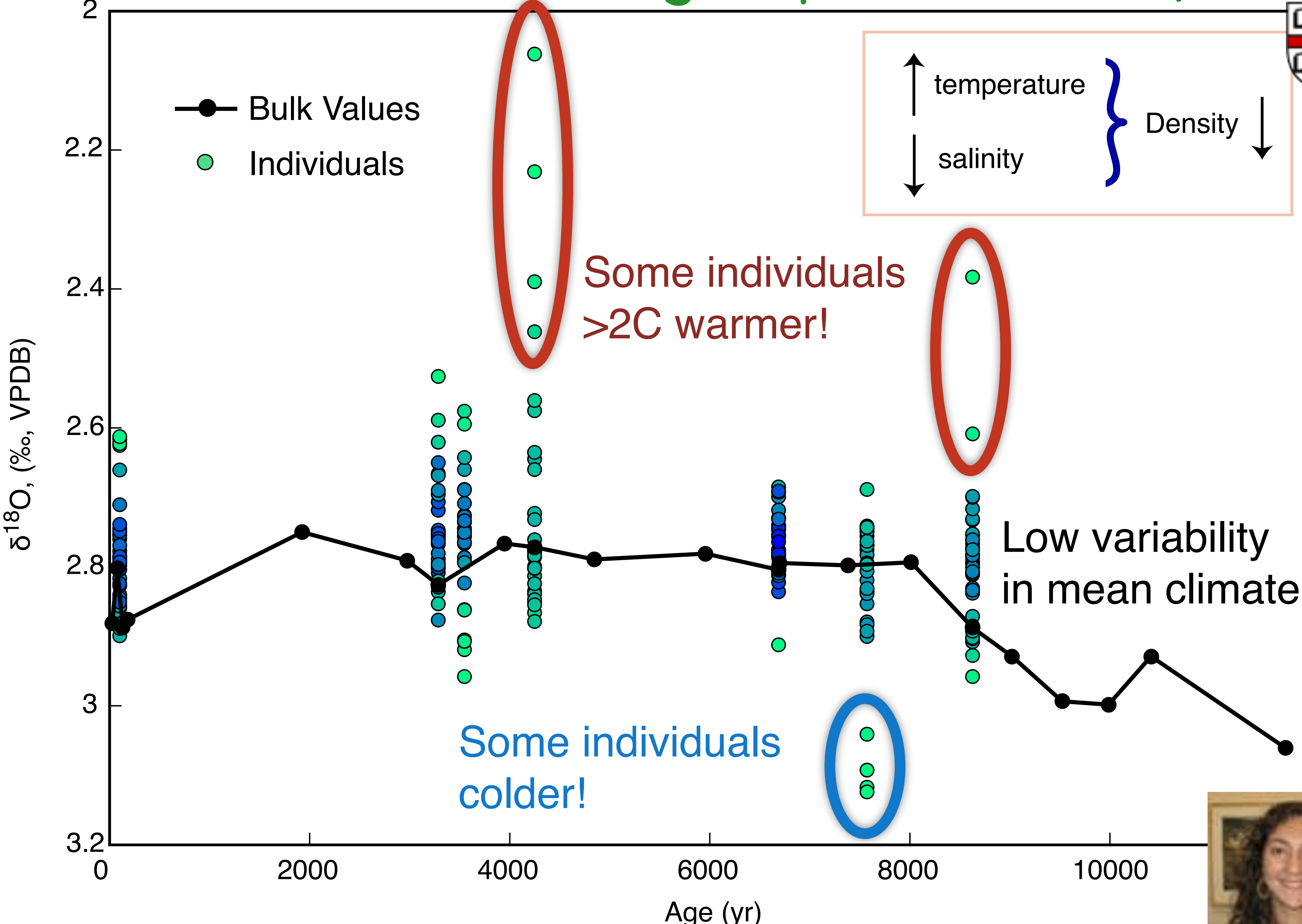
Understanding of past variability



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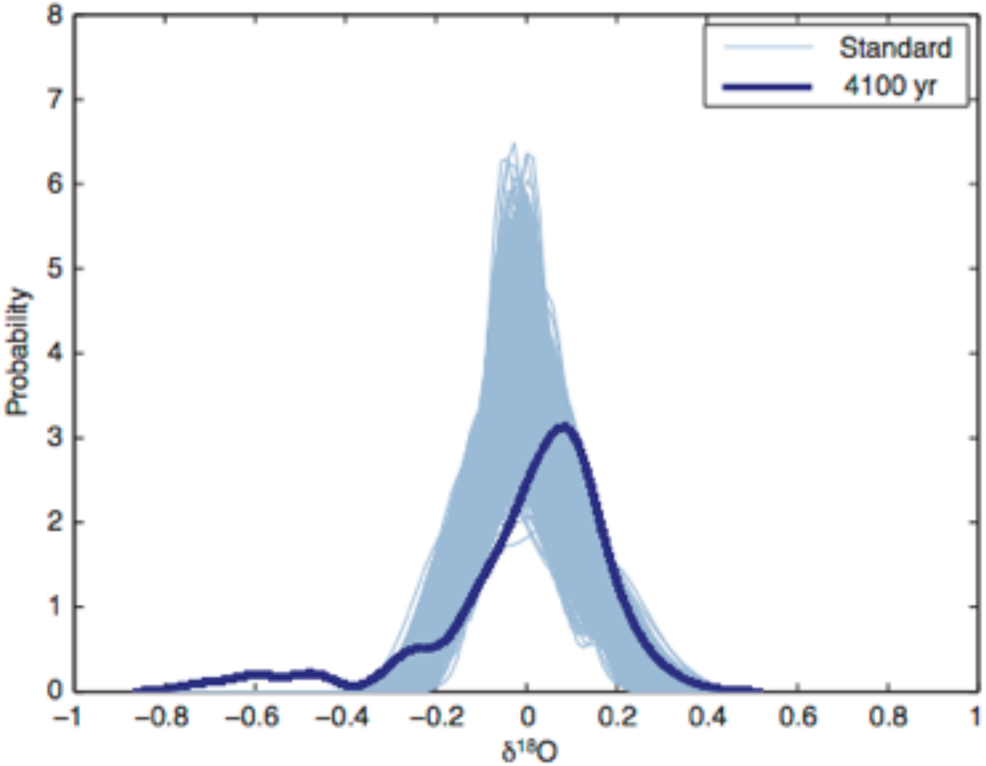
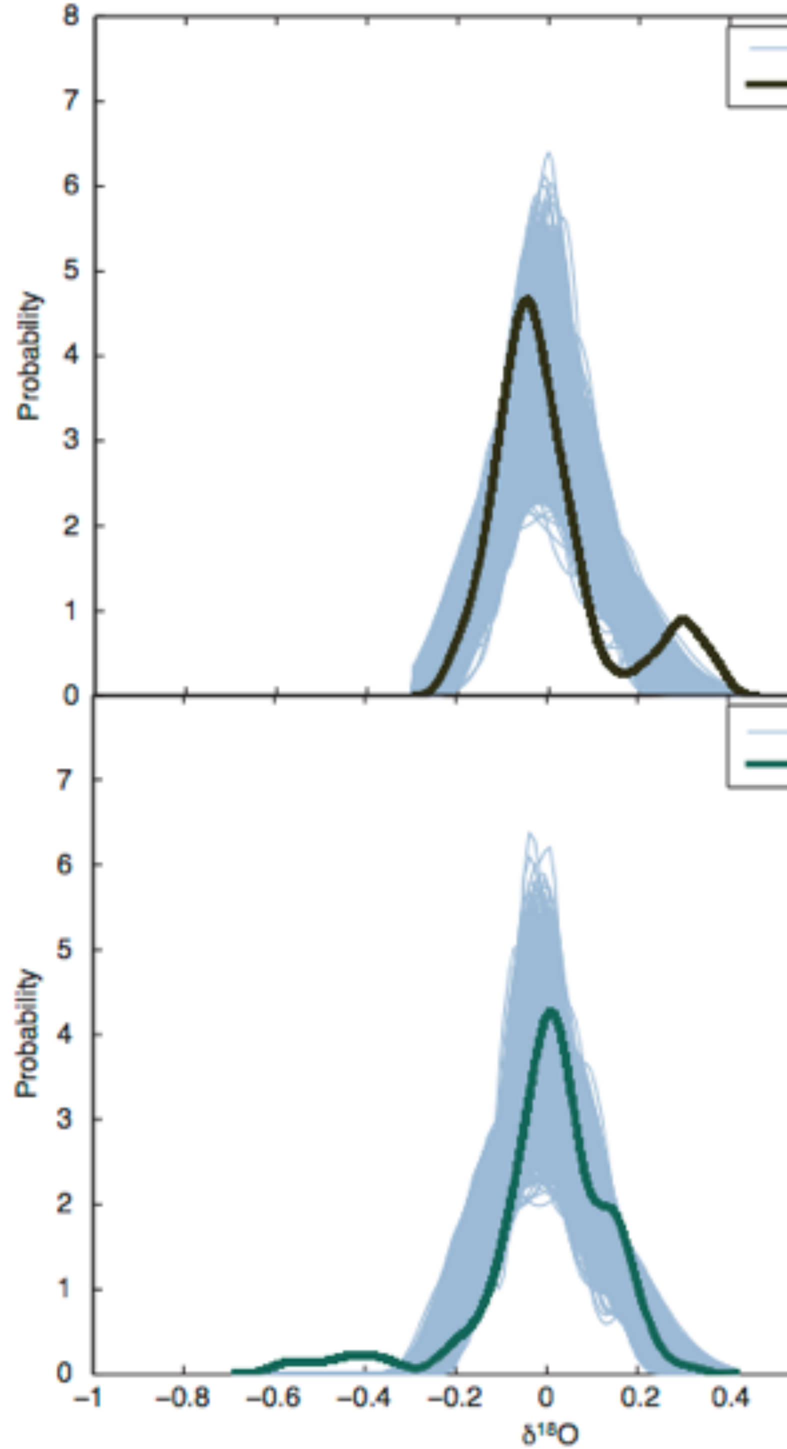
S. Bova, T. D. Herbert, and B. Fox-Kemper. Deep ocean variability detected with individual benthic foraminifera. 2016. In preparation.

p<0.01



p<0.10



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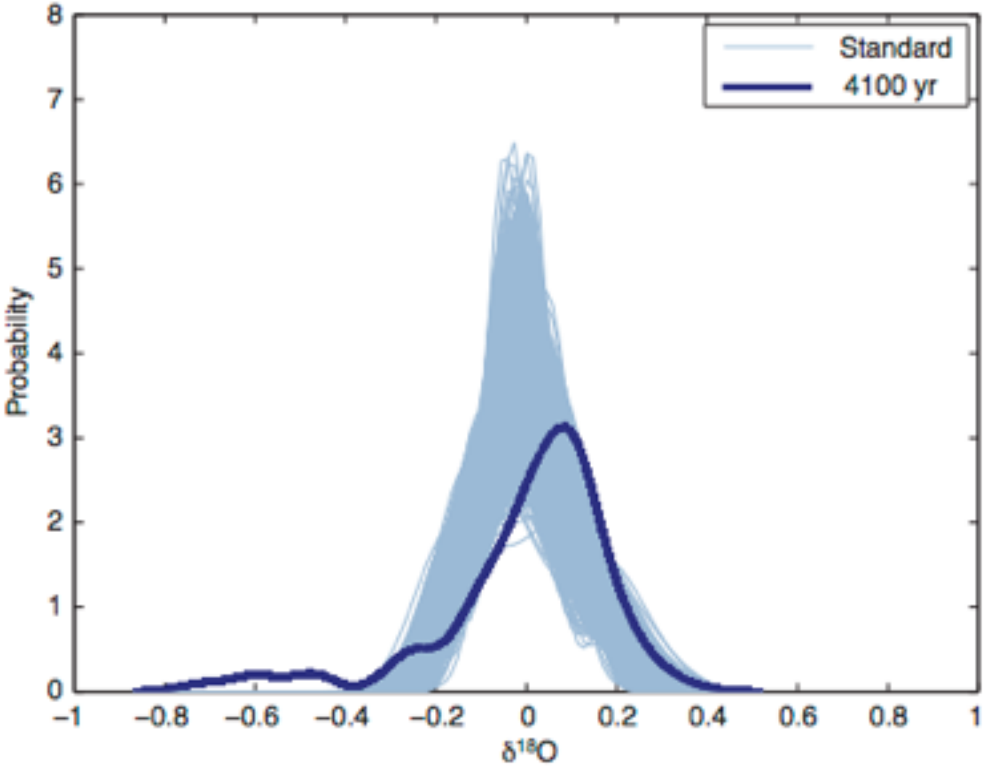
p<0.01



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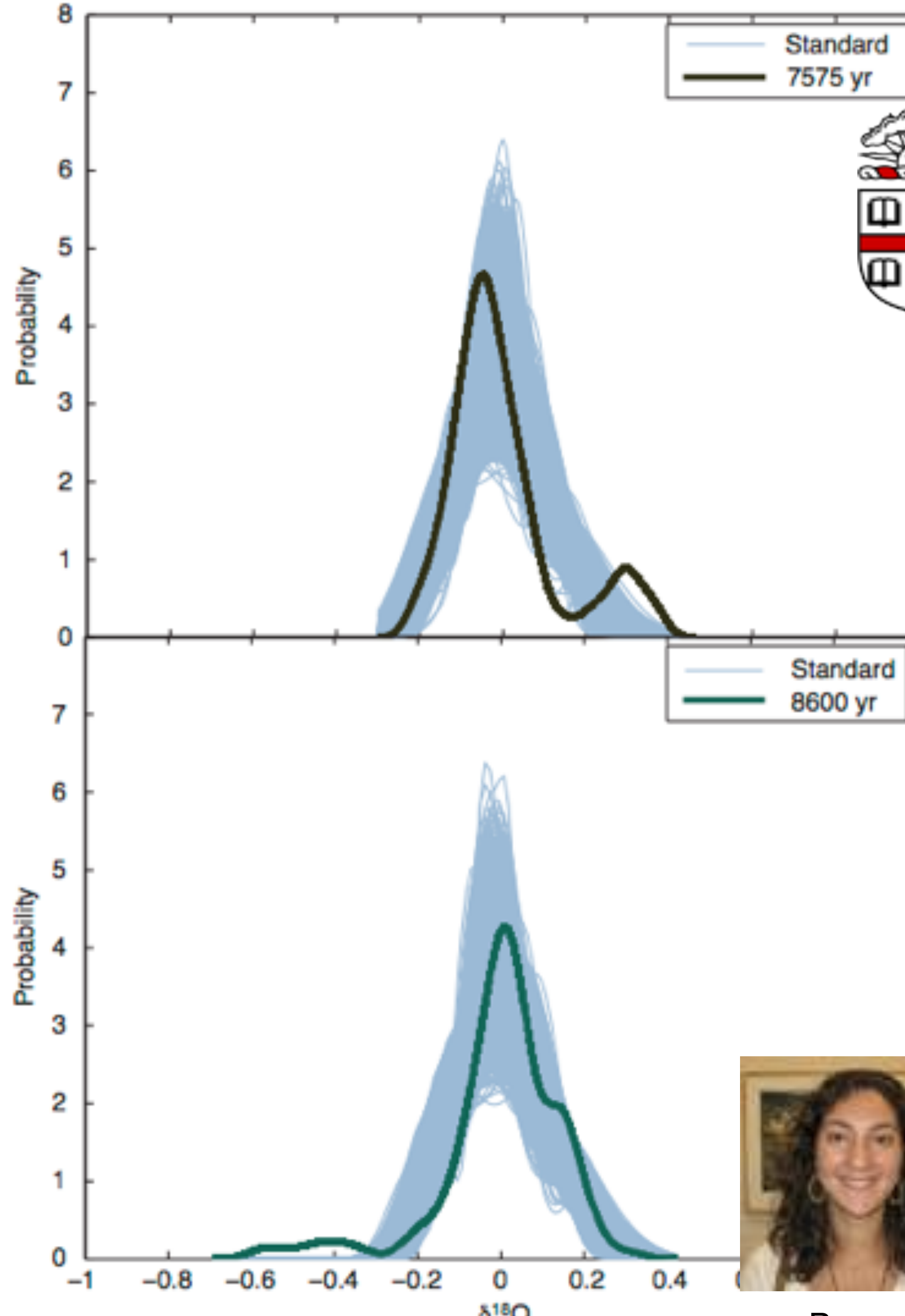


At these three time intervals, the spread of individual values exceeds a size-matched spread of instrumental standards.

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

If this is right—abyssal variability may have an **unexpectedly important role, intermittently** through the past!

Brown

Some timescales from theory—What is this variability?

- Advective timescale—``water age", estimated by Gebbie & Huybers from tracers.
- Baroclinic waves
  - https://www.youtube.com/watch?v=oljinlD2yho
  - Baroclinic Kelvin & Rossby

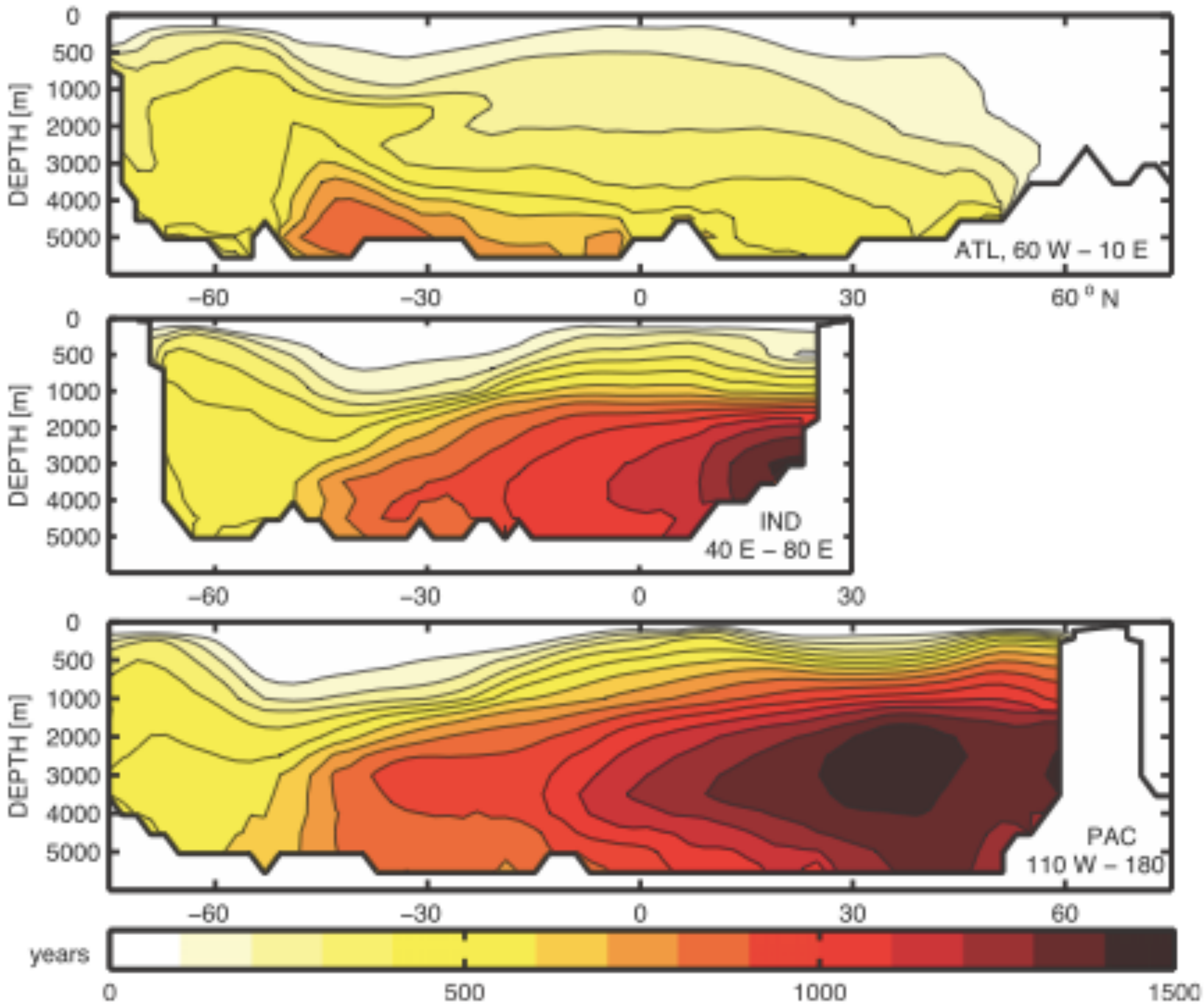


FIG. 8. Latitude–depth sections of mean age: (top) the Atlantic averaged between 60°W and 10°E, (middle) the Indian Ocean between 40° and 80°E, and (bottom) the Pacific between the date line and 110°W. The contour interval is 100 years in all panels.

Advective Timescale

500-1500 yr below 2000m

too slow for global warming

The Mean Age of Ocean Waters Inferred from Radiocarbon Observations: Sensitivity to Surface Sources and Accounting for Mixing Histories

GEOFFREY GEBBIE

Department of Physical Oceanography, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts

PETER HUYBERS

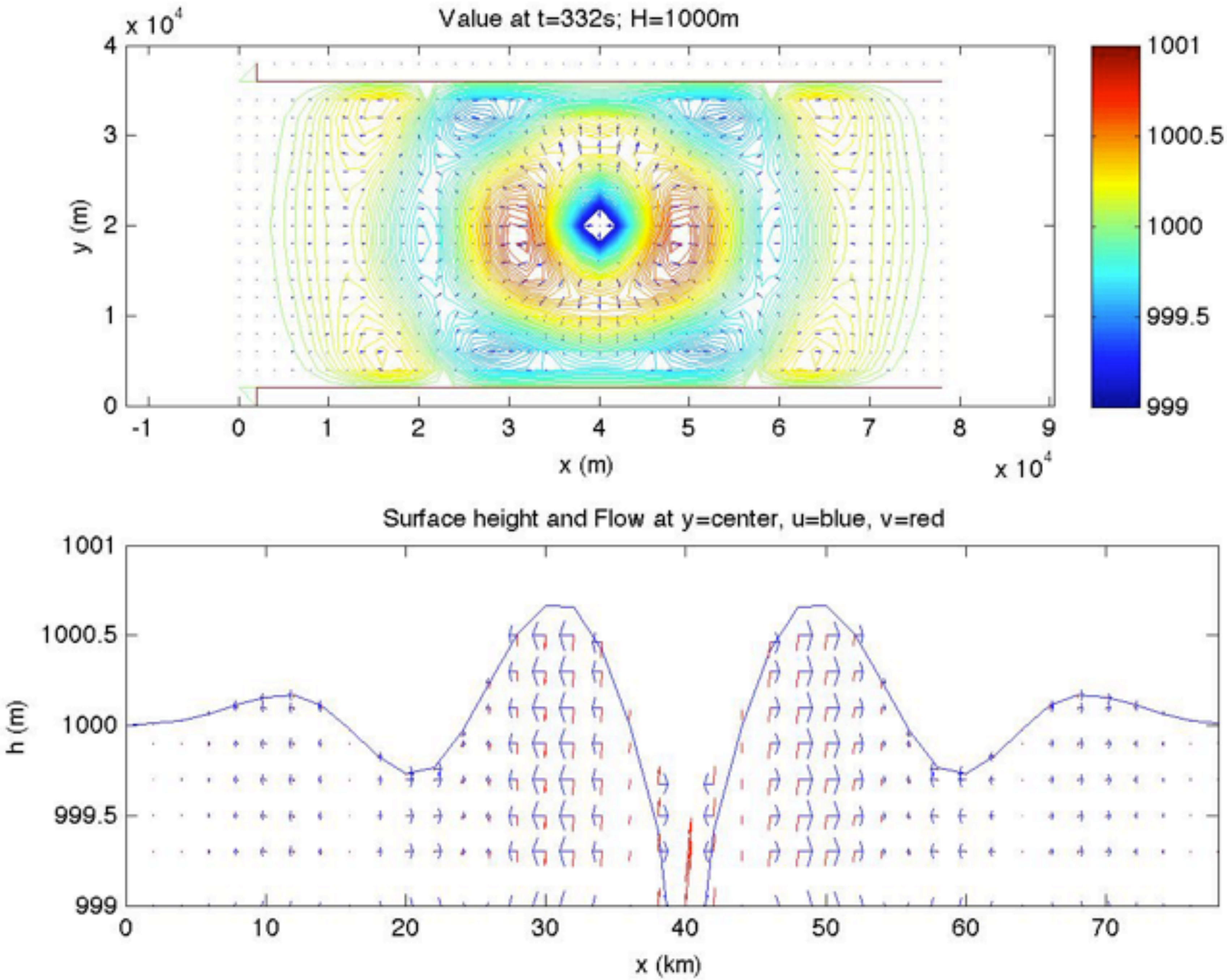
Harvard University, Cambridge, Massachusetts

Simpler: Reduced Gravity

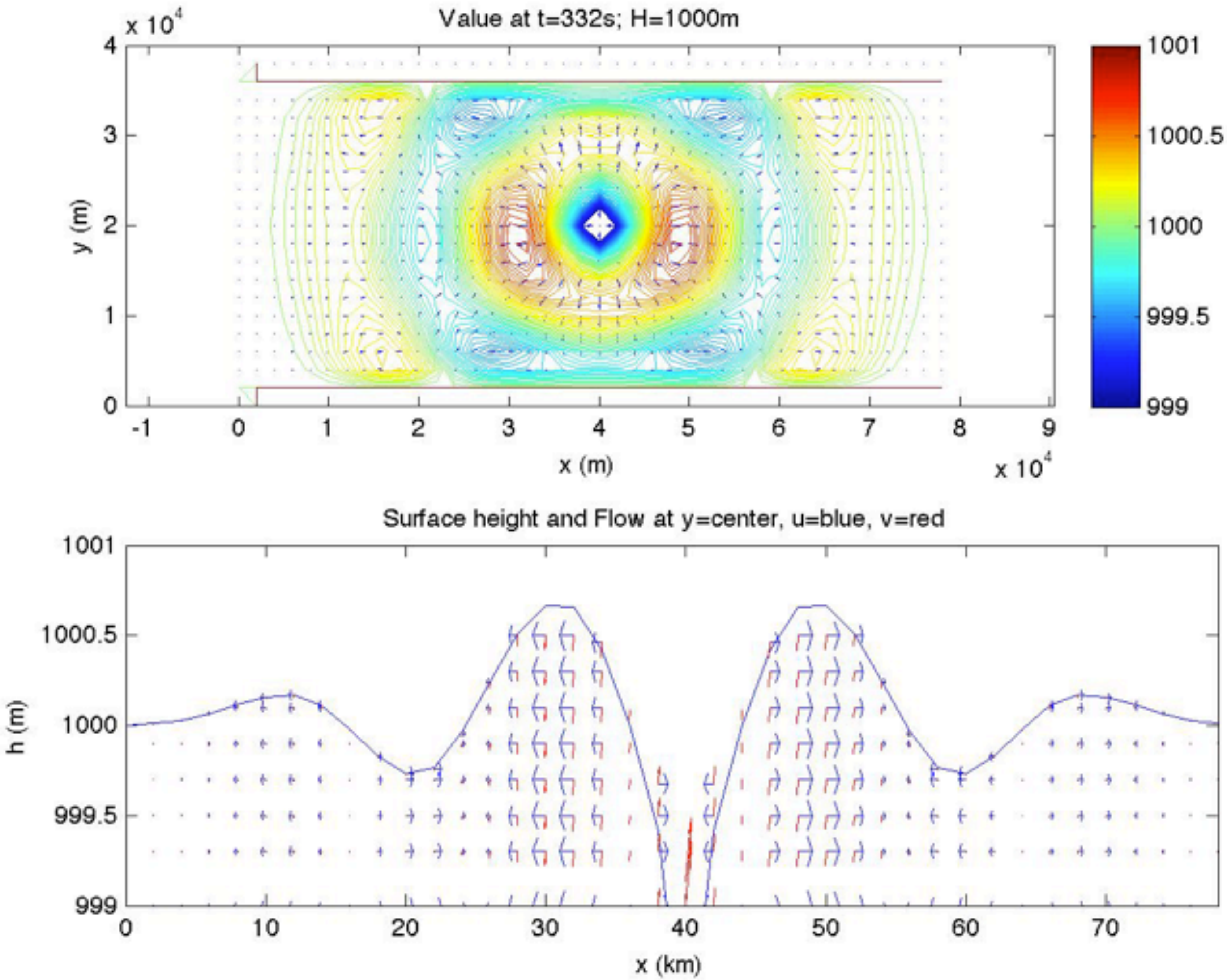
- If motions are coherent only below a given level -h, and zero above this level, then bottom layer dynamics are just the shallow water equations with g′ as g.
- g′=g (ratio of density difference to total density)
- For AABW vs overlying water—potential density ratio is about 0.02%. Layer is roughly 2km thick.
- Internal gravity wave speed is $c^2=g'(H-h)=(2\ m/s)^2$
- 4 months to traverse the Pacific N-S.

But, PV not affected by gravity waves—circulation will not adjust this fast

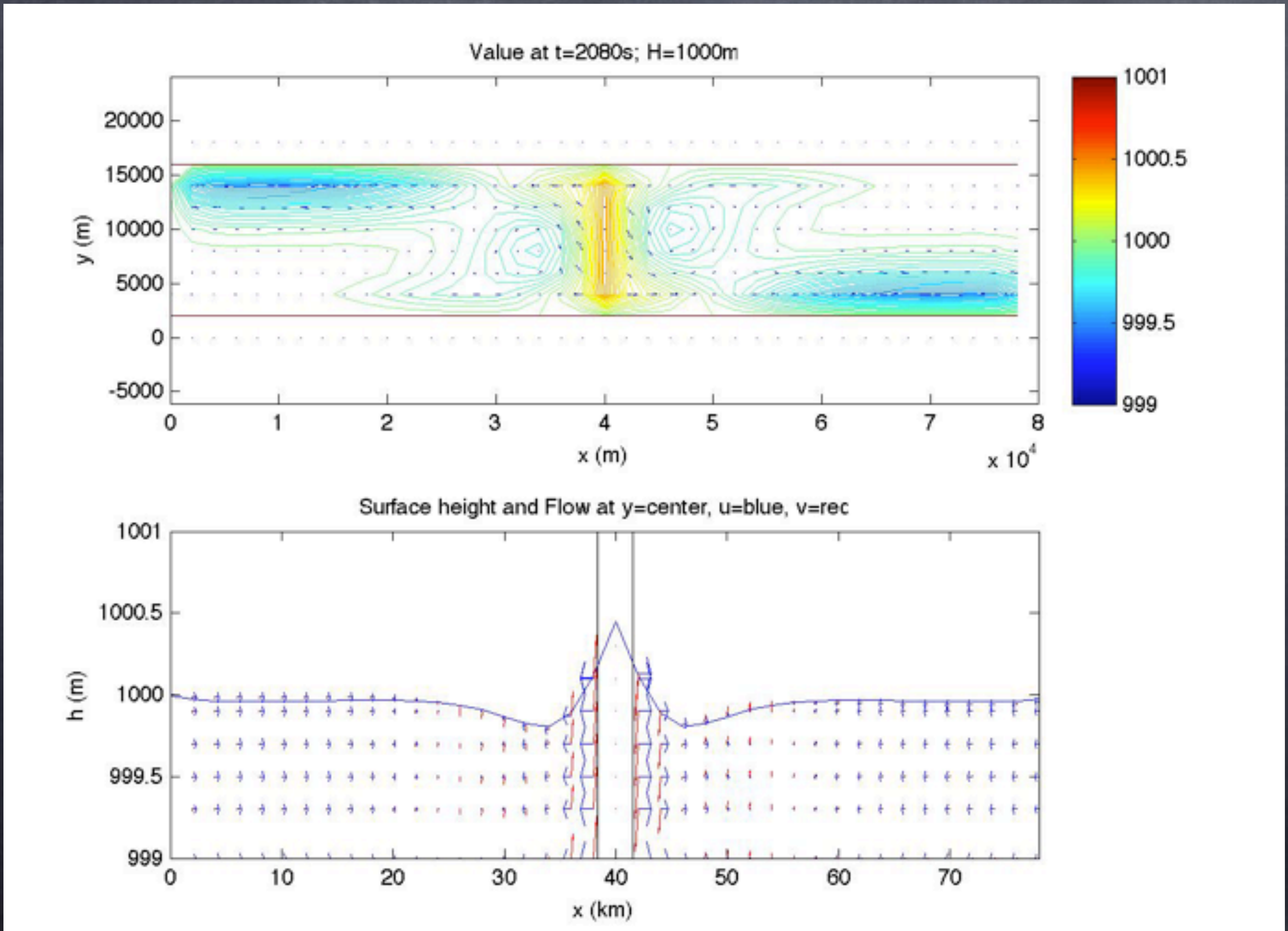
A plunger in a nonrotating channel



A plunger in a nonrotating channel



A plunger in a rotating channel drives a different wave



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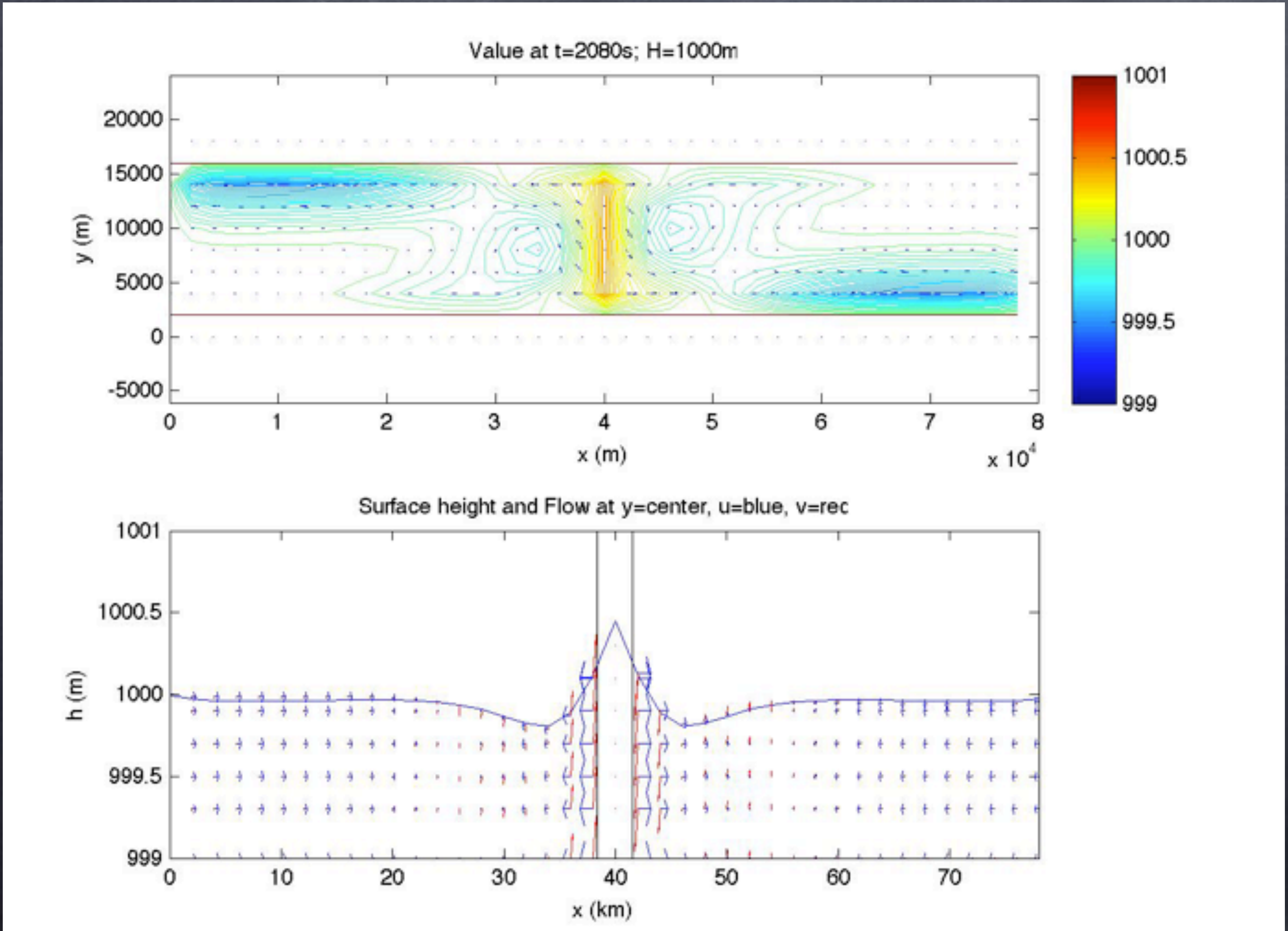
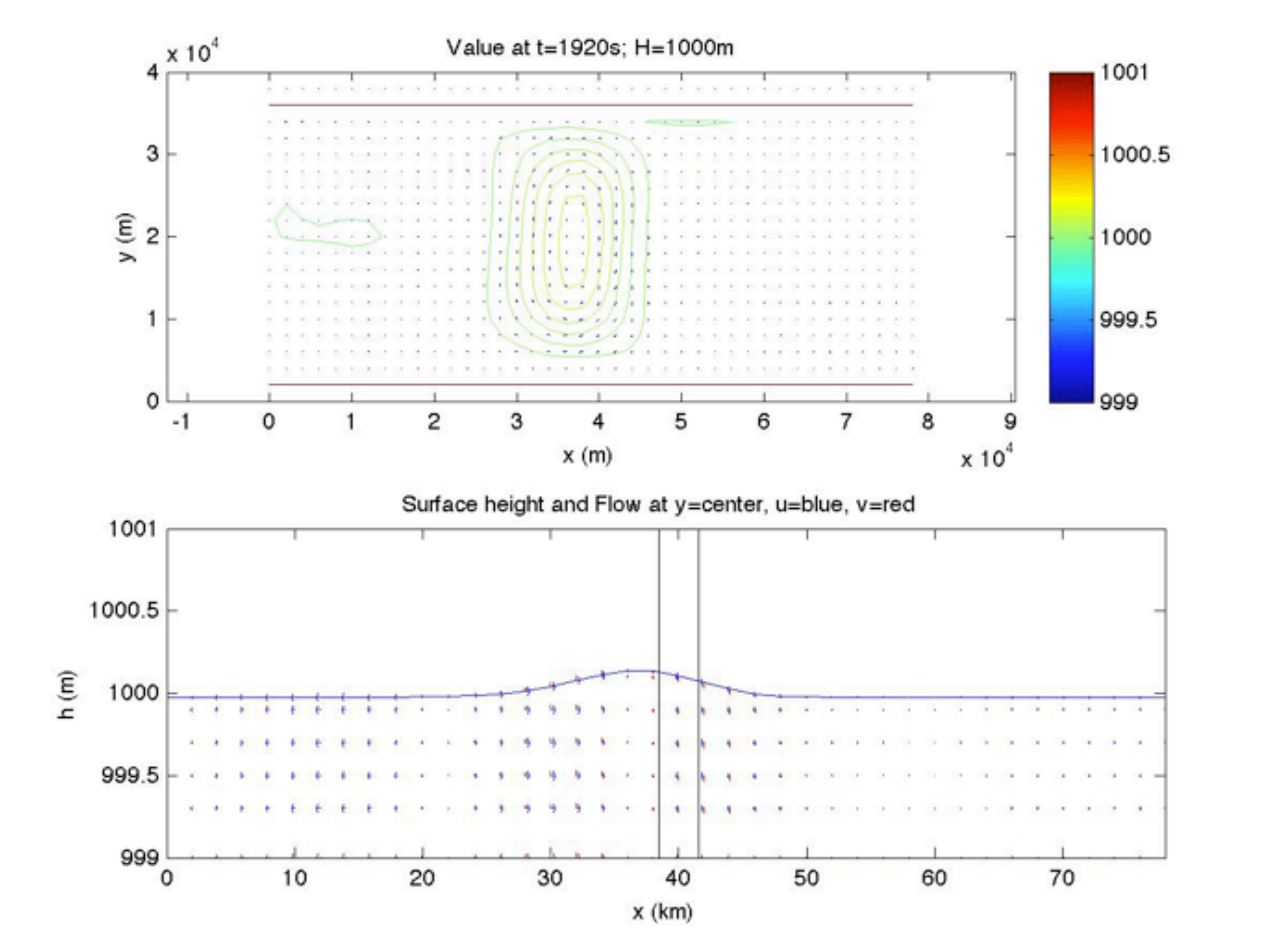


A blob of water in a beta-plane rotating channel leaves a rotating high--slow westward propagation



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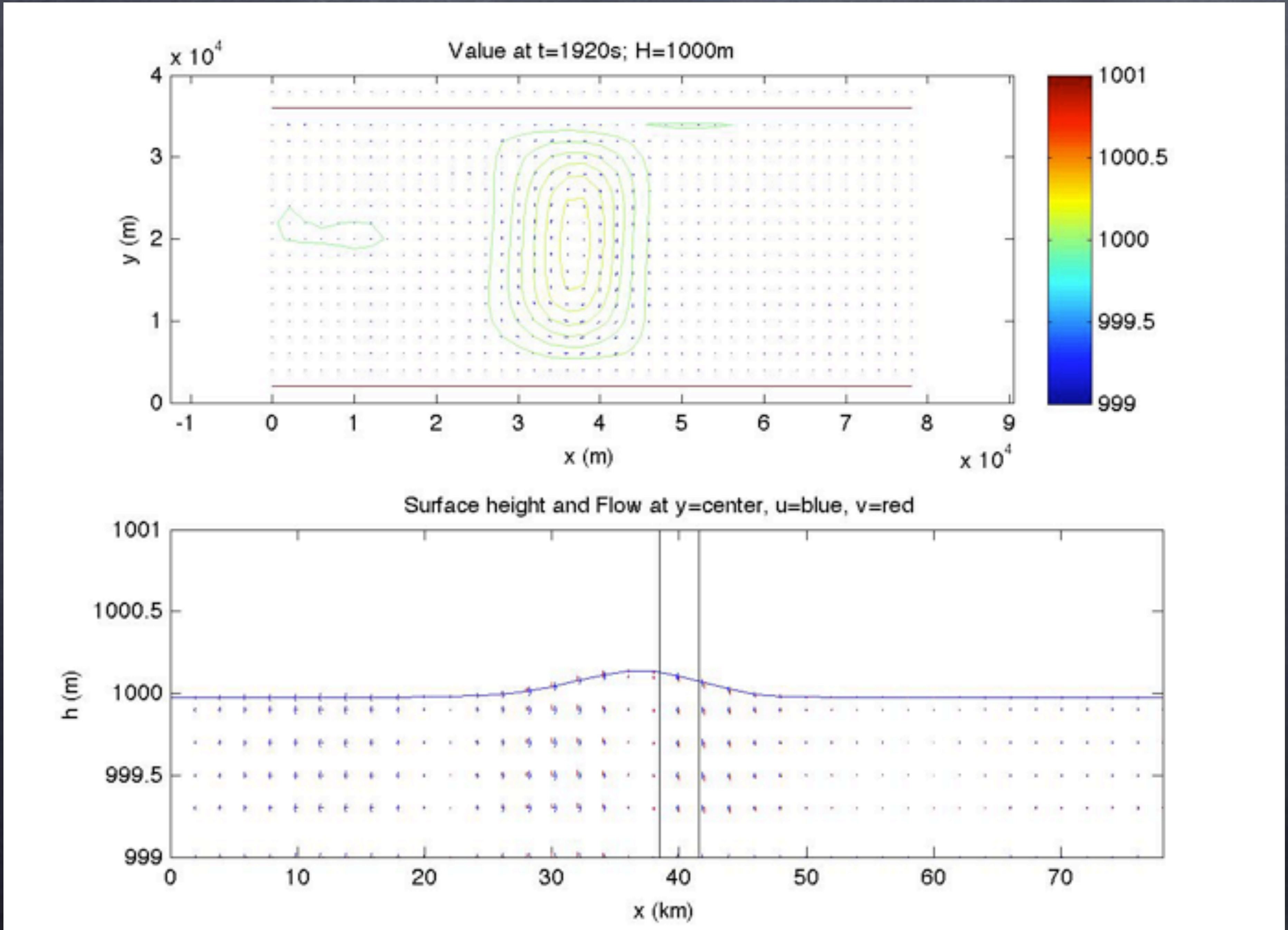


Kelvin & Rossby Waves

- Kelvin have same speed as gravity waves, but trapped against coastlines. Kelvin waves speed along the coastlines (<1 yr), and generate Rossby waves to adjust the basin interior. Based on the reduced gravity estimate, it will take at least 25 years.

- The low stratification of the abyssal water gives only a 20km Rossby radius, so speed is slow and waves are hard to resolve in numerical models.

$$T = \frac{L_B}{\beta L_D^2} \approx \frac{L_B |f|^2}{\beta g'(H-h)} \approx 25\text{yr}$$

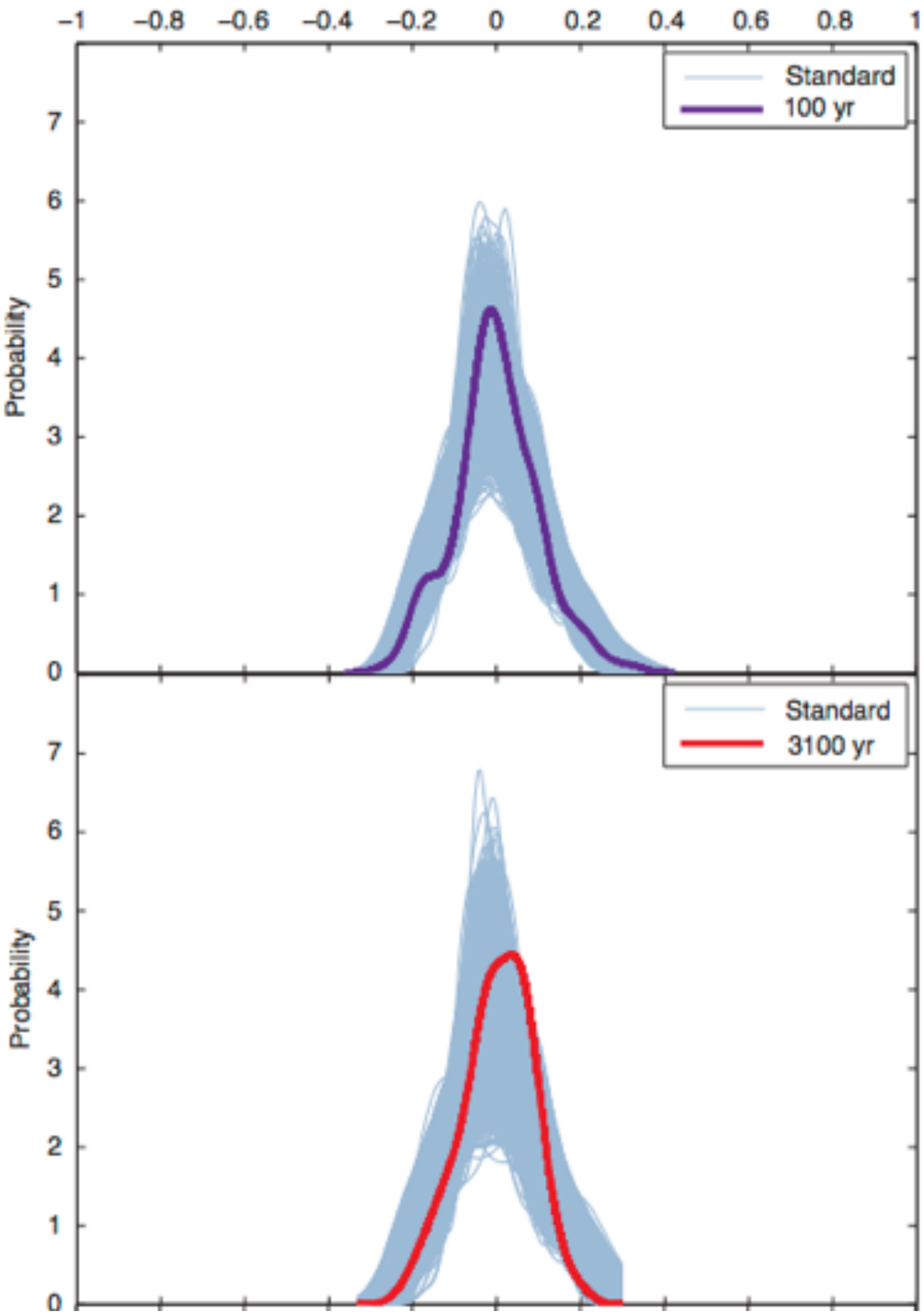
Converging over Bottom Topography & Downward Control

- Estimates were for flat bottom oceans, horizontally constant stratification, and non-equatorial rotation.
- As there is probably much more variability in the near surface, it is possible that including these effects will make the continuation of upper ocean variability create significant near bottom variability
- However, as the movies only depict heat content (and not PV), more to do to see exactly how this works and quantitatively estimate.

Conclusions

- **Presence** of observable variability
  - Regional O(100 W/m^2), Global Net O(1 W/m^2)
  - Difficult due to sampling, obs. density & duration
  - Many problems require paleothermometry!
- **Understanding** of past variability
  - Not always a path to progress w/o models & predictions
  - But, discovery of new processes & unexpected variability is a way forward to better predictions!
- **Modeling** of variability
  - Stochastic models work-but not very predictive.
  - Deterministic models: discrepancies in tuning, params, resolution.
  - Fun to work on parameterizations & process understanding, though!
- **Prediction** of variability
  - Possible in some regions, chaos limits the forecast window.
  - Accurate global budgets need process-level understanding and modeling.

Null Results



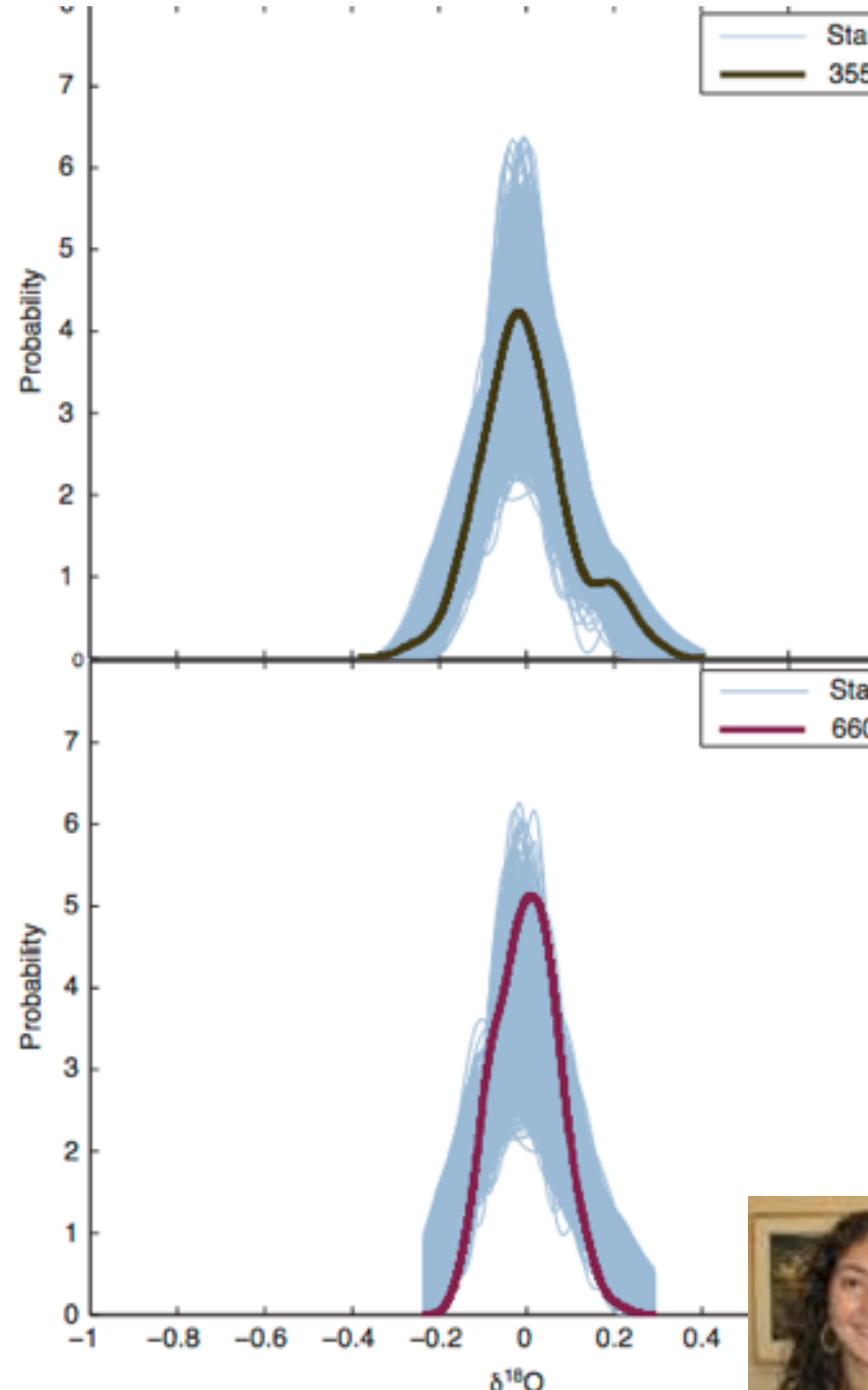
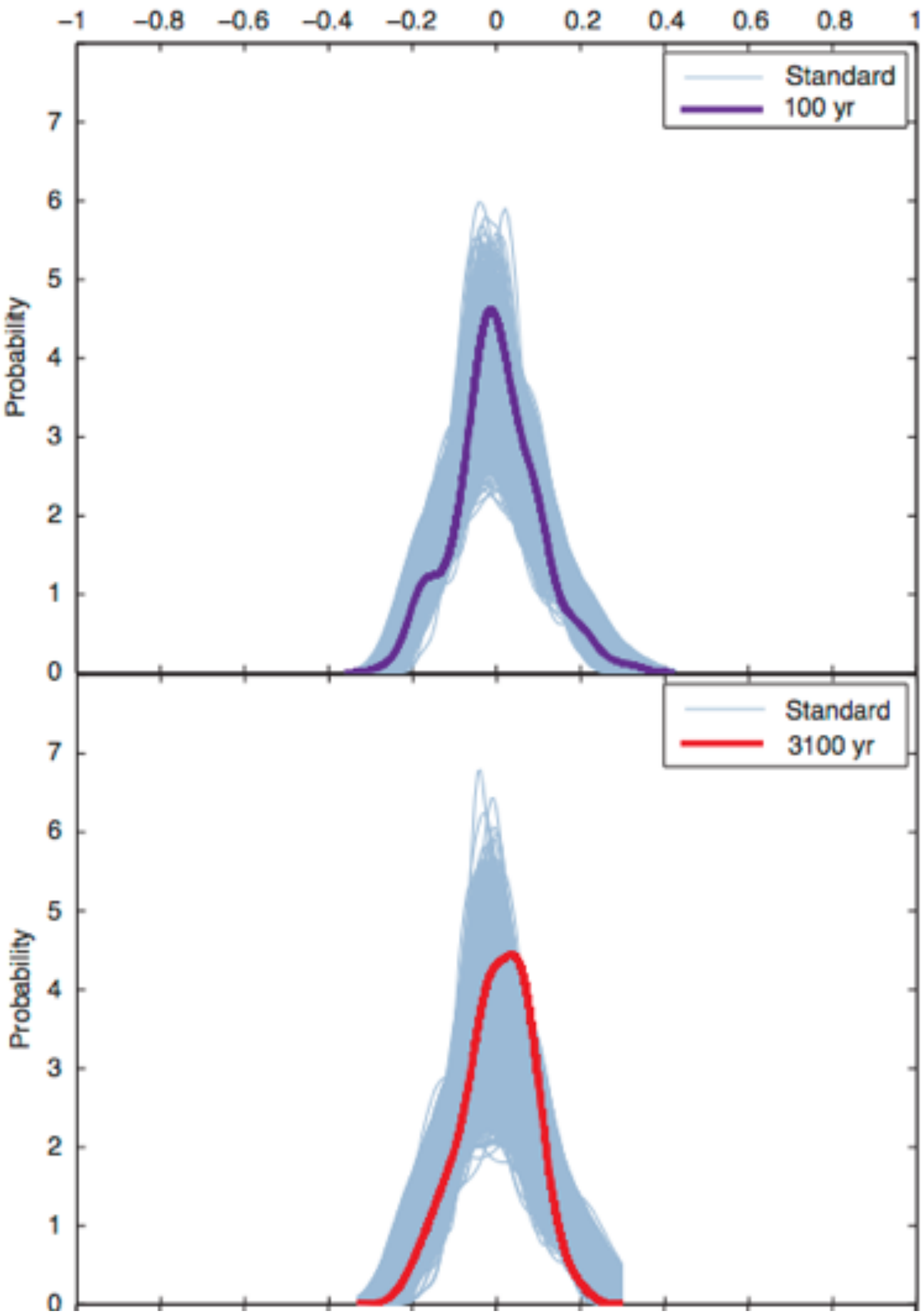


Figure Credit: Sam Bova

Brown

Null Results



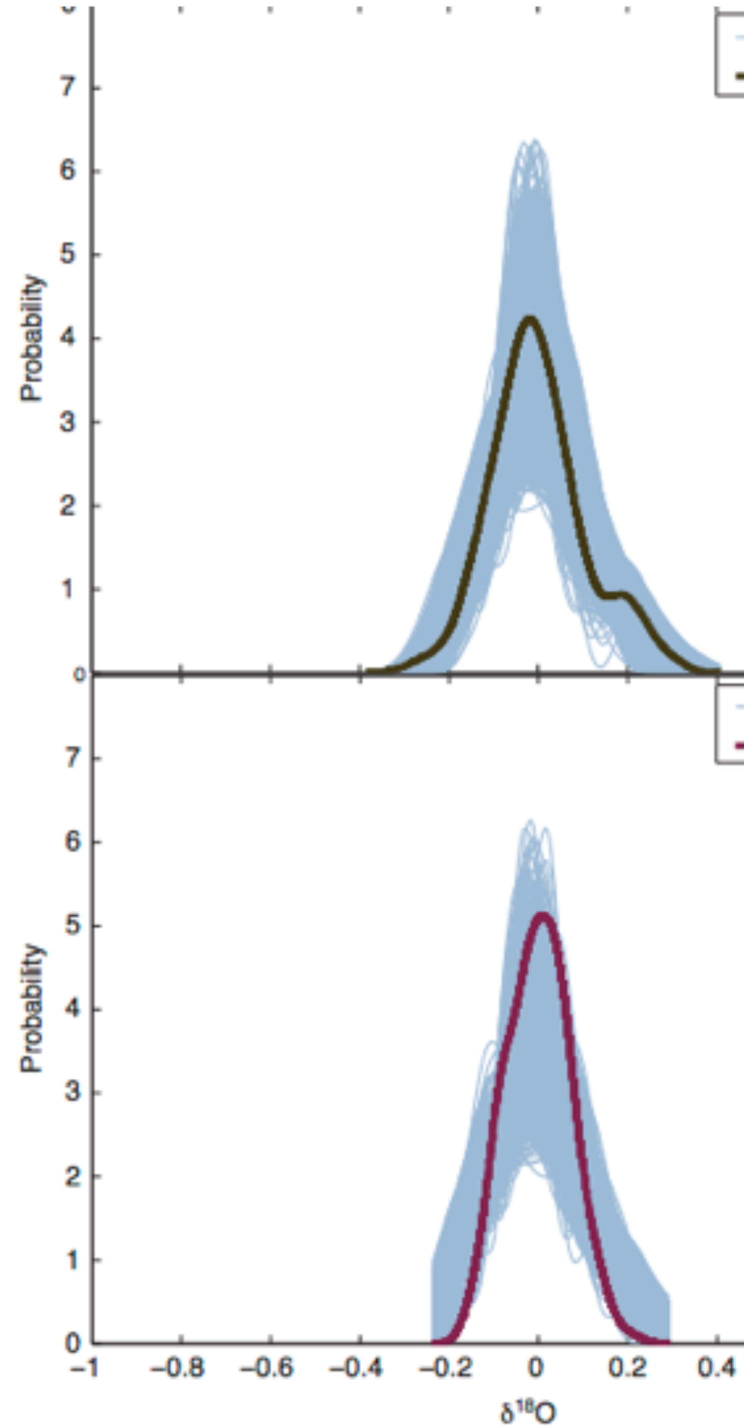


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Figure Credit: Sam Bova

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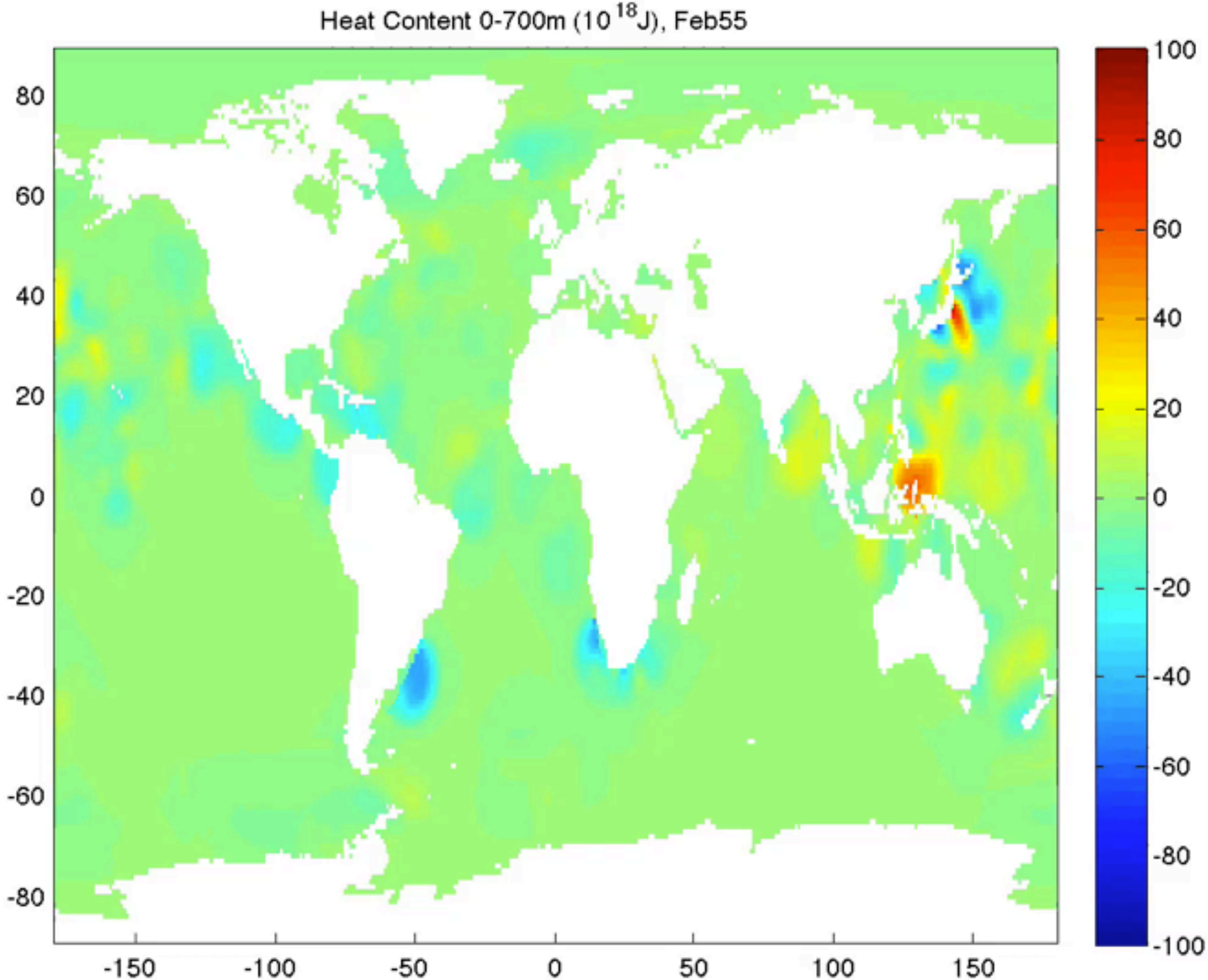
Compare to Observational Product



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"

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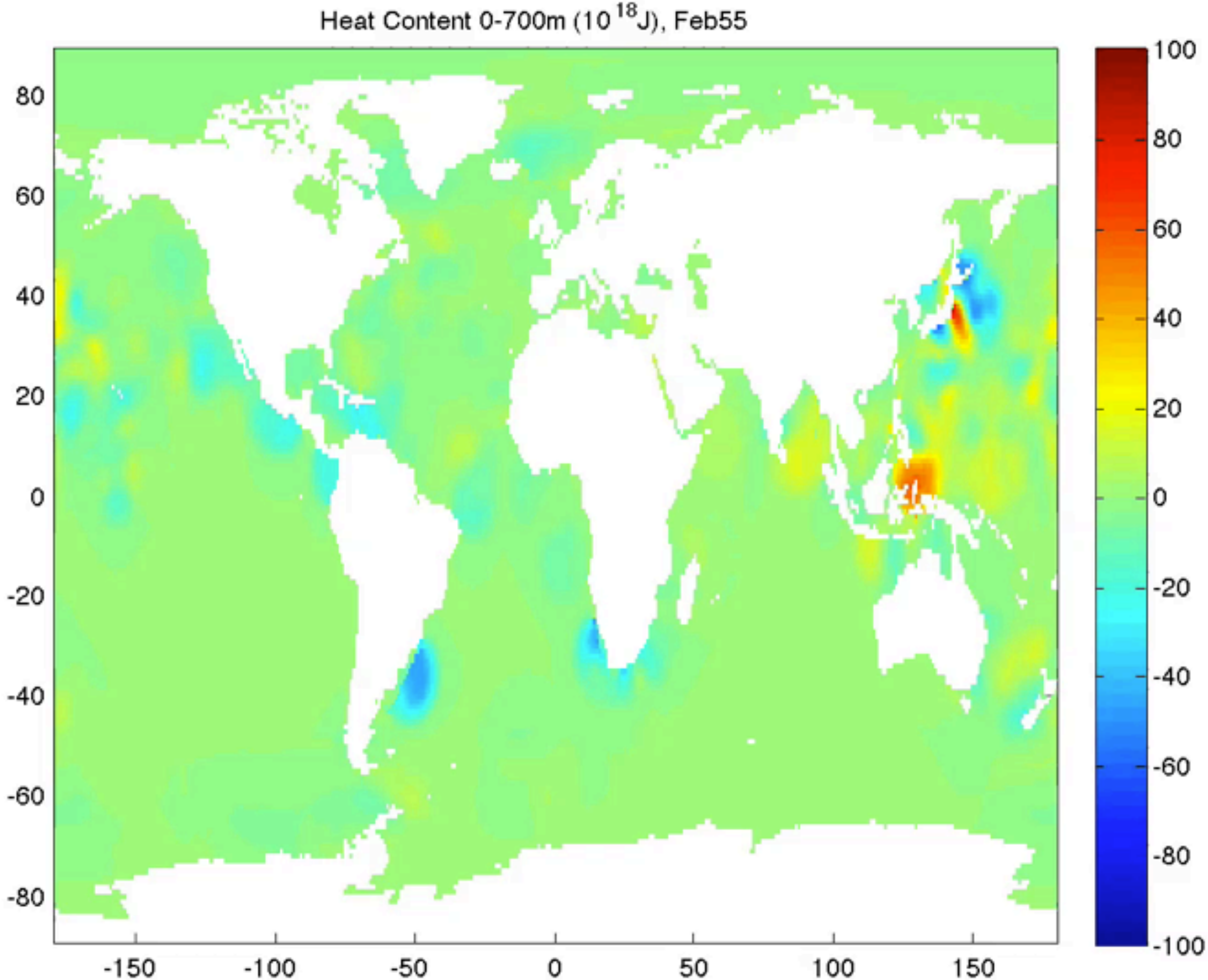

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