Langmuir Mixing Effects on Global Climate: WAVEWATCH III in CESM

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with Adrean Webb (TUMST), Tony Craig, Mariana Vertenstein (NCAR), Gokhan Danabasoglu (NCAR), Bill Large (NCAR)

NCAR OMWG, 1/15/15

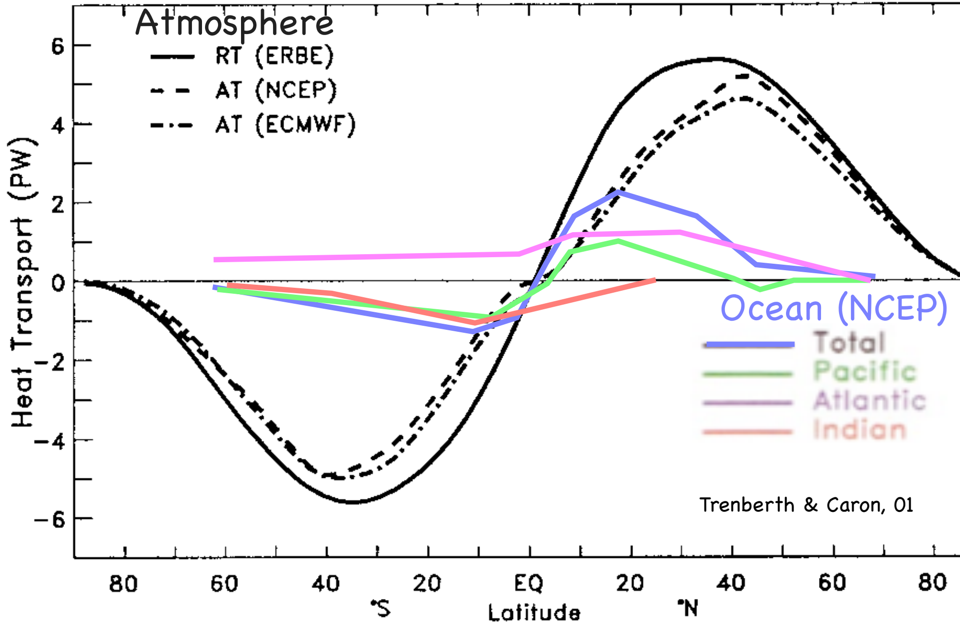
Sponsors: NSF 1258907, 0934737, NASA NNX09AF38G, CARTHE/GoMRI

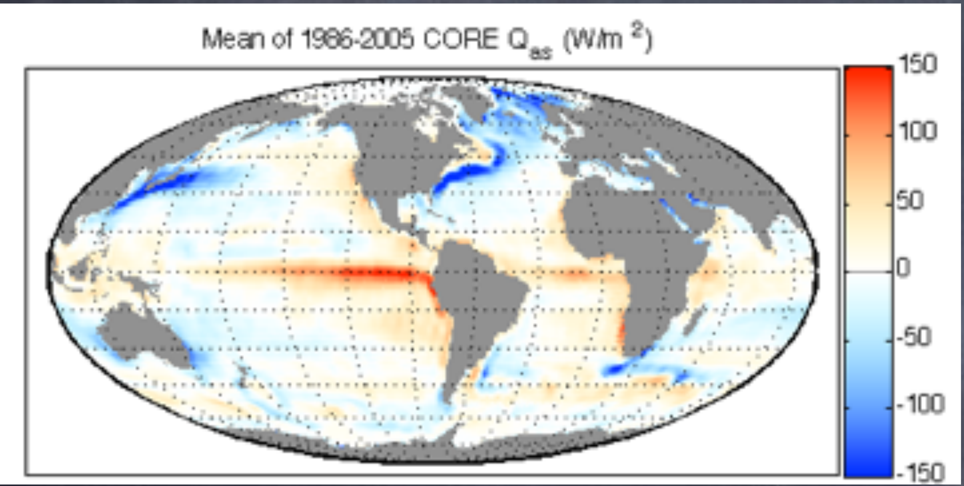
Air-Sea Flux Errors vs. Data

Heat capacity & mode of transport is different in A vs. O

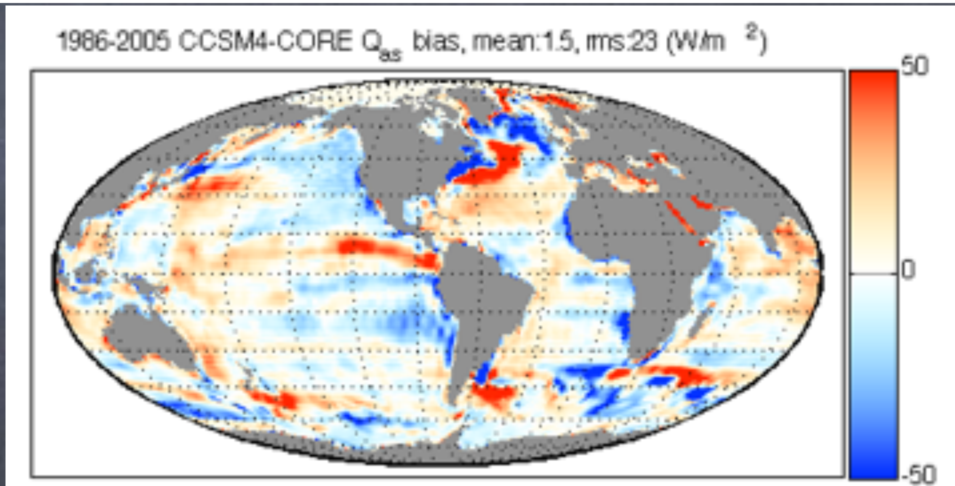
>90% of GW is oceanic, 10m O=whole A

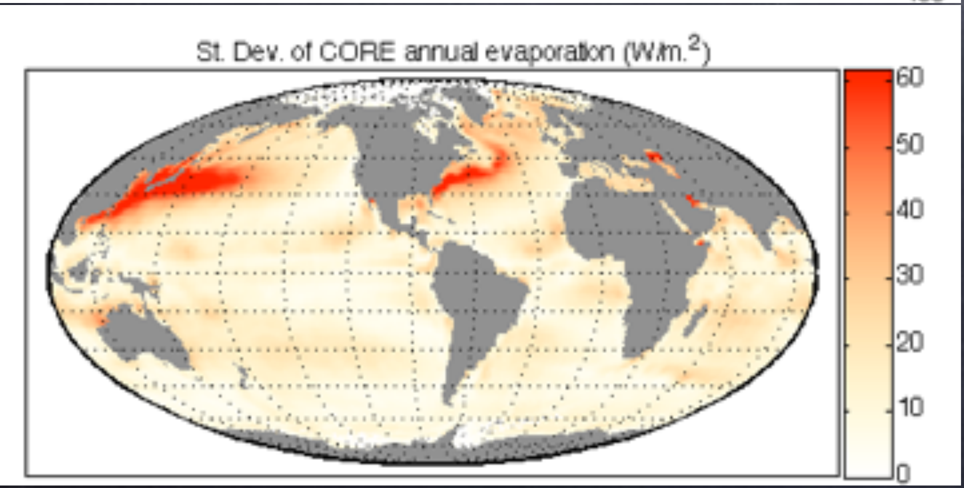
S. C. Bates, BFK, S. R. Jayne, W. G. Large, S. Stevenson, and S. G. Yeager. Mean biases, variability, and trends in air-sea fluxes and SST in the CCSM4.Journal of Climate, 25(22):7781-7801, 2012.



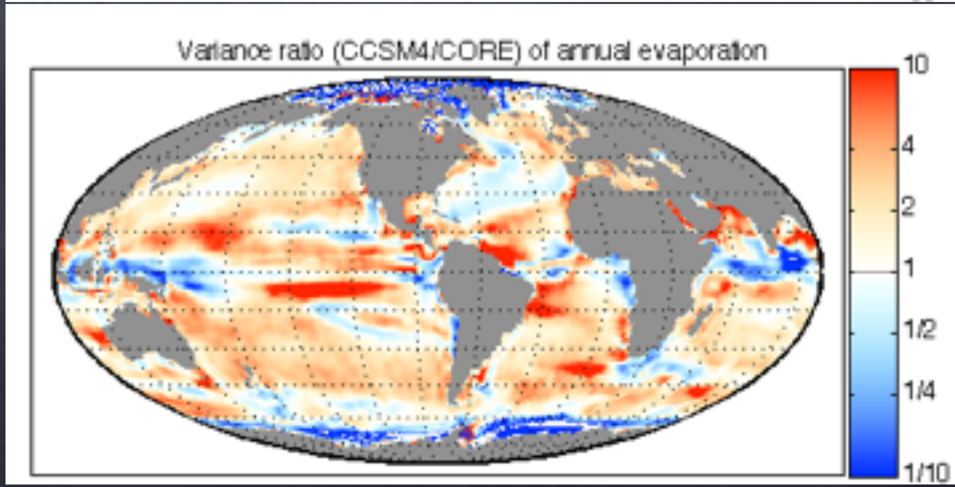


Mean

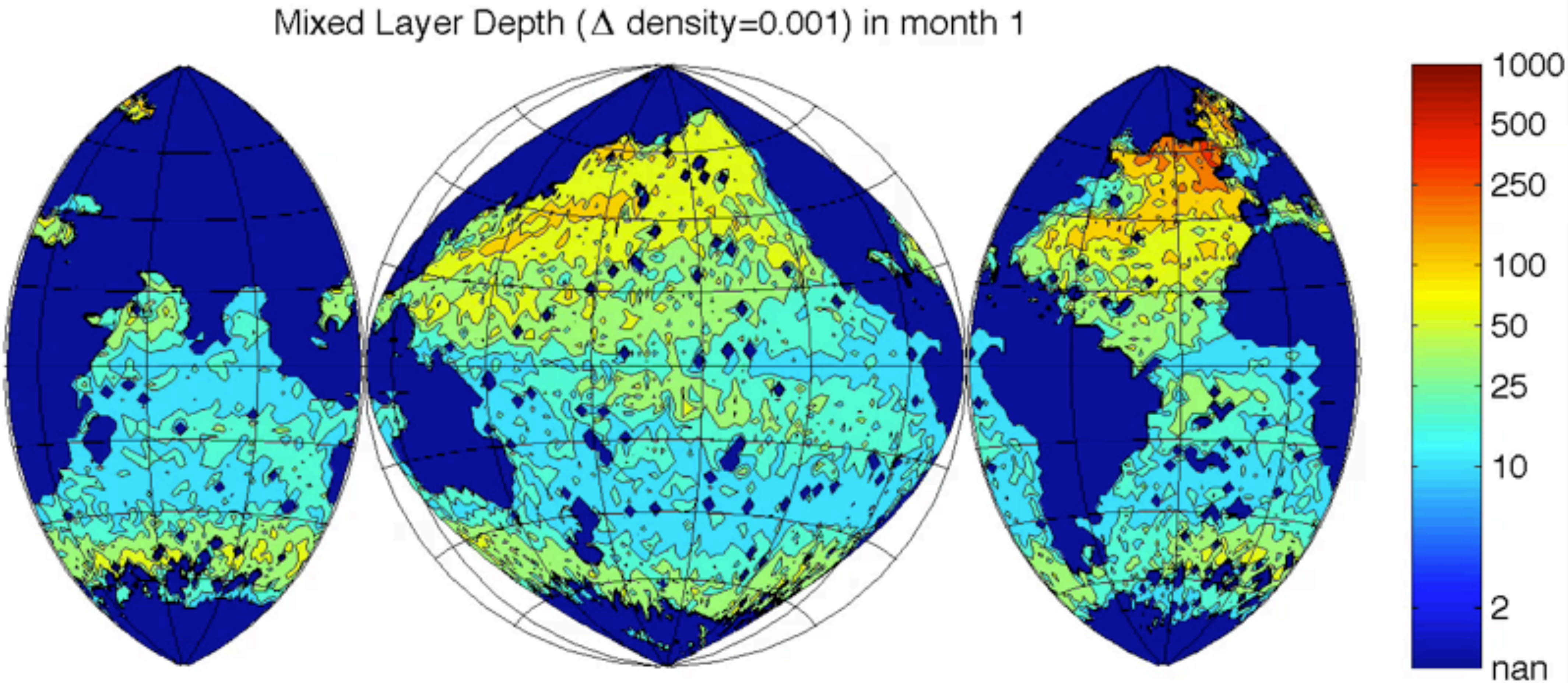




Annual 9-15mo



The Ocean Mixed Layer



Stommel's Demon: ocean properties at depth set by deepest wintertime mixed layer & its properties

From Argo float data courtesy C. de Boyer-Montegut

The Character of the Langmuir Scale

image: Thorpe, 04

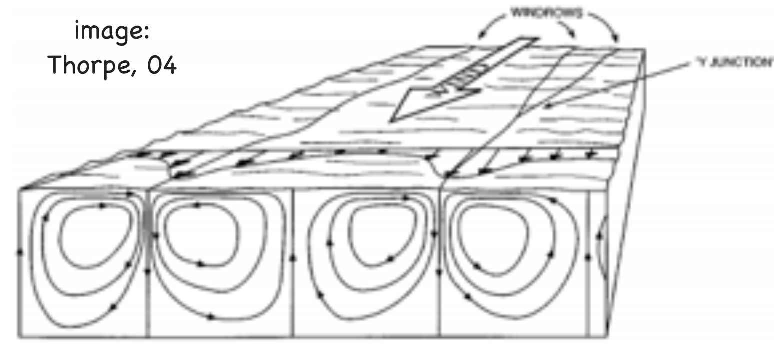


Figure 1 Sketch showing the pattern of mean flow in idealized Langmuir circulation. The windrows may be 2 m to 300 m apart, and the cell form is roughly square (as shown). In practice the flow is turbulent, especially near the water surface, and the windrows (Figure 2 amalgamate and meander in space 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. 2011
- 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 slope (ka), irrotational --> Deep Water Waves!
  - Average over deep water waves in space & time,
  - Arrive at Large, Slow equation set.
- THE BASIS FOR ALL LARGE EDDY SIMULATIONS OF WAVE-DRIVEN OSBL TURBULENCE

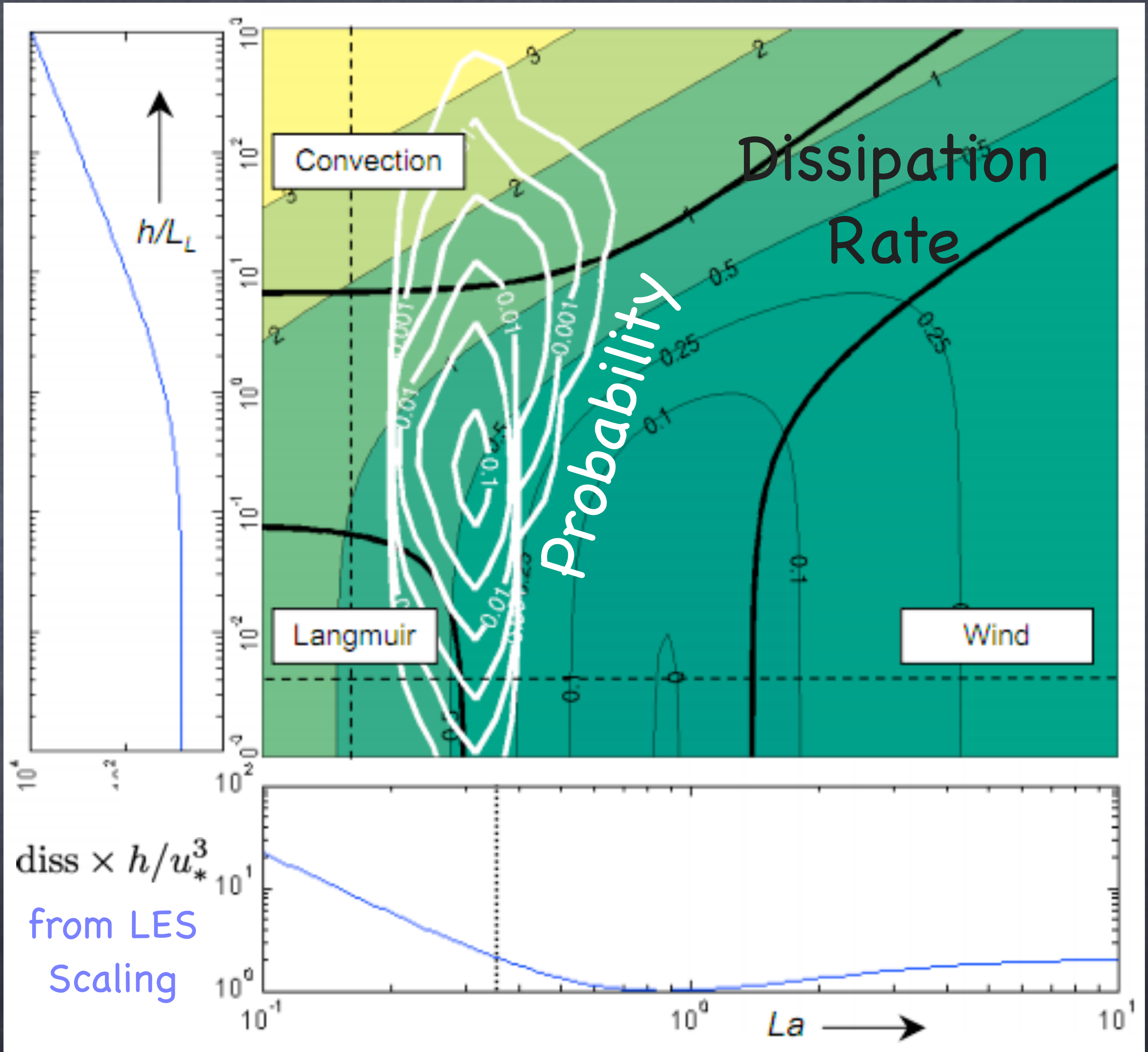
All Wave-Mean coupling terms involve the Stokes Drift

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

Data + Large Eddy Simulation scaling, Southern Ocean mixing energy:

One way to estimate

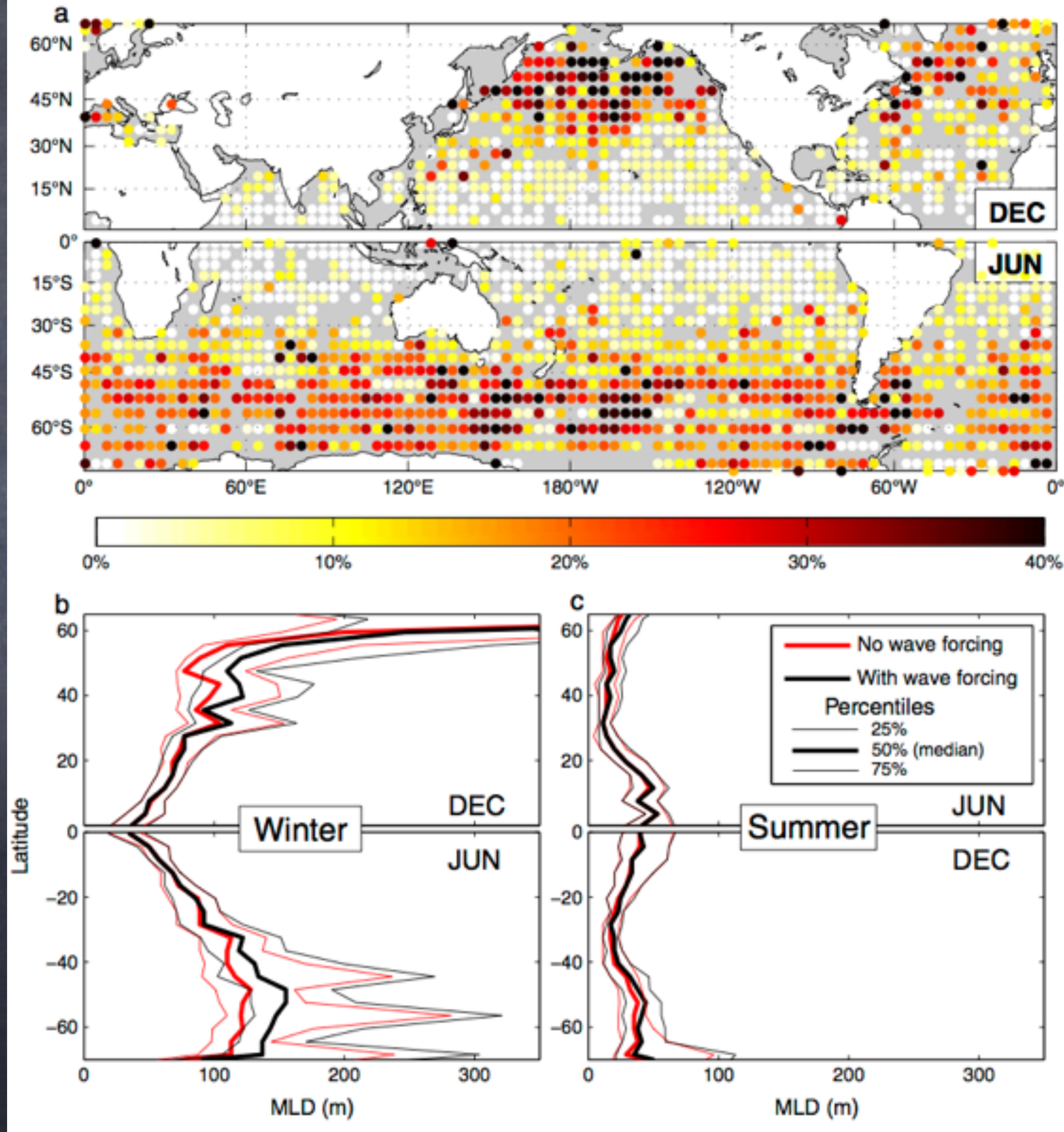
So, waves can drive mixing via Stokes drift (combines with cooling & winds)



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.

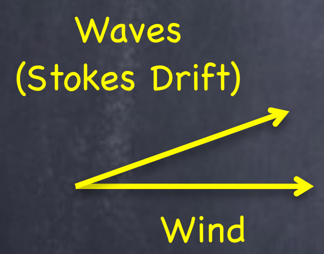
Offline obs-driven parameterization:

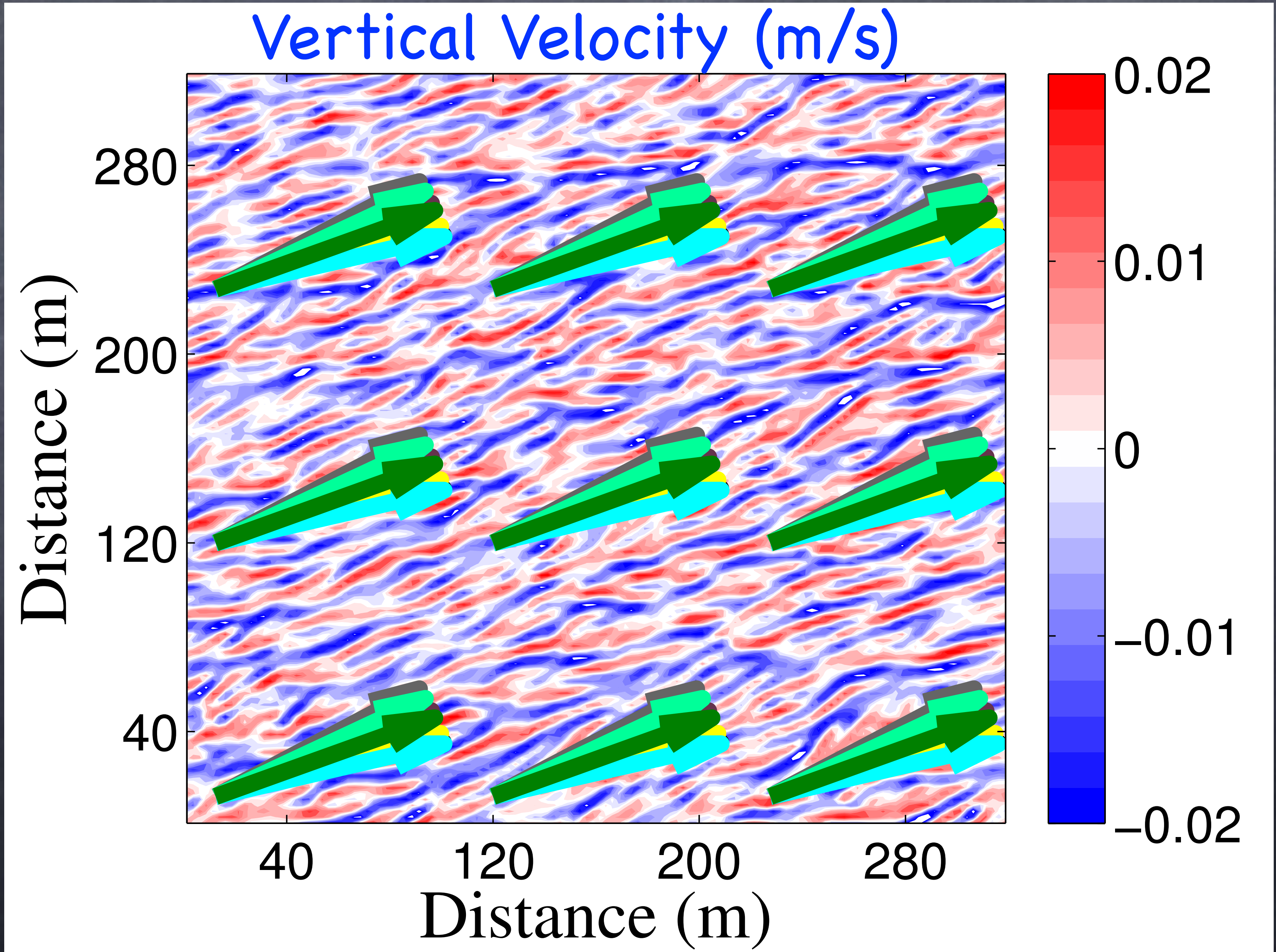
Including Stokes-driven Mixing (Harcourt 2013) Deepens the Mixed Layer!



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.

CLB as equations for Large Eddy Simulations: Tricky: Misaligned Wind & Waves

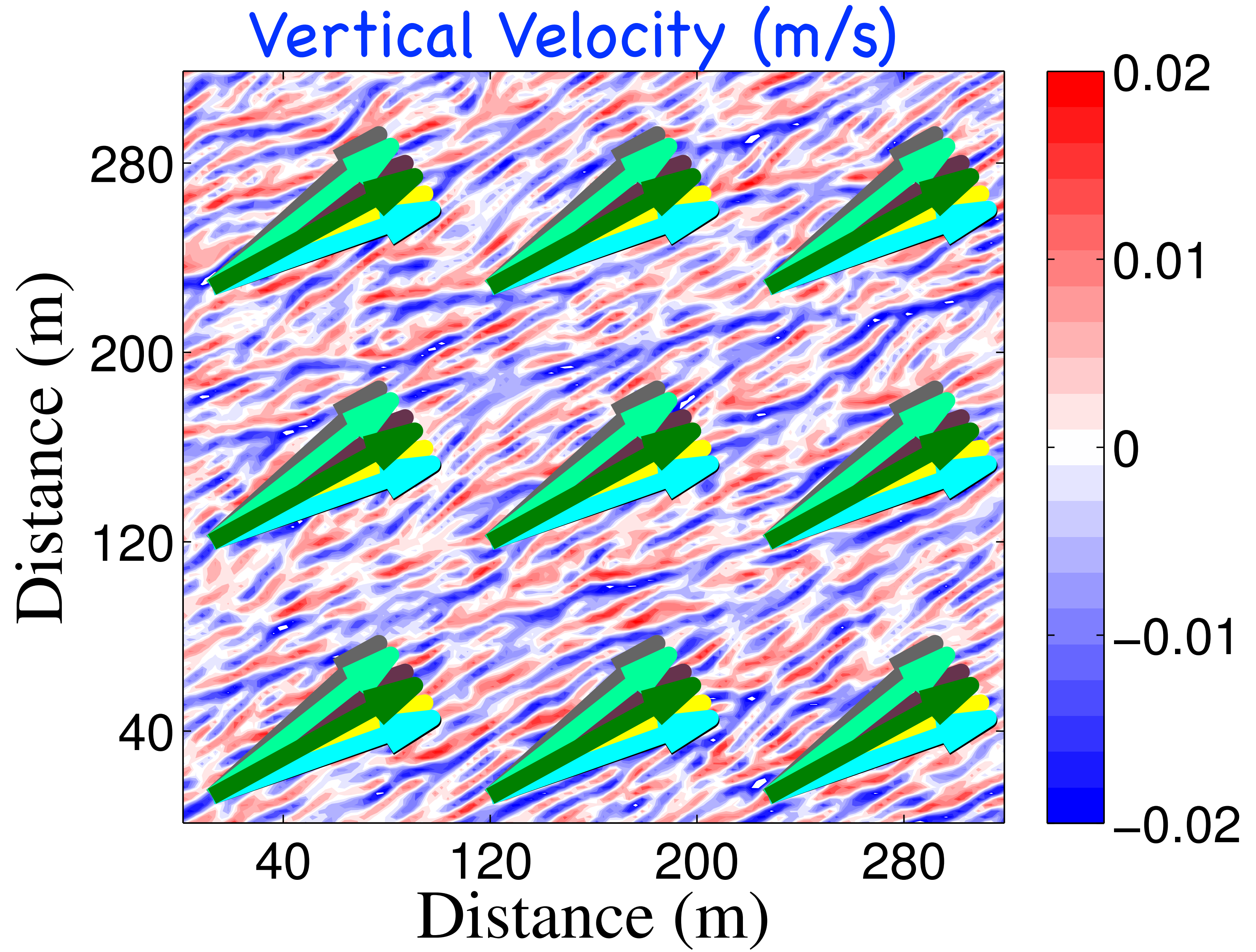




L. P. Van Roekel, B. Fox-Kemper, P. P. Sullivan, P. E. Hamlington, and S. R. Haney. The form and orientation of Langmuir cells for misaligned winds and waves. Journal of Geophysical Research-Oceans, 117:C05001, 22pp, May 2012.

Tricky: Misaligned Wind & Waves

L. P. Van Roekel, B. Fox-Kemper, 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.



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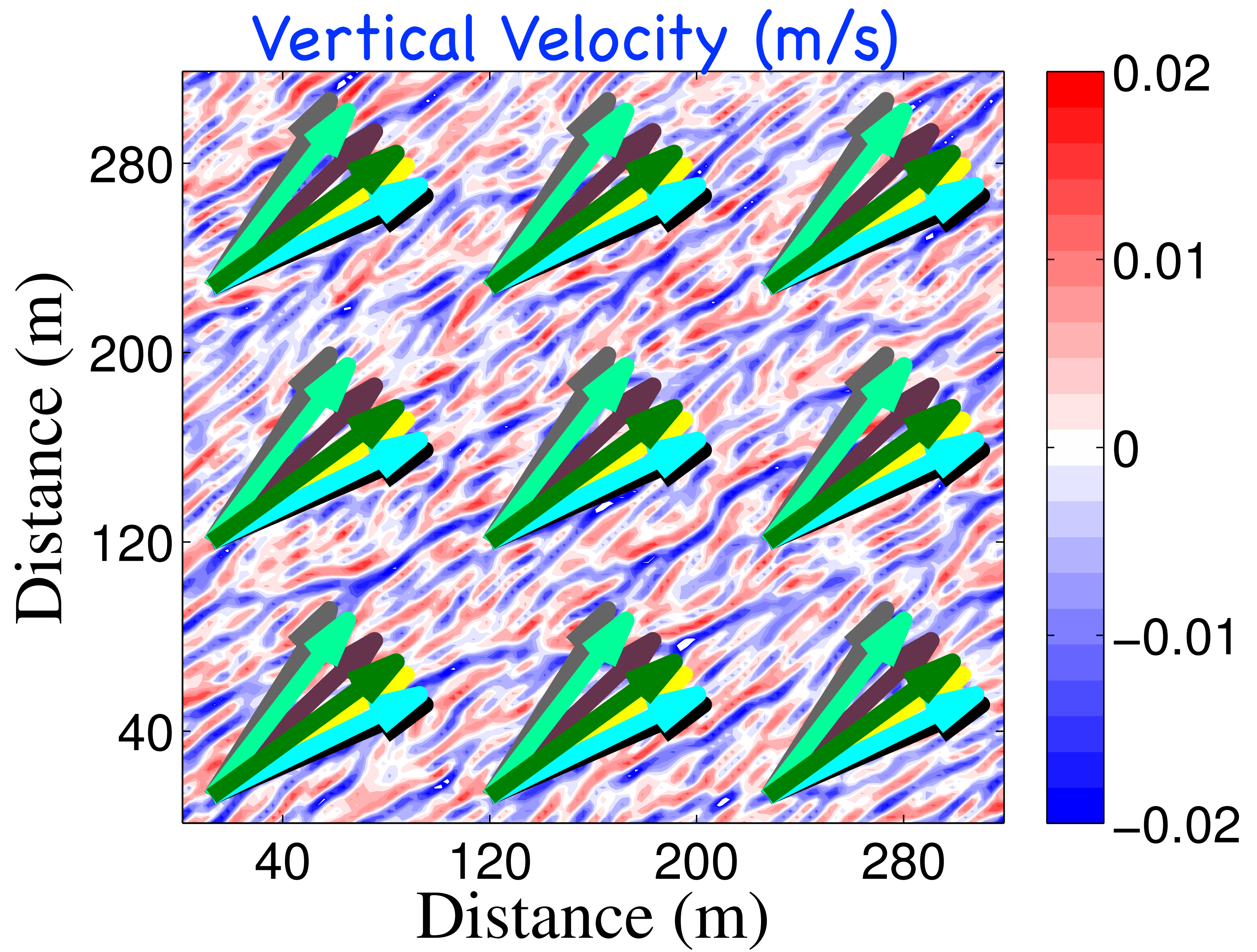
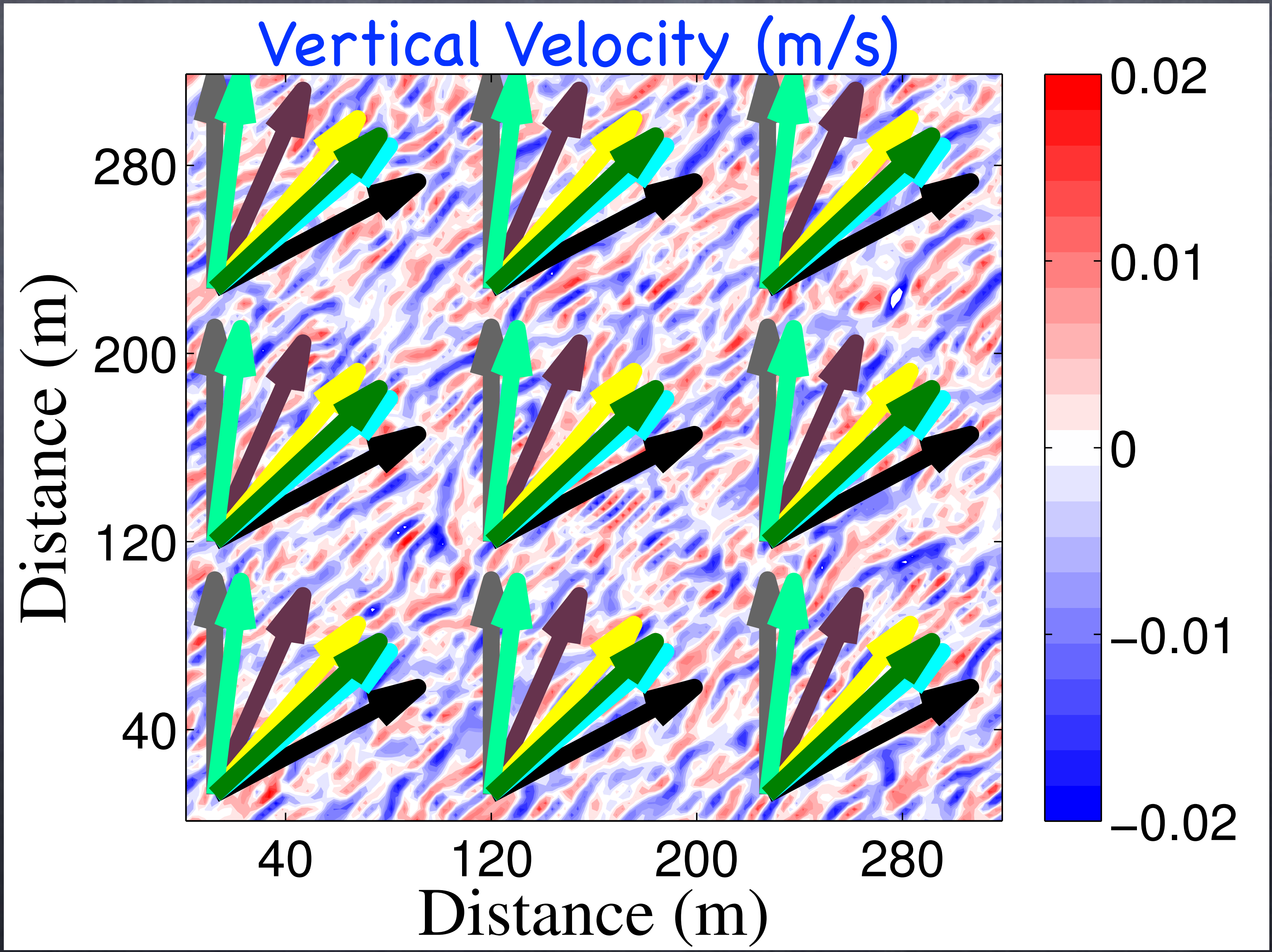


Tricky: Misaligned Wind & Waves

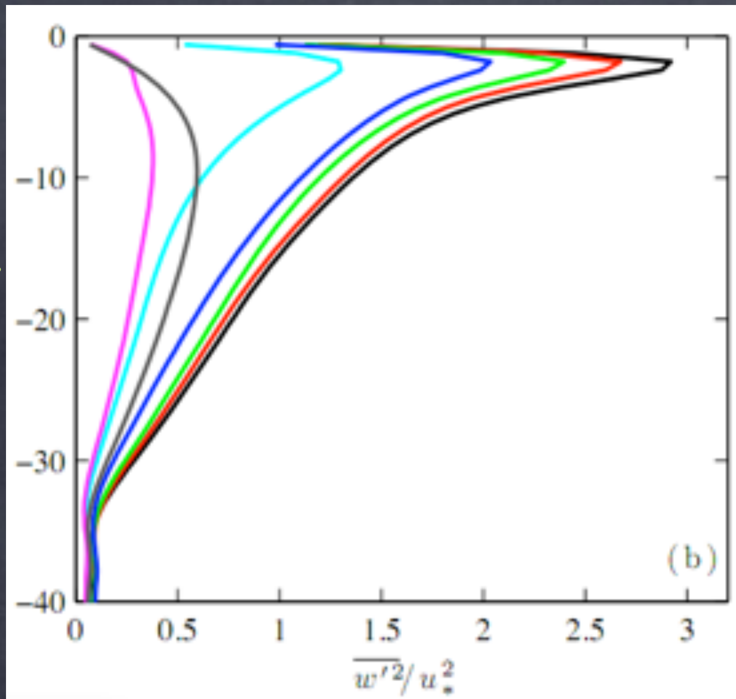


L. P. Van Roekel, B. Fox-Kemper, P. P. Sullivan, P. E. Hamlington, and S. R. Haney. The form and orientation of Langmuir cells for misaligned winds and waves. Journal of Geophysical Research-Oceans, 117:C05001, 22pp, May 2012.

Generalized Turbulent Langmuir No., Projection of u*, u_s into Langmuir Direction

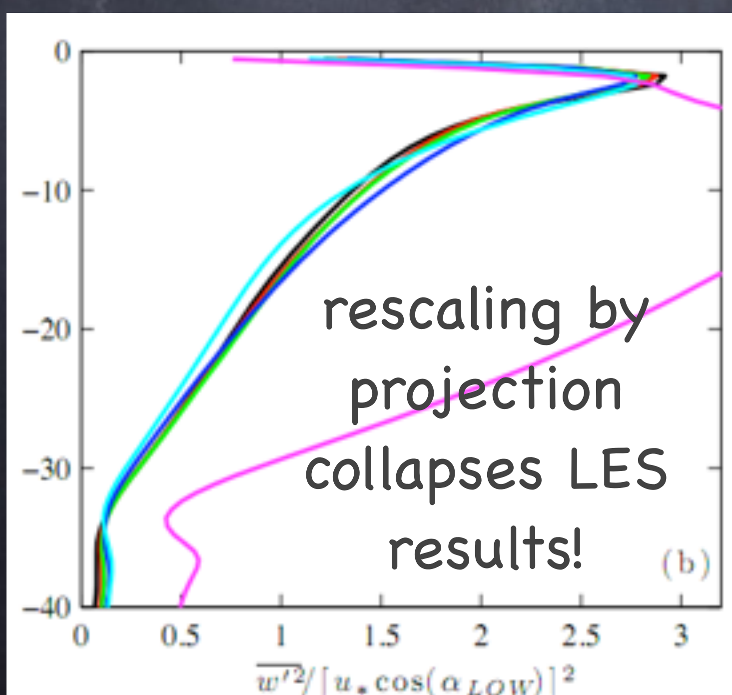
$\langle w^2 \rangle$

depth



rescaled $\langle w^2 \rangle$

depth



$$
\begin{aligned}
\frac{\left\langle \overline{w'^2} \right\rangle_{ML}}{u_*^2} &= 0.6\cos^2(\alpha_{LOW})\left[1.0 + (3.1 La_{proj})^{-2}\right. \\
&\quad \left. + (5.4 La_{proj})^{-4}\right], \\
La_{proj}^2 &= \frac{|u_*|\cos(\alpha_{LOW})}{|u_s|\cos(\theta_{ww} - \alpha_{LOW})}, \\
\alpha_{LOW} &\approx \tan^{-1}\left(\frac{\sin(\theta_{ww})}{\frac{u_*}{u_s(0)\kappa}\ln\left(\left|\frac{H_{ML}}{z_1}\right|\right) + \cos(\theta_{ww})}\right)
\end{aligned}
$$

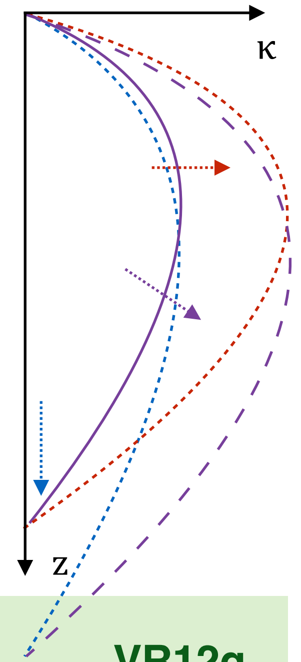
A scaling for LC strength & direction!

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, 2012.

Langmuir Mixing in KPP

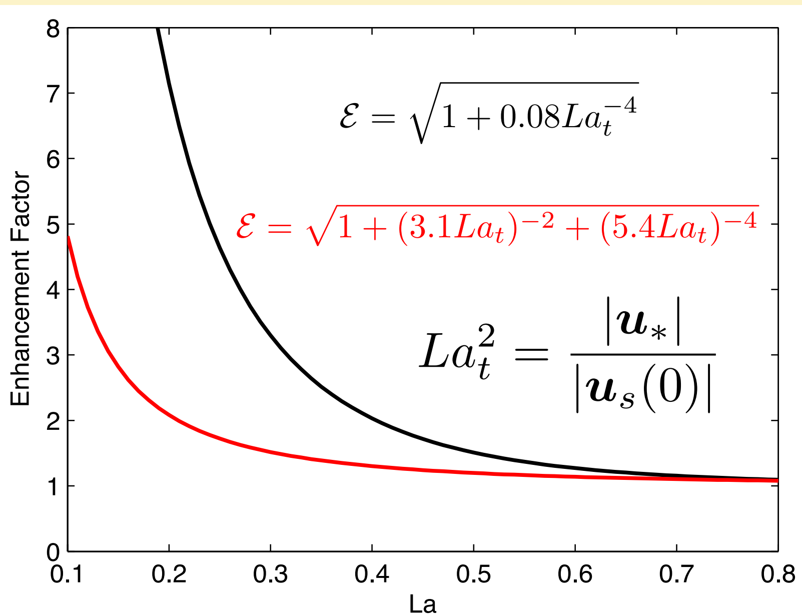
Q. Li, BFK, T. Arbetter, A. Webb , 2014. Assessing the Influence of Surface Wind Waves to the Global Climate by Incorporating WAVEWATCH III in CESM, 2014 AGU Ocean Sciences Meeting Poster, related paper in prep. Available as draft.

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



MS2K

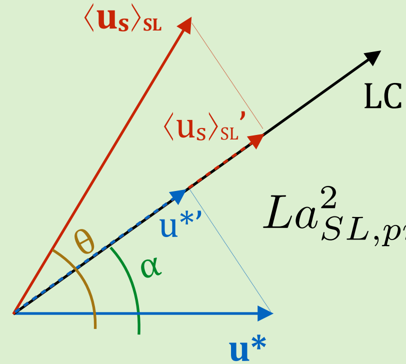
VR12a



Enhancement factor to vertical velocity scale W

Aligned wind and waves

VR12g



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

Misaligned wind and waves

VR12h

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

Including Stokes shear

McWilliams and Sullivan, 2000; Van Roekel et al., 2012

Evaluating the turbulence scalings based on forcing by Wind & Waves

January

July

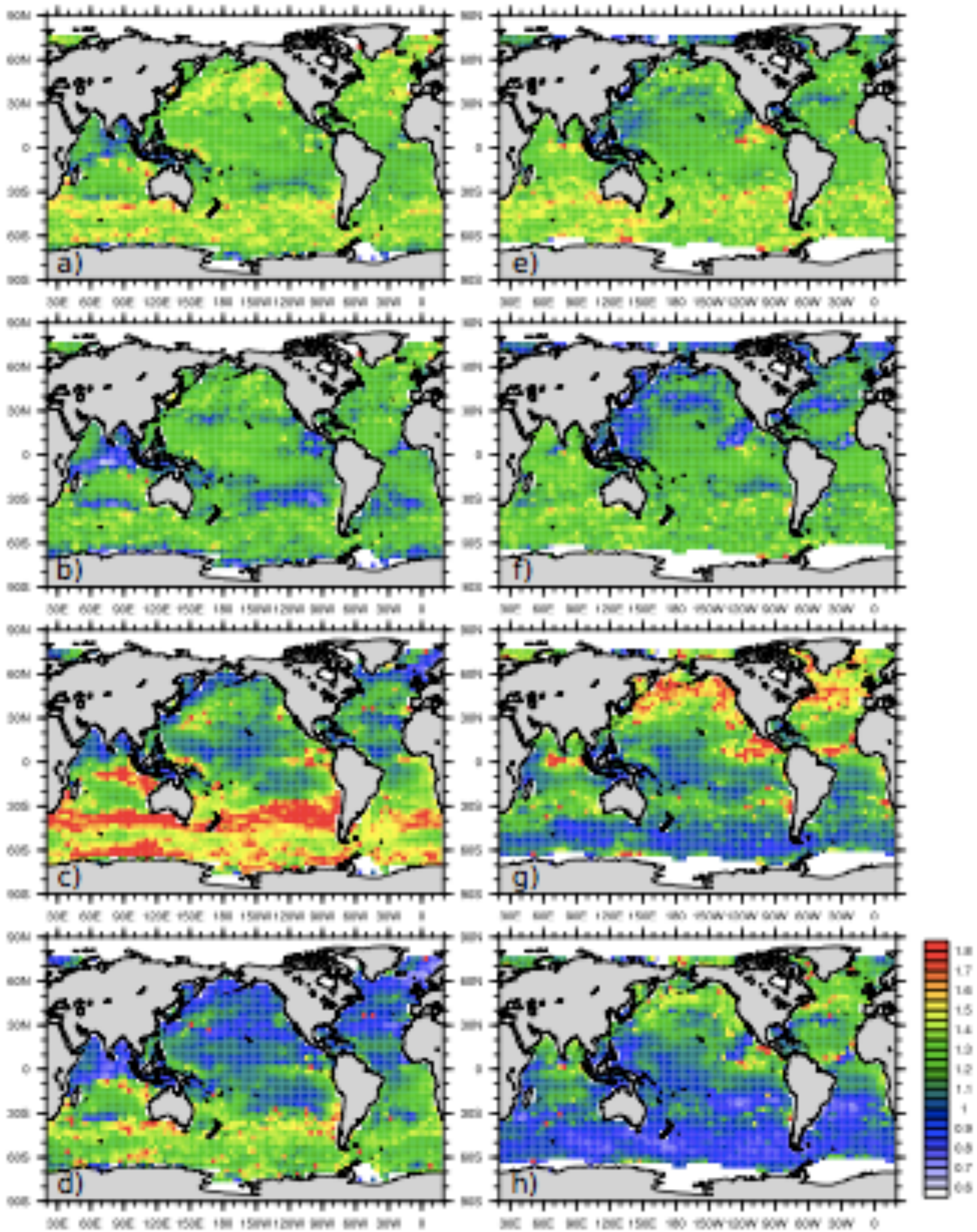


Figure 2: Effects of misaligned wind and waves and Stokes depth shown by the normalized vertical turbulent kinetic energy (VKE; w'^2/u_*^2). VKEs are scaled by (a)(e) La_t; (b)(f) La_{proj}; (c)(g) La_{SL} and (d)(h) $La_{SL,proj}$, following Van Roekel et al. (2012), averaged over Jan. (a) - (d) and Jul. (e) - (h) of the model year 247. Note that (a)(e) and (d)(h) are corresponding to test VR12-AL and VR12-MA, respectively.

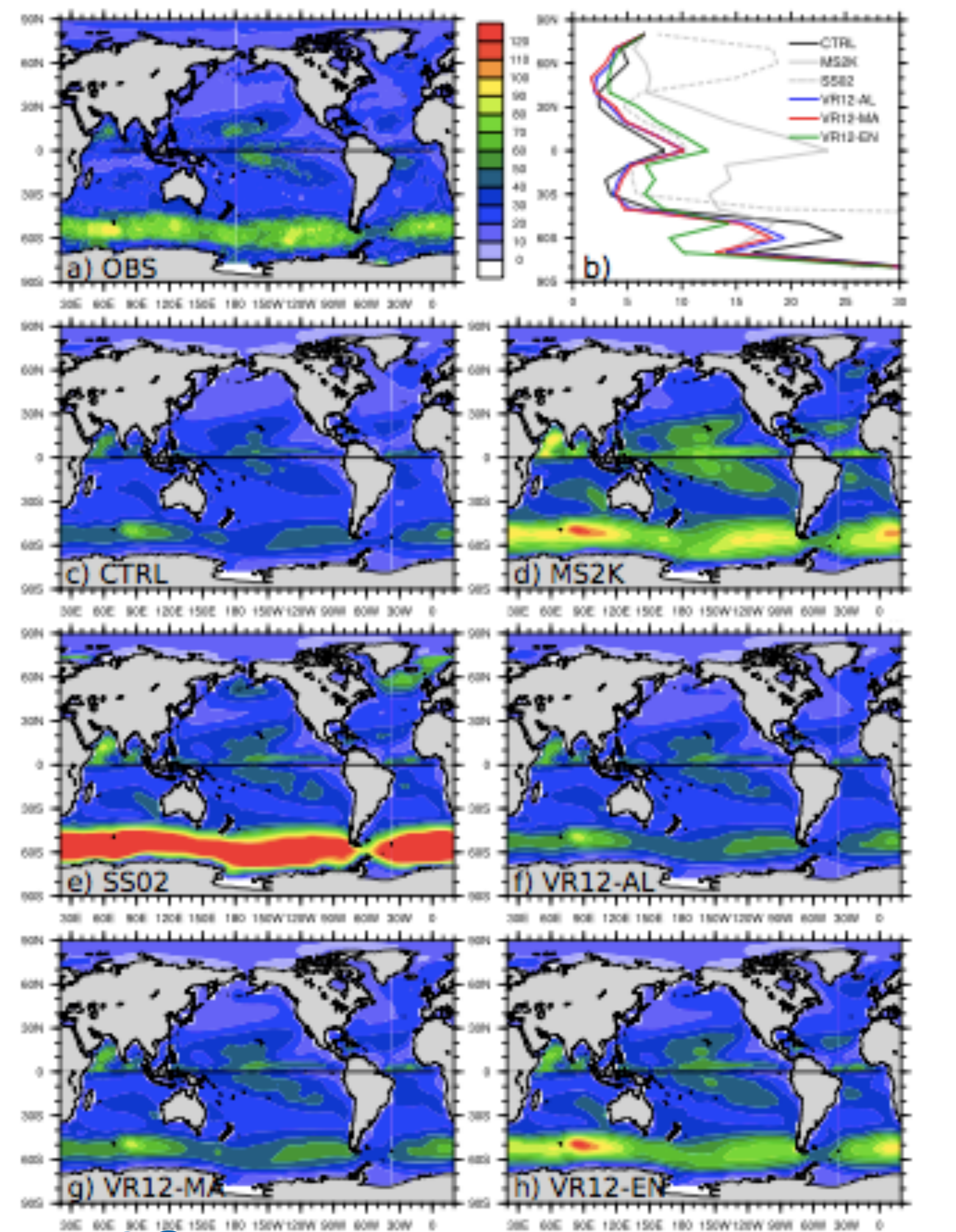
Vertical Kinetic Energy (w^2)
with basic Wave & Wind forcing

Vertical Kinetic Energy (w^2)
accounting for
Wind-Wave Misalignment

Vertical Kinetic Energy (w^2)
accounting for
Stokes depth vs. MLD

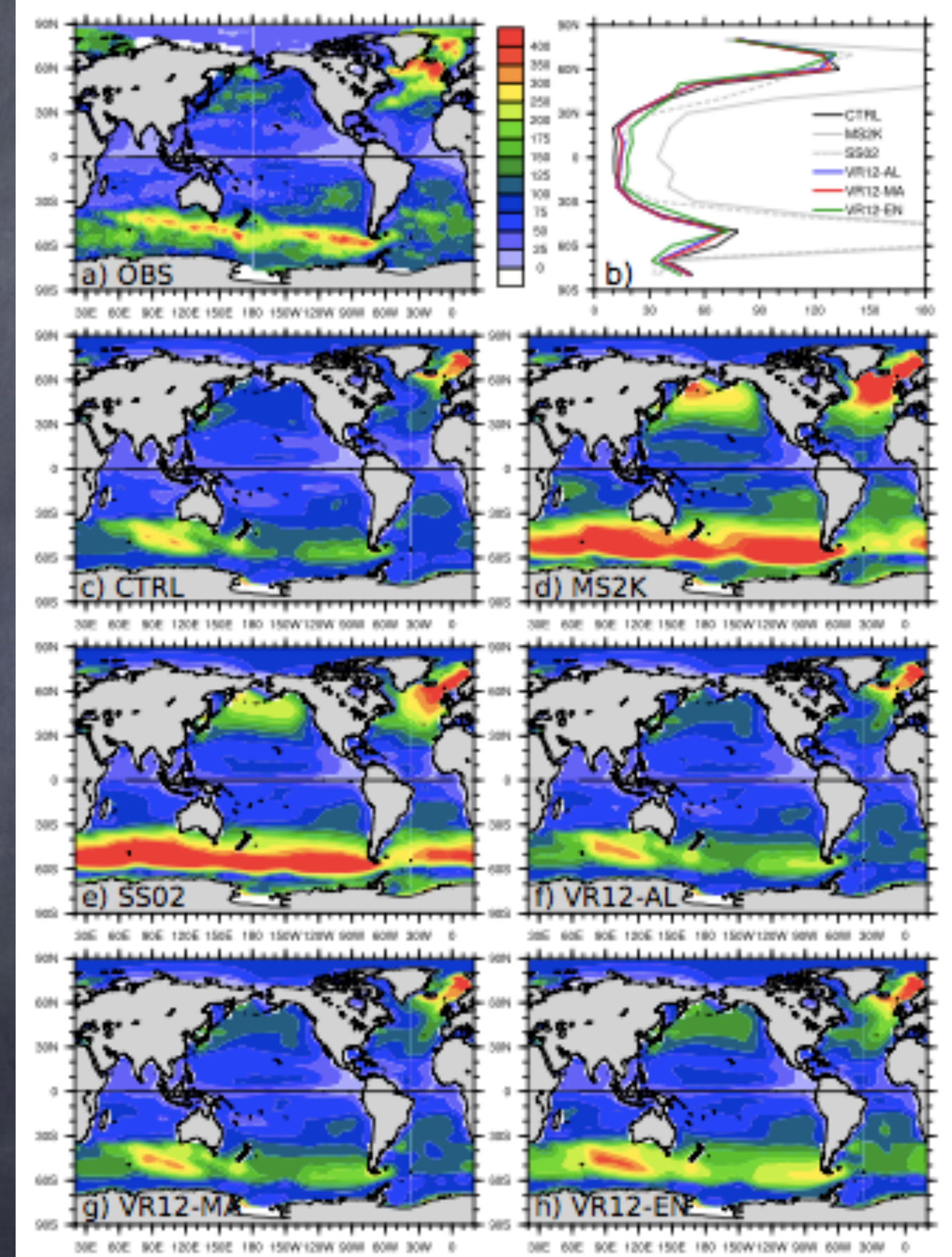
Vertical Kinetic Energy (w^2)
accounting for
Stokes depth vs. MLD
and
Wind-Wave Misalignment

Results—Summer & Winter MLD



CORE2 Mean Summer MLD

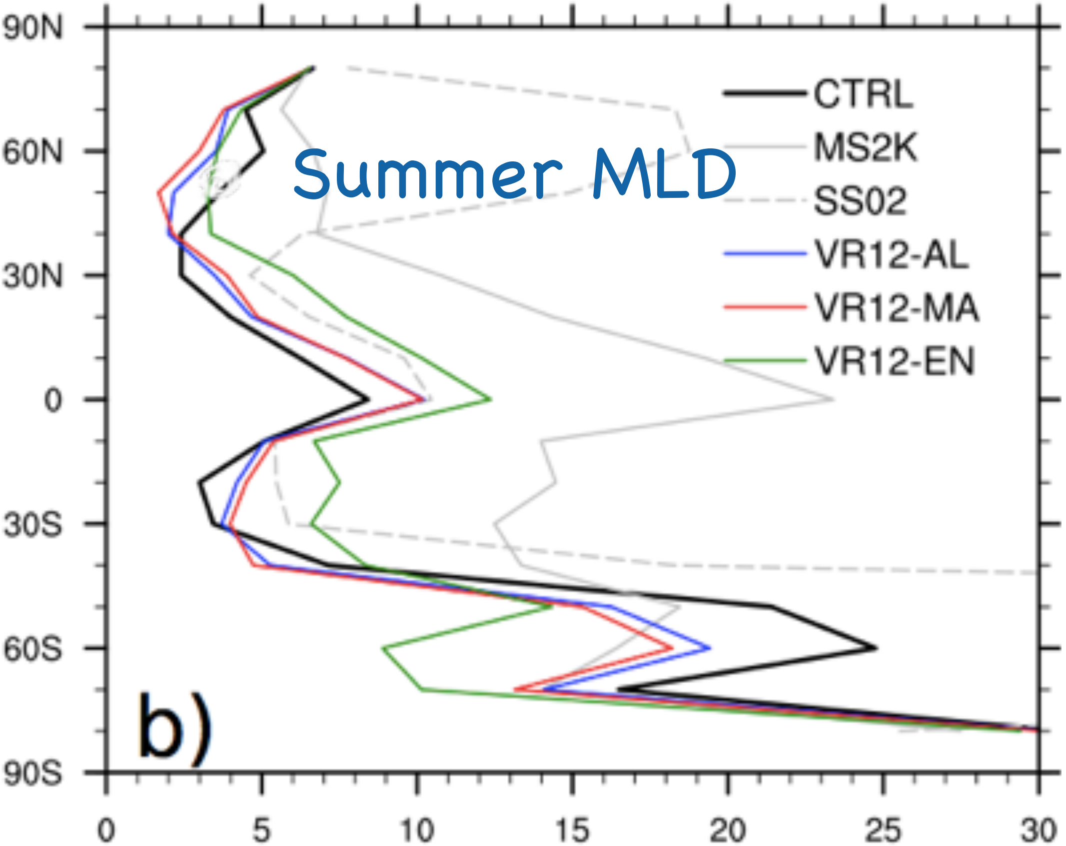
Figure 3: Impact of Langmuir mixing on the summer mean mixed layer depth (MLD; m) for



CORE2 Mean Winter MLD

Figure 4: As ... but for ... mixed layer depth. Averages over ... for the NH and JAS for the SH.

Results—Summer & Winter MLD



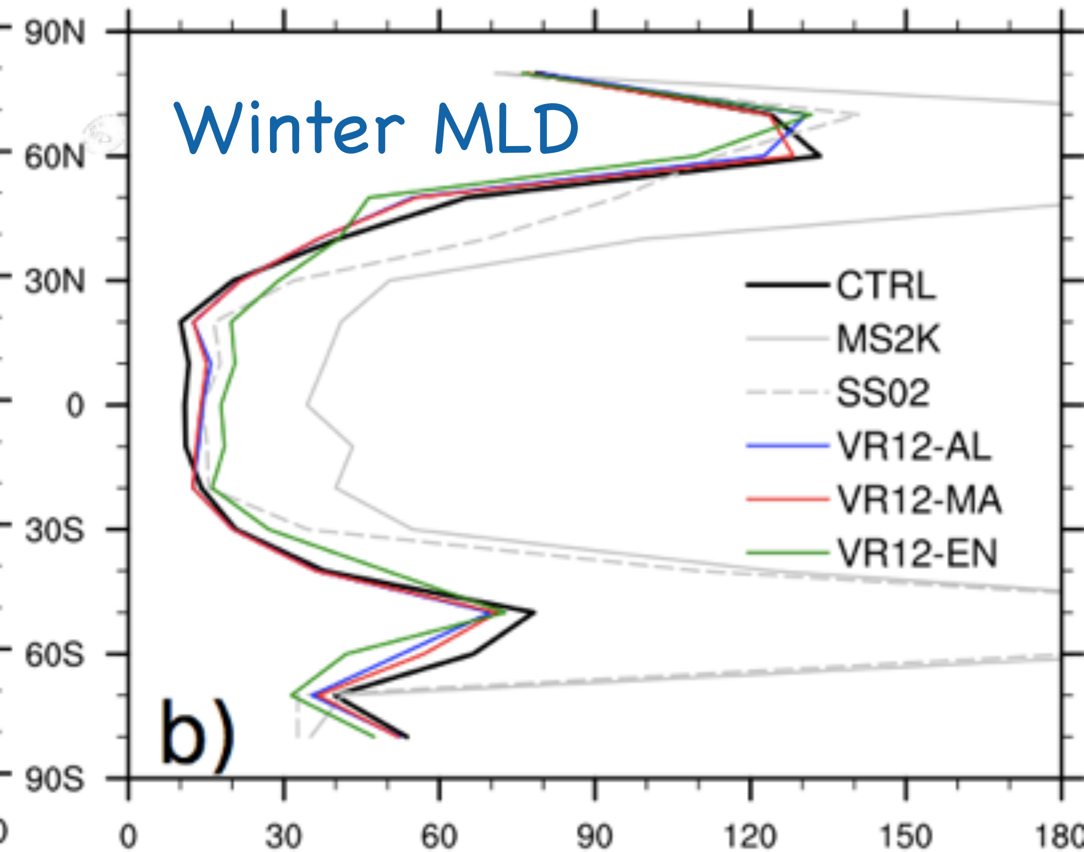


Table 3: Root mean square difference (m) of summer and winter mean mixed layer depth in comparison with observation (de Boyer Montégut et al. (2004), updated to include the ARGO data to 2012).[a]

Case	Summer			Winter		
	Global	South of 30S	20S-20N	Global	South of 30S	20S-20N
CTRL	10.62 (13.40)	17.24 (21.73)	6.11 (7.06)	43.85 (45.50)	57.19 (56.53)	11.01 (14.49)
MS2K	15.37	15.47	18.15	119.91	171.92	38.58
SS02	36.79	63.83	8.07	99.32	164.34	15.14
VR12-AL	9.06	13.47	7.20	40.45	50.33	13.54
VR12-MA	8.73 (11.83)	12.65 (18.13)	7.27 (6.79)	40.99 (42.02)	51.78 (50.78)	13.06 (13.09)
VR12-EN	8.95	10.52	9.35	41.94	52.98	18.00

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

Less of an effect in coarse-res coupled model () vs. CORE2, as storminess is a major contributor to additional wave mixing

Enhancing ocean ventilation

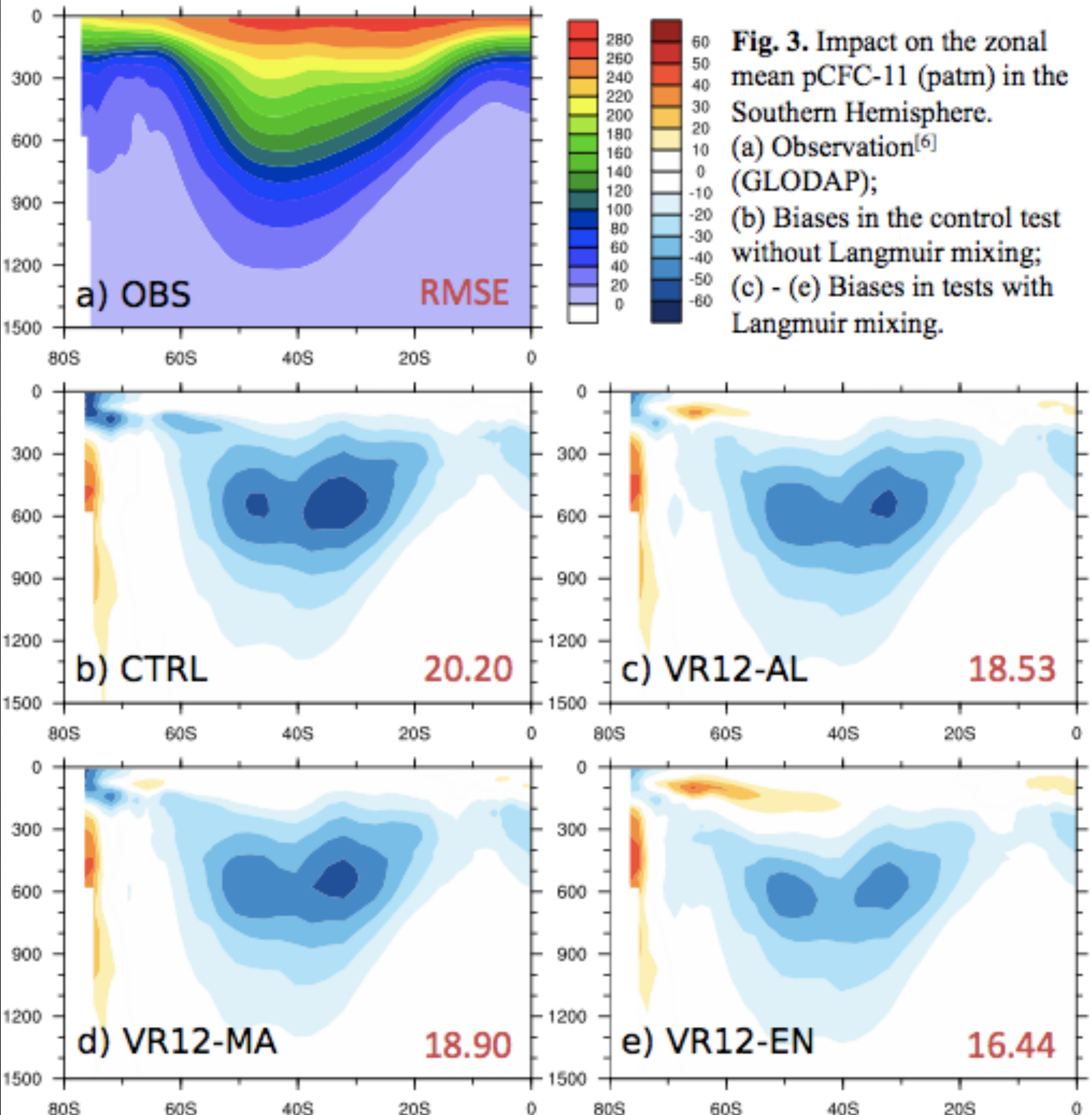


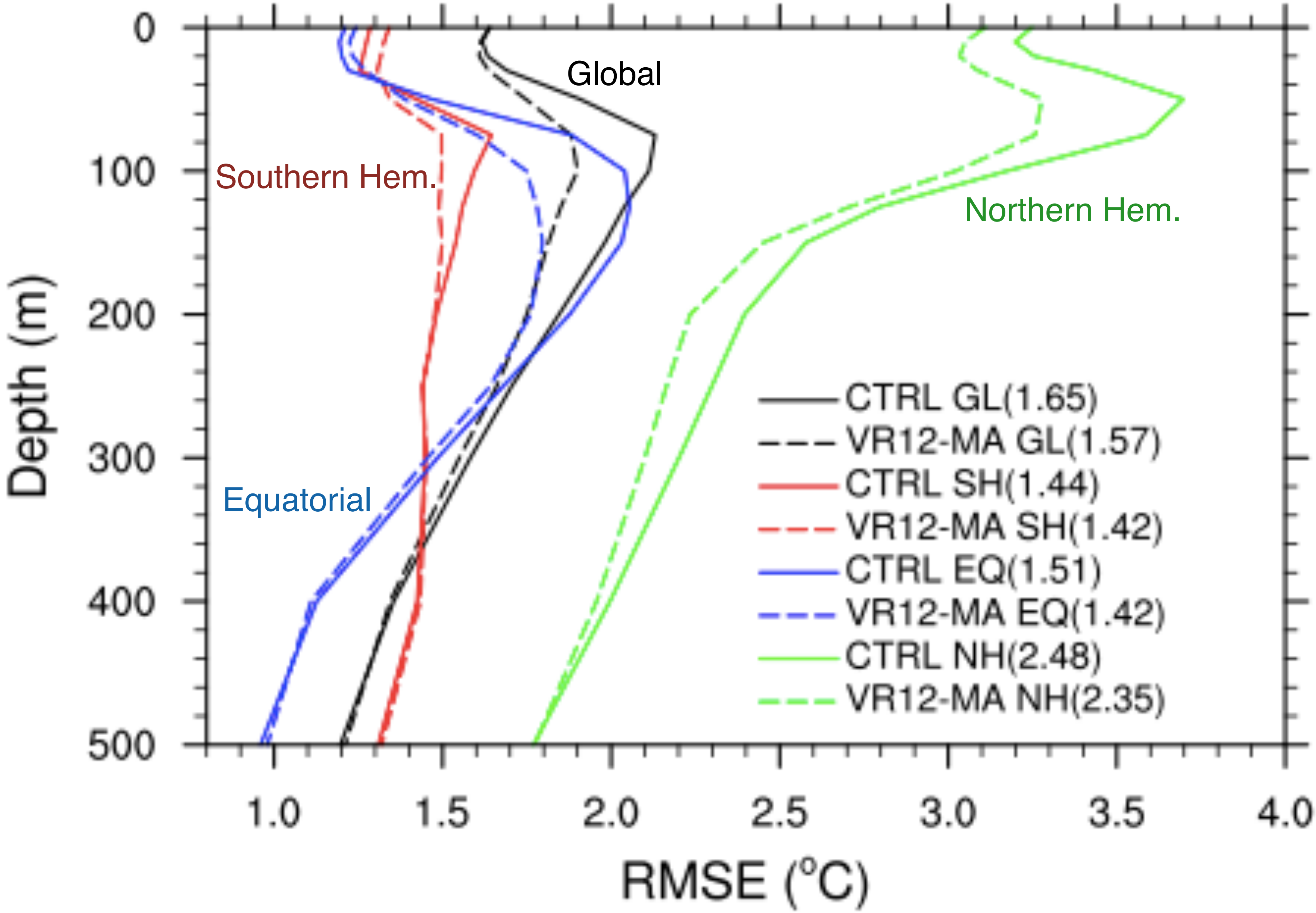
Fig. 3. Impact on the zonal mean pCFC-11 (patm) in the Southern Hemisphere. (a) Observation[6] (GLODAP); (b) Biases in the control test without Langmuir mixing; (c) - (e) Biases in tests with Langmuir mixing.

pCFC-11 from CORE2 forced runs shown here

Case	Global	Southern Hemi
CTRL	23.90	20.20
MS2K	29.89	30.99
SS02	34.16	41.90
VR12-AL	22.14	18.53
VR12-MA	23.23	18.90
VR12-EN	20.67	16.44

Temperature RMS errors (monthly means vs. PHC3)

Case (depth)	Global	90°S - 30°S	30°S - 30°N	30°N - 90°N
CTRL (0 m)	1.53	0.90	1.10	3.01
VR12-MA (0 m)	1.54	1.04	1.14	2.90
CTRL (100 m)	1.96	1.39	1.92	2.88
VR12-MA (100 m)	1.75	1.29	1.60	2.76



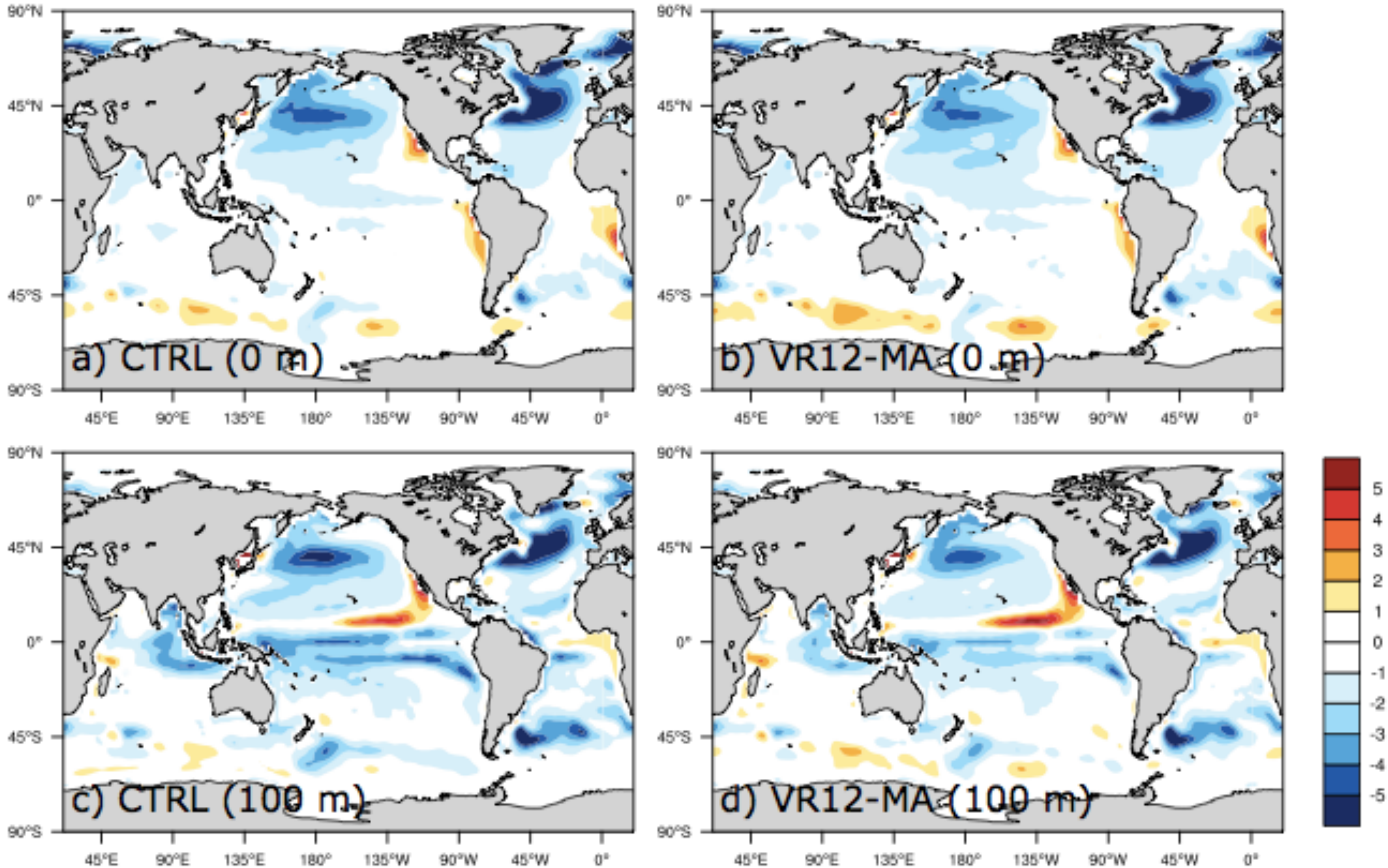
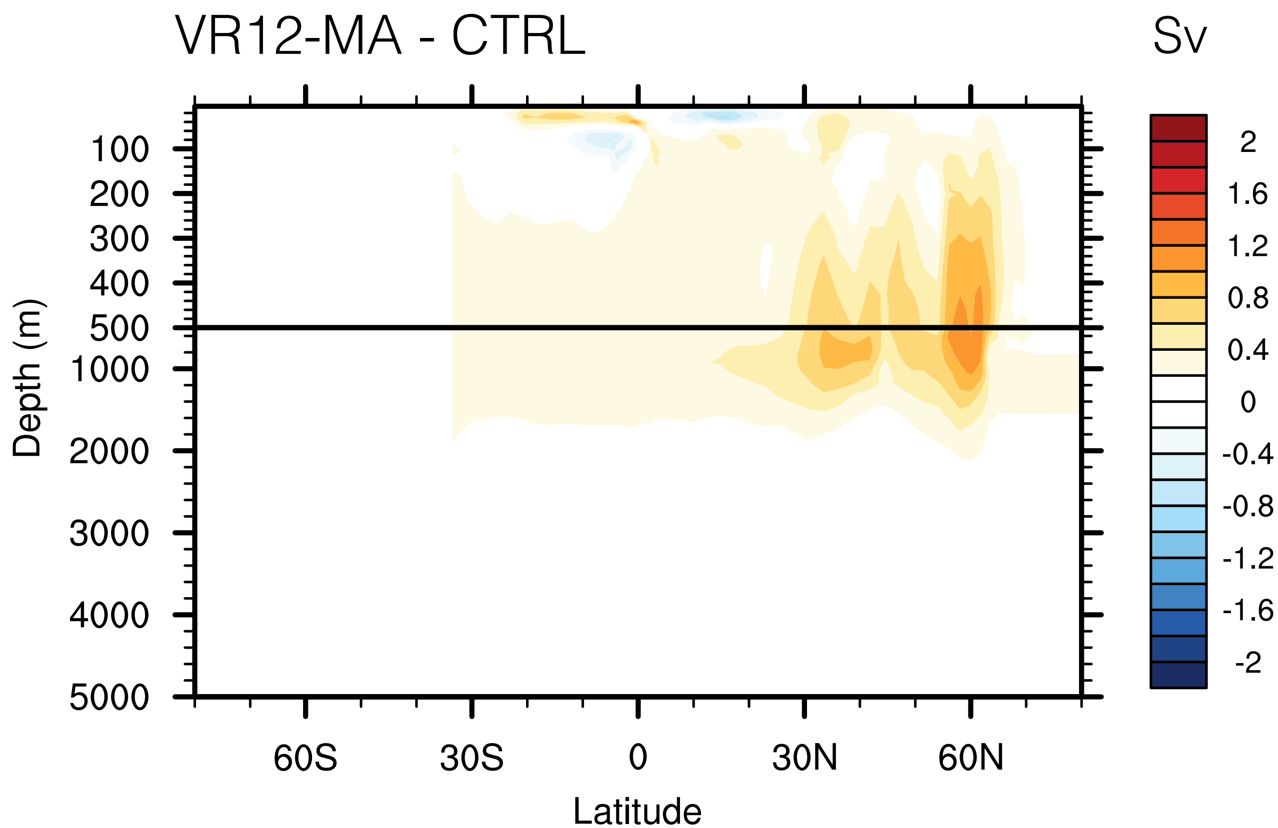


Figure 8: Maps of errors in the simulations of annual mean SST (upper panels) and ocean temperature at depth of 100 m (lower panels) in CTRL and VR12-MA. The errors are computed as model minus observation, where the observations are from the PHC3 dataset.

Total AMOC change



- Difference of AMOC between VR12-MA and CTRL in the fully coupled tests, averaged over the model year 51-70.
- AMOC is increased by ~1 Sv when Langmuir mixing is included.

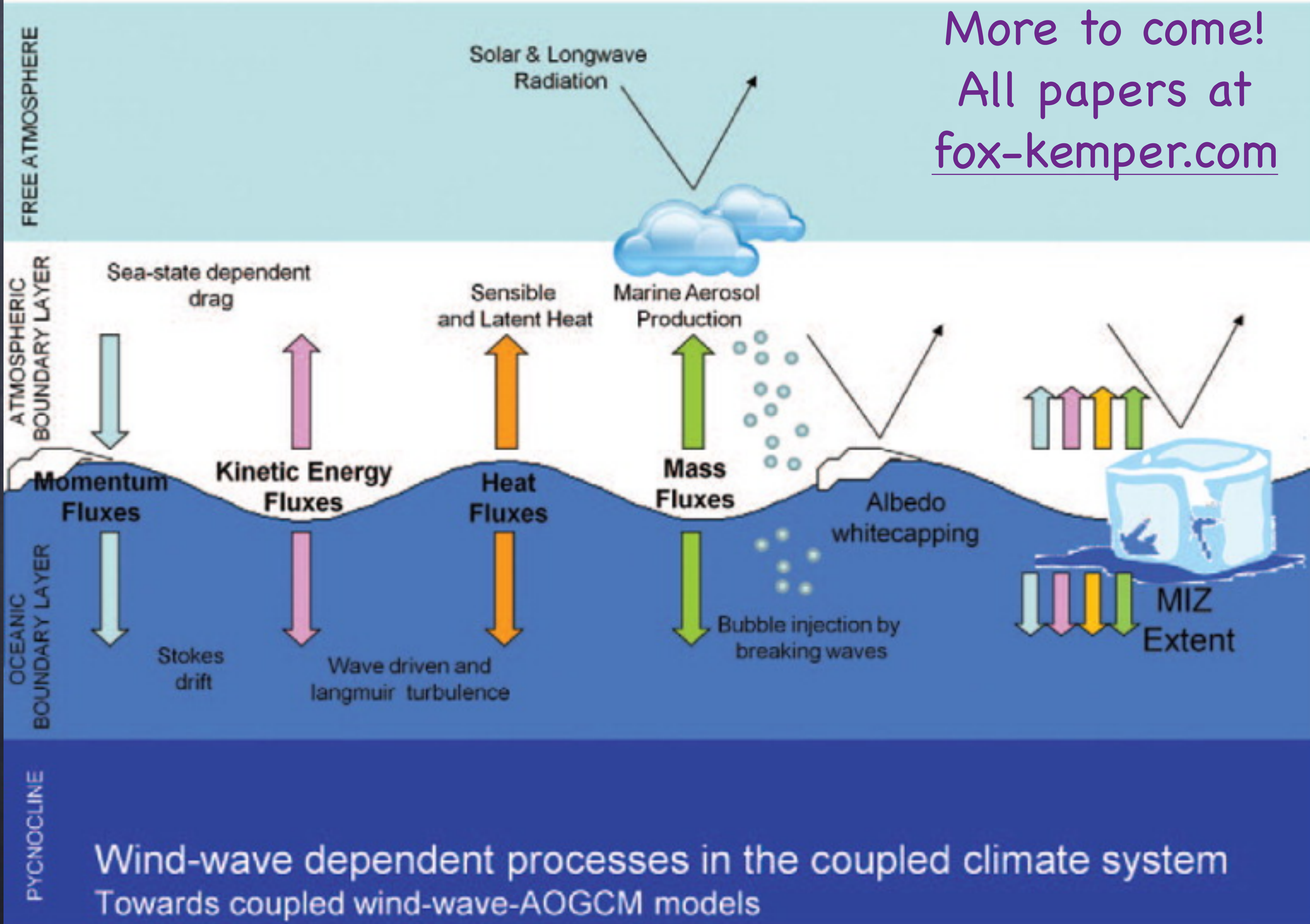
Computationally cheaper solution?

- Running WAVEWATCH III in CESM increases the computational cost by ~35% in our ocean-wave only tests and ~25% in our fully coupled tests, both with the nominal 3° resolution.

- If wave info is also used to improve other processes, e.g., air-sea momentum & gas flux, aerosols, etc., then the cost may be justified
- We are working to develop a "data waves" version of the model, where wave properties are a combination of known wave scalings (Pierson-Moskowitz) and a climatology of wave-wind misalignment & Stokes depth effects. Without these, too much wave mixing occurs.
- It may be possible to use other, cheaper, wave models. WAM is a little cheaper, and 2nd generation (80s technology) are *much* cheaper, although would have to be rewritten/parallelized. Adrean's unstructured grid model would be ideal, but is far future

Conclusions

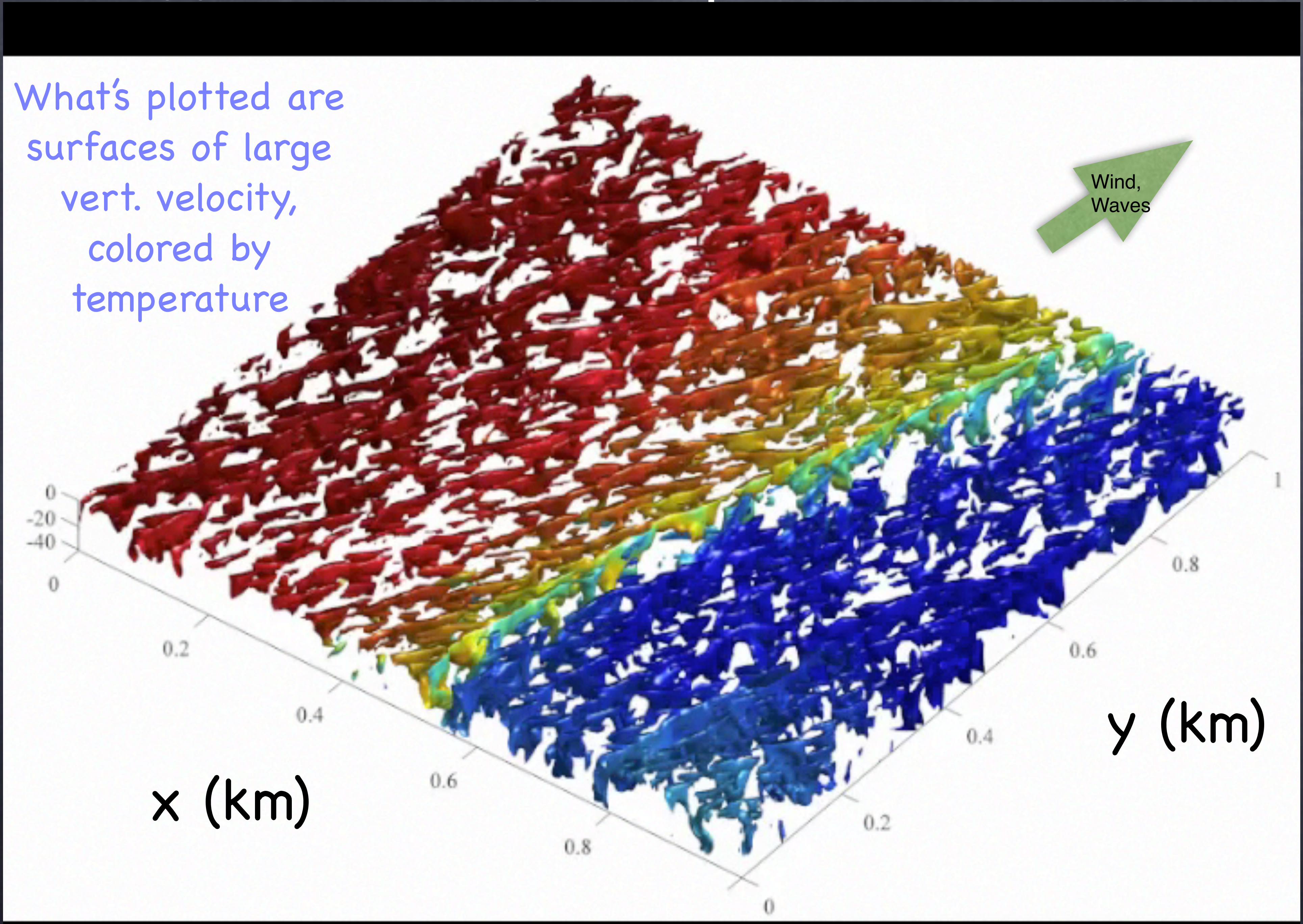
- Fair quantitative agreement now exists between Large Eddy Simulations of wave-driven OSBL turbulence. LES & Obs. validated scalings and parameterizations exist.
- Including wave-driven (Langmuir) mixing in climate models improves the simulated boundary layer, in mean and seasonal variability of T, S, CFCs.
- It would be helpful if WAVEWATCH were cheaper—it is about 25% of the coupled model cost in x3 CESM.
- The effects of the Stokes forces on boundary layer and submesoscale dynamics are under-appreciated.
- All papers at: fox-kemper.com/pubs



More to come!
All papers at
fox-kemper.com

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

Zoom: Submeso-Langmuir Interaction!



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

So, Waves can Drive turbulence that affect larger scales indirectly:

What about direct effects of waves on larger scales?

$$\mathbf{f} \times \frac{\partial \mathbf{v}}{\partial z} = -\nabla b$$

Becomes Lagrangian Thermal Wind Balance

$$\mathbf{f} \times \frac{\partial}{\partial z}(\mathbf{v} + \mathbf{v}_s) = \mathbf{f} \times \frac{\partial \mathbf{v}_L}{\partial z} = -\nabla b$$

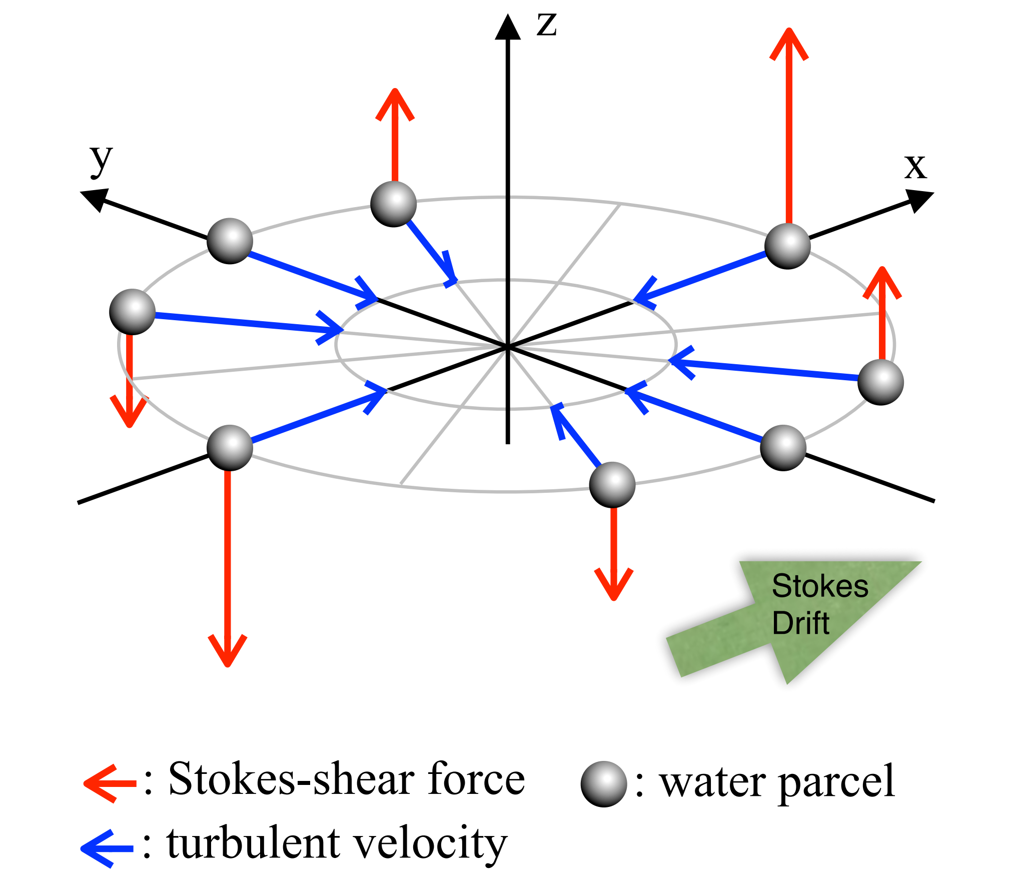
Now the temperature gradients govern the Lagrangian flow, not the not the Eulerian!

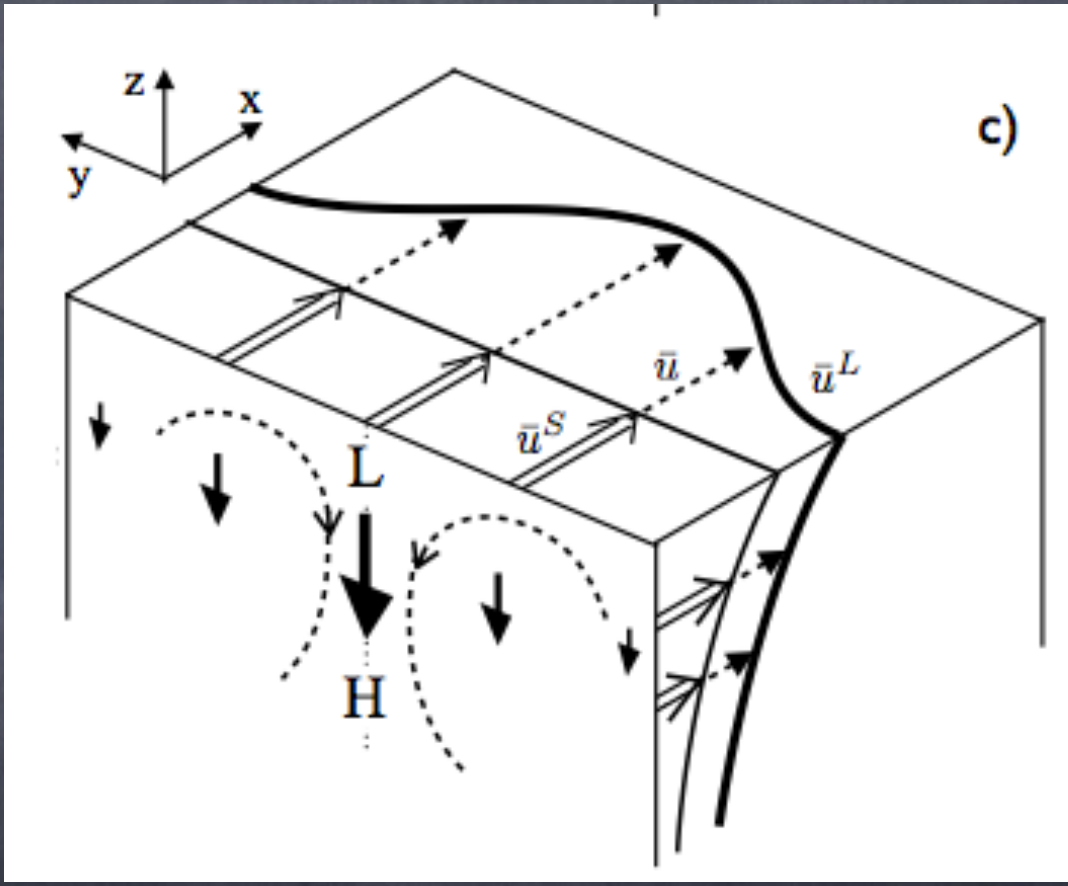
J. C. McWilliams and B. F-K. Oceanic wave-balanced surface fronts and filaments. Journal of Fluid Mechanics, 730:464-490, 2013.

Stokes Shear Force:

Craik-Leibovich mechanism for Langmuir circulations

Flow directed along Stokes shear=downward force

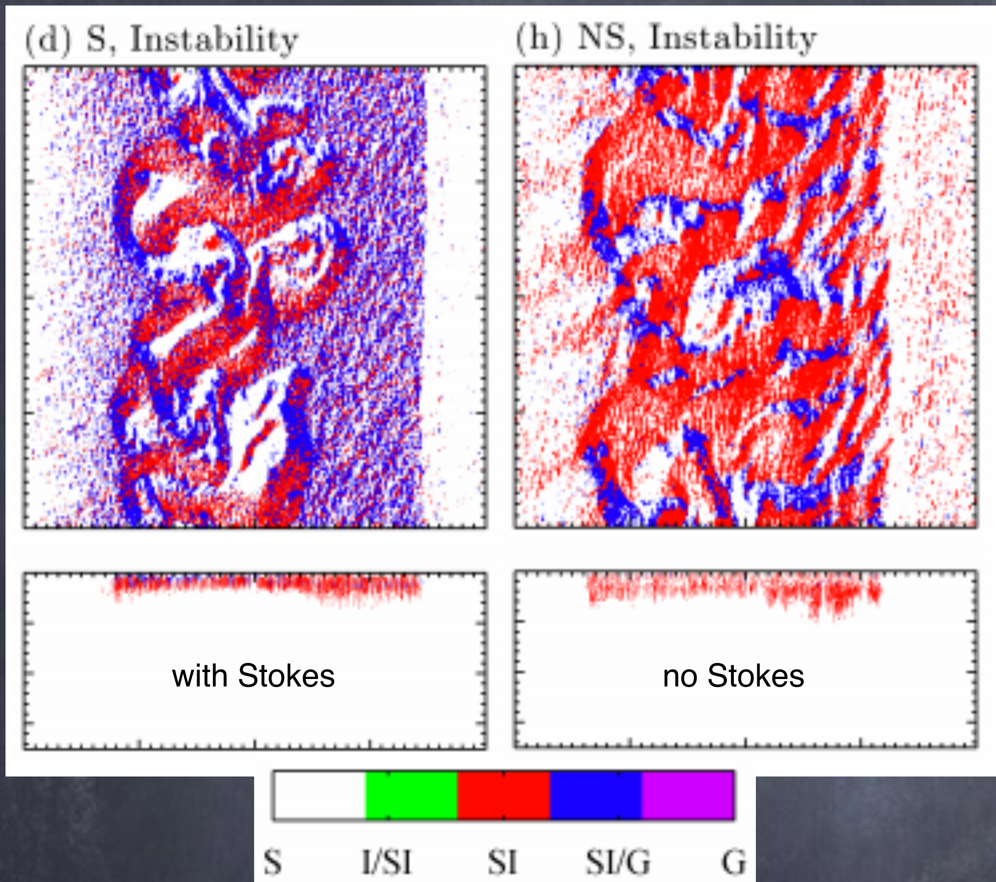


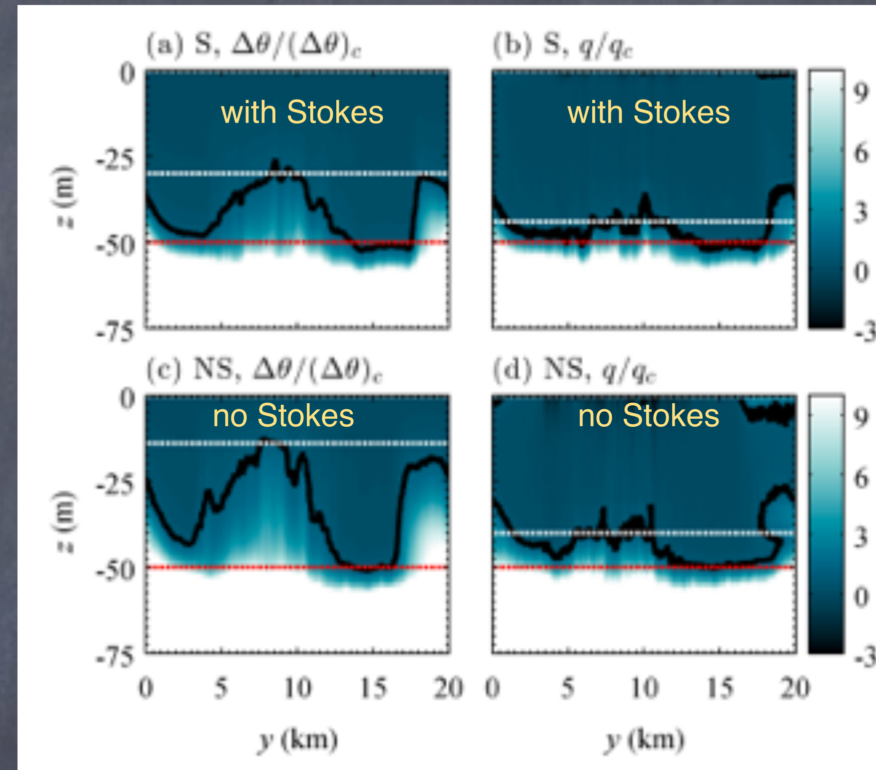


$$\frac{\alpha^2}{Ri}\left[w_{,t} + v_j^L w_{,j} + \frac{M_{Ro}}{RoRi} w w_{,z}\right] = -\pi_{,z} + b - \varepsilon v_j^L v_{j,z}^s + \frac{\alpha^2}{ReRi} w_{,jj}$$

N. Suzuki and BFK. Understanding Stokes Forces in the Wave-Averaged Equations, JPO, in prep, 2014.

Stokes influences Submesoscale & Langmuir-scale Instabilities through Lagrangian shear (Holm '96) & Lagrangian Thermal Wind





$$Ri_L = \frac{N^2}{\left(dv^L/dz\right)^2} \approx \frac{N^2 f^2}{|\nabla_h b|^2}$$

So, $q < 0$

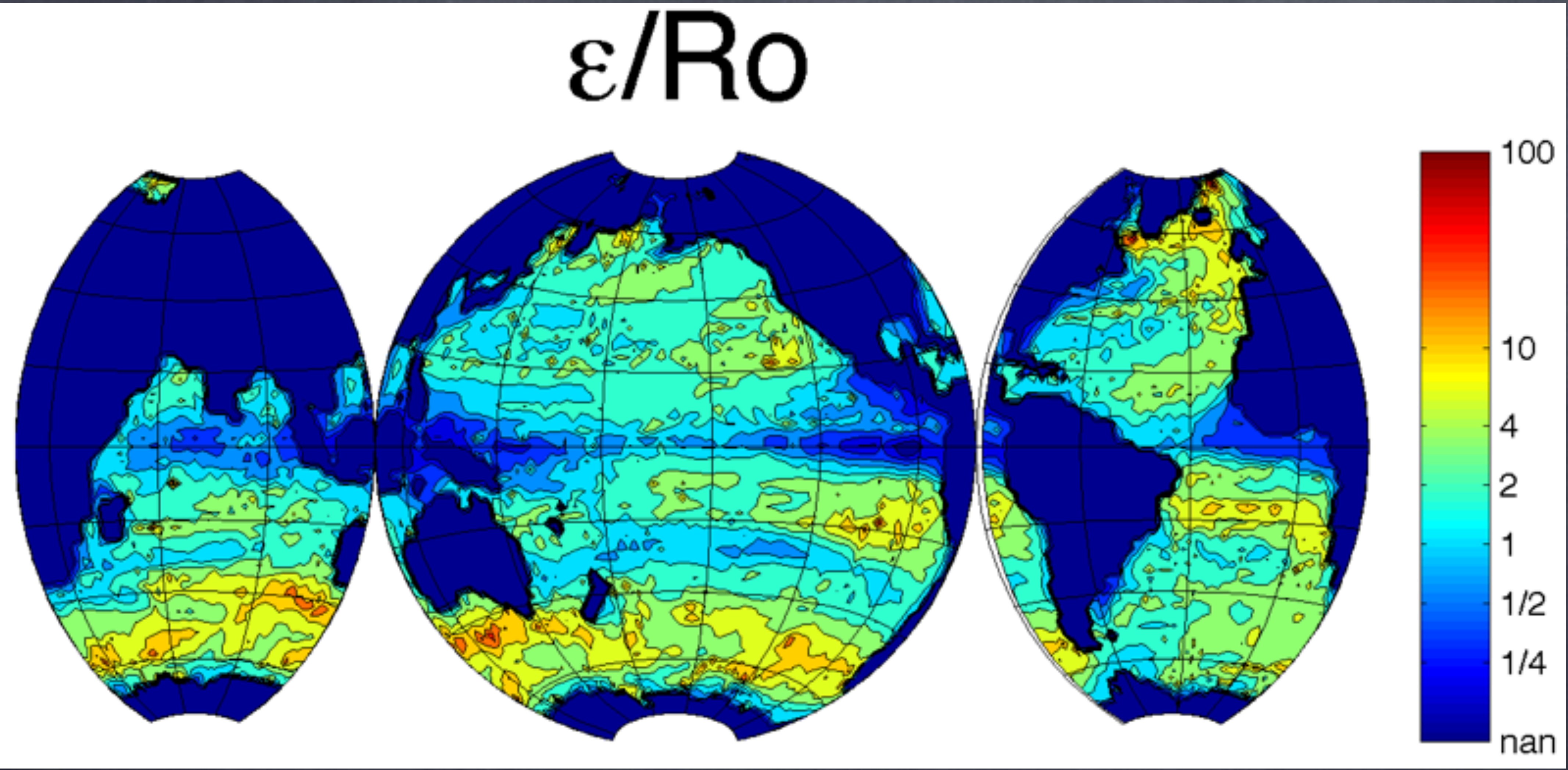
Is not the same as $Ri < \frac{f}{\zeta}$

Reinterpret Hoskins, Stone, & Charney-Stern-Pedlosky with care!

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.

S. Haney, BFK, and K. Julien. Stability of the ocean mixed layer in the presence of surface gravity wave forcing. In TOS/ALSO/AGU 2014 Ocean Sciences Meeting. American Geophysical Union, 2014. Paper in prep.

Stokes force directly affects the (sub)mesoscale!!



$$\frac{\varepsilon}{Ro} = \frac{V_s}{fL}\frac{H}{H_s}\frac{fL}{V} = \frac{V_s}{V}\frac{H}{H_s}$$

$$\varepsilon = \frac{V^s H}{fLH_s} \qquad Ro = \frac{U}{fL}$$

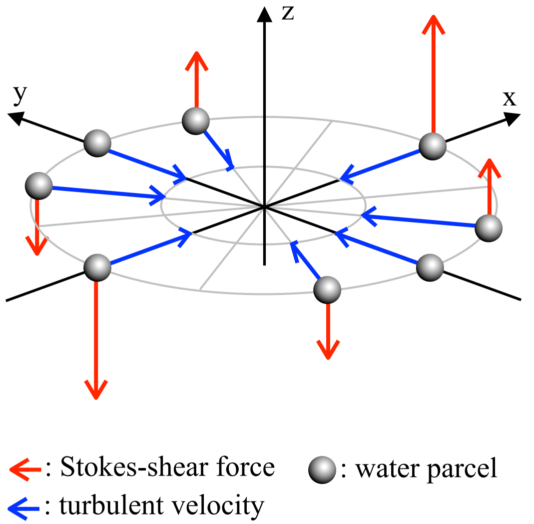
J. C. McWilliams and BFK. Oceanic wave-balanced surface fronts and filaments. Journal of Fluid Mechanics, 730:464-490, 2013.

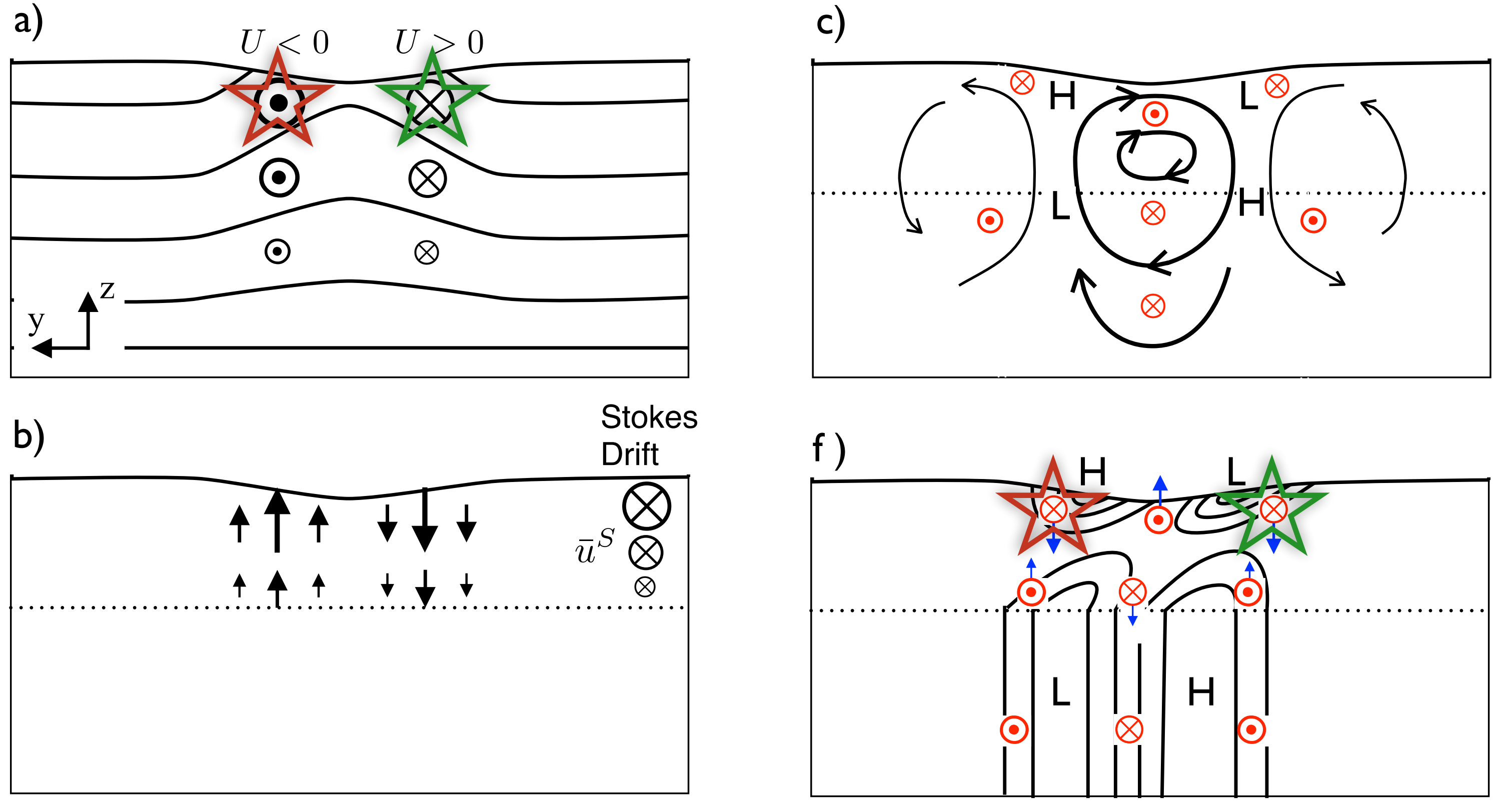
When is $\varepsilon = \dfrac{V^s H}{f L H_s}$ big?

$$\varepsilon = \frac{V_s}{fL}\frac{H}{H_s} = \underbrace{\frac{V_s}{fH_s}}_{O(10-100)} \overbrace{\frac{H}{L}}^{\text{slope}}$$

- Isopycnal slope (H/L) is O(0.1—0.01) for submesoscale
- Isopycnal slope (H/L) is $O(10^{-4})$ for mesoscale

Stokes Shear Force on Submesoscale Cold Filament





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N. Suzuki and BFK. Understanding Stokes Forces in the Wave-Averaged Equations, In prep, 2014.

Enhances Fronts for Down-Front Stokes

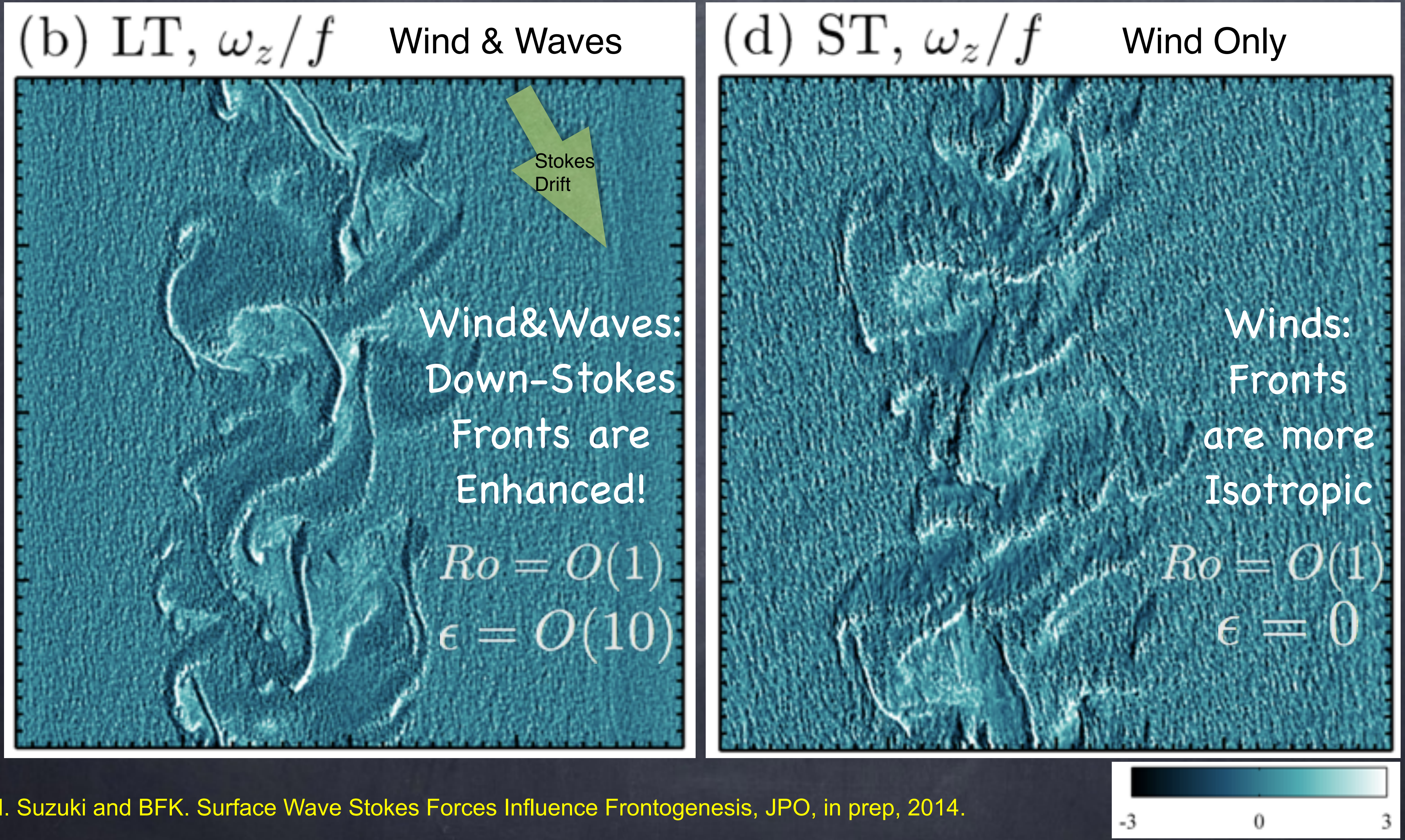
Opposes Fronts for Up-Front Stokes

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

Waves Give 30-40% of Power Produced at Front

Are Fronts and Filaments different with Stokes shear force?

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



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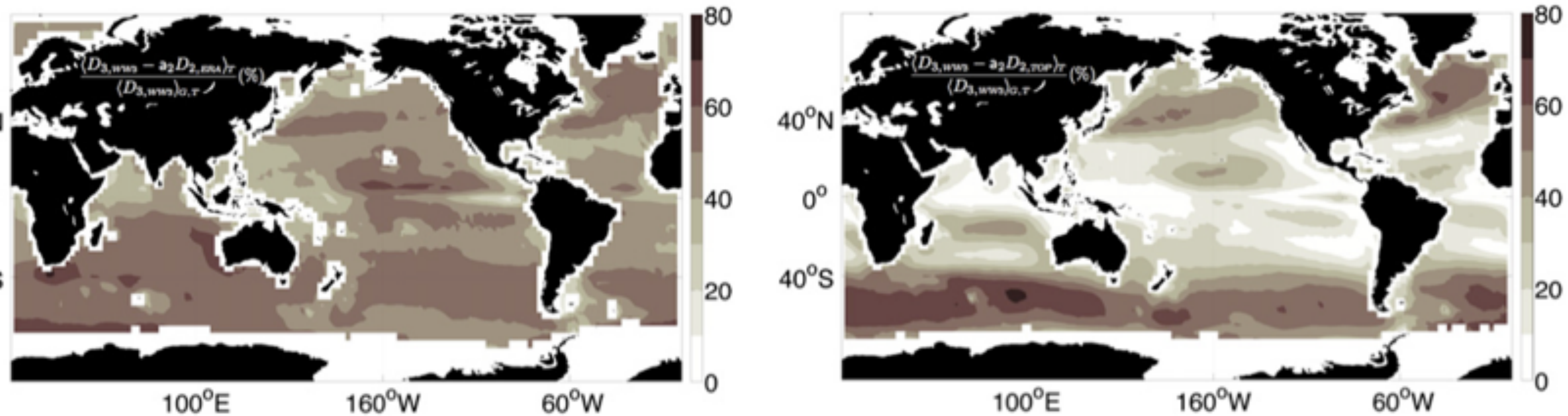
J. C. McWilliams and BFK. Oceanic wave-balanced surface fronts and filaments. Journal of Fluid Mechanics, 730:464-490, 2013.

P. E. Hamlington, L. P. Van Roekel, BFK, K. Julien, and G. P. Chini. Langmuir-submesoscale interactions: Descriptive analysis of multiscale frontal spin-down simulations. Journal of Physical Oceanography, 2014. In press.

How well do we know Stokes Drift? <50% discrepancy



(e) $\langle D_{3,WW3} - a_2 D_{2,ERA} \rangle_T / \langle D_{3,WW3} \rangle_{G,T}$ (%)   (f) $\langle D_{3,WW3} - a_2 D_{2,TOP} \rangle_T / \langle D_{3,WW3} \rangle_{G,T}$ (%)

RMS error in measures of surface Stokes drift, 2 wave models (left), model vs. altimeter (right)

Year 2000 data & models

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

Why? Vortex Tilting Mechanism

In CLB: Tilting occurs in direction of $\mathbf{u}_L = \mathbf{v} + \mathbf{v}_s$

$$\frac{\partial \xi}{\partial t} + \underbrace{(\mathbf{u}_L \cdot \nabla)\xi}_{\text{AD}} = \underbrace{(\omega_a \cdot \nabla)(\mathbf{u}_L \cdot \hat{\mathbf{x}}')}_{\text{TS}} + \underbrace{(\nabla b \times \hat{\mathbf{z}}) \cdot \hat{\mathbf{x}}'}_{\text{BV}} + \text{SGS},$$

Misalignment enhances degree of wave-driven LT

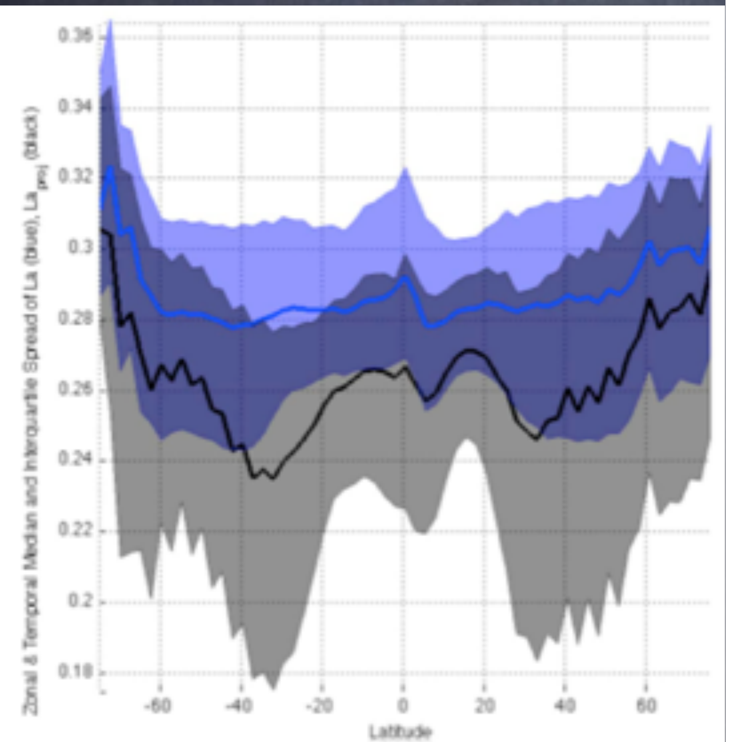


Figure 17. Temporal and zonal median and interquartile range of La_t and La_{proj} for a realistic simulation of 1994–2002 using Wave Watch III.

image: Thorpe, 04

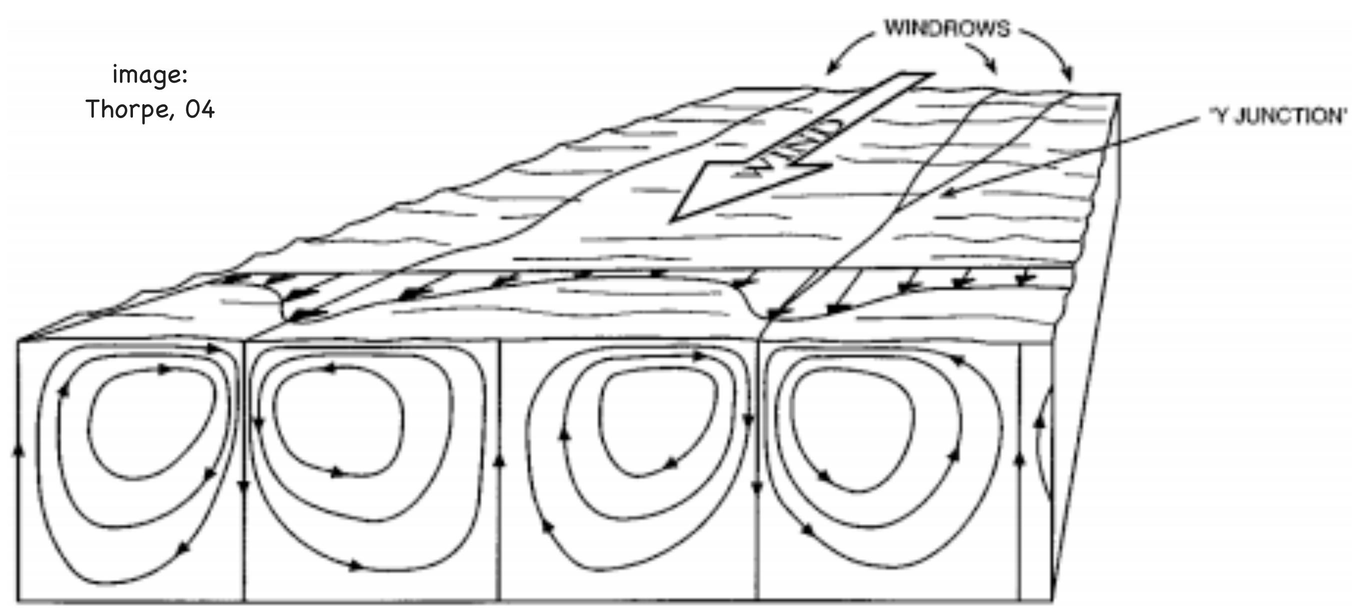


Figure 1 Sketch showing the pattern of mean flow in idealized Langmuir circulation. The windrows may be 2 m to 300 m apart, and the cell form is roughly square (as shown). In practice the flow is turbulent, especially near the water surface, and the windrows (Figure 2) amalgamate and meander in space and time. Bands of bubbles or buoyant algae may form within the downward-going (or downwelling) flow (see Figure 3).