

# Effects of Ocean Surface Waves: on Turbulence, Climate, and Frontogenesis



Expanding on past work with:

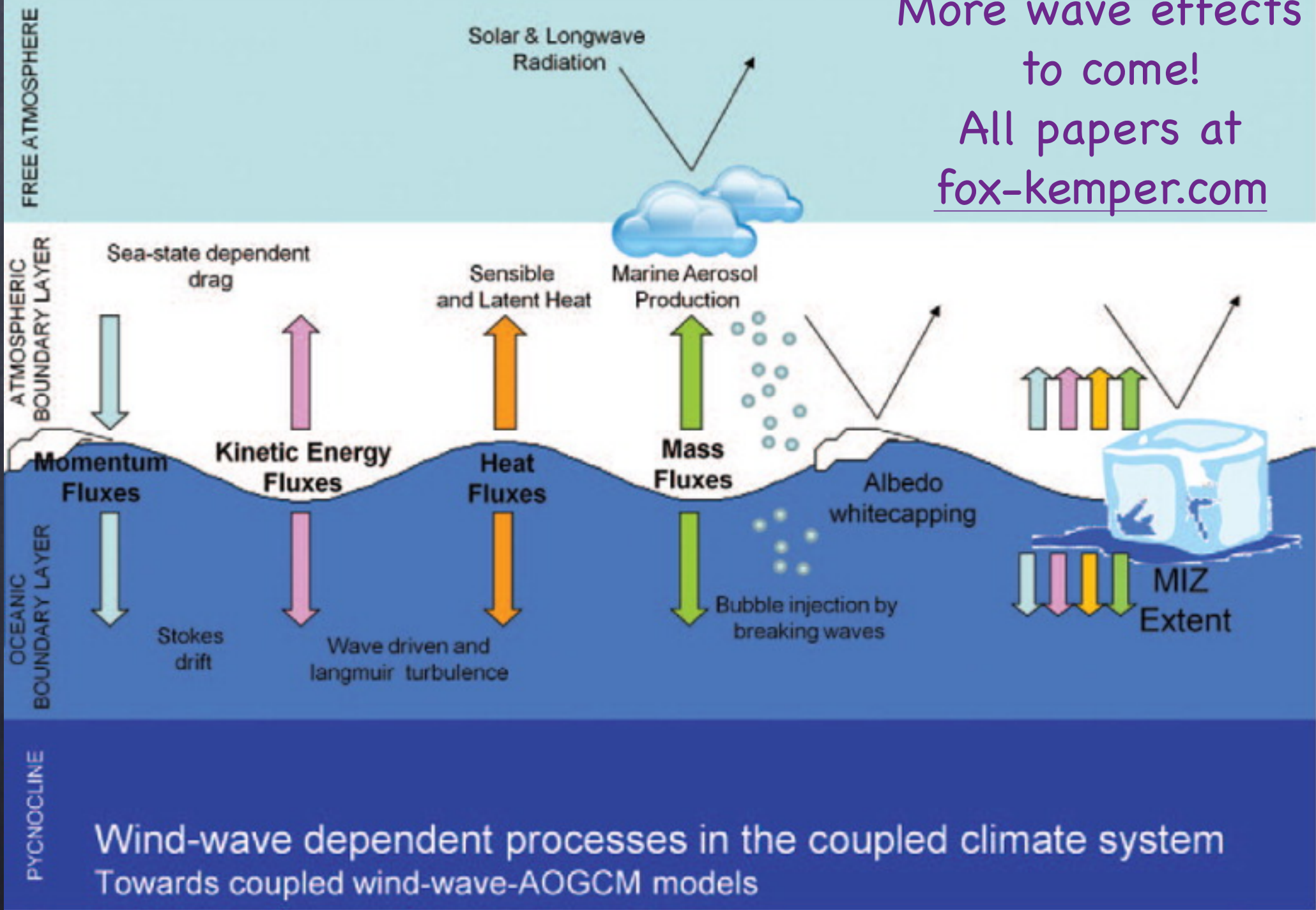
Jim McWilliams (UCLA), Peter Hamlington (CU-Boulder), Eric D'Asaro & Ramsey Harcourt (UW), Luke Van Roekel (LANL), Qing Li (Brown), Sean Haney (CU), Adrean Webb (TUMST), Keith Julien (CU-APPM), Greg Chini (UNH), Peter Sullivan (NCAR), Mark Hemer (CSIRO)

**Baylor Fox-Kemper**  
with **Nobuhiro Suzuki (Brown)**

**Friday, 13/01/16**  
**16:00-17:00**

AO Group Seminar  
Sponsors: NSF 1258907,  
Gulf of Mexico Research Initiative

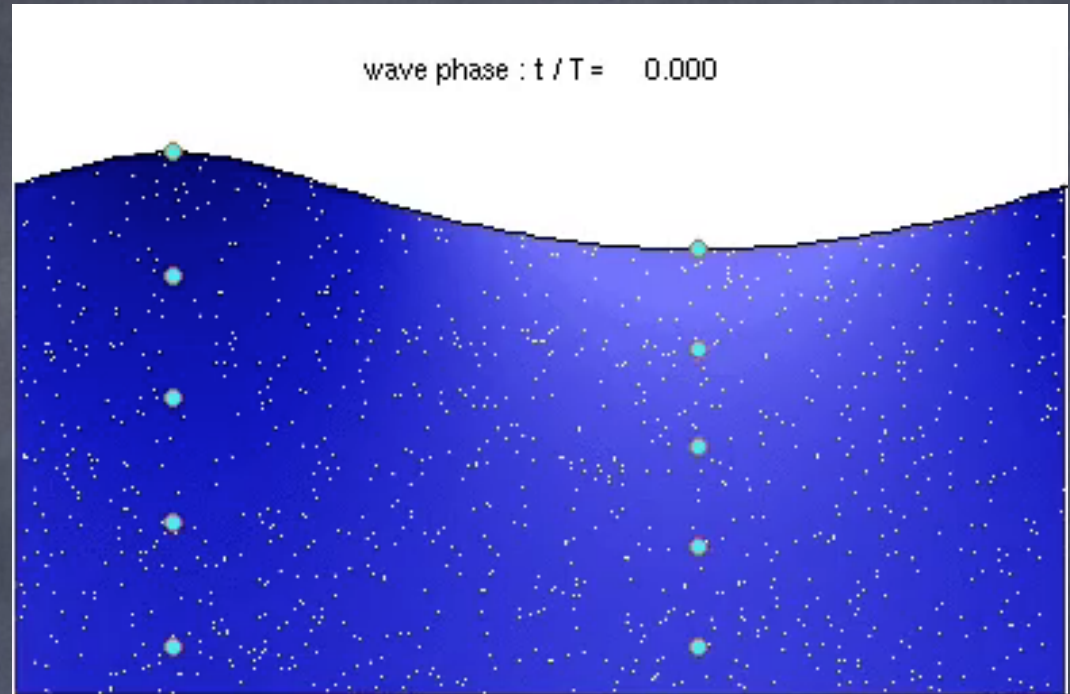
More wave effects  
to come!  
All papers at  
[fox-kemper.com](http://fox-kemper.com)



# Surface Waves are...

Fast, small, irrotational  
solutions of the  
Boussinesq Equations

Have a Stokes drift  
depending on sea state  
(wave age, winds)



A. Webb and B. Fox-Kemper. 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*, 96(1):49-64, 2015.

# Wave-Averaged Equations

following Lane et al. (07), McWilliams & F-K (13)  
and Suzuki & F-K (16)

$$\underbrace{v_j^L}_{\text{Lagrangian}} = \underbrace{v_j}_{\text{Eulerian}} + \underbrace{v_j^S}_{\text{Stokes}}$$

Coupling Depends on Stokes drift–WAVE effects in YELLOW

Boundary conditions, plus:

$$Ro [v_{i,t} + v_j^L v_{i,j}] + \frac{M_{Ro}}{Ri} w v_{i,z} + \boxed{\epsilon_{izj} v_j^L} = \text{(Lagrangian) geostrophic} \quad -M_{Ro} \pi_{,i} + \frac{Ro}{Re} v_{i,jj}$$

$$\frac{\alpha^2}{Ri} \left[ w_{,t} + v_j^L w_{,j} + \frac{M_{Ro}}{Ro Ri} w w_{,z} \right] = \boxed{-\pi_{,z} + b} \text{ hydrostatic} - \epsilon v_j^L v_{j,z}^S + \frac{\alpha^2}{Re Ri} w_{,jj}$$

$$b_t + v_j^L b_{,j} + \frac{M_{Ro}}{Ro Ri} w b_z = \frac{1}{Pe} b_{,jj}$$

$$v_{j,j} + \frac{M_{Ro}}{Ro Ri} w_z = 0$$

$$\boxed{\epsilon = \frac{V^S H}{f L H_s}}$$

$$Re = \frac{UL}{\nu} \quad Ro = \frac{U}{fL} \quad Ri = \frac{N^2}{(U_{,z})^2} \quad \alpha = H/L \quad M_{Ro} \equiv \max(1, Ro)$$

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

N. Suzuki and BFK. Understanding Stokes forces in the wave-averaged equations. JGR-Oceans, December 2015. Submitted.

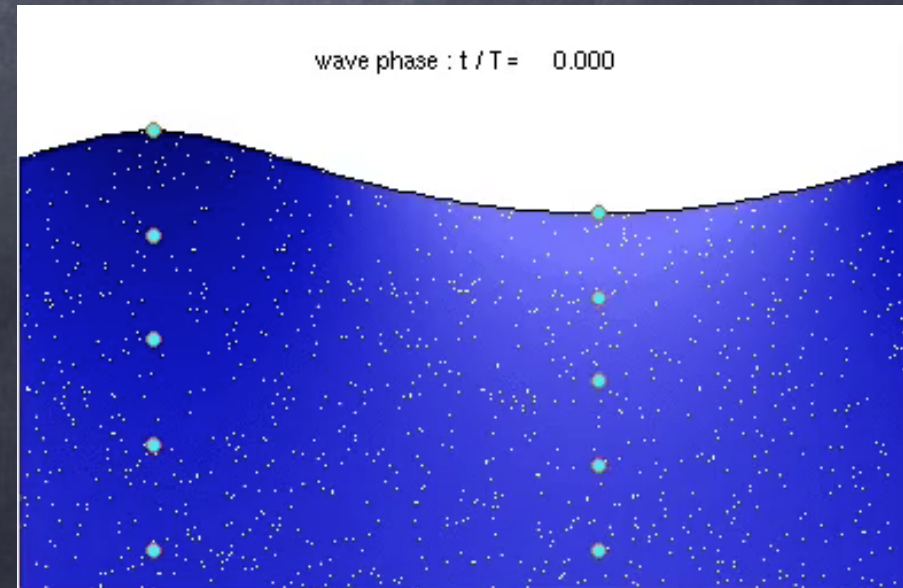
### 3 Wave Effects, 1: Lagrangian Advection:

Particles, tracers, momentum flow with Lagrangian, not Eulerian flow

$$\begin{aligned}
 Ro [v_{i,t} + v_j^L v_{i,j}] + \frac{M_{Ro}}{Ri} w v_{i,z} + \epsilon_{izj} v_j^L &= -M_{Ro} \pi_{,i} + \frac{Ro}{Re} v_{i,jj} \\
 \frac{\alpha^2}{Ri} \left[ w_{,t} + v_j^L w_{,j} + \frac{M_{Ro}}{Ro Ri} w w_{,z} \right] &= -\pi_{,z} + b - \epsilon v_j^L v_{j,z}^s + \frac{\alpha^2}{Re Ri} w_{,jj} \\
 b_t + v_j^L b_{,j} + \frac{M_{Ro}}{Ro Ri} w b_z &= \frac{1}{Pe} b_{,jj}
 \end{aligned}$$

Adding a Stokes advection term converts total to Lagrangian advection

$$\underbrace{v_j^L}_{\text{Lagrangian}} = \underbrace{v_j}_{\text{Eulerian}} + \underbrace{v_j^s}_{\text{Stokes}}$$



### 3 Wave Effects, 2: Lagrangian Coriolis:

Particles, tracers, momentum flow with Lagrangian, not Eulerian flow—Experience Coriolis force during this motion

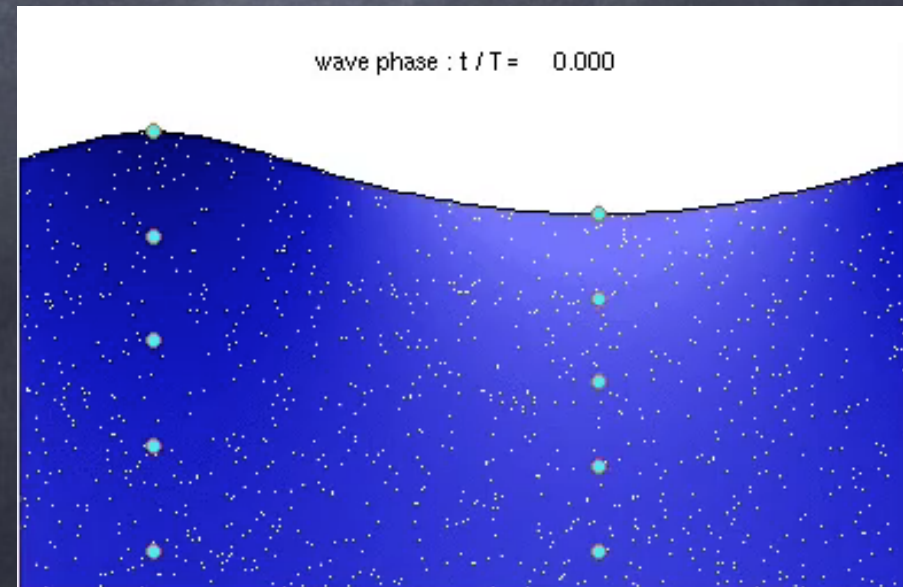
$$Ro [v_{i,t} + v_j^L v_{i,j}] + \frac{M_{Ro}}{Ri} w v_{i,z} - \epsilon_{izj} v_j^L = -M_{Ro} \pi_{,i} + \frac{Ro}{Re} v_{i,jj}$$

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

$$b_t + v_j^L b_{,j} + \frac{M_{Ro}}{Ro Ri} w b_z = \frac{1}{Pe} b_{,jj}$$

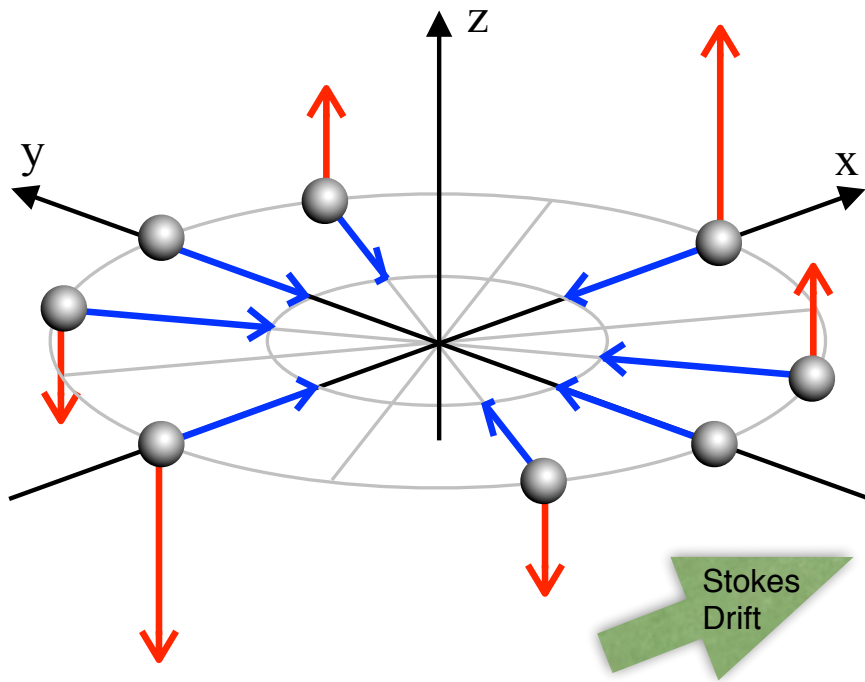
Adding a Stokes Coriolis term converts total to Lagrangian

$$\underbrace{v_j^L}_{\text{Lagrangian}} = \underbrace{v_j}_{\text{Eulerian}} + \underbrace{v_j^S}_{\text{Stokes}}$$



# 3 Wave Effects, 3: Stokes Shear Force and the CL2 mechanism for Langmuir circulations

Flow directed along Stokes shear=downward force



← : Stokes-shear force    ● : water parcel  
← : turbulent velocity

$$\epsilon = \frac{V^s H}{f L H_s}$$

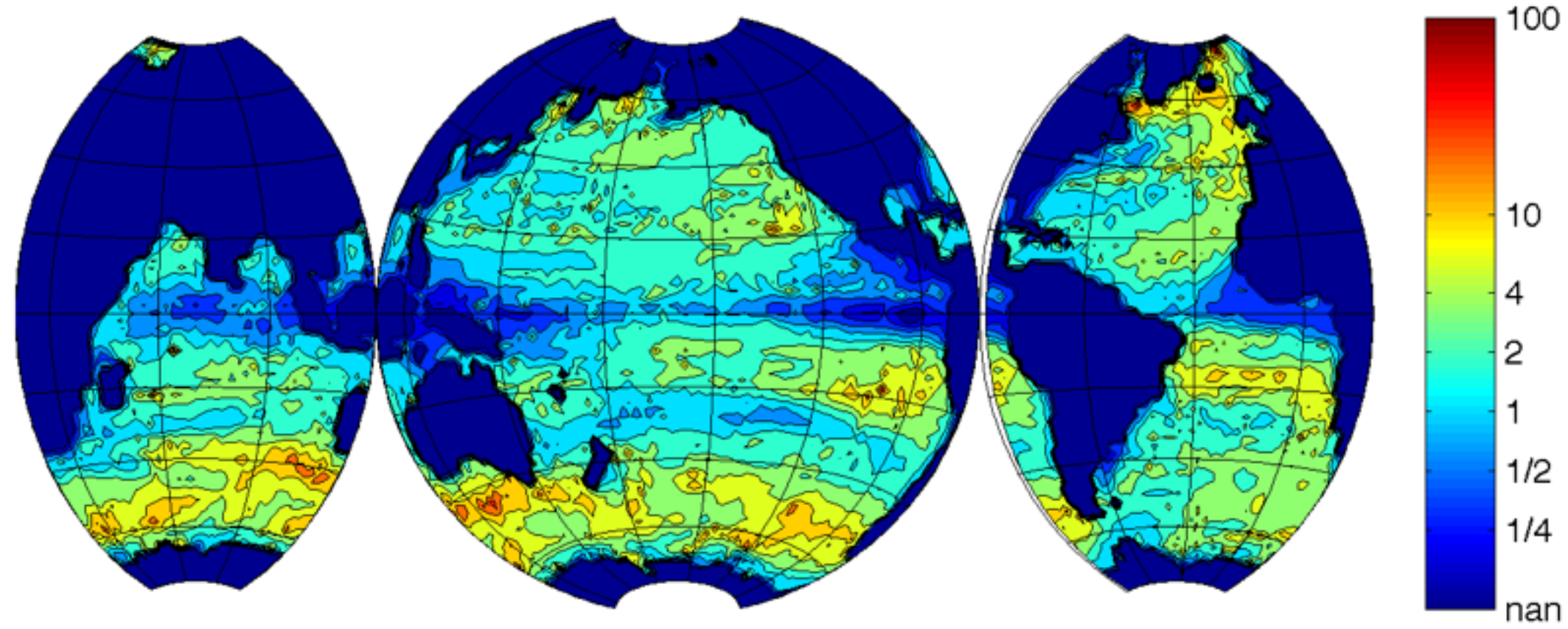
"wavy hydrostatic" if

hydrostatic  $\epsilon \gg 1$

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

# Stokes force directly affects larger scales?

$\varepsilon/Ro$



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

$$\varepsilon = \frac{V^s H}{f L H_s} \quad Ro = \frac{U}{f L}$$



# The Character of Langmuir Turbulence

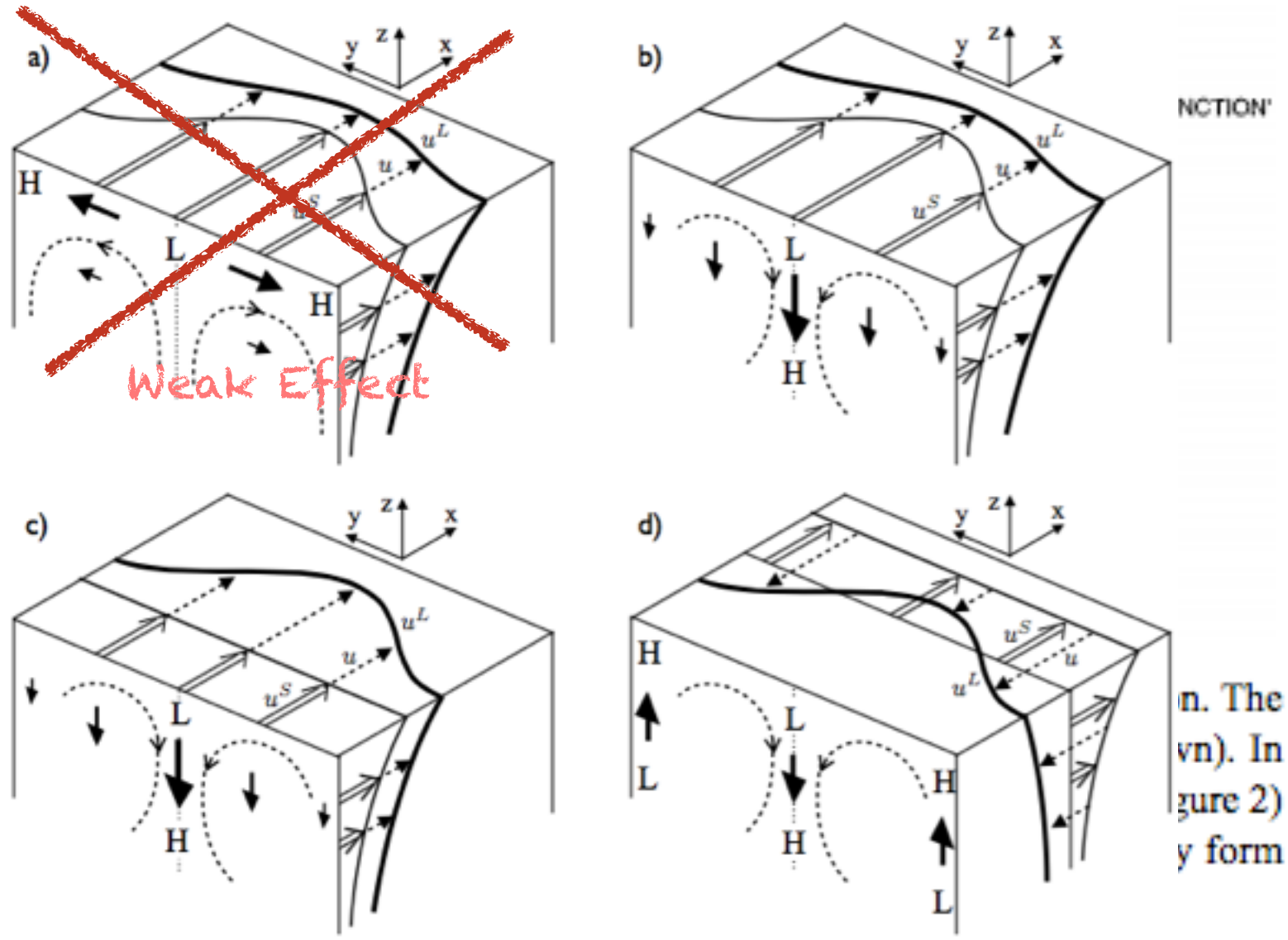
- Near-surface
- Langmuir Cells & Langmuir Turb.
- $Ro \gg 1$
- $Ri < 1$ : Nonhydro
- 1-100m ( $H=L$ )
- 10s to 1hr
- $w, u = O(10\text{cm/s})$
- Stokes drift
- Eqtns: Wave-Averaged
- Params: McWilliams & Sullivan, 2000, Van Roekel et al. 2011
- Resolved routinely in 2170

Image: NPR.org,  
Deep Water  
Horizon Spill

image:  
Thorpe, 0



**Figure 1**  
windrows  
practice th  
amalgama  
within the



n. The  
vn). In  
figure 2)  
y form

Typical effect: Downward Force for down-Flow Stokes Drift

$$\frac{\alpha^2}{Re} \left[ w_{,t} + v_j^L w_{,j} + \frac{M_{Ro}}{RoRe} \right] = -\pi_{,z} + b + \epsilon v_j^L v_{j,z}^S + \frac{\alpha^2}{ReRe} w_{,jj}$$

# 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

Langmuir  
important



No Retuning! ALL coefficients from LES

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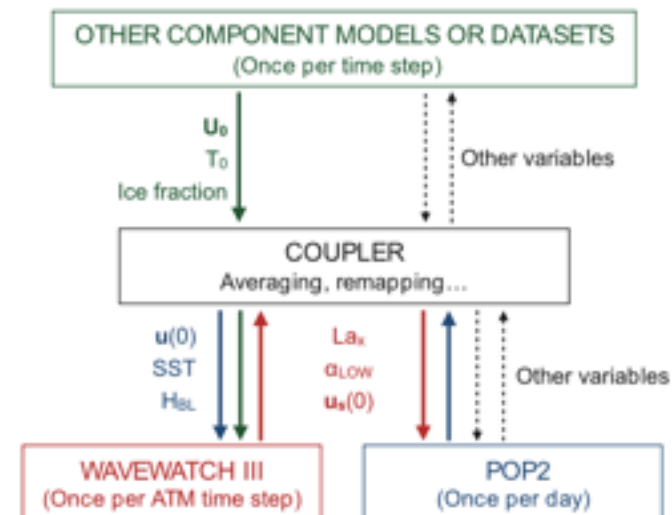
U. S. Department of Commerce  
National Oceanic and Atmospheric Administration  
National Weather Service  
National Centers for Environmental Prediction  
5200 Auth Road  
Camp Springs, MD 20746

## Technical Note

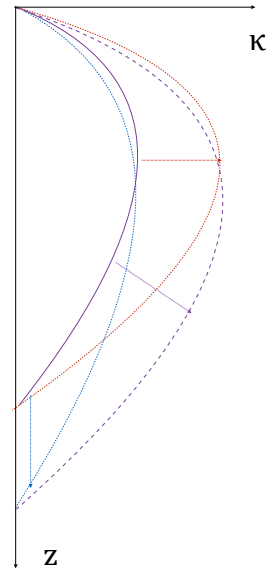
# User manual and system documentation of WAVEWATCH III™ version 3.14 †

Hendrik L. Tolman ‡

Environmental Modeling Center  
Marine Modeling and Analysis Branch

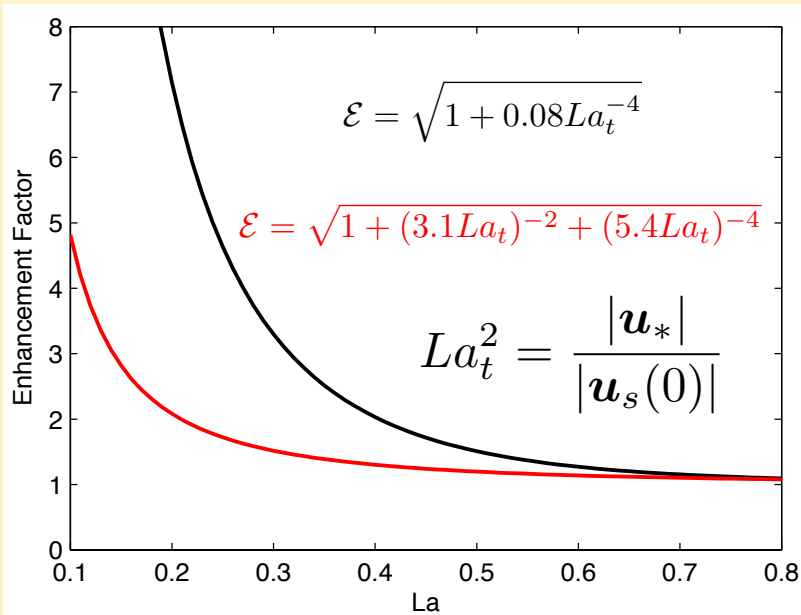


# Langmuir Mixing in KPP for use in CESM1.2



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. In press.

- WaveWatch-III (Stokes drift) <-> POP2 (U, T, H<sub>BL</sub>)
- CORE2 interannual forcing (Large and Yeager, 2009), or fully coupled
- 4 IAF cycles; average over last 50 years for climatology (over 200 years total)
- Or fully coupled climate model—active atmosphere.

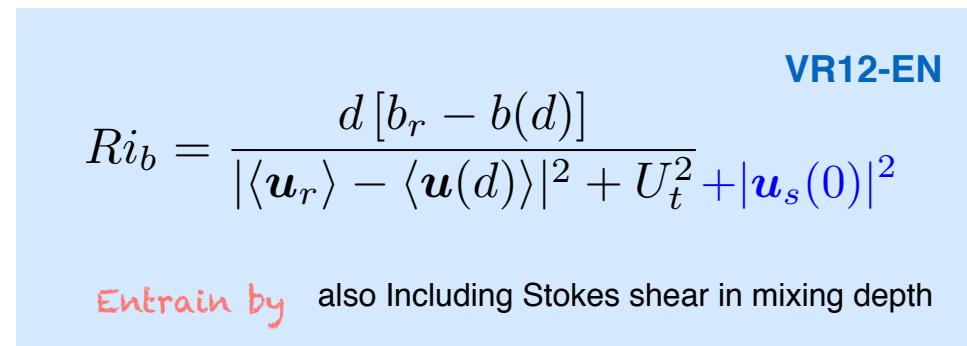
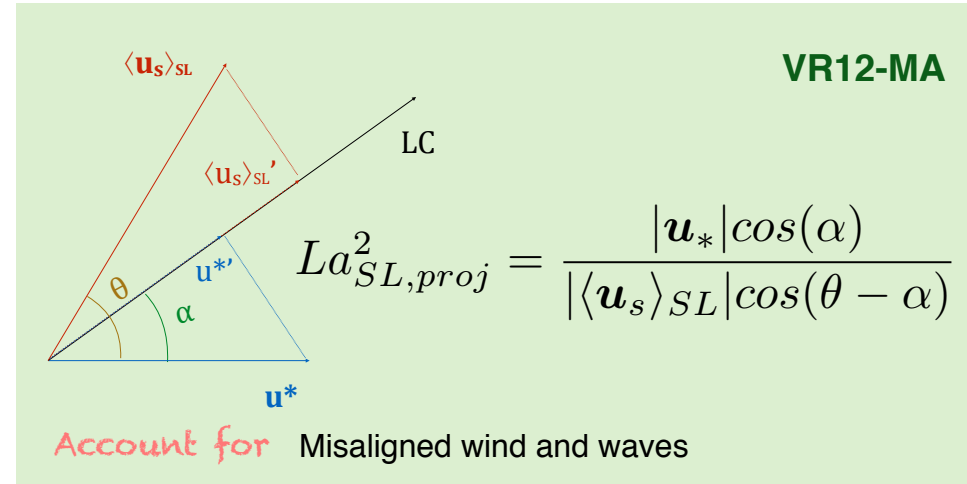


**MS2K**

**VR12-AL**

**Revise** Enhancement factor to vertical velocity scale W

Aligned wind and waves



# Langmuir Mixing in Climate: Boundary Layer Depth Improved

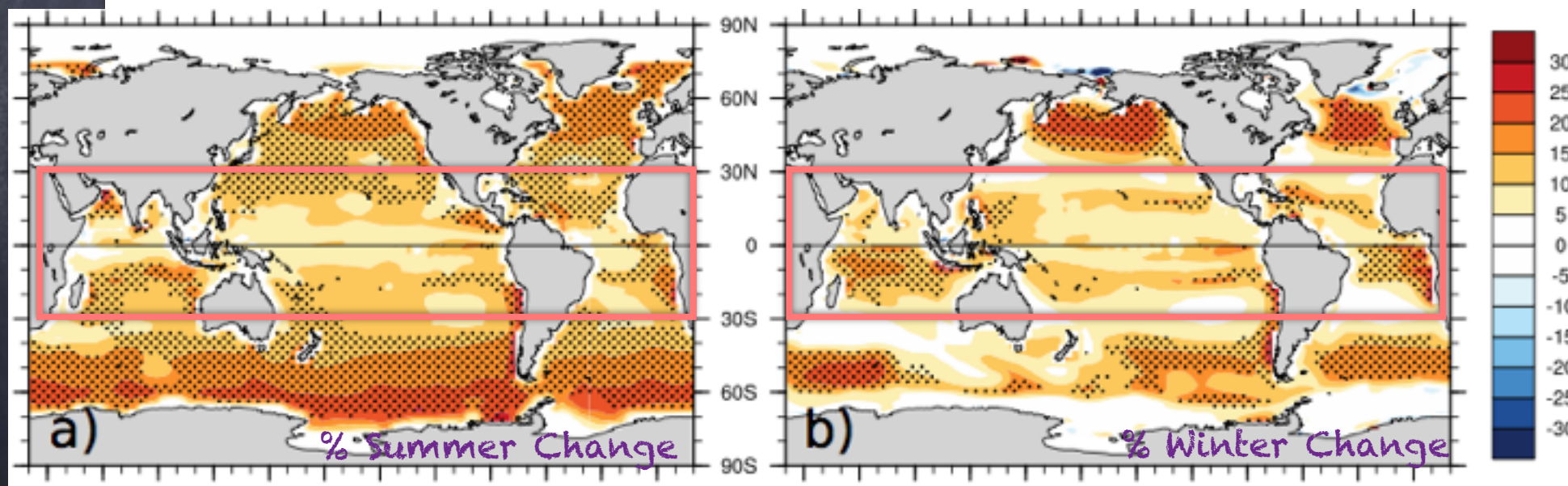
Control

Competition

3 versions of  
Van Roekel et  
al

Case	Summer			Winter		
	Global	South of 30°S	30°S-30°N	Global	South of 30°S	30°S-30°N
CTRL	10.62±0.27 <sup>a</sup> (13.40±0.19) <sup>b</sup>	17.24±0.48 (21.73±0.32)	5.38±0.14 (6.71±0.09)	43.85±0.38 (45.50±0.40)	57.19±0.76 (56.53±0.59)	12.57±0.28 (16.16±0.29)
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±0.30 (11.83±0.29)	12.65±0.47 (18.13±0.62)	6.61±0.22 (7.52±0.16)	40.99±0.37 (42.02±0.39)	51.78±0.65 (50.78±0.67)	14.23±0.30 (15.67±0.35)
VR12-EN	8.95	10.52	8.91	41.94	52.98	19.58

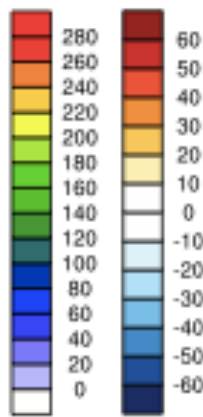
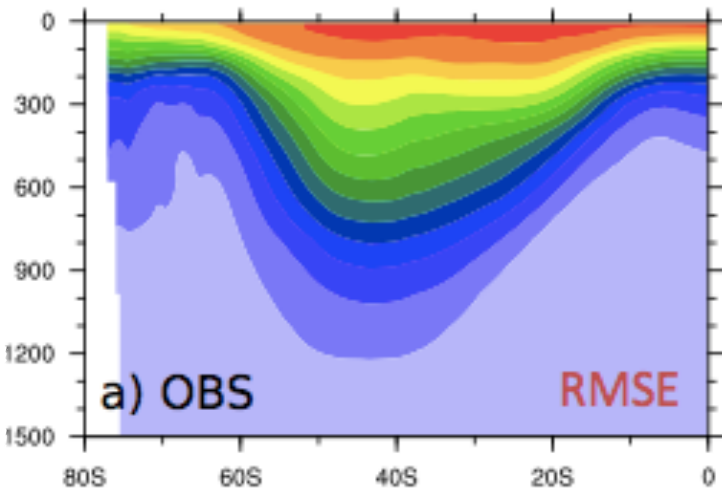
dotted  
when  
statistically  
significant



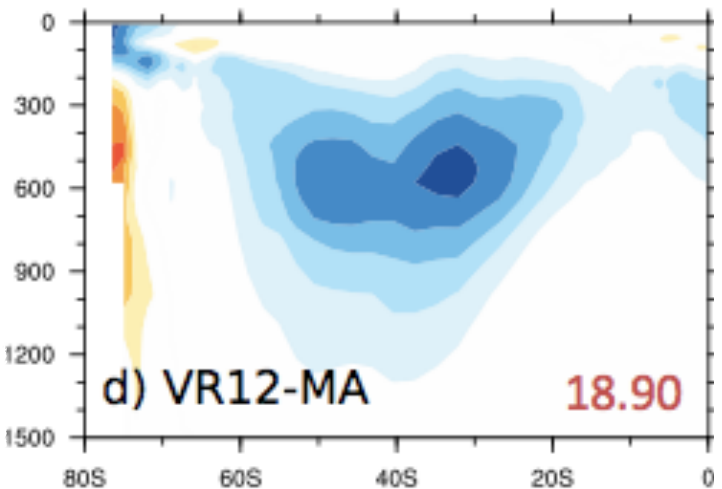
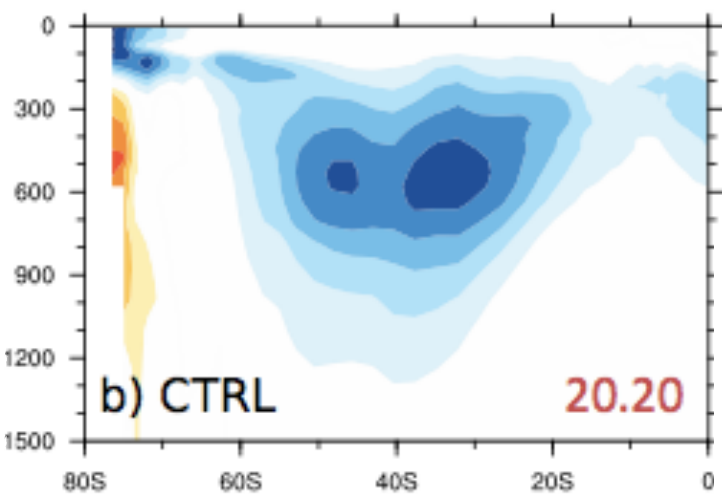
L. P. Van Roekel, BFK, P. P. Sullivan, P. E. Hamlington, and S. R. Haney. The form and orientation of Langmuir cells for misaligned winds and waves. *Journal of Geophysical Research-Oceans*, 117:C05001, 22pp, May 2012.

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*, August 2015. in press.

# Enhancing ocean ventilation



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



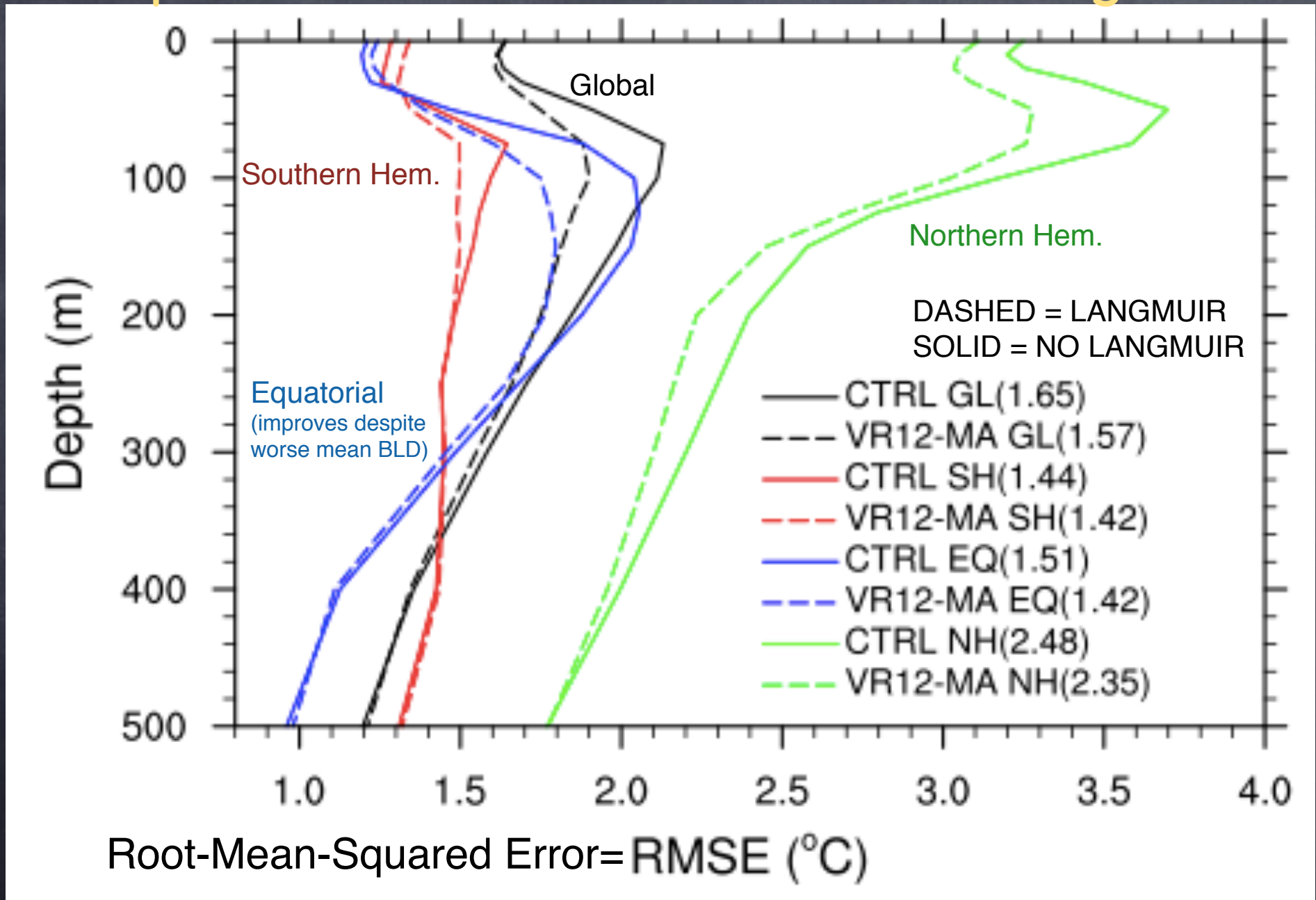
Q. Li, A. Webb, BFK, A. Craig, G. Danabasoglu, W. G. Large, and M. Vertenstein. Langmuir mixing effects on global climate: WAVEWATCH III in CESM. Ocean Modelling, August 2015. in press.

Ocean Uptake:  
 Chlorofluorocarbons  
 (manmade pollutant,  
 detectable & known  
 source)  
 Improved vs.  
 Observations with  
 Langmuir Mixing

Case	Global	Southern Hemisphere
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



# Subsurface Temperature: Improved vs. Observations with Langmuir



# So, we'll quantify Langmuir effects on climate

- 1) From OBSERVATIONS, estimate wave effects on key parameters ( $\langle w^2 \rangle$ , sources of energy) using scalings from Large Eddy Simulations. MODEL INDEPENDENT Langmuir important ✓
- 2) OFFLINE 1d mixing with waves parameterized, mixing into observed Argo profiles, reanalysis winds, waves, cooling. ROBUST TO MODEL ERRORS Langmuir important ✓
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No Retuning! ALL coefficients from LES

# Mid-way Conclusions

- Stokes forces may accelerate upper ocean mixing, leading to a wind-wave-convective turbulence driven partly by Stokes forces: Langmuir turbulence
- Three effects of Stokes drift are important: Stokes Advection, Stokes Coriolis, and Stokes Shear Force
- The Stokes Shear Force enhances downward and upward velocities in boundary layer turbulence.
- Including Langmuir mixing in climate models improves the climate model MLD, T, and uptake of CFCs.
- All papers at: [fox-kemper.com/pubs](http://fox-kemper.com/pubs)

# The Character of the Submesoscale

(Capet et al., 2008)

←  
10  
km

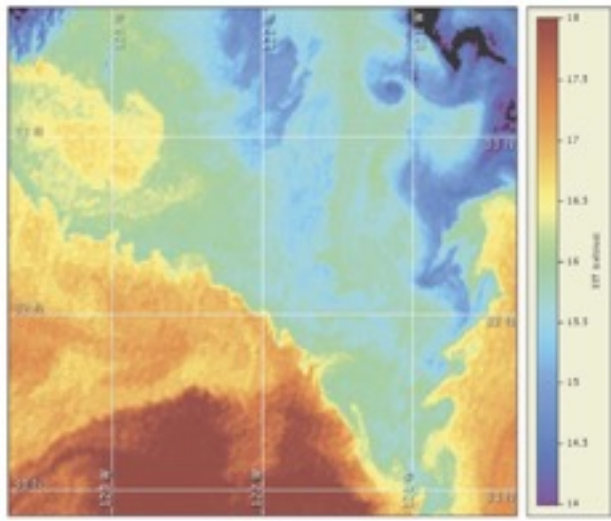
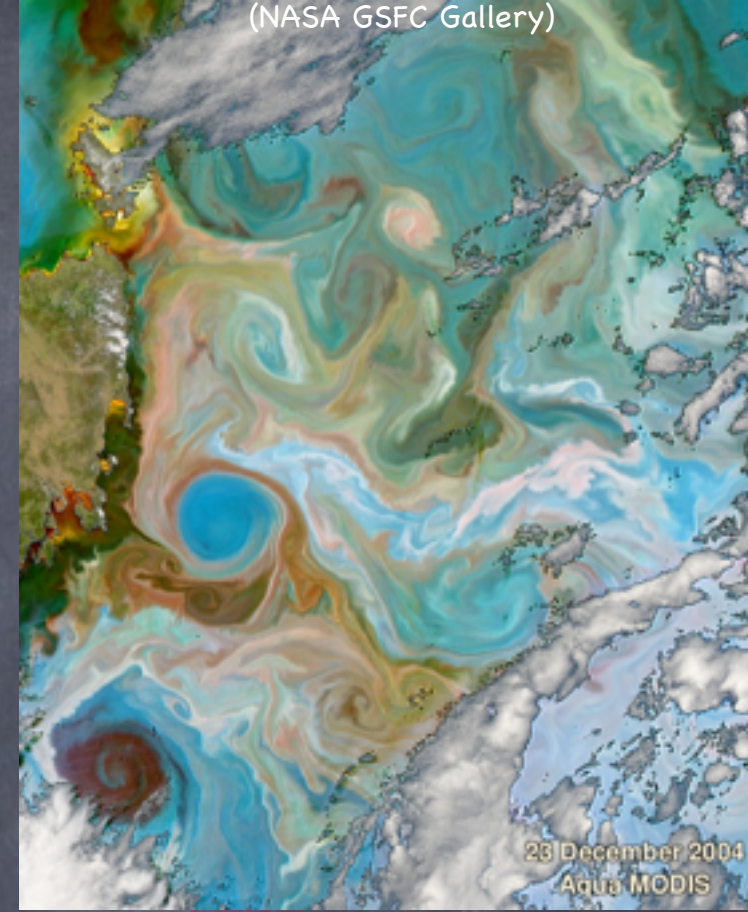
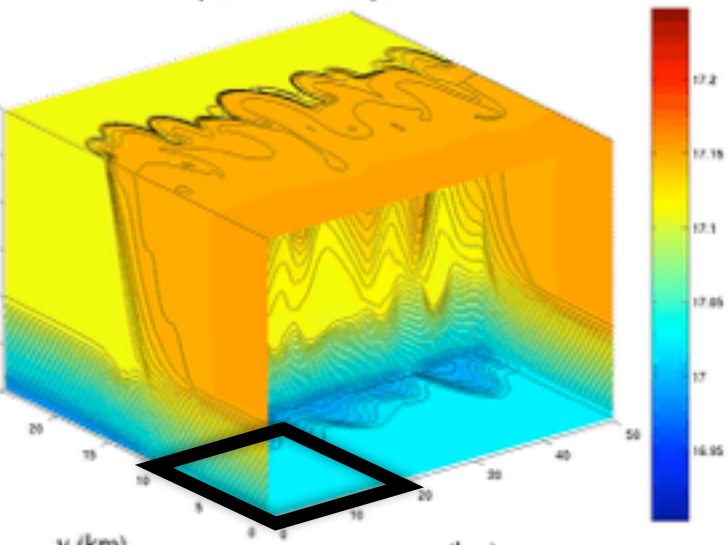


FIG. 16. Sea surface temperature measured at 1832 UTC 3 Jan 2006 off Point Conception in the California Current from CoastWatch (<http://coastwatch.pfeg.noaa.gov>). The fronts between recently

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

Temperature on day:17.375



Eddy processes often  
baroclinic instability

Parameterizations =  
BFK et al (08-11).

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

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

# LES of Langmuir-Front Interactions?

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

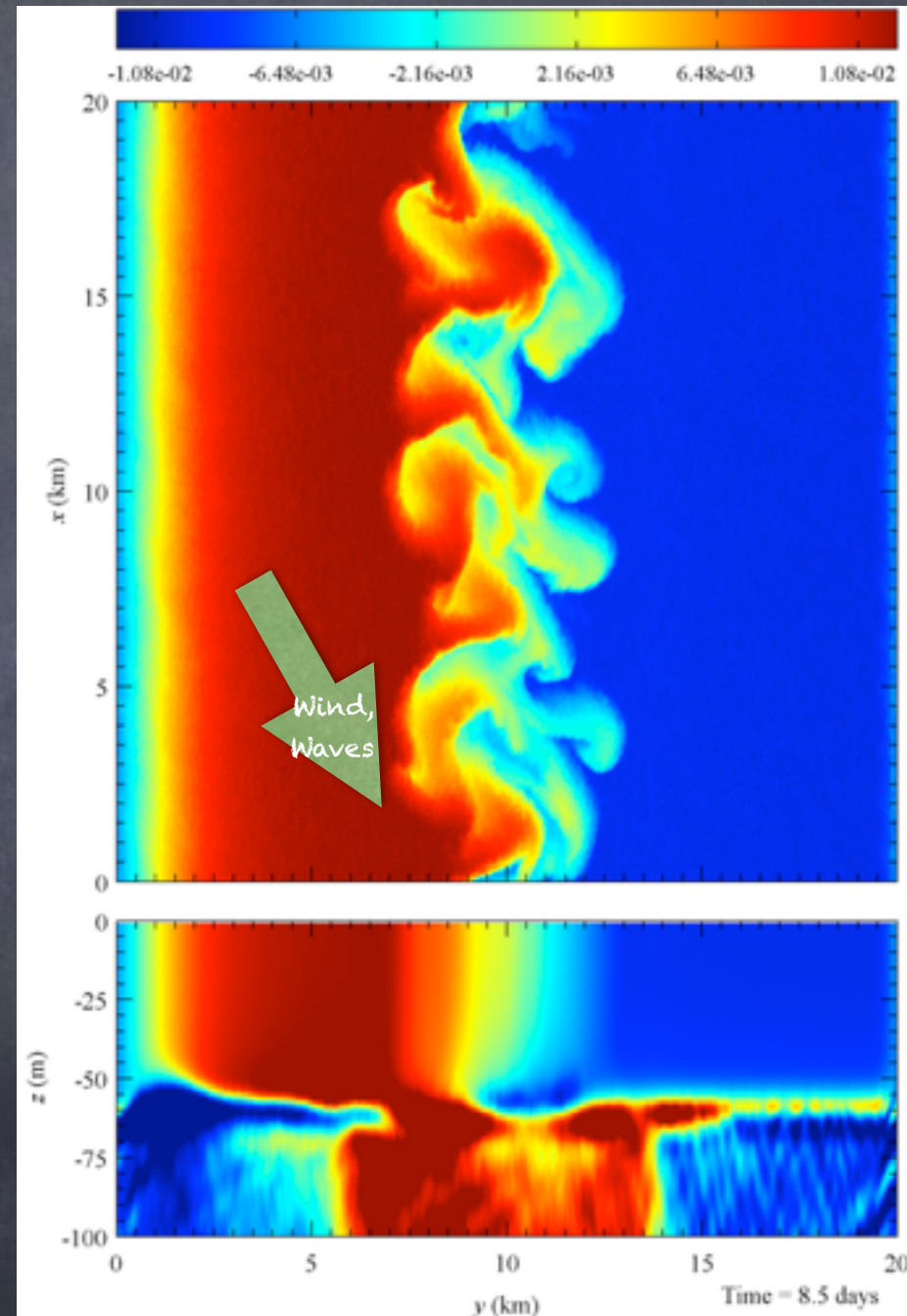
Computational parameters:

Domain size: 20km x 20km x -160m

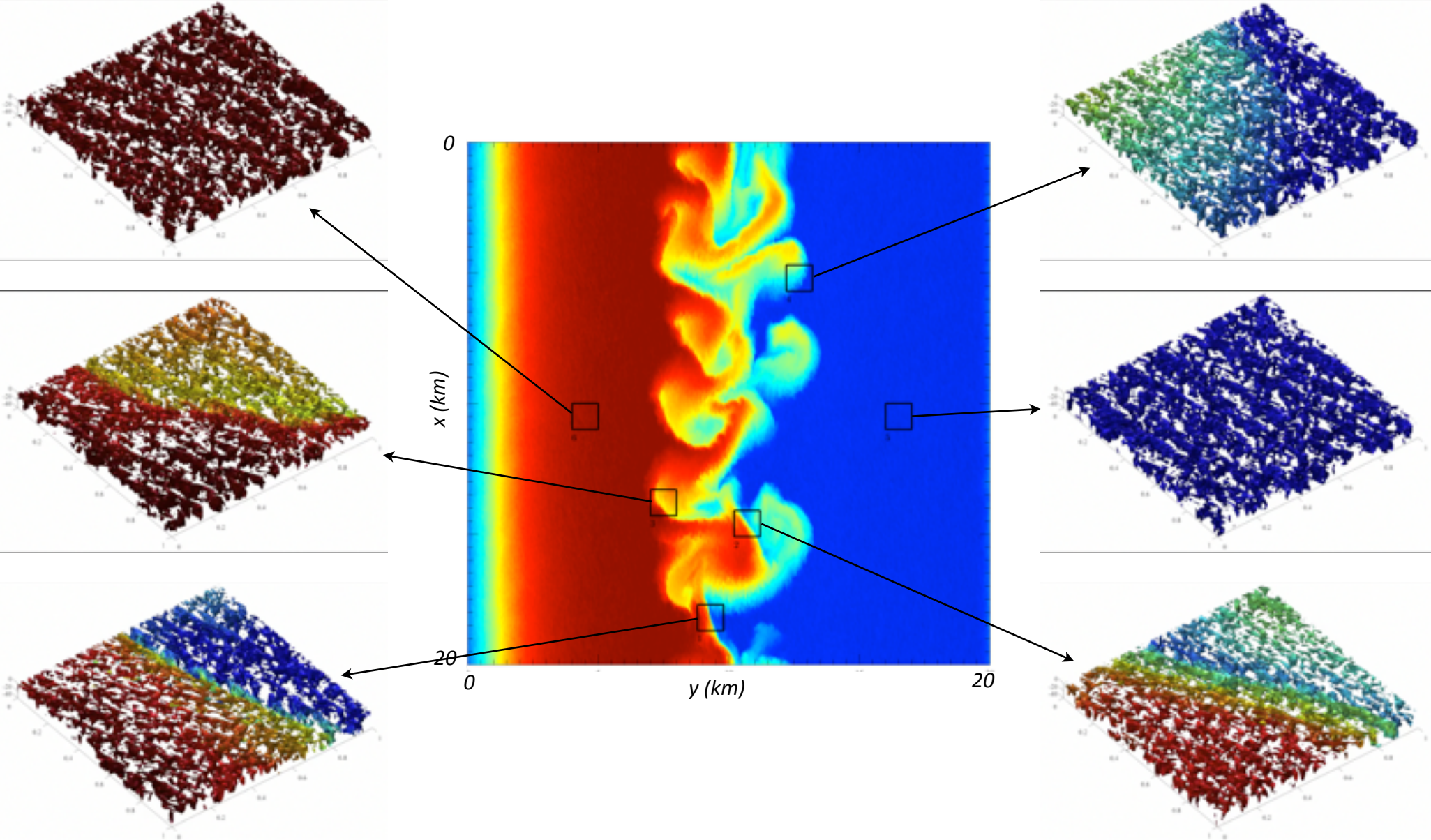
Grid points: 4096 x 4096 x 128

Resolution: 5m x 5m x -1.25m

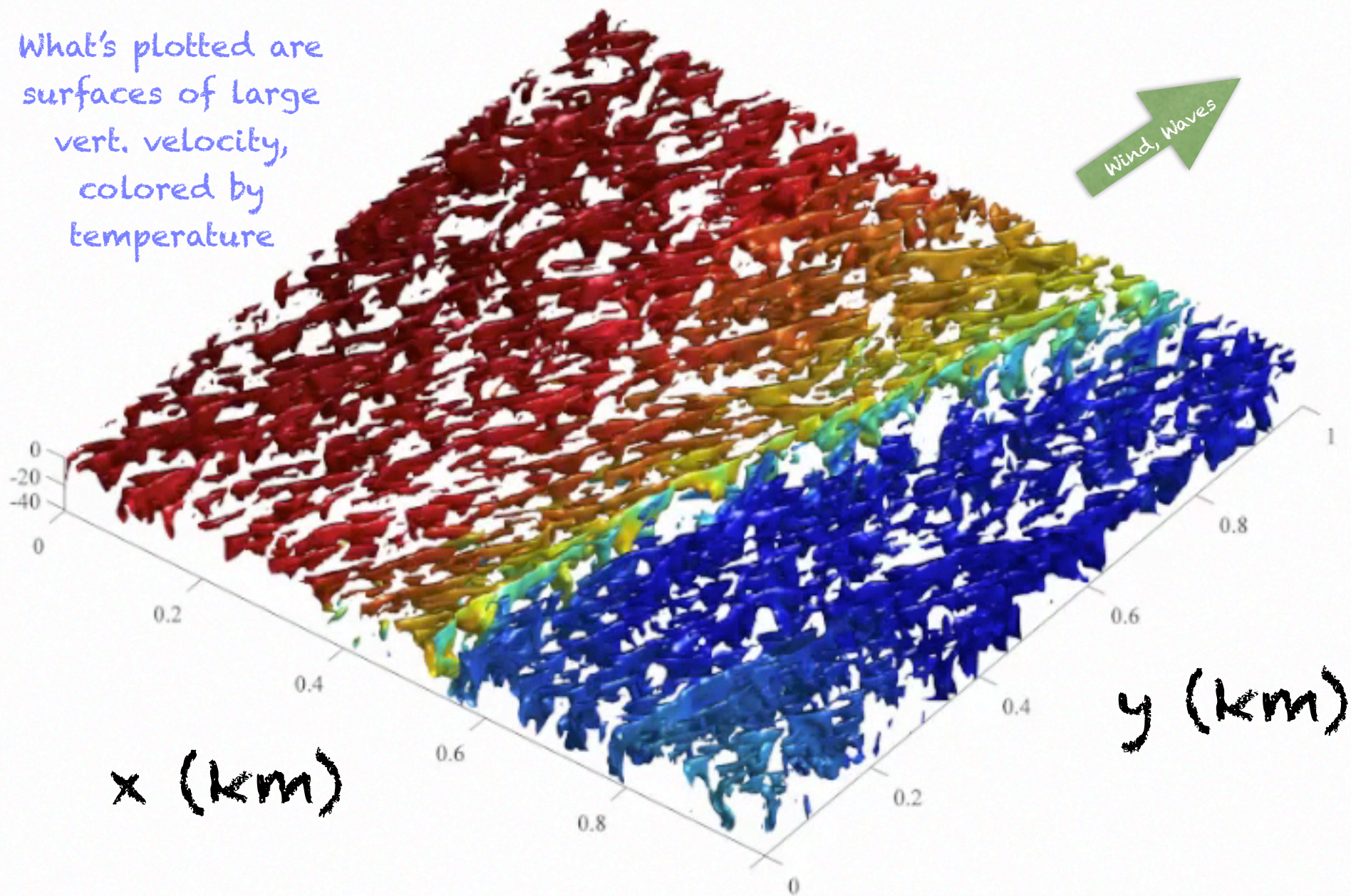
Movie: P. Hamlington



# Diverse types of interaction



What's plotted are  
surfaces of large  
vert. velocity,  
colored by  
temperature



As we've seen, waves can drive turbulence that affect larger scales indirectly. This is expected.

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 Eulerian!

The Eulerian response to Stokes is often to cancel it out!  
(Anti-Stokes flow, Lab: Monismith et al., Obs: Lentz et al.)



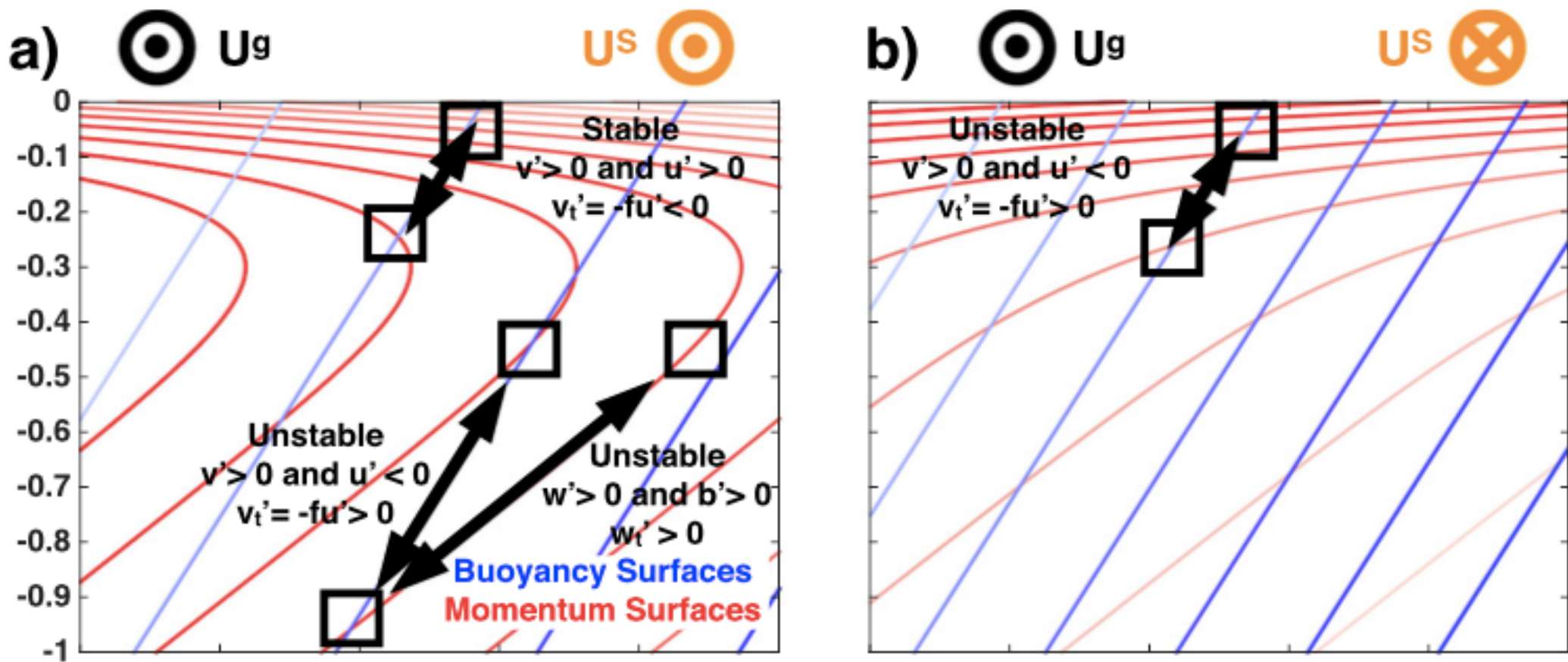



FIG. 1. A schematic of the (a) downfront and (b) upfront Stokes drift scenarios. The blue lines show isopycnals, with darker blue indicating denser water. The red lines show surfaces of constant downfront absolute Eulerian momentum, with darker red indicating greater momentum. The perturbation equations are written from the perspective of the lower of the two parcels. A change of all signs would be from the perspective of the upper parcel and have the same stability. For example, in (b) the lower parcel moves to the right ( $v' > 0$ ) along an isopycnal and brings with it lower downfront momentum than its surroundings ( $u' < 0$ ). This exerts an acceleration in the cross-front  $v'$  direction due to the Coriolis force that further enhances the initial perturbation ( $v' > 0$ ). In both cases,  $Ri = 0.5$ . Lines of constant buoyancy and absolute momentum are only parallel when  $Ri = 1$ .

# Analytic & Numerical Wavy Submesoscale Stability: Geostrophic Instabilities

Charney, Stern, Pedlosky criteria (appropriately generalized) apply:

• Instability if and only if:

- 1)  $Q_Y^L$  changes sign in the interior of the domain;
- 2)  $Q_Y^L$  is the opposite sign as  $U_z^L$  at  $z = 0$ ;
- 3)  $Q_Y^L$  is the same sign as  $U_z^L$  at  $z = -H$ ;
- 4)  $U_z^L$  has the same sign at  $z = -H$  and  $z = 0$ .

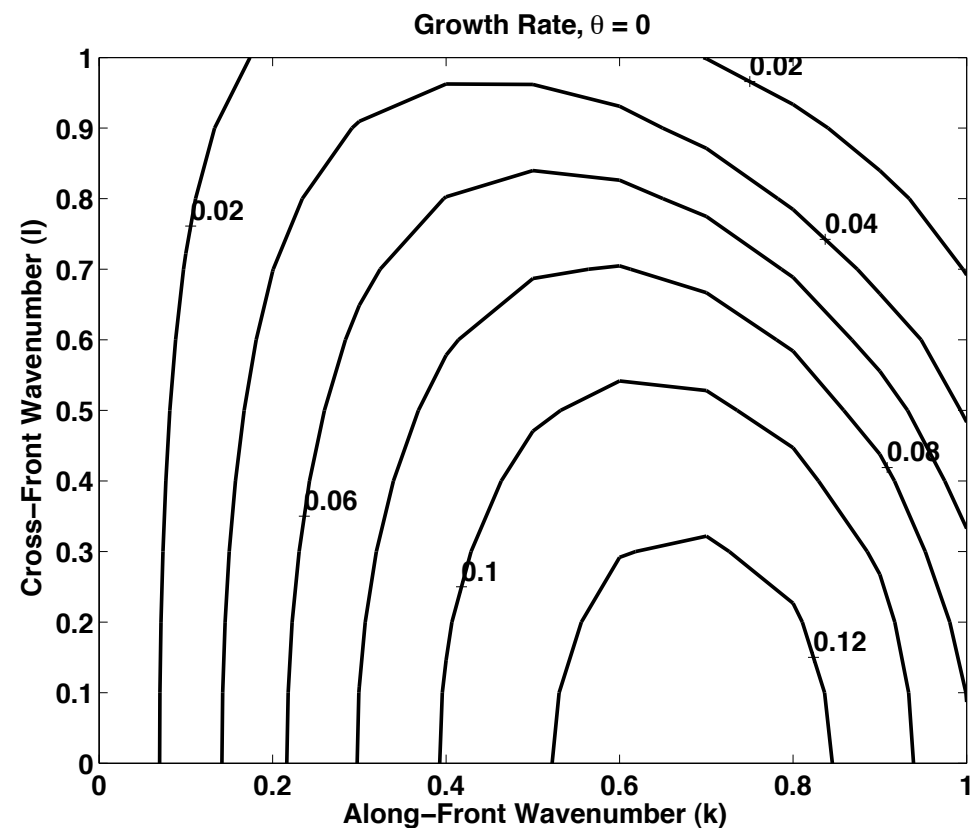
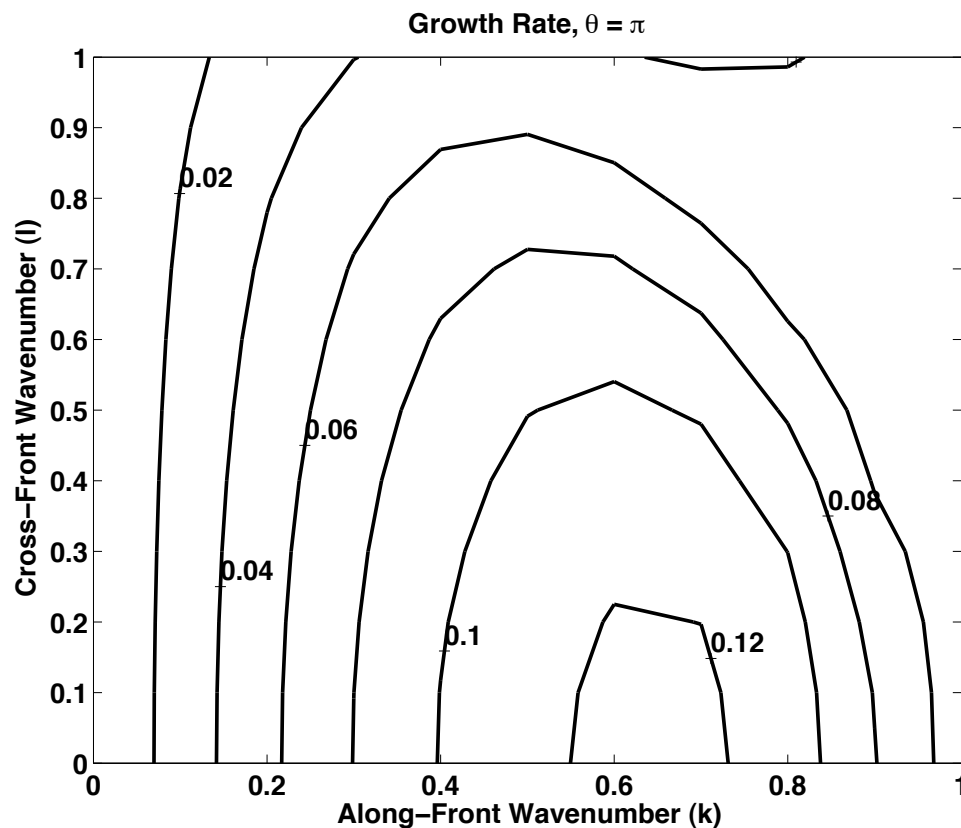
$$Q^L = \nabla_H^2 \Psi + \beta Y + \partial_z \left( \frac{f_0^2}{N^2} \frac{\Psi_z^L}{B_z} \right)$$


$$U + U^S = -\Psi_y^L, \quad \text{such that} \quad U = -\Psi_y, \quad \text{and}$$
$$V + V^S = \Psi_x^L = 0.$$

Streamfunctions  
with and w/o Stokes

# Analytic & Numerical Wavy Submesoscale Stability: Geostrophic Instabilities

- \* When the Stokes drift and geostrophic flow are aligned, the anti-Stokes flow yields reduced Eulerian shear.
- \* Less Eulerian shear near the surface results in lower growth rates and wavenumbers for GI.



# Analytic Wavy Stability Criterion: Symmetric Instability

- \* Hoskins (1974) showed that if a front in thermal wind balance is symmetrically unstable, the PV must be anticyclonic.
- \* Haney et al extend Hoskins analysis to flows in Lagrangian thermal wind balance in the special case that the Stokes shear is constant.

$$U^S = \mu z$$

$$SI \Rightarrow f\bar{Q} = f^2 N^2 - M^4 - fM^2 U_z^S < 0$$

- \* In the absence of Stokes drift, this gives the familiar criteria on  $Ri^g$ .

$$SI \Rightarrow Ri^g \equiv \frac{f^2 N^2}{M^4} < 1$$

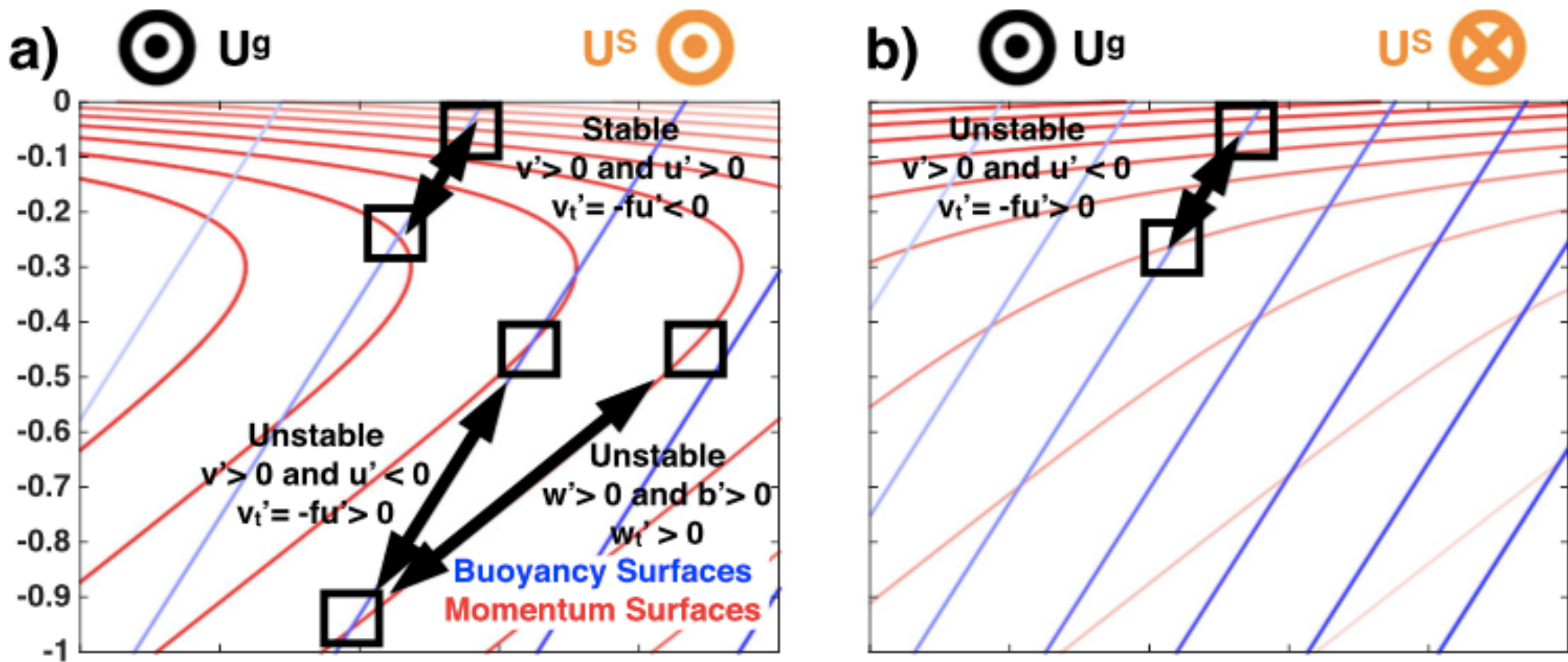


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~~$Ri < 1 \Rightarrow SI$~~

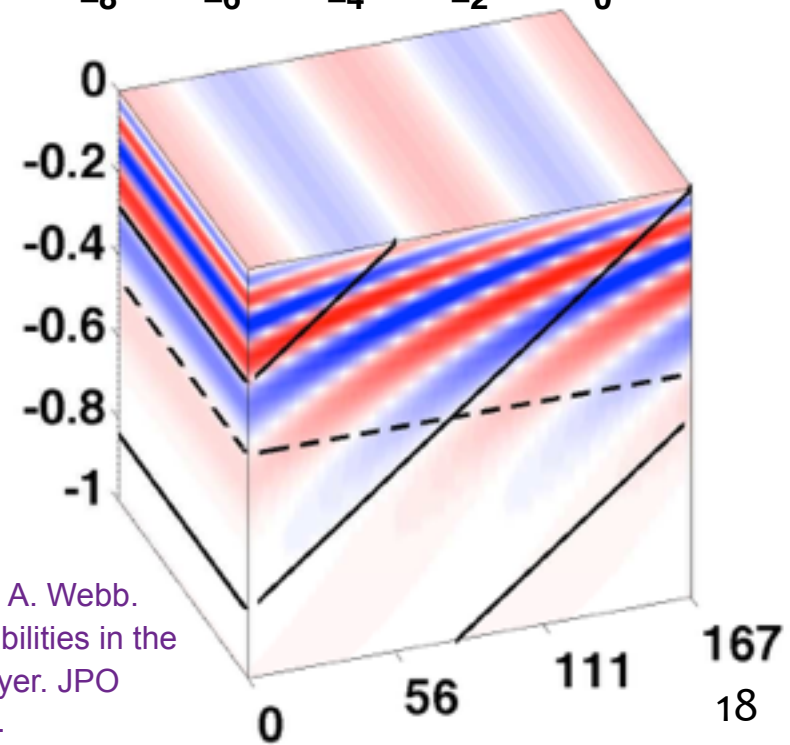
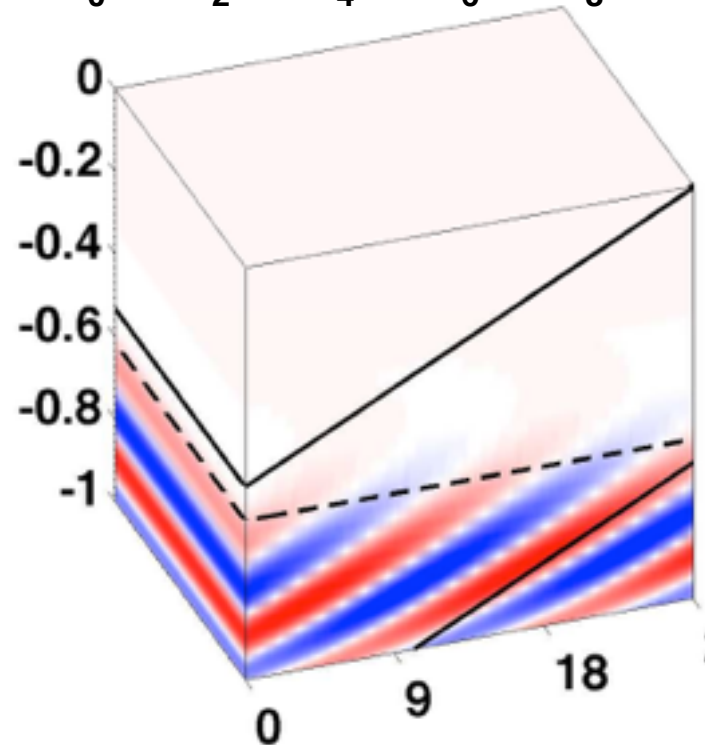
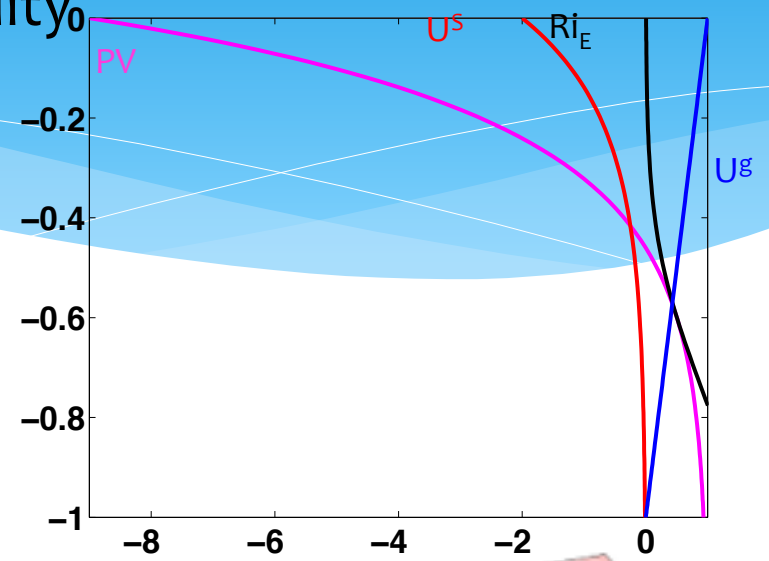
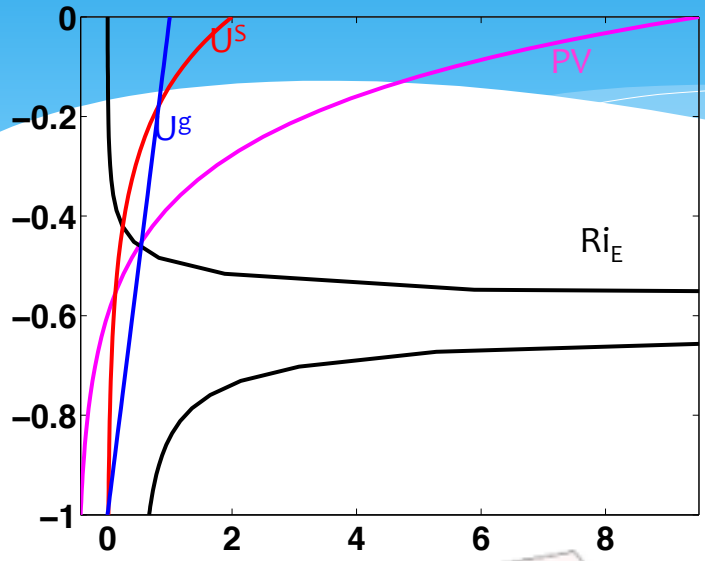
★  $fQ < 0 \Rightarrow SI$

Numerical Wavy Stability Criterion:

Symmetric Instability

$Ri = 0.5$

$Ri = 2$

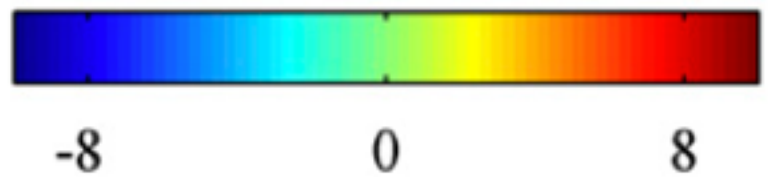
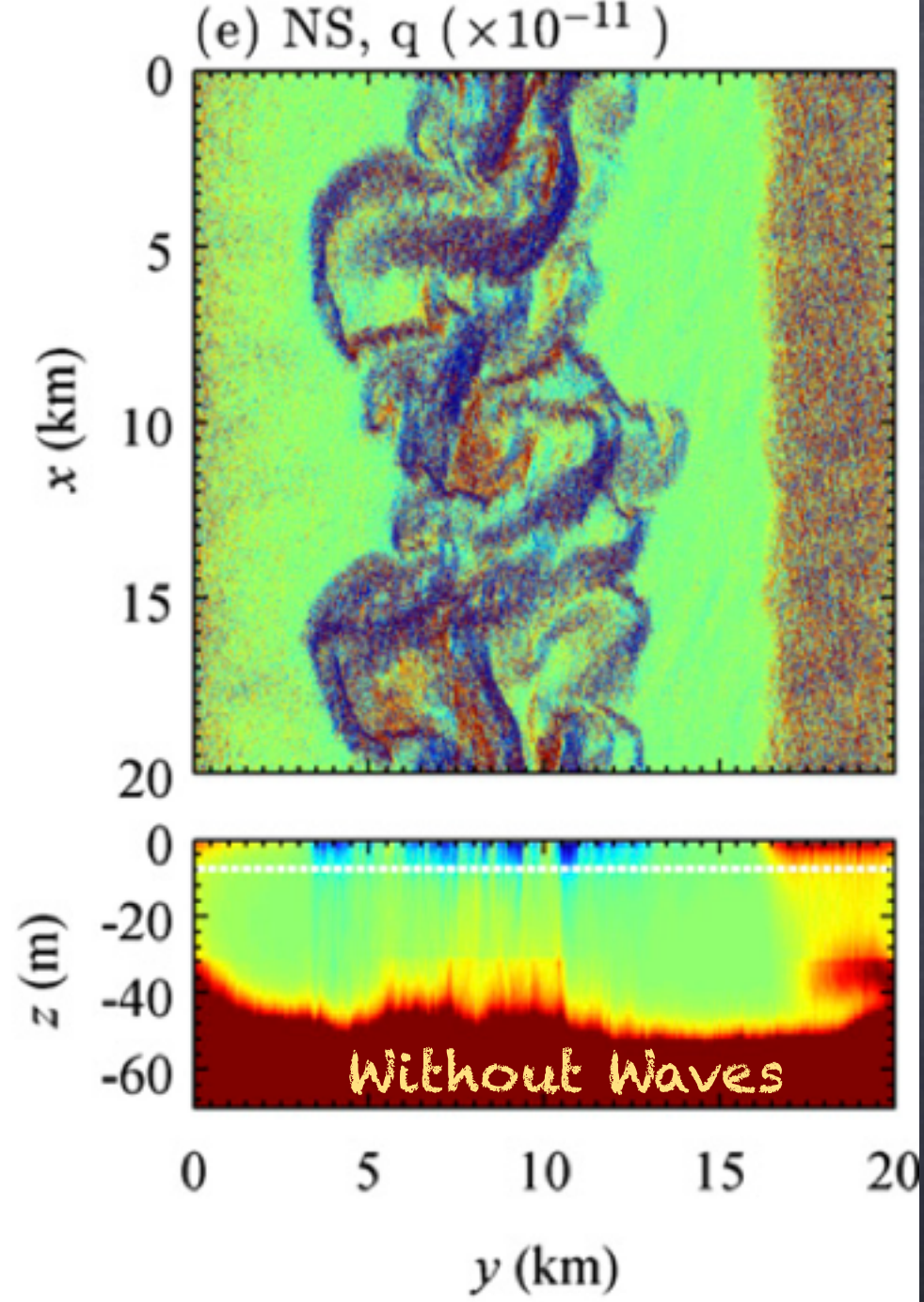
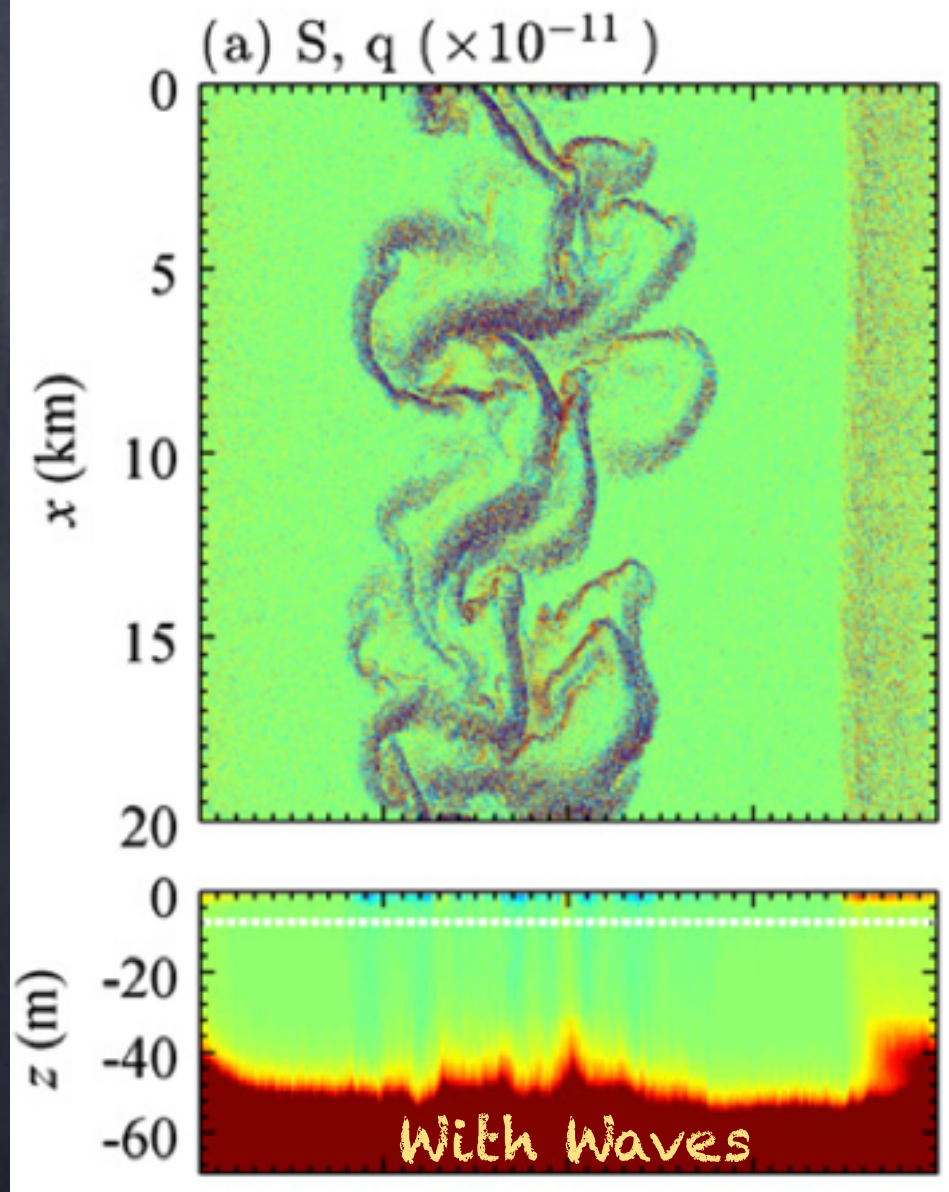


— Isopycnals

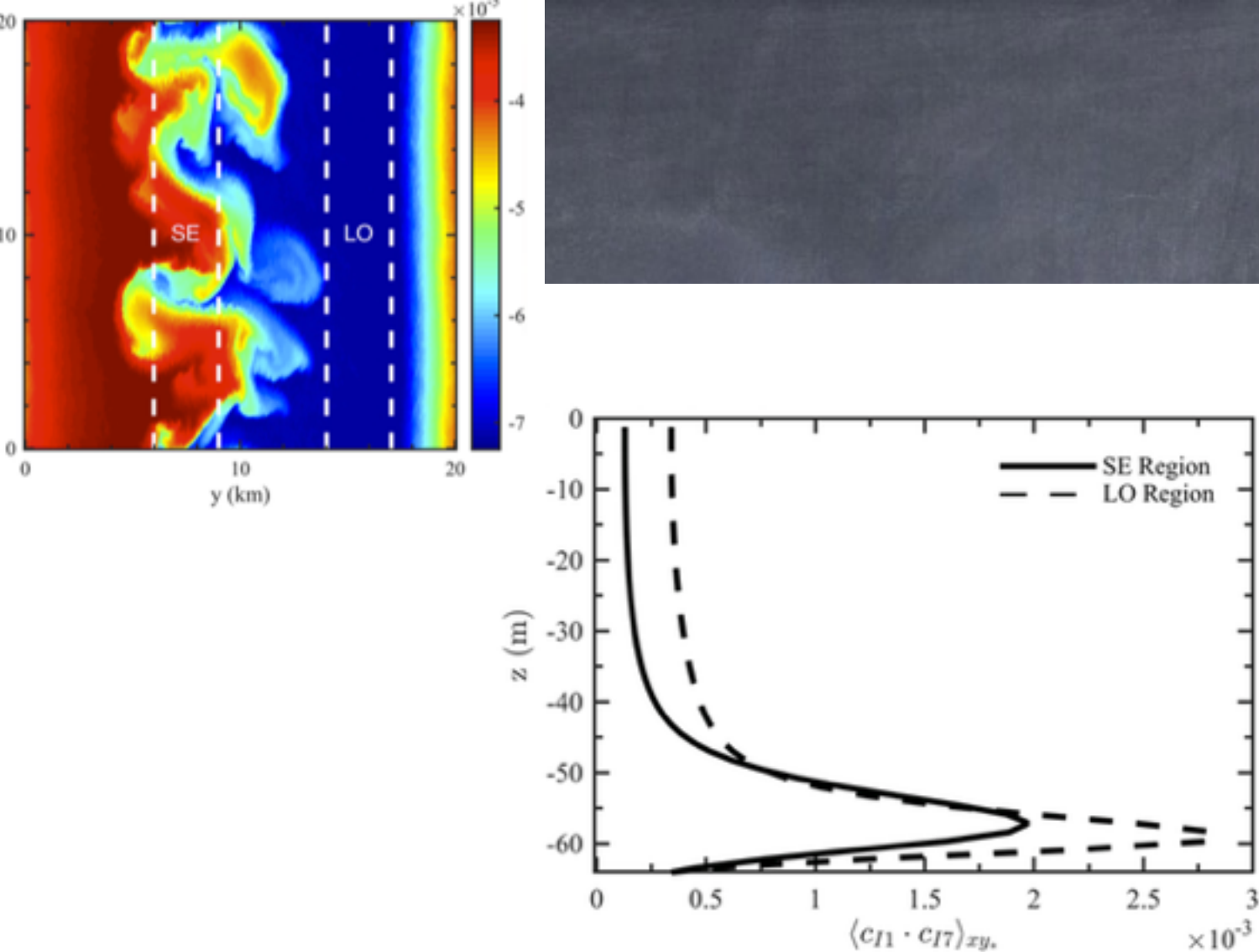
-- PV=0

Cross front velocity for the fastest growing mode

S. Haney, BFK, K. Julien, and A. Webb.  
Symmetric and geostrophic instabilities in the wave-forced ocean mixed layer. JPO 45:3033-3056, 2015.



So, if  $f_{q<0}$  indicates likely regions of symmetric instability—Surface Waves STRONGLY affect SI!

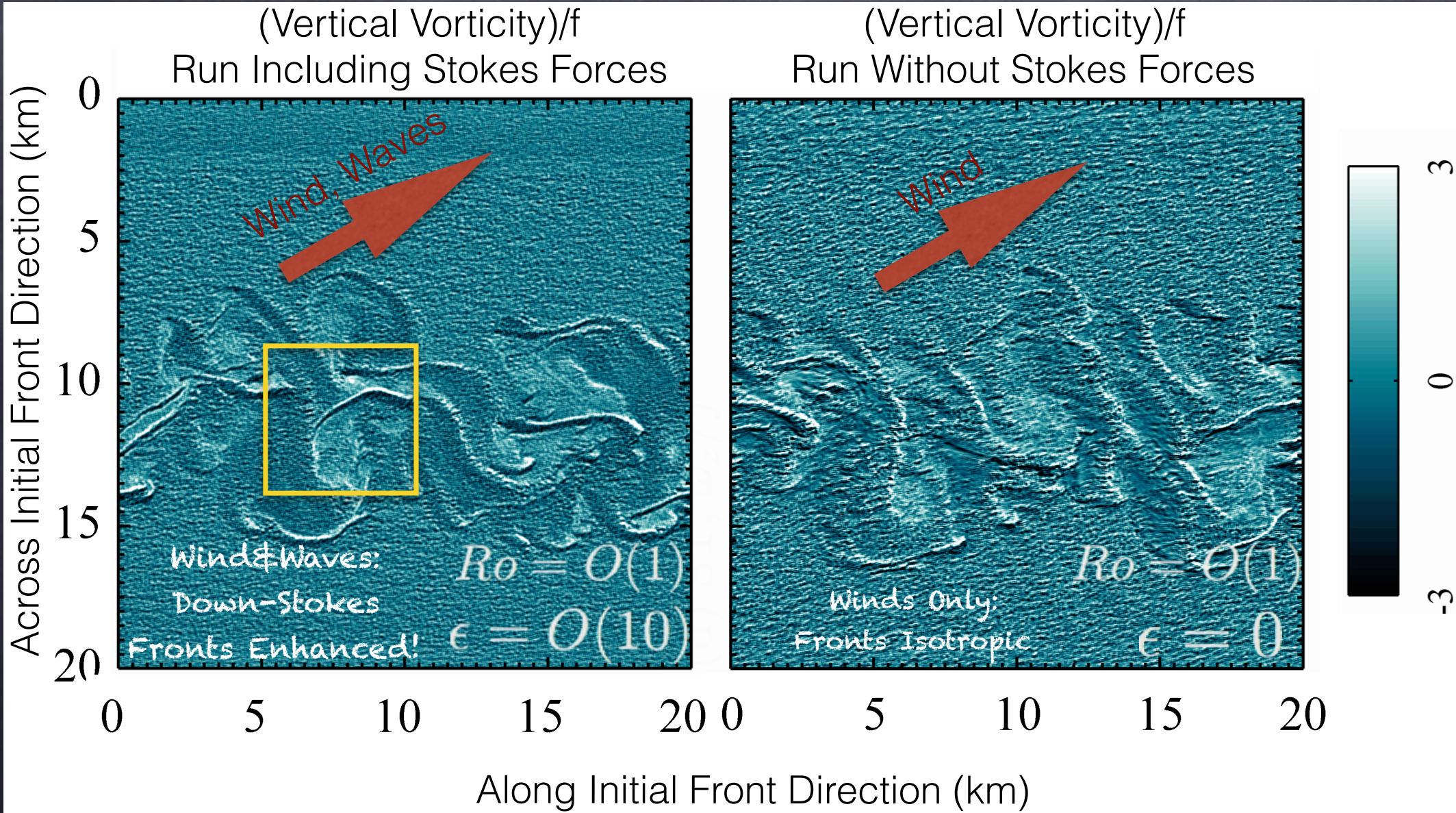


**Figure 17.** Vertical profiles of the  $x - y$  averaged pseudo-production, defined as the product  $c_{I1} \cdot c_{I7}$ , where tracer  $c_{I1}$  has an initial source at the surface and  $c_{I7}$  has an initial source at  $z = -60\text{m}$ . Profiles are shown approximately 8 hours after the start of the simulations for the SE region (solid line) and the LO region (dashed line).



# Are Fronts and Filaments different with Stokes shear force?

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

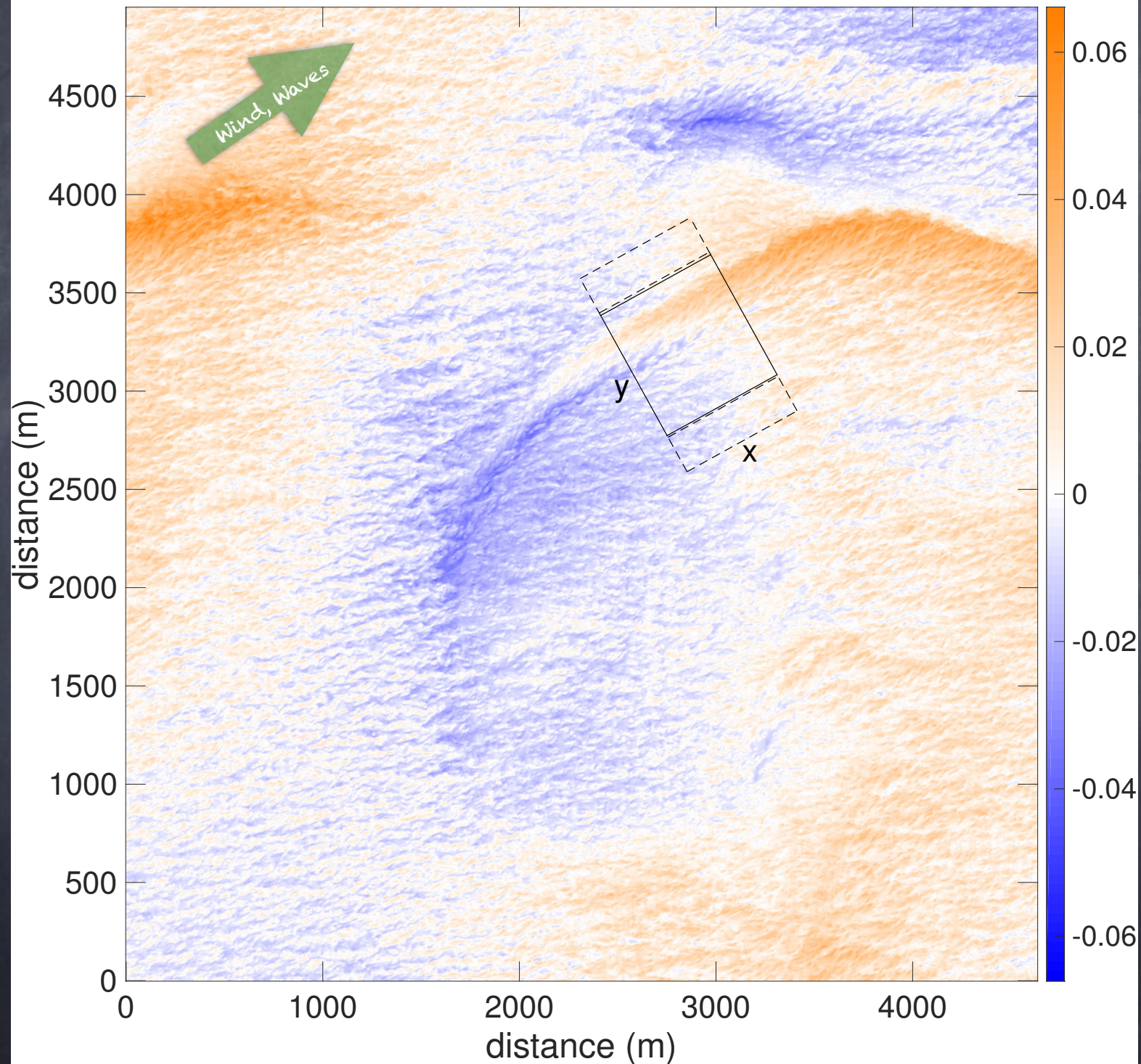


N. Suzuki, BFK, P. E. Hamlington, and L. P. Van Roekel. Surface waves affect frontogenesis. JGR-Oceans, December 2015. Submitted.

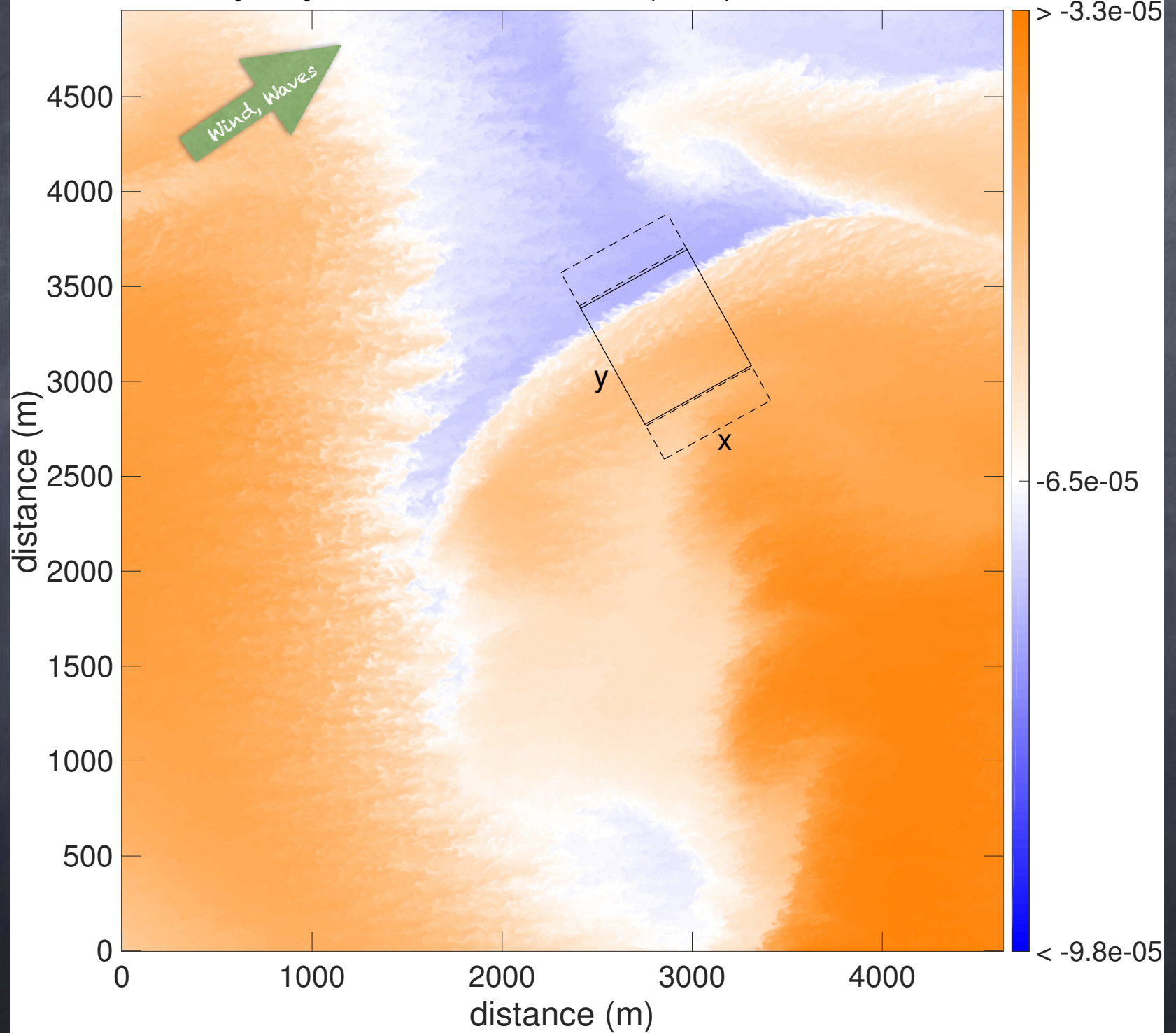
J. C. McWilliams and BFK. Oceanic wave-balanced surface fronts and filaments. Journal of Fluid Mechanics, 730:464-490, 2013.

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

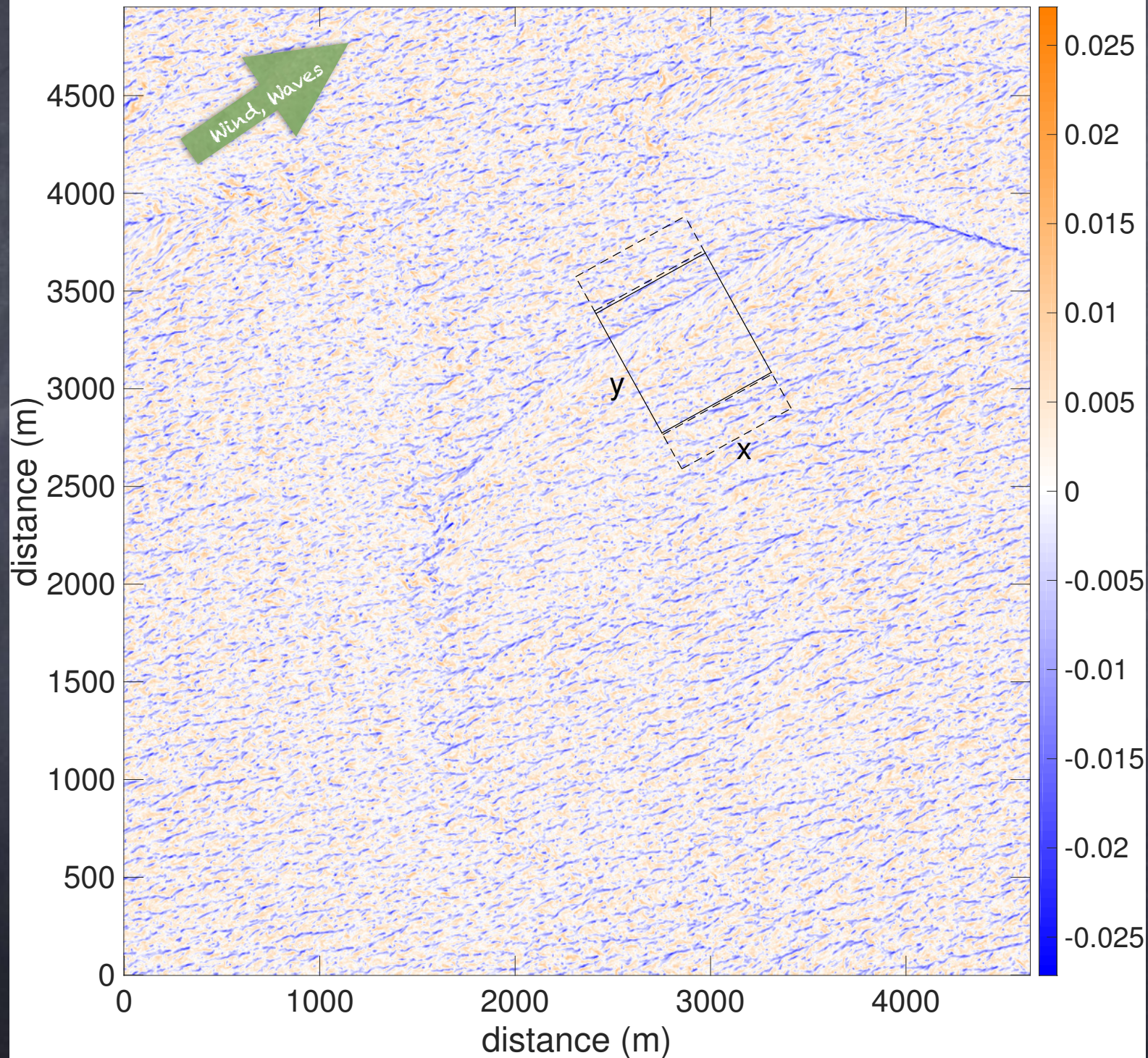
velocity in the x-direction - the horizontal mean ( $\text{ms}^{-1}$ ) at  $z = -11.25\text{m}$

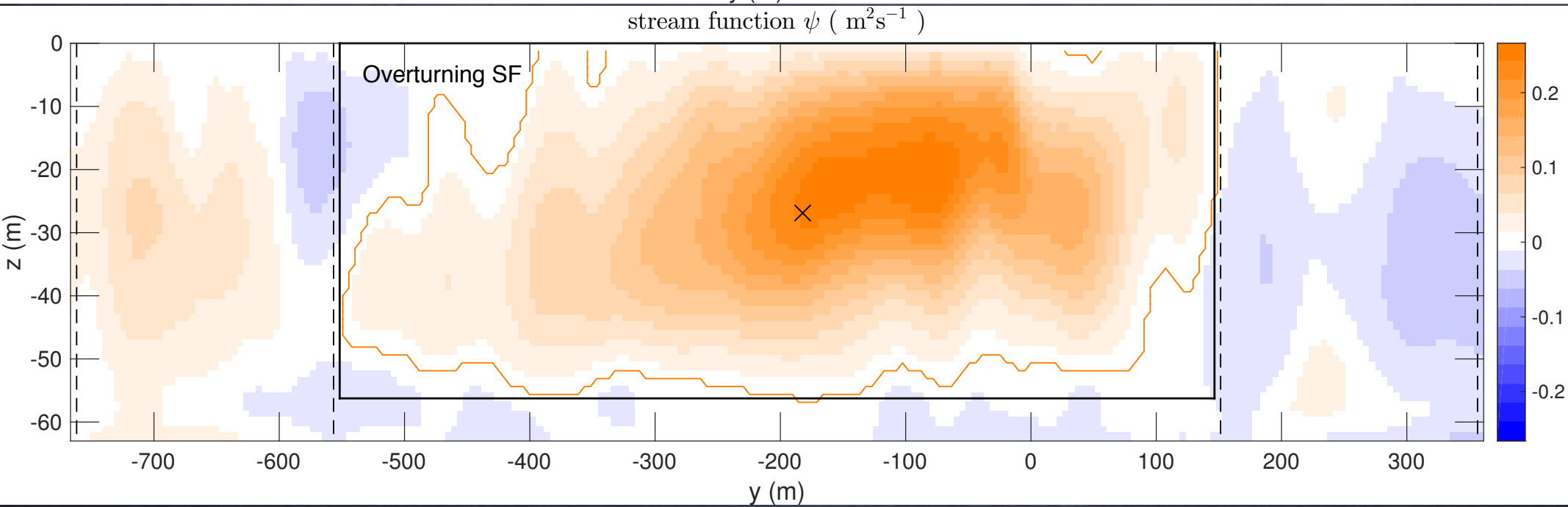
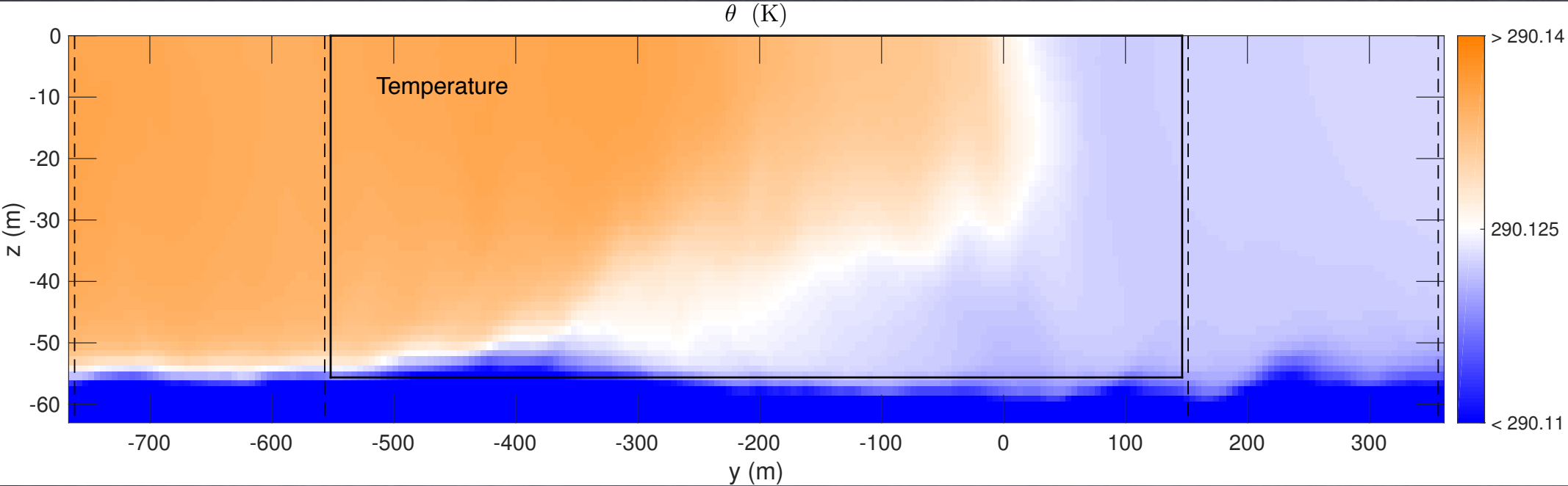


buoyancy - the horizontal mean ( $\text{ms}^{-2}$ ) at  $z = -11.25\text{m}$



vertical velocity ( $\text{ms}^{-1}$ ) at  $z = -11.25\text{m}$



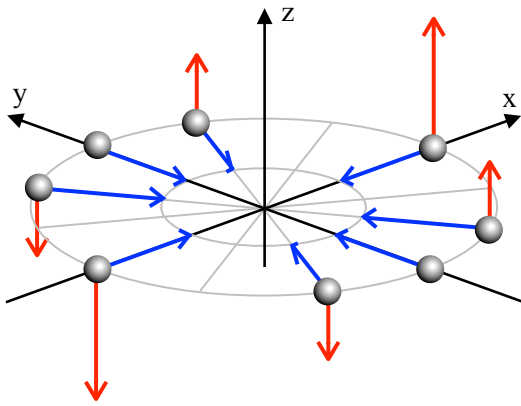


# Stokes Shear Force in Budgets for Overturning

- 2nd Largest Source in Ang. Momentum (26% of buoyancy)
- 3rd Largest Source in Overturning KE (24% of buoyancy)
- 2nd Largest Source of Overturning Vorticity (44% of buoyancy)

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

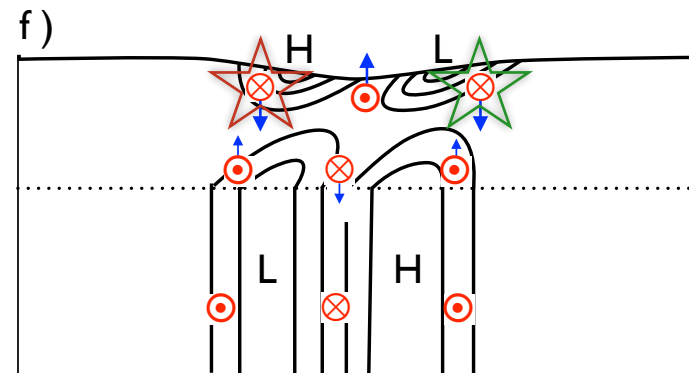
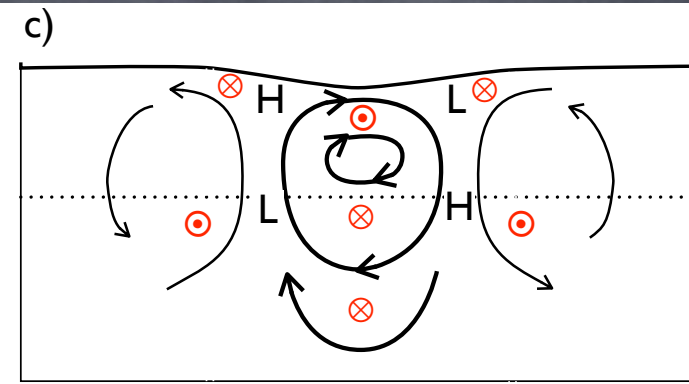
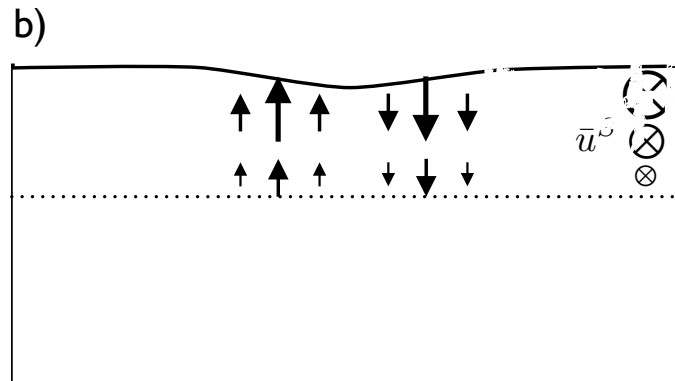
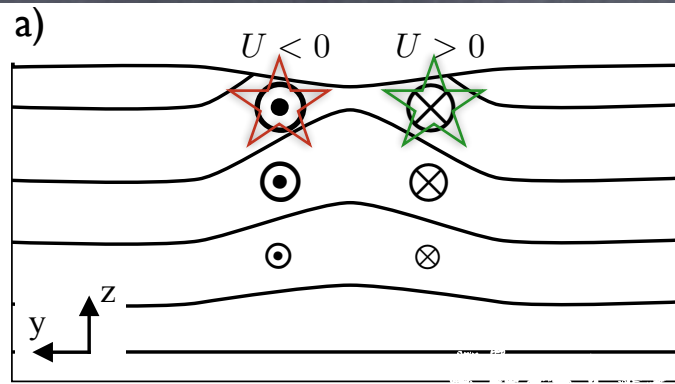
# Stokes Shear Force Affects Fronts and Filaments



←: Stokes-shear force    ●: water parcel  
←: turbulent velocity

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

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



Enhances Fronts for Down-Front Stokes

Opposes Fronts for Up-Front Stokes

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

Can it be observed?

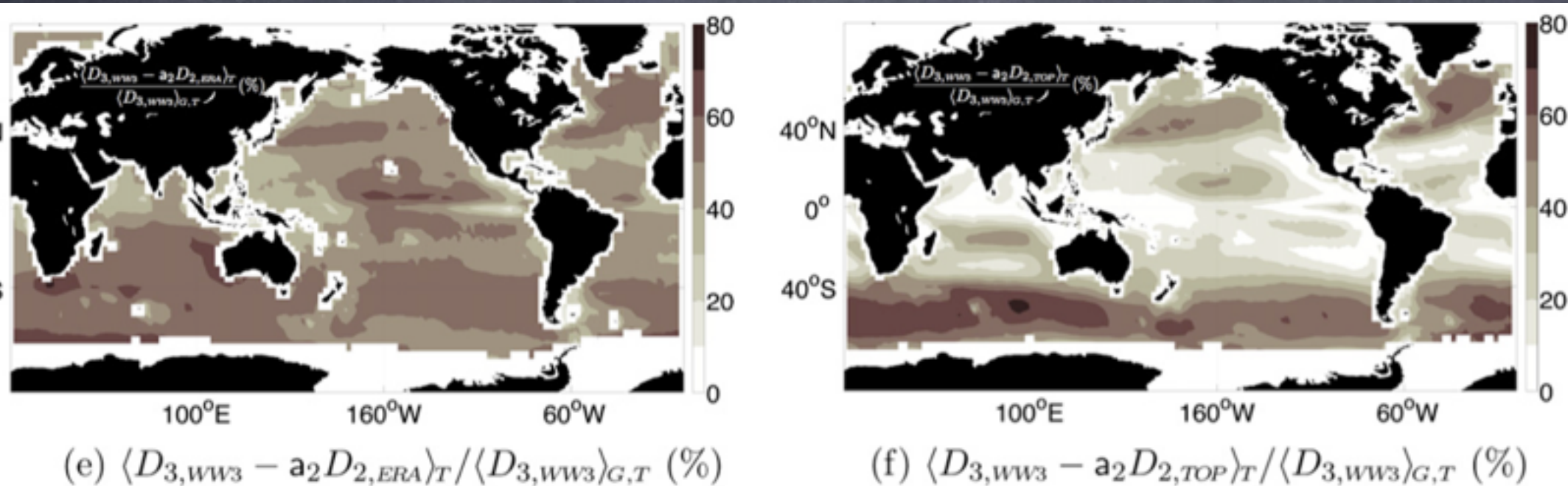




# Conclusions

- In the upper ocean, horizontal scales as big as basins, and as small as meters contribute non-negligibly to the air-sea exchange and climate
- Interesting transition occurs on the Submeso to Langmuir scale boundary, as nonhydro. & ageostrophic effects begin to dominate
- Langmuir mixing scalings consistent with LES & obs., reduce climate model biases in MLD, T, CFCs vs. observations by 5-25%.
- The 25-45% forcing effects of the Stokes Shear force on submesoscale dynamics are under-appreciated.
- All papers at: [fox-kemper.com/pubs](http://fox-kemper.com/pubs)

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



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

Year 2000 data & models

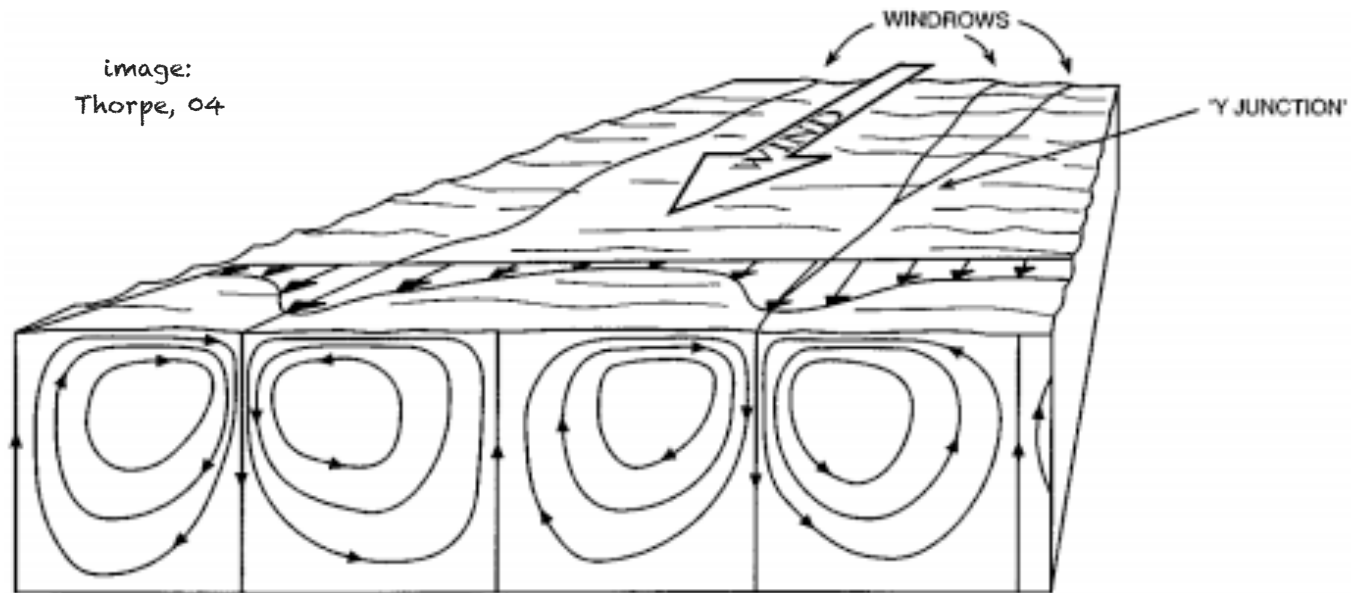
# Why? Vortex Tilting Mechanism

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

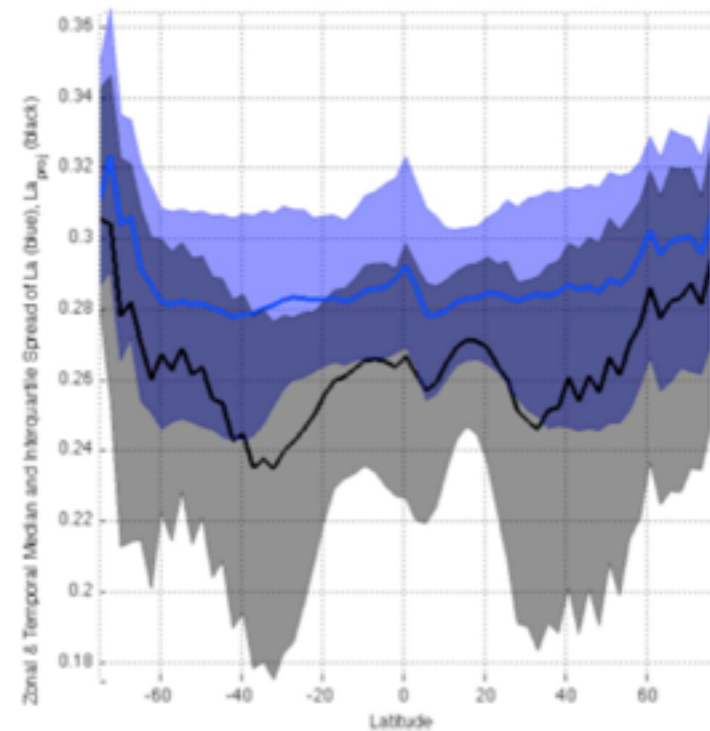
$$\frac{\partial \xi}{\partial t} + \underbrace{(\mathbf{u}_L \cdot \nabla)}_{AD} \xi = \underbrace{(\boldsymbol{\omega}_a \cdot \nabla)}_{TS} (\mathbf{u}_L \cdot \hat{\mathbf{x}}') + \underbrace{(\nabla b \times \hat{\mathbf{z}})}_{BV} \cdot \hat{\mathbf{x}}' + \text{SGS},$$

Misalignment enhances degree of wave-driven LT

image:  
Thorpe, 04



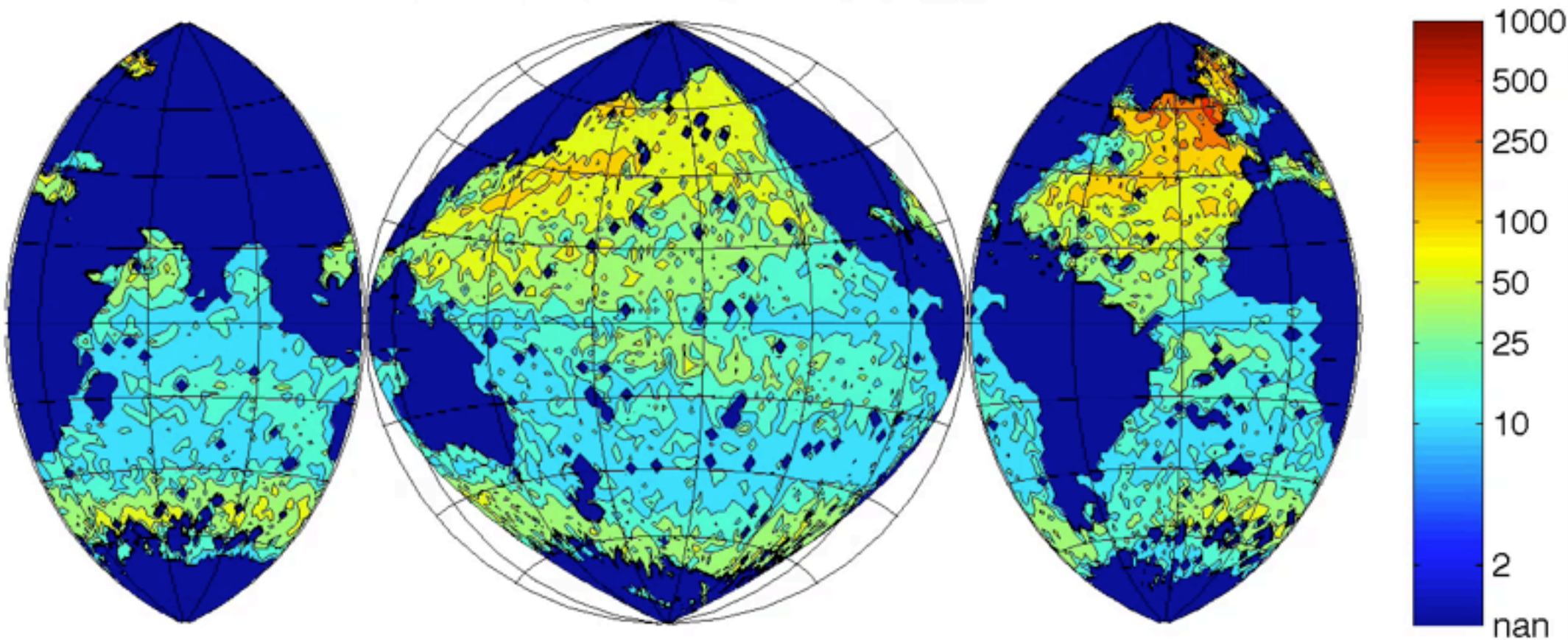
**Figure 1** Sketch showing the pattern of mean flow in idealized Langmuir circulation. The windrows may be 2 m to 300 m apart, and the cell form is roughly square (as shown). In practice the flow is turbulent, especially near the water surface, and the windrows (Figure 2) amalgamate and meander in space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



**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.

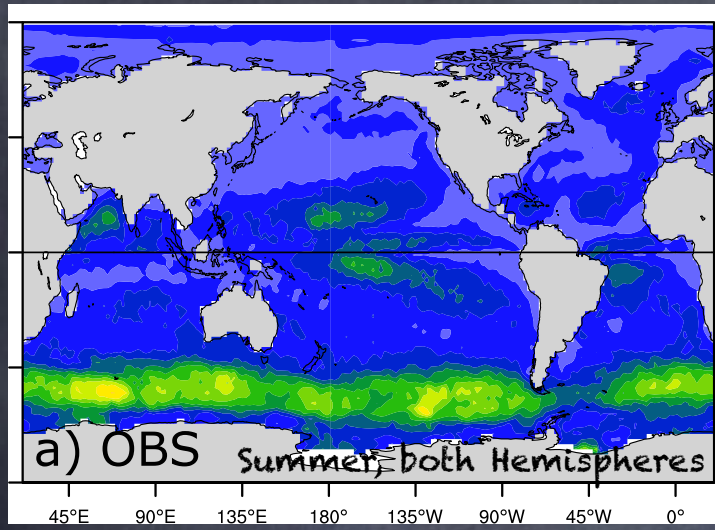
# The Ocean Mixed Layer

Mixed Layer Depth ( $\Delta$  density=0.001) in month 1

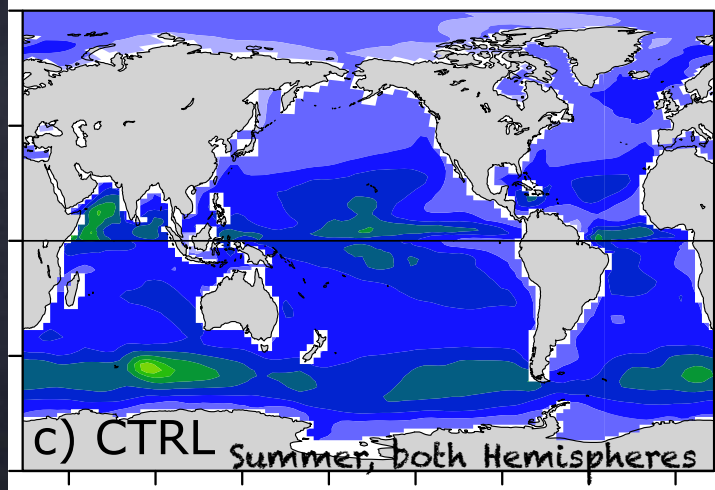
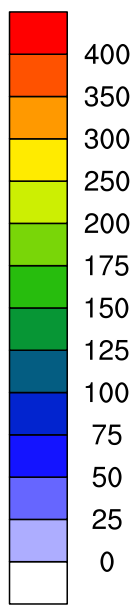
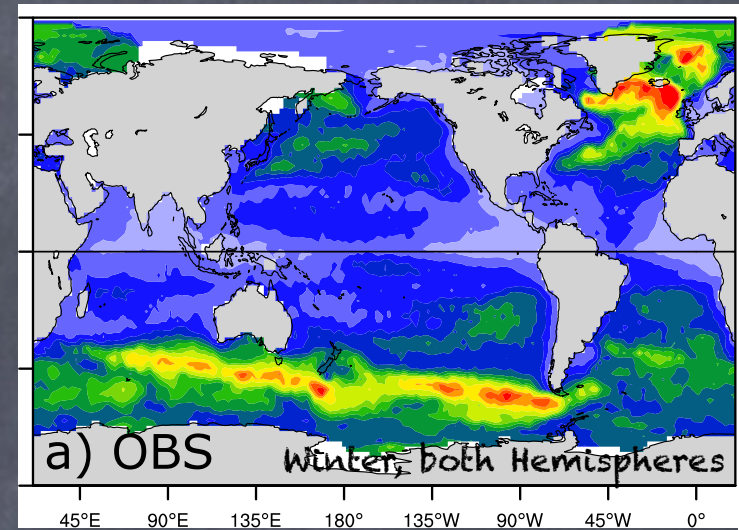
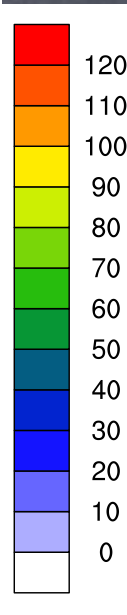


**Stommel's Demon:** ocean properties at depth set by deepest wintertime mixed layer & its properties  
From Argo float data courtesy C. de Boyer-Montegut

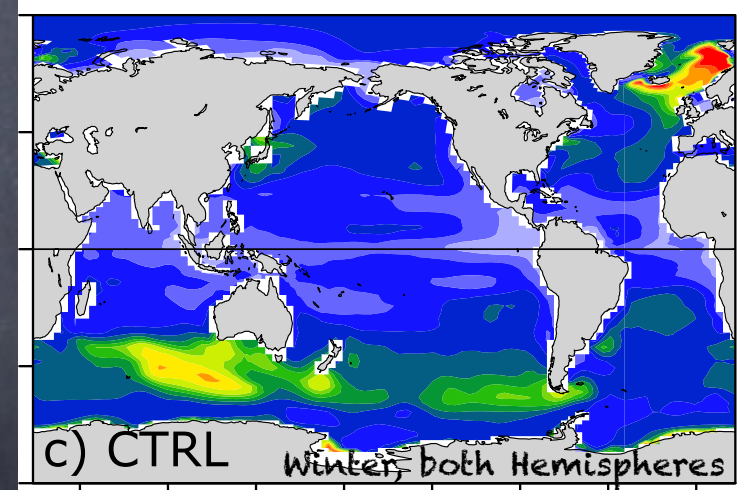
# The State of the Art: Observations vs. Mixed Layers in CESM1.2



Observed



Climate  
Model



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.

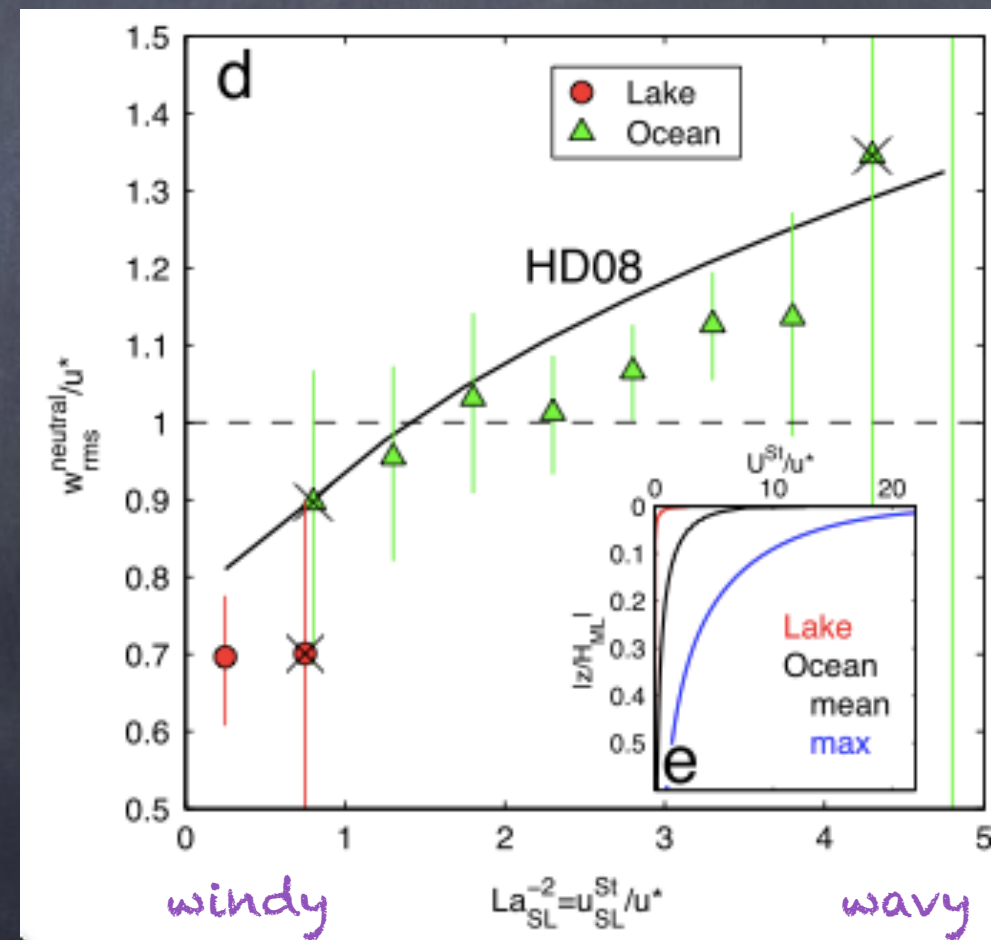
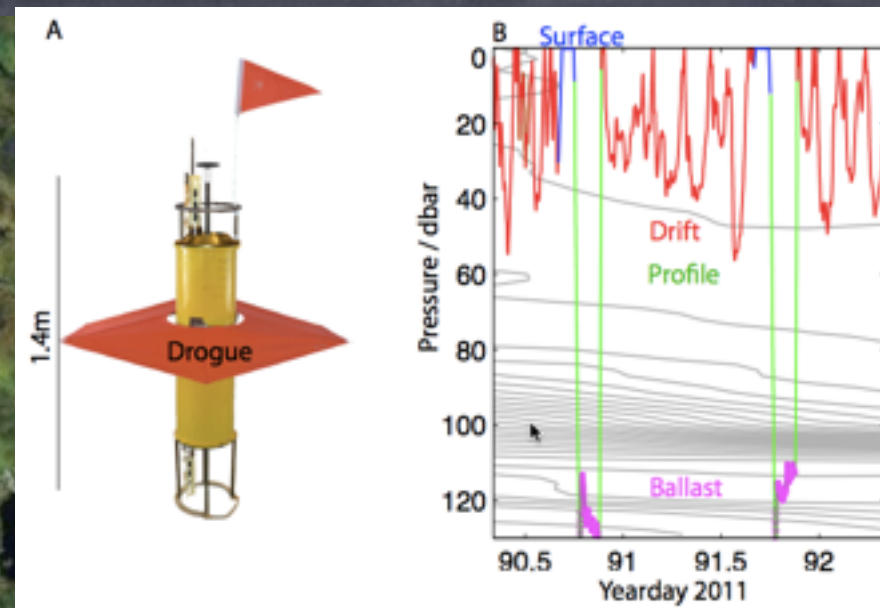
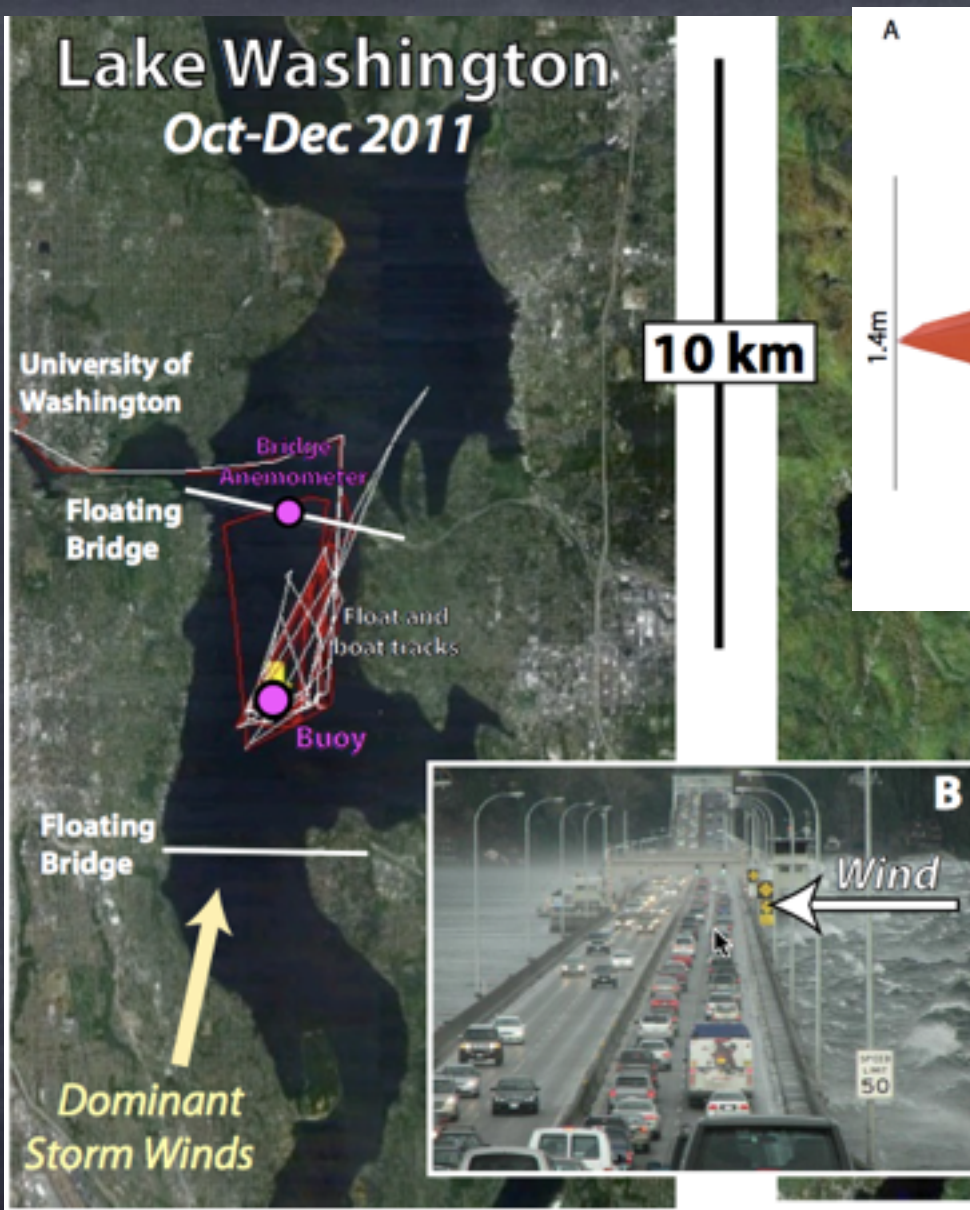
May partly account for large annual cycle errors.

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.

# 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 coefficients from LES

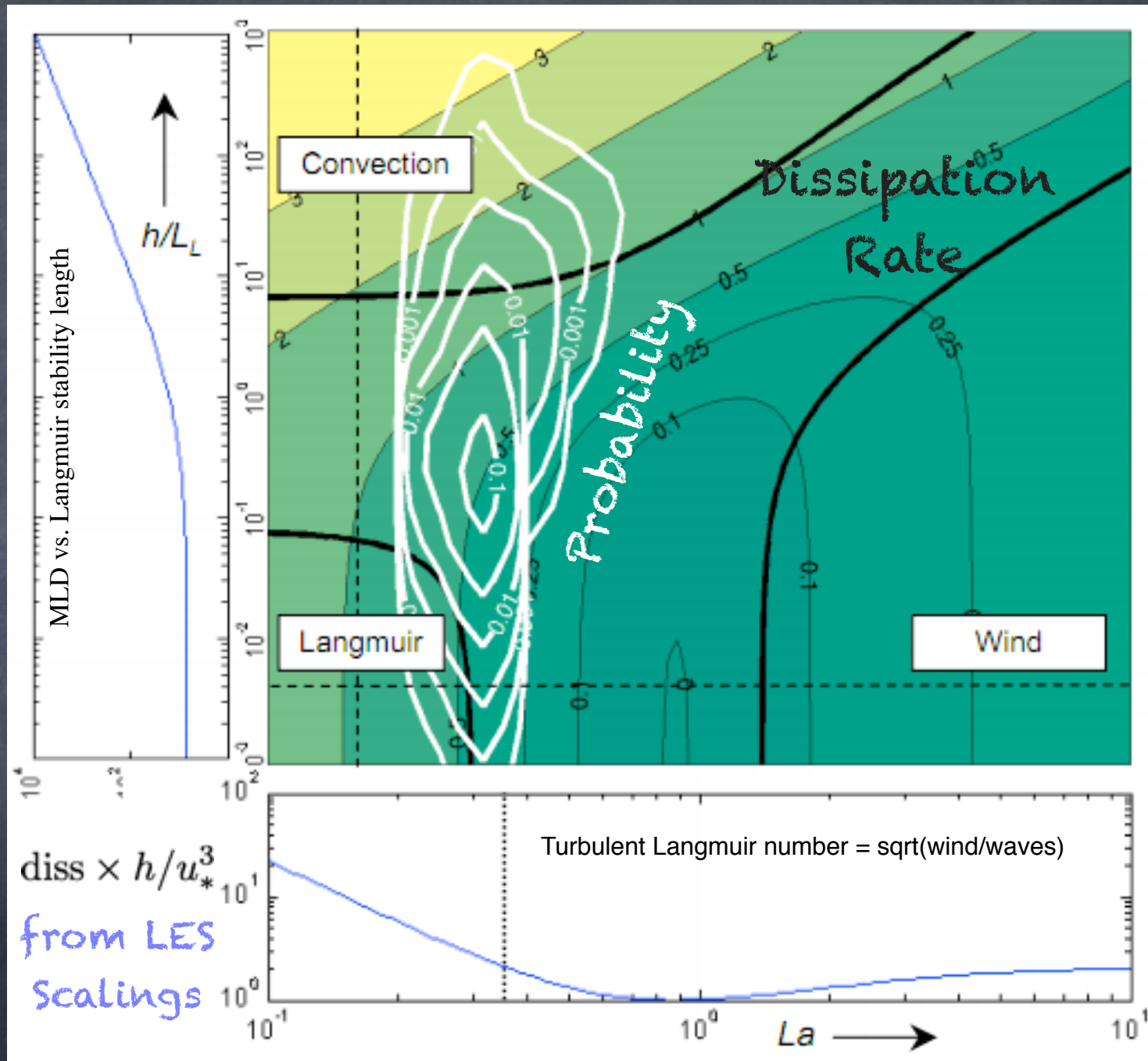


1) Observations obey a particular scaling for  $\langle w^2 \rangle$ !

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.

Data + Large Eddy Simulation for scaling laws, Southern Ocean data to determine available mixing energy

So, waves are likely to drive mixing via Stokes drift (combines with cooling & winds)



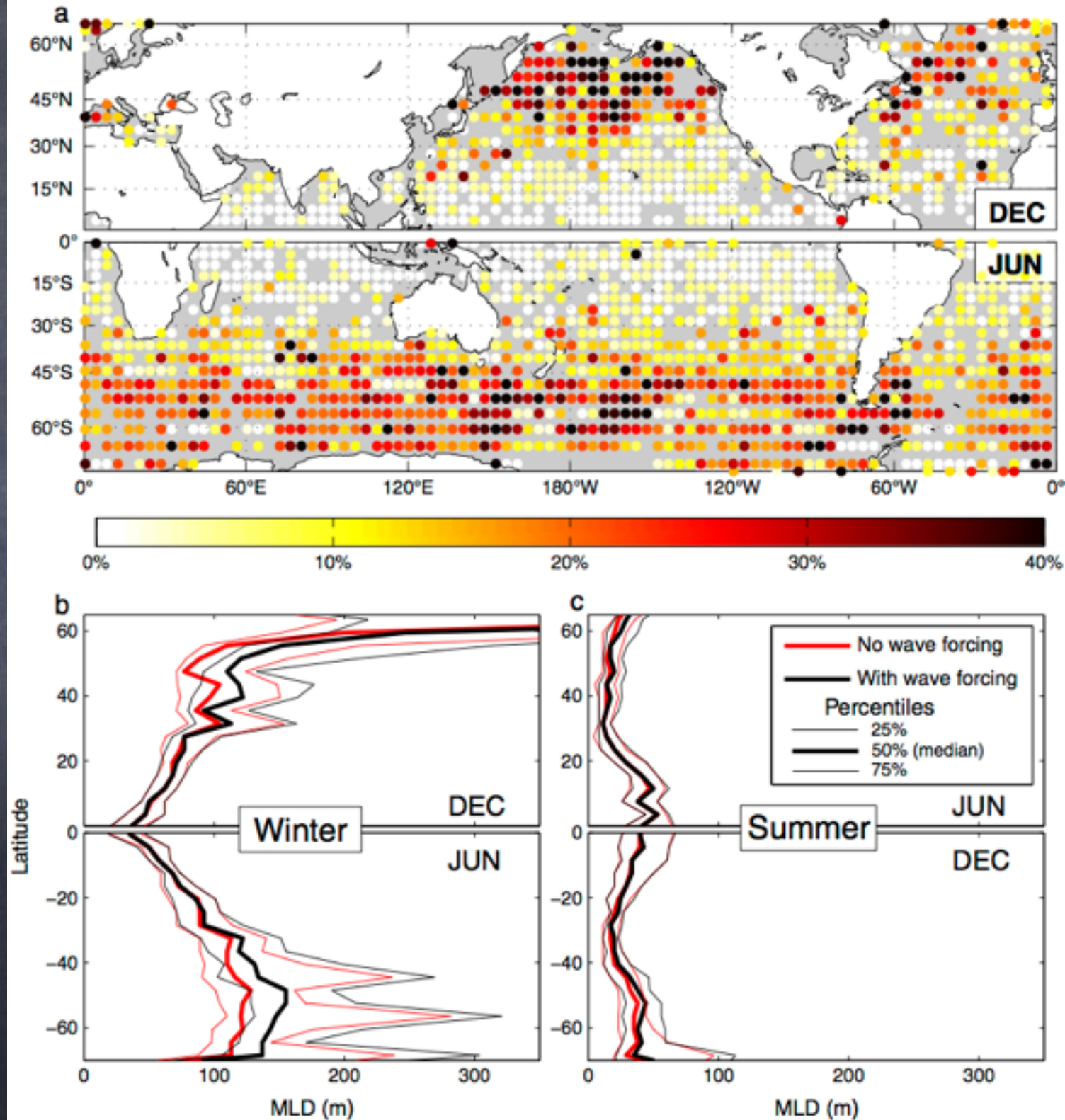
S. E. Belcher, A. A. L. M. Grant, K. E. Hanley, BFK, L. Van Roekel, P. P. Sullivan, W. G. Large, A. Brown, A. Hines, D. Calvert, A. Rutgersson, H. Petterson, J. Bidlot, P. A. E. M. Janssen, and J. A. Polton. A global perspective on Langmuir turbulence in the ocean surface boundary layer. *Geophysical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



# Including Stokes-driven Mixing should deepen the Mixed Layer!

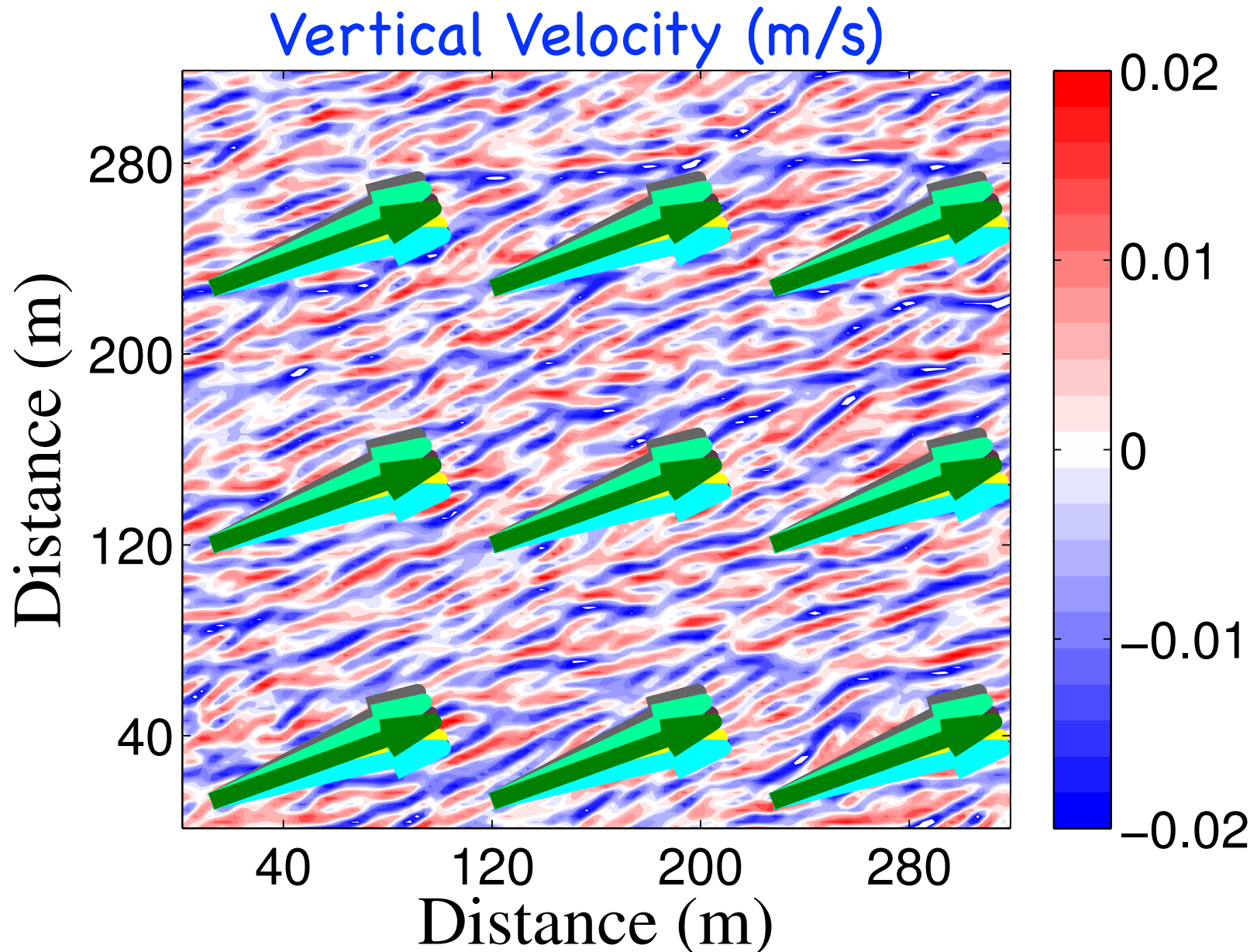
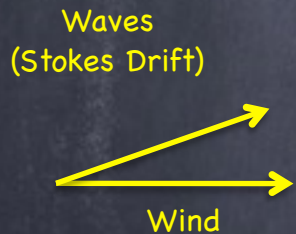
E. A. D'Asaro, J. Thomson, A. Y. Shcherbina, R. R. Harcourt, M. F. Cronin, M. A. Hemer, and BFK. Quantifying upper ocean turbulence driven by surface waves. *Geophysical Research Letters*, 41(1):102-107, January 2014.

As estimated with:  
Argo-observed stratification,  
modeled waves,  
an LES-validated mixing parameterization,  
and observed winds, solar, latent, etc.



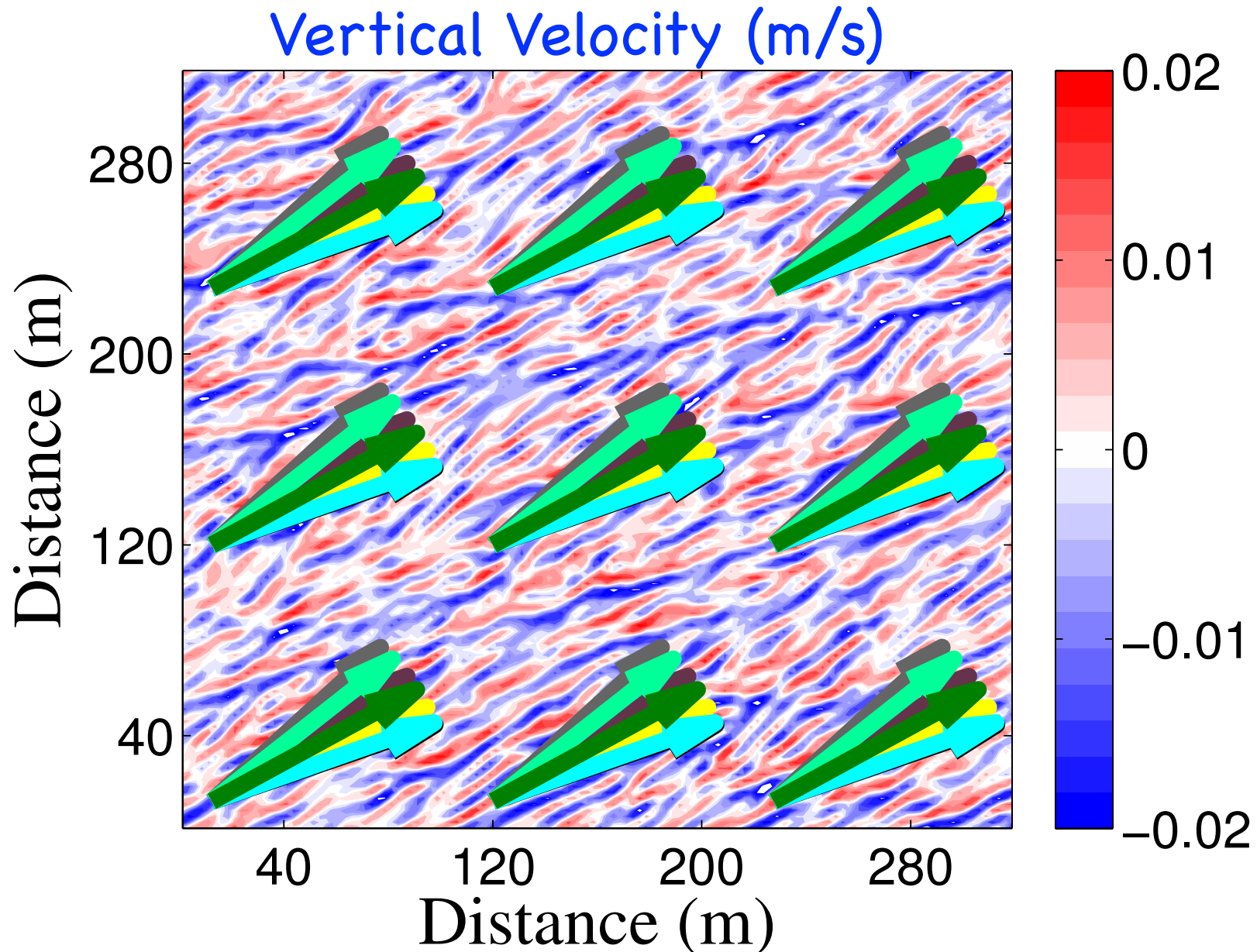
# Something that happens often with waves: Tricky: Misaligned Wind & Waves

A. Webb and BFK. Impacts of wave spreading and multidirectional waves on estimating Stokes drift. *Ocean Modelling*, 96(1): 49-64, December 2015.



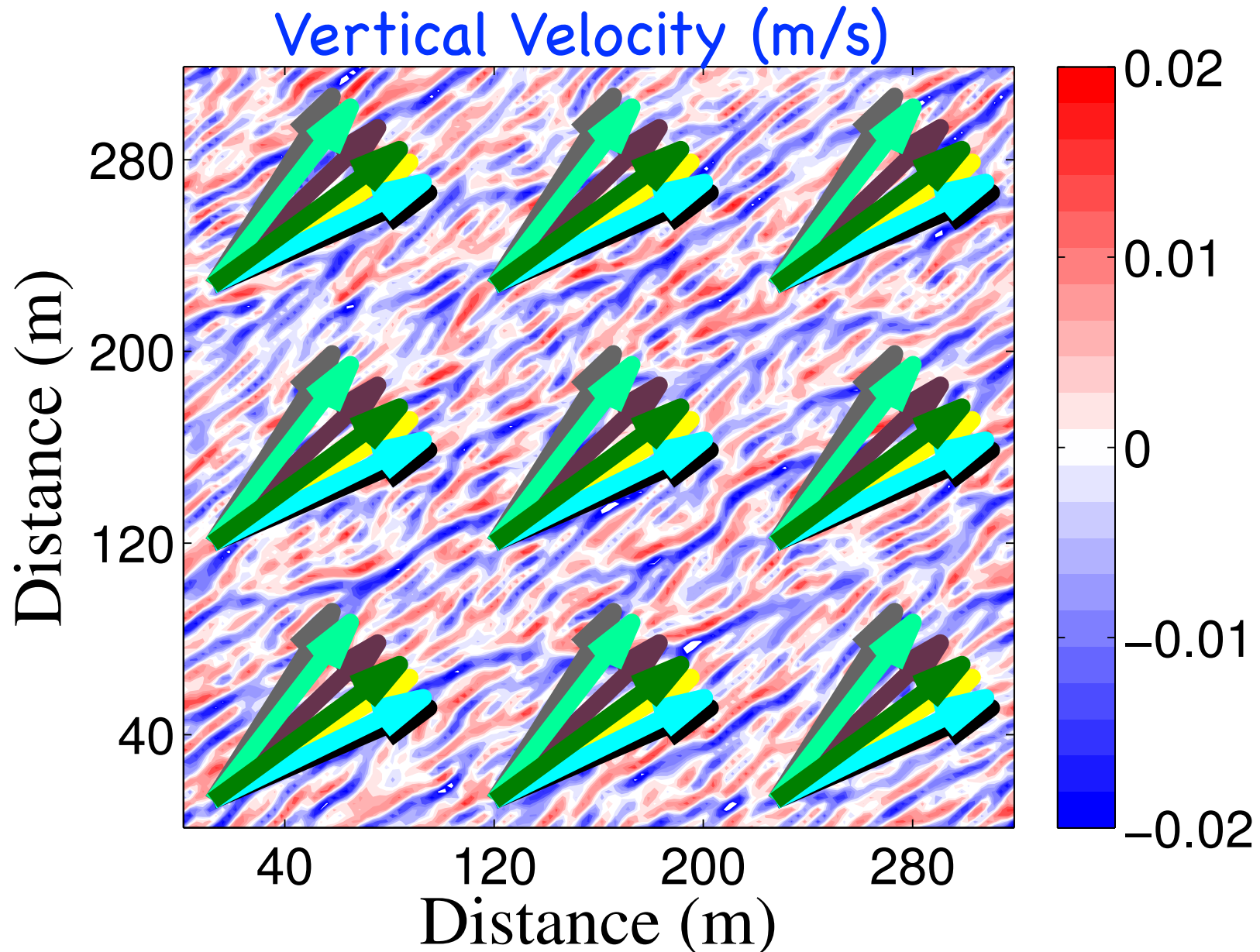
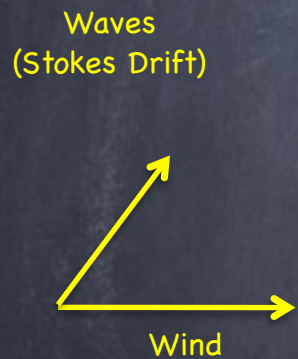
L. P. Van Roekel, BFK, P. P. Sullivan, P. E. Hamlington, and S. R. Haney. The form and orientation of Langmuir cells for misaligned winds and waves. *Journal of Geophysical Research-Oceans*, 117:C05001, 22pp, May 2012.

# Tricky: Misaligned Wind & Waves



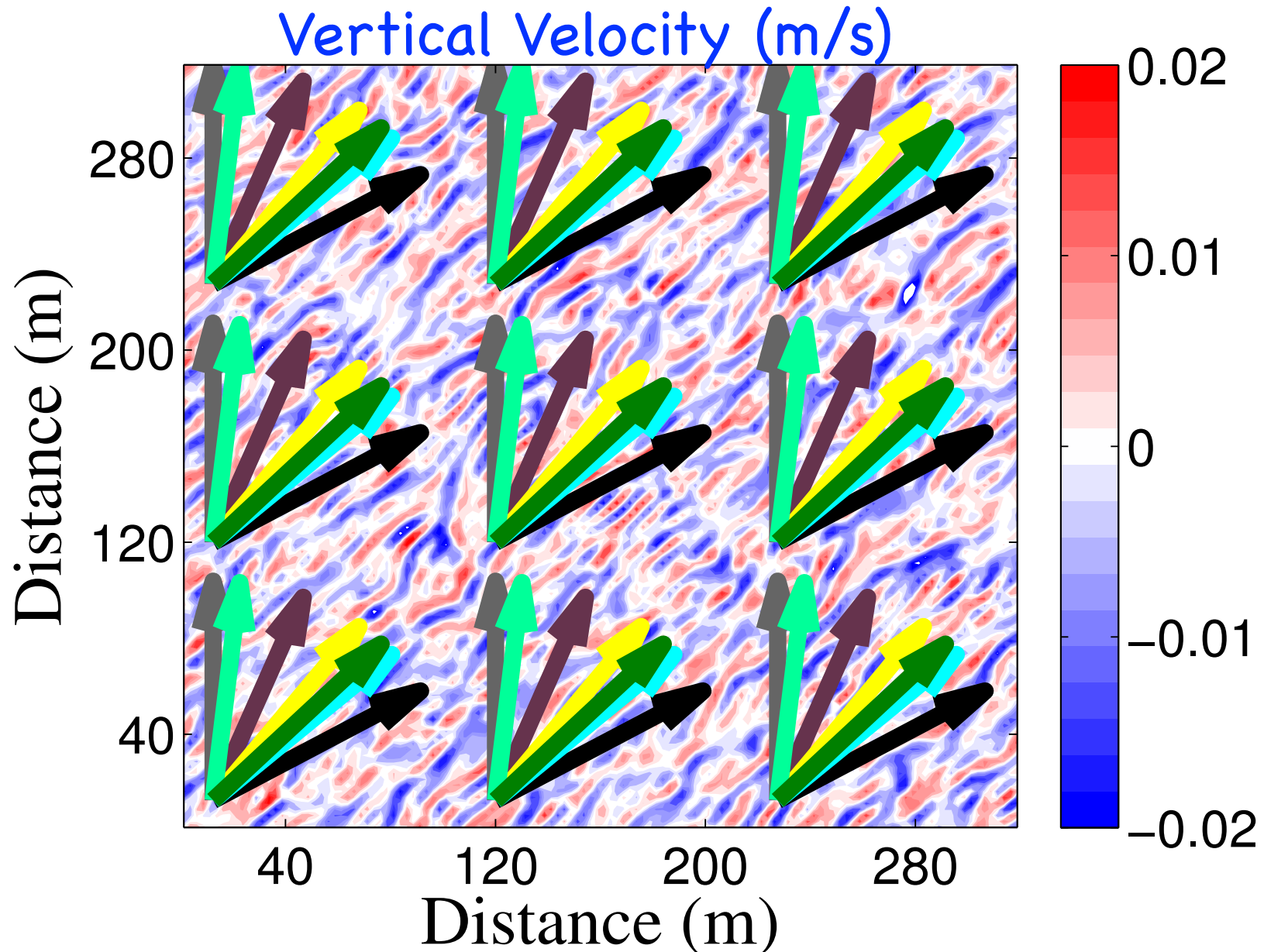
L. P. Van Roekel, BFK, P. P. Sullivan, P. E. Hamlington, and S. R. Haney. The form and orientation of Langmuir cells for misaligned winds and waves. *Journal of Geophysical Research-Oceans*, 117:C05001, 22pp, May 2012.

# Tricky: Misaligned Wind & Waves



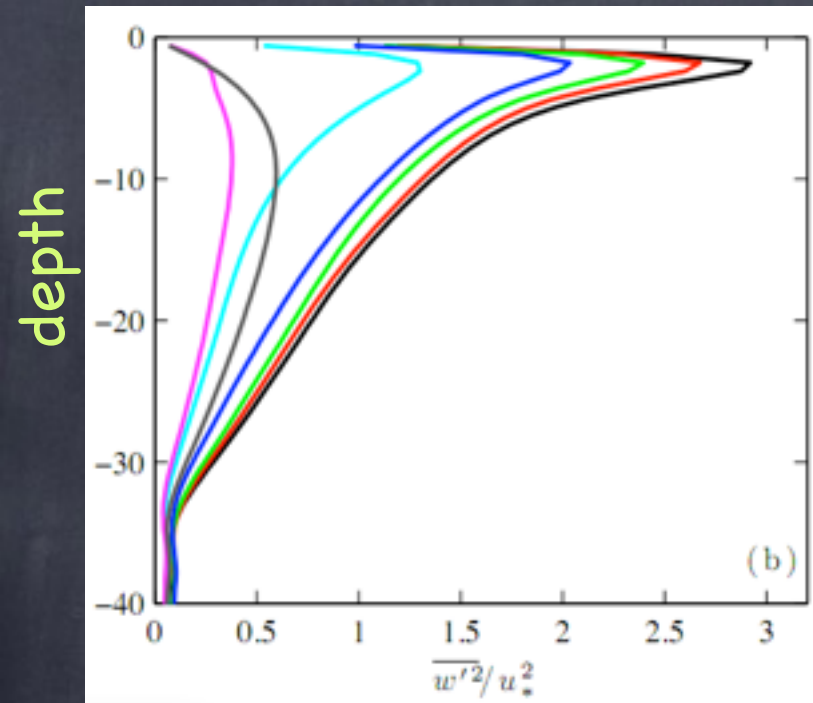
L. P. Van Roekel, BFK, P. P. Sullivan, P. E. Hamlington, and S. R. Haney. The form and orientation of Langmuir cells for misaligned winds and waves. *Journal of Geophysical Research-Oceans*, 117:C05001, 22pp, May 2012.

# Tricky: Misaligned Wind & Waves

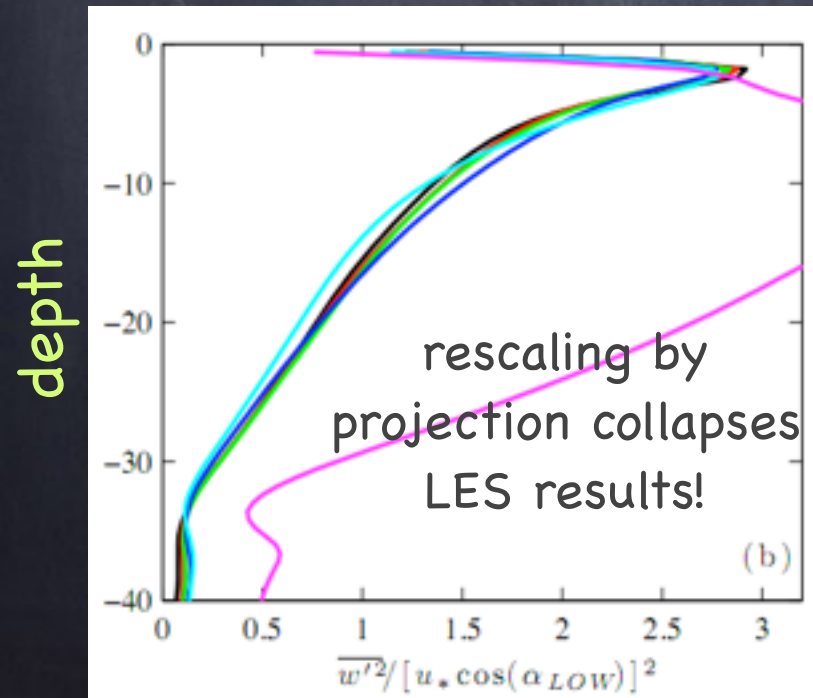


L. P. Van Roekel, BFK, P. P. Sullivan, P. E. Hamlington, and S. R. Haney. The form and orientation of Langmuir cells for misaligned winds and waves. *Journal of Geophysical Research-Oceans*, 117:C05001, 22pp, May 2012.

$\langle w^2 \rangle$



rescaled  $\langle w^2 \rangle$



# Generalized Turbulent Parameter (Langmuir Number) Projection of $u^*$ , $u_s$ into Langmuir Direction

$$La_{proj}^2 = \frac{|u_*| \cos(\alpha_{LOW})}{|u_s| \cos(\theta_{ww} - \alpha_{LOW})},$$

A scaling for LC strength & direction!

Enough for climate model application

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.