Consequences of Uncertainty in Air-Sea Exchange

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Frontiers in Decadal Climate Variability Workshop,
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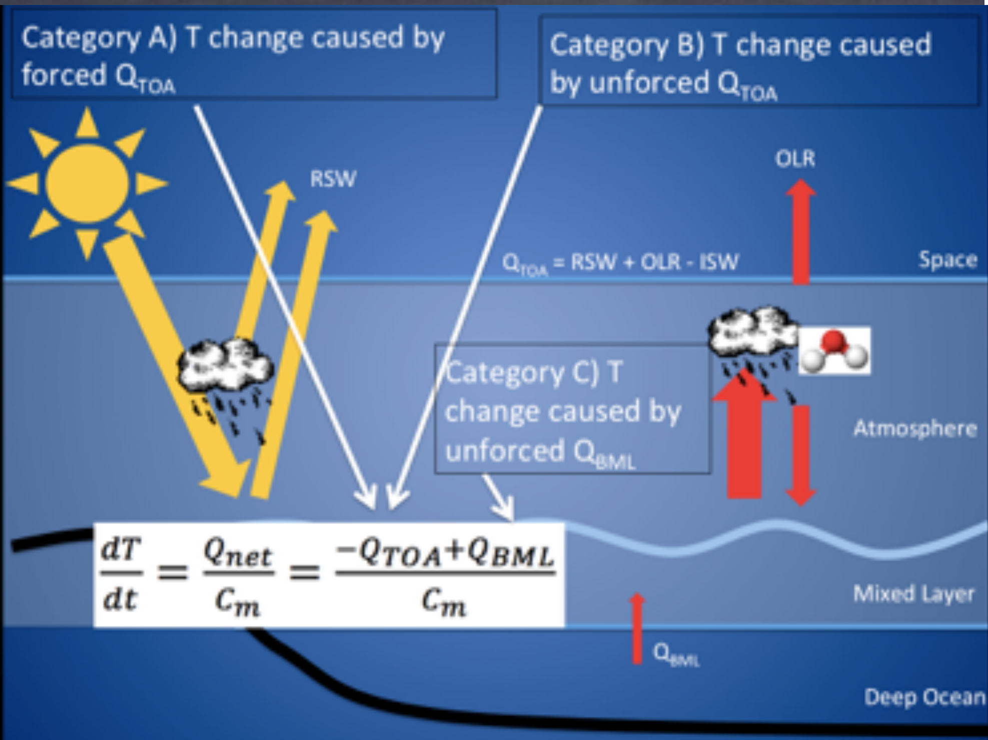
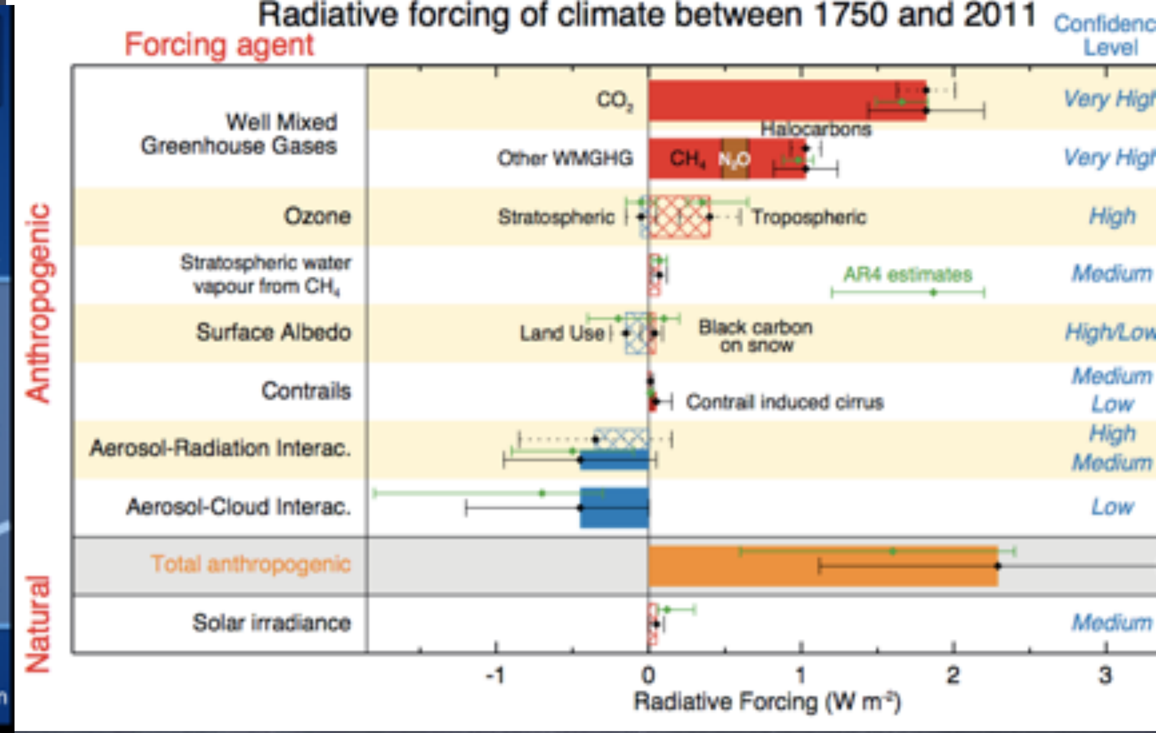
To understand air-sea effects on decadal variability, and our observation of the consequences, is important to distinguish:

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



Brown et al., 2014



IPCC AR5, 2013

- **Presence** of observable decadal variability

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

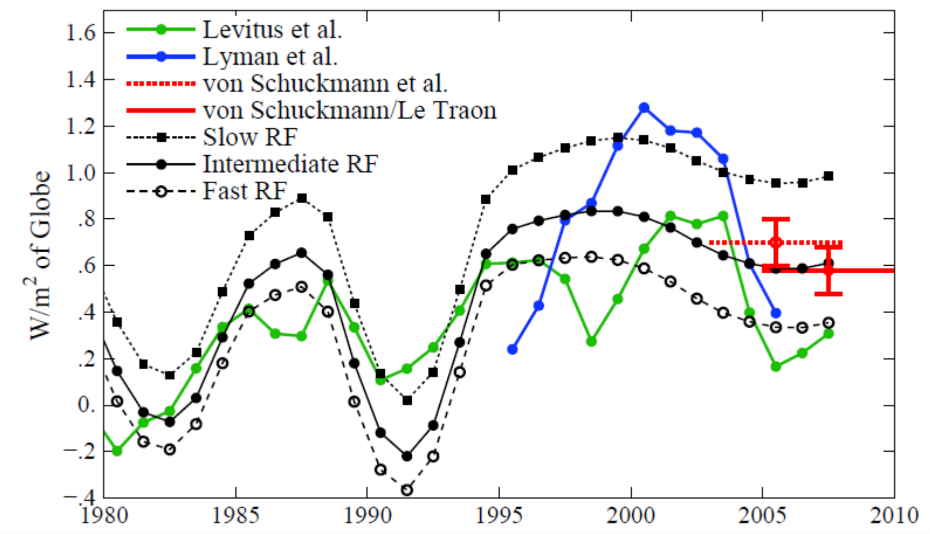
However, problematic **prediction** and **attribution**

What does hydrography show?

OHCs and fluxes are not fixed!

Hansen et al. (2011).

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



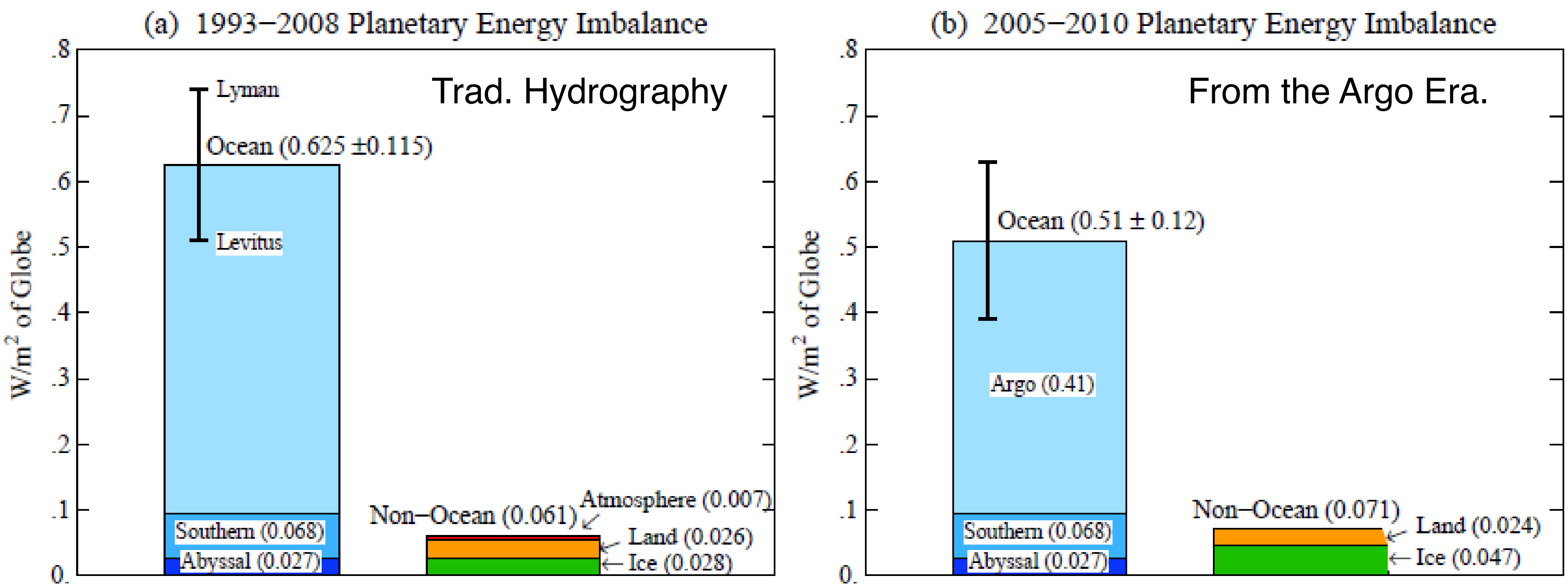
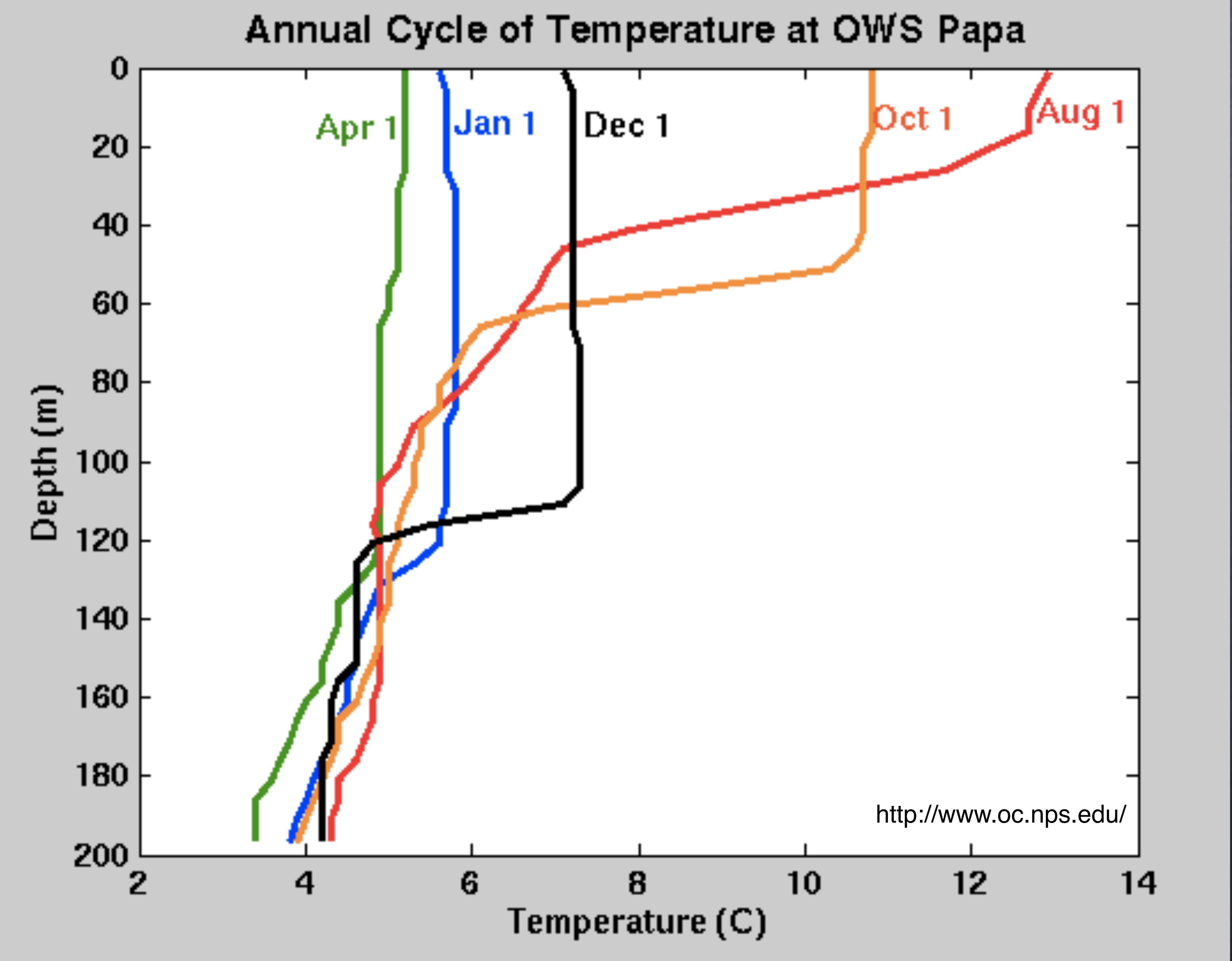


Fig. 10. **(a)** Estimated contributions to planetary energy imbalance in 1993–2008, and **(b)** in 2005–2010. Except for heat gain in the abyssal ocean and Southern Ocean, ocean heat change beneath the upper ocean (top 700 m for period 1993–2008, top 2000 m in period 2005–2010) is assumed to be small 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).

GMST vs. SST vs. MLT vs. OHC

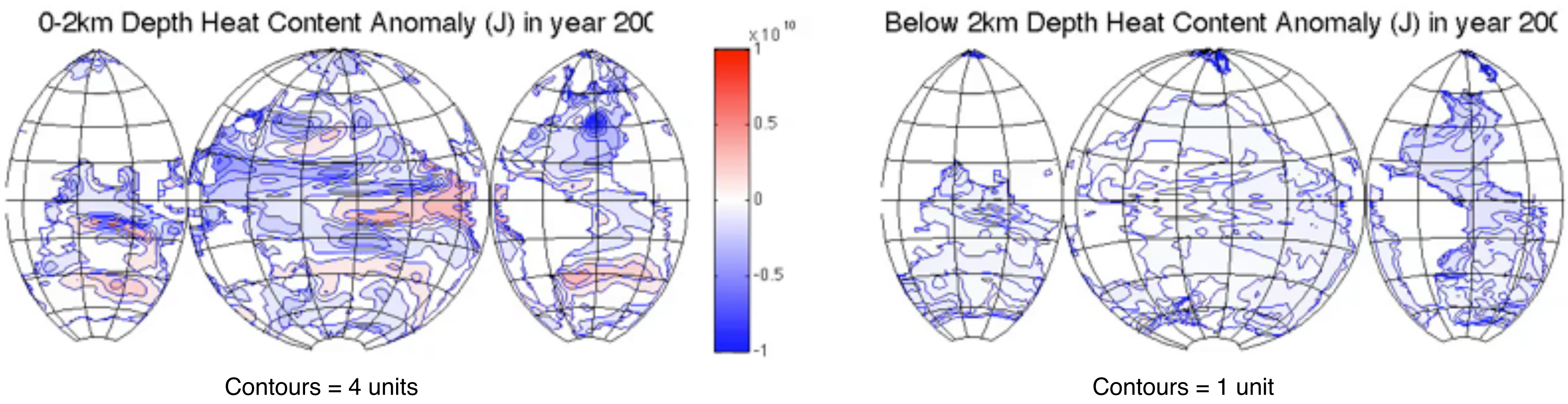
Heat Content

Atmosphere:
0.15K/decade
=
3.4m Ocean:
0.15K/decade
=
34m Ocean:
0.15K/century
<
0.01% this seasonality



What does a climate model—WITHOUT WARMING—look like in OHC variability?

Doesn't even include mesoscale eddies



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

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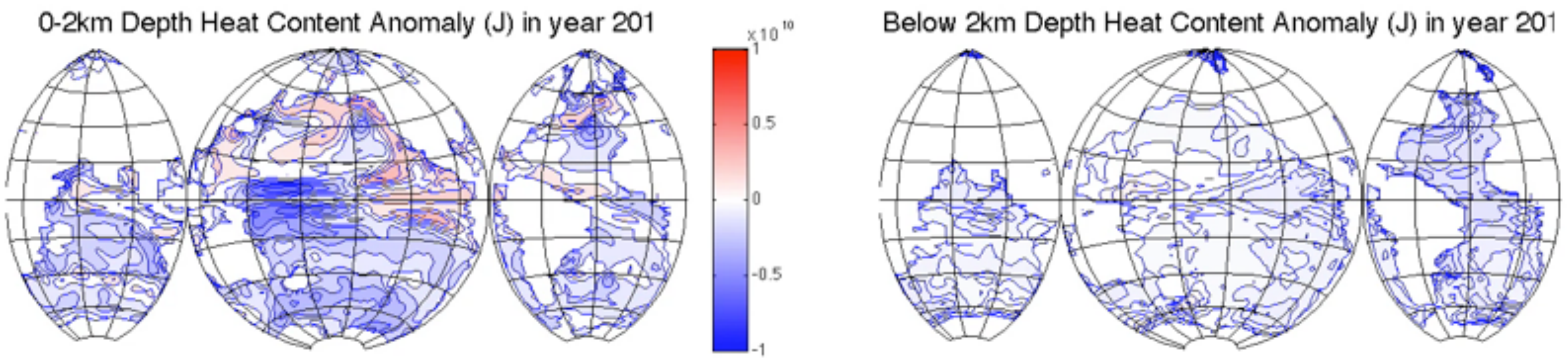

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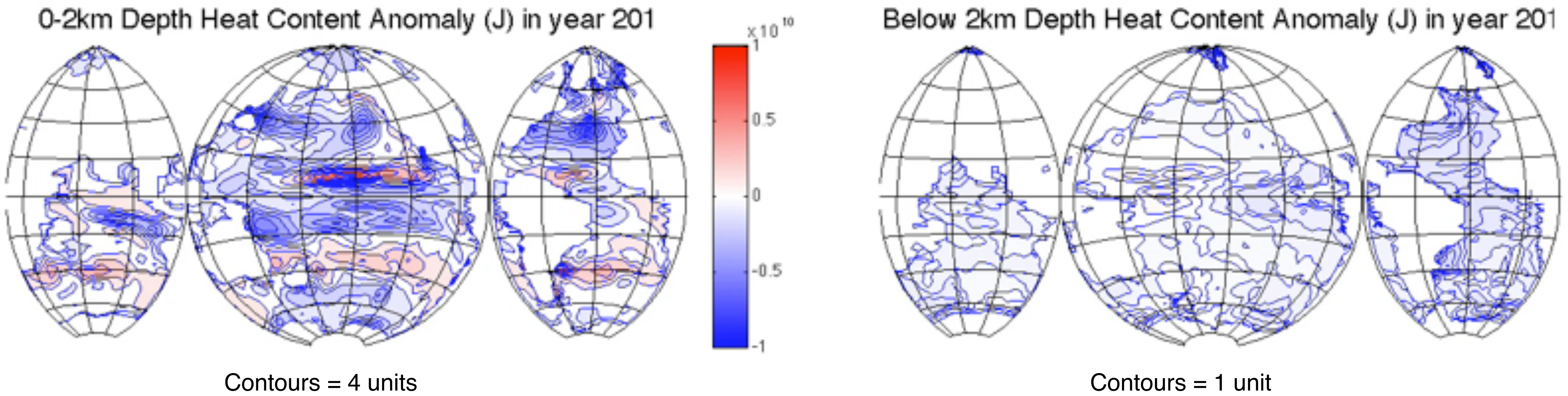

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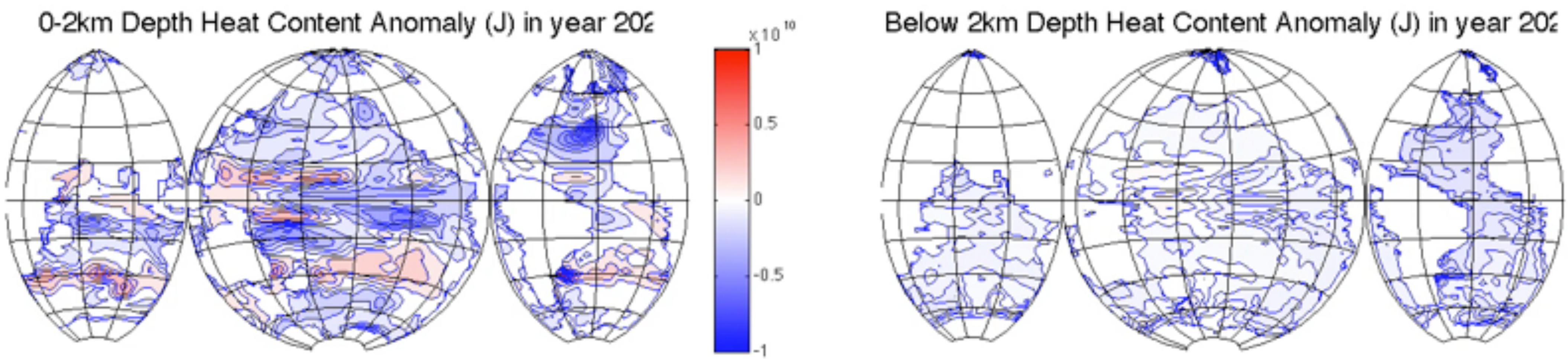

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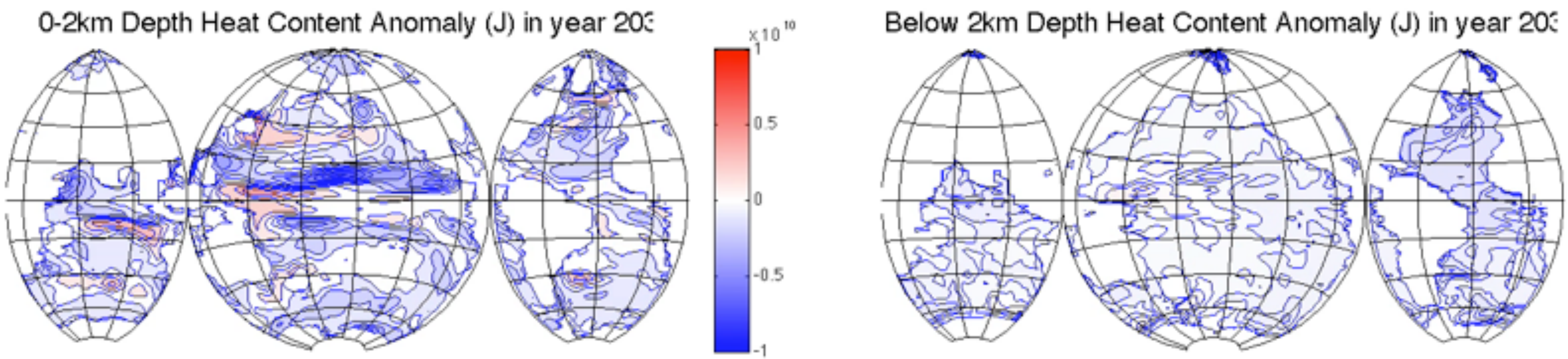

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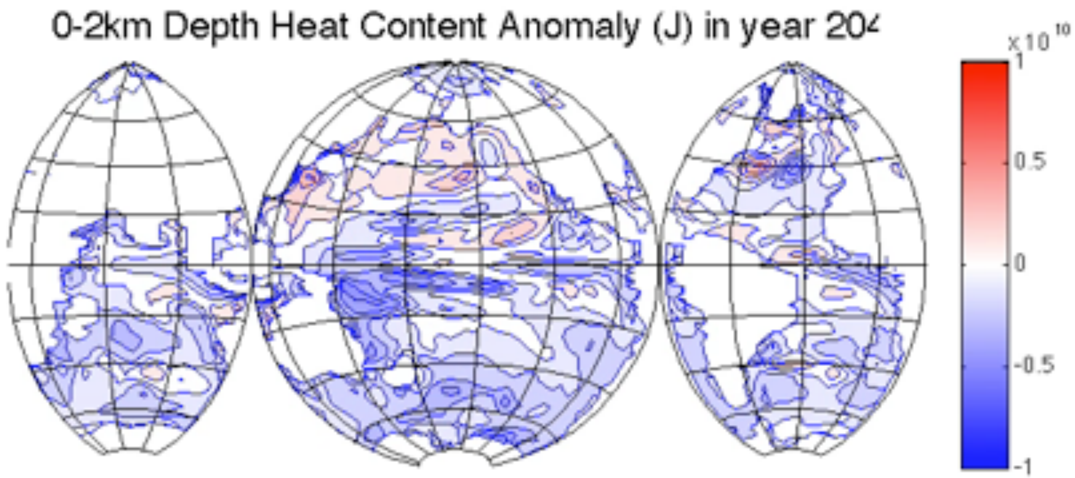

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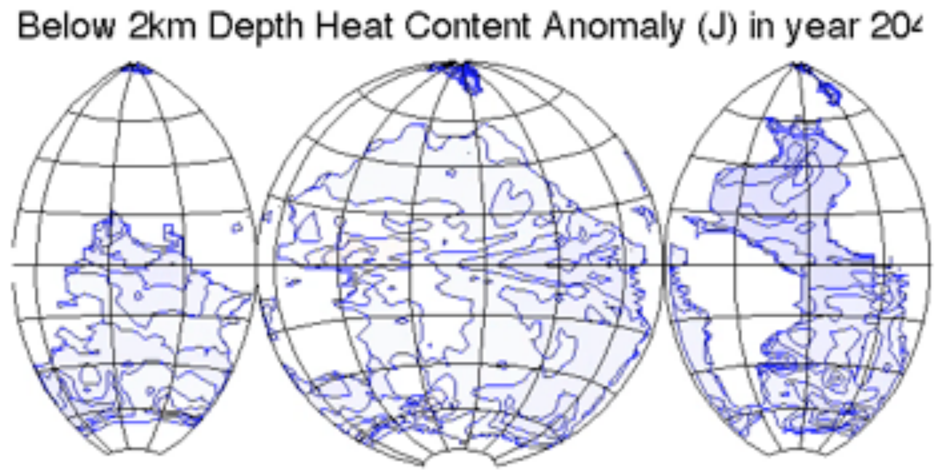

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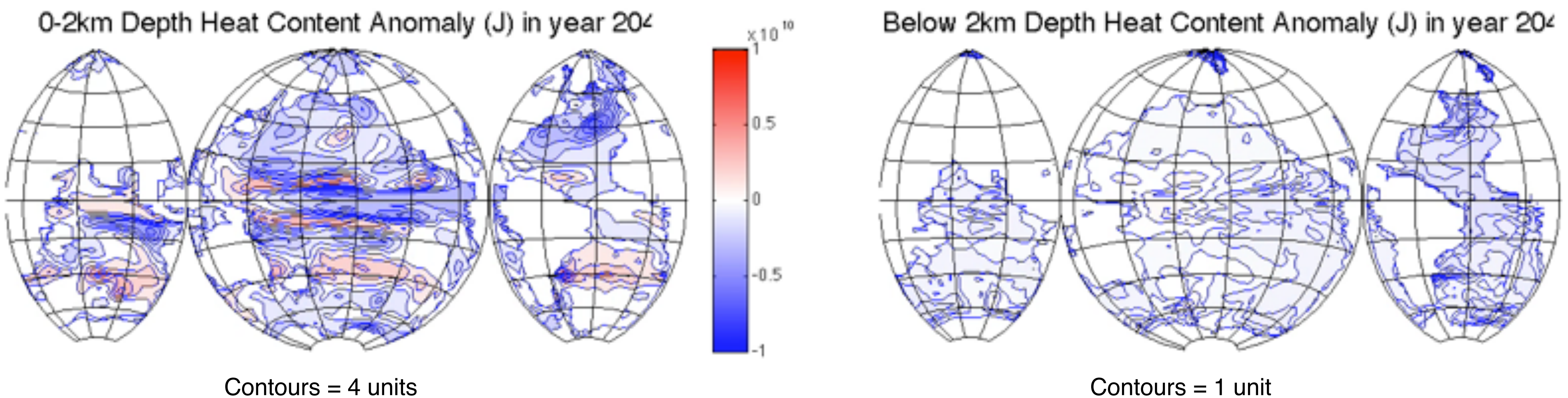

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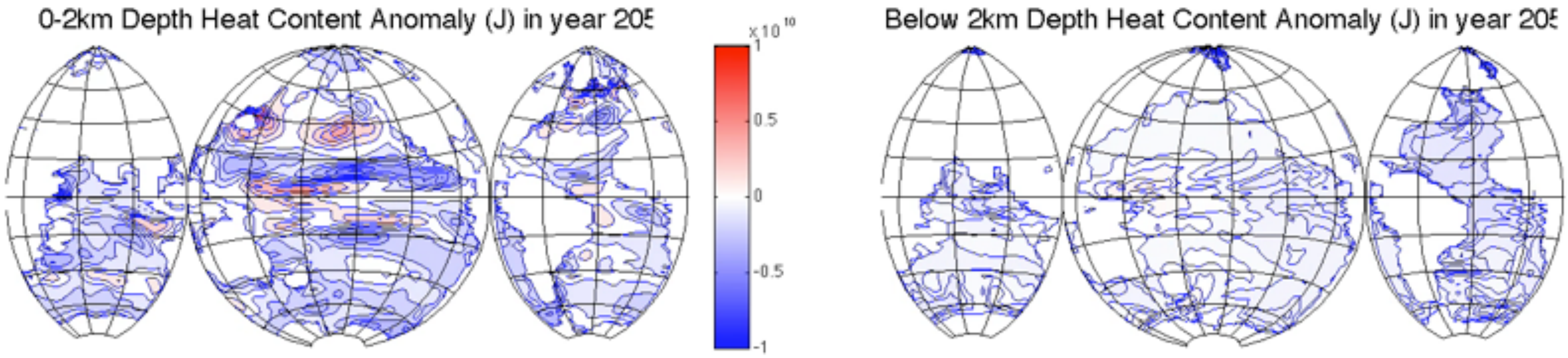

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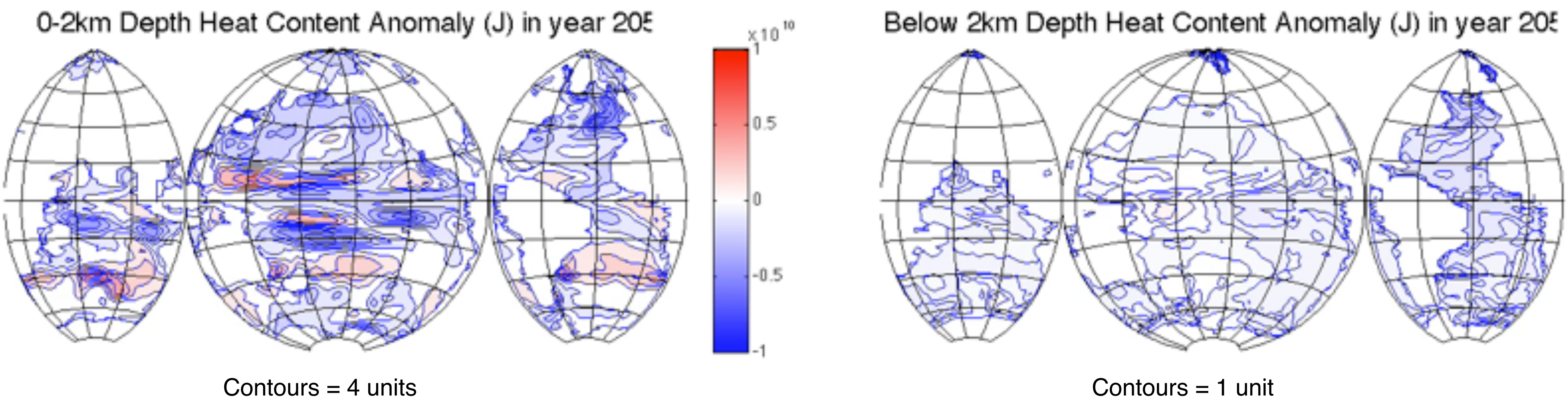

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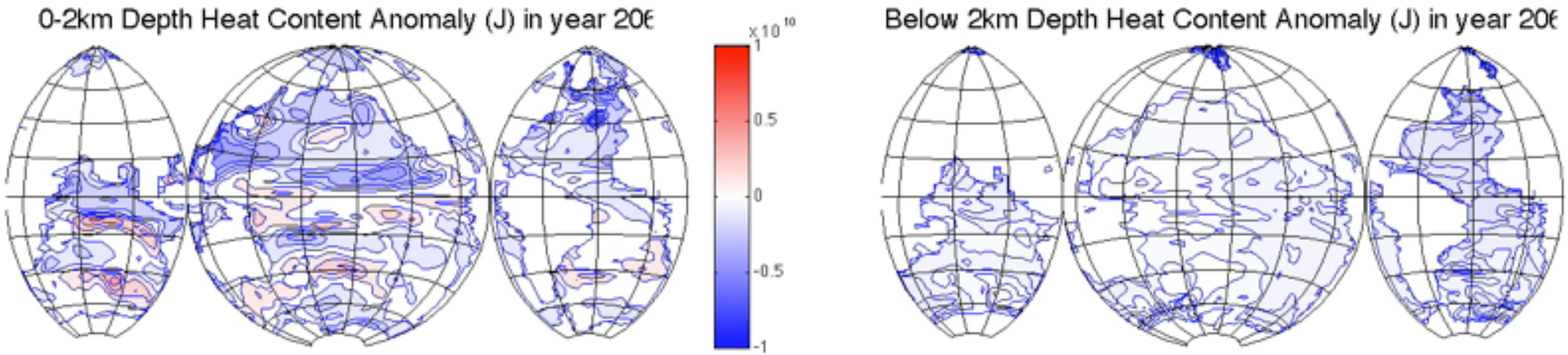

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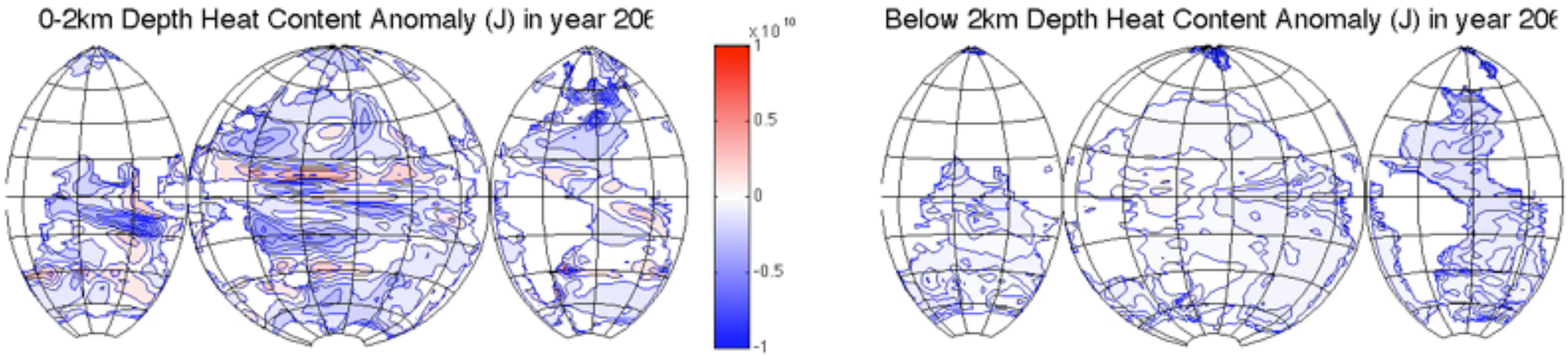

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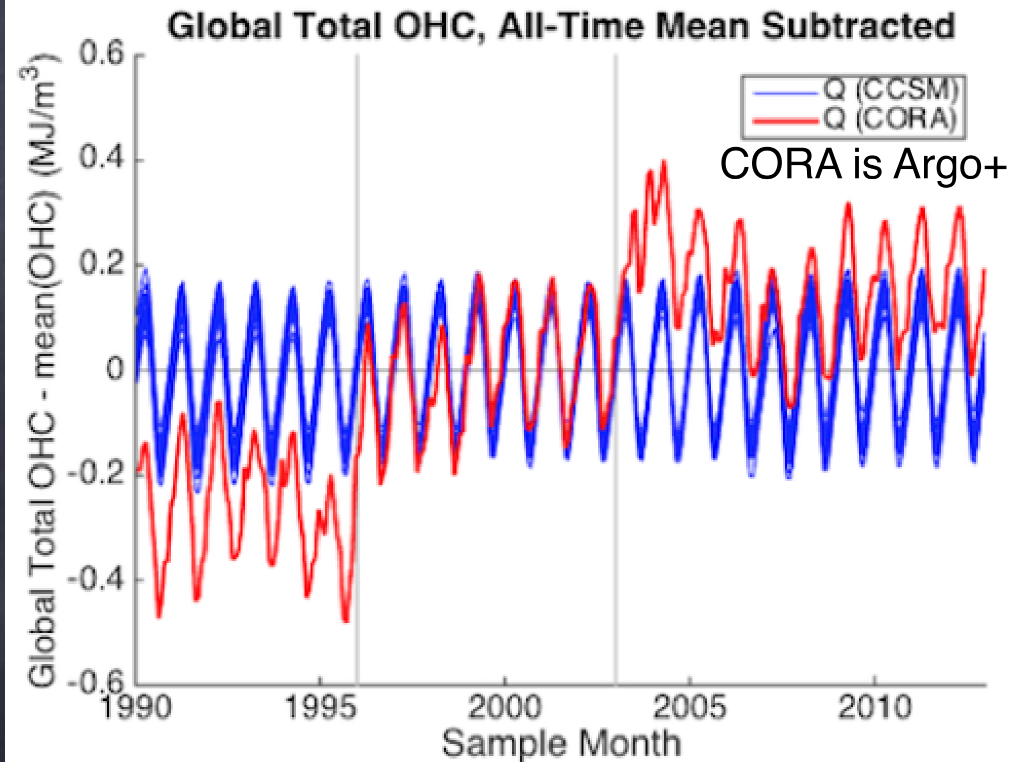
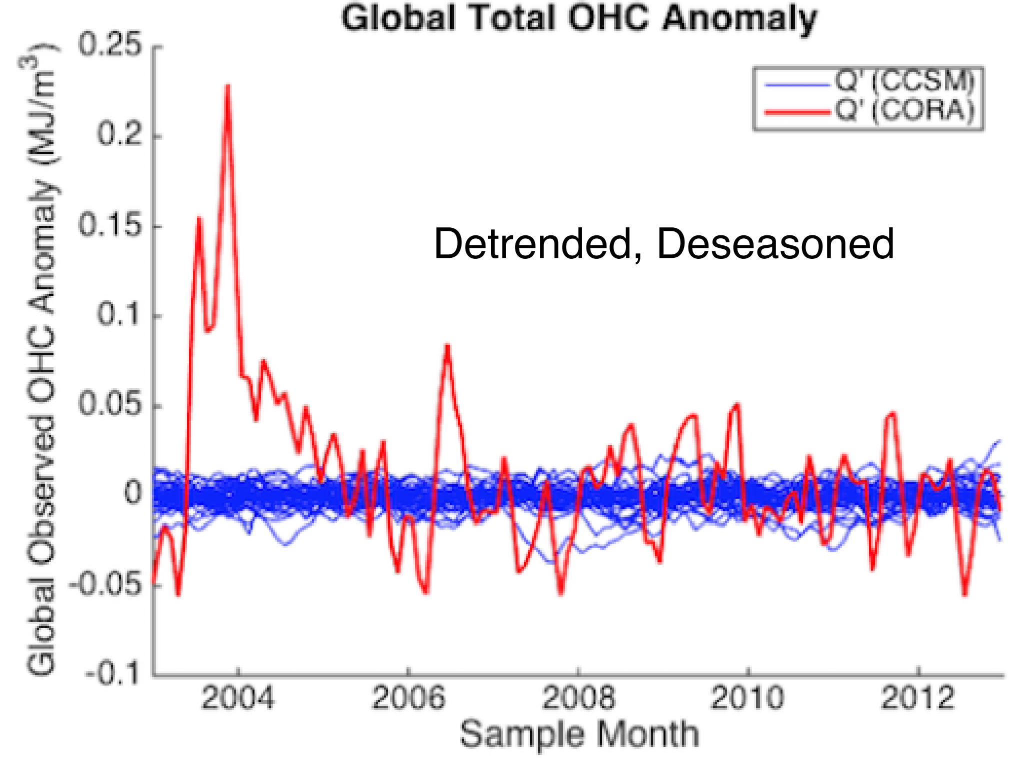
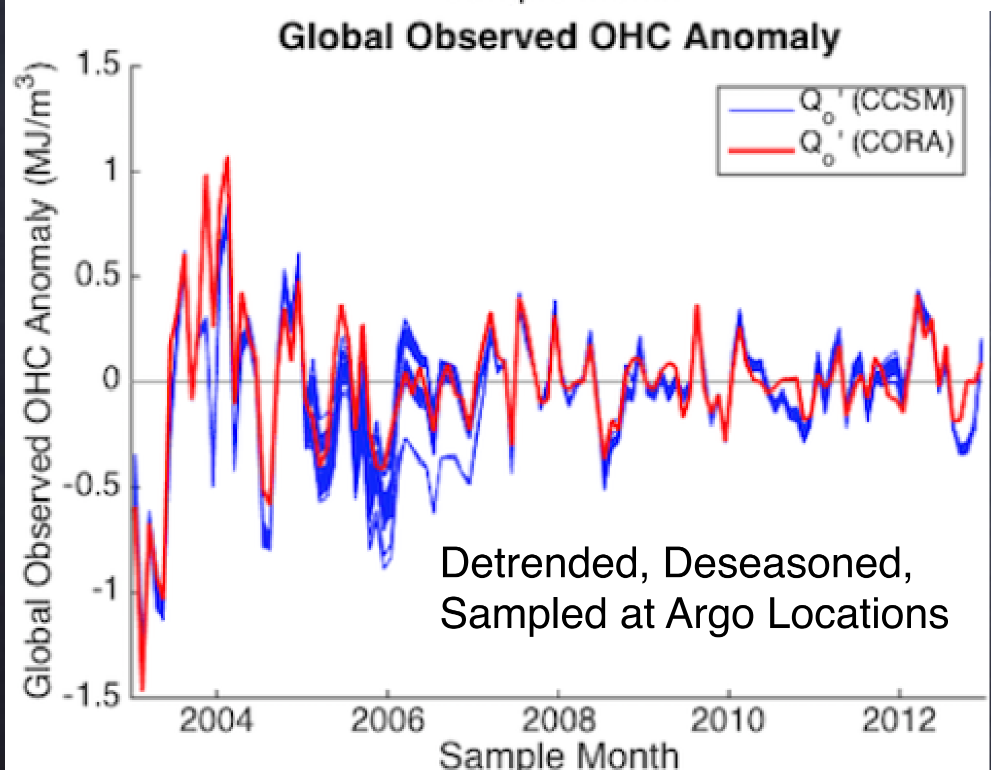






Sophisticated analysis is required to overcome Argo sampling problems—inherent uncertainty, $O(0.2W/m^2)$, on interannual to decadal timescales in global average. $O(10W/m^2)$ without analysis.

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

- **Understanding** of past decadal 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...
- Maybe explanations, but little predictive power.

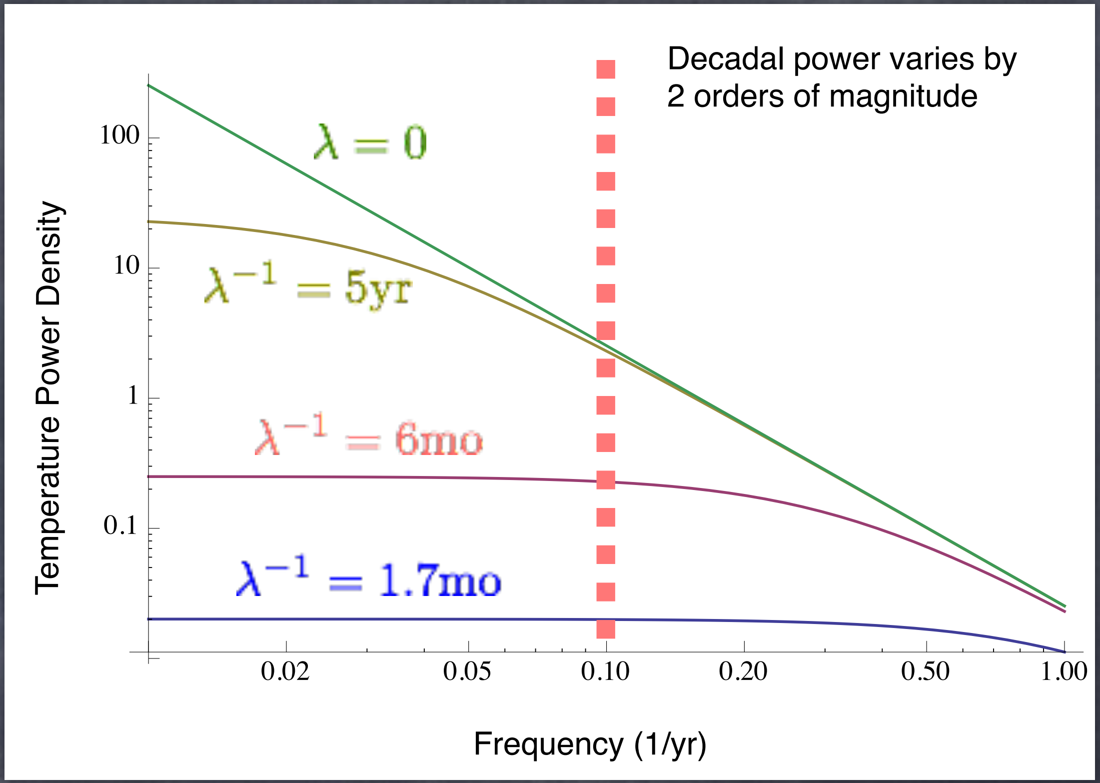
Modeling of decadal variability

Stochastic, Unpredictable Model: Frankignoul & Hasselmann (77)

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

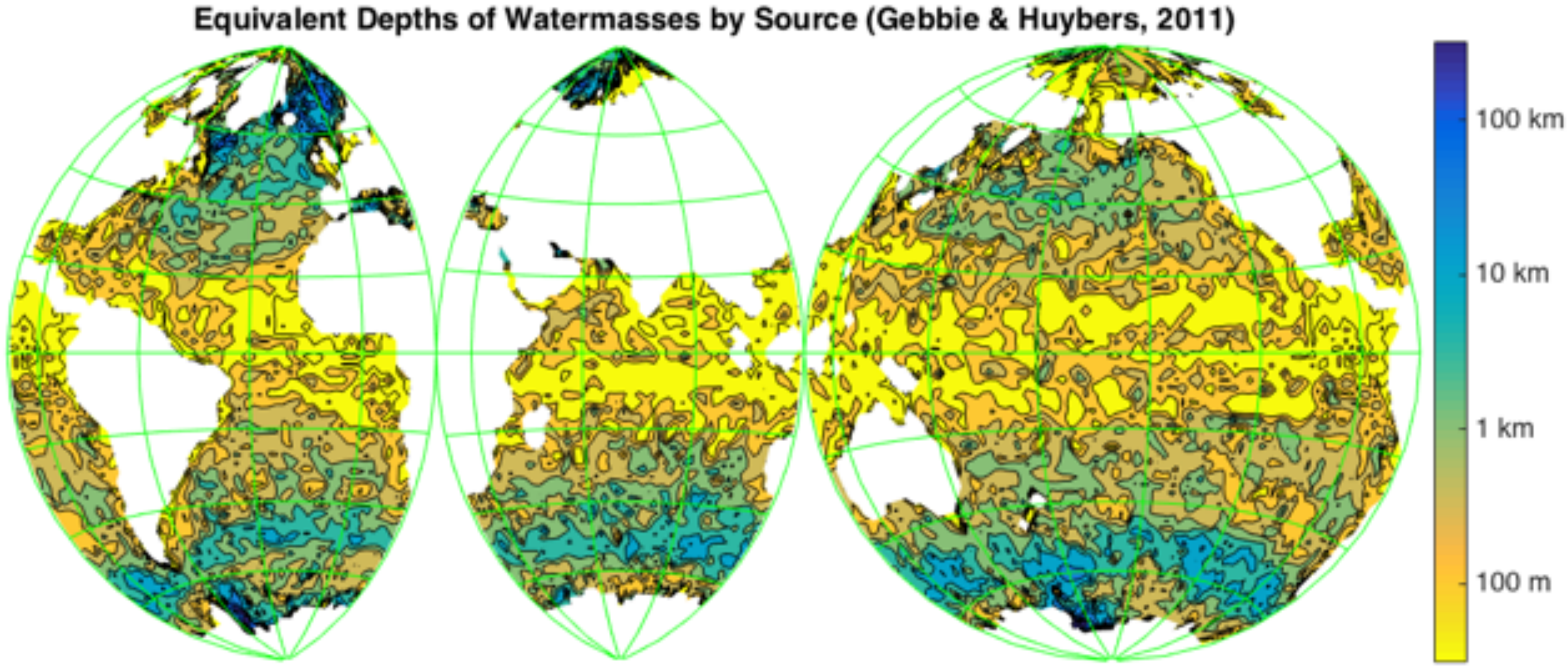
$$\lambda = \rho^a C_p^a (\rho^w C_p^w)^{-1} C_H (1 + B) \langle |\mathrm{U}| \rangle h^{-1}$$

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

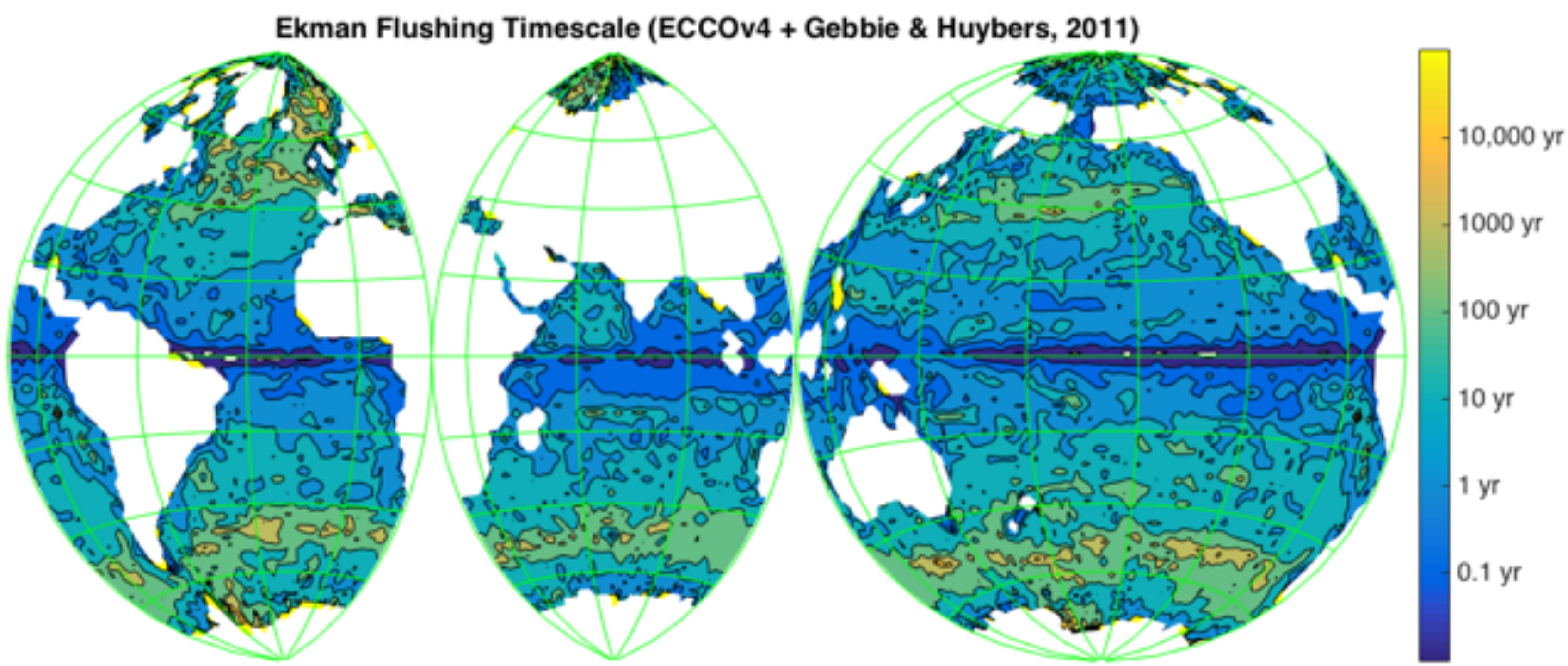


- Air: 1000 J/kg/K, Water: 4186 J/kg/K
- Density: Weight Atmosphere=10m Ocean
- Area: 71% of Surface => Weight Atmo=14m ocean
- Heat Cap: 3.4m Ocean=Whole Atmo
- Ocean = 1000x Atmo. in Heat Capacity

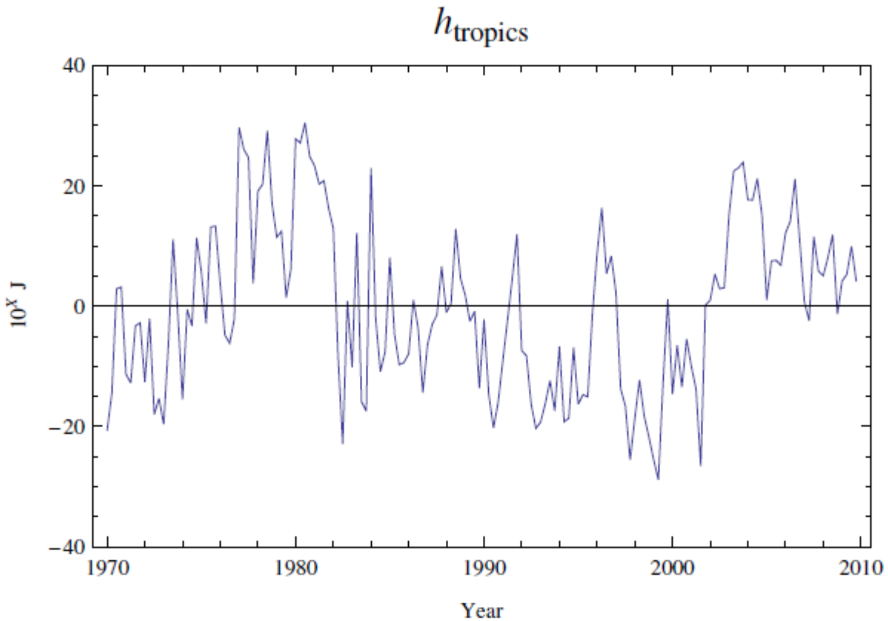
Consider 1D Oceans: one per watermass

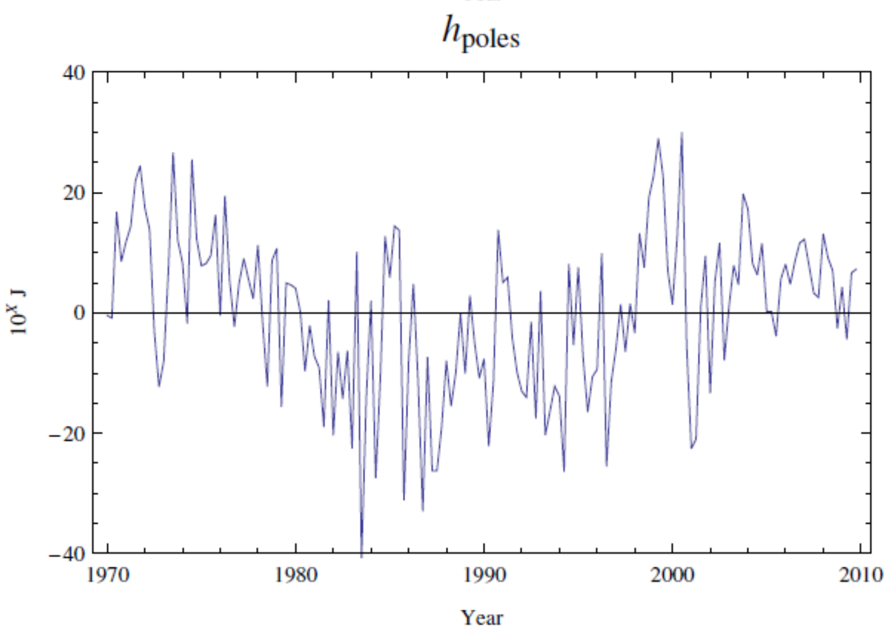


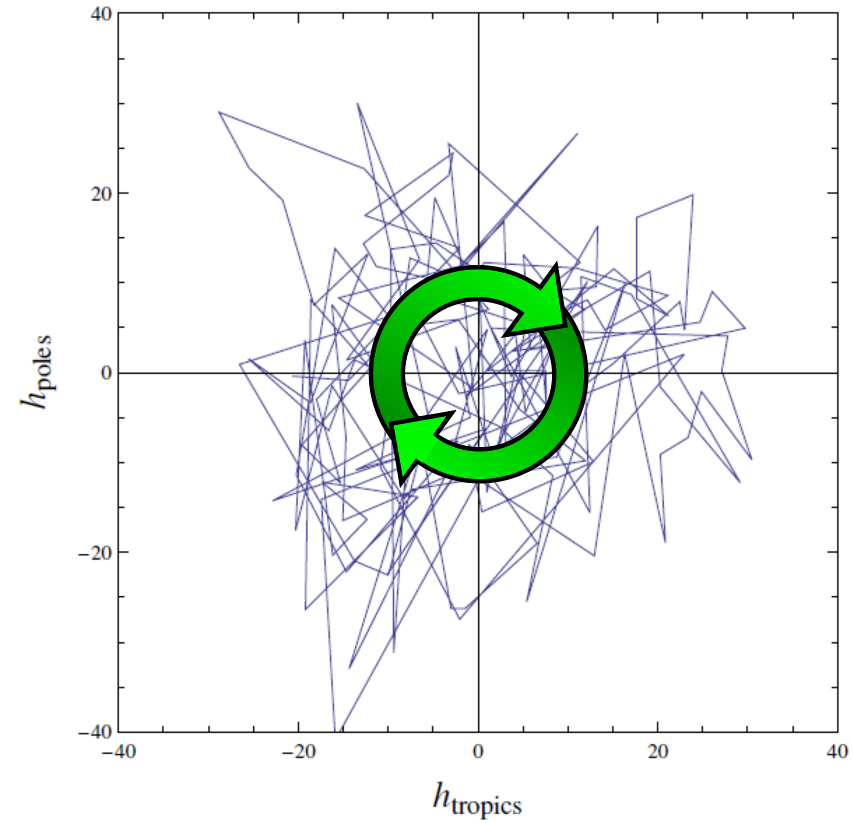
Ekman flushing gives upper limit to λ^{-1} damping timescale



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







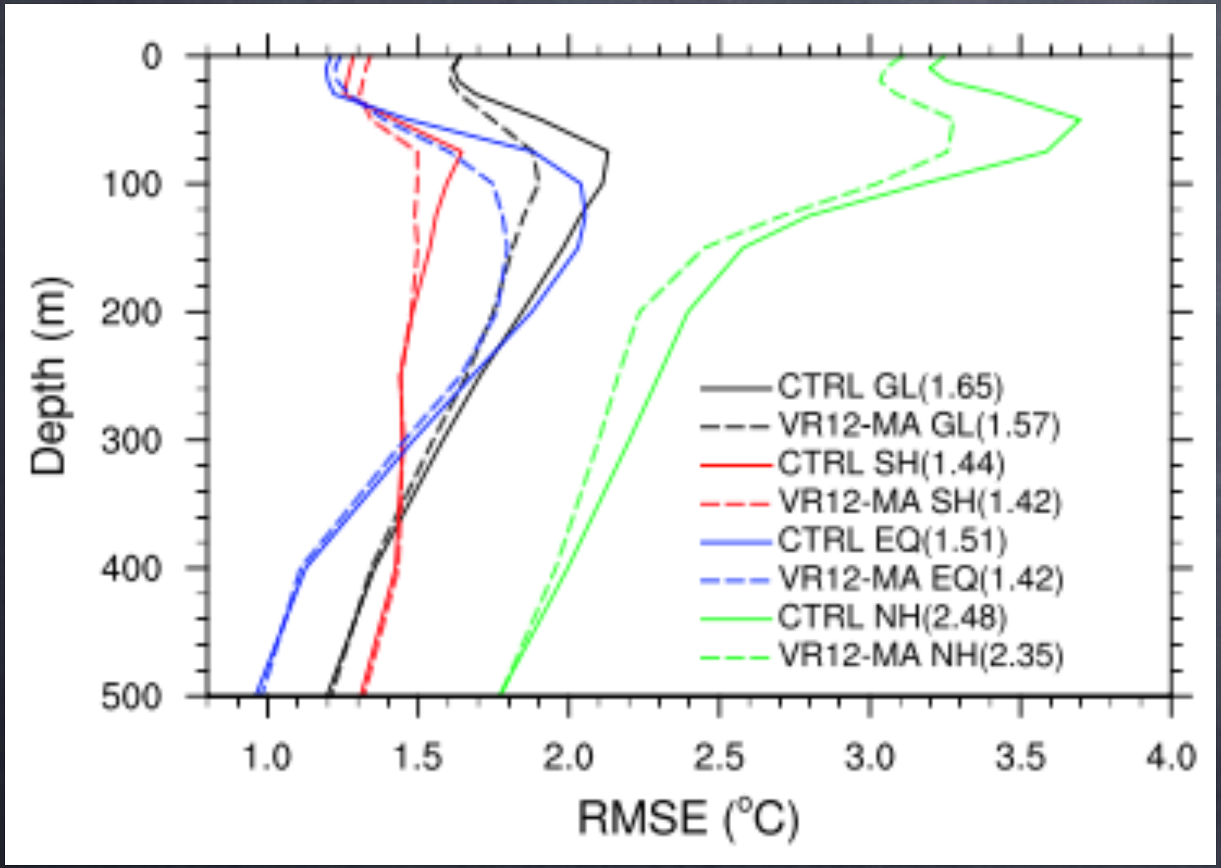
This is the fundamental root cause of LIM predictability

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.

Modeling of decadal variability

First-Principle Process & GCM Modeling: Predictions and Biases

Quantify process uncertainty, how much do Langmuir mixing or anisotropy of mesoscale eddies affect OHC?



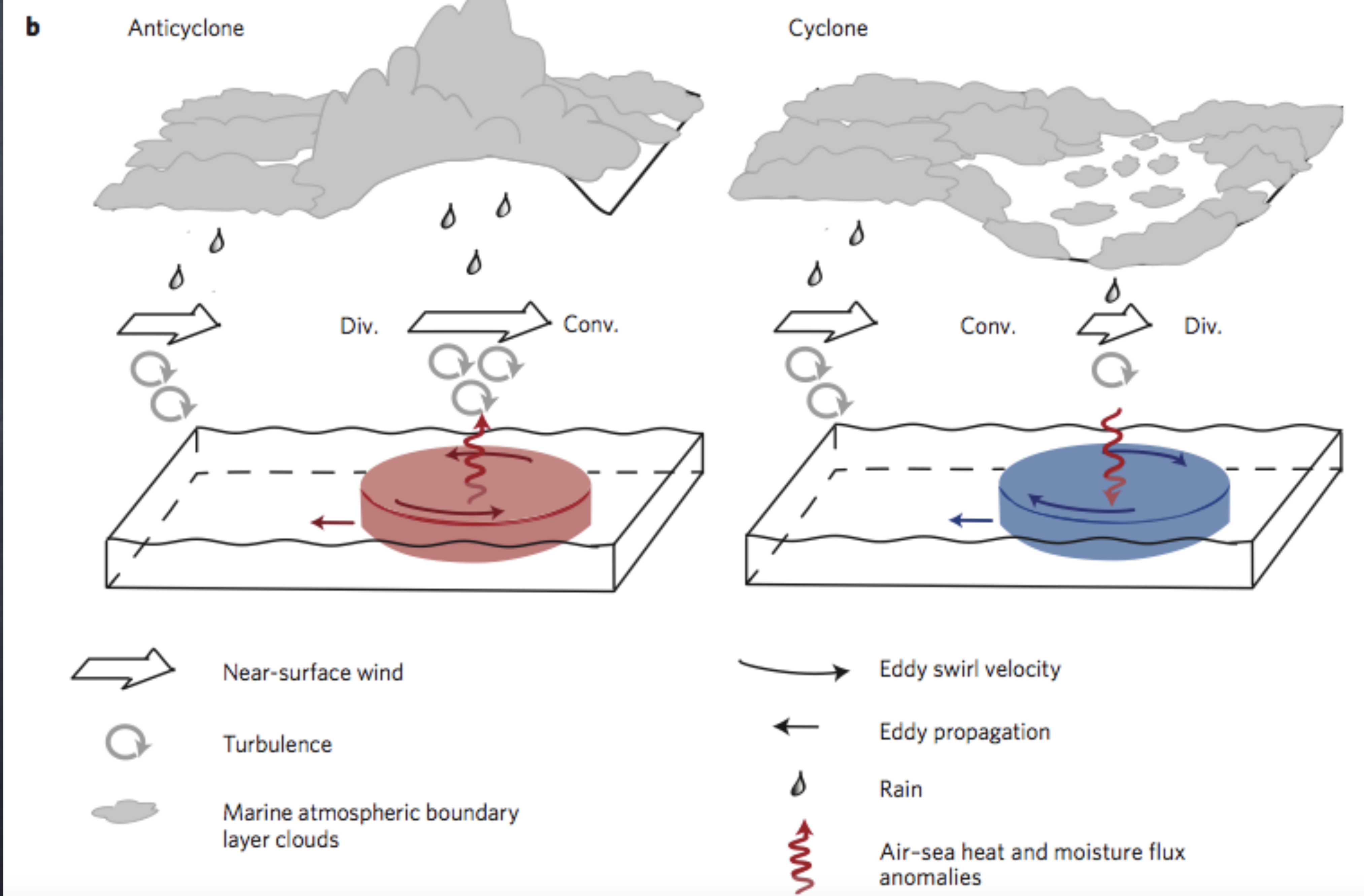
Roughly 1 W/m^2 each as estimated by integrated T difference from control run.

Model versions differ in net air-sea fluxes by 1-6 W/m^2 in mean and rms. This is 2-10x the observed trend!

Retuning, parameterizations, resolution.

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.

S. C. Bates, B. Fox-Kemper, 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.

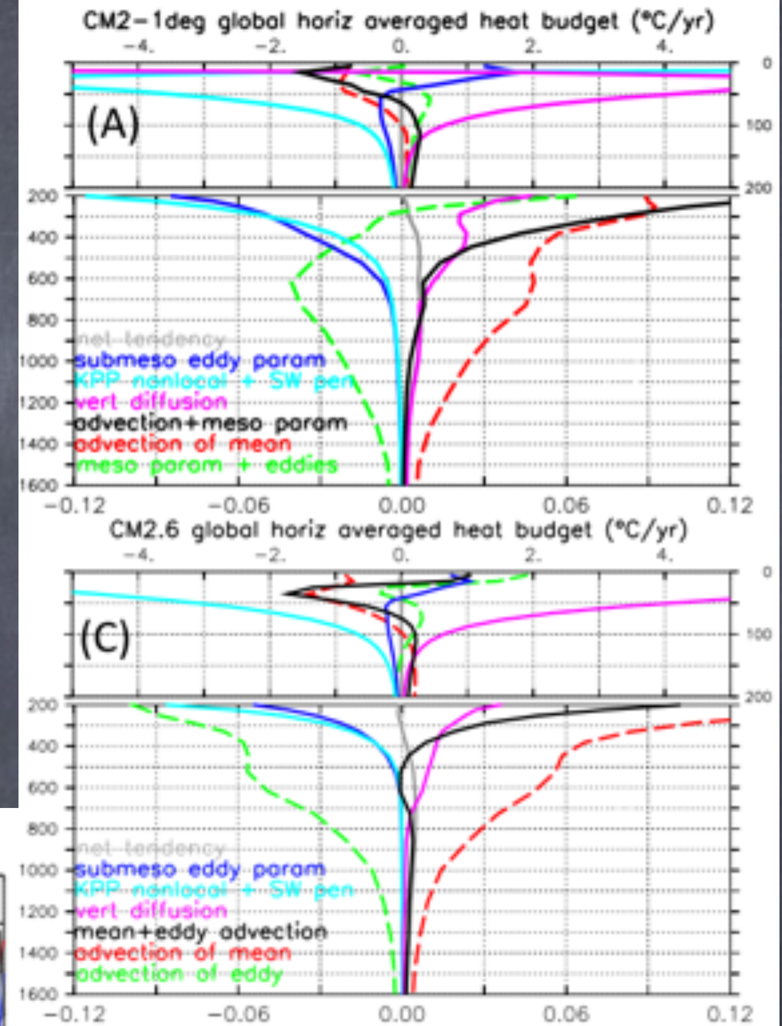


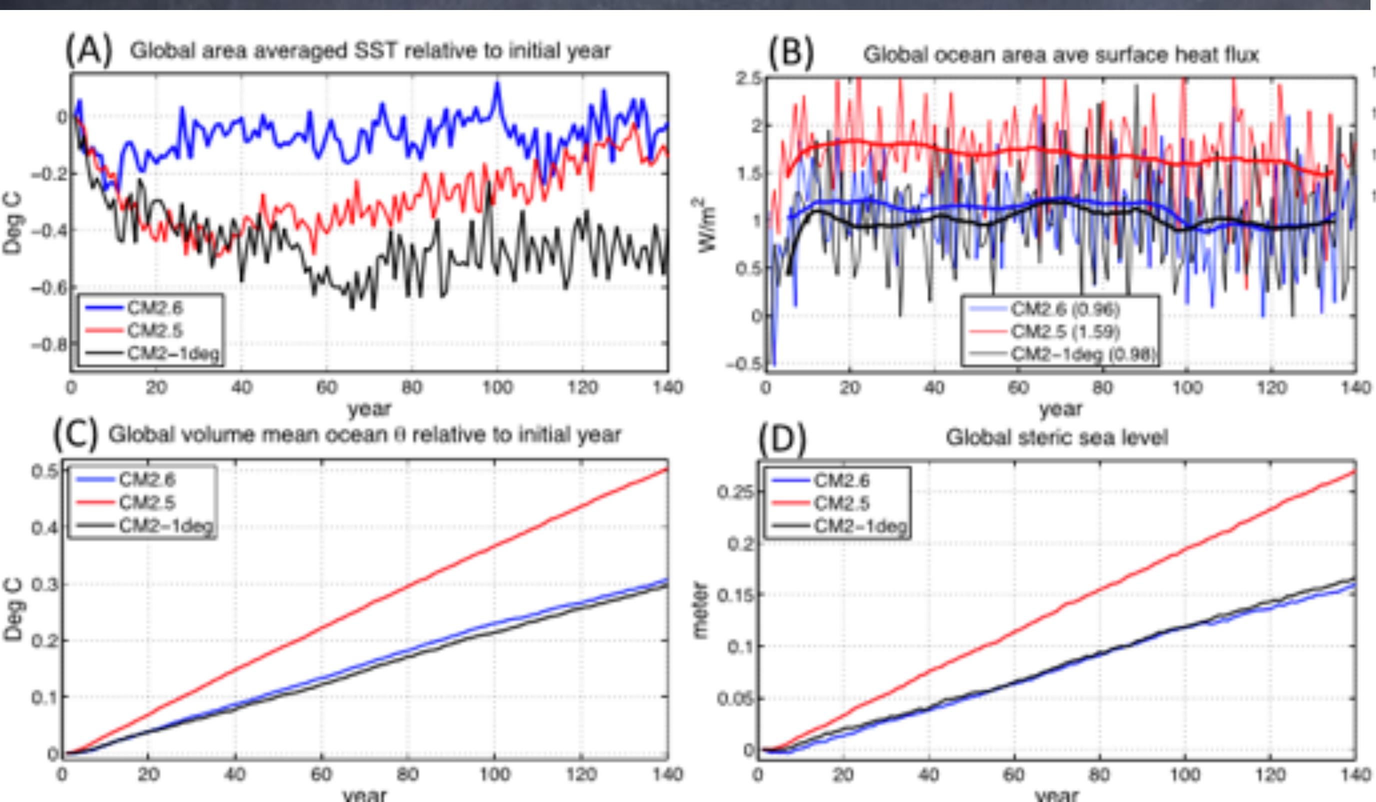
Mesoscale Eddy Air-Sea Feedbacks?

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

Bryan et al. 2010, Frenger et al. 2013

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.
doi: http://dx.doi.org/10.1175/JCLI-D-14-00353.1





By comparing resolved mesoscale eddies to parameterized ones (with same 50km atmosphere), Griffies et al show global differences of

O(0.7 W/m^2) or O(0.14 K/century)

Prediction of decadal variability

- While **observations**, **understanding**, and **modeling** of decadal variability are within present capabilities
- Models & experience reveal **prediction** requires:
  - Regions of modest stochastic variability (i.e. rapid damping) versus internal modes
  - Parameters & sensitivity better known (or data-assimilation, state estimation, UQ, etc.)
  - Unparameterized processes which affect air-sea fluxes & entrainment to be represented
  - Observation network (e.g., satellite, Argo, TAO) to constrain air-sea, entrainment, and TOA fluxes.
  - Change of culture from exploration to operation—skill scores, repeat experience, etc.
- An order of magnitude reduction in uncertainty is required to extend from seasonal to decadal.

Conclusions

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

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

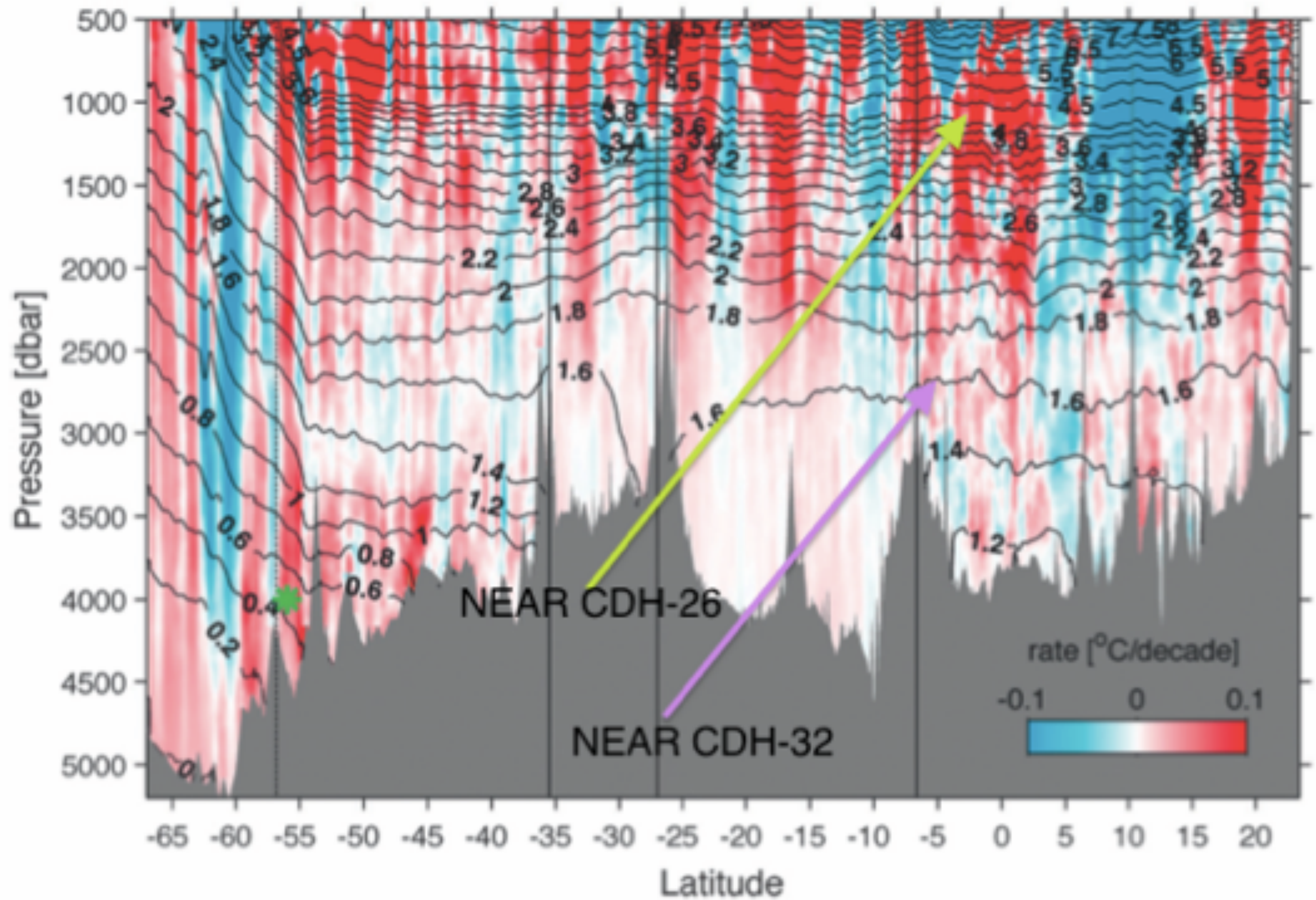


FIG. 4. Time rate of change of potential temperature $d\theta/dt$ (color bar), along the trackline of P18 (see Fig. 1 for location). Areas of warming are shaded in red, and regions of cooling are shaded in blue with intensity scaled by the magnitude of the change. Mean θ values over all occupations are 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

Figure from 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 δ^{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

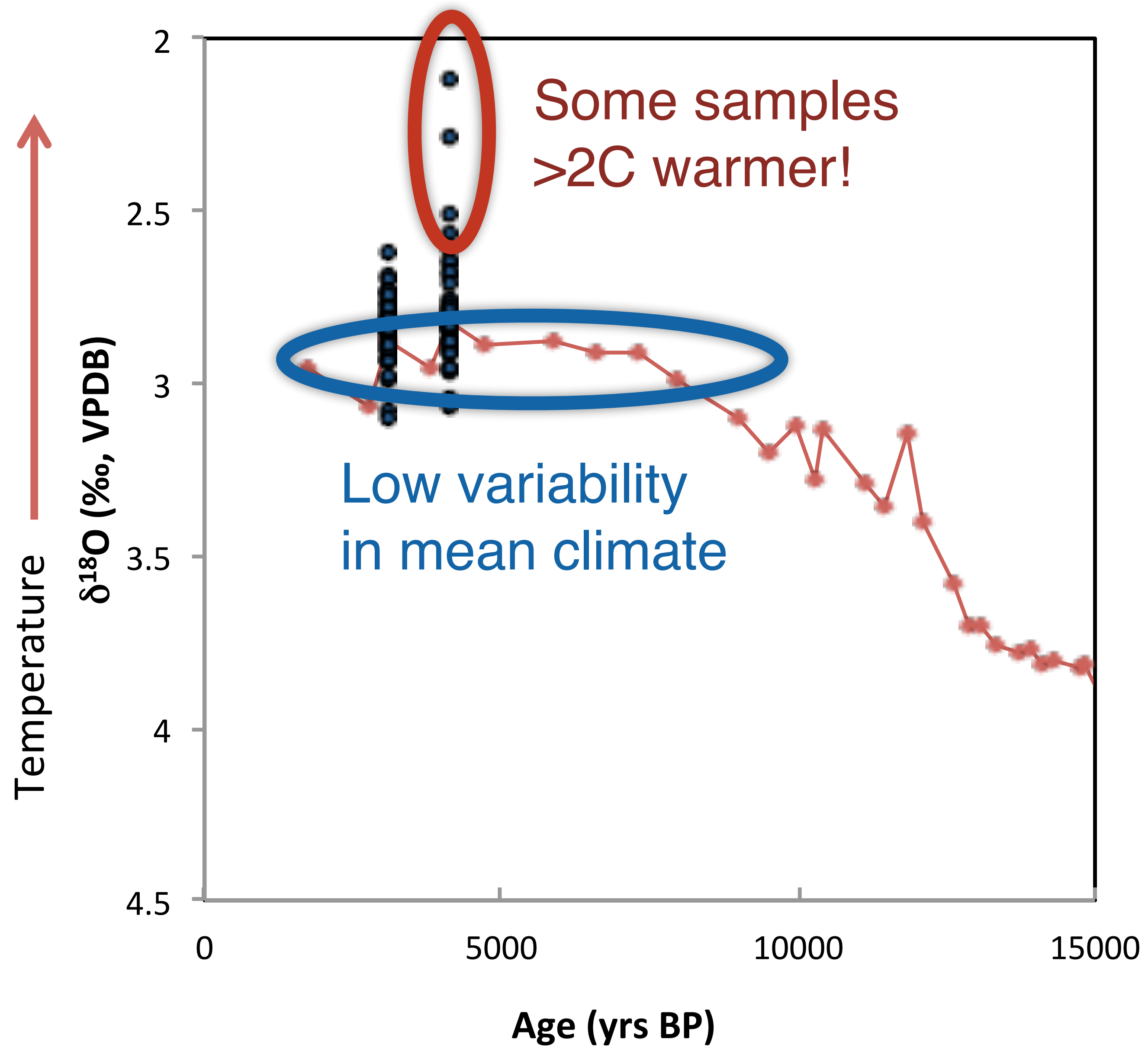
- Individual foraminifera provide 2-3 week snapshots of seawater properties

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

Uvigerina spp.

Slide Credit: Sam Bova

Preliminary Results



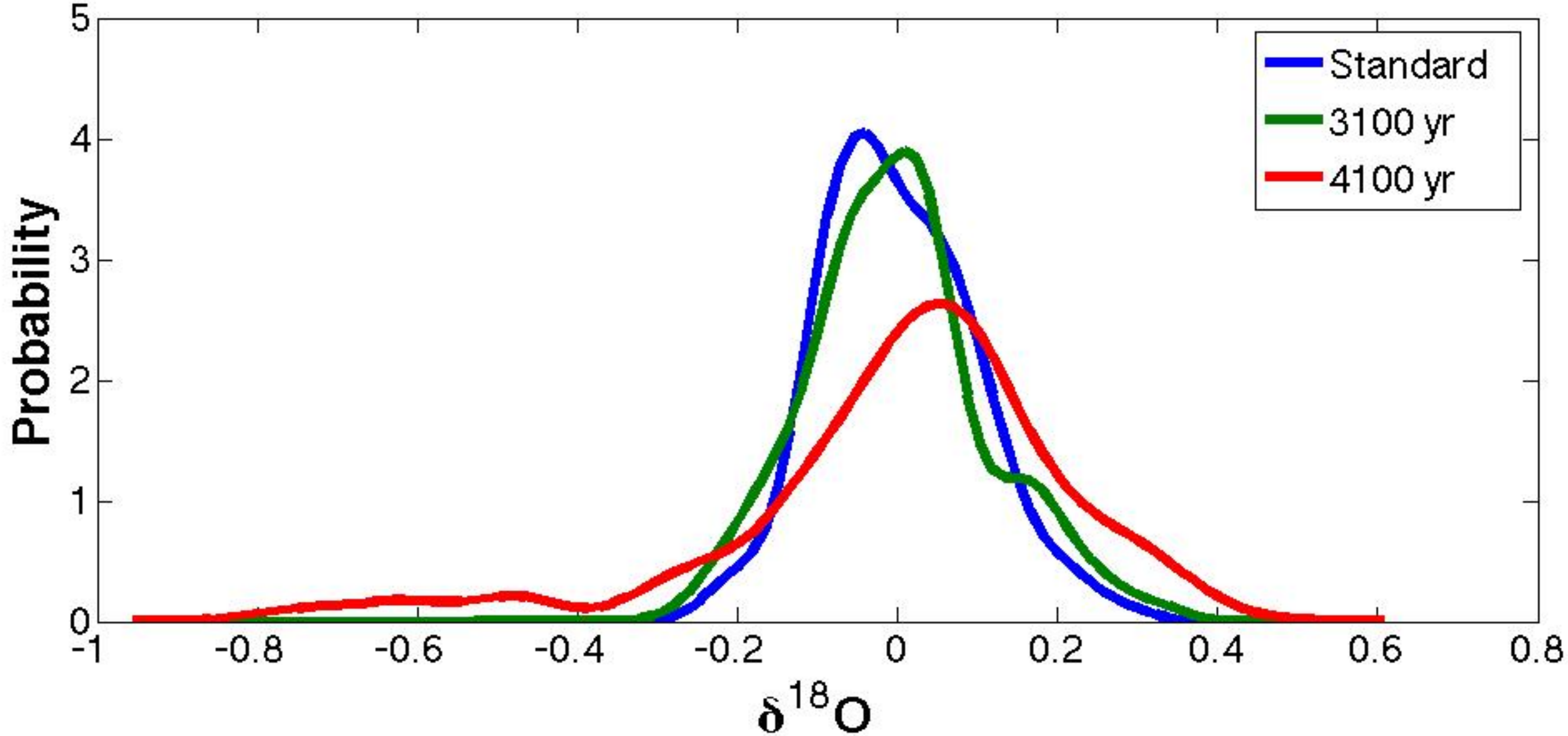
<u>3000-3200 yrs BP</u>
Max: 3.10‰
Min: 2.63‰
Range: 0.48‰

<u>4000-4200 yrs BP</u>
Max: 3.07‰
Min: 2.12‰
Range:0.95‰

~0.25‰ per °C

Slide Credit: Sam Bova

Hypothesis Testing Using Kolmogorov-Smirnov



- No signal at 3100 yrs BP (not distinguishable from standard even at weak 0.1 significance level)
- Signal at 4100 yrs BP (0.01 significance level)