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

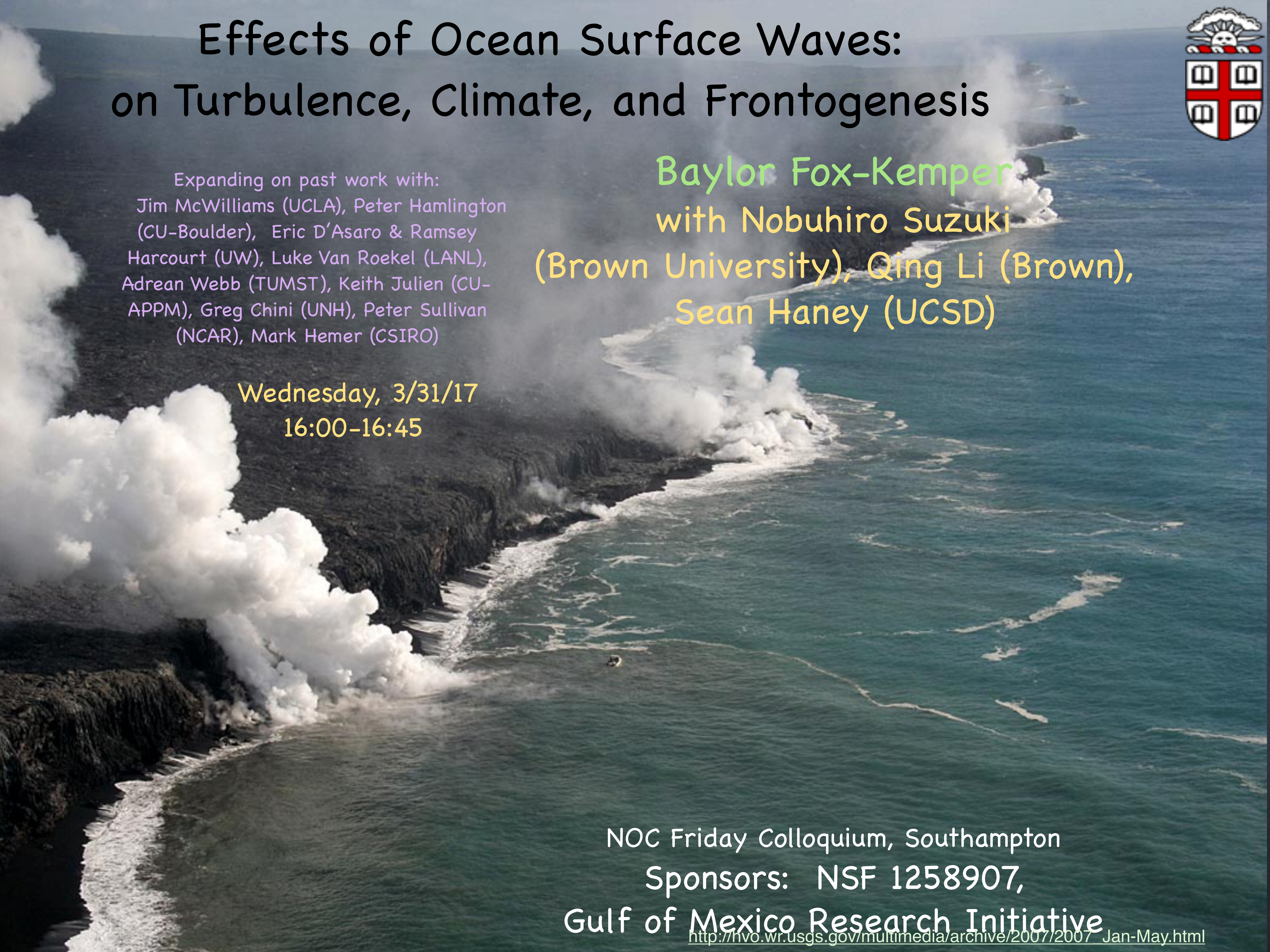
Expanding on past work with:
Jim McWilliams (UCLA), Peter Hamlington (CU-Boulder), Eric D'Asaro & Ramsey Harcourt (UW), Luke Van Roekel (LANL), Adrean Webb (TUMST), Keith Julien (CU-APPM), Greg Chini (UNH), Peter Sullivan (NCAR), Mark Hemer (CSIRO)

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

Wednesday, 3/31/17
16:00-16:45

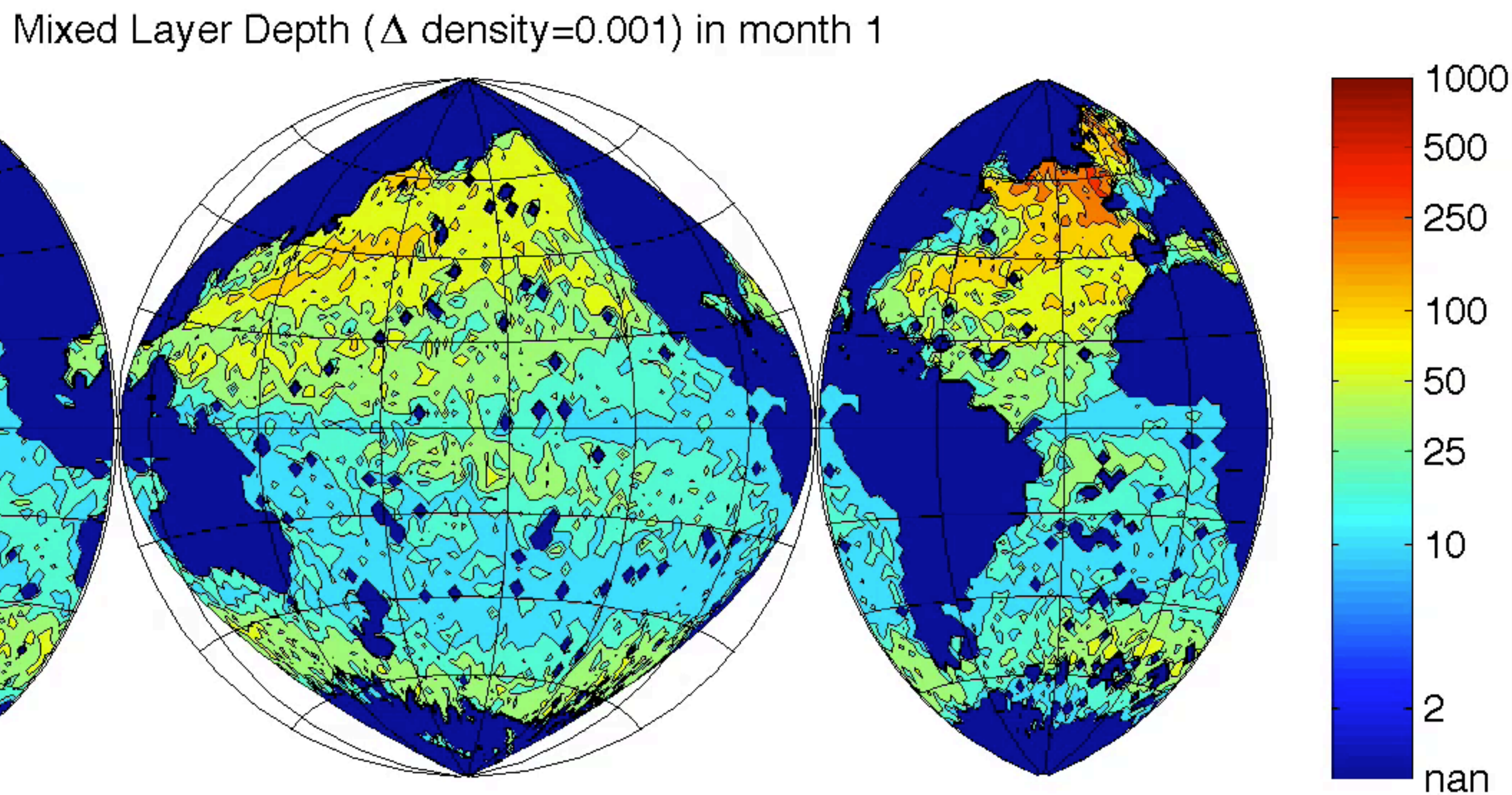
NOC Friday Colloquium, Southampton

Sponsors: NSF 1258907,
Gulf of Mexico Research Initiative



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

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

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)

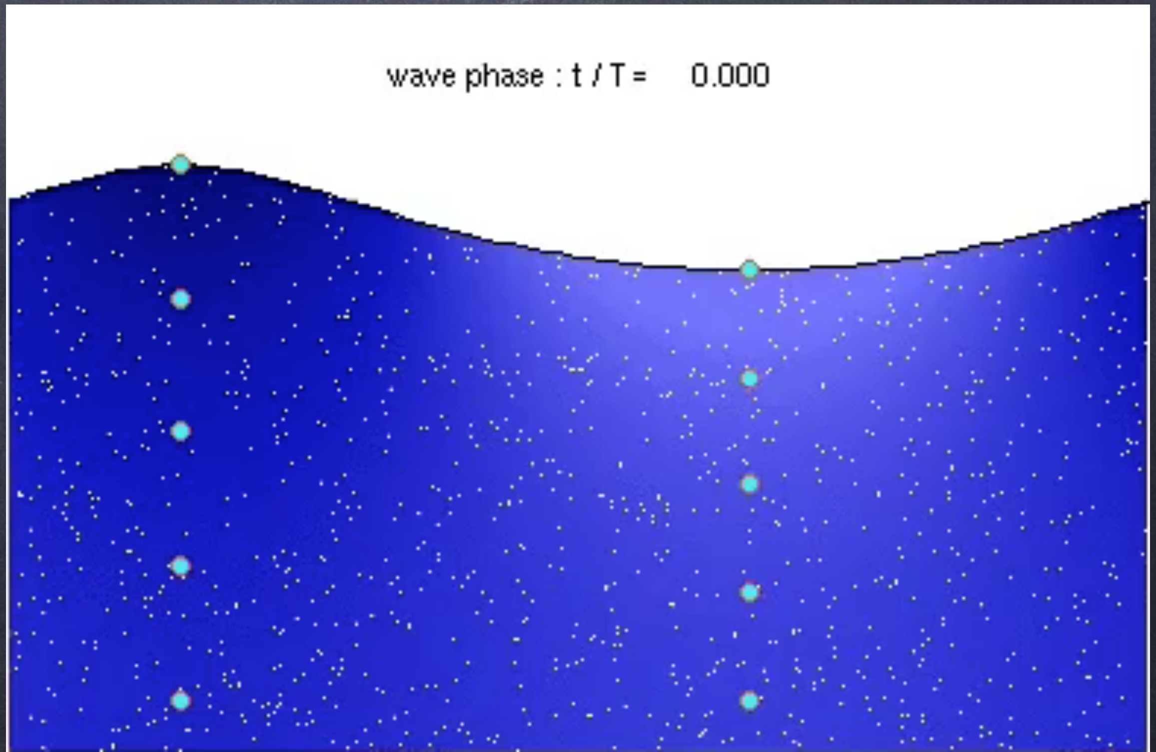
3 Effects Dominate open ocean "Wave-Averaged Equations": (Craik, Leibovich, McWilliams et al. 1997)

All rely only on Stokes drift of waves

1: Stokes Advection: parcels, tracers, momentum move with Lagrangian, not Eulerian flow

2: Stokes Coriolis: water parcels experience Coriolis force during this motion

3: Stokes Shear Force

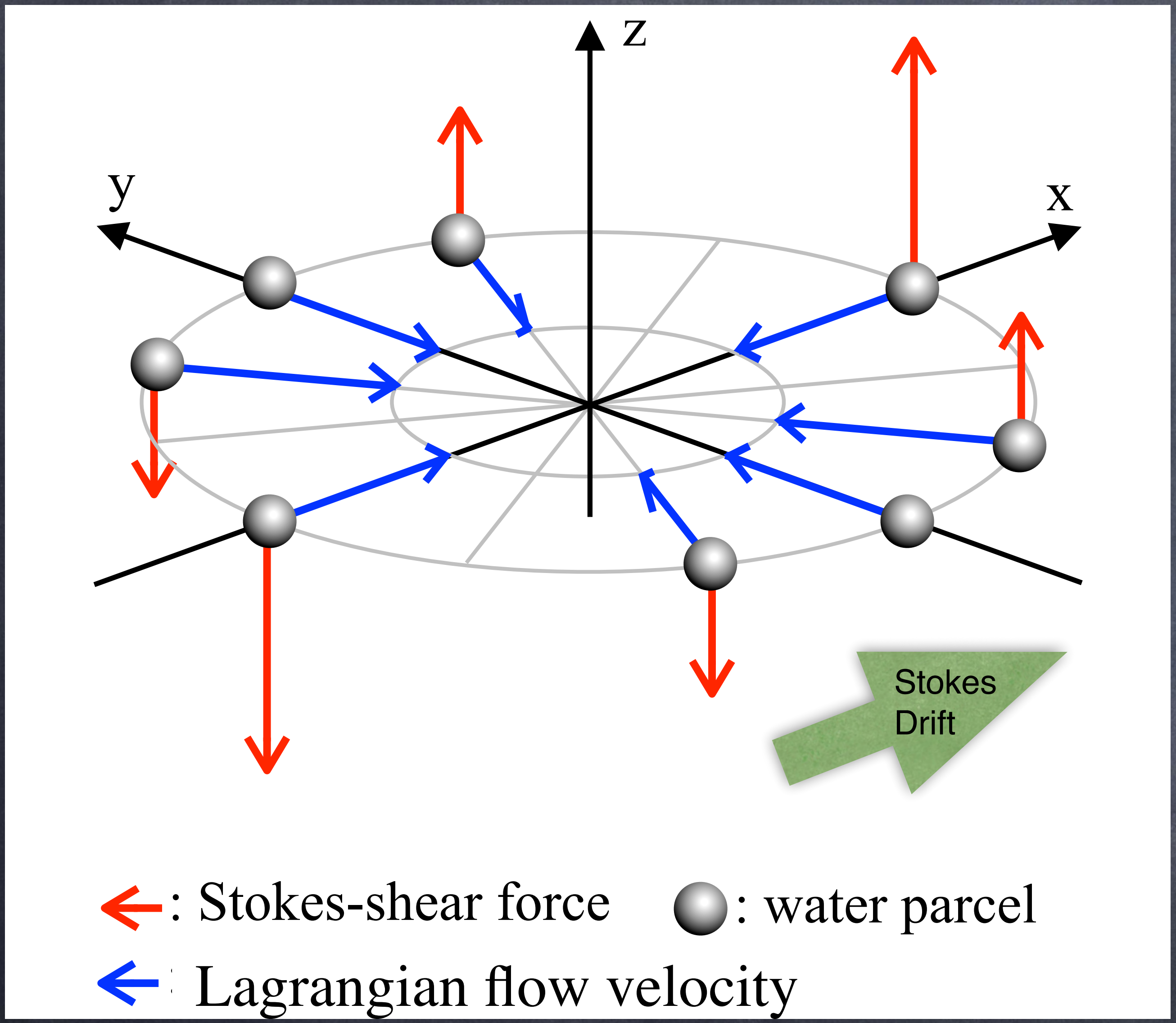


N. Suzuki and BFK. Understanding Stokes forces in the wave-averaged equations. Journal of Geophysical Research-Oceans, 121:1-18, 2016.

3 Wave Effects, 3: Stokes Shear Force

and the CL2 mechanism for Langmuir circulations

Flow directed along Stokes shear=downward force



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

"wavy hydrostatic" if

hydrostatic $\epsilon \gg 1$

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

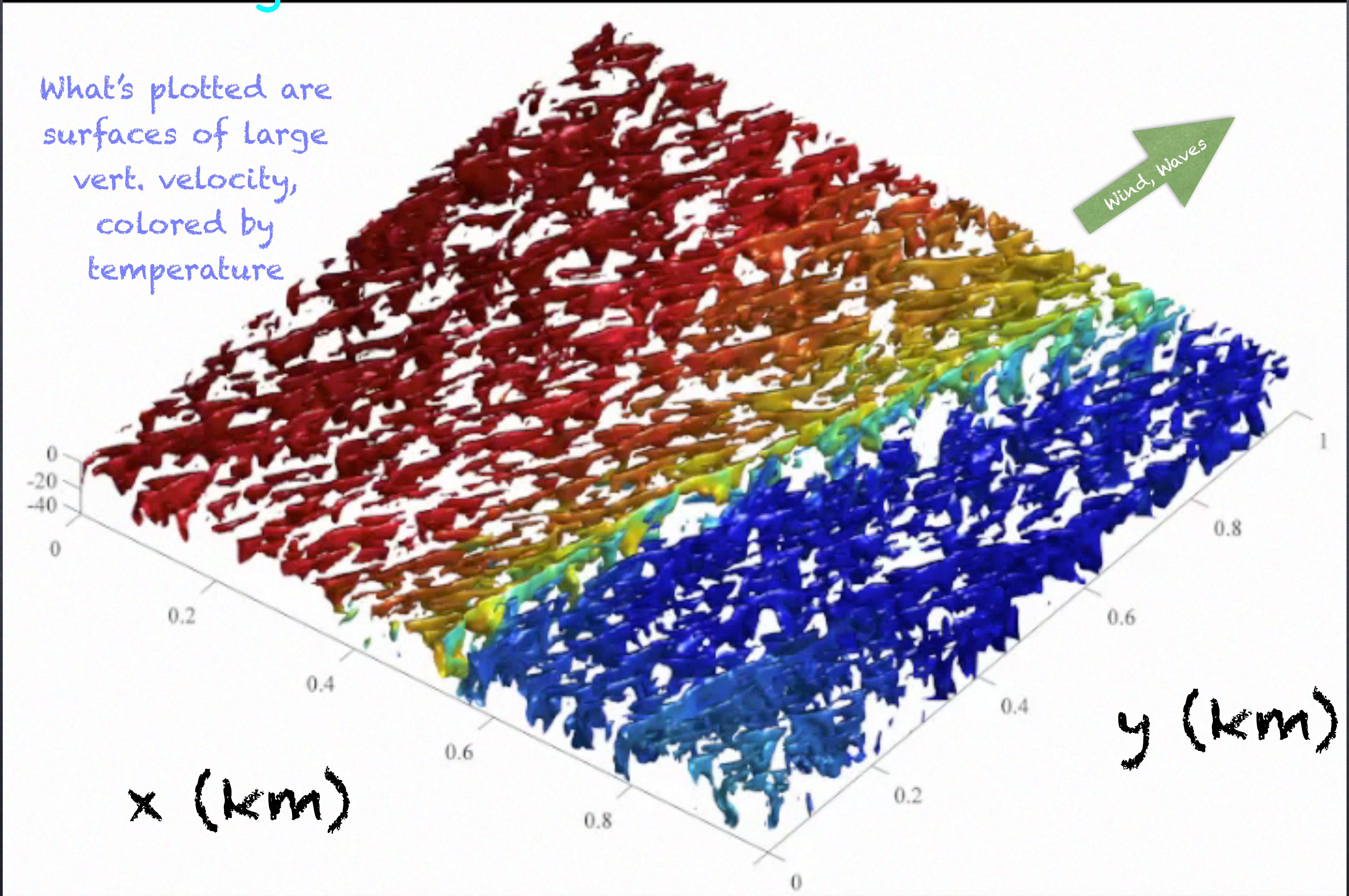
N. Suzuki and BFK. Understanding Stokes forces in the wave-averaged equations. Journal of Geophysical Research-Oceans, 121:1-18, 2016.

The Character of Langmuir Turbulence

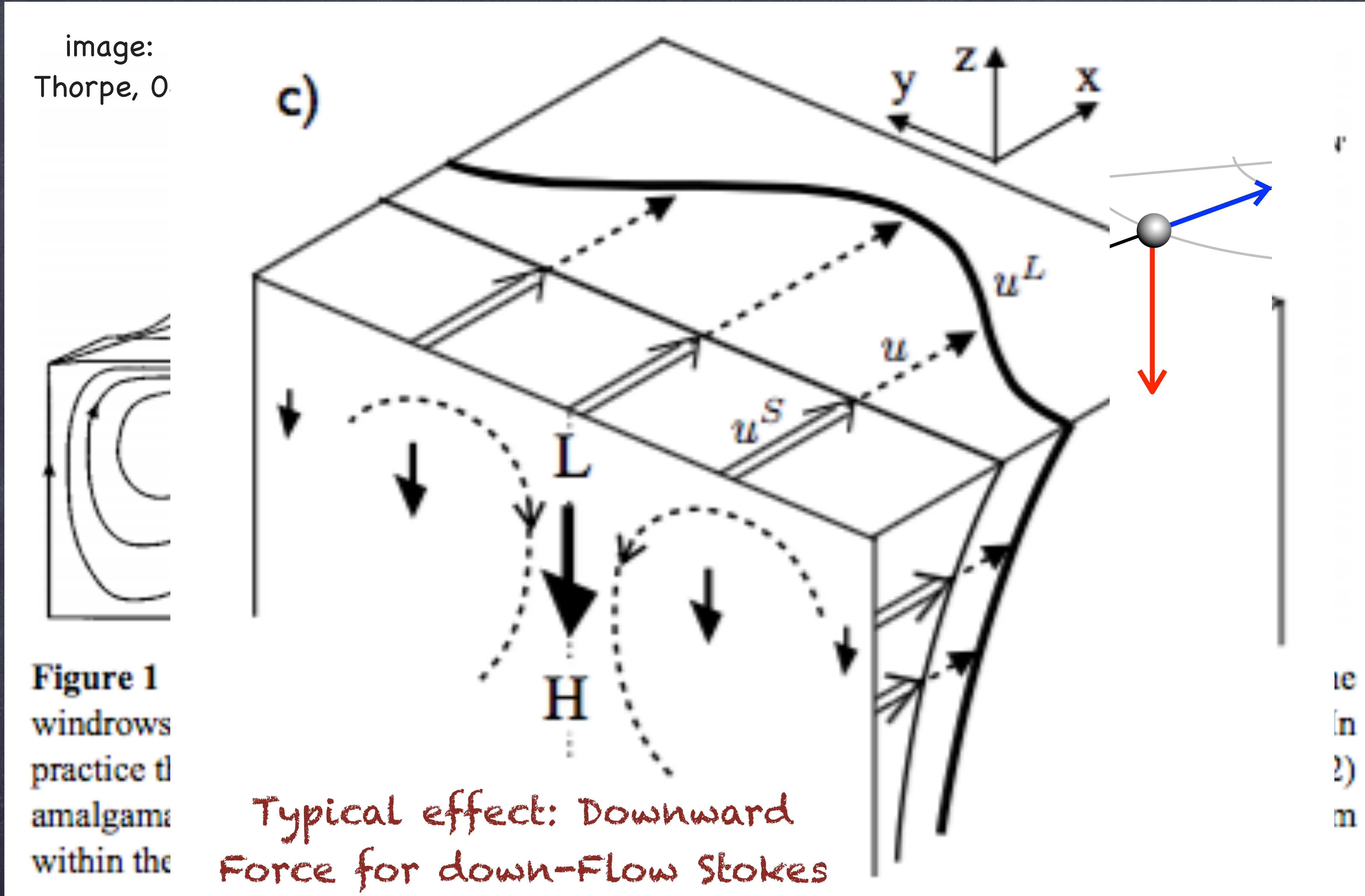
- Near-surface
- Langmuir Cells & Langmuir Turb.
- Ro>>1
- Ri<1: Nonhydro
- 1-100m (H=L)
- 10s to 1hr
- w, u=O(10cm/s)
- Stokes drift
- Eqtns: Wave-Averaged
- Params: McWilliams & Sullivan, 2000, Van Roekel et al. 2011
- Resolved routinely in 2170

Image: NPR.org, Deep Water Horizon Spill

Large Eddy Simulations, Observations, Constrain Langmuir Turbulence Parameterizations



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. JPO, 44(9):2249-2272, 2014.



"wavy hydrostatic" if $\epsilon \gg 1$

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

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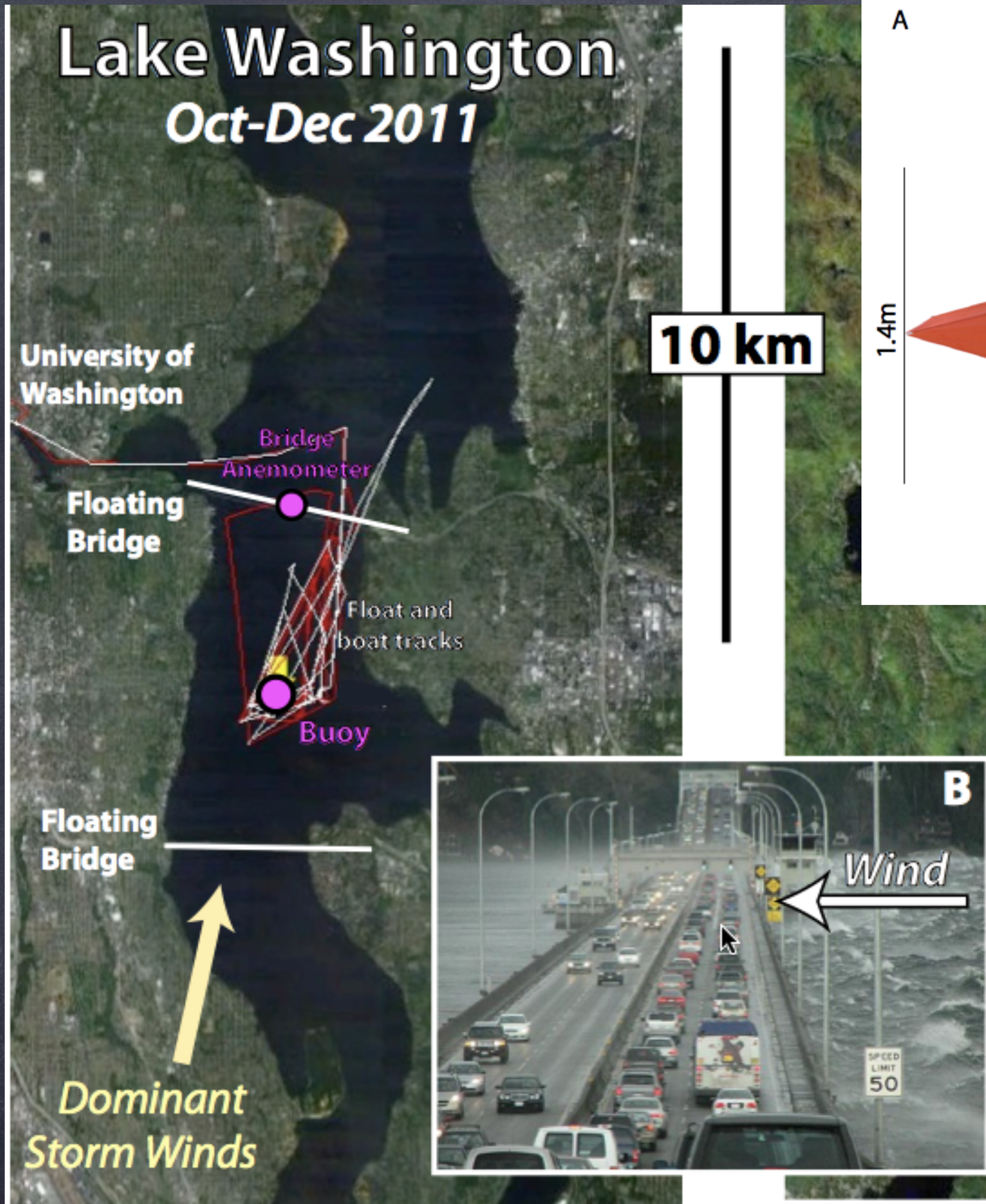
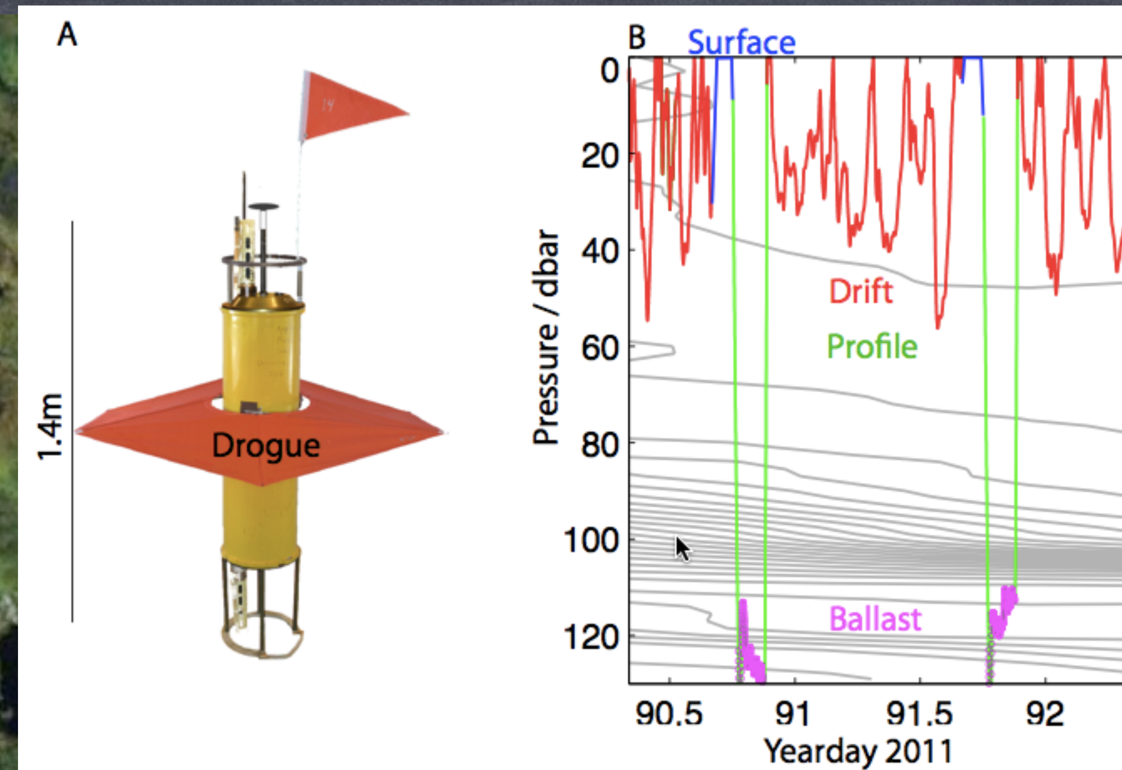
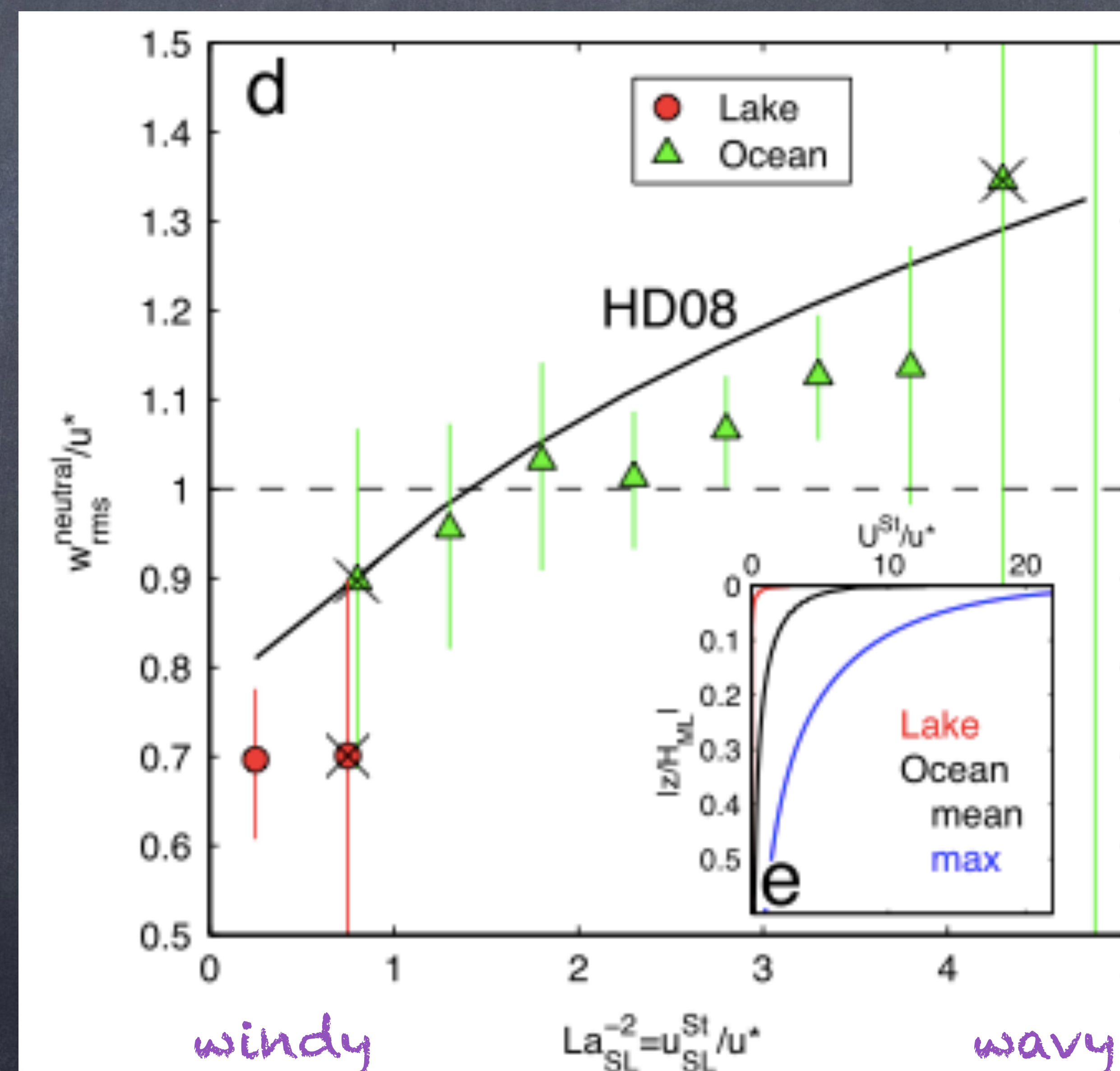






E. A. D'Asaro, J. Thomson, A. Y. Shcherbina, R. R. Harcourt, M. F. Cronin, M. A. Hemer, and BFK. Quantifying upper ocean turbulence driven by surface waves. Geophysical Research Letters, 41(1):102-107, January 2014.

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

Langmuir Mixing in Climate: Boundary layer Depth Improved

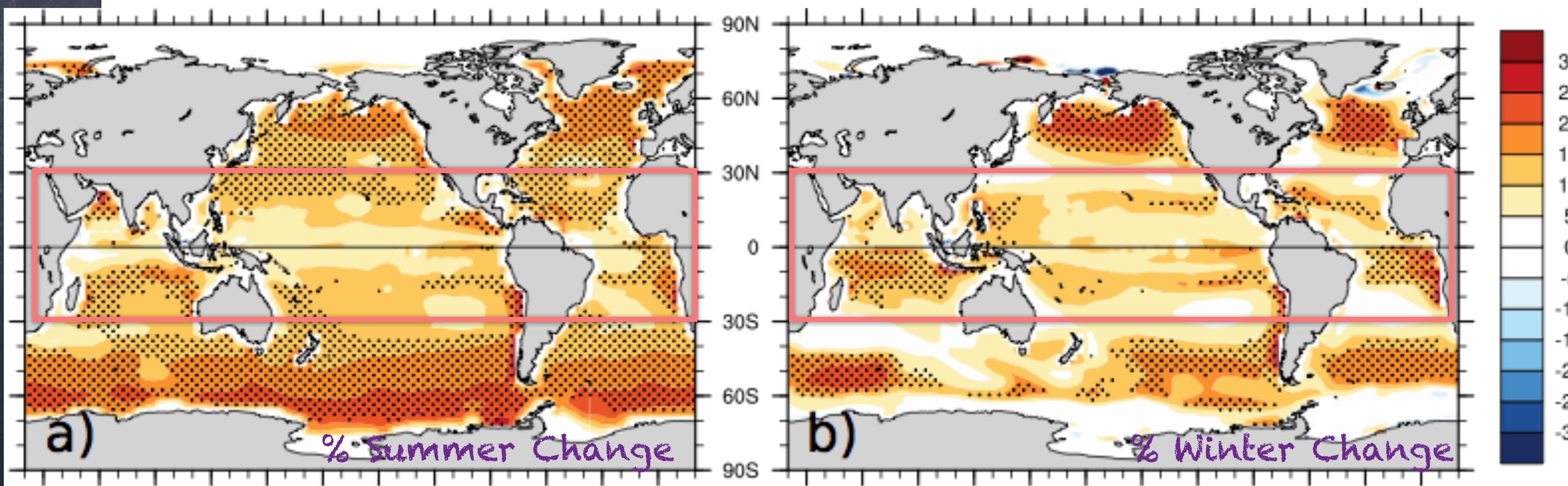
Case	Summer Global	Summer South of 30°S	Summer 30°S-30°N	Winter Global	Winter South of 30°S	Winter 30°S-30°N
CTRL	10.62±0.27[a]	17.24±0.48	5.38±0.14	43.85±0.38	57.19±0.76	12.57±0.28
	(13.40±0.19)[b]	(21.73±0.32)	(6.71±0.09)	(45.50±0.40)	(56.53±0.59)	(16.16±0.29)
MS2K	15.37	15.47	17.03	119.91	171.92	40.31
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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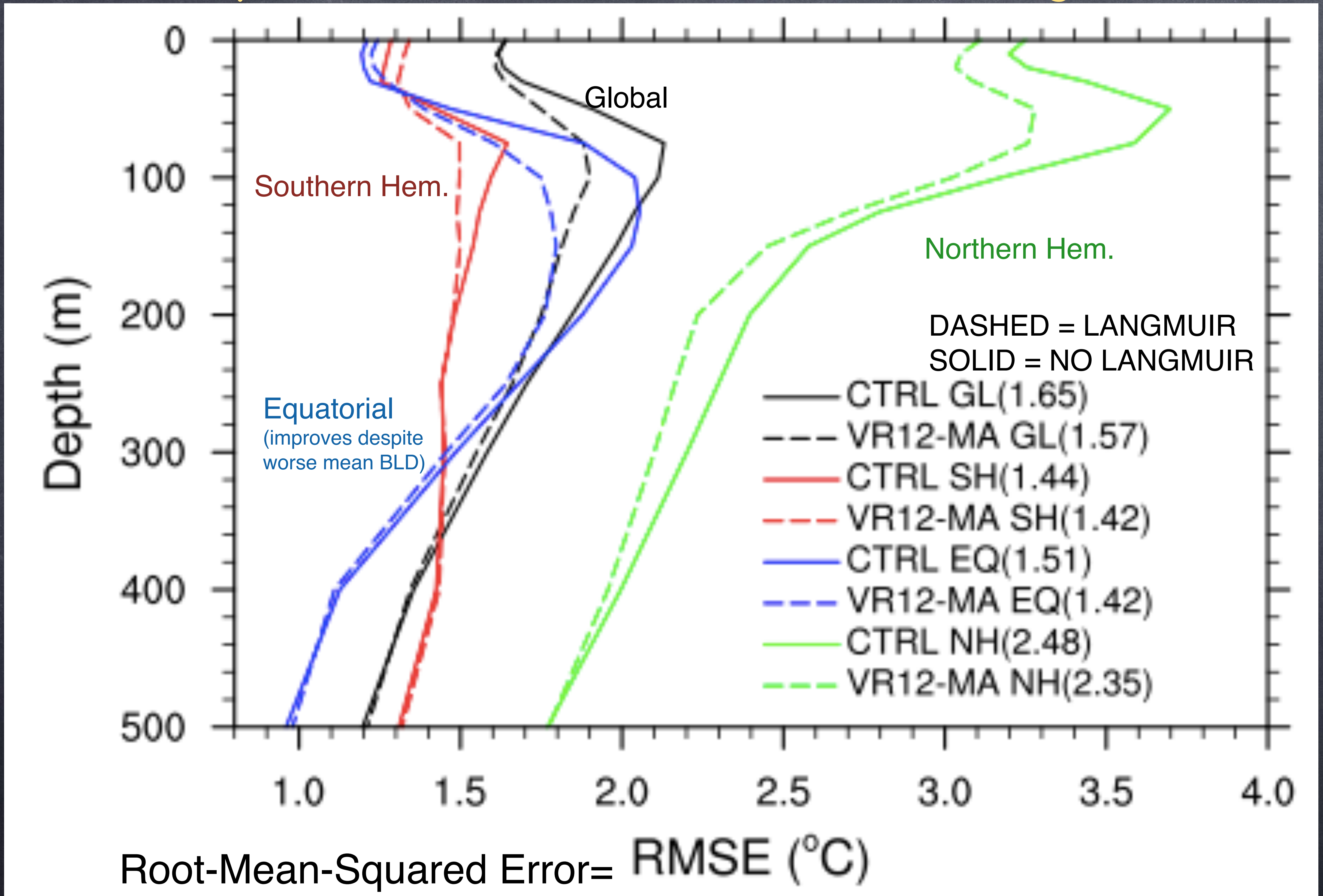
Q. Li, A. Webb, BFK, A. Craig, G. Danabasoglu, W. G. Large, and M. Vertenstein. Langmuir mixing effects on global climate: WAVEWATCH III in CESM. Ocean Modelling, 103:145-160, July 2016.

Stommel Demon, Subsurface Temperature (also CFCs, S, etc.): Improved vs. Observations with Langmuir



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How accurate do we need the waves to be?

Langmuir Turbulence Parameterizations are robust to large approximations in wave modeling, e.g., replacing wave models with climatology, theoretical scalings

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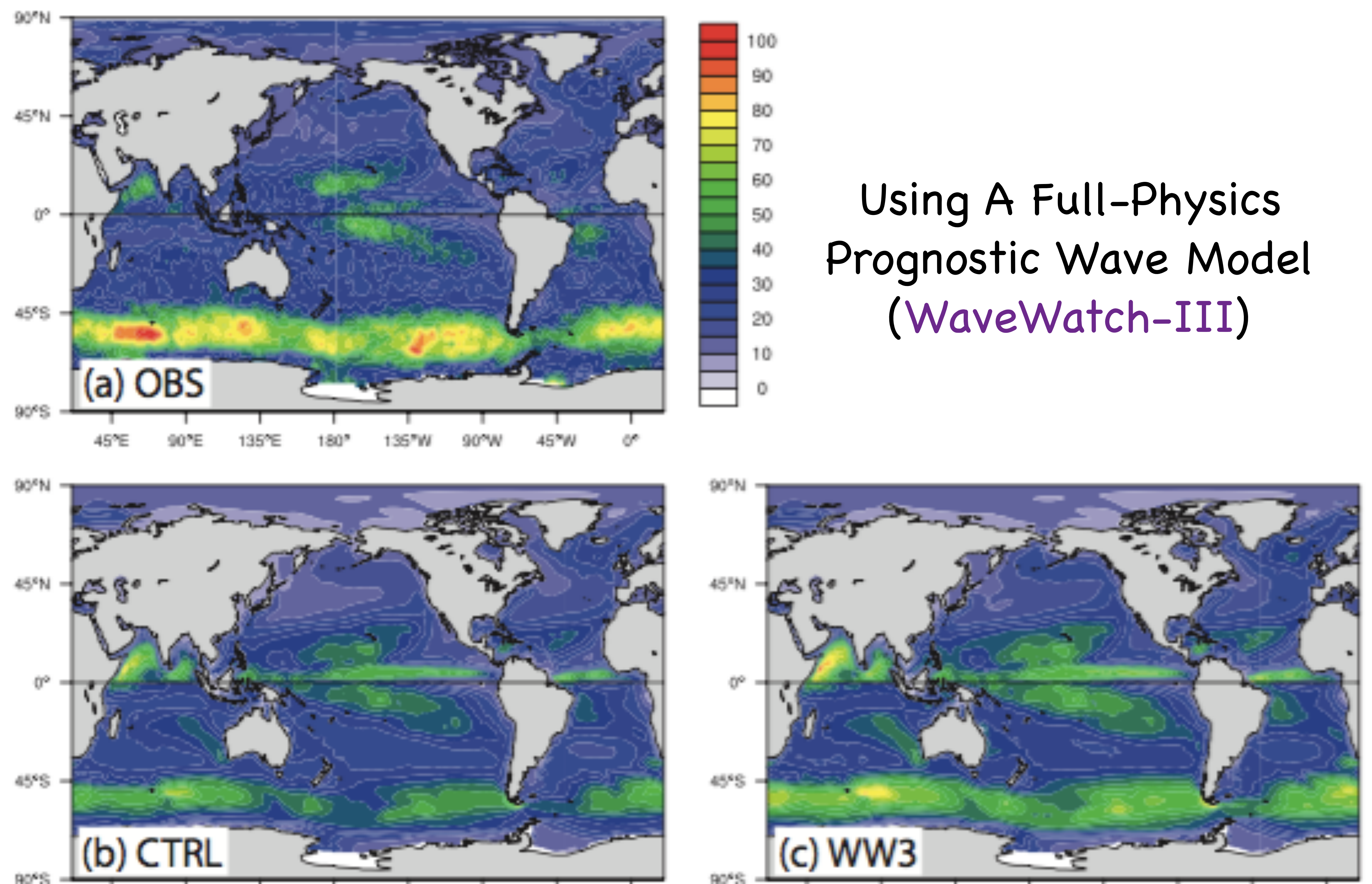

Using A Full-Physics Prognostic Wave Model (WaveWatch-III)

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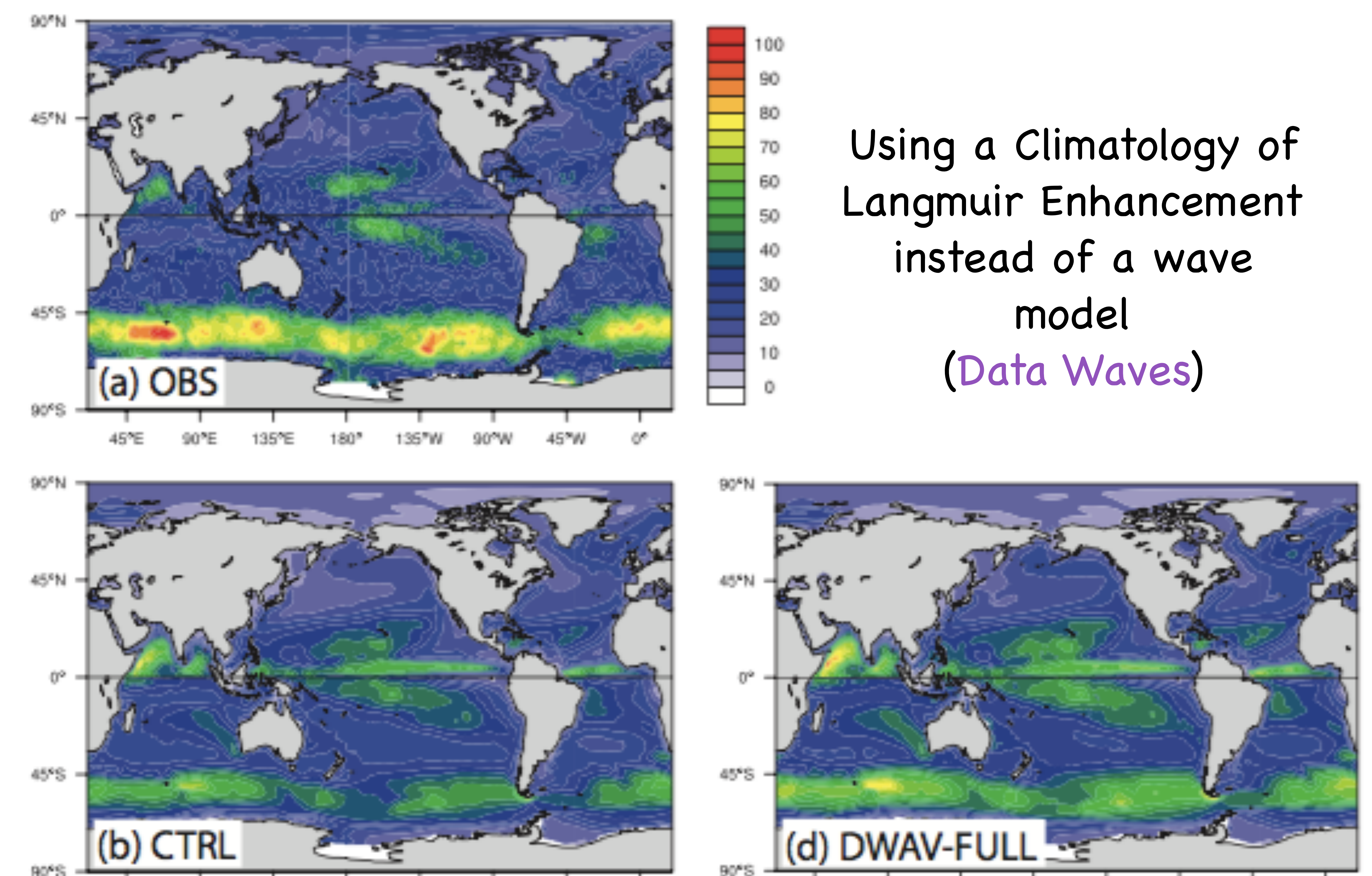

Using a Climatology of Langmuir Enhancement instead of a wave model
(Data Waves)

How accurate do we need the waves to be?

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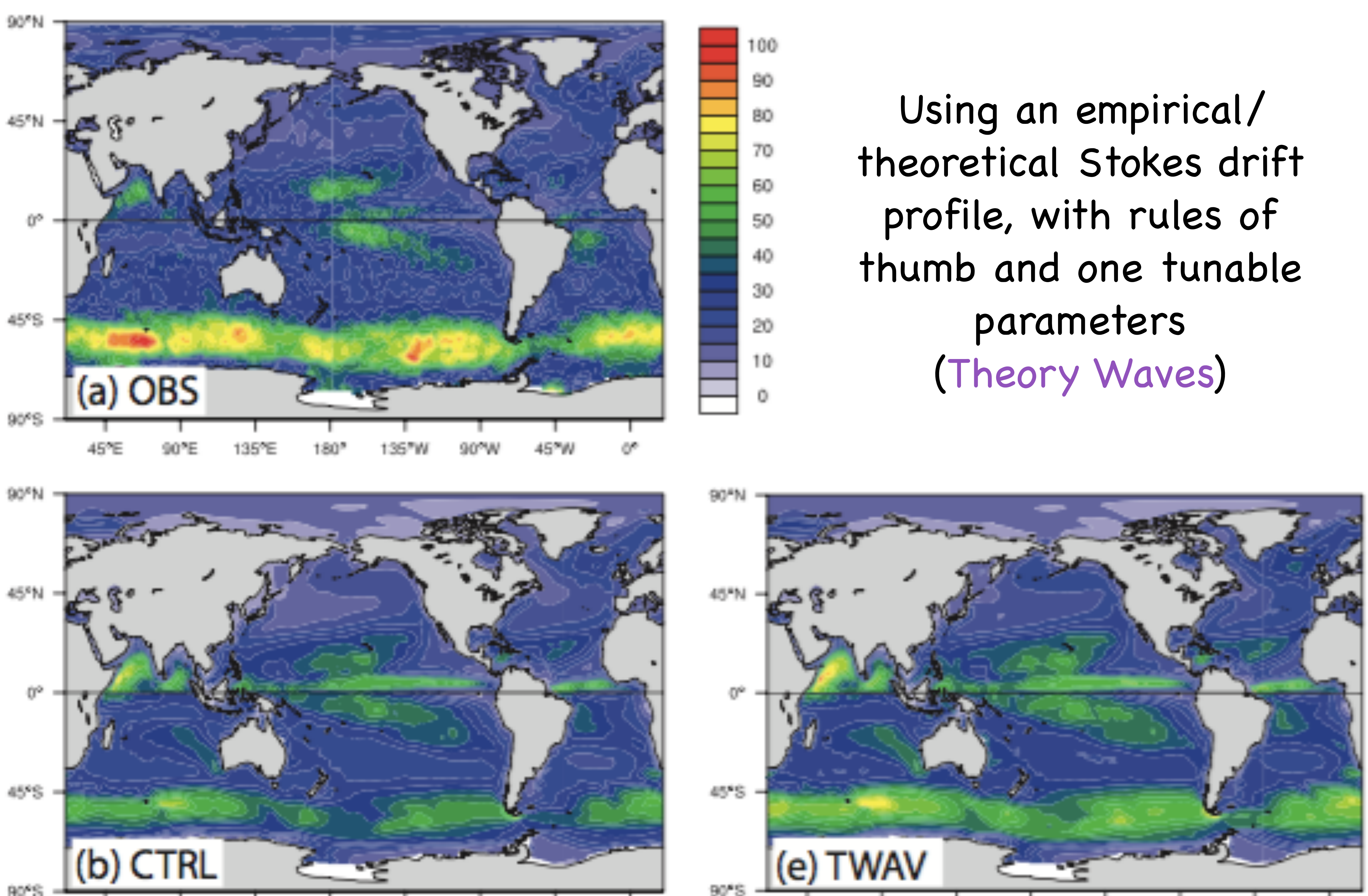

Using an empirical/ theoretical Stokes drift profile, with rules of thumb and one tunable parameters (Theory Waves)

Do Details of Turbulence Matter Much?

- Our parameterization of Langmuir Turbulence comes in 2 parts:
  - Enhanced mixing within the boundary layer (based on Stokes parameters)
  - Enhanced entrainment (recasting the predicted boundary layer depth in terms of Stokes-dependent unresolved shear)

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.

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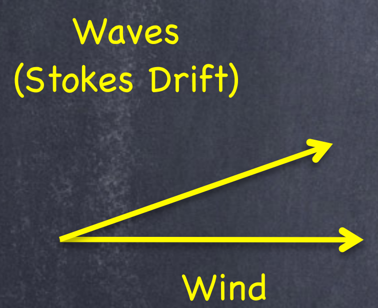
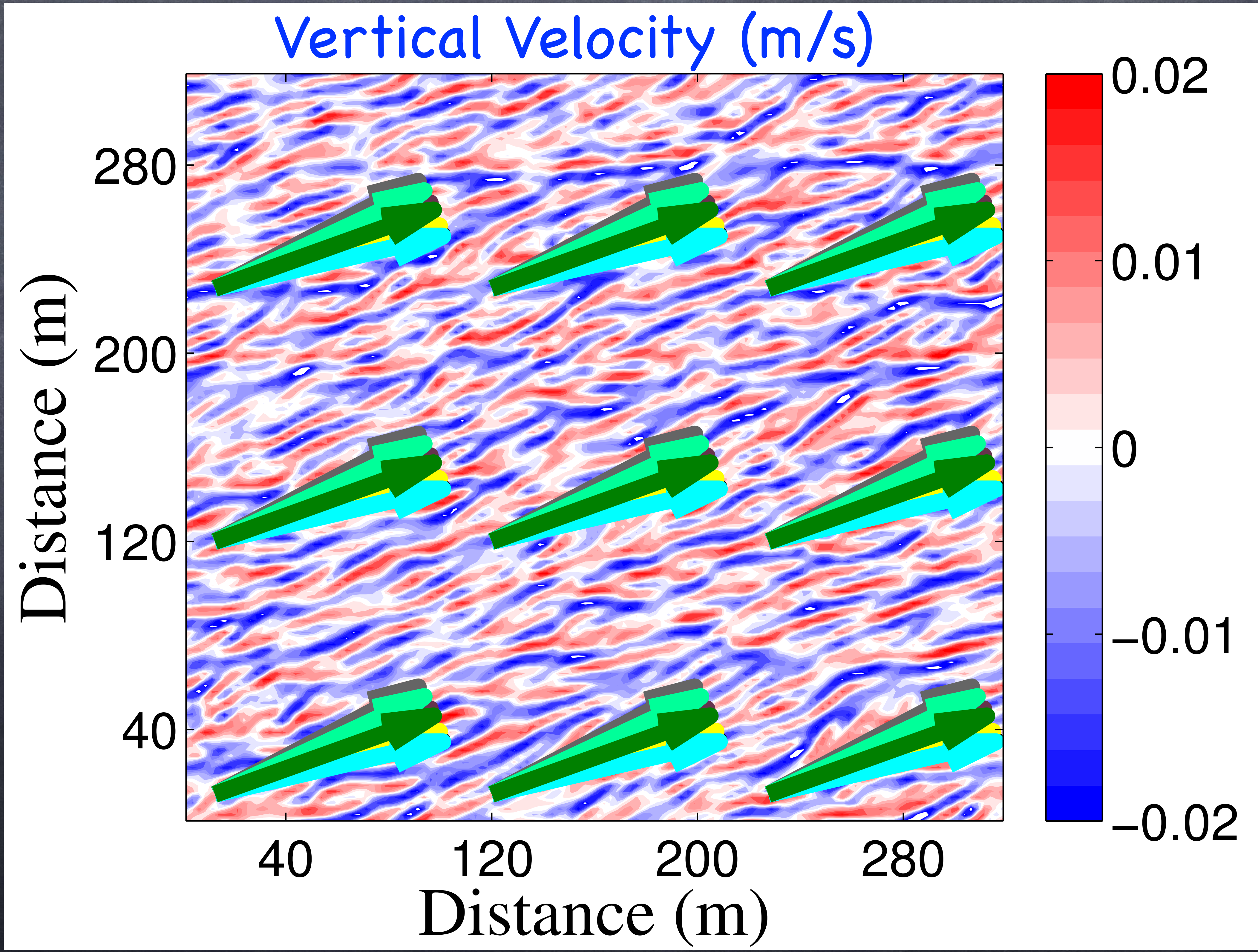
Q. Li, B. Fox-Kemper, 2017: Assessing the effects of Langmuir turbulence on the entrainment buoyancy flux in the ocean surface boundary layer. JPO. In Preparation.

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.

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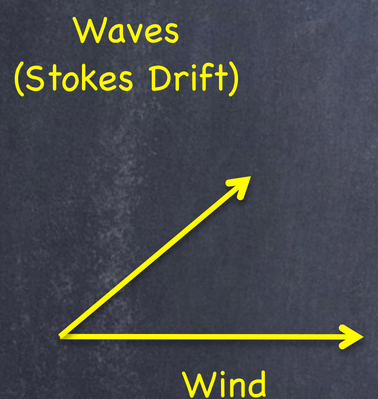

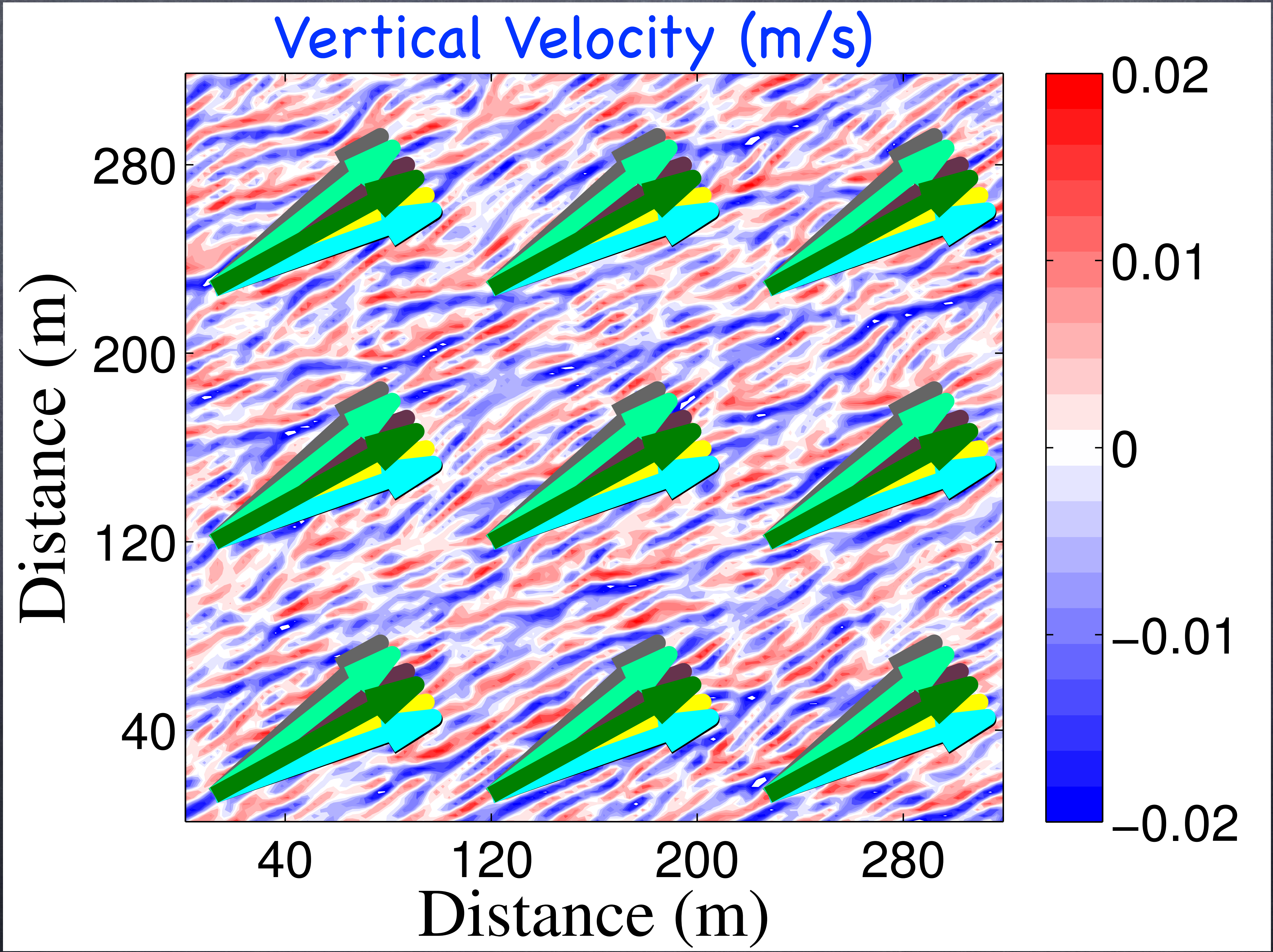

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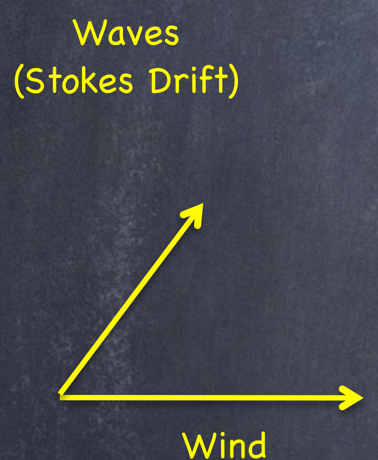

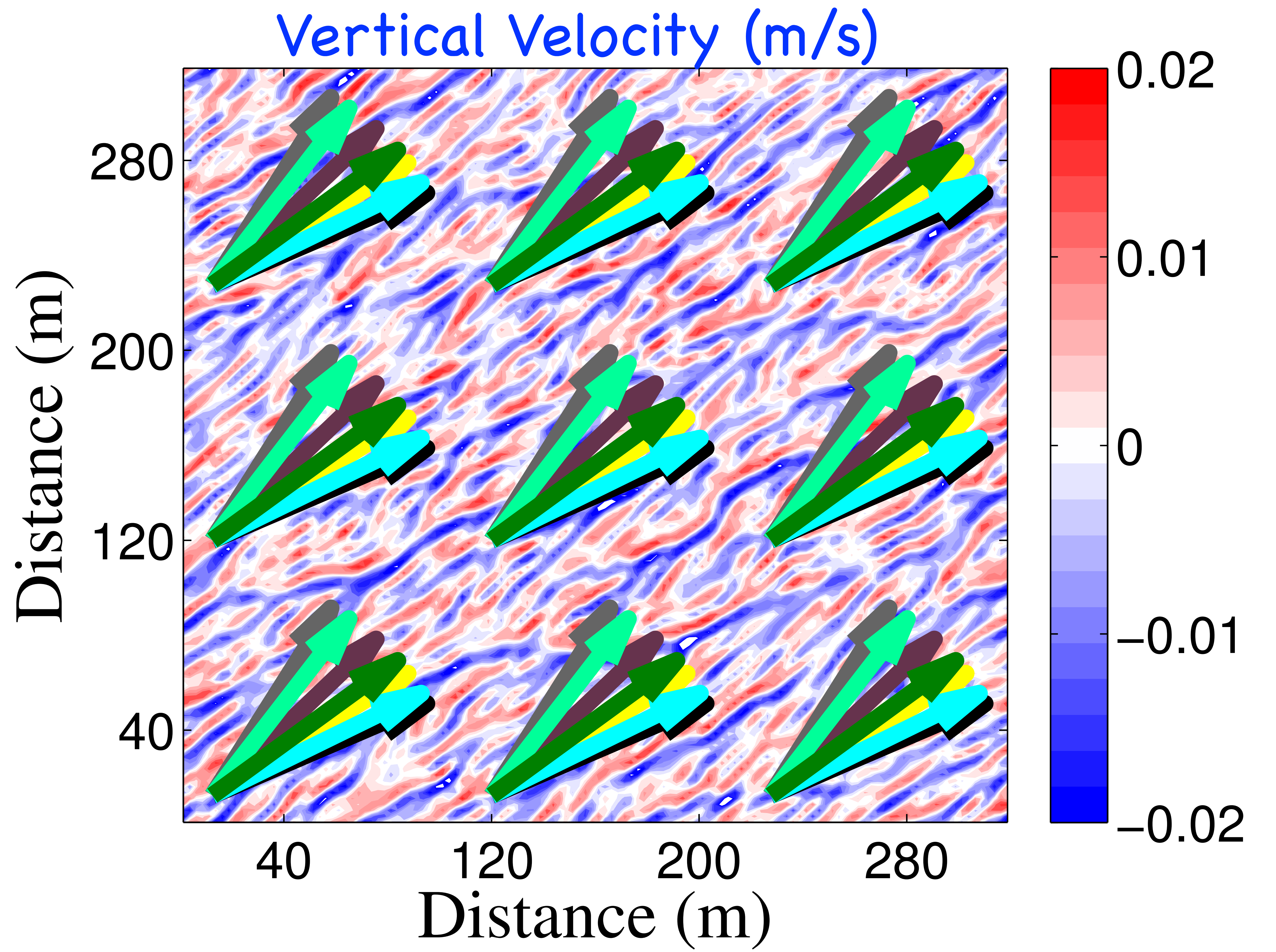

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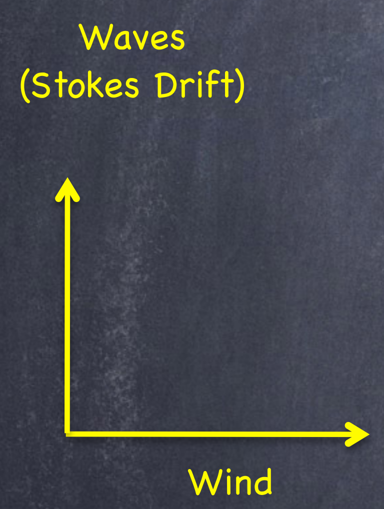

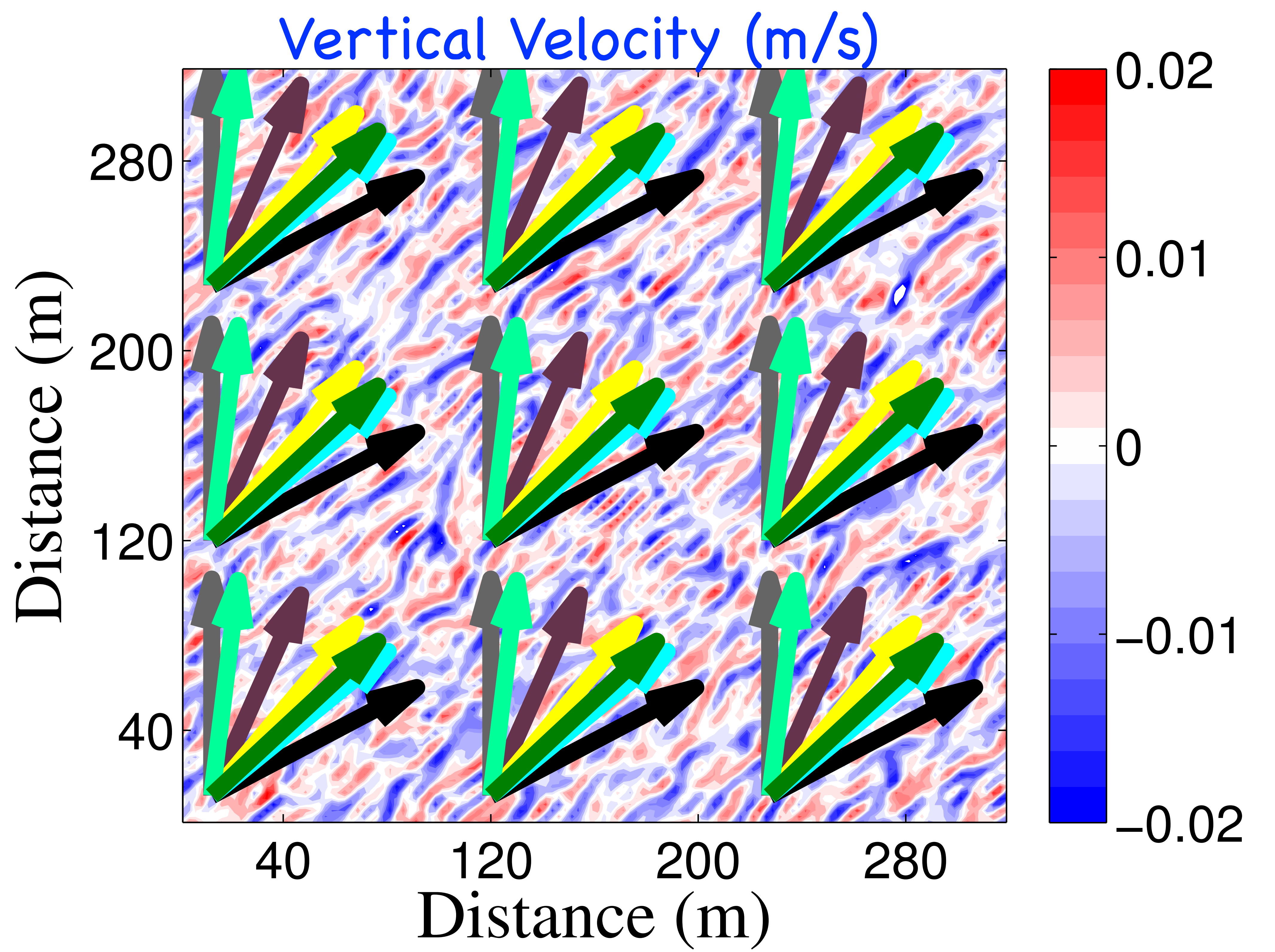

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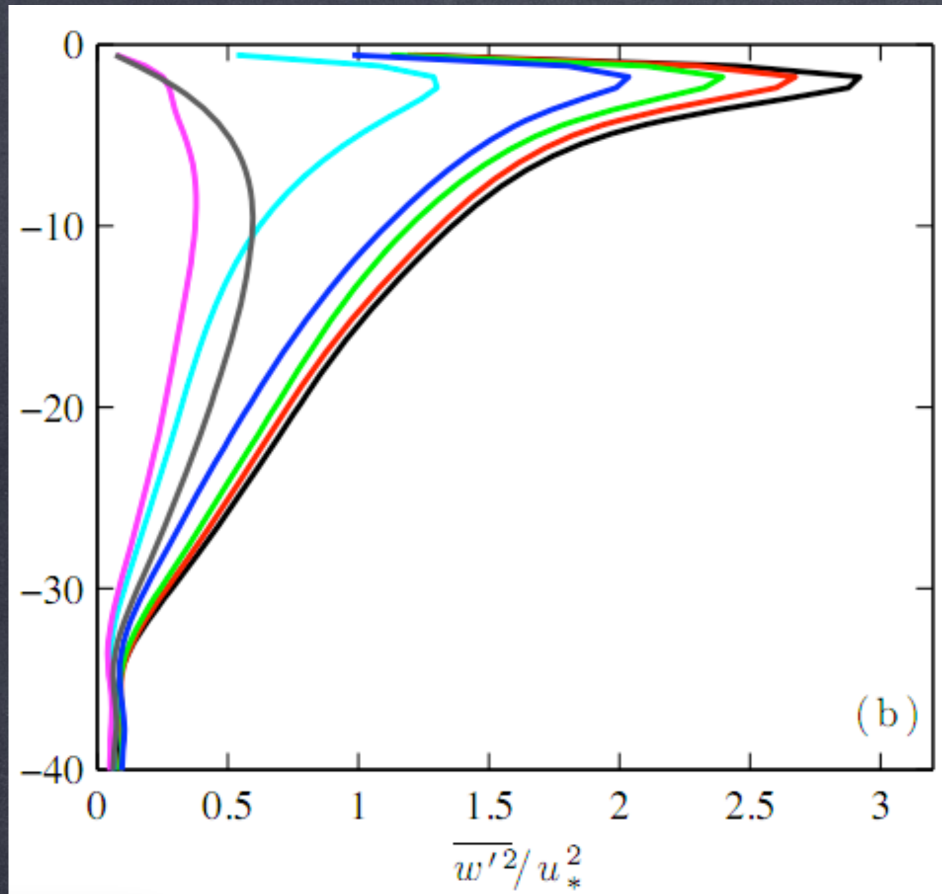
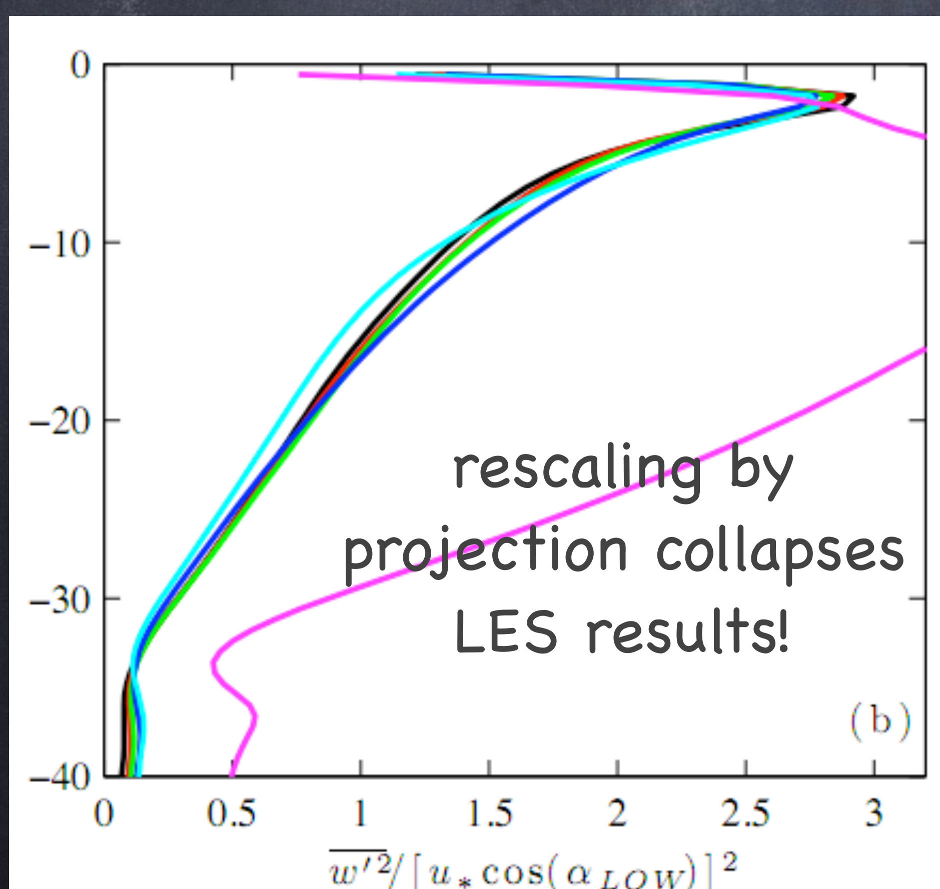
<w^2>

depth



rescaled <w^2>

depth



Generalized Turbulent Parameter (Langmuir Number)

Projection of u*, u_s into Langmuir Direction

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

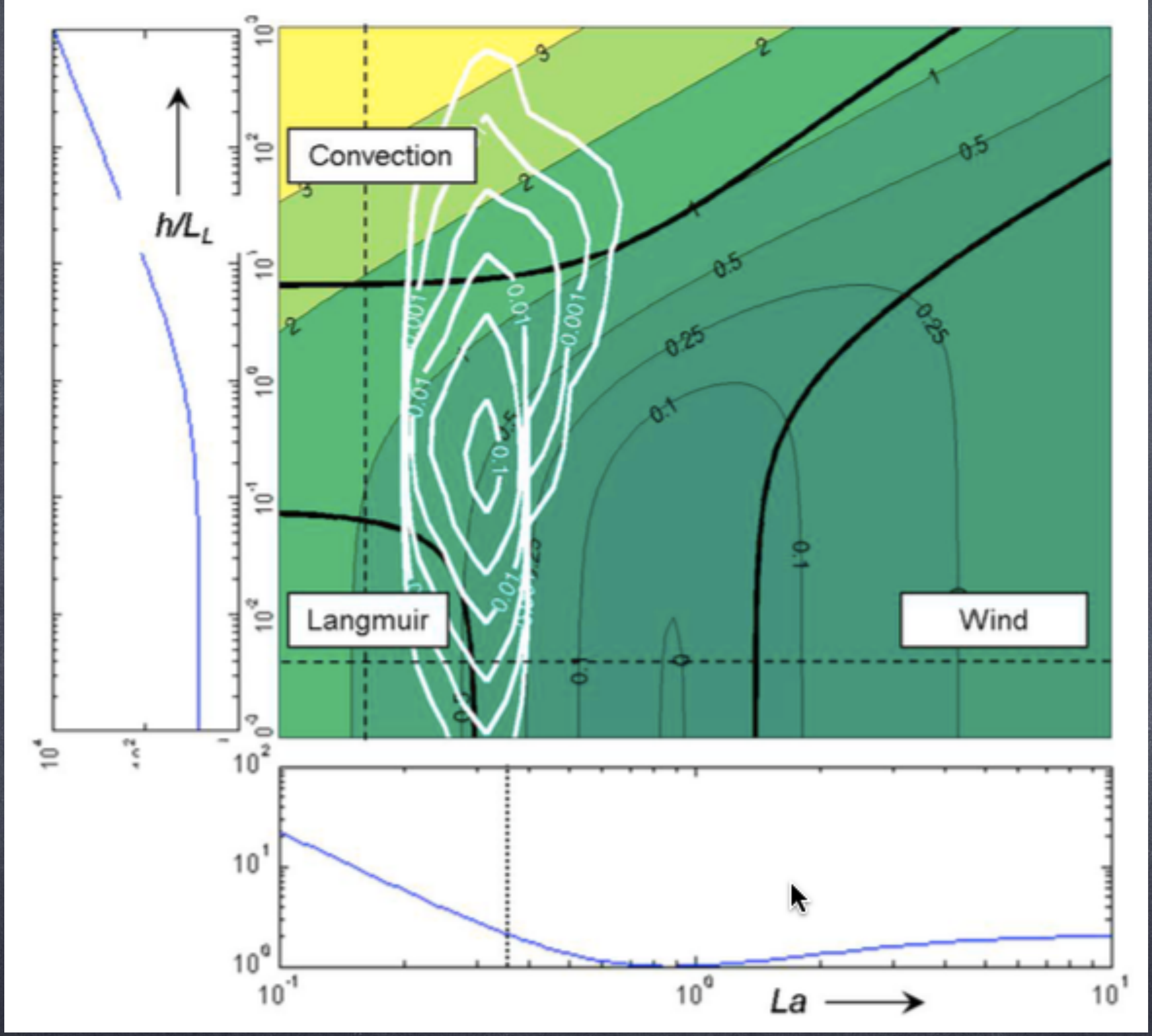
A scaling for LC strength & direction!
Enough for climate model application

Also, benefit from Harcourt & D'Asaro (2008) to use a Surface Layer Average, rather than surface La to be robust to wind waves vs. monochromatic

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.

Do Details of Turbulence Matter Much?

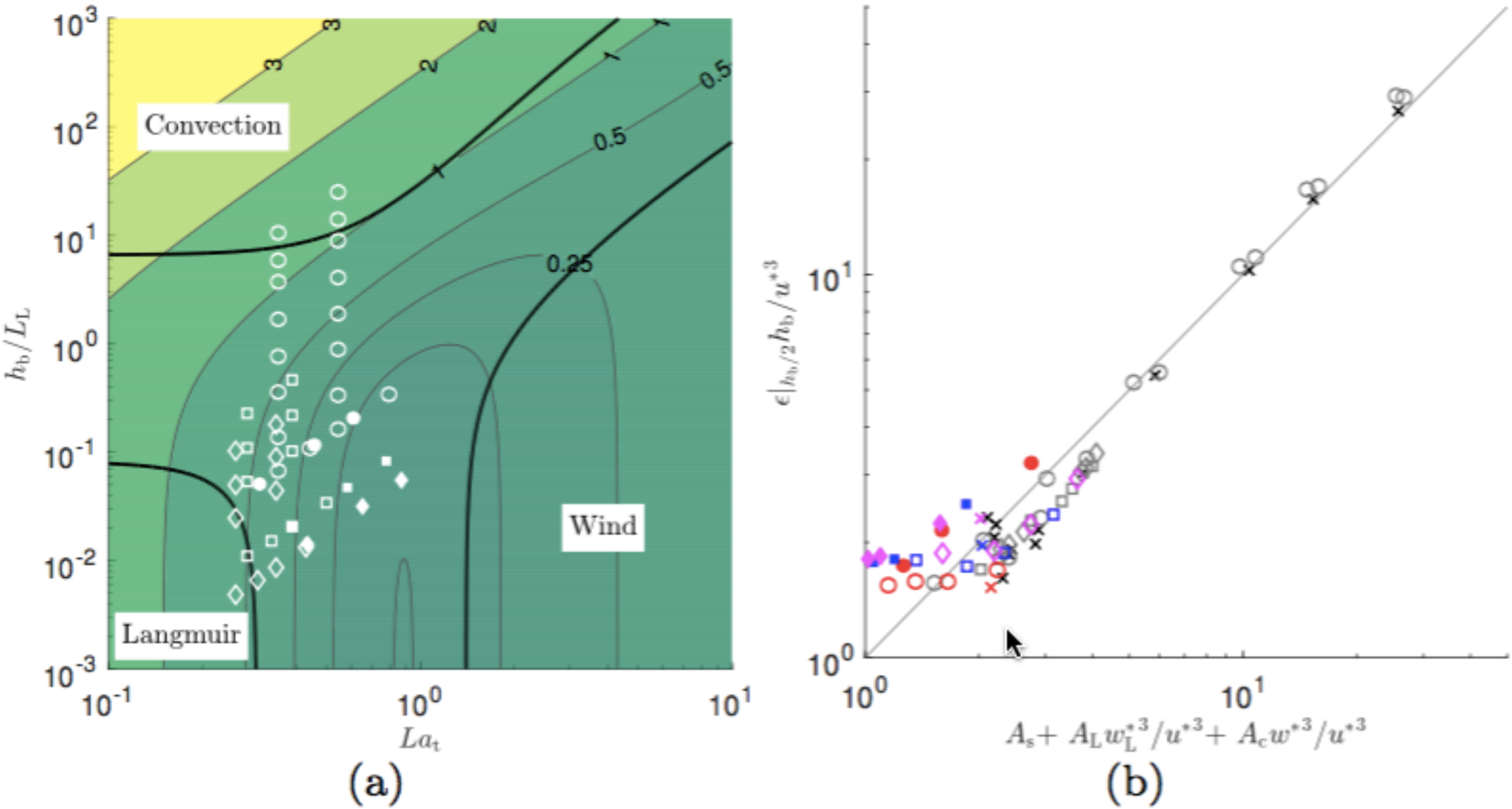
Dissipation Rate Regimes of S. Ocean



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, 2012: A global perspective on Langmuir turbulence in the ocean surface boundary layer. Geophysical Research Letters, 39(18):L18605

Do Details of Turbulence Matter Much?

Dissipation Rate Evaluation using LES



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Langmuir Mixing in Climate: Boundary layer Depth Improved

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3 versions of Van Roekel et al

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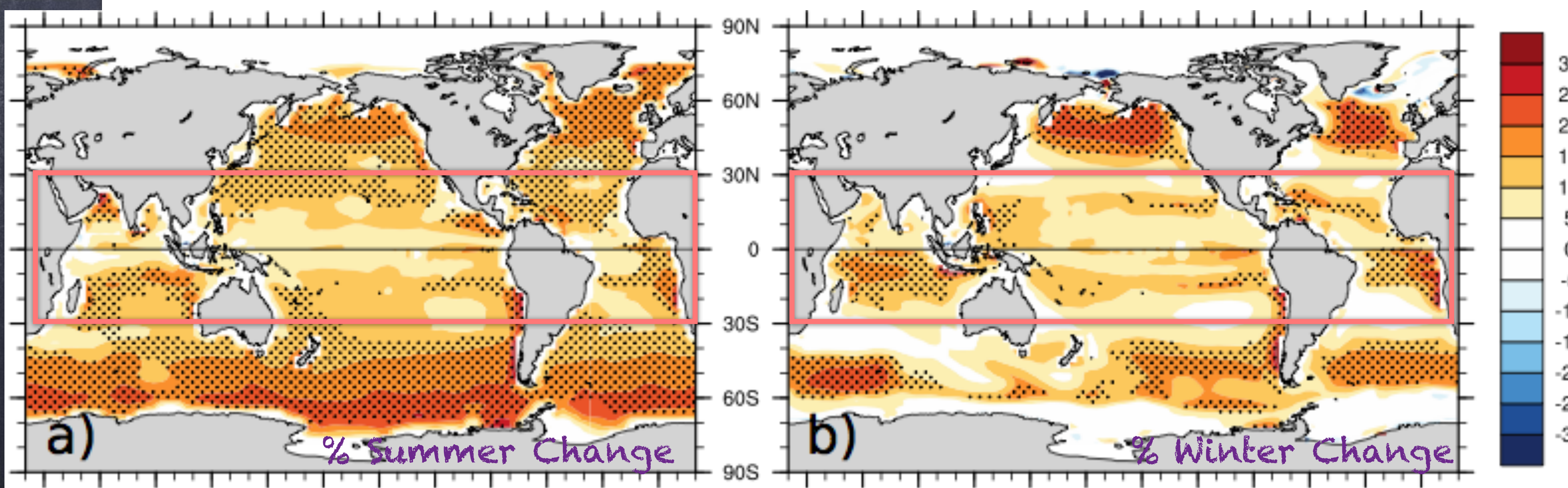

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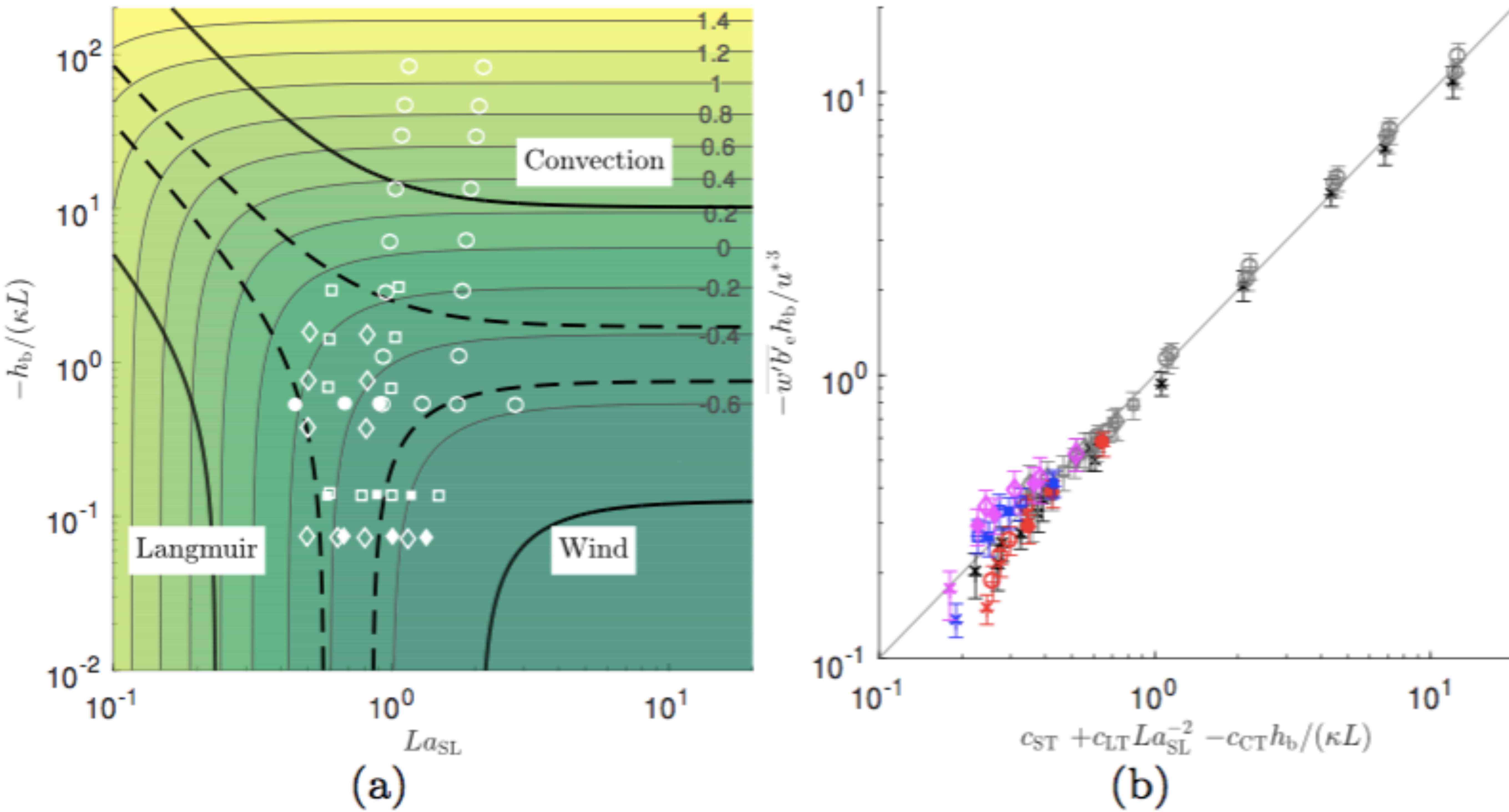
Entrainment Rate Evaluation using LES



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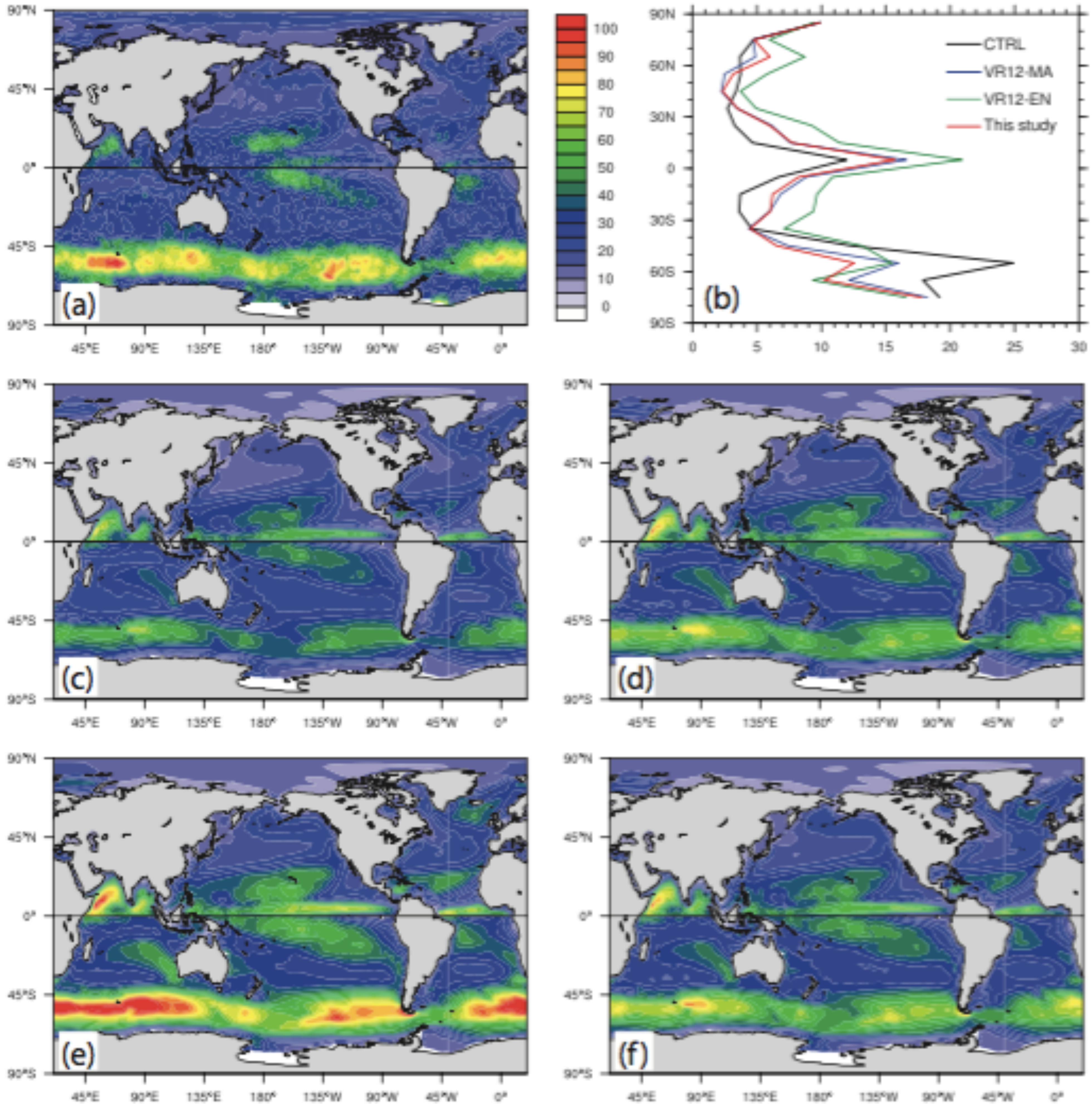
Obs.

No Lang.

Early Entrain Guess.



Mixing w/o Entrain Eval.

Mixing & Refined Entrain.

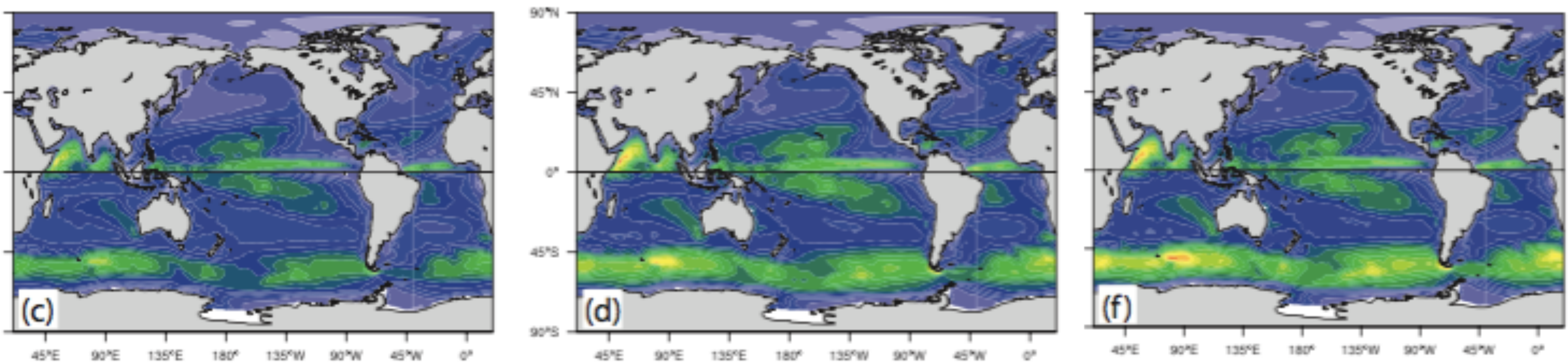
Langmuir Mixing in Climate: Boundary layer Depth Improved

Control

3 versions of Van Roekel et al

New Scheme

	Summer			Winter		
Case	Global	South of 30°S	30°S-30°N	Global	South of 30°S	30°S-30°N
CTRL	10.28 ± 0.29	16.00 ± 0.48	6.57 ± 0.23	50.24 ± 1.42	52.52 ± 0.54	15.89 ± 0.33
VR12-MA	9.31 ± 0.28	10.64 ± 0.49	9.60 ± 0.33	47.65 ± 1.15	48.47 ± 0.49	22.98 ± 0.42
VR12-EN	11.65 ± 0.29	11.91 ± 0.83	12.79 ± 0.39	56.85 ± 0.93	61.30 ± 1.21	33.60 ± 0.55
LF17	8.48 ± 0.24	8.92 ± 0.39	9.15 ± 0.30	47.78 ± 1.08	49.98 ± 0.77	22.43 ± 0.43



No Lang.

Mixing w/o Entrain Eval.

Mixing & Refined Entrainment

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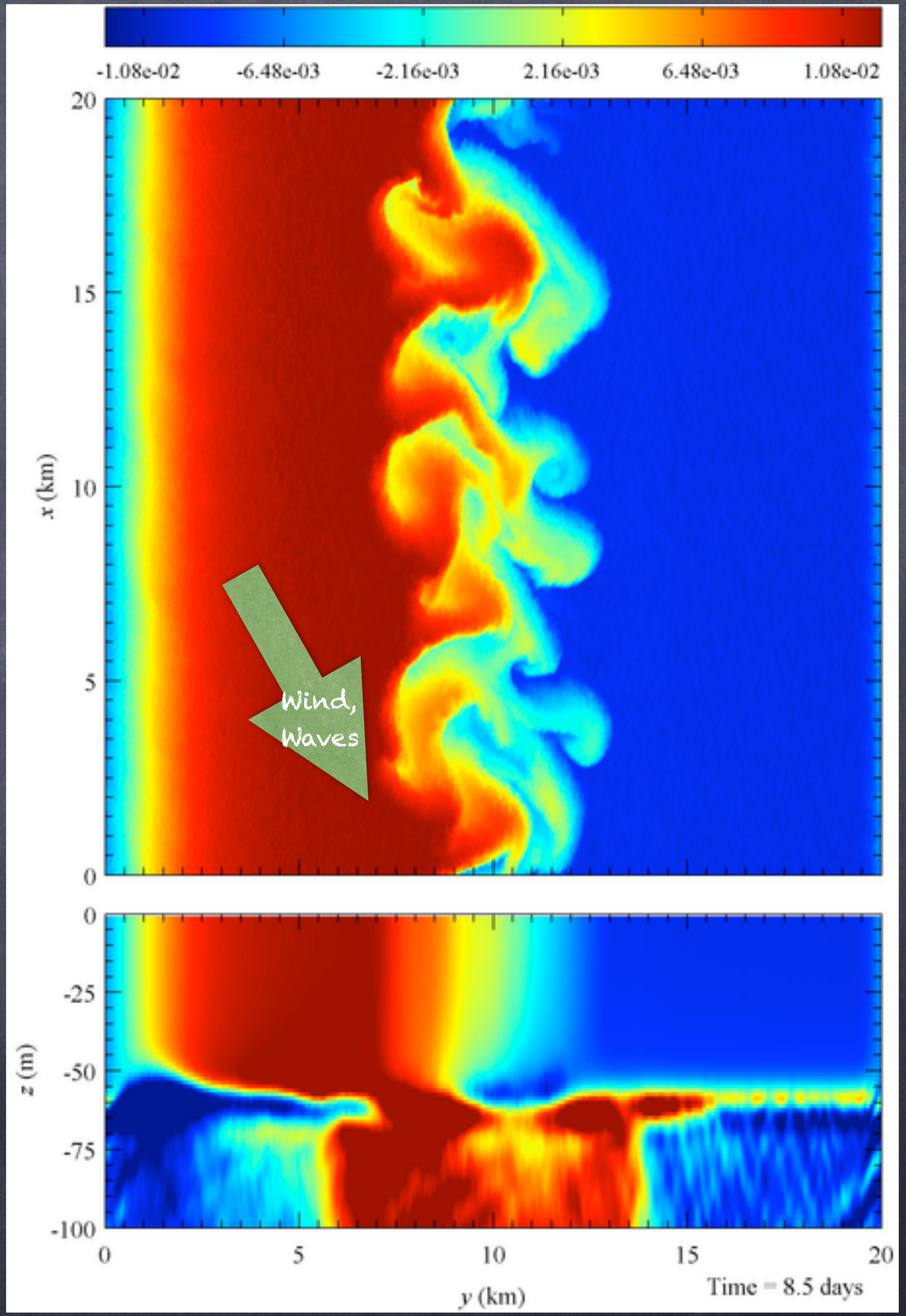
Conclusions:
Waves on Turbulence & Climate

- The inclusion of Langmuir (wave-driven) mixing is justified by obs., LES, and reduction of climate model bias.
- Generally, these schemes make mixed layer deeper—affecting air-sea, CFCs, carbon exchange, etc.
- The Data Waves and Theory Waves versions of our scheme are available through CVmix—no wave model required!
- Improvement of scalings vs. LES has worked very well to date, but as nearly all present schemes agree well with LES—returns are diminishing.

Do Stokes forces affect (sub)Meso-Scales?

Movie: P. Hamlington



LES of Langmuir turbulence with a submesoscale temperature front

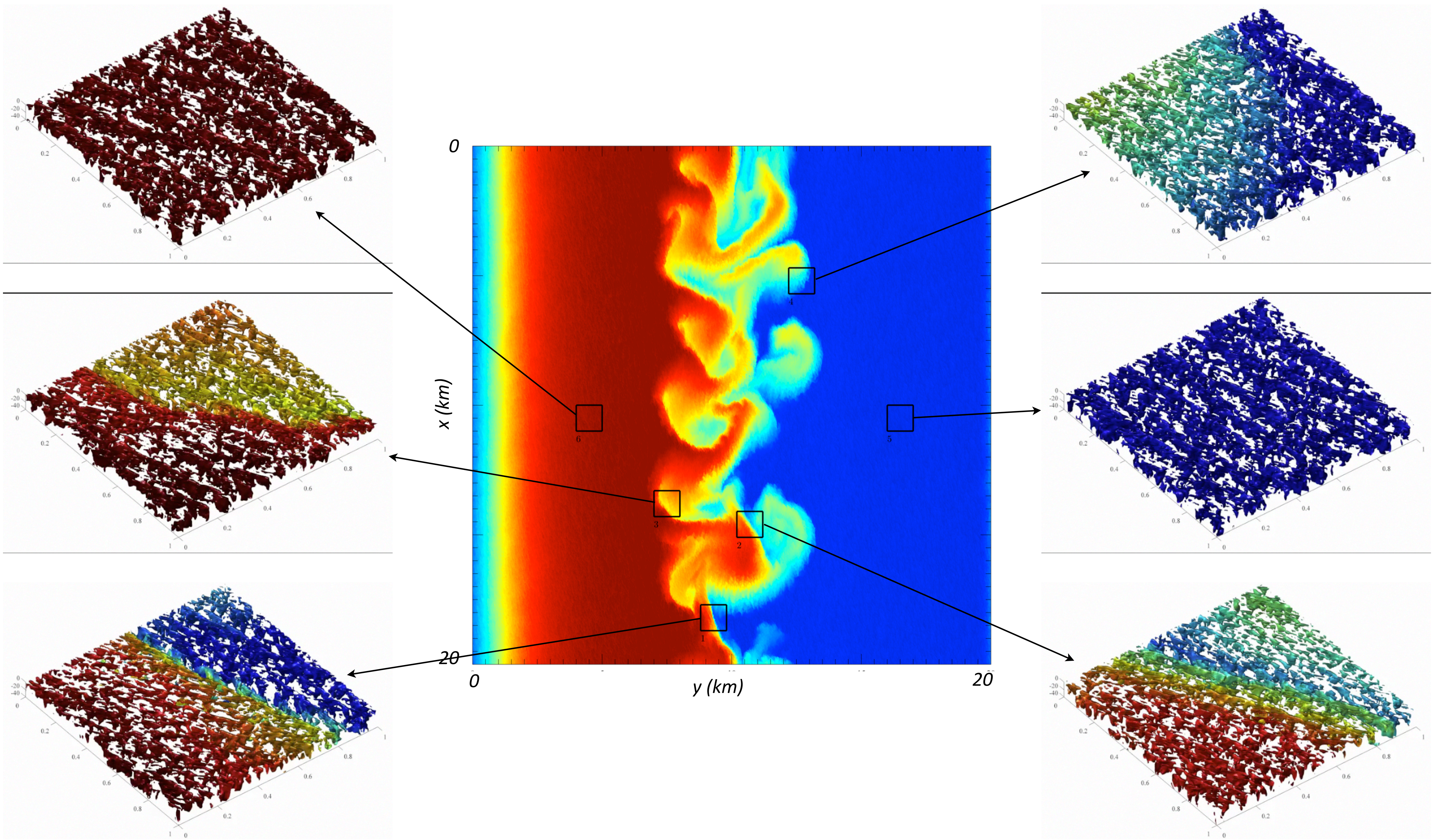
Use NCAR LES model to solve Wave-Averaged Eqtns.

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

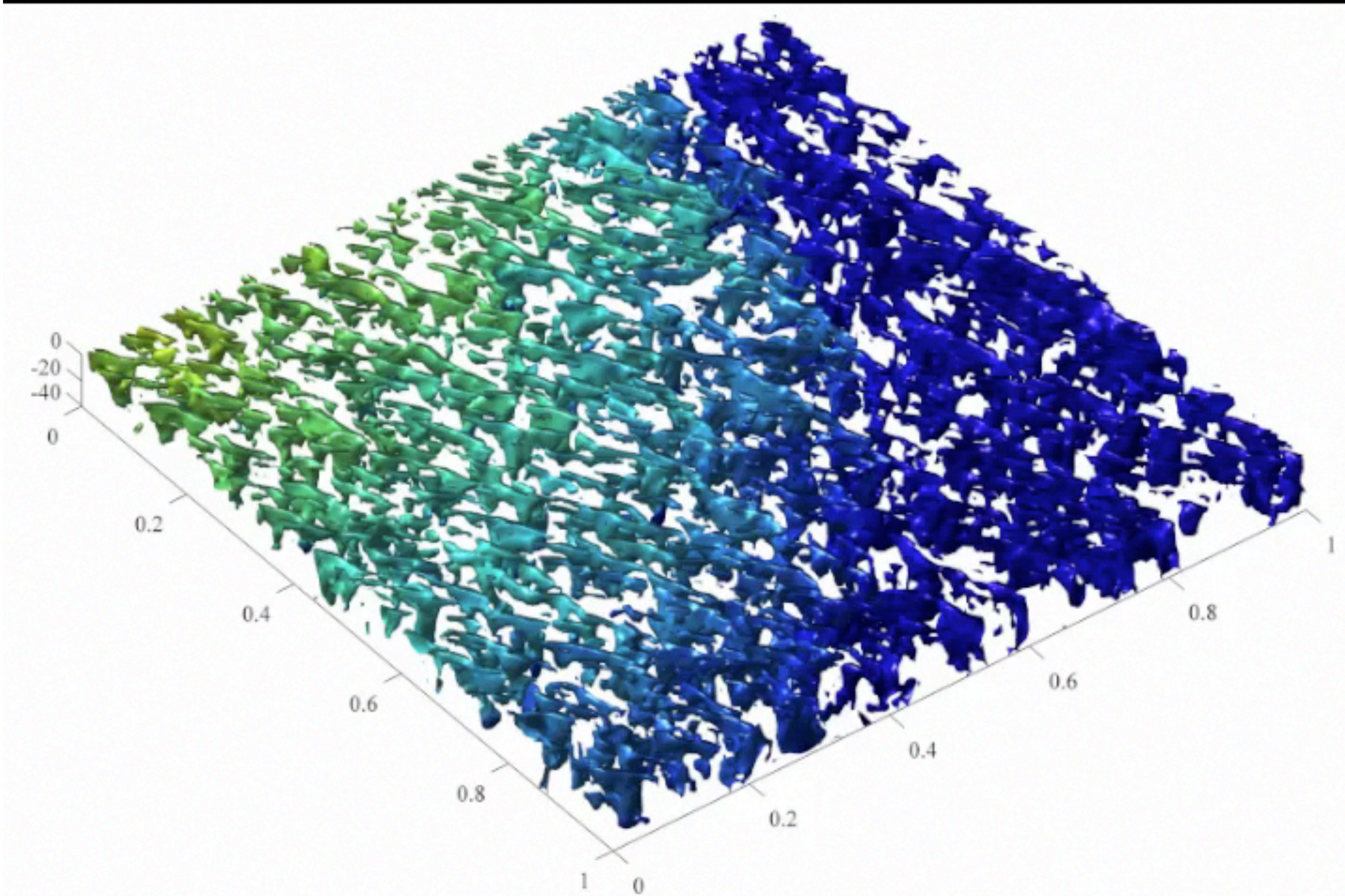
Computational parameters:
Domain size: 20km x 20km x -160m
Grid points: 4096 x 4096 x 128
Resolution: 5m x 5m x -1.25m

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: Stronger Langmuir (small) Turbulence



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.


0
-20
-40
0
0.2
0.4
0.6
0.8
1
0
0.2
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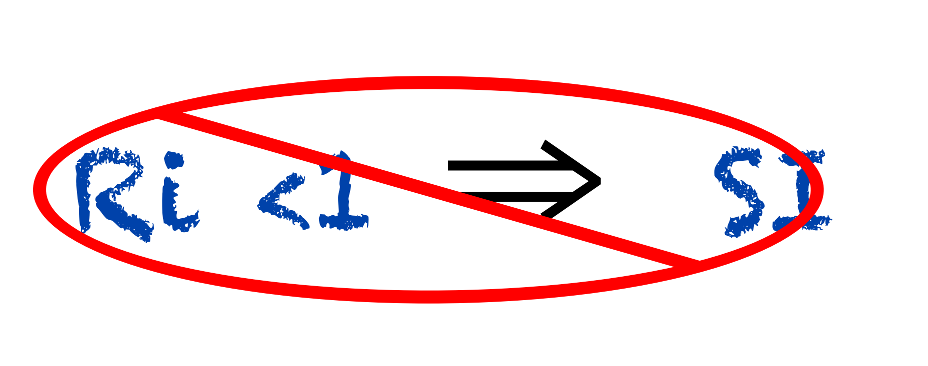
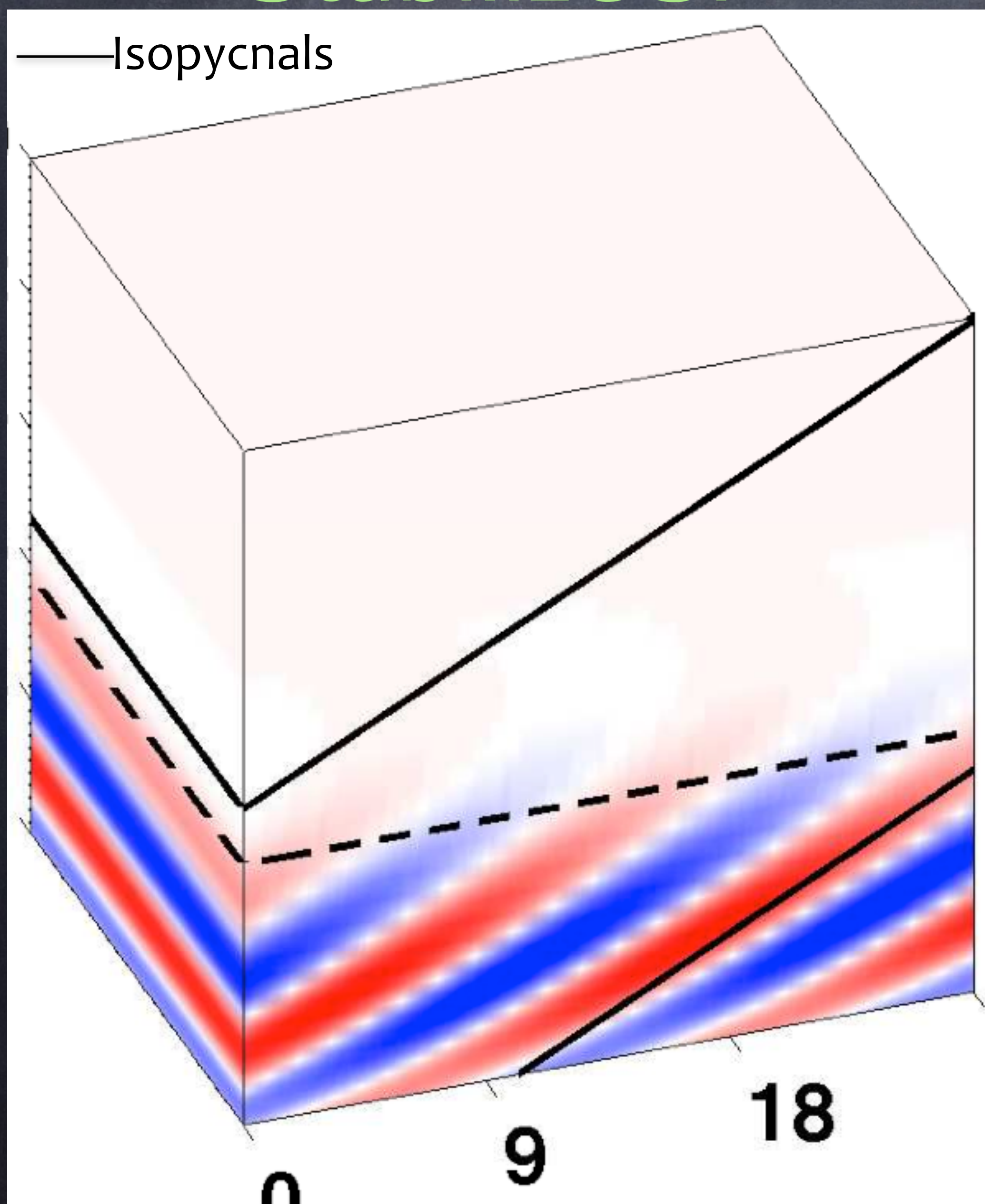
0.8
1



Wavy Submesoscale Instability Different: Symmetric Instability

★ $fQ<0 \Rightarrow SI$

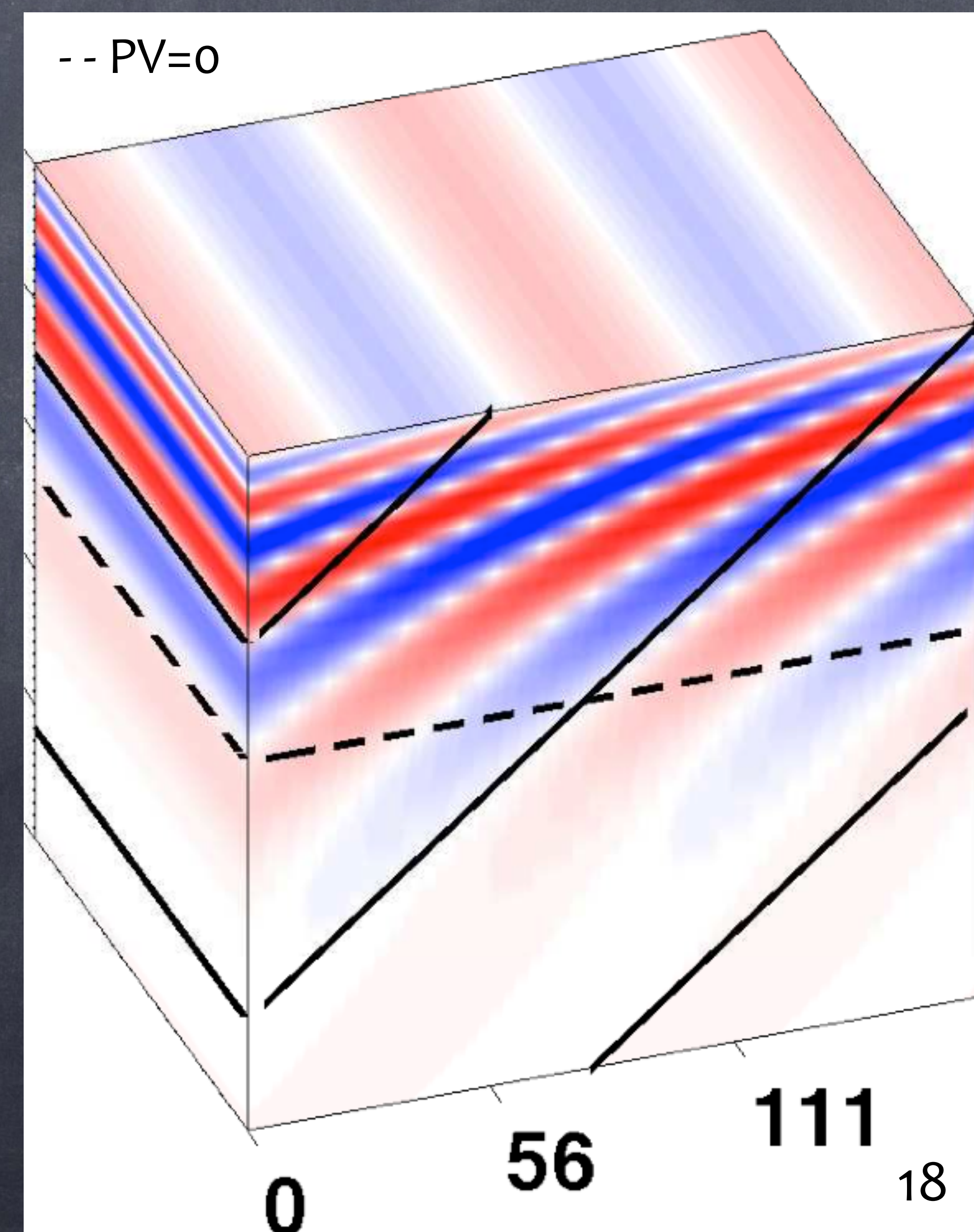
Ri = 0.5
Stokes Forces Stabilize SI



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.

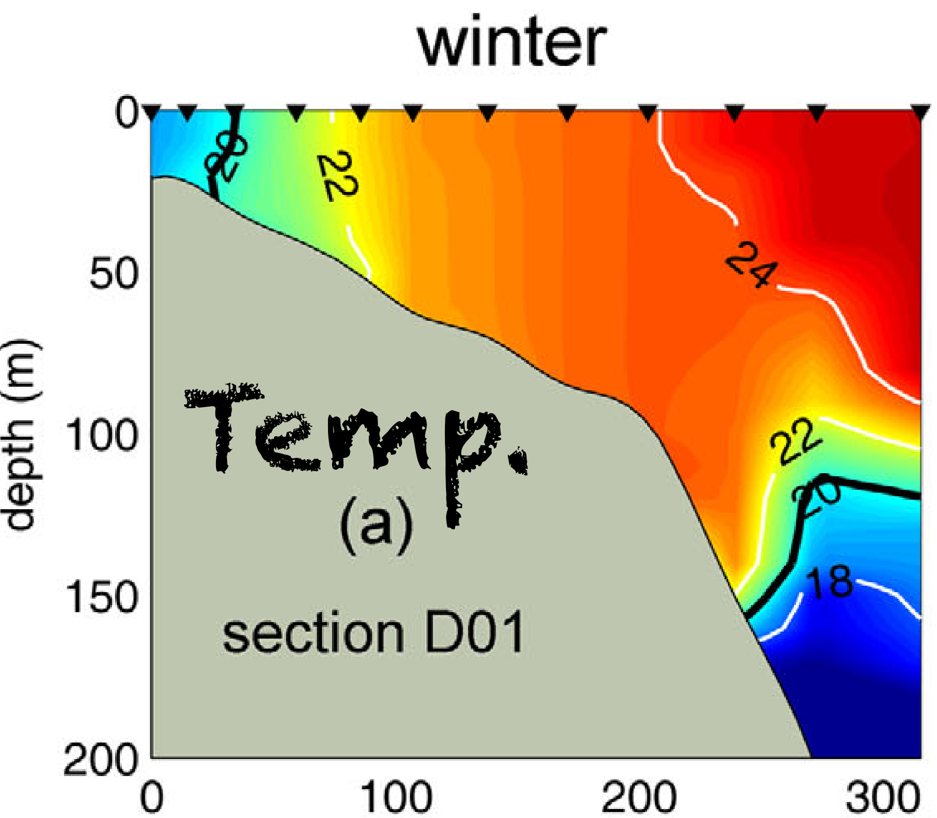
Ri = 2
Stokes Forces Destabilize SI



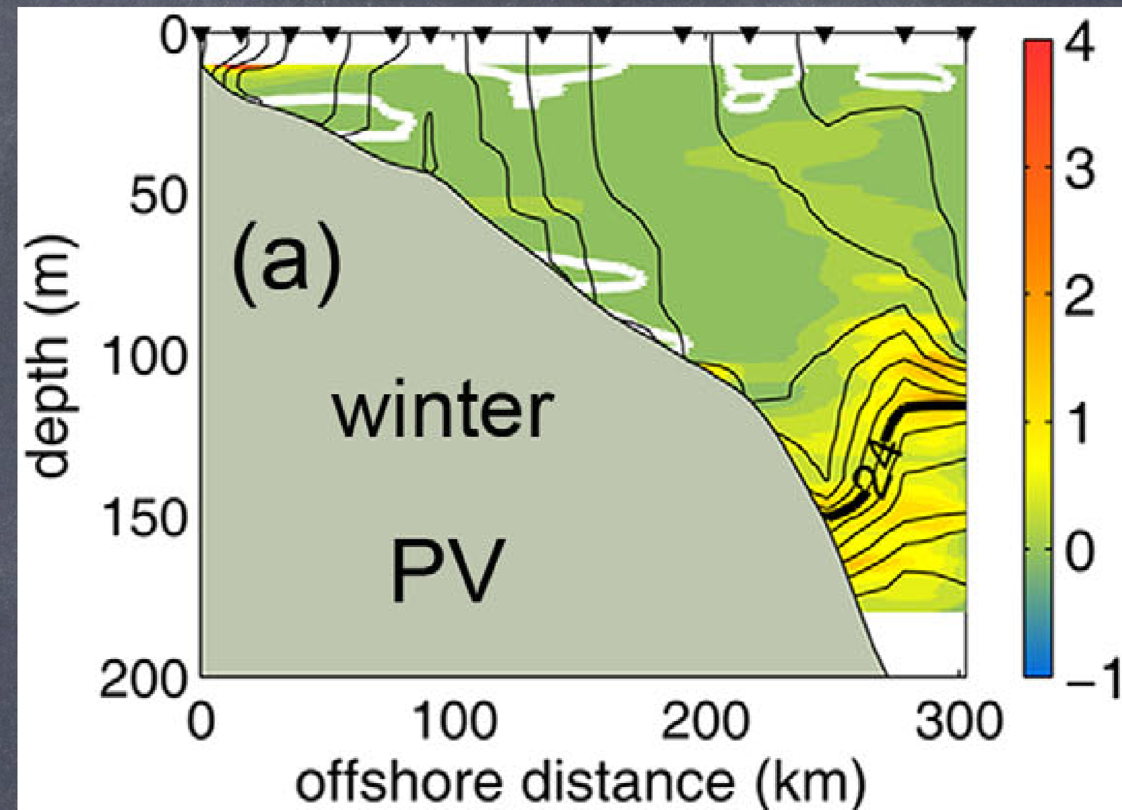
~~$Ri < 1 \Rightarrow SI$~~

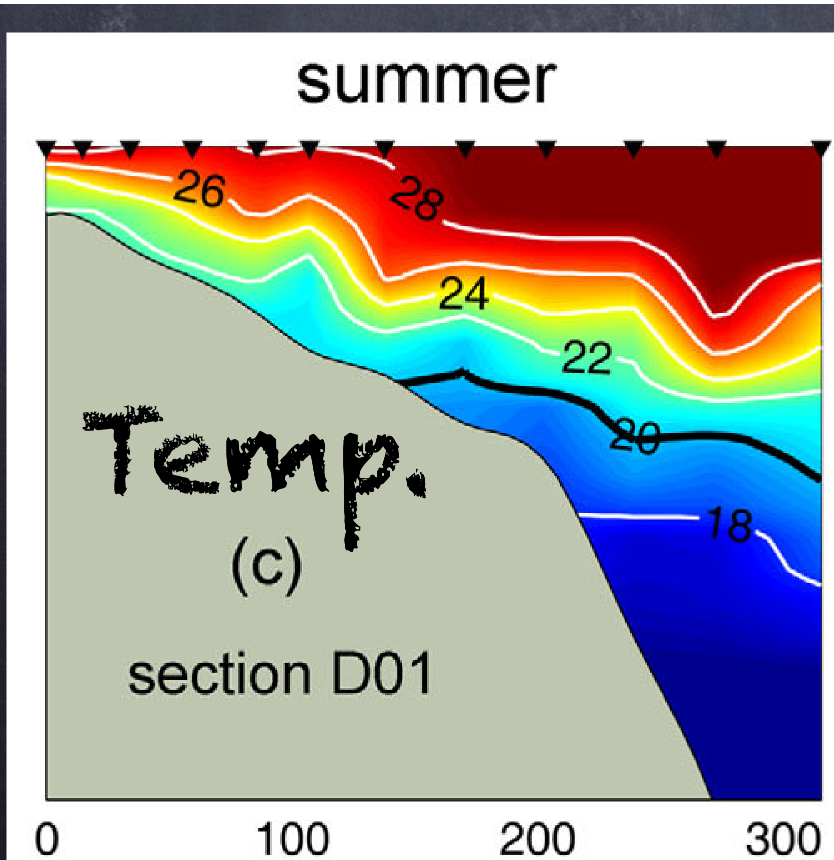
Wavy Submesoscale Instability Different: Symmetric Instability

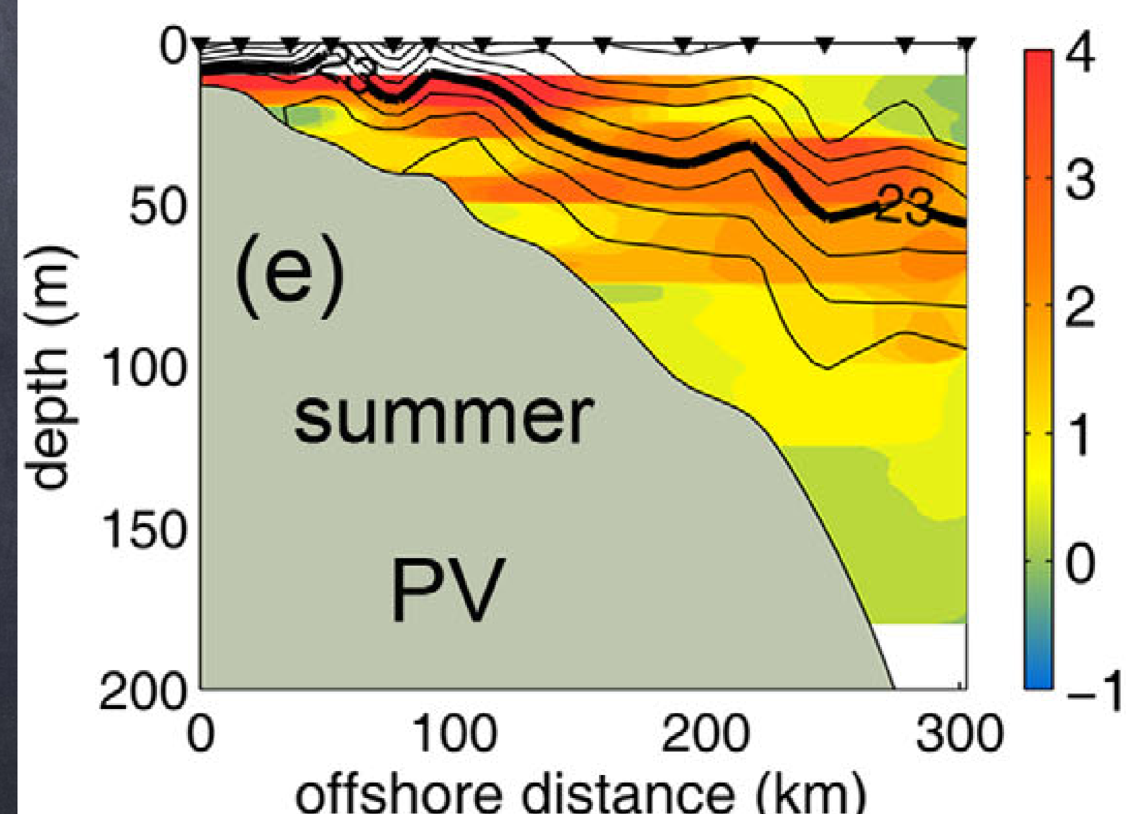
$fQ < 0 \Rightarrow SI$



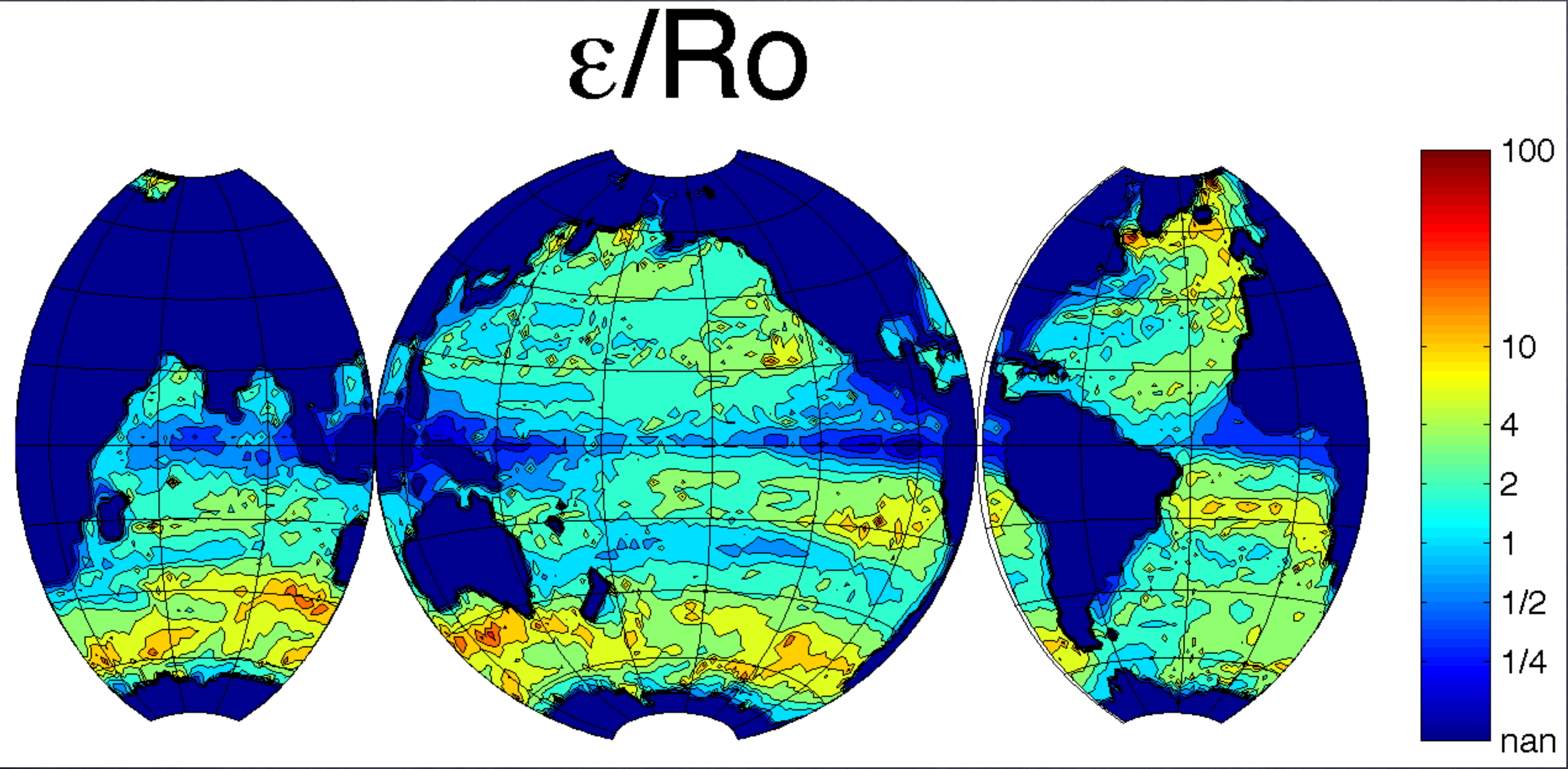
Z. Jing, Y. Qi, BFK, Y. Du, and S. Lian. Seasonal thermal fronts and their associations with monsoon forcing on the continental shelf of northern South China Sea: Satellite measurements and three repeated field surveys in winter, spring and summer. Journal of Geophysical Research-Oceans, 121:1914-1930, April 2016.







Do Stokes force directly affect larger scales?



"wavy hydrostatic" if

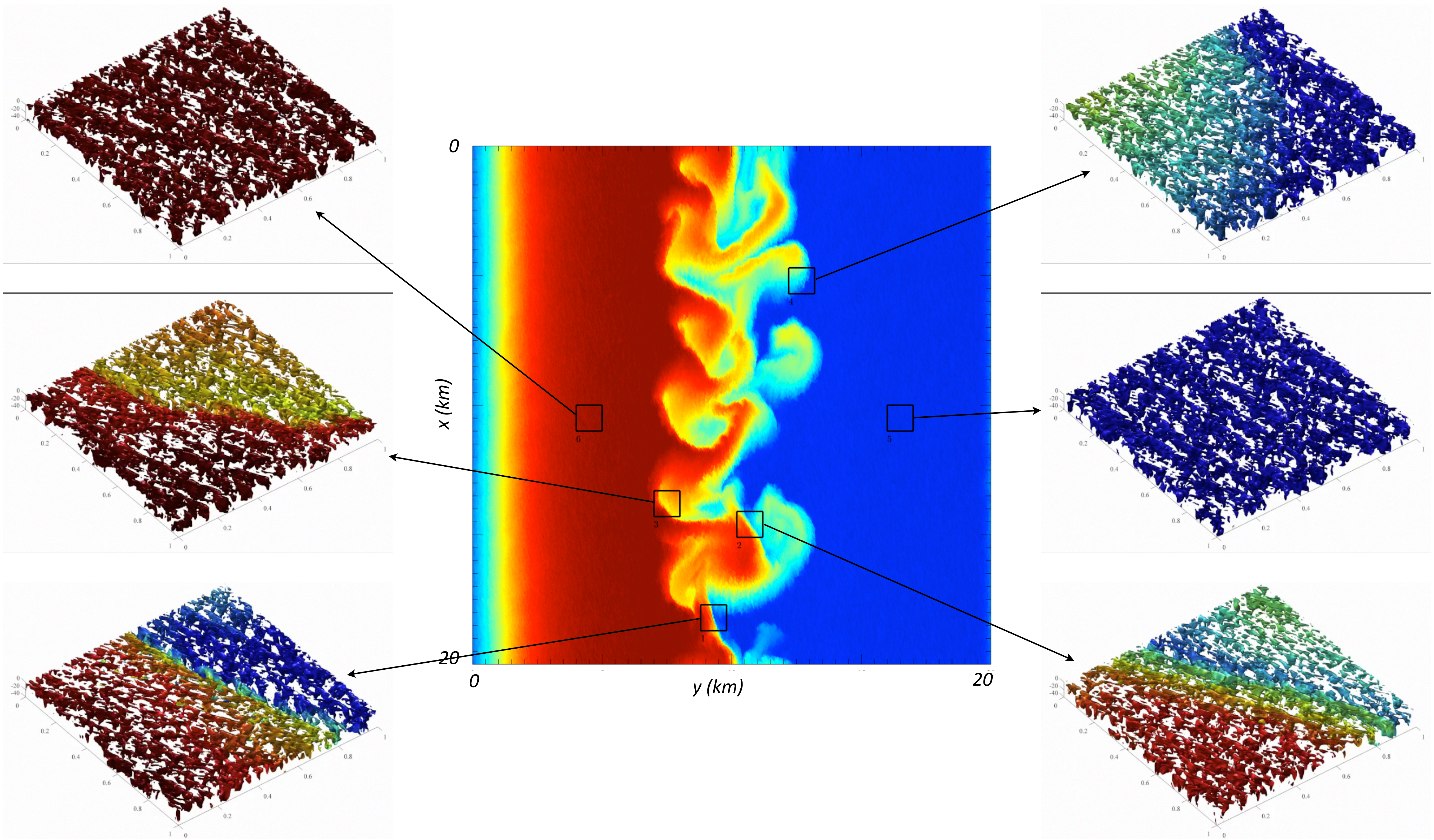
$$\epsilon \gg 1$$

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

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

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

Diverse types of interaction



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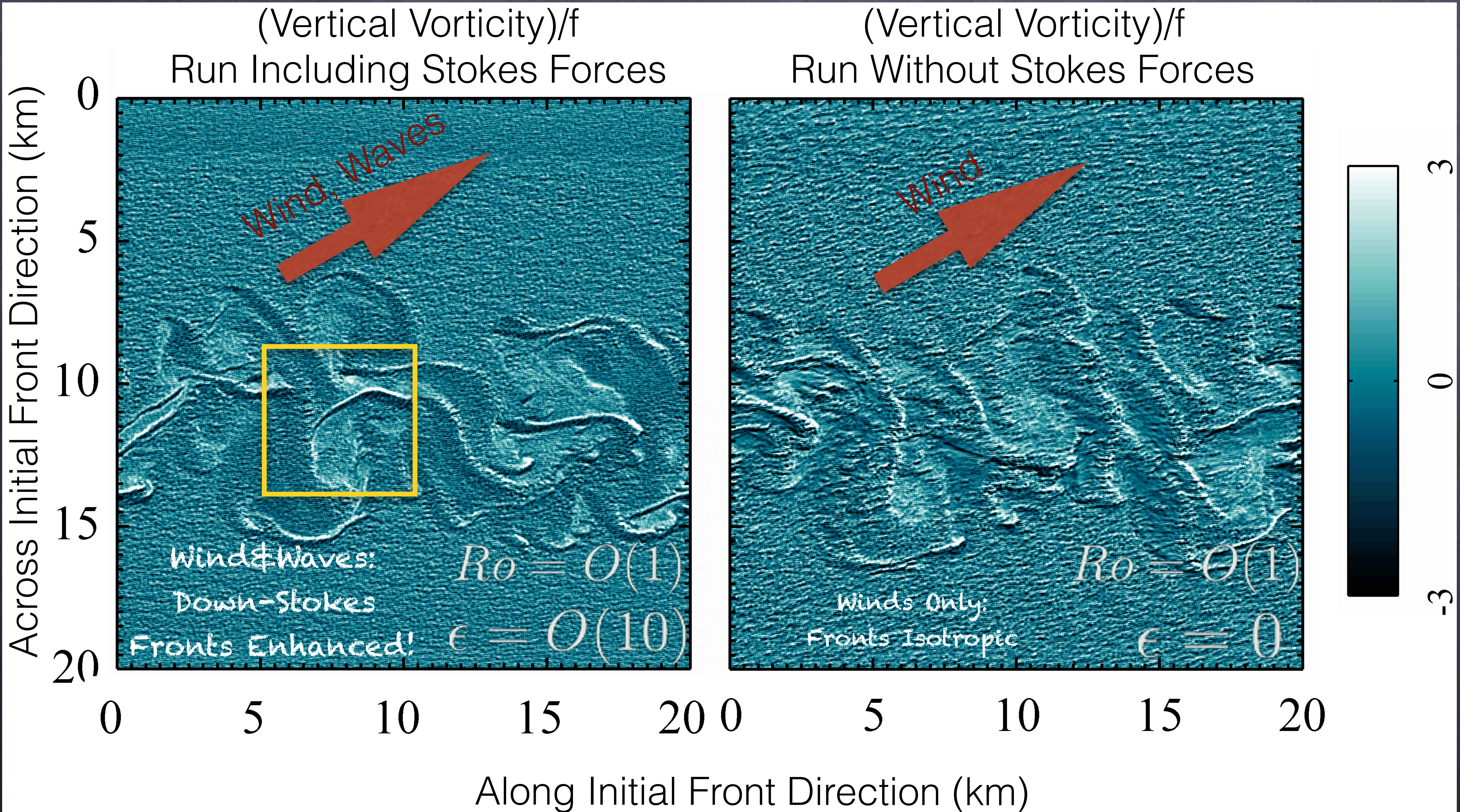
Are Fronts and Filaments different with Stokes shear force?

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



N. Suzuki, BFK, P. E. Hamlington, and L. P. Van Roekel. Surface waves affect frontogenesis. Journal of Geophysical Research-Oceans, 121:1-28, 2016.

N. Suzuki and BFK. Understanding Stokes forces in the wave-averaged equations. Journal of Geophysical Research-Oceans, 121:1-18, 2016.

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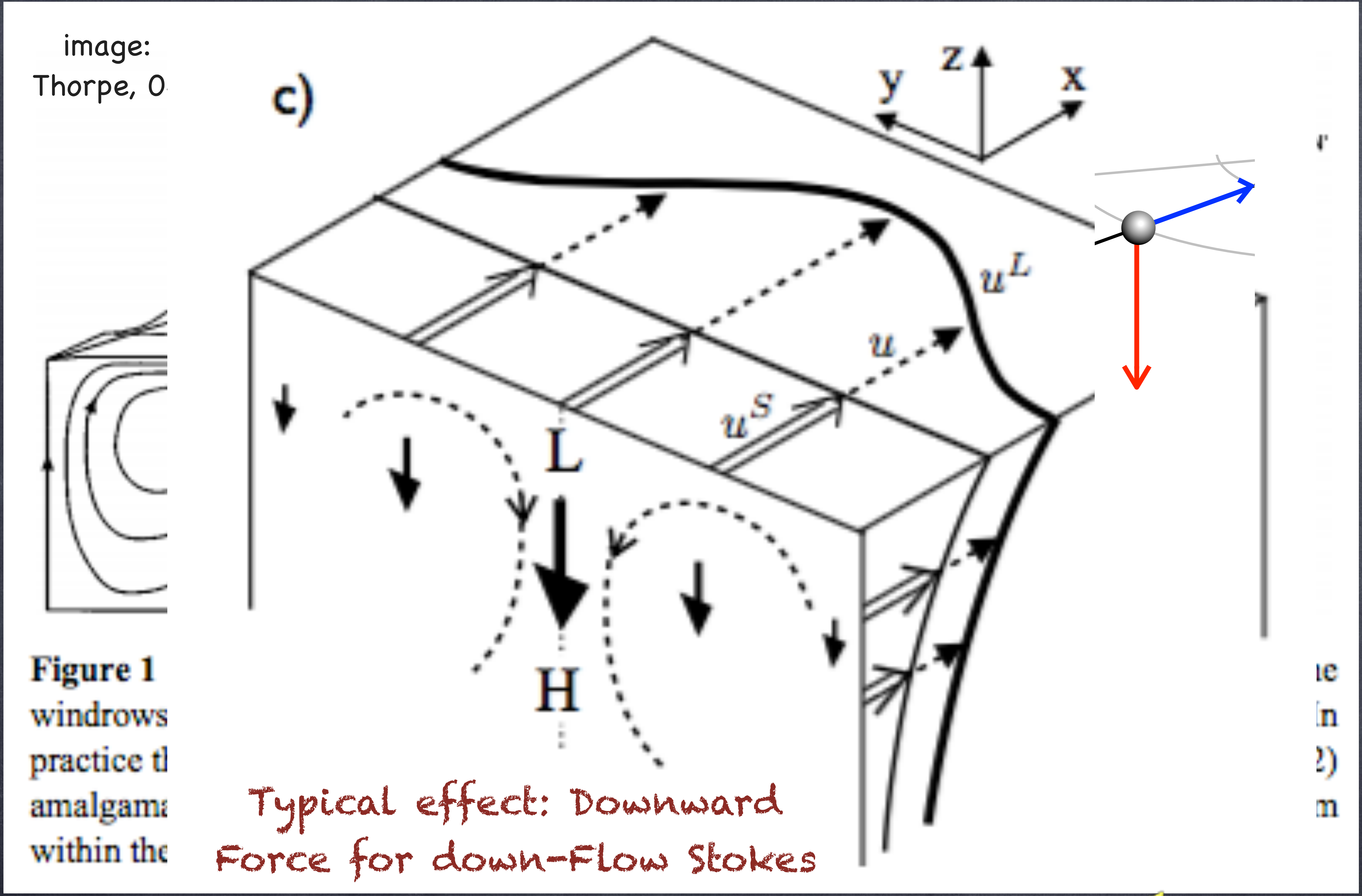
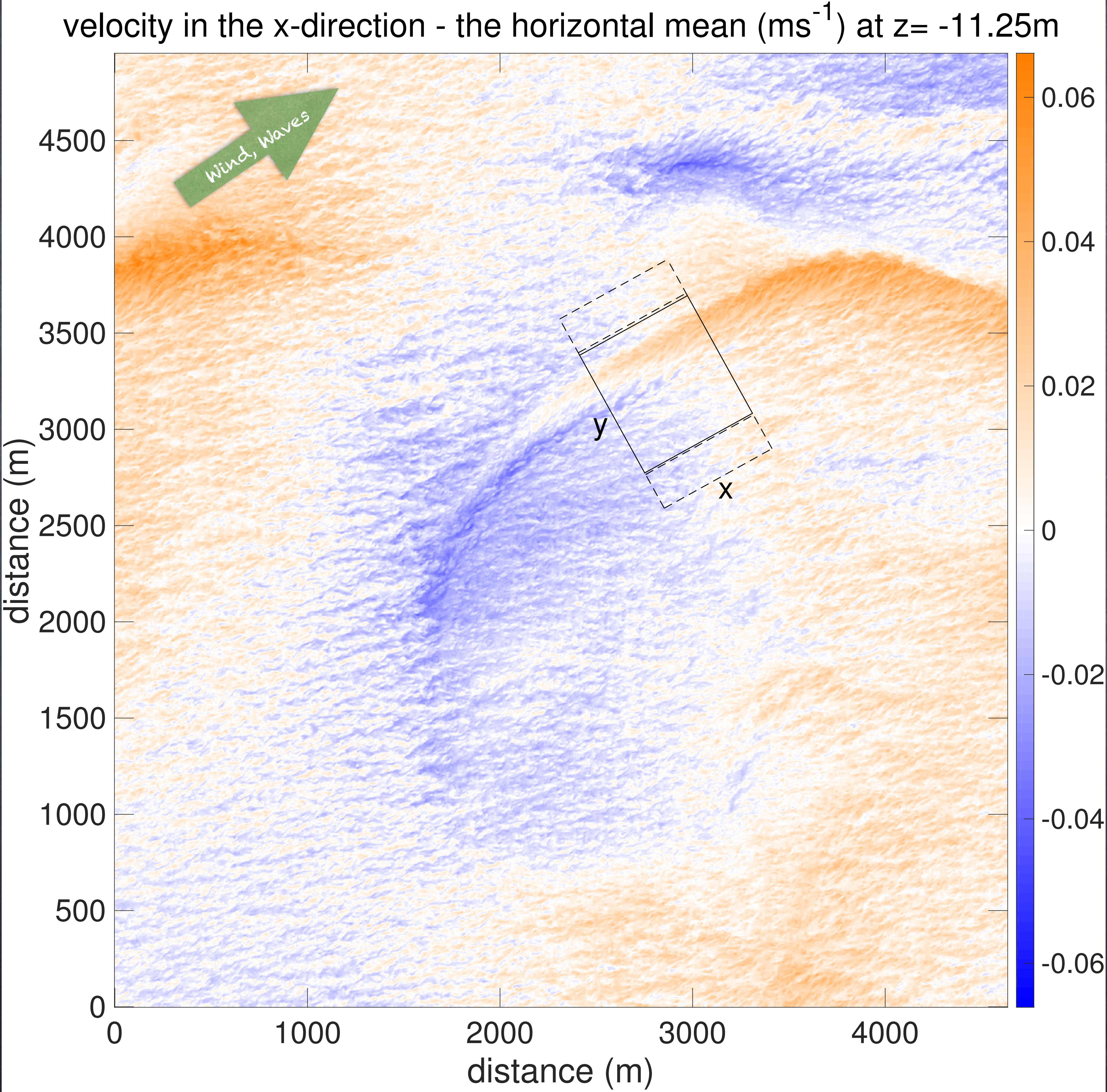


"wavy hydrostatic" if $\epsilon \gg 1$

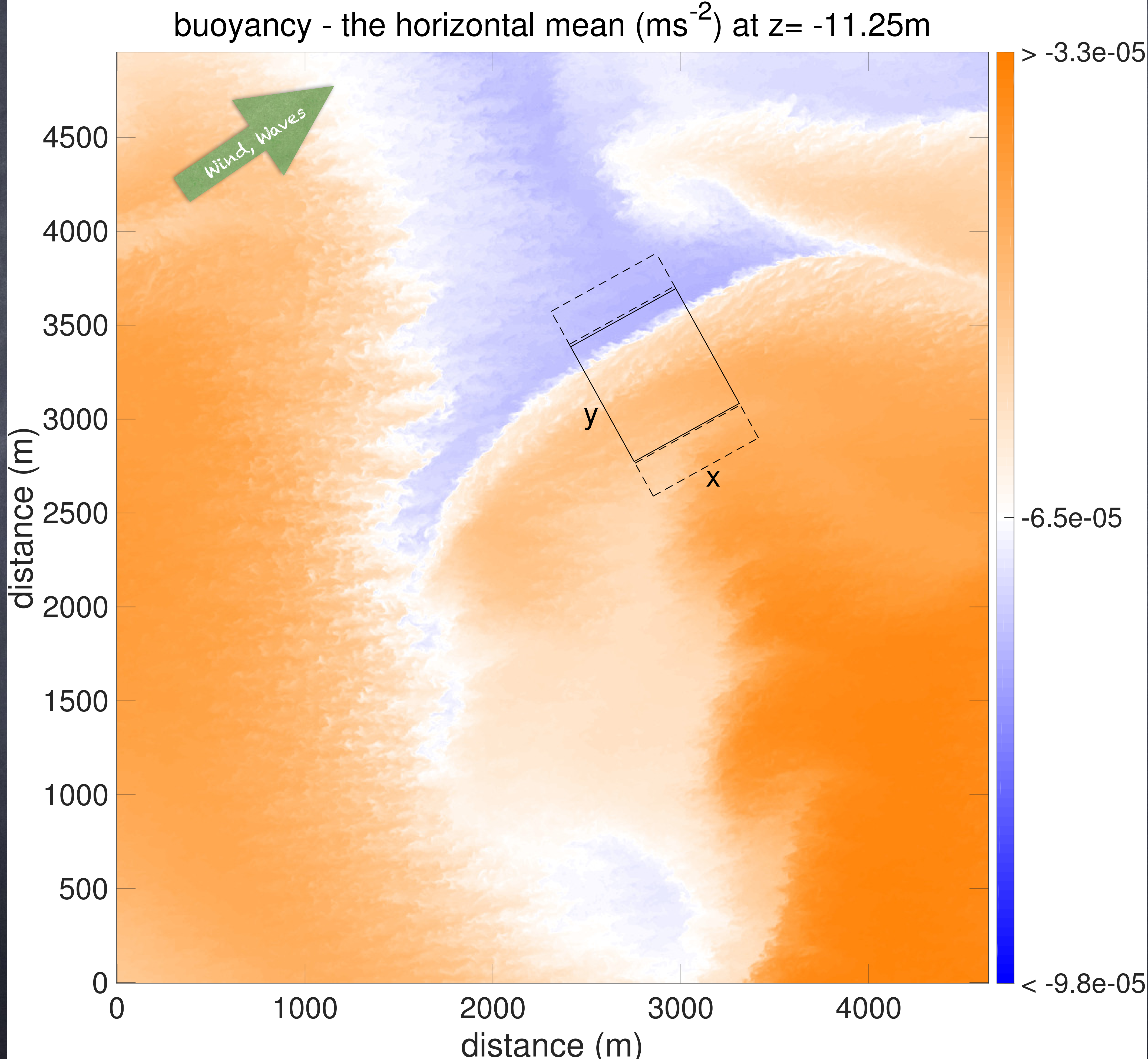
$$\frac{\alpha^2}{Ri}\left[w_{,t} + v_j^L w_{,j} + \frac{M_{Ro}}{RoRi} w w_{,z}\right] = \boxed{-\pi_{,z} + b - \varepsilon v_j^L v_{j,z}^s} + \frac{\alpha^2}{ReRi} w_{,jj}$$

N. Suzuki and BFK. Understanding Stokes forces in the wave-averaged equations. Journal of Geophysical Research-Oceans, 121:1-18, 2016.

V



N. Suzuki, B. Fox-Kemper, P. E. Hamlington, and L. P. Van Roekel. Surface waves affect frontogenesis. Journal of Geophysical Research-Oceans, 121:1-28, May 2016.



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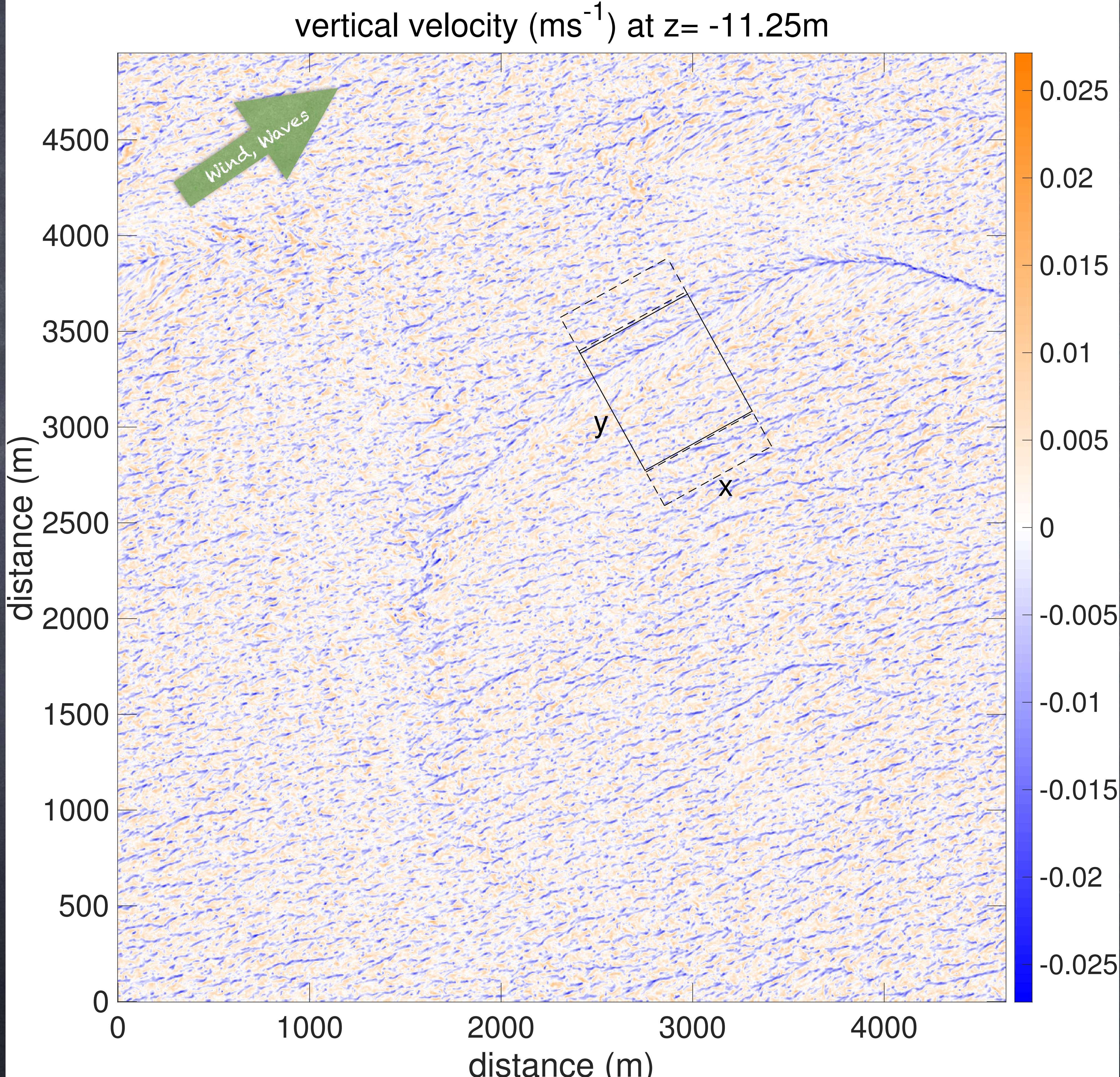
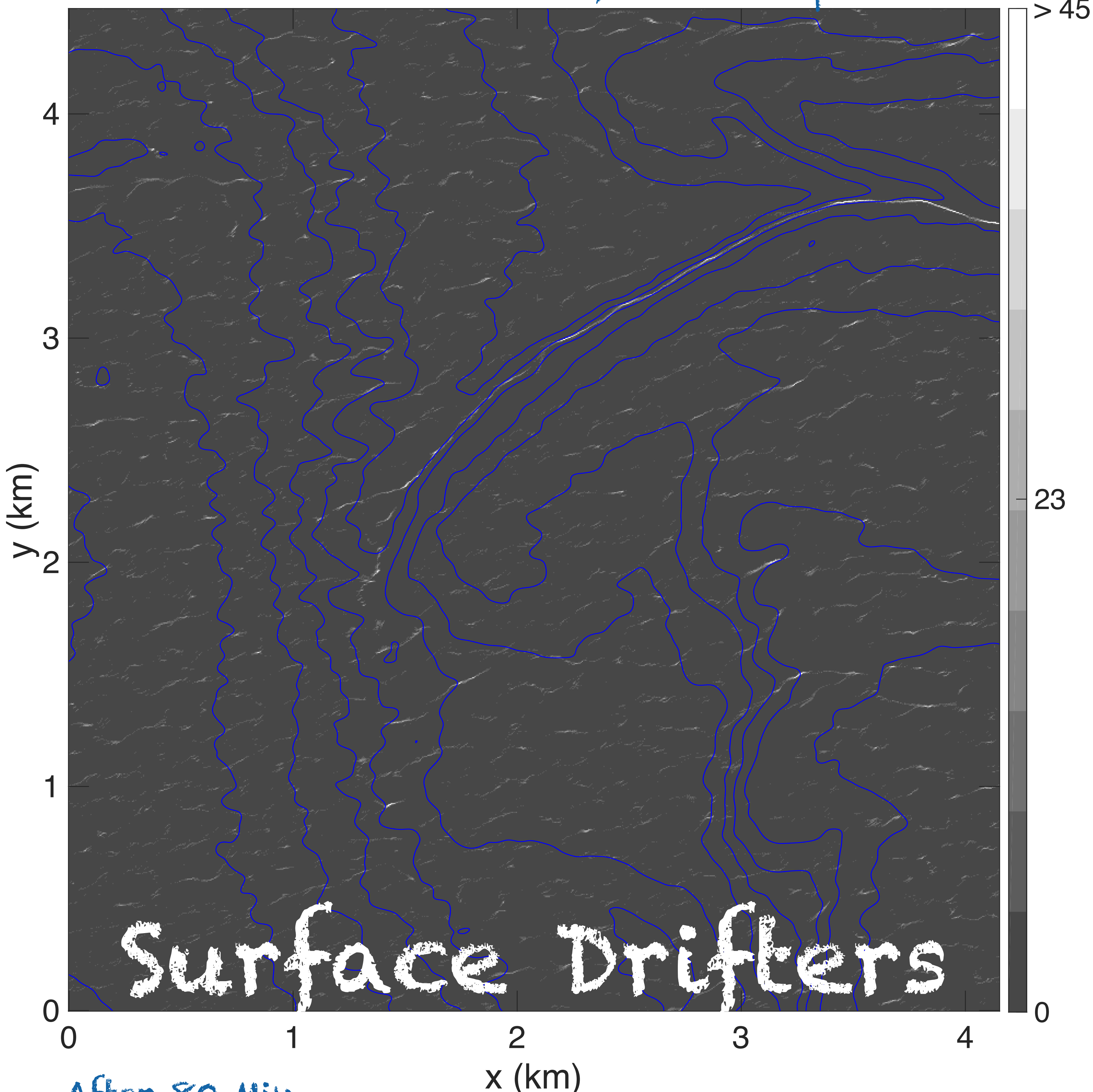
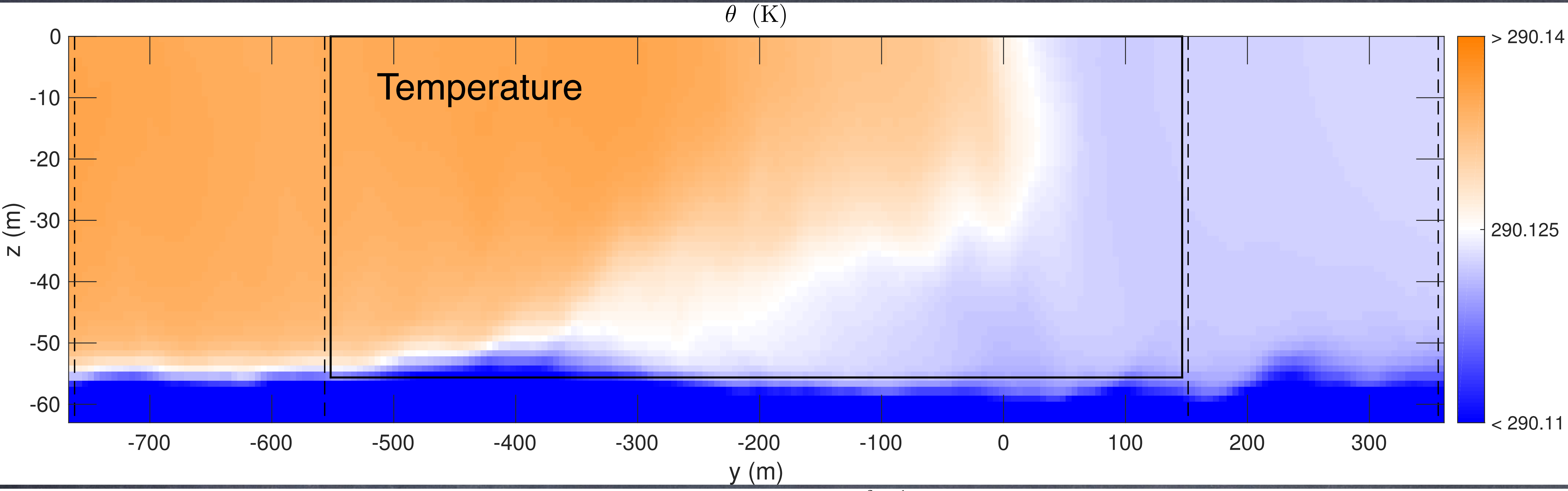


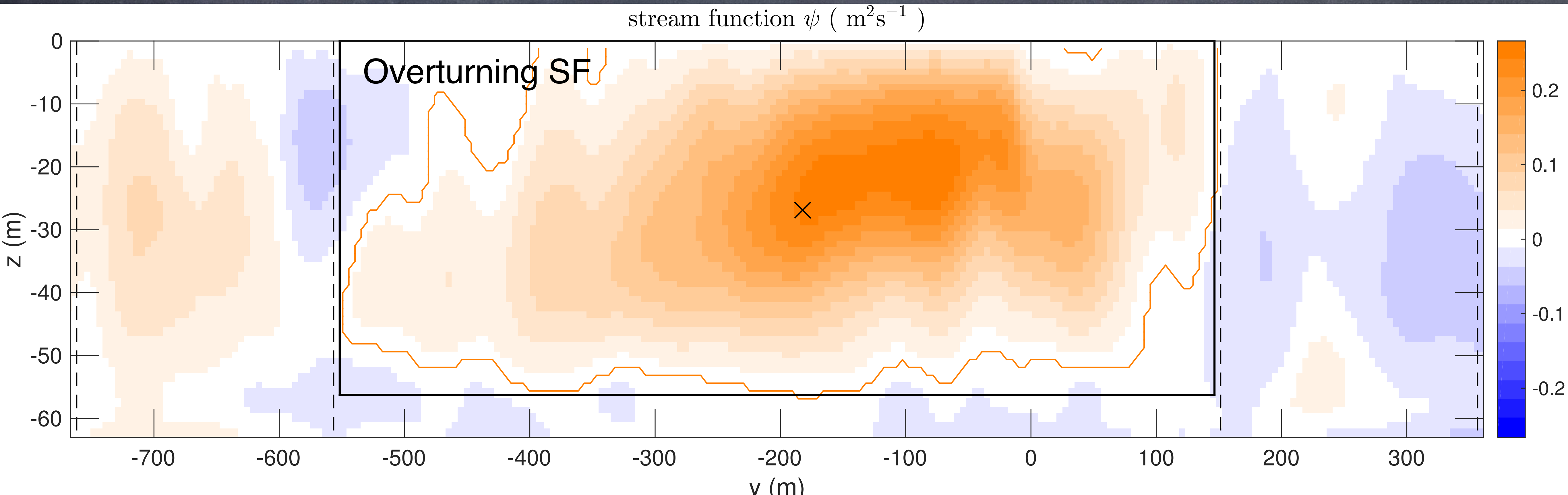
N. Suzuki, B. Fox-Kemper, P. E. Hamlington, and L. P. Van Roekel. Surface waves affect frontogenesis. Journal of Geophysical Research-Oceans, 121:1-28, May 2016.

Initially every surface node has 1 drifter, so there are 851796 drifters in the picture



After 80 Min





N. Suzuki, BFK, P. E. Hamlington, and L. P. Van Roekel. Surface waves affect frontogenesis. Journal of Geophysical Research-Oceans, 121:1-28, 2016.

Do (wavy hydrostatic) Stokes Forces Matter?

Yes! At Leading Order (in LES)

Table 3. Integrated Budget for Overturning Vorticity[a]

Responsible Force	Relative Value
Relative Tendency of Overturning Circulation along the Cell Boundary	
Net tendency	11 ± 8%
Sources	
Buoyancy anomaly	100%
Stokes shear force anomaly	44 ± 4%
Interaction with v^H	44 ± 8%
Frontal anomaly in pressure gradient	6 ± 9%
Nonlinear interaction with v^B:	2 ± 1%
Sinks	
Frontal turbulence anomaly (mostly, imbalance in wavy Ekman relation)	−82 ± 11%
Coriolis on along-front jet	−66 ± 2%
Lagrangian advection of (v^ψ, w^ψ)	−36 ± 7%

N. Suzuki and BFK. Understanding Stokes forces in the wave-averaged equations. Journal of Geophysical Research-Oceans, 121:1-18, April 2016.

N. Suzuki, BFK, P. E. Hamlington, and L. P. Van Roekel. Surface waves affect frontogenesis. Journal of Geophysical Research-Oceans, 121:1-28, May 2016.

Conclusions

- Langmuir mixing scalings consistent with LES & observations, reduce climate model biases in MLD, T, CFCs vs. observations by 5-25%.
- Stokes forces, as treated here, can be included in hydrostatic models like GCMs (wavy hydrostatic)
- Stokes forces affect Langmuir turbulence, but also (sub)mesoscale fronts (more energy, anisotropy) and submesoscale instabilities. Need to assess climate & environmental impact!
- All papers at: fox-kemper.com/pubs

Kavli Institute for Theoretical Physics

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Planetary Boundary Layers in Atmospheres, Oceans, and Ice on Earth and Moons

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Scientific Advisors:
Stephen Belcher,
Carter Ohlmann,
and Jim McWilliams

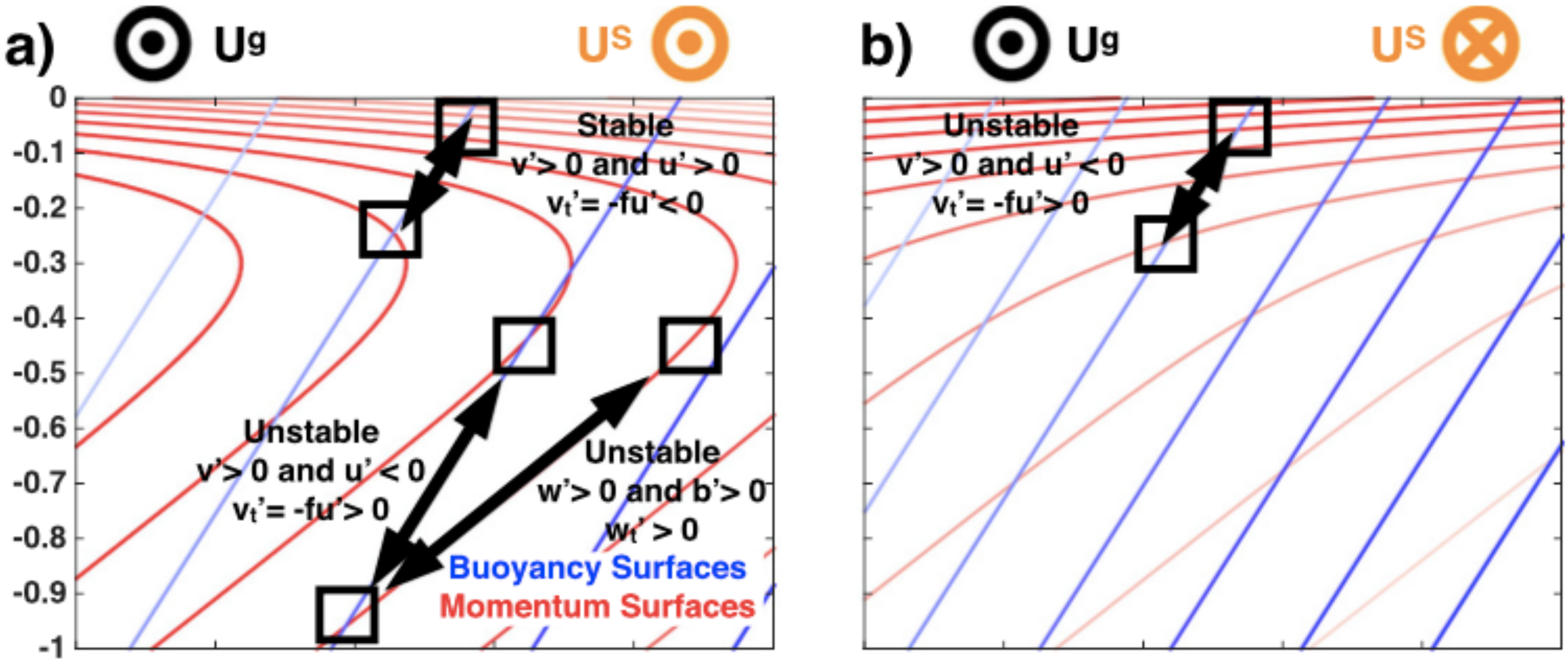


FIG. 1. A schematic of the (a) downfront and (b) upfront Stokes drift scenarios. The blue lines show isopycnals, with darker blue indicating denser water. The red lines show surfaces of constant downfront absolute Eulerian momentum, with darker red indicating greater momentum. The perturbation equations 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, $\mathrm{Ri} = 0.5$. Lines of constant buoyancy and absolute momentum are only parallel when $\mathrm{Ri} = 1$.

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

Analytic & Numerical Wavy Submesoscale Stability:

Geostrophic Instabilities

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

- Instability allowed if:

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

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

Streamfunctions with and w/o Stokes

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

$$V + V^S = \Psi_x^L = 0.$$

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

Analytic & Numerical Wavy Submesoscale Stability: Symmetric Instabilities

- 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.

Vert. Density Gradient — Horiz. Density Gradient — Anti-Stokes Shear

$$fQ = \underbrace{f^2N^2 - M^4}_{\text{geostrophic } fQ} - \underbrace{fM^2U_z^S}_{\text{Stokes-modified } fQ} < 0.$$

- In the absence of Stokes drift, this is equivalent to the familiar criteria on Richardson Number, with Stokes drift is distinct.

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

Do Stokes forces affect Larger Scales?

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

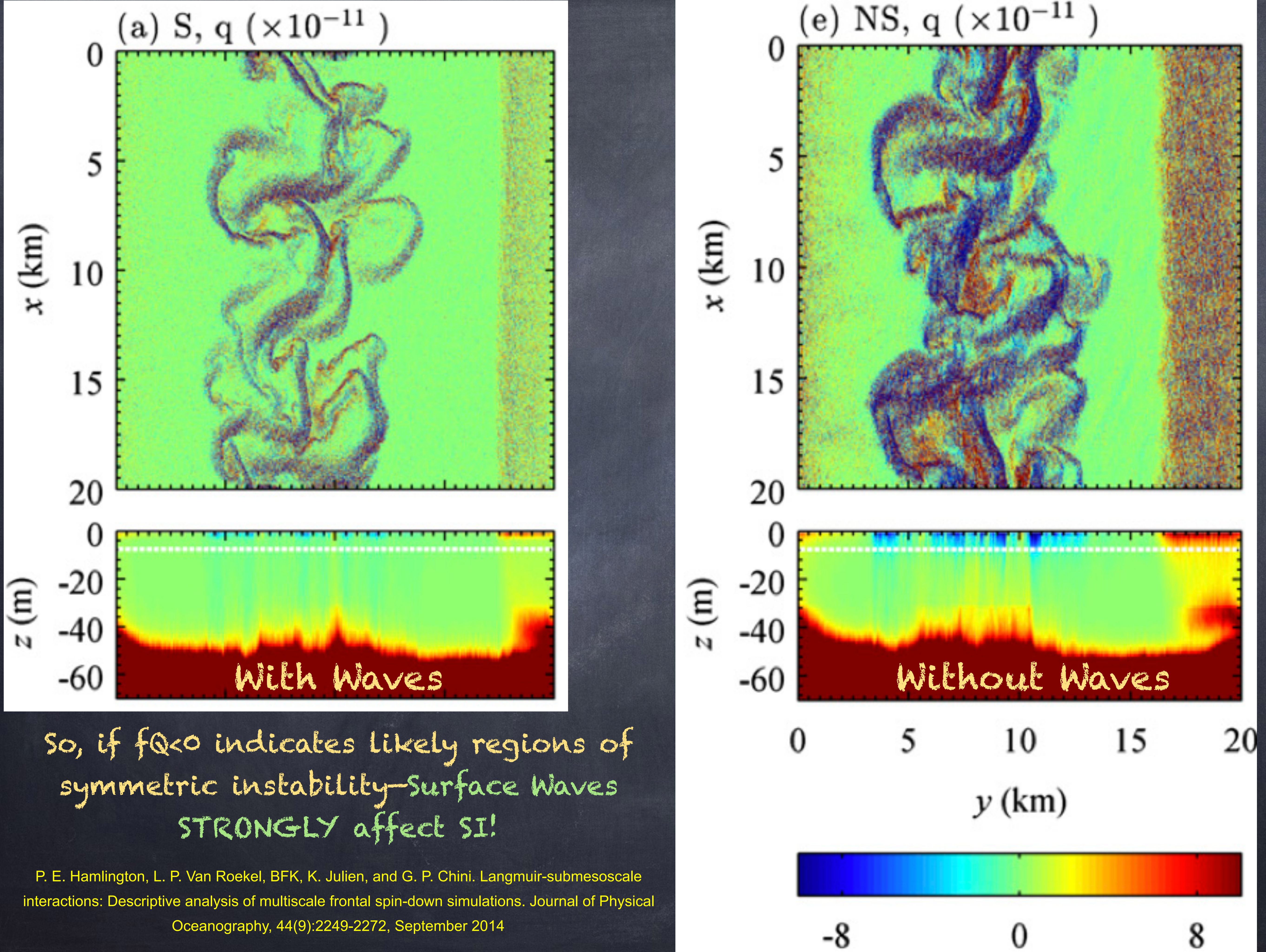
Becomes Lagrangian Thermal Wind Balance

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

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

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

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



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

Lagrangian Thermal Wind Linear Stability

Like Eady, but with Lagrangian Thermal Wind Background State

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

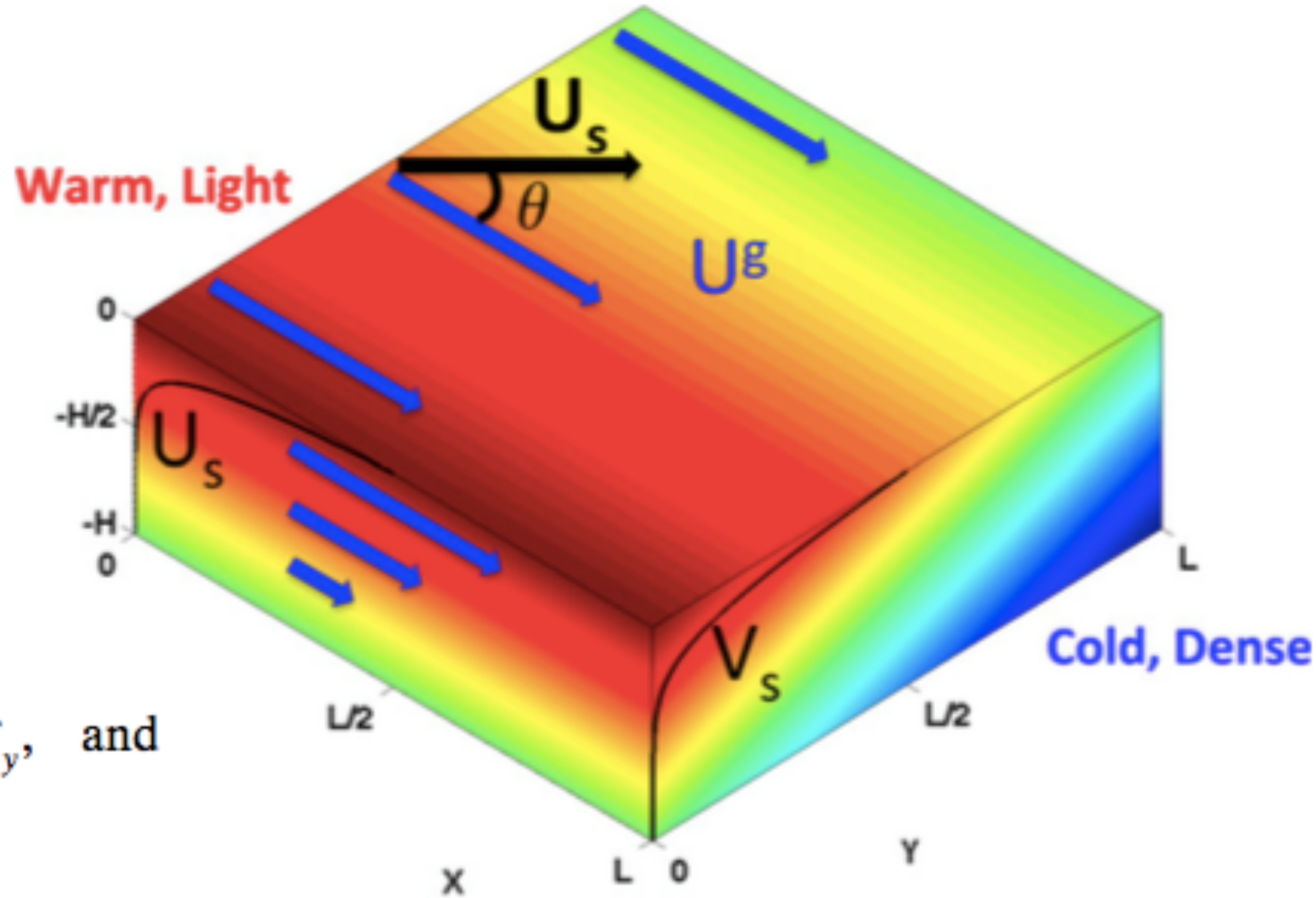
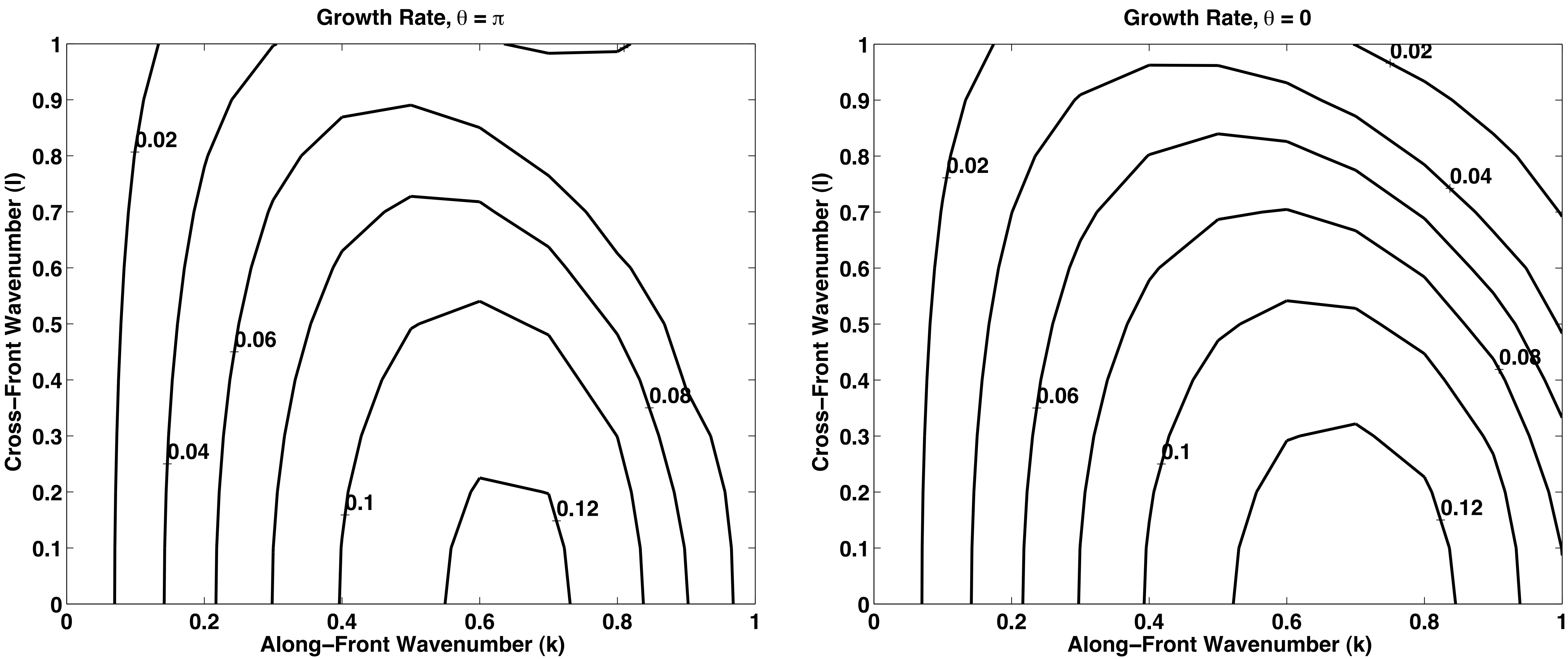


FIG. 2. The background flow with arbitrary θ (the angle between the Stokes drift and the geostrophic flow) and a prescribed exponential Stokes drift U^S, V^S profile. The geostrophic flow U^G, corresponding to the imposed buoyancy gradient, is shown with blue arrows.

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

Analytic & Numerical Wavy Submesoscale Stability:
Geostrophic Instabilities

- For typical conditions, the Stokes effect amounts to a small change in geostrophic instability (mixed layer eddy) growth rates.



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Do (wavy hydrostatic) Stokes Forces Matter? Yes! At Leading Order (in LES)

Table 2. Integrated Budget for the Kinetic Energy of the Overturning Circulation[a]

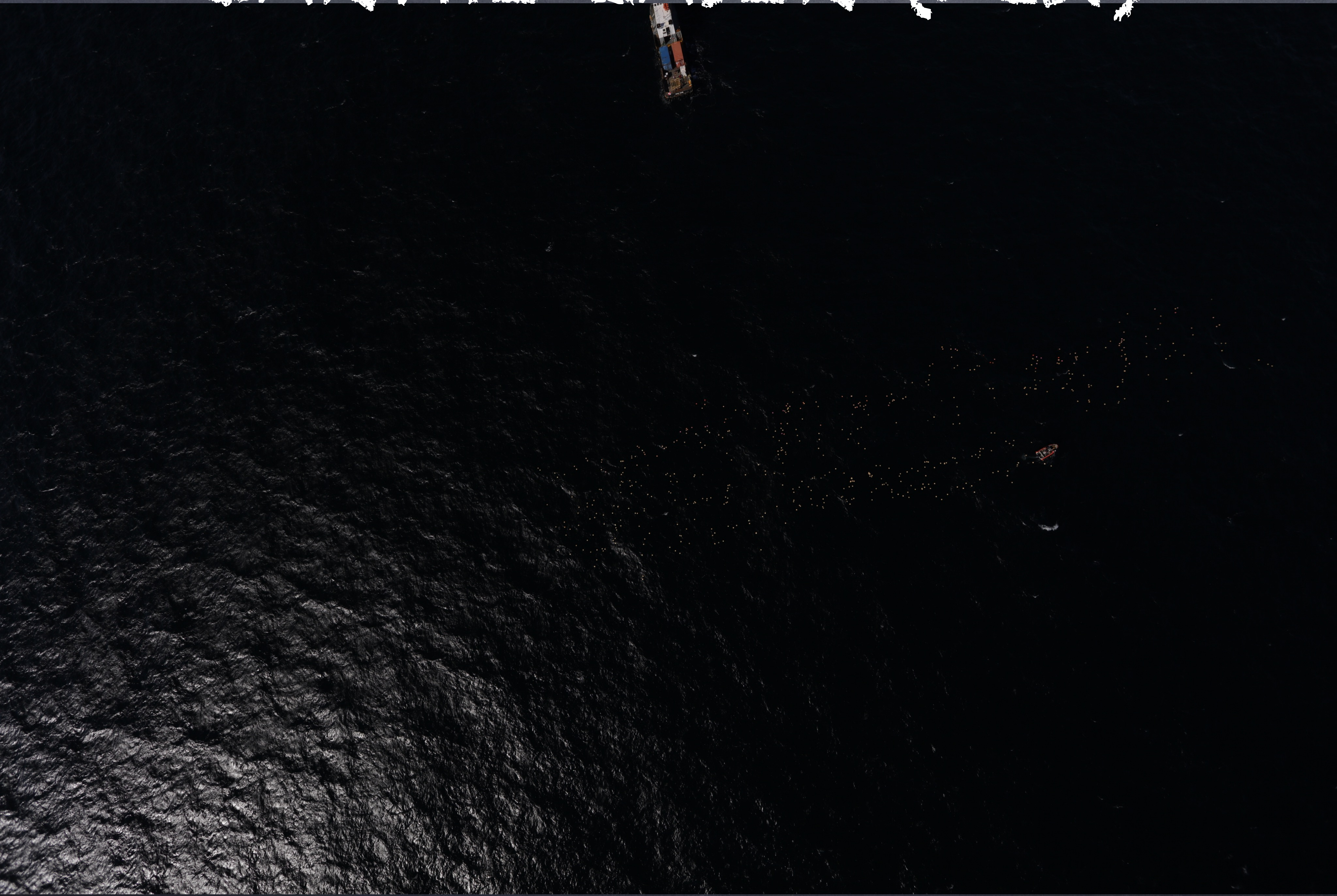
Name	Term	Relative Value
Rate of Change of Overturning Circulation KE		
Total	$(\partial_t + u_j^L \partial_j)\overline{\frac{v^\psi v^\psi + w^\psi w^\psi}{2}}$	$45 \pm 6\%$
Sources		
Buoyancy production	$w^\psi b'$	100%
Energy increase due to interaction with v^H	$v^\psi(-F^h)$	$49 \pm 5\%$
Stokes shear force work	$w^\psi(-u_j' \partial_z u_j^S)$	$24 \pm 1\%$
Energy increase due to nonlinear interaction with v^B	$v^\psi(-F^v)$	$7 \pm 1\%$
Sinks		
Generation of along-front jet by Coriolis turning of v^ψ	$-fv^\psi u^H$	$-69 \pm 3\%$
Work done against Coriolis of background flows	$v^\psi(\overline{\partial_y p'}^B + \overline{\partial_j L_{2j}}^B)$	$-45 \pm 3\%$
Generation of shear turbulence	$L_{kj} \partial_j u_k^\psi$	$-16 \pm 1\%$
Turbulent transport through the cell boundary	$-\partial_j(u_k^\psi L_{kj})$	$-2 \pm 0.4\%$

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

N. Suzuki and B. Fox-Kemper. Understanding Stokes forces in the wave-averaged equations. Journal of Geophysical Research-Oceans, 121:1-18, April 2016.

N. Suzuki, B. Fox-Kemper, P. E. Hamlington, and L. P. Van Roekel. Surface waves affect frontogenesis. Journal of Geophysical Research-Oceans, 121:1-28, May 2016.

CARTHE LASER (Feb.)



CARTHE LASER (Feb.)

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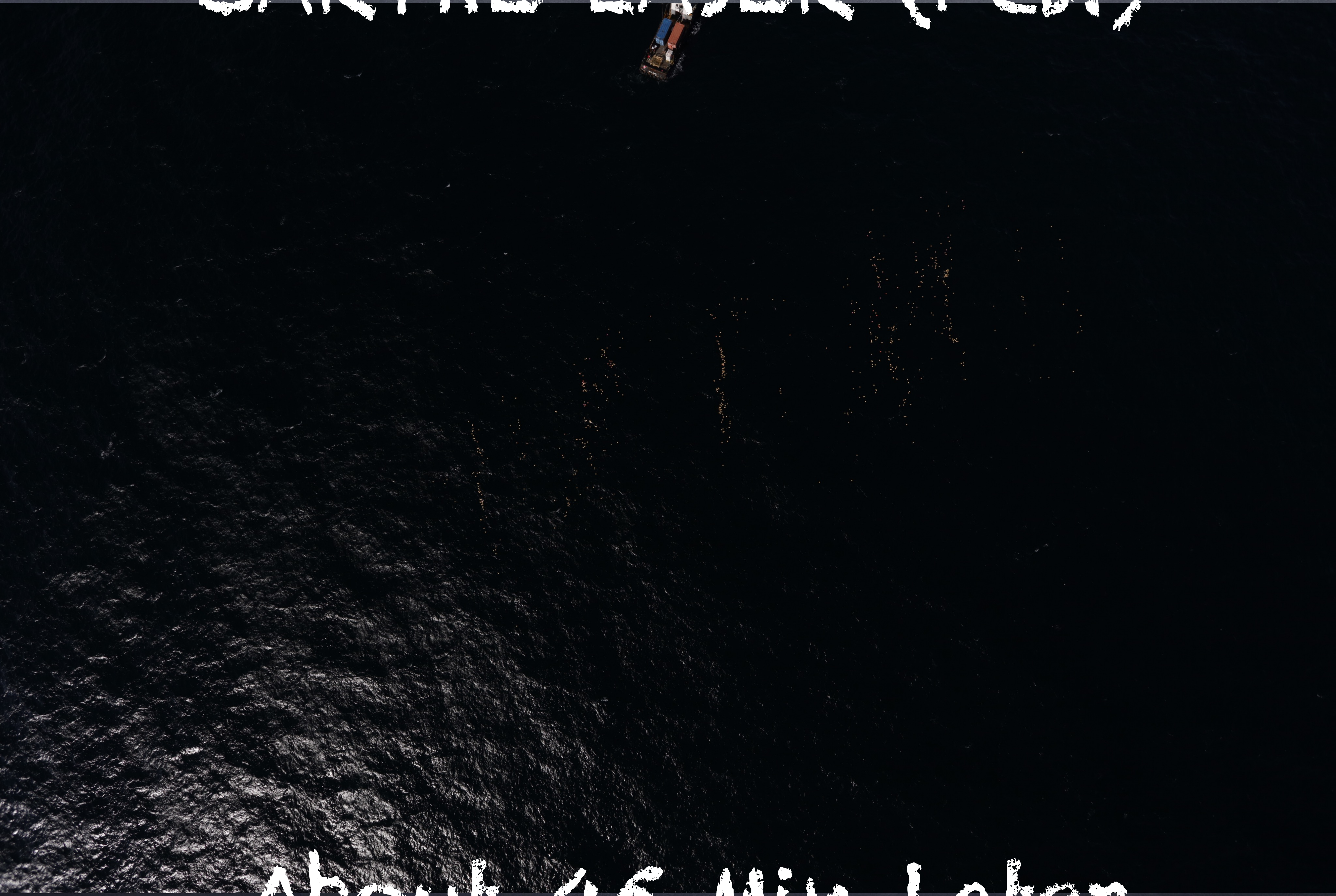

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