Surface Waves Drive a Turbulent Ocean

Baylor Fox-Kemper (Brown)

with Jim McWilliams (UCLA), Nobu Suzuki (Brown), and Sean Haney (Scripps), Qing Li (Brown), Peter Hamlington (CU-Boulder), Luke Van Roekel (LANL), Adrean Webb (U. Tokyo), Keith Julien (CU-Boulder)

SIAM Geosciences Conference,

Stanford, Palo Alto, CA, 6/30/15

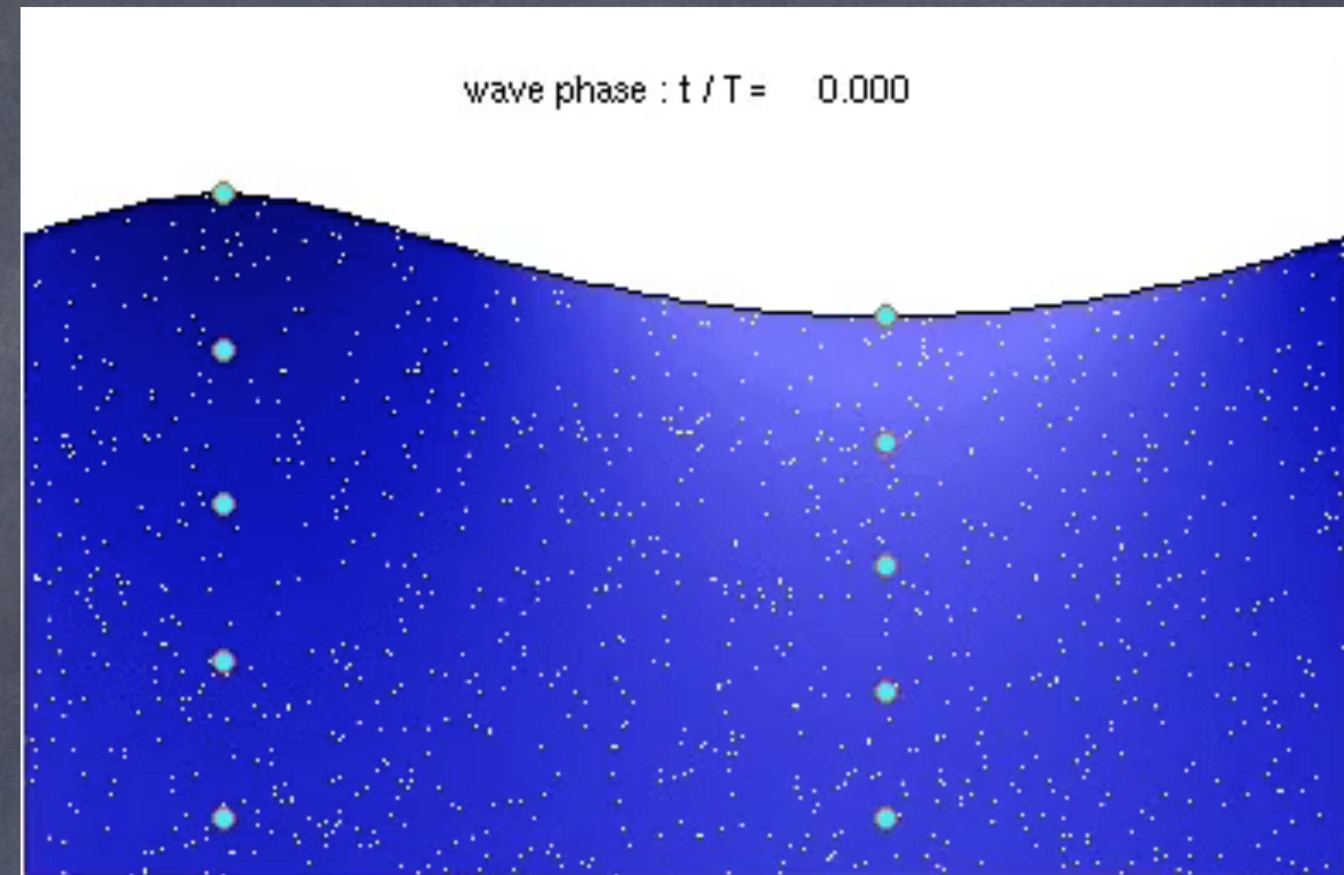
Sponsors: GoMRI/CARTHE, NSF 1258907 & 1350795

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

Waves Provide Stokes Drift

& Stokes Drift drives Langmuir Turbulence

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



Movie: Creative Commons

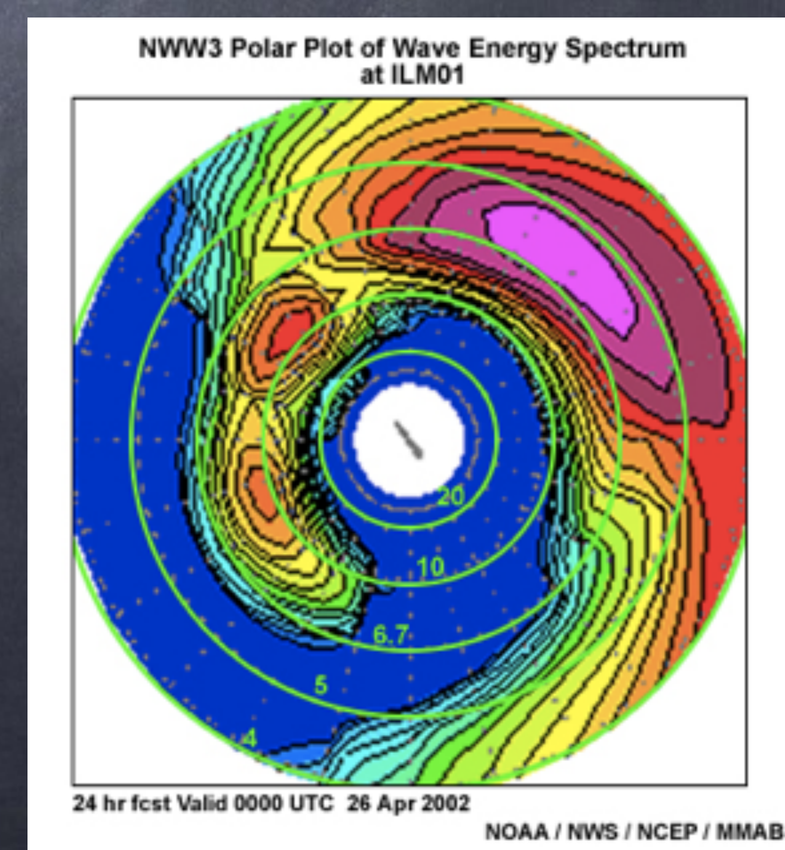
Monochromatic:

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

Wave Spectrum:

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

Typical Wave Spectrum:



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.

Wave-Averaged Equations

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

following Lane et al. (07), McWilliams & F-K (13)
and Suzuki & F-K (15): Multiscale Asymptotic Red. Dynamics
(for horizontally uniform Stokes drift)

$$v_j^L = v_j + v_j^s$$

Lagrangian advection!

Lagrangian geostrophic!

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

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

nonhydrostatic Stokes Shear Force!

$$b_t + v_j^L b_{,j} + \frac{M_{Ro}}{RoRi} w b_z + w = 0$$

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

Plus boundary conditions

LAGRANGIAN (Eulerian+Stokes) advection & Coriolis

Stokes shear force is NEW *nonhydrostatic* term in Vert. Mom.

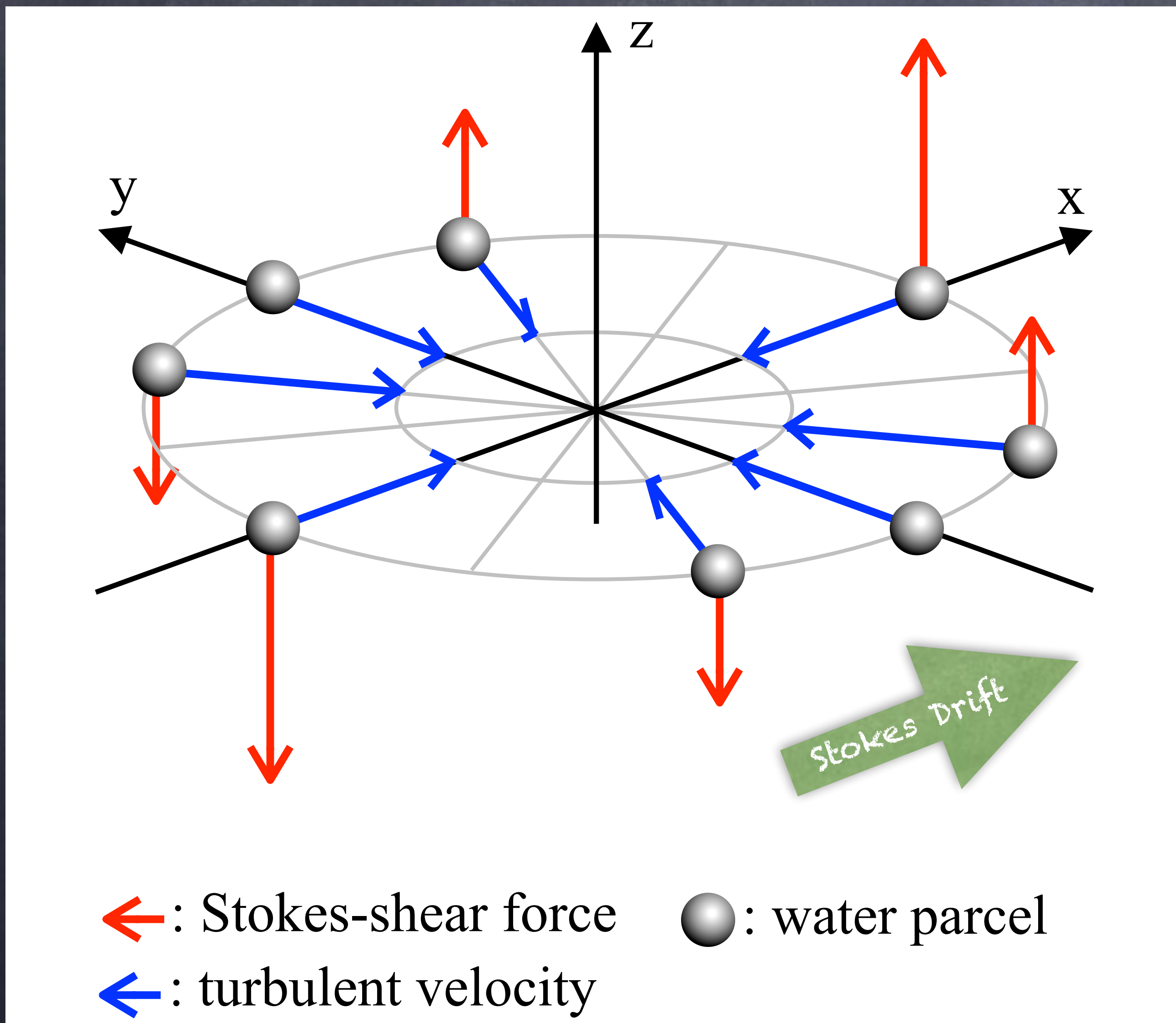
J. C. McWilliams and BFK. Oceanic wave-balanced surface fronts and filaments. Journal of Fluid Mechanics, 730:464-490, 2013.

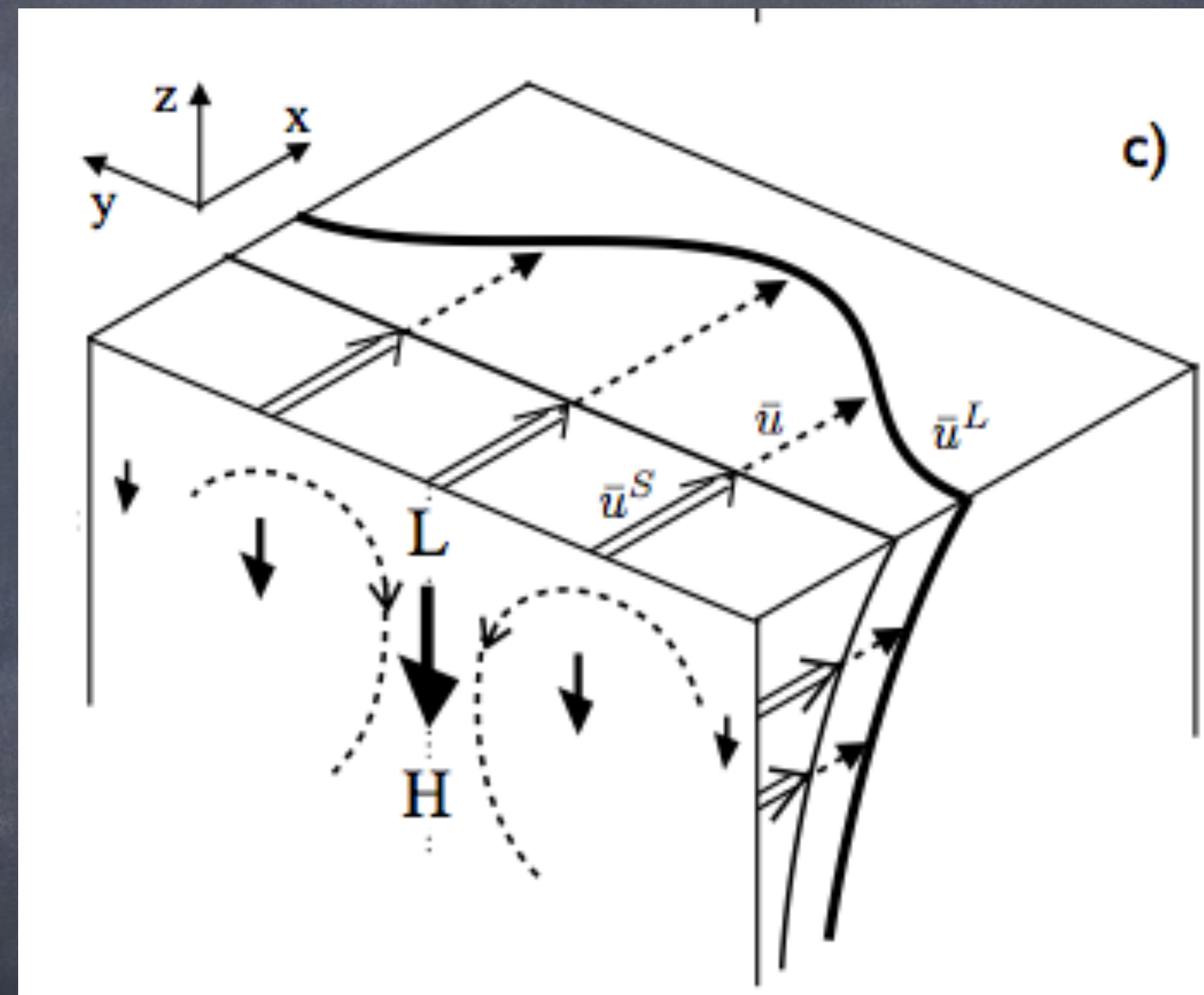
N. Suzuki and BFK. Understanding Stokes Forces in the Wave-Averaged Equations, JPO, in prep, 2015.

Stokes Shear Force:

Craik-Leibovich mechanism for Langmuir circulations

Flow along Stokes shear=>nonhydrostatic downforce





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

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

Traditional Stokes effect: Langmuir Turbulence

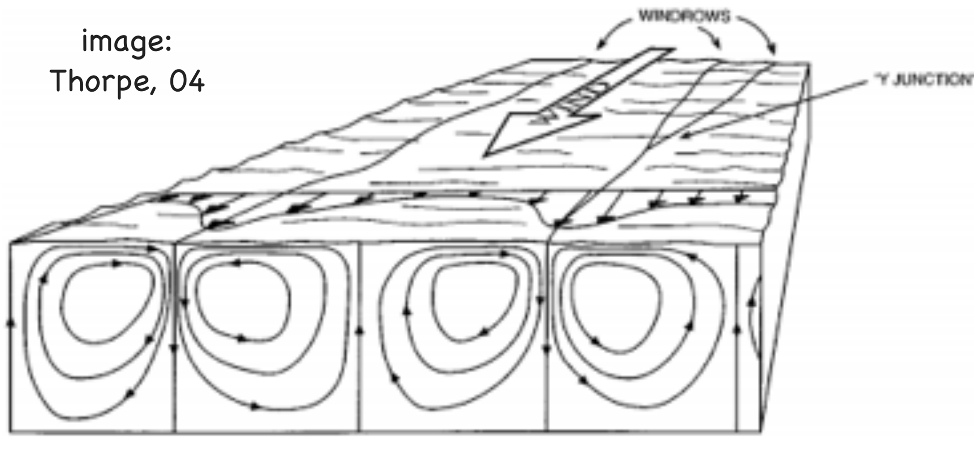


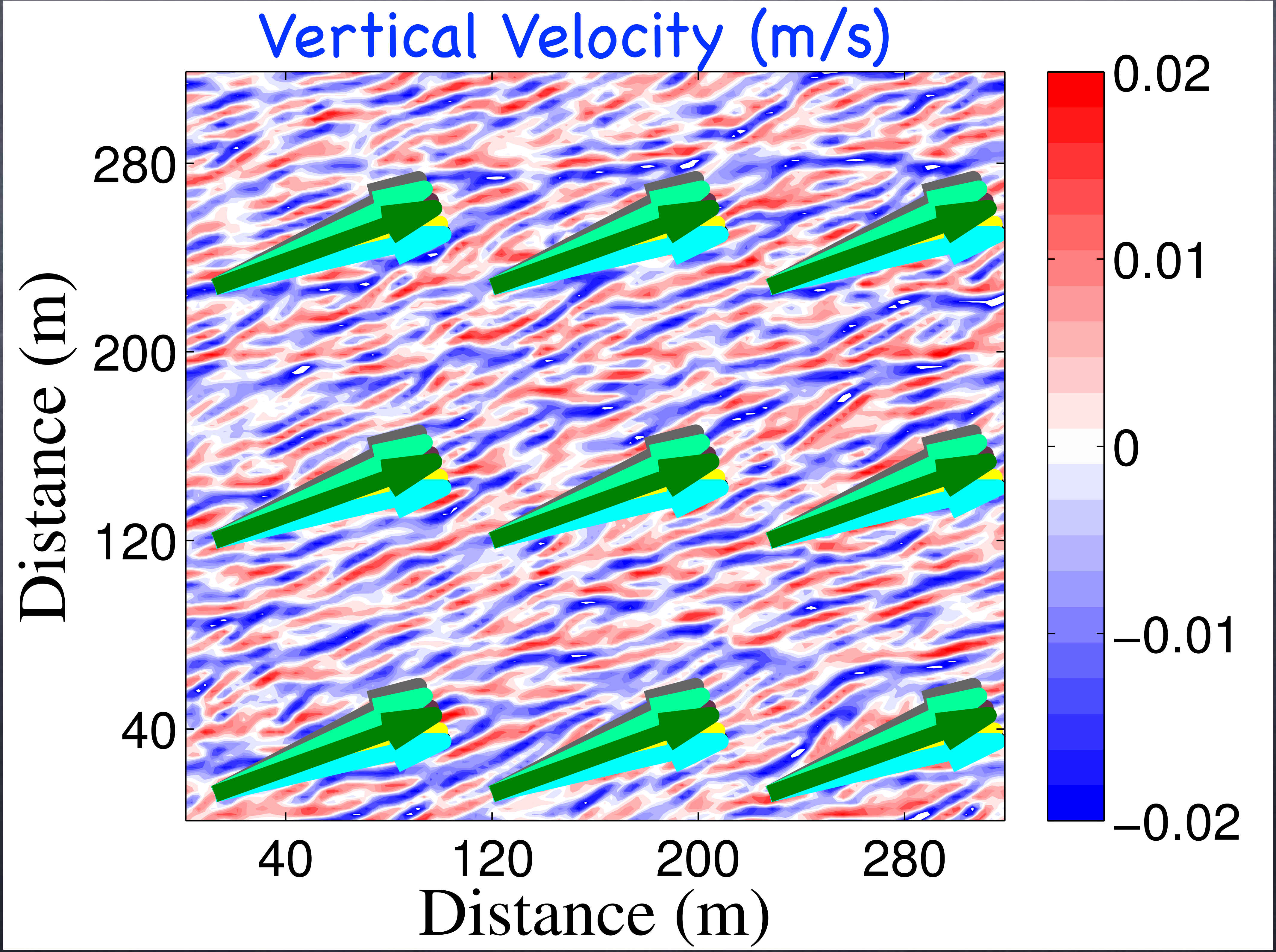
Figure 1 Sketch showing the pattern of mean flow in idealized Langmuir circulation. The windrows may be 2 m to 300 m apart, and the cell form is roughly square (as shown). In practice the flow is turbulent, especially near the water surface, and the windrows (Figure 2) amalgamate and meander in space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

- Near-surface
- Convection, Wind & Langmuir Turb.
- $Ro \gg 1$
- $Ri < 1$: Nonhydro
- 1-100m (H=L)
- 10s to 1hr
- w, u=O(10cm/s)
- Stokes drift
- Eqtns: Wave-averaged, Nonhydrostatic
- Params: McWilliams & Sullivan, 2000, Van Roekel et al. 2012, Li et al. 2015

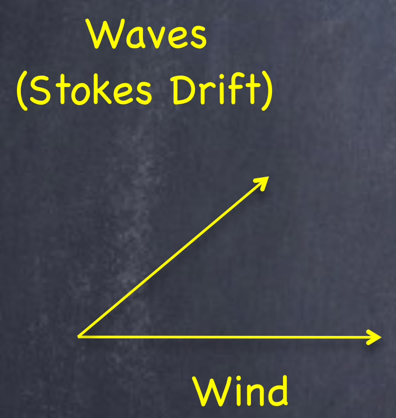
Image: NPR.org, Deep Water Horizon Spill

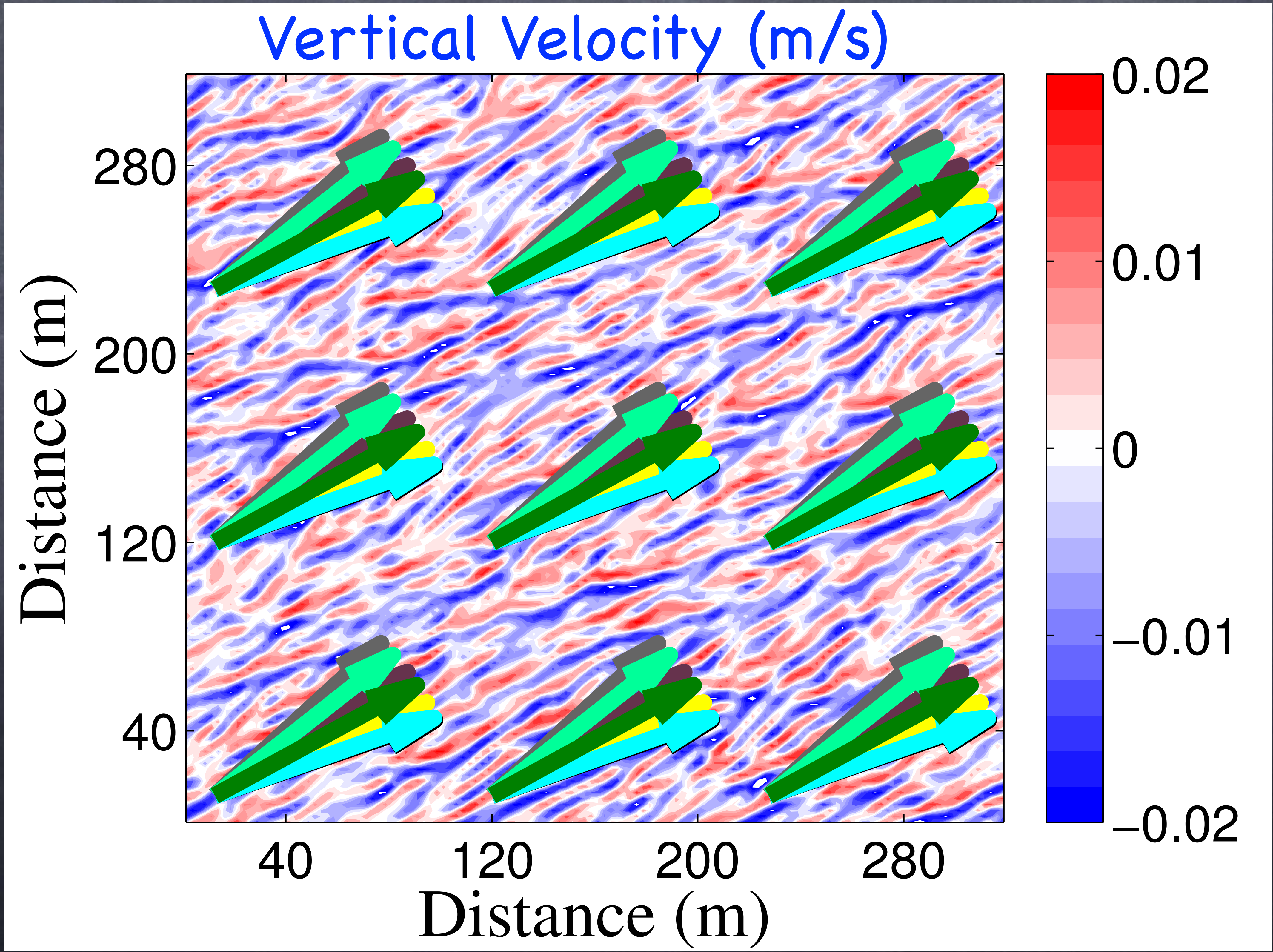
Climate Model Parameterization based on Large Eddy Simulations of Langmuir Turbulence. Tricky: Misaligned Wind & Waves

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





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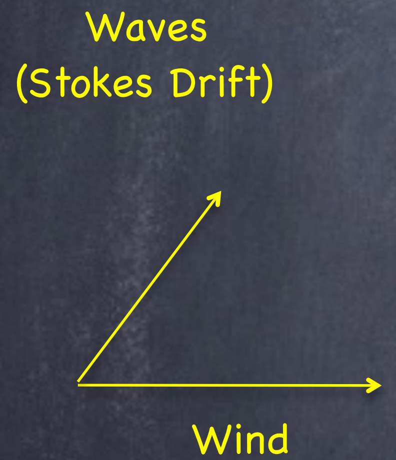

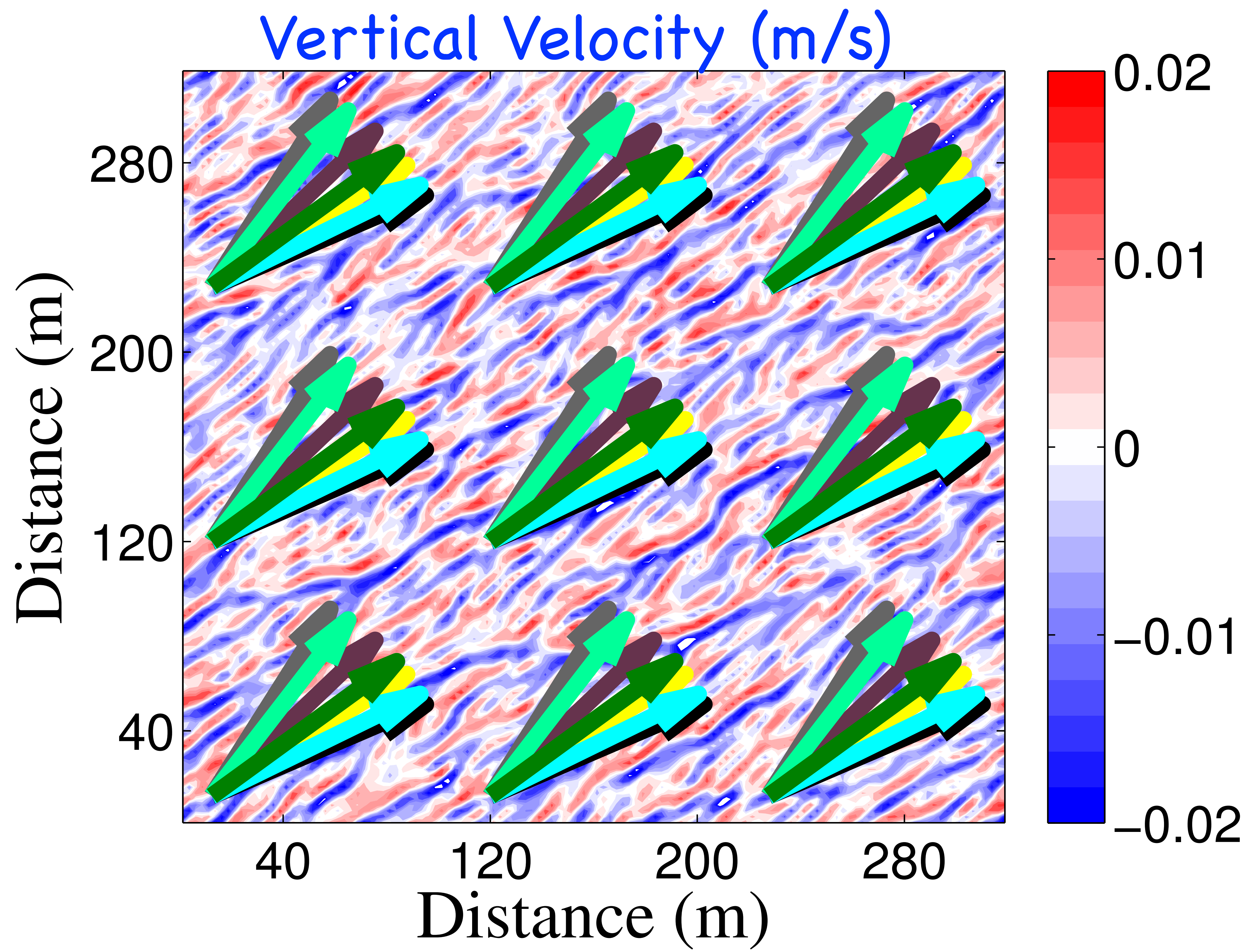

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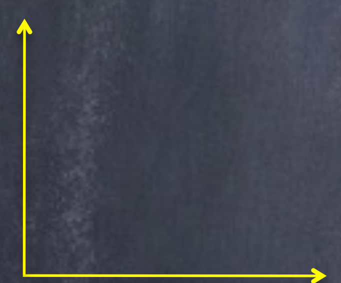

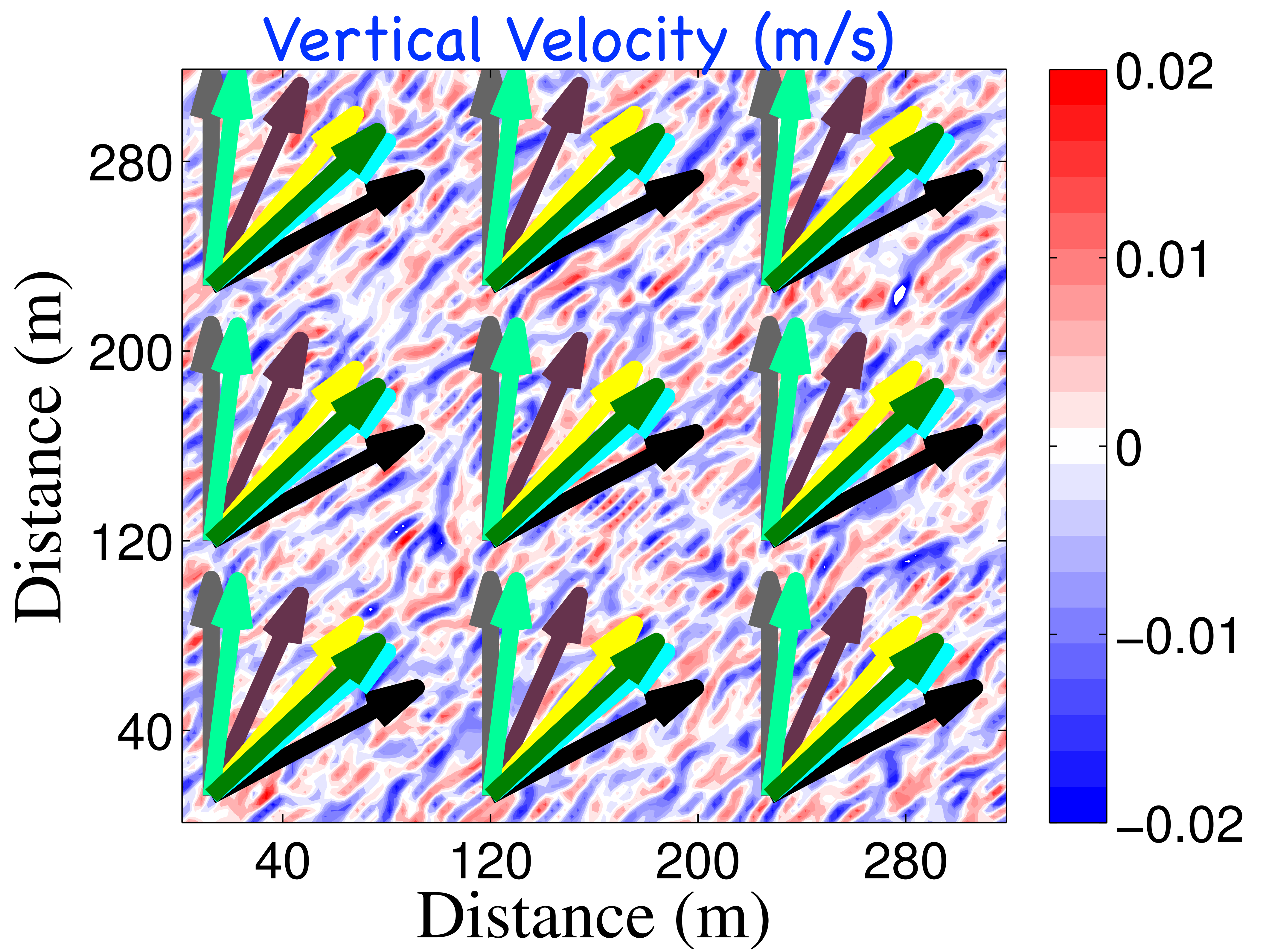

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Langmuir Mixing in Climate: Bndy layer Depth Improved

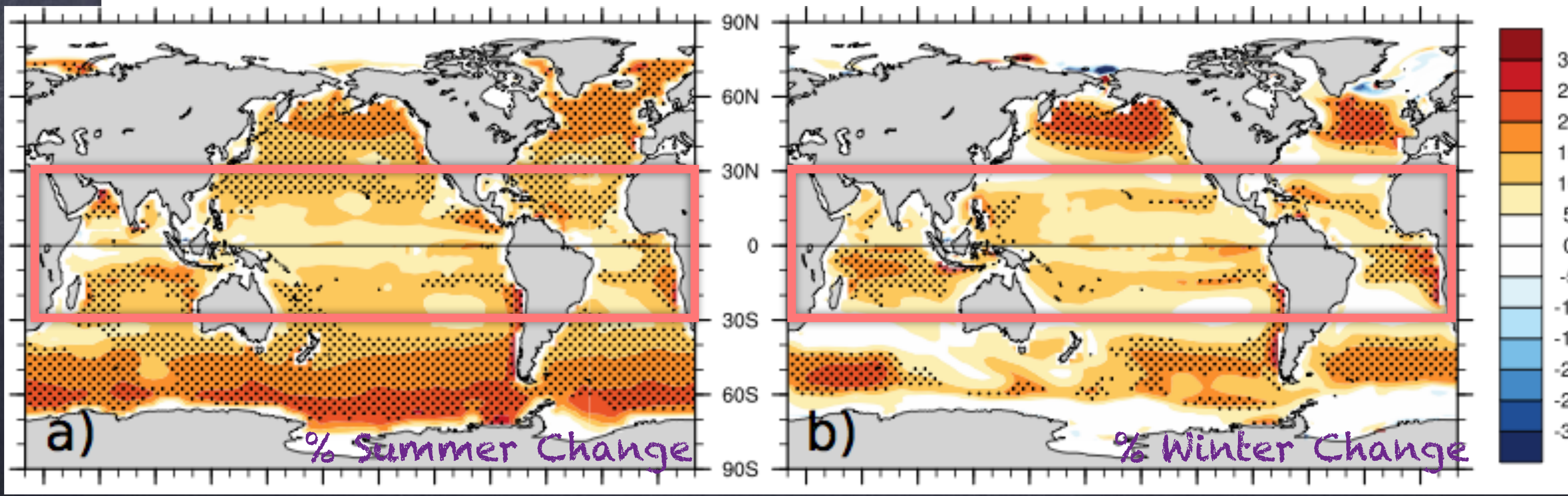
Case	Summer			Winter		
	Global	South of 30°S	30°S-30°N	Global	South of 30°S	30°S-30°N
CTRL	10.62±0.27[a]	17.24±0.48	5.38±0.14	43.85±0.38	57.19±0.76	12.57±0.28
	(13.40±0.19)[b]	(21.73±0.32)	(6.71±0.09)	(45.50±0.40)	(56.53±0.59)	(16.16±0.29)
MS2K	15.37	15.47	17.03	119.91	171.92	40.31
SS02	36.79	63.83	7.54	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

Control

Competition

3 versions of Van Roekel et al

dotted when statistically significant



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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.

Enhancing ocean ventilation

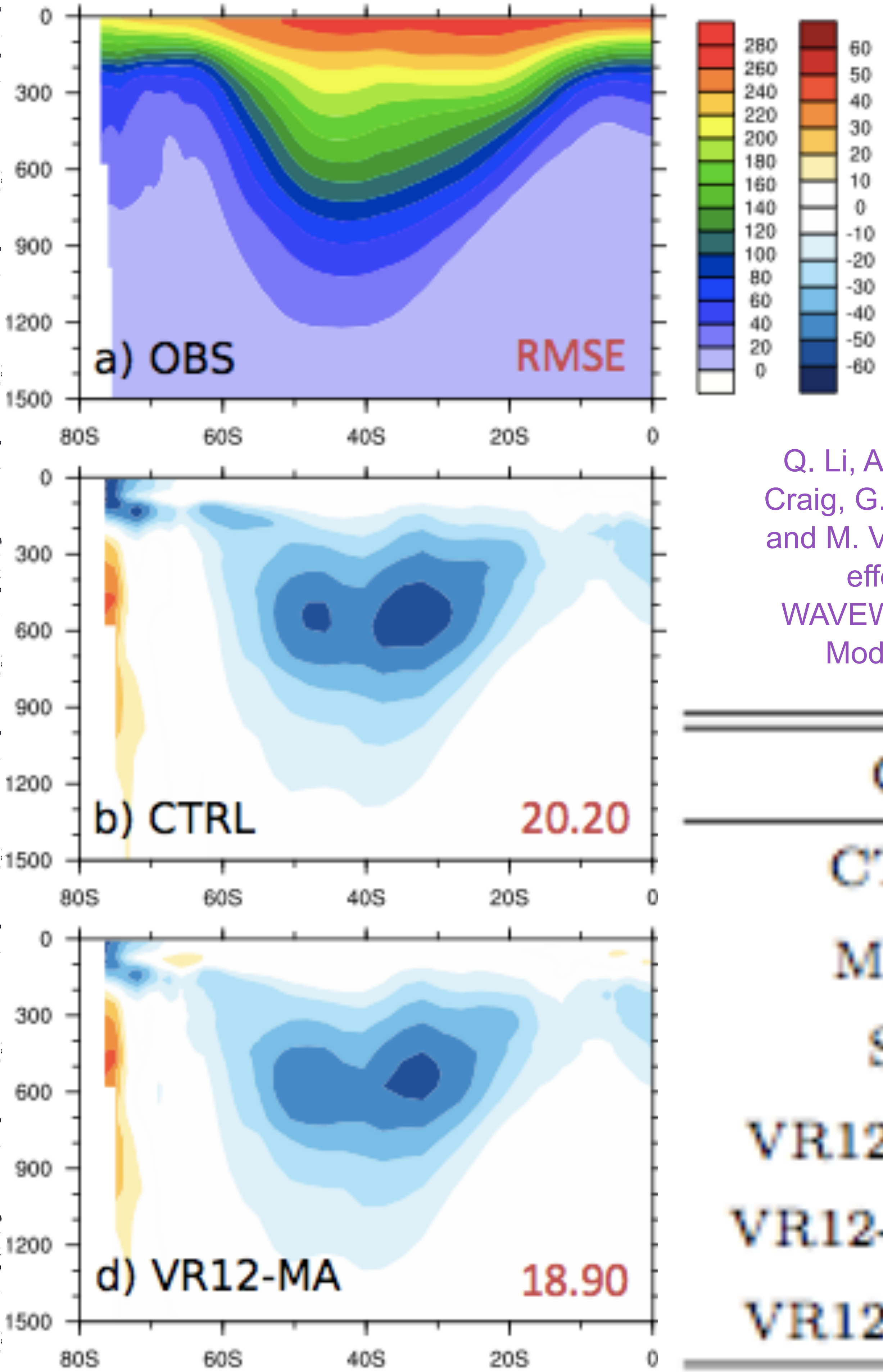


Fig. 3. Impact on the zonal mean pCFC-11 (patm) in the Southern Hemisphere. (a) Observation[6] (GLODAP); (b) Biases in the control test without Langmuir mixing; (c) - (e) Biases in tests with Langmuir mixing.

Q. Li, A. Webb, 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.

Ocean Uptake:

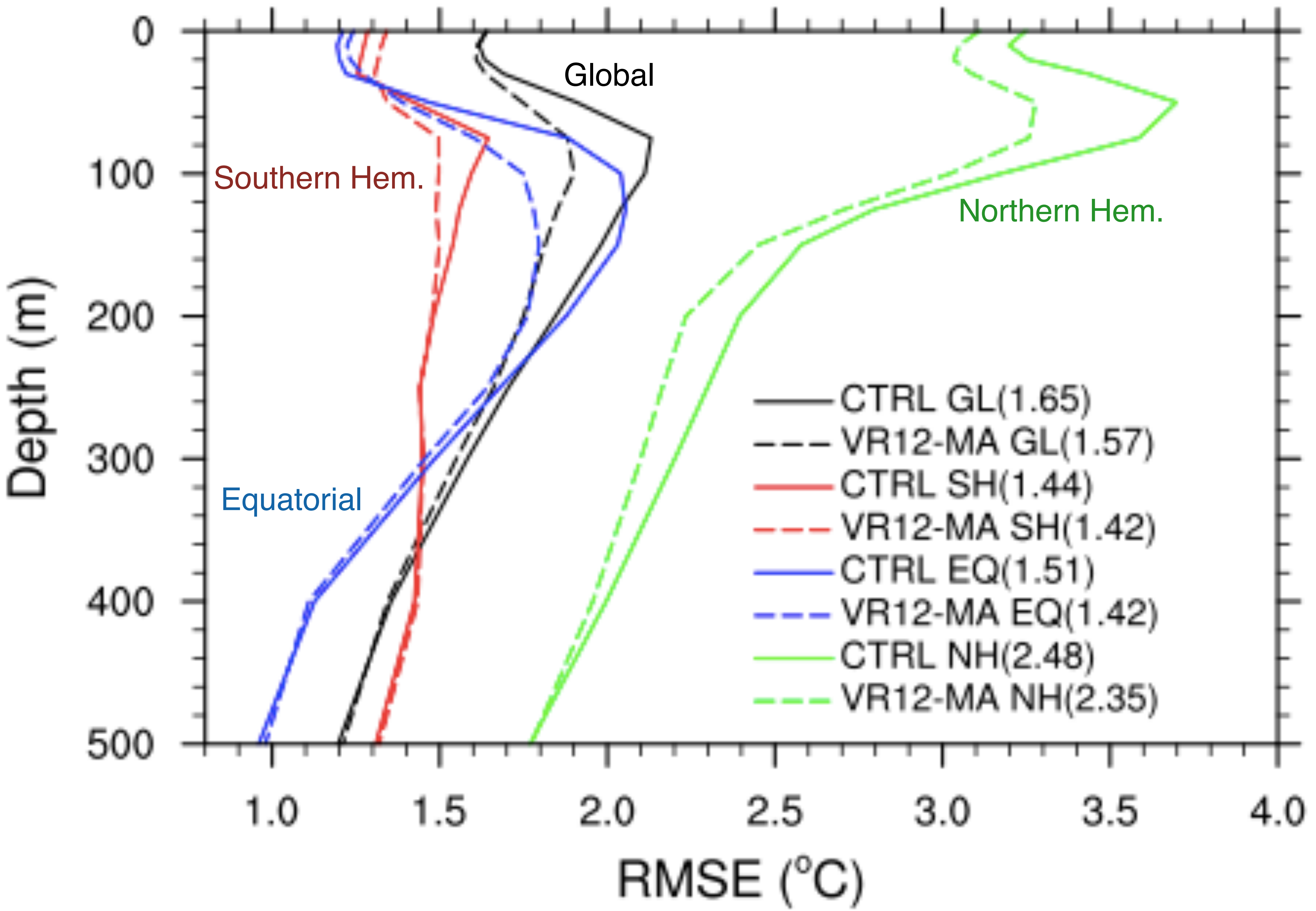
Chlorofluorocarbons (manmade pollutant, detectable & known source)

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 errors reduced (monthly means vs. Observations)

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



Not Traditional: Stokes forces affect Submesoscale Fronts & Instabilties

← 10 km

(Capet et al., 2008)

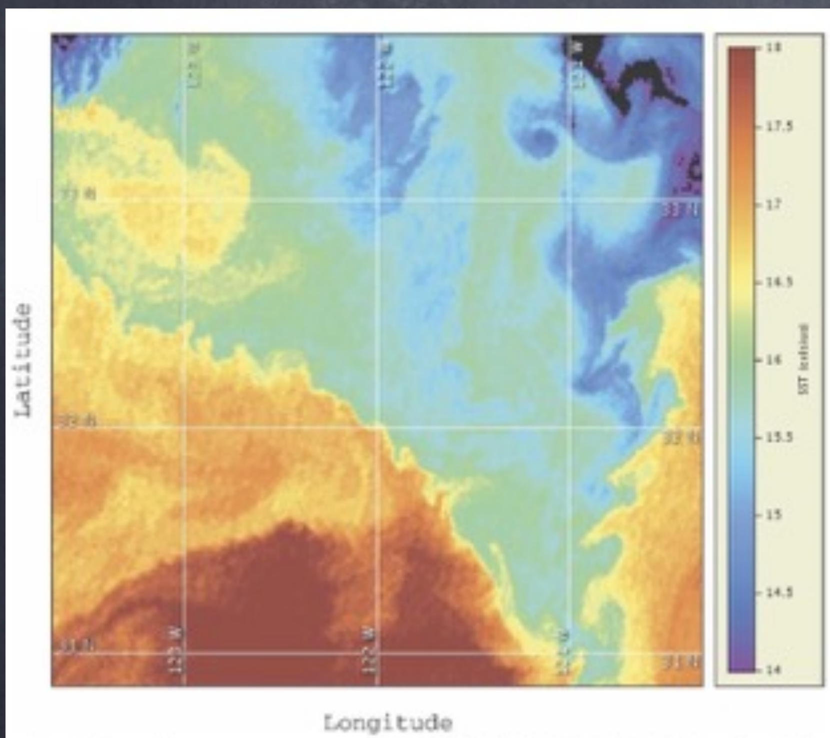
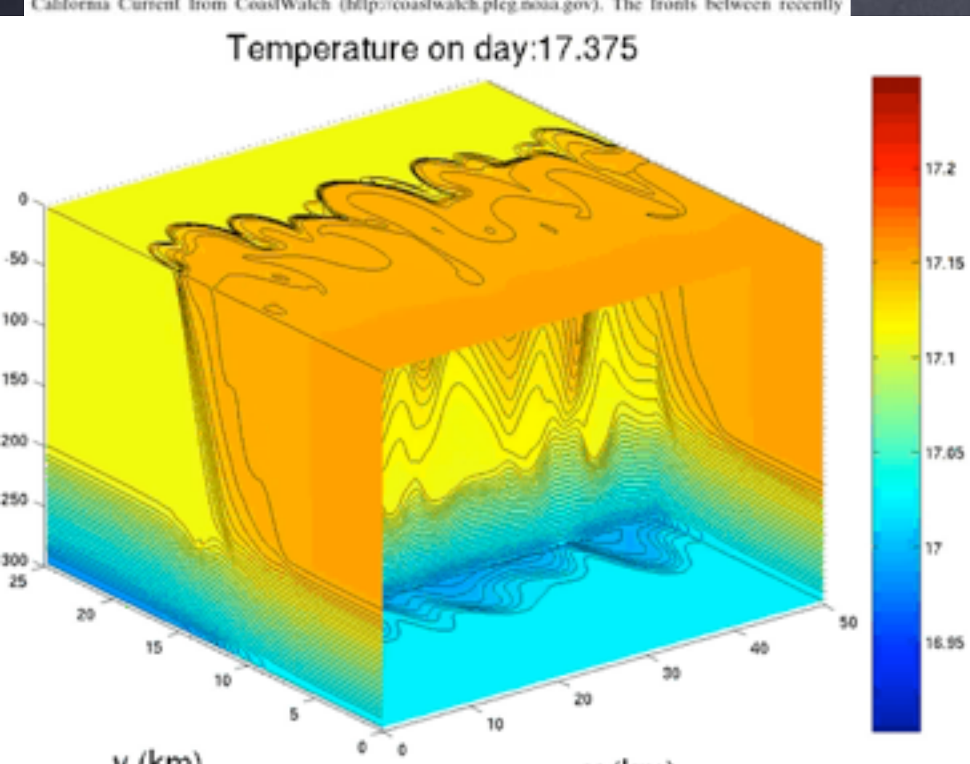


FIG. 16 Sea surface temperature measured at 1832 UTC 3 Jan 2006 off Point Conception in the California Current from CoastWatch (http://coastwatch.pfeg.noaa.gov). The fronts between recently



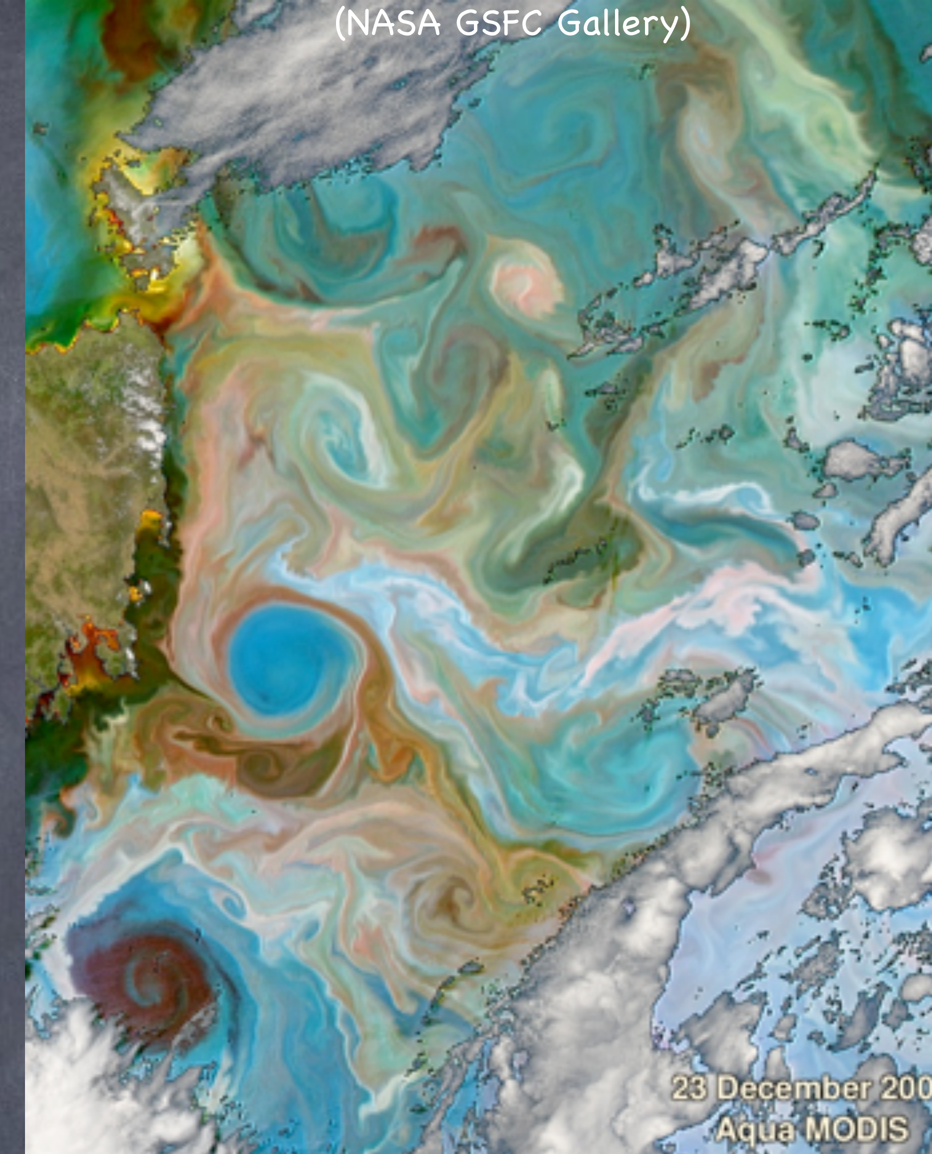
- Fronts
- Eddies
- Ro=O(1)
- Ri=O(1)
- near-surface (H=100m)
- 1-10km, days

Eddy processes often baroclinic instability

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

Routinely resolved in 2100

(NASA GSFC Gallery)

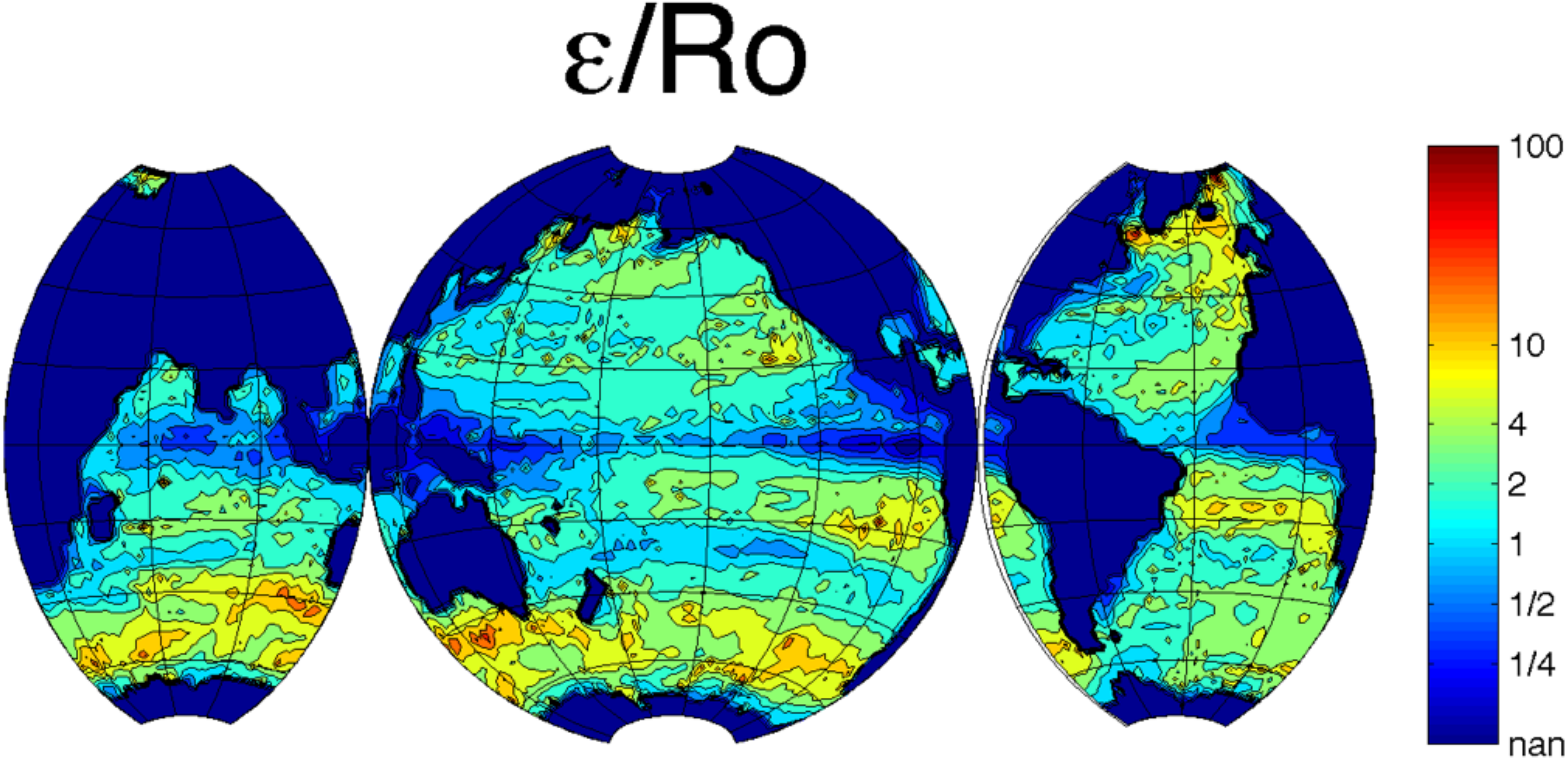


BFK, R. Ferrari, and R. W. Hallberg. Parameterization of mixed layer eddies. Part I: Theory and diagnosis. Journal of Physical Oceanography, 38(6):1145-1165, 2008

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

Obs. Indicate Stokes force directly affects the 1km-100km (sub)mesoscale!!



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

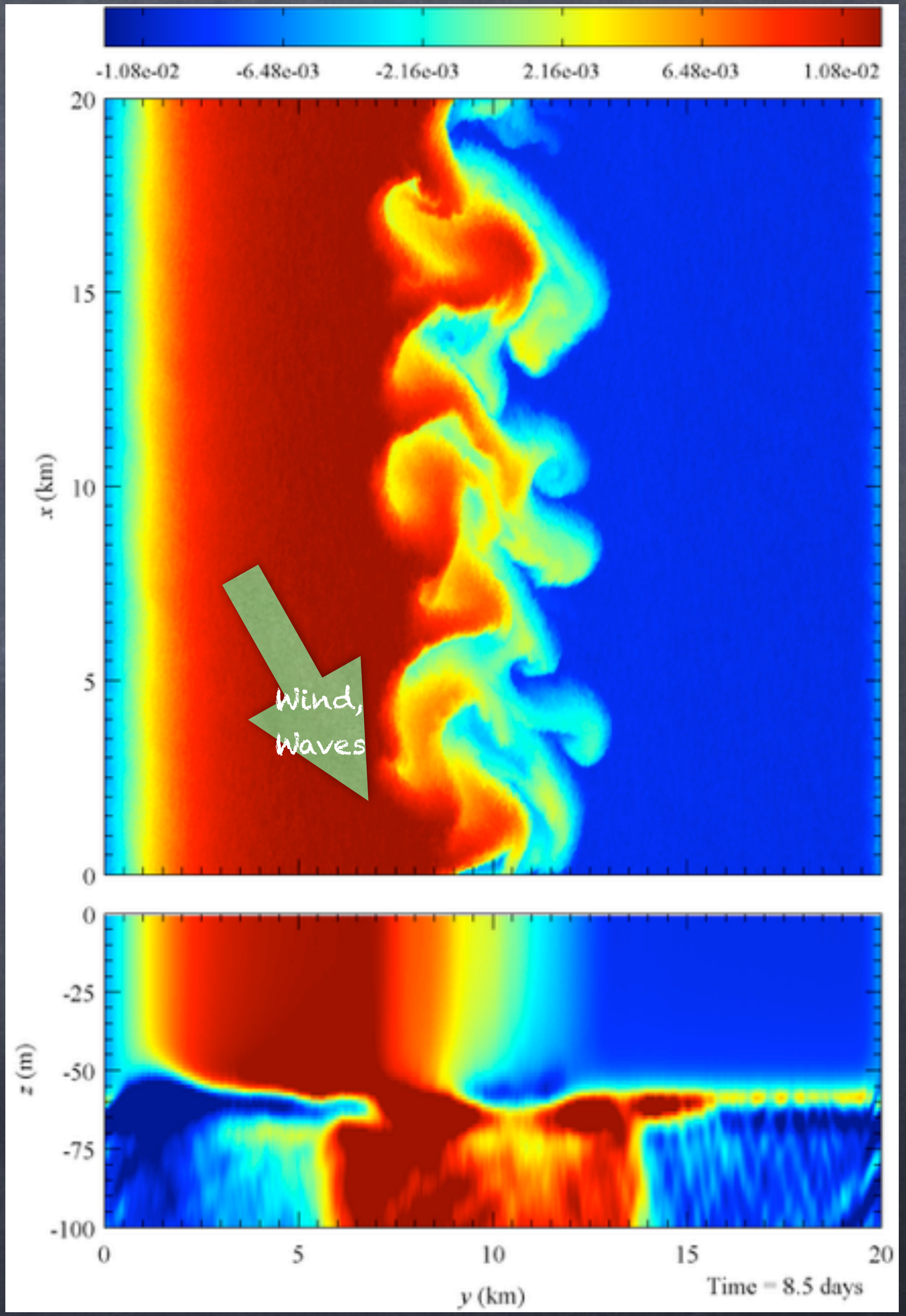
$$\varepsilon = \frac{V^s H}{fLH_s}$$

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

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

LES of Langmuir-Submeso Multiscale?

Movie: P. Hamlington



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

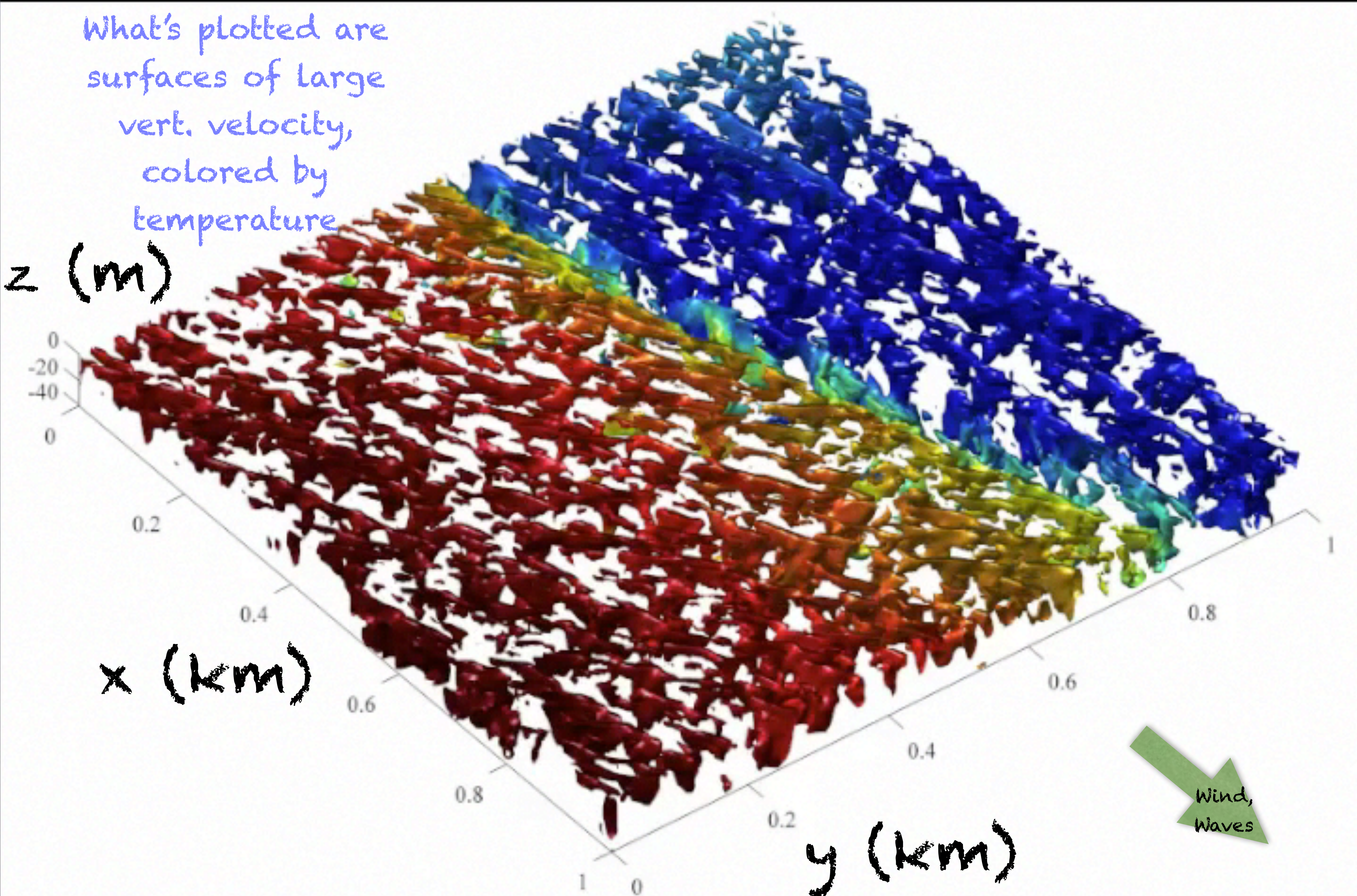
Use NCAR LES model to solve Wave-Averaged Eqtns.

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

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

1000x more gridpoints than CESM

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



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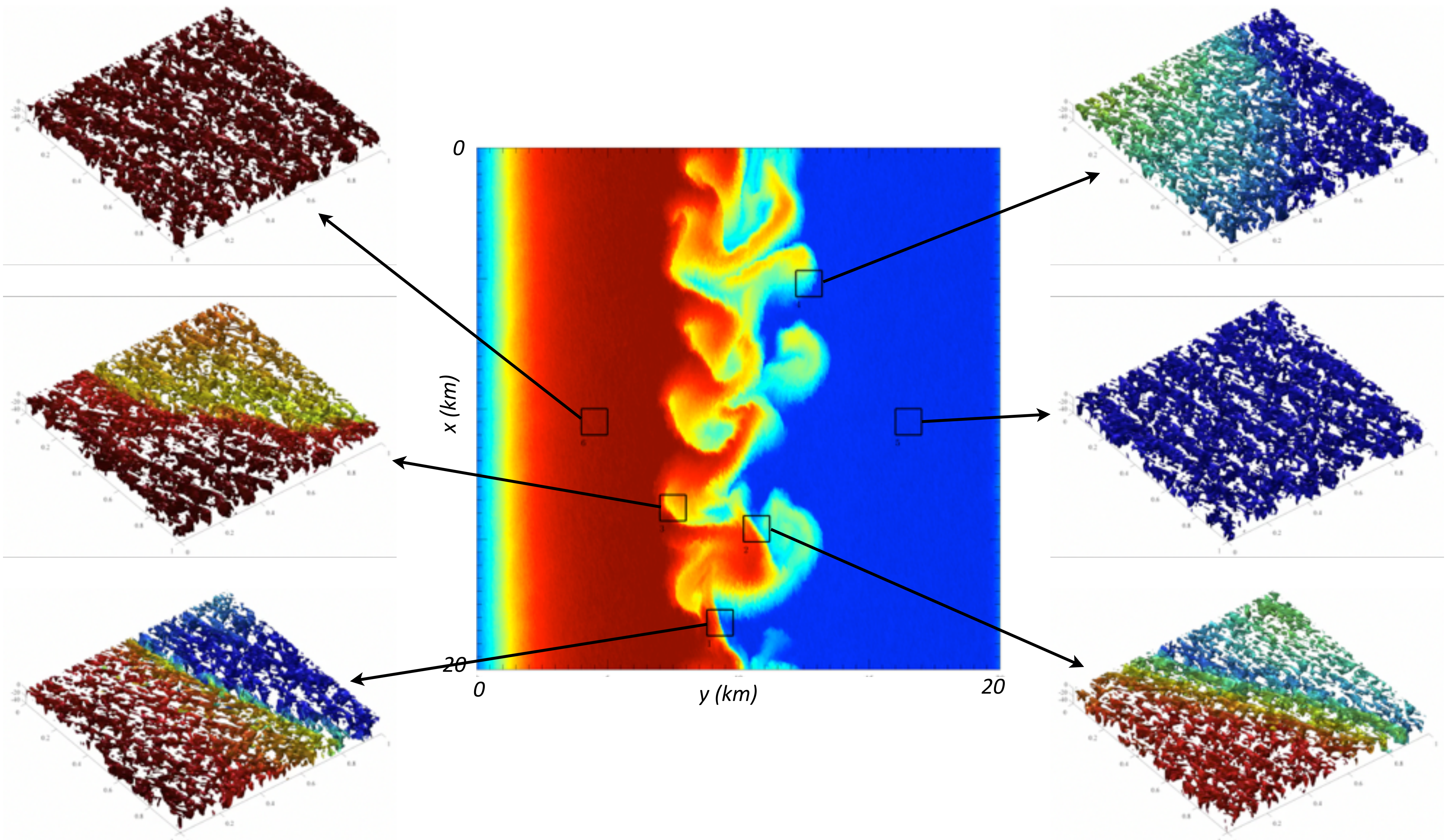
Diverse types of interaction



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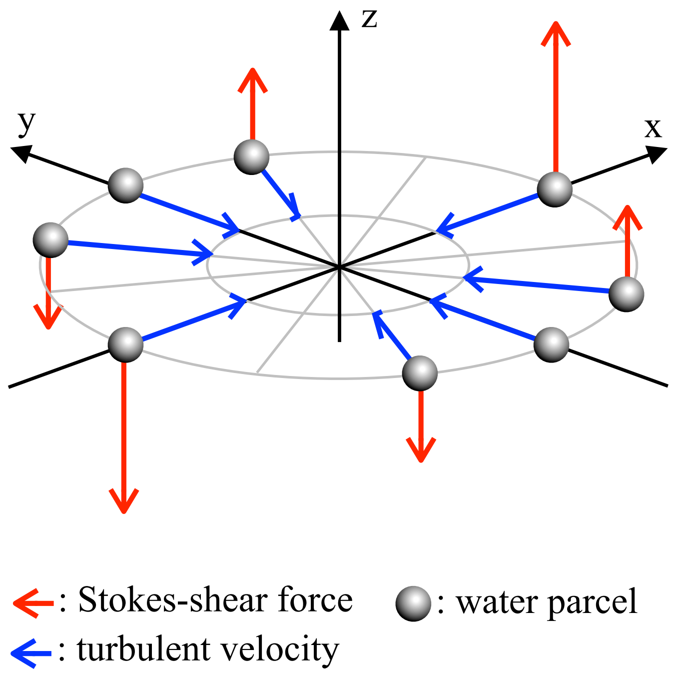
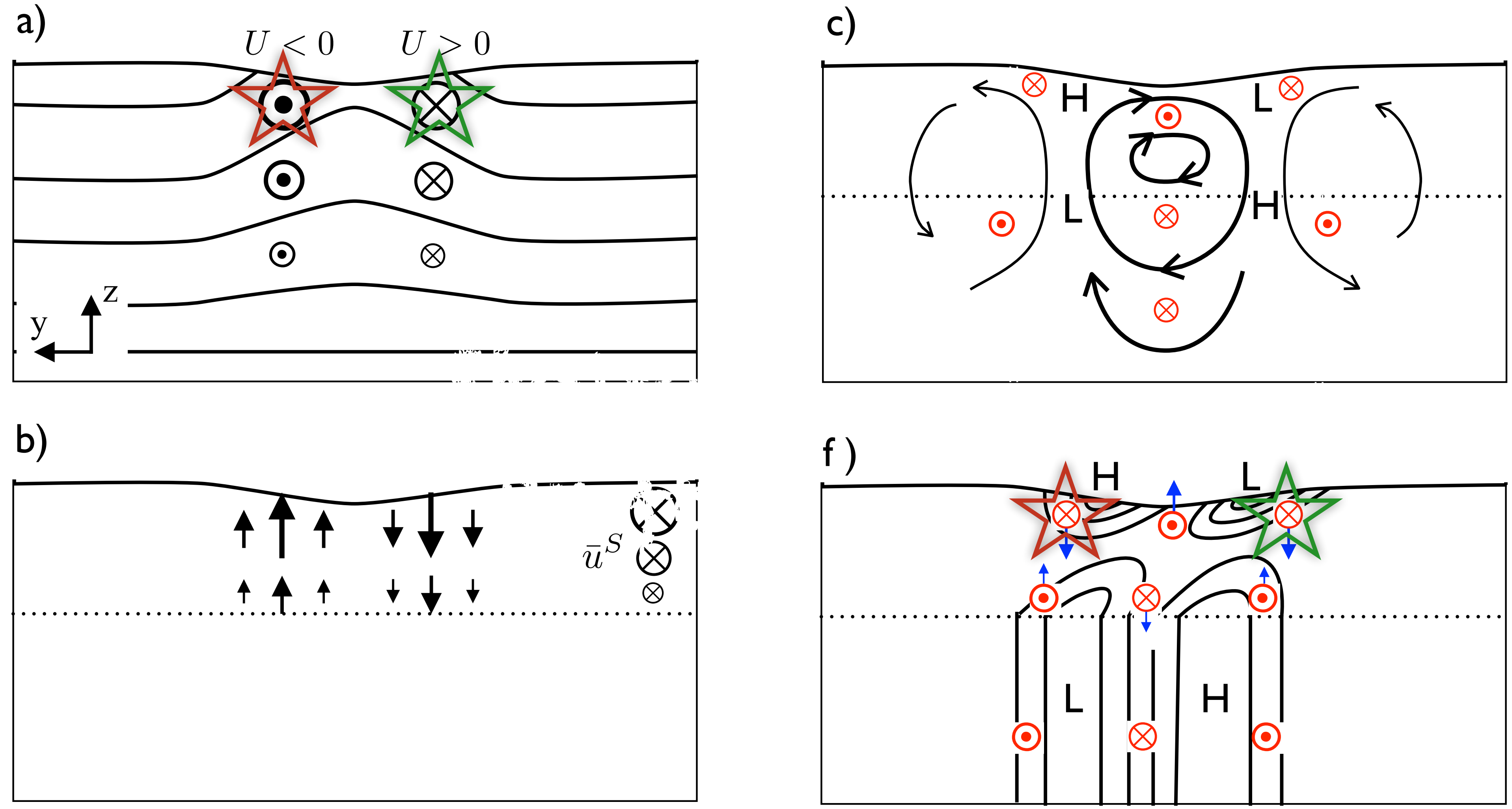
Stokes Shear Force Affects Fronts and Filaments





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

Enhances Fronts for Down-Front Stokes

Opposes Fronts for Up-Front Stokes

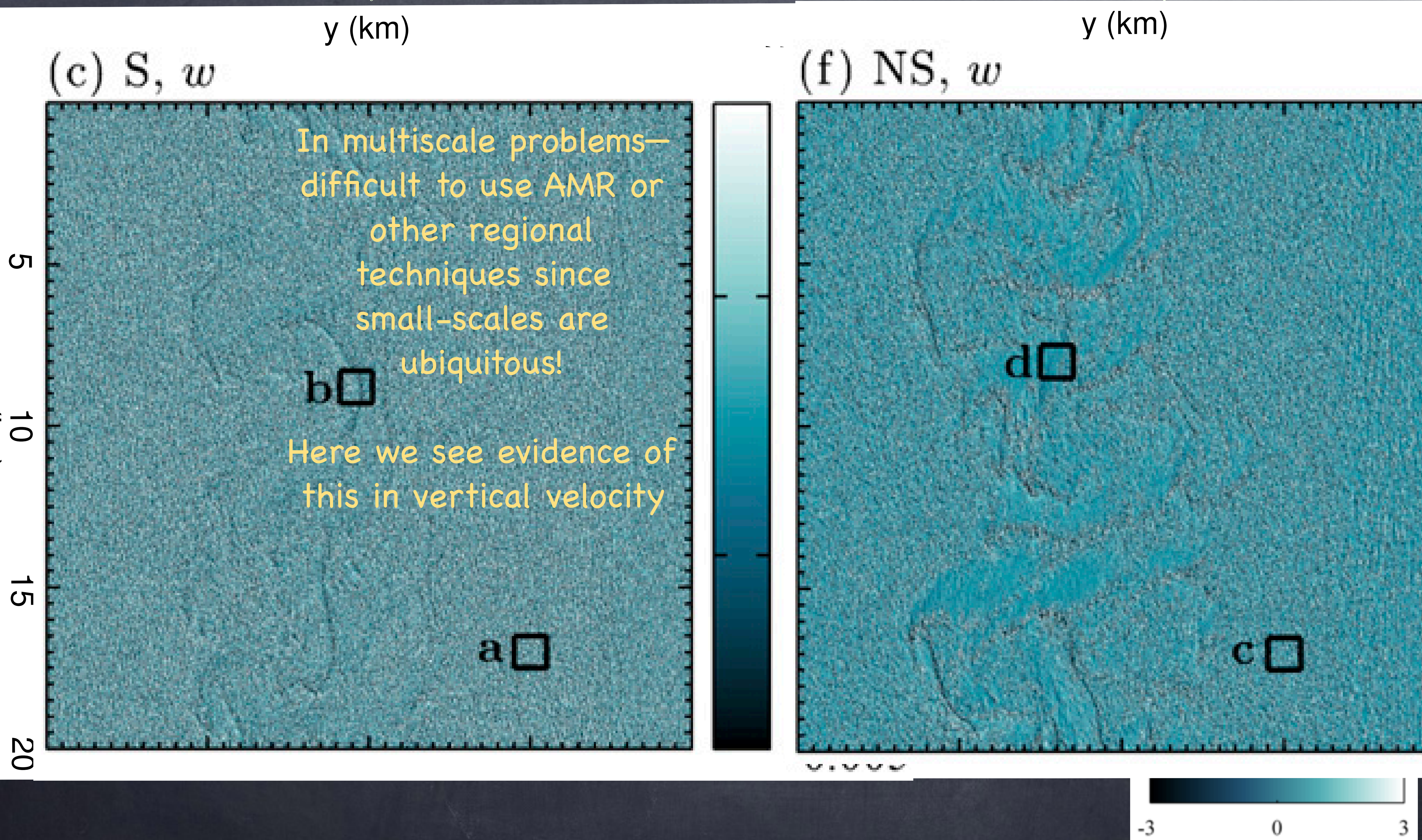
$$\frac{\alpha^2}{Ri}\left[w_{,t} + v_j^L w_{,j} + \frac{M_{Ro}}{RoRi} w w_{,z}\right] = -\pi_{,z} + b - \varepsilon v_j^L v^s_{j,z} + \frac{\alpha^2}{ReRi} w_{,jj}$$

Waves May Give 30% of Power Produced at Front

Vertical Vorticity in two simulations, same time after initialization

In Temperature, it's hard to tell the difference!

Wind & Waves Wind Only



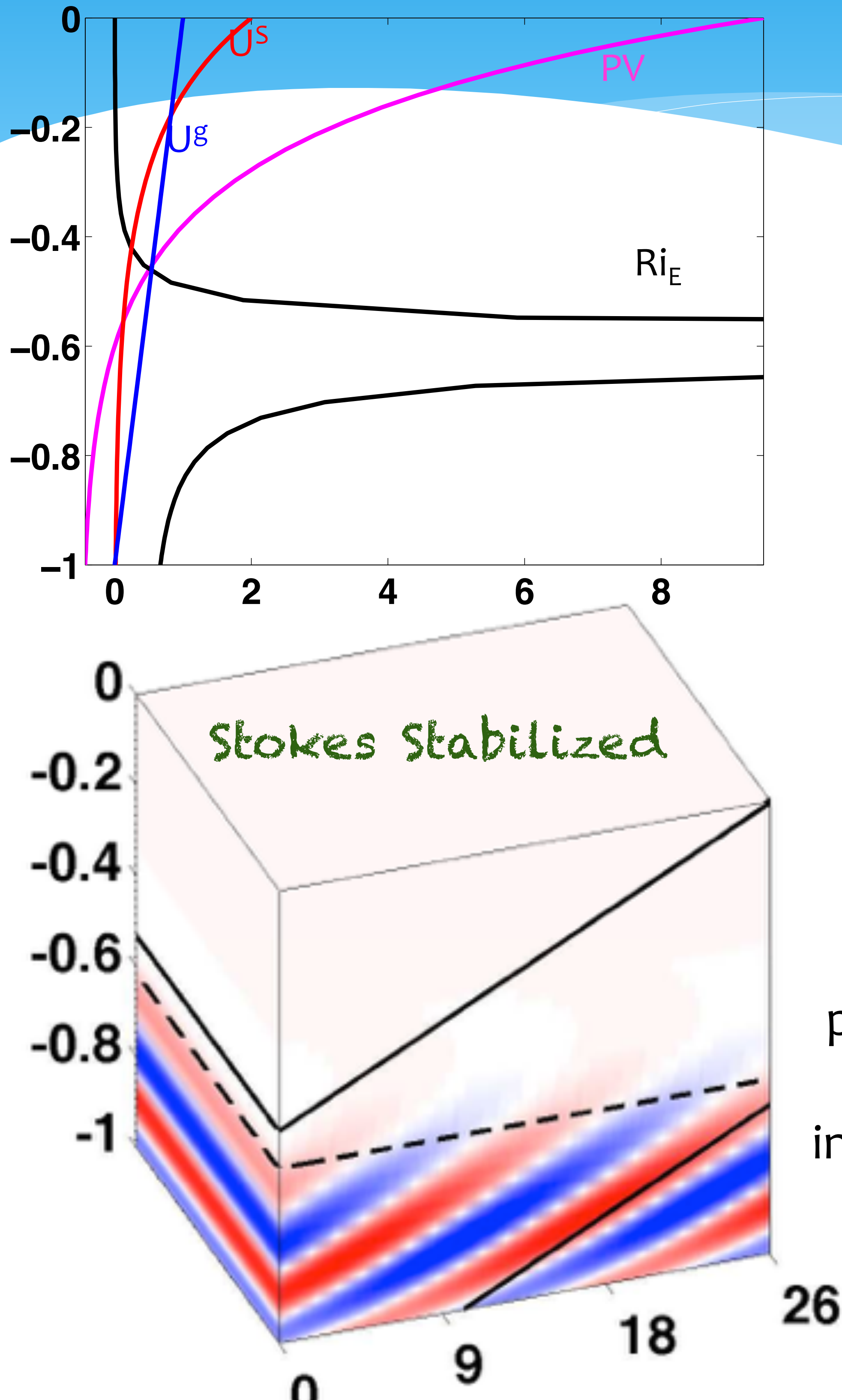
In multiscale problems—difficult to use AMR or other regional techniques since small-scales are ubiquitous!

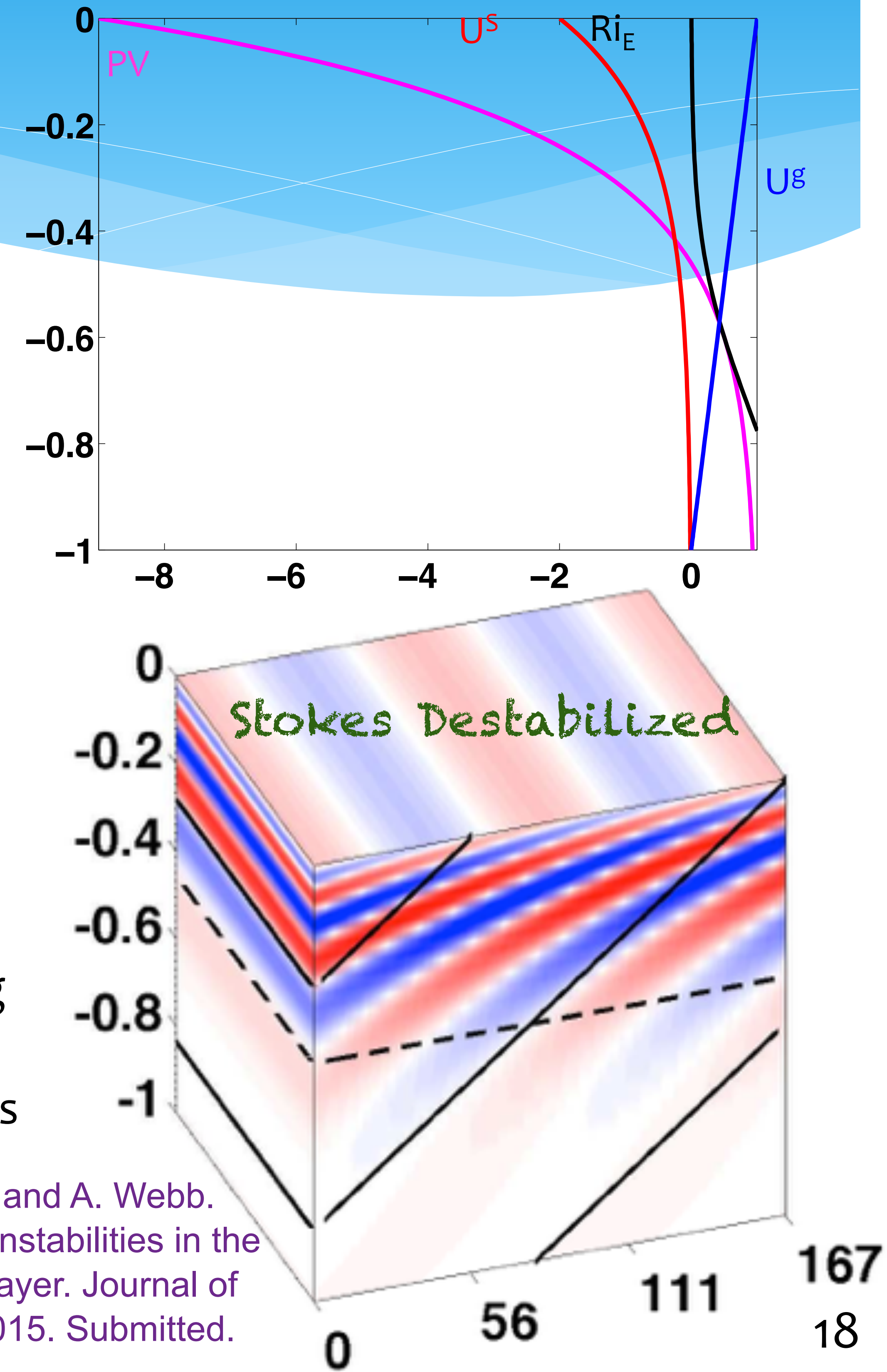
Here we see evidence of this in vertical velocity

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.

Stokes Shear force affects O(100m) Symmetric Instabilities (criterion & effects)

fq<0 ⇒SI



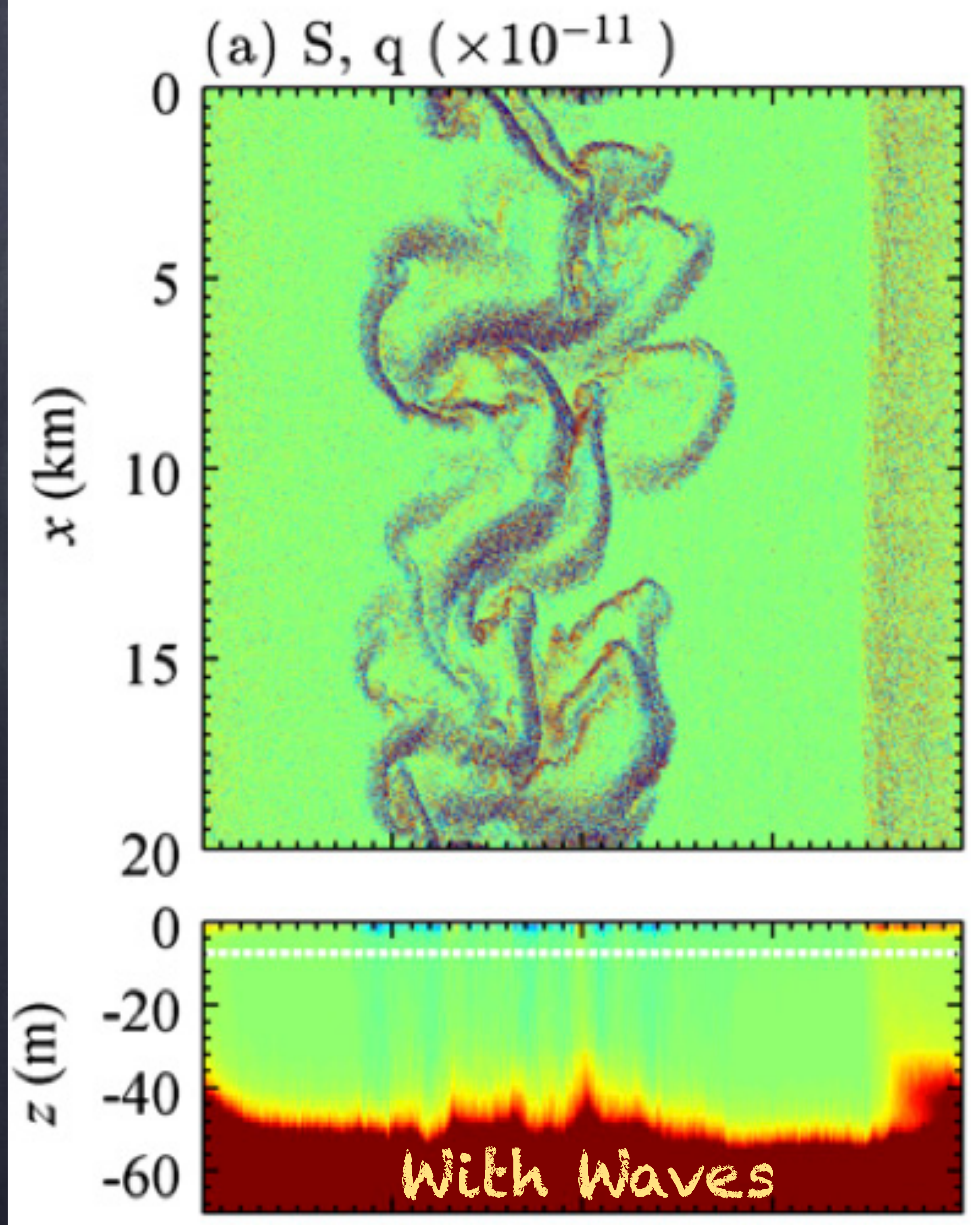


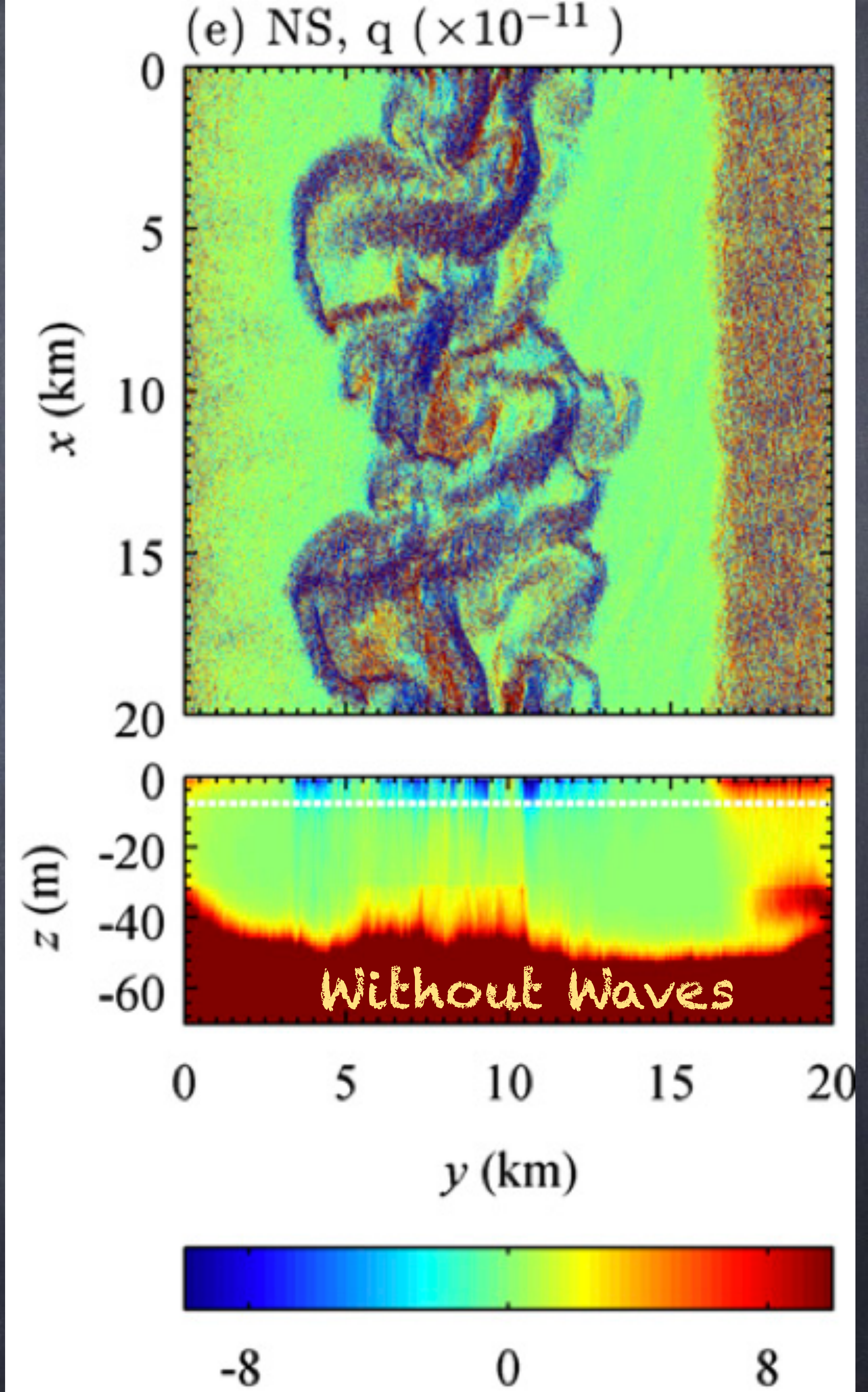
——Isopycnals

- - PV=0

Cross front velocity pattern shows growing mode—black lines indicate density surfaces

S. Haney, BFK, K. Julien, and A. Webb. Symmetric and geostrophic instabilities in the wave-forced ocean mixed layer. Journal of Physical Oceanography, 2015. Submitted.





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.

Conclusions

- Upper Ocean Turbulence, Fronts, & Instabilites are important, and are beautiful to contemplate
- Interesting transition in physics, as nonhydro. & ageostrophic effects begin to dominate
- Nonhydrostatic effects of the Stokes forces on 1m to 10km dynamics are under-appreciated.
- Applications & parameterizations just beginning!
- All papers at: fox-kemper.com/pubs