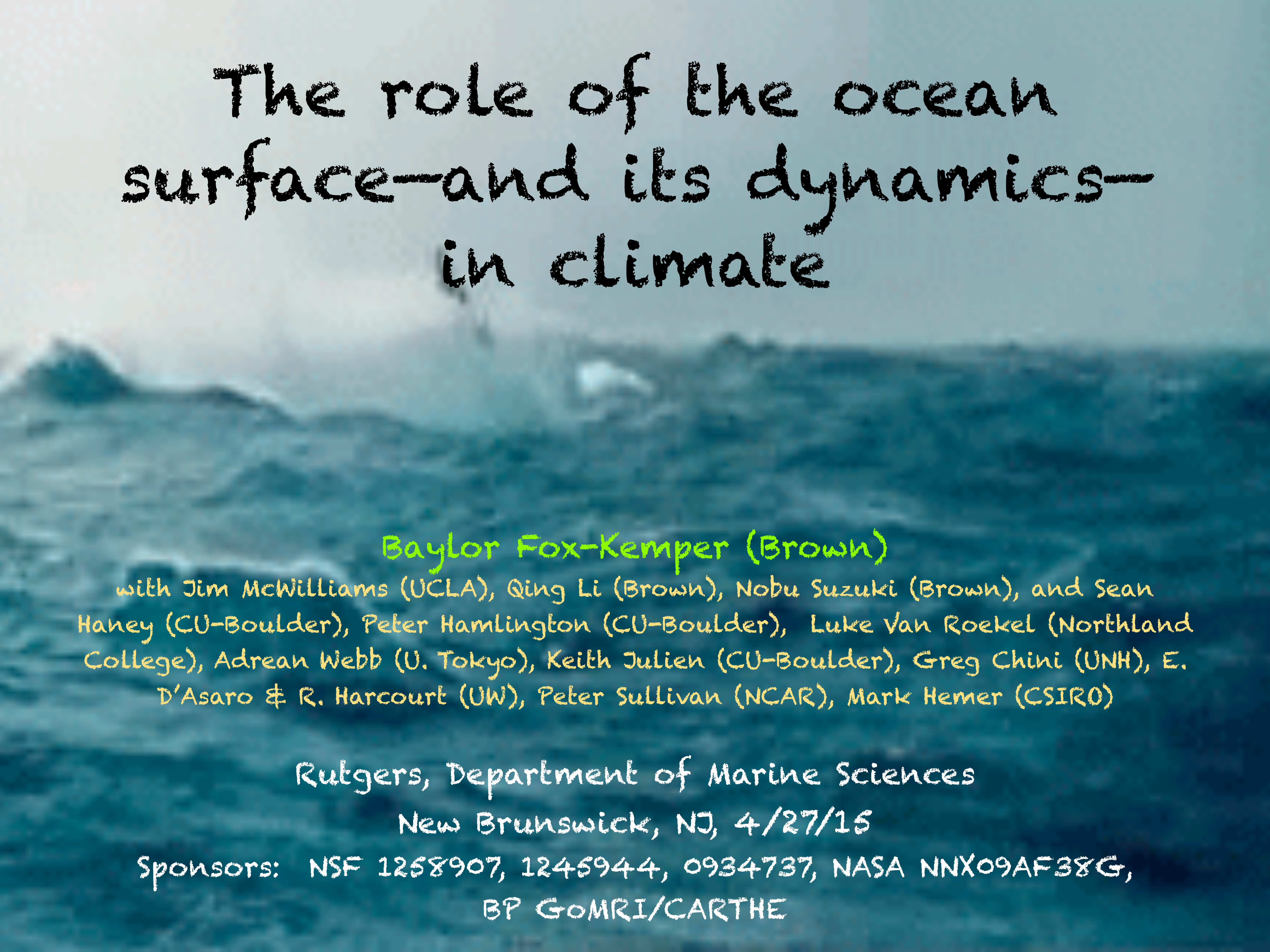


The role of the ocean surface–and its dynamics–in climate

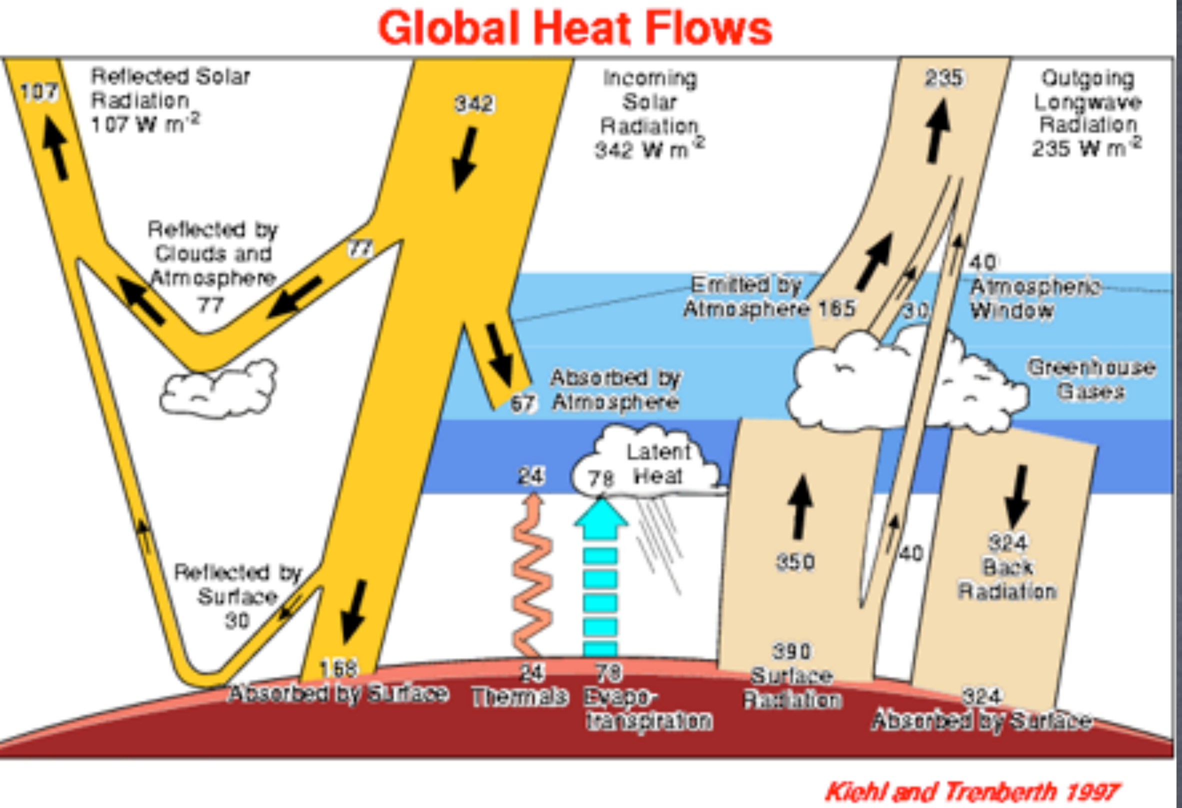
Baylor Fox-Kemper (Brown)

with Jim McWilliams (UCLA), Qing Li (Brown), Nobu Suzuki (Brown), and Sean Haney (CU-Boulder), Peter Hamlington (CU-Boulder), Luke Van Roekel (Northland College), Adrean Webb (U. Tokyo), Keith Julien (CU-Boulder), Greg Chini (UNH), E. D'Asaro & R. Harcourt (UW), Peter Sullivan (NCAR), Mark Hemer (CSIRO)

Rutgers, Department of Marine Sciences

New Brunswick, NJ, 4/27/15

Sponsors: NSF 1258907, 1245944, 0934737, NASA NNX09AF38G, BP GoMRI/CARTHE

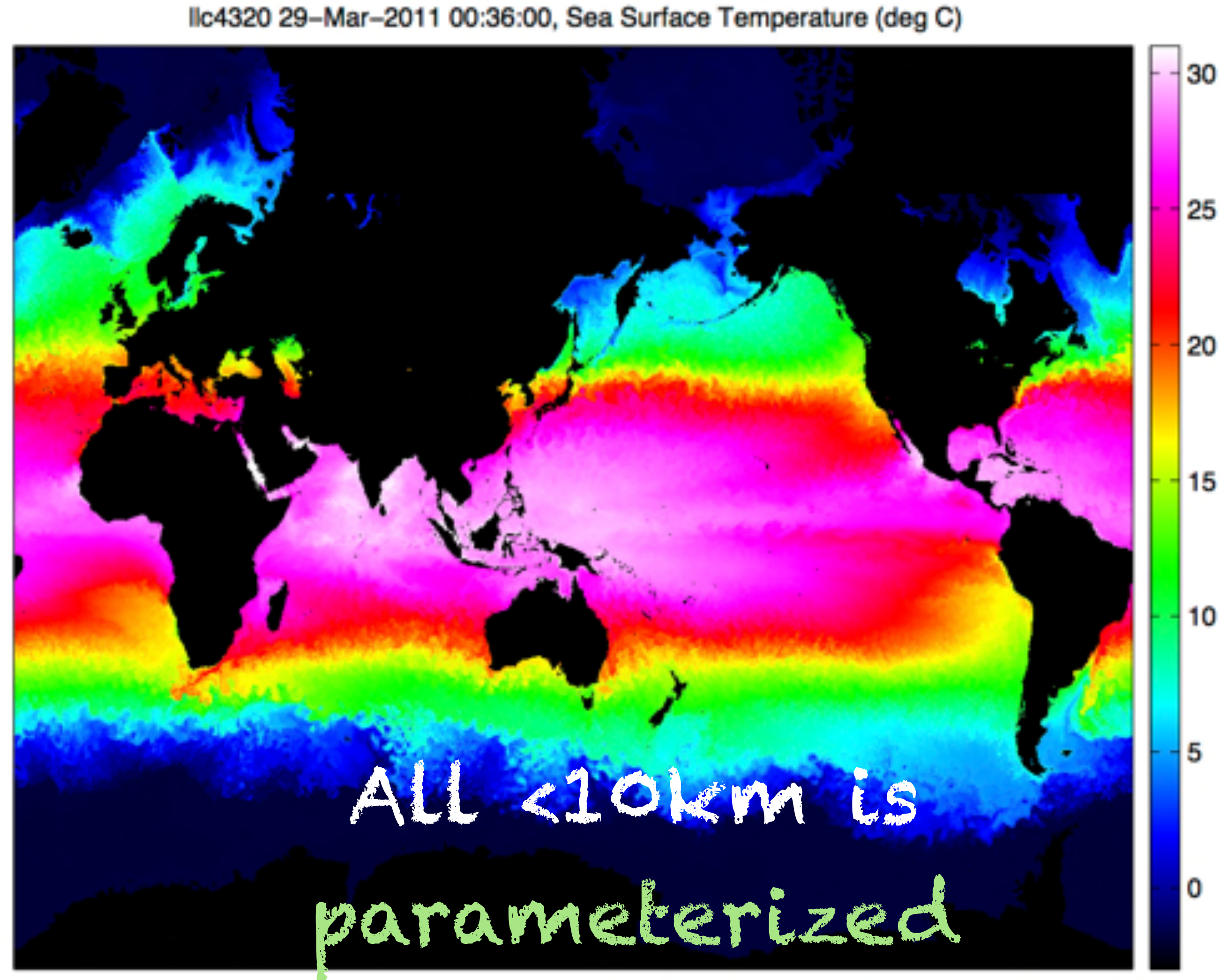


Kiehl and Trenberth 1997

The Earth's Climate System is forced by the Sun on a global scale (20,000-40,000km)

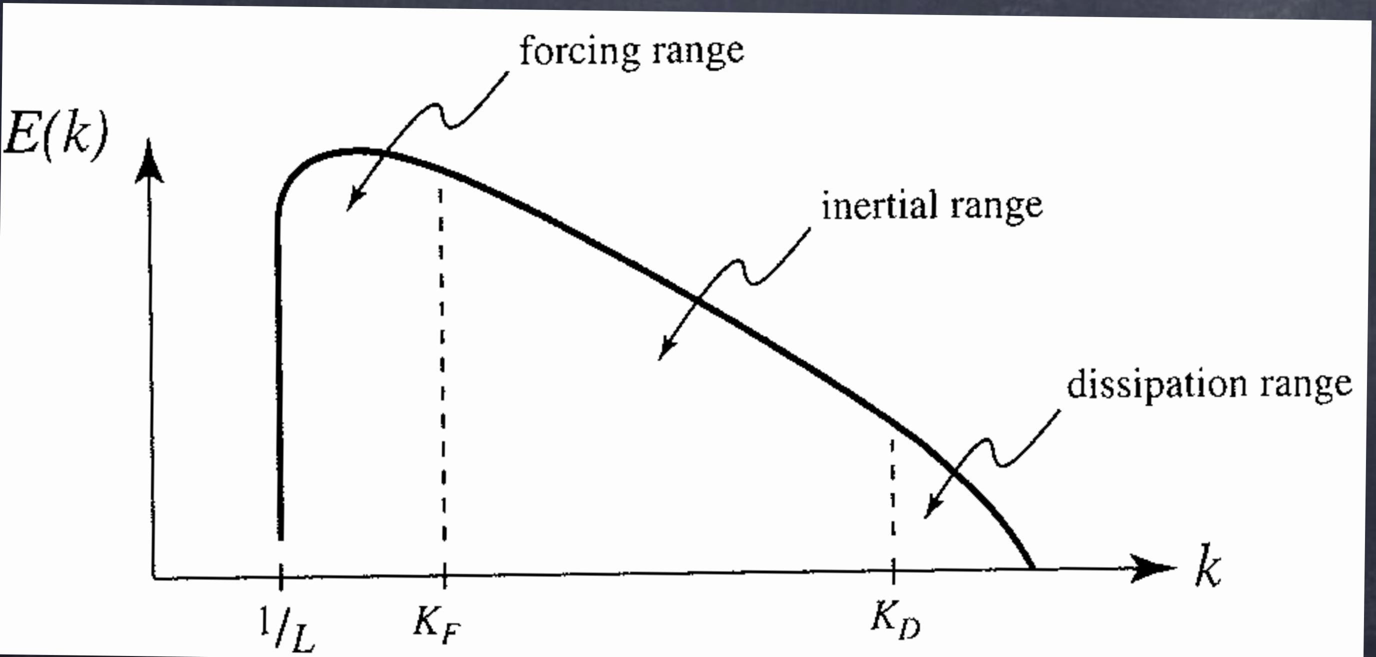
Next-gen. ocean climate models simulate globe to 10km: Mesoscale Ocean Large Eddy Simulations (MOLES)

llc4320 29-Mar-2011 00:36:00, Sea Surface Temperature (deg C)

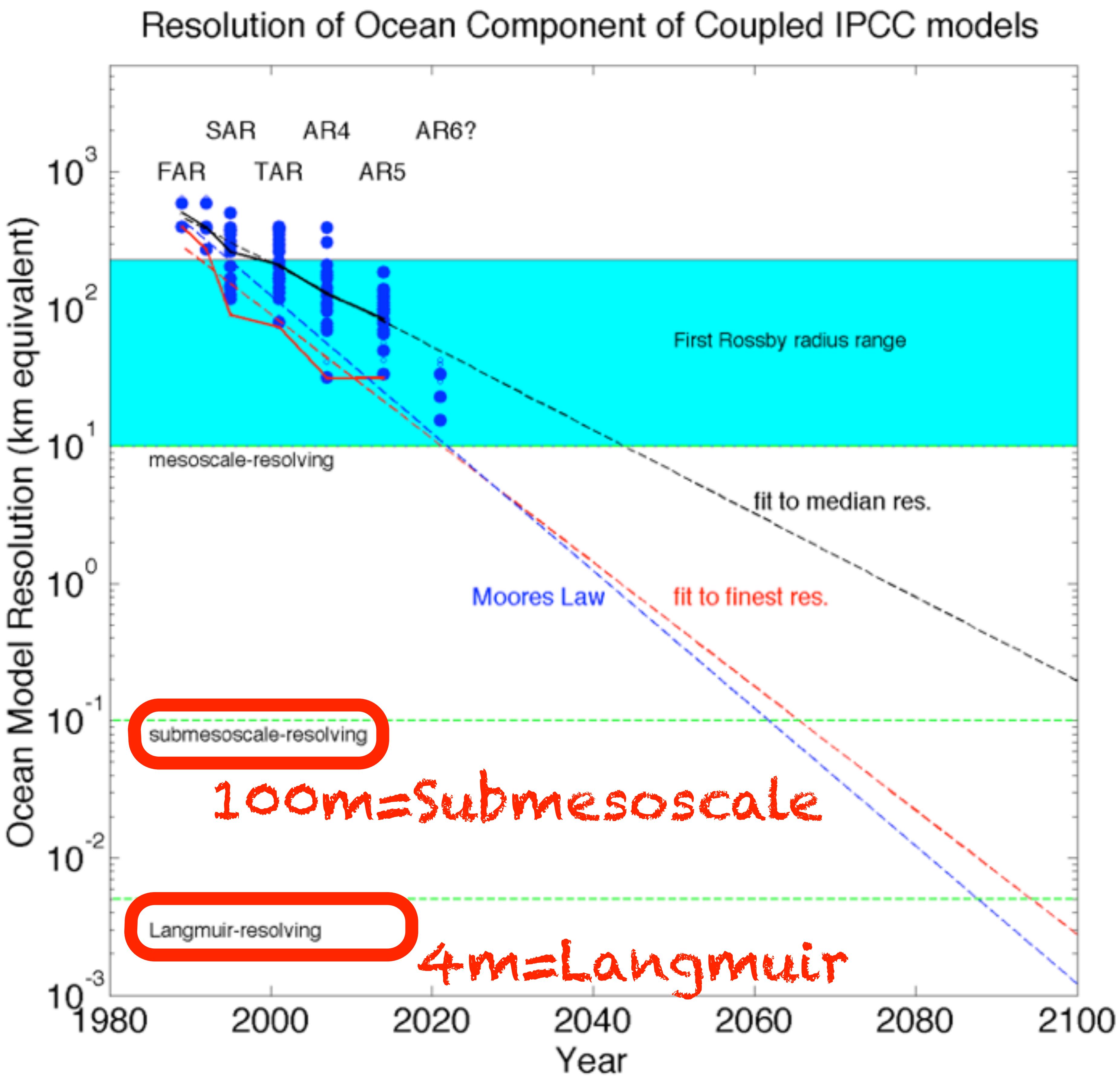


All <10km is parameterized

Turbulence cascades to scales about 10 billion times smaller O(1mm)



Resolution will be an issue for centuries to come!



100m=Submesoscale

4m=Langmuir

Here are the collection of IPCC models...

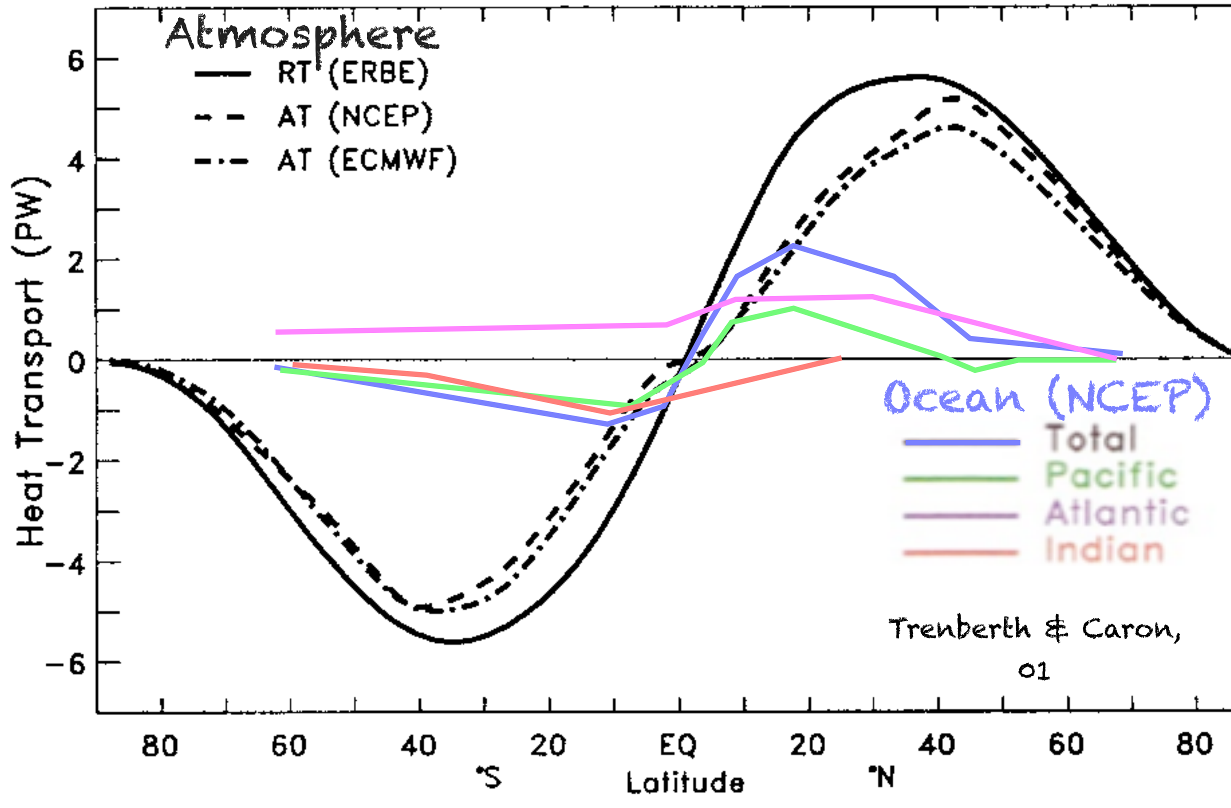
If we cant resolve a process, we need to develop a parameterization or subgrid model of its effect

Air-Sea Flux Errors vs. Data

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

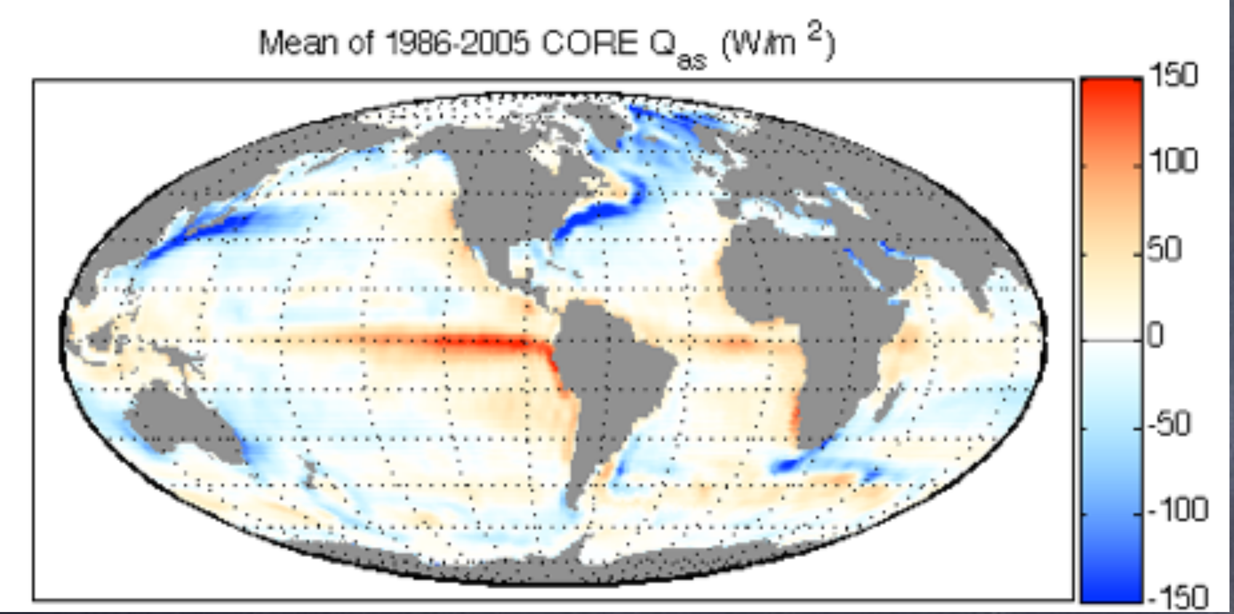
>90% of GW is oceanic, 10m O=whole A

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

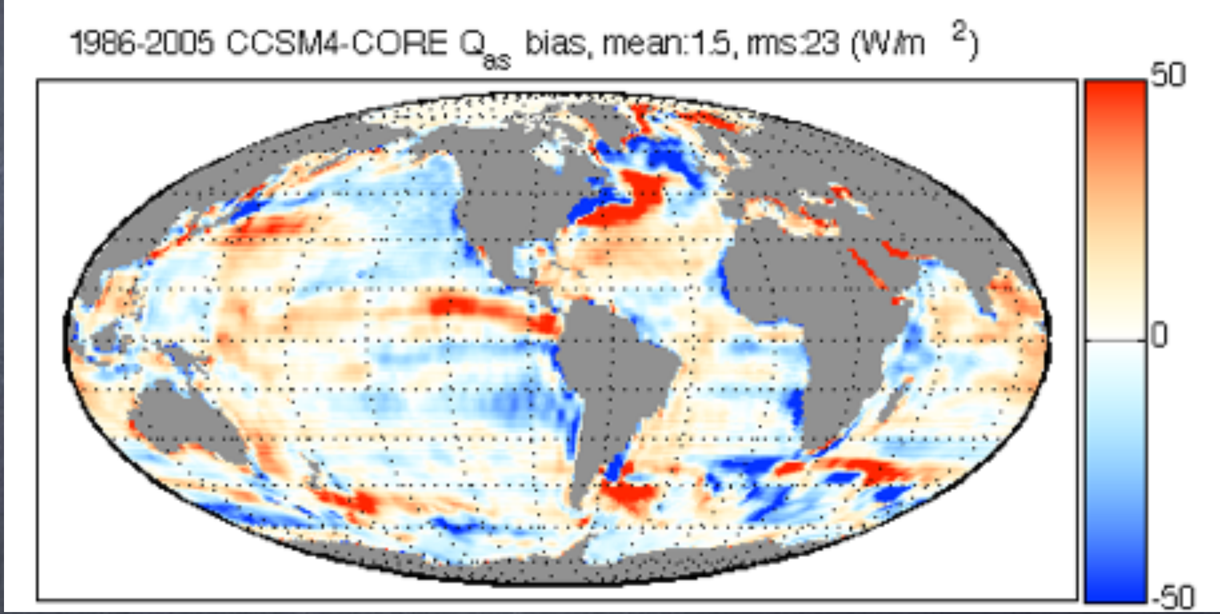


Trenberth & Caron, 01

Mean

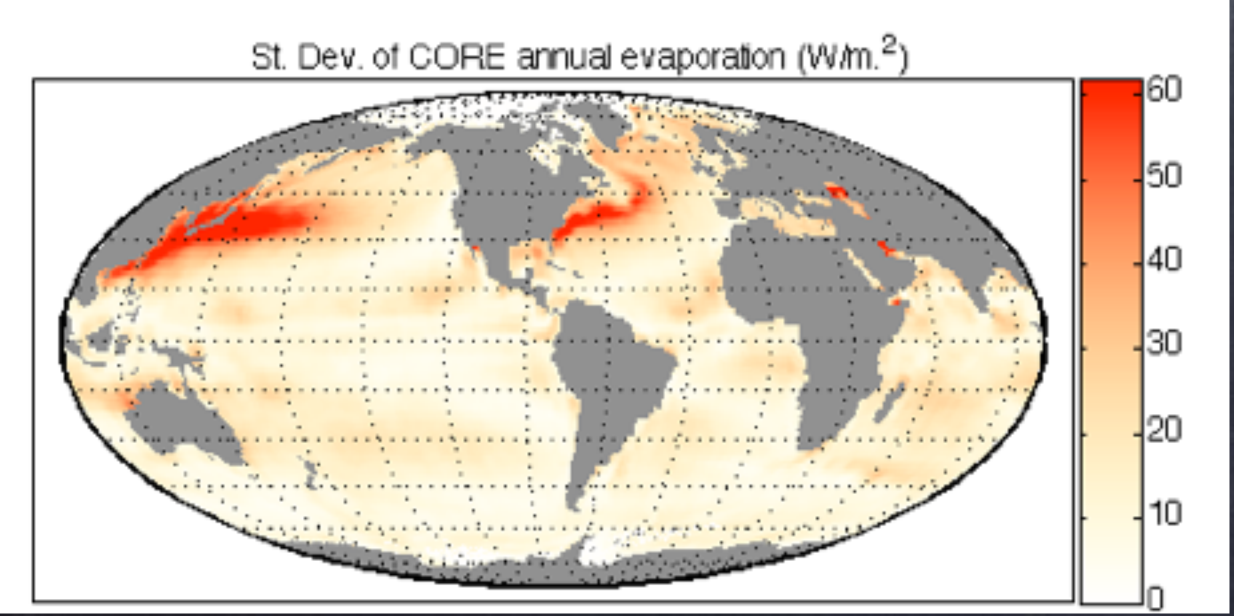


Mean of 1986-2005 CORE Q_{as} (W/m ^{2})

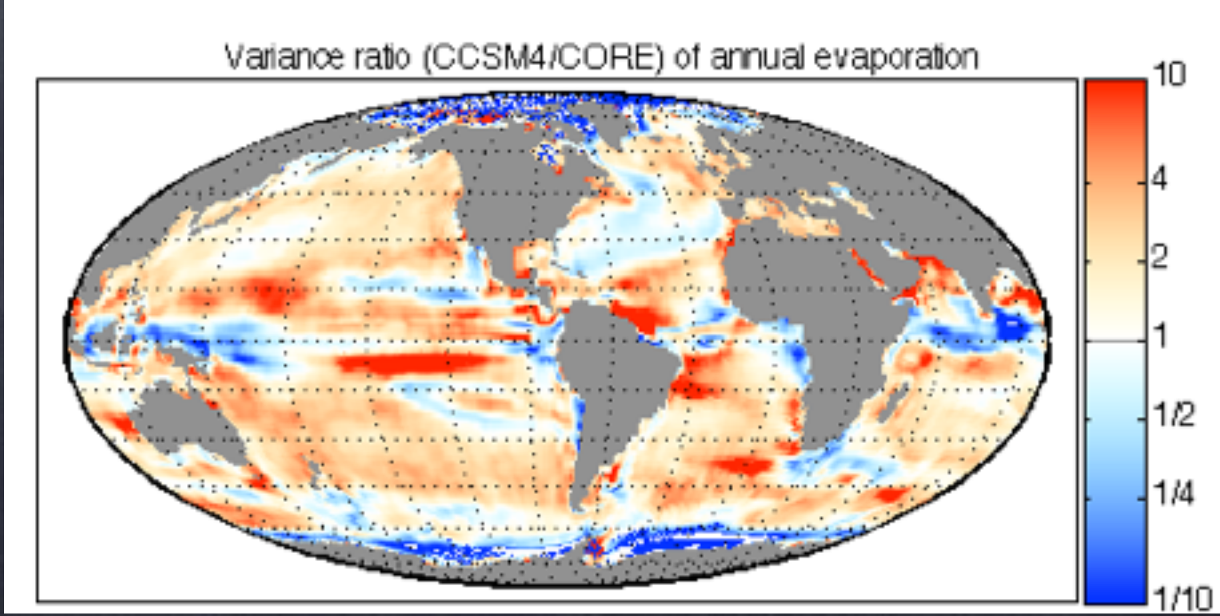


1986-2005 CCSM4-CORE Q_{as} bias, mean:1.5, rms:23 (W/m ^{2})

Annual 9-15mo

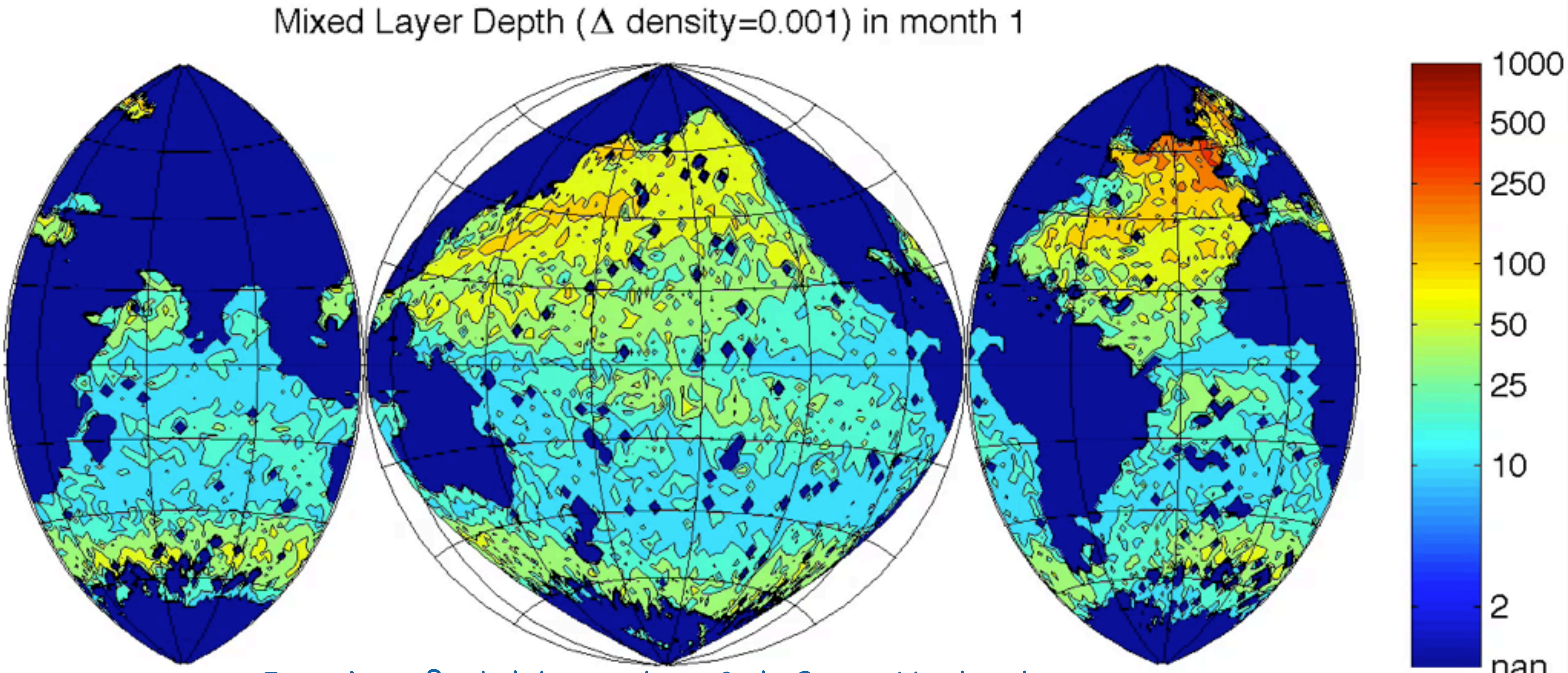


St. Dev. of CORE annual evaporation (W/m.^{2})



Variance ratio (CCSM4/CORE) of annual evaporation

The Ocean Mixed Layer

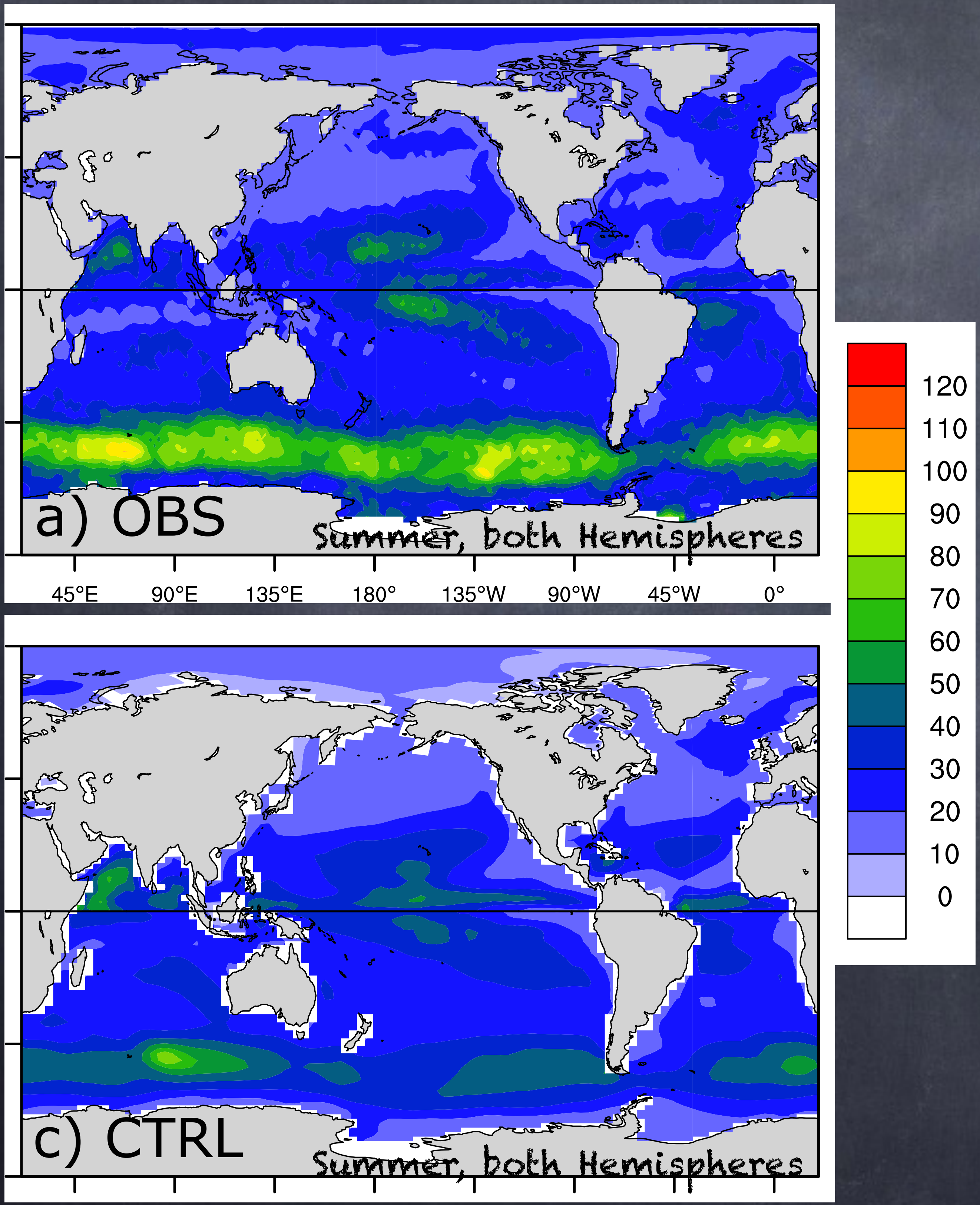


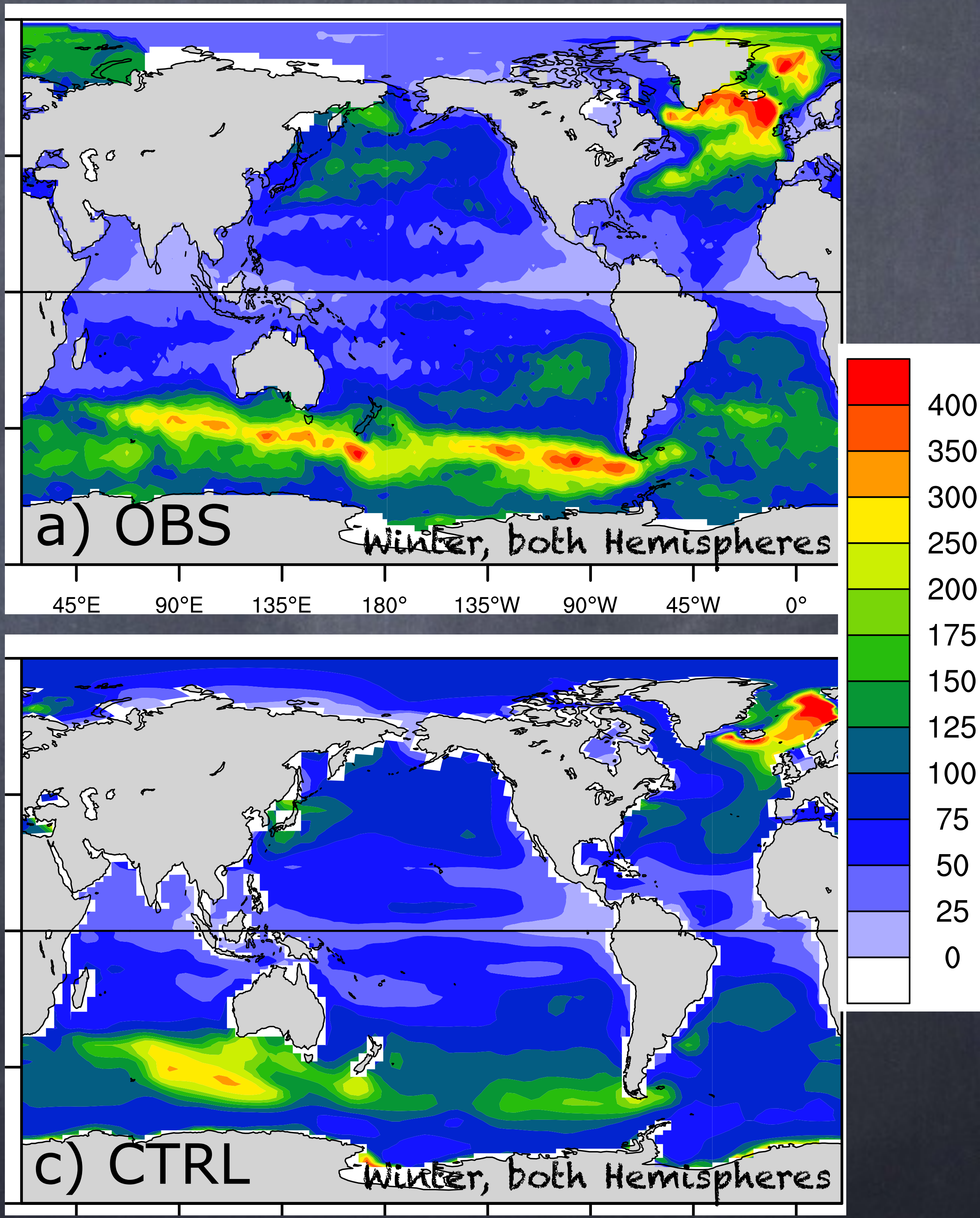
From Argo float data courtesy C. de Boyer-Montegut

Stommel's Demon: ocean properties at depth set by deepest wintertime mixed layer & its properties: Subsurface T, S, CFCs, etc., affected. Use to check!

The State of the Climate Modeling Art:

Observations vs. Mixed Layers in CESM1.2

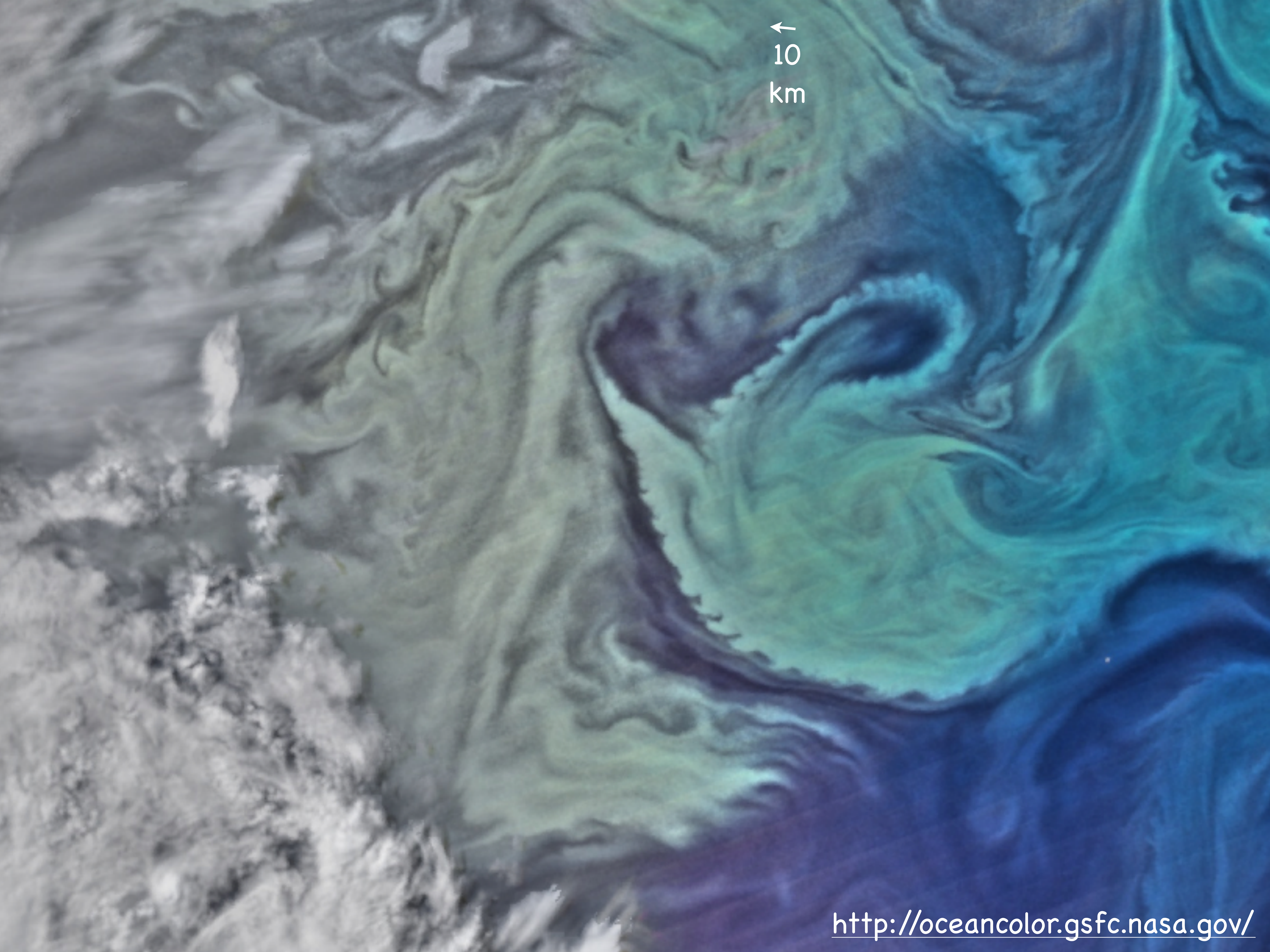




Q. Li, A. Webb, B. Fox-Kemper, A. Craig, G. Danabasoglu, W. G. Large, and M. Vertenstein. Langmuir mixing effects on global climate: WAVEWATCH III in CESM
Ocean Modelling, 2015. Submitted.

So, climate models arent perfect. Now what?

- Resolve more! (marginally possible)
- Make existing parameterizations better! (not today)
- Look for important neglected physics!
  - Submesoscale Eddies (100m resolution req'd)
  - Langmuir (Wave-Driven) Mixing (4m resolution req'd)
  - Combinations?

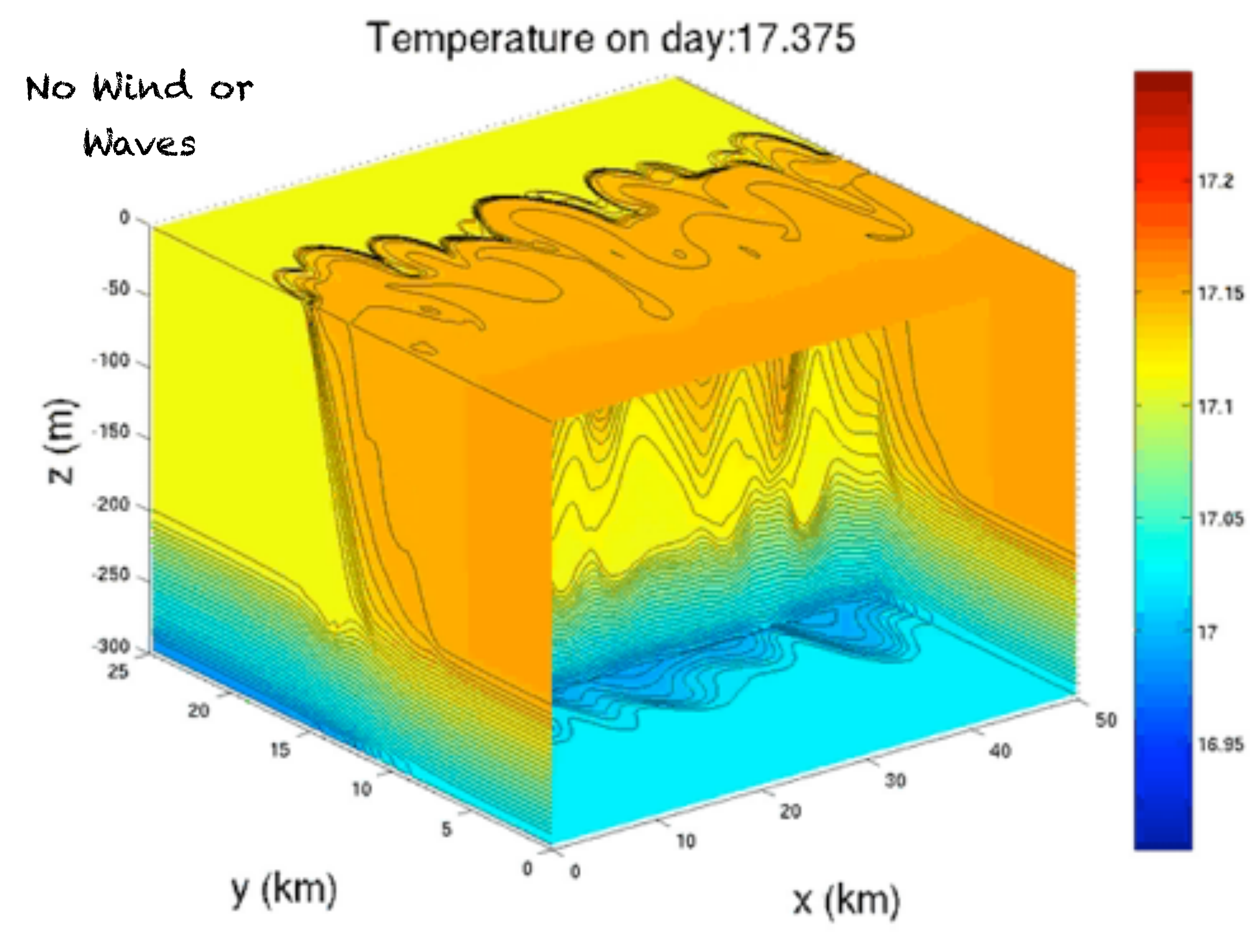


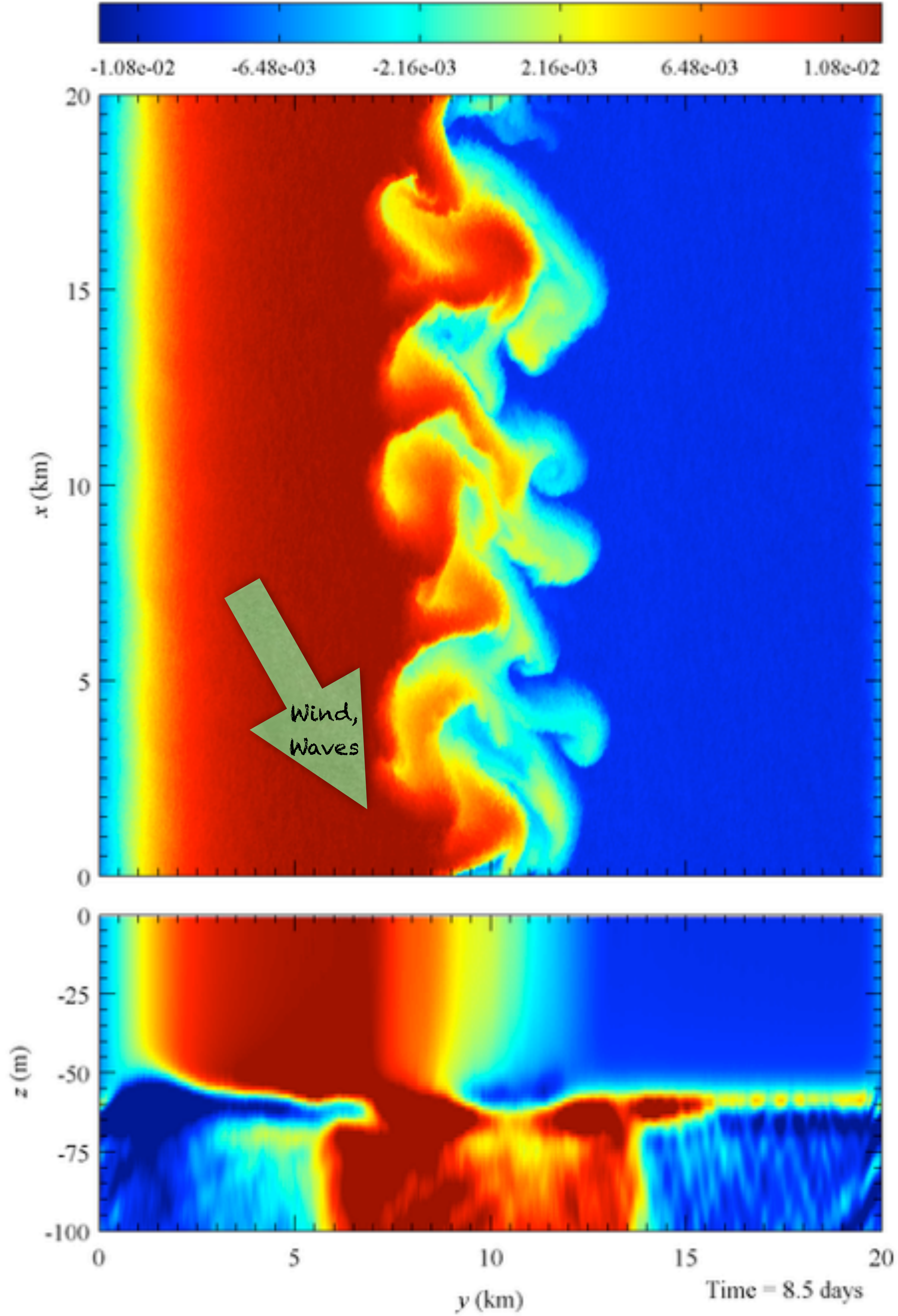
http://oceancolor.gsfc.nasa.gov/

Submesoscale?

Submesoscale (1-10km) fronts & the eddies that form on them help restratify the boundary layer

Mixing balances restratification





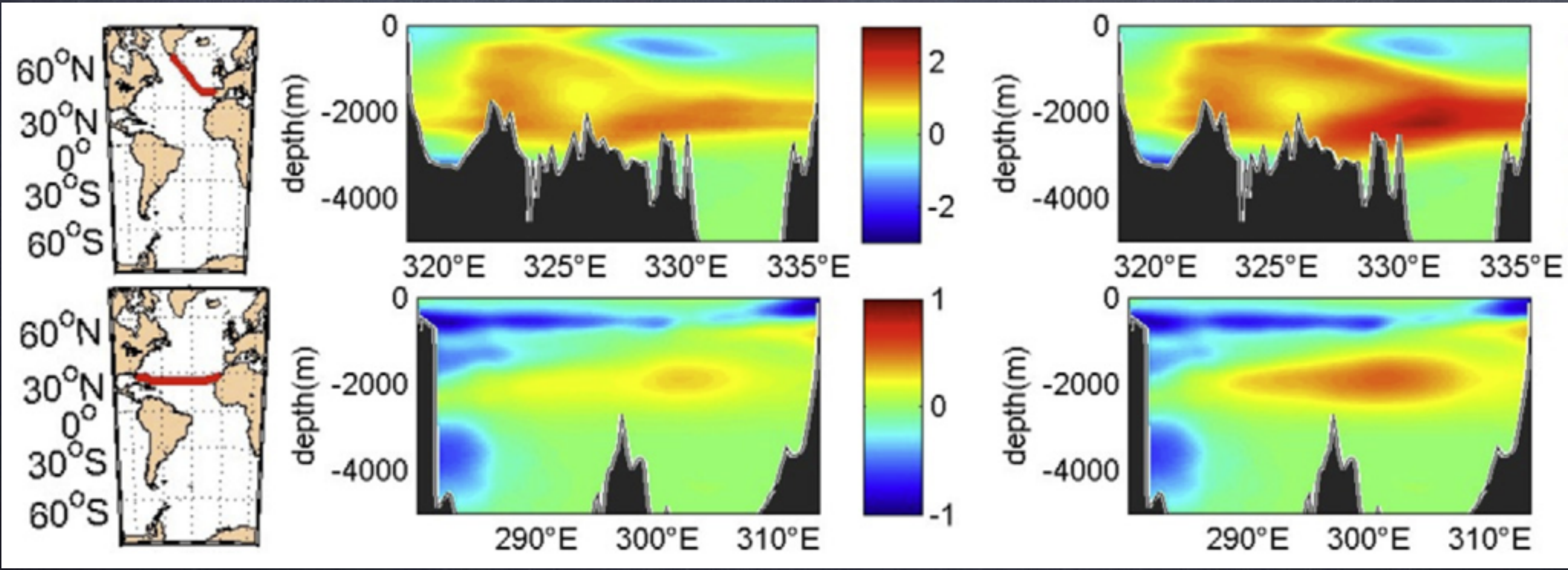
Movie: P. Hamlington

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.

Physical Sensitivity of Ocean Climate to Submesoscale Mixed Layer Eddy Restratification:

MLE implemented in NCAR, GFDL, Hadley, NEMO,...

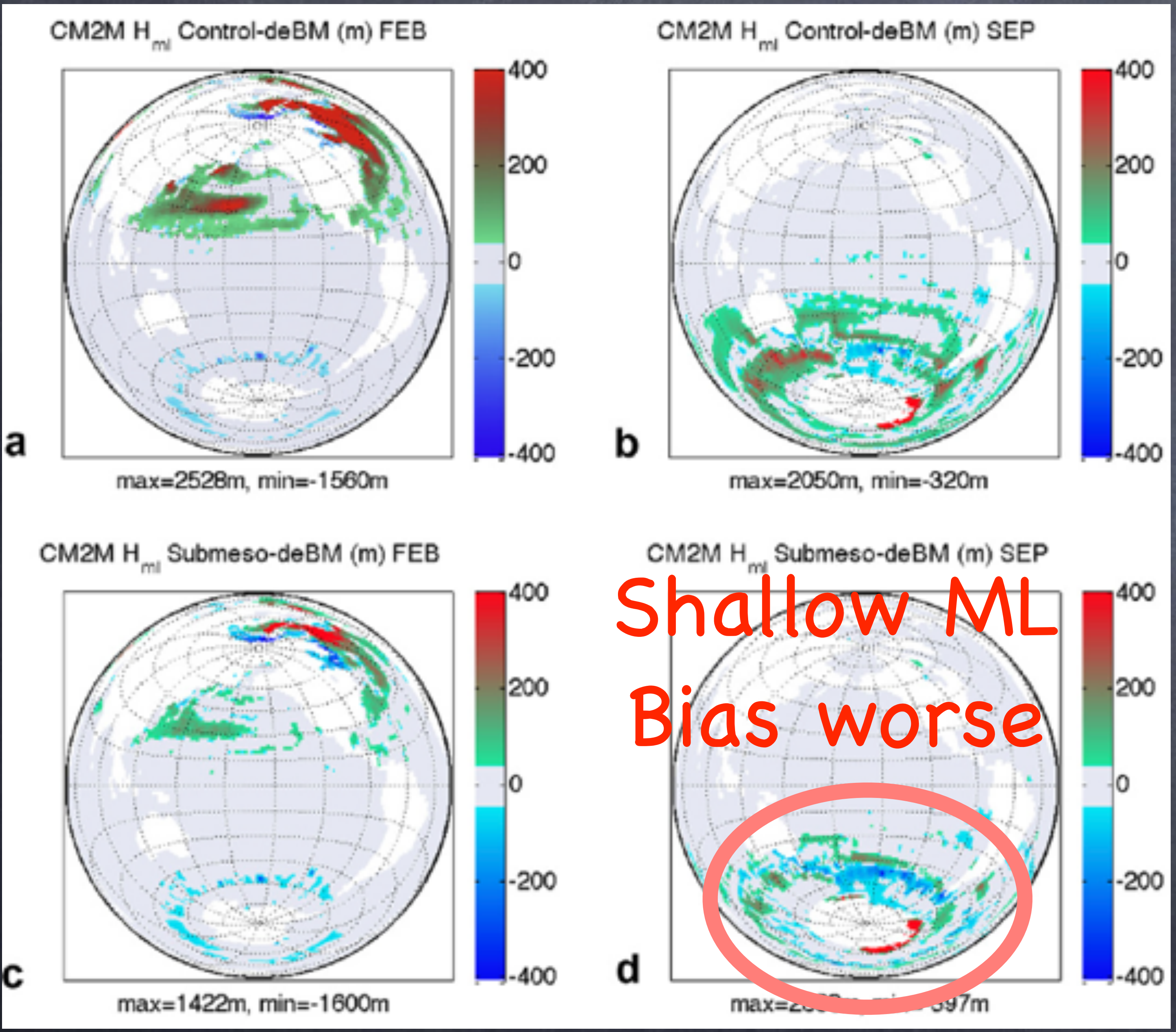
Improves CFC uptake (Atlantic water masses)


With MLE Parameterization

Bias w/o MLE

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 eddi III: Implementation and impact in global ocean climate simulations. *Ocean Modelling*, 39:61-78, 2011.

A problem with Mixed Layer Eddy Restratification— Southern Ocean already too shallow!



Shallow ML Bias worse

Bias w/o MLE

Bias with MLE

Sallee et al. (2013) show a shallow S. Ocean MLD bias is in most* climate models even those with MLE parameteriation!

salinity forcing or ocean physics?

*CMIP5 ensemble

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.

So, climate models arent perfect. Now what?

- Resolve more! (marginally possible)
- Make existing parameterizations better! (not today)
- Look for important neglected physics!
  - Submesoscale Eddies (100m resolution req'd)
  - Langmuir (Wave-Driven) Mixing (4m resolution req'd)
  - Combinations?

The Character of Langmuir (Wave-driven) Turbulence

image: Thorpe, 04

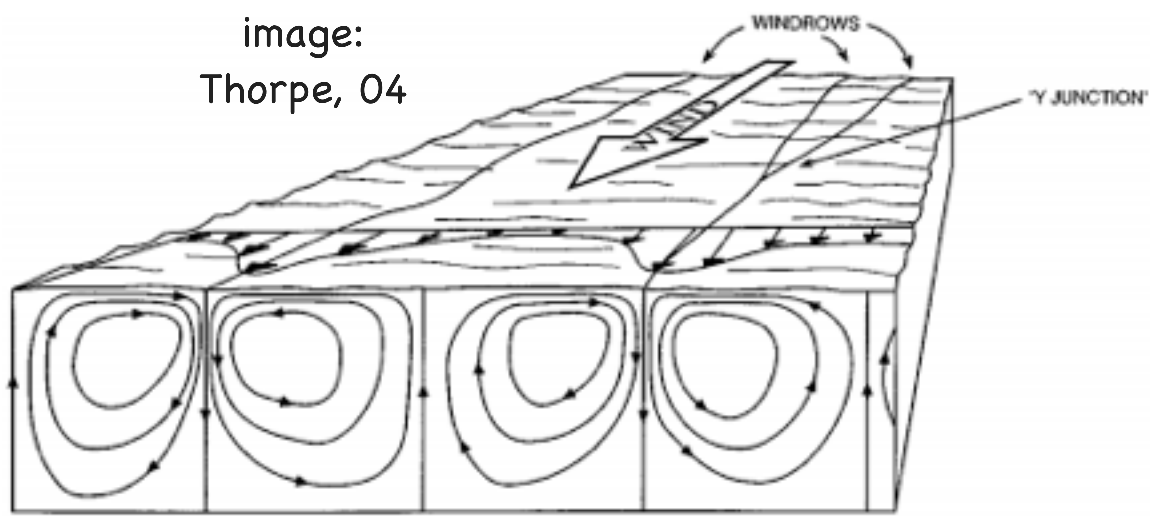


Figure 1 Sketch showing the pattern of mean flow in idealized Langmuir circulation. The windrows may be 2 m to 300 m apart, and the cell form is roughly square (as shown). In practice the flow is turbulent, especially near the water surface, and the windrows (Figure 2) amalgamate and meander in space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

- Near-surface
- Langmuir Cells & Langmuir Turb.
- Ro>>1
- Ri<1: Nonhydro
- 1-100m (H=L)
- 10s to 1hr
- w, u=O(10cm/s)
- Stokes drift
- Eqtns: Craik-Leibovich, Wave-Averaged Equations
- Params: McWilliams & Sullivan, 2000, Van Roekel et al. 2012
- Resolved routinely in 2170

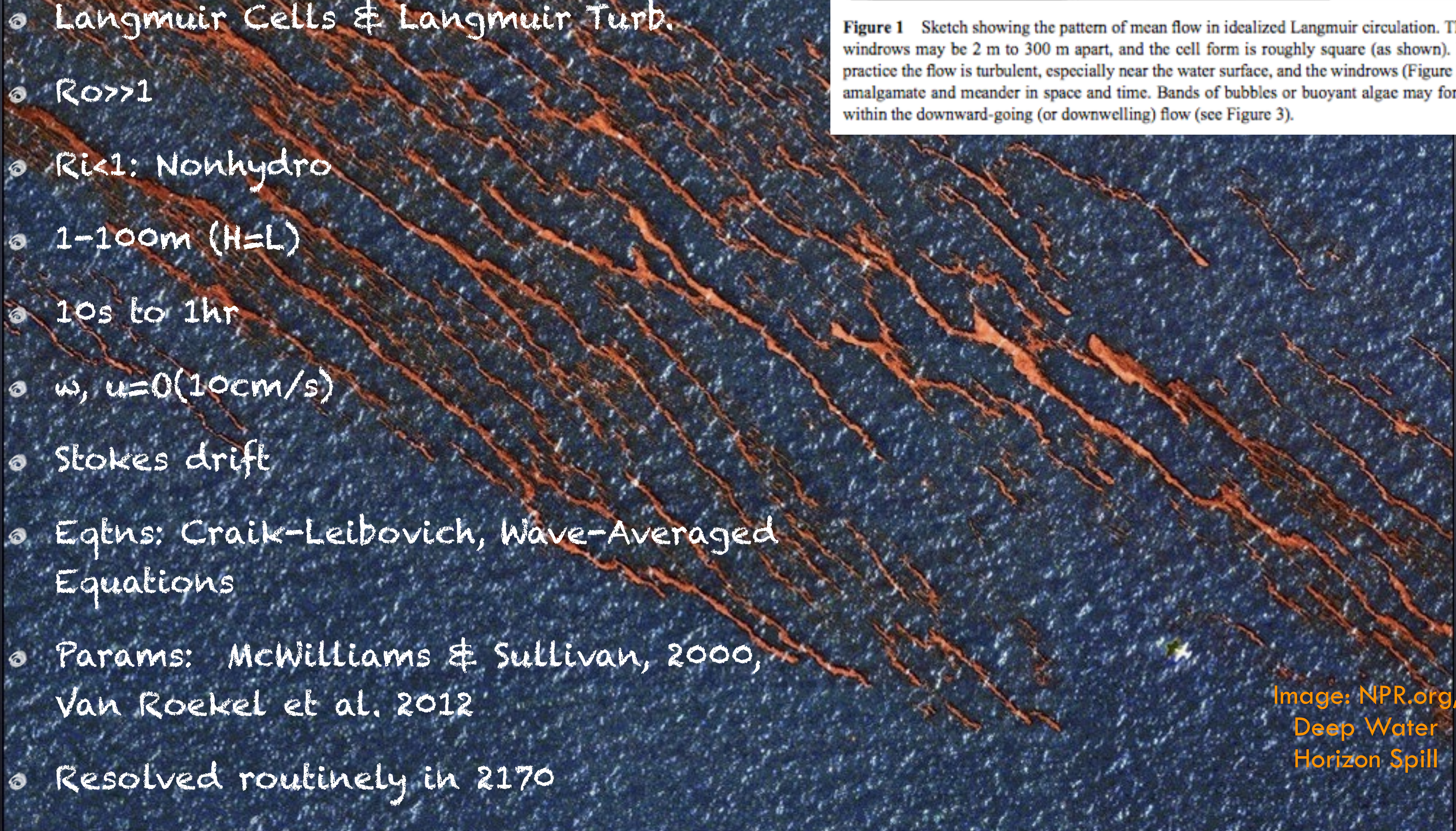


Image: NPR.org, Deep Water Horizon Spill

Wave-Averaged Eqtns:

Stokes Drift Affects Slower Phenomena

- Formally a multiscale asymptotic equation set:
  - 3 classes: Small, Fast; Large, Fast; Large, Slow
  - Solve first 2 types of motion in the case of limited wave steepness, irrotational --> Deep Water Waves!
  - Average over deep water waves in space & time,
  - Arrive at Large, Slow equation set with wave effects

In these equations all Wave Effects involve the Stokes Drift

Turbulent Langmuir # $La_t^2 = \frac{u^*}{u_s}$

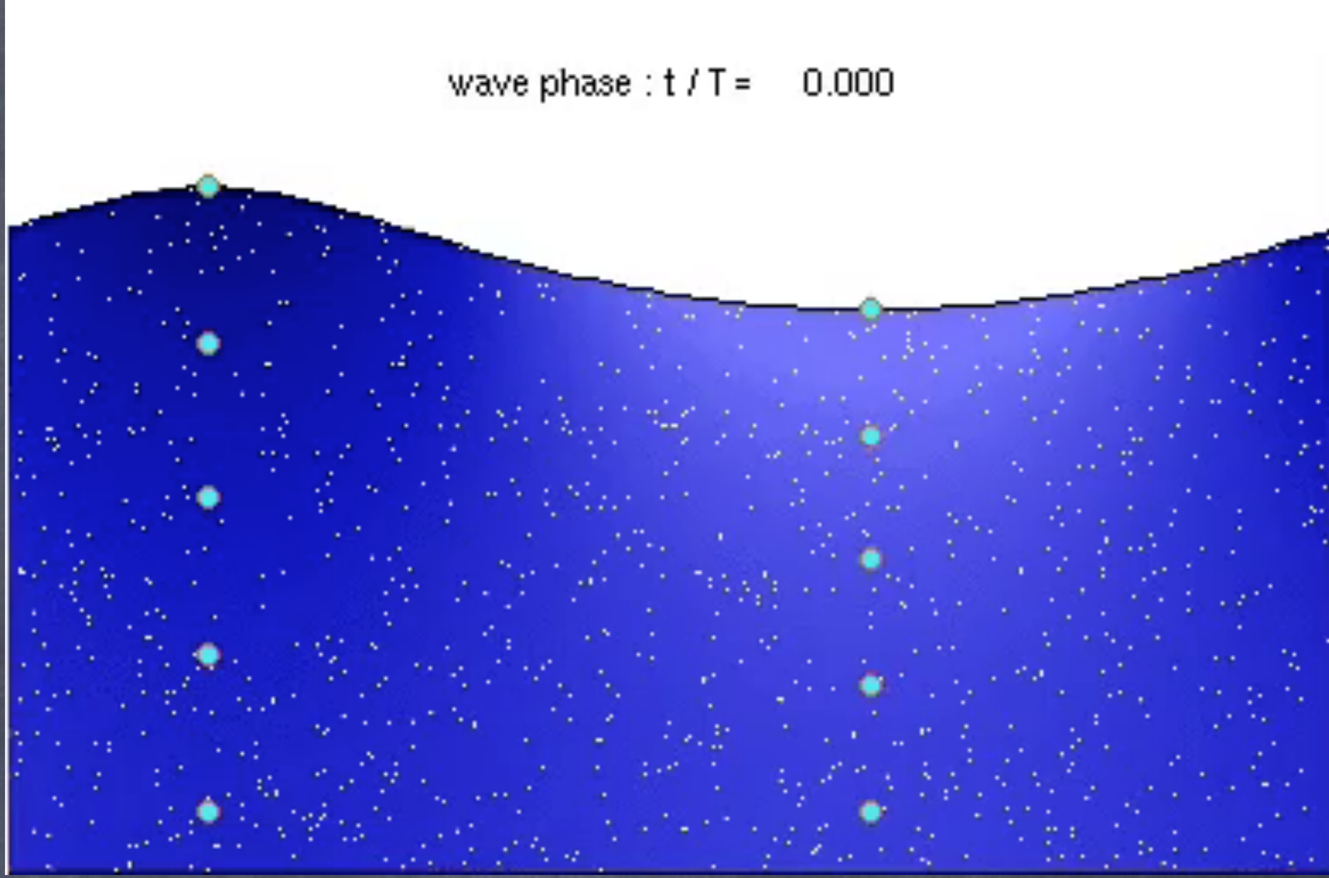
Friction Velocity

$u^* = \sqrt{\tau/\rho}$

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

Waves Provide Stokes Drift

& Stokes Drift drives Langmuir Turbulence



Movie: Creative Commons

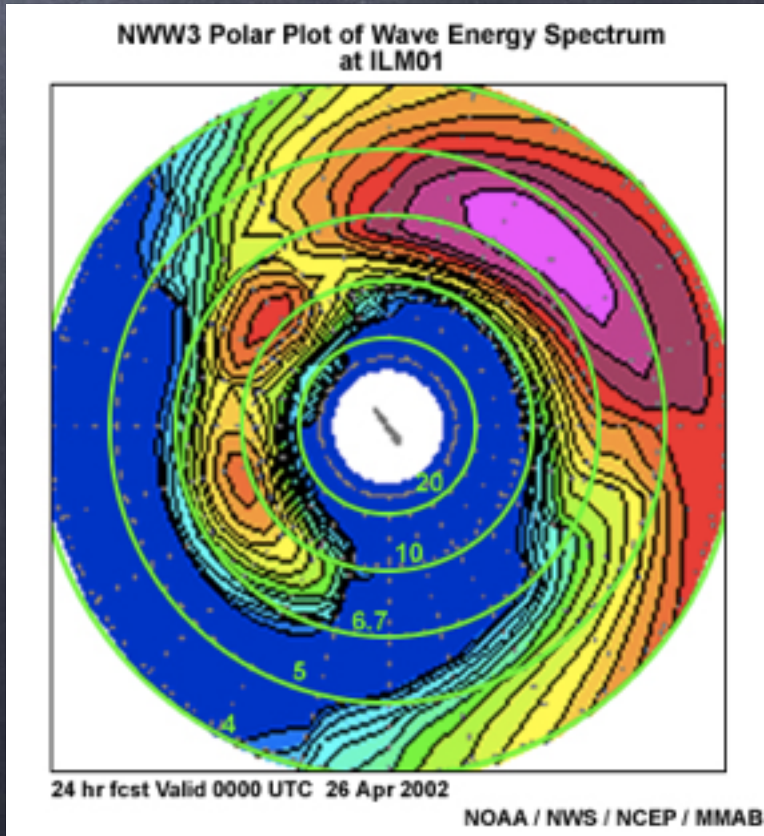
Stokes: Compare the velocity of wave trajectories vs. Eulerian velocity; leading difference=Stokes:

Monochromatic:

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

Wave Spectrum:

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



Turbulent Langmuir #

$$La_t^2 = \frac{u^*}{u_s}$$

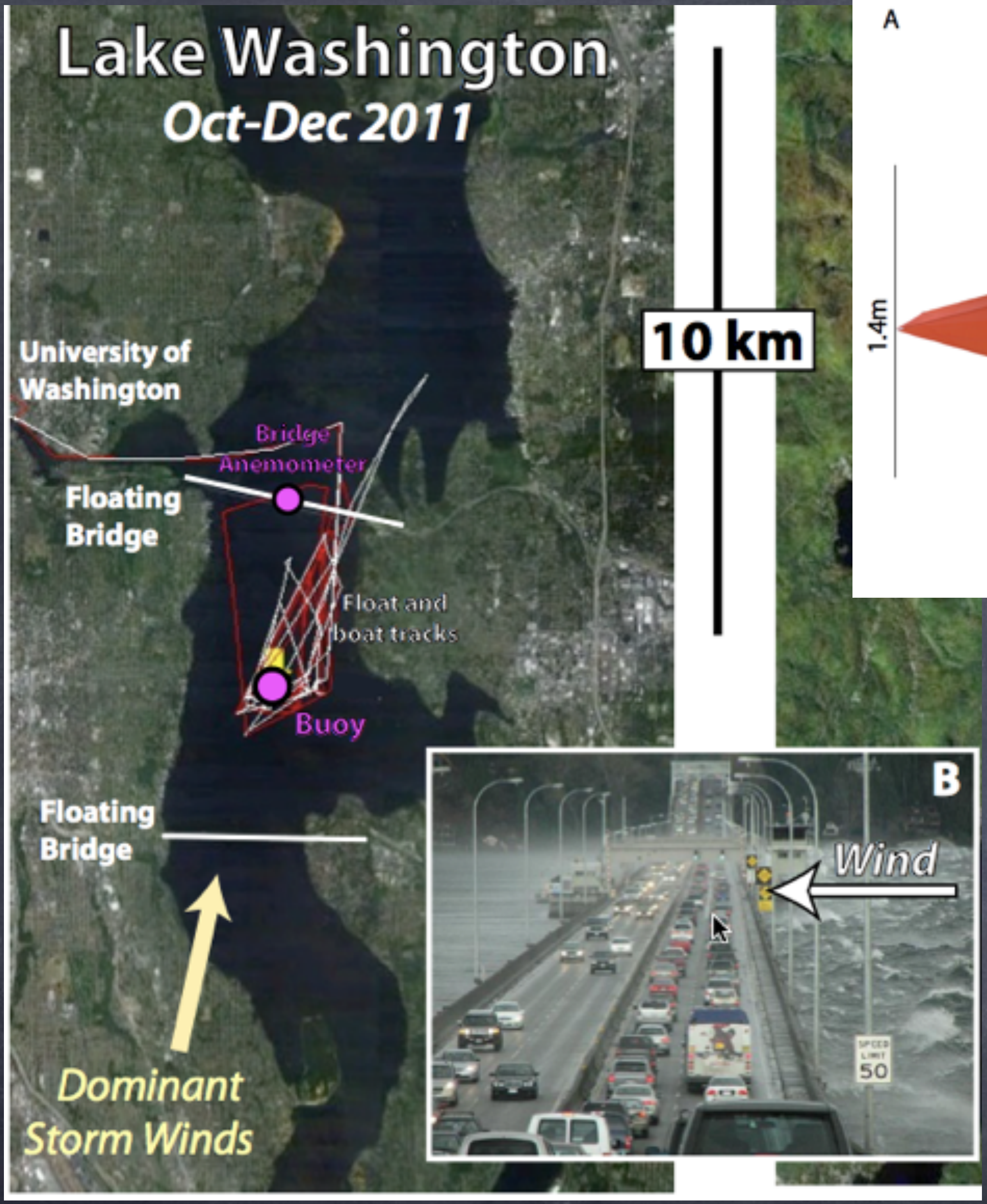
A. Webb and BFK. Wave spectral moments and Stokes drift estimation. Ocean Modelling, 40(3-4):273-288, 2011.

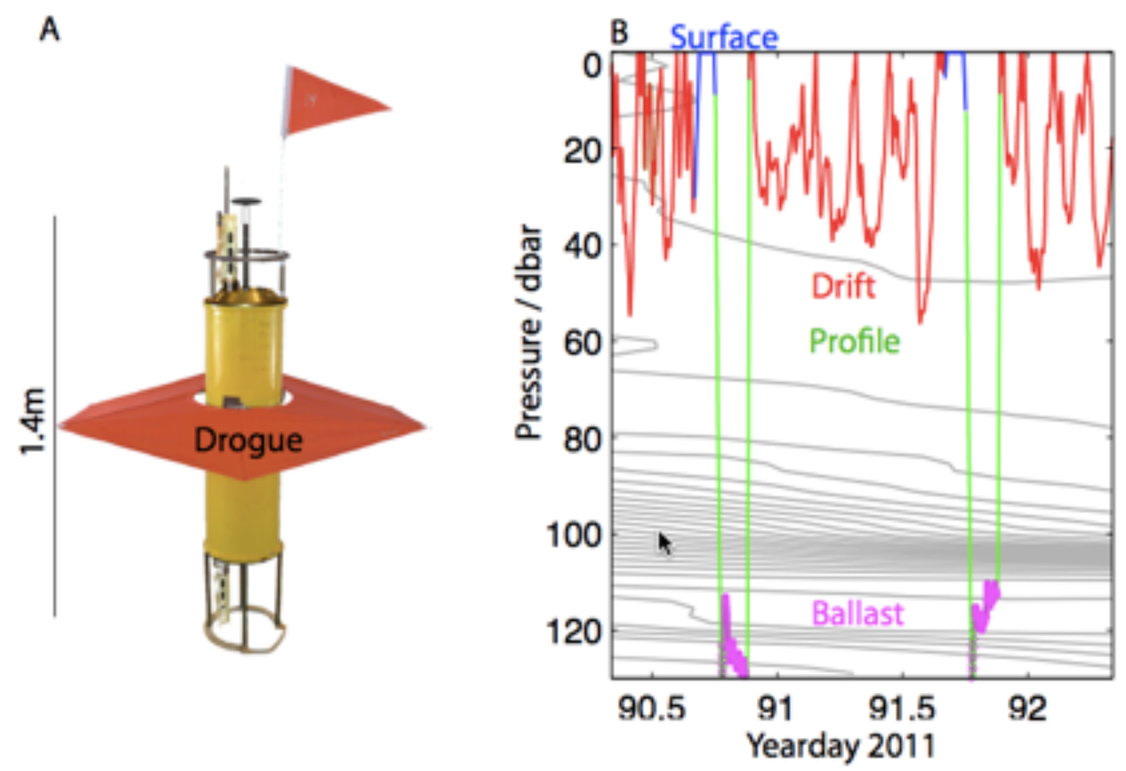
A. Webb and B. Fox-Kemper. Impacts of wave spreading and multidirectional waves on estimating Stokes drift. Ocean Modelling, June 2014. Accepted.

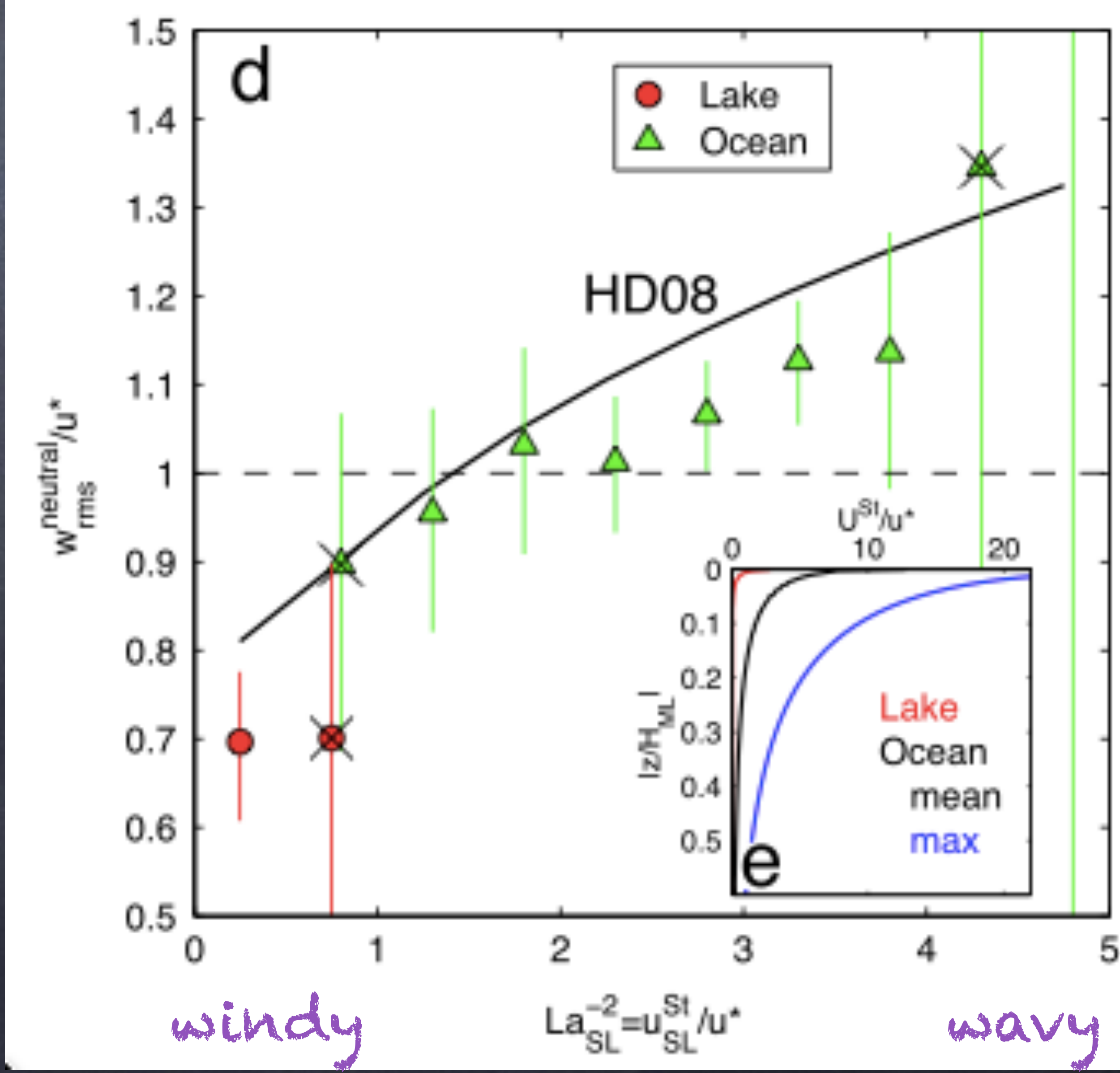
To quantify Langmuir Turb. effects on climate: 3 WAYS

- 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 coefficents from LES







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 $\langle w^2 \rangle$!

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

Langmuir important
✓

- 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

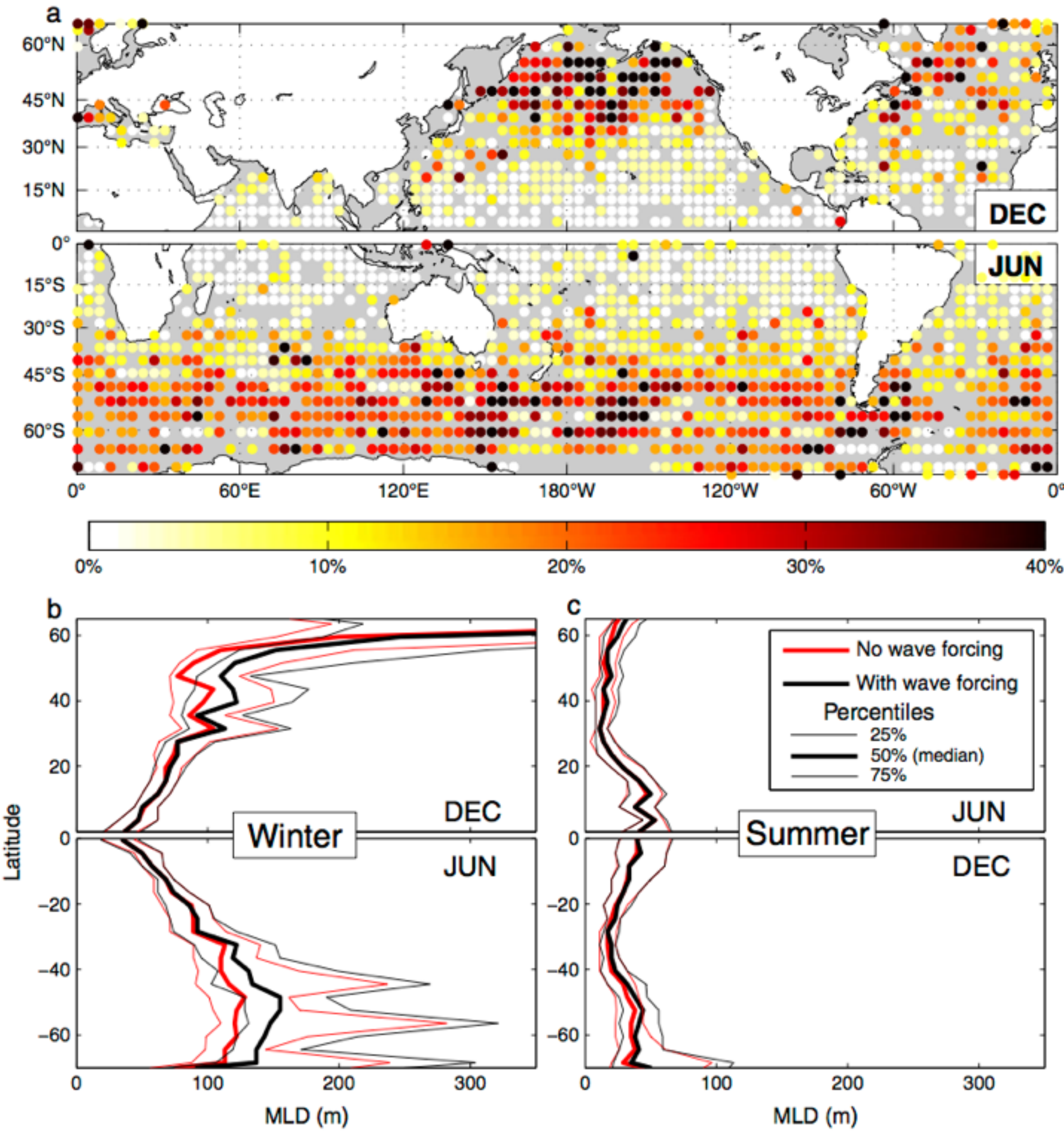
No Retuning! All coefficents from LES

Including Stokes-driven Mixing (Harcourt 2013) Deepens the Winter Mixed Layer about 30%!

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.

Waves can be dominant source of energy for OSBL mixing!

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



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

Langmuir important
✓

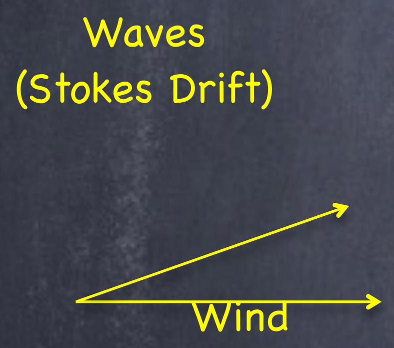
- 2) OFFLINE 1d mixing with waves parameterized, mixing into observed Argo profiles, reanalysis winds, waves, cooling. ROBUST TO MODEL ERRORS

Langmuir important
✓

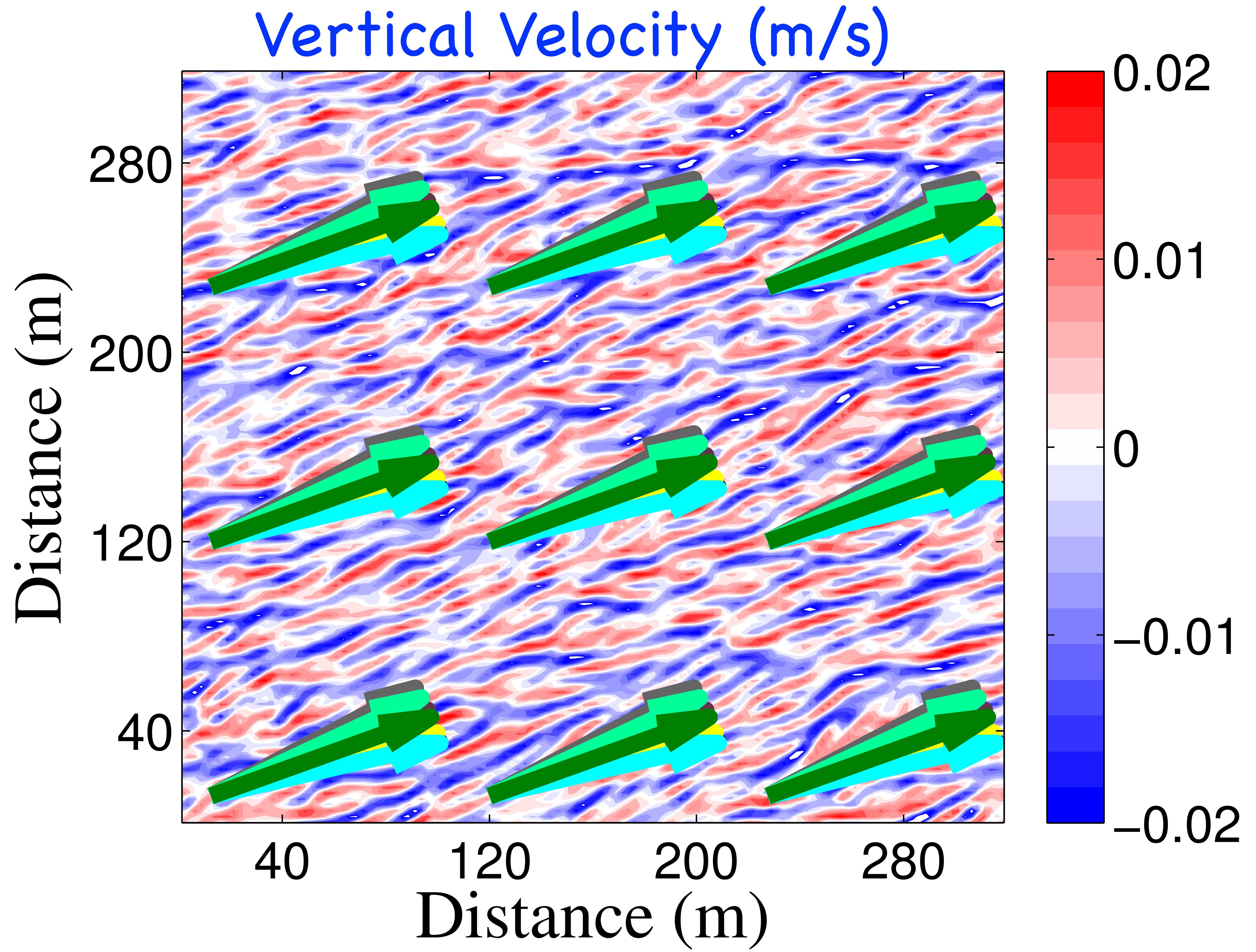
- 3) In a climate model, *add in a wave forecast model as a new component in addition to atmosphere, ocean, ice, etc.*, use this to drive parameterizations of wave mixing in ocean component. FEEDBACKS PRESENT

No Retuning! All coefficents from LES

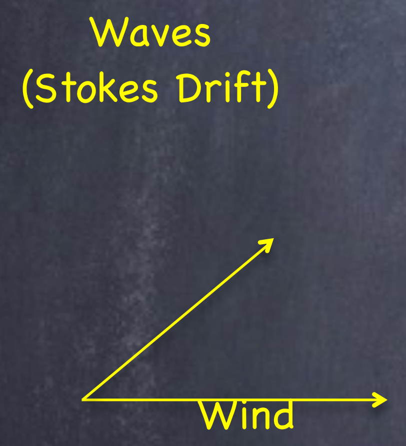
Climate Model Parameterization based on Large Eddy Simulations of Langmuir Turbulence. Tricky: Misaligned Wind & Waves



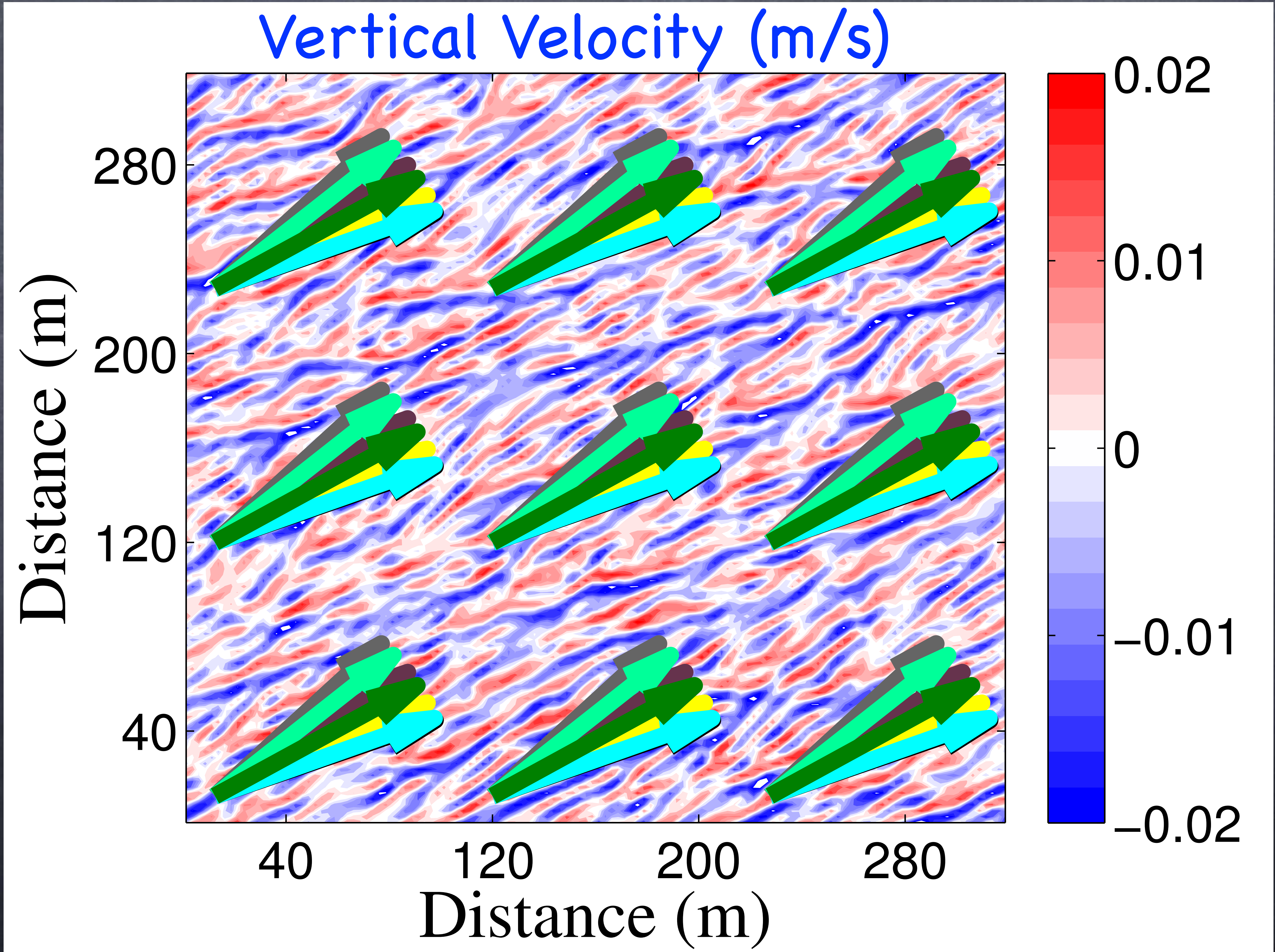
L. P. Van Roekel, B. Fox-Kemper, P. P. Sullivan, P. E. Hamlington, and S. R. Haney. The form and orientation of Langmuir cells for misaligned winds and waves. Journal of Geophysical Research-Oceans, 117:C05001, 22pp, May 2012.



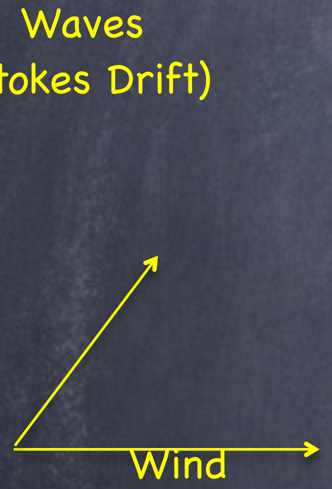
Tricky: Misaligned Wind & Waves



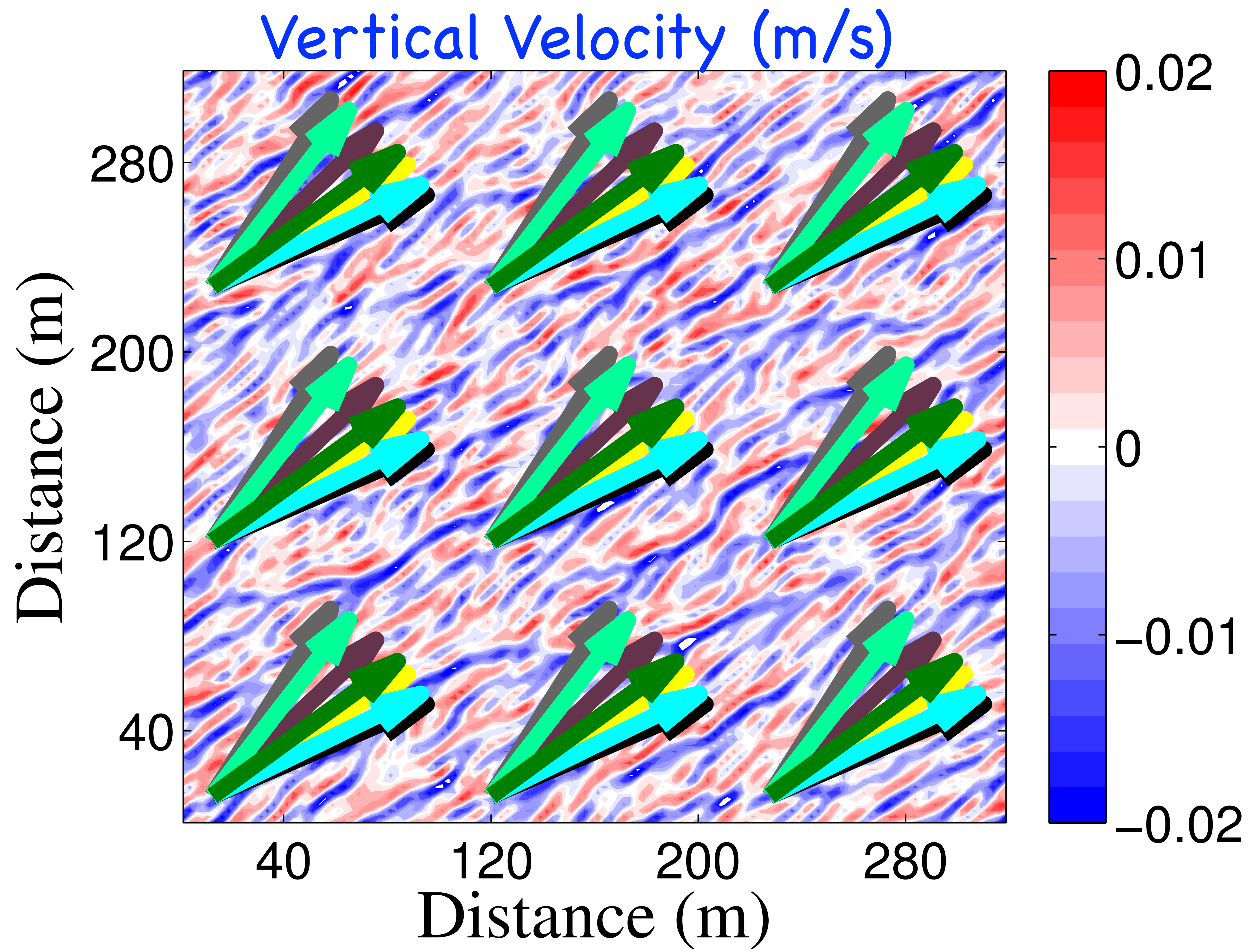
L. P. Van Roekel, B. Fox-Kemper, P. P. Sullivan, P. E. Hamlington, and S. R. Haney. The form and orientation of Langmuir cells for misaligned winds and waves. Journal of Geophysical Research-Oceans, 117:C05001, 22pp, May 2012.



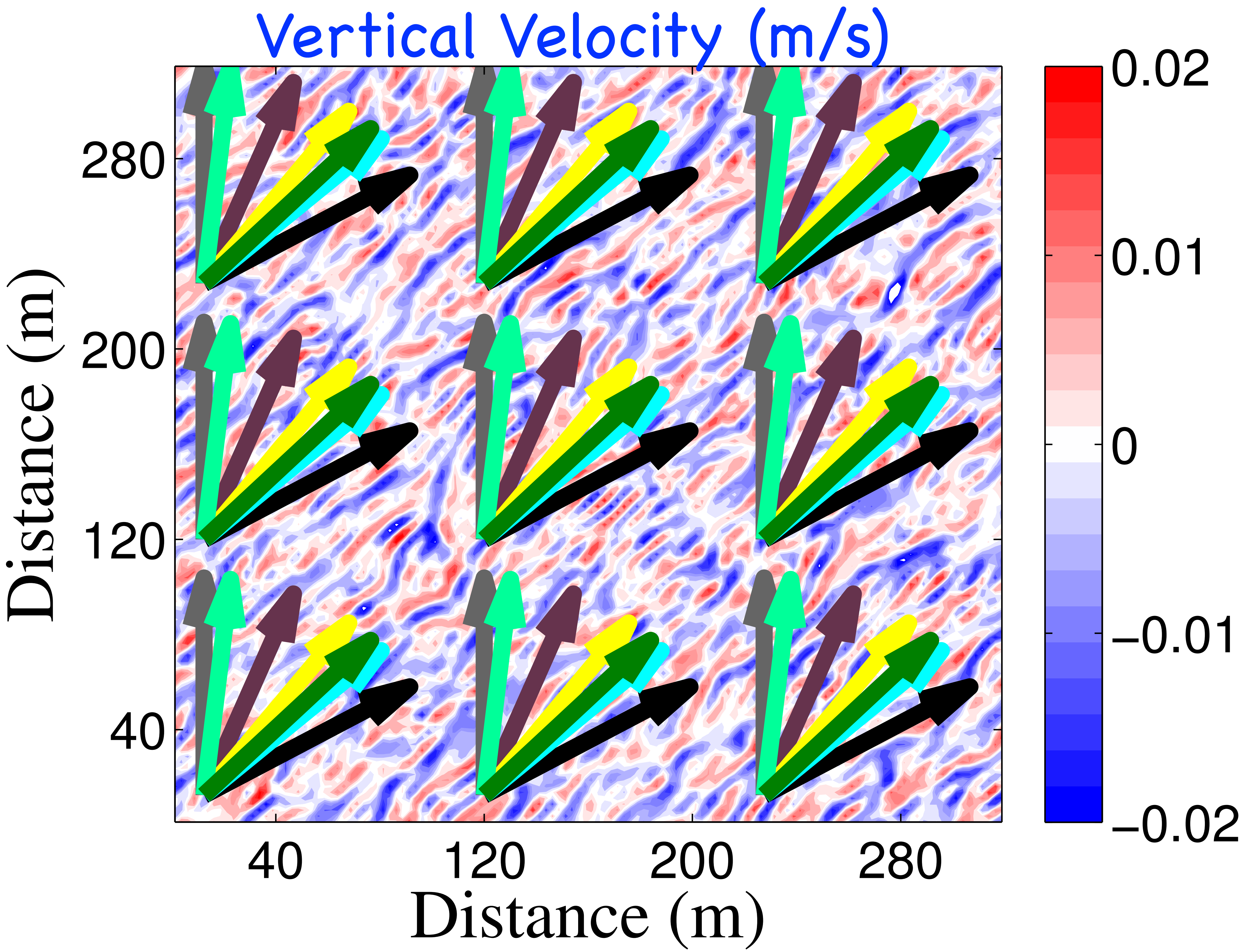
Tricky: Misaligned Wind & Waves



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



Tricky: Misaligned Wind & Waves

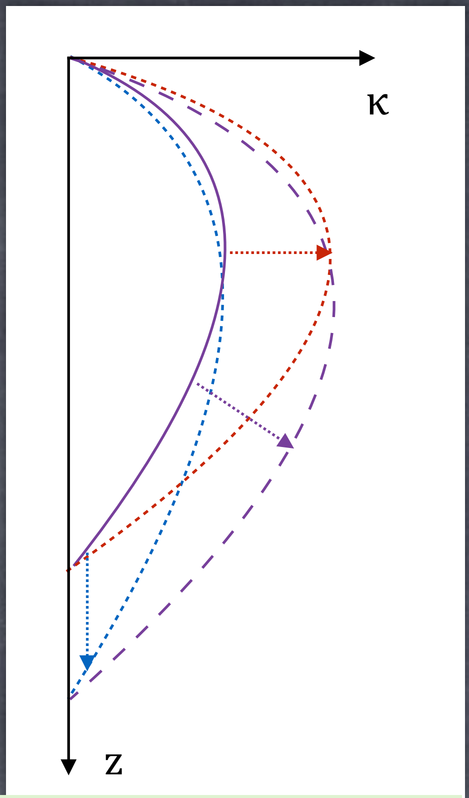


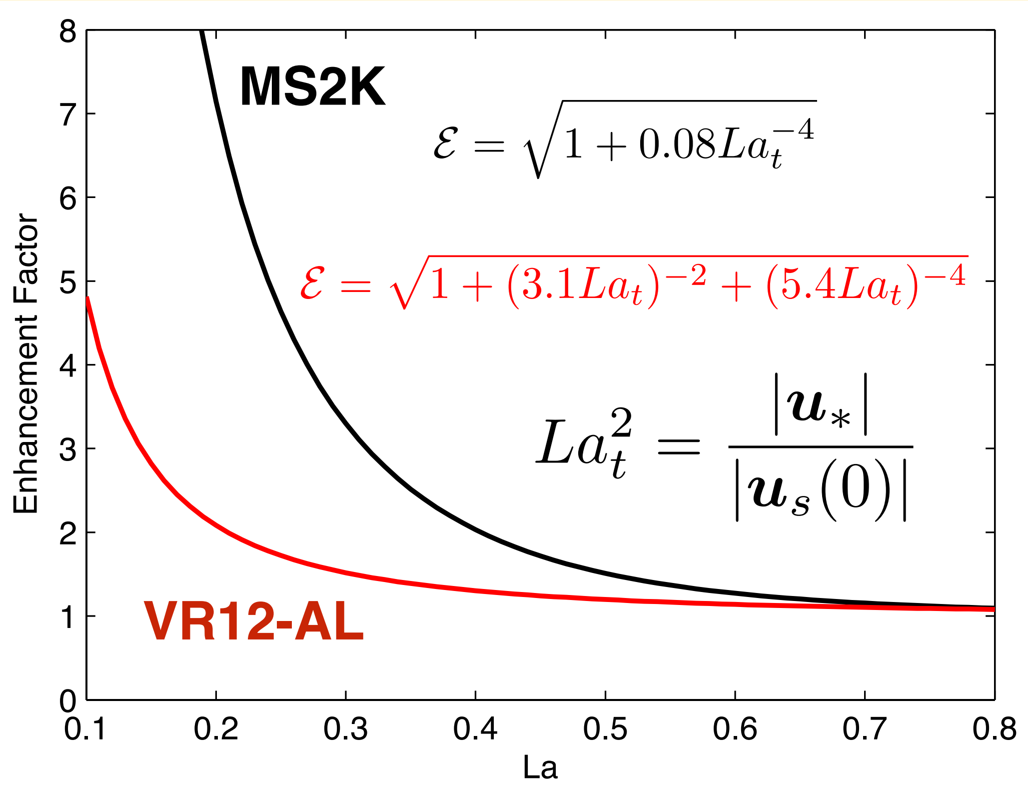
L. P. Van Roekel, B. Fox-Kemper, P. P. Sullivan, P. E. Hamlington, and S. R. Haney. The form and orientation of Langmuir cells for misaligned winds and waves. Journal of Geophysical Research-Oceans, 117:C05001, 22pp, May 2012.

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. Submitted.

- WaveWatch-III (Stokes drift) <-> POP2 (U, T, H_{BL})
- CORE2 interannual forcing (Large and Yeager,2009), or fully coupled climate
- 4 IAF cycles; average over last 50 years for climatology (over 200 years total)

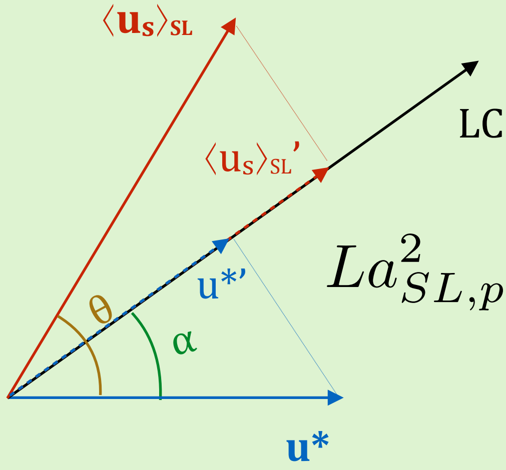




Revise Enhancement factor to vertical velocity scale W

1) Assume aligned wind and waves

VR12-MA



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

Account for 2) Misaligned wind and waves

VR12-EN

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

Entrain by also Including Stokes shear in mixing depth

McWilliams and Sullivan, 2000; 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.

Wave Mixing in CESM: Reduces MLD Errors

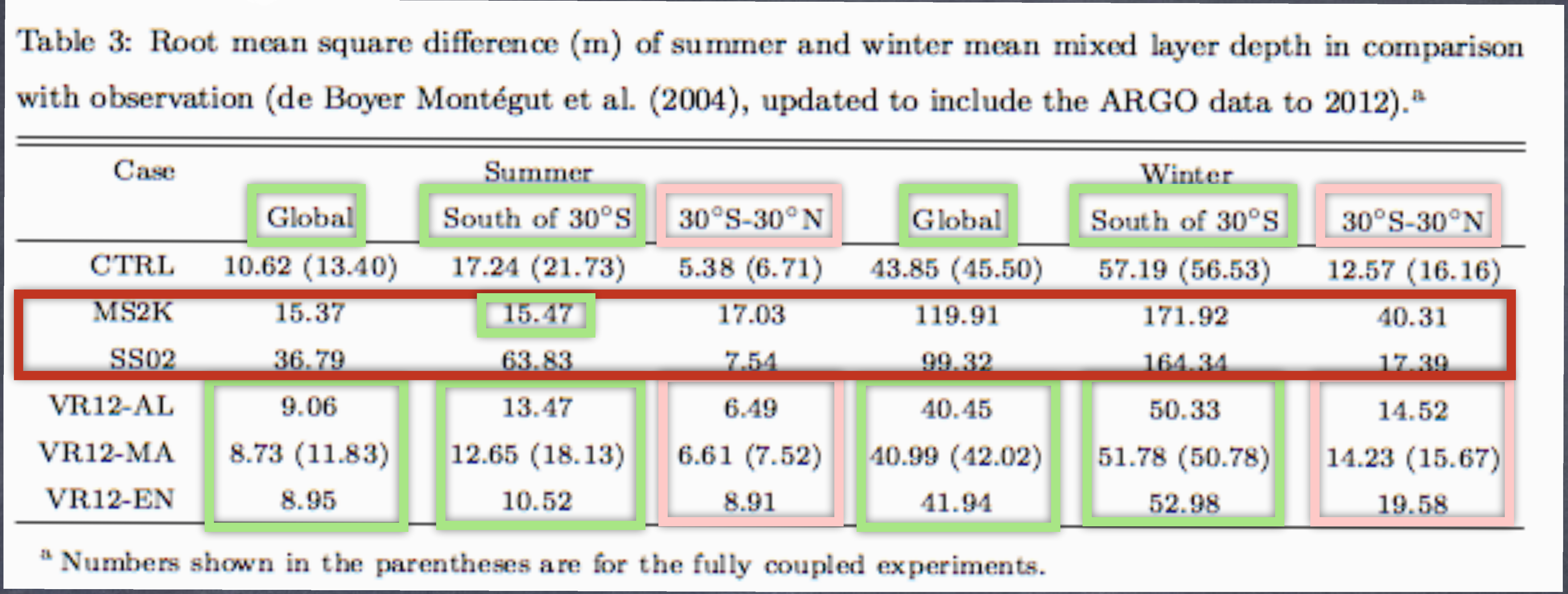


Table 3: Root mean square difference (m) of summer and winter mean mixed layer depth in comparison with observation (de Boyer Montégut et al. (2004), updated to include the ARGO data to 2012).[a]

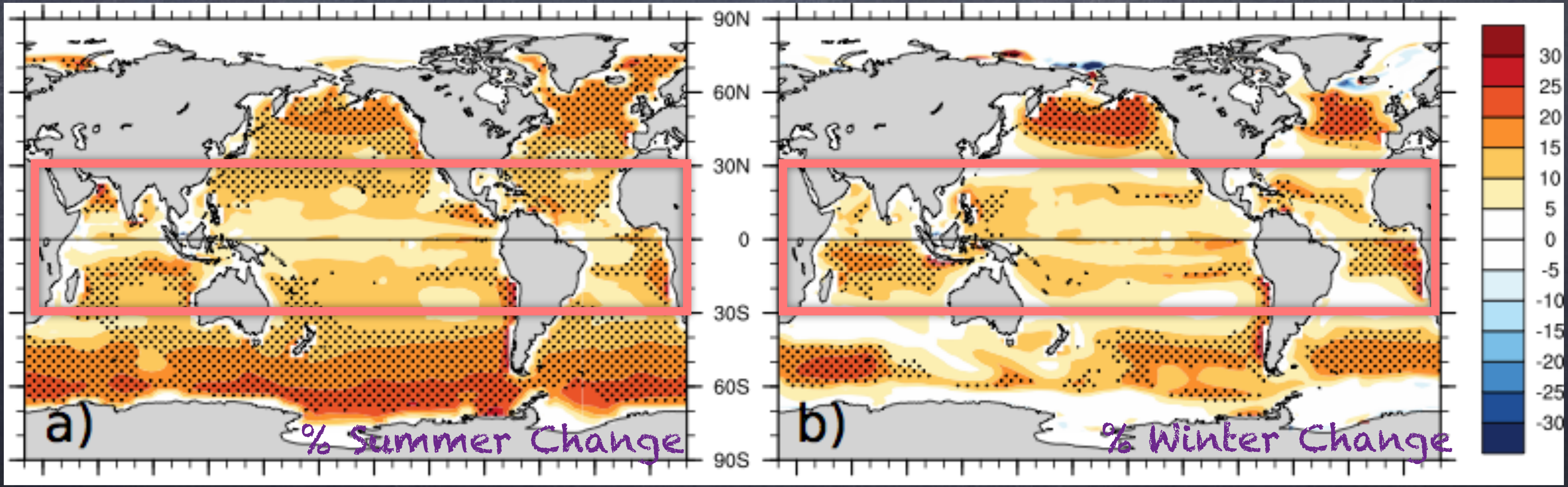
Case	Summer			Winter		
	Global	South of 30°S	30°S-30°N	Global	South of 30°S	30°S-30°N
CTRL	10.62 (13.40)	17.24 (21.73)	5.38 (6.71)	43.85 (45.50)	57.19 (56.53)	12.57 (16.16)
MS2K	15.37	15.47	17.03	119.91	171.92	40.31
SS02	36.79	63.83	7.54	99.32	164.34	17.39
VR12-AL	9.06	13.47	6.49	40.45	50.33	14.52
VR12-MA	8.73 (11.83)	12.65 (18.13)	6.61 (7.52)	40.99 (42.02)	51.78 (50.78)	14.23 (15.67)
VR12-EN	8.95	10.52	8.91	41.94	52.98	19.58

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

Control

Competition

3 versions of
Van Roekel
et al

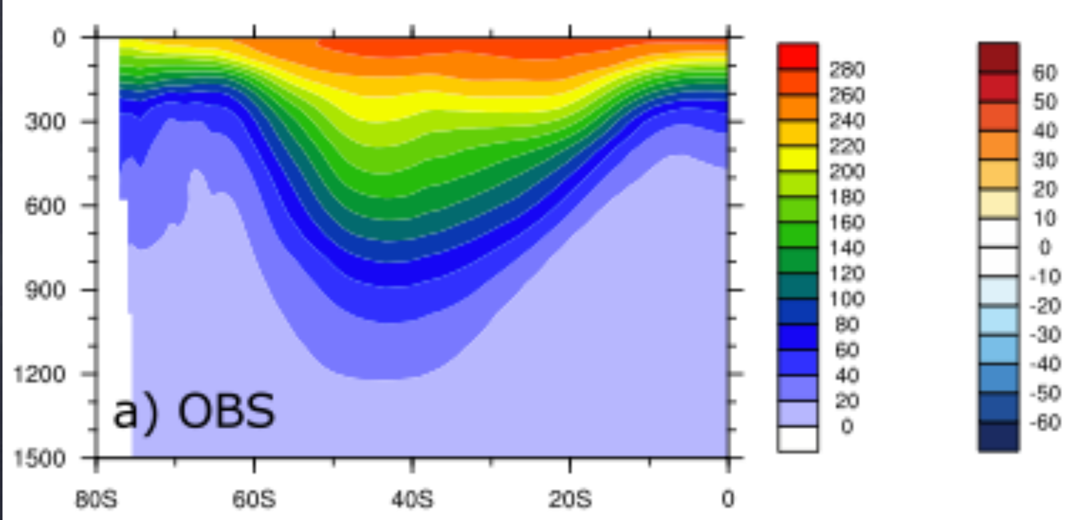


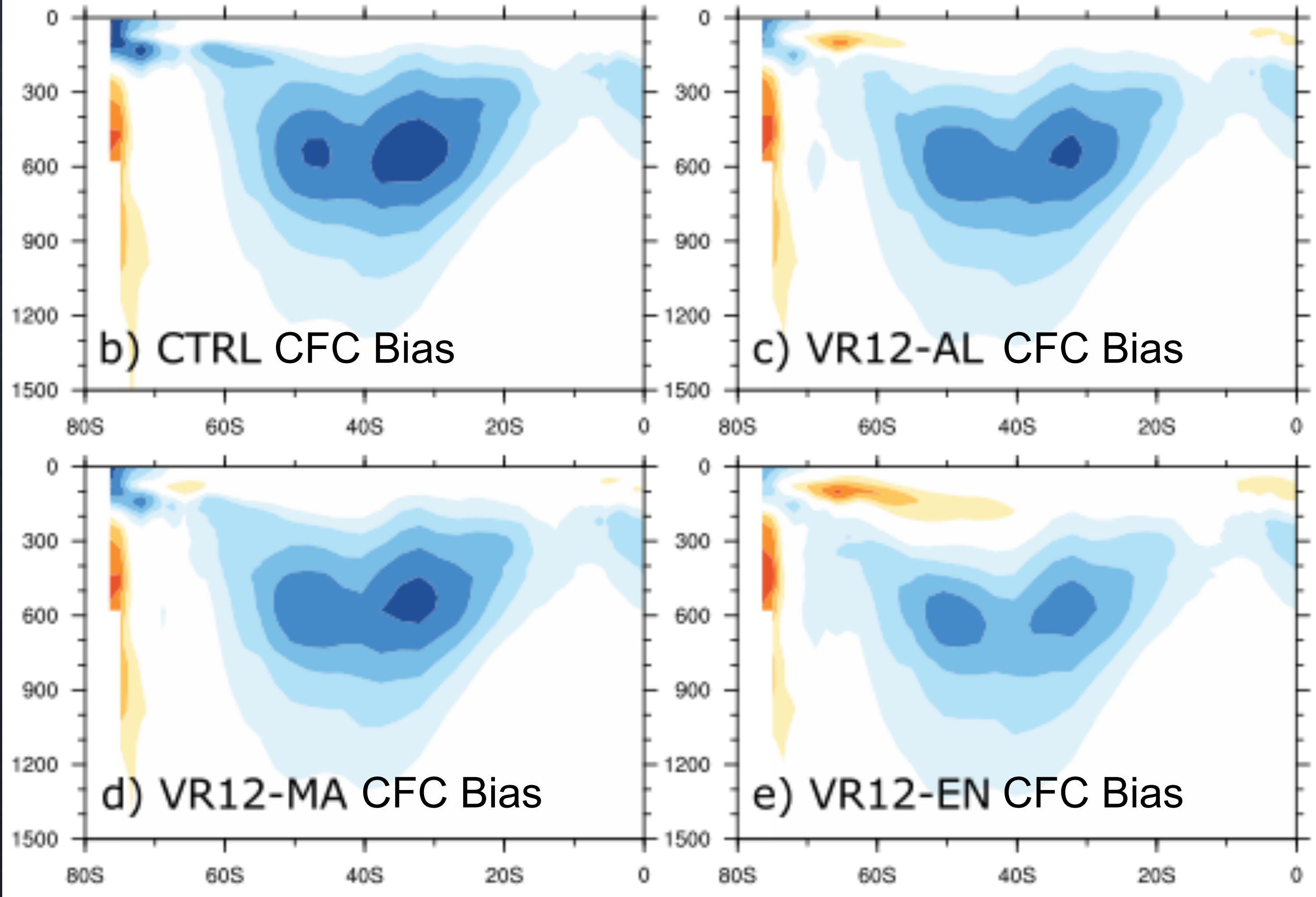
dotted
when
statistically
significant

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, 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.

Despite MLD bias increase in near Equator—better ventilation and subsurface effects when Langmuir is included, even near Equator!



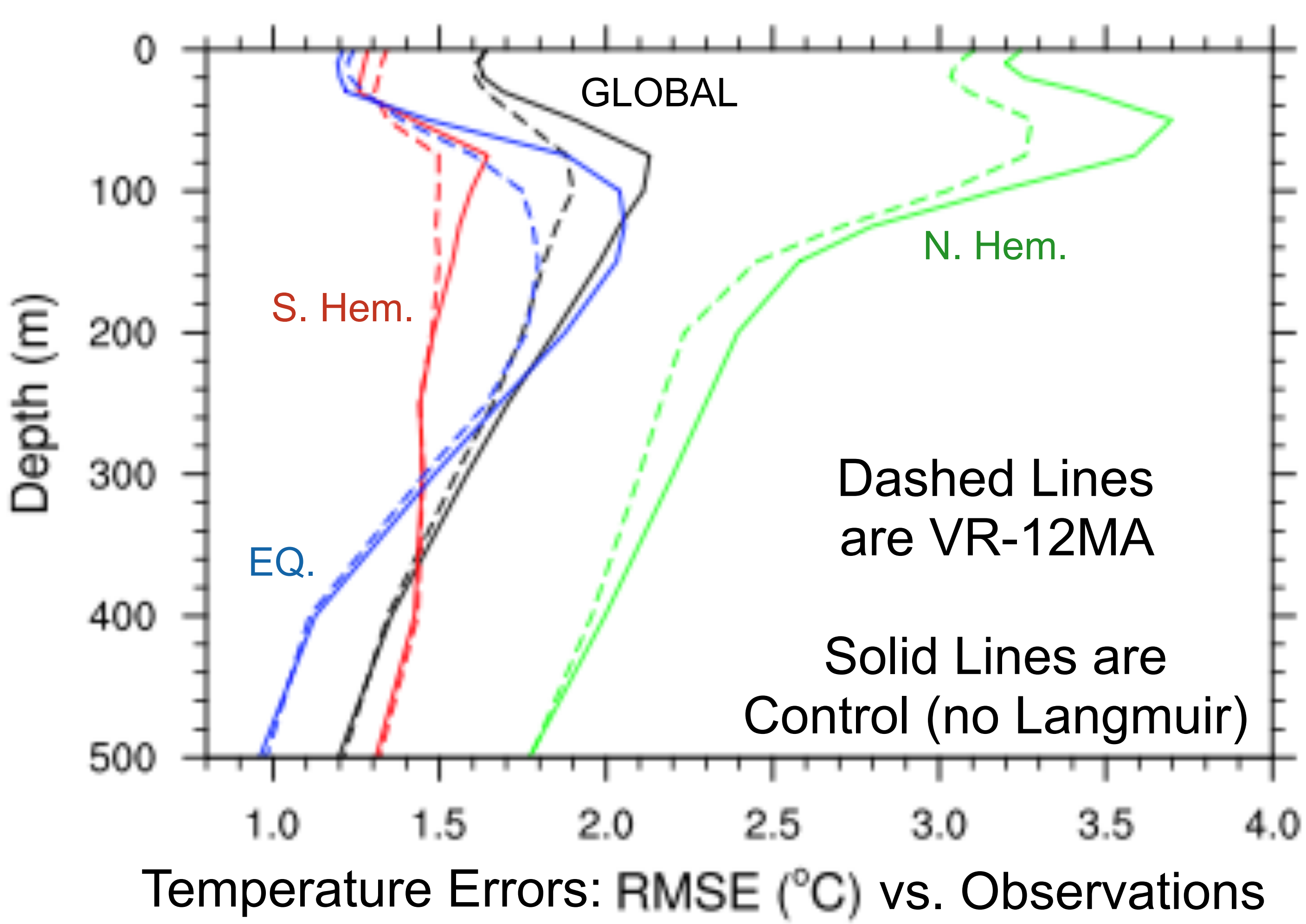


b) CTRL CFC Bias

c) VR12-AL CFC Bias

d) VR12-MA CFC Bias

e) VR12-EN CFC Bias



Temperature Errors: RMSE (°C) vs. Observations

Wave Mixing in CESM Improves Subsurface Properties & Stommel's Demon!

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.

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 ✓

- 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 coefficents from LES

Something Else?

- Including submesoscale restratification in climate models improves the boundary layer. ✓
- Including wave-driven (Langmuir) mixing in climate models improves the boundary layer. ✓
- But, fundamental physics remains!
  - What if these are combined? What interactions?
  - How do Stokes effects change submesoscale?
    - Fronts? Geostrophic Instabilities? Symmetric Instabilities?

Dimensionless Boussinesq Eqtns.

Spanning Global to Stratified Turbulence

following McWilliams (85)

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

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

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

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

Plus boundary conditions

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

$$M_{Ro} \equiv \max(1, Ro) \quad v = \text{horiz. vel.} \quad w = \text{vert. vel.}$$

Wave-Averaged Equations

following Lane et al. (07), McWilliams & F-K (13)
and Suzuki & F-K (15)

(for horizontally uniform Stokes drift)

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

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

Lagrangian geostrophic!

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

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

nonhydrostatic!

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

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

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.

LES of Langmuir-Submeso Interactions?

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

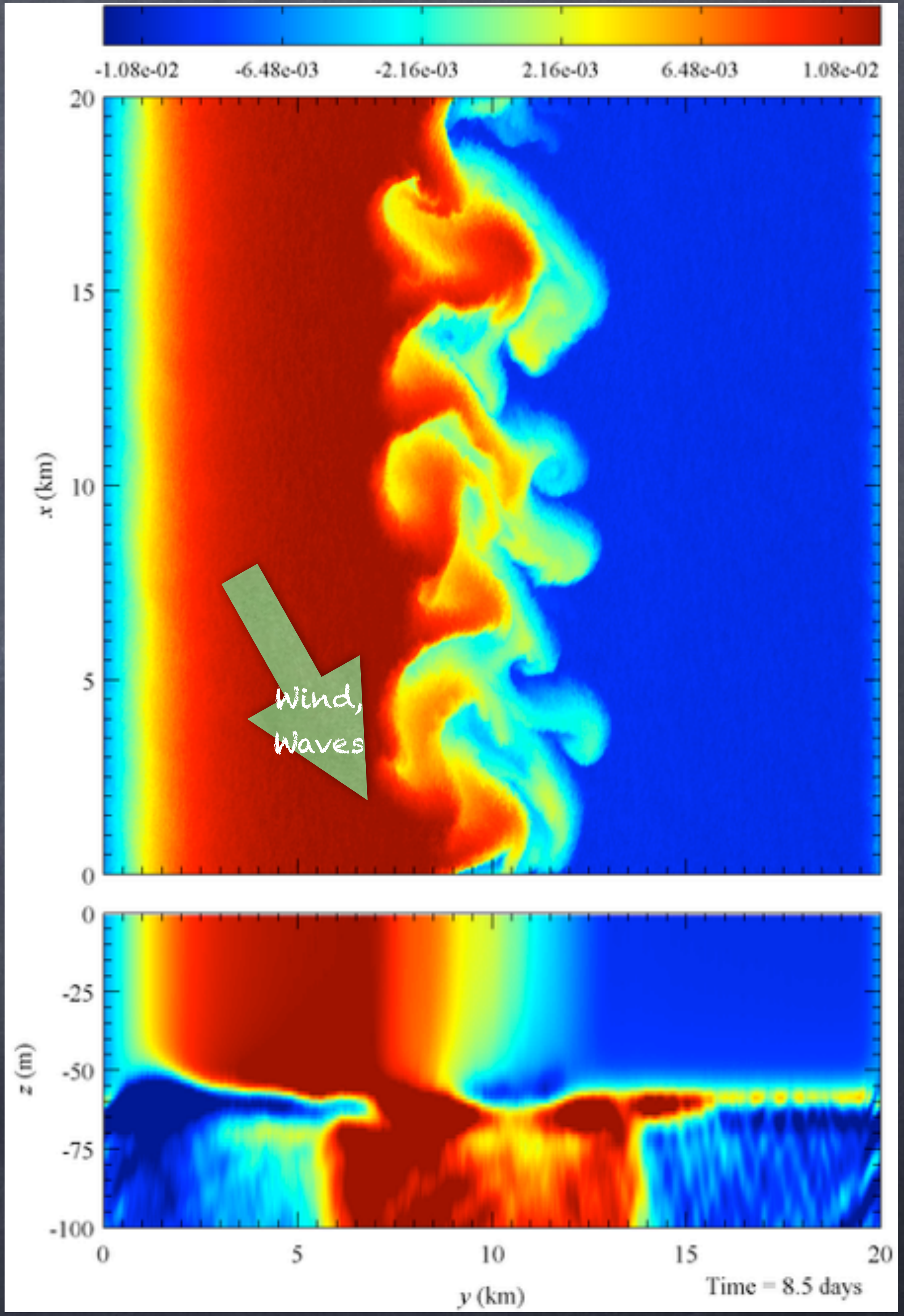
Computational parameters:

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

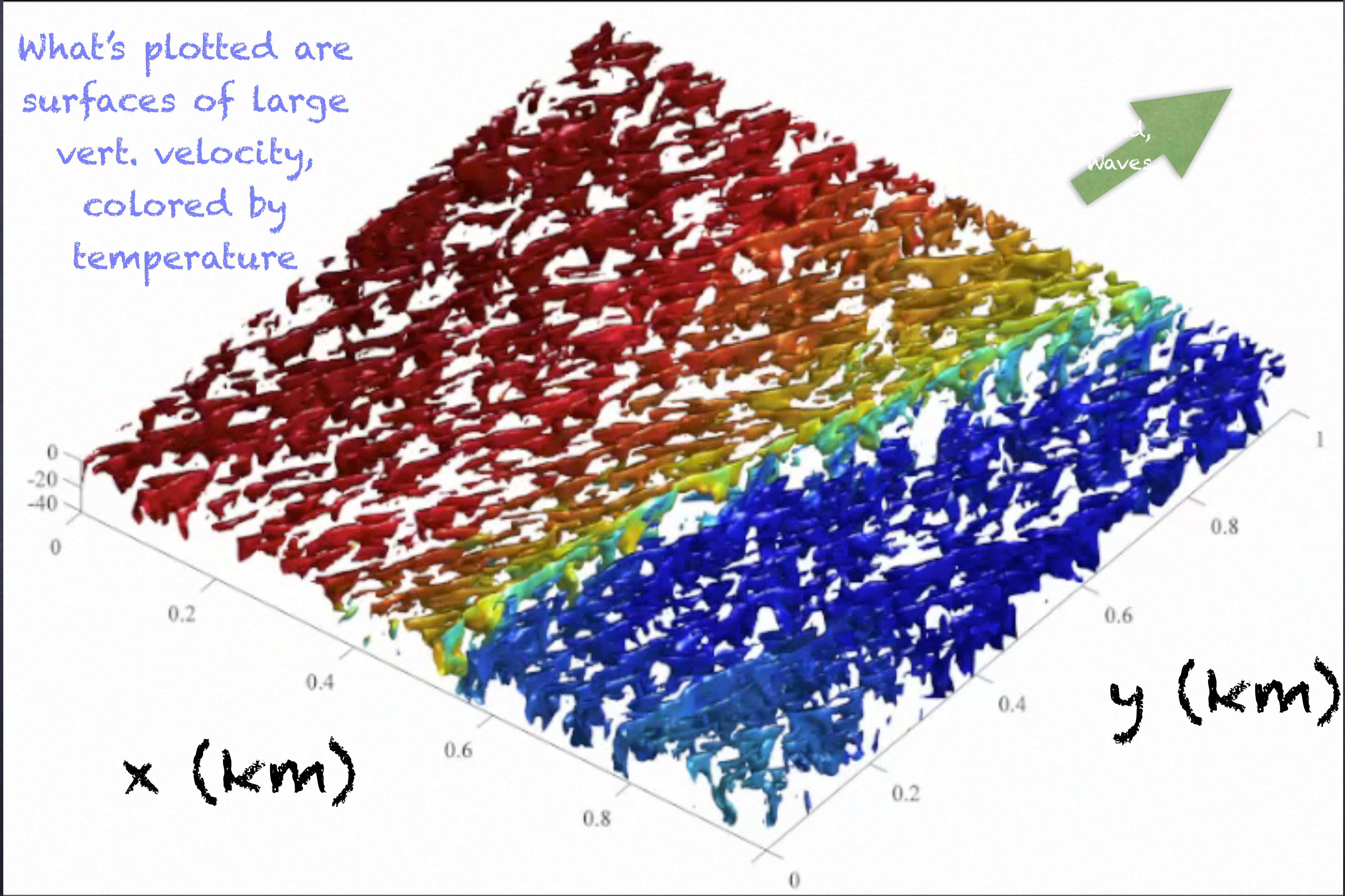
Grid points: 4096 x 4096 x 128

Resolution: 5m x 5m x -1.25m

Movie: P. Hamlington



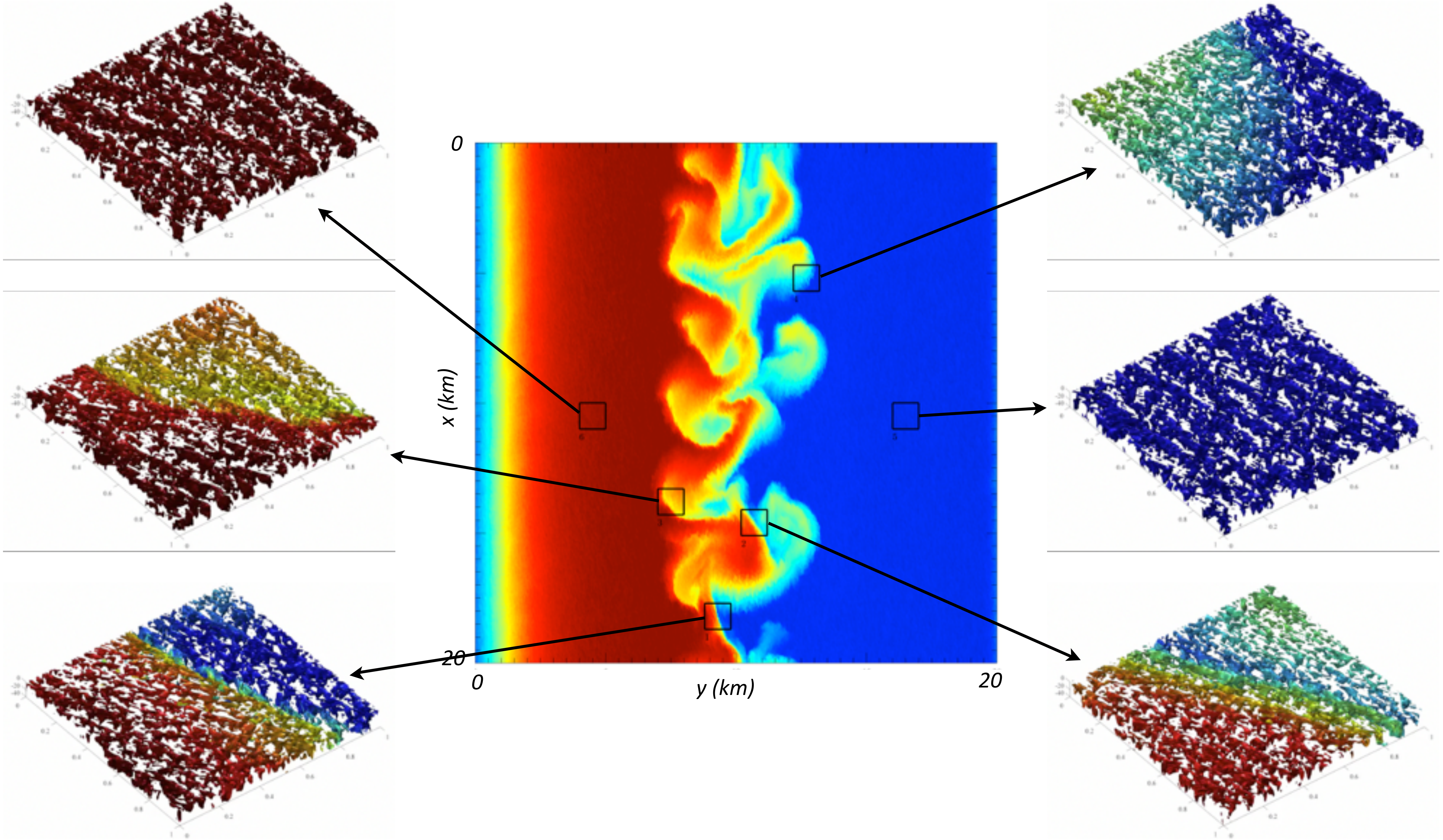
P. E. Hamlington, L. P. Van Roekel, BFK, K. Julien, and G. P. Chini. Langmuir-submesoscale interactions: Descriptive analysis of multiscale fro down simulations. Journal of Physical Oceanography, 44(9):2249-2272, September 2014.



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 fro
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 are some direct effects of waves on larger scales?

Thermal Wind Balance

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

Becomes Lagrangian Thermal Wind Balance

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

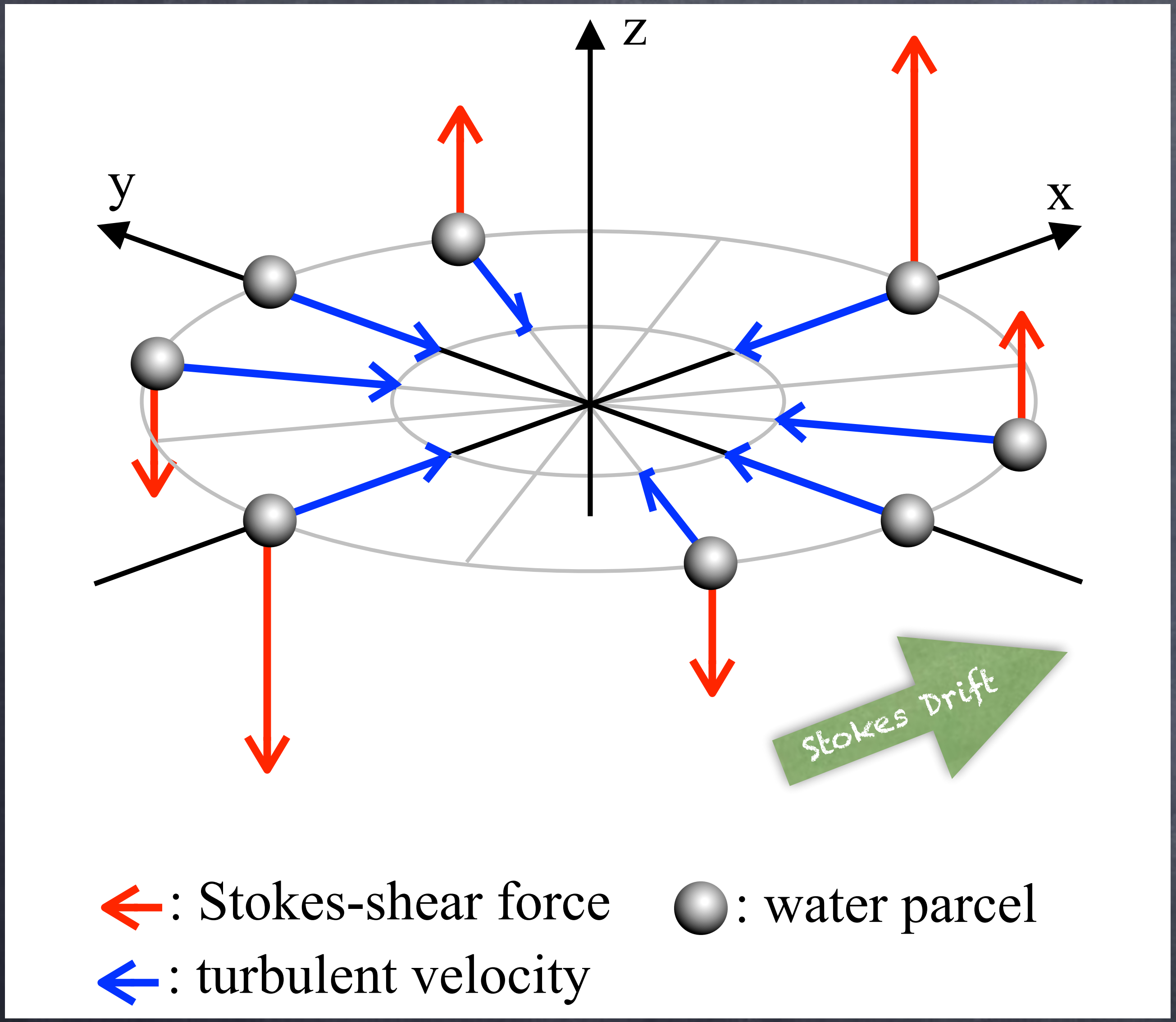
Now the temperature gradients govern the Lagrangian flow, not the not the Eulerian!

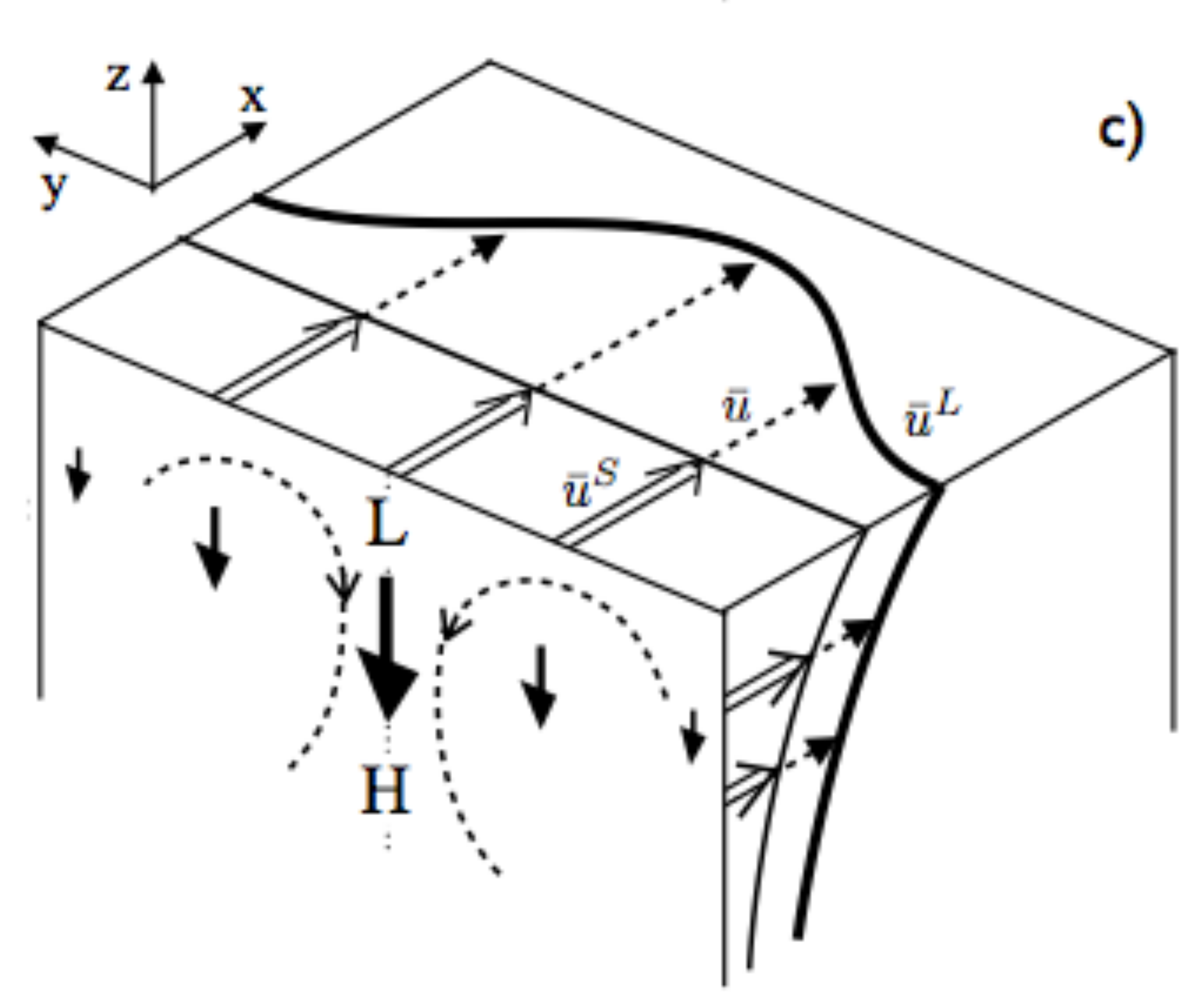
J. C. McWilliams and B. F-K. Oceanic wave-balanced surface fronts and filaments. Journal of Fluid Mechanics, 730:464-490, 2013.

Stokes Shear Force:

Mechanism for Langmuir circulations & Stokes effects on fronts!

Flow directed along Stokes shear = downward force





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

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

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)

(for horizontally uniform Stokes drift)

Lagrangian geostrophic!

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

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

nonhydrostatic!

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

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

Plus boundary conditions

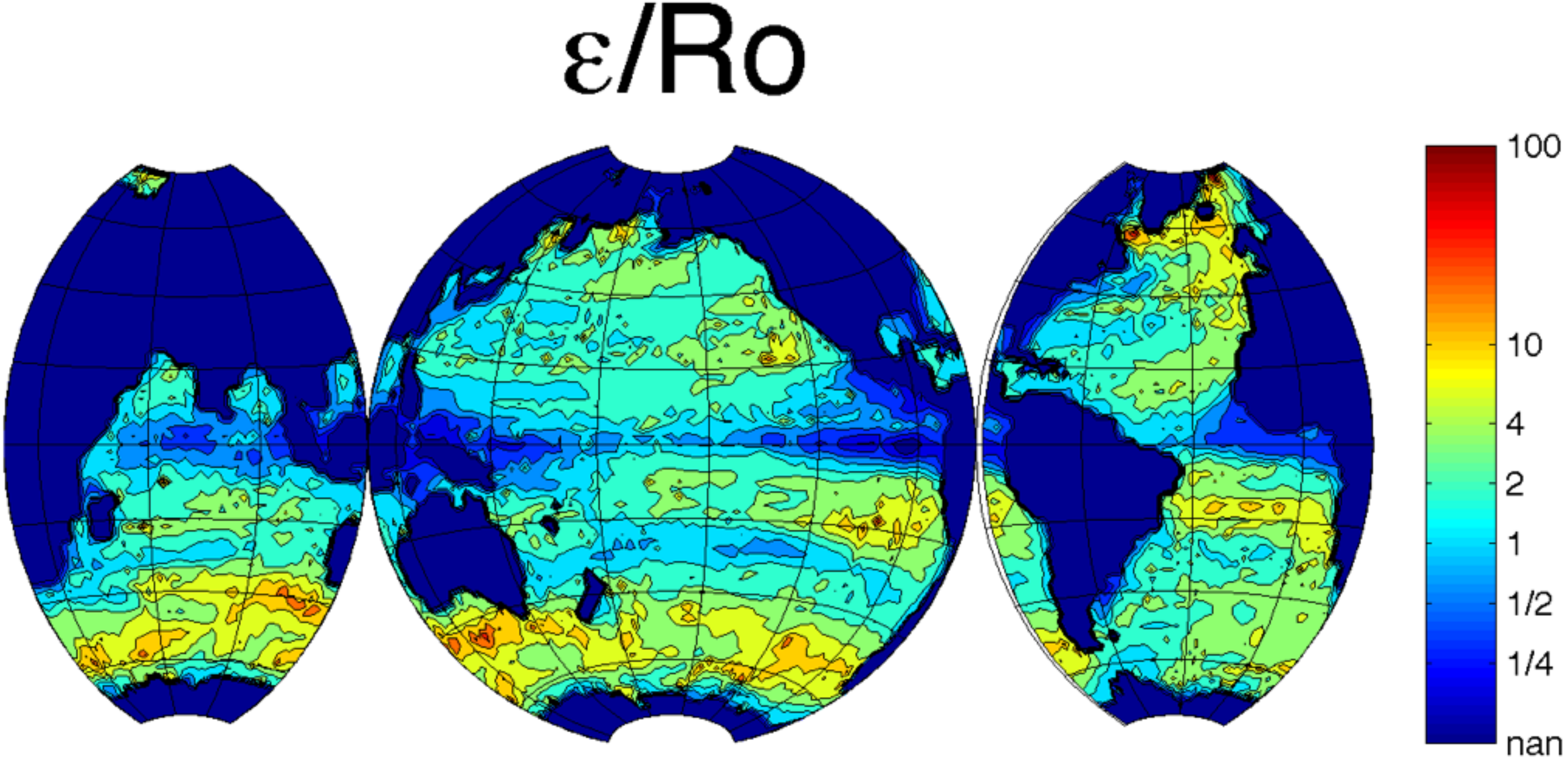
LAGRANGIAN (Eulerian+Stokes) advection & Coriolis

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 directly affects the (sub)mesoscale!!



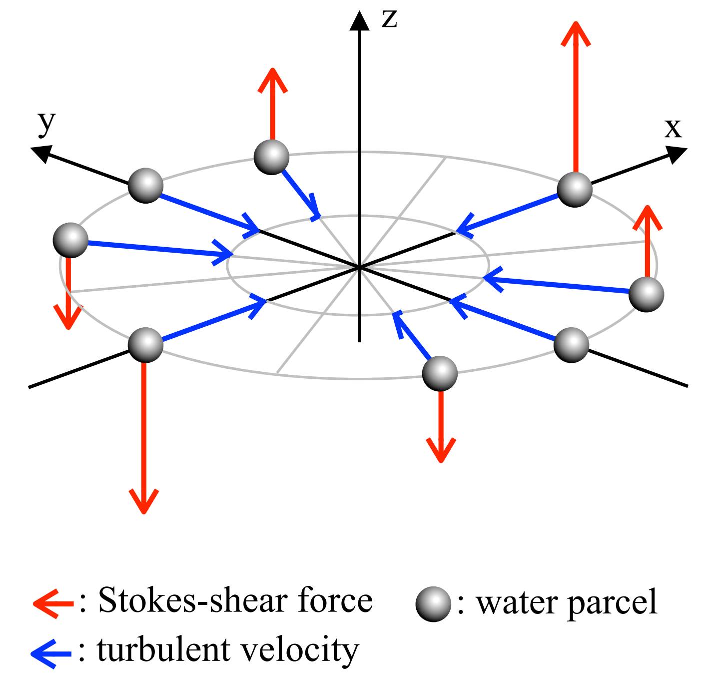
$$\frac{\varepsilon}{Ro} = \frac{V_s}{fL}\frac{H}{H_s}\frac{fL}{V} = \frac{V_s}{V}\frac{H}{H_s}$$

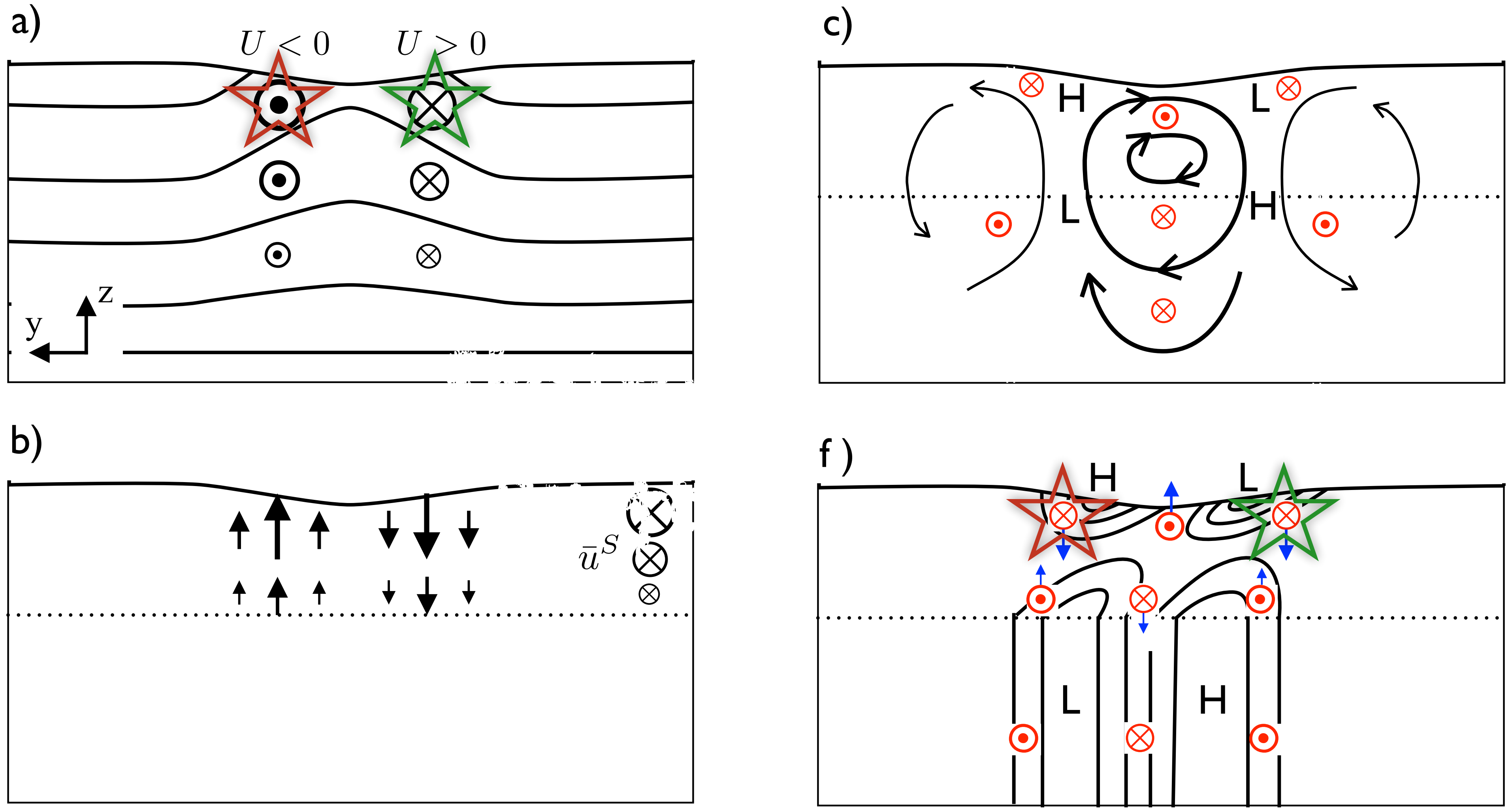
$$\varepsilon = \frac{V^s H}{fLH_s}$$

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

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

Example: Stokes Shear Force on Submesoscale Cold Filament





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, In prep, 2015.

Enhances Fronts for Down-Front Stokes

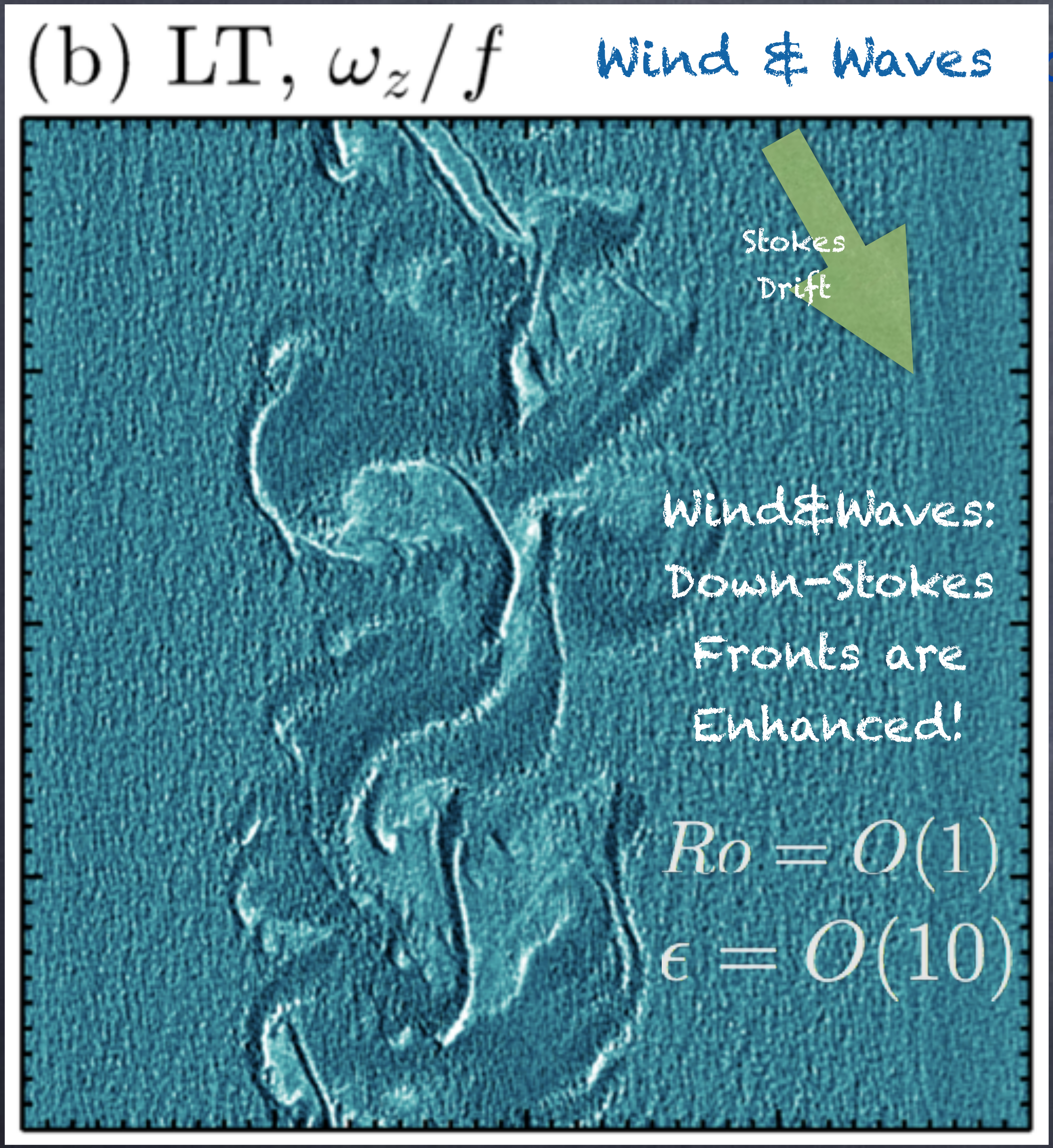
Opposes Fronts for Up-Front Stokes

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

Waves Give 30-40% of Power Produced at Front

Are Fronts and Filaments different with Stokes shear force?

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



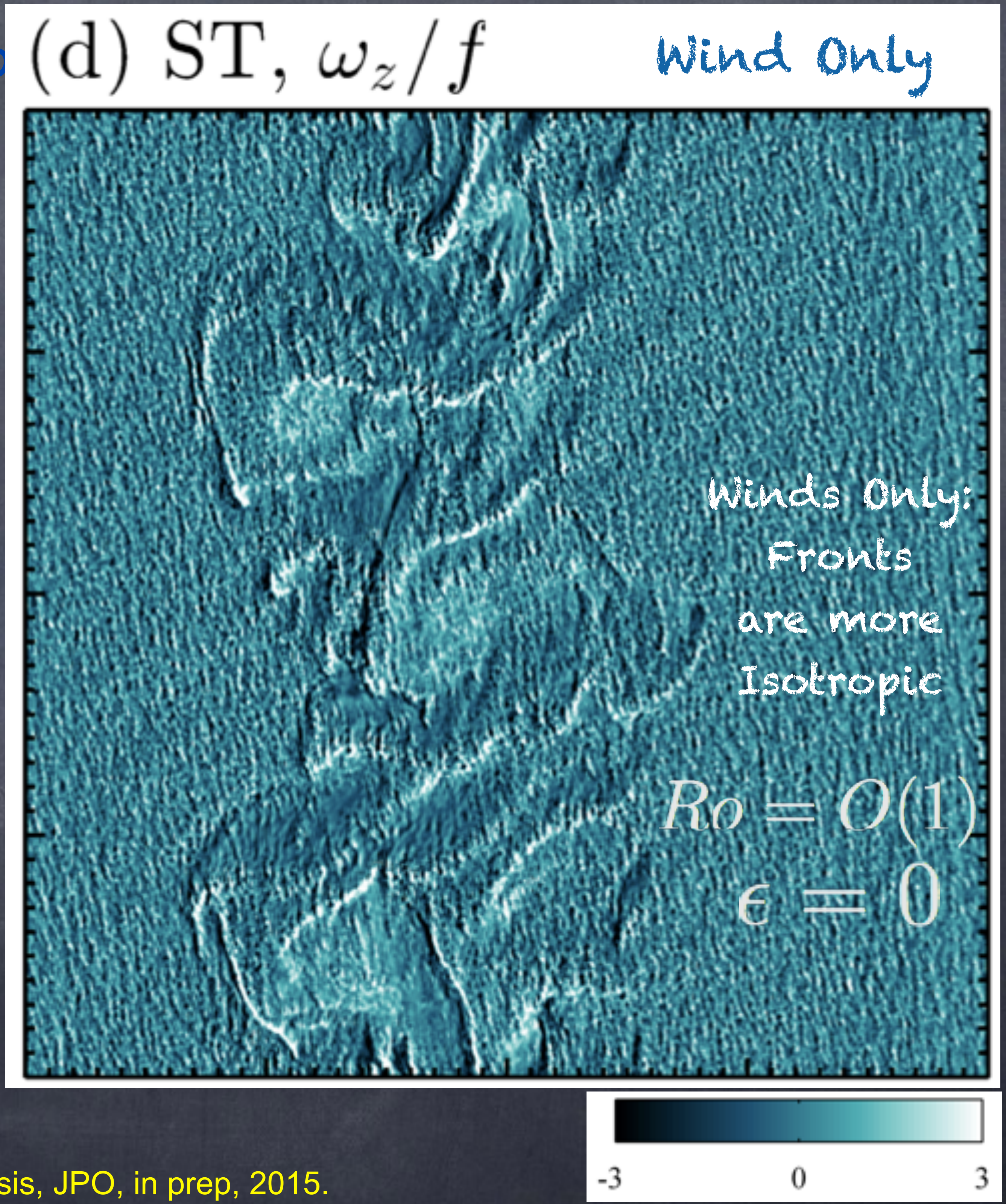
Wind & Waves

Stokes Drift

Wind&Waves: Down-Stokes Fronts are Enhanced!

$Ro = O(1)$

$\epsilon = O(10)$



Wind Only

Winds Only: Fronts are more Isotropic

$Ro = O(1)$

$\epsilon = 0$

N. Suzuki and BFK. Surface Wave Stokes Forces Influence Frontogenesis, JPO, in prep, 2015.

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

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

Analytic Stability Criterion:
Stokes Affects Submesocale Instability?

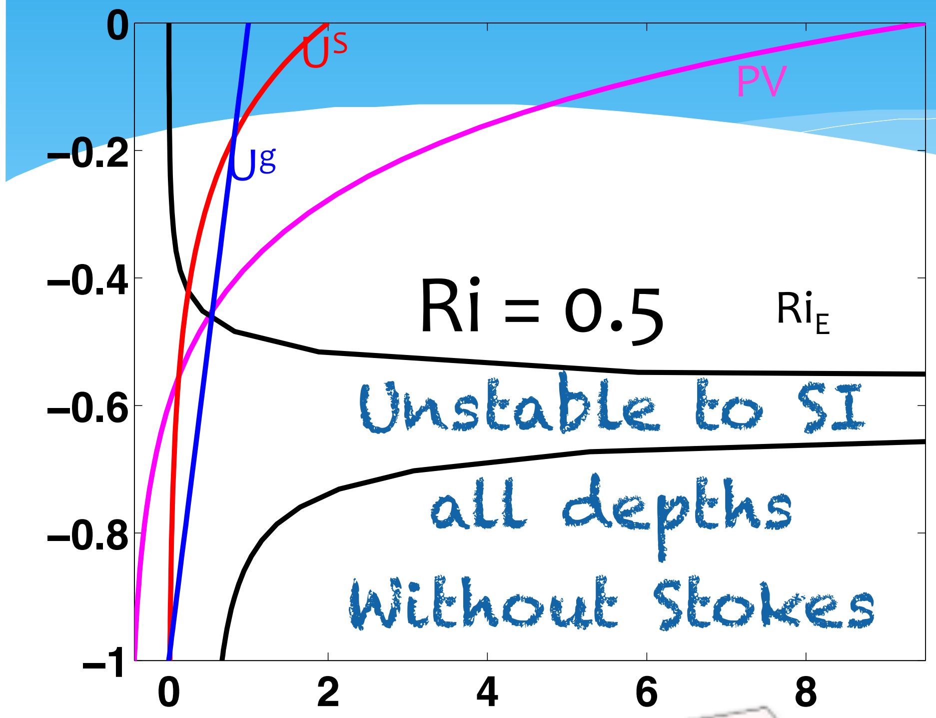
- Charney-Stern-Pedlosky found criteria for quasigesotrophic baroclinic instability (i.e. Mixed Layer Eddies)
- Hoskins (1974) criterion: symmetrically unstable fronts must have PV<0
- Haney et al extend both results to flows in Lagrangian (i.e. with Stokes drift) thermal wind balance.
    - Minor Stokes effects on Mixed Layer Eddies
    - Major Stokes effects on Symmetric Instabilities

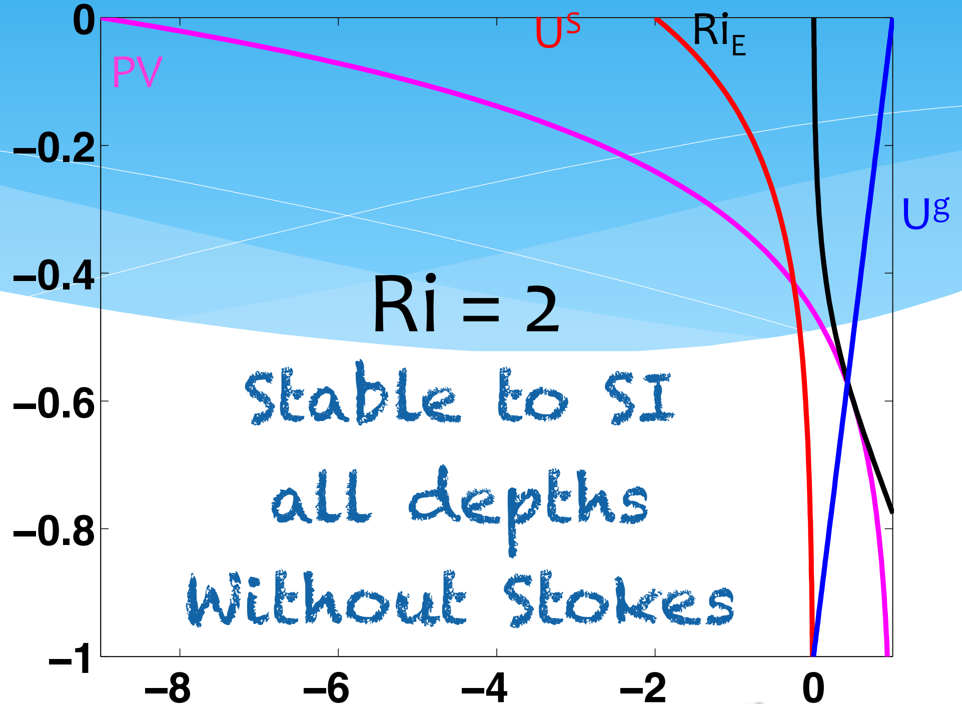
S. Haney, B. Fox-Kemper, K. Julien, and A. Webb. Symmetric and geostrophic instabilities in the wave-forced ocean mixed layer. Journal of Physical Oceanography, 2015. Submitted.

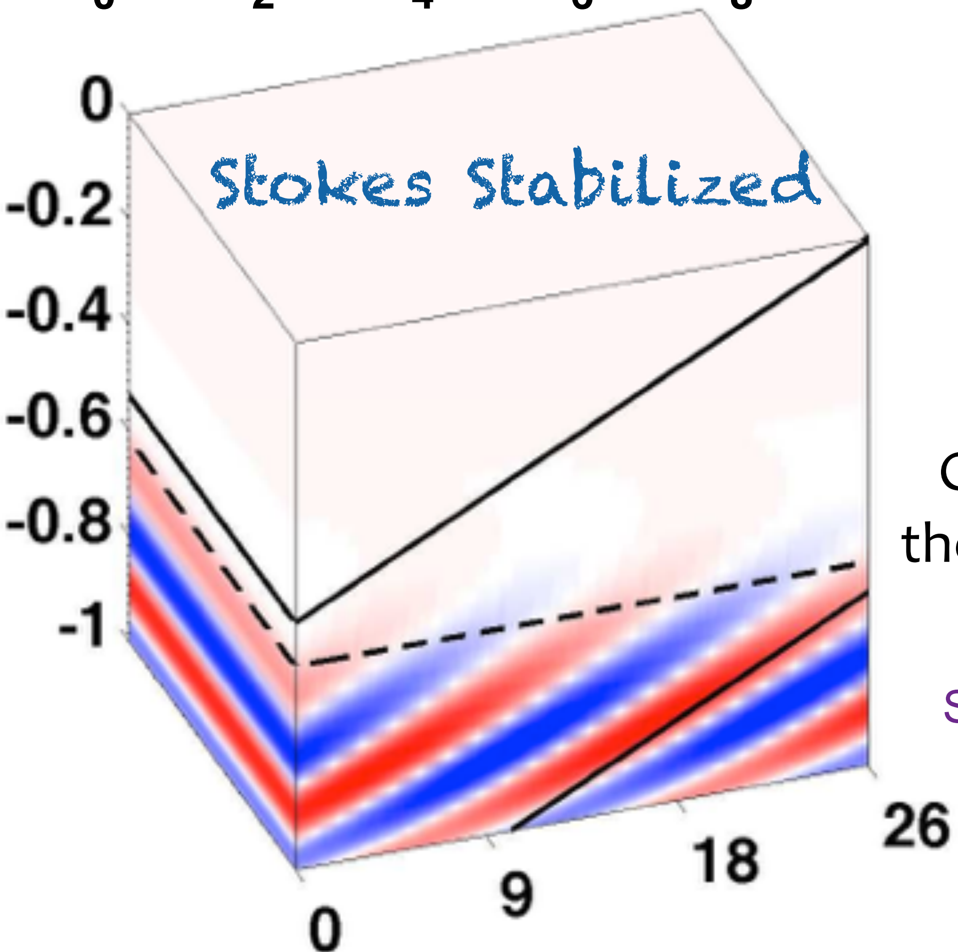
$fQ<0 \Rightarrow SI$

Realistic amounts of Stokes Drift strongly affect Symmetric Instability!

PV in Lagrangian TW affected by Stokes



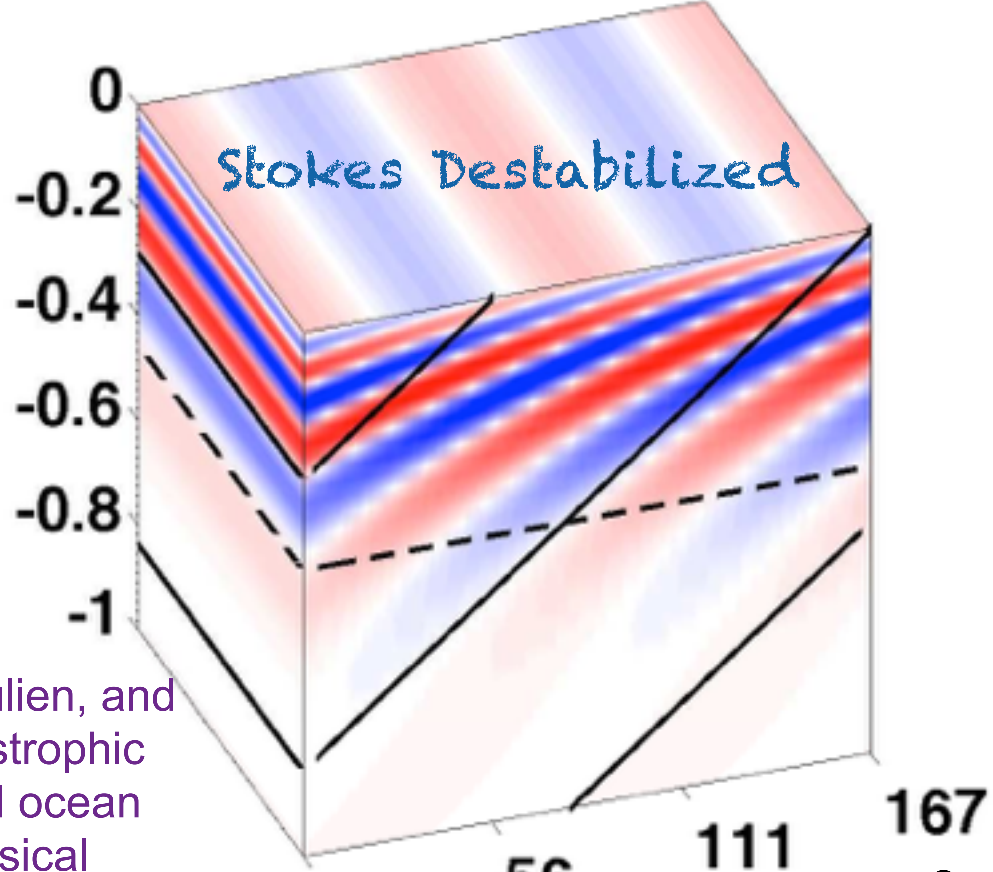




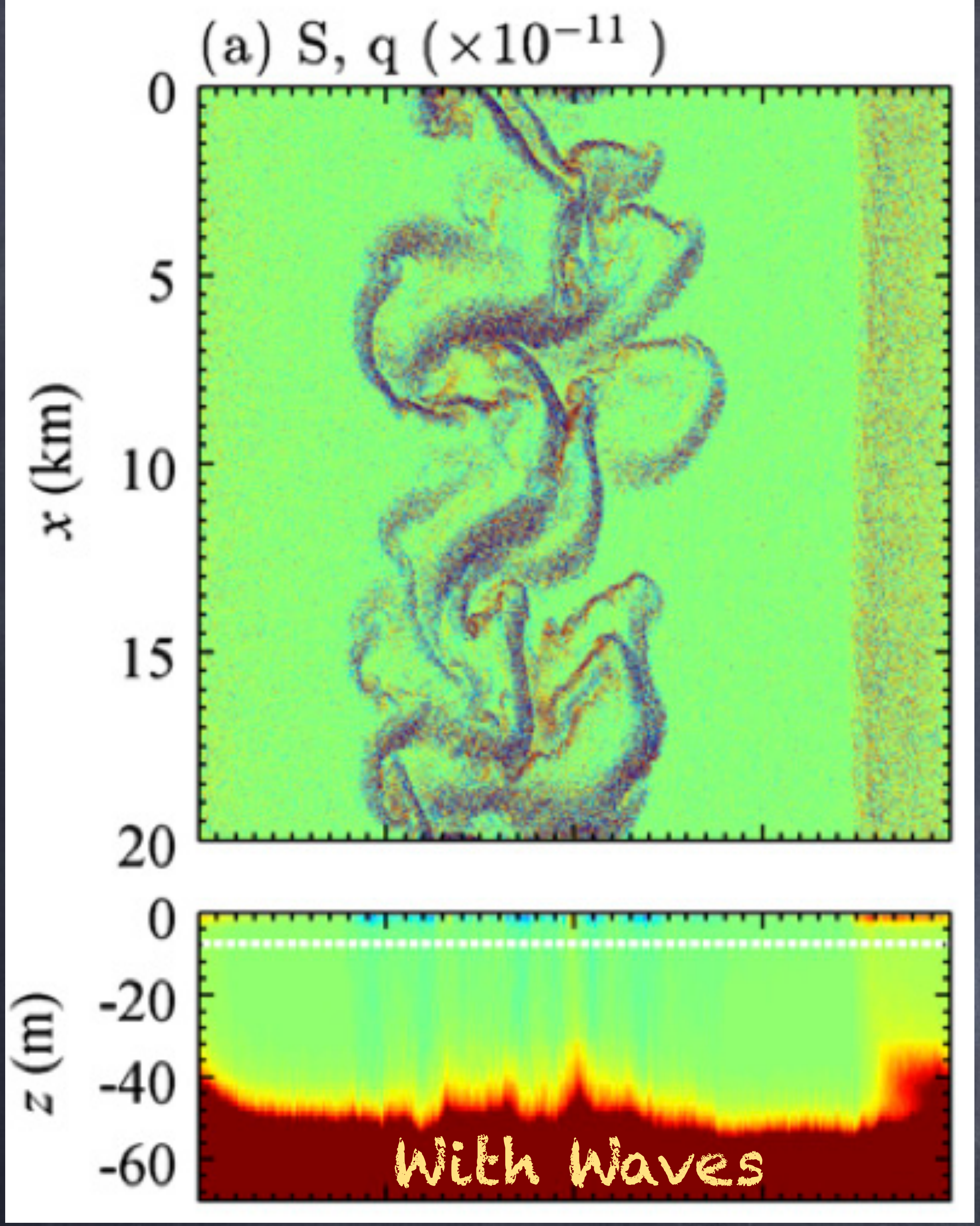
—Isopycnals

- - PV=0

Cross front velocity for the fastest growing mode

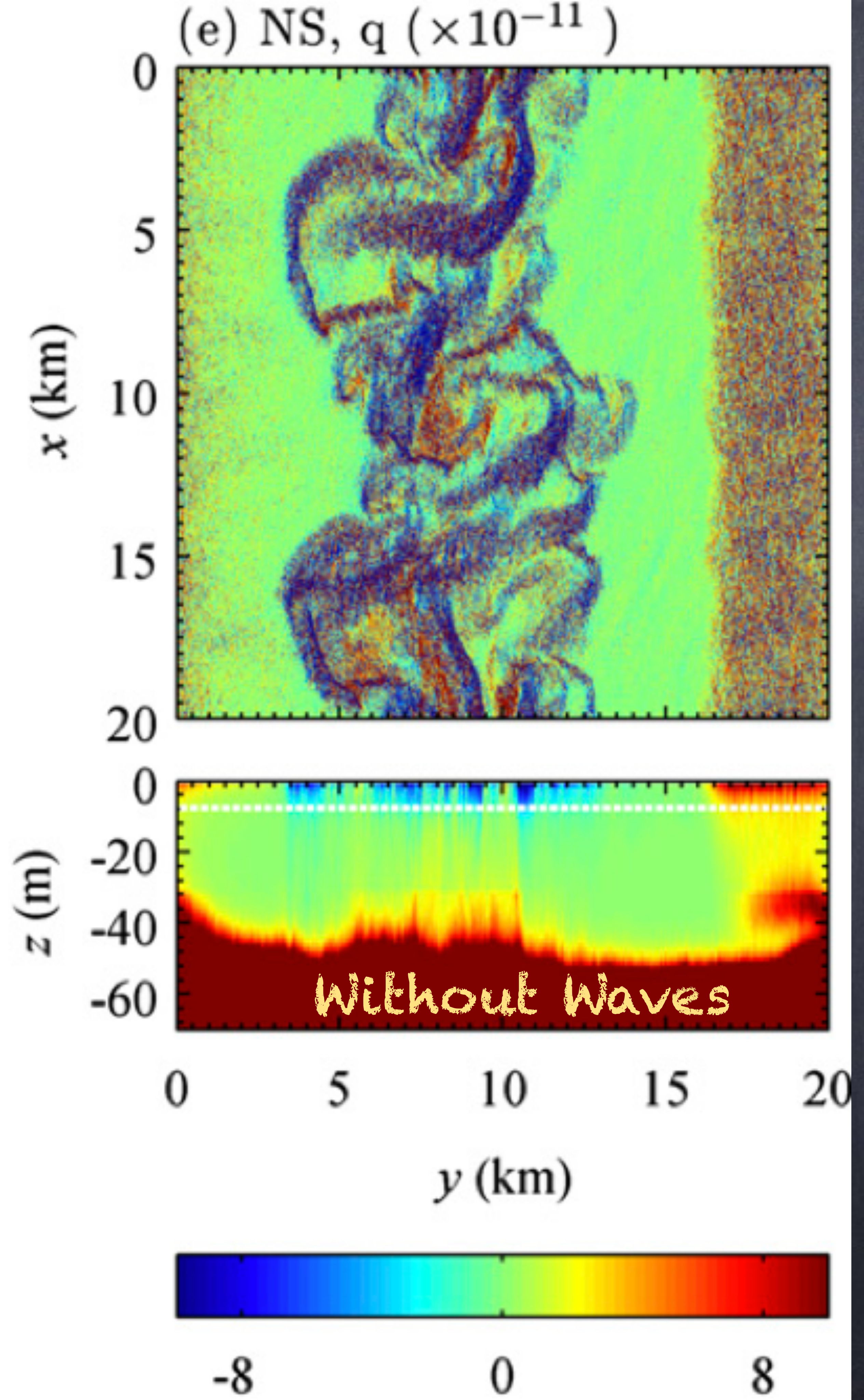


S. Haney, B. Fox-Kemper, K. Julien, and A. Webb. Symmetric and geostrophic instabilities in the wave-forced ocean mixed layer. Journal of Physical Oceanography, 2015. Submitted.



So, if negative PV indicates likely regions of symmetric instability–Surface Waves STRONGLY affect SI!

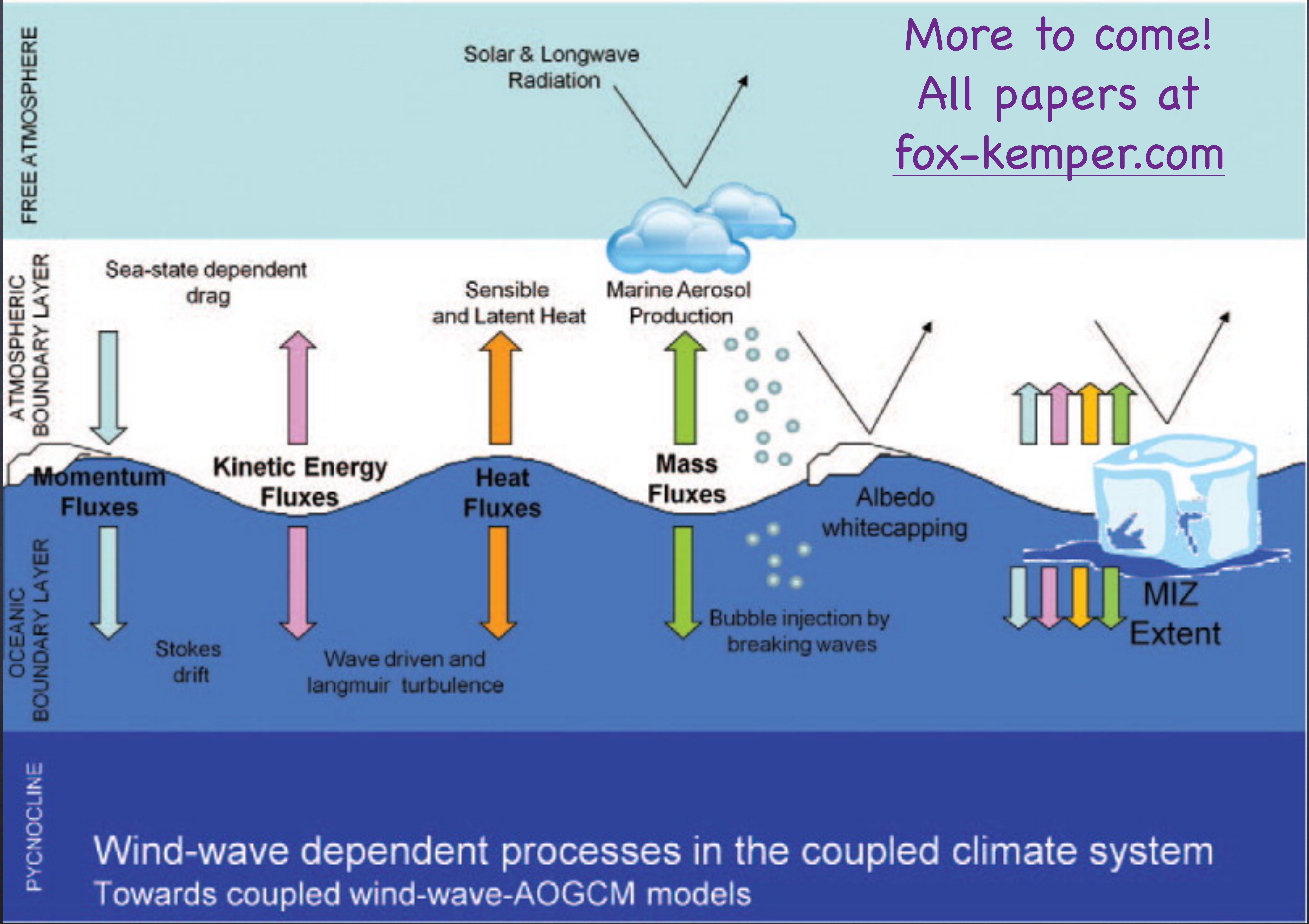
P. E. Hamlington, L. P. Van Roekel, BFK, K. Julien, and G. P. Chini. Langmuir-submesoscale interactions: Descriptive analysis of multiscale frontal spin-down simulations. Journal of Physical Oceanography, 44(9):2249-2272, September 2014.



Conclusions

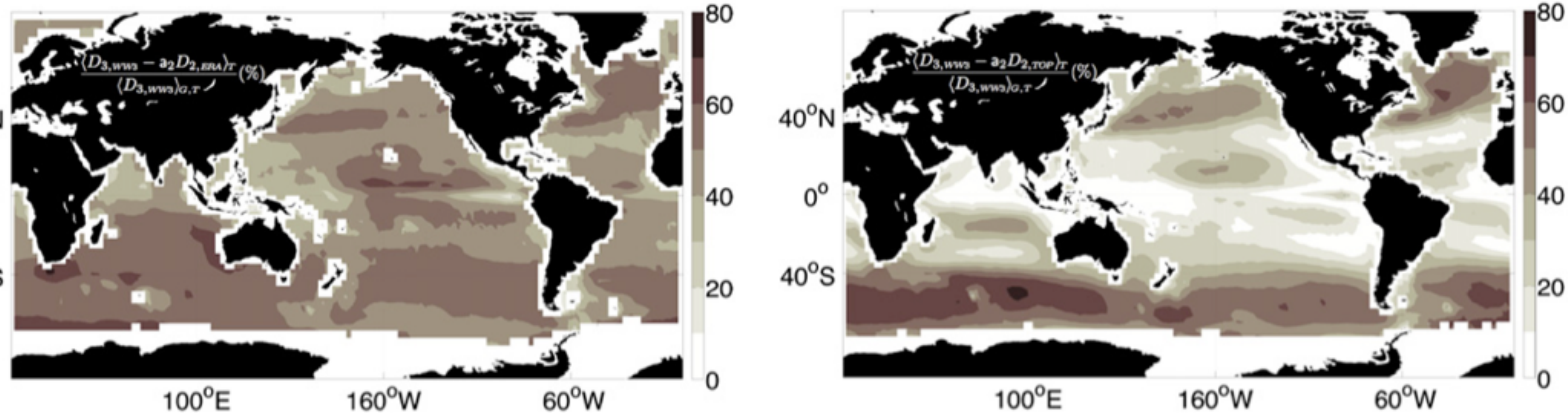
- Climate modeling is challenging partly due to the vast and diverse scales of fluid motions
- In the upper ocean, horizontal scales as big as basins, and as small as meters contribute non-negligibly to the air-sea exchange and climate
- The Submeso & Langmuir scales are dynamically interesting, as nonhydro. & ageostrophic effects begin to dominate
- The effects of the Stokes forces on boundary layer and submesoscale dynamics are under-appreciated.
- Stokes forces affect fronts, filaments, and instabilities at the submesoscale as well as driving Langmuir turbulence on smaller scales
- All papers at: fox-kemper.com/pubs

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



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

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



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

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

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

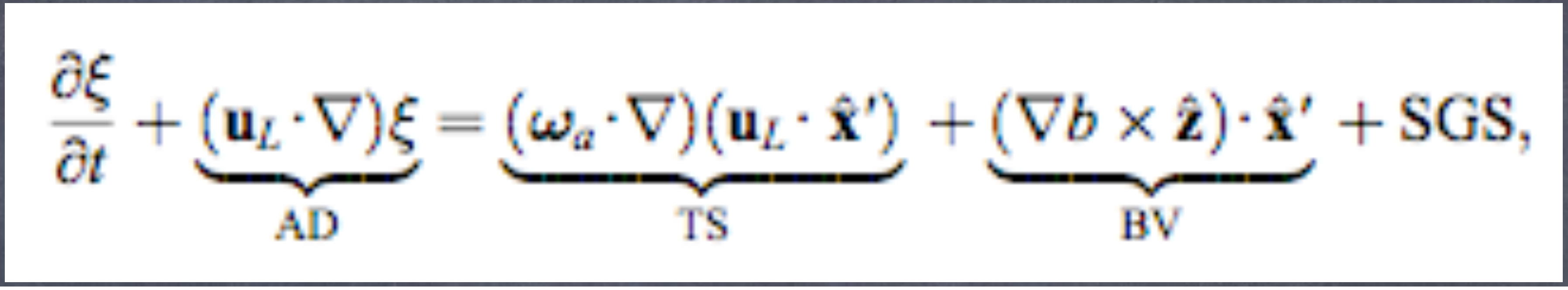
Year 2000 data & models

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

Why? Vortex Tilting Mechanism

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

Misalignment enhances degree of wave-driven LT



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

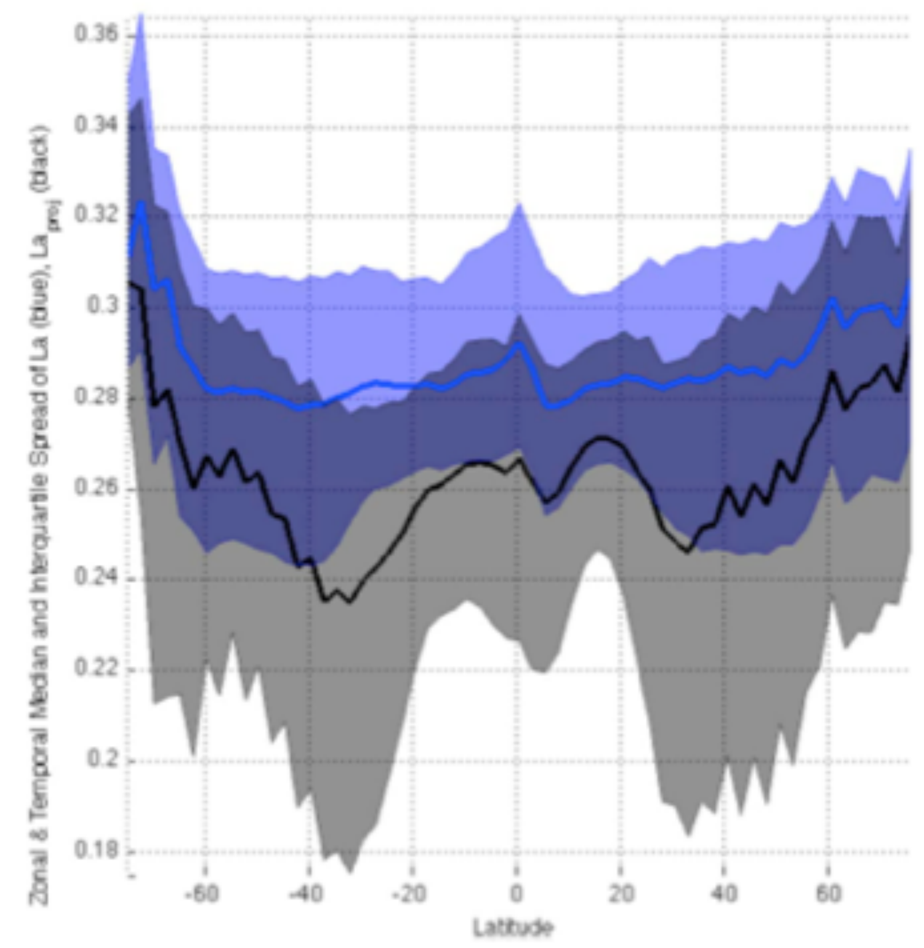


Figure 17. Temporal and zonal median and interquartile range of La_t and La_{proj} for a realistic simulation of 1994–2002 using Wave Watch III.

image: Thorpe, 04

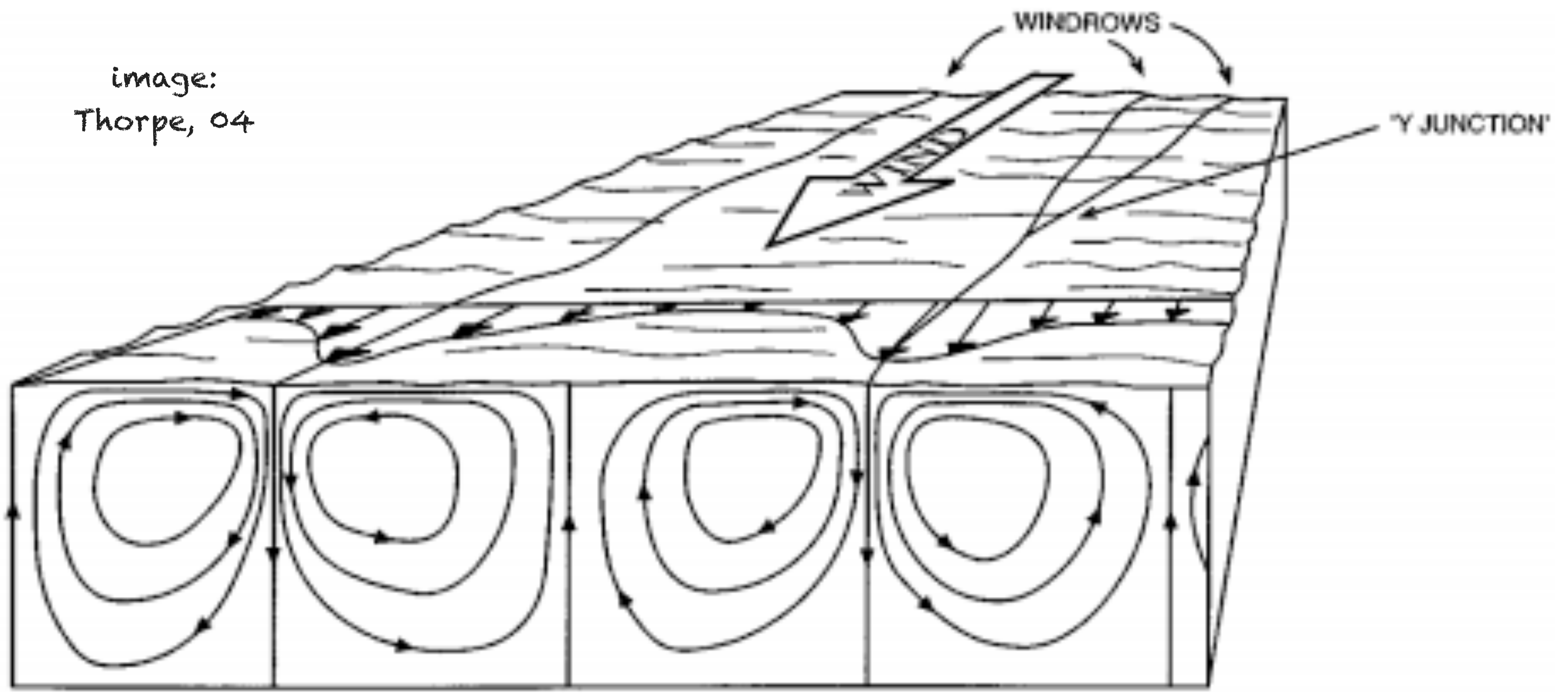
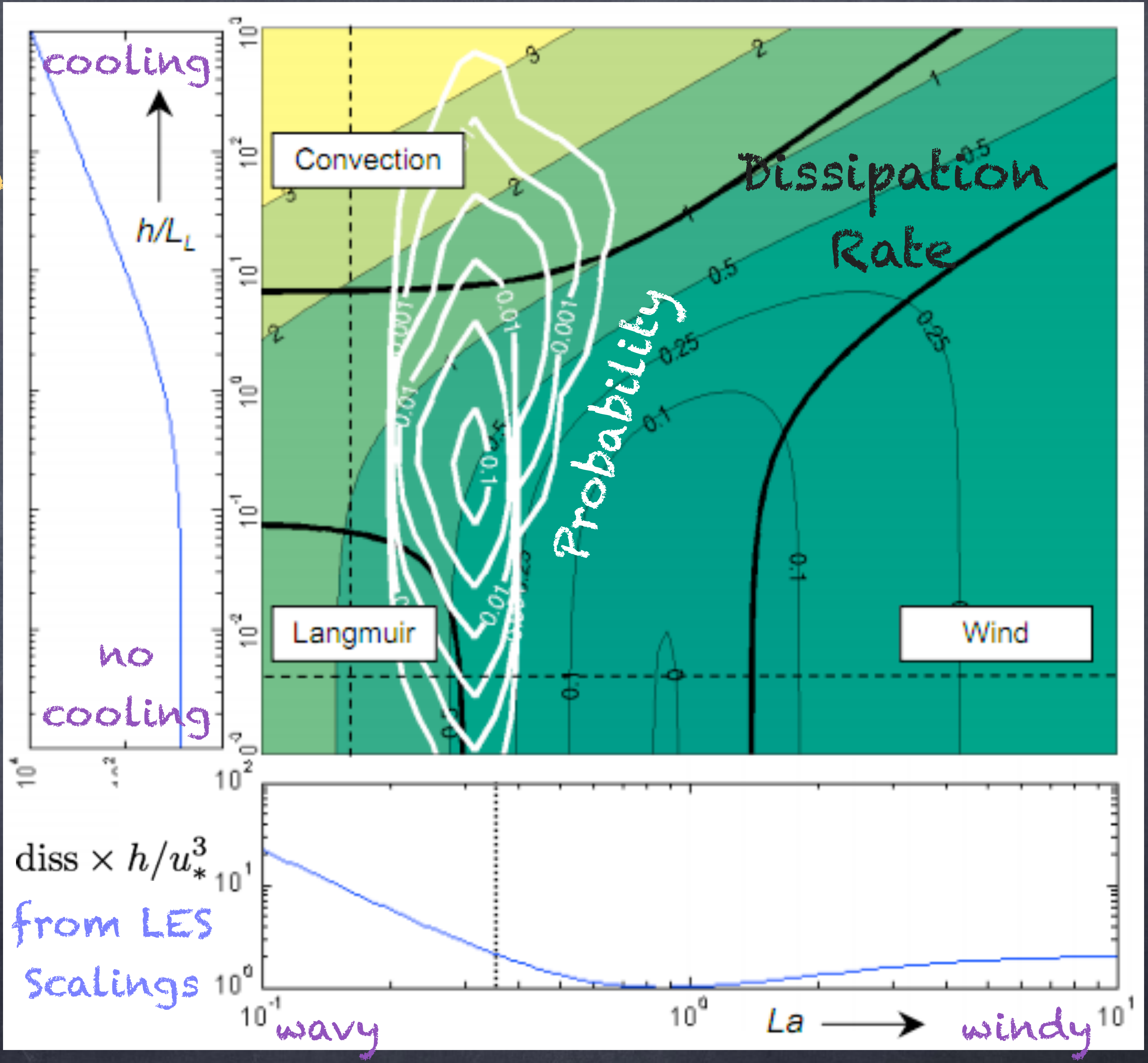


Figure 1 Sketch showing the pattern of mean flow in idealized Langmuir circulation. The windrows may be 2 m to 300 m apart, and the cell form is roughly square (as shown). In practice the flow is turbulent, especially near the water surface, and the windrows (Figure 2) amalgamate and meander in space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

Data + scaling laws consistent with preceding

But, how Southern Ocean data to determine available mixing energy

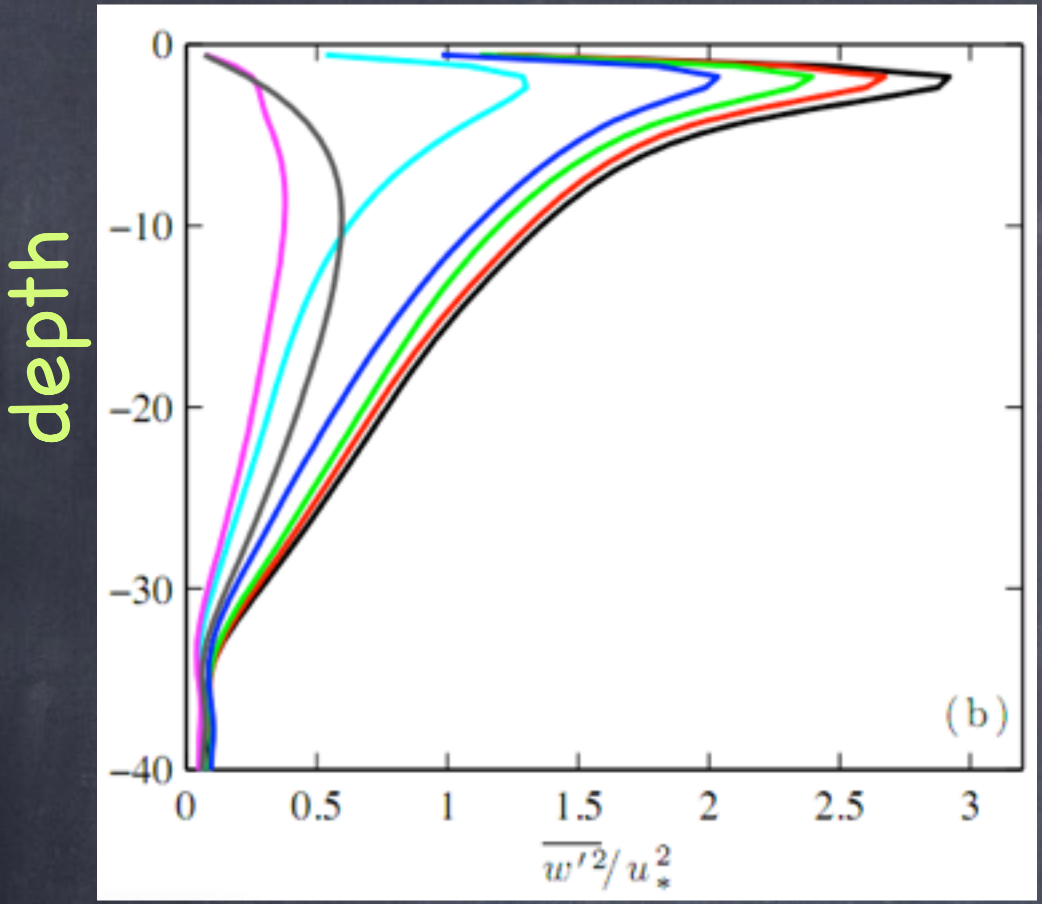
So, waves are likely to drive mixing via Stokes drift (combines with cooling & winds)



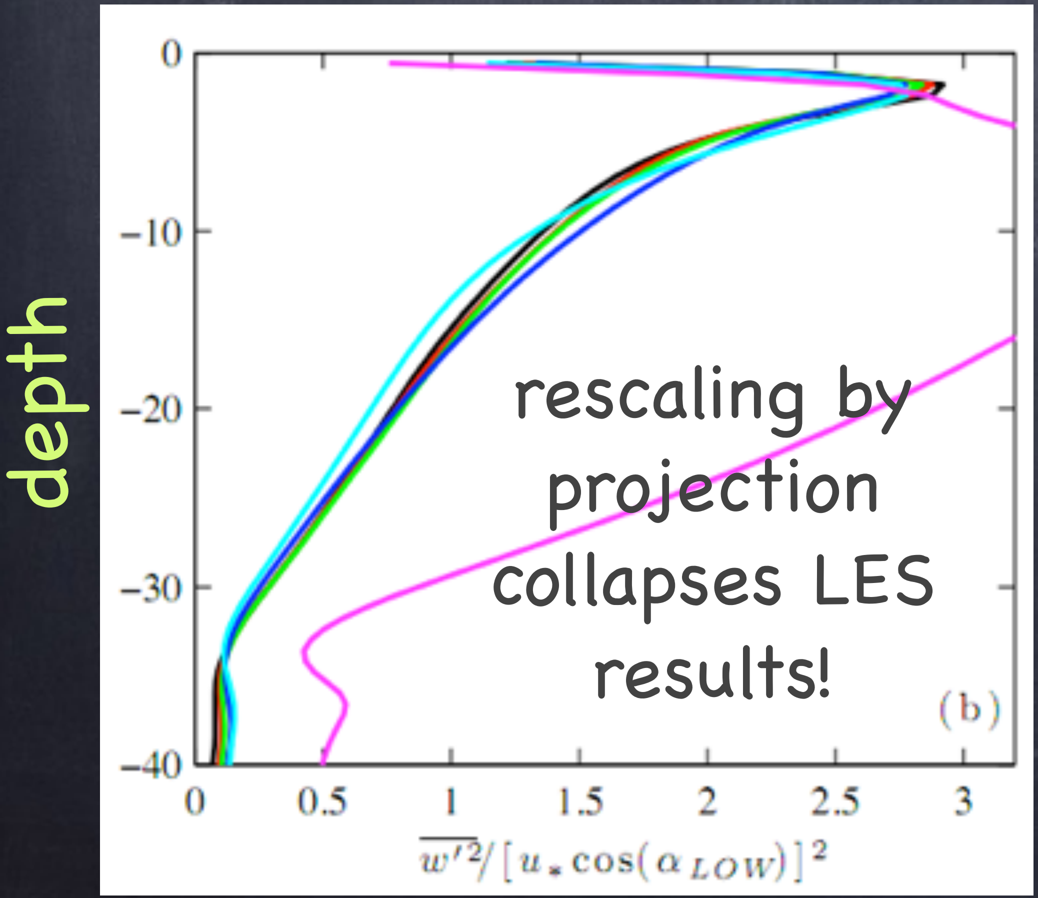
S. E. Belcher, A. A. L. M. Grant, K. E. Hanley, B. Fox-Kemper, L. Van Roekel, P. P. Sullivan, W. G. Large, A. Brown, A. Hines, D. Calvert, A. Rutgersson, H. Petterson, J. Bidlot, P. A. E. M. Janssen, and J. A. Polton. A global perspective on Langmuir turbulence in the ocean surface boundary layer. Geophysical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

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

$\langle w^2 \rangle$



rescaled $\langle w^2 \rangle$



rescaling by projection collapses LES results!

$$\frac{\left\langle \overline{w'^2}\right\rangle_{ML}}{u_*^2} = 0.6\cos^2(\alpha_{LOW})\left[1.0+(3.1La_{proj})^{-2} + (5.4La_{proj})^{-4}\right],$$

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

$$\alpha_{LOW} \approx \tan^{-1}\left(\frac{\sin(\theta_{ww})}{\frac{u_*}{u_s(0)\kappa}\ln\left(\left|\frac{H_{ML}}{z_1}\right|\right)+\cos(\theta_{ww})}\right)$$

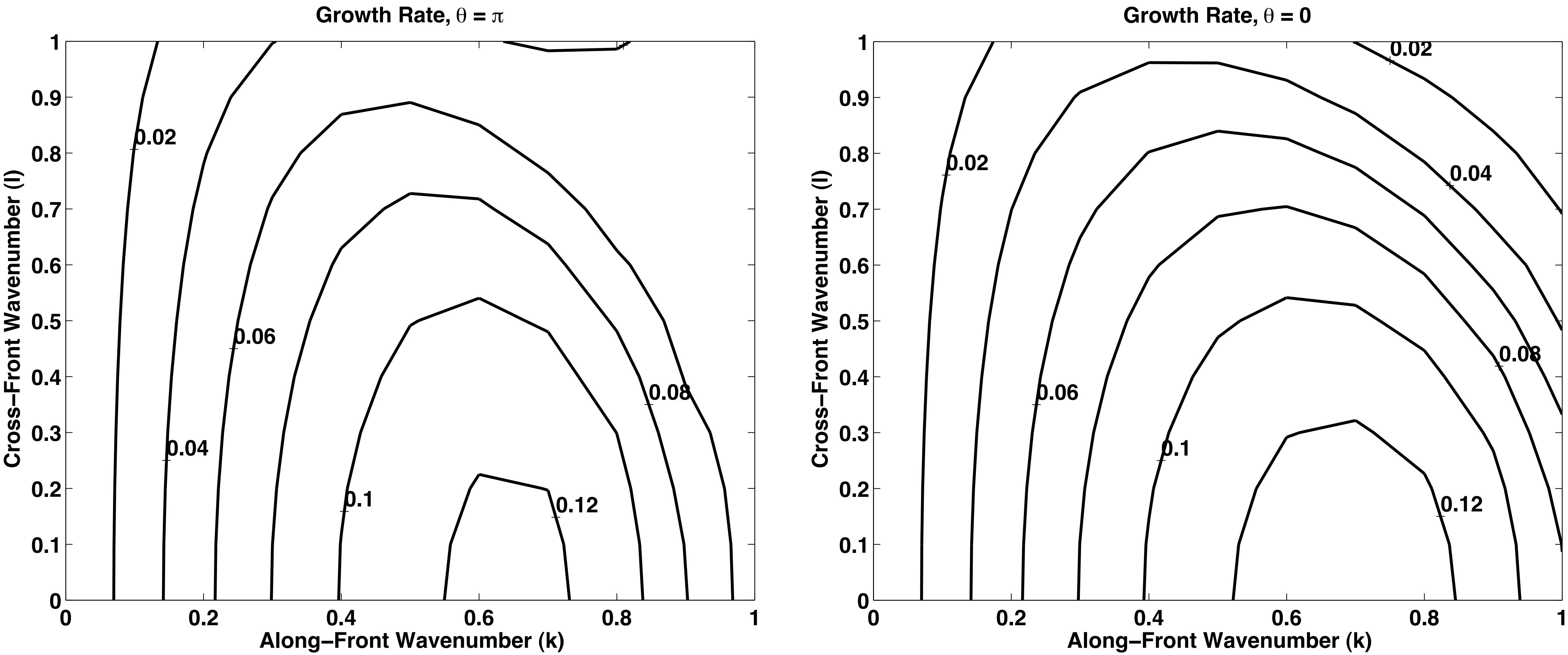
A scaling for LC strength & direction!

Enough to use in a climate model

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.

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.



S. Haney, BFK, and K. Julien Symmetric and Geostrophic Instabilities in the Wave-Forced Ocean Mixed Layer, Submitted, 2015.