Polar Upper Ocean Dynamics: Waves, Eddies, Turbulence, Spectra, Modelling

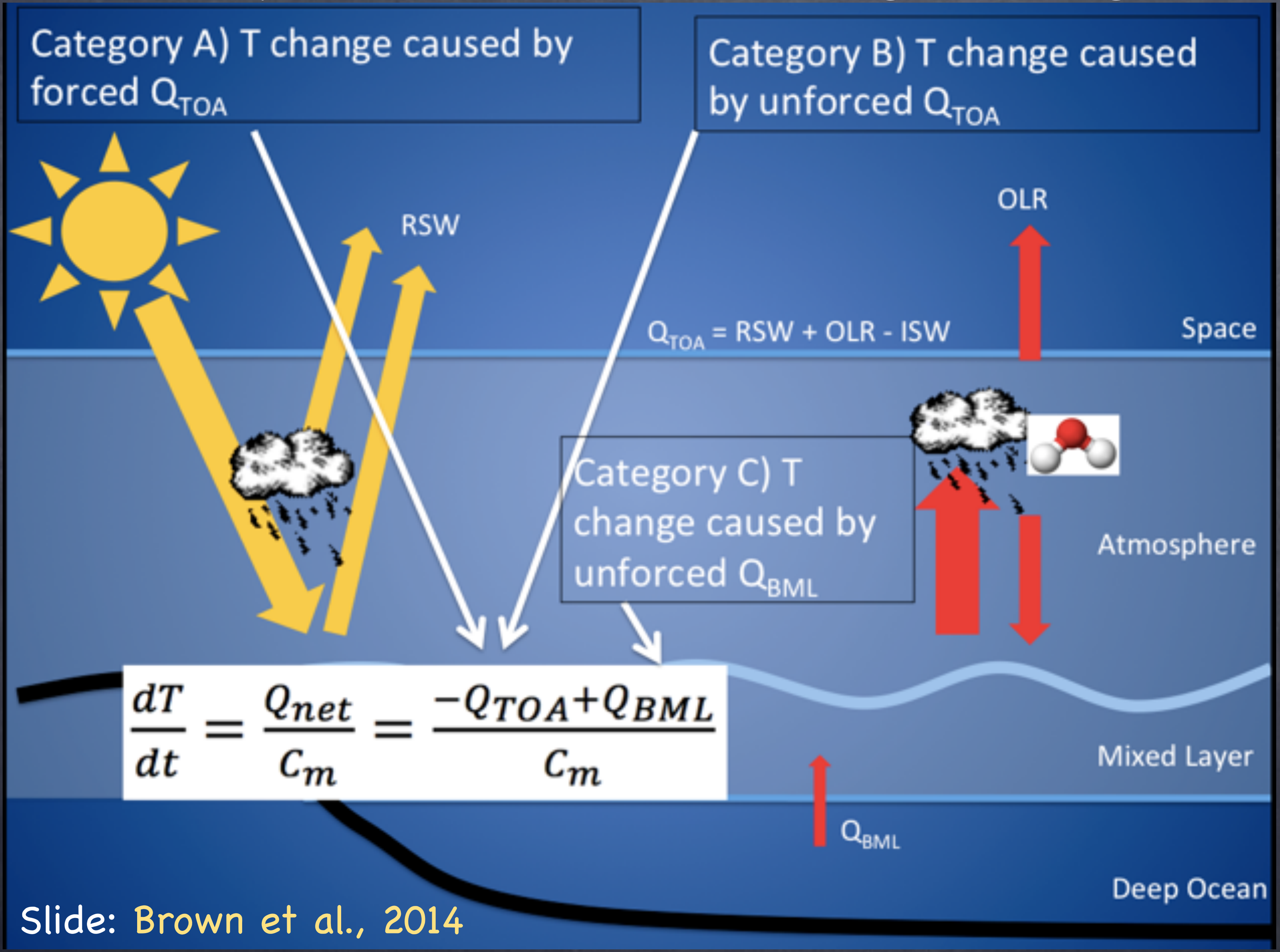
Baylor Fox-Kemper (Brown DEEP Sciences)

in Collaboration with: R. Ferrari (MIT), R. Hallberg, S. Griffies (GFDL), A. Nelson, J. Weiss (Colorado), Qing Li (Brown), Scott Reckinger (Montana State), Adrean Webb (Tokyo), Gokhan Danabasoglu, Bill Large, Mariana Vertenstein (NCAR), others

British Antarctic Survey: 10/2/16

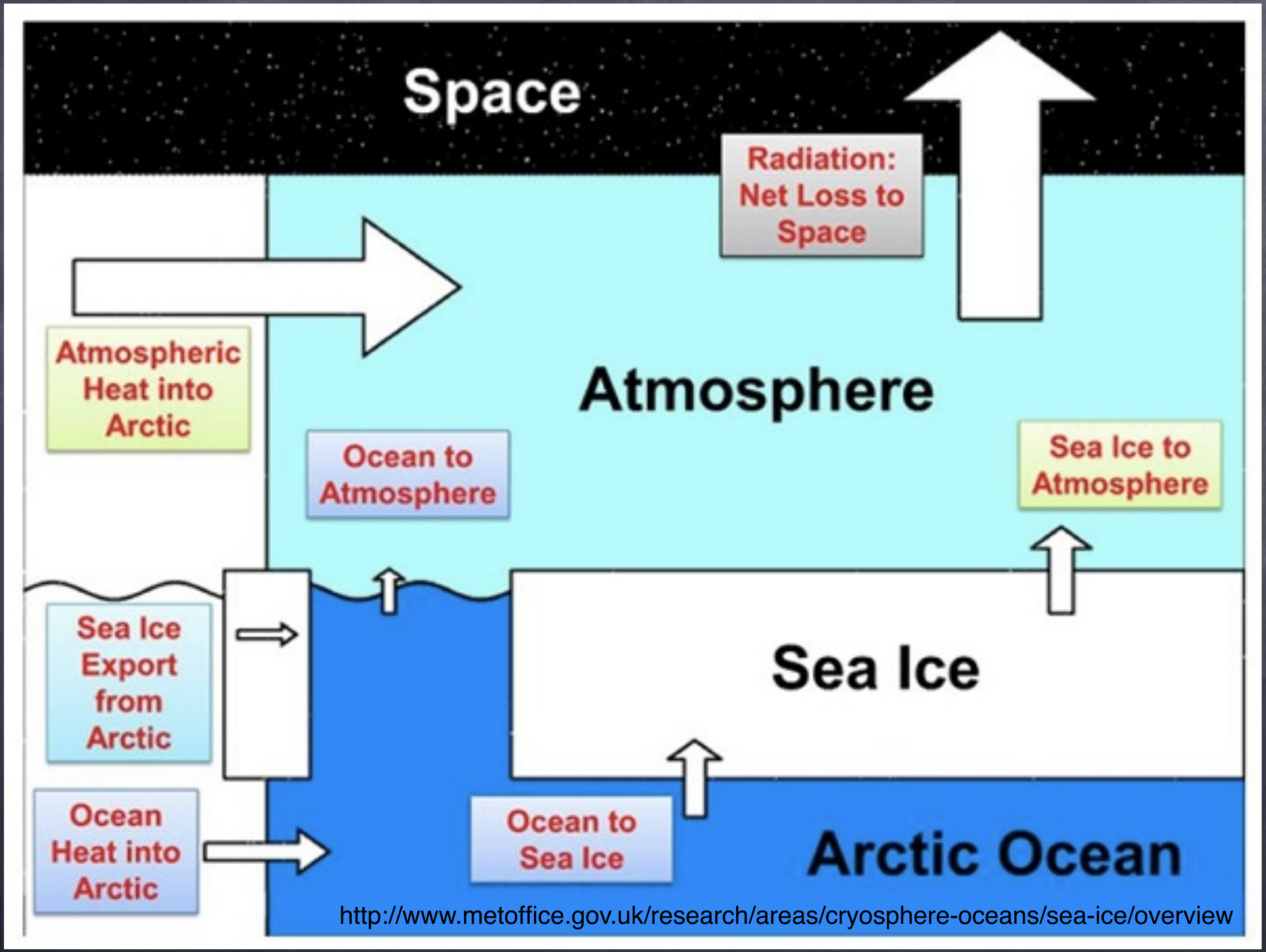
Sponsors: NSF 1245944, 1258907, 1350795
and Institute at Brown for Environment and Society (IBES)

Extrapolar Surface Energy Budget



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

Arctic Surface Energy Budget



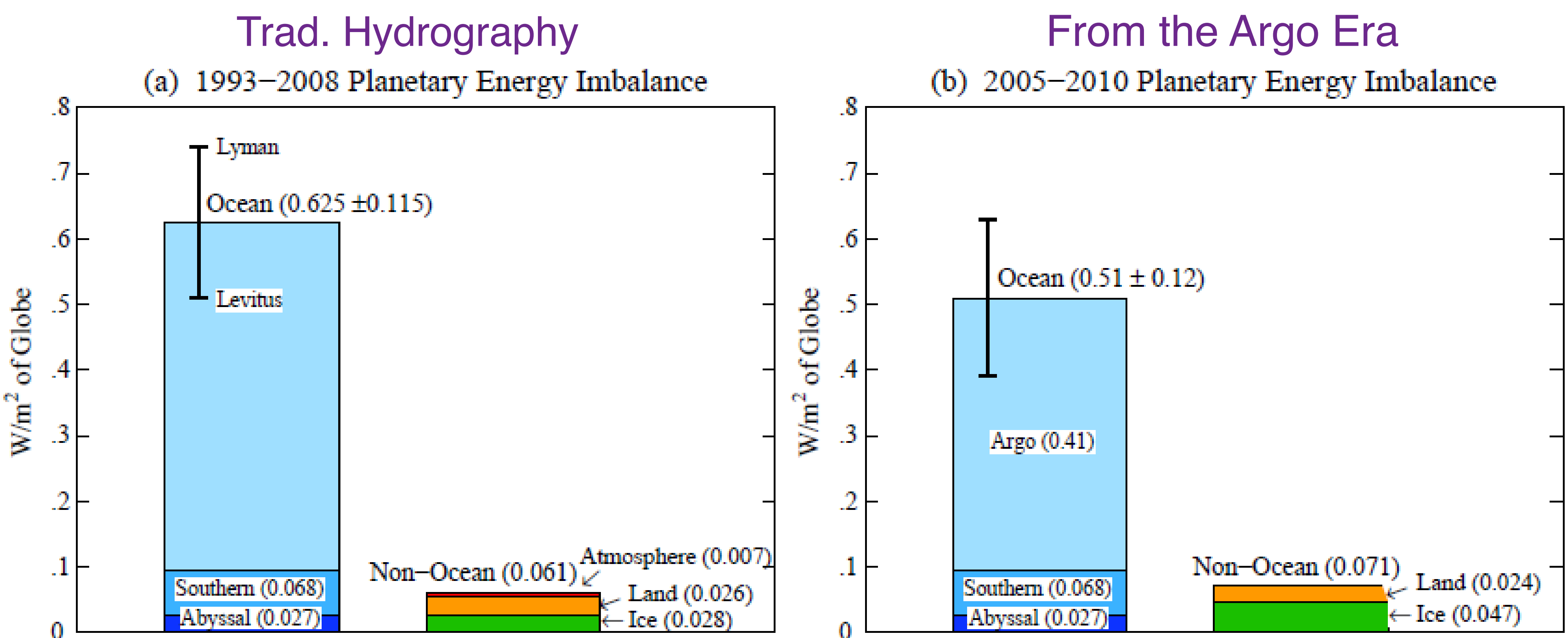
What do hydrographic observations show?

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.

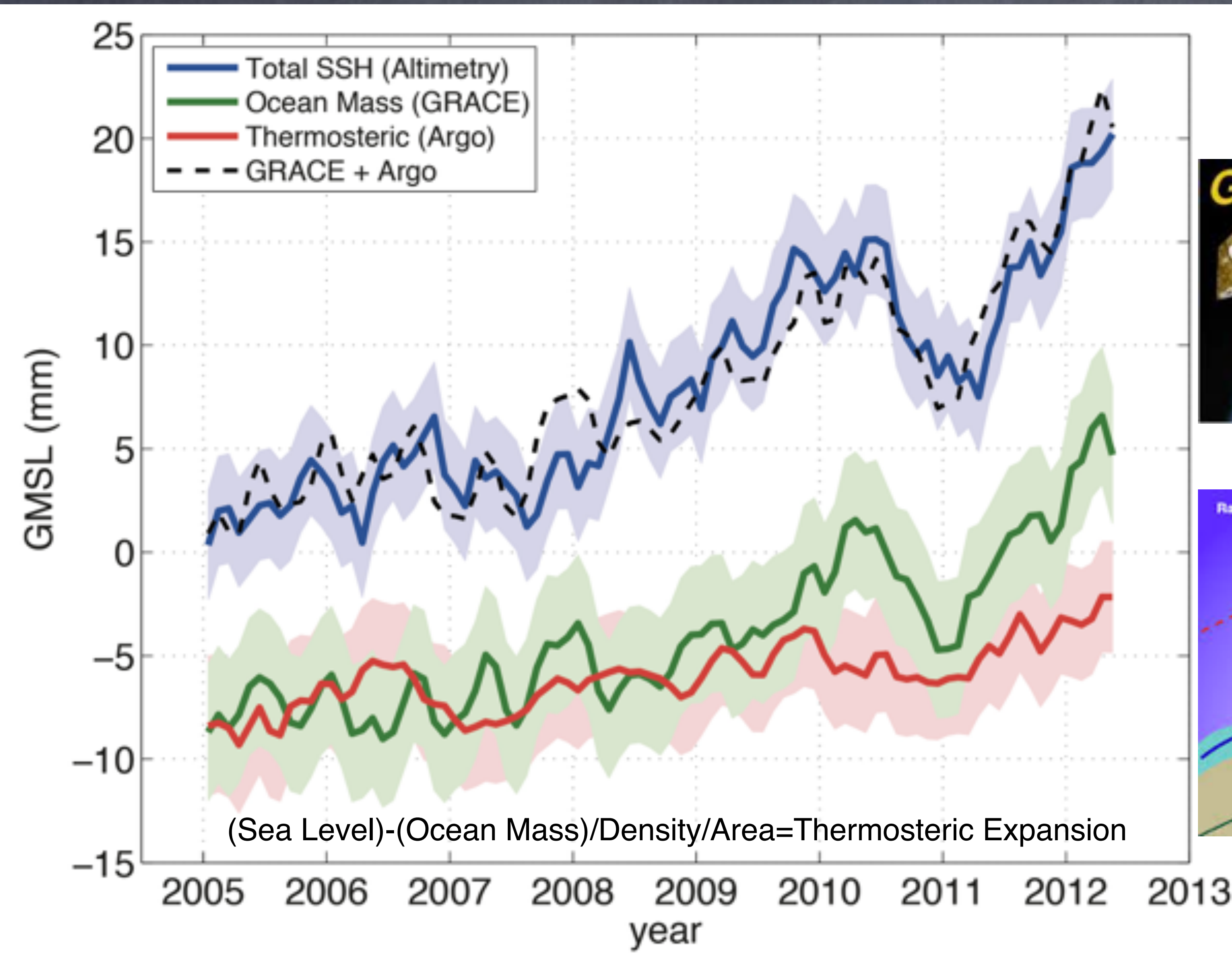
90% of anomalous warming is in the oceans.

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

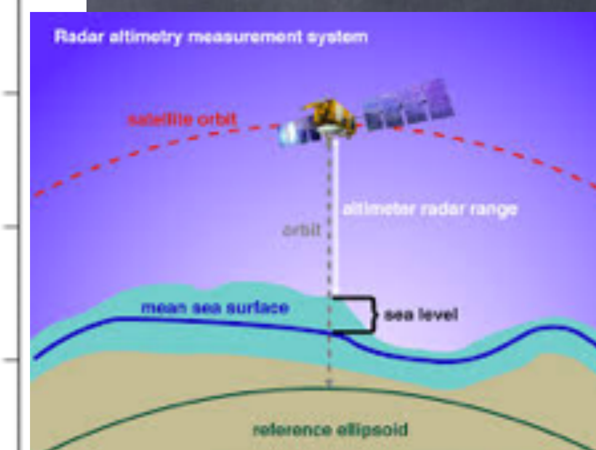


Hansen et al. (2011)

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



podaac.jpl.nasa.gov

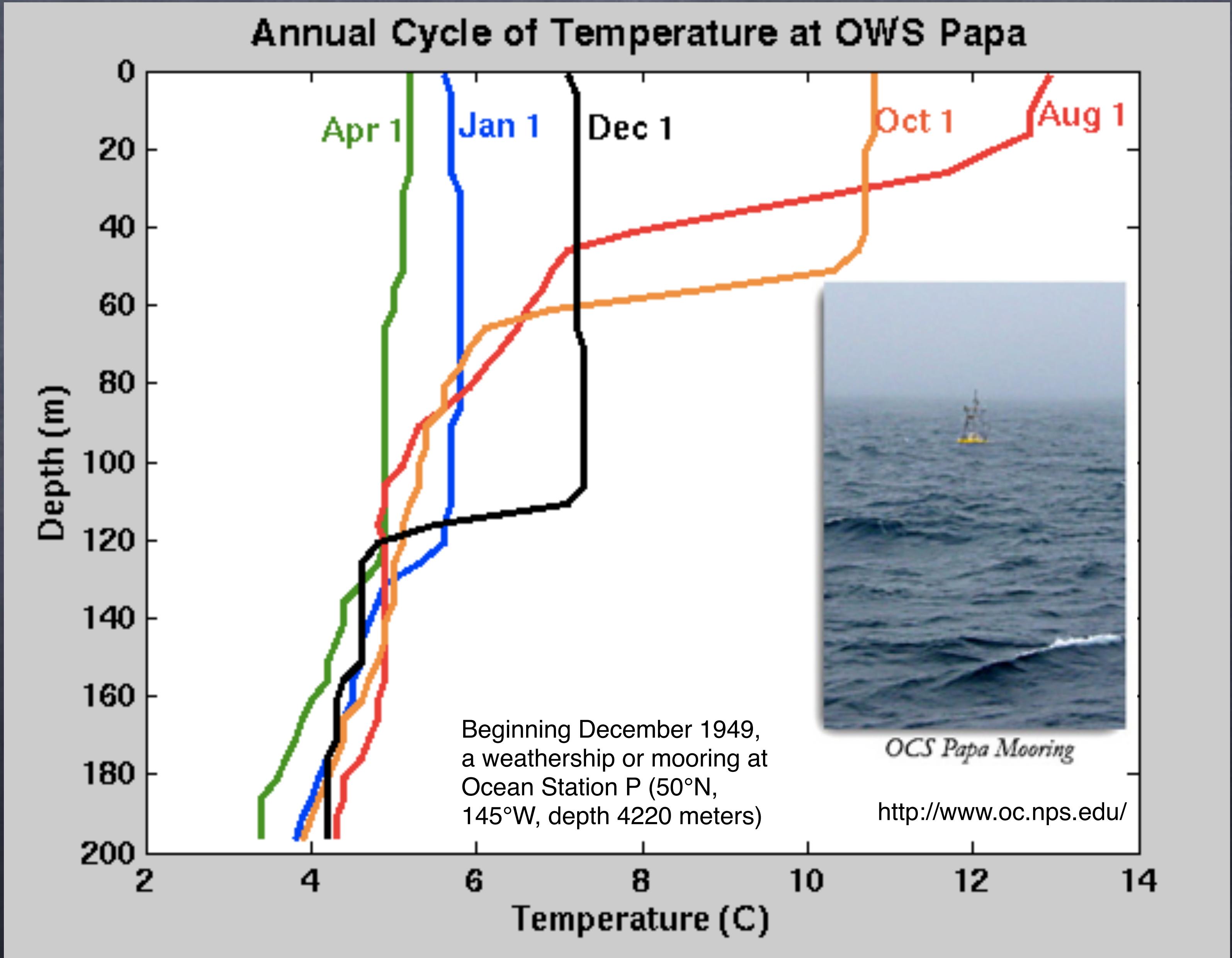


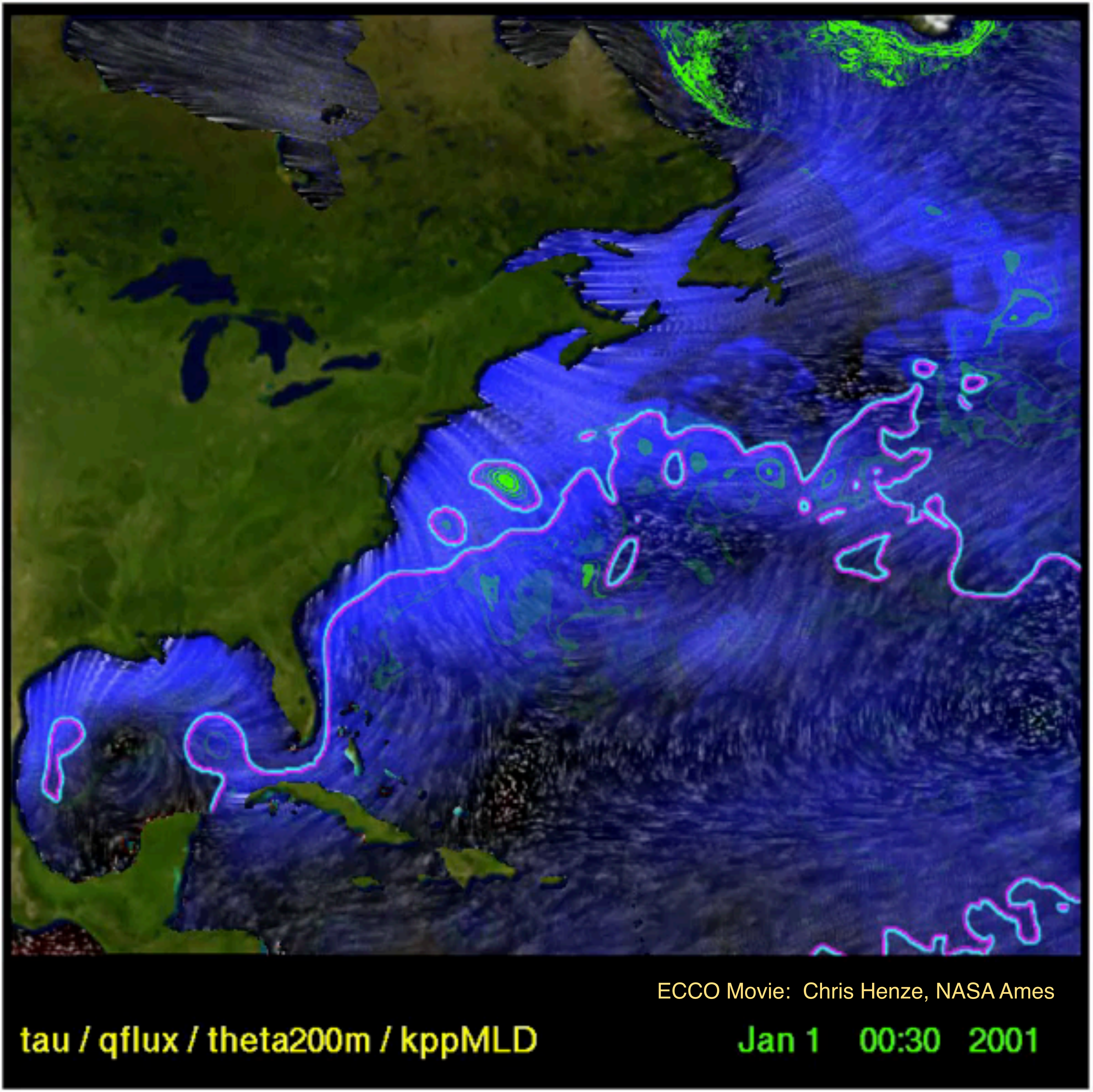
nesdis.noaa.gov

IPCC AR5, 2013

Surface, Mixed Layer, Seasons?

0.7 W/m²
=
Atmosphere:
1.5K/yr
=
3.4m Ocean:
1.5K/yr
=
34m Ocean:
0.15K/yr
=1% of
mixed layer
seasonality

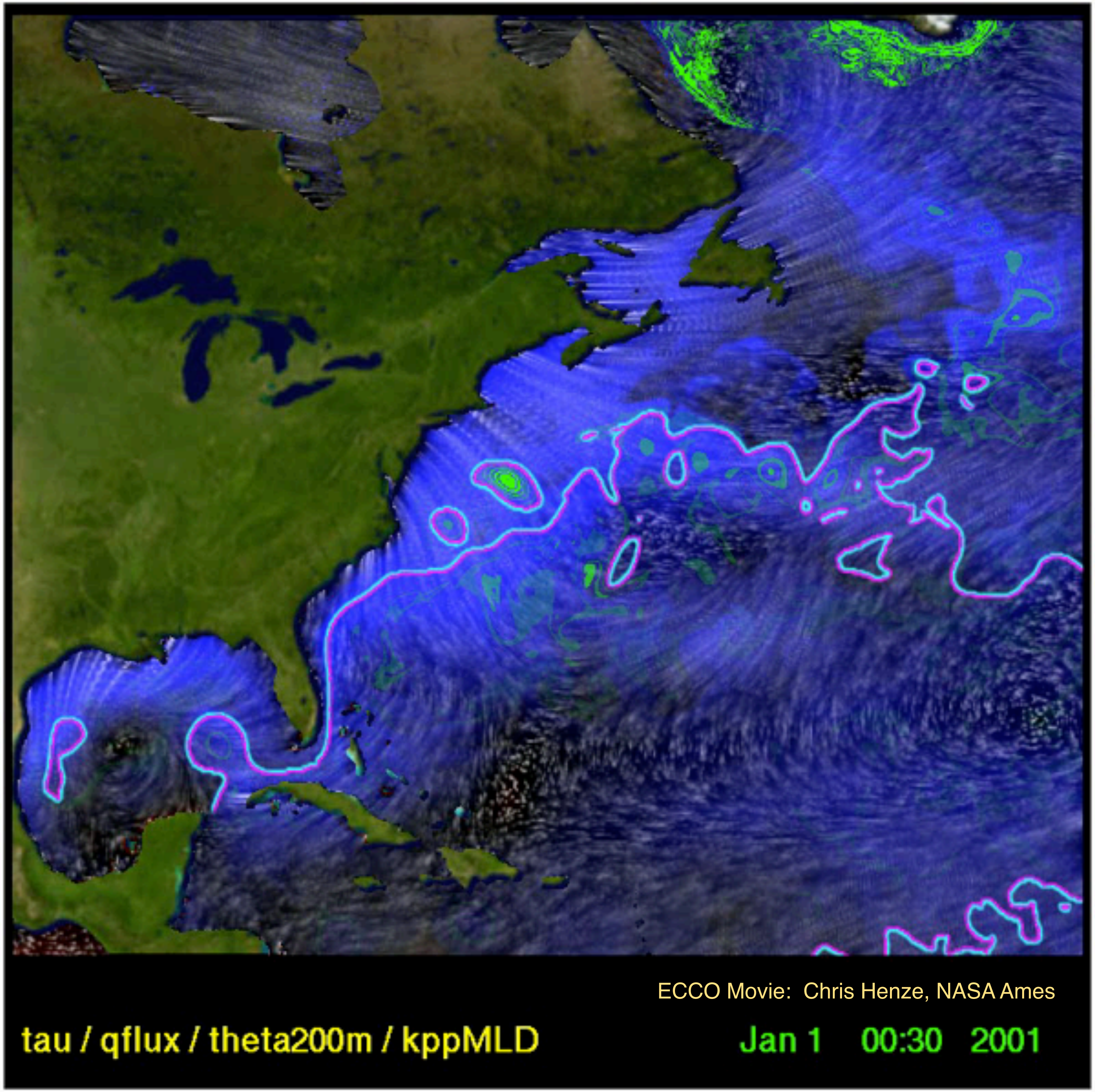




Weather,
Atmosphere
Fast

Ocean,
Climate
Slow

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



Weather,
Atmosphere
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Ocean,
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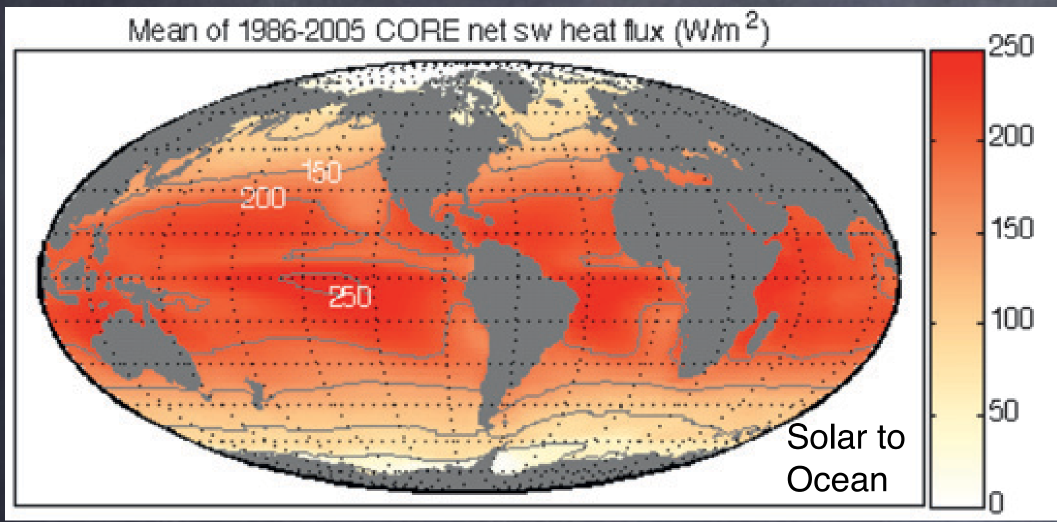
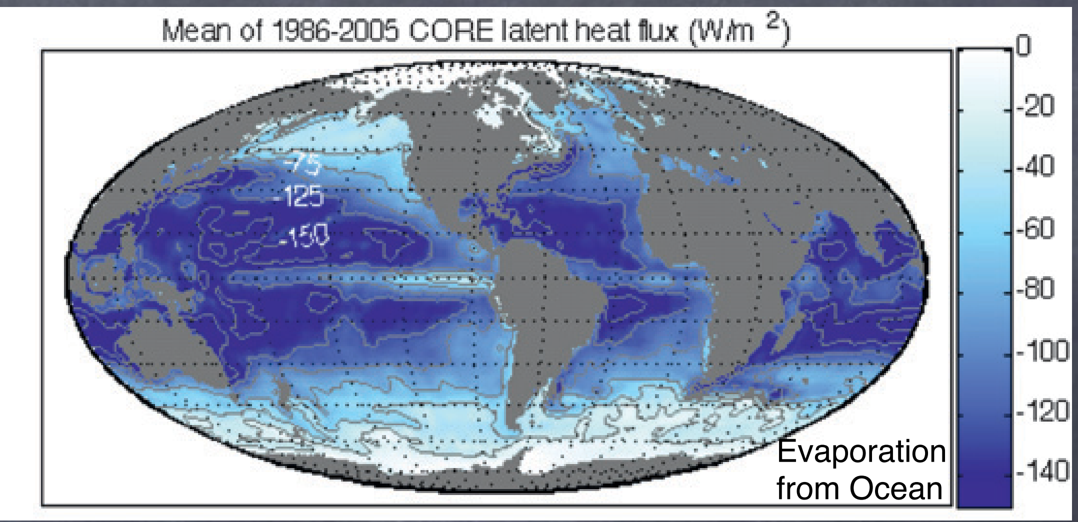
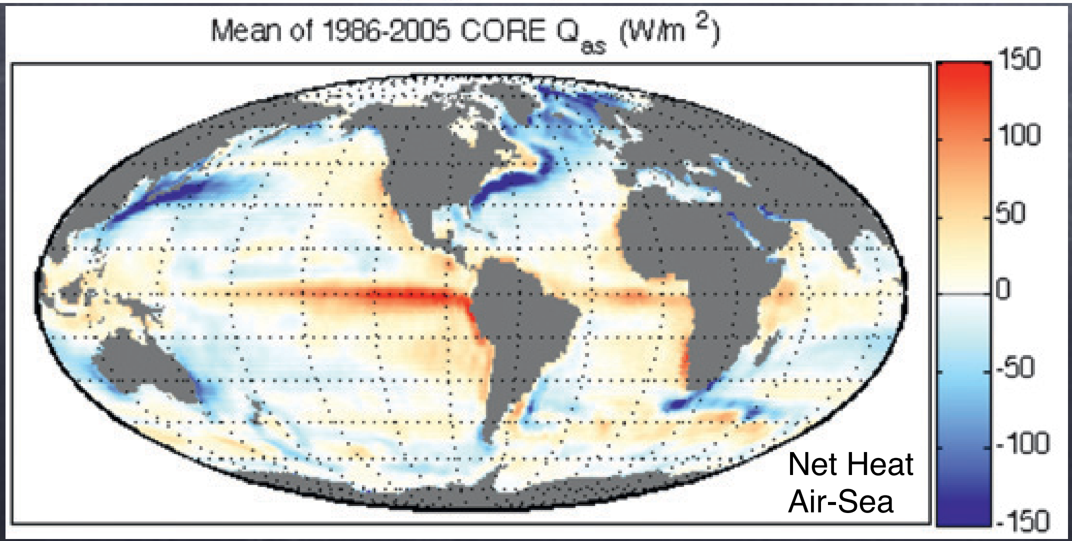
Slow

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

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

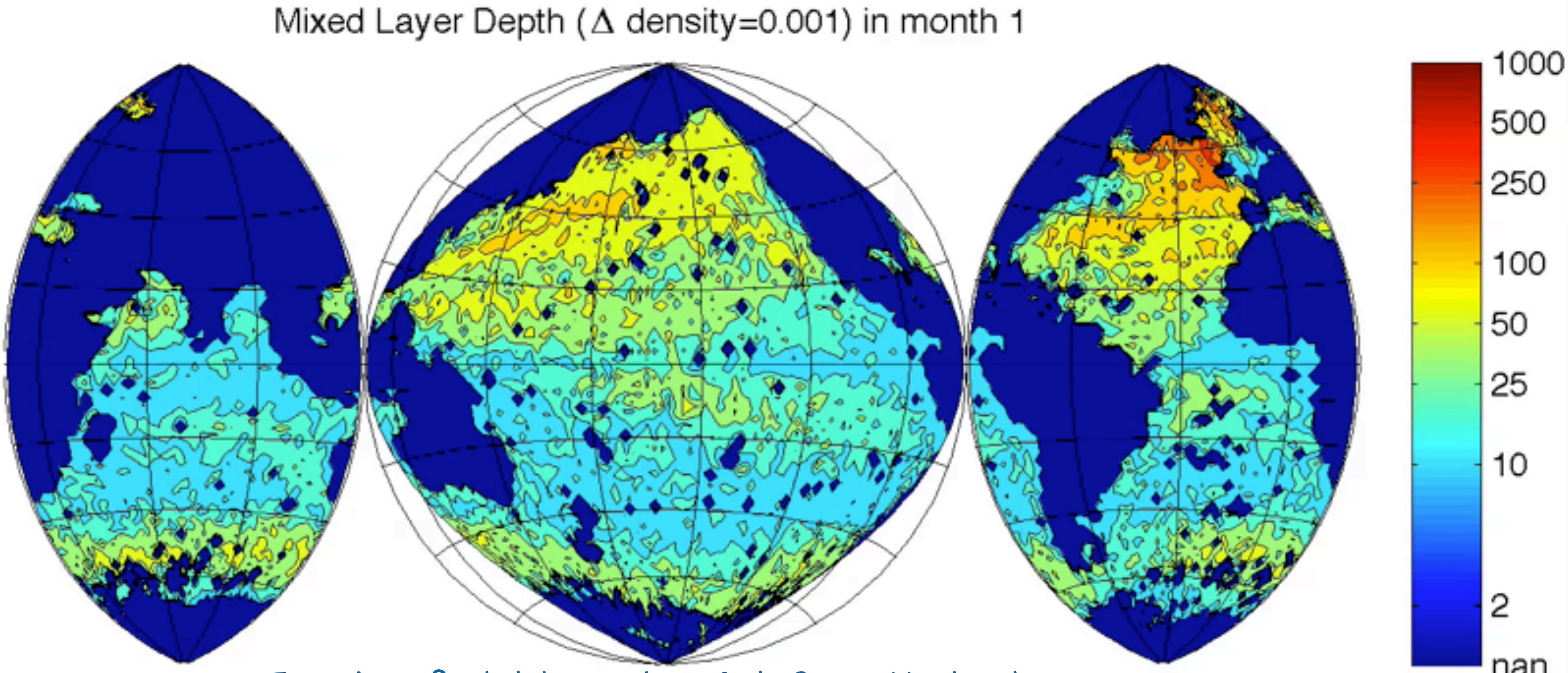






S. C. Bates, BFK, S. R. Jayne, W. G. Large, S. Stevenson, and S. G. Yeager. Mean biases, variability, and trends in air-sea fluxes and SST in the CCSM4. Journal of Climate, 25(22):7781-7801, November 2012.

The Ocean Mixed Layer



From Argo float data courtesy C. de Boyer-Montegut

Stommel's Demon: ocean properties at depth set by deepest wintertime mixed layer & its properties: Subsurface T, S, CFCs, etc., affected. Use to check!

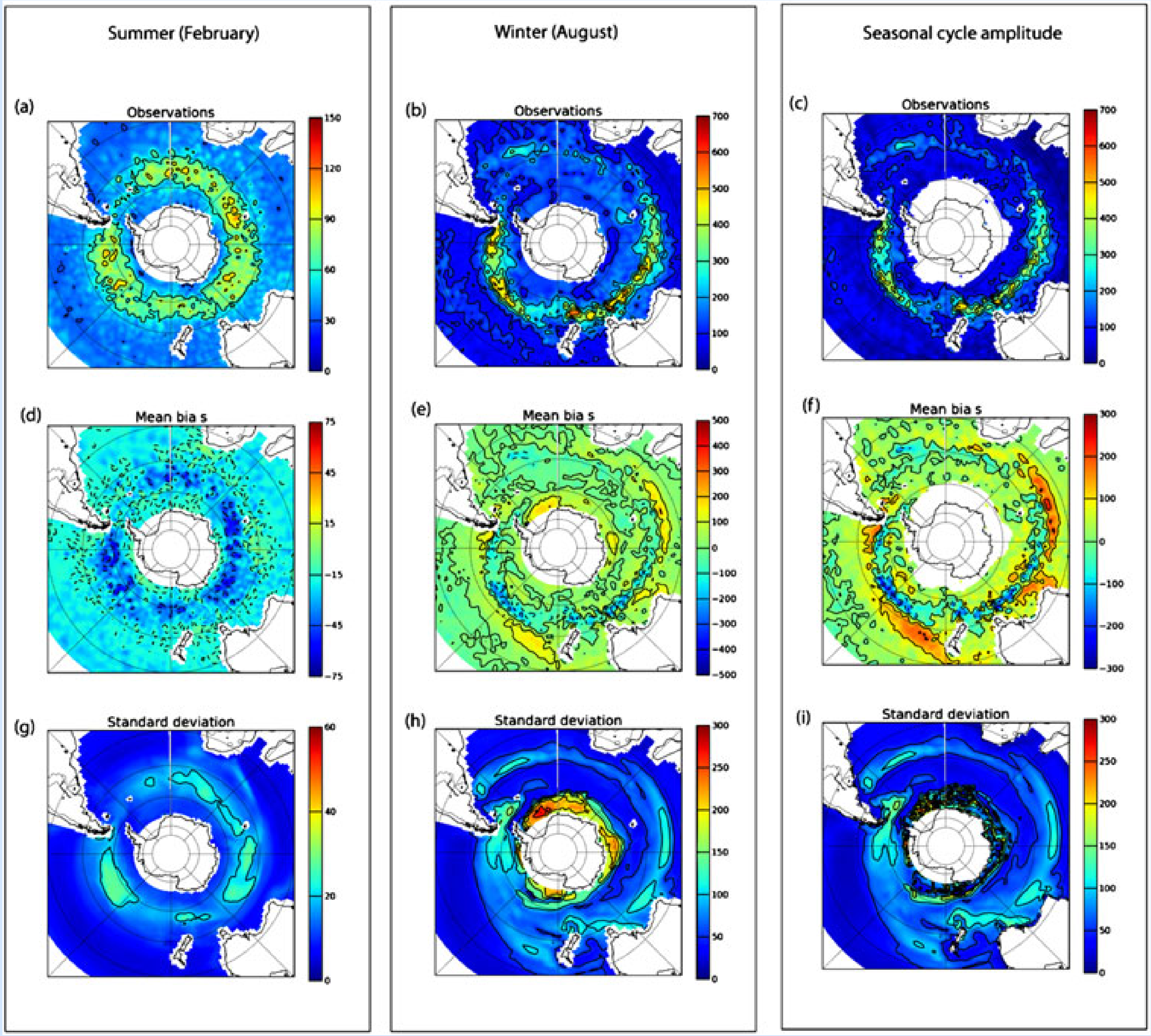


Figure 1. Multi-model representation of summer, winter and amplitude of MLD seasonal cycle (in meters; climatological mean over the "historic" period). (a–c) Observed MLD, (d–f) multi-model mean bias, (g–i) multi-model standard deviation of bias. Analysis for summer is shown on the left column (i.e., Figures 1a, 1d, and 1g), for winter on the middle column (i.e., Figures 1b, 1e, and 1h) and for the amplitude of the seasonal cycle on the right column (i.e., Figures 1c, 1f, and 1i).

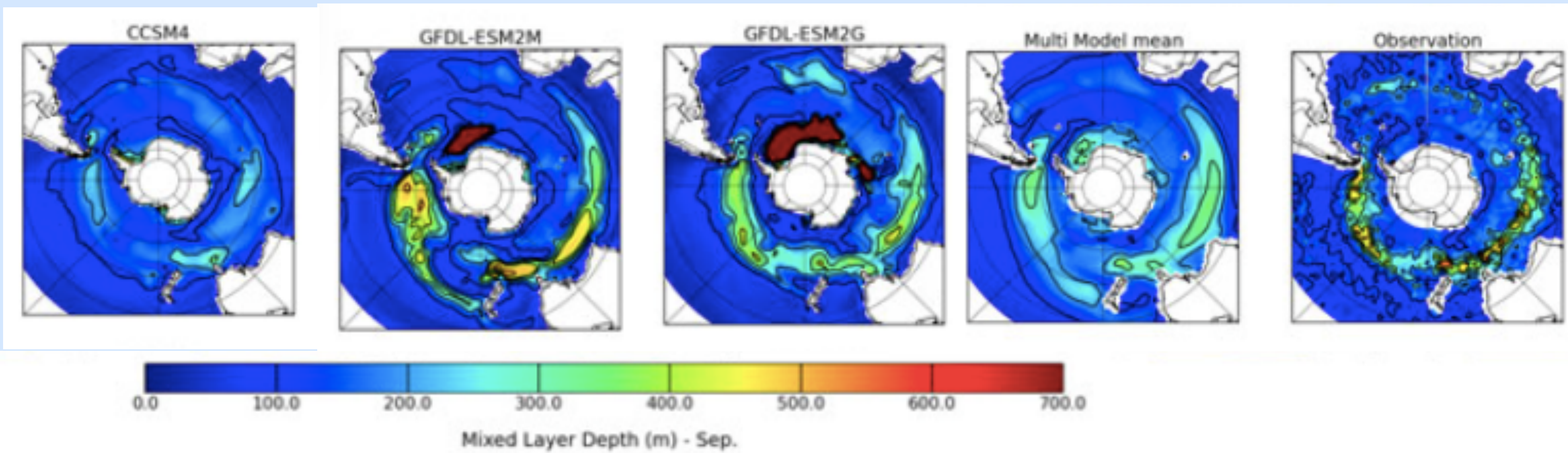


Figure 2. September mixed-layer depth (in meters) averaged over the "historic" period in each model. The multi-model mean and observation-based estimate are in the bottom right corner.

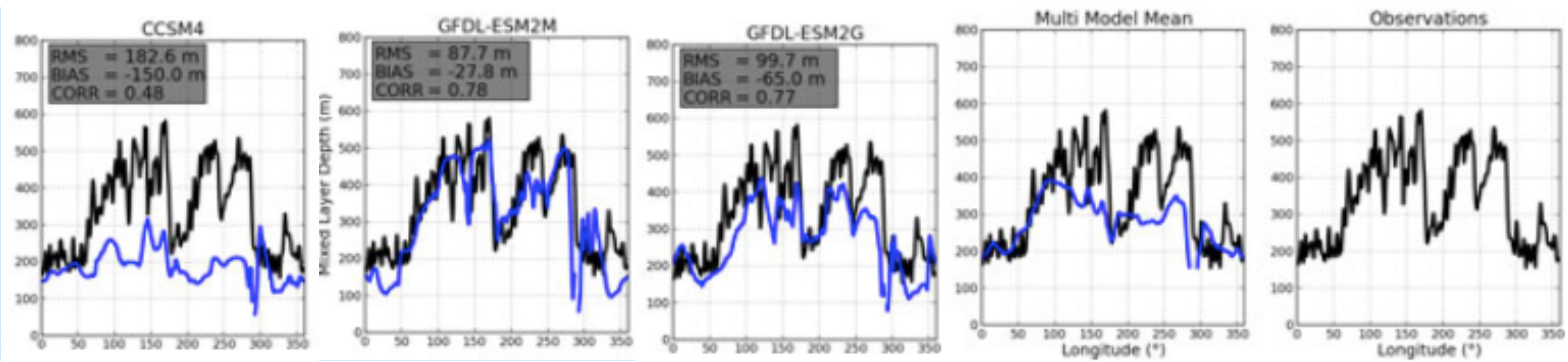
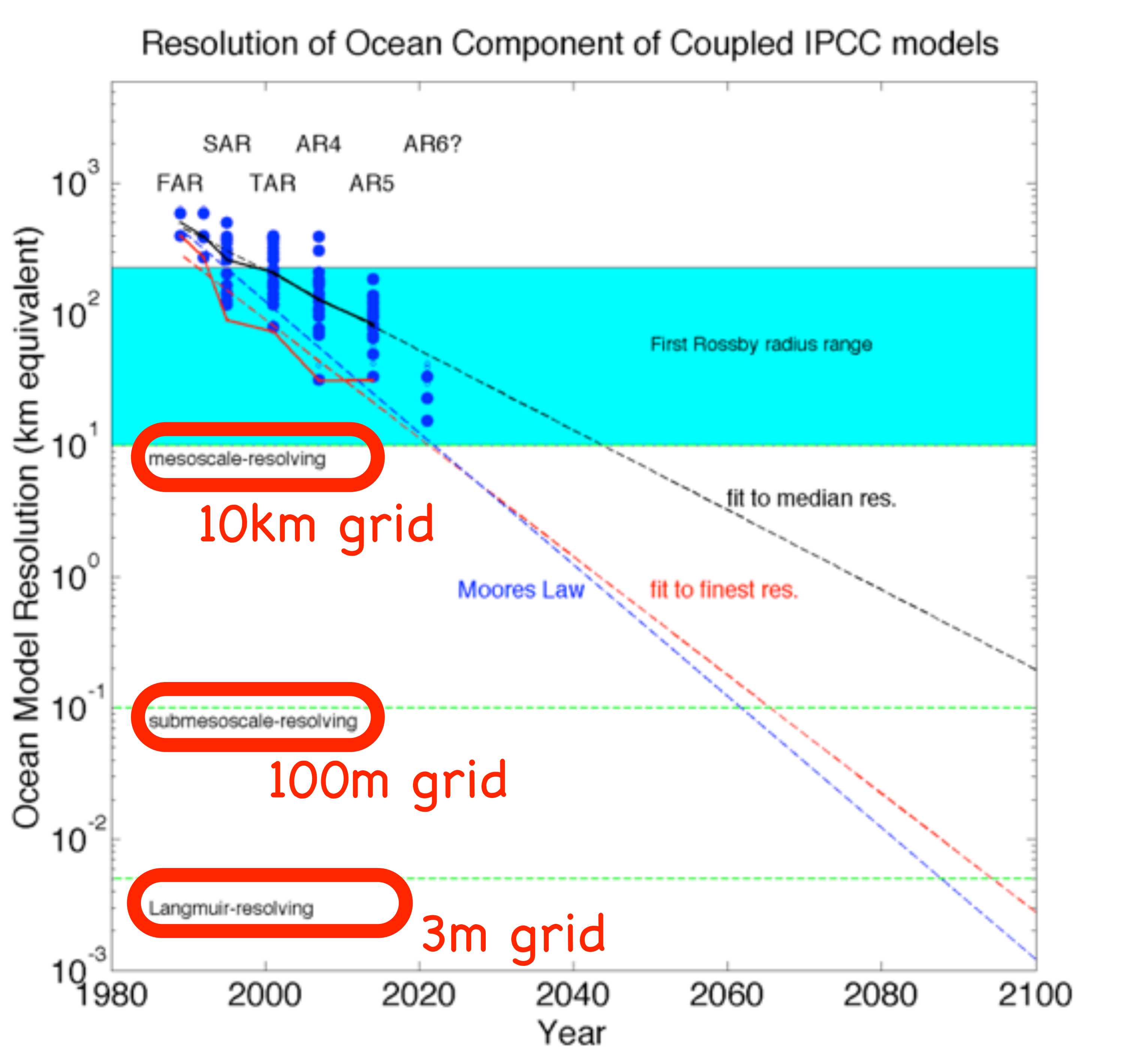


Figure 3. September mixed-layer depth (in meters) at MLD_{max} averaged over the "historic" period in each model. Multi-model mean and observation-based estimate are in the bottom right corner. In each panel, the root mean square of MLD_{max} is given (RMS), along with the mean bias between observation-based and model MLD_{max} (BIAS, negative means model shallower than observation), and the along-stream correlation between observation-based and model MLD_{max} (CORR).

So, processes important in the Polar Upper Ocean?

- Submesoscale Eddies—A review of F-K et al. 2011 parameterization effects
  - What is the EKE spectrum under ice?
- Langmuir Turbulence—A review of Li et al. 2015 parameterization effects
  - Atmosphere-Ocean-Ice-Wave coupling?
- Mesoscale Eddies—Anisotropy and MLD

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

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.

The Character of the Submesoscale

← 10 km

(Capet et al., 2008)

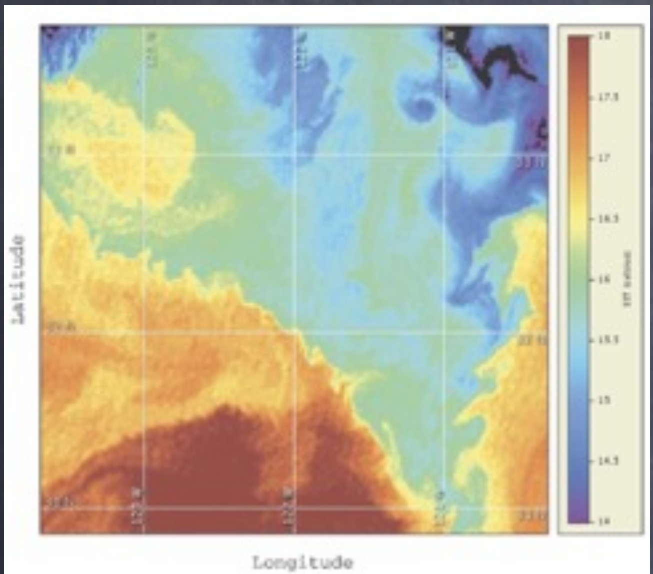
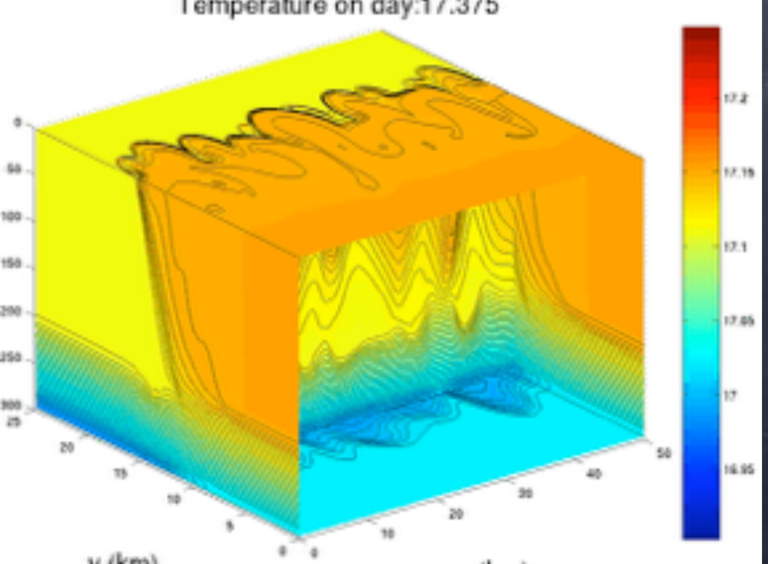


FIG. 16. Sea surface temperature measured at 1832 UTC 3 Jan 2006 off Point Conception in the California Current from CoastWatch (http://coastwatch.pfeg.noaa.gov). The fronts between recently



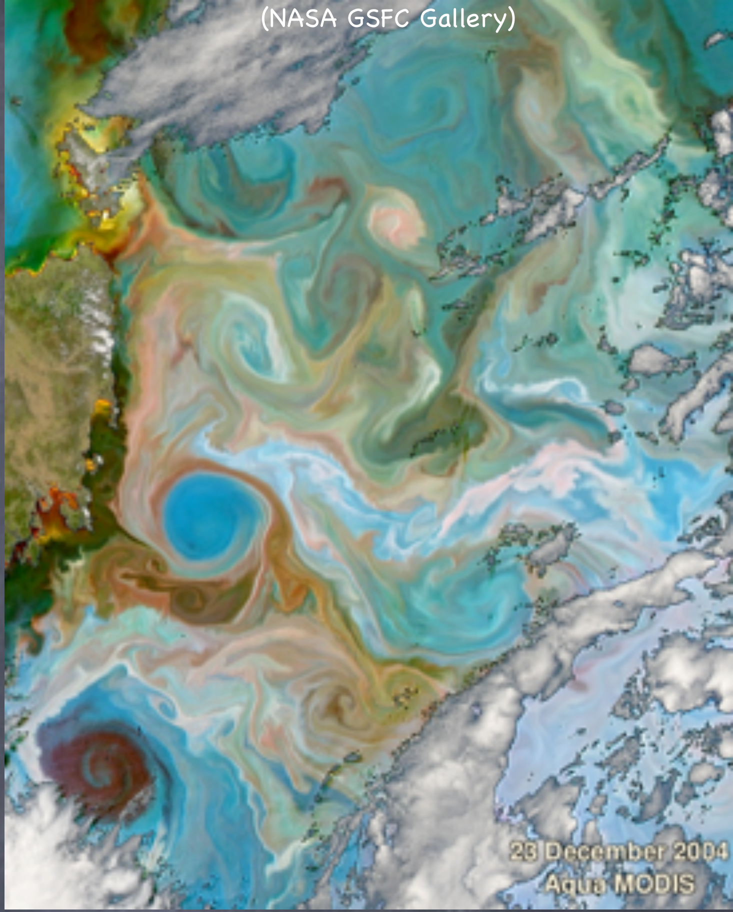
- Fronts
- Eddies
- Ro=O(1)
- Ri=O(1)
- near-surface (H=100m)
- 1-10km, days

Eddy processes often baroclinic instability

Parameterizations = F-K, Ferrari et al (08-11).

Routinely resolved in 2100

(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.

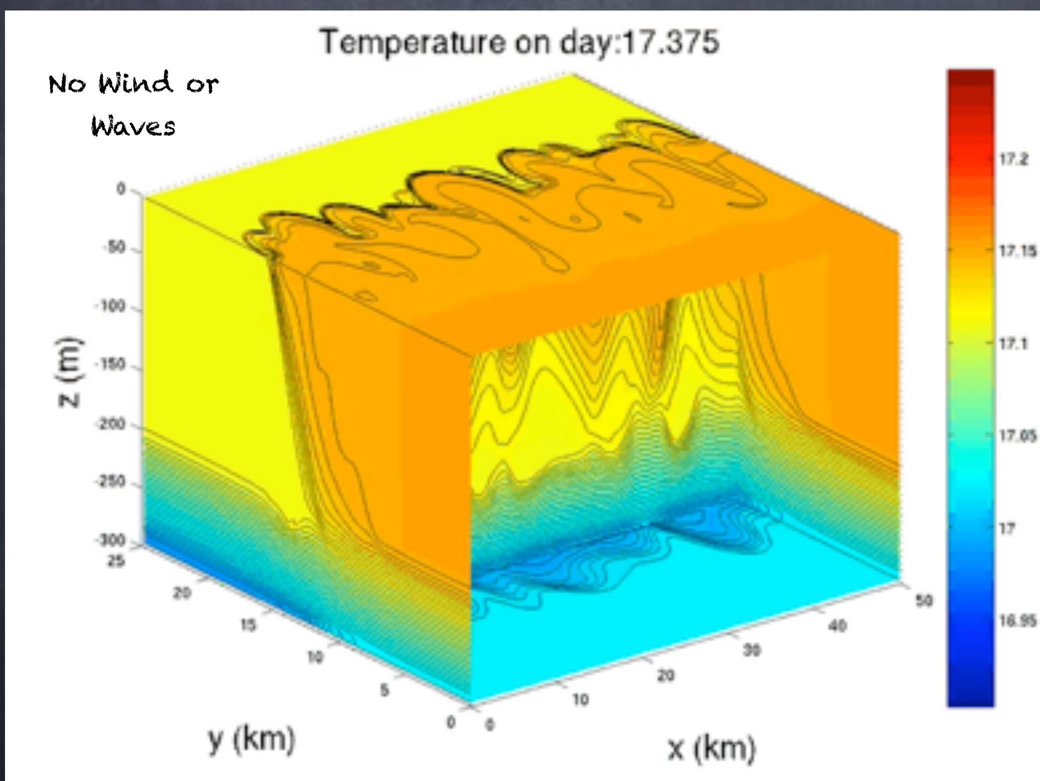
S. Bachman and BFK. Eddy parameterization challenge suite. I: Eady spindown. Ocean Modelling, 64:12-28, 2013

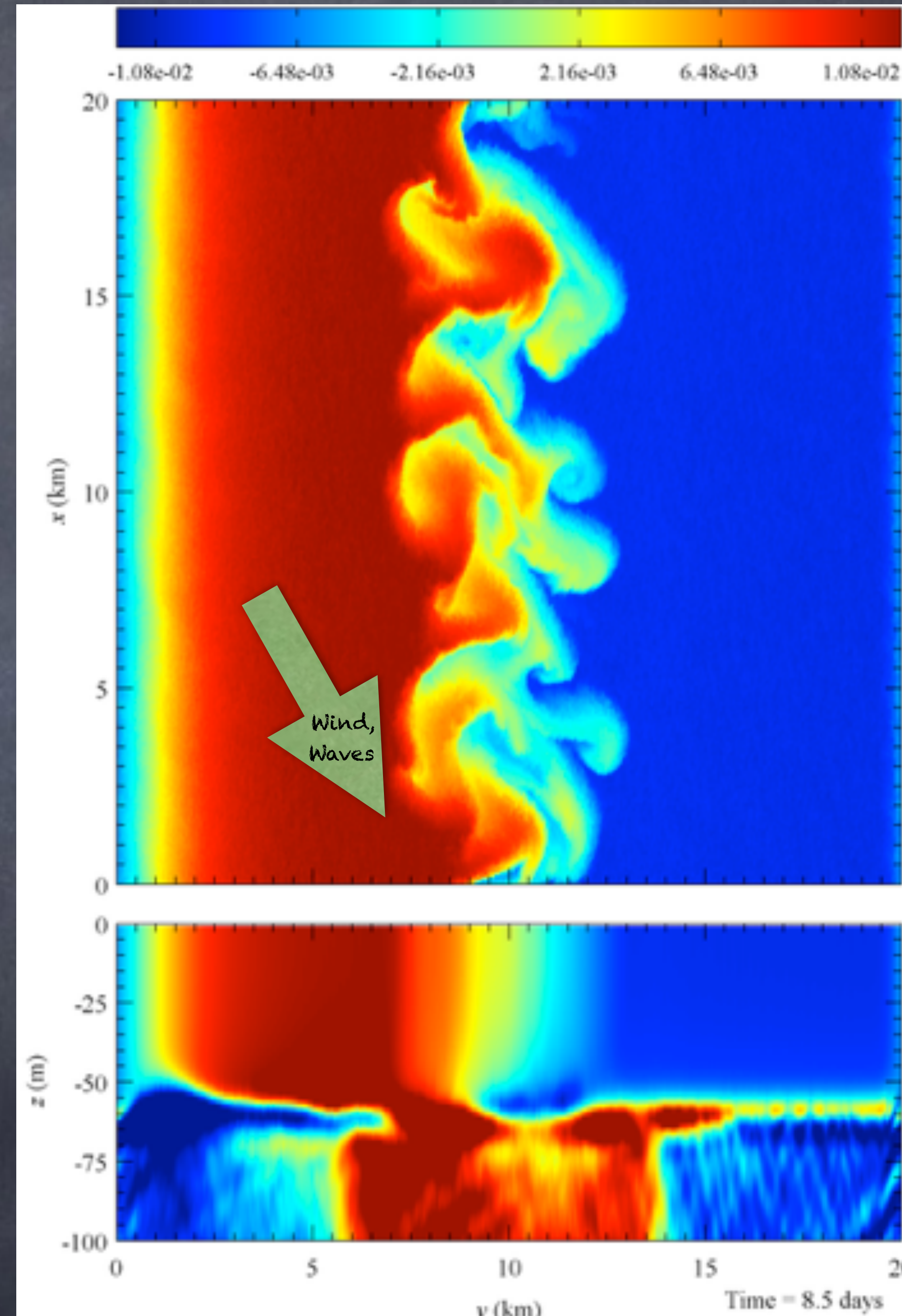
http://oceancolor.gsfc.nasa.gov/

Submesoscale?

Submesoscale (1-10km)
fronts & the eddies that form on them help restratify the boundary layer

Mixing balances restratification





Movie: 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.

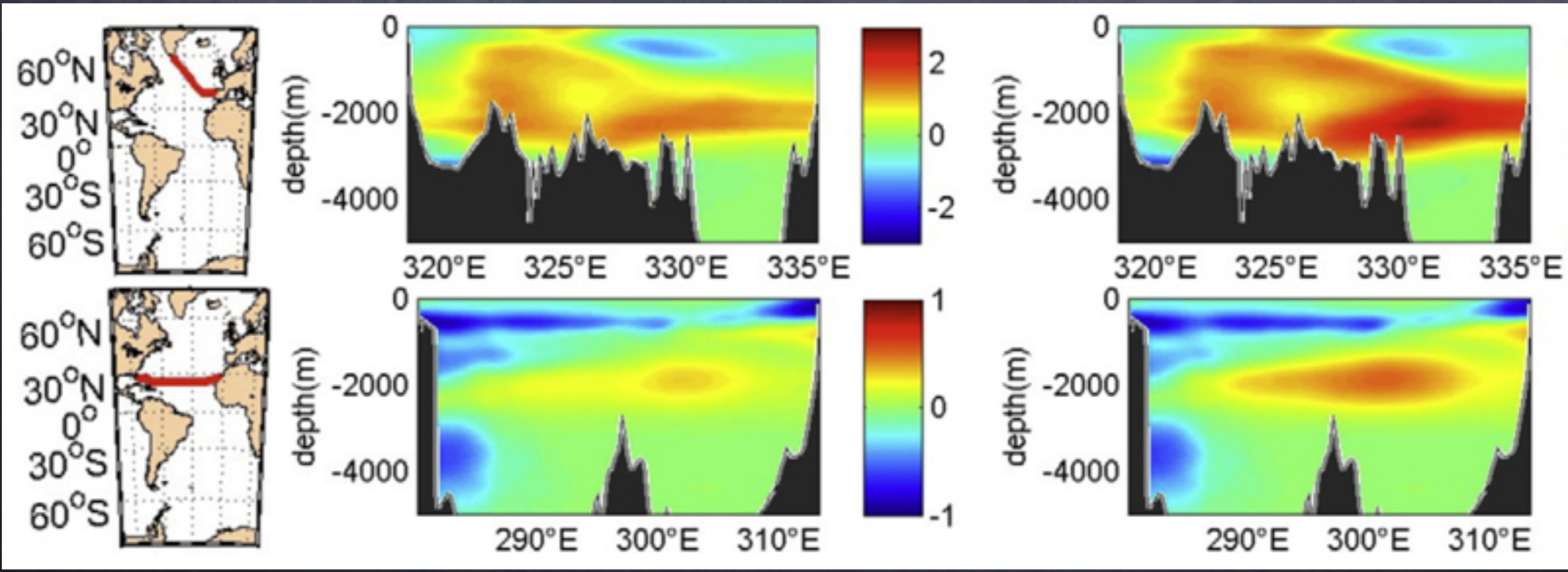
Physical Sensitivity of Ocean Climate to Submesoscale Mixed Layer Eddy Restratification:

MLE implemented in NCAR, GFDL, Hadley, NEMO, ...

Improves CFC uptake (Atlantic water masses)

Bias with MLE Parameterization

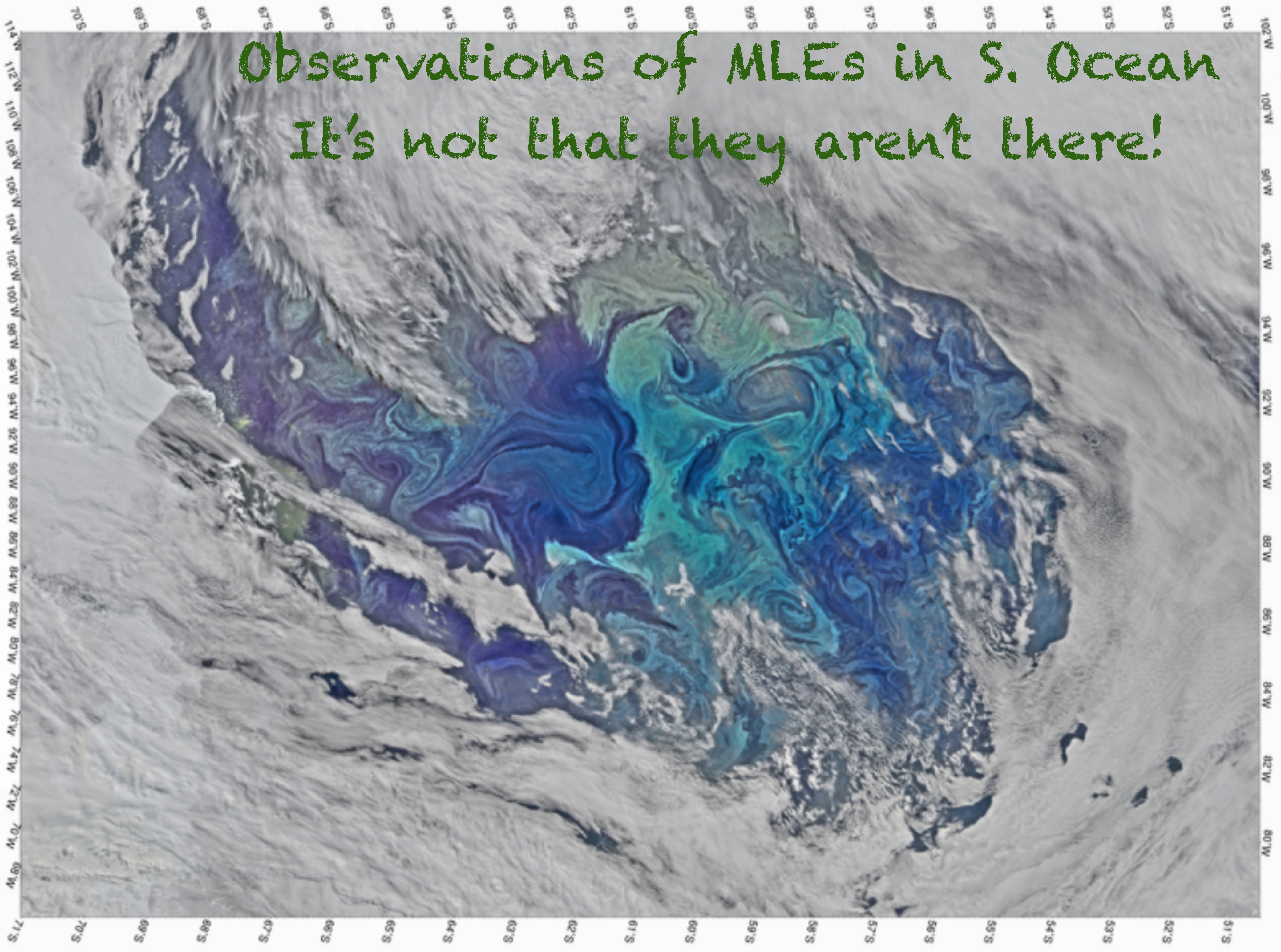
Bias w/o MLE



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.

Observations of MLEs in S. Ocean

It's not that they arent there!



A Global Parameterization of Mixed Layer Eddy Flow & Scale Aware Restratification validated against simulations

B. Fox-Kemper, G. Danabasoglu, R. Ferrari, S. M. Griffies, R. W. Hallberg, M. M. Holland, M. E. Maltrud, S. Peacock, and B. L. Samuels. Parameteriza of mixed layer eddies. III: Implementation and impact in global ocean climate simulations. Ocean Modelling, 39:61-78, 2011.

$$\overline{\mathbf{u}'b'} \equiv \mathbf{\Psi} \times \nabla \bar{b}$$

$$\mathbf{\Psi} = \left[\frac{\Delta x}{L_f}\right] \frac{C_e H^2 \mu(z)}{\sqrt{f^2 + \tau^{-2}}} \nabla \bar{b} \times \hat{\mathbf{z}}$$

Compare to the original singular, unrescaled version

$$\mathbf{\Psi} = \frac{C_e H^2 \mu(z)}{|f|} \nabla \bar{b} \times \hat{\mathbf{z}}$$

New version handles the equator, and averages over many fronts

Different Eddy Spectra Under Ice?

If accurate, k^{-3} implies a reduction of submesoscale effect by about 20x.

B. Fox-Kemper, 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.

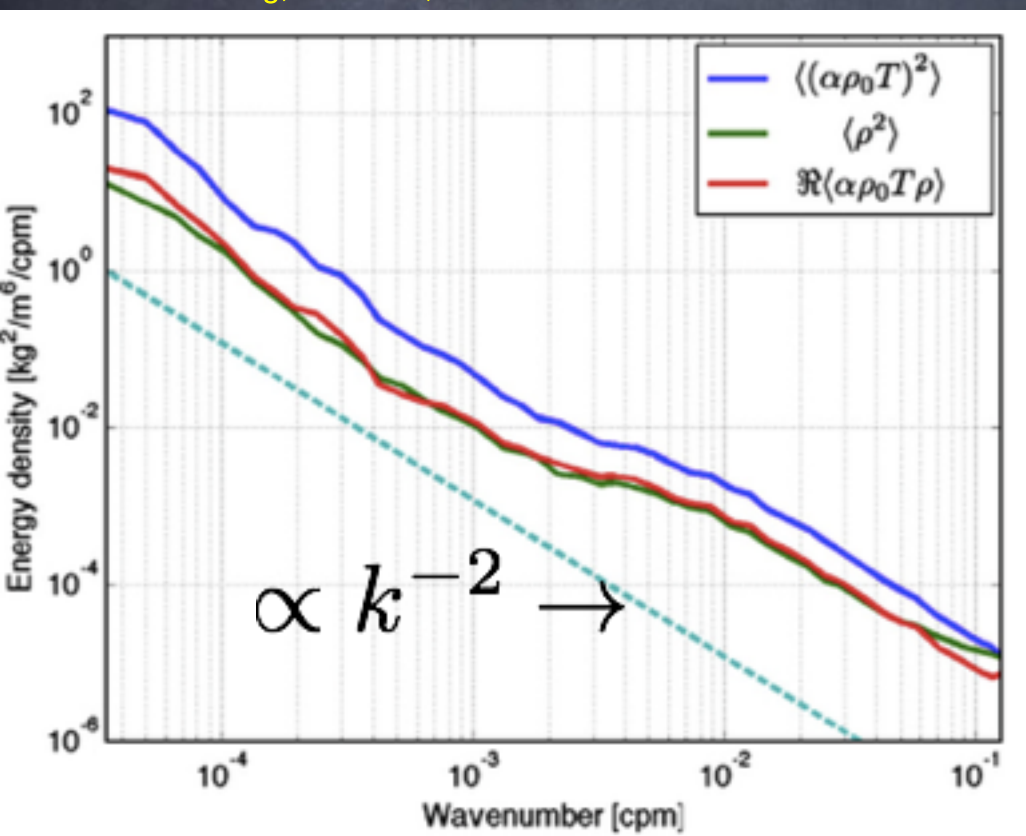
Horizontal Density Structure and Restratification of the Arctic Ocean Surface Layer

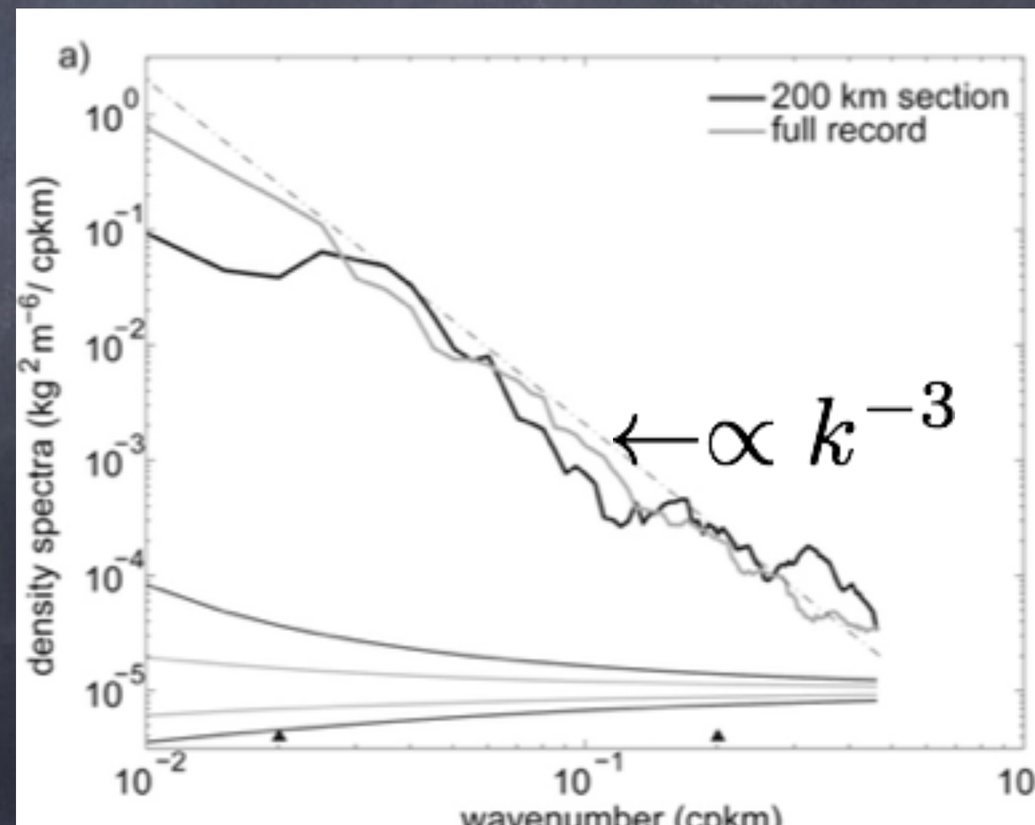
MARY-LOUISE TIMMERMANS

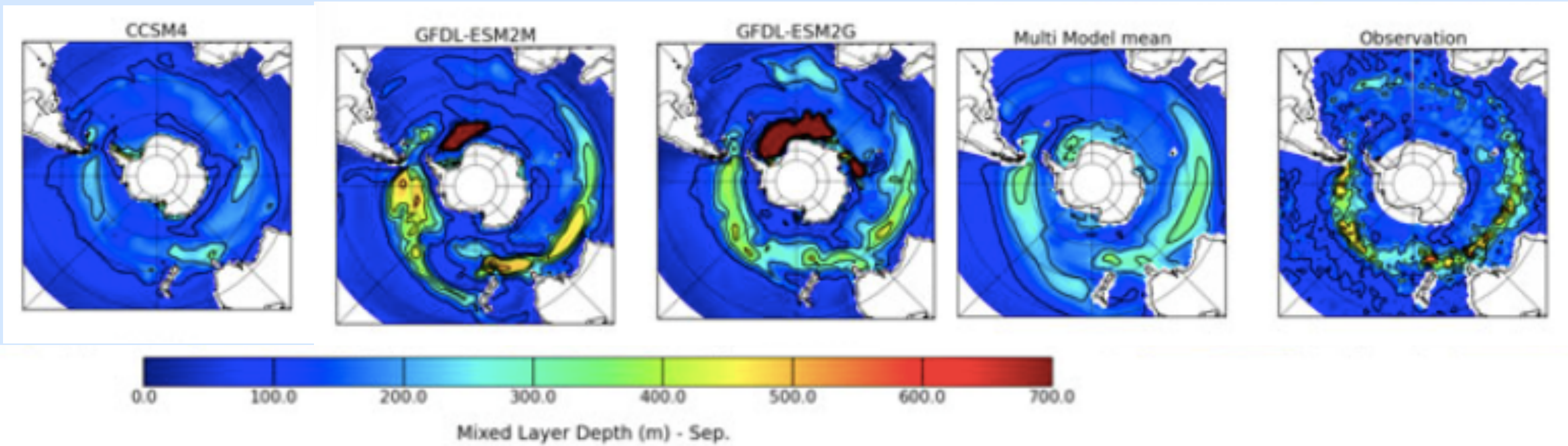
Department of Geology and Geophysics, Yale University, New Haven, Connecticut

SYLVIA COLE AND JOHN TOOLE

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







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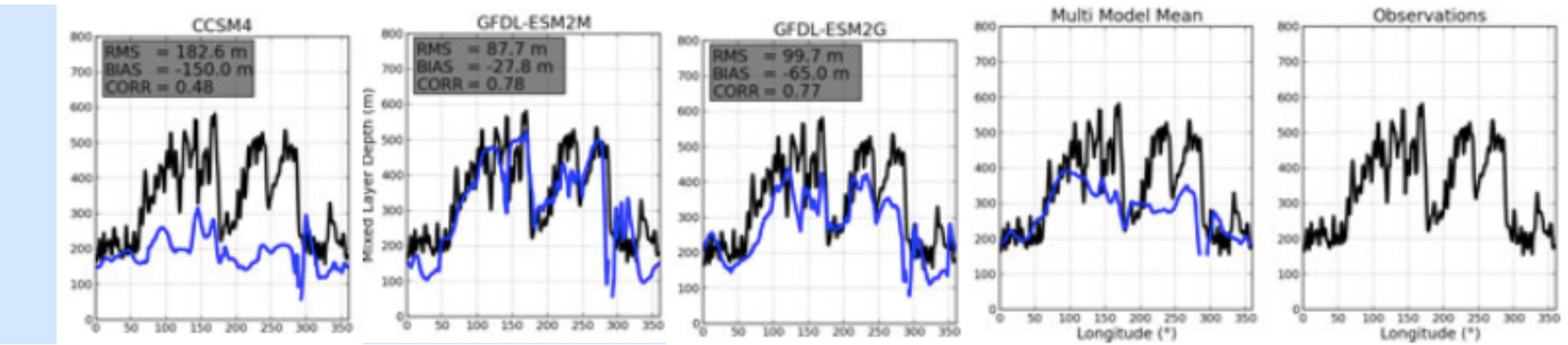

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The Character of Langmuir (Wave-driven) Turbulence

image: Thorpe, 04

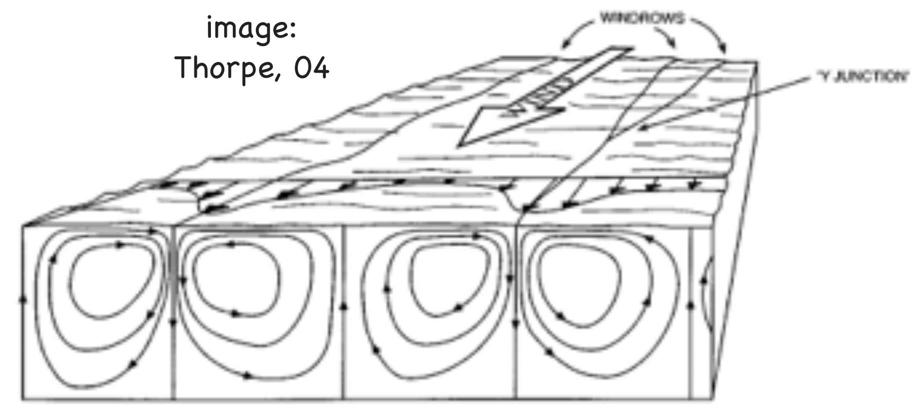
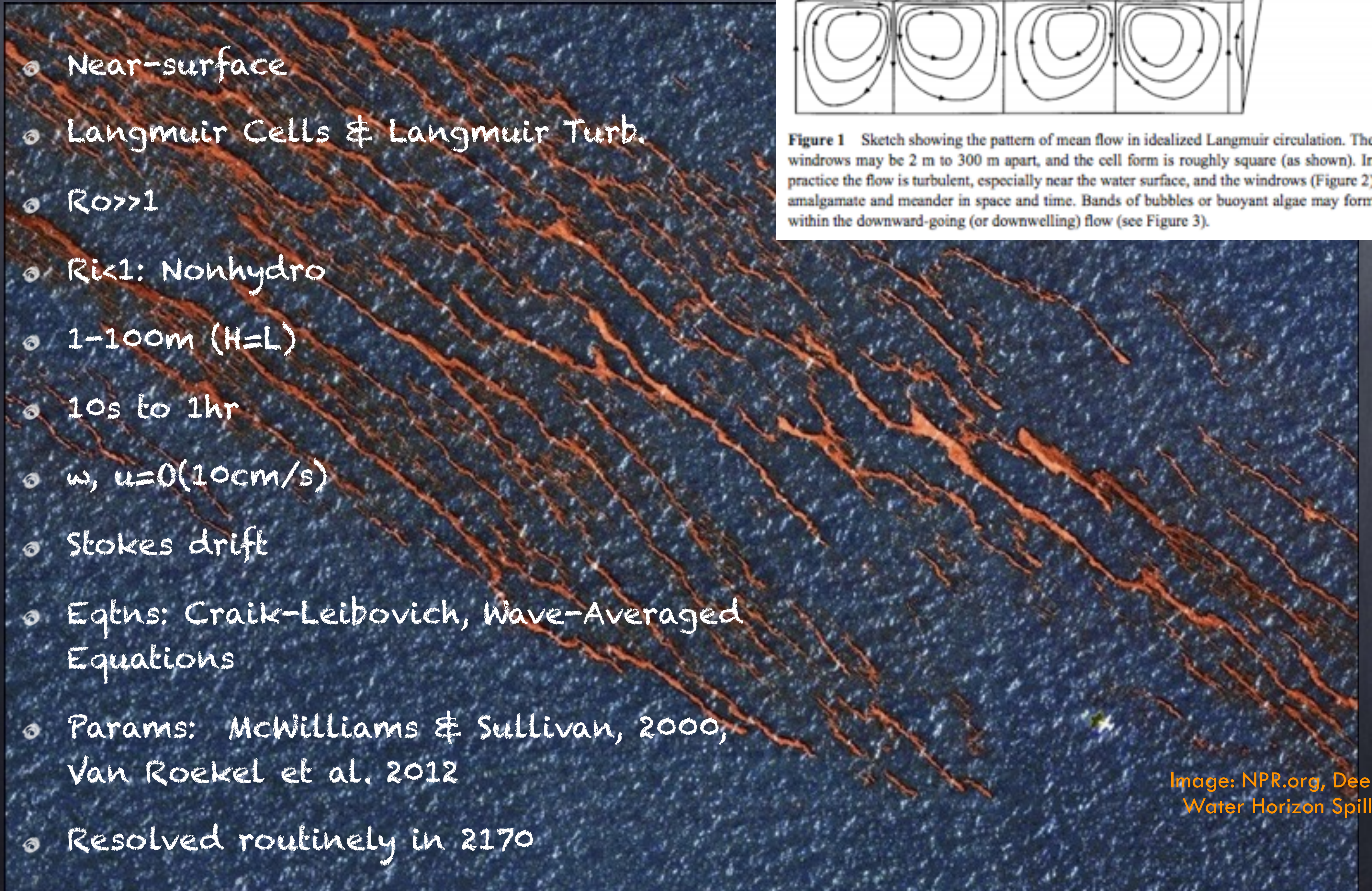


Figure 1 Sketch showing the pattern of mean flow in idealized Langmuir circulation. The windrows may be 2 m to 300 m apart, and the cell form is roughly square (as shown). In practice the flow is turbulent, especially near the water surface, and the windrows (Figure 2) amalgamate and meander in space 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, Wave-Averaged Equations
- Params: McWilliams & Sullivan, 2000, Van Roekel et al. 2012
- Resolved routinely in 2170

Image: NPR.org, Deep Water Horizon Spill

Wave-Averaged Eqtns:

Stokes Drift Affects Slower Phenomena

- Formally a multiscale asymptotic equation set:
  - 3 classes: Small, Fast; Large, Fast; Large, Slow
  - Solve first 2 types of motion in the case of limited wave steepness, irrotational --> Deep Water Waves!
  - Average over deep water waves in space & time,
  - Arrive at Large, Slow equation set with wave effects

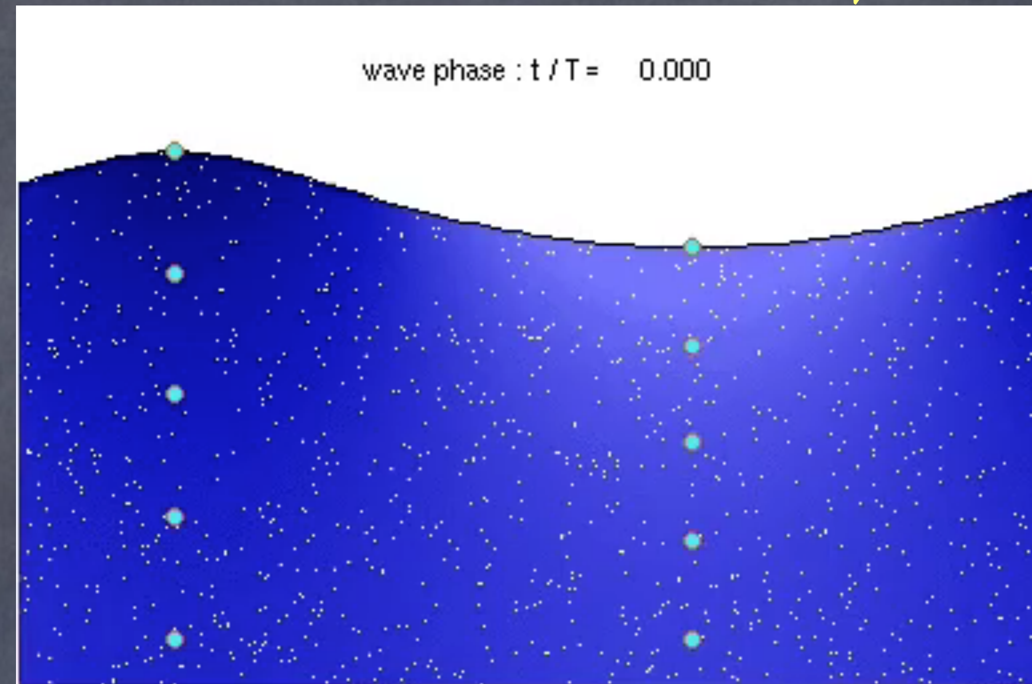
In these equations all Wave Effects involve the Stokes Drift

Turbulent Langmuir # $La_t^2 = \frac{u^*}{u_s}$

Friction Velocity $u^* = \sqrt{\tau/\rho}$

Craik & Leibovich 1976; Gjaja & Holm 1996; McWilliams *et al.* 2004

Waves Provide Stokes Drift



Movie: Creative Commons

& Stokes Drift drives Langmuir Turbulence

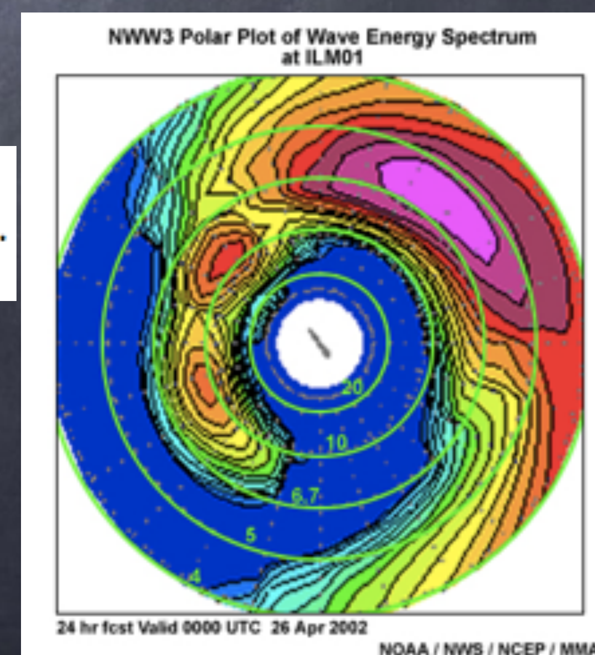
Stokes: Compare the velocity of wave trajectories vs. Eulerian velocity; leading difference=Stokes:

Monochromatic:

$$\boldsymbol{u}^S = \hat{\mathbf{e}}^w \frac{8\pi^3 a^2 f_p^3}{g} e^{\frac{8\pi^2 f_p^2}{g} z}$$

Wave Spectrum:

$$\boldsymbol{u}^S = \frac{16\pi^3}{g} \int_0^\infty \int_{-\pi}^{\pi} (\cos\theta, \sin\theta, 0) f^3 \mathcal{S}_{f\theta}(f,\theta) e^{\frac{8\pi^2 f^2}{g} z} d\theta df.$$



Turbulent Langmuir #

$$La_t^2 = \frac{u^*}{u_s}$$

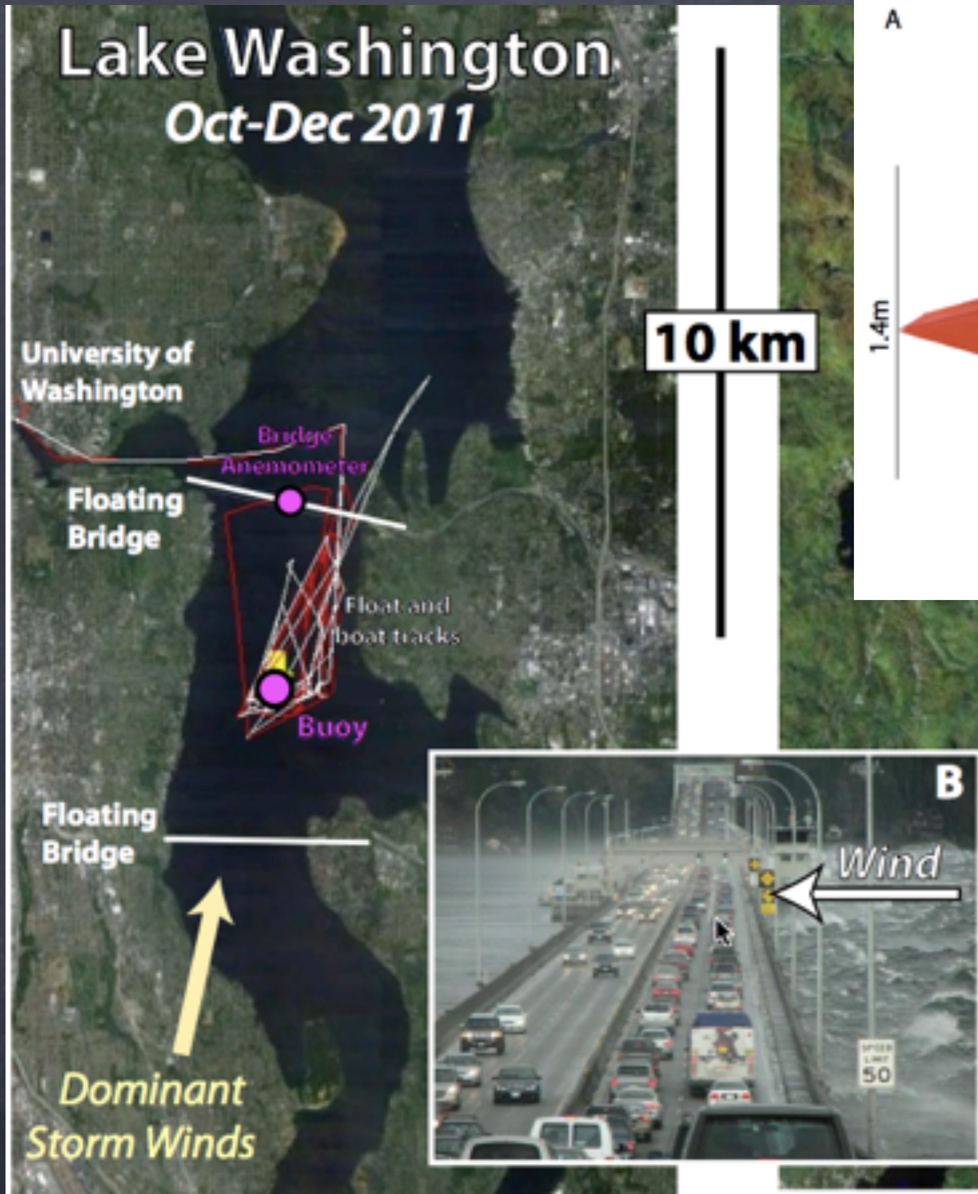
A. Webb and BFK. Wave spectral moments and Stokes drift estimation. Ocean Modelling, 40(3-4):273-288, 2011.

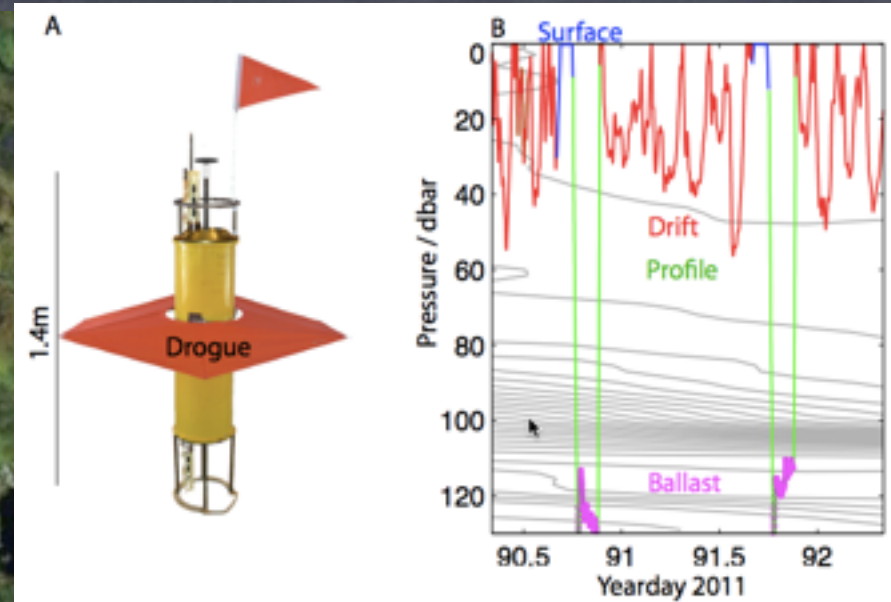
A. Webb and B. Fox-Kemper. Impacts of wave spreading and multidirectional waves on estimating Stokes drift. Ocean Modelling, June 2014. Accepted.

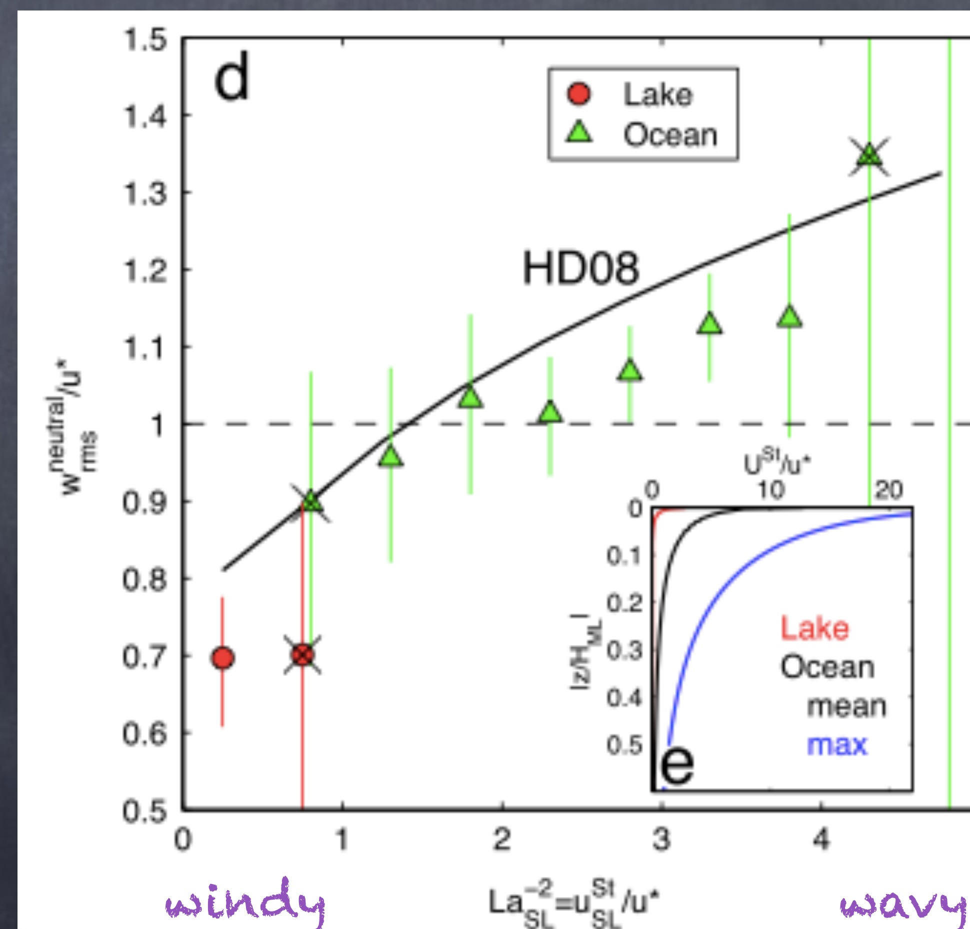
To quantify Langmuir Turb. effects on climate: 3 WAYS

- 1) From OBSERVATIONS, estimate wave effects on key parameters ($\langle w^2 \rangle$, sources of energy) using scalings from Large Eddy Simulations. MODEL INDEPENDENT
- 2) OFFLINE 1d mixing with waves parameterized, mixing into observed Argo profiles, reanalysis winds, waves, cooling. ROBUST TO MODEL ERRORS
- 3) In a climate model, *add in a wave forecast model as a new component in addition to atmosphere, ocean, ice, etc.*, use this to drive parameterizations of wave mixing in ocean component. FEEDBACKS PRESENT

No Retuning! All coefficents from LES







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

1) Observations obey a particular scaling for <w^2>!

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Langmuir important

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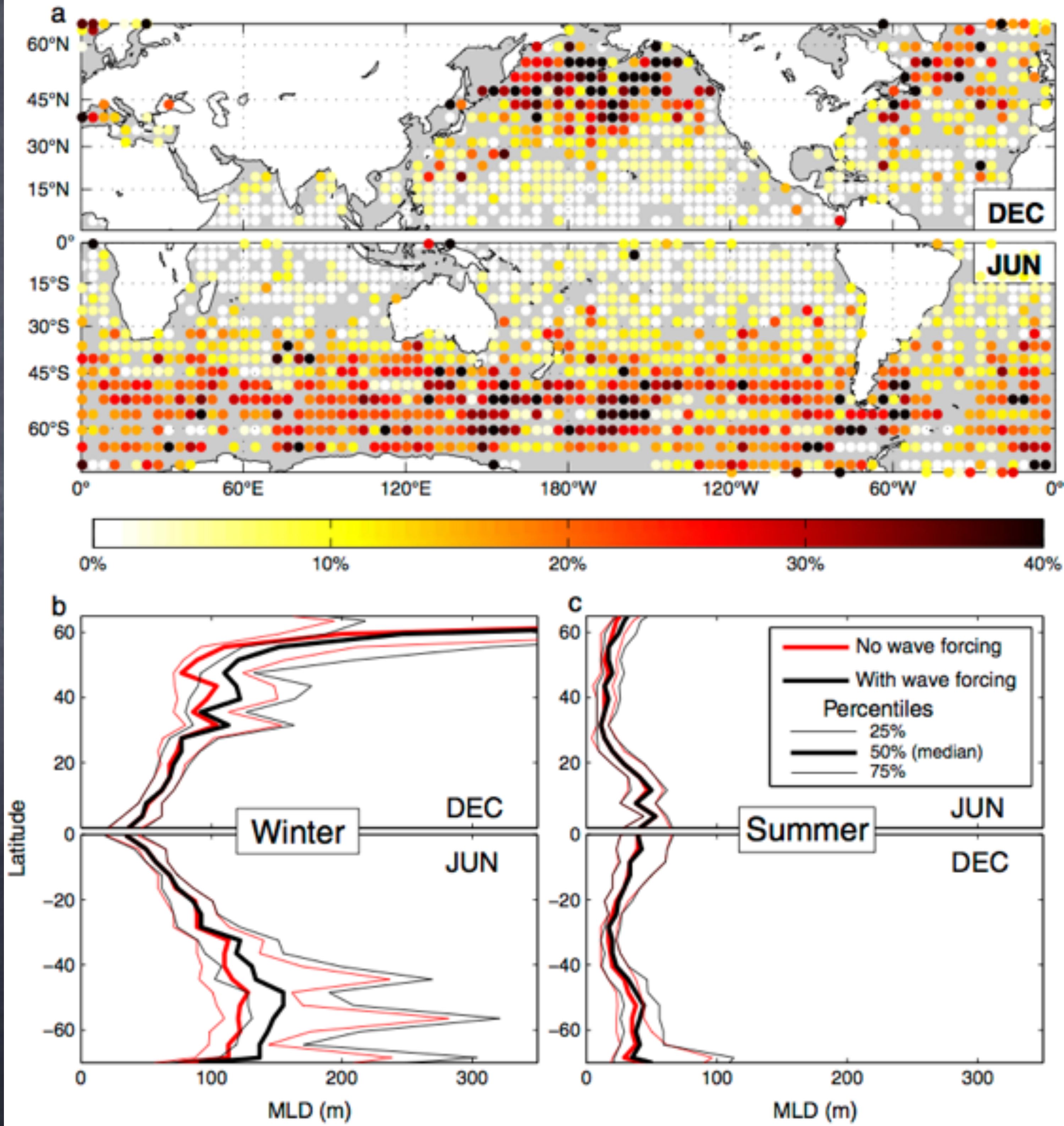
Including Stokes-driven Mixing (Harcourt 2013) Deepens the Winter Mixed Layer about 30%!

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

Waves can be dominant source of energy for OSBL mixing!

S. E. Belcher, A. A. L. M. Grant, K. E. Hanley, B. Fox-Kemper, L. Van Roekel, P. P. Sullivan, W. G. Large, A. Brown, A. Hines, D. Calvert, A. Rutgersson, H. Petterson, J. Bidlot, P. A. E. M. Janssen, and J. A. Polton. A global perspective on Langmuir turbulence in the ocean surface boundary layer. Geophysical Research Letters, 39(18):L18605, 9pp, 2012.



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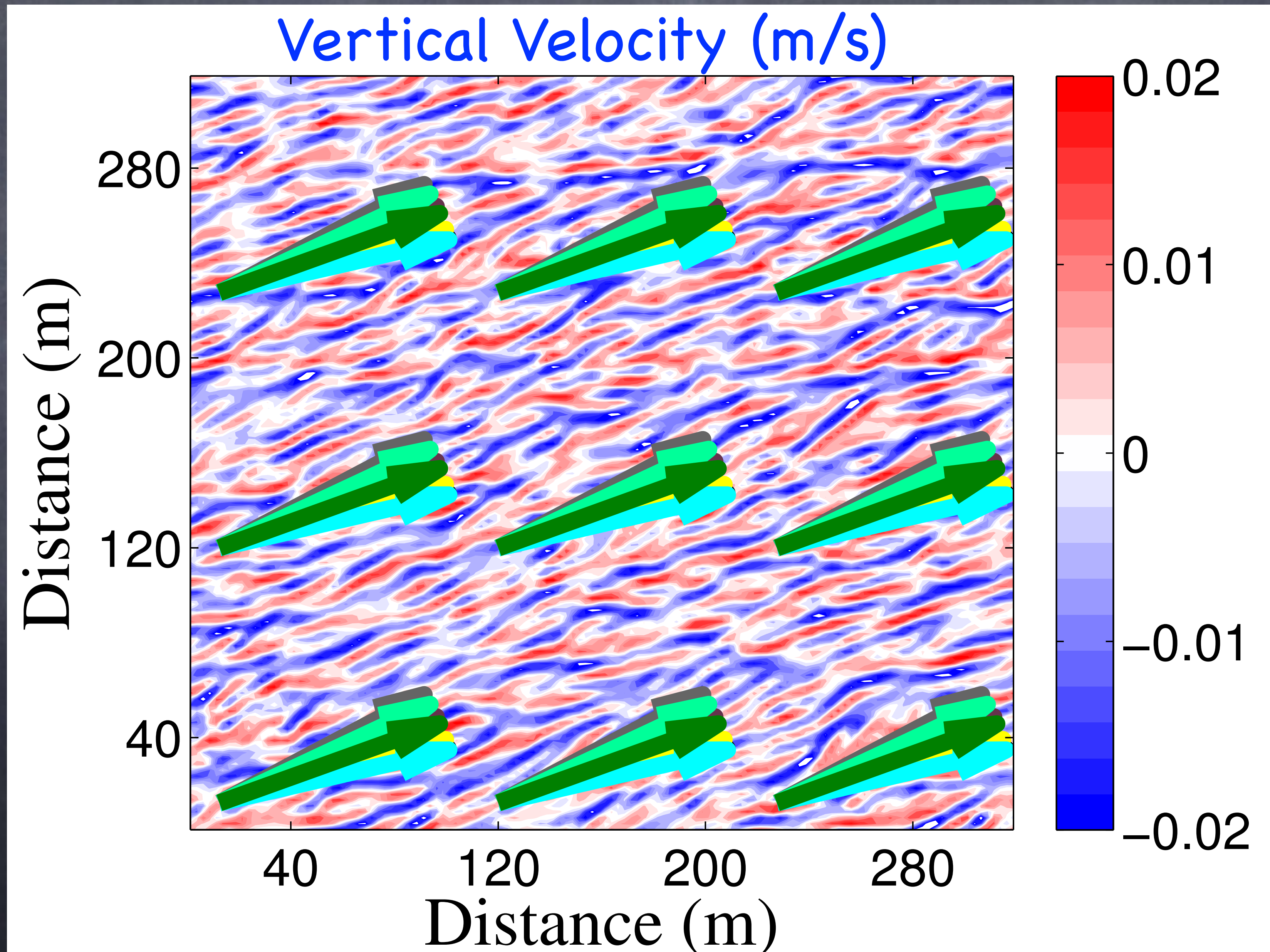
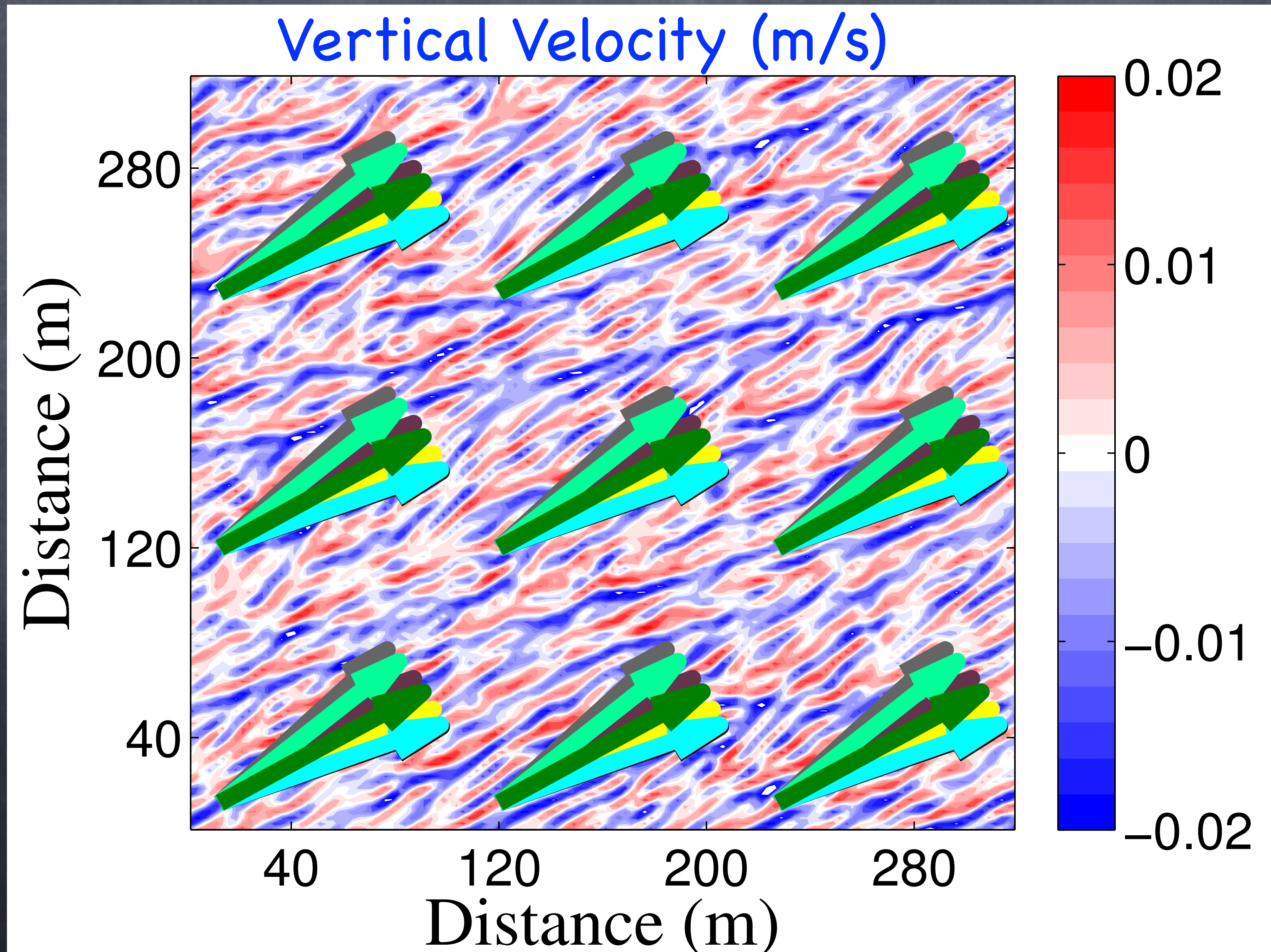
Climate Model Parameterization based on Large Eddy Simulations of Langmuir Turbulence.



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.

Tricky: Misaligned Wind & Waves



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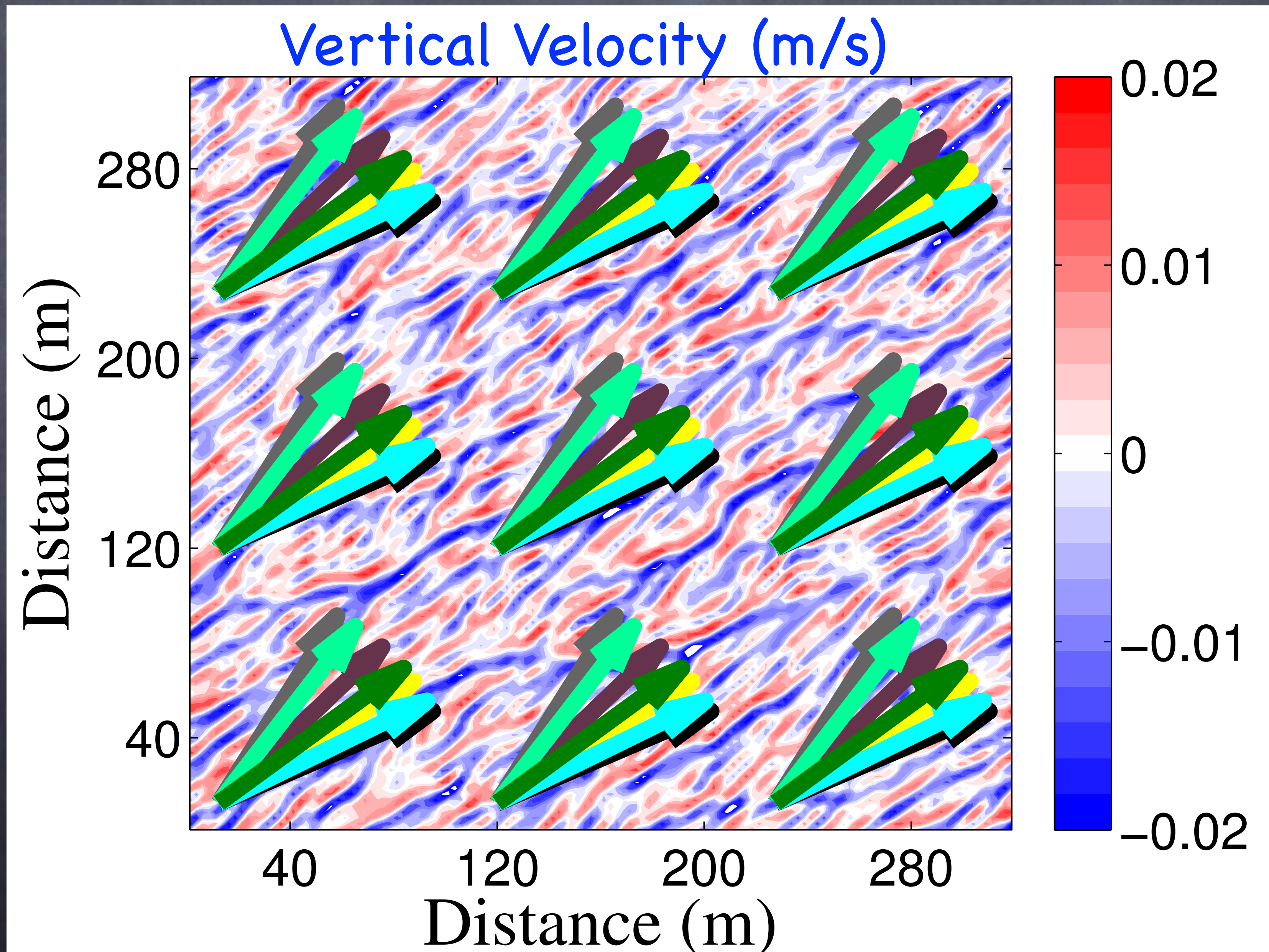
Tricky: Misaligned Wind & Waves



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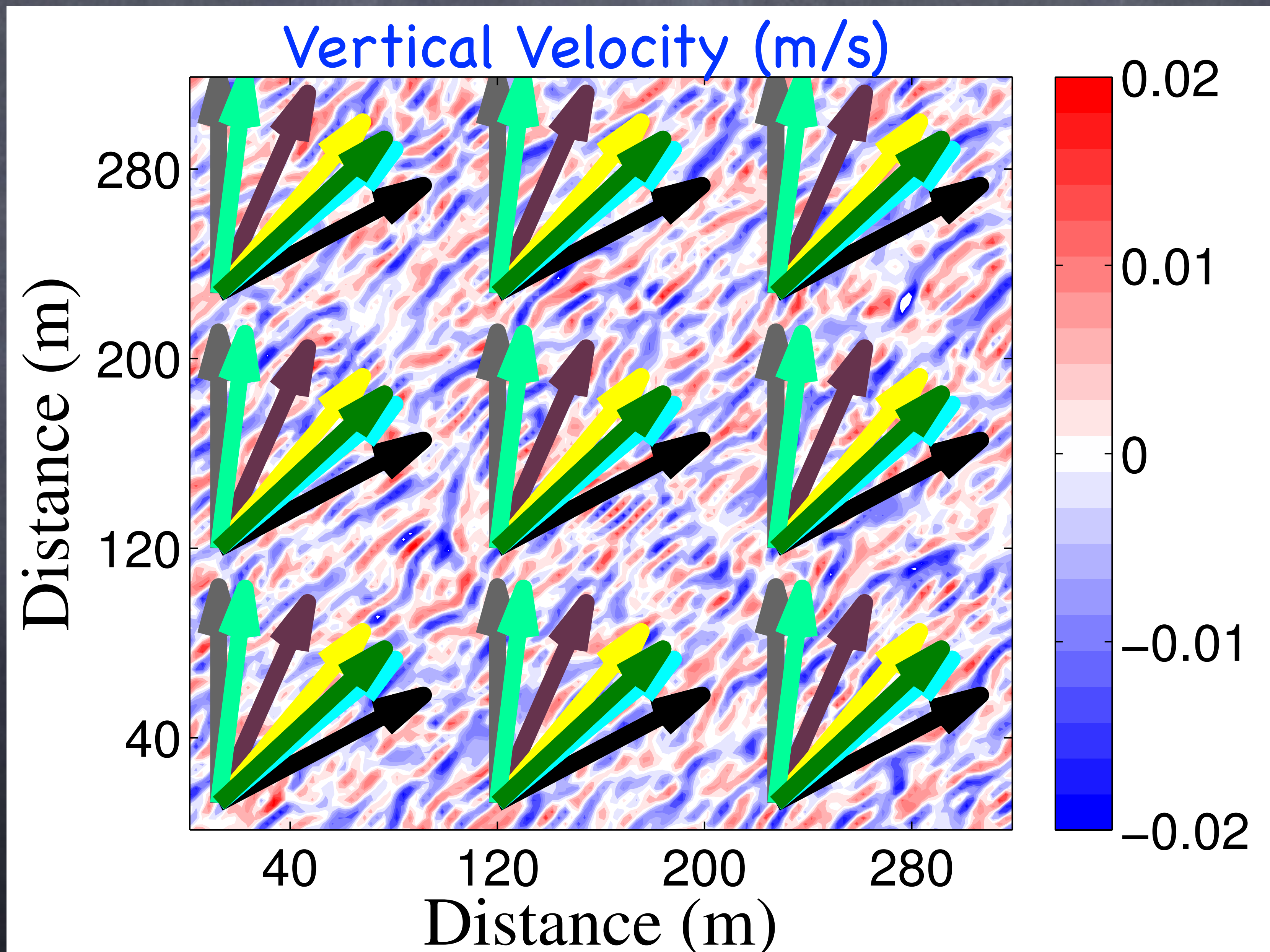
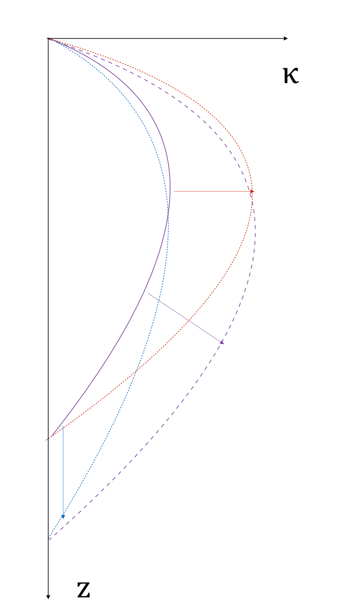
Tricky: Misaligned Wind & Waves



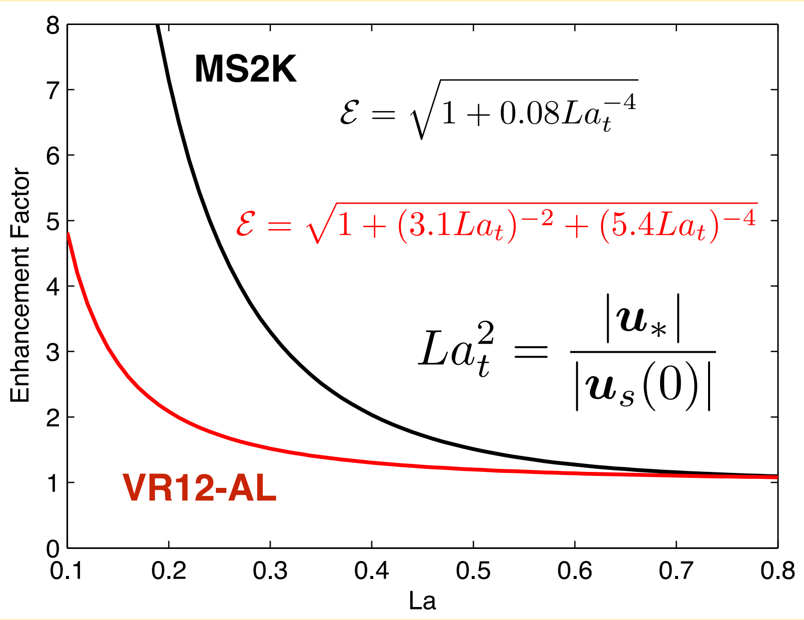
Van Roekel, BFK, P. P. Sullivan, P. E. Hamlington, and S. R. Haney. The form and orientation of Langmuir cells for misaligned winds and waves. Journal of Geophysical Research-Oceans, 117:C05001, 22pp, May 2012.

Langmuir Mixing in KPP for use in CESM1.2

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, 2015. Submitted.



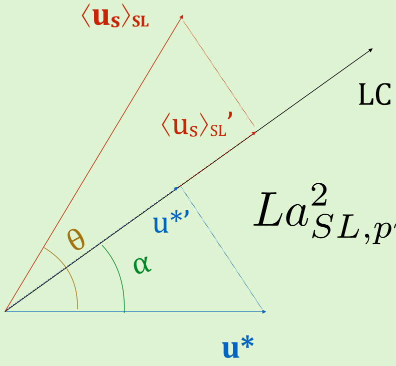
- WaveWatch-III (Stokes drift) <-> POP2 (U, T, H_{BL})
- CORE2 interannual forcing (Large and Yeager,2009), or fully coupled climate
- 4 IAF cycles; average over last 50 years for climatology (over 200 years total)



Revise Enhancement factor to vertical velocity scale W

1) Assume aligned wind and waves

VR12-MA



$$La^2_{SL,proj} = \frac{|\boldsymbol{u}_*| cos(\alpha)}{|\langle \boldsymbol{u}_s \rangle_{SL}| cos(\theta - \alpha)}$$

Account for 2) Misaligned wind and waves

VR12-EN

$$Ri_b = \frac{d\,[b_r - b(d)]}{|\langle \boldsymbol{u}_r \rangle - \langle \boldsymbol{u}(d) \rangle|^2 + U_t^2 + |\boldsymbol{u}_s(0)|^2}$$

Entrain by also Including Stokes shear in mixing depth

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.

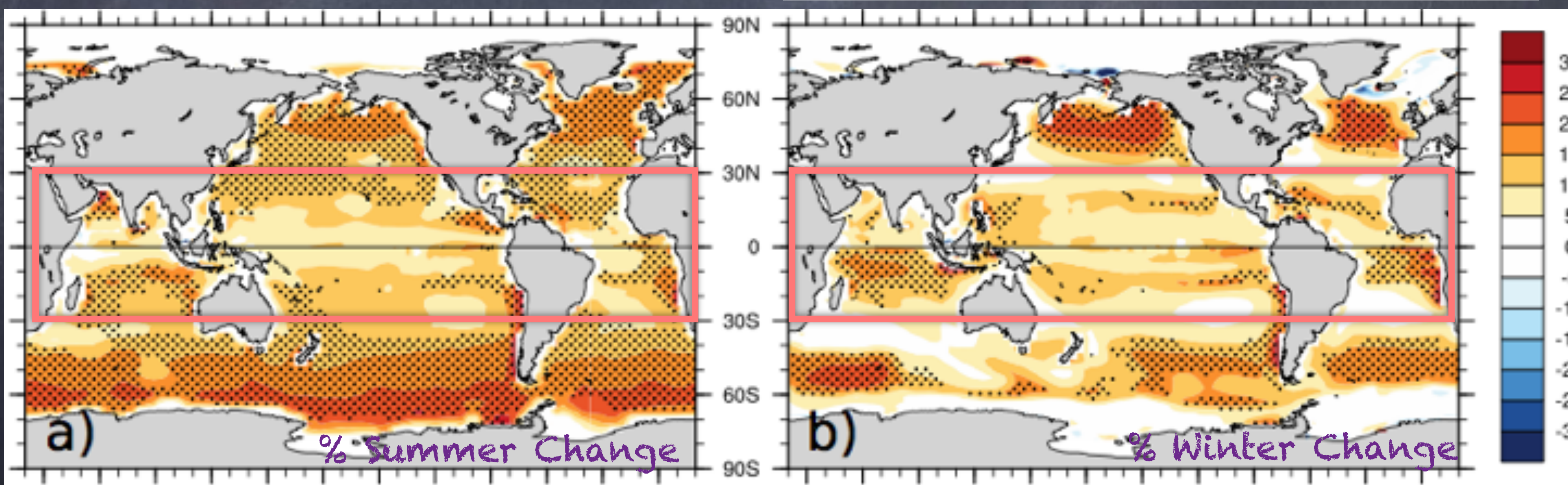
Wave Mixing in CESM: Reduces MLD Errors

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
Control	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)
Competition	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
3 versions of Van Roekel et al	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.

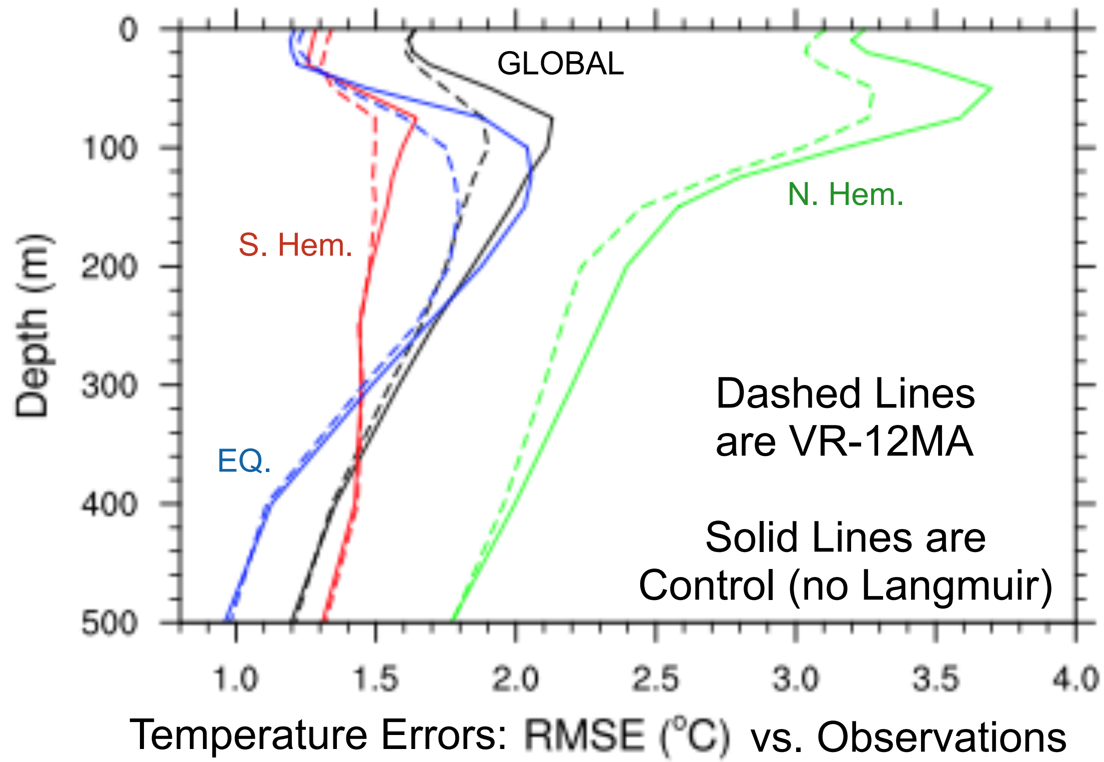
dotted when statistically significant

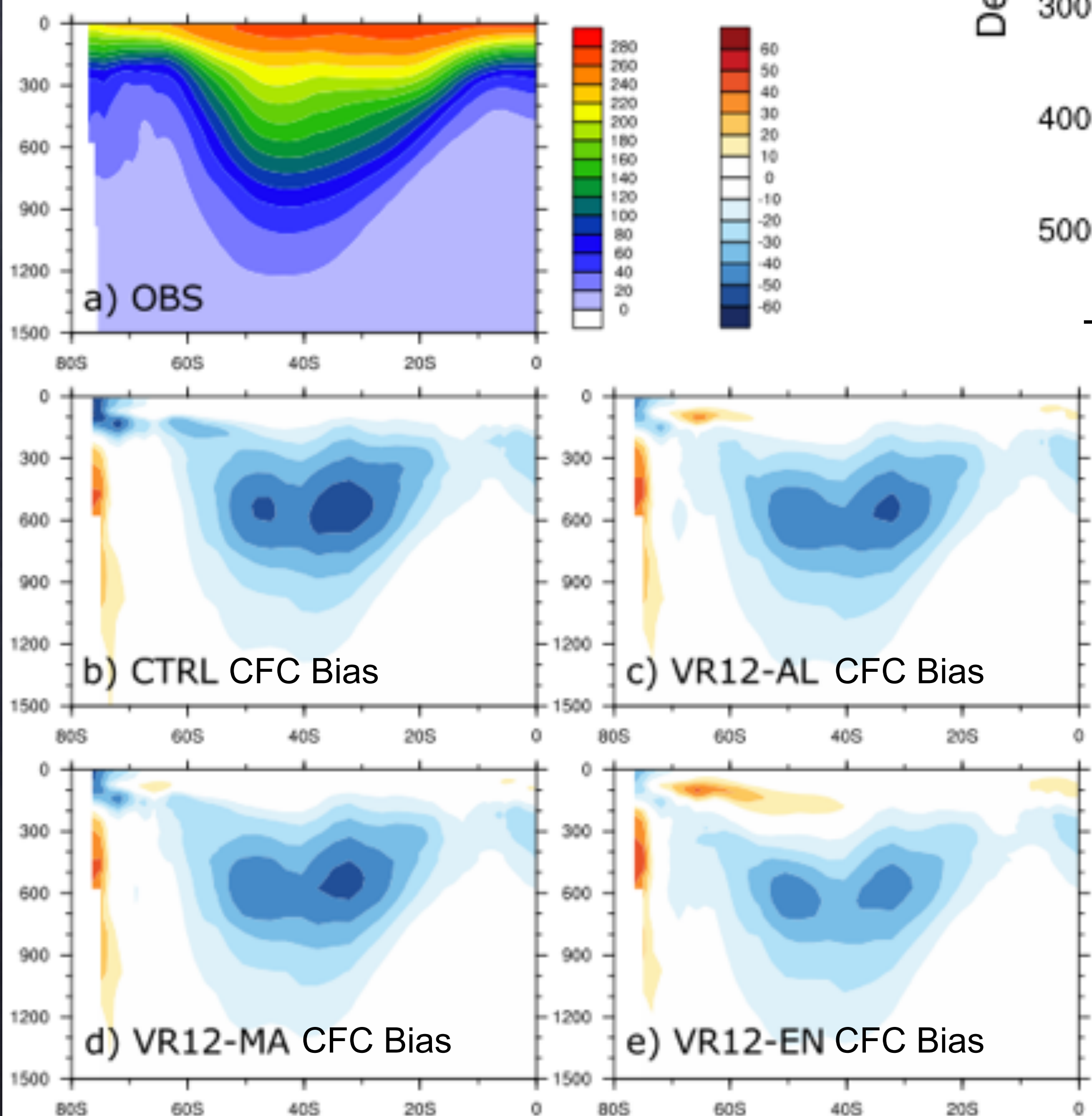


L. P. Van Roekel, BFK, P. P. Sullivan, P. E. Hamlington, and S. R. Haney. The form and orientation of Langmuir cells for misaligned winds and waves. Journal of Geophysical Research-Oceans, 117:C05001, 22pp, May 2012.

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, 2015. In press.

Despite MLD bias increase in near Equator—better ventilation and subsurface effects when Langmuir is included, even near Equator!

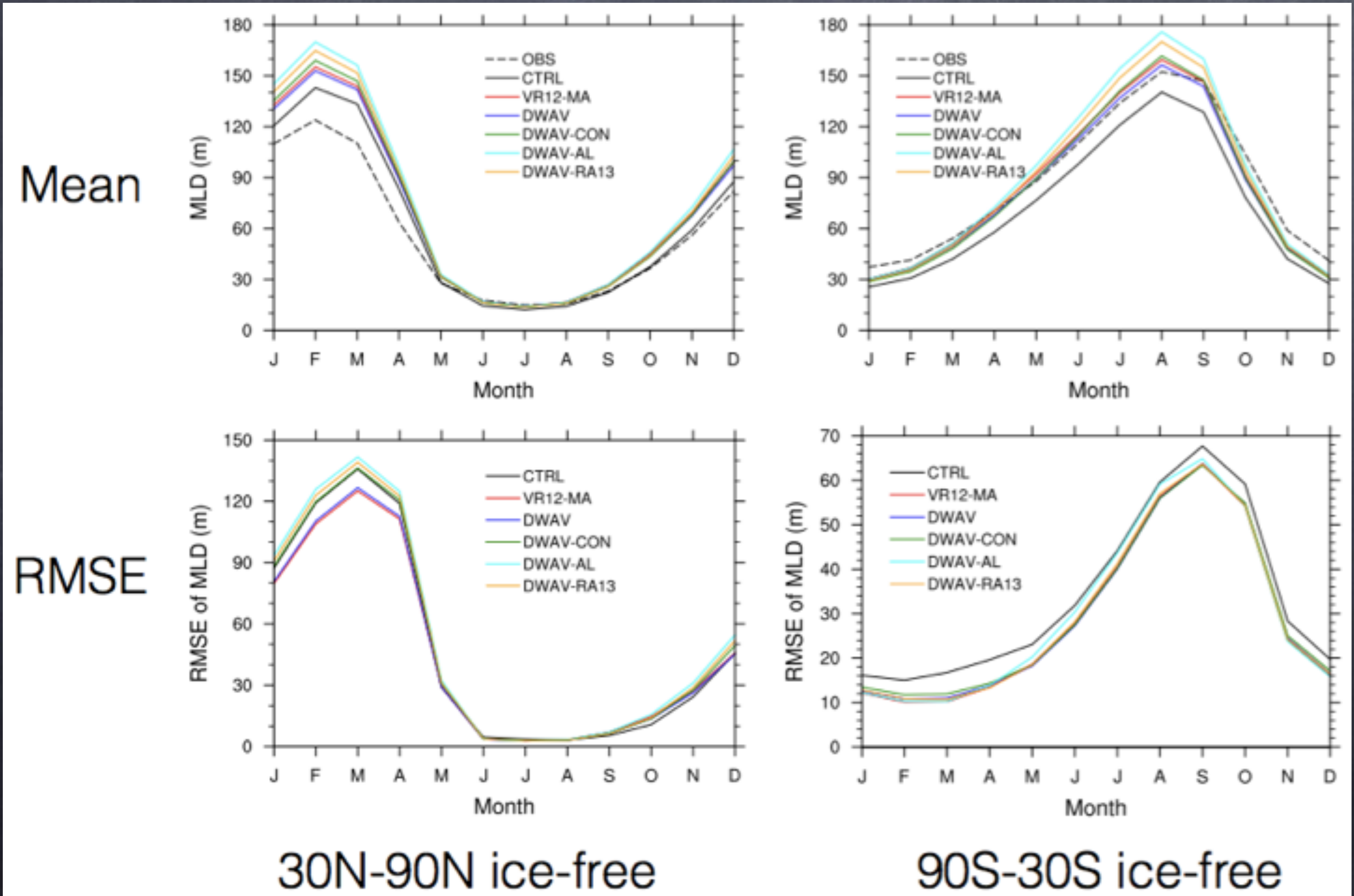




Wave Mixing in CESM Improves Subsurface Properties & Stommel's Demon!

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, 2015. In press.

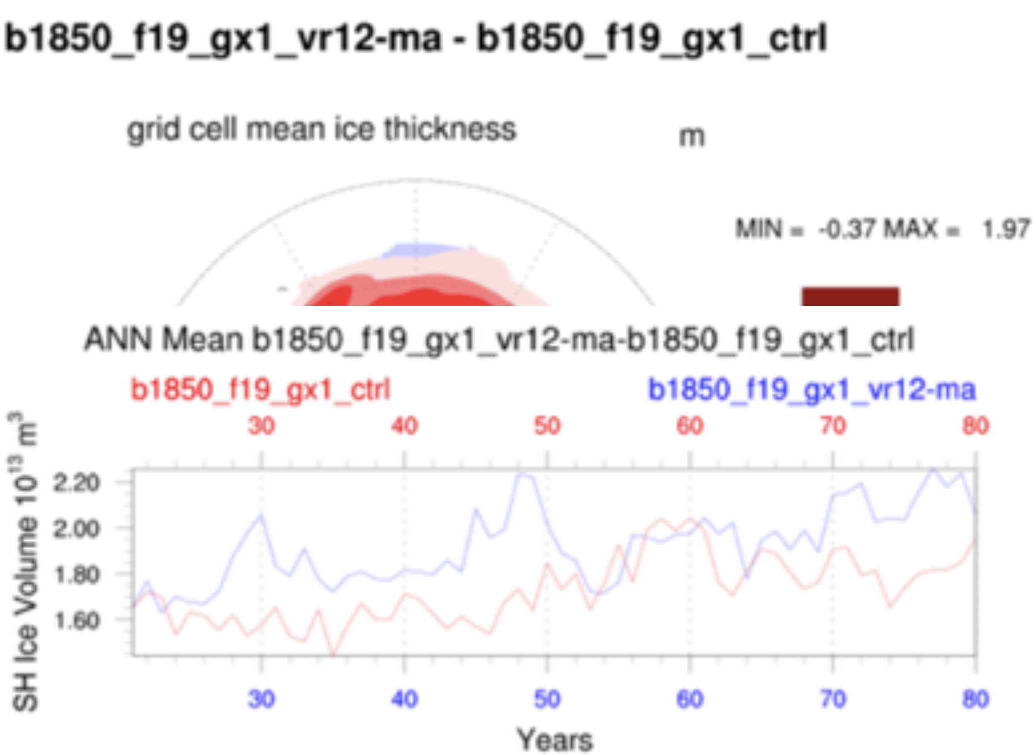
Prognostic Waves versus "Data Waves"



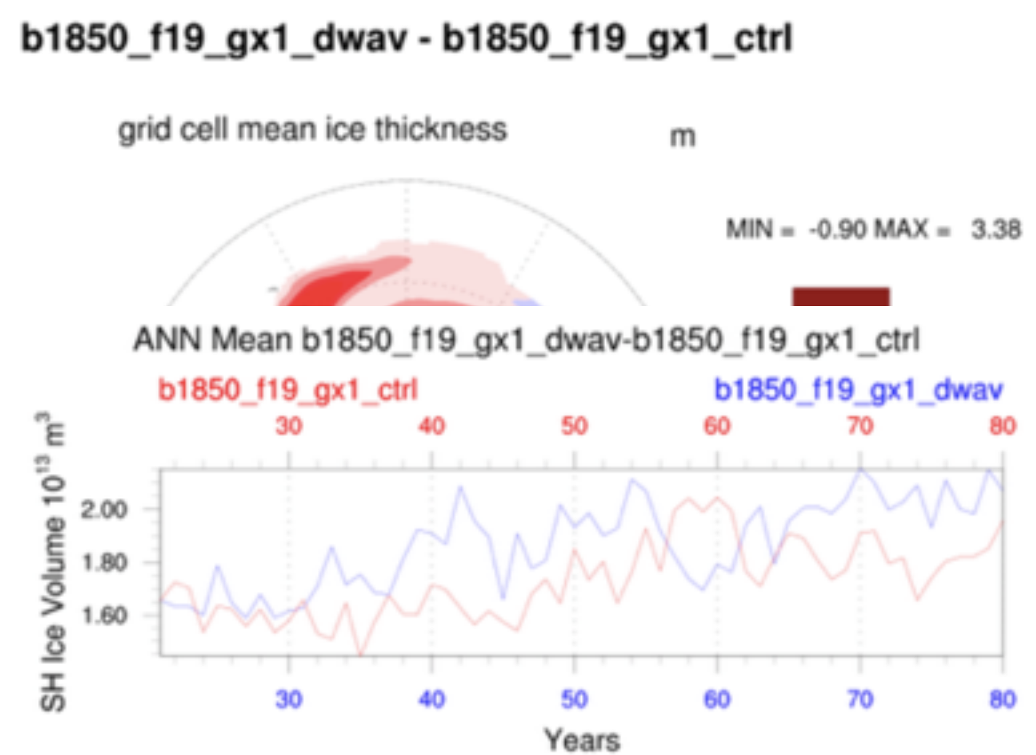
Prognostic Waves versus "Data Waves"

There are minimal differences in most places—data waves usually closer to prognostic waves than differences among different Langmuir parameterizations.

Prognostic Waves



Data Waves



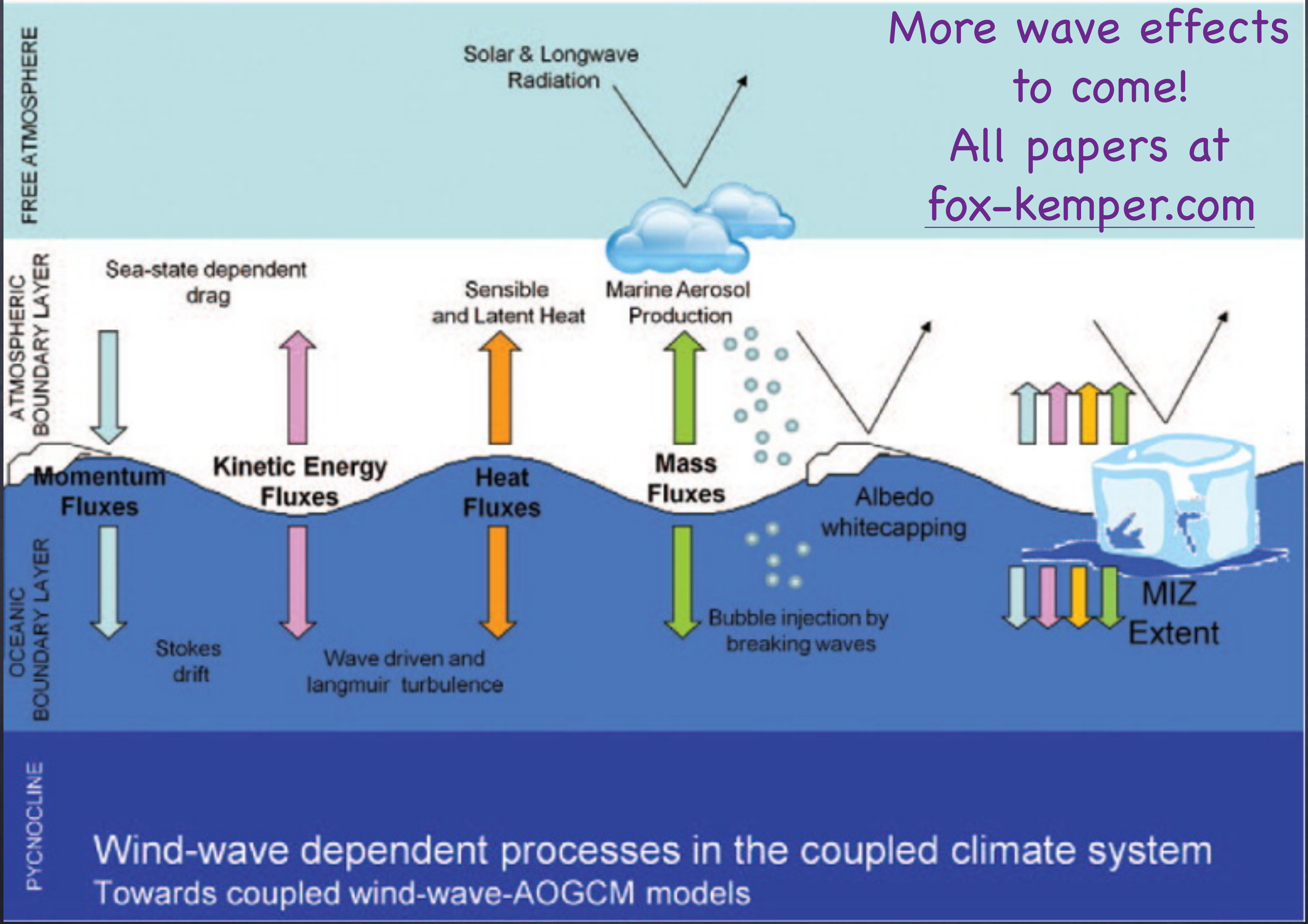
As you can see, there is some difference in West Antarctic sea ice response between the data waves and the prognostic waves… we are working to figure out exactly what causes it.

Preliminary trends indicate more increase with prognostic waves—needs more time to run!

Langmuir effects on climate

- 1) From observational, offline, and climate model estimates, including Langmuir mixing generally improves the mixed layer depths in many regions and improves ventilation.
- A prognostic wave model is generally thought to be required to force the Langmuir mixing.
- By comparison against a "data waves" climatology, it is found that feedbacks to the wave model are weak. Thus, this cheaper option is available.

No Retuning! All coefficents from LES



L. Cavaleri, BFK, and M. Hemer. Wind waves in the coupled climate system. Bulletin of the American Meteorological Society, 93(11):1651-1661, 2012.

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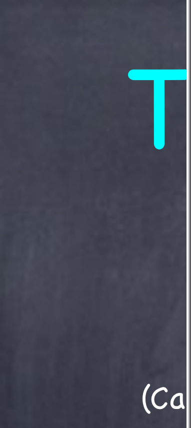
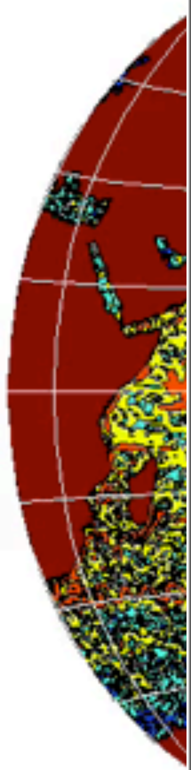
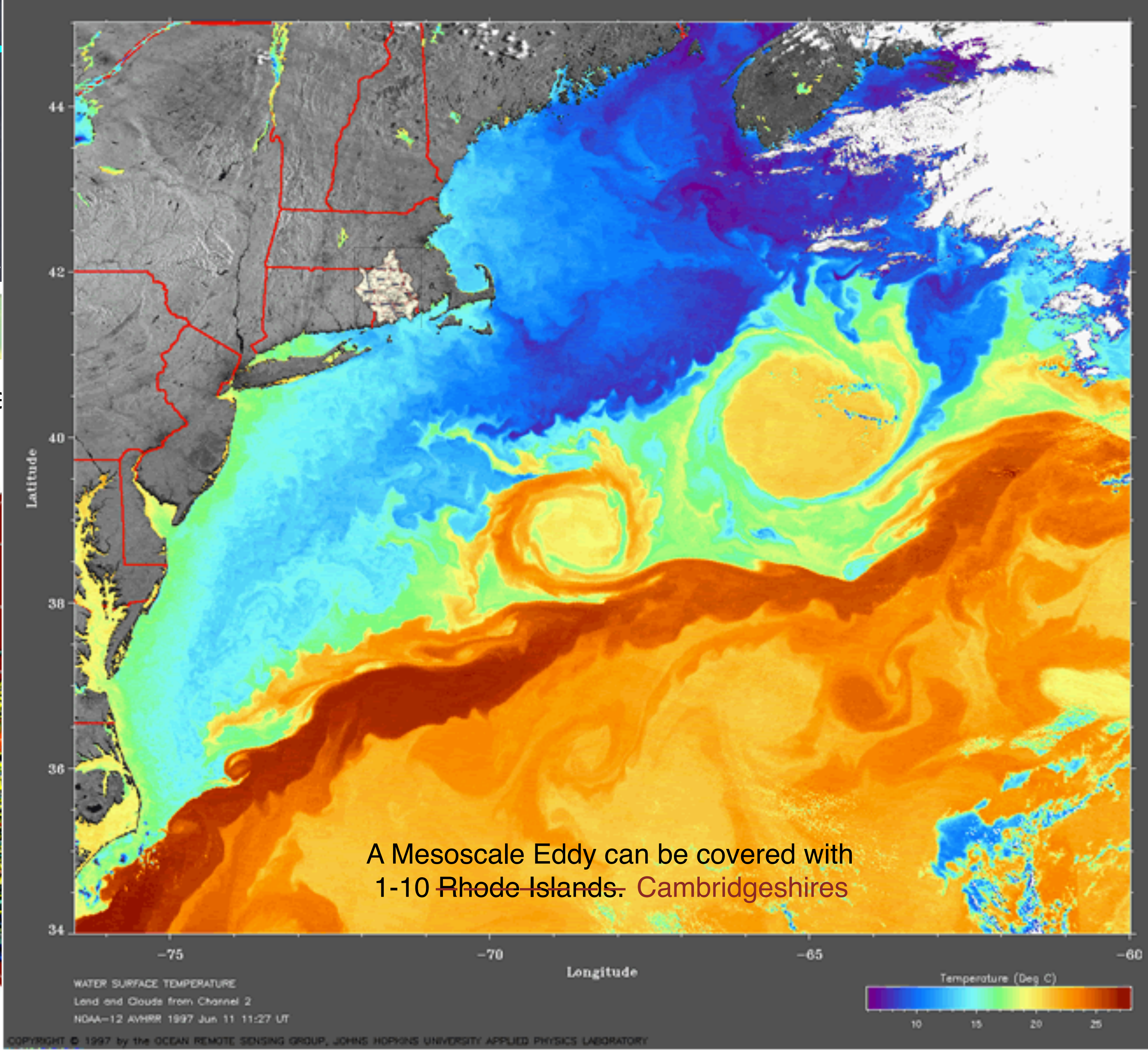
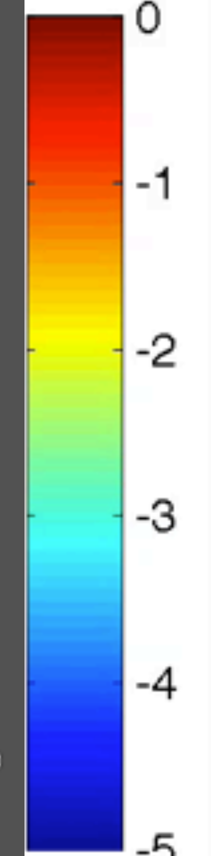


Satellite view of flows

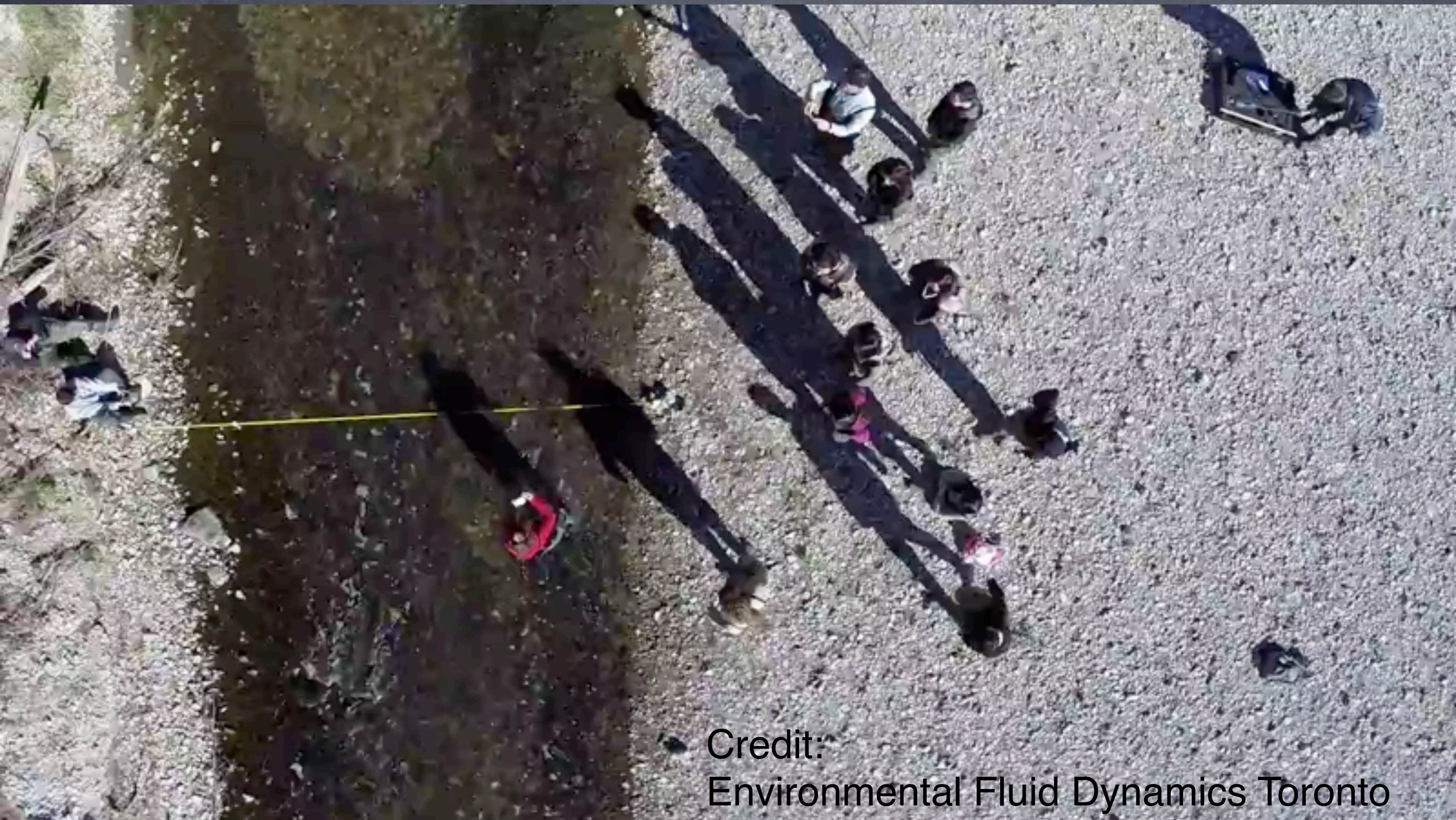






Shear Dispersion:

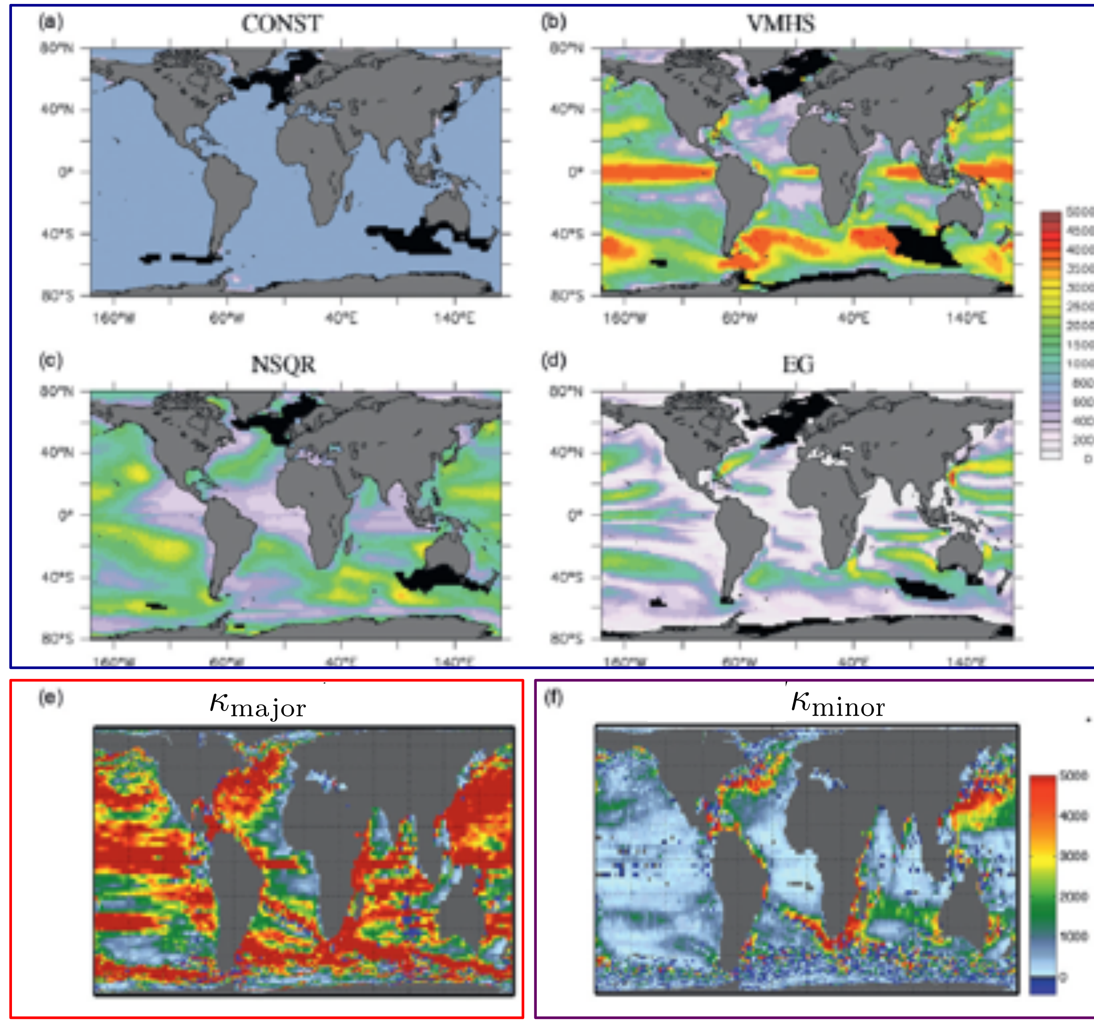
More along-flow than cross-flow diffusivity



Credit:
Environmental Fluid Dynamics Toronto

Mesoscale Eddy Parameterization

- Parameterizations currently use isotropic diffusivity
- Extend for anisotropy*
  - Principal axis alignment
  - $\kappa_{\text{major}} / \kappa_{\text{minor}}$
- What will be gained?
  - Shear dispersion
  - PV-gradient suppression
  - Better ventilation of passive and biogeochemical tracers



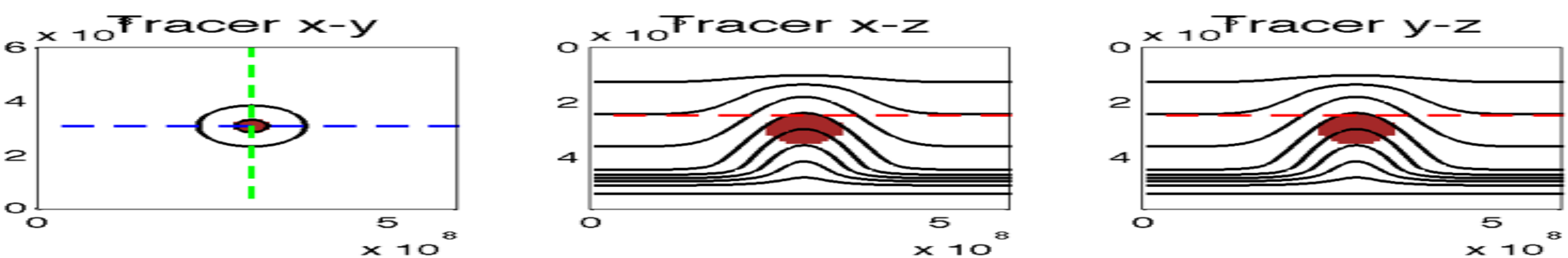
*Bachman & Fox-Kemper (2013)
*Fox-Kemper et al (2013)

Mesoscale Eddy Parameterization

- Baroclinic instability drives eddies through a conversion of available potential energy to kinetic energy
- Eddies anisotropically…

diffuse along isopycnals | flatten isopycnal slopes

$$\partial_t \phi + \vec{u} \cdot \nabla \phi = \nabla \cdot \left(\bar{\bar{K}} + \bar{\bar{A}} \right) \cdot \nabla \phi$$

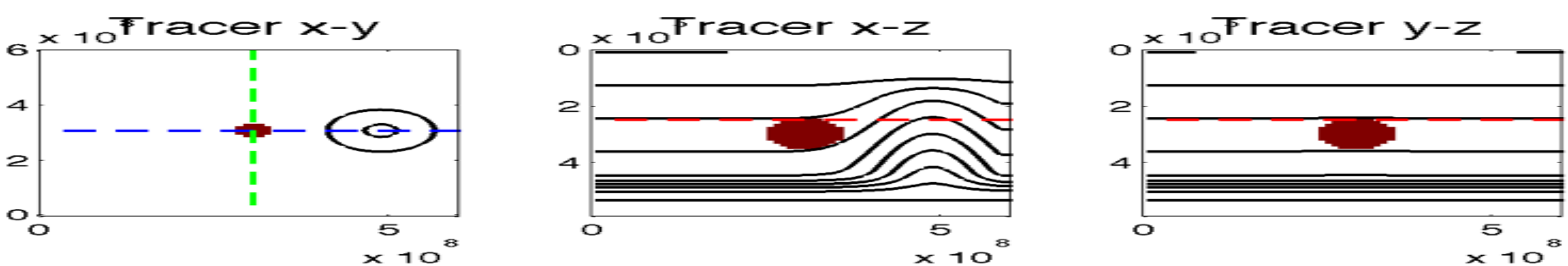


Anisotropic GM/Redi

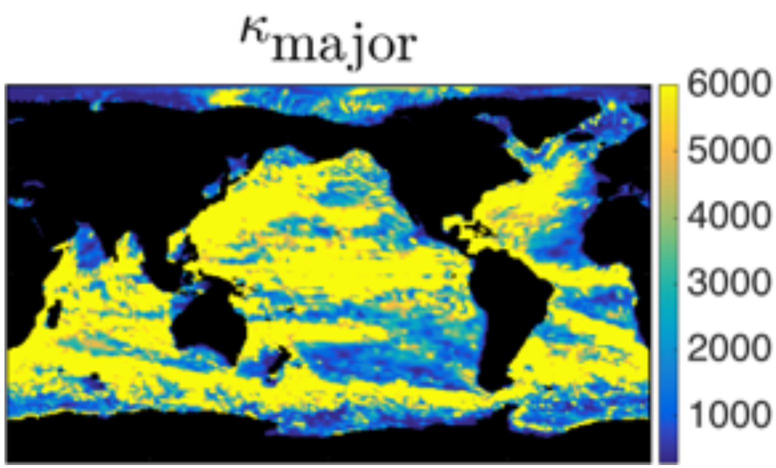
- Parameterize anisotropic transport mechanisms in the ocean:

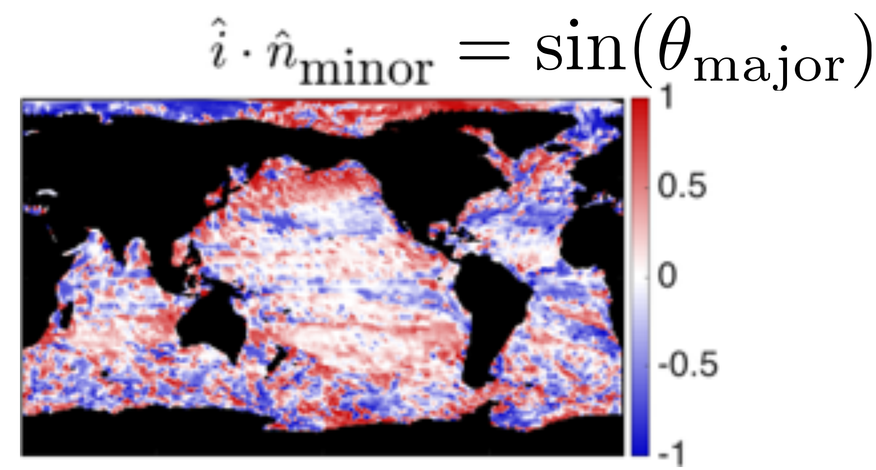
κ →

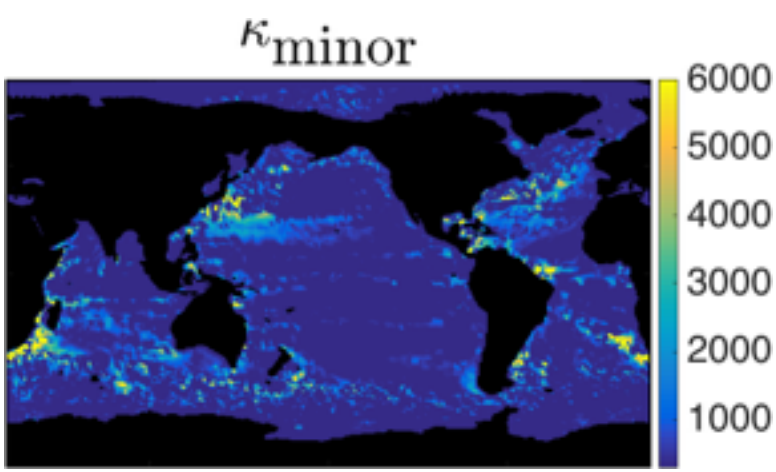
1. κ_{minor} (suppression from background diffusivity)
2. κ_{major} (enhancement from background diffusivity)
3. $\sin(\theta)$ (alignment of principal axis of diffusion)



Hi-res Diagnosed Tensor







- 0.1 degree POP2 with 9 passive tracers (various orientation restoring)*
- Diffusivities calculated using least-squares
- Tensor applied statically in 1-degree tests

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*Bachman & Fox-Kemper (2013)

*Fox-Kemper et al (2013)

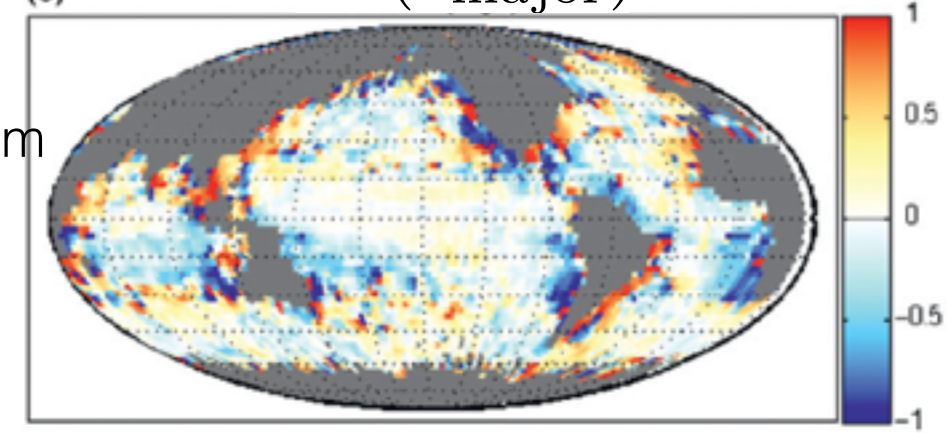
Drifter Observation Diffusivity Tensor

- Principal axis alignment
  - Major axis **aligned zonally** away from boundary currents
  - Major axis **aligned with the flow** near boundary currents

- $\kappa_{\mathrm{major}}/\kappa_{\mathrm{minor}}$
  - **> 16** in equatorial region
  - Typical ratio is **≈ 5**

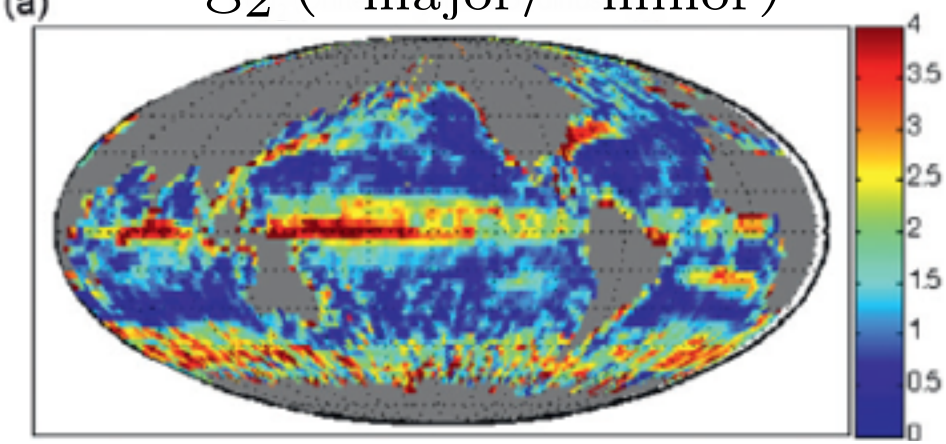
$\sin(\theta_{\mathrm{major}})$

(e)



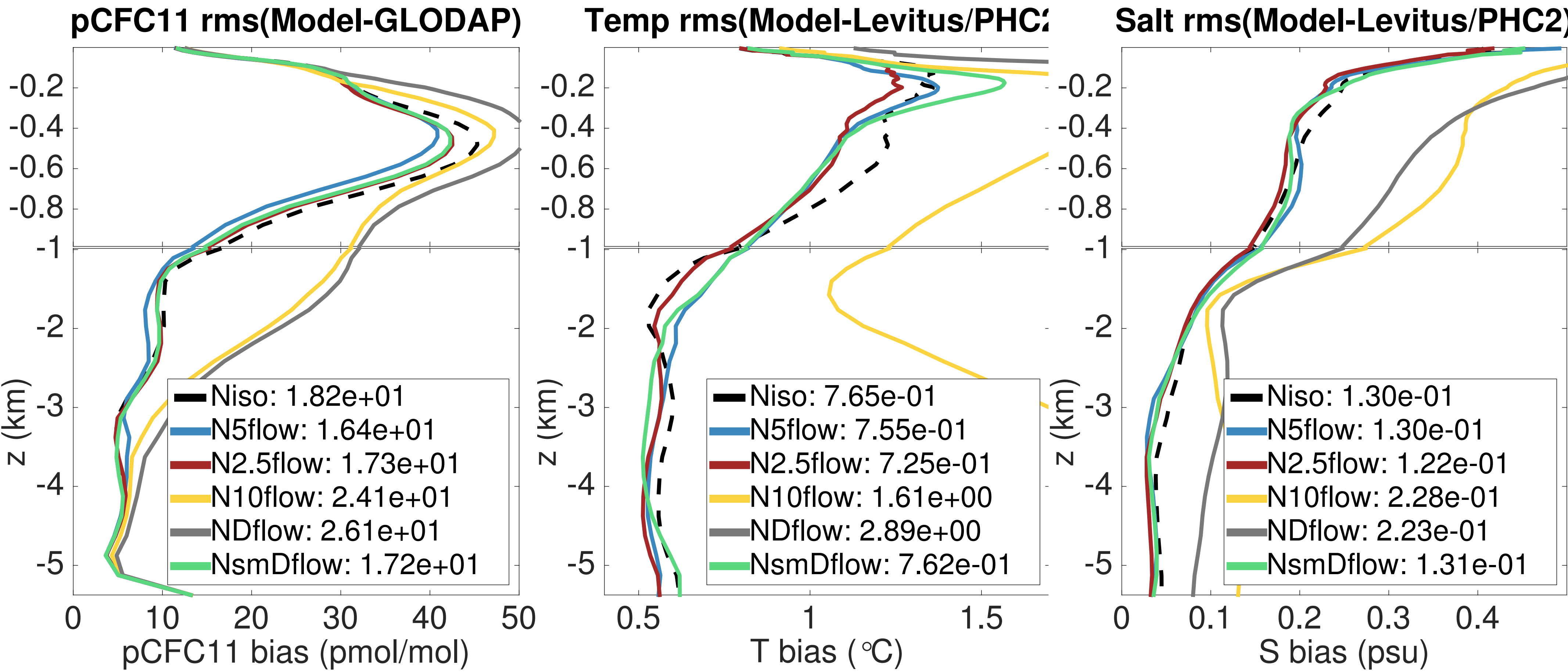
$\log_2\left(\kappa_{\mathrm{major}}/\kappa_{\mathrm{minor}}\right)$

(a)



*Fox-Kemper et al (2013)

Diffusivity Ratio Study



N² isotropic | ratio=5 | ratio=2.5 | ratio=10 | diagnosed | smoothed diagnosis

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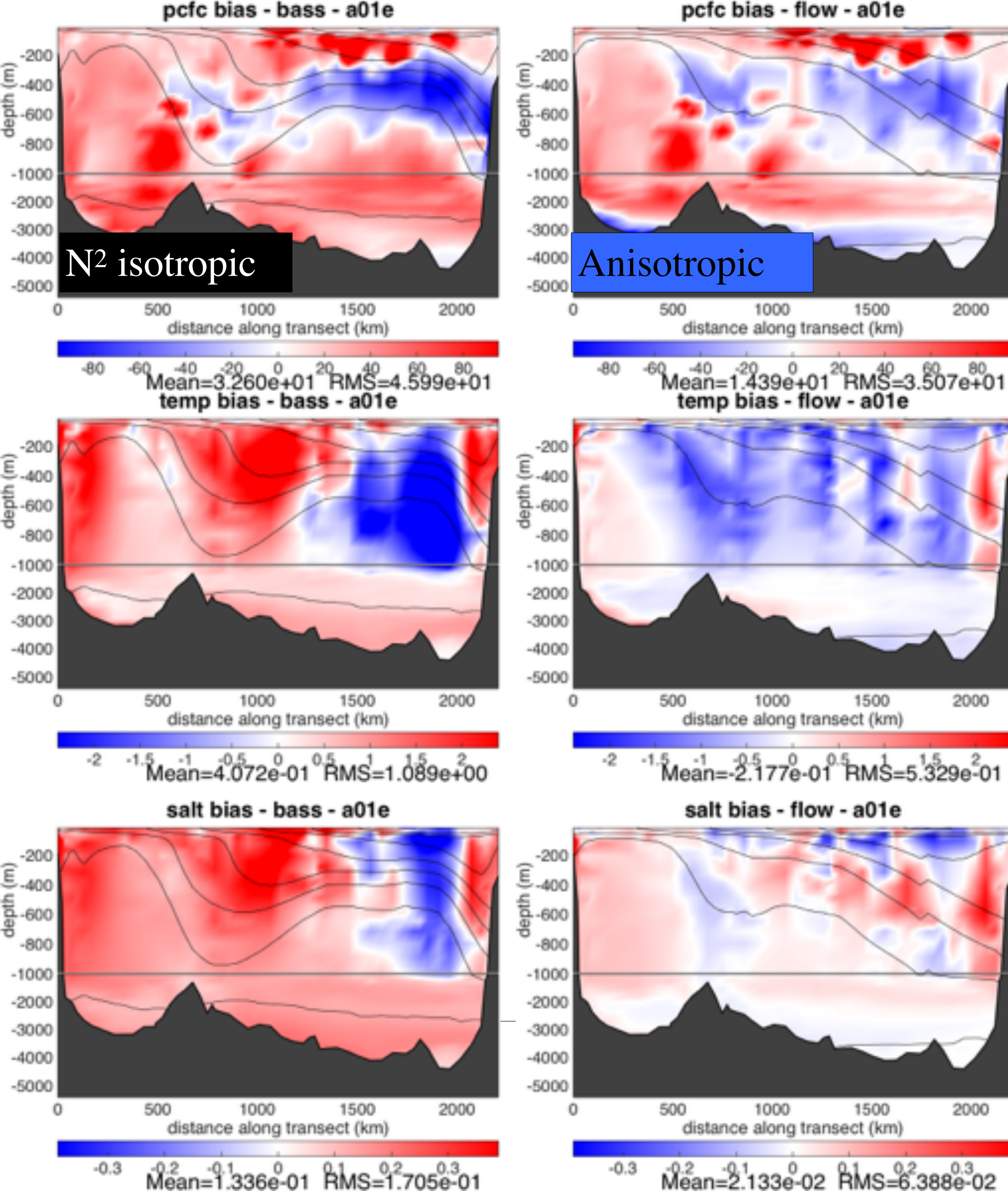
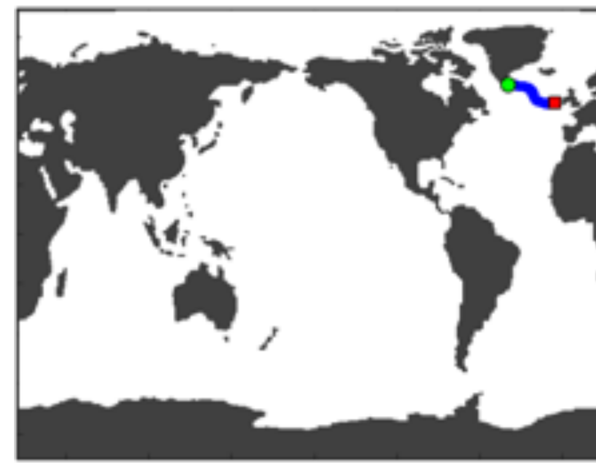
High diffusivity ratios introduce drastic biases likely due to suppression of deep water formation & AMOC shutdown

Along WOCE Transect



Map for a01e

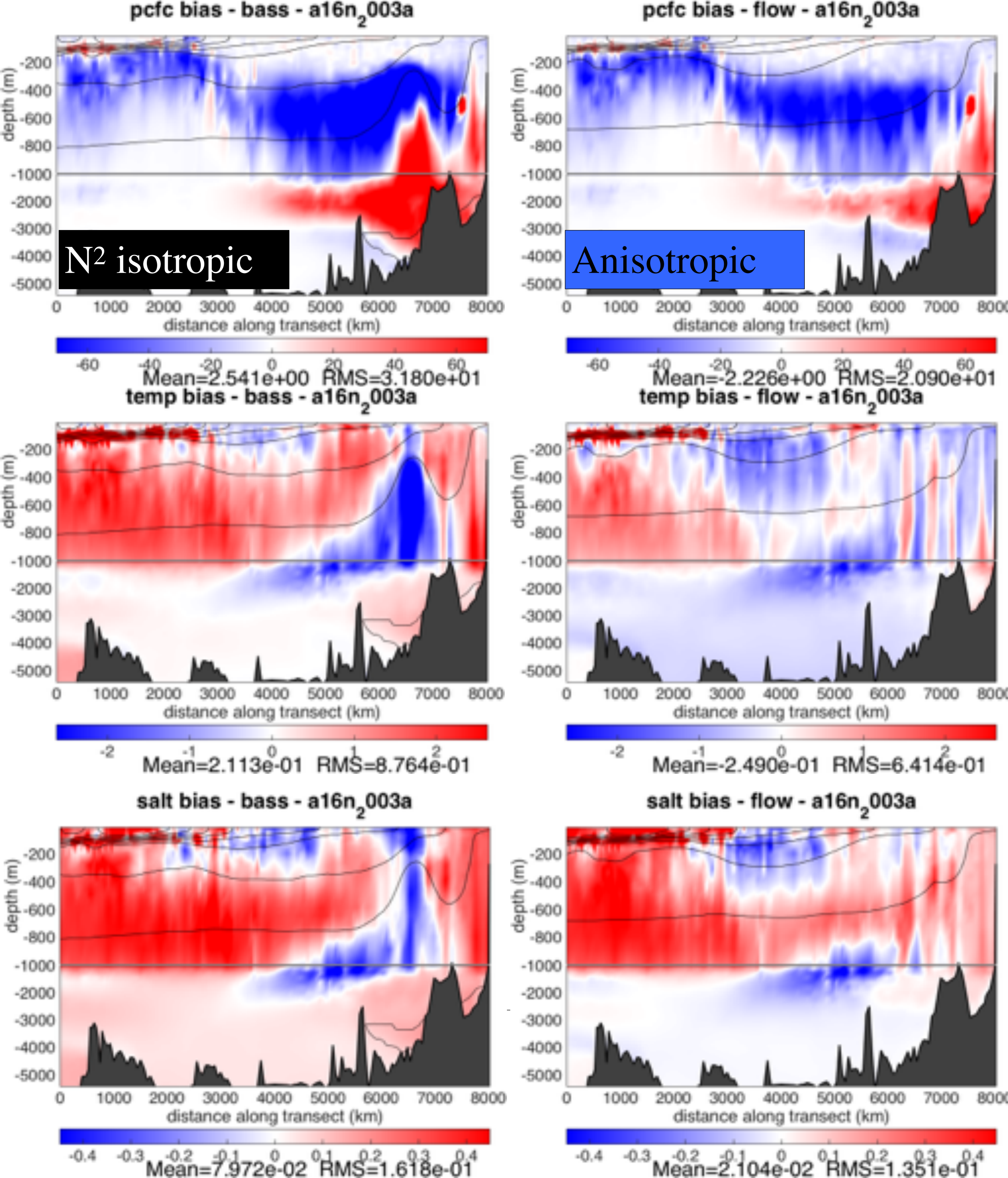


Anisotropy drastically reduces biases:

pCFC by 24%

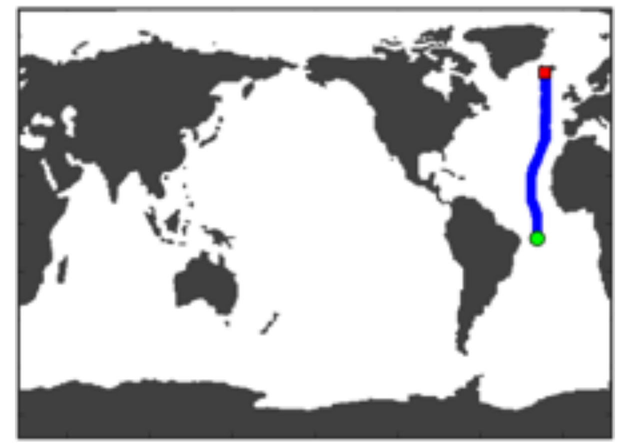
Temp by 48%

Salinity by 63%



Along WOCE Transect

Map for a16n$_2$003a

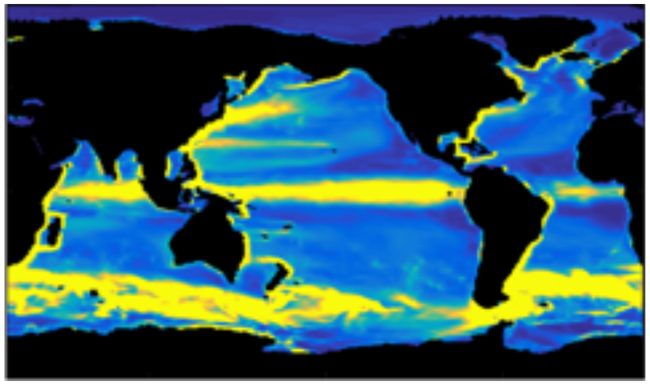


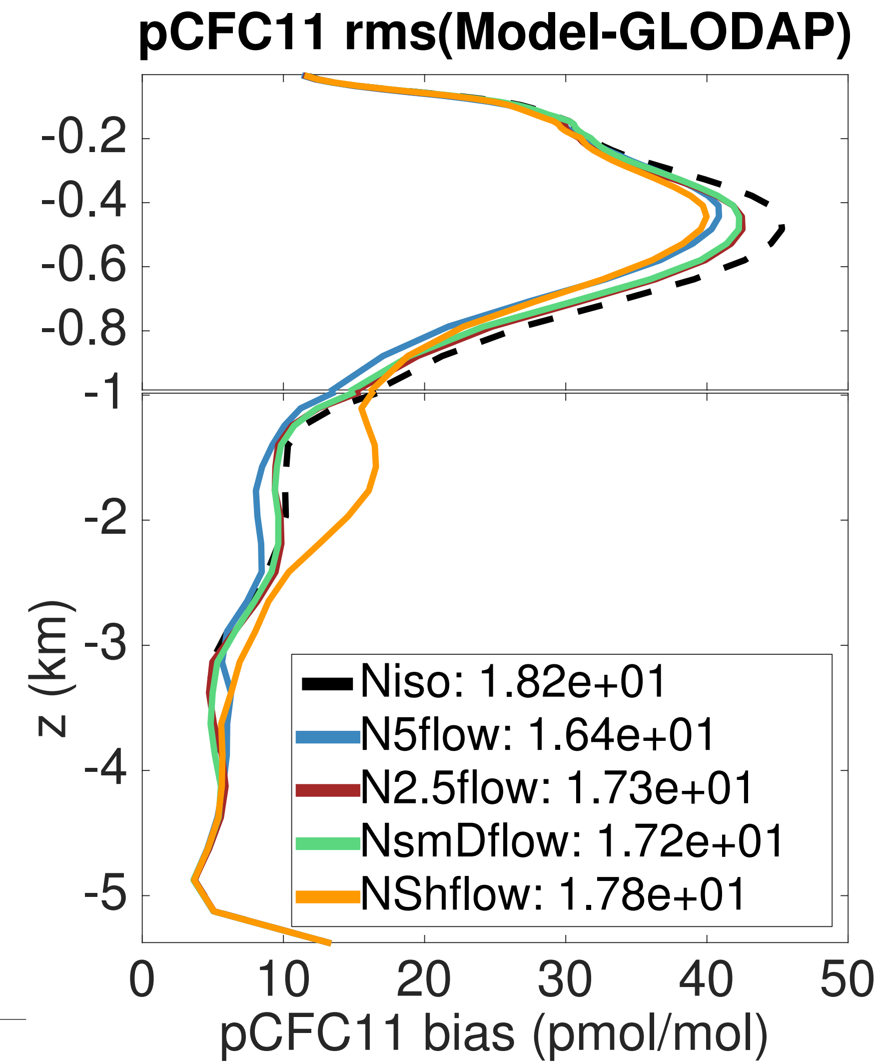
Anisotropy also reduces biases in equatorial Atlantic

Shear Dispersion Parameterization

$$\kappa_{\text{major}} = \kappa + \kappa^{-1} \left\langle (u\Delta y)^2 + (v\Delta x)^2 \right\rangle$$

shear dispersion





Current version reduces CFC bias, but does not maintain AMOC, likely due to strong shear (strong diffusion) in Labrador Sea, preventing deep water formation

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Shear Dispersion Parameterization

Taylor (1953) pipe flow	$\kappa_{\text{flow}} = \kappa + \frac{U^2 R^2}{48\kappa}$

κ = background diffusivity

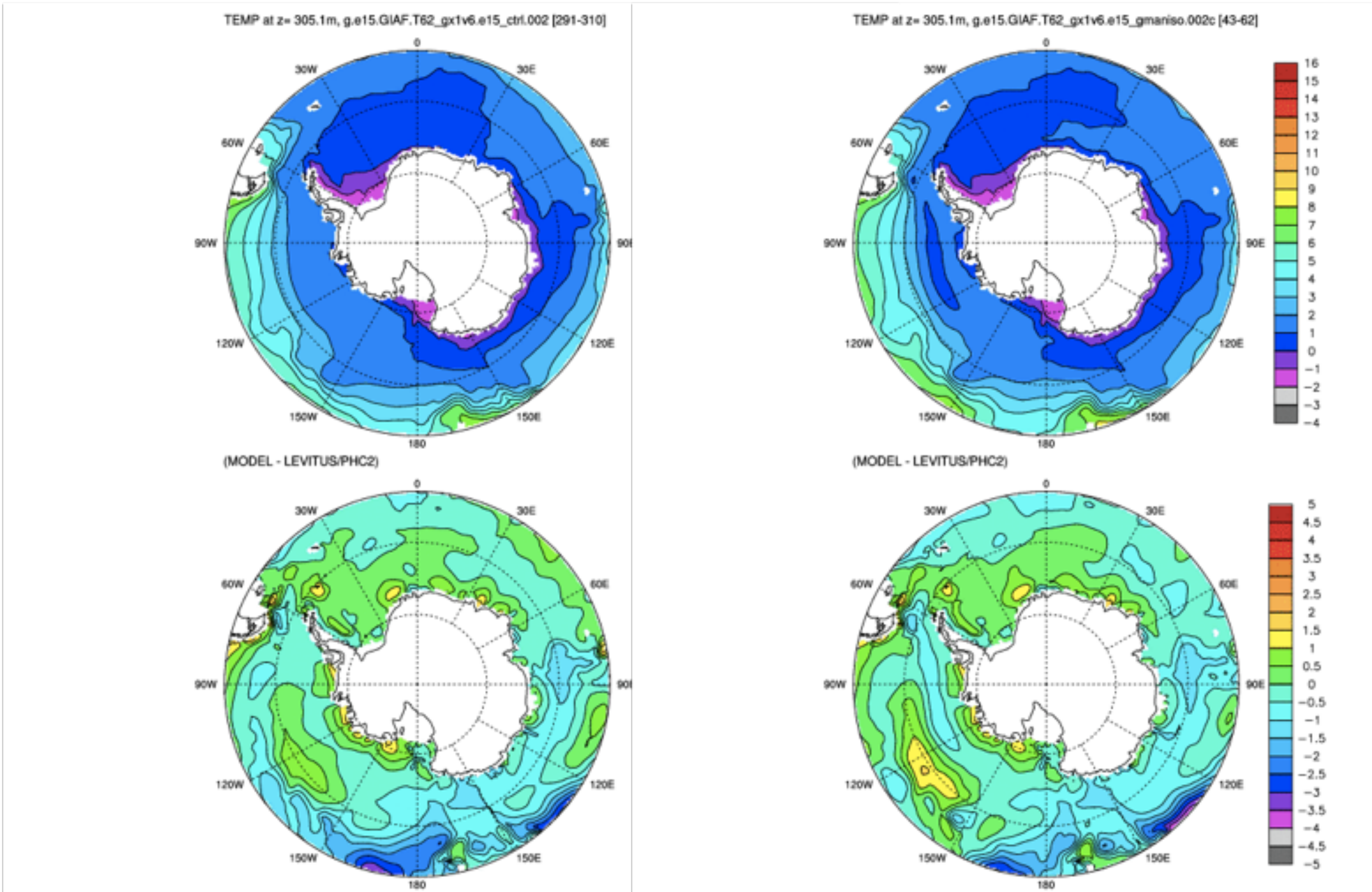
Smith (2005) QG jet (shear dispersion)	$\kappa_{\text{flow}} = \kappa + \kappa^{-1} \sum_n \frac{\lvert \hat{U}_n^2 \rvert}{k_n^2}$
$U(y) = \sum_{n=-\infty}^{\infty} \hat{U}_n e^{-ik_n y}$	$\kappa_{\text{flow}} = \kappa + \kappa^{-1} \left\langle \left[\int U(y) dy \right]^2 \right\rangle$

Shear dispersion parameterization	$\kappa_{\text{major}} = \kappa + \frac{a}{2\pi^2 \kappa} \langle (u\Delta y)^2 + (v\Delta x)^2 \rangle$
Parameter a sets scale of shear dispersion.	Average over neighboring 4 U-cells
Use reduction of κ_{minor} to fix AMOC suppression and temperature drift?	Model shear dispersion effects at largest unresolved scale: $a = 1$

Temperature at 300m

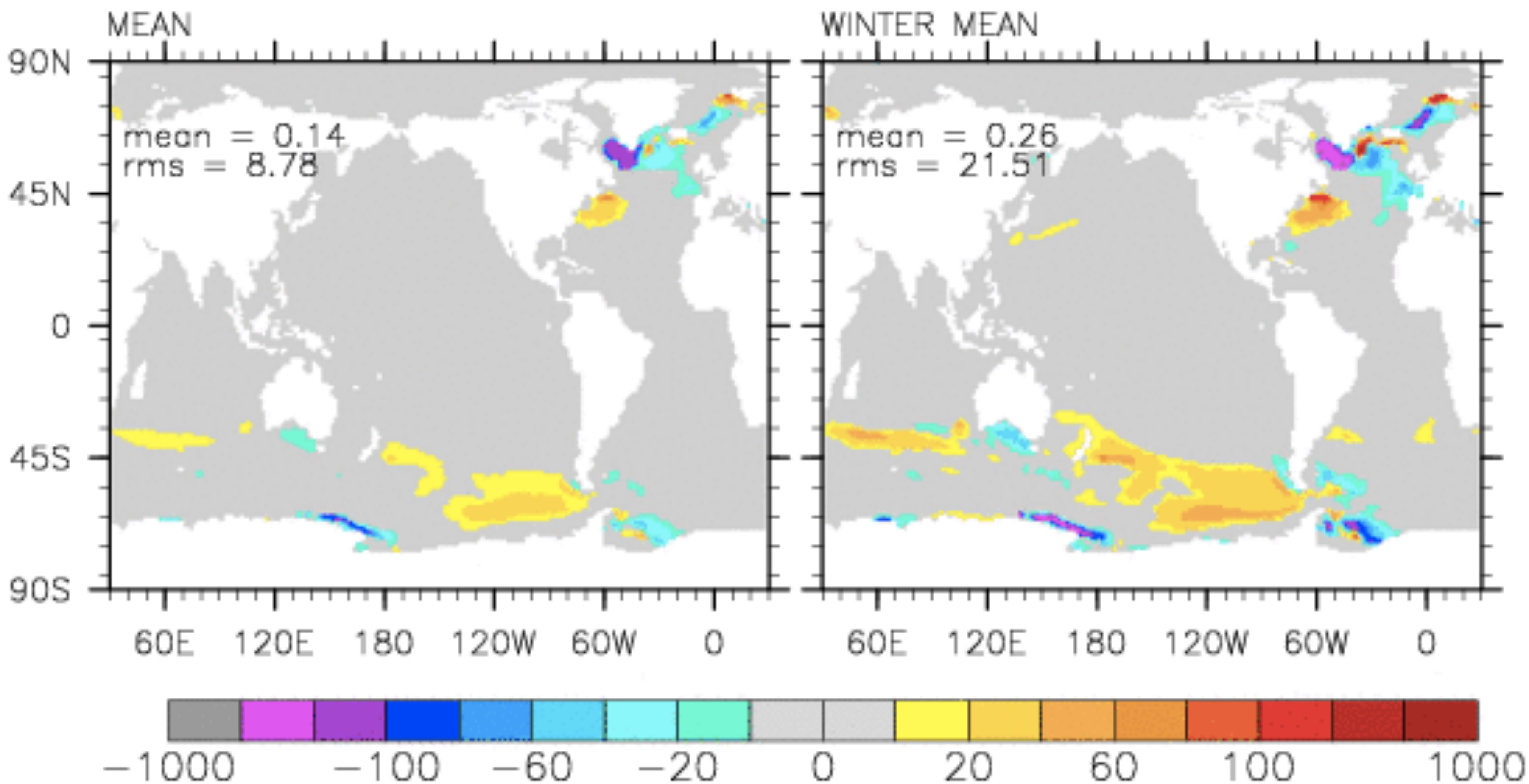
Control

Shear Dispersion



Mixed Layer Depth

Shear Dispersion minus Control



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Conclusions

- **Submesoscale Parameterization**
  - Mature parameterization
  - Significant impact on MLD—model dependent
  - Removing param doesn't fix S. Ocean MLD bias
- **Langmuir Mixing**
  - Mature parameterization
  - Significant improvement of MLD & ventilation
  - Can be run with prognostic or "data waves"
  - Interesting feedbacks with sea ice not understood
- **Mesoscale Anisotropy**
  - Basic physics understood
  - Significant bias reductions under controlled circumstances
  - Shear dispersion parameterization less well developed