Ocean Variability from the Surface to the Abyss

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Arin Nelson & Jeff Weiss (CU-ATOC), Scott Reckinger (Montana State)
Royce Zia (Va. Tech.)

DEEP Sciences Colloquium
Brown University 10/1/15

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

Key:

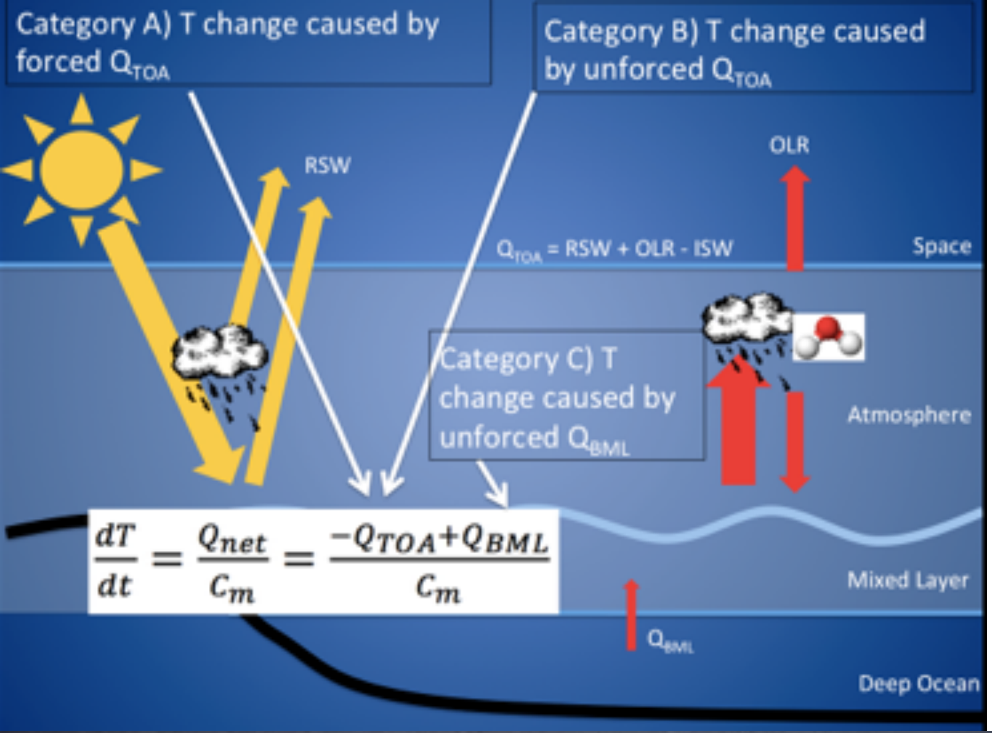
= Work Active Since at Brown

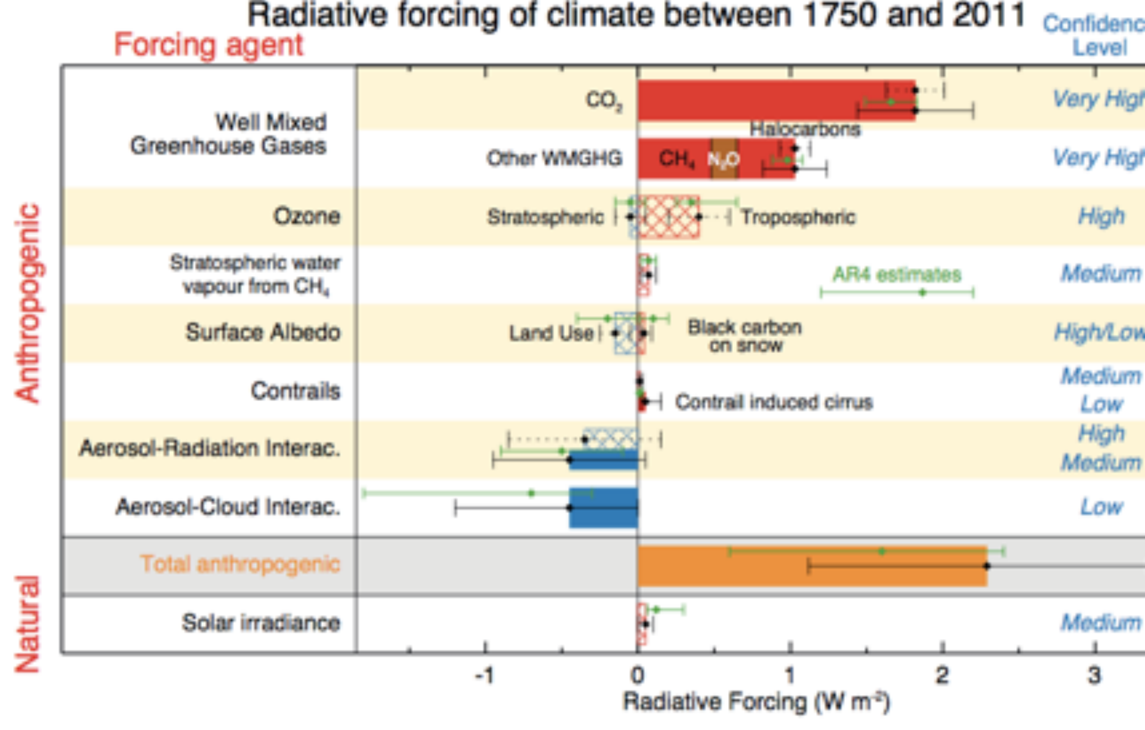
= Notable Contribution of F-K Group Member

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

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

Focus Today: diurnal to centennial variability





Brown et al., 2014

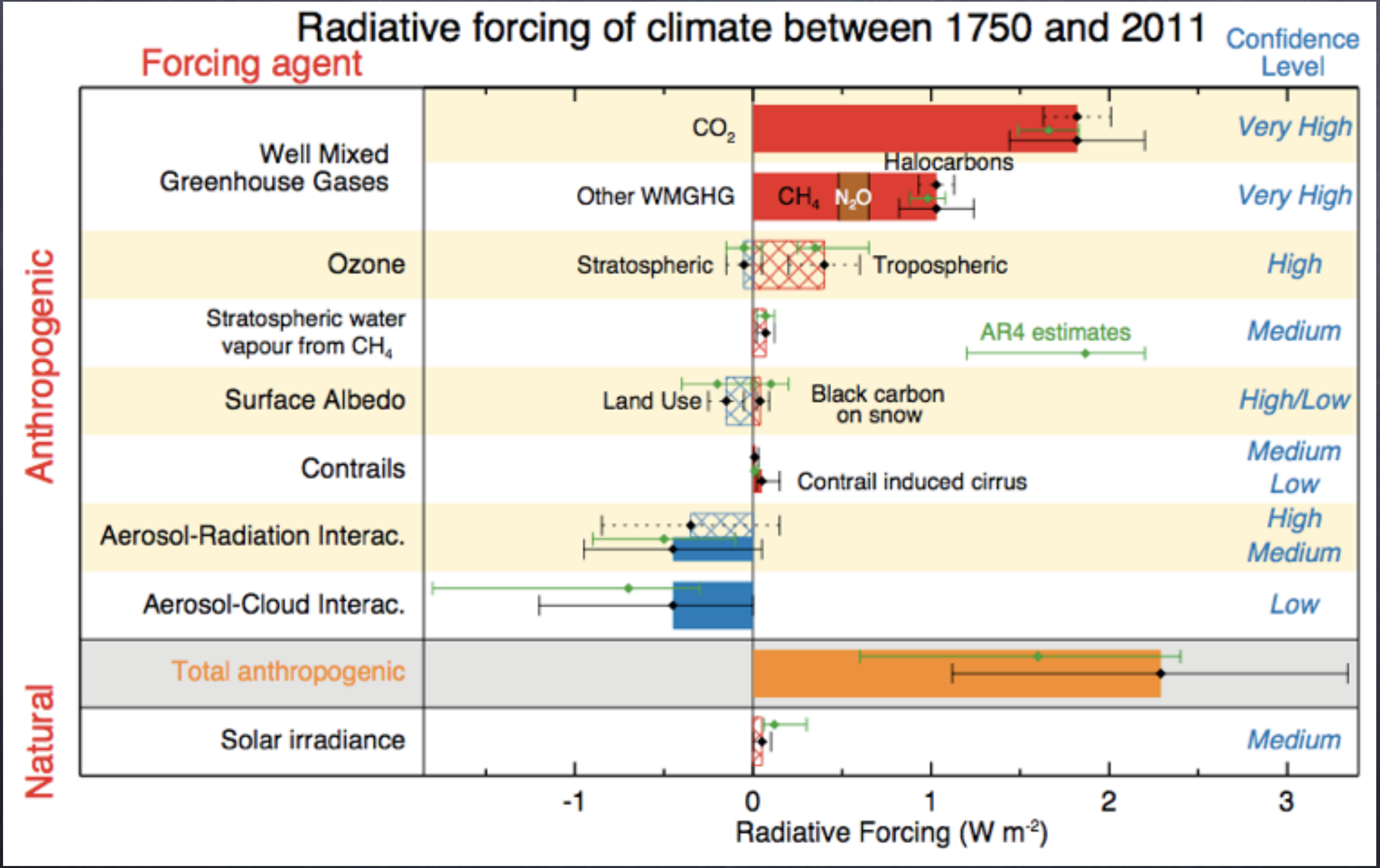
IPCC AR5, 2013

- **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

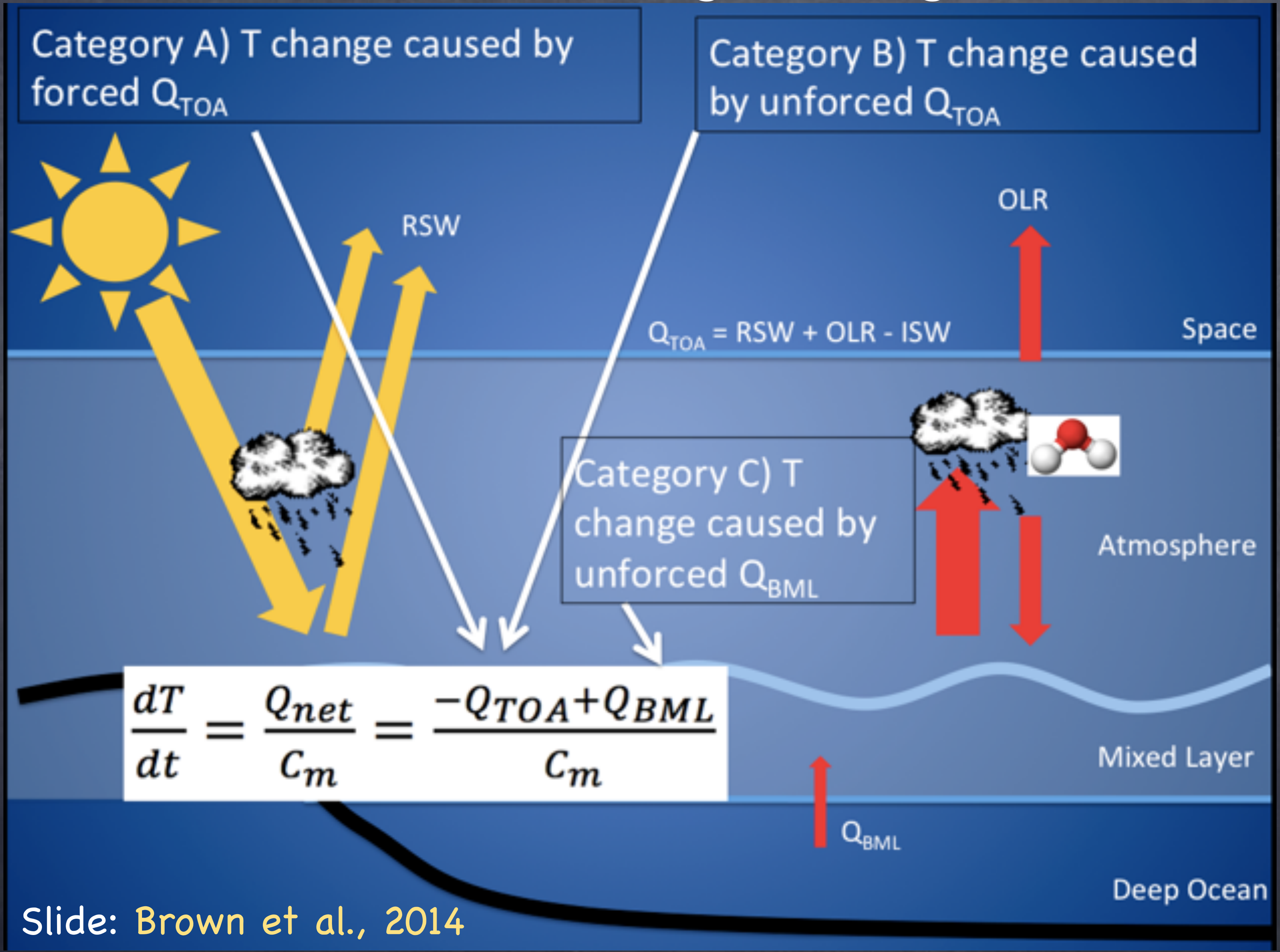
Question: By Show of Hands Indicate Whether You Have Heard that the IPCC is

- A) Wrong
- B) Independent Police Complaints Commission of England & Wales
- C) Together with Al Gore, they invented the internet
- D) The Intergovernmental Panel on Climate Change, a nonpolitical group that reviews peer-reviewed climate science and summarizes it for policymakers, who won a Nobel Peace Prize shared with Al Gore.

Image: Al Gore's Google+

Image: fotobridge.com

Surface Energy Budget



Category A) T change caused by forced Q_{TOA}

Category B) T change caused by unforced Q_{TOA}

Category C) T change caused by unforced Q_{BML}

$$\frac{dT}{dt} = \frac{Q_{net}}{C_m} = \frac{-Q_{TOA}+Q_{BML}}{C_m}$$

Slide: Brown et al., 2014

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

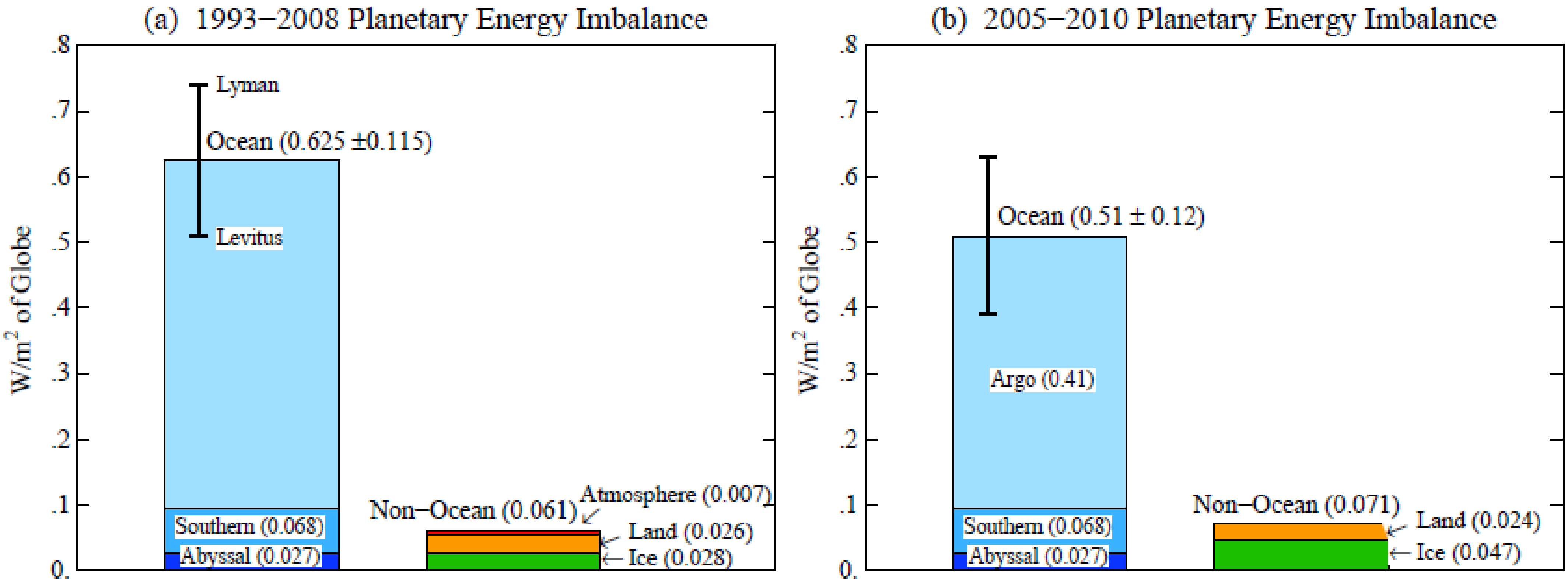
What do hydrographic observations show?

Ocean Heat Content not fixed: Q_{BML} not zero (it even 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



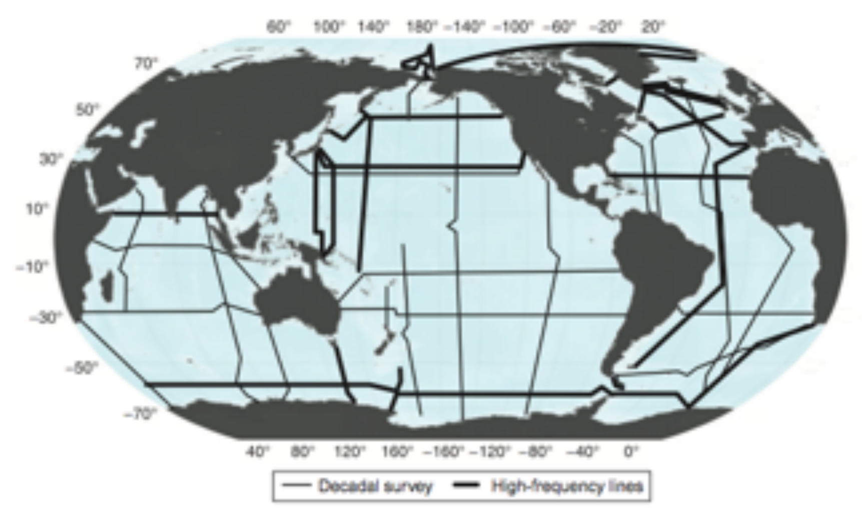
Trad. Hydrography

From the Argo Era

Hansen et al. (2011)

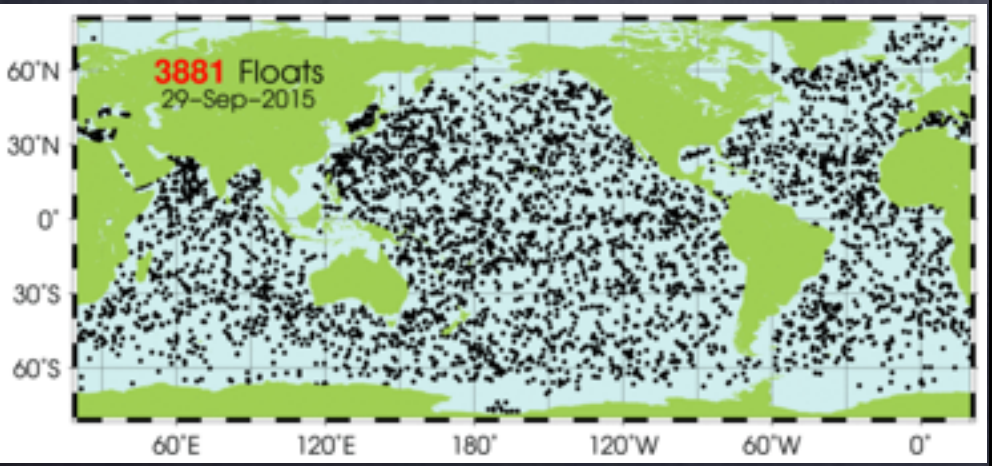
How do we know OHC?

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



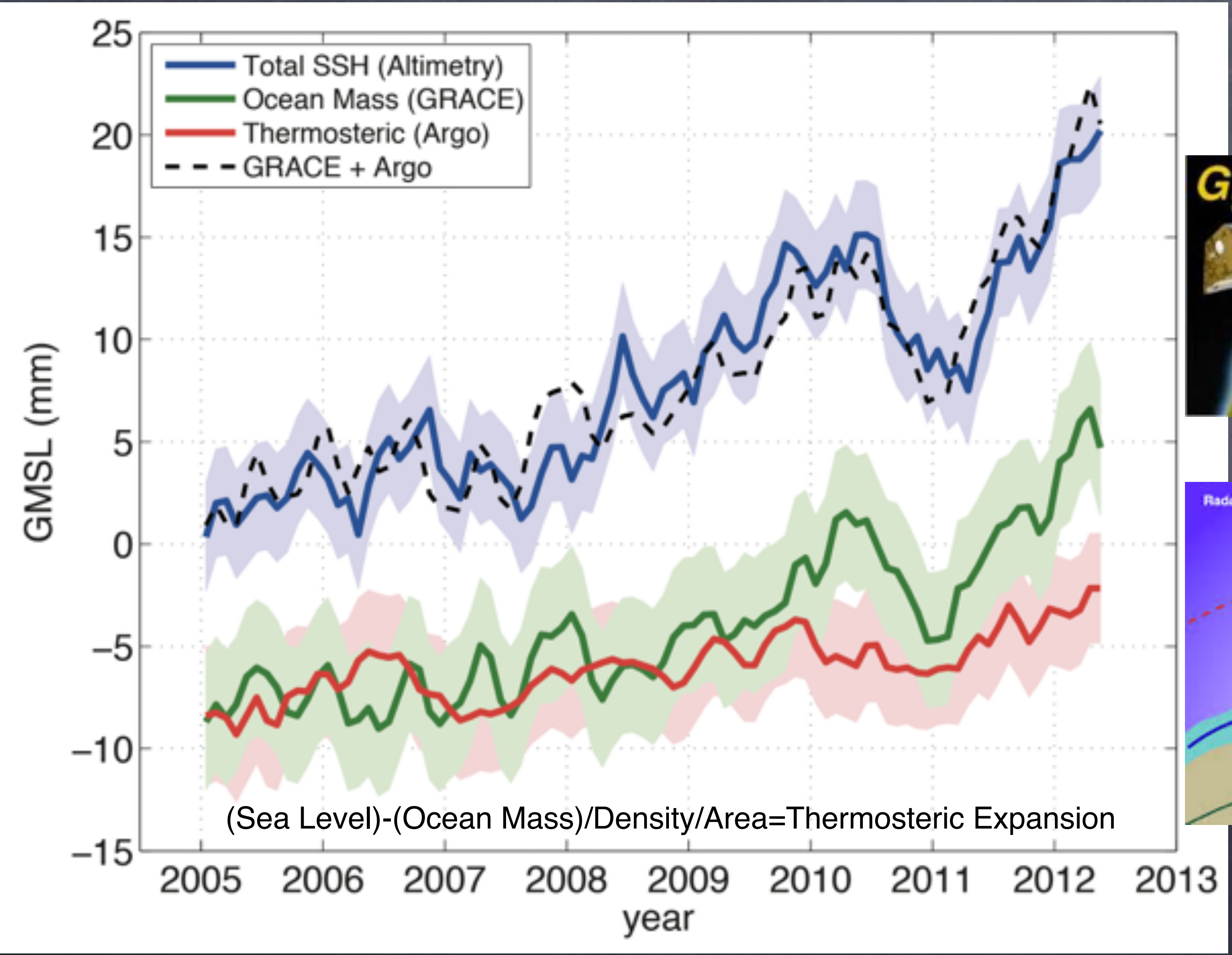
GO-SHIP repeat sections: Siedler et al. 2013

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

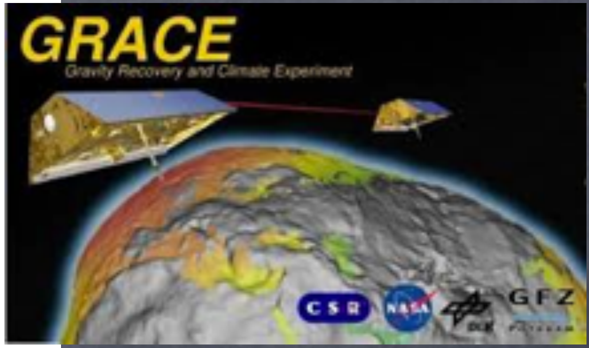


Argo floats presently active

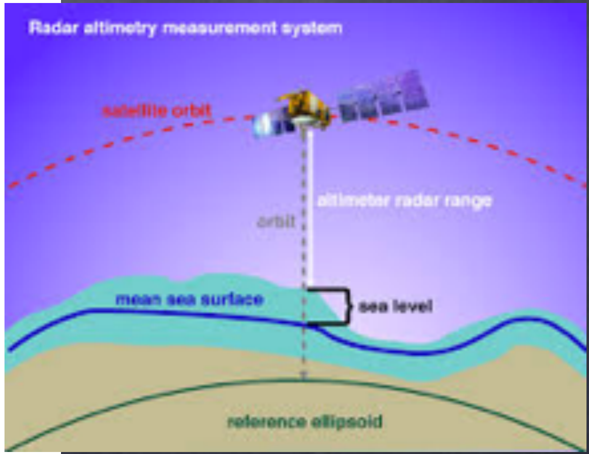
Another reason to care about ocean warming—and to observe it (by subtraction): Sea Level Rise



(Sea Level)-(Ocean Mass)/Density/Area=Thermosteric Expansion



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

=

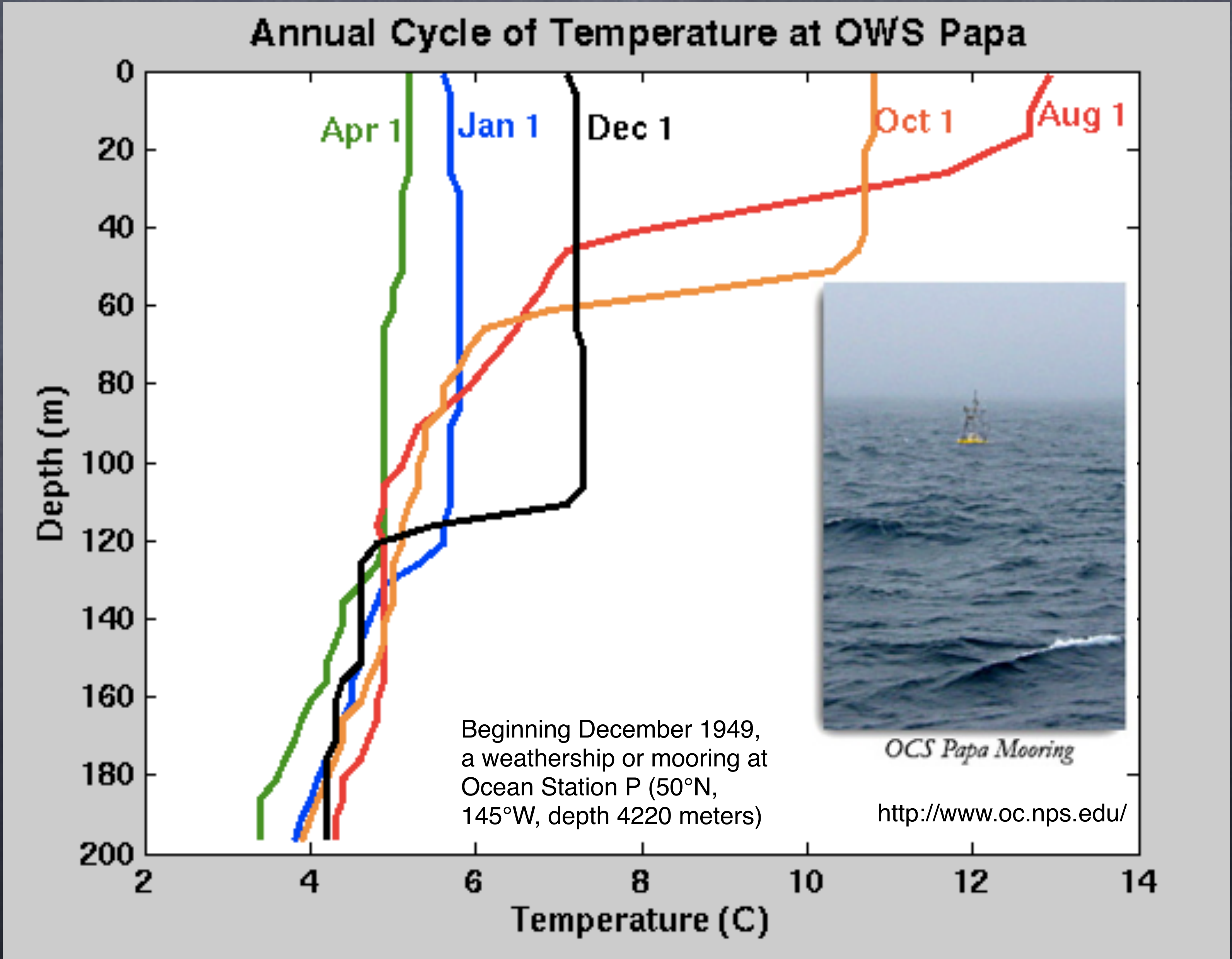
34m Ocean:

0.15K/yr

=1% of

mixed layer

seasonality



Beginning December 1949, a weathership or mooring at Ocean Station P (50°N, 145°W, depth 4220 meters)

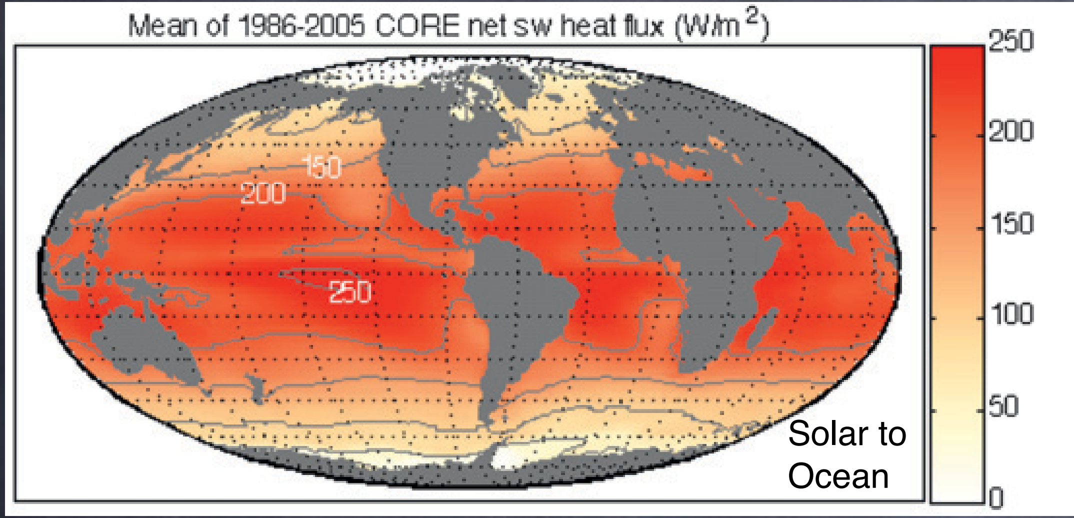
OCS Papa Mooring

http://www.oc.nps.edu/

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

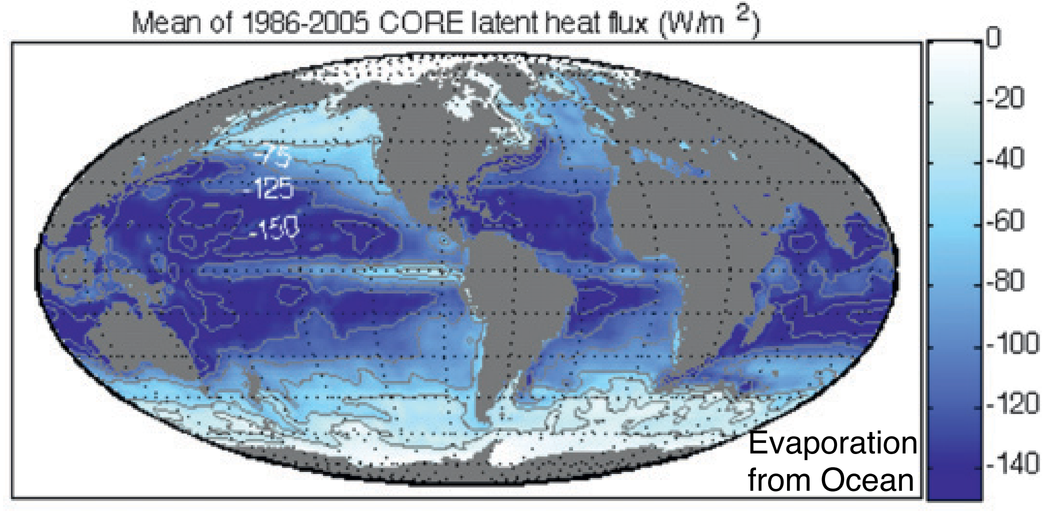
CU, now NCAR

CU, now NCAR



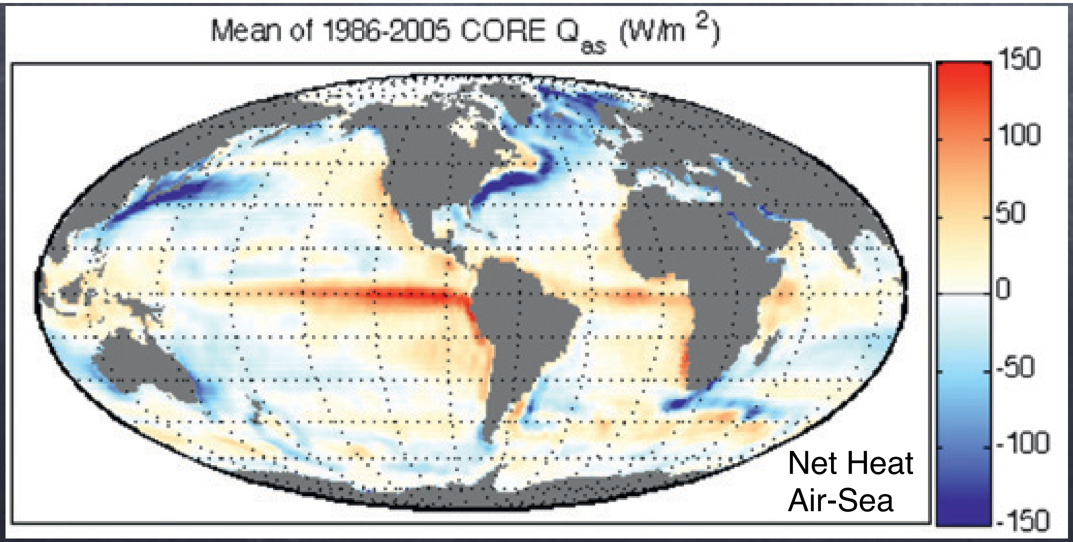
Mean of 1986-2005 CORE net sw heat flux (W/m ^{2})

Solar to Ocean



Mean of 1986-2005 CORE latent heat flux (W/m ^{2})

Evaporation from Ocean



Mean of 1986-2005 CORE Q_{as} (W/m ^{2})

Net Heat Air-Sea

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.

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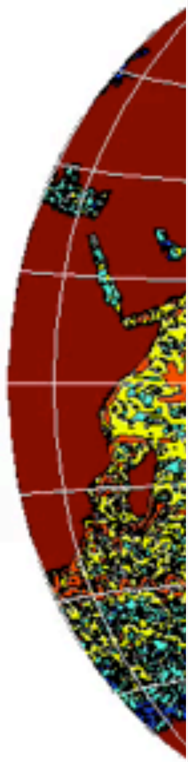
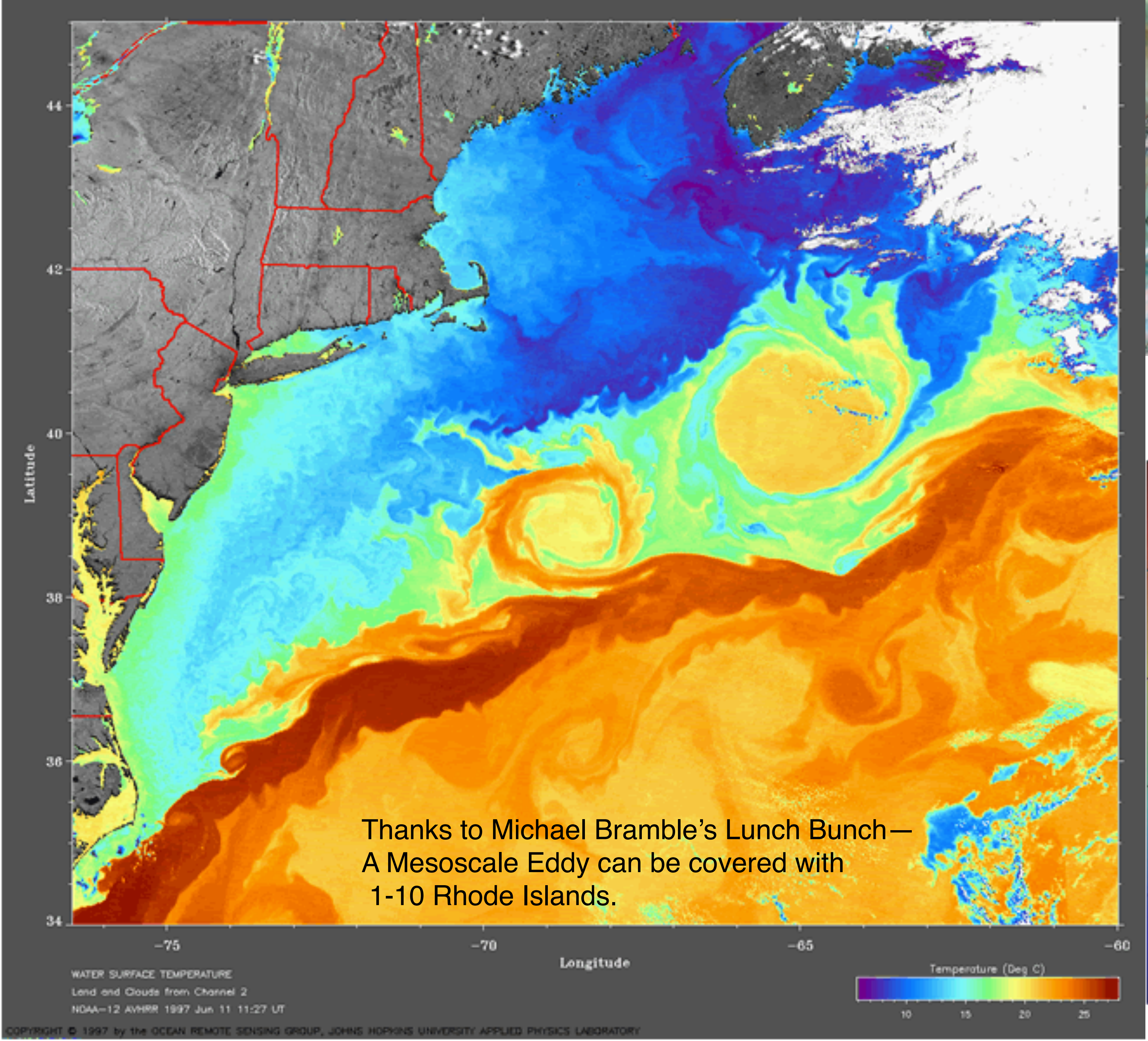
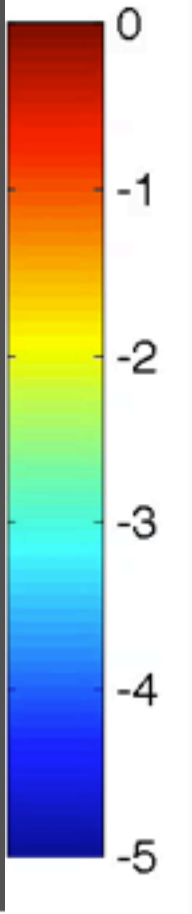
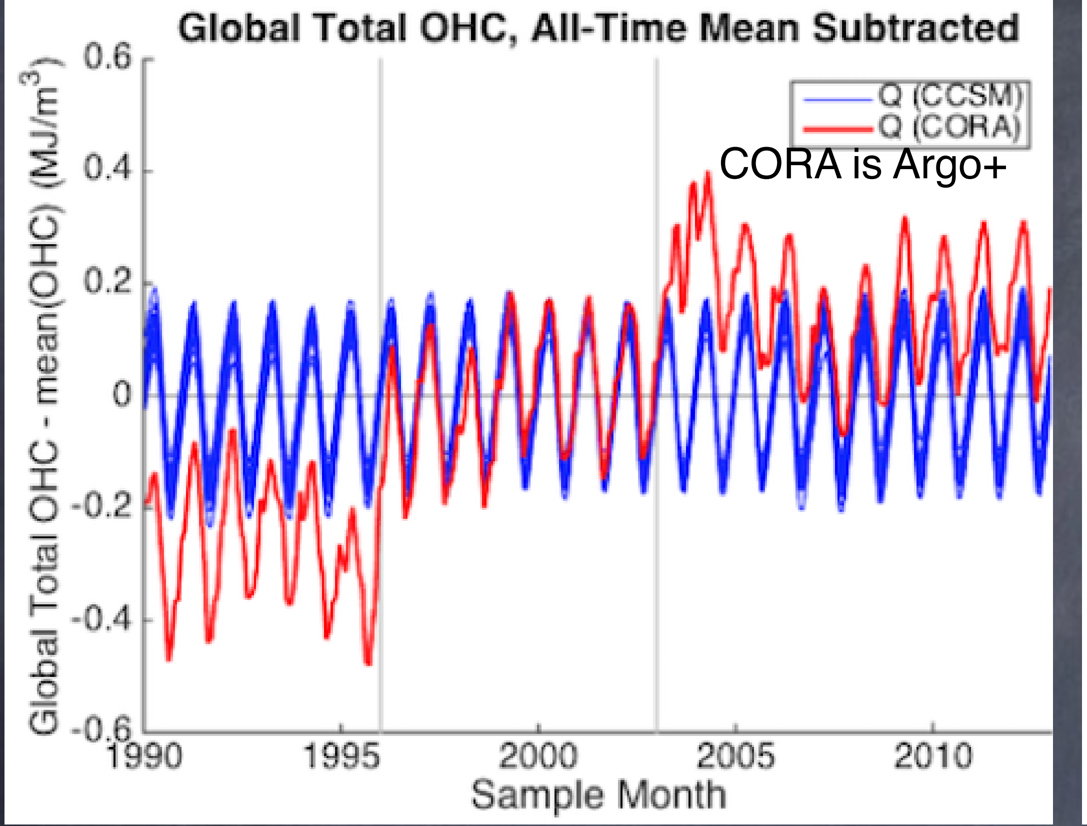
Satellite
view of
flows



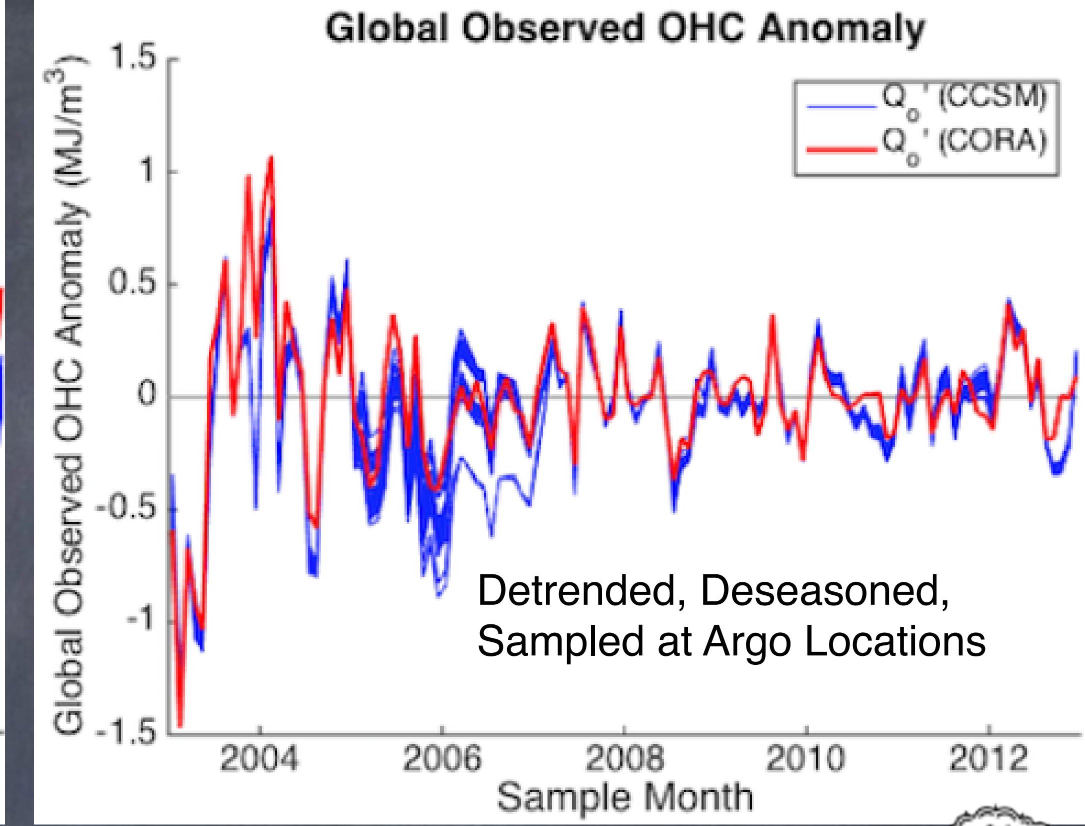


Thanks to Michael Bramble's Lunch Bunch—
A Mesoscale Eddy can be covered with
1-10 Rhode Islands.





CORA is Argo+



Detrended, Deseasoned,
Sampled at Argo Locations

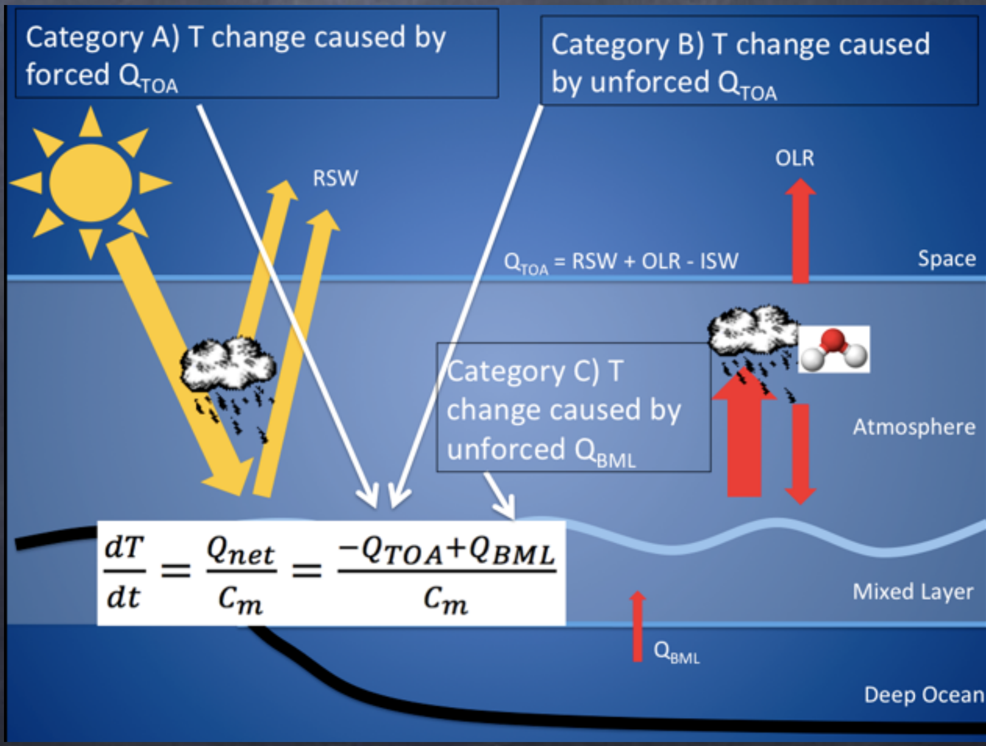
Sophisticated analysis to overcome Ship & Argo sampling problems—inherent uncertainty, O(0.2W/m^2), on interannual to decadal timescales in global average.
O(10W/m^2) without analysis.

CU, soon
Brown

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

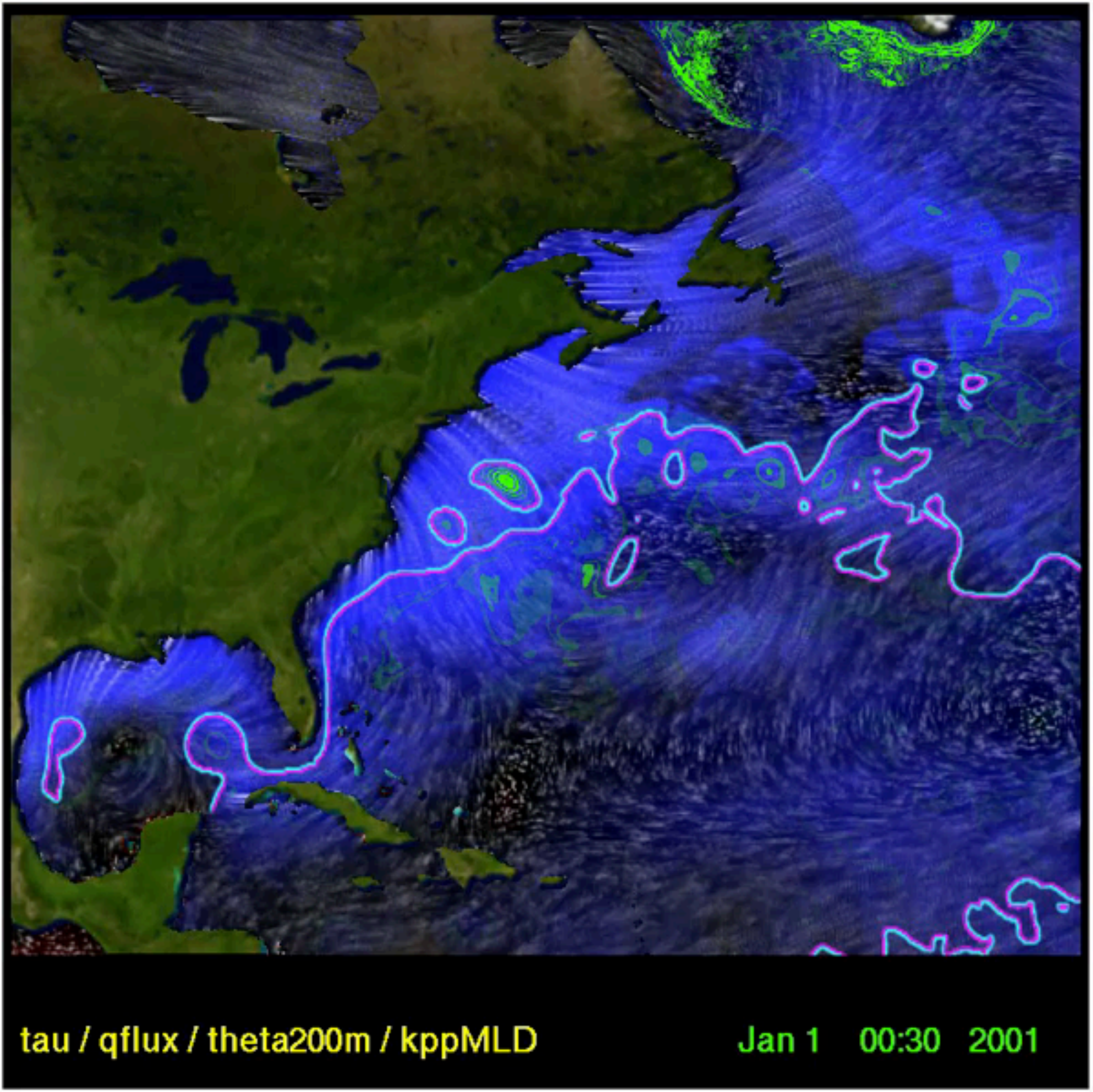
Presence of observable variability

- 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 & Satellite agree.



$$\frac{dT}{dt} = \frac{Q_{net}}{C_m} = \frac{-Q_{TOA}+Q_{BML}}{C_m}$$

- **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.

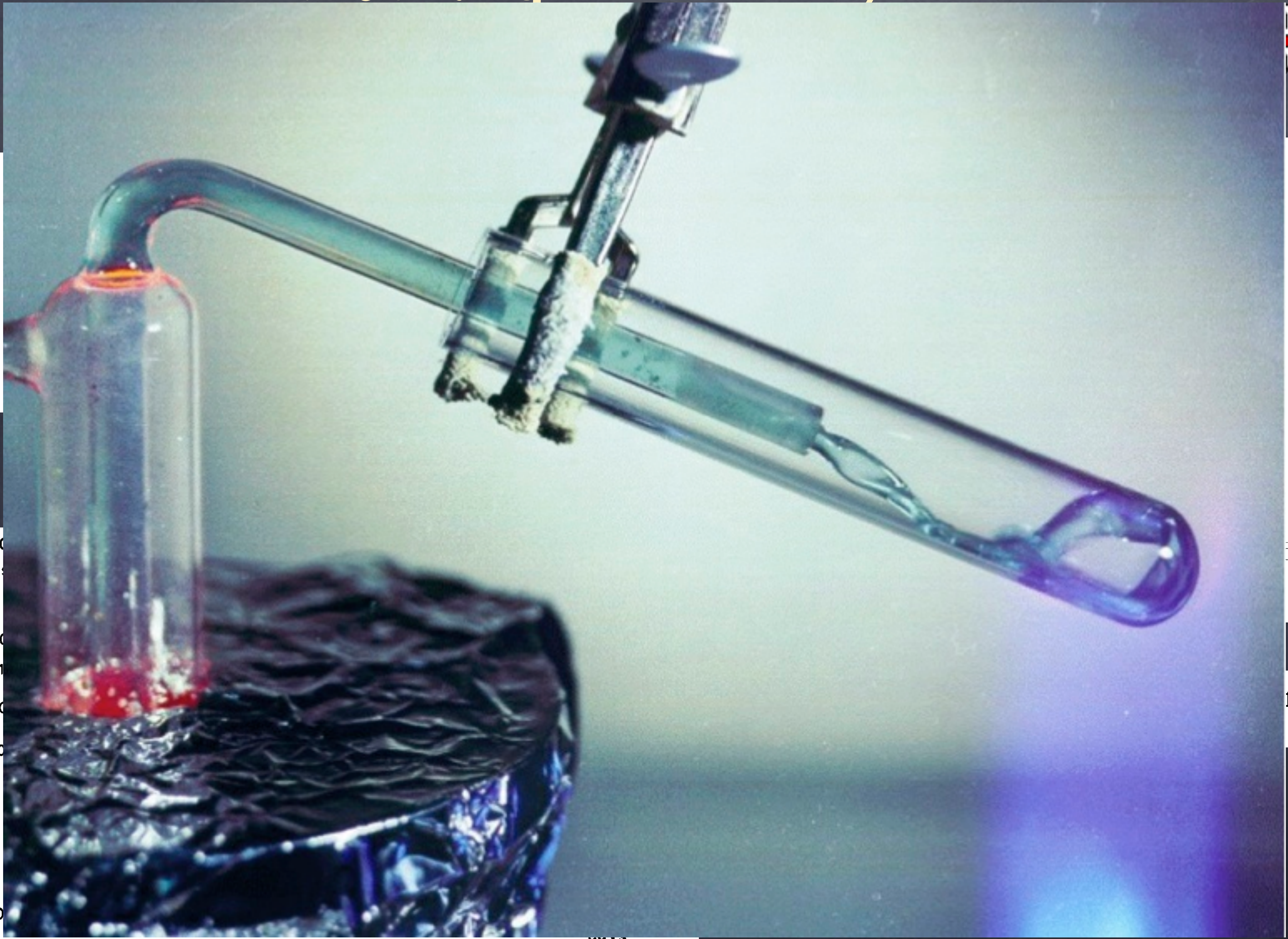


Weather,
Atmosphere
Fast

Ocean,
Climate
Slow

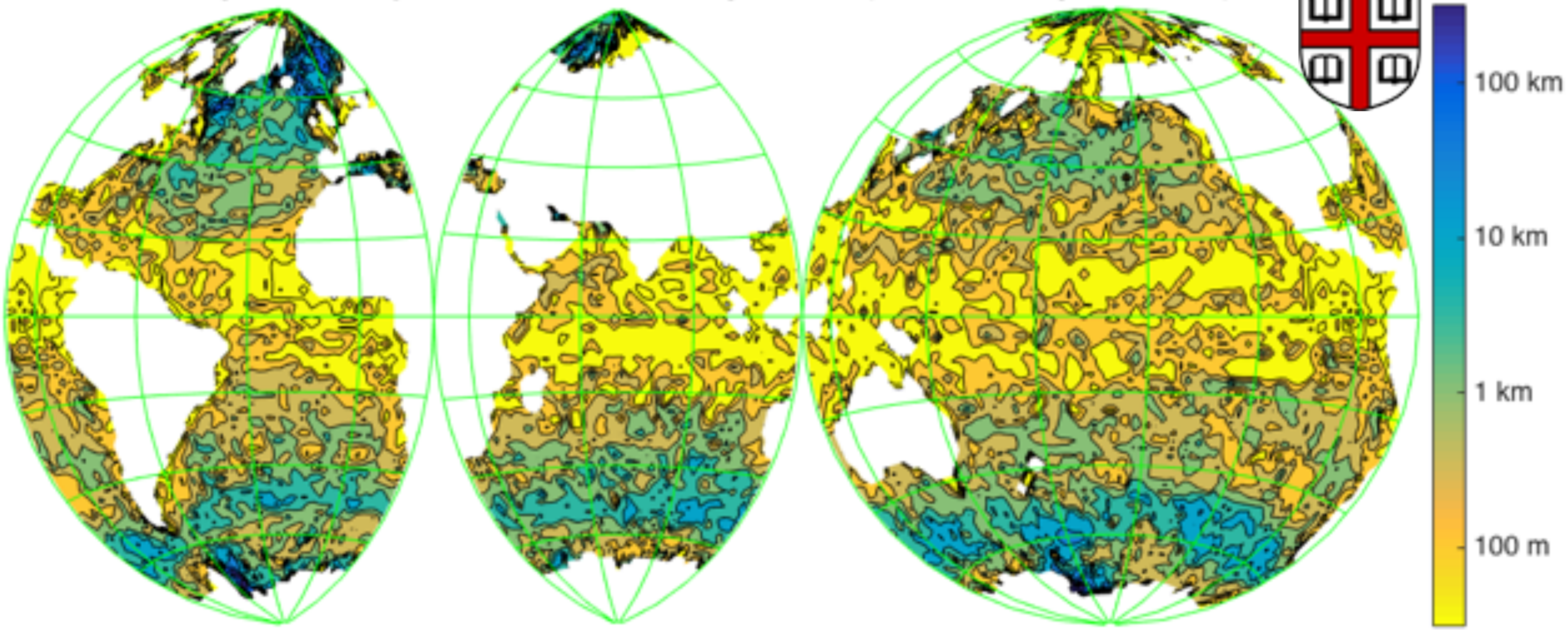
3.4m of ocean water has same heat capacity as the WHOLE atmosphere

Modeling of variability

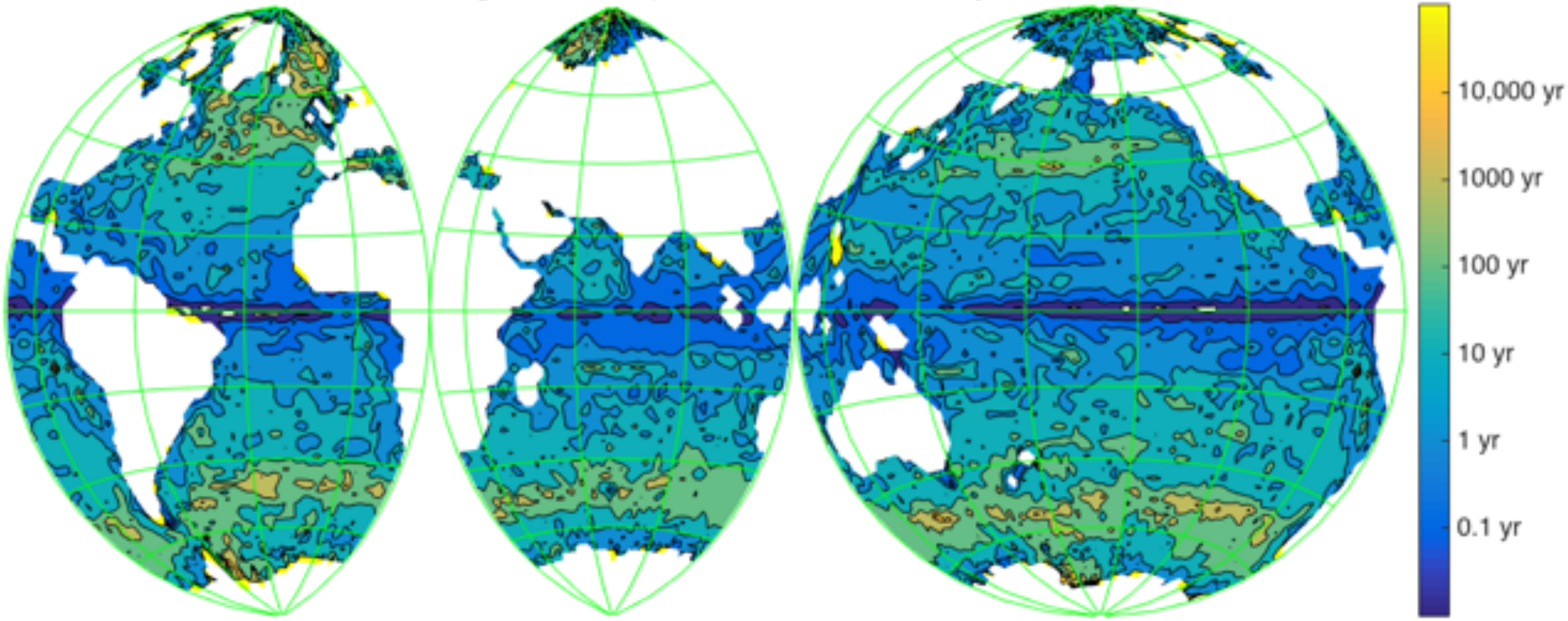


Consider lots of 1D Oceans: one per watermass

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



Equivalent Depths of Watermasses by Source (Gebbie & Huybers, 2011)

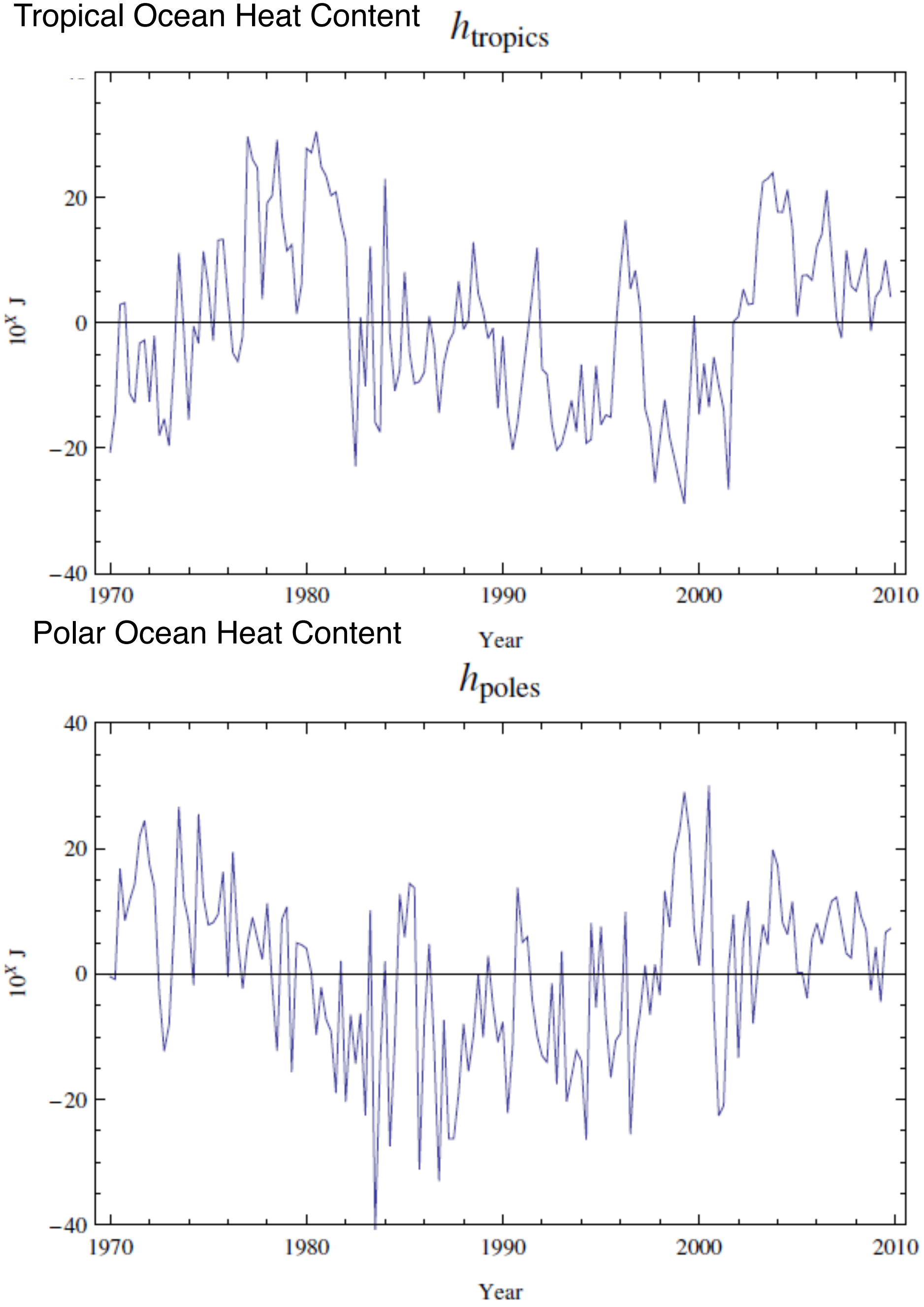


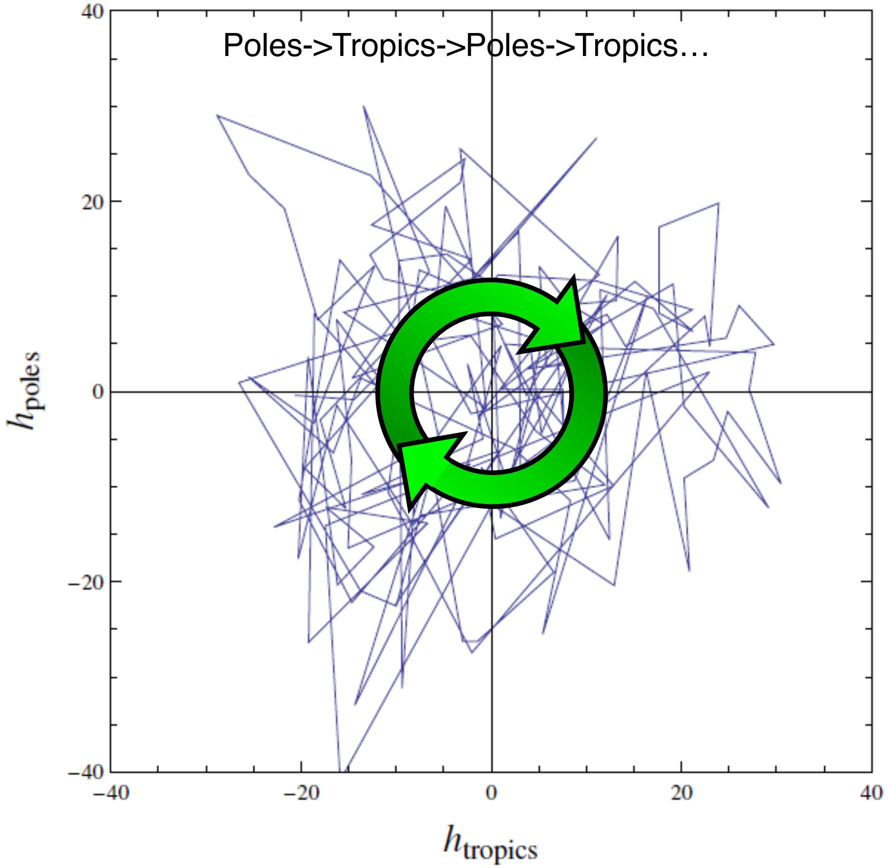
Ekman Flushing Timescale (ECCOv4 + Gebbie & Huybers, 2011)

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

Tropical Ocean Heat Content

Polar Ocean Heat Content





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.

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/m^2)

Models get better every generation due to improved resolution and parameterizations

What does it take to make these improvements?

CU, now NCAR

CU, now NCAR

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.

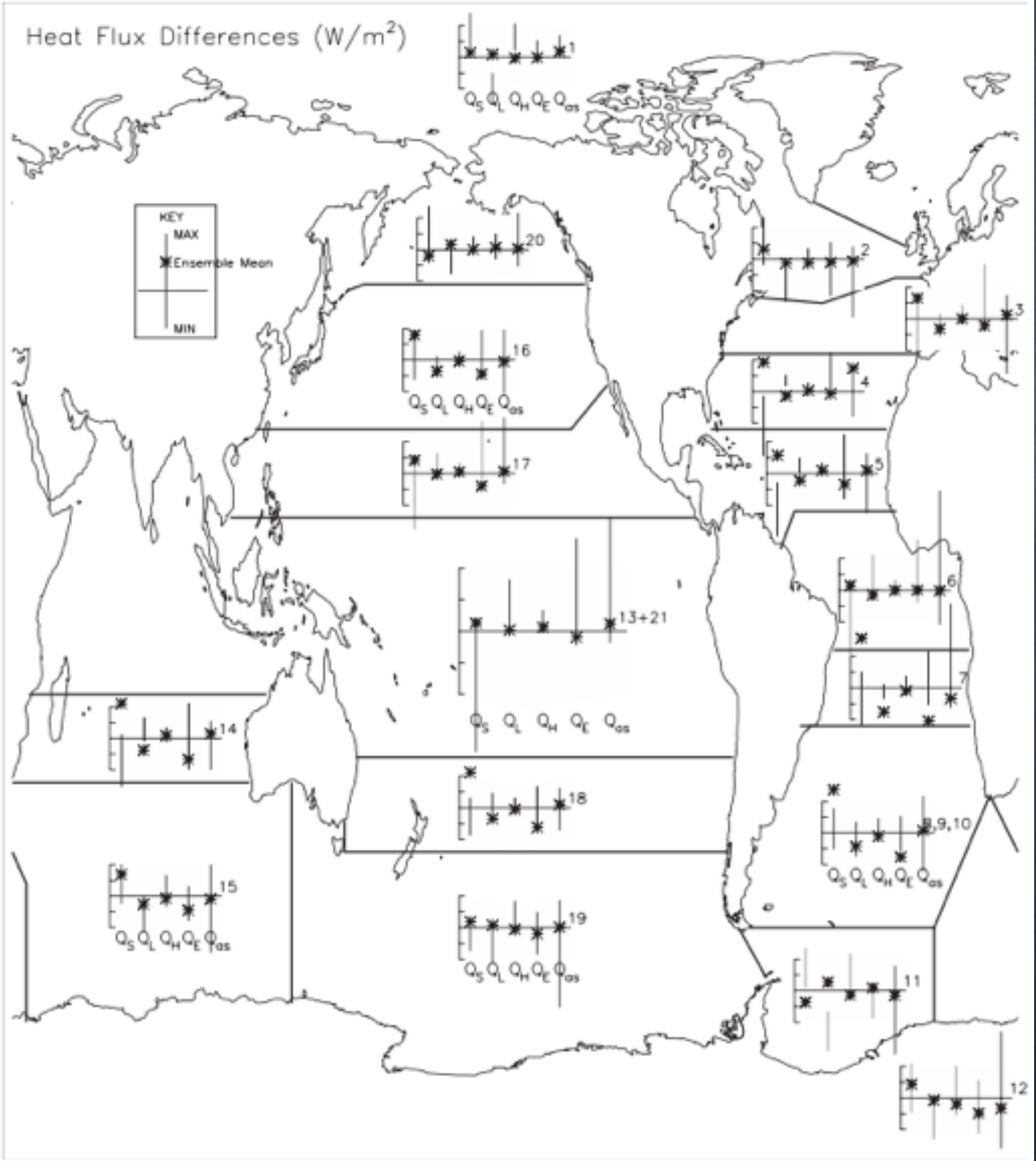
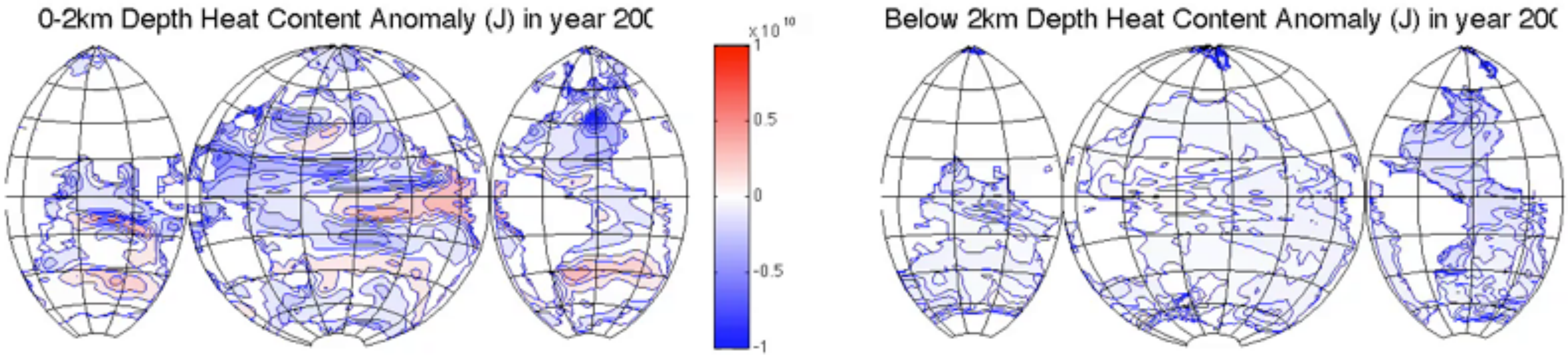


FIG. 4. Regional averages of the CCSM4 20C ensemble mean heat flux components differenced with the CORE

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

Doesn't even include mesoscale eddies

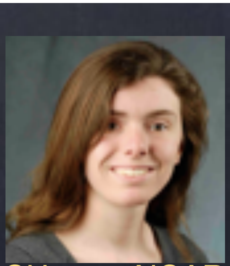


Contours = 4 units

Contours = 1 unit

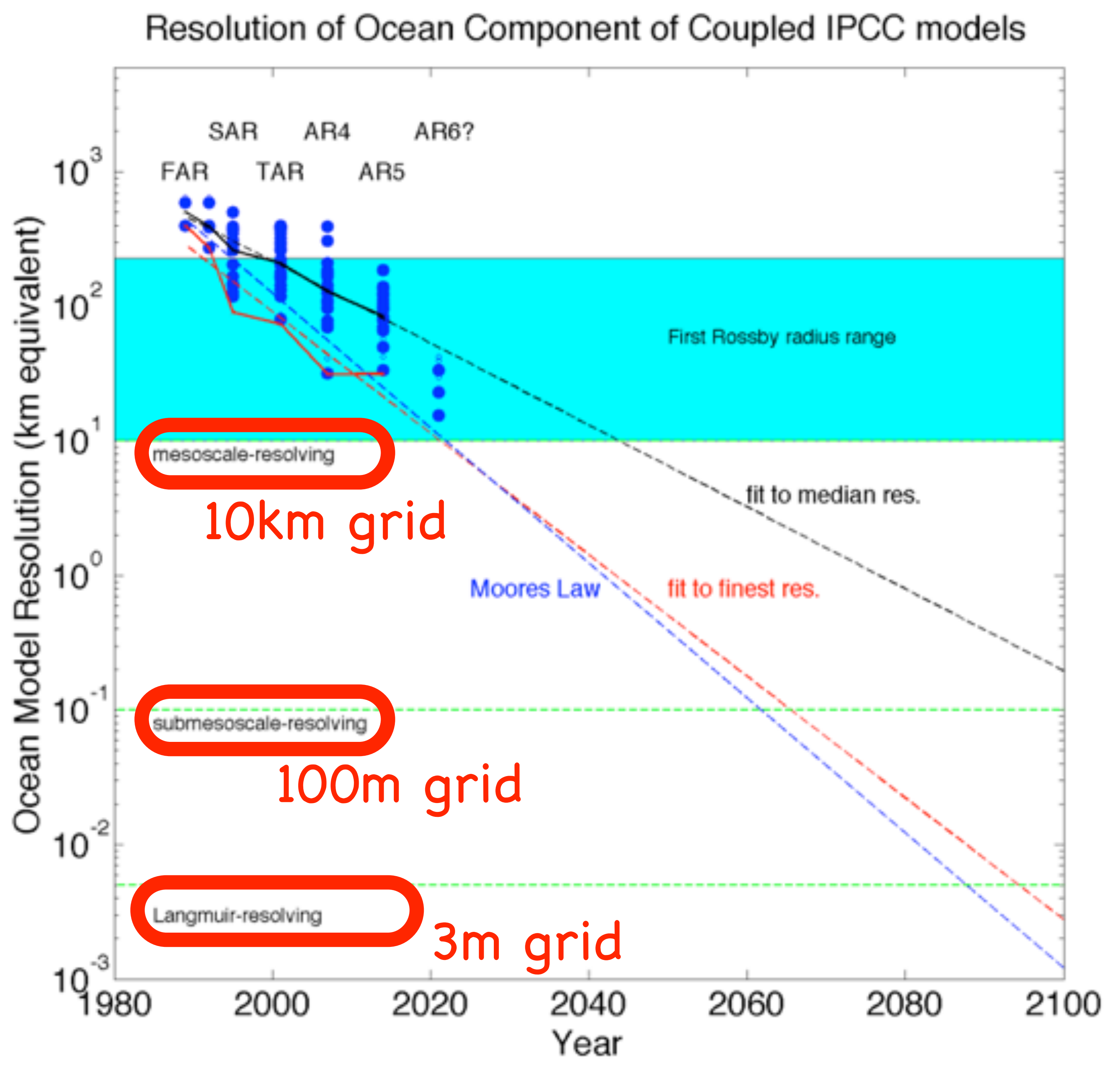
From the >1000yr steady forcing CCSM3.5 runs of Stevenson et al. 2012

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



CU, now NCAR

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

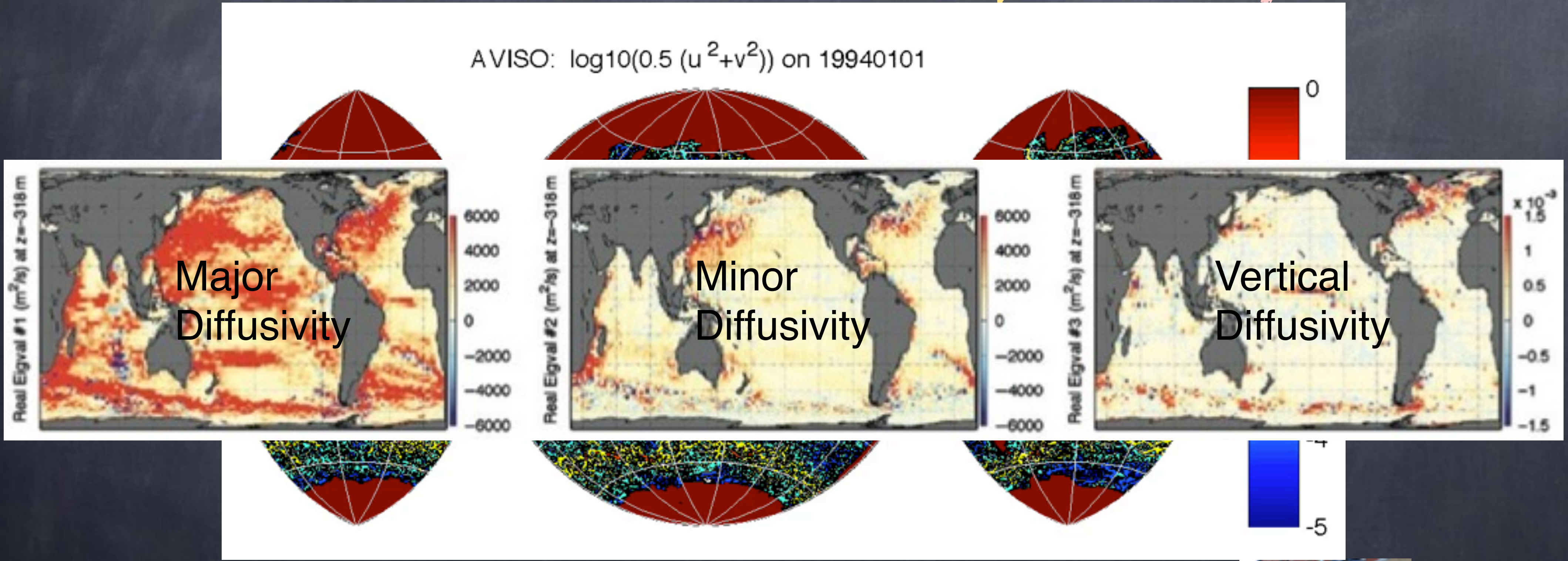
Anisotropic Mesoscale Eddy Advective & Diffusive Transport

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

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.

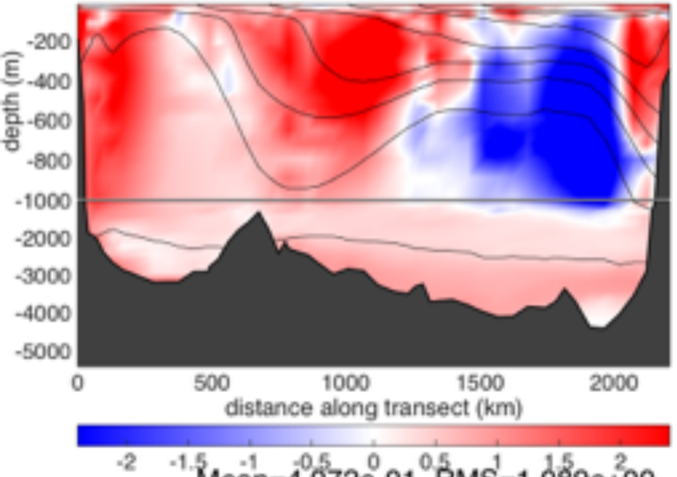

Brown now
Montana State


CU now
U. Cambridge

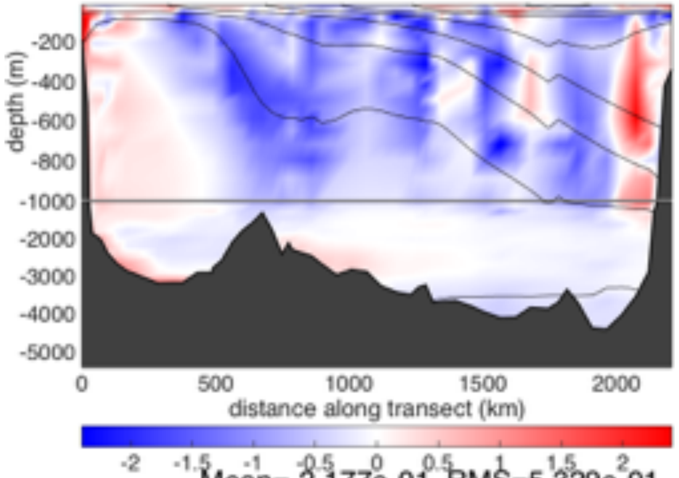
Along transects

Control: Isotropic

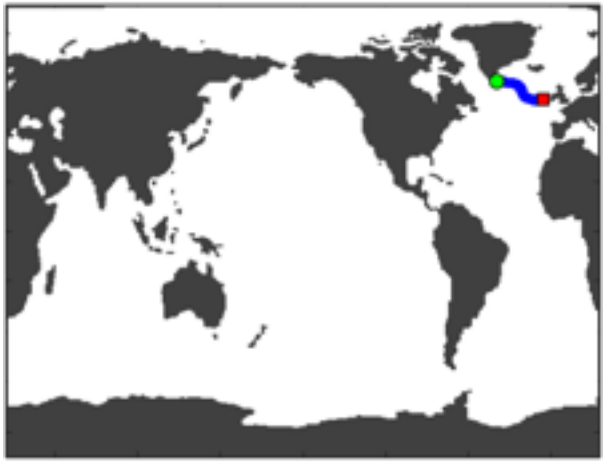
Anisotropic

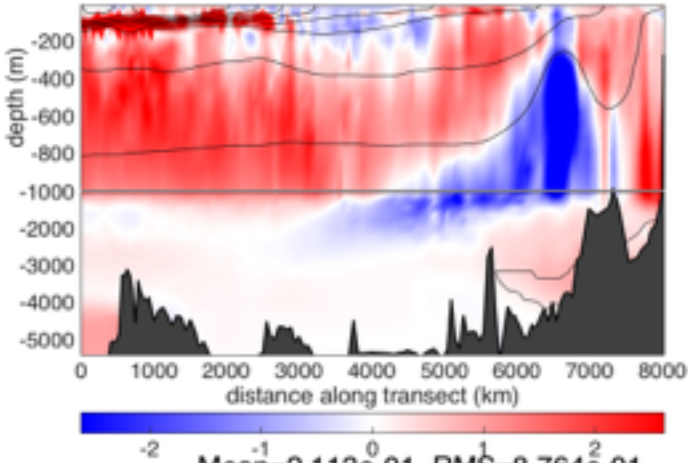

temp bias - bass - a01e

Mean=4.072e-01 RMS=1.089e+00

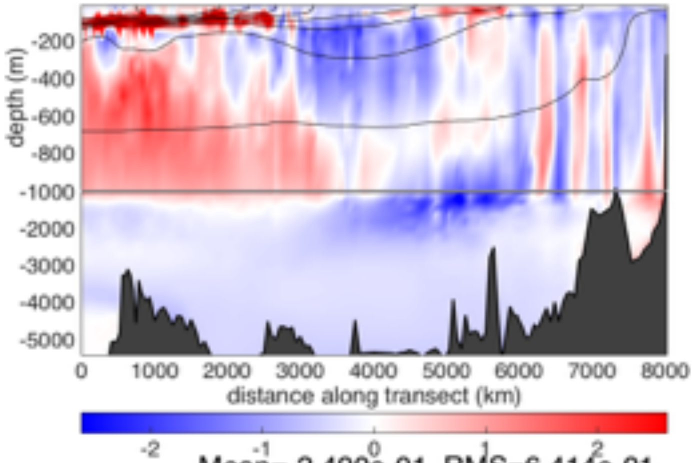

temp bias - flow - a01e

Mean=-2.177e-01 RMS=5.329e-01

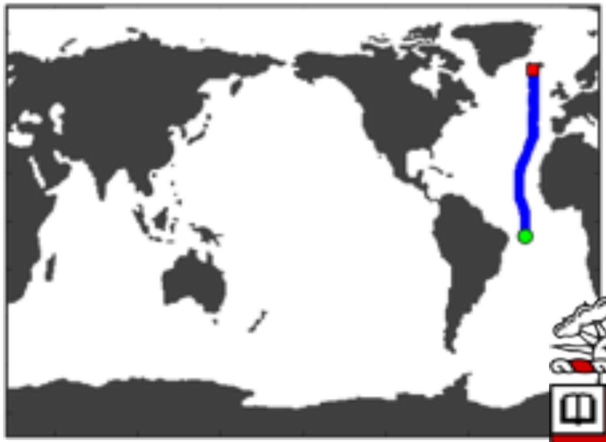

Map for a01e


temp bias - bass - a16n$_2$003a

Mean=2.113e-01 RMS=8.764e-01


temp bias - flow - a16n$_2$003a

Mean=-2.490e-01 RMS=6.414e-01

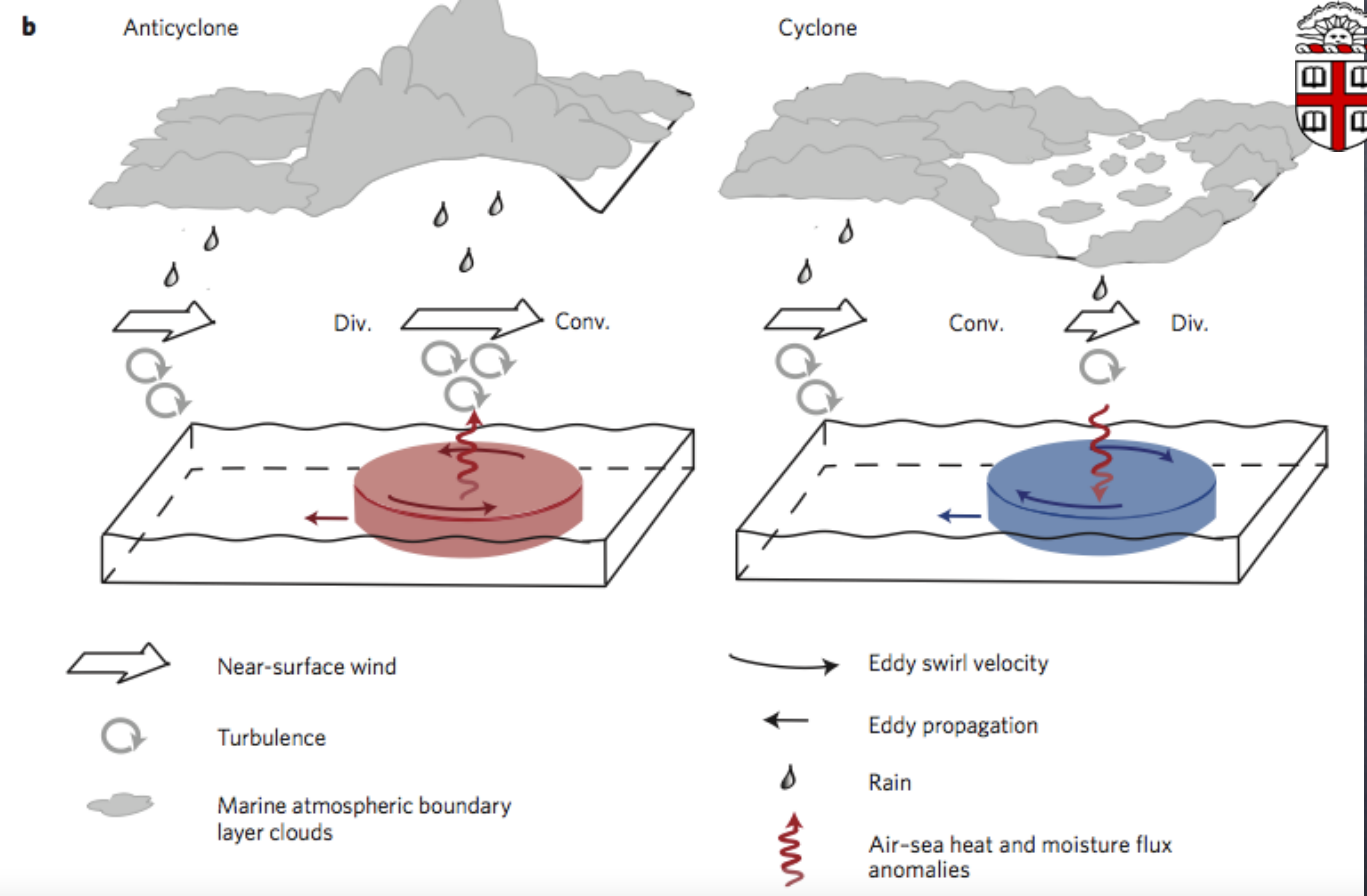

Map for a16n$_2$003a


Brown now
Montana State

Anisotropy often reduces biases:

pCFC by up to 24%
Temp by up to 48%
Salinity by up to 63%

Mesoscale Eddies have a profound effect on Q_{BML}
Even small changes affect surface warming budget



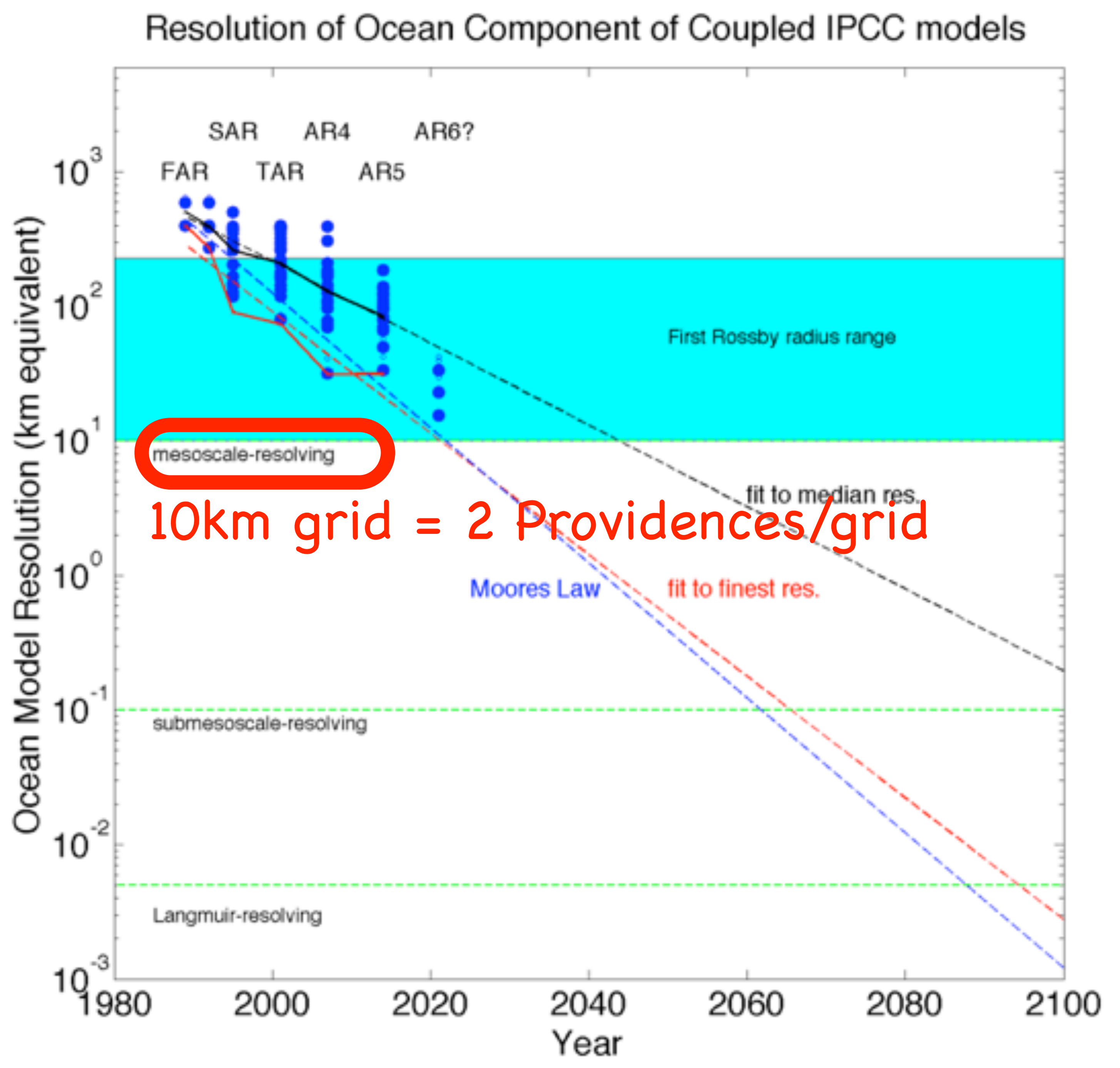
Complicated Mesoscale Eddy Air-Sea Feedbacks? Resolve!

Effect on net air-sea fluxes observed, parameterization unknown.

Bryan et al. 2010, Frenger et al. 2013

What about modeling important processes in climate models?

Don't we have big enough computers? or won't we soon?



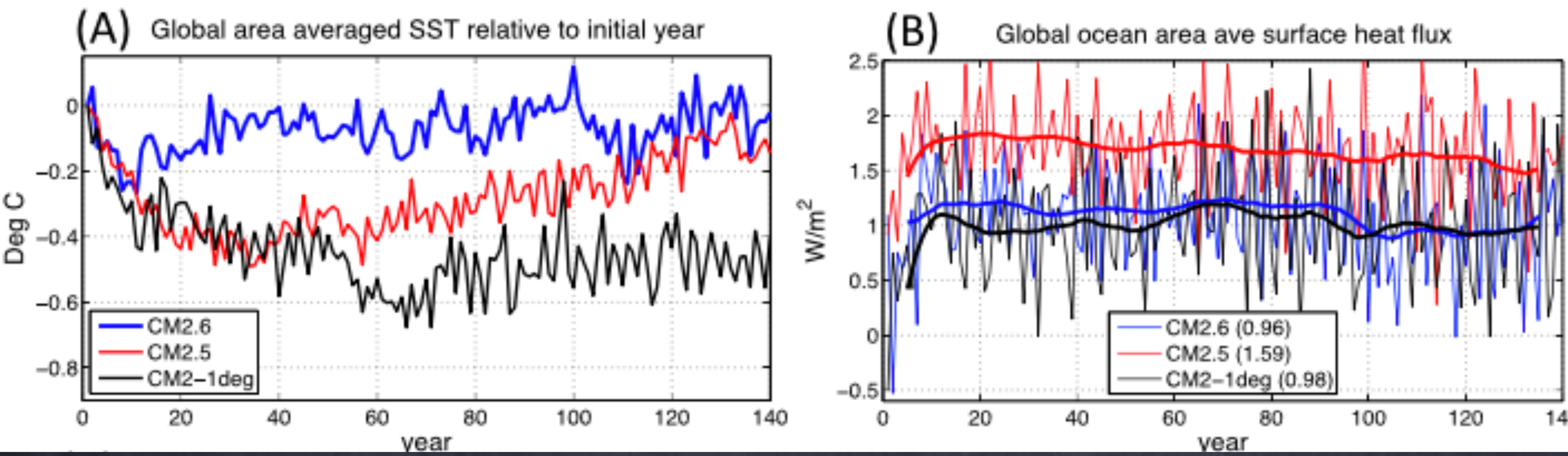
10km grid = 2 Providences/grid

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/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.

Estimating the Circulation & Climate of the Ocean

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.

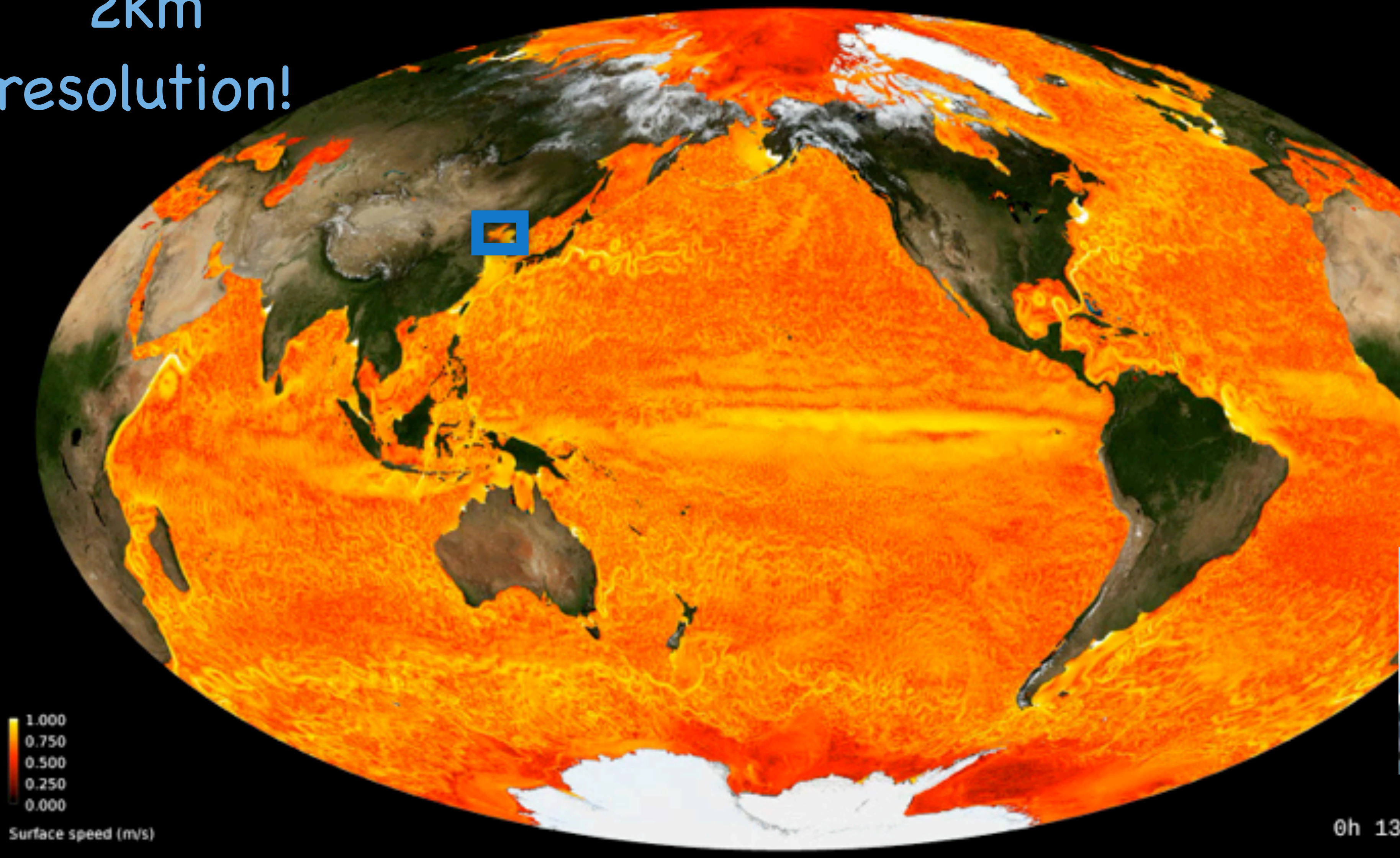
MILLIONS OF CPUHRS!

Brown

Estimating the Circulation & Climate of the Ocean

LLC4320 Model

2km resolution!



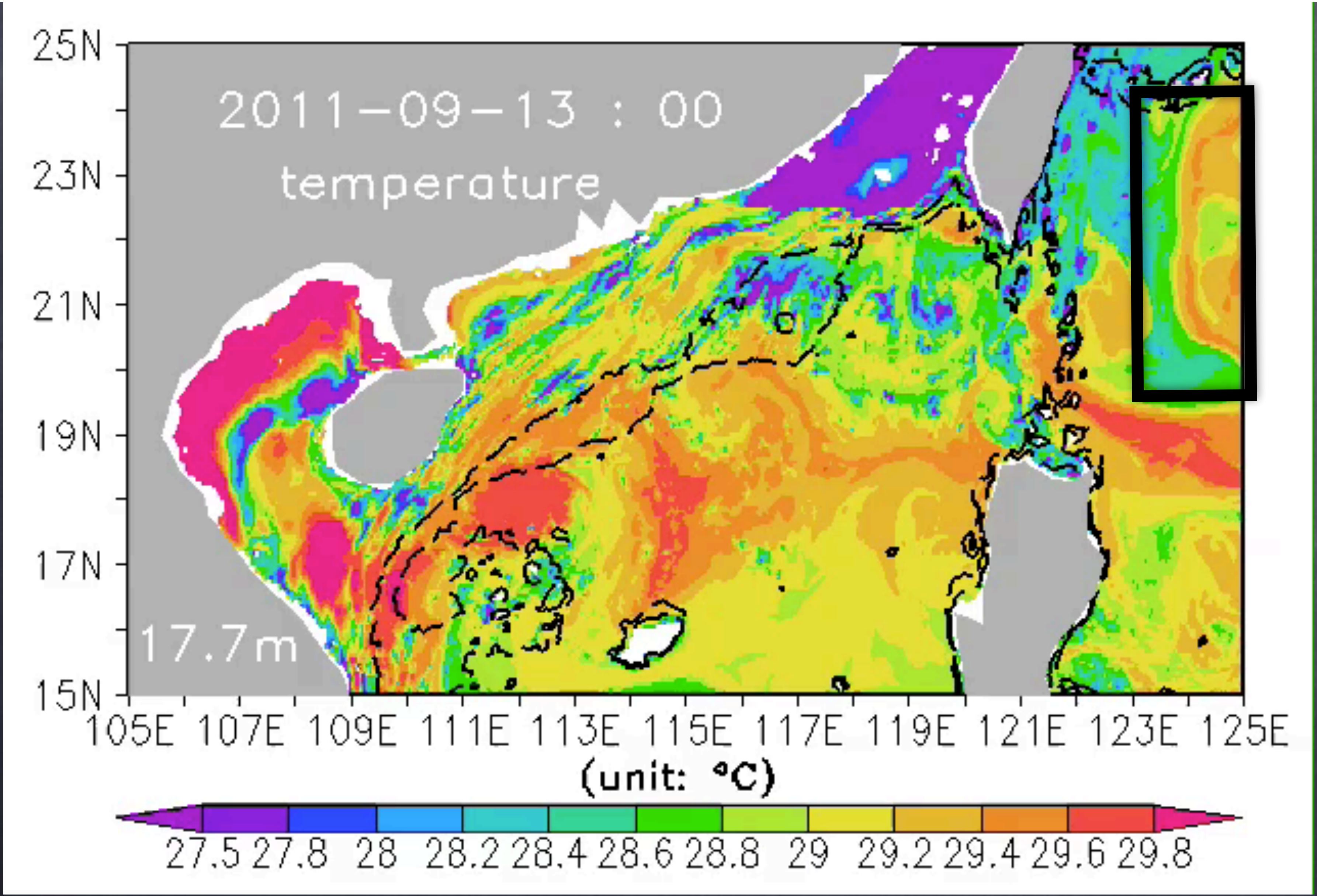
0h 13 Sep 2011

Movie:
D. Menemenlis

Brown

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.

LLC4320 Model



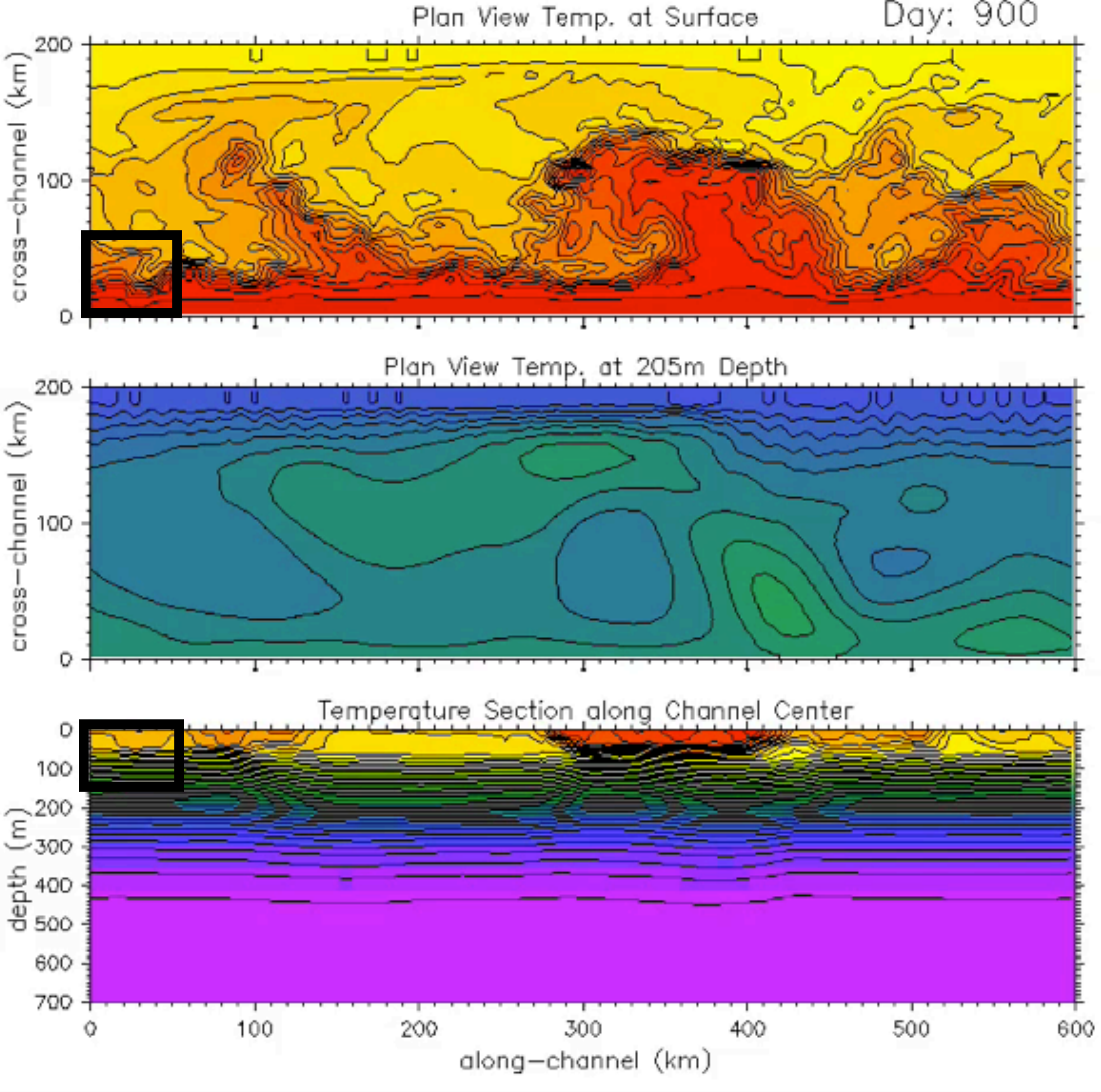
Movie:
Z. Jing

Brown Visitor from S. China Sea Institute of Ocean.

Local Analysis: Z. Jing, Y. Qi, BFK, Y. Du, and S. Lian. Seasonal thermal fronts and their associations with monsoon forcing on the continental shelf of northern South China Sea: Satellite measurements and three repeated field surveys in winter, spring and summer. Journal of Geophysical Research-Oceans, August 2015. Submitted.

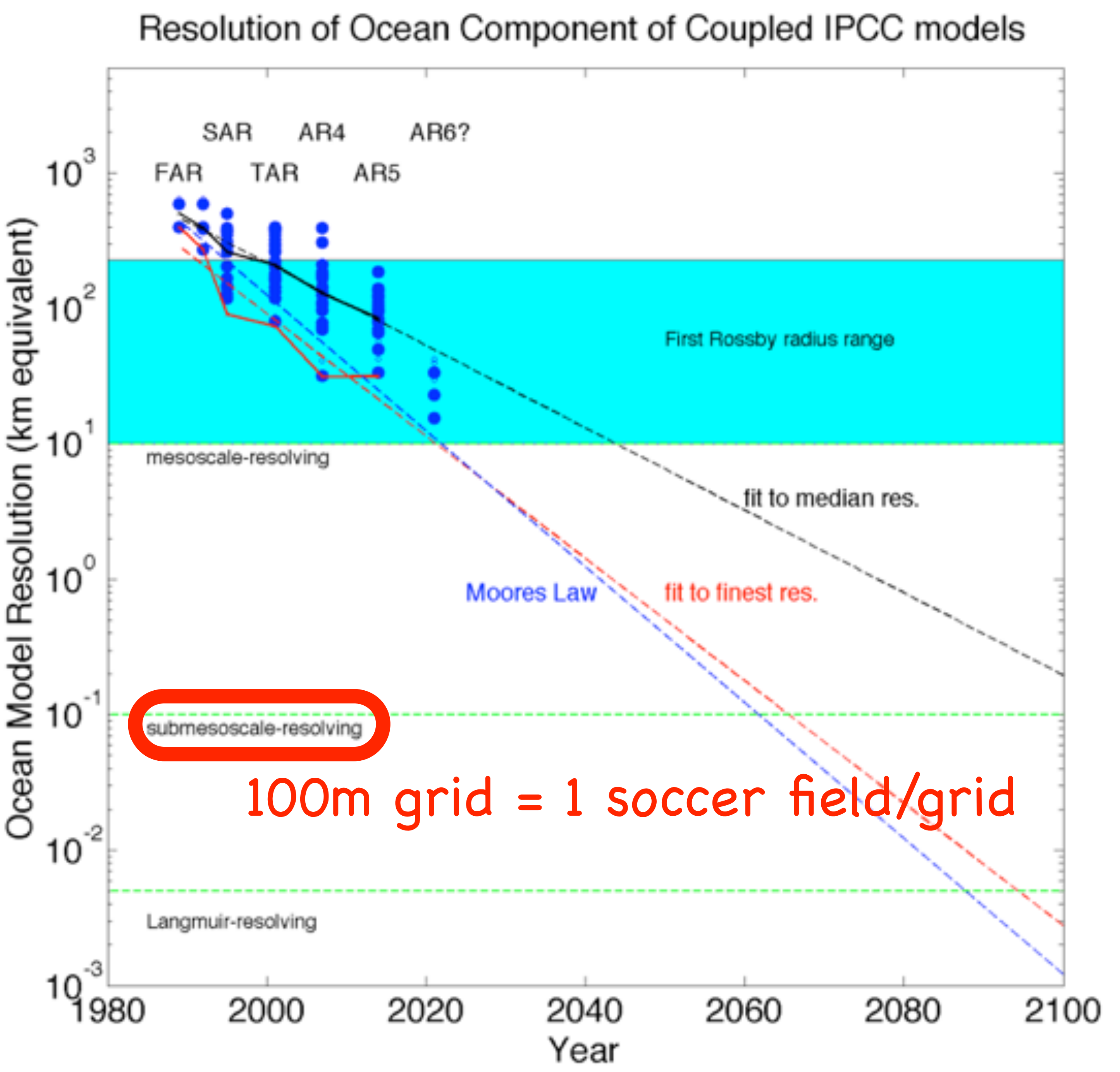
200km x 600km x 700m domain

1000 Day Simulation



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

What about modeling important processes in climate models? Don't we have big enough computers? or won't we soon?


Resolution of Ocean Component of Coupled IPCC models

100m grid = 1 soccer field/grid

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)

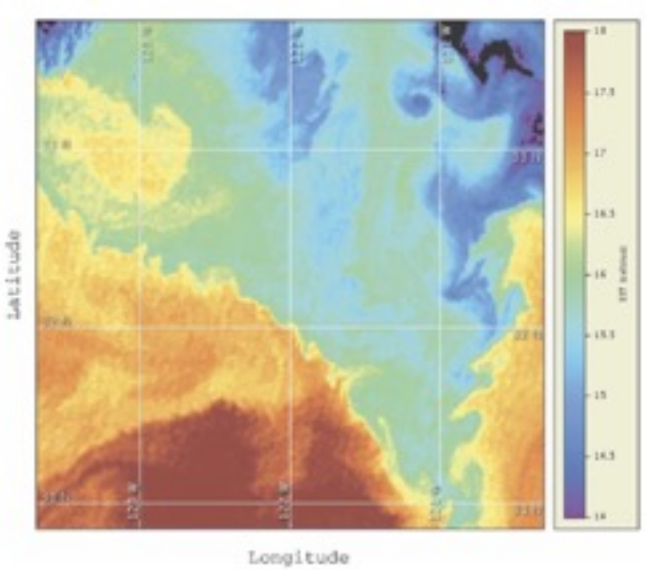
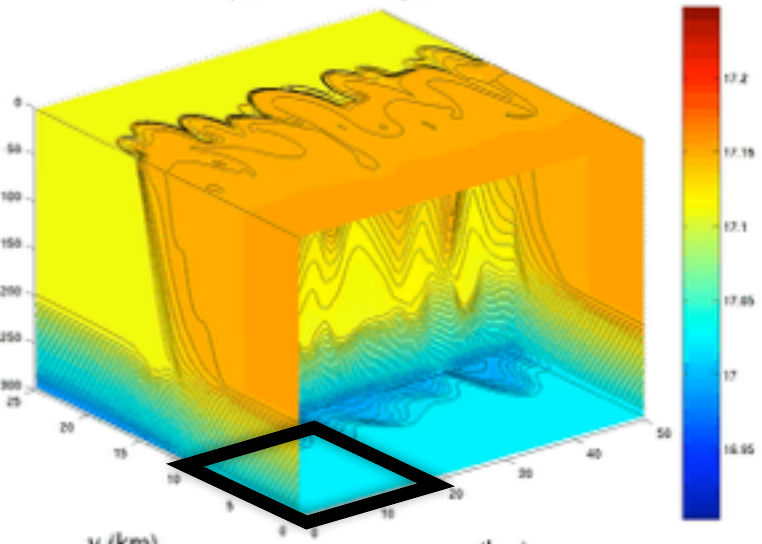


Fig. 16. Sea surface temperature measured at 1832 UTC 3 Jan 2006 off Point Conception in the California Current from CoastWatch (http://coastwatch.pfeg.noaa.gov). The fronts between recently

Temperature on day:17.375

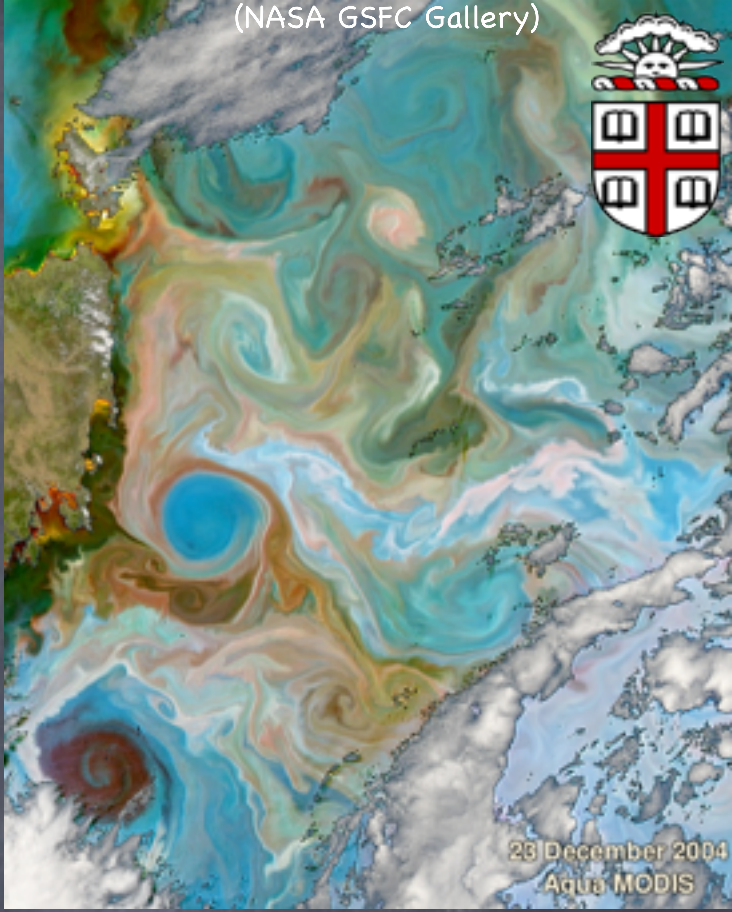


- Fronts
- Eddies
- Ro=O(1)
- Ri=O(1)
- near-surface (H=100m)
- 1-10km, days

Eddy processes often baroclinic instability

Parameterizations = BFK et al (08-11).

(NASA GSFC Gallery)



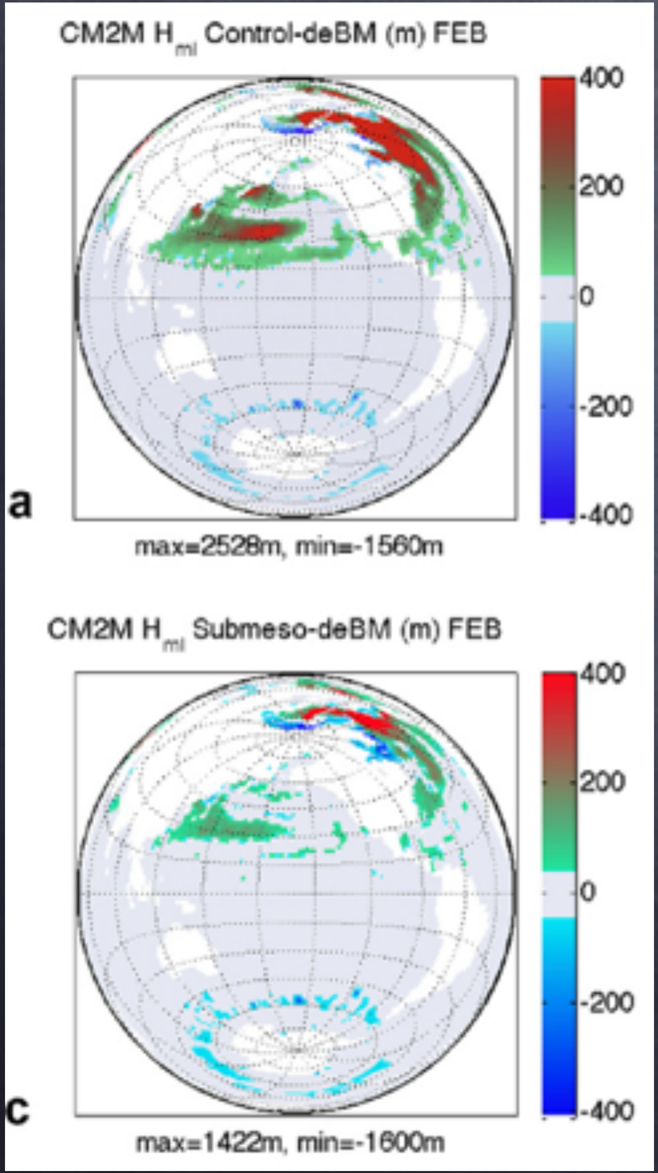
BFK, R. Ferrari, and R. W. Hallberg. Parameterization of mixed layer eddies. Part I: Theory and diagnosis. Journal of Physical Oceanography, 38(6):1145-1165, 2008

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 these Submesoscale Eddies! At least in parameterized form

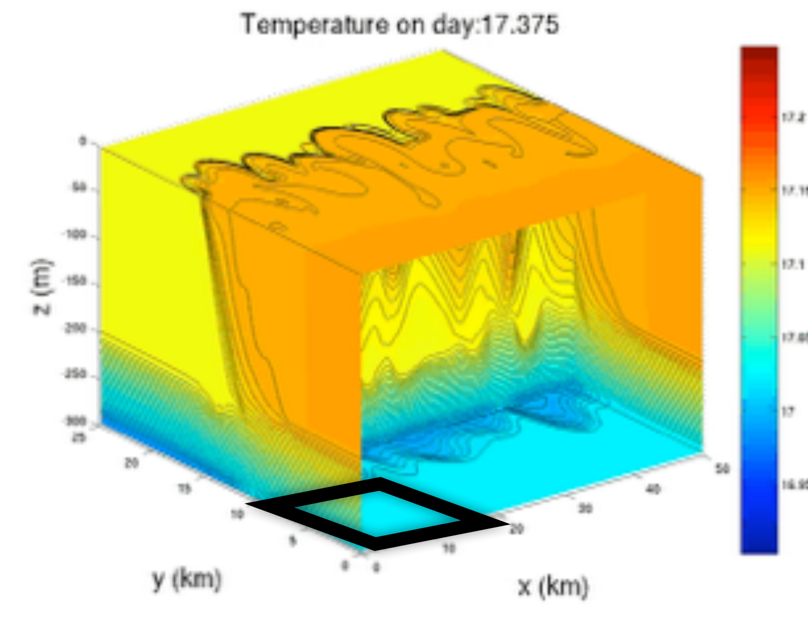
Implemented in IPCC AR5 & 6: NCAR, GFDL, Hadley, NEMO,...



February
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

Deep Mixed Layer
Bias reduced

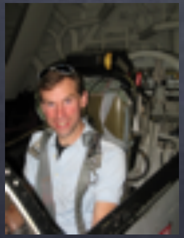


February
MLD Bias
With MLE
Parameterization

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

20km x 20km x 150m domain

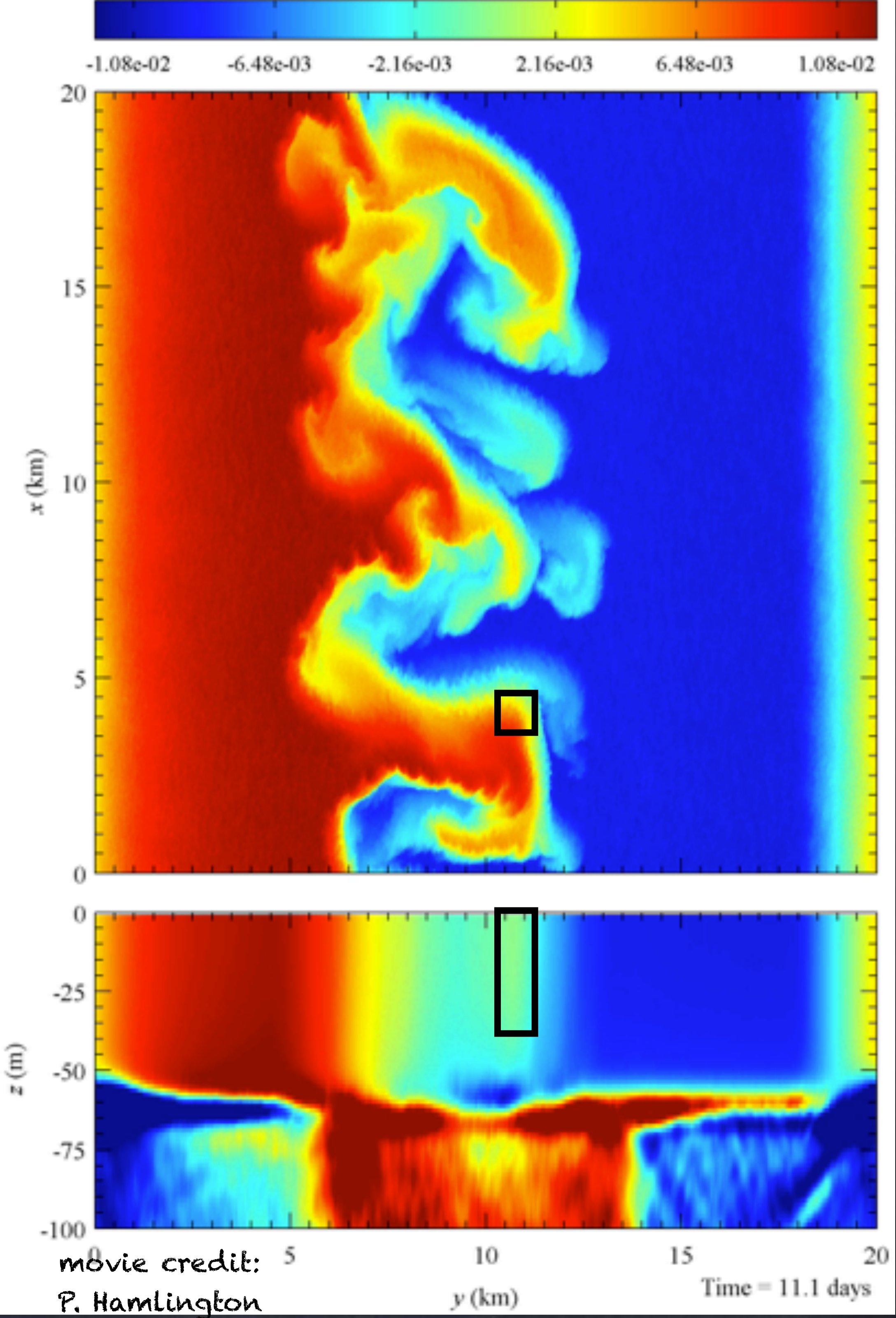
10 Day Simulation



CU, now CU

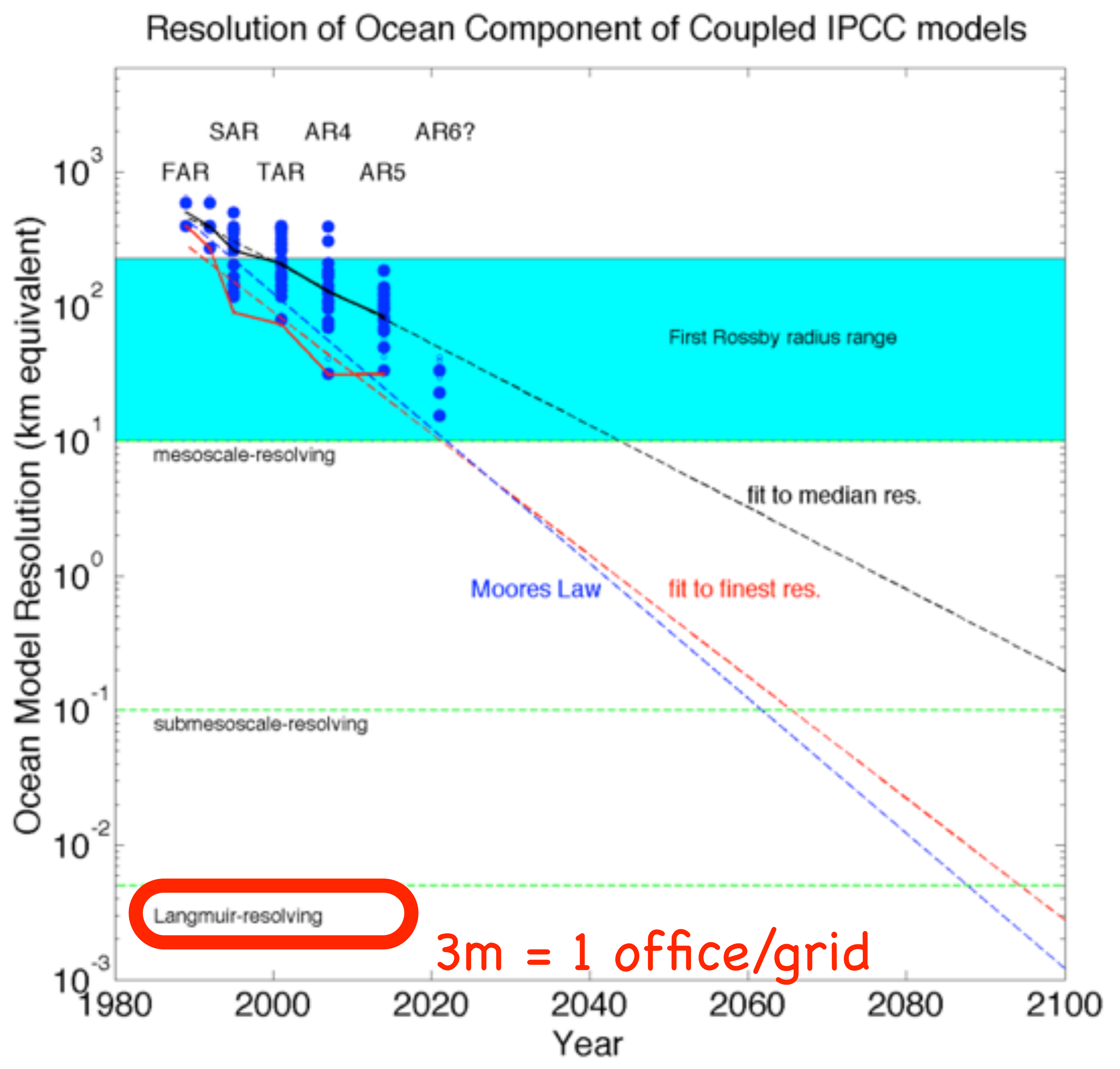
CU, now LANL

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



movie credit: P. Hamlington

Climate Model Resolution: an issue for centuries to come!



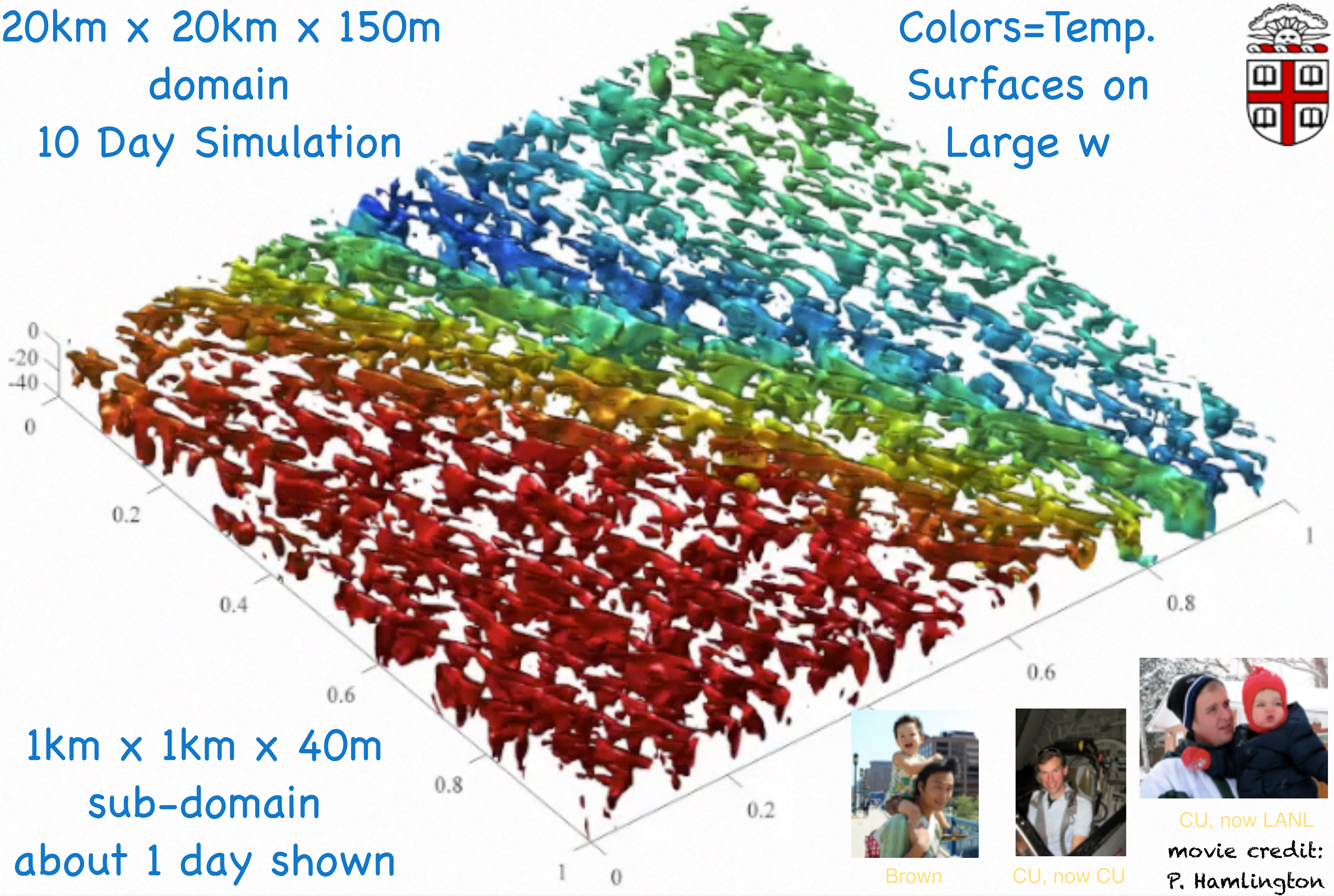
3m = 1 office/grid

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=Temp.
Surfaces on
Large w



1km x 1km x 40m
sub-domain
about 1 day shown

Brown

CU, now CU

CU, now LANL

movie credit:
P. Hamlington

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

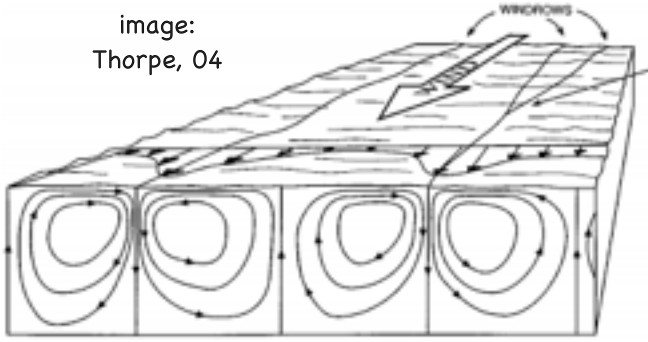


Figure 1 Sketch showing the pattern of mean flow in idealized Langmuir circulation. The windrows may be 2 m to 300 m apart, and the cell form is roughly square (as shown). In practice the flow is turbulent, especially near the water surface, and the windrows (Figure 2) amalgamate and meander in space 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. 2012
- Resolved routinely in 2170

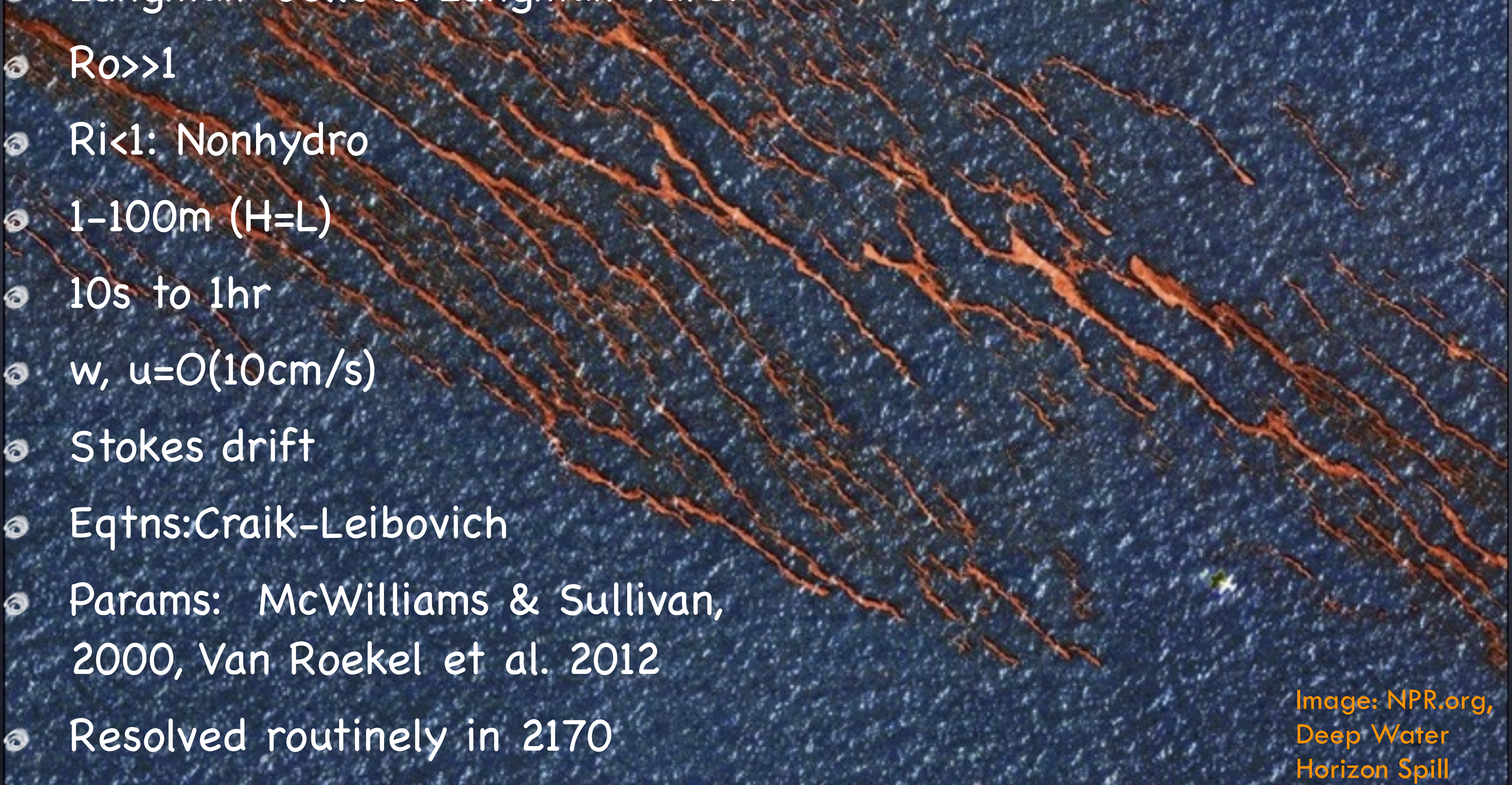
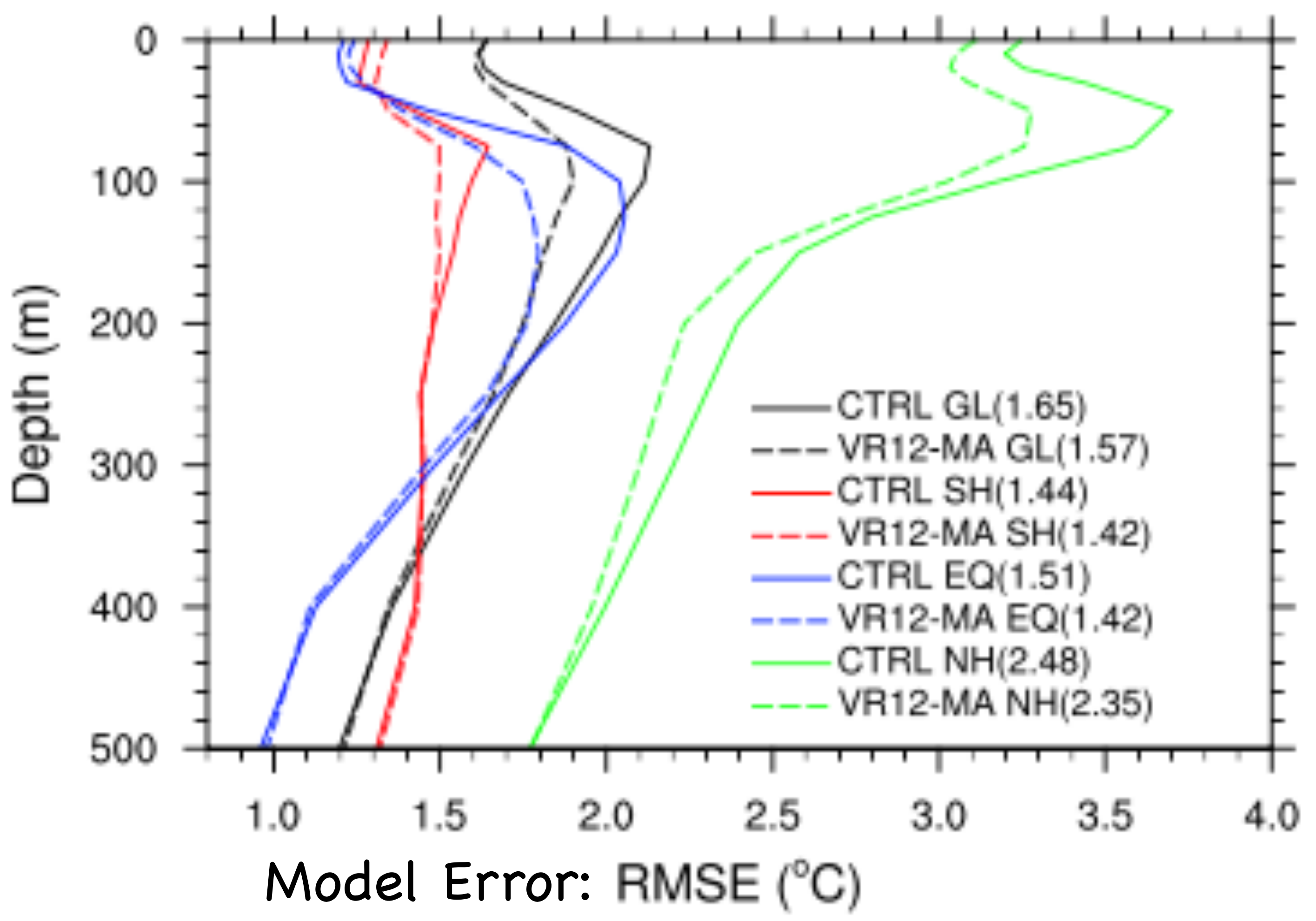


Image: NPR.org, Deep Water Horizon Spill

Modeling of variability

First-Principle Process & GCM Modeling: Predictions and Biases

How much does Langmuir mixing affect Globe?

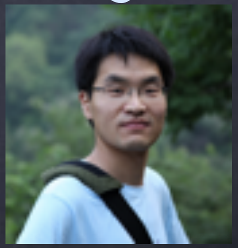


Global Air-sea flux changes by 0.26 W/m^2 when Langmuir mixing is introduced

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

Dashed lines include wave mixing


CU, now Tokyo

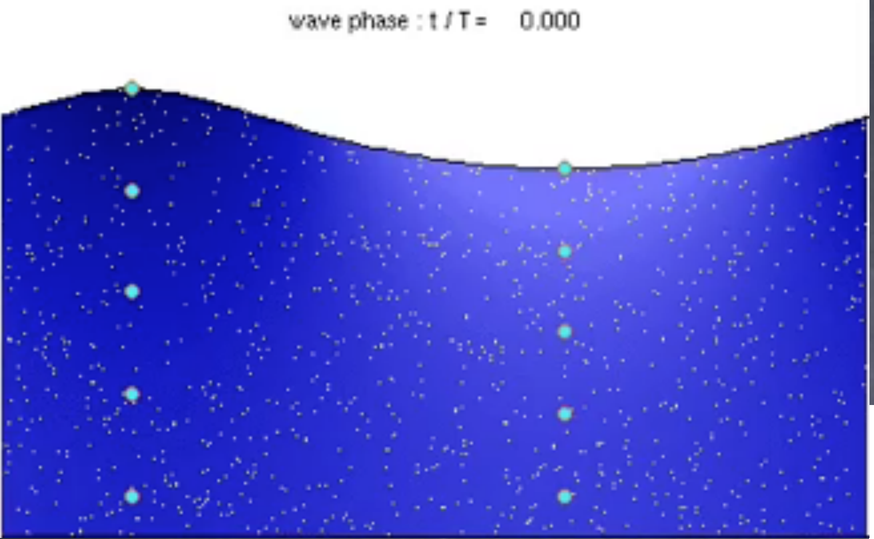

Brown

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.

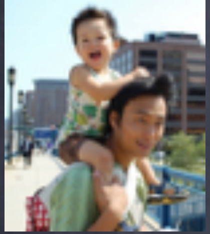
Stokes drift does more than boundary layer mixing!

Making our way to new parameterizations—

Coastal models, oil spills, etc.



Movie: Creative Commons



Brown

CU, now Scripps

CU, now Tokyo

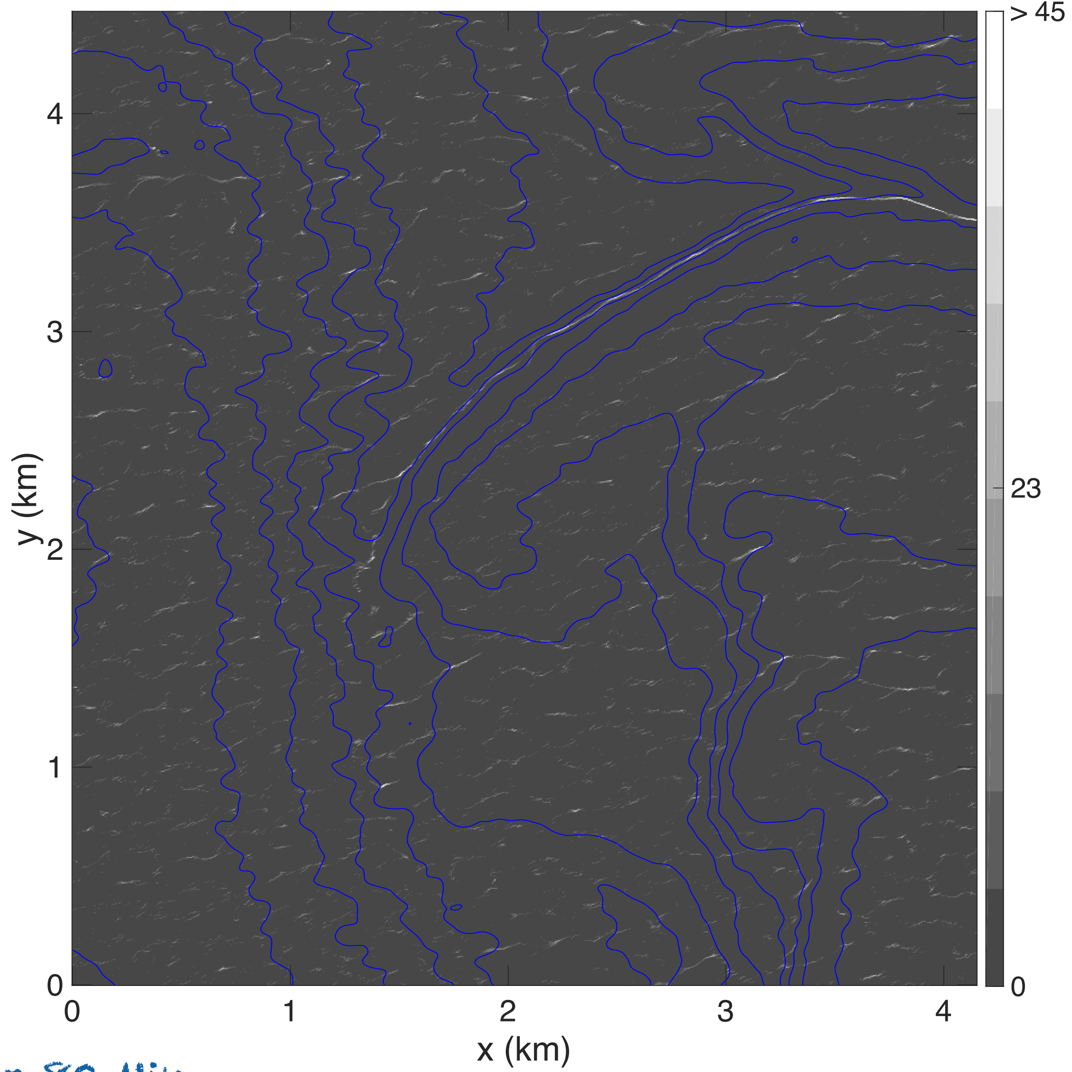
N. Suzuki and BFK. Understanding Stokes Forces in the Wave-Averaged Equations, JGR, in prep, 2015.

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.

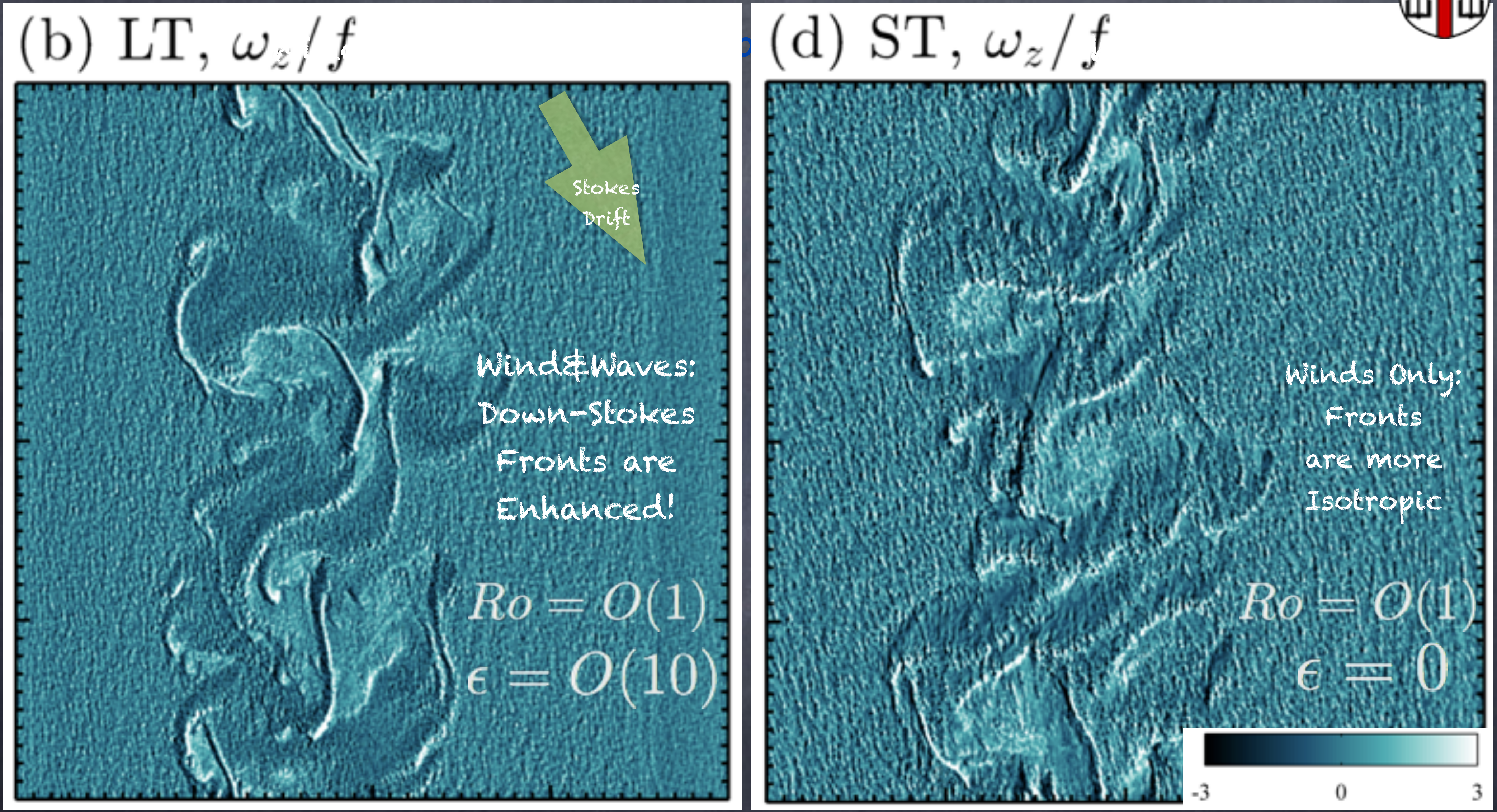
There are 851796 drifters in the picture



After 80 Min

Are Fronts and Filaments different with Stokes shear force?

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

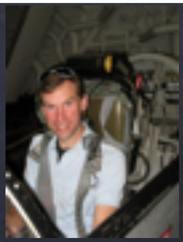


N. Suzuki, BFK, Hamlington, Van Roekel, Sullivan. Stokes Forces Affect Frontogenesis, JGR, in prep, 2015.

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.


Brown


CU, now CU


CU, now LANL

Turbulence Obs & Stats!

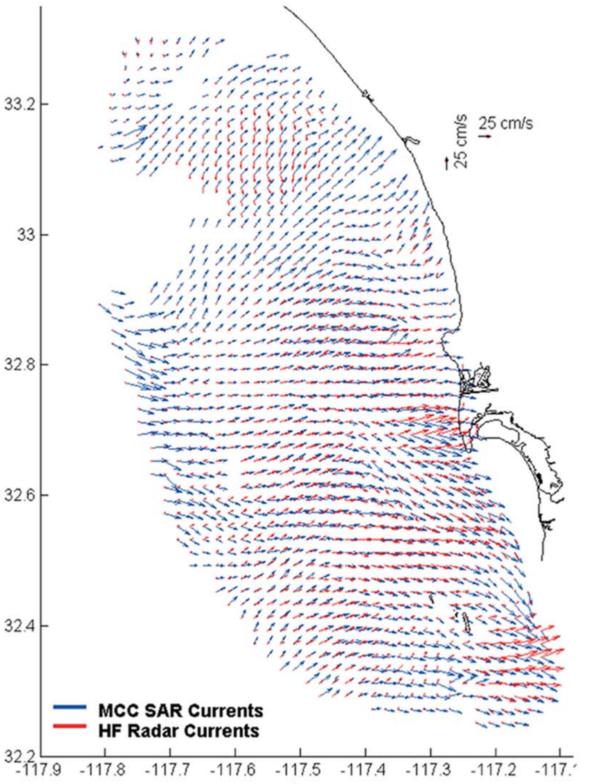
We try to check all of the high-resolution models and turbulence parameterizations against data. There is a lot of statistical work that goes along with doing so.

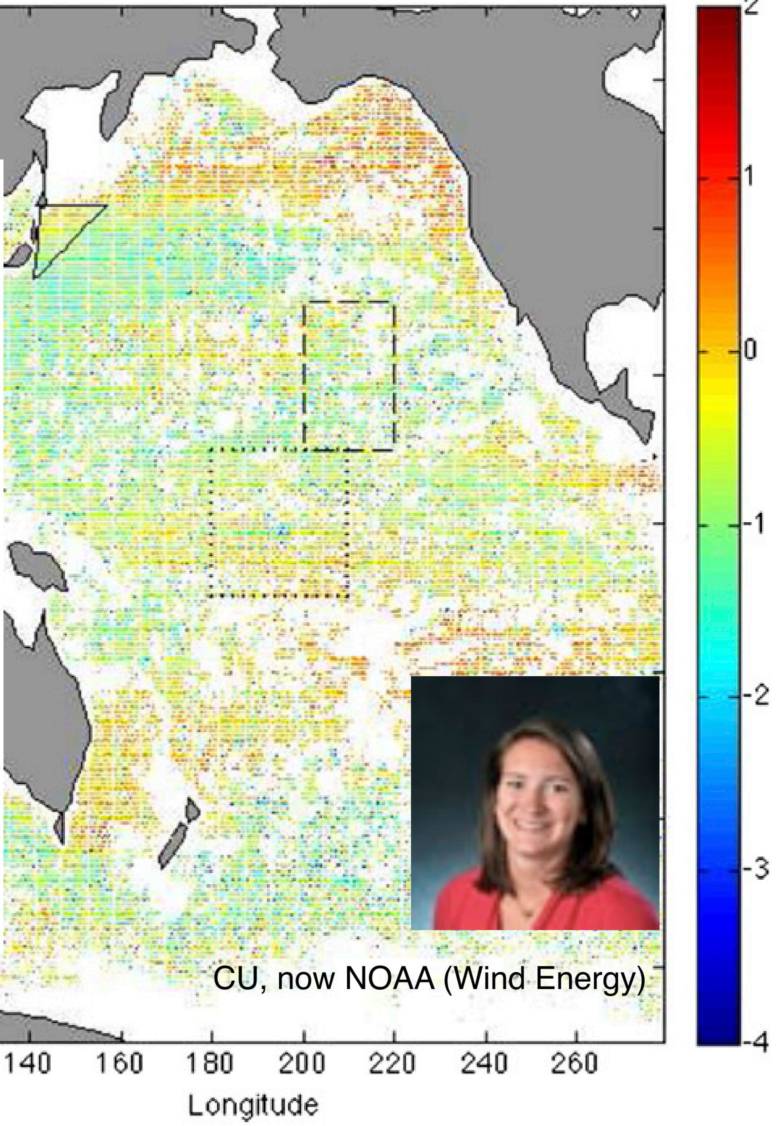
K. McCaffrey, B. Fox-Kemper, P. Hamlington, and J. Thomson. Characterization of turbulence anisotropy, coherence, and intermittency at a prospective tidal energy site: Observational data analysis. Renewable Energy, 76:441-453, April 2015.

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

W. A. Qazi, W. J. Emery, and B. Fox-Kemper. Computing ocean surface currents over the coastal California Current System using 30-minute lag sequential SAR images. IEEE Transactions on Geoscience and Remote Sensing, 52(12): 7559-7580, June 2014.

E. A. D'Asaro, J. Thomson, A. Y. Shcherbina, R. R. Harcourt, M. F. Cronin, M. A. Hemer, and B. Fox-Kemper. Quantifying upper ocean turbulence driven by surface waves. Geophysical Research Letters, 41(1):102-107, January 2014.





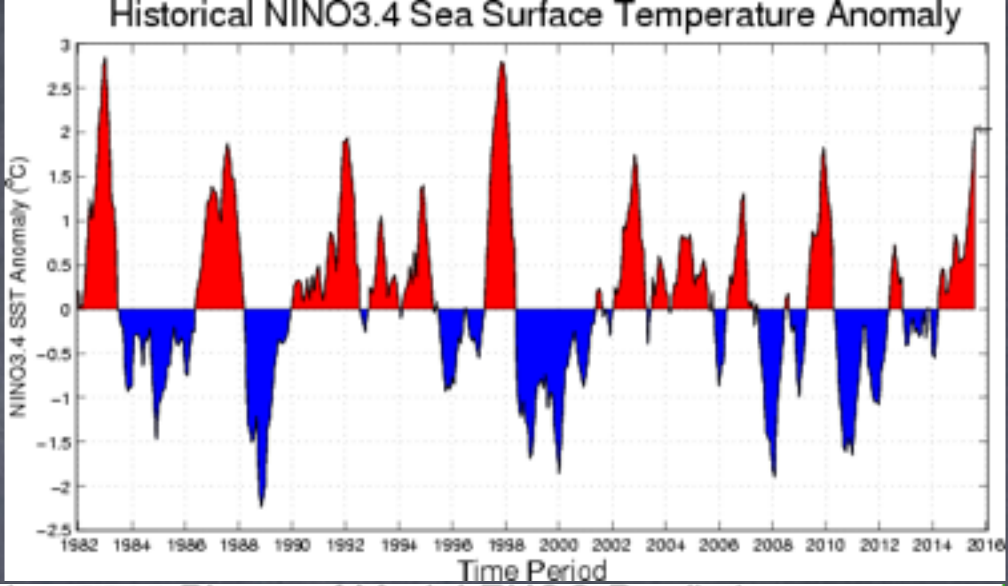
CU, now NOAA (Wind Energy)

FIG. 5. The log of salinity variance at 5 m with a solid box around the chosen near-homogeneous region in the Kuroshio. The dashed line

Prediction of variability

Predictability of ENSO events limited to < 1yr

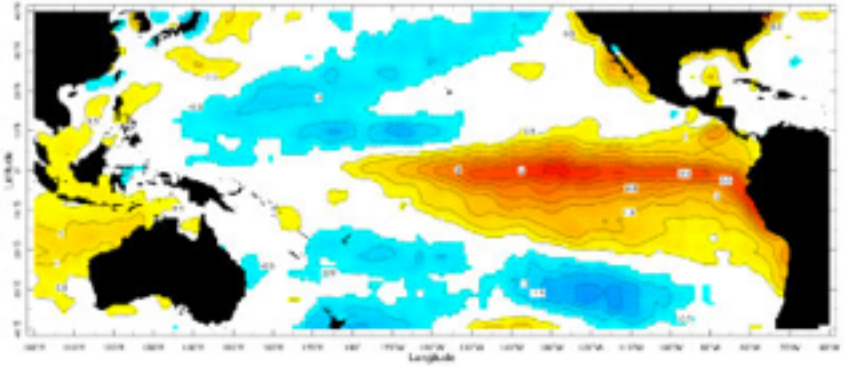
ENSO statistics more predictable?



El Niño Episode Sea Surface Temperatures

Departure from average in degrees Celsius

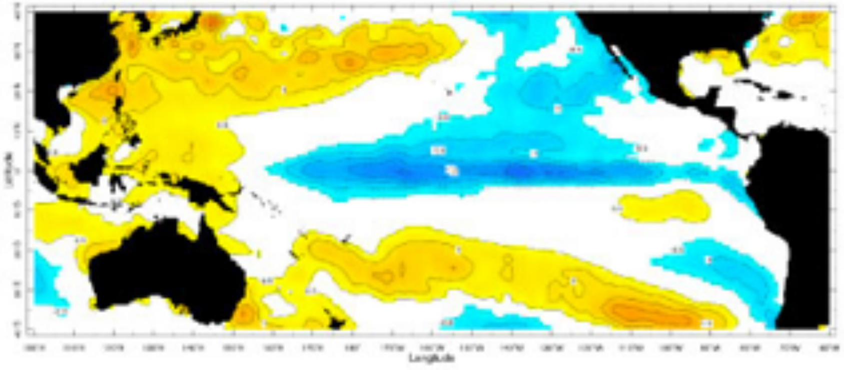
Dec 1982 - Feb 1983

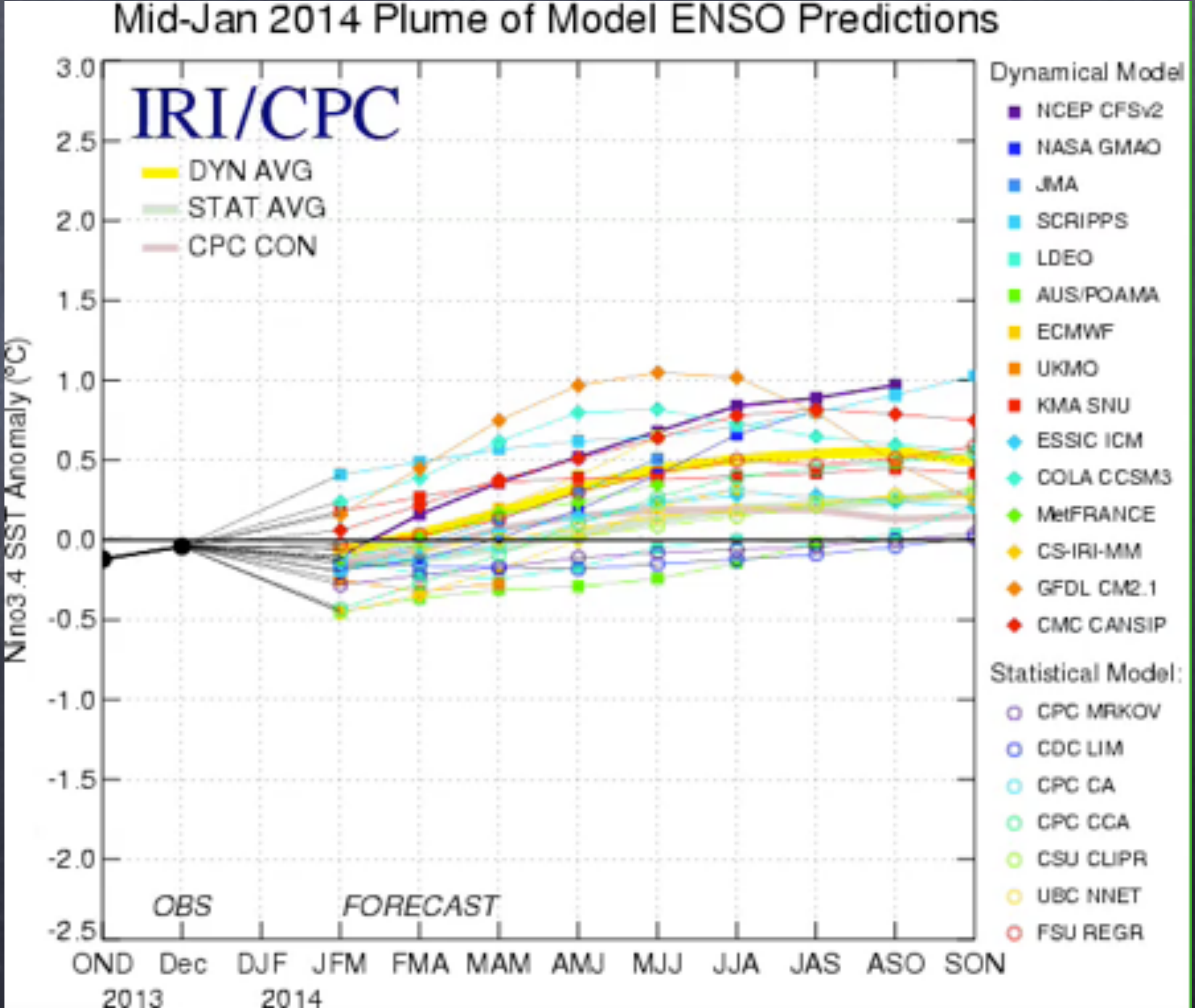


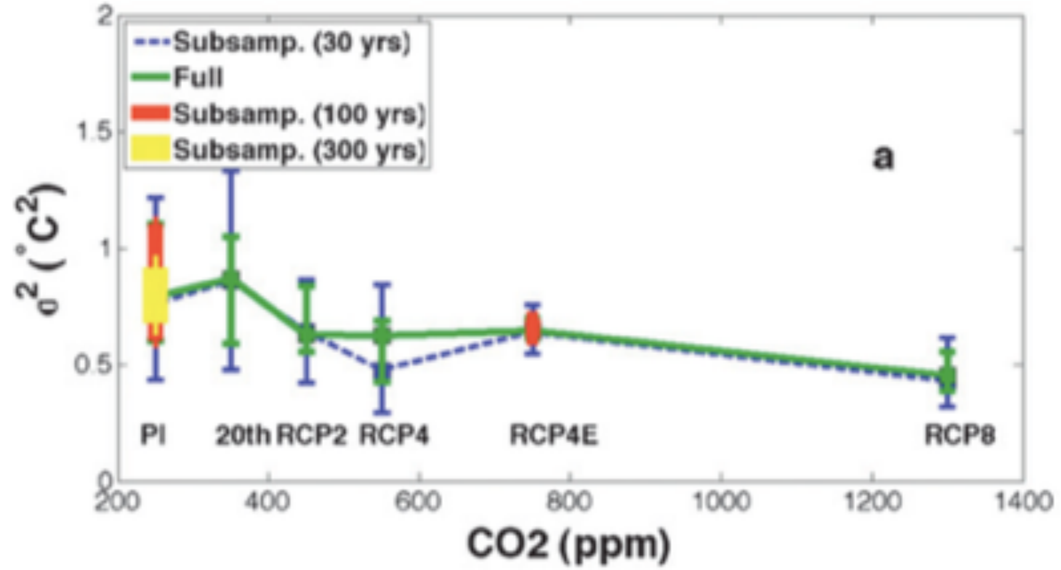
La Niña Episode Sea Surface Temperatures

Departure from average in degrees Celsius

Dec 1998 - Feb 1999







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

(>200 yr to detect)

CU, now NCAR

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.

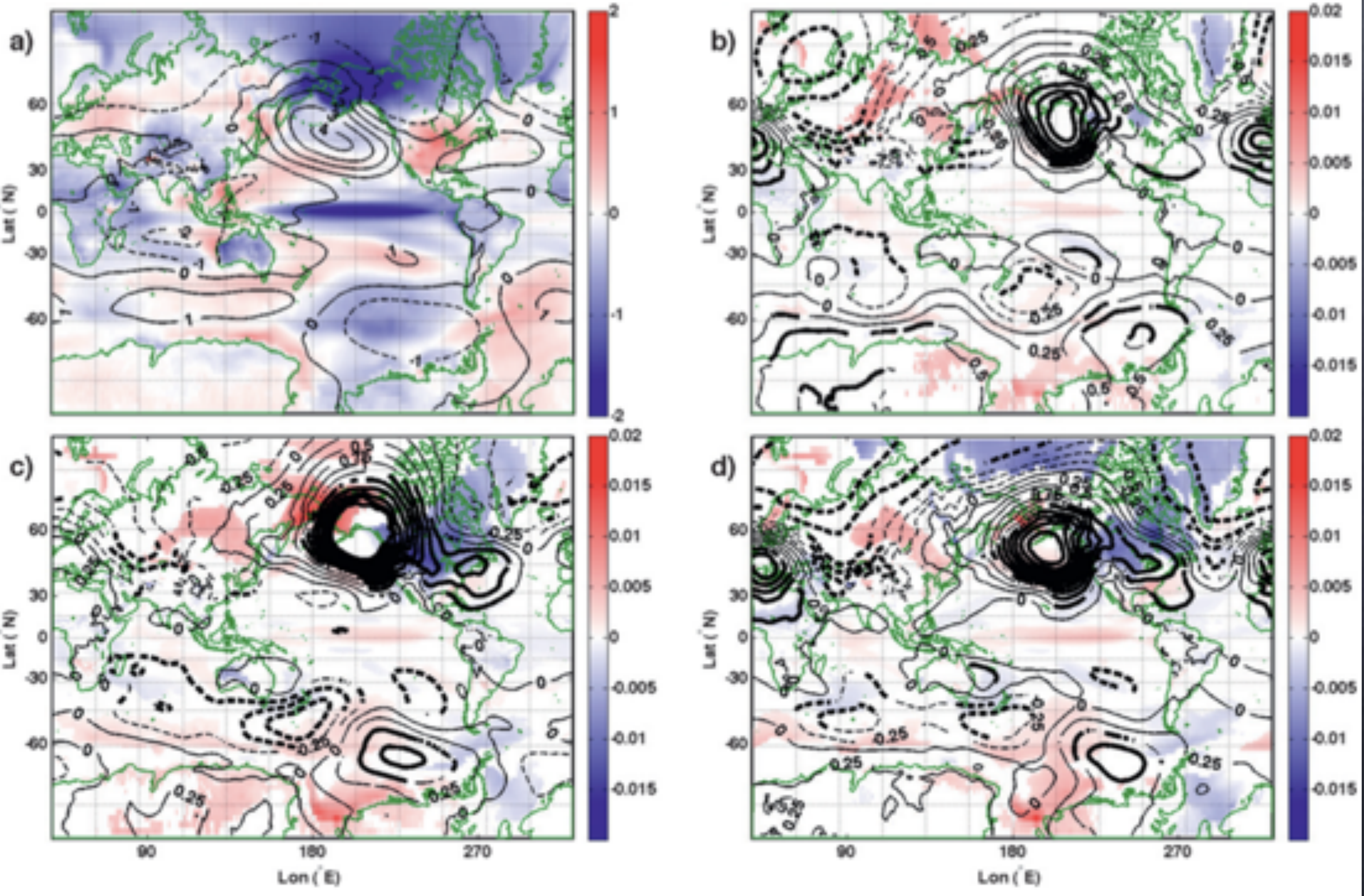
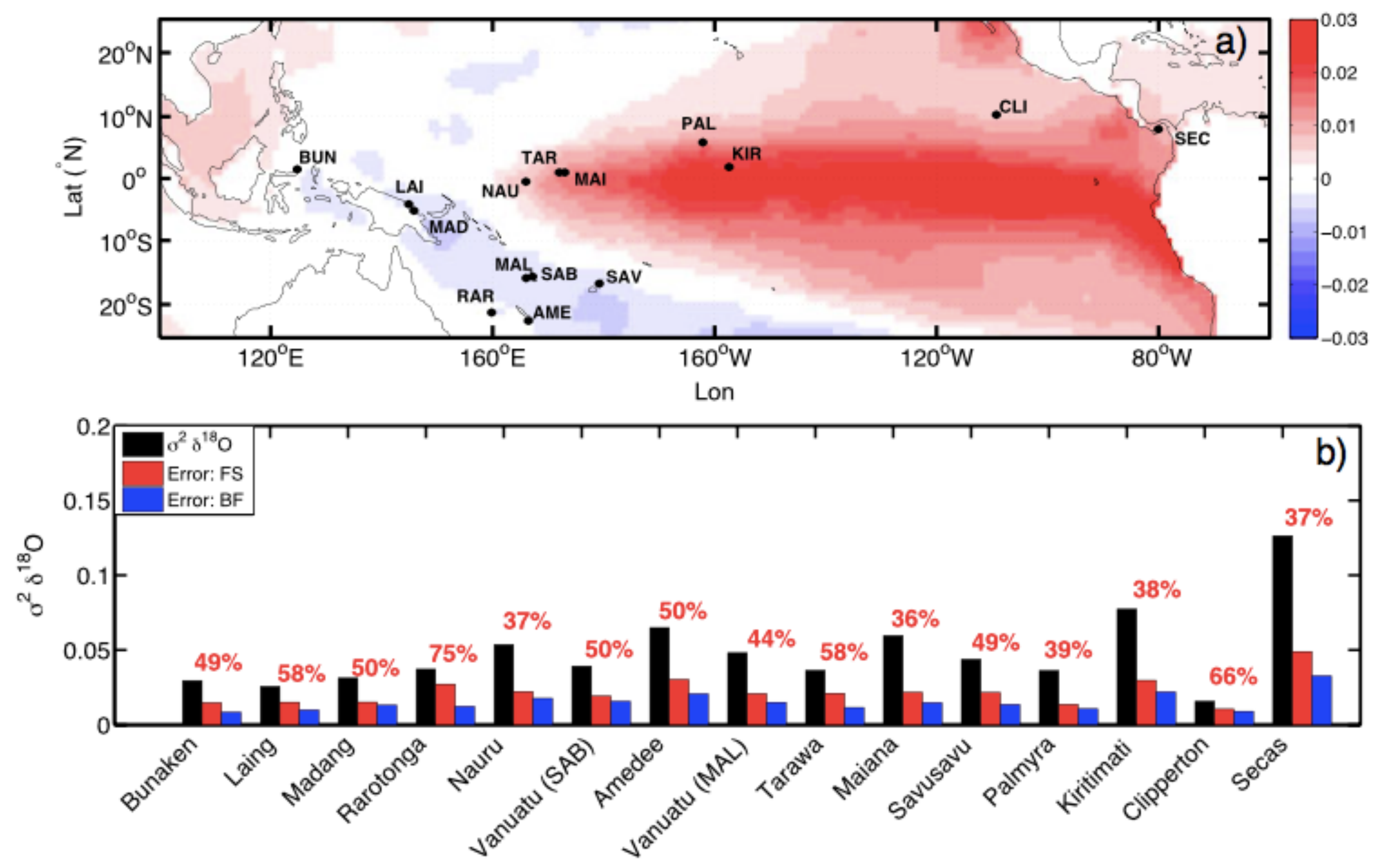


FIG. 6. As in Fig. 5 but for La Niña DJF



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!

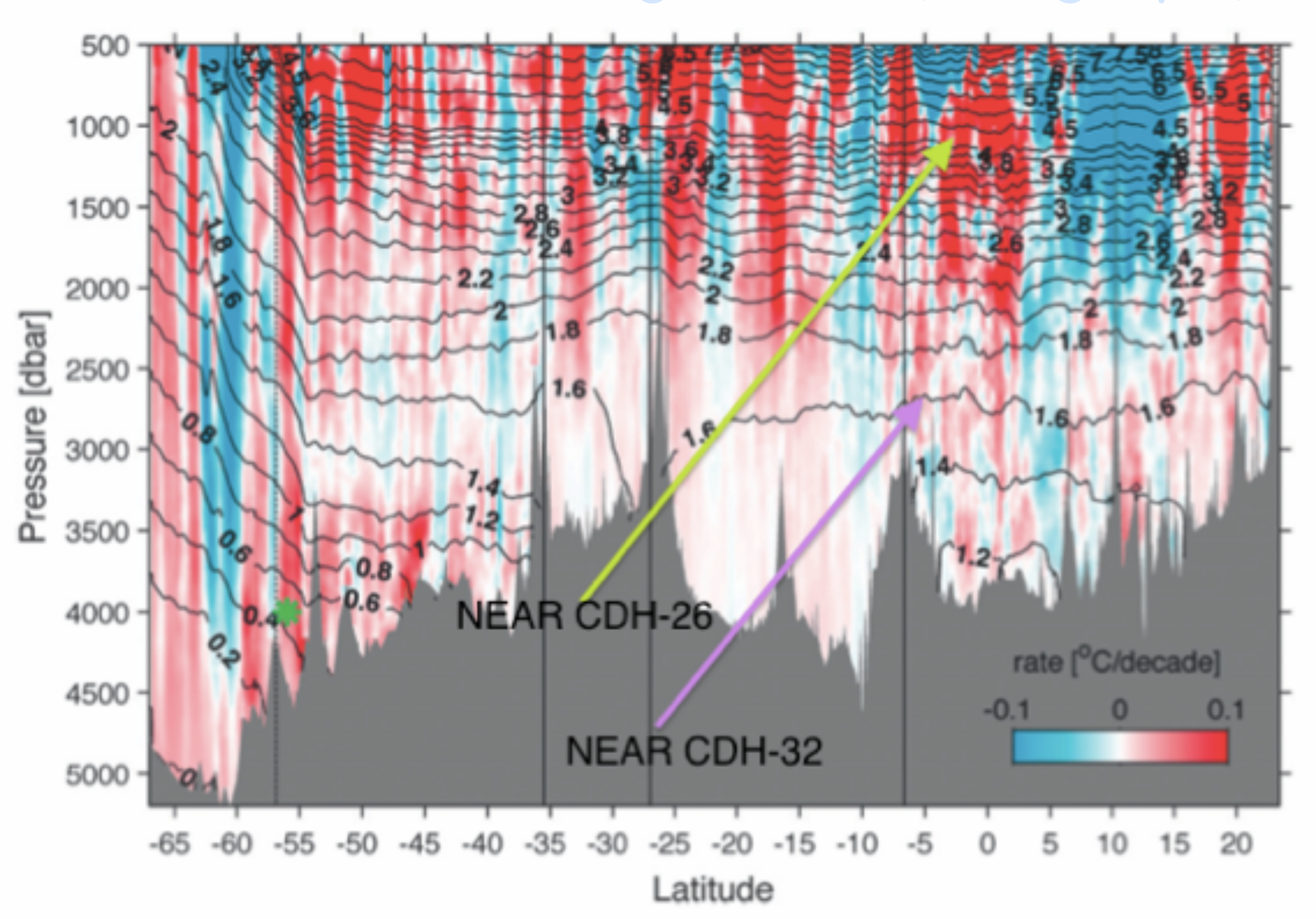
- Stochastic damping very slow!
  - huge heat capacity (biggest watermasses on Earth)!
- Timescales may be very long!
  - Watermasses O(1500yr) old by radiocarbon
- Lengthscales may be very short!
  - (weak stratification implies a Rossby radius of O(2km) for modes trapped in AABW only)
- Water “formed” 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

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 × ($\delta^{18}O_c$-$\delta^{18}O_{sw}$)

  Bemis et al. 2002

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

  Conroy et al. 2014

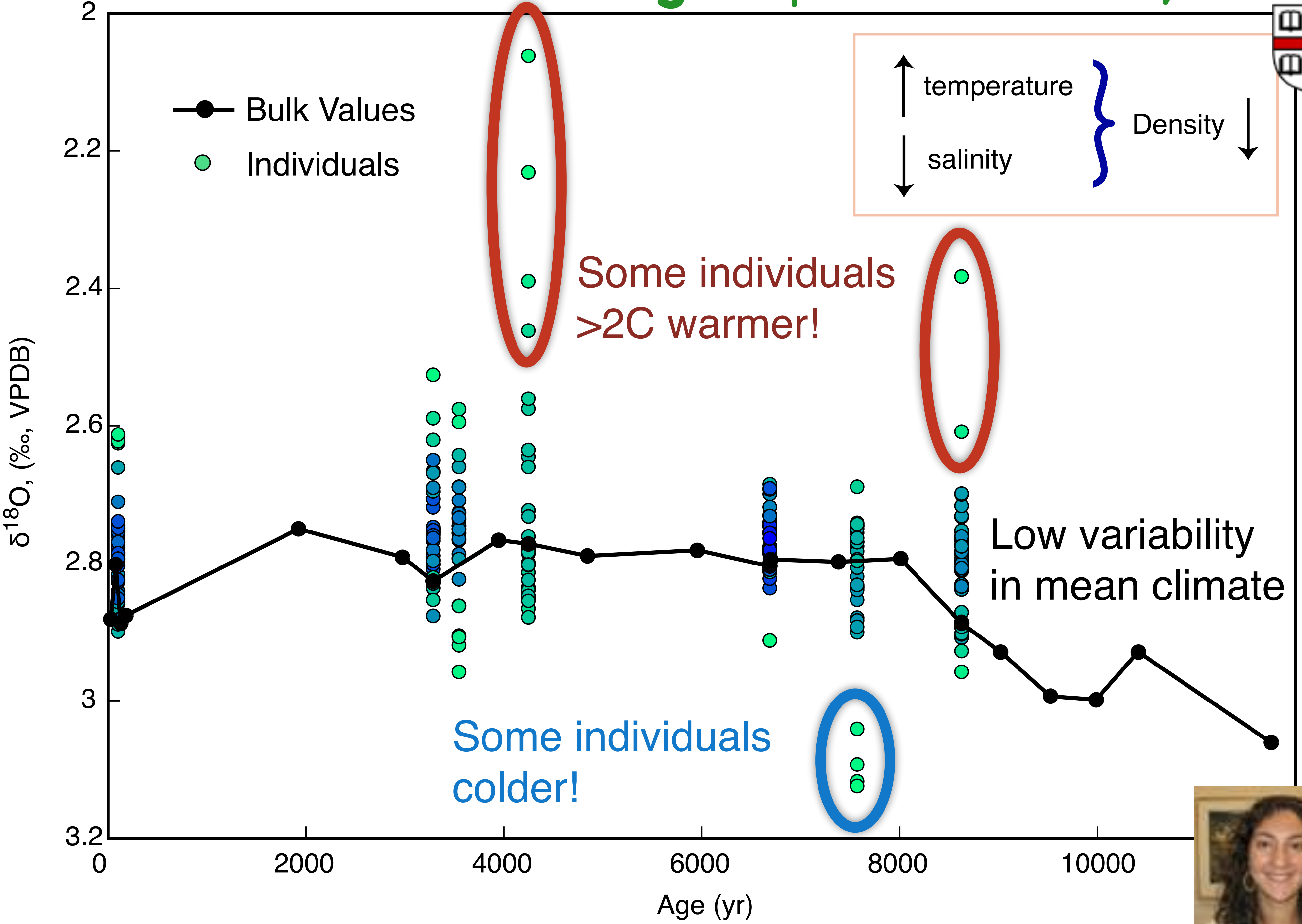
- Individual foraminifera provide 2-3 week snapshots of seawater properties
- We analyze 30-40 individuals within 200 year windows to assess the mean and variance of foraminiferal δ^{18}O values On roughly decadal timescales

Uvigerina spp.

Brown

Slide: Sam Bova

Understanding of past variability



Some individuals >2C warmer!

Low variability in mean climate

Some individuals colder!

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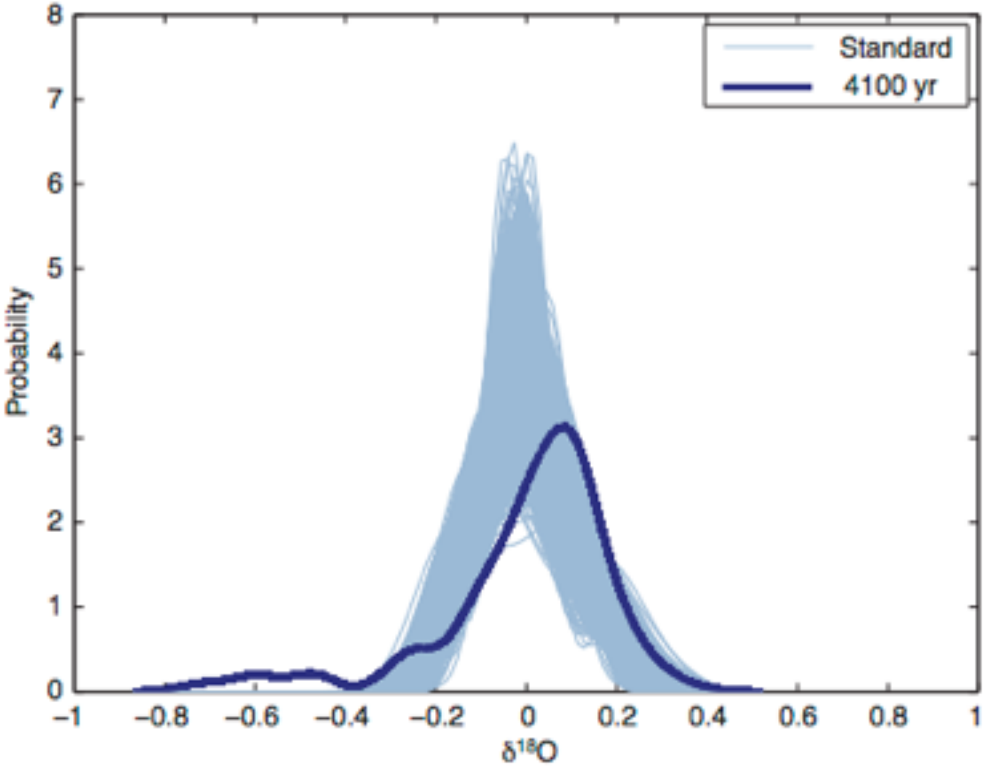
Figure Credit: Sam Bova

p<0.01

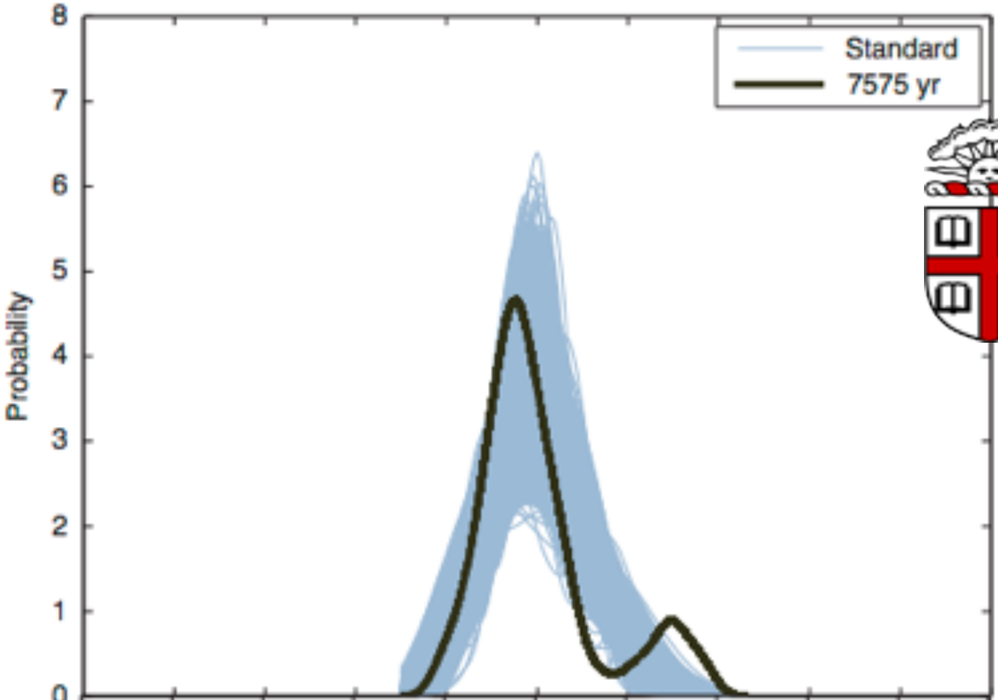


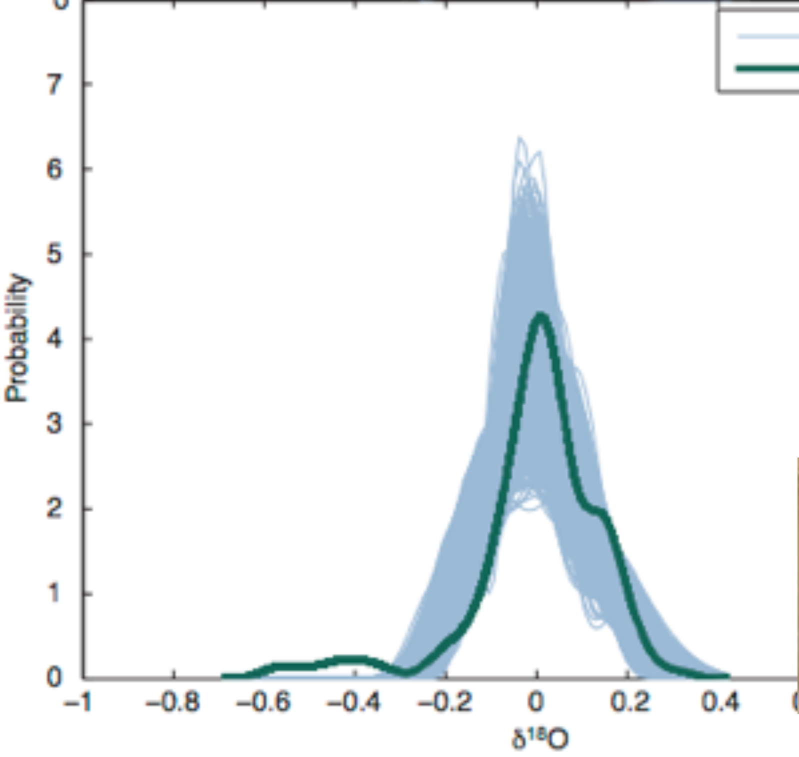
At these three time intervals, the spread of individual values exceeds a size-matched spread of instrumental standards.

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

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

p<0.10





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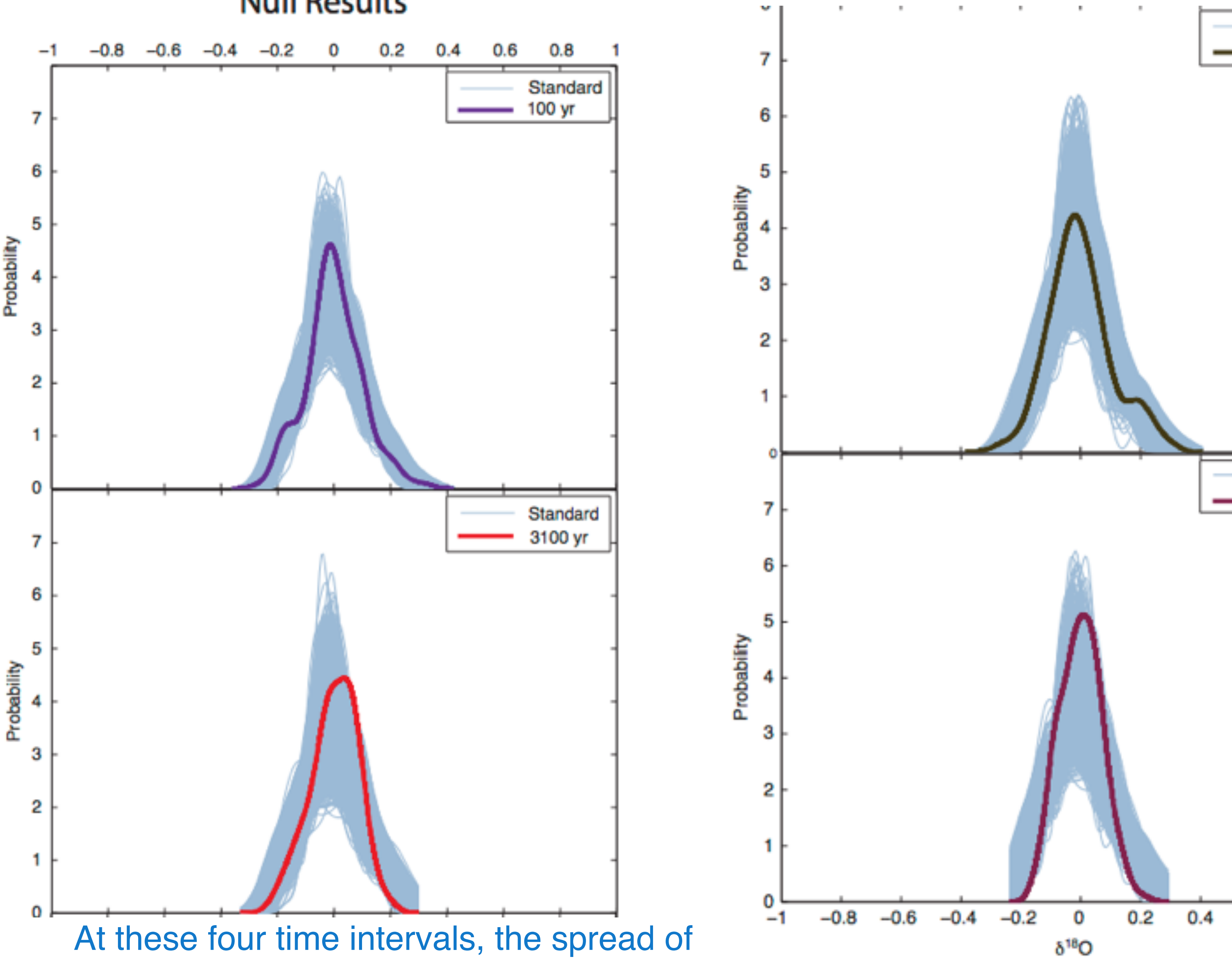
Conclusions

- **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



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

Figure Credit: Sam Bova

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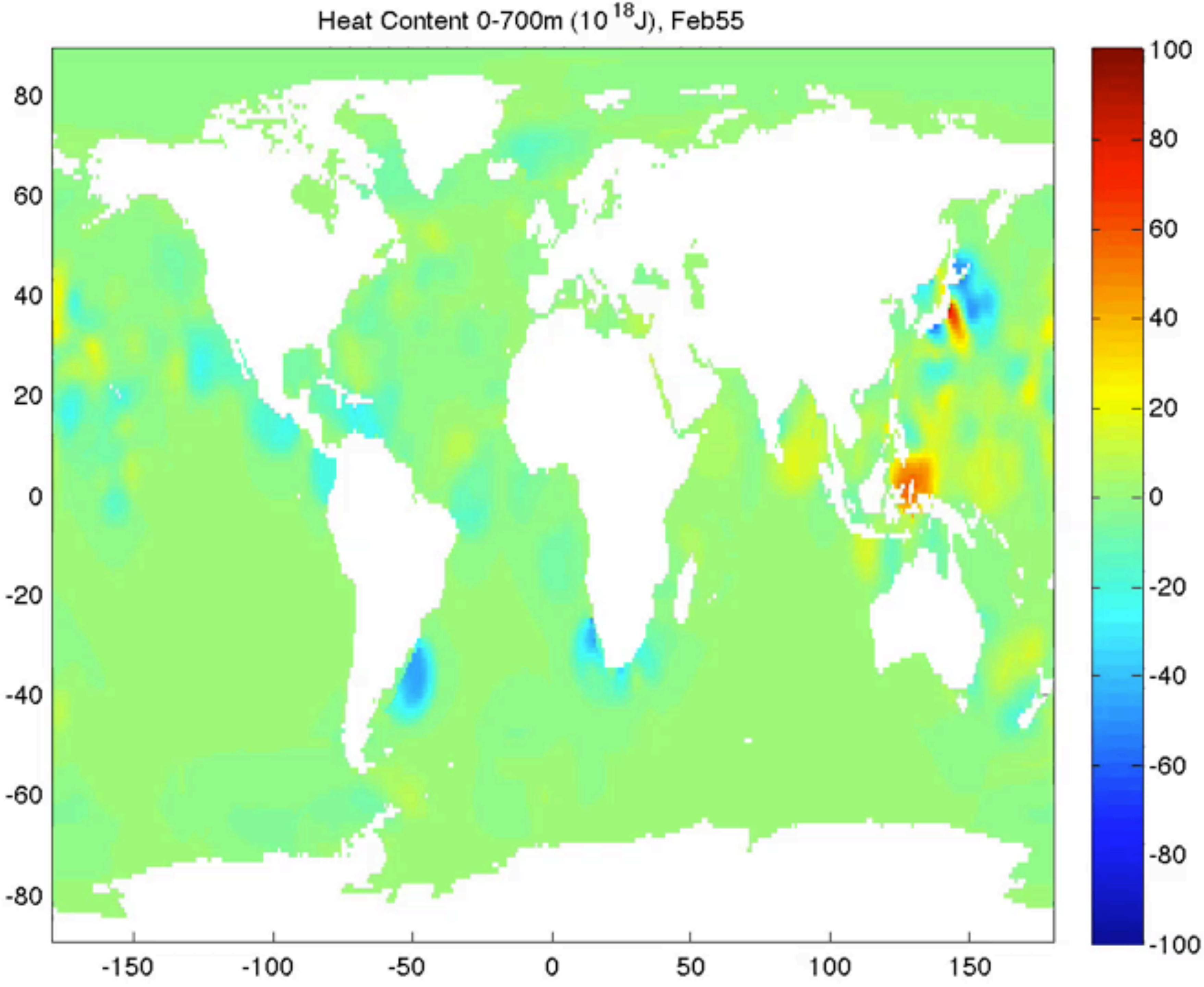
Compare to Observational Product



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"