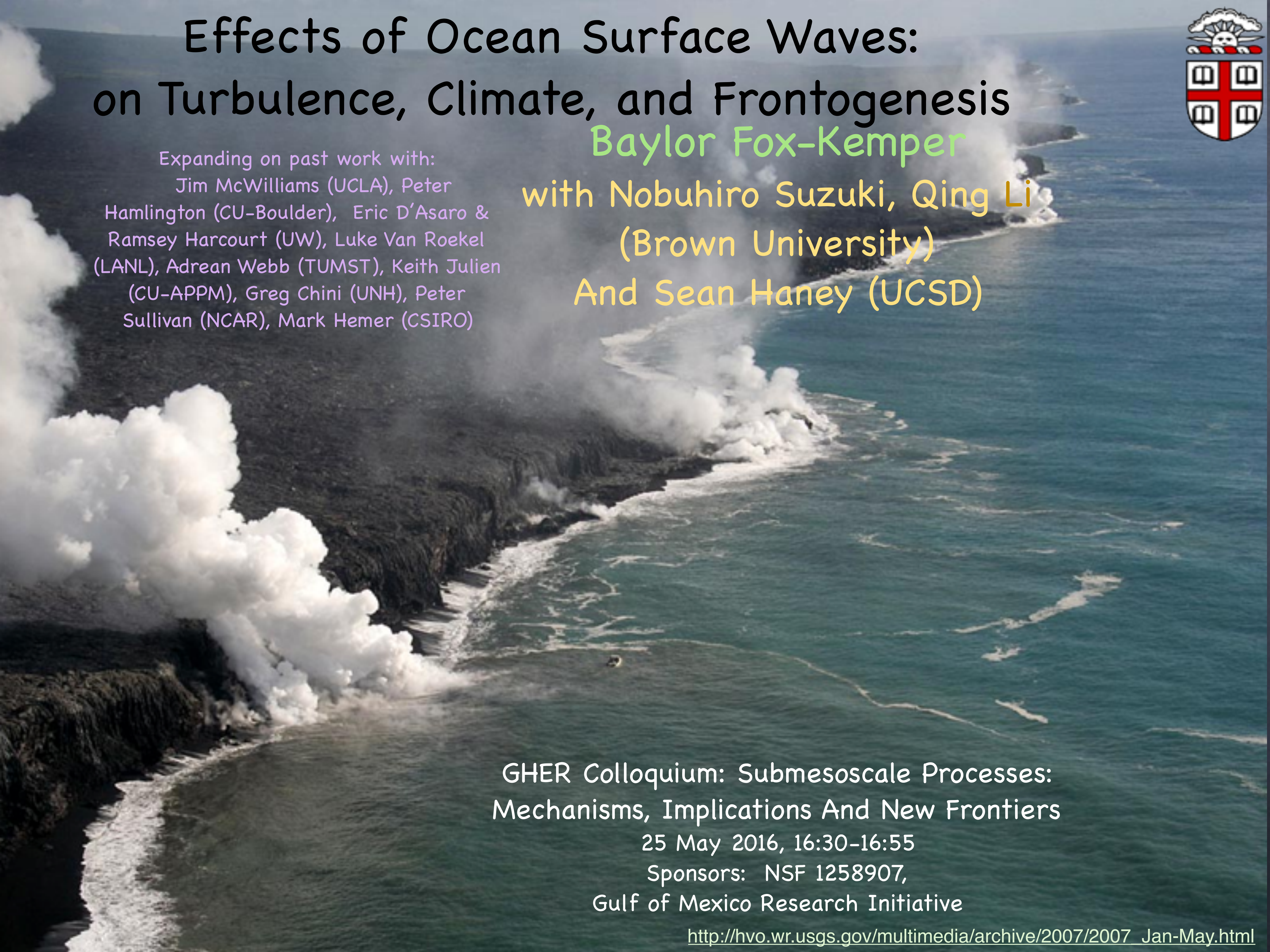
Effects of Ocean Surface Waves: on Turbulence, Climate, and Frontogenesis

Baylor Fox-Kemper
with Nobuhiro Suzuki, Qing Li
(Brown University)
And Sean Haney (UCSD)

Expanding on past work with: Jim McWilliams (UCLA), Peter Hamlington (CU-Boulder), Eric D'Asaro & Ramsey Harcourt (UW), Luke Van Roekel (LANL), Adrean Webb (TUMST), Keith Julien (CU-APPM), Greg Chini (UNH), Peter Sullivan (NCAR), Mark Hemer (CSIRO)



GHER Colloquium: Submesoscale Processes: Mechanisms, Implications And New Frontiers
25 May 2016, 16:30-16:55

Sponsors: NSF 1258907,
Gulf of Mexico Research Initiative

http://hvo.wr.usgs.gov/multimedia/archive/2007/2007_Jan-May.html

We Will Examine the Effects of Surface Waves on:

- Boundary Layer Turbulence
  (wave-driven or Langmuir Turbulence)
- Climate through Langmuir Turbulence
  (via MLD changes)
- Submesoscale Fronts & Instabilities
  within the Mixed Layer
  (Stokes forces and Langmuir coupling)

Wave-Averaged Equations

following Holm (96), 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:

(Lagrangian) geostrophic

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

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

hydrostatic

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

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

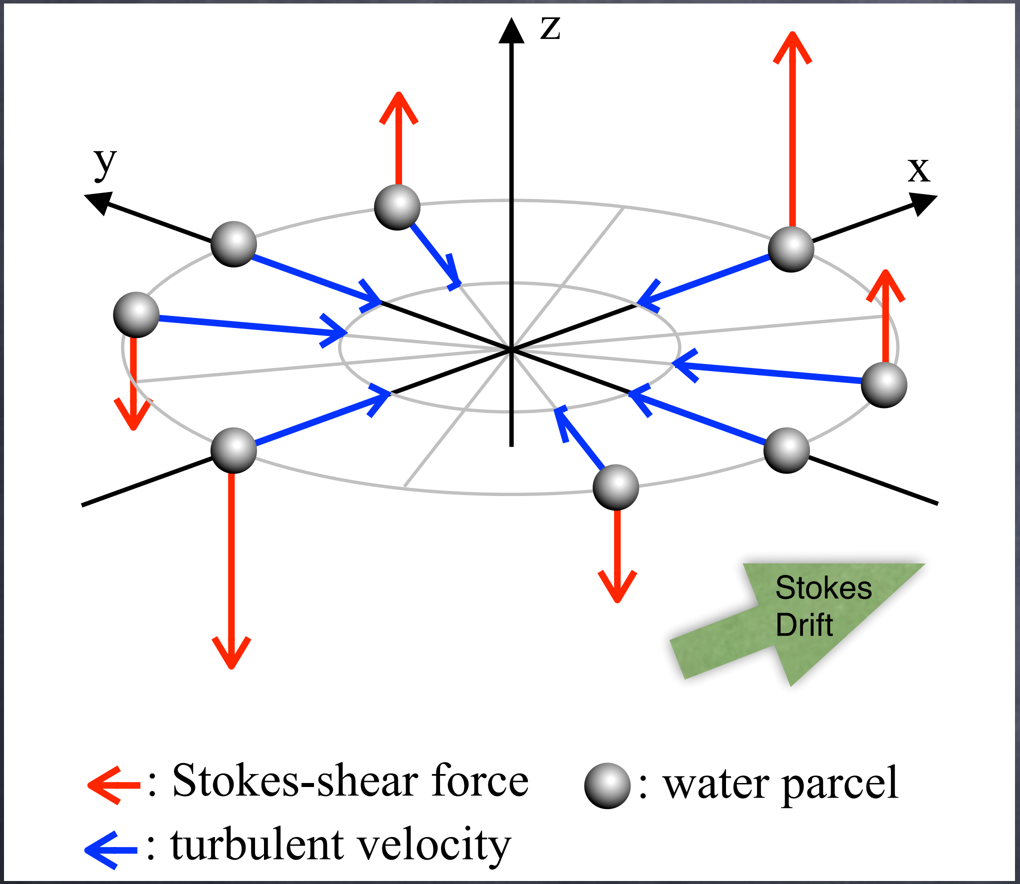
$$\boxed{\varepsilon = \frac{V^s H}{f L H_s}}$$

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

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, 2016. In press.

3 Wave Effects, 3: Stokes Shear Force
and the CL2 mechanism for Langmuir circulations
Flow directed along Stokes shear=downward force



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

"wavy hydrostatic" if

hydrostatic $\epsilon \gg 1$

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

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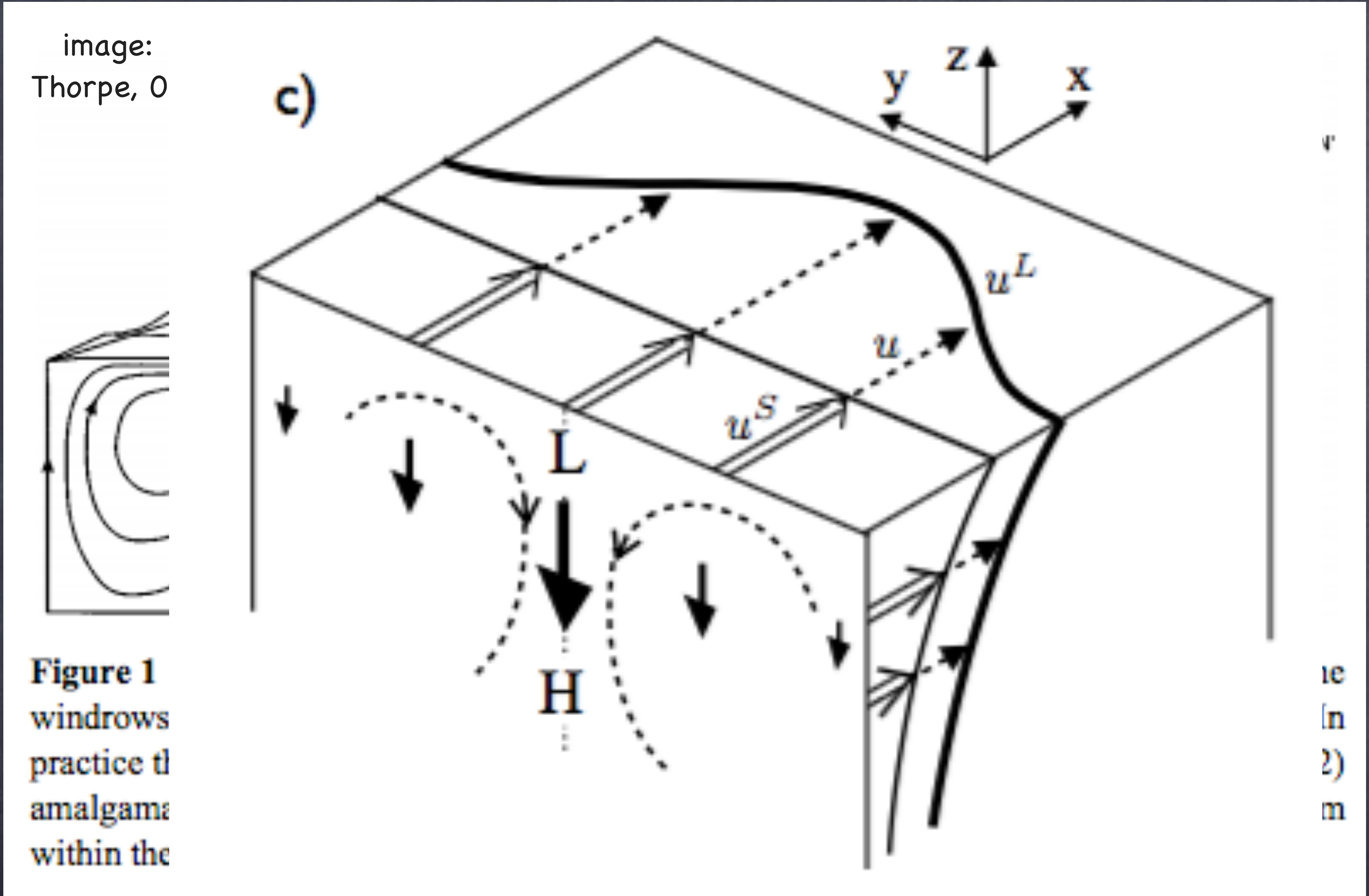

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Figure 1
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Typical effect: Downward Force for down-Flow Stokes Drift

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

N. Suzuki and BFK. Understanding Stokes forces in the wave-averaged equations. JGR-Oceans, 2016. In press.

To quantify Langmuir Turb. effects on climate: 3 WAYS

- 1) From OBSERVATIONS, estimate wave effects on key parameters (<w^2>, sources of energy) compare to scalings from Large Eddy Simulations. MODEL INDEPENDENT

- 2) OFFLINE 1d mixing with/without 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

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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.

Langmuir important ✓

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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, September 2012.

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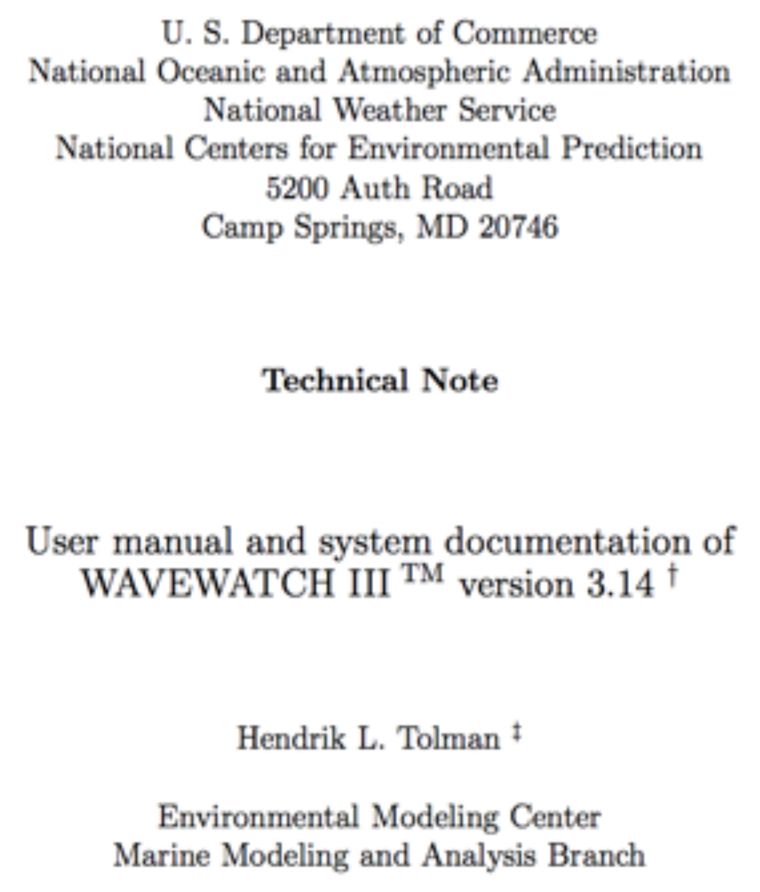


U. S. Department of Commerce
National Oceanic and Atmospheric Administration
National Weather Service
National Centers for Environmental Prediction
5200 Auth Road
Camp Springs, MD 20746

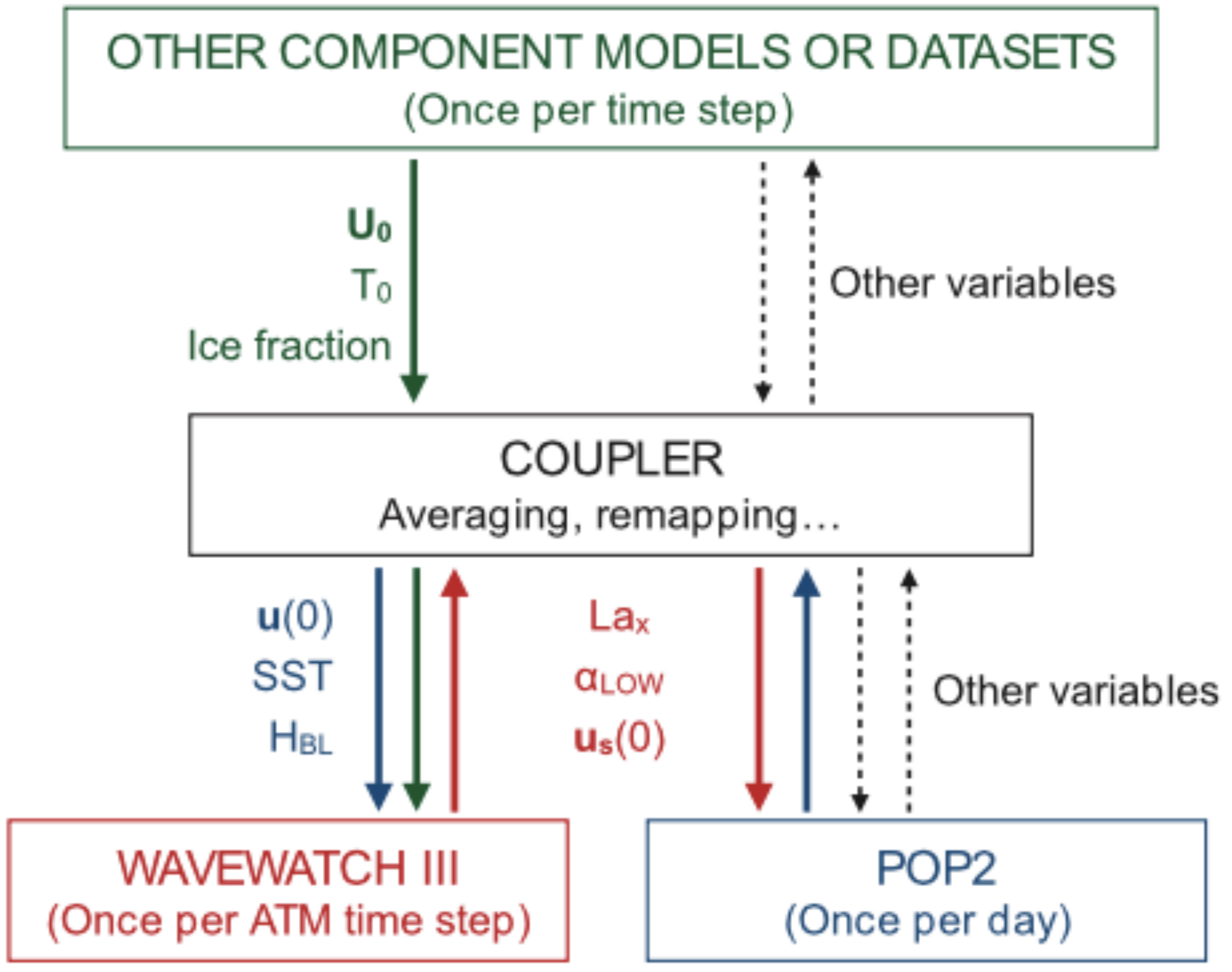
Technical Note

User manual and system documentation of
WAVEWATCH III ^{TM} version 3.14 †

Hendrik L. Tolman ‡

Environmental Modeling Center
Marine Modeling and Analysis Branch

See Qing Li's Poster tomorrow for a cheaper approach



WaveWatch-III is slated for CESM2/CMIP6

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.

Langmuir Mixing in Climate: Boundary layer Depth, &tc. Improved

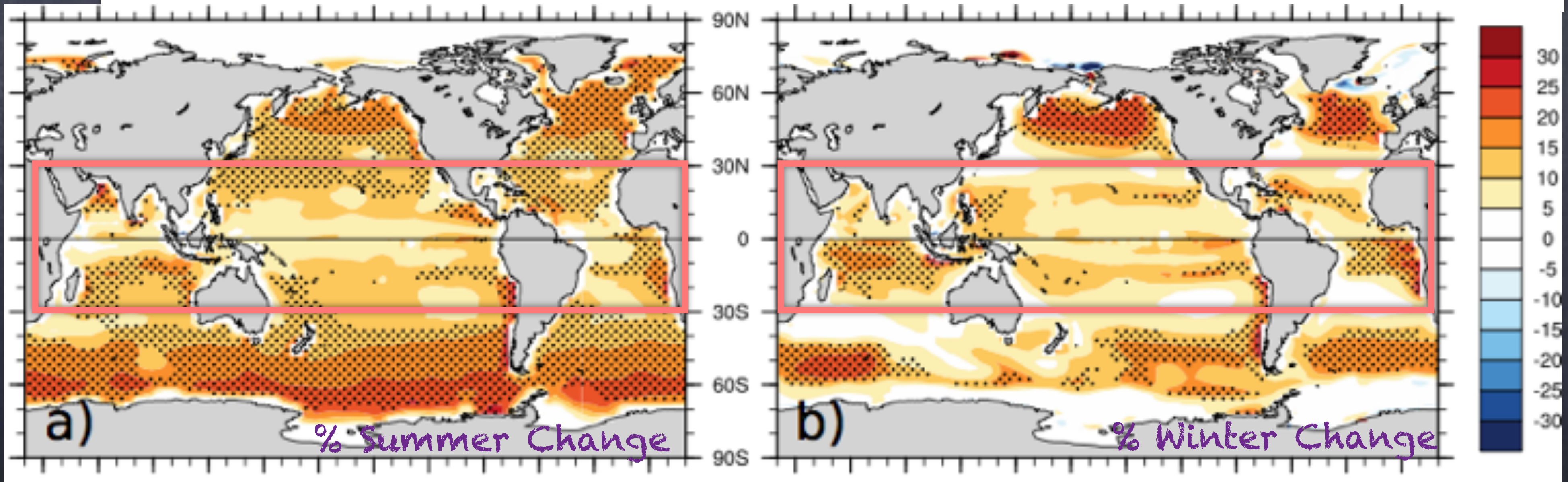
Control

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[a]	17.24±0.48	5.38±0.14	43.85±0.38	57.19±0.76	12.57±0.28
	(13.40±0.19)[b]	(21.73±0.32)	(6.71±0.09)	(45.50±0.40)	(56.53±0.59)	(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	12.65±0.47	6.61±0.22	40.99±0.37	51.78±0.65	14.23±0.30
	(11.83±0.29)	(18.13±0.62)	(7.52±0.16)	(42.02±0.39)	(50.78±0.67)	(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.

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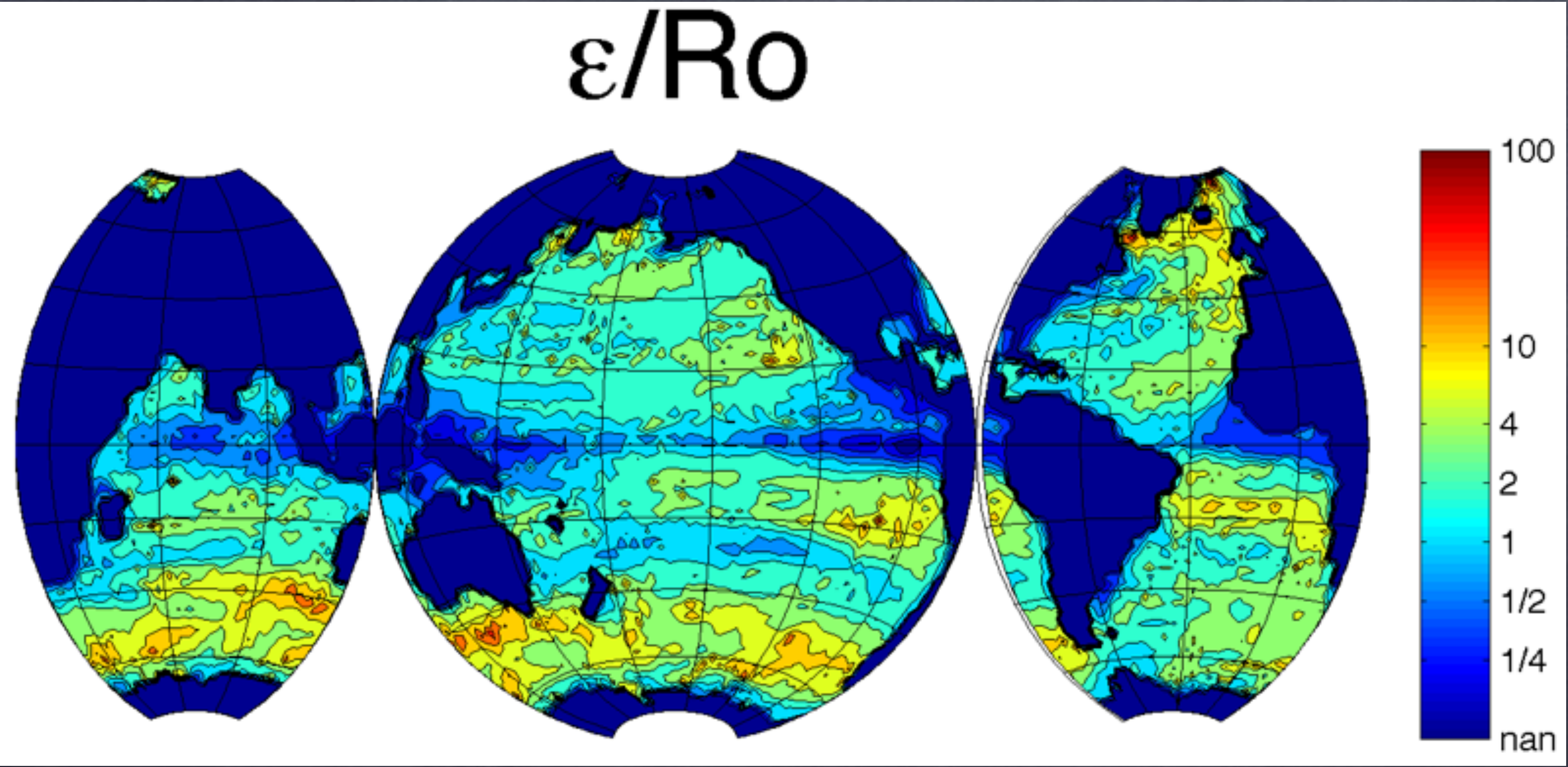
Mid-way Conclusions

- 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 vertical velocities in Langmuir turbulence–it is the proximal energy source.
- Including Langmuir mixing in climate models improves the climate model MLD, T, and uptake of CFCs.
- All papers at: fox-kemper.com/pubs

Stokes force directly affects larger scales?



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

$$\varepsilon = \frac{V^s H}{fLH_s}$$

$$Ro = \frac{U}{fL}$$

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

Langmuir-Submesoscale Front Interactions?

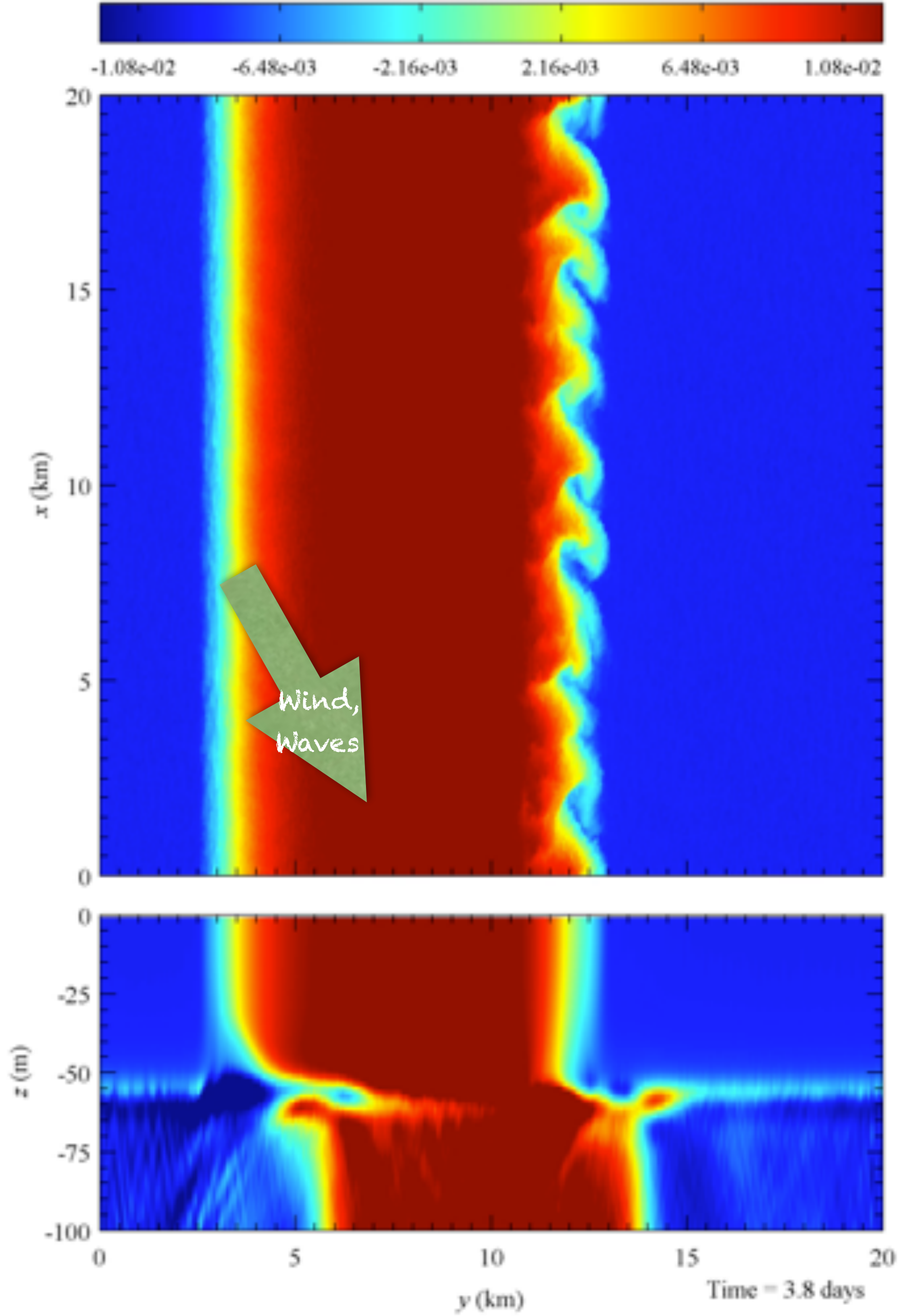
LES of Langmuir turbulence with a submesoscale temperature front

Use NCAR LES model to solve Wave-Averaged Eqtns.

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

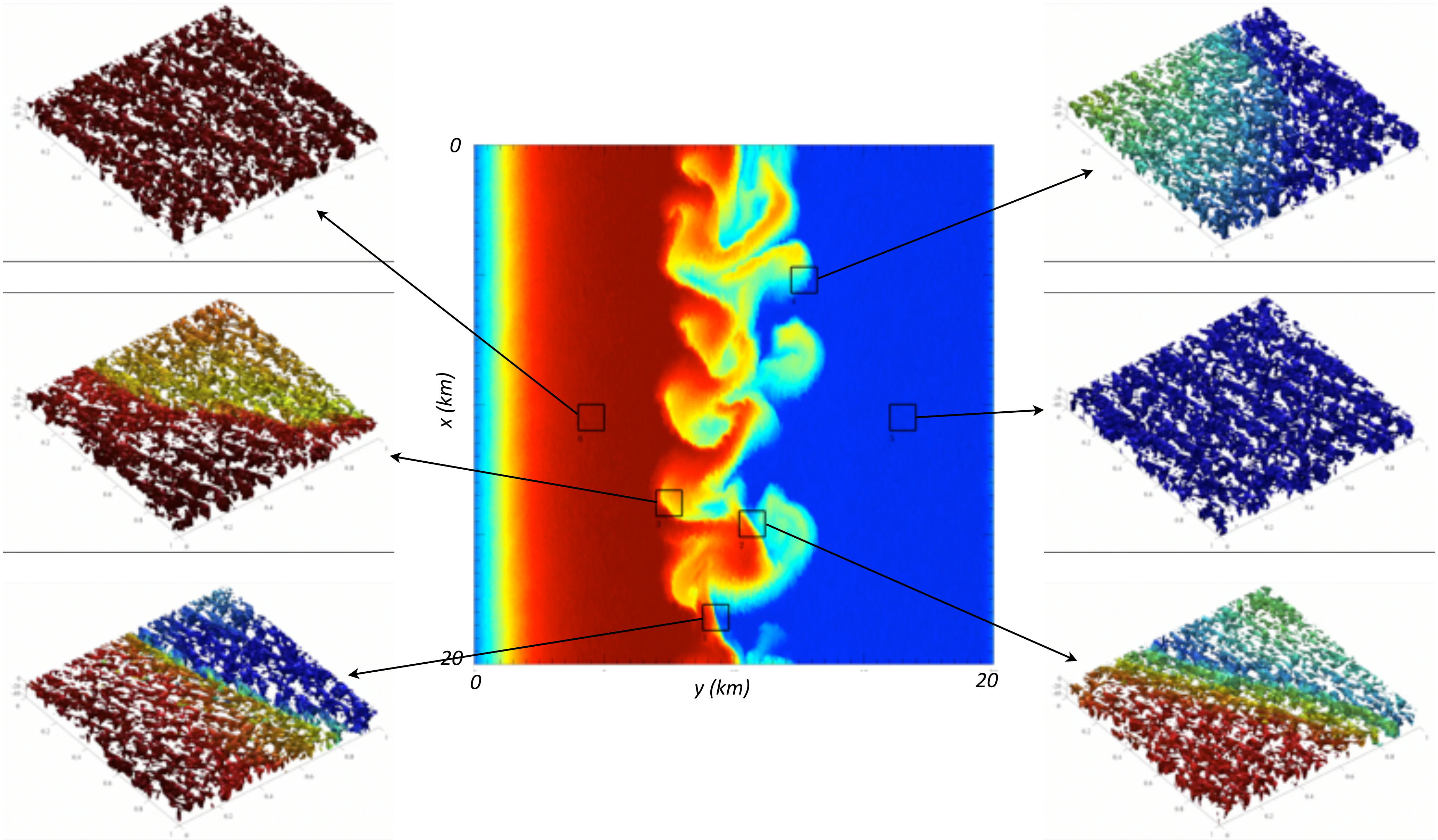
Computational parameters:
Domain size: 20km x 20km x -160m
Grid points: 4096 x 4096 x 128
Resolution: 5m x 5m x -1.25m

Movie: P. Hamlington

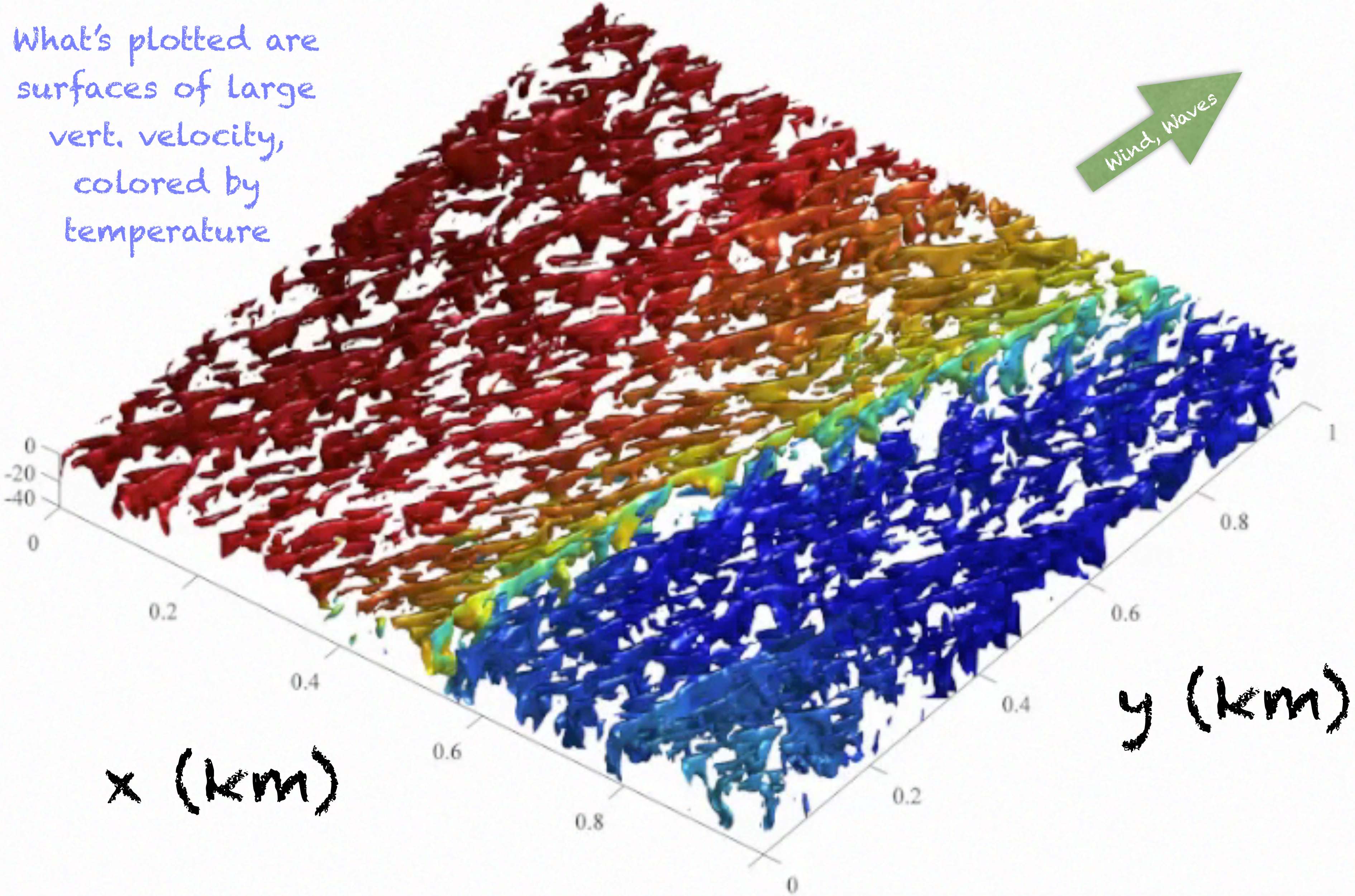


P. E. Hamlington, L. P. Van Roekel, BFK, K. Julien, and G. P. Chini. Langmuir-submesoscale interactions: Descriptive analysis of multiscale frontal spin-down simulations. Journal of Physical Oceanography, 44(9):2249-2272, September 2014.

Diverse types of interaction

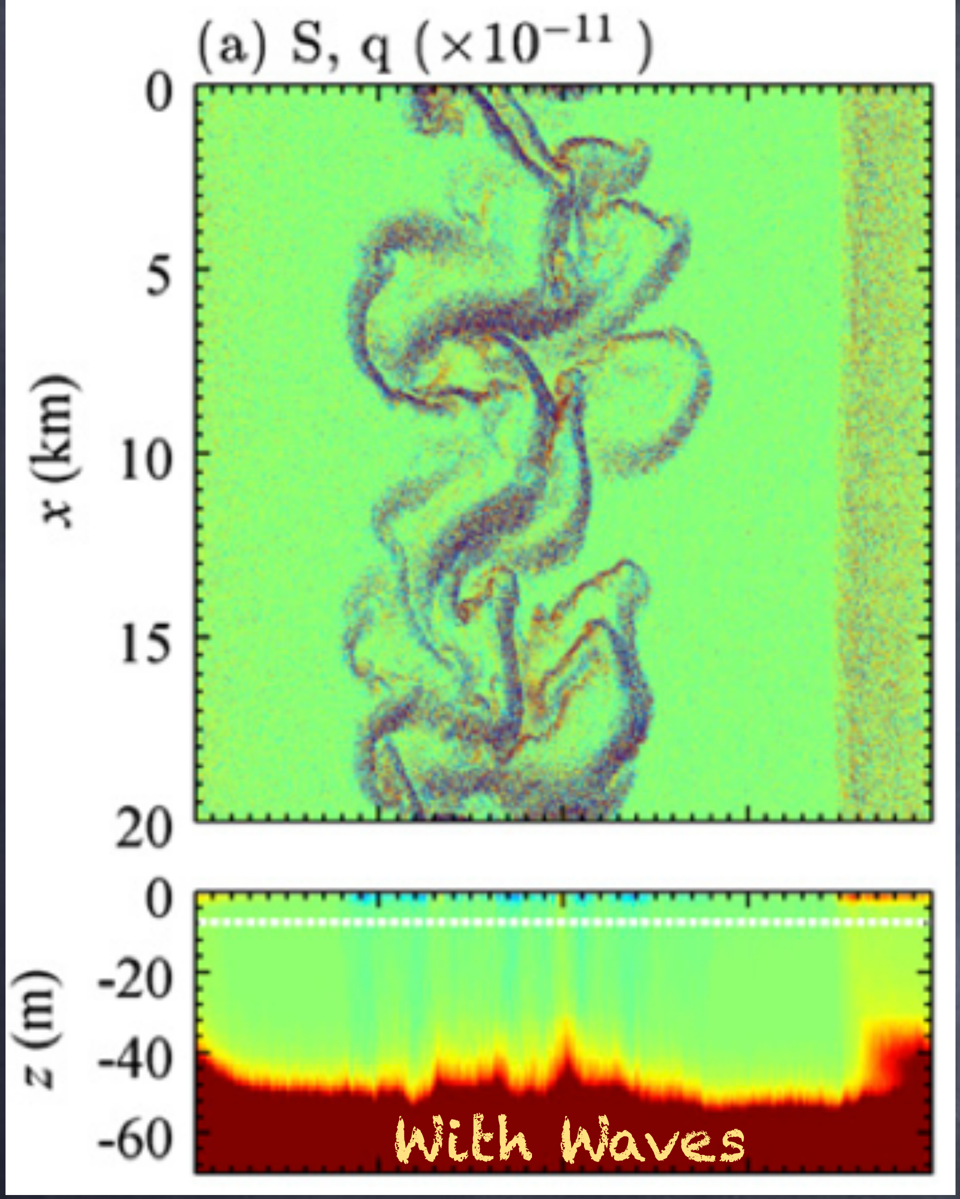


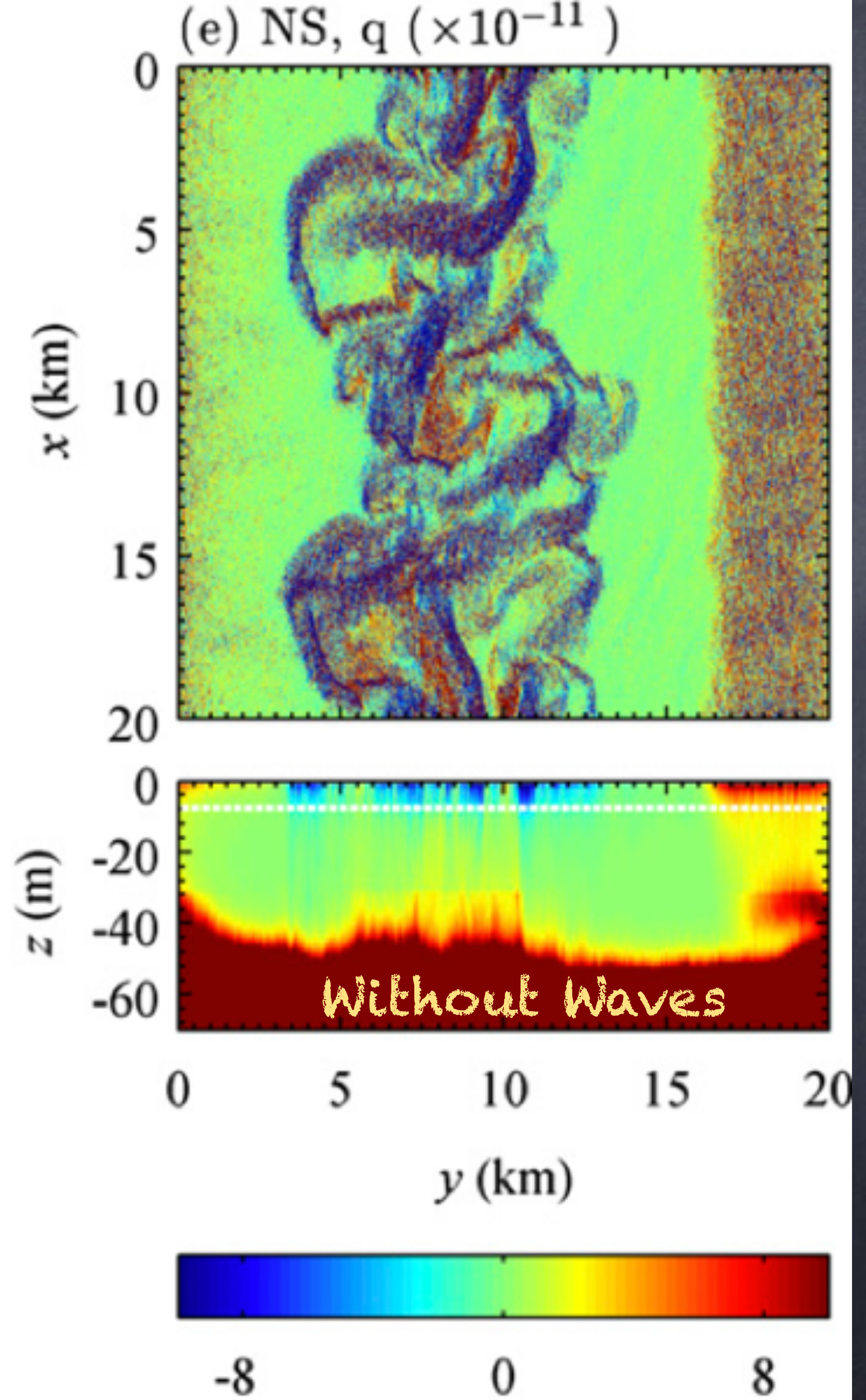
P. E. Hamlington, L. P. Van Roekel, BFK, K. Julien, and G. P. Chini. Langmuir-submesoscale interactions: Descriptive analysis of multiscale frontal spin-down simulations. Journal of Physical Oceanography, 44(9): 2249-2272, September 2014.



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

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.





So, if fQ<0 indicates likely regions of symmetric instability—Surface Waves STRONGLY affect SI!

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

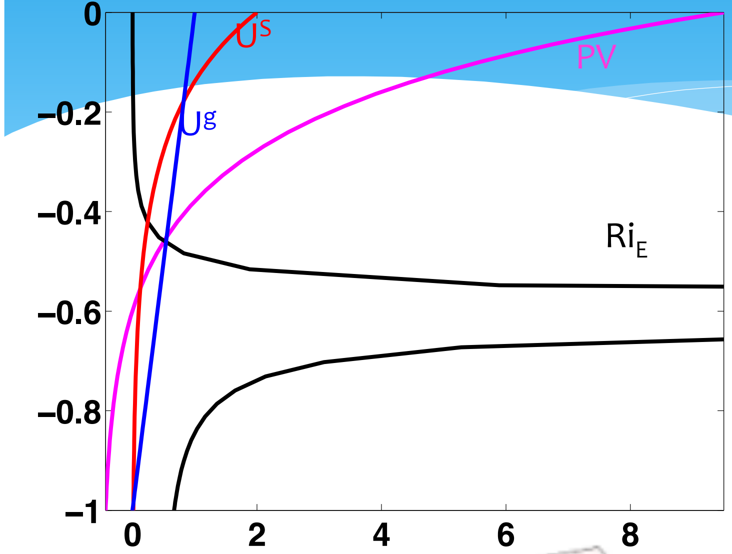
~~Ri <1 ⇒ SI~~

★ fQ<0 ⇒ SI

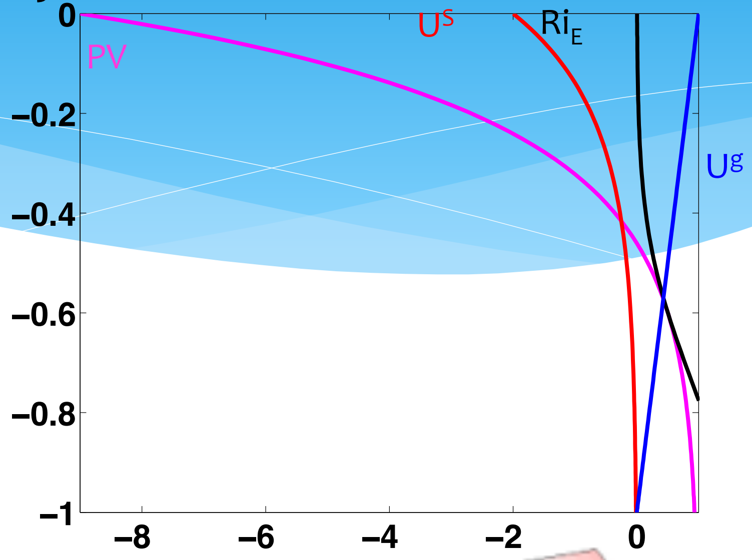
Numerical Wavy Stability Criterion:

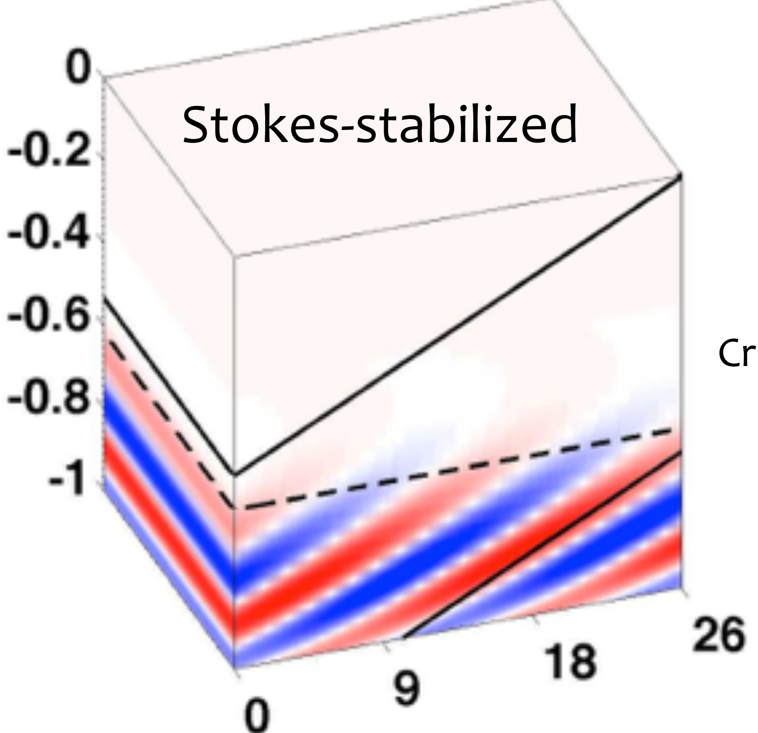
Symmetric Instability

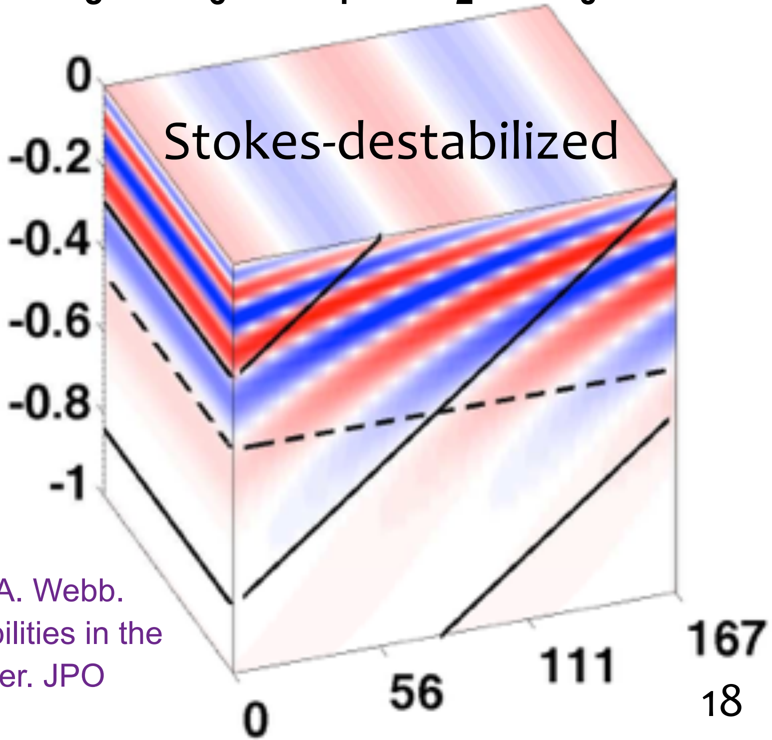
Ri = 0.5



Ri = 2







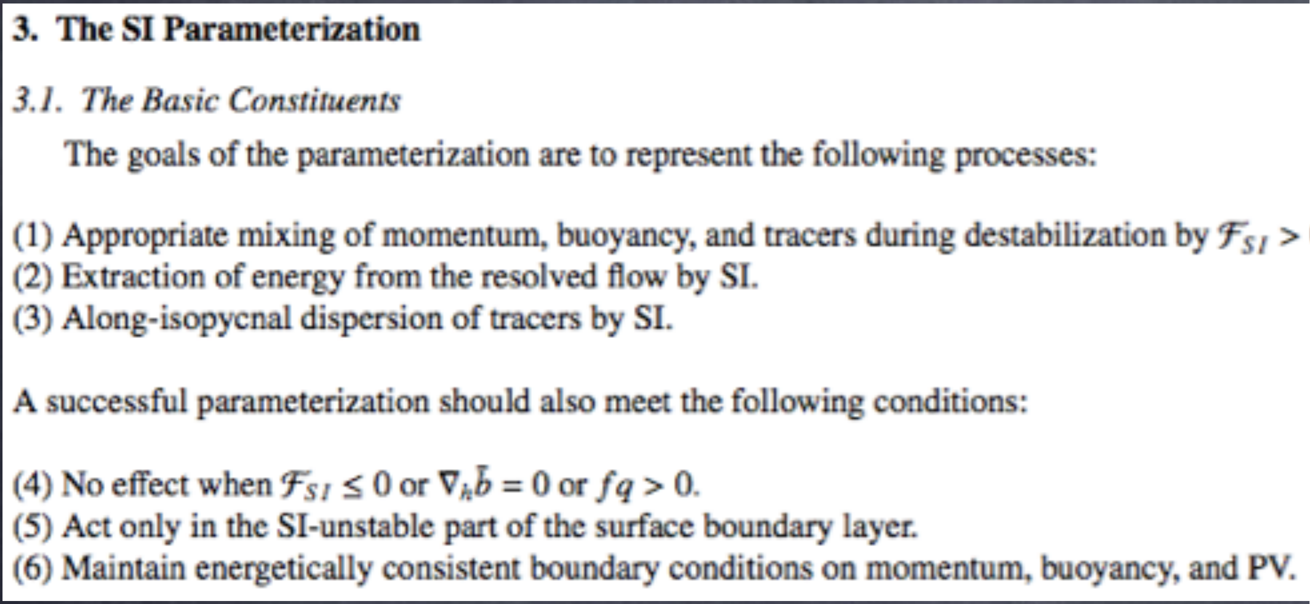
—— Isopycnals

- - 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.

Aside: A new parameterization of Symmetric Instability!!



3. The SI Parameterization

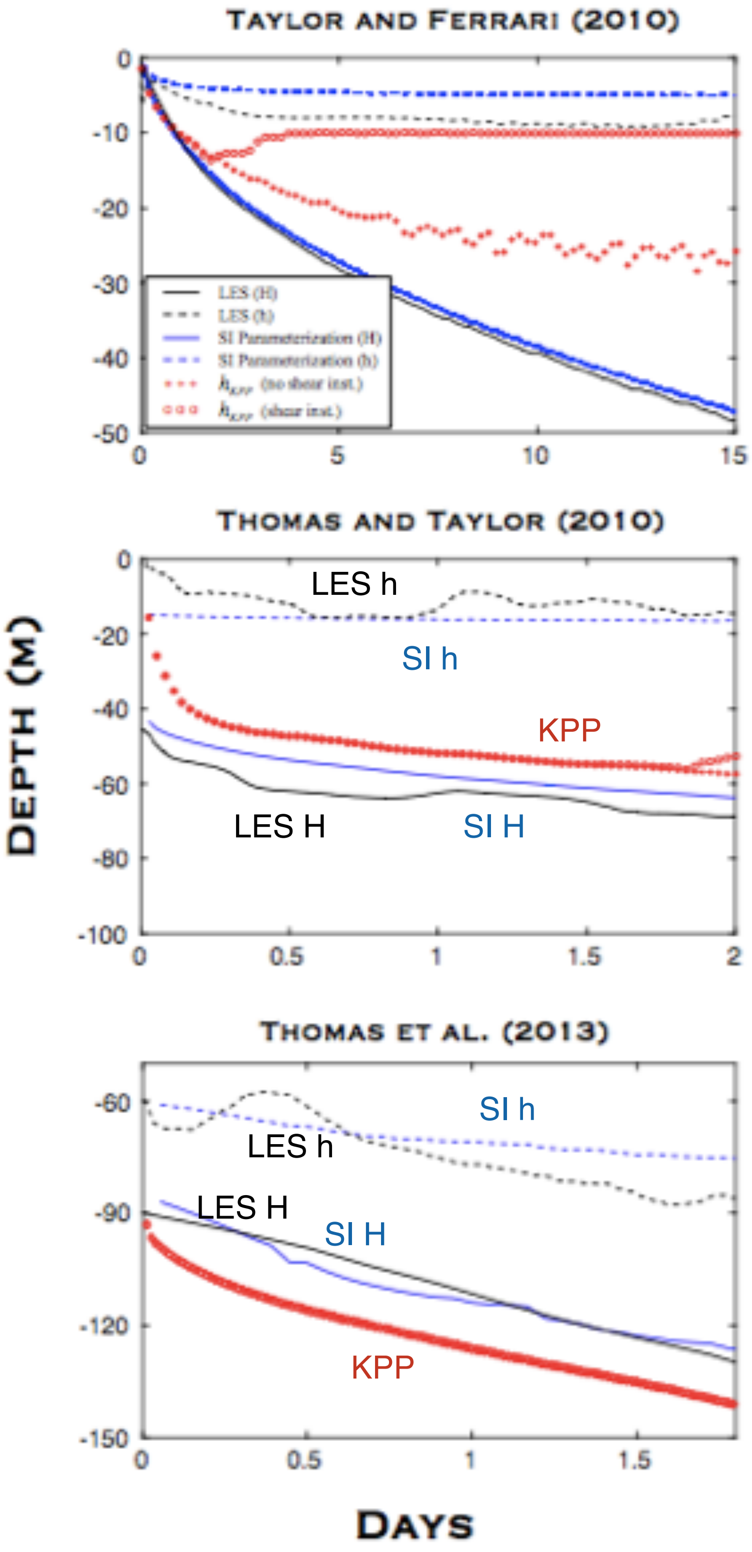
3.1. *The Basic Constituents*

The goals of the parameterization are to represent the following processes:

(1) Appropriate mixing of momentum, buoyancy, and tracers during destabilization by $\mathcal{F}_{SI} > 0$.
(2) Extraction of energy from the resolved flow by SI.
(3) Along-isopycnal dispersion of tracers by SI.

A successful parameterization should also meet the following conditions:

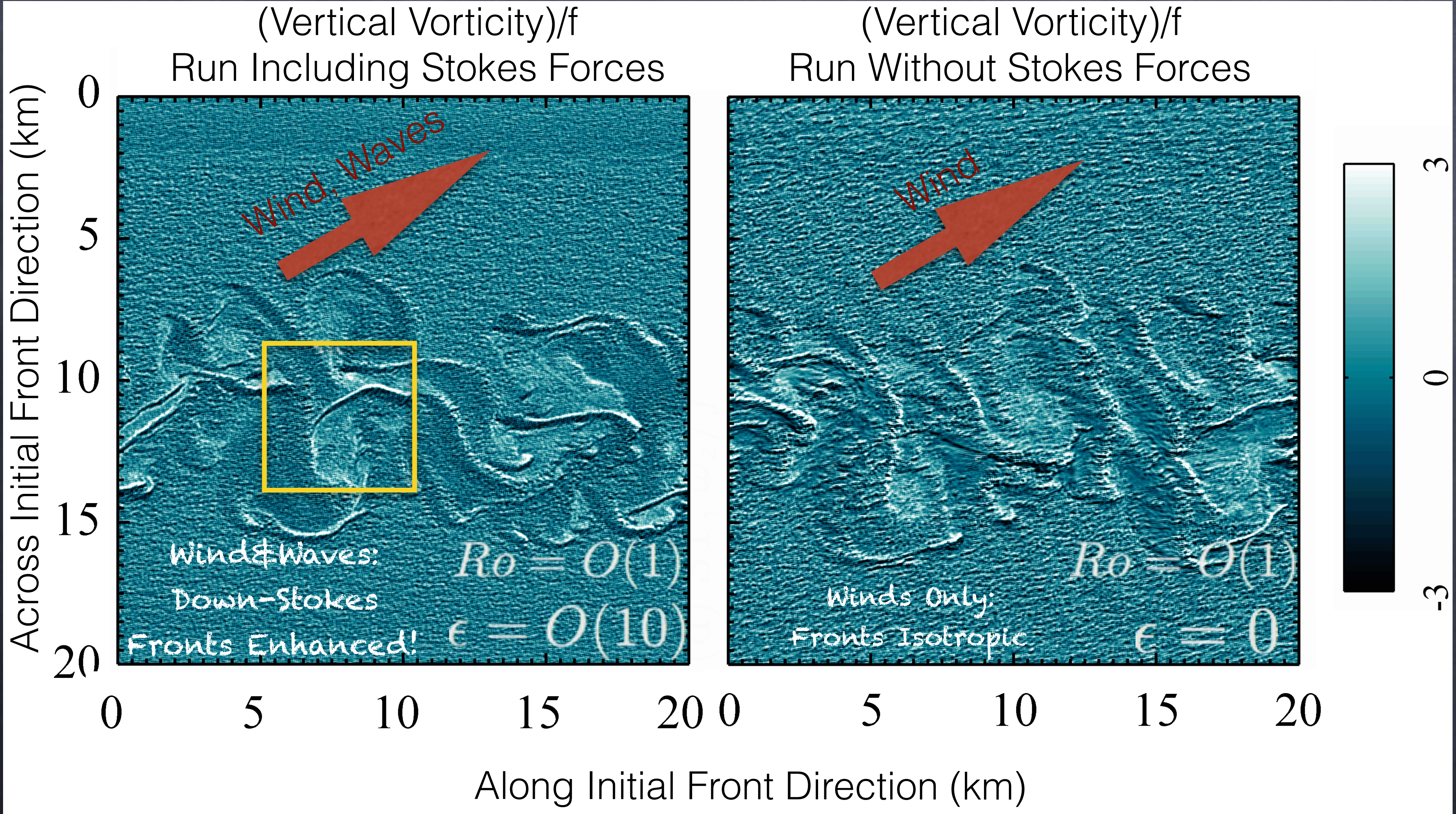
(4) No effect when $\mathcal{F}_{SI} \leq 0$ or $\nabla_h \bar{b} = 0$ or $fq > 0$.
(5) Act only in the SI-unstable part of the surface boundary layer.
(6) Maintain energetically consistent boundary conditions on momentum, buoyancy, and PV.



S. D. Bachman, B. Fox-Kemper, J. R. Taylor, and L. N. Thomas. Parameterization of frontal symmetric instabilities. i: Theory for resolved fronts. Ocean Modelling, April 2016. Submitted.

Are Fronts and Filaments different with Stokes shear force?

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



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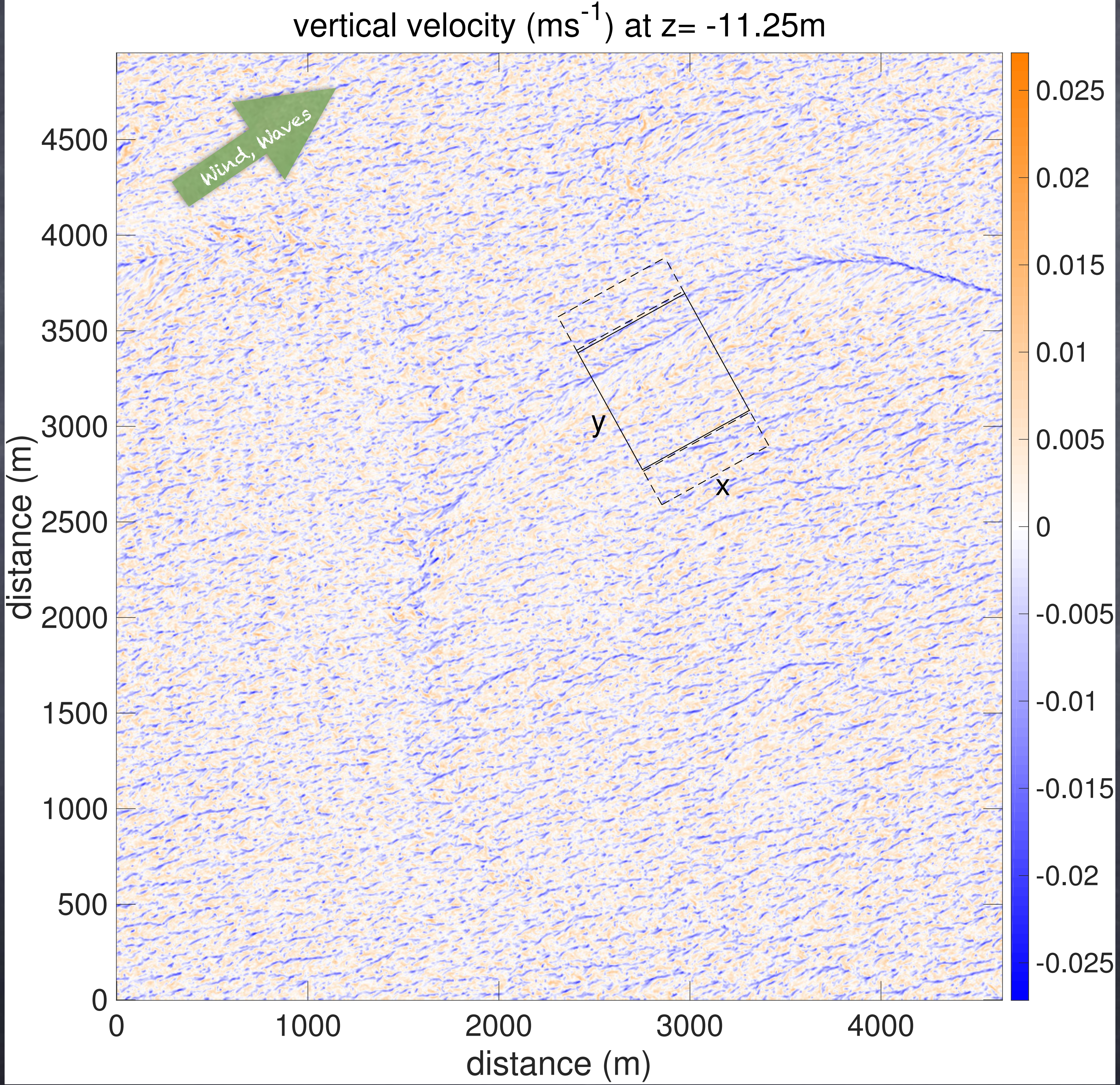
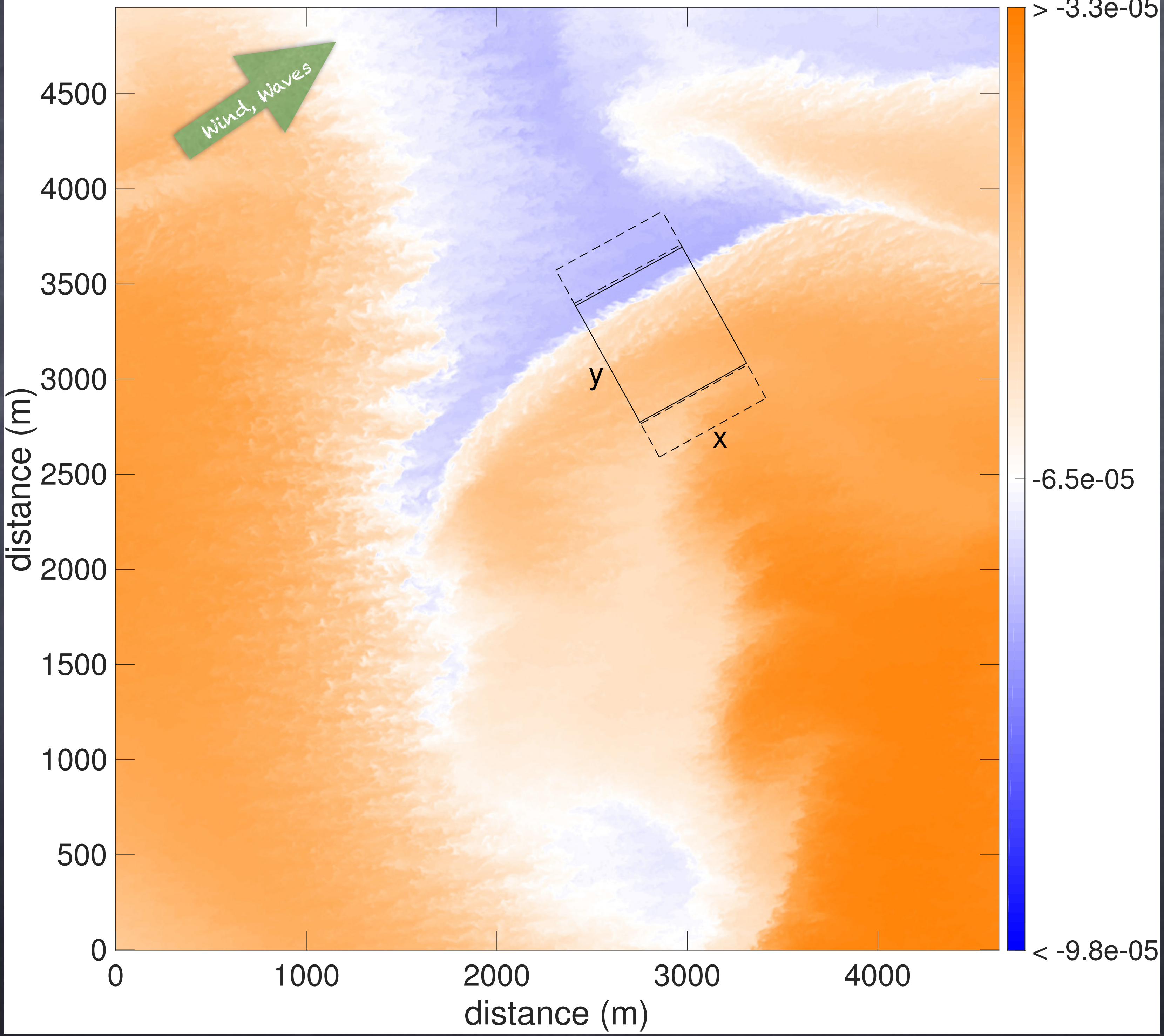


N. Suzuki, BFK, P. E. Hamlington, and L. P. Van Roekel. Surface waves affect frontogenesis. JGR-Oceans, December 2015. Submitted.

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



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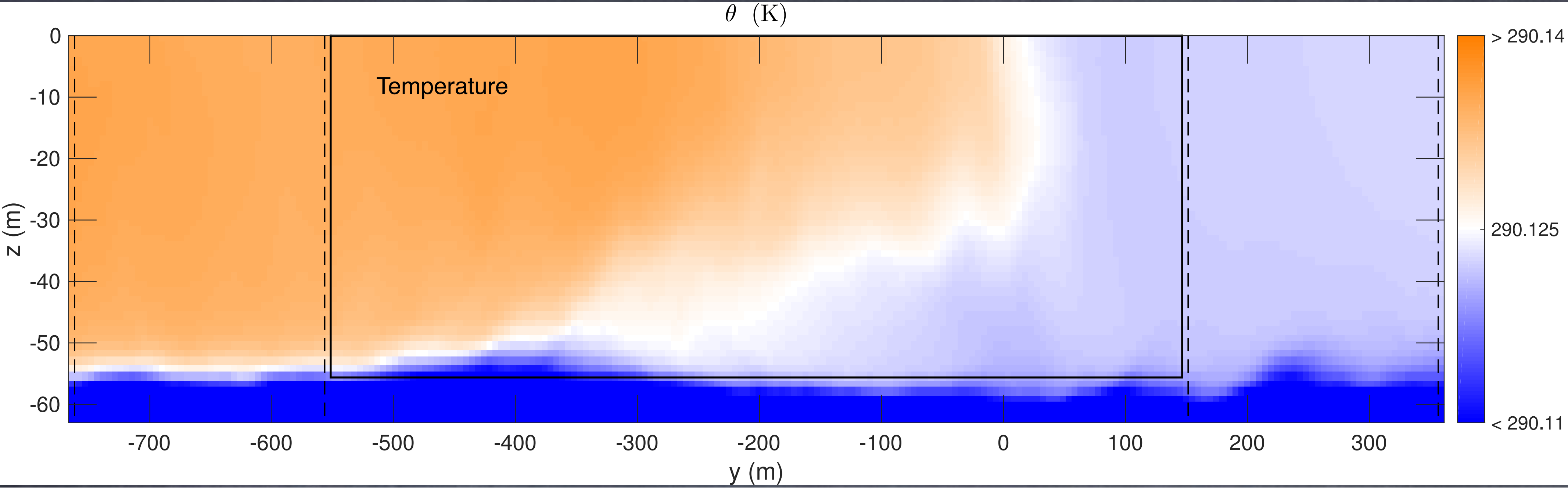
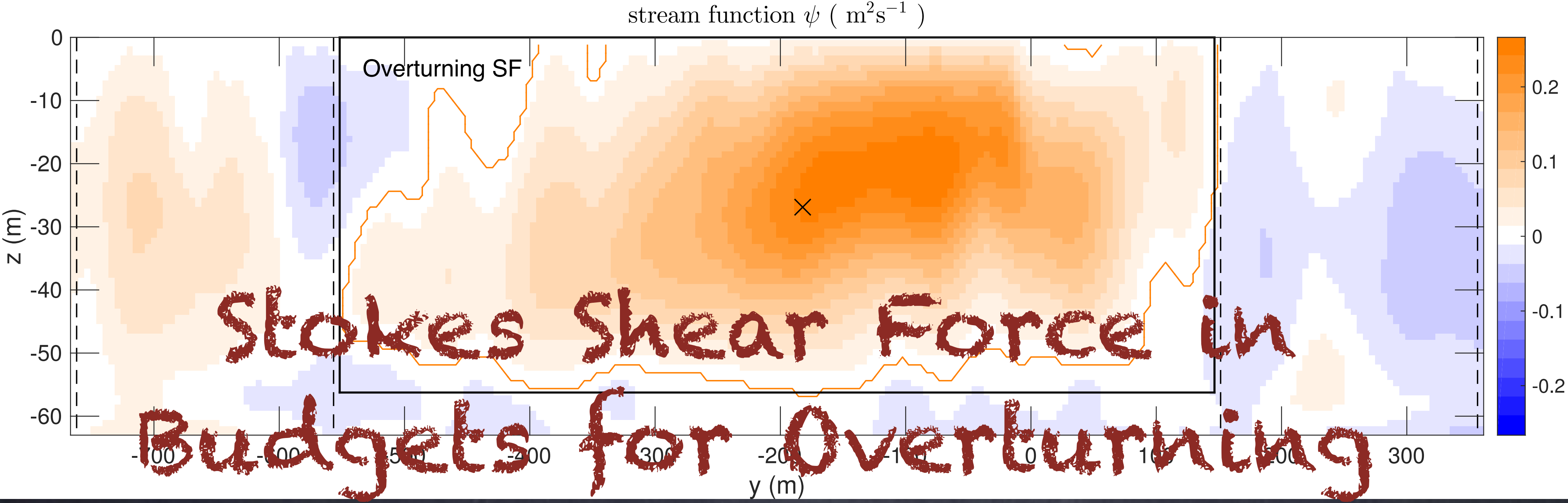


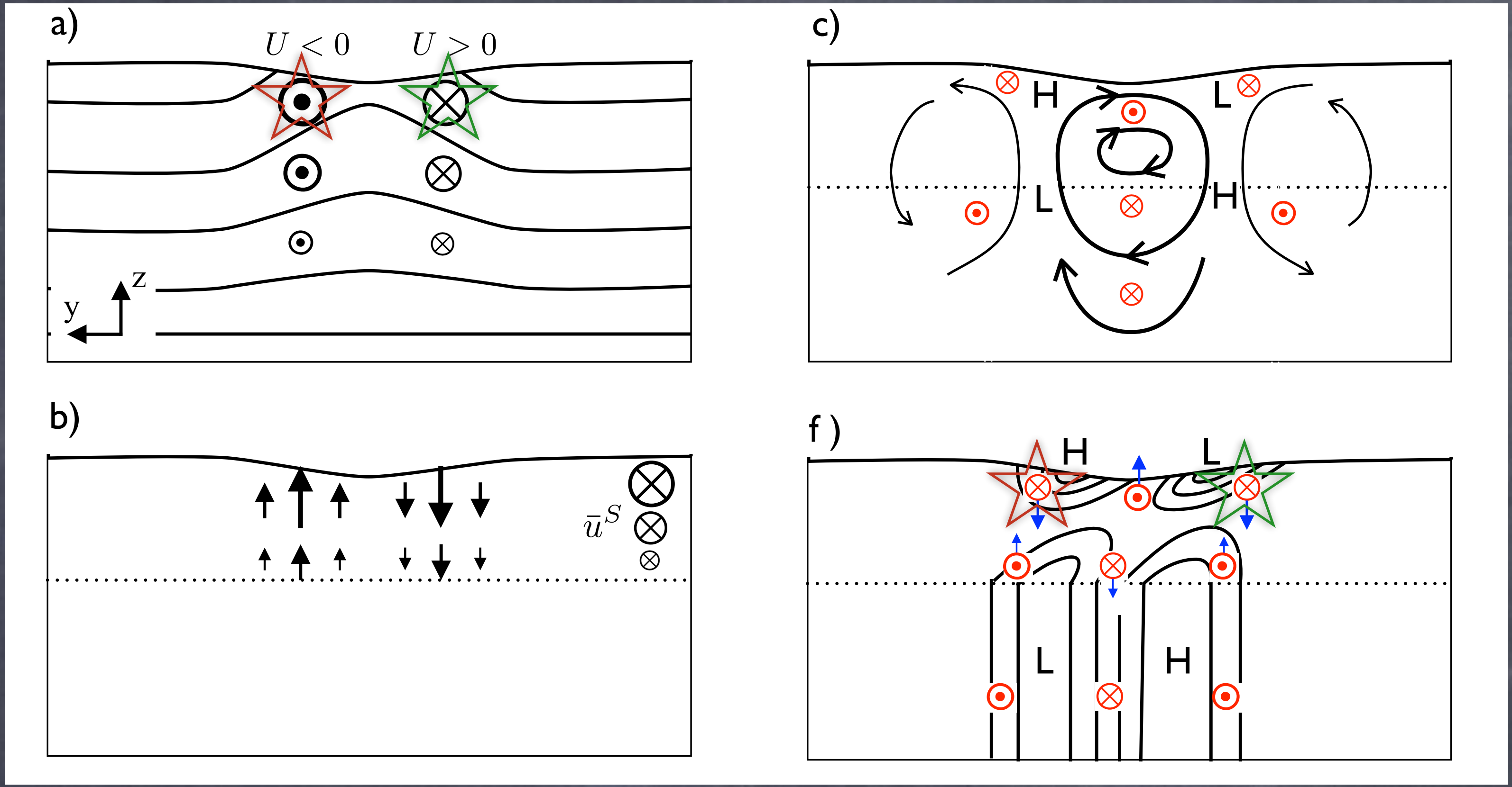


Stokes Shear Force in Budgets for Overturning

- 2nd Largest Source in Overturning Vorticity (24% of buoyancy)

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

Stokes Shear Force Affects Fronts and Filaments



Enhances Fronts for Down-Front Stokes

Opposes Fronts for Up-Front Stokes

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

N. Suzuki and BFK. Understanding Stokes Forces in the Wave-Averaged Equations, in press, 2016.

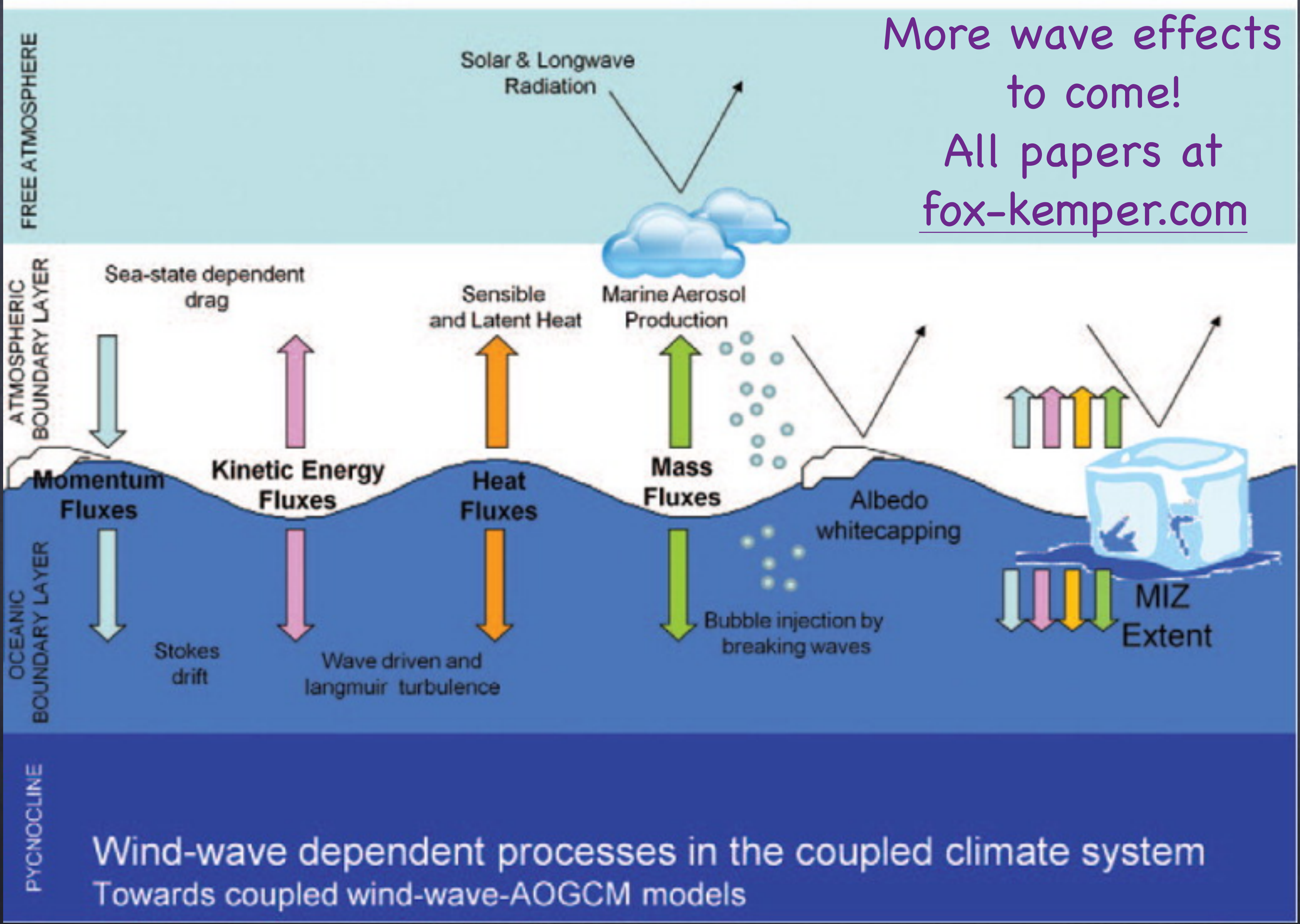
J. C. McWilliams and BFK. Oceanic wave-balanced surface fronts and filaments. Journal of Fluid Mechanics, 730:464-490, 2013.

Conclusions

- In the upper ocean, horizontal scales as big as basins, and as small as meters contribute to the air-sea exchange and climate.
- Interesting transition occurs on the Submeso to Langmuir scale boundary, as nonhydro. & ageostrophic effects begin to dominate—Yet Stokes forces affect even larger scales.
- 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 fronts & dynamics are under-appreciated.
- Including Stokes forces in mesoscale and submesoscale permitting hydrostatic simulations is easy in the Stokes shear force formulation—just pair it wherever buoyancy appears.
- All papers at: fox-kemper.com/pubs

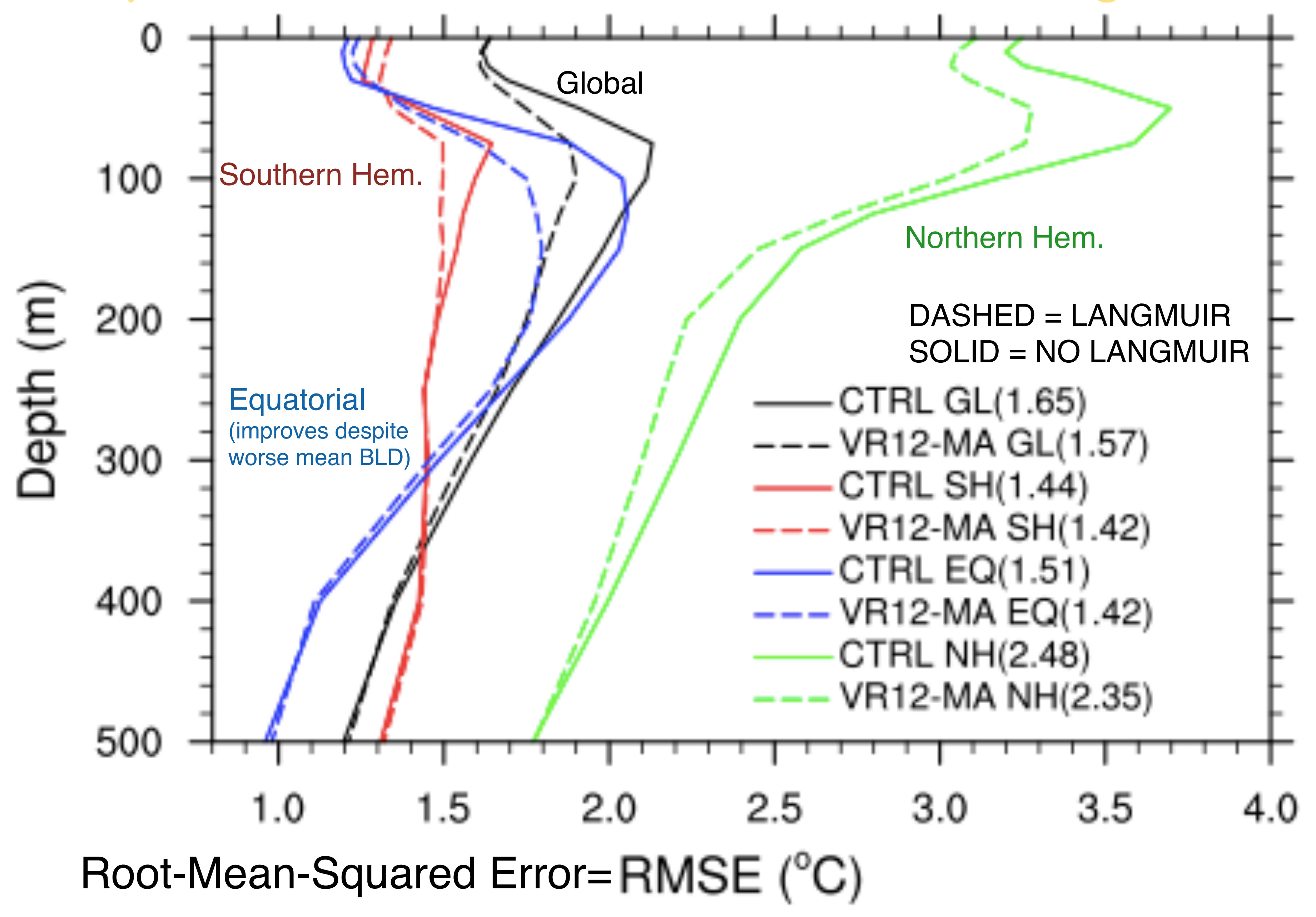
More wave effects to come!

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.

Subsurface Temperature:
Improved vs. Observations with Langmuir



DASHED = LANGMUIR
SOLID = NO LANGMUIR

Root-Mean-Squared Error=RMSE (°C)

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

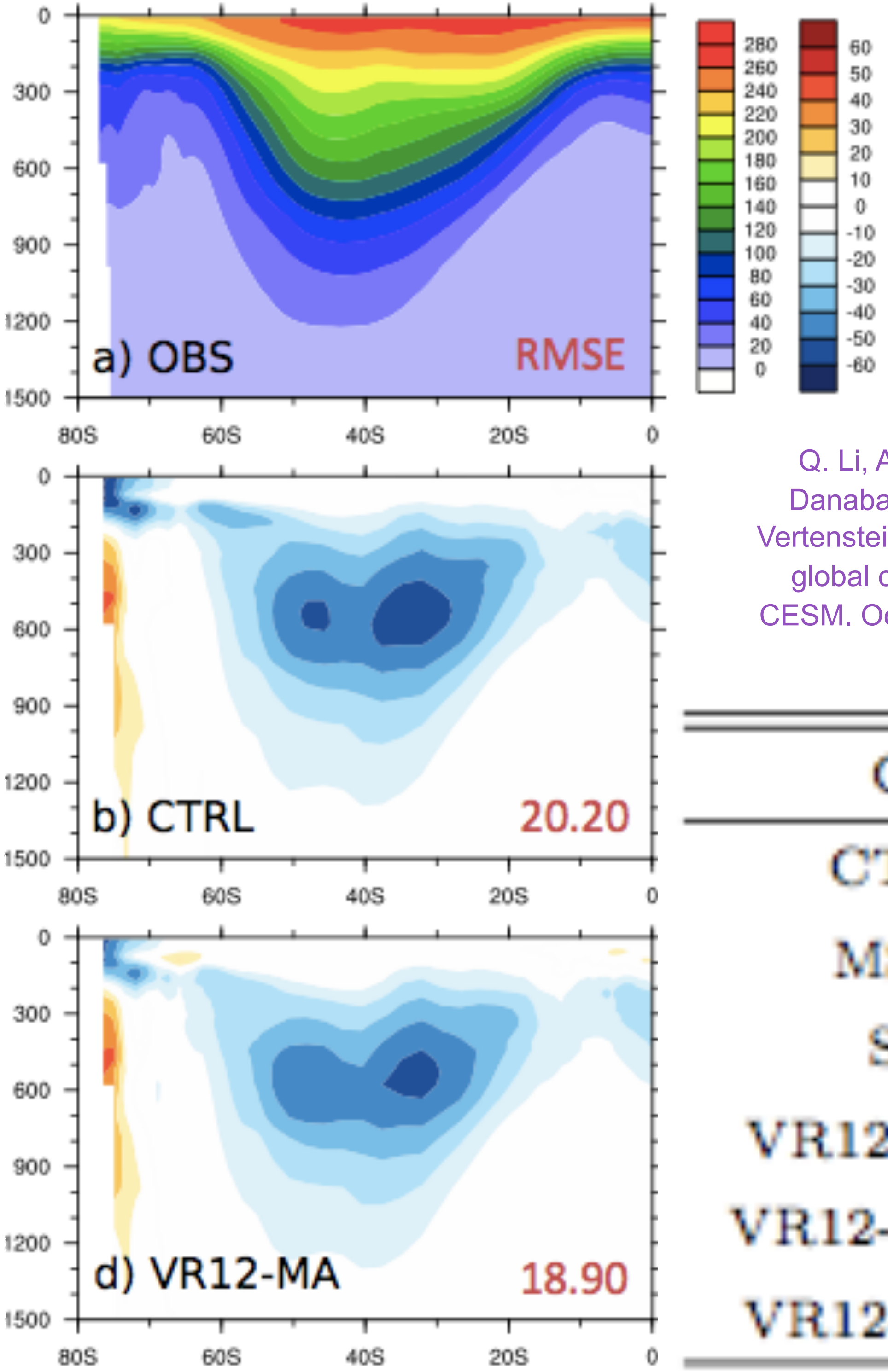


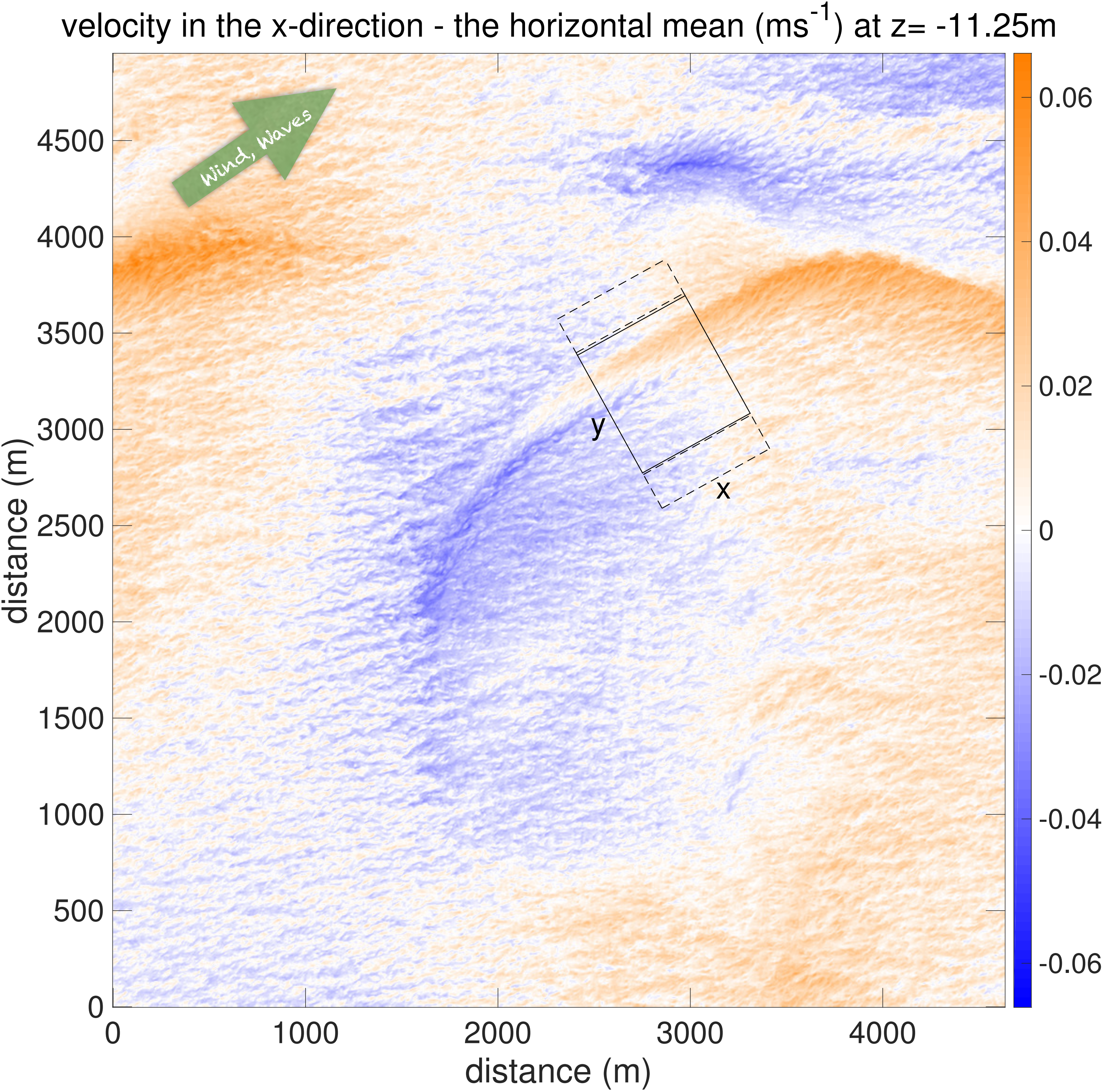
Fig. 3. Impact on the zonal mean pCFC-11 (patm) in the Southern Hemisphere. (a) Observation[6] (GLODAP); (b) Biases in the control test without Langmuir mixing; (c) - (e) Biases in tests with Langmuir mixing.

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



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

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