Atmosphere-ocean boundary layers and fluxes

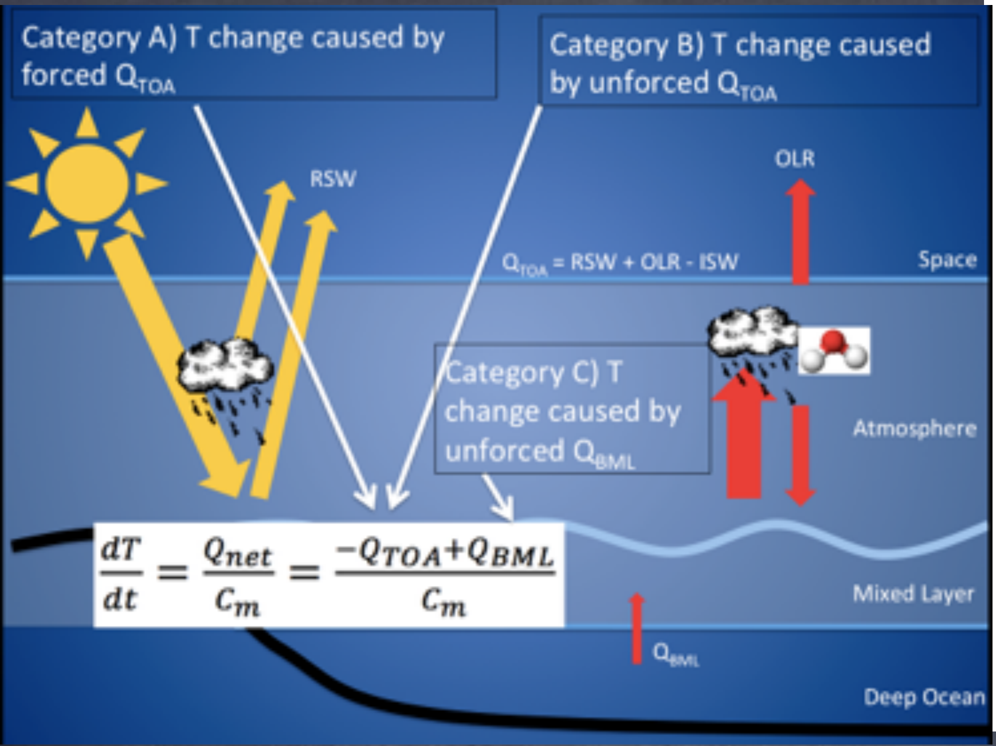
Baylor Fox-Kemper (Brown DEEP Sci.)

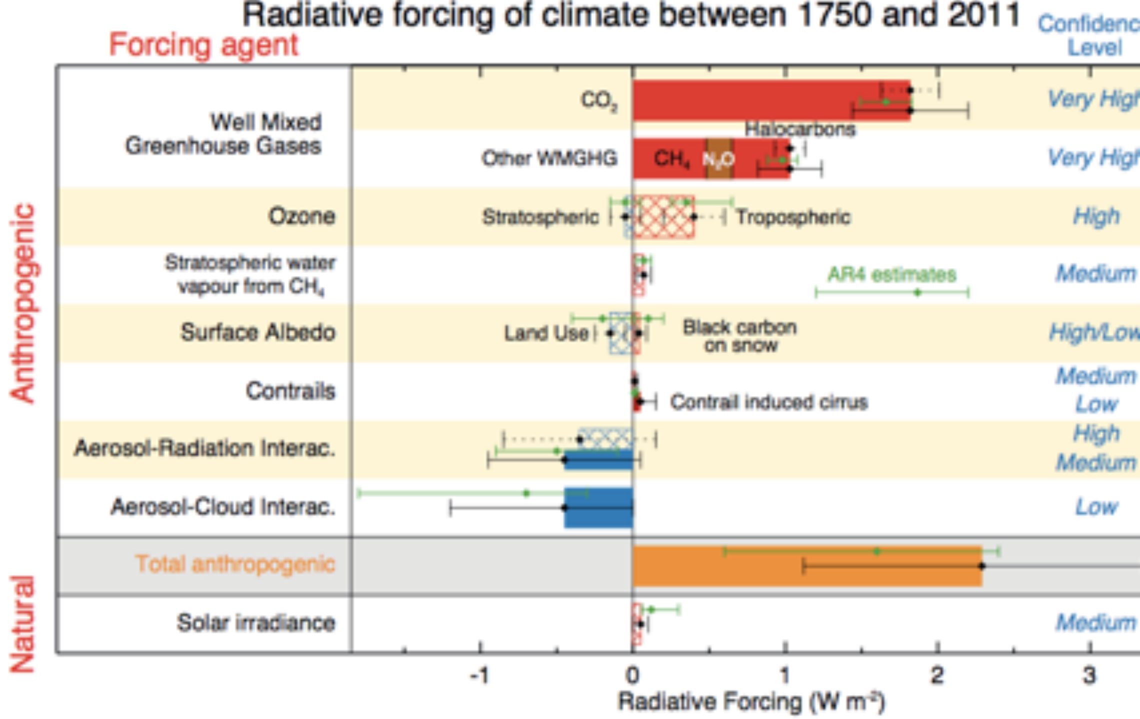
with Qing Li & Nobu Suzuki (Brown), Scott Reckinger (Montana), and Sean Haney & Peter Hamlington (CU-Boulder), Luke Van Roekel (LANL), Adrean Webb (U. Tokyo), Keith Julien (CU-Boulder) Greg Chini (UNH), E. D'Asaro & R. Harcourt (UW), Peter Sullivan (NCAR) & Jim McWilliams (UCLA), Frank O. Bryan, Gokhan Danabasoglu & Bill Large (NCAR), Mark Hemer (CSIRO)

Translating Process Understanding to Improve Climate Models

NOAA GFDL, Princeton, NJ, 10/15/15, 11:20-11:40

Sponsors: NSF, NASA, BP GoMRI





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.

  However, problematic **prediction** and **attribution**— **this is where modeling helps!**

What does hydrography show?

OHCs and fluxes are not fixed!

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

Hansen et al. (2011).

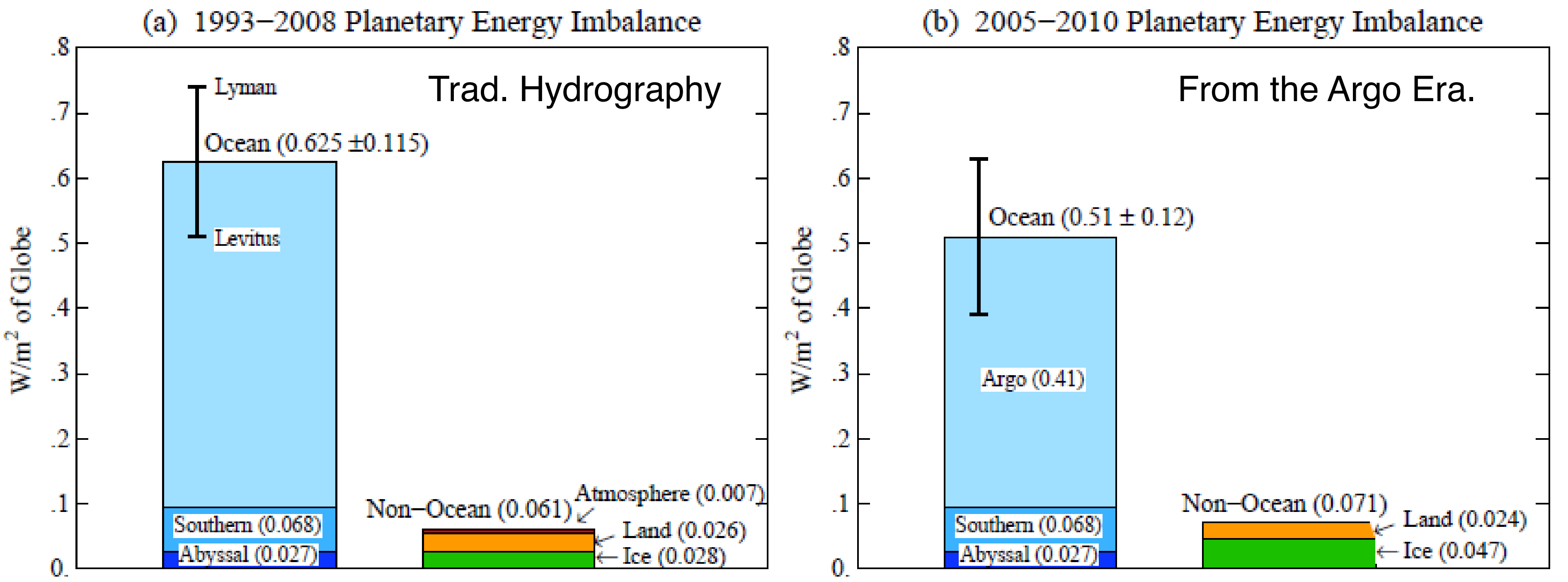
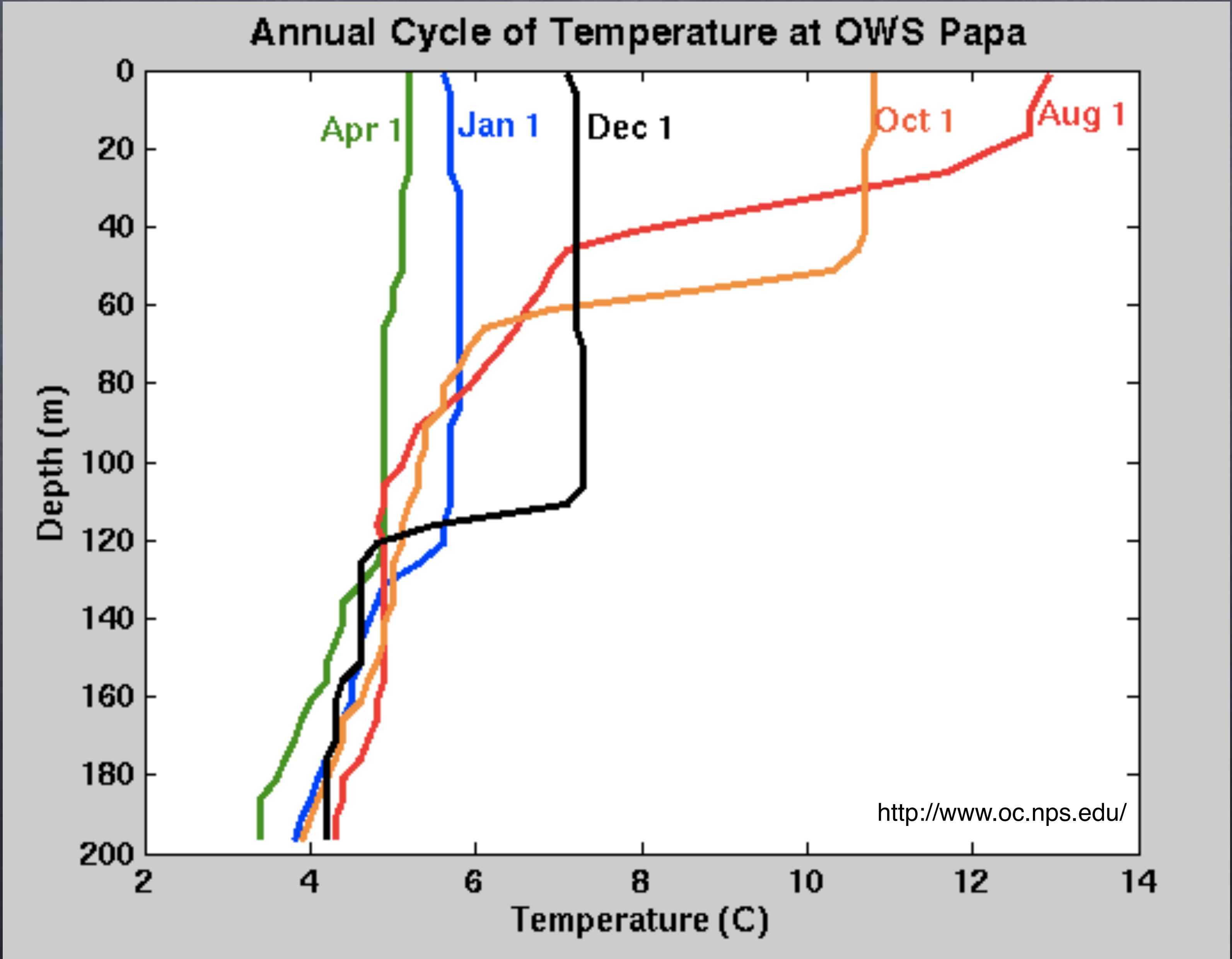


Fig. 10. **(a)** Estimated contributions to planetary energy imbalance in 1993–2008, and **(b)** in 2005–2010. Except for heat gain in the abyssal ocean and Southern Ocean, ocean heat change beneath the upper ocean (top 700 m for period 1993–2008, top 2000 m in period 2005–2010) is assumed to be small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

BUDGET is for Heat Content

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



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

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

Models get better every generation due to improved resolution and parameterizations

What do we usually do to make these improvements?

Changes to model physics, clouds, resolution, numerics, etc. Updates of the flux laws (but not recently)

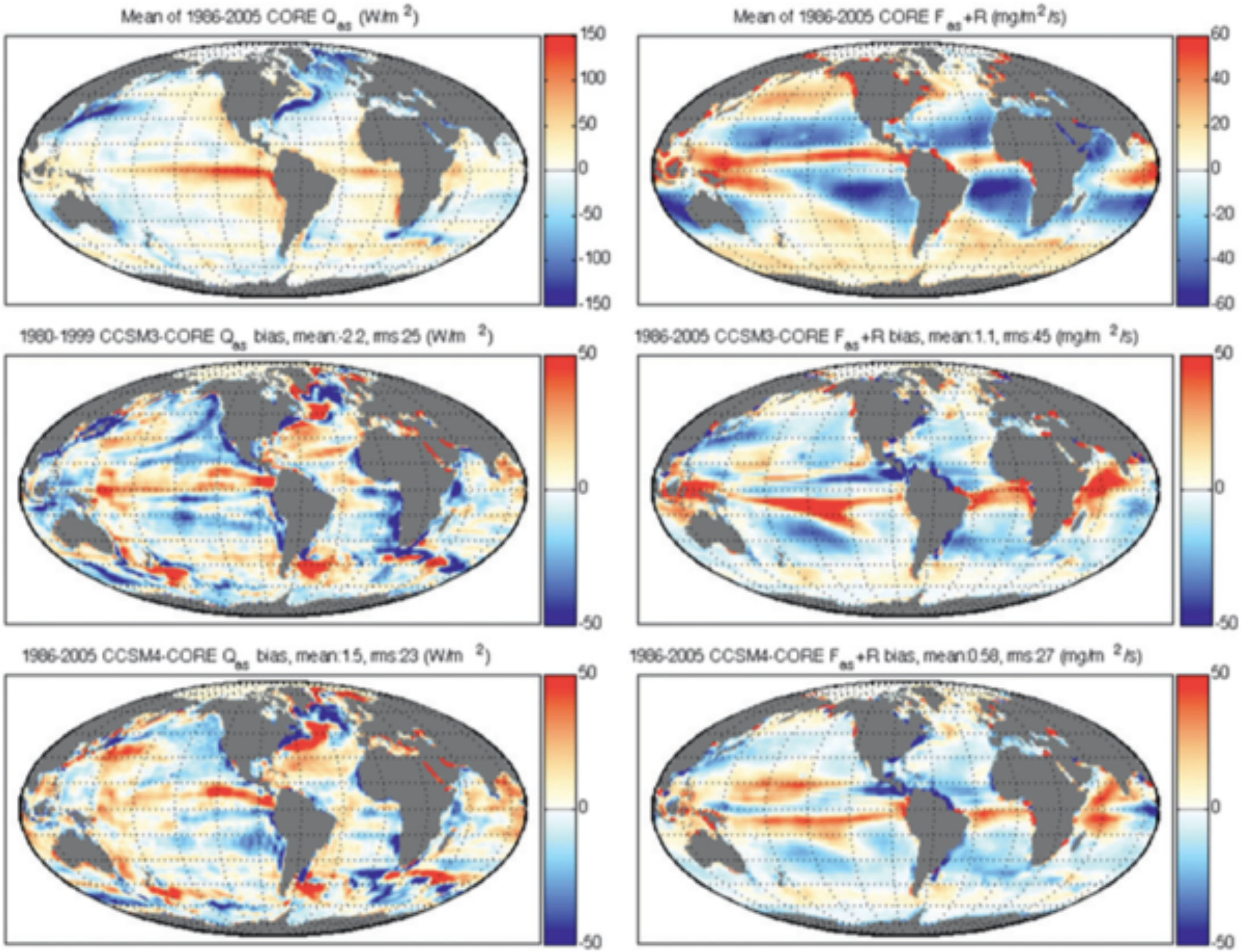


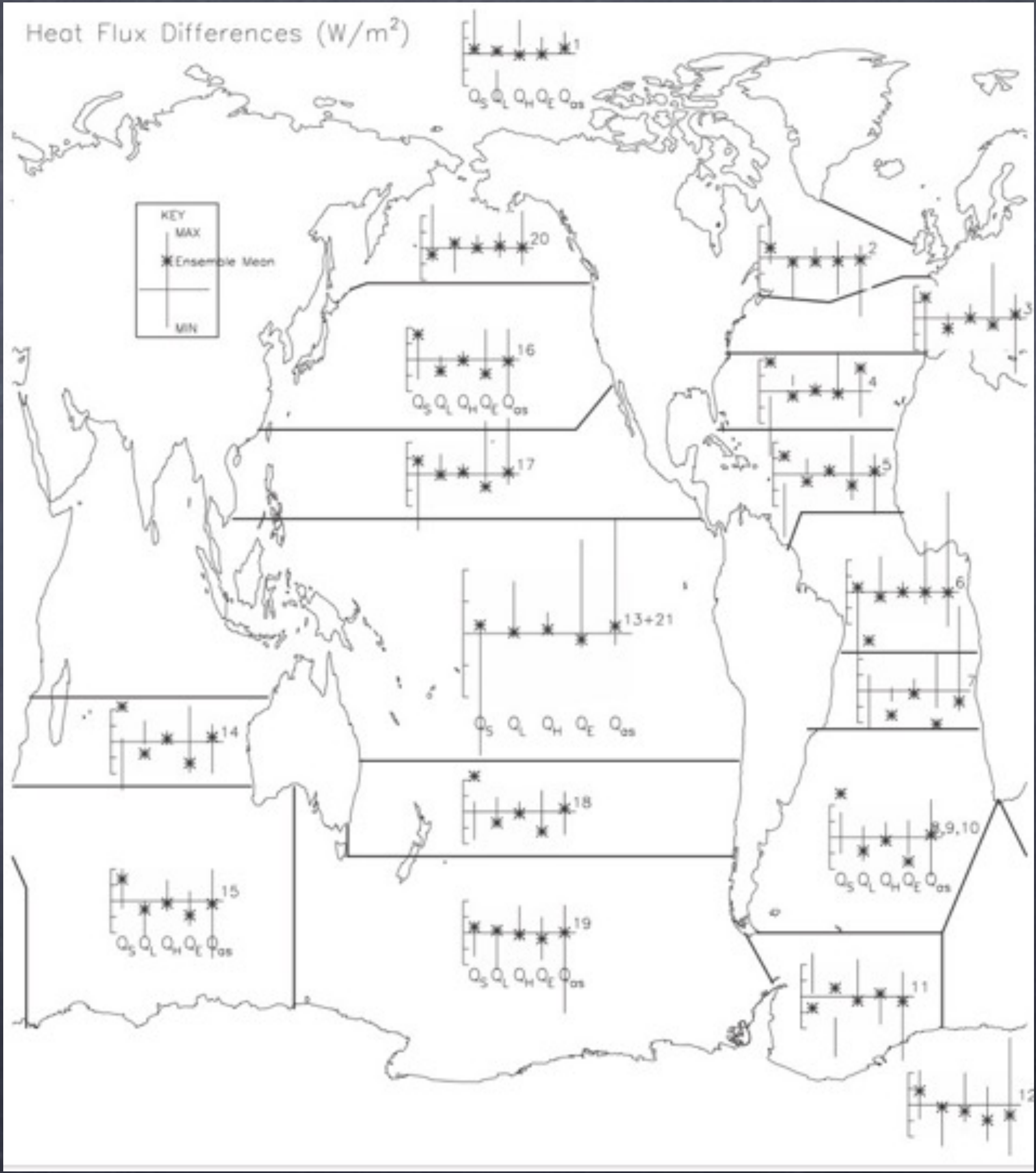
FIG. 1. (top) CORE (left) total air–sea heat flux and (right) total freshwater flux (air–sea + runoff) into the ocean. Also shown are biases in the present-day mean of these fluxes from the (middle) CCSM3 and (bottom) CCSM4 20C ensemble means. Units: W m^{-2}. The increment in latitude is 15°.

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.

Often agreement in time mean fluxes

Often disagreement in annual band flux variability

Region	Q_E	P	Q_H	Q_L	Q_S
1	0.85	**1.00**	**0.97**	0.71	**0.99**
2	**1.00**	0.73	**0.94**	0.01	0.06
3	0.78	0.00	0.76	0.32	0.87
4	0.11	0.35	**1.00**	**0.98**	0.01
5	**1.00**	**0.92**	0.04	**1.00**	0.21
6	**0.93**	**1.00**	**1.00**	**0.99**	**1.00**
7	**1.00**	**1.00**	0.79	**1.00**	**0.97**
8	0.86	0.68	0.26	0.80	**1.00**
9	**1.00**	0.80	0.25	**1.00**	**1.00**
10	0.84	**1.00**	0.19	**1.00**	**1.00**
11	**0.99**	0.19	0.05	**1.00**	**1.00**
12	0.23	0.17	0.83	**1.00**	0.09
13	**1.00**	0.53	**1.00**	0.75	0.53
14	**0.99**	0.22	**0.92**	**1.00**	**0.97**
15	0.75	**0.99**	0.42	**1.00**	**1.00**
16	**1.00**	**0.99**	0.16	0.23	0.13
17	**1.00**	0.89	0.55	**1.00**	0.19
18	**1.00**	**1.00**	0.82	**1.00**	**1.00**
19	0.33	0.74	0.32	0.23	0.51
20	**0.90**	0.15	0.42	0.05	**1.00**
21	**0.91**	0.78	0.50	**1.00**	0.86

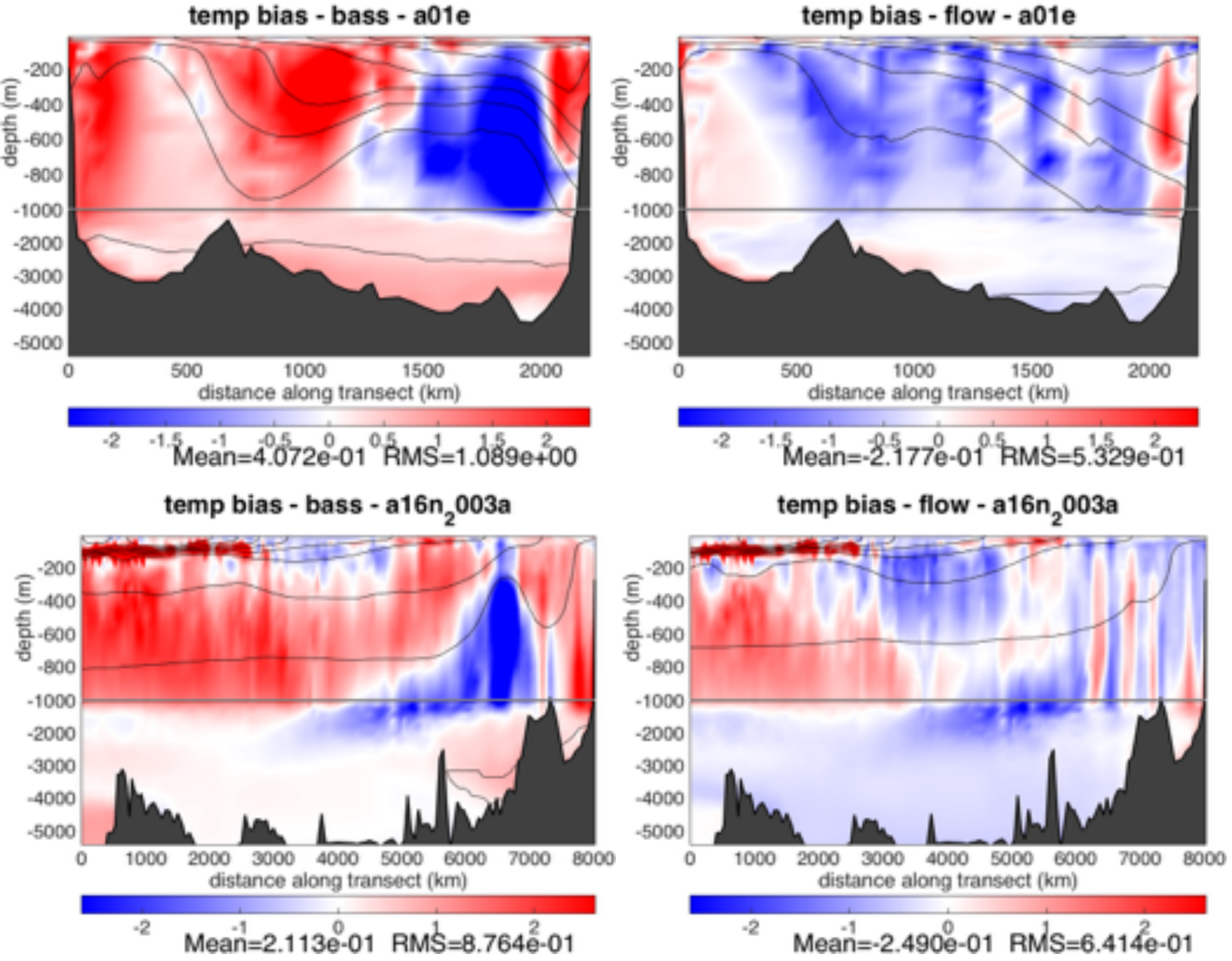


S. C. Bates, BFK, S. R. Jayne, W. G. Large, S. Stevenson, and S. G. Yeager. Mean biases, variability, and trends in air-sea fluxes and SST in the CCSM4. Journal of Climate, 25(22):7781-7801, November 2012.

Along transects

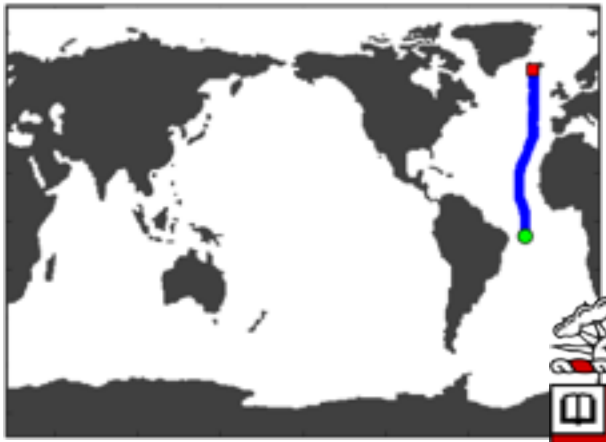
Control: Isotropic

Anisotropic



Map for a01e

Map for a16n$_2$003a



S. Reckinger, BFK, S. Bachman, F. O. Bryan, G. Danabasoglu. Anisotropic shear dispersion parameterization for mesoscale eddy transport. Ocean Modelling, In prep, 2015.

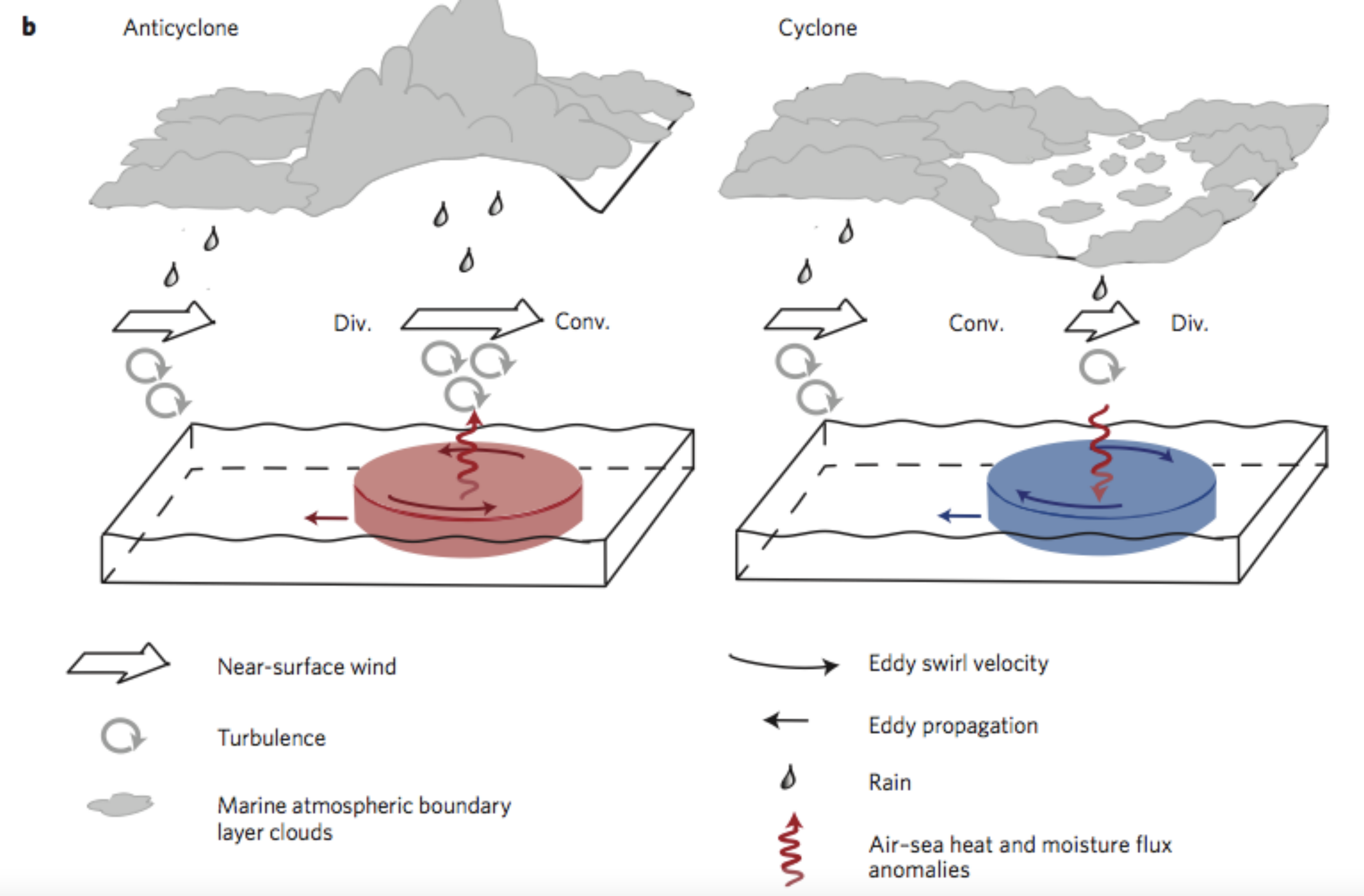
Mesoscale anisotropy often reduces mean biases:

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

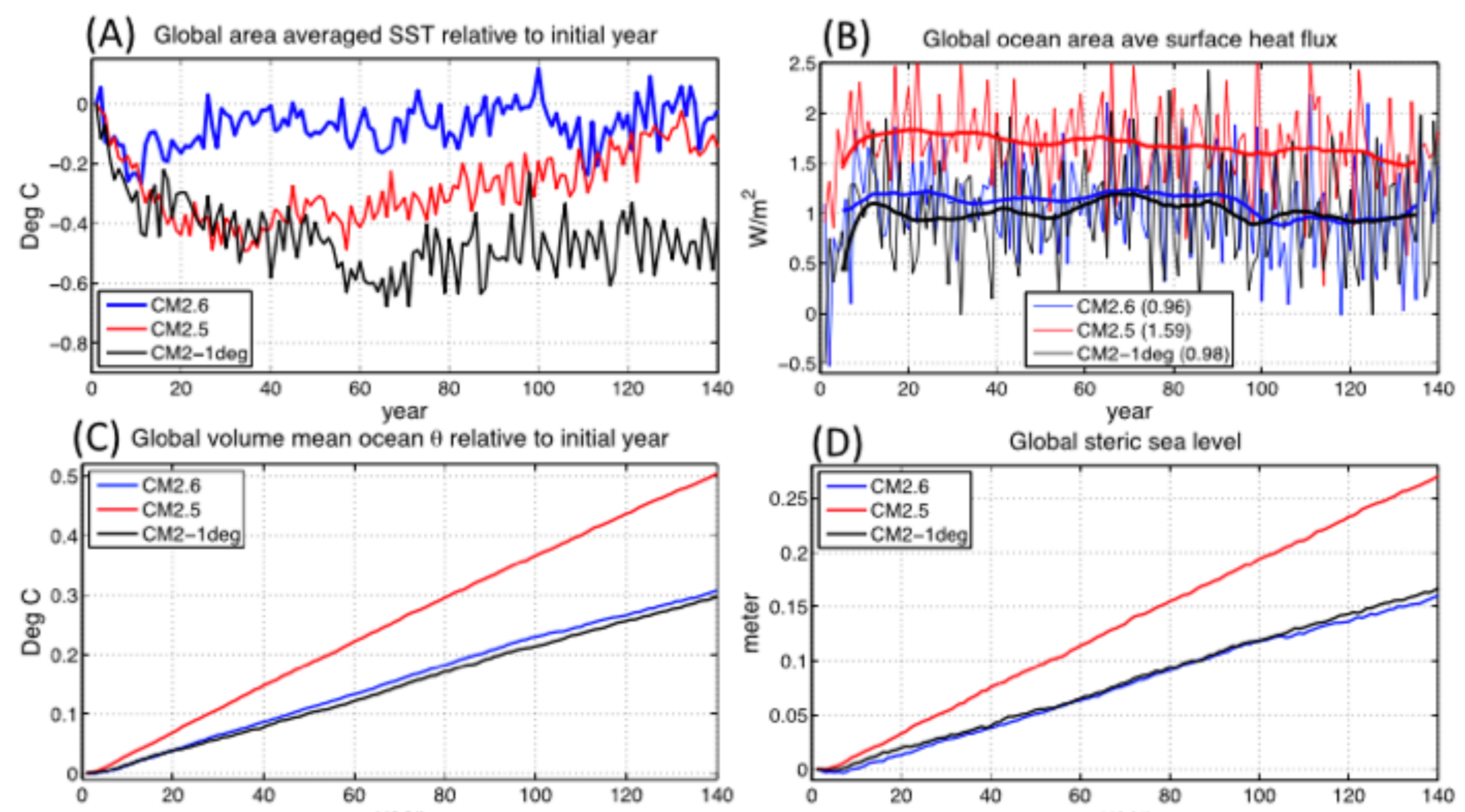


Mesoscale Eddy Air-Sea Feedbacks?

Effect on net air-sea fluxes observed: too hard to parameterize?

Bryan et al. 2010, Frenger et al. 2013

By comparing resolved mesoscale eddies to parameterized ones (with same 50km atmosphere), Griffies et al show global differences of O(0.7 W/m²) or O(0.14 K/century)



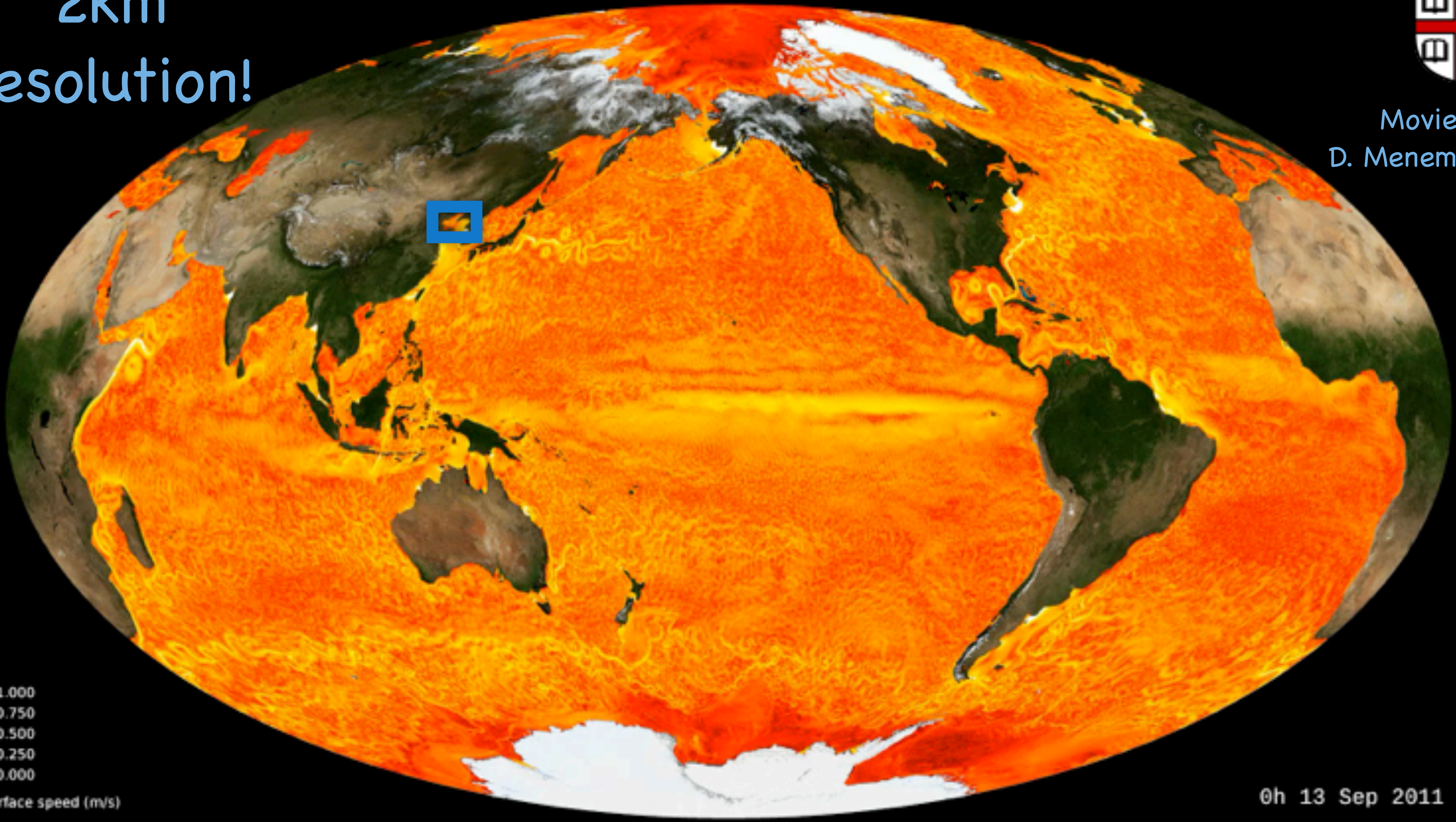
Stephen M. Griffies, Michael Winton, Whit G. Anderson, Rusty Benson, Thomas L. Delworth, Carolina O. Dufour, John P. Dunne, Paul Goddard, Adele K. Morrison, Anthony Rosati, Andrew T. Wittenberg, Jianjun Yin, and Rong Zhang, 2015: Impacts on Ocean Heat from Transient Mesoscale Eddies in a Hierarchy of Climate Models. J. Climate, 28, 952–977. doi: http://dx.doi.org/10.1175/JCLI-D-14-00353.1

Estimating the Circulation & Climate of the Ocean

LLC4320 Model

2km resolution!

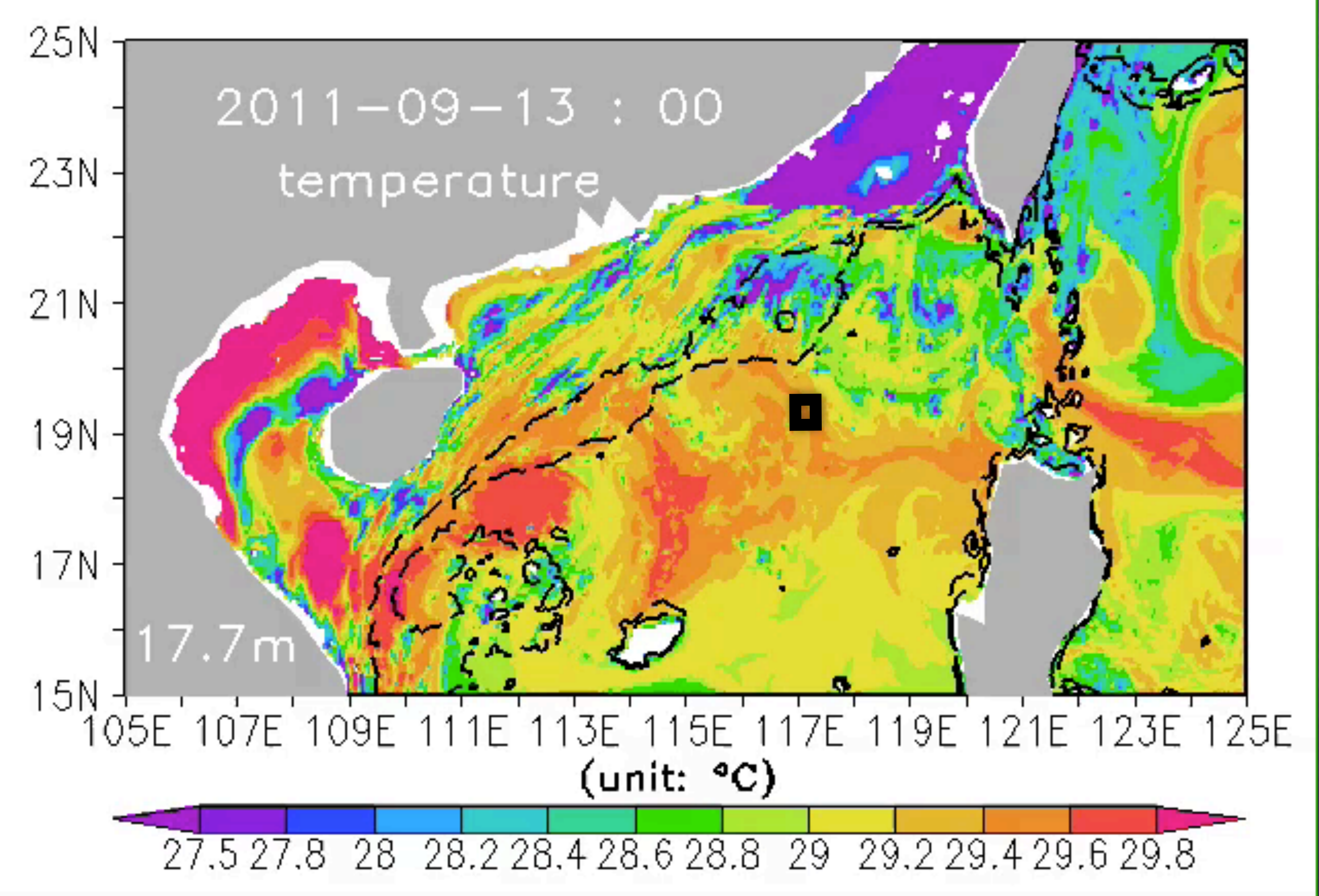
Movie:
D. Menemenlis



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

Estimating the Circulation & Climate of the Ocean

LLC4320 Model



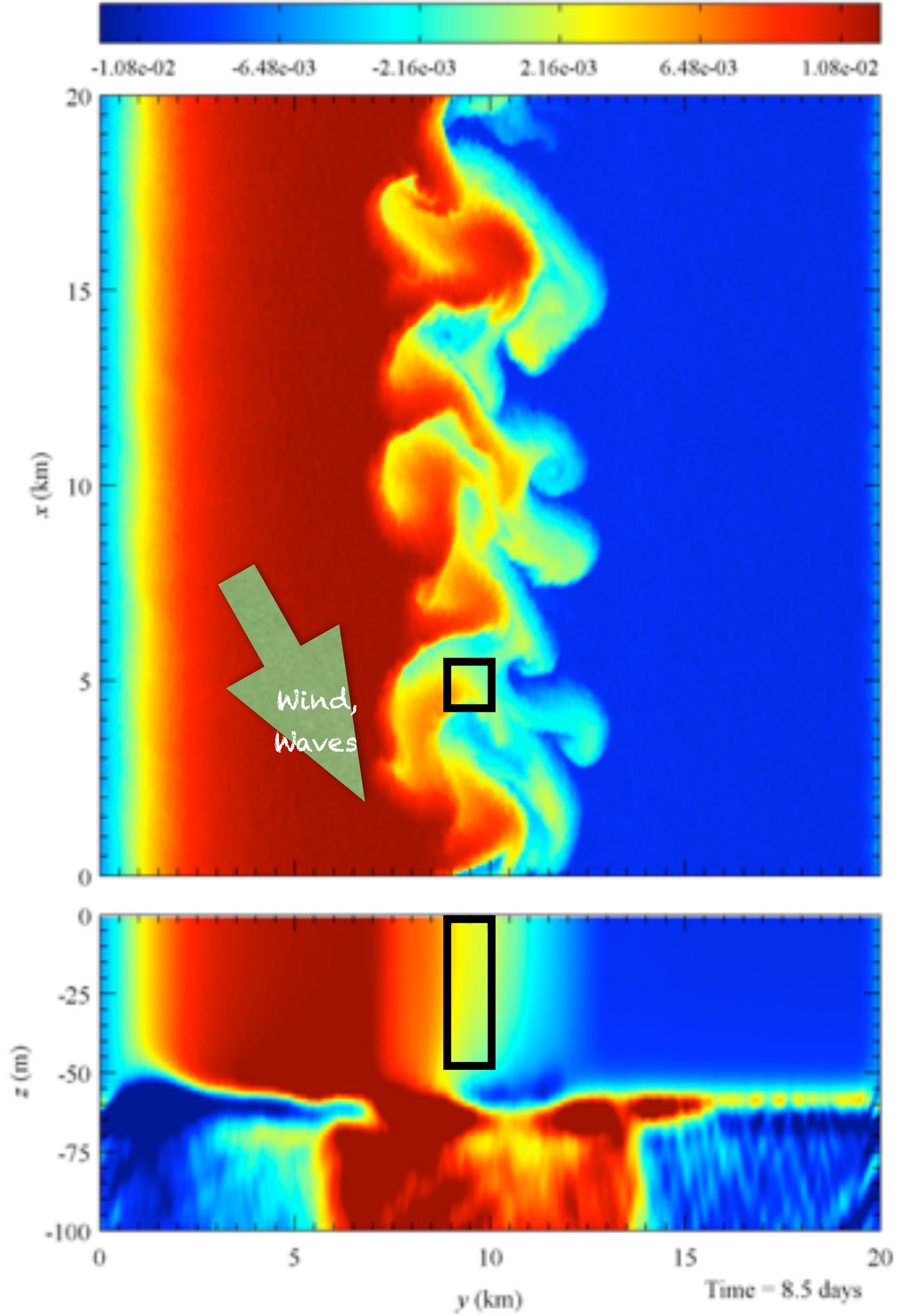
Movie:
Z. Jing

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.

LES as big as we can?

Movie: P. Hamlington



Perform large eddy simulations (LES) of Langmuir turbulence with a submesoscale temperature front

Use NCAR LES model to solve Wave-Averaged Eqtns.

2 Versions: 1 With Waves & Winds
1 With only Winds

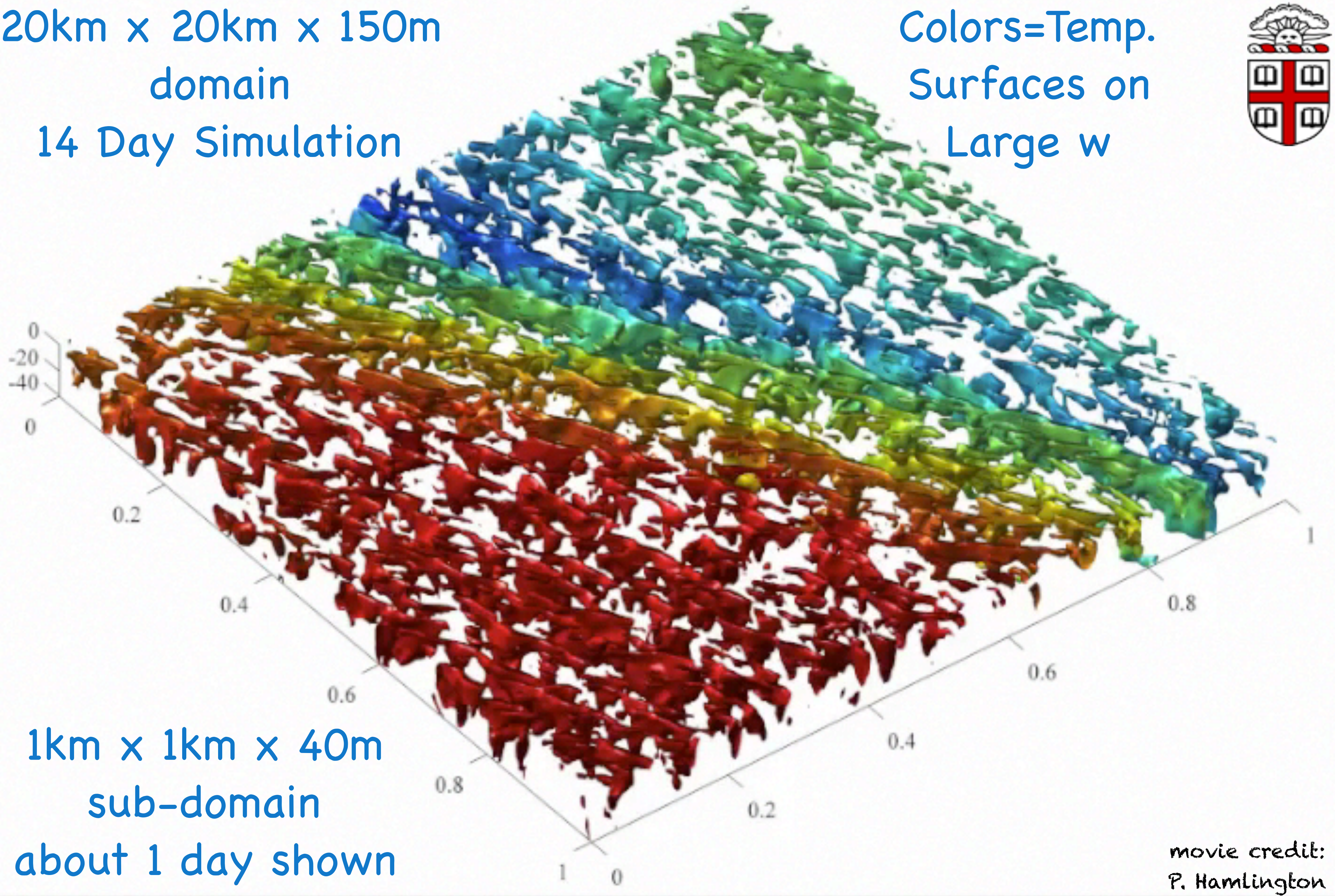
Computational parameters:
Domain size: 20km x 20km x -160m
Grid points: 4096 x 4096 x 128
Resolution: 5m x 5m x -1.25m

1000x more gridpoints than CESM

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

20km x 20km x 150m
domain
14 Day Simulation

Colors=Temp.
Surfaces on
Large w



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

movie credit:
P. Hamlington

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

Near Future of Modeling

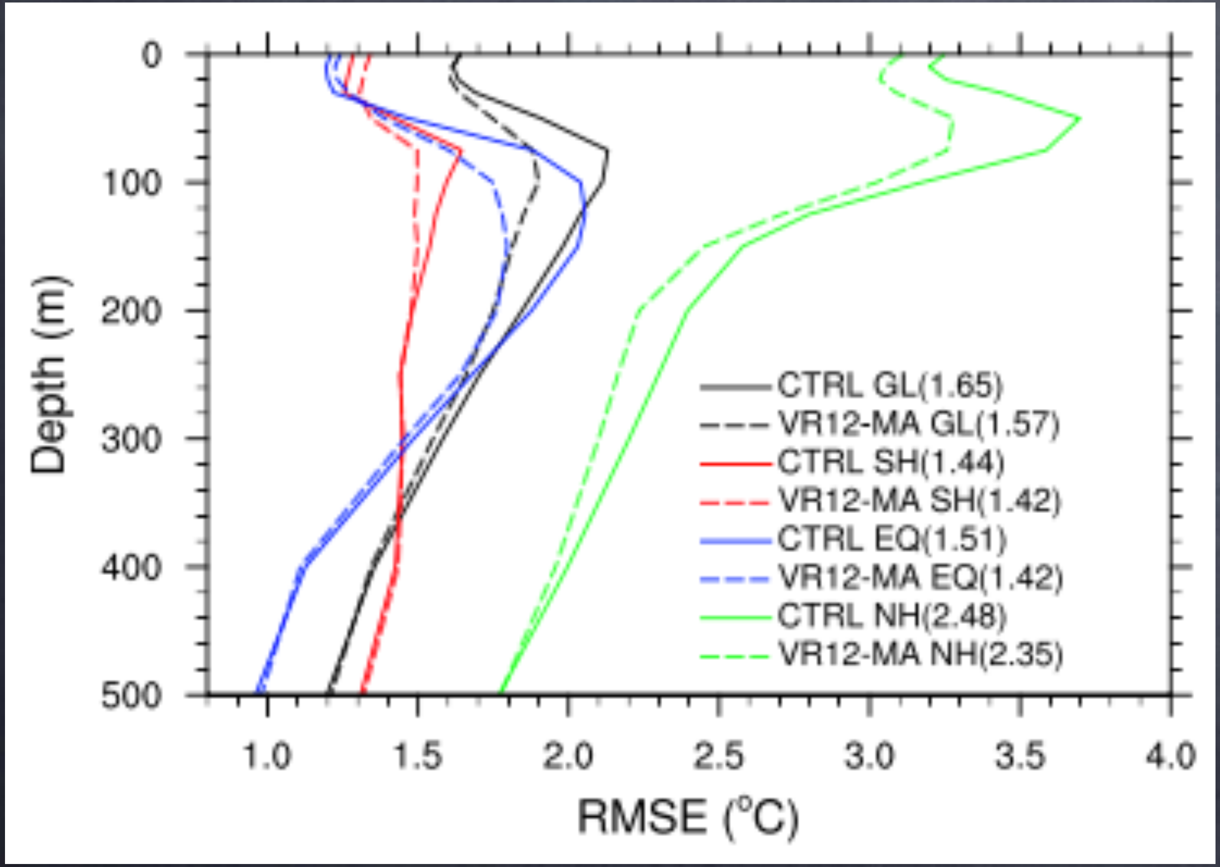
- LES 5m, 20km x 20km, weeks. Atmosphere & Ocean separate—not coupled.
- NCOM 3-4 km, Global, Forecasts < Annual, ocean-only
- JPL ECCO MITgcm LLC4320, 2km, Global, Months, ocean-only
- CFSv2, CFSR, 50km, Global, Decades, coupled
- CESM 10km, 100km, Global, Centuries, coupled
- GFDL 10km, 25km, 100km, Global, Centuries, coupled

For foreseeable future, air-sea flux & boundary layer turbulence will be parameterized except on very small domains—on both climate & weather timescales.

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, BFK, 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, 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.

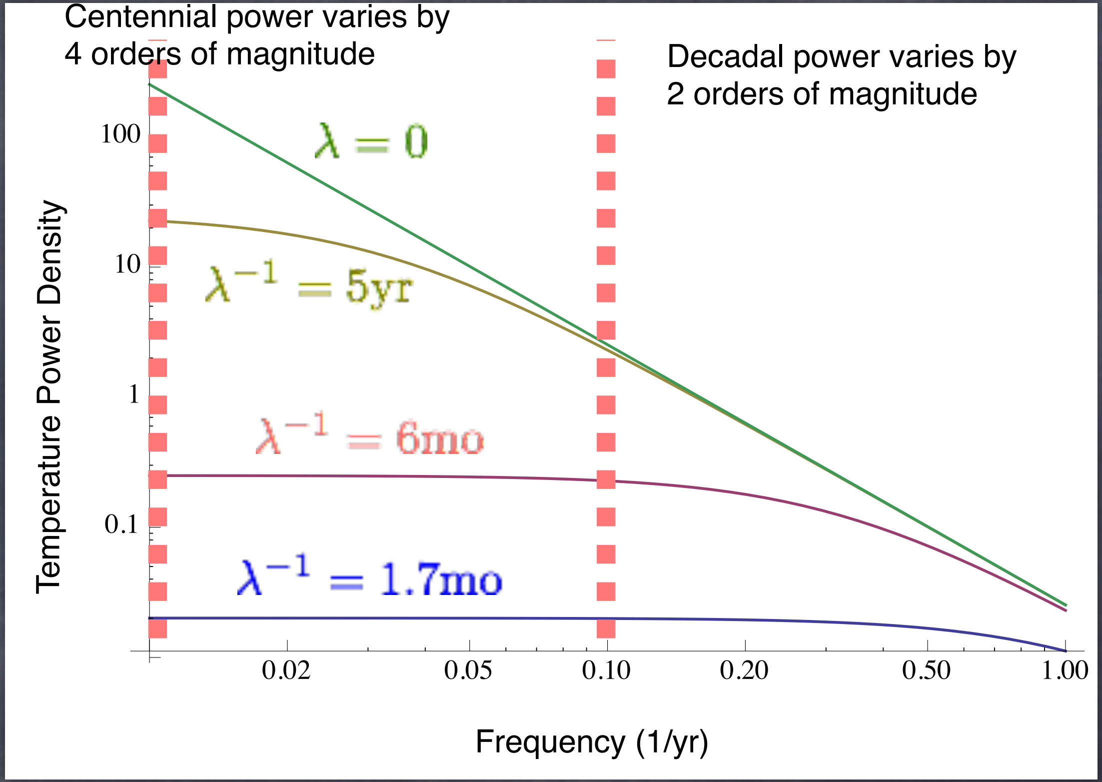
Modeling of decadal variability

Stochastic (unpredictable beyond persistence) Model: Frankignoul & Hasselmann (77)

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

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

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


Centennial power varies by 4 orders of magnitude

Decadal power varies by 2 orders of magnitude

One difficulty is getting the reservoir in communication with the atmospheric variability right.

Another is getting predictable variability right!

These factors are affected by mixed layer depth.

Langmuir Mixing in CESM: Reduces MLD Errors

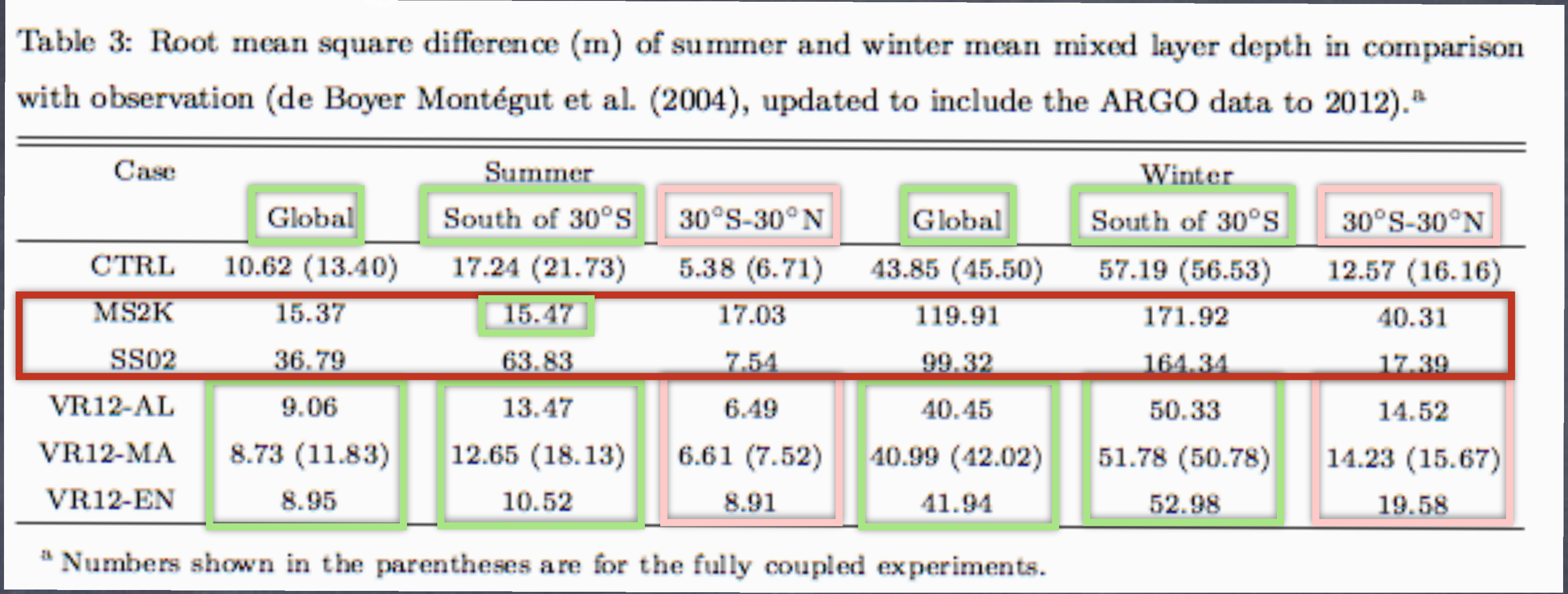


Table 3: Root mean square difference (m) of summer and winter mean mixed layer depth in comparison with observation (de Boyer Montégut et al. (2004), updated to include the ARGO data to 2012).[a]

Case	Summer			Winter		
	Global	South of 30°S	30°S-30°N	Global	South of 30°S	30°S-30°N
CTRL	10.62 (13.40)	17.24 (21.73)	5.38 (6.71)	43.85 (45.50)	57.19 (56.53)	12.57 (16.16)
MS2K	15.37	15.47	17.03	119.91	171.92	40.31
SS02	36.79	63.83	7.54	99.32	164.34	17.39
VR12-AL	9.06	13.47	6.49	40.45	50.33	14.52
VR12-MA	8.73 (11.83)	12.65 (18.13)	6.61 (7.52)	40.99 (42.02)	51.78 (50.78)	14.23 (15.67)
VR12-EN	8.95	10.52	8.91	41.94	52.98	19.58

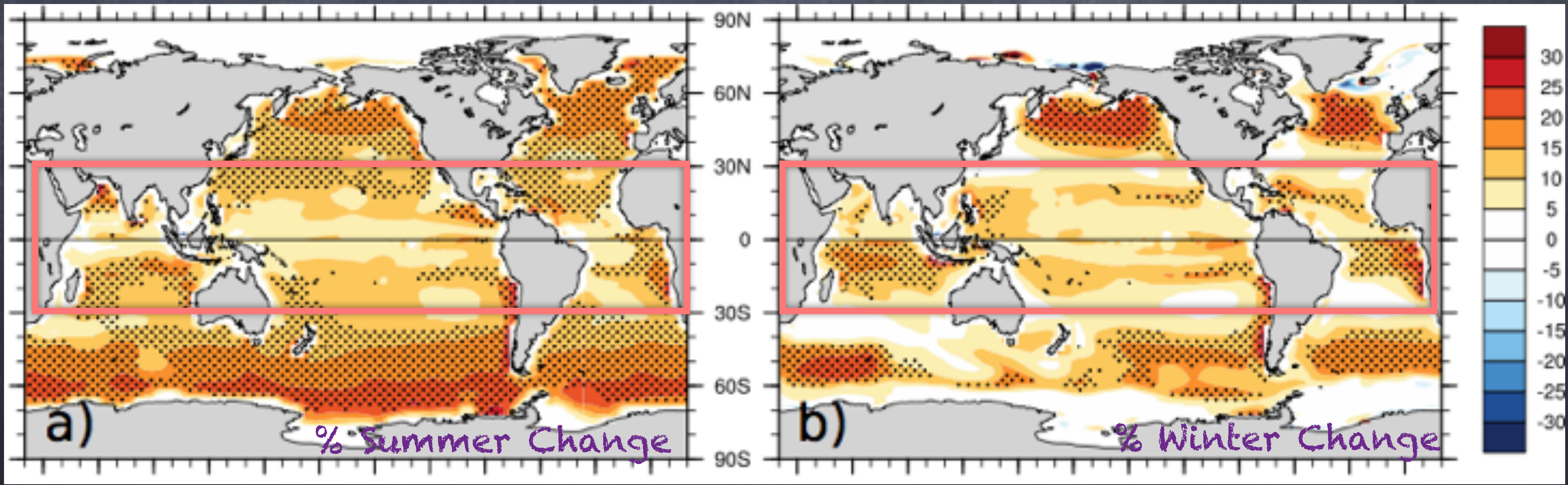
[a] Numbers shown in the parentheses are for the fully coupled experiments.

Control

Competition

3 versions of Van Roekel et al

dotted when statistical significant

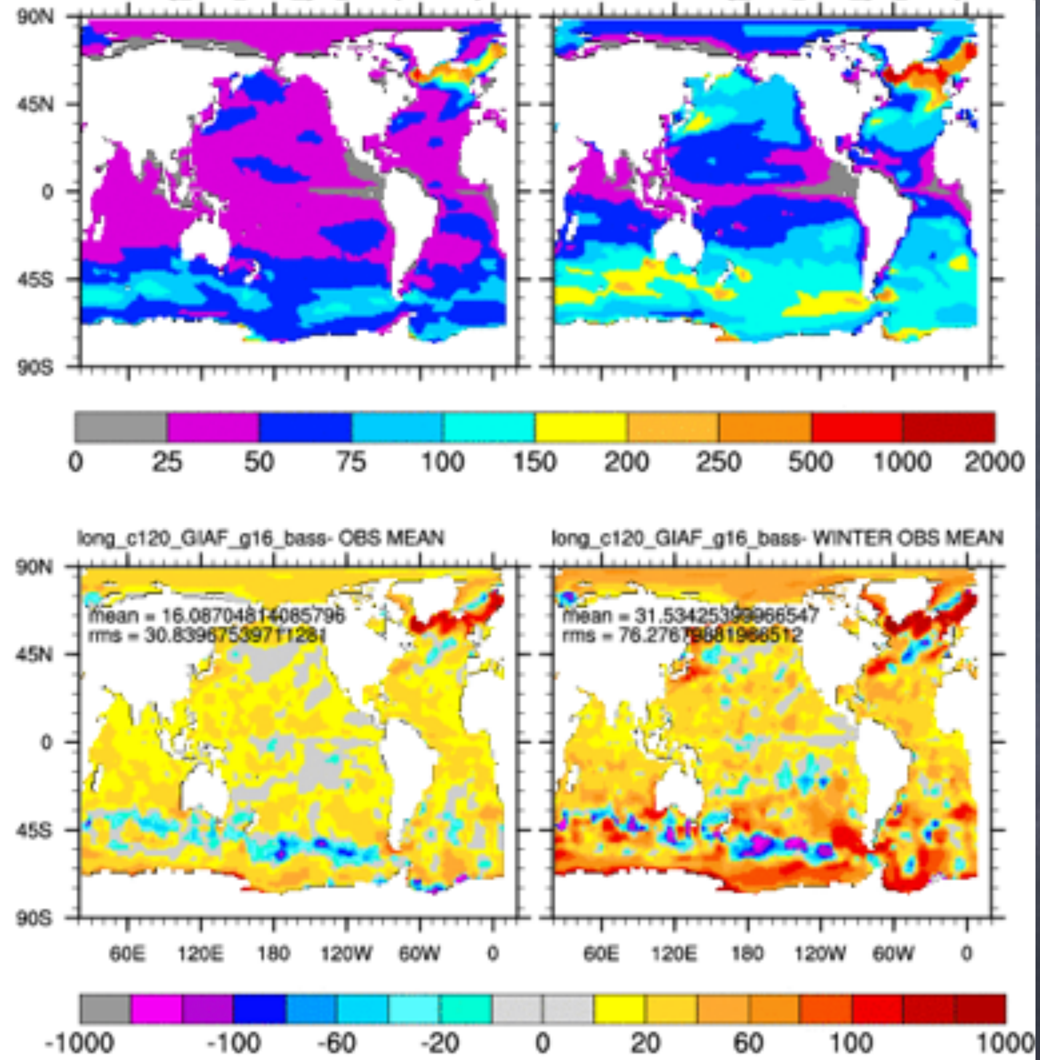


L. P. Van Roekel, BFK, P. P. Sullivan, P. E. Hamlington, and S. R. Haney. The form and orientation of Langmuir cells for misaligned winds and waves. Journal of Geophysical Research-Oceans, 117:C05001, 22pp, May 2012.

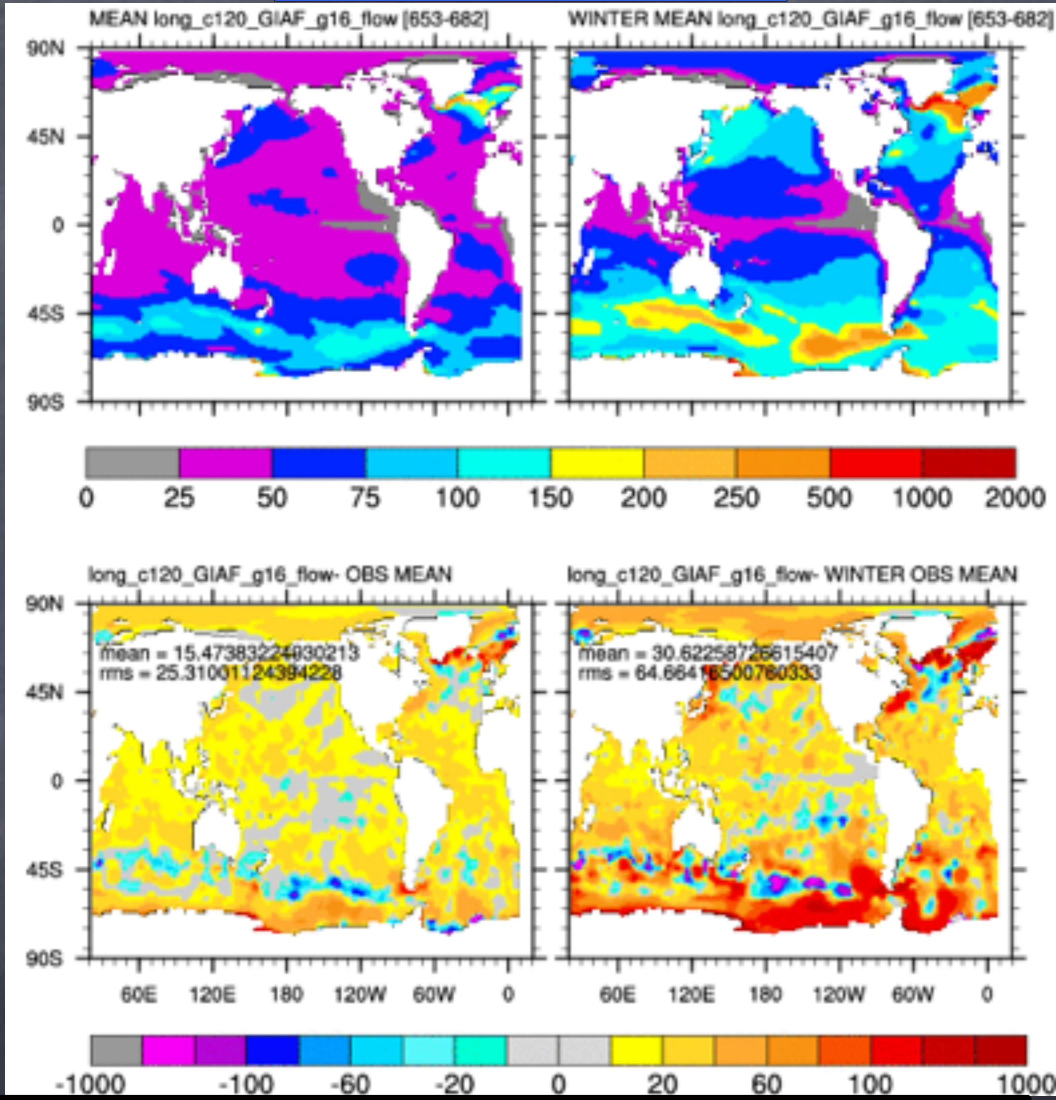
Q. Li, A. Webb, BFK, A. Craig, G. Danabasoglu, W. G. Large, and M. Vertenstein. Langmuir mixing effects on global climate: WAVEWATCH III in CESM. Ocean Modelling, August 2015. in press.

Mesoscale Anisotropy & Mixed Layer Depth

N² isotropic



Anisotropic: ratio=5



Anisotropy deepens MLD in Southern Ocean, shallows MLD in North Atlantic, and reduces winter mean rms bias by 15% (annual by 18%)

S. Reckinger, BFK, S. Bachman, F. O. Bryan, G. Danabasoglu. Anisotropic shear dispersion parameterization for mesoscale eddy transport. Ocean Modelling, In prep, 2015.

- “Twenty years ago, bulk flux schemes were considered to be uncertain by about 30%; the authors find COARE 3.0 to be accurate within 5% for wind speeds of 0-10 m/s and 10% for wind speeds of between 10 and 20 m/s.” (Fairall et al. 2003).

- Since then, COARE has been updated to v3.5 (Edson et al. 2013). Other observation-based schemes exist as well.

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

- GFDL uses a version of Beljaars (1994)

- CESM uses a version of Bryan et al. (1996).

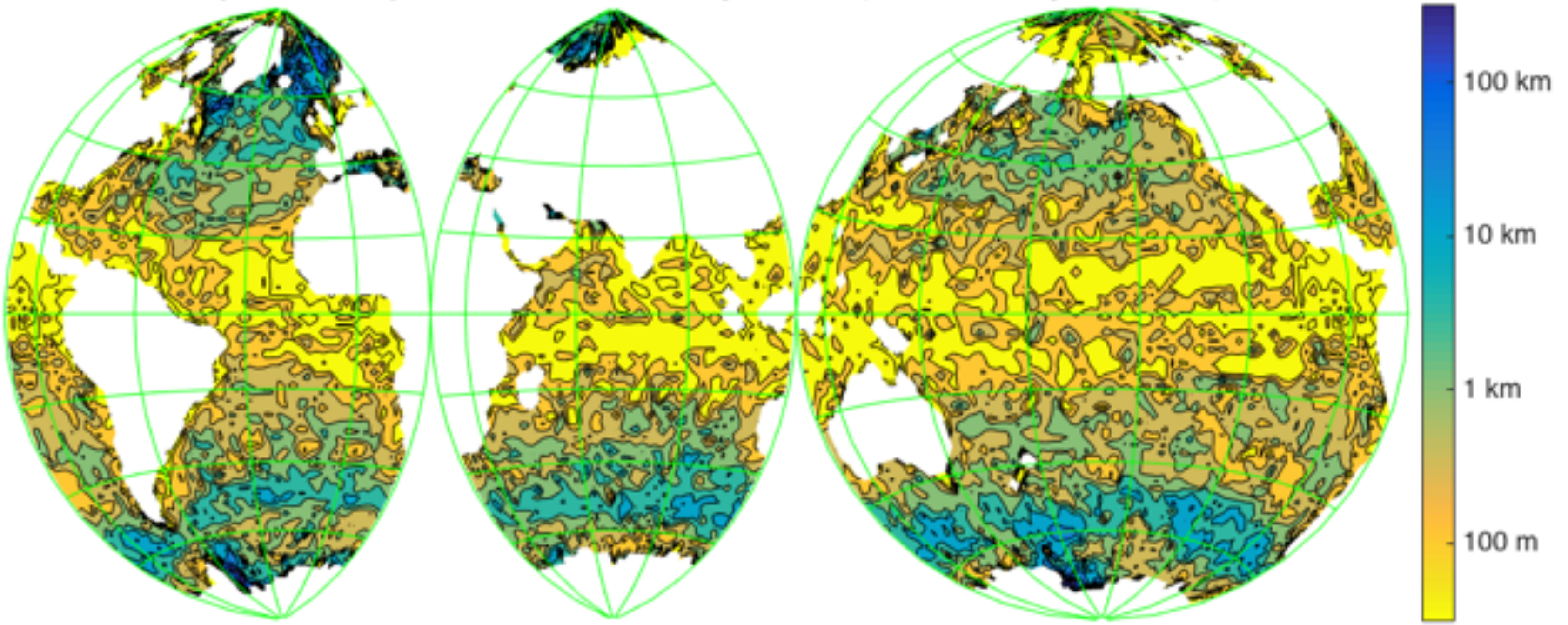
This factor is affected by flux laws.

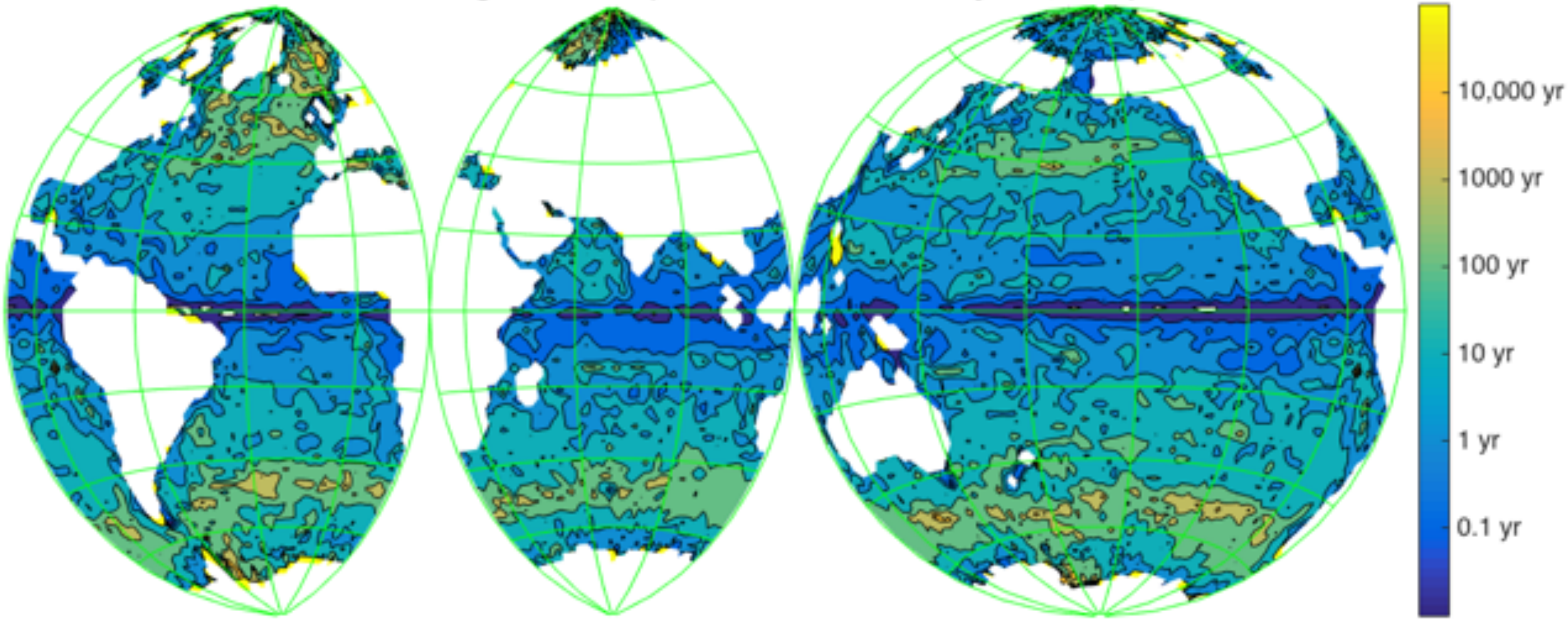
Conclusions

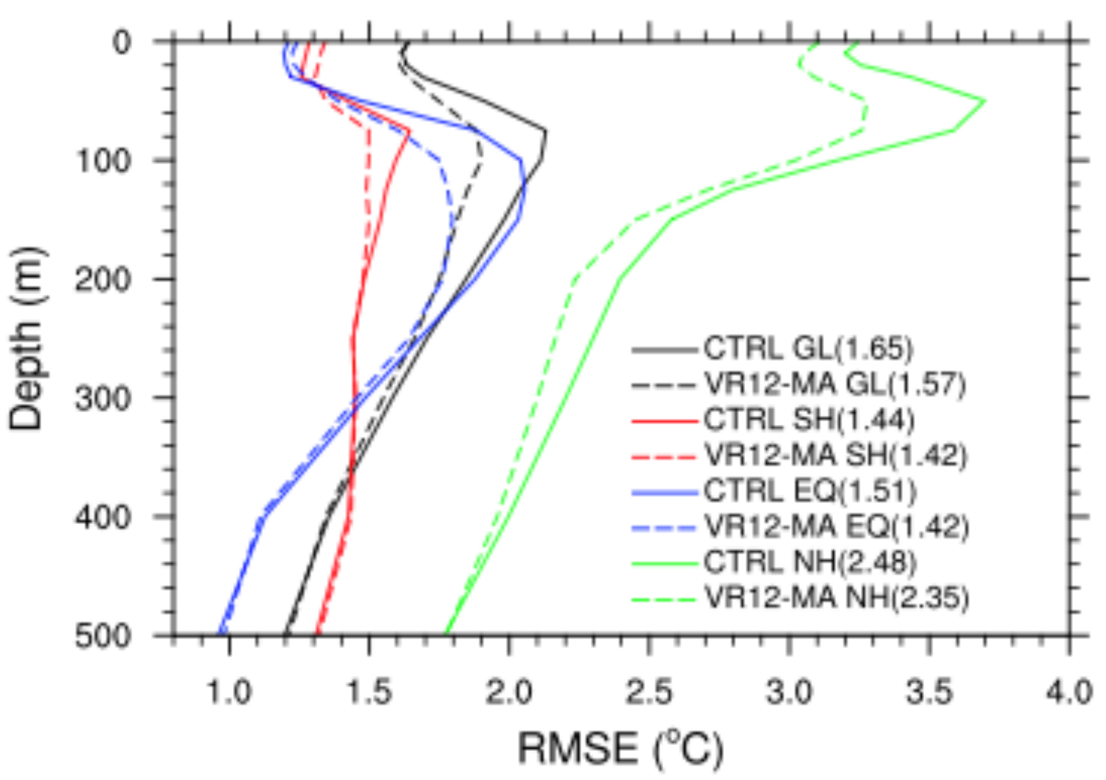
- Improvements to mesoscale, fluxes, boundary layer schemes are similar in bias change magnitude to introducing new physics (submesoscale, Langmuir).
- Mesoscale resolution will soon fix many problems—some difficulty to parameterization (e.g., mesoscale air-sea coupling)
- Scale-aware subgrid models needed for mesoscale resolution
- Climate model air-sea flux schemes have not been refreshed in 20 years, progress has been made in obs, process, theory since then.
- Entrainment, subduction, seasonality are critical to determining the reservoir of OHC and its timescale—which relate to variability, persistence, predictability. They depend on getting many things right—some easy (Ekman pumping), some hard (turbulent entrainment under diverse forcing)

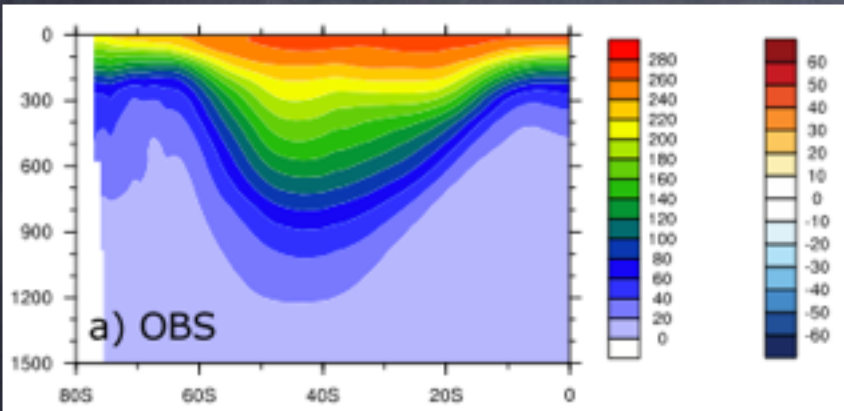
Consider 1D Oceans: one per watermass

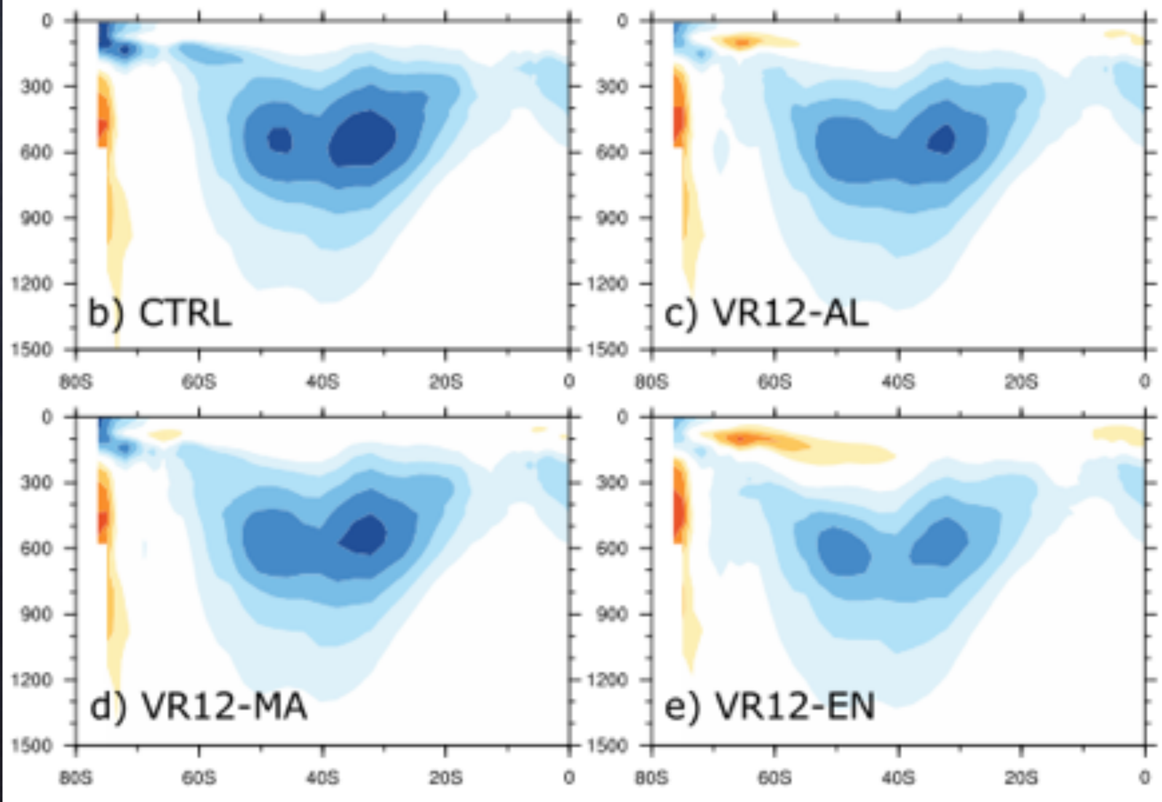
Ekman flushing gives upper limit to λ^{-1} damping timescale


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


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







Wave Mixing in CESM: Reduces Subsurface CFC & Temperature Errors

Q. Li, A. Webb, BFK, A. Craig, G. Danabasoglu, W. G. Large, and M. Vertenstein. Langmuir mixing effects on global climate: WAVEWATCH III in CESM. Ocean Modelling, 2015. In Press.