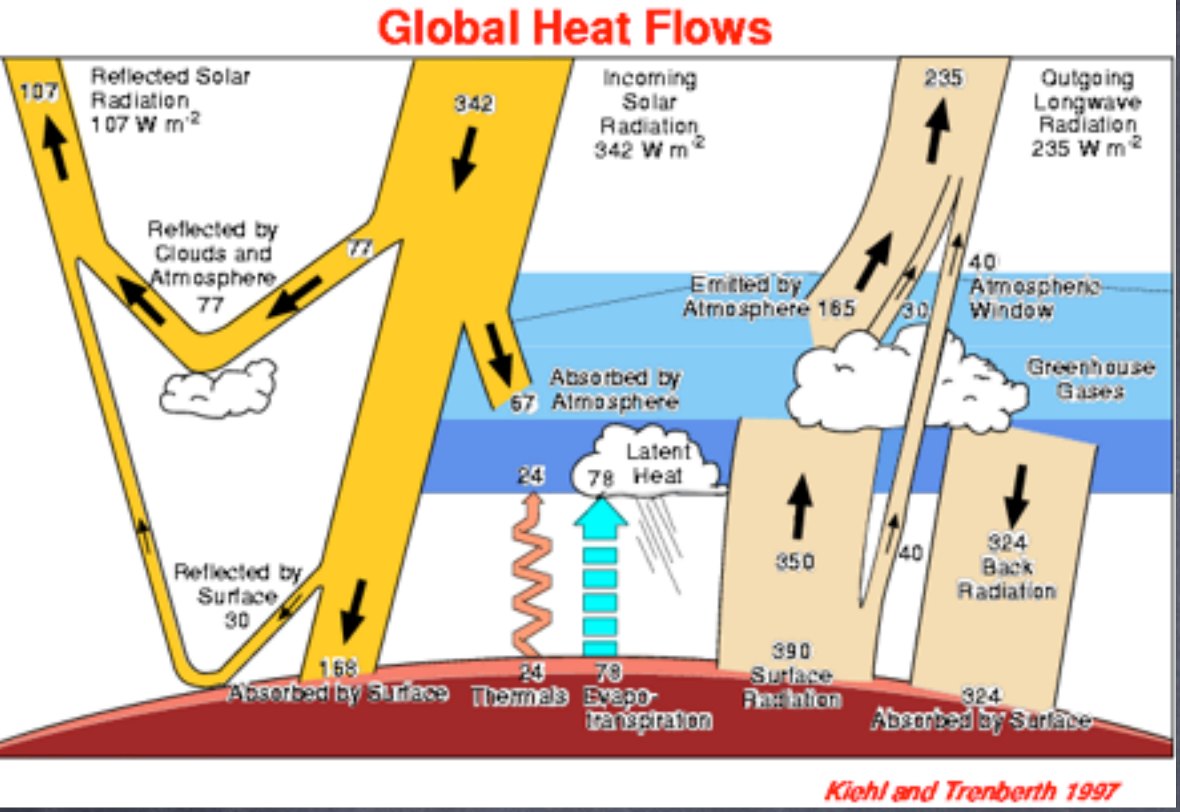
The role of the ocean surface—and its dynamics—in climate

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)

U. Connecticut Marine Sciences, Avery Point, 2/6/15

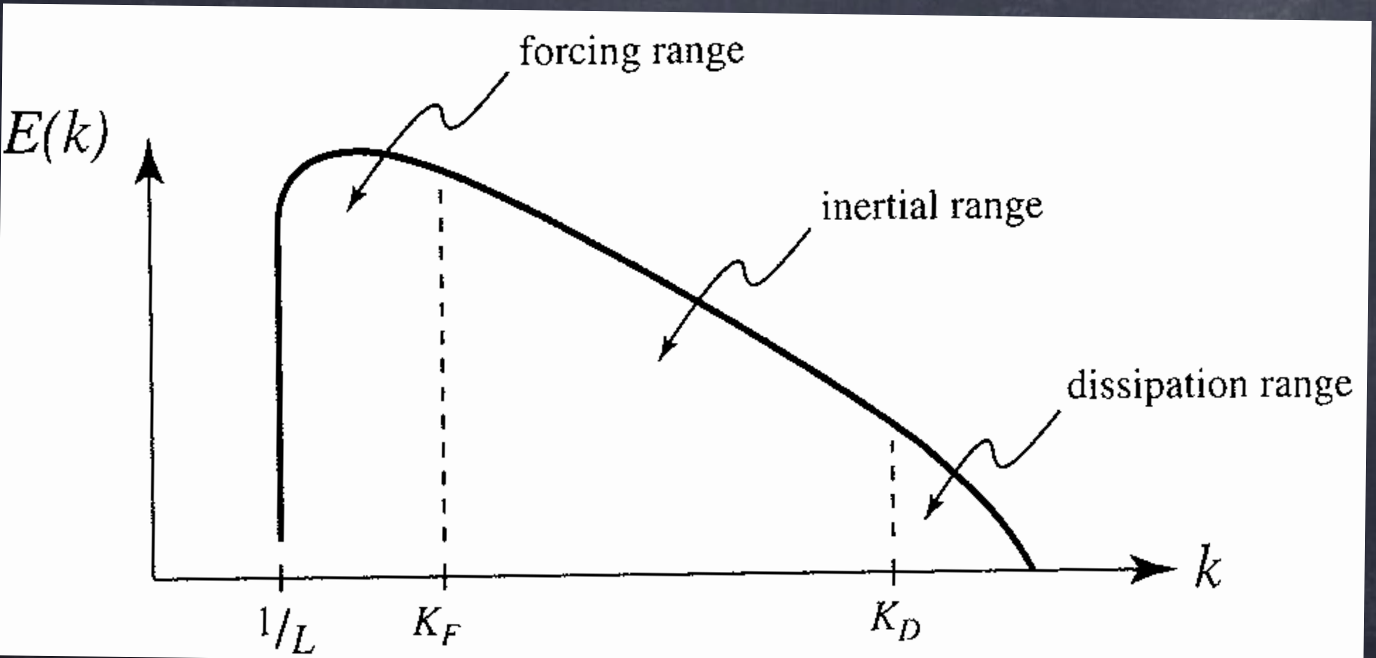
Sponsors: NSF 1258907, 1245944, 0934737, NASA NNX09AF38G

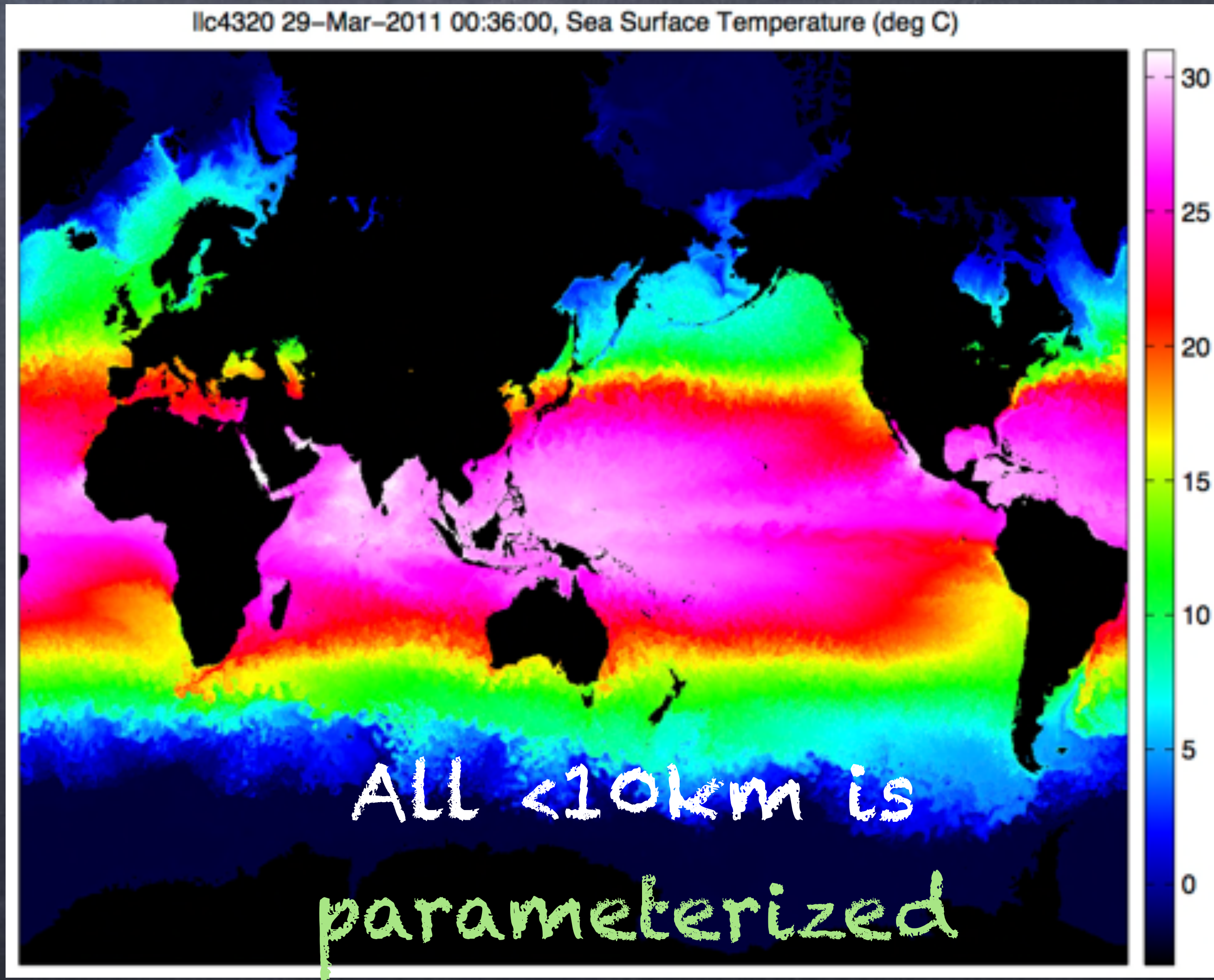


The Earth's Climate System is forced by the Sun on a global scale (20,000-40,000km)

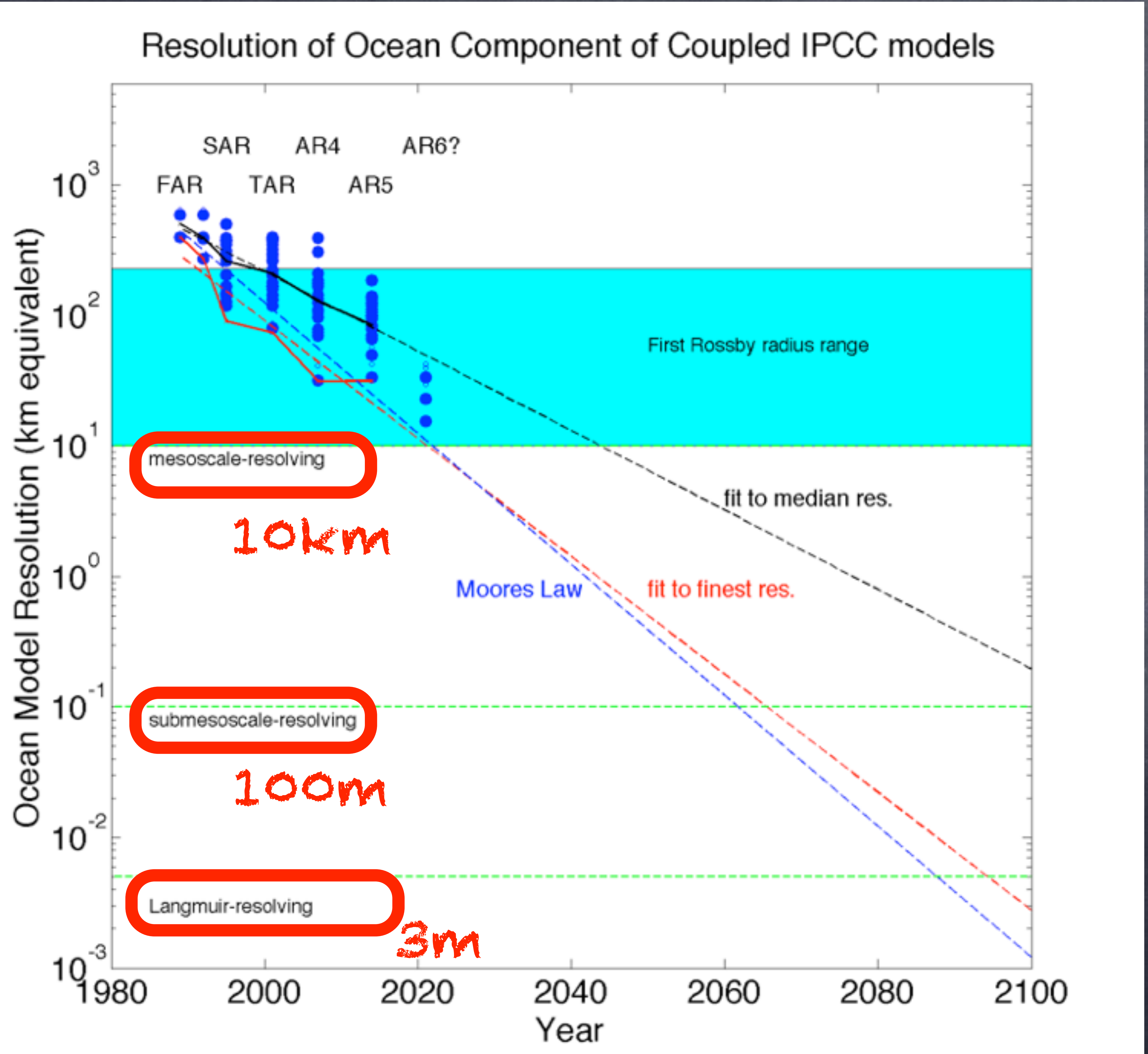
Next-gen. ocean climate models simulate globe to 10km: Mesoscale Ocean Large Eddy Simulations (MOLES)

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





Resolution will be an issue for centuries to come!



Here are the collection of IPCC models...

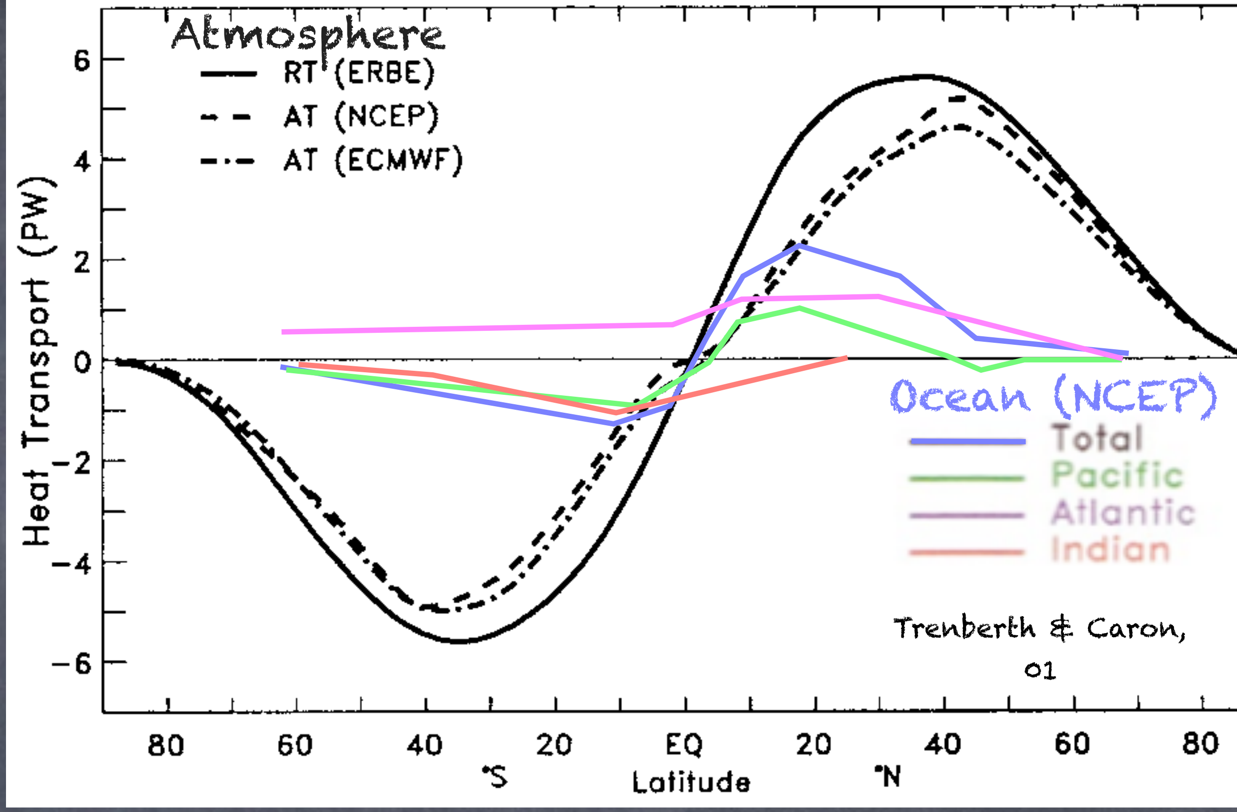
If we cant resolve a process, we need to develop a parameterization or subgrid model of its effect

Air-Sea Flux Errors vs. Data

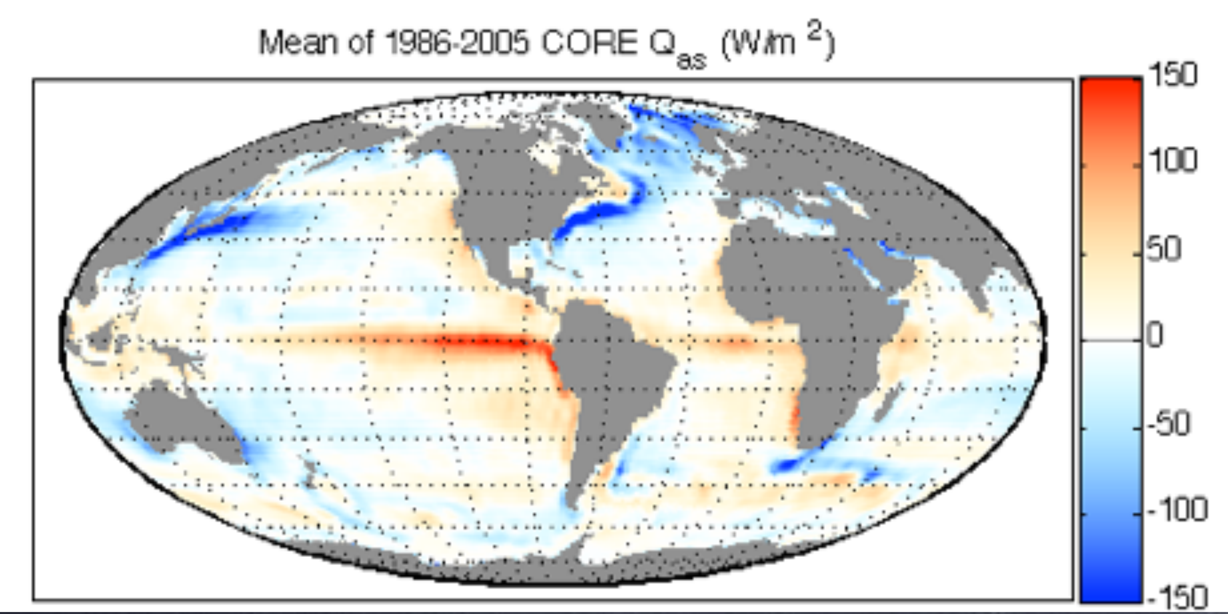
Heat capacity & mode of transport is different in A vs. O

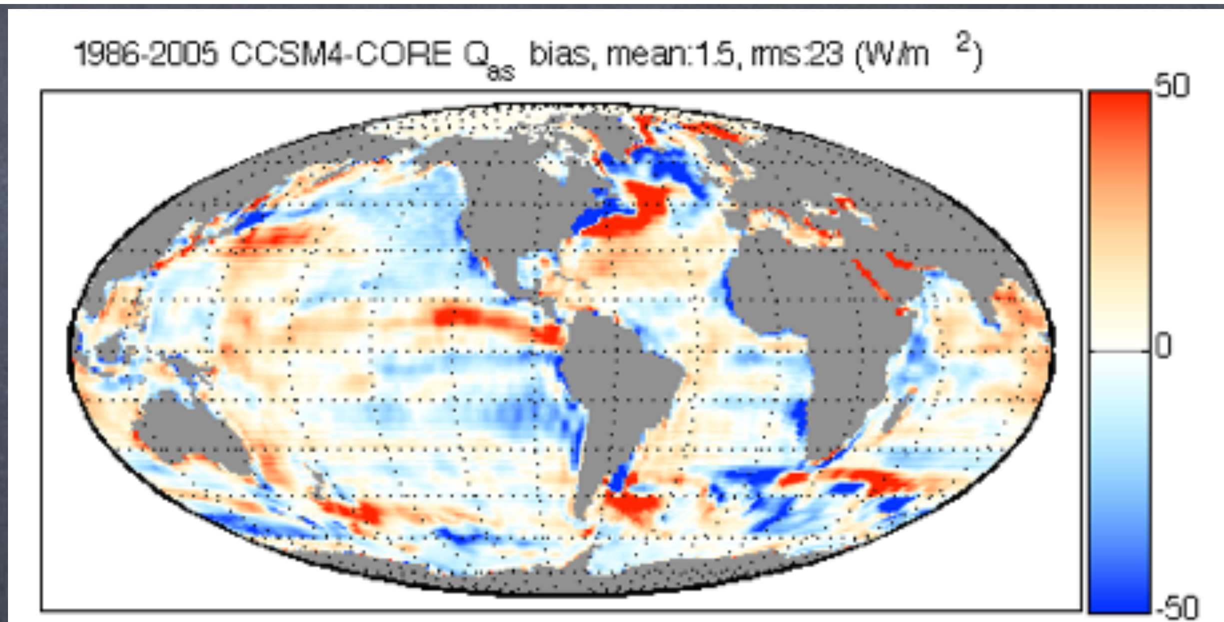
>90% of GW is oceanic, 10m O=whole A

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.

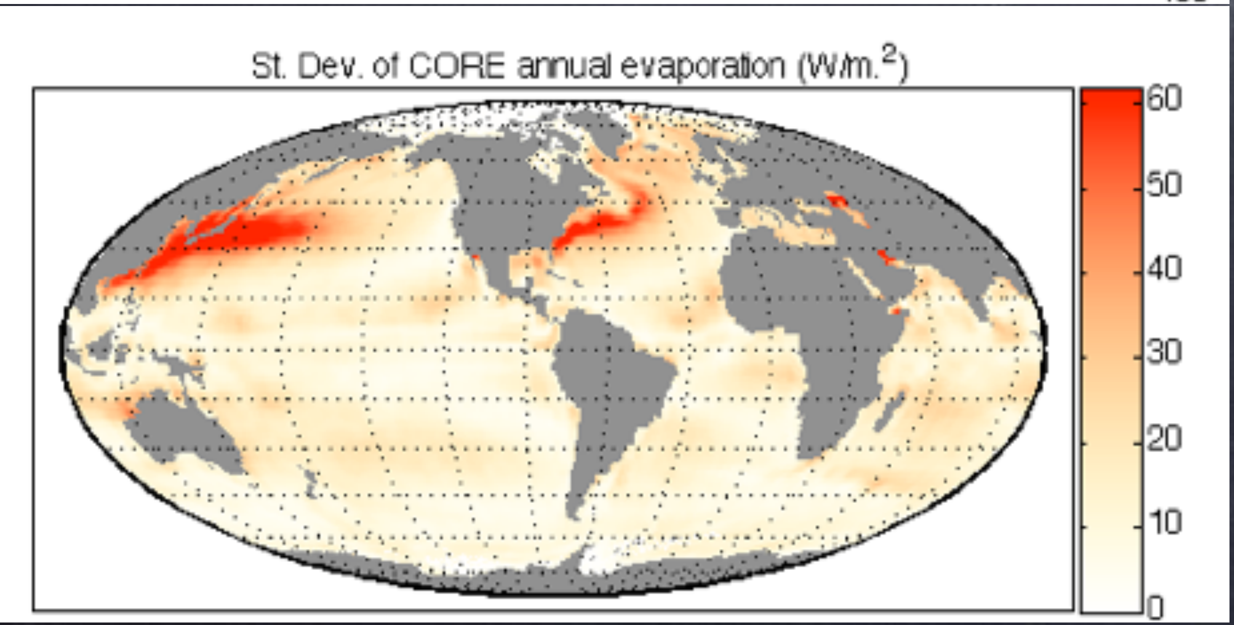


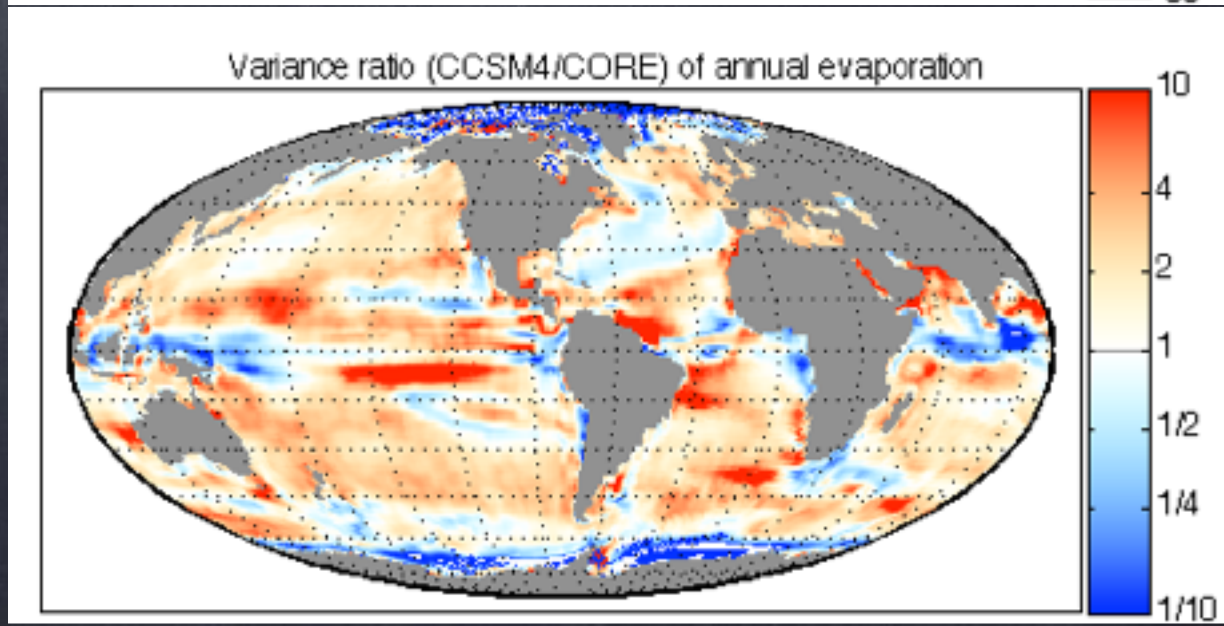
Mean



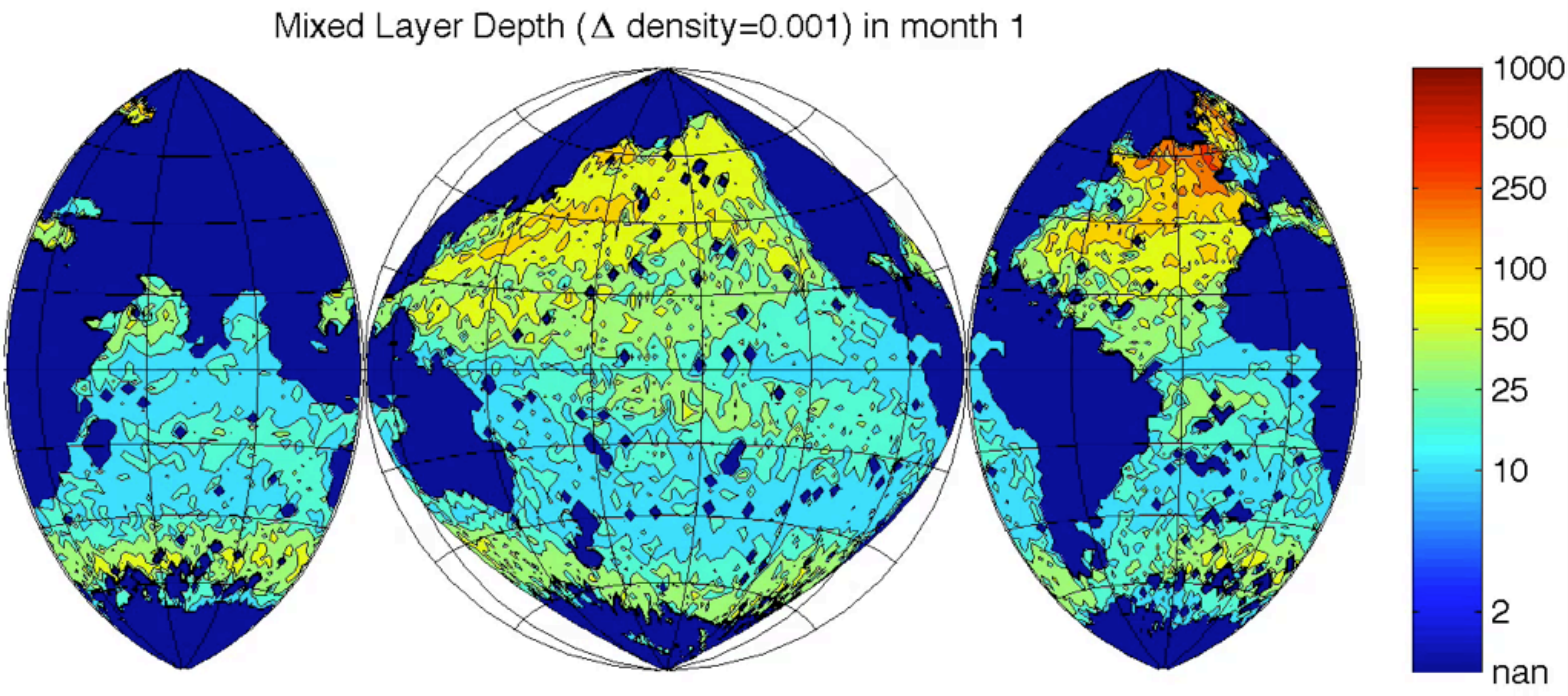


Annual 9-15mo





The Ocean Mixed Layer

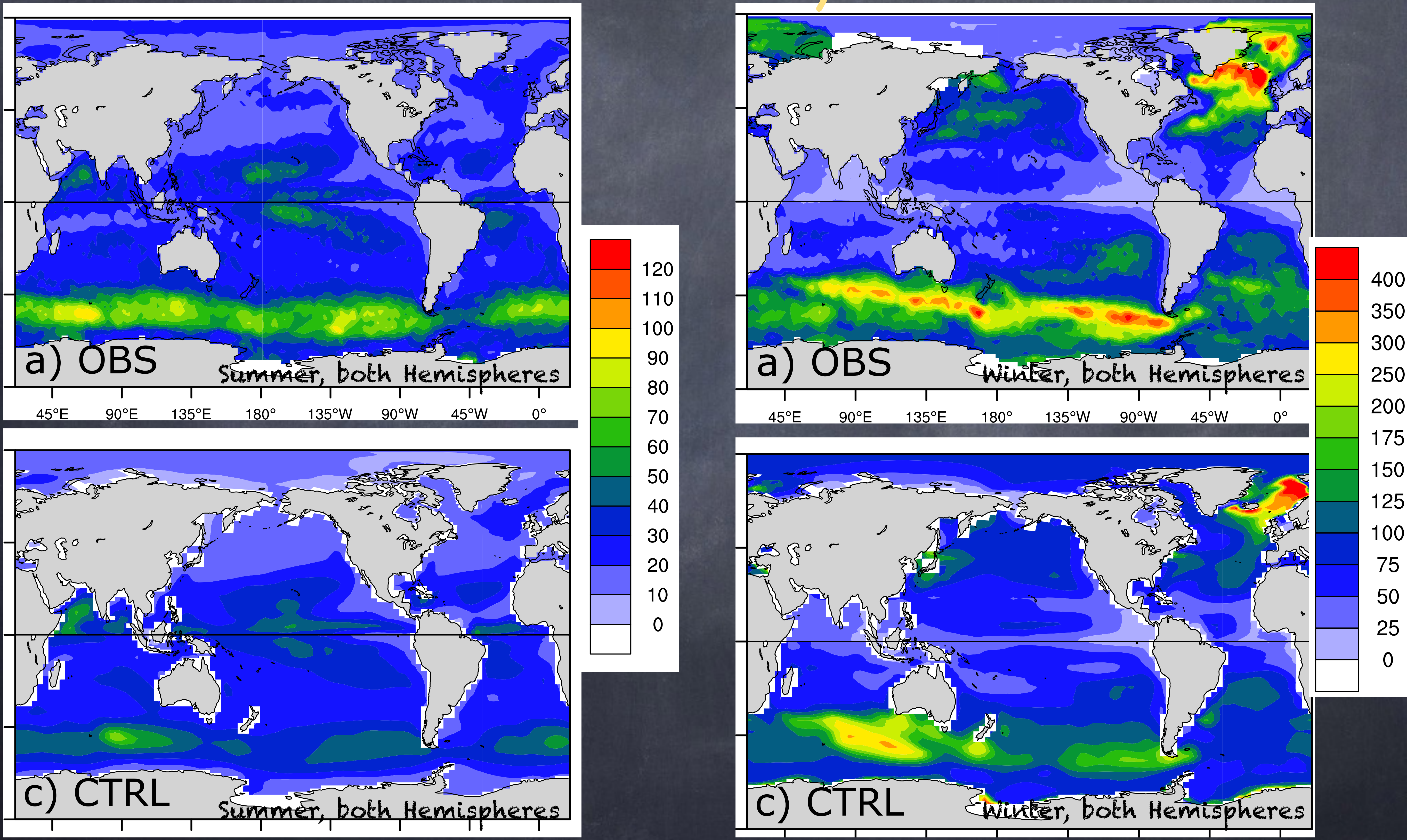


Stommel's Demon: ocean properties at depth set by deepest wintertime mixed layer & its properties

From Argo float data courtesy C. de Boyer-Montegut

The State of the 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
  - Langmuir (Wave-Driven) Mixing
  - Combinations?

The Character of the Submesoscale

← 10 km

(Capet et al., 2008)

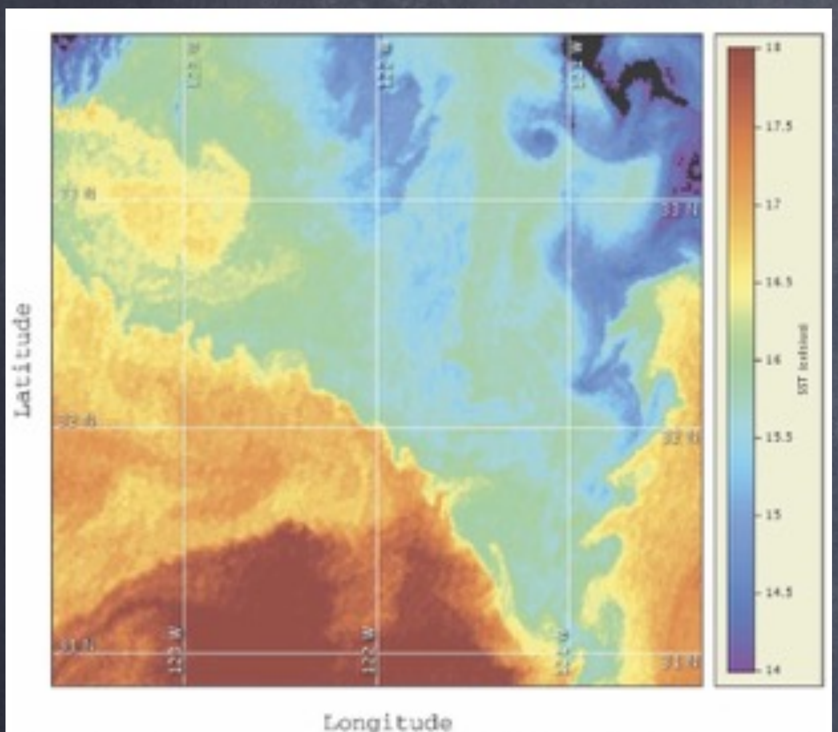
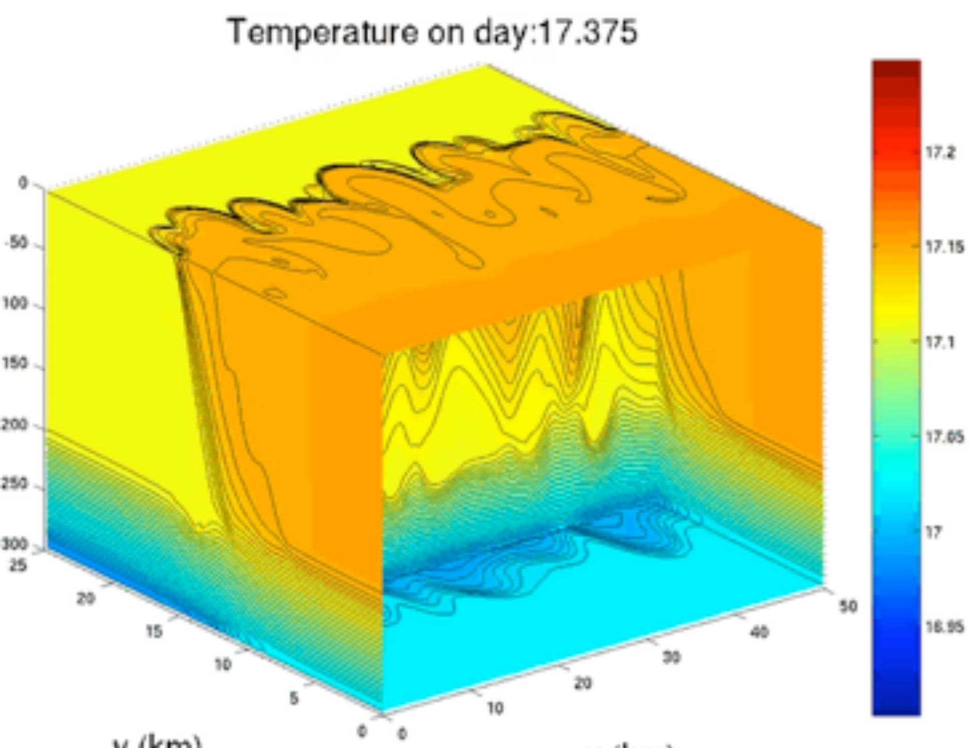


FIG. 16. Sea surface temperature measured at 1832 UTC 3 Jan 2006 off Point Conception in the California Current from CoastWatch (http://coastwatch.pfeg.noaa.gov). The fronts between recently



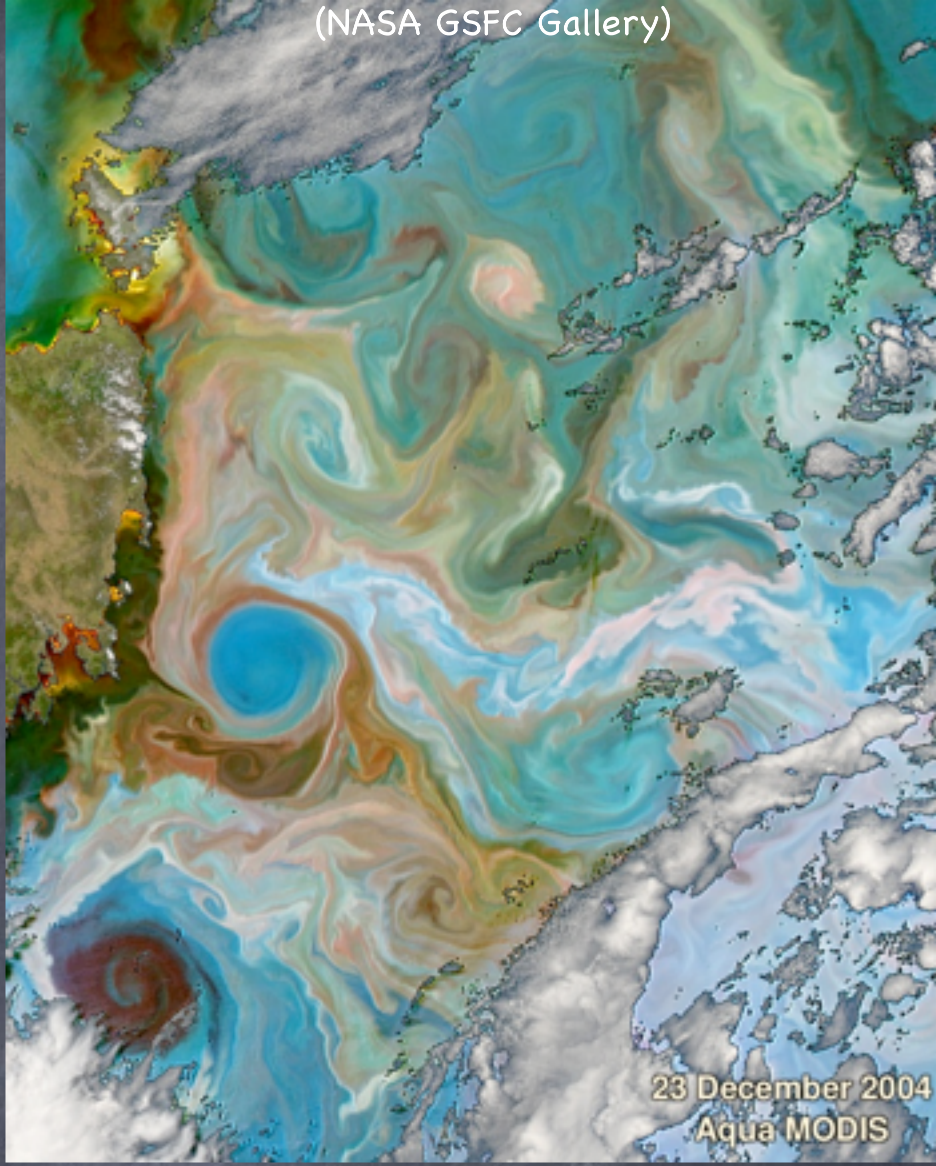
- Fronts
- Eddies
- Ro=O(1)
- Ri=O(1)
- near-surface (H=100m)
- 1-10km, days

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

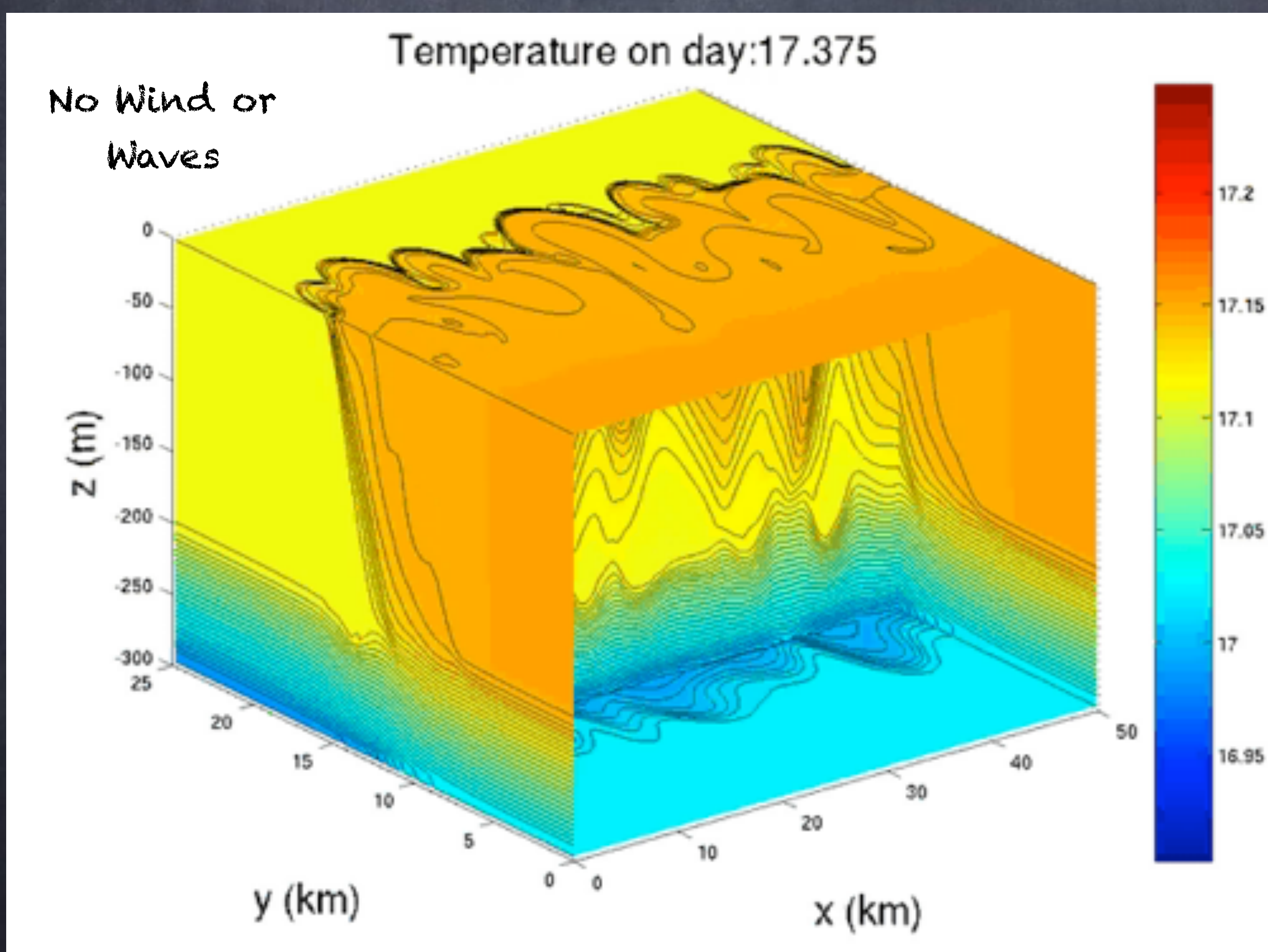
BFK, G. Danabasoglu, R. Ferrari, S. M. Griffies, R. W. Hallberg, M. M. Holland, M. E. Maltrud, S. Peacock, and B. L. Samuels. Parameterization of mixed layer eddies. III: Implementation and impact in global ocean climate simulations. Ocean Modelling, 39:61-78, 2011.

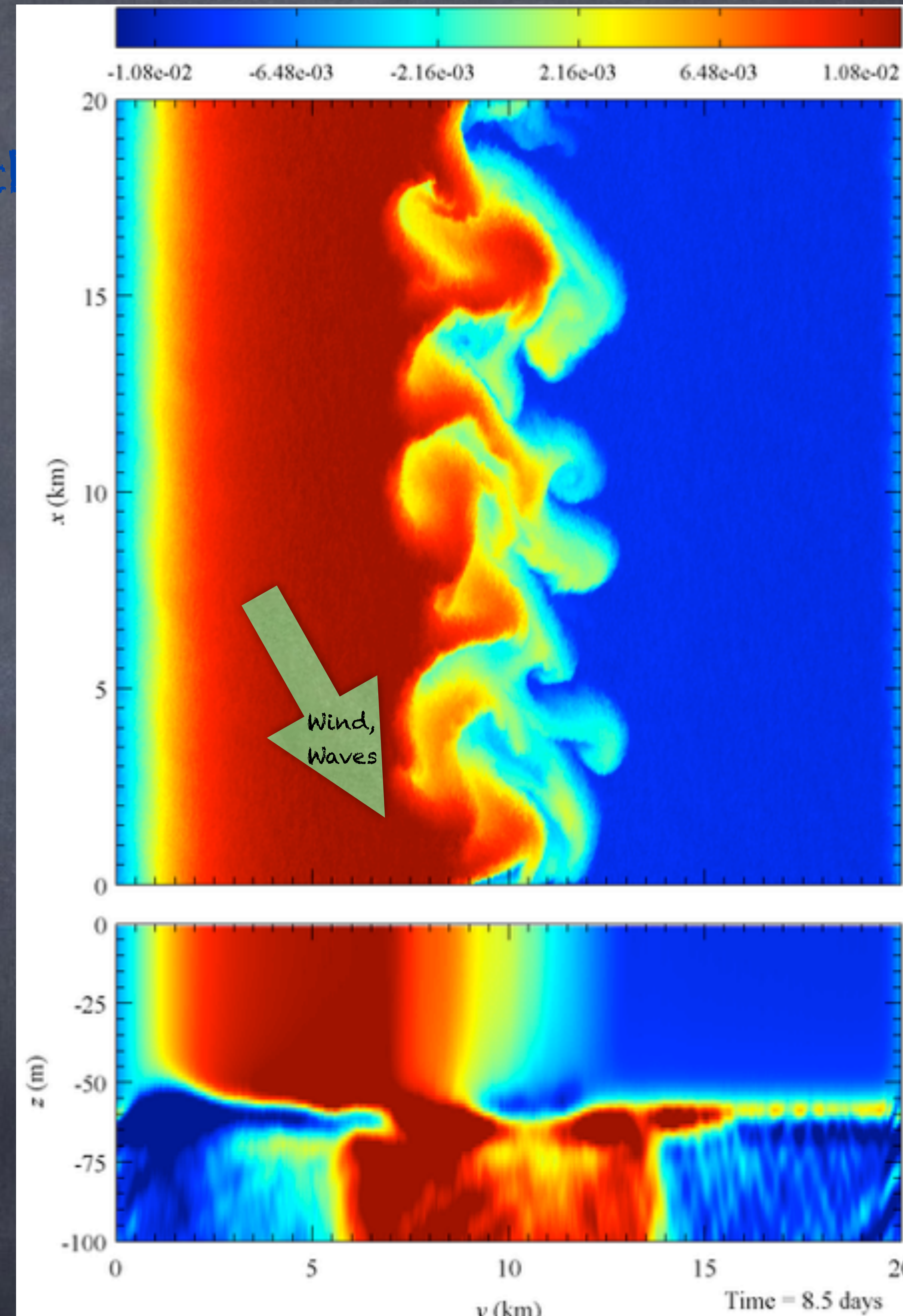
S. Bachman and BFK. Eddy parameterization challenge suite. I: Eady spindown. Ocean Modelling, 64:12-28, 2013

Submesoscale?

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

Mixing balances restratification

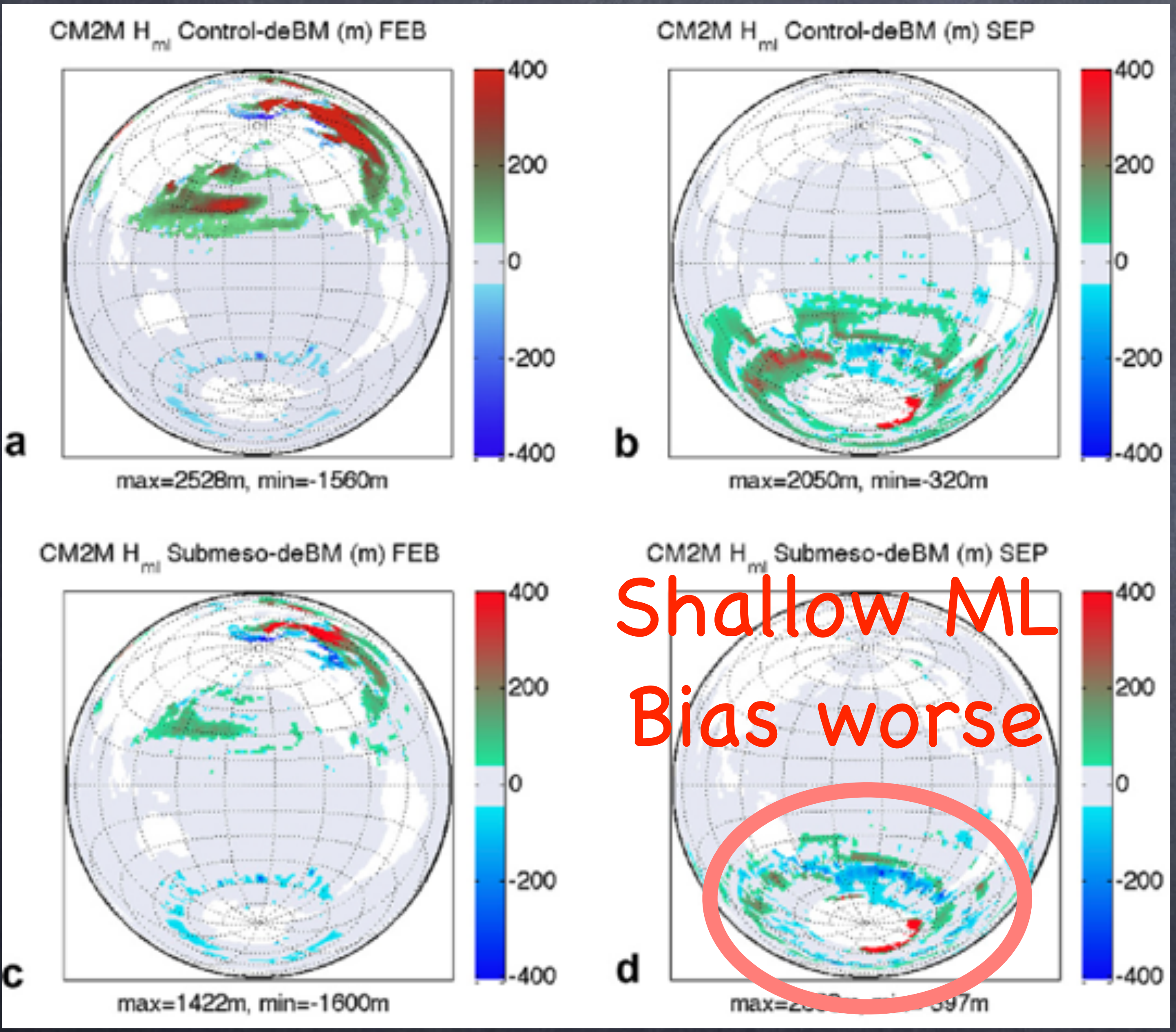




Movie: P. Hamlington

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.

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



Bias w/o 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.

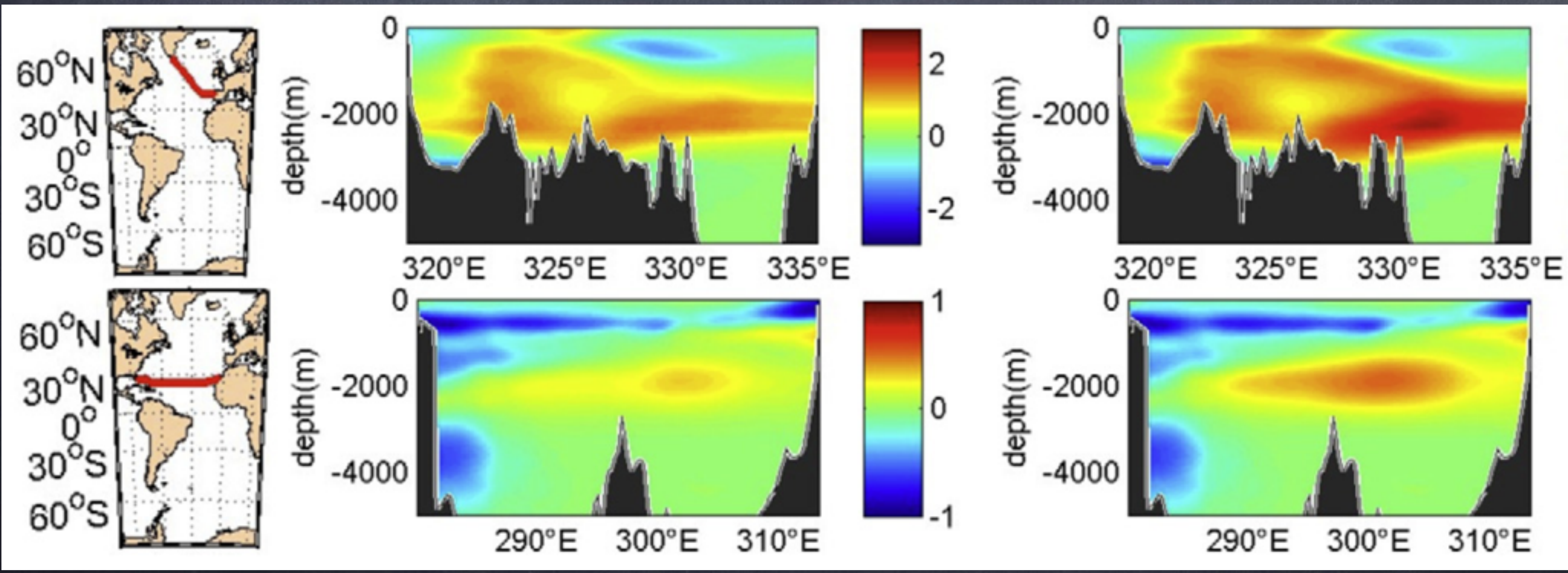
Physical Sensitivity of Ocean Climate to Submesoscale Mixed Layer Eddy Restratification:

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

So, climate models still arent perfect. Now what?

- Resolve more! (marginally possible)
- Make existing parameterizations better! (not today)
- Look for important neglected physics!
  - Submesoscale Eddies (help, but not enough)
  - Langmuir (Wave-Driven) Mixing
  - Combinations?

The Character of the Langmuir Scale

image:
Thorpe, 04

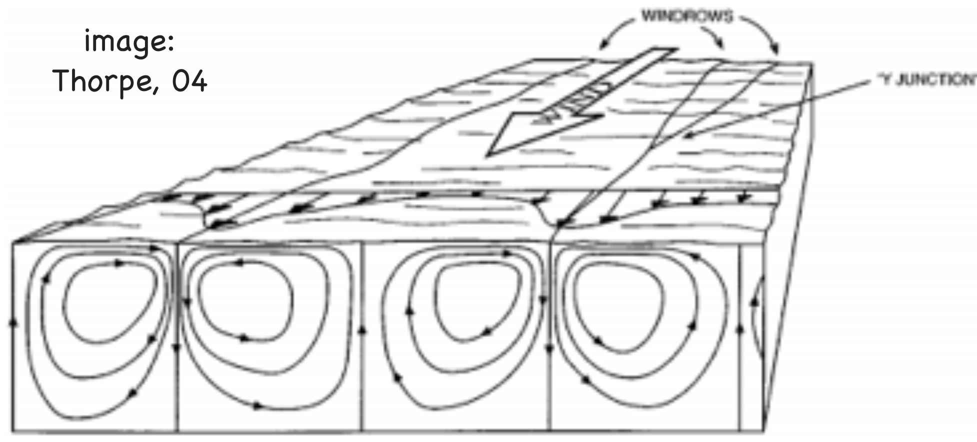


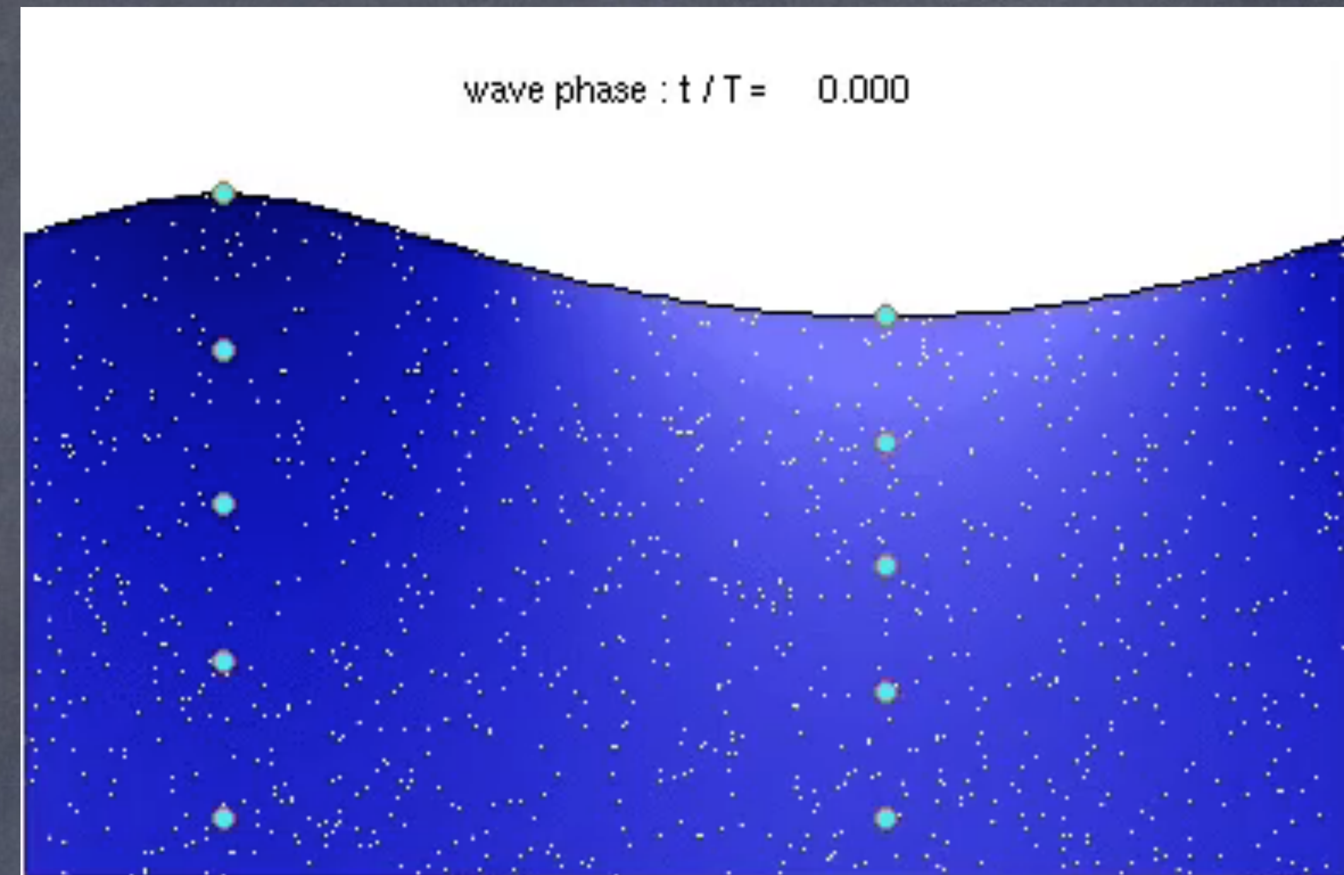
Figure 1 Sketch showing the pattern of mean flow in idealized Langmuir circulation. The windrows may be 2 m to 300 m apart, and the cell form is roughly square (as shown). In practice the flow is turbulent, especially near the water surface, and the windrows (Figure 2) amalgamate and meander in space 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
- Params: McWilliams & Sullivan, 2000, Van Roekel et al. 2011
- Resolved routinely in 2170

Image: NPR.org, Deep Water Horizon Spill

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:

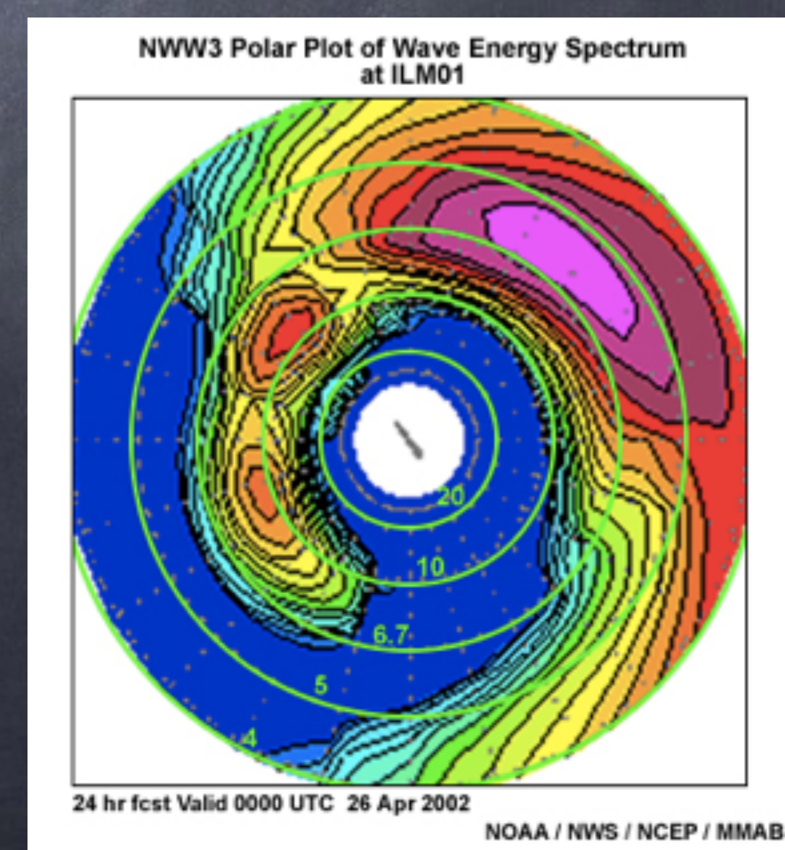
Monochromatic: $$\mathbf{u}^S = \hat{\mathbf{e}}^w \frac{8\pi^3 a^2 f_p^3}{g} e^{\frac{8\pi^2 f_p^2}{g} z}$$

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

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.

Typical Wave Spectrum:



So, we'll quantify Langmuir effects vs. a control without wave effects

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

- 2) From OBSERVATIONS, estimate wave effects on key parameters ($\langle w^2 \rangle$, sources of energy) using scalings from Large Eddy Simulations. MODEL INDEPENDENT

- 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

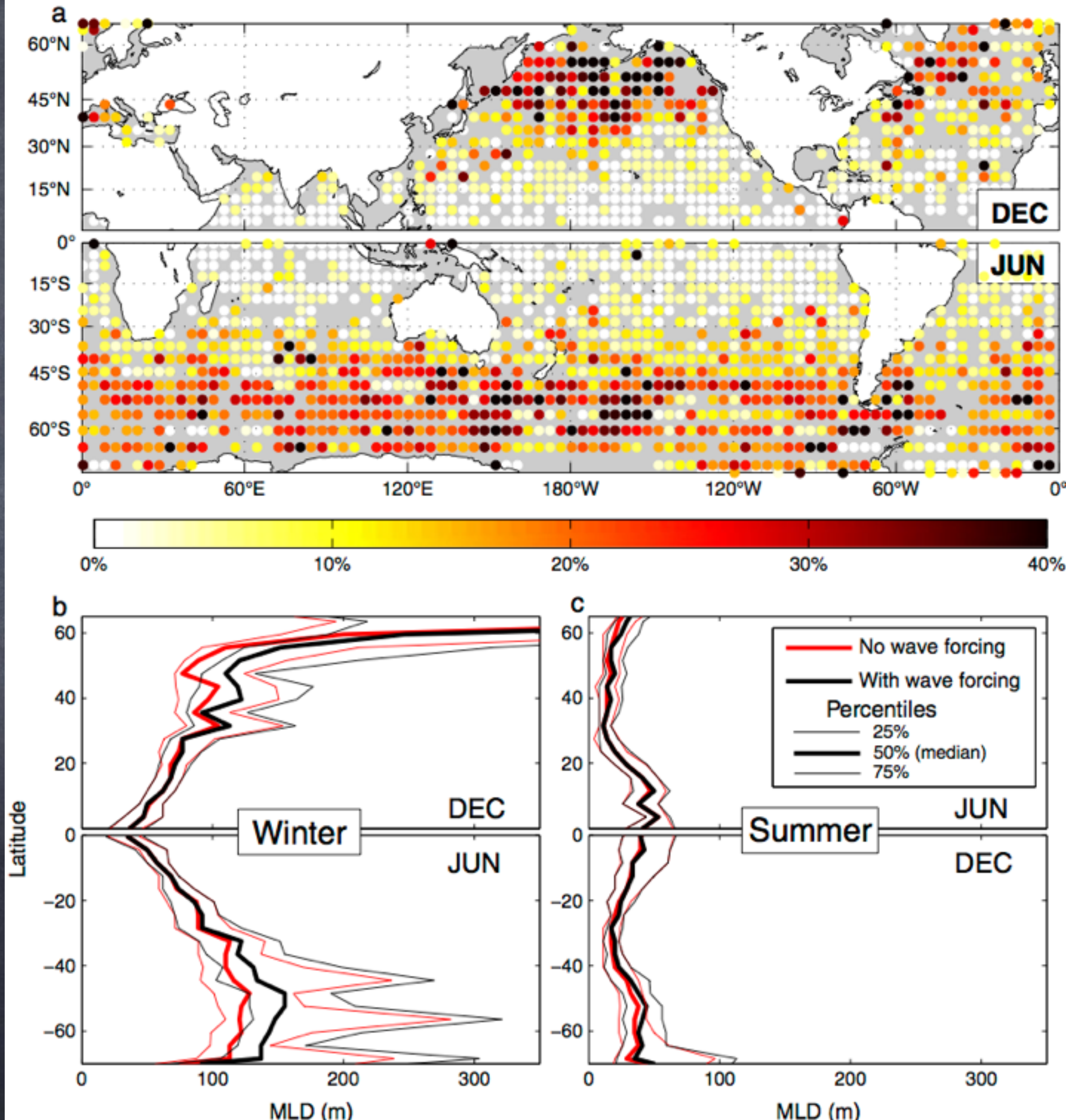
No Retuning! All coefficents from LES

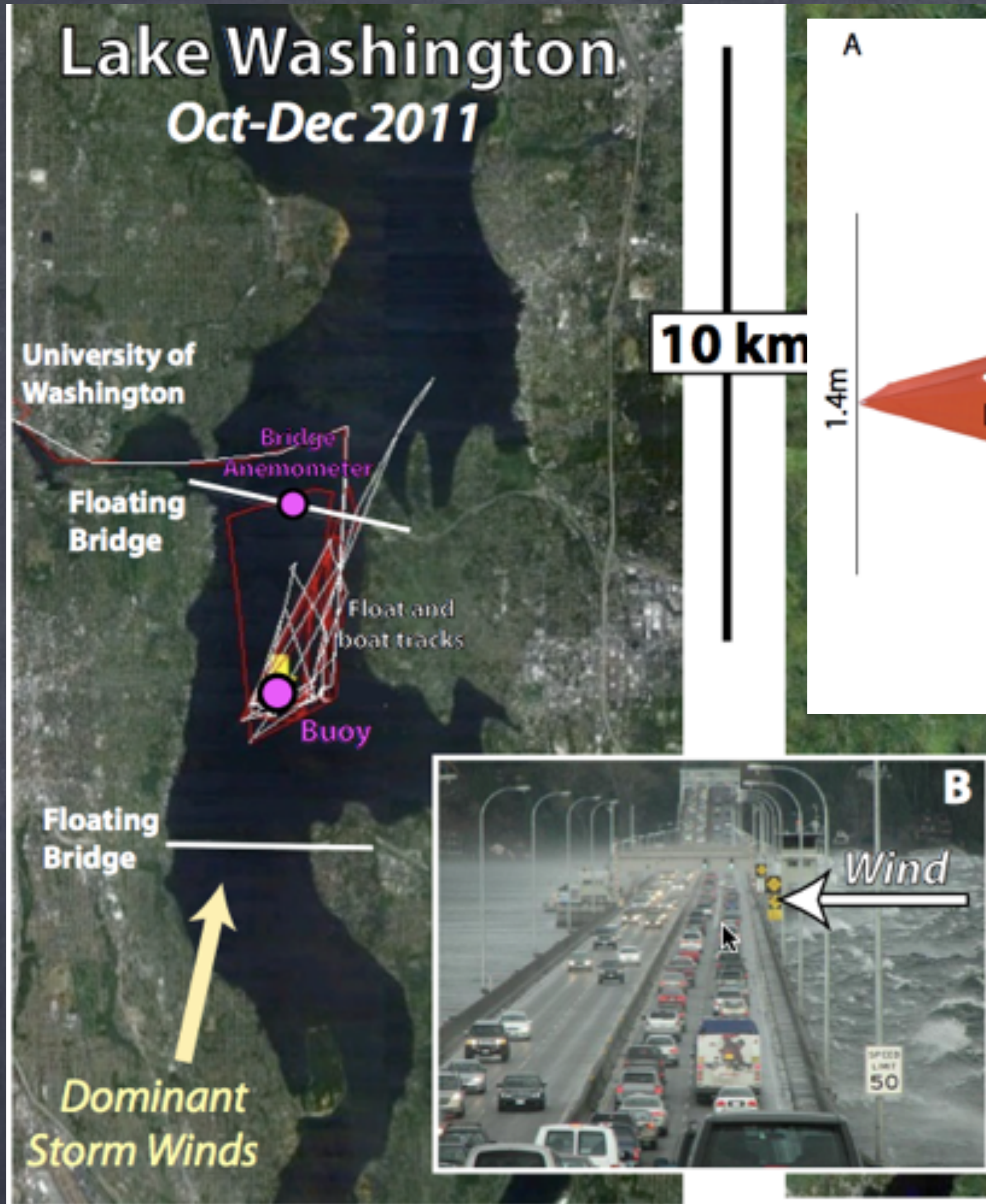
Offline obs-driven parameterization:

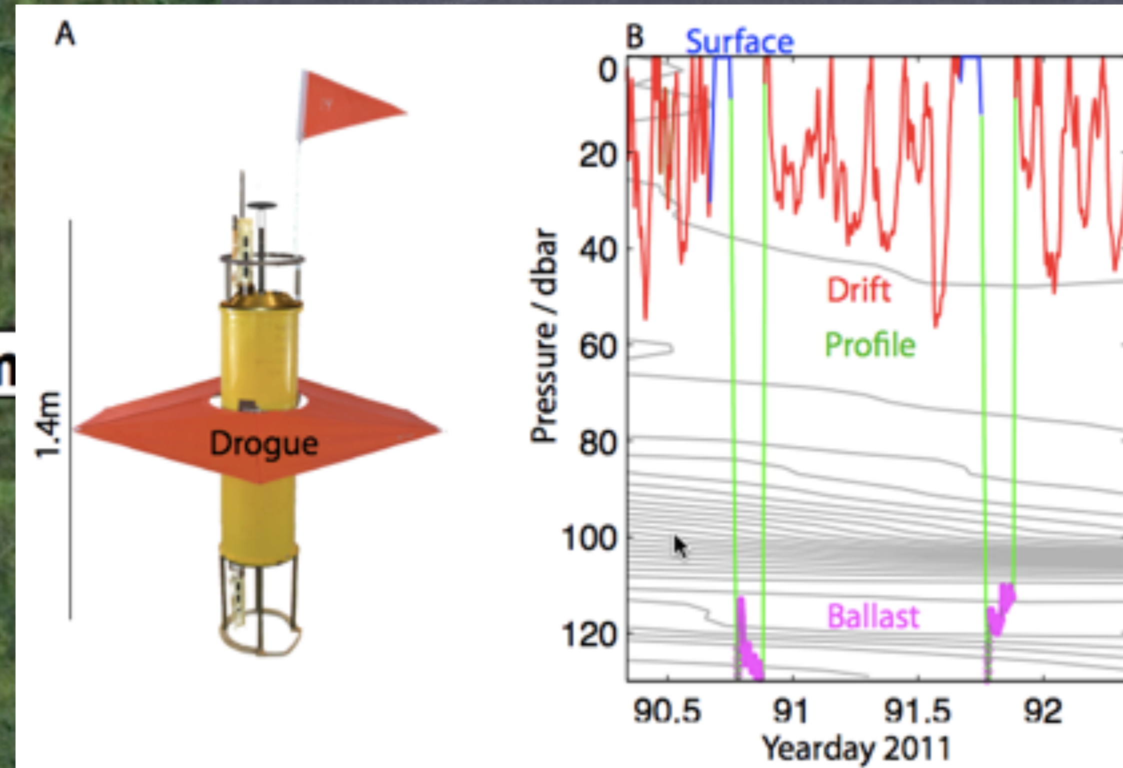
Including Stokes-driven Mixing (Harcourt 2013 parameterization)

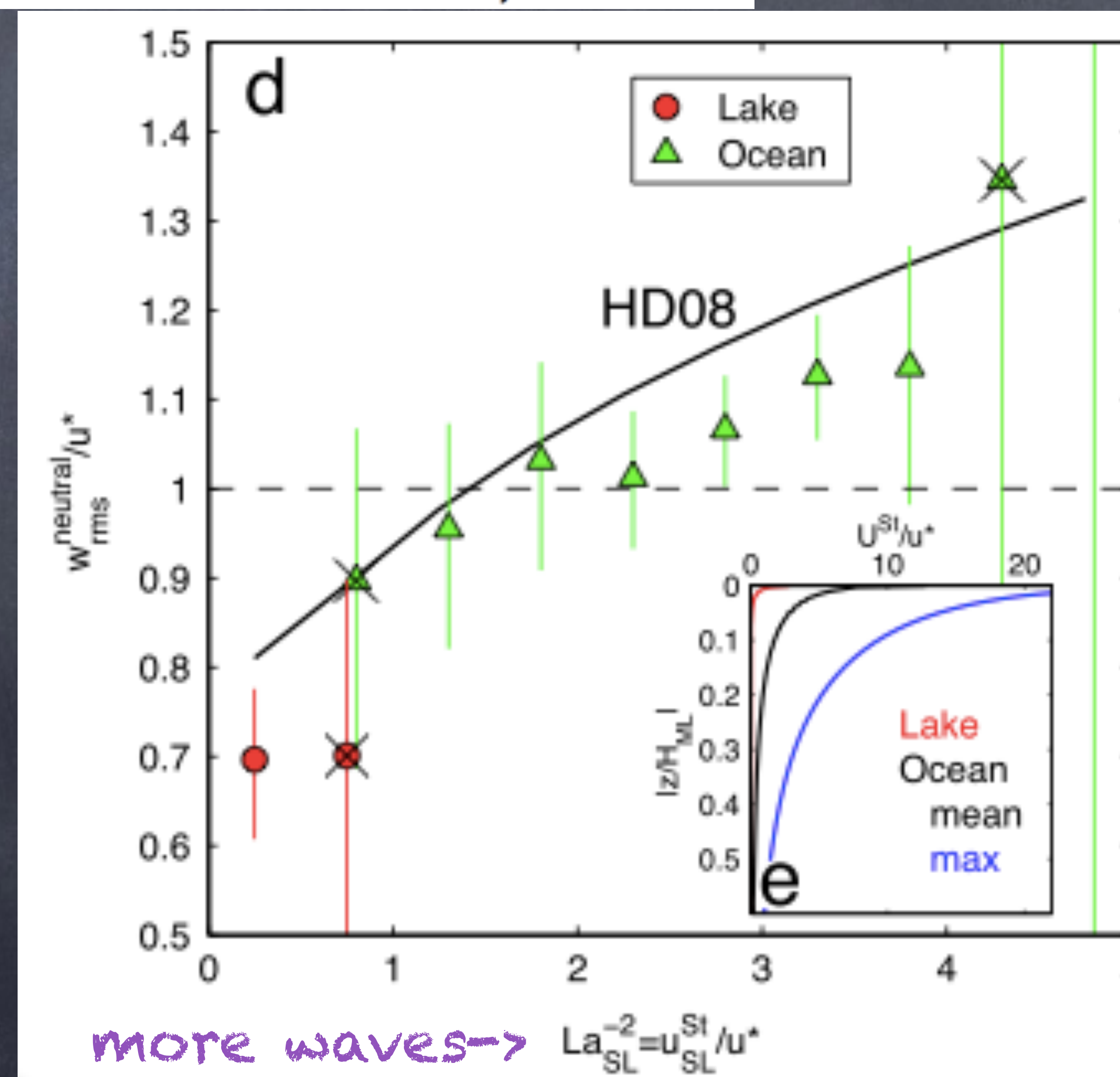
Deepens the Mixed Layer about 30%!

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.







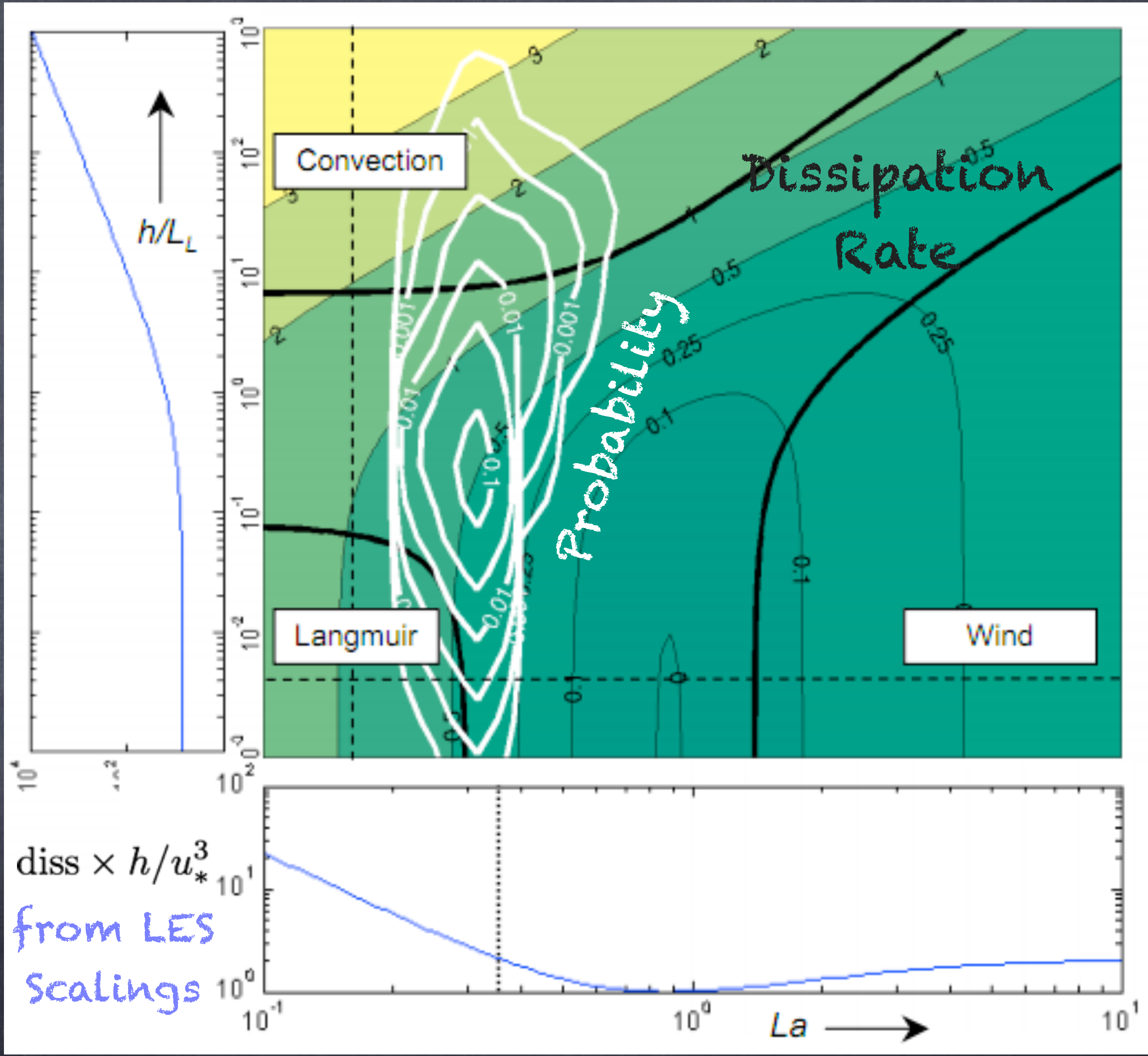


E. A. D'Asaro, J. Thomson, A. Y. Shcherbina, R. R. Harcourt, M. F. Cronin, M. A. Hemer, and BFK. Quantifying upper ocean turbulence driven by surface waves. Geophysical Research Letters, 41(1):102-107, January 2014.

Direct observations obey the same scaling for $<w^2>$!

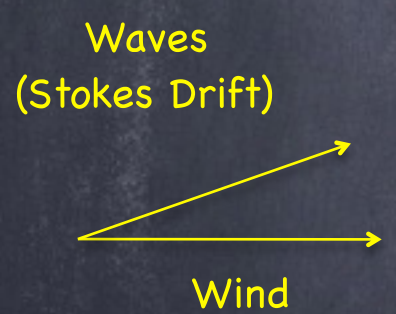
Data + Large Eddy Simulation for scaling laws, Southern Ocean data to determine available mixing energy

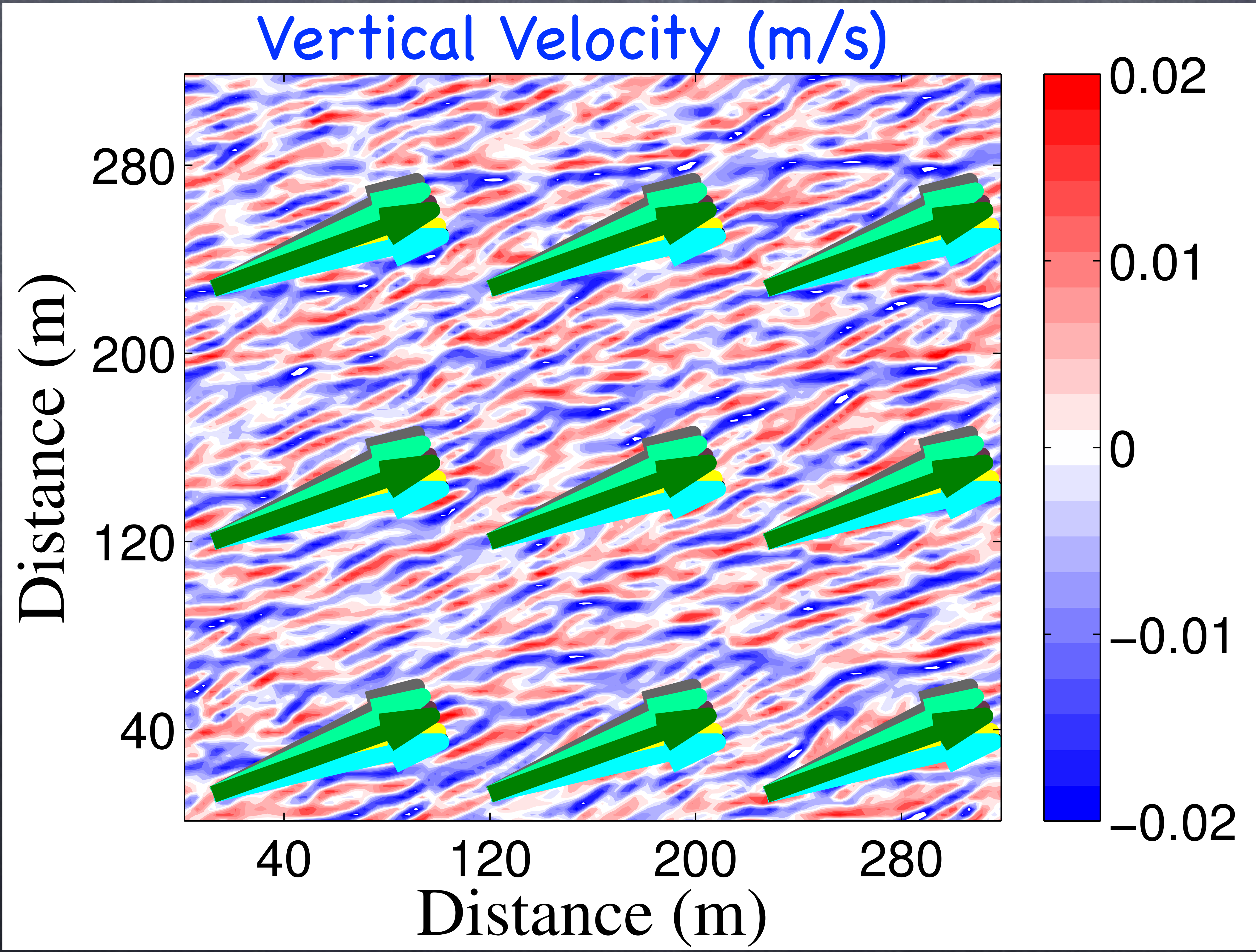
So, waves are likely to drive mixing via Stokes drift (combines with cooling & winds)



S. E. Belcher, A. A. L. M. Grant, K. E. Hanley, 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.

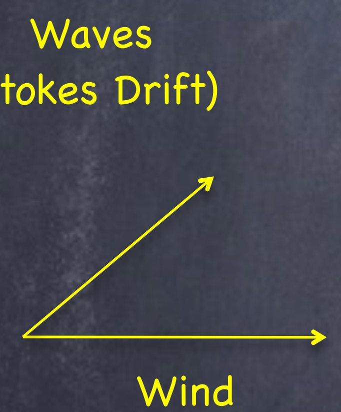
Climate Model Parameterization based on Large Eddy Simulations of Langmuir Turbulence. Tricky: Misaligned Wind & Waves



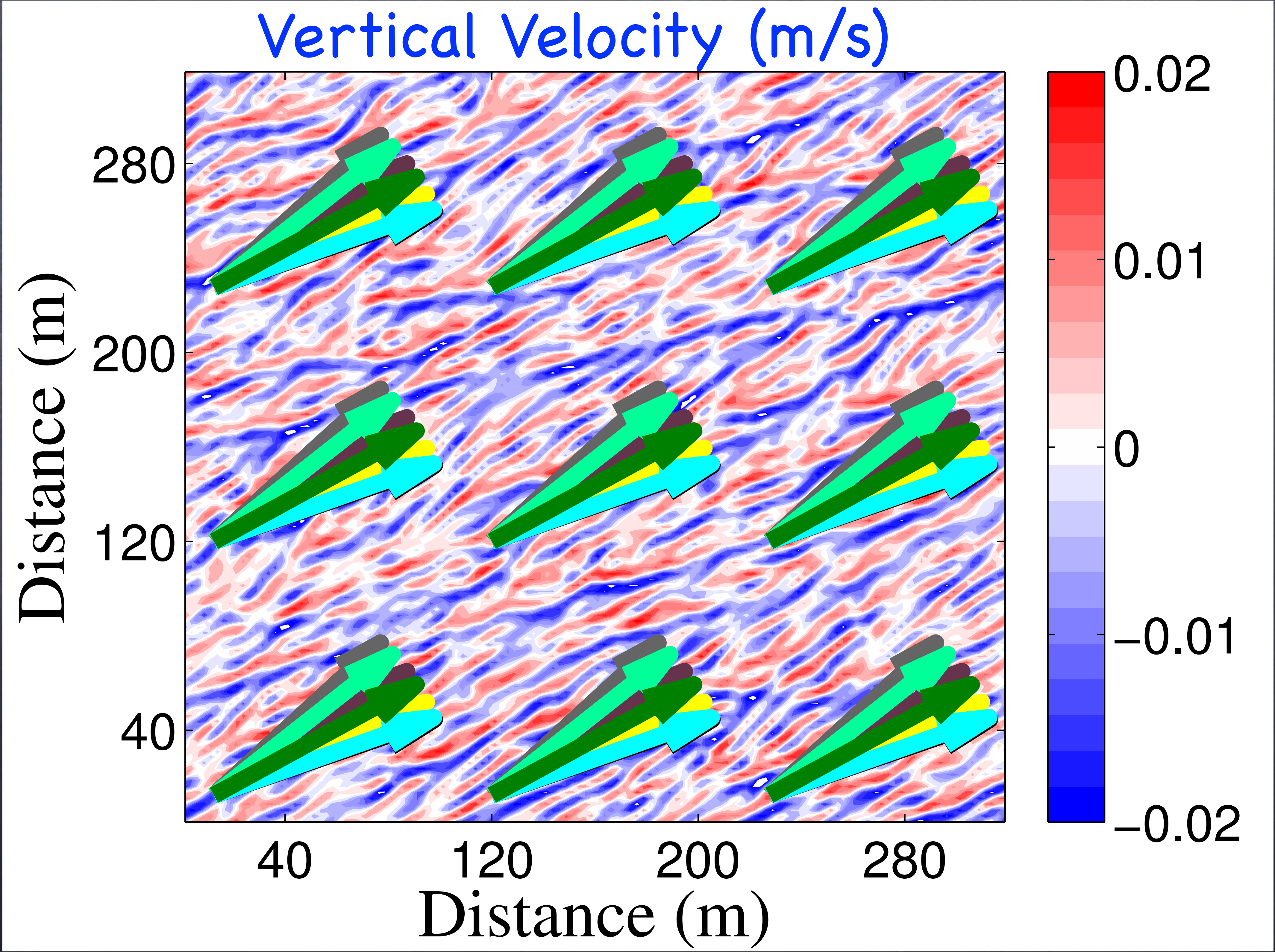


L. P. Van Roekel, B. Fox-Kemper, P. P. Sullivan, P. E. Hamlington, and S. R. Haney. The form and orientation of Langmuir cells for misaligned winds and waves. Journal of Geophysical Research-Oceans, 117:C05001, 22pp, May 2012.

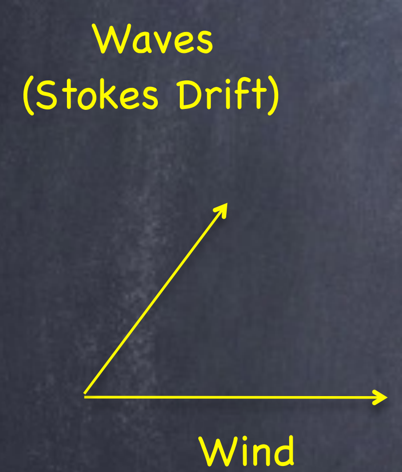
Tricky: Misaligned Wind & Waves

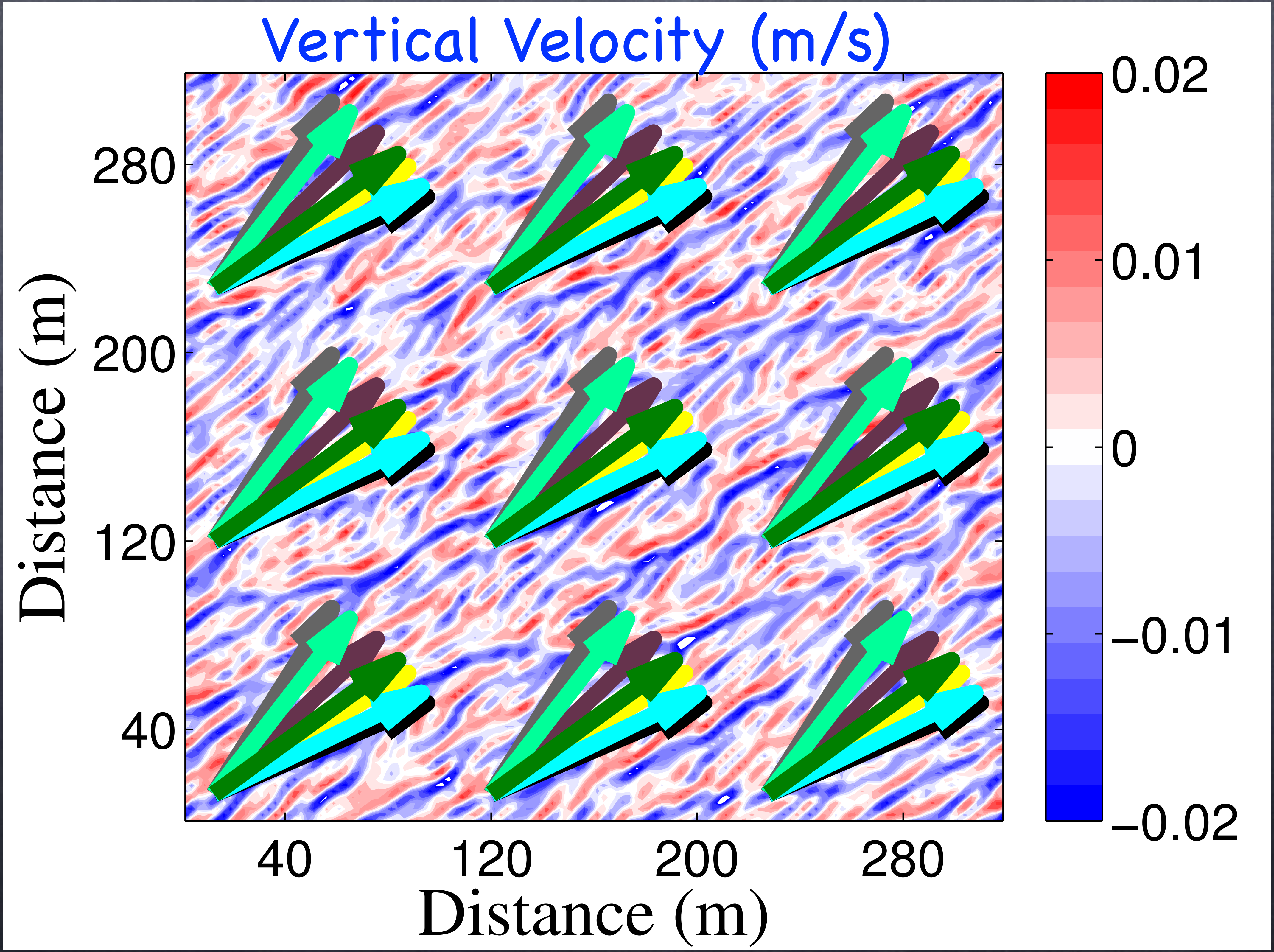


L. P. Van Roekel, B. Fox-Kemper, P. P. Sullivan, P. E. Hamlington, and S. R. Haney. The form and orientation of Langmuir cells for misaligned winds and waves. Journal of Geophysical Research-Oceans, 117:C05001, 22pp, May 2012.



Tricky: Misaligned Wind & Waves

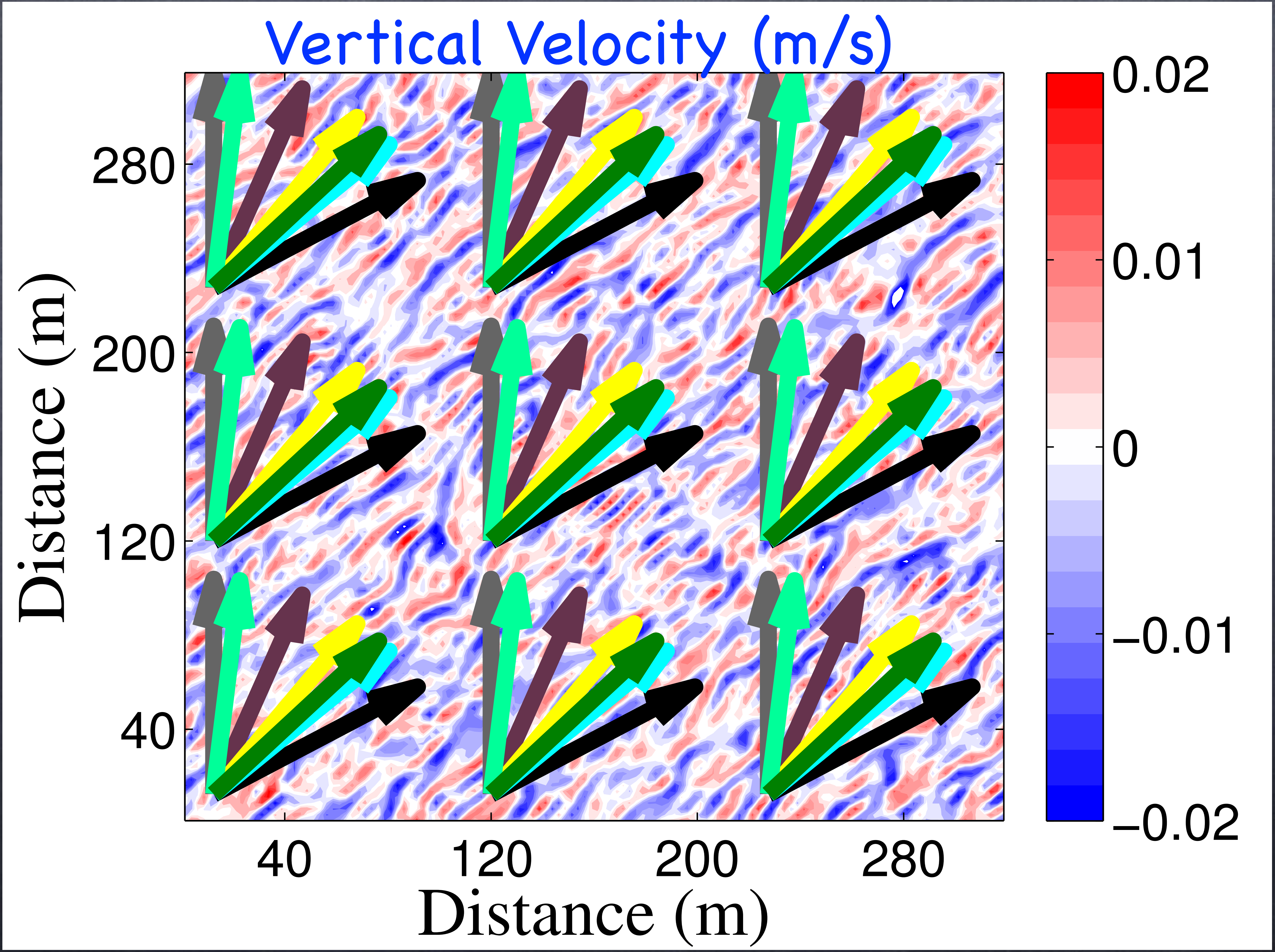




L. P. Van Roekel, B. Fox-Kemper, P. P. Sullivan, P. E. Hamlington, and S. R. Haney. The form and orientation of Langmuir cells for misaligned winds and waves. Journal of Geophysical Research-Oceans, 117:C05001, 22pp, May 2012.

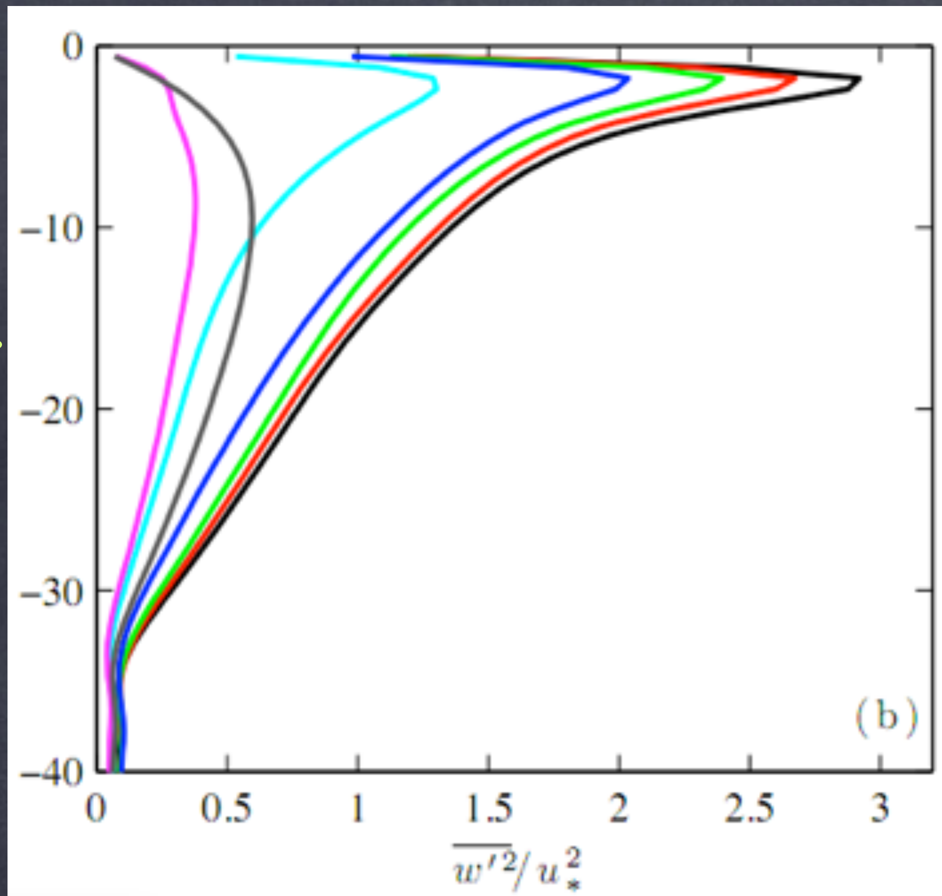
Tricky: Misaligned Wind & Waves

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.



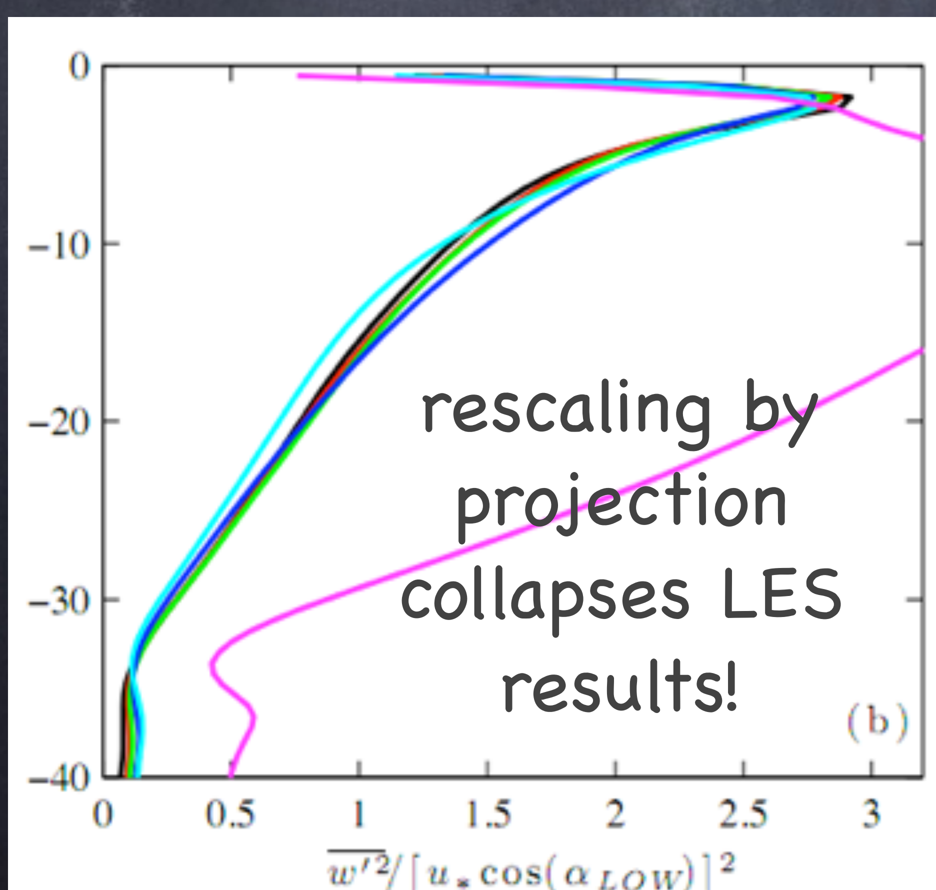
$\langle w^2 \rangle$

depth



rescaled $\langle w^2 \rangle$

depth



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

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

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

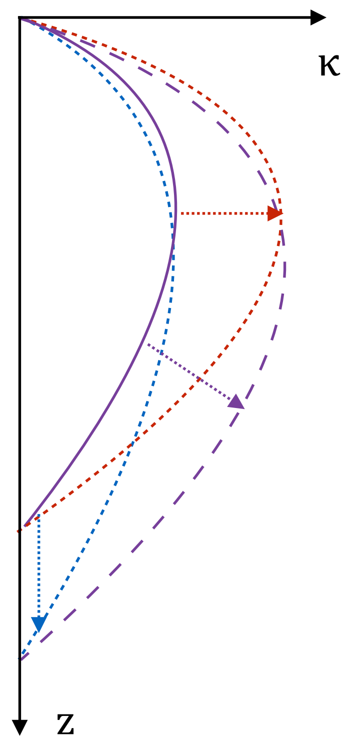
$$\alpha_{LOW} \approx \tan^{-1}\left(\frac{\sin(\theta_{ww})}{\frac{u_*}{u_s(0)\kappa} \ln\left(\left|\frac{H_{ML}}{z_1}\right|\right) + \cos(\theta_{ww})}\right)$$

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.

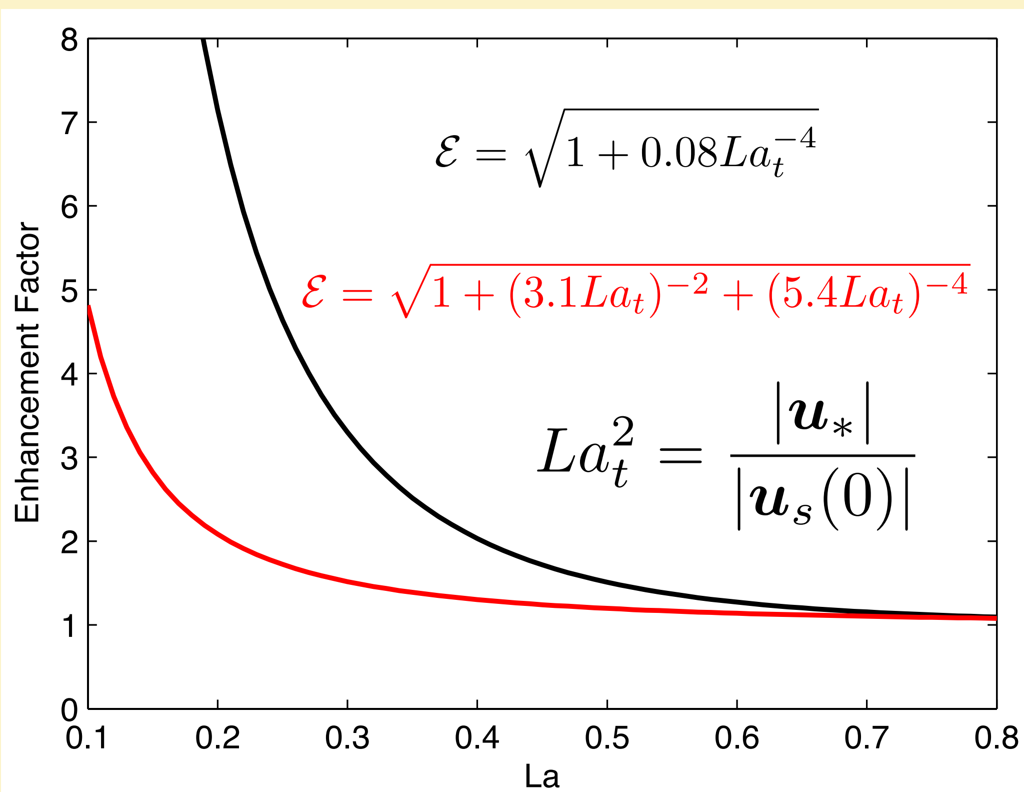
Langmuir Mixing in KPP for use in CESM1.2



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
- 4 IAF cycles; average over last 50 years for climatology (over 200 years total)

MS2K

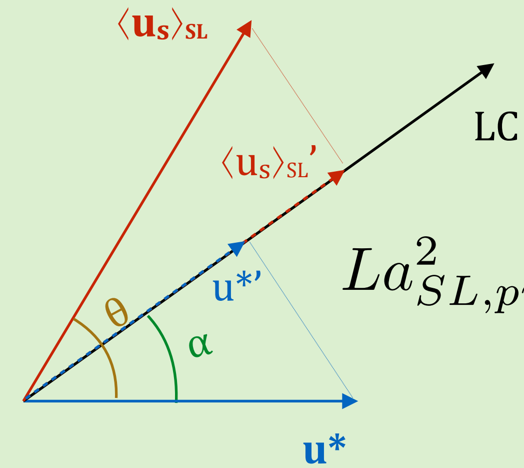


VR12-AL

Revise Enhancement factor to vertical velocity scale W

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 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 et al., 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

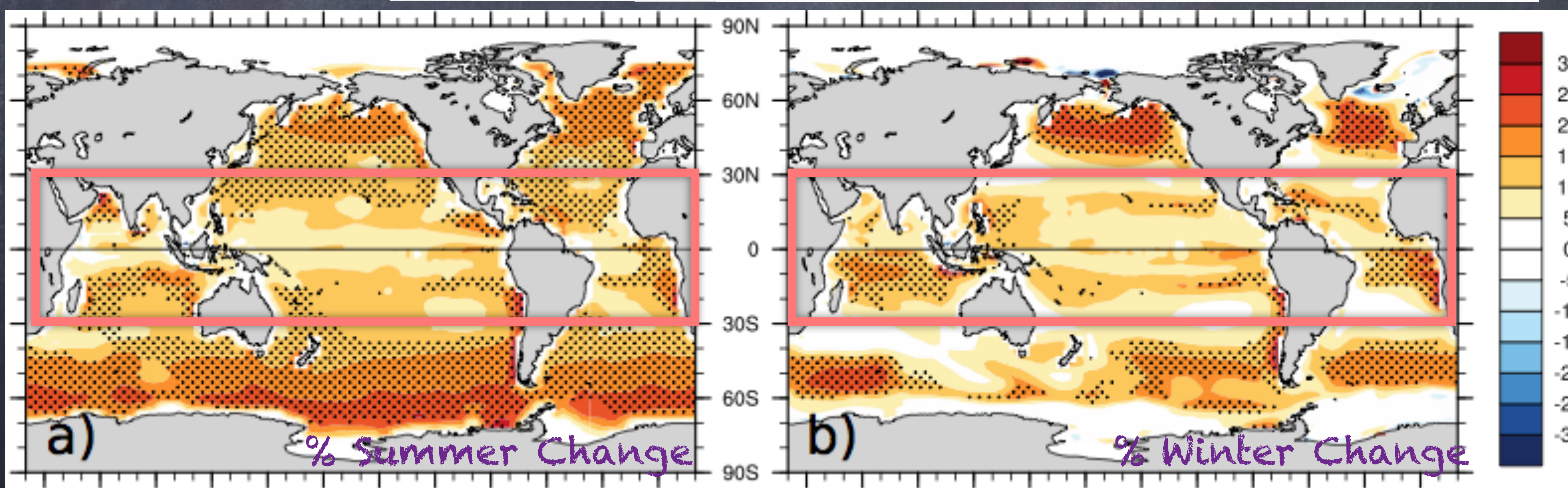
[a] Numbers shown in the parentheses are for the fully coupled experiments.

Control

Competition

3 versions of Van Roekel et al

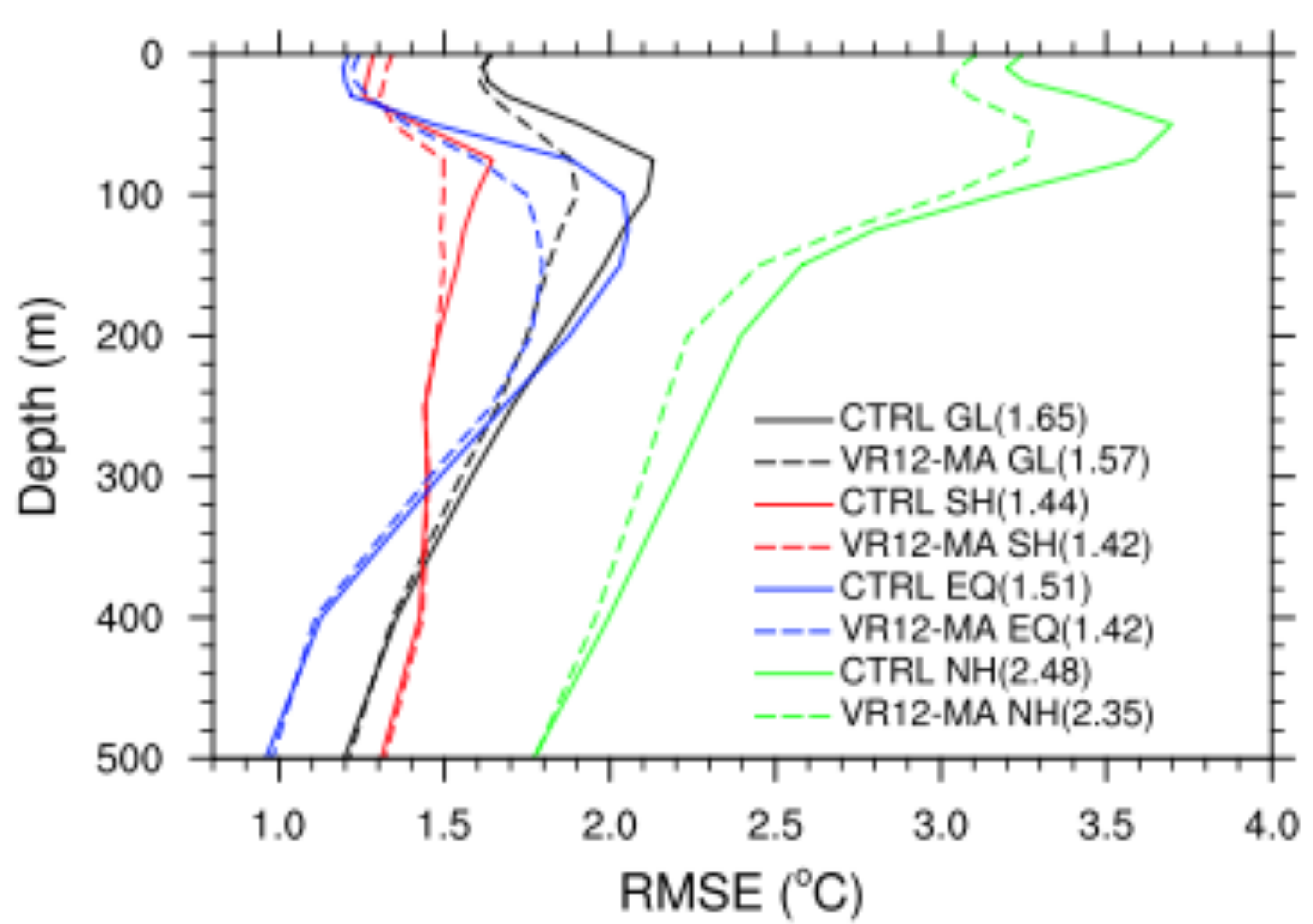
dotted when statistical significant

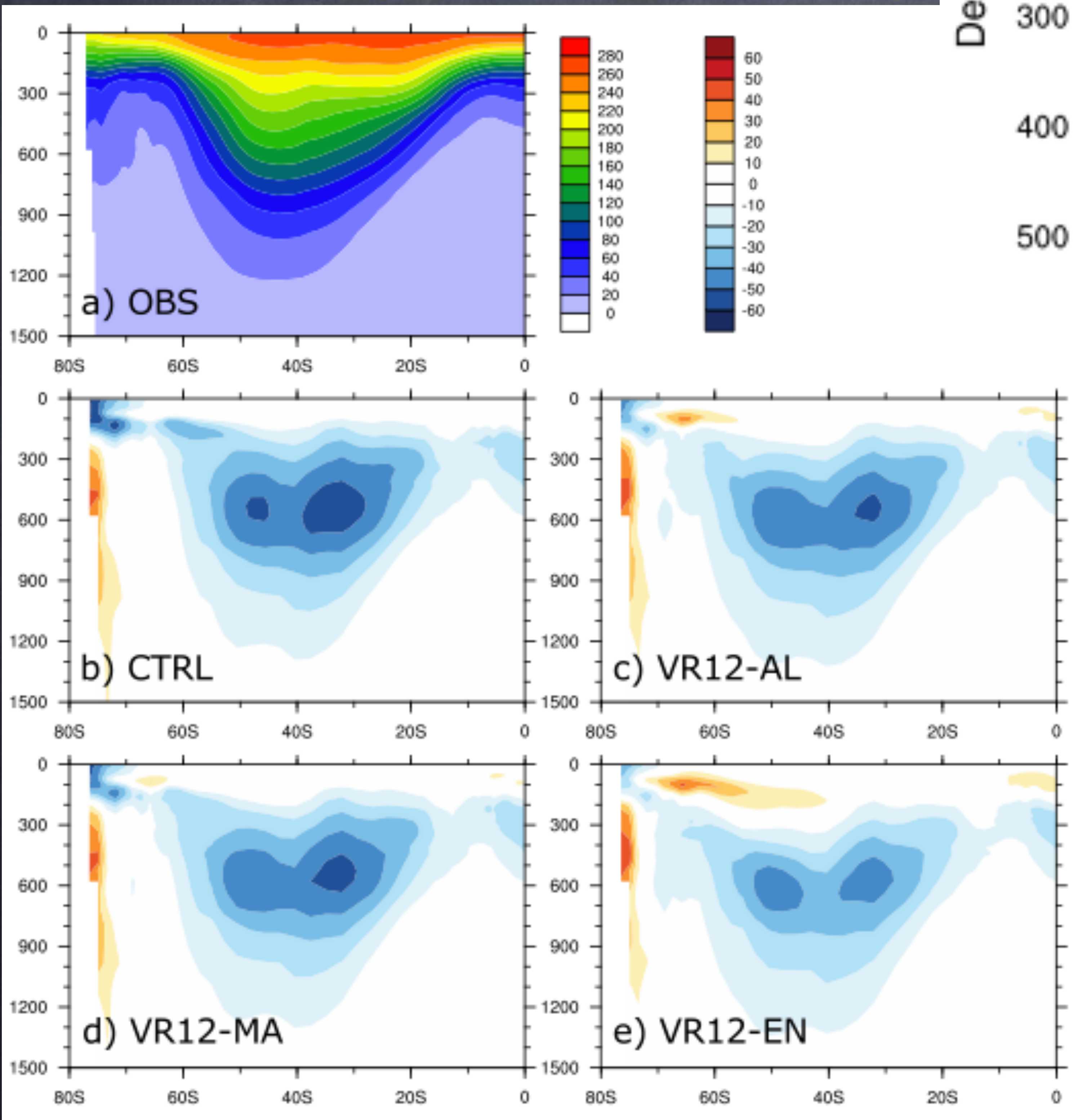


L. P. Van Roekel, BFK, P. P. Sullivan, P. E. Hamlington, and S. R. Haney. The form and orientation of Langmuir cells for misaligned winds and waves. Journal of Geophysical Research-Oceans, 117:C05001, 22pp, May 2012.

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.

Wave Mixing in CESM: Reduces Subsurface CFC & Temperature Errors





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.

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)

geostrophic

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

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

hydrostatic

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

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

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 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 slope (ka), irrotational --> Deep Water Waves!
  - Average over deep water waves in space & time,
  - Arrive at Large, Slow equation set.

All Wave-Mean coupling terms involve the Stokes Drift

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

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!

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

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

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

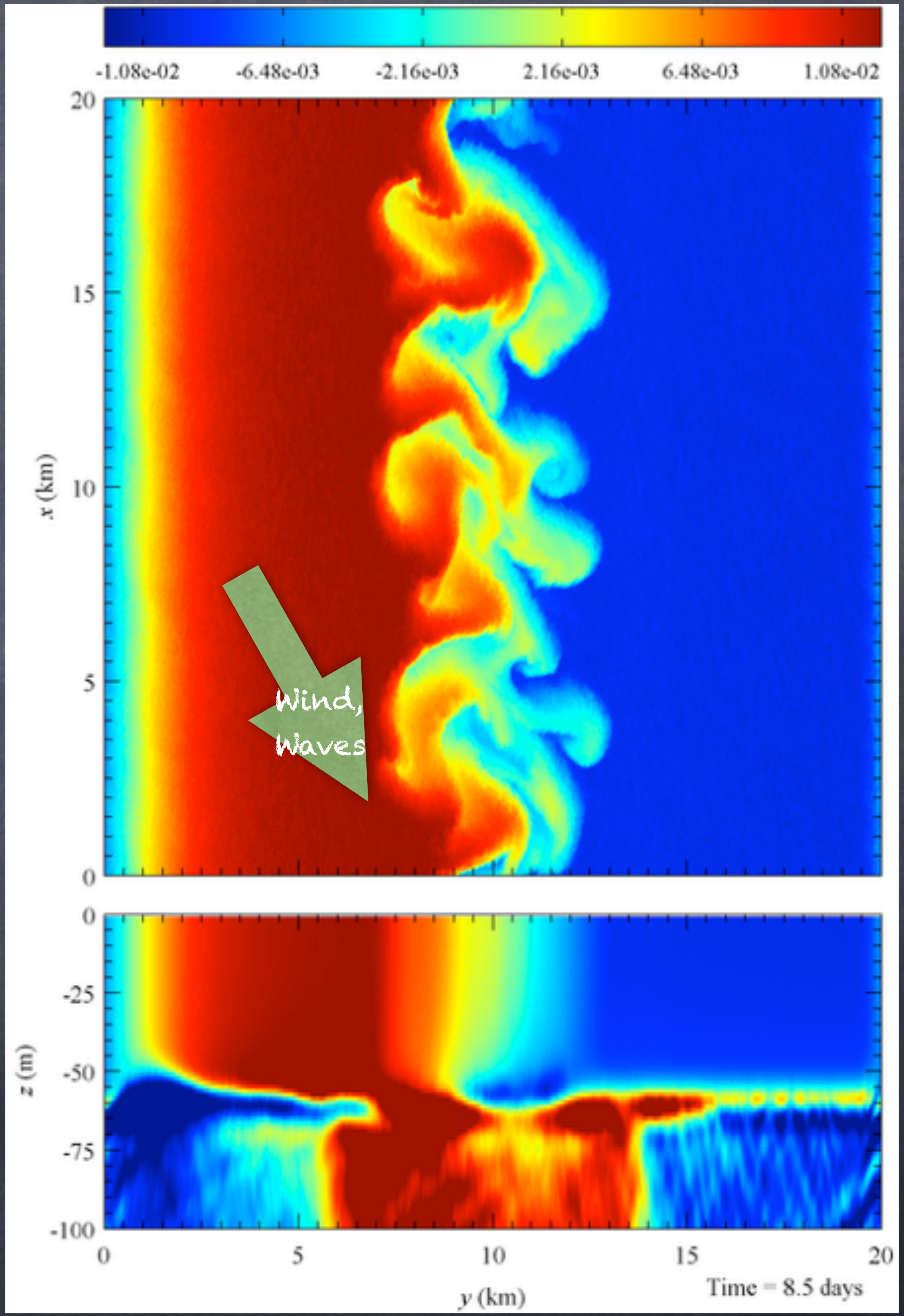
Stokes shear force is NEW *nonhydrostatic* term in Vert. Mom.

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?

Movie: P. Hamlington



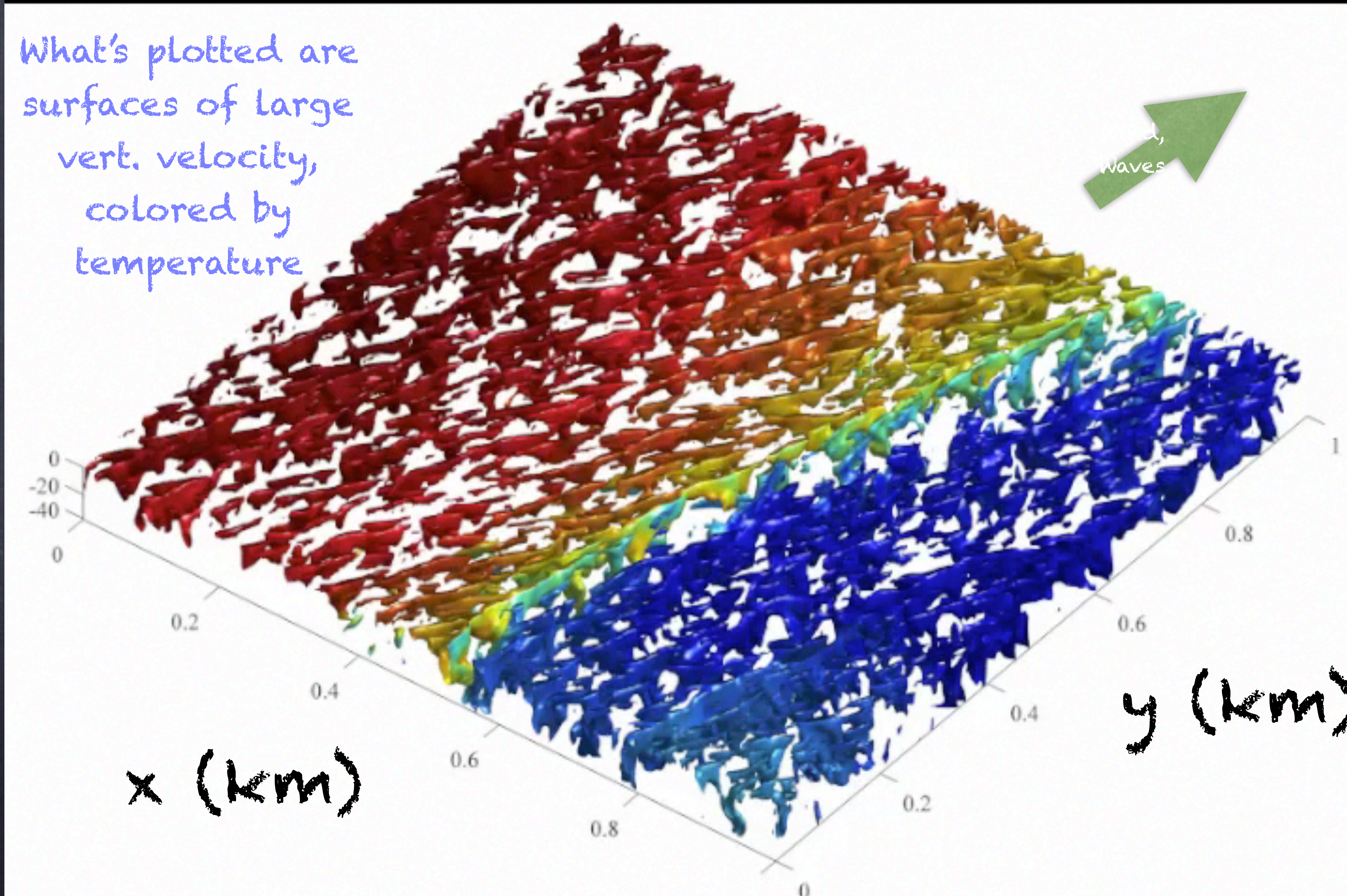
Perform large eddy simulations (LES) of Langmuir turbulence with a submesoscale temperature front

Use NCAR LES model to solve Wave-Averaged Eqtns.

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

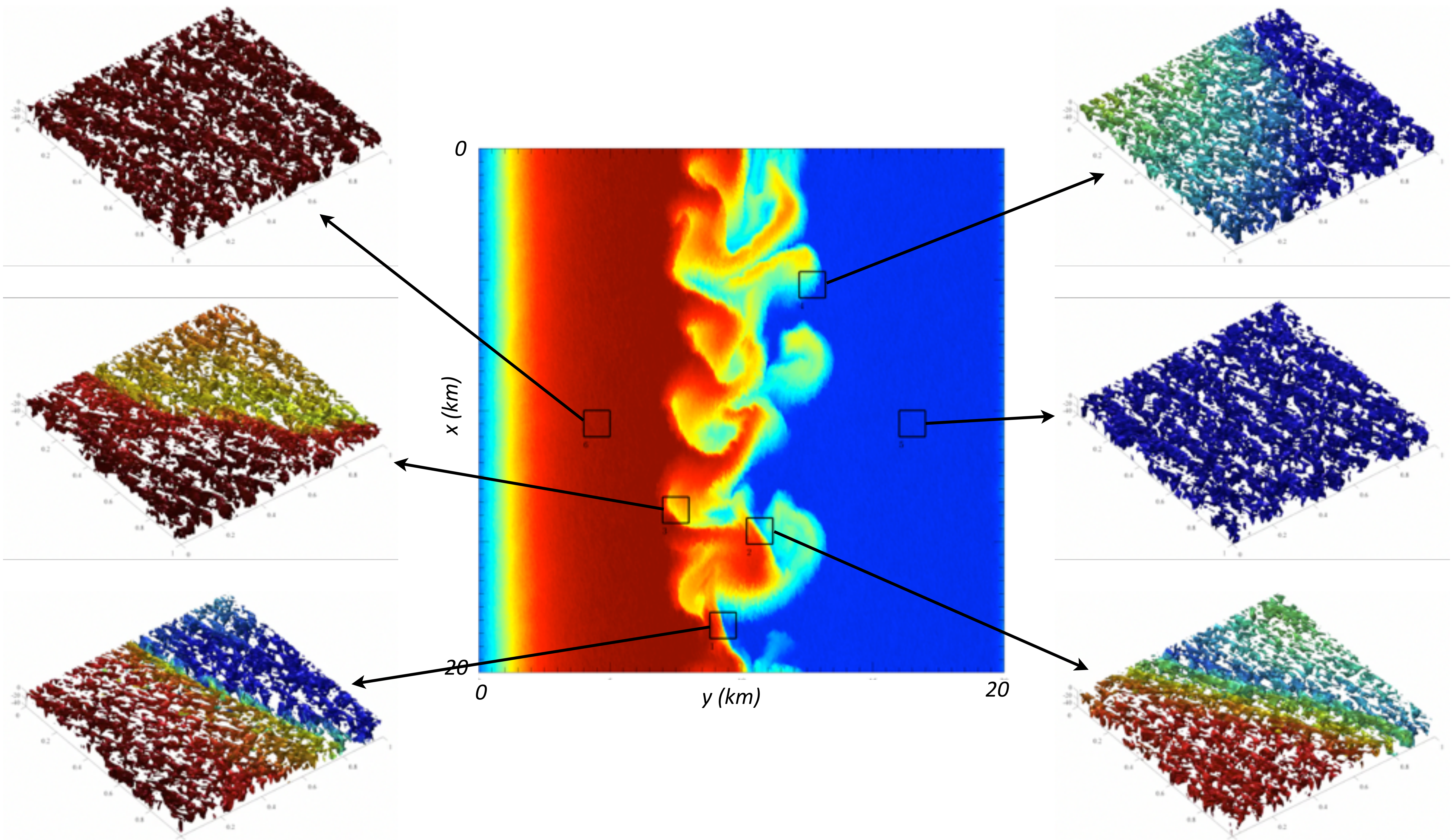
Computational parameters:
Domain size: 20km x 20km x -160m
Grid points: 4096 x 4096 x 128
Resolution: 5m x 5m x -1.25m
1000x more gridpoints than CESM

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.



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.

So, Waves can Drive turbulence that affect larger scales indirectly:

What about direct effects of waves on larger scales?

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

Becomes Lagrangian Thermal Wind Balance

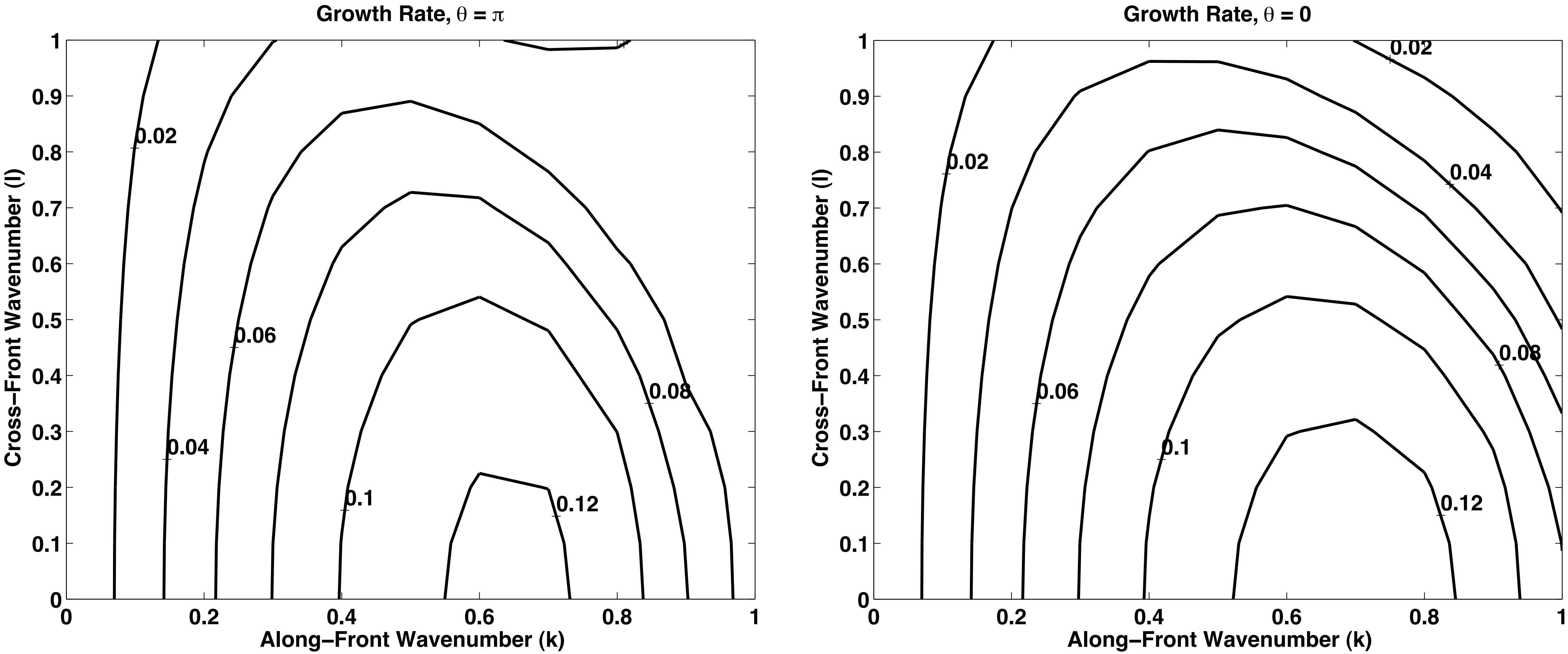
$$\mathbf{f} \times \frac{\partial}{\partial z}(\mathbf{v} + \mathbf{v}_s) = \mathbf{f} \times \frac{\partial \mathbf{v}_L}{\partial z} = -\nabla b$$

Now the temperature gradients govern the Lagrangian flow, not the 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.

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, In preparation, 2015.

Analytic Stability Criterion: Symmetric Instability

* Hoskins (1974) showed that if a front in thermal wind balance is symmetrically unstable, the PV must be negative.
* Haney et al extend to flows in Lagrangian (i.e. with Stokes drift) thermal wind balance in the special case that the Stokes drift is horizontally and time invariant, and the Stokes shear is constant.

$$U^S = \mu z$$

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

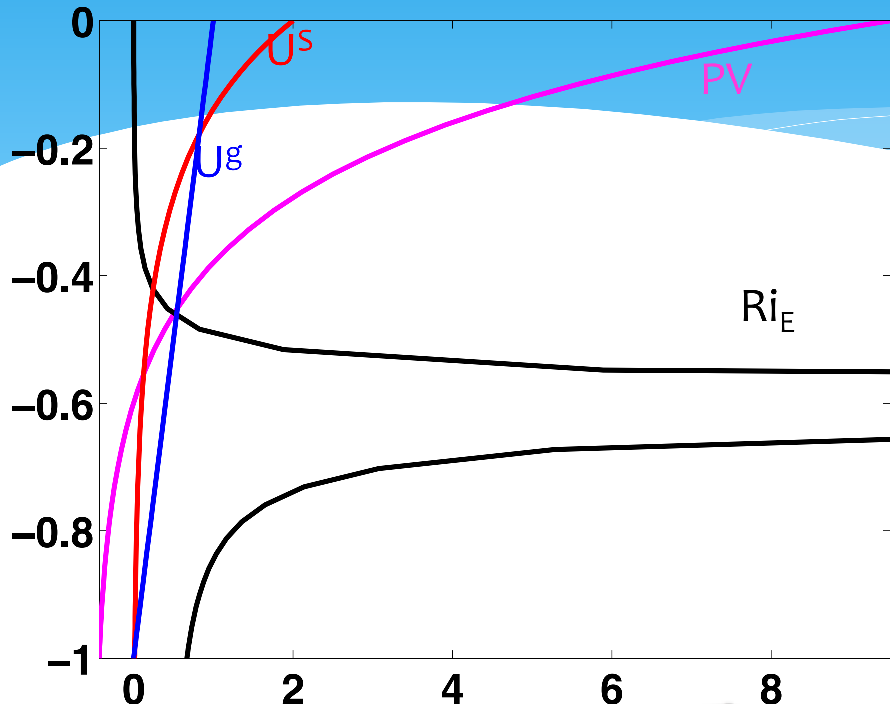
* In the absence of Stokes drift, this gives the familiar criteria on Ri^g.

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

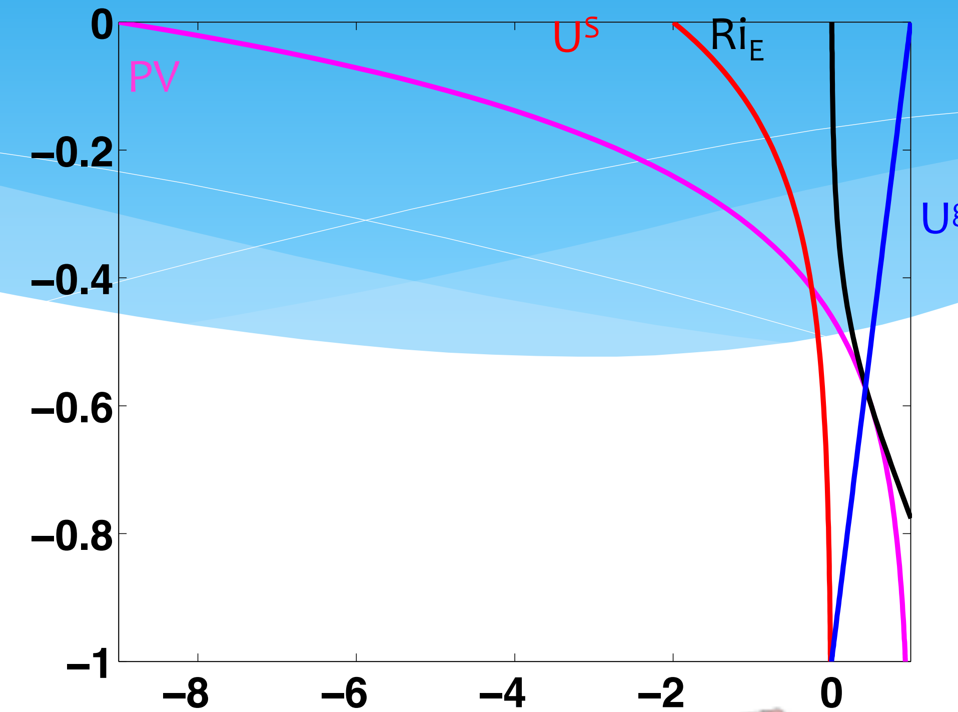
S. Haney, BFK, and K. Julien Symmetric and Geostrophic Instabilities in the Wave-Forced Ocean Mixed Layer, In preparation, 2015.

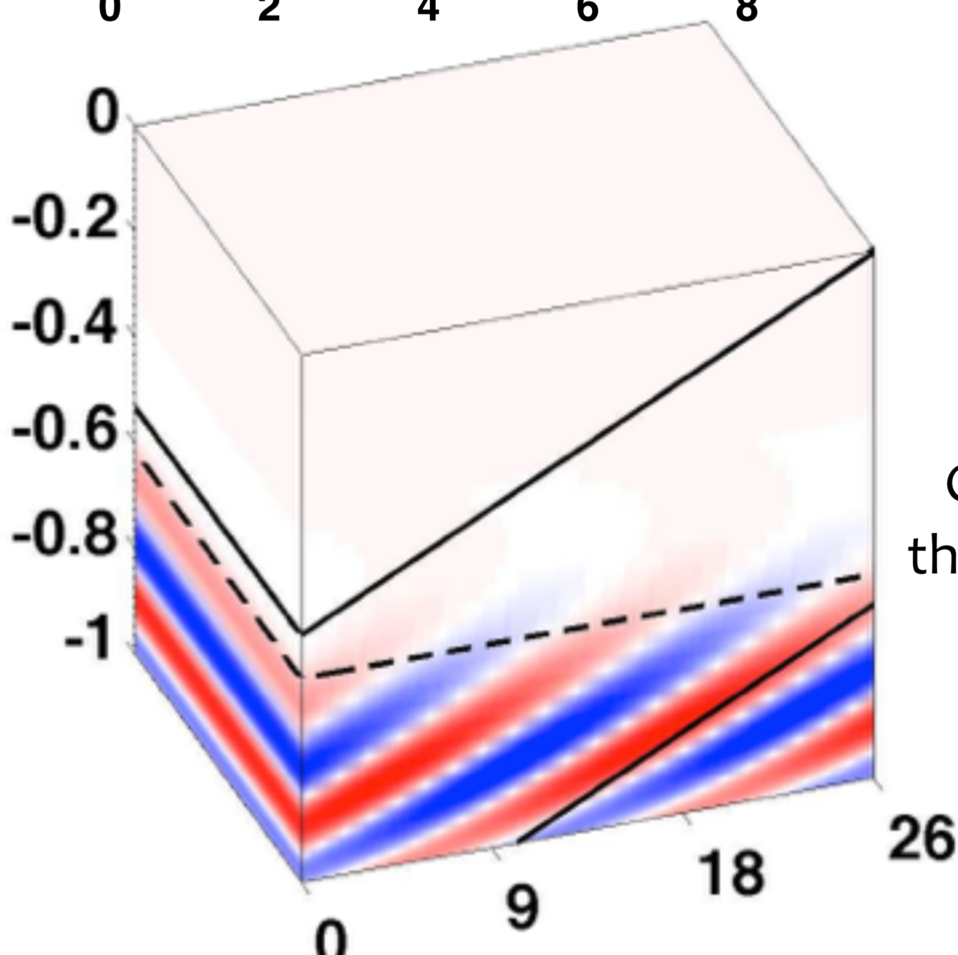
~~$Ri < 1 \Rightarrow SI$~~ $fQ < 0 \Rightarrow SI$

Ri = 0.5



Ri = 2

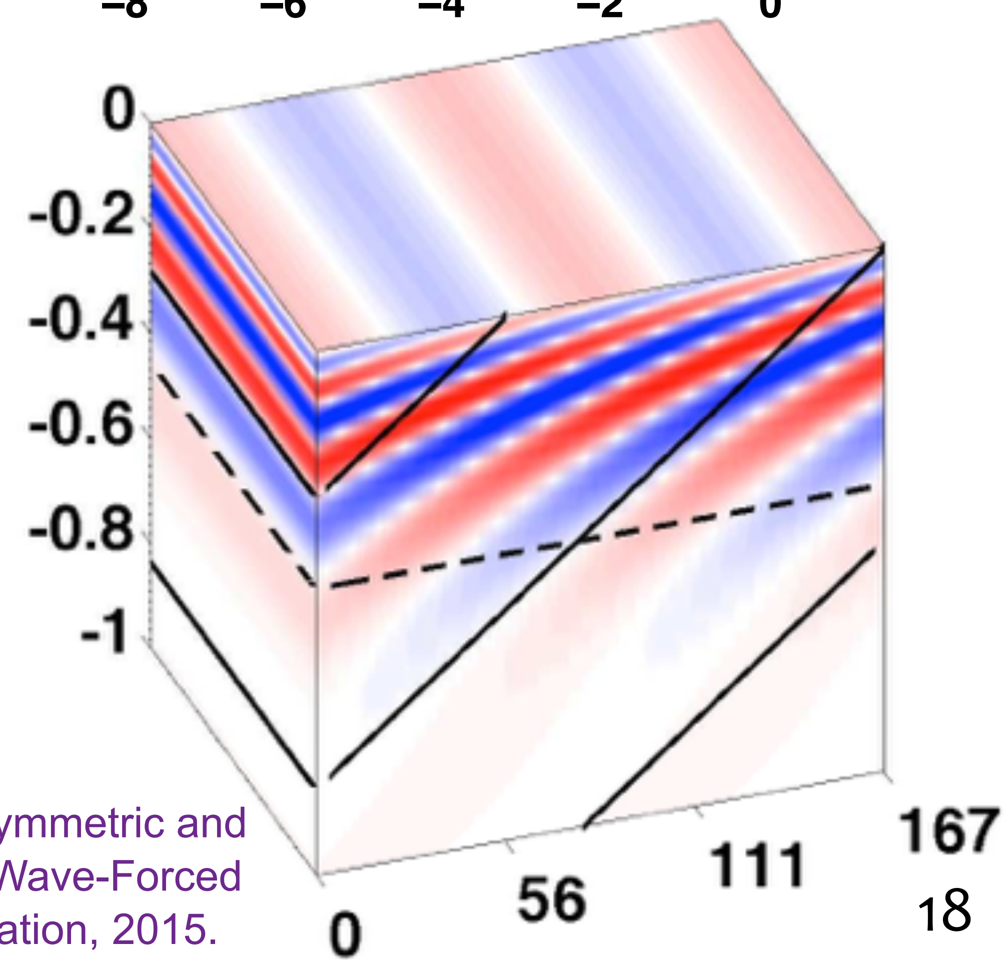




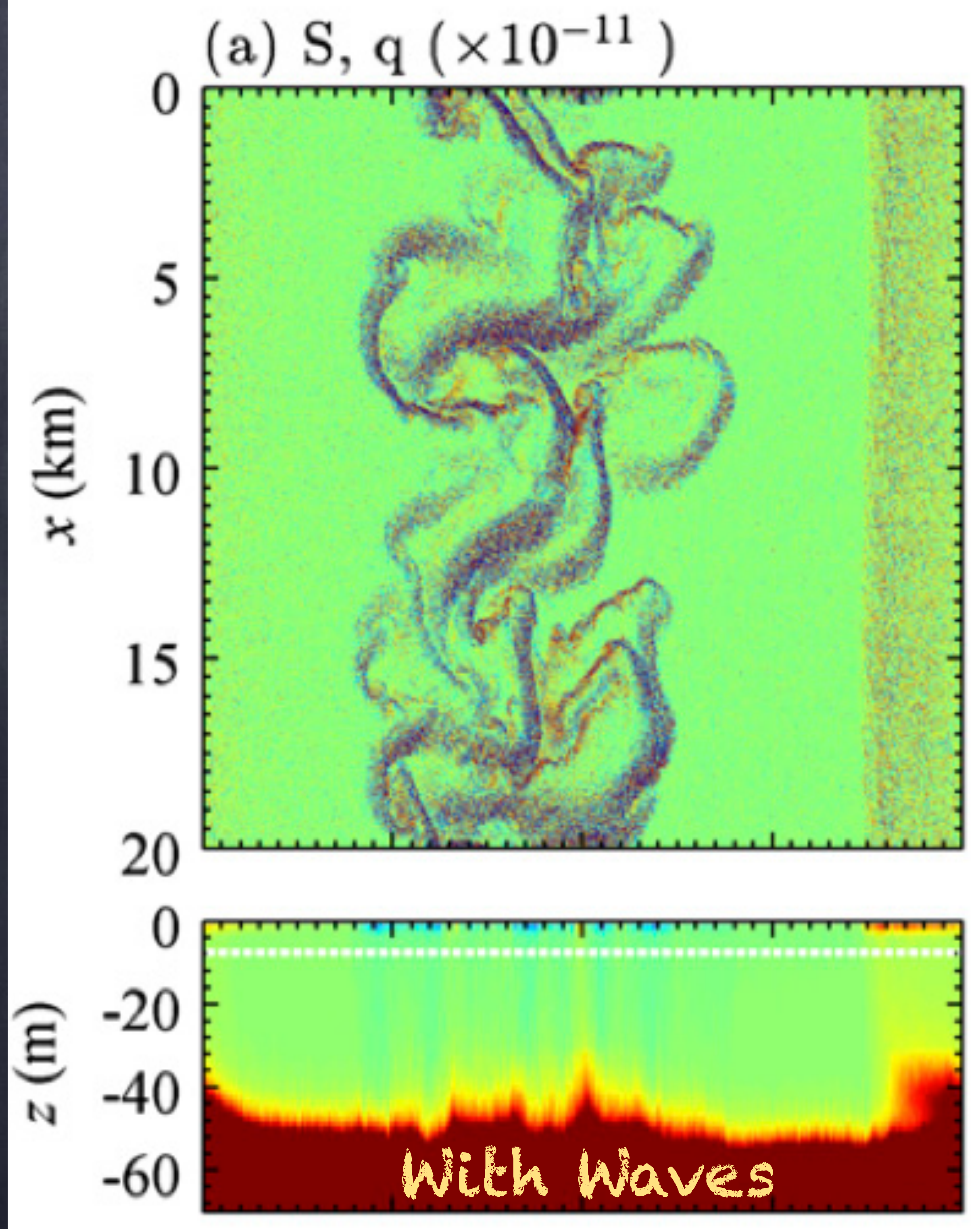
——Isopycnals

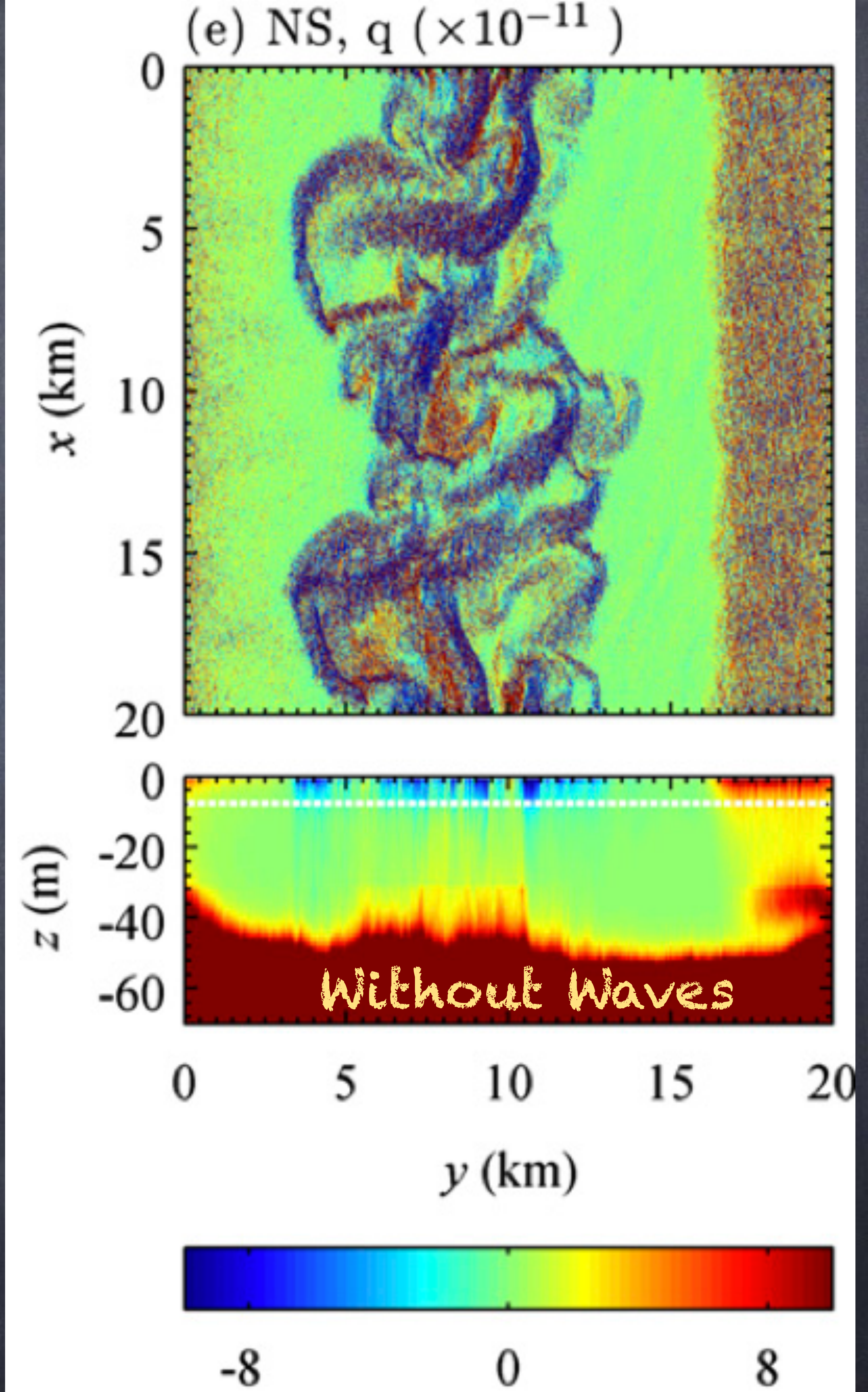
- - PV=0

Cross front velocity for the fastest growing mode



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





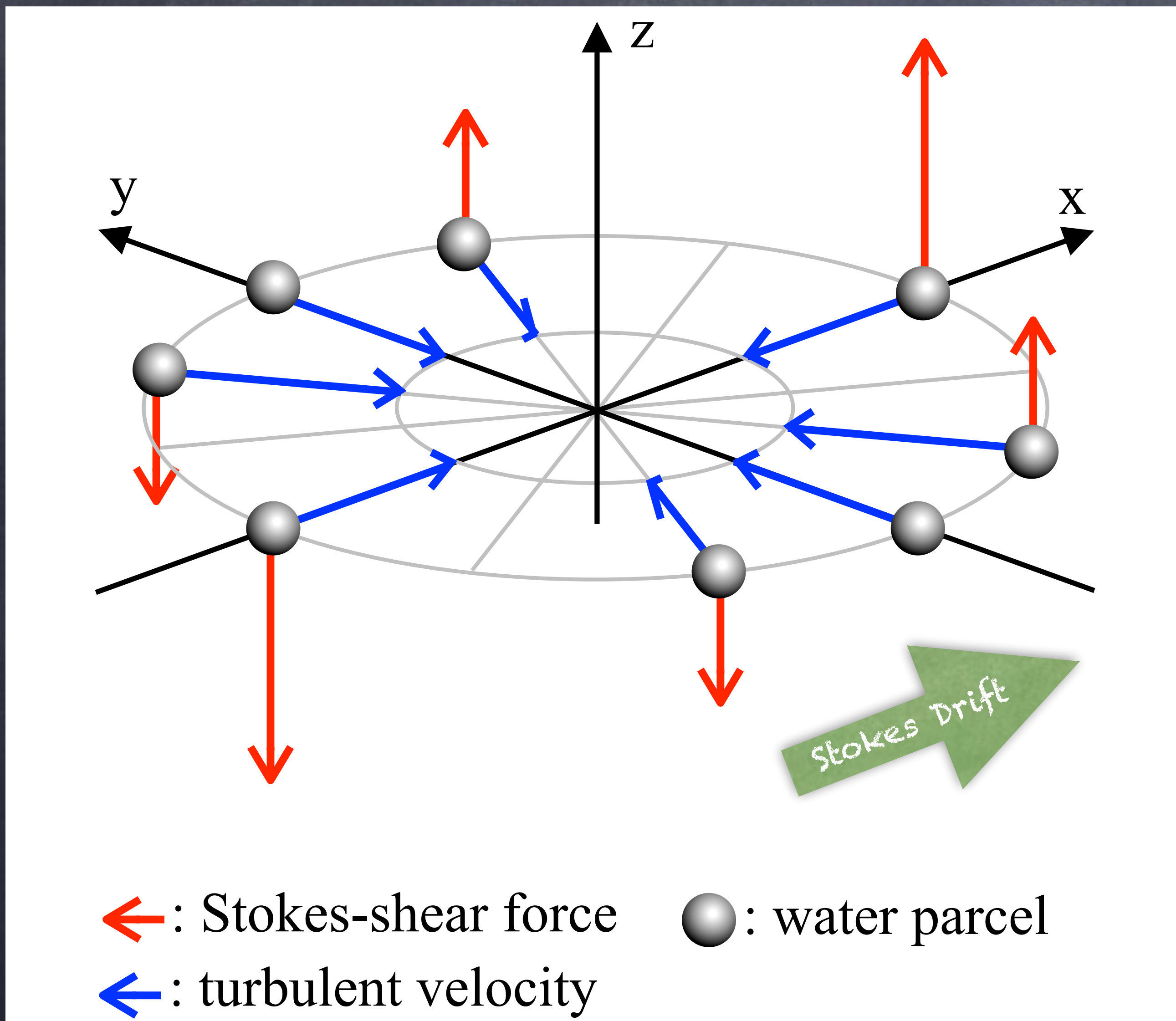
So, if negative PV indicates likely regions of symmetric instability— Surface Waves STRONGLY affect SI!

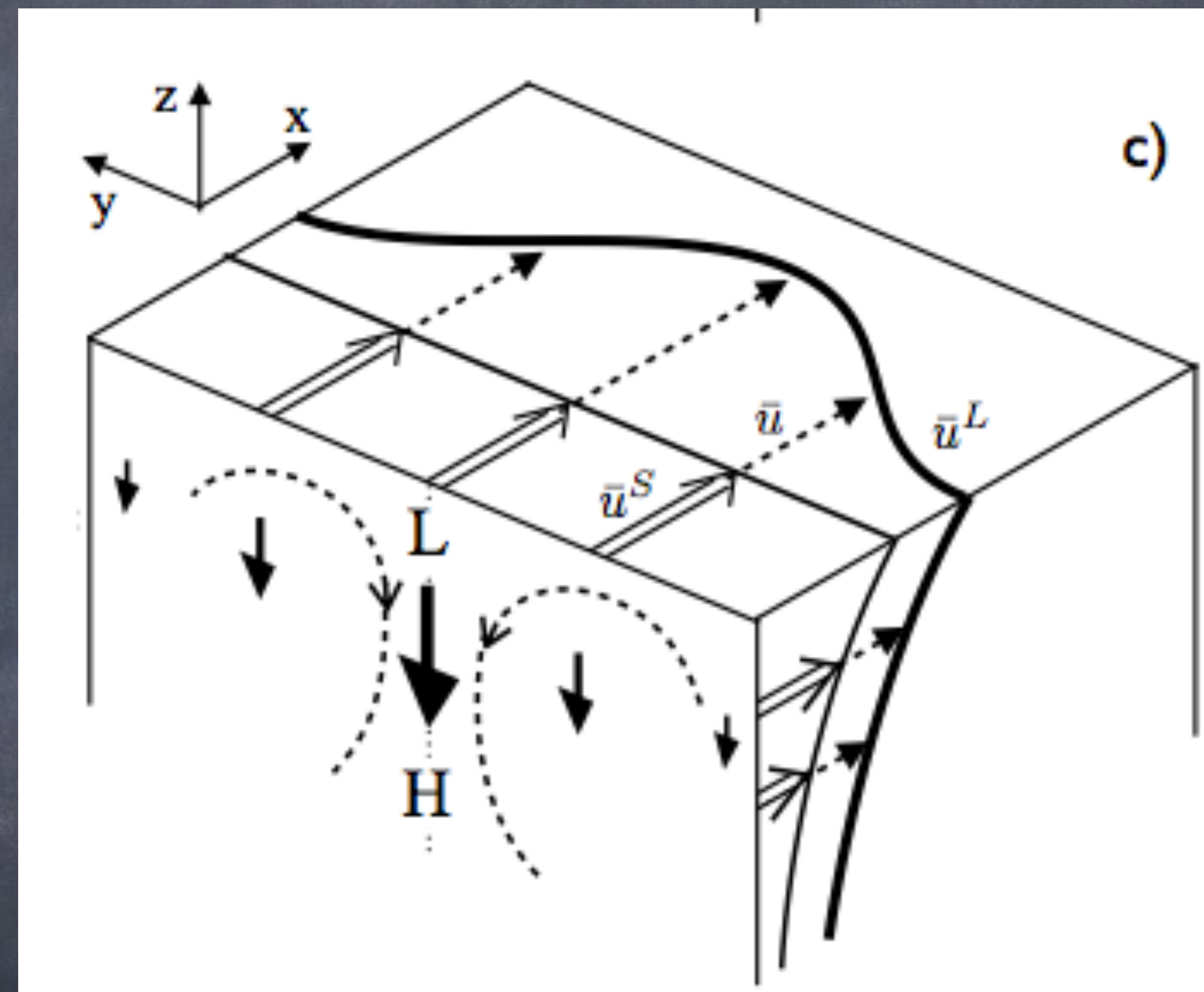
P. E. Hamlington, L. P. Van Roekel, BFK, K. Julien, and G. P. Chini. Langmuir-submesoscale interactions: Descriptive analysis of multiscale frontal spin-down simulations. Journal of Physical Oceanography, 44(9):2249-2272, September 2014.

Stokes Shear Force:

Craik-Leibovich mechanism for Langmuir circulations

Flow directed along Stokes shear=downward force

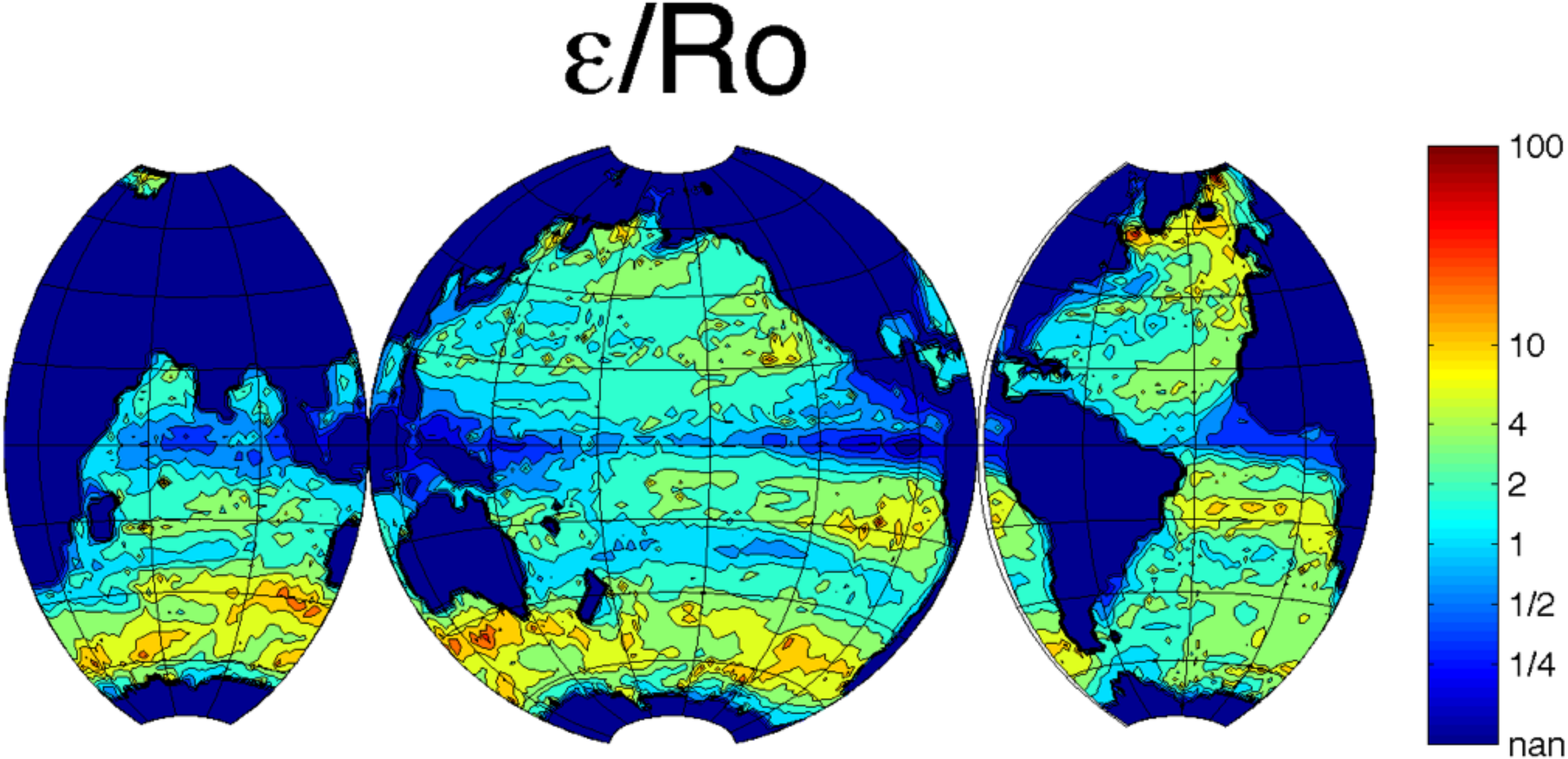




$$\frac{\alpha^2}{Ri}\left[w_{,t} + v_j^L w_{,j} + \frac{M_{Ro}}{RoRi} w w_{,z}\right] = -\pi_{,z} + b - \varepsilon v_j^L v_{j,z}^s + \frac{\alpha^2}{ReRi} w_{,jj}$$

N. Suzuki and BFK. Understanding Stokes Forces in the Wave-Averaged Equations, JPO, in prep, 2014.

Stokes force directly affects the (sub)mesoscale!!



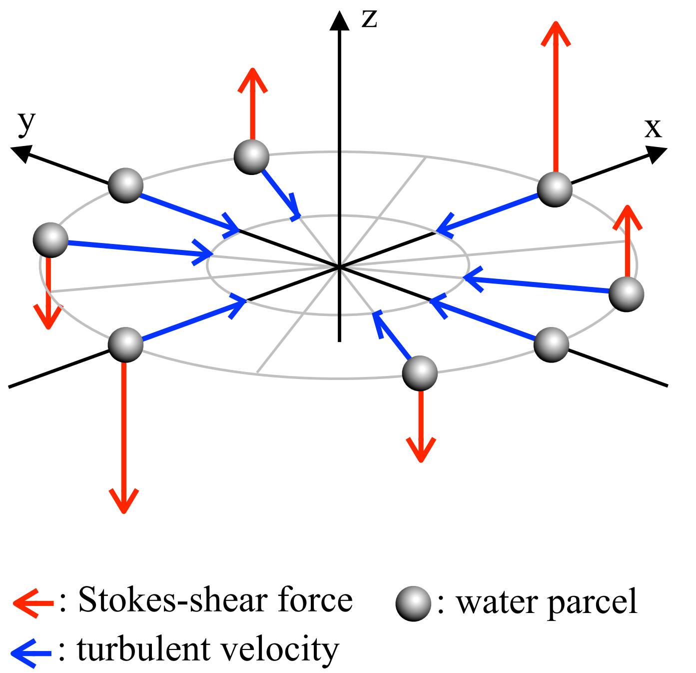
$$\frac{\varepsilon}{Ro} = \frac{V_s}{fL}\frac{H}{H_s}\frac{fL}{V} = \frac{V_s}{V}\frac{H}{H_s}$$

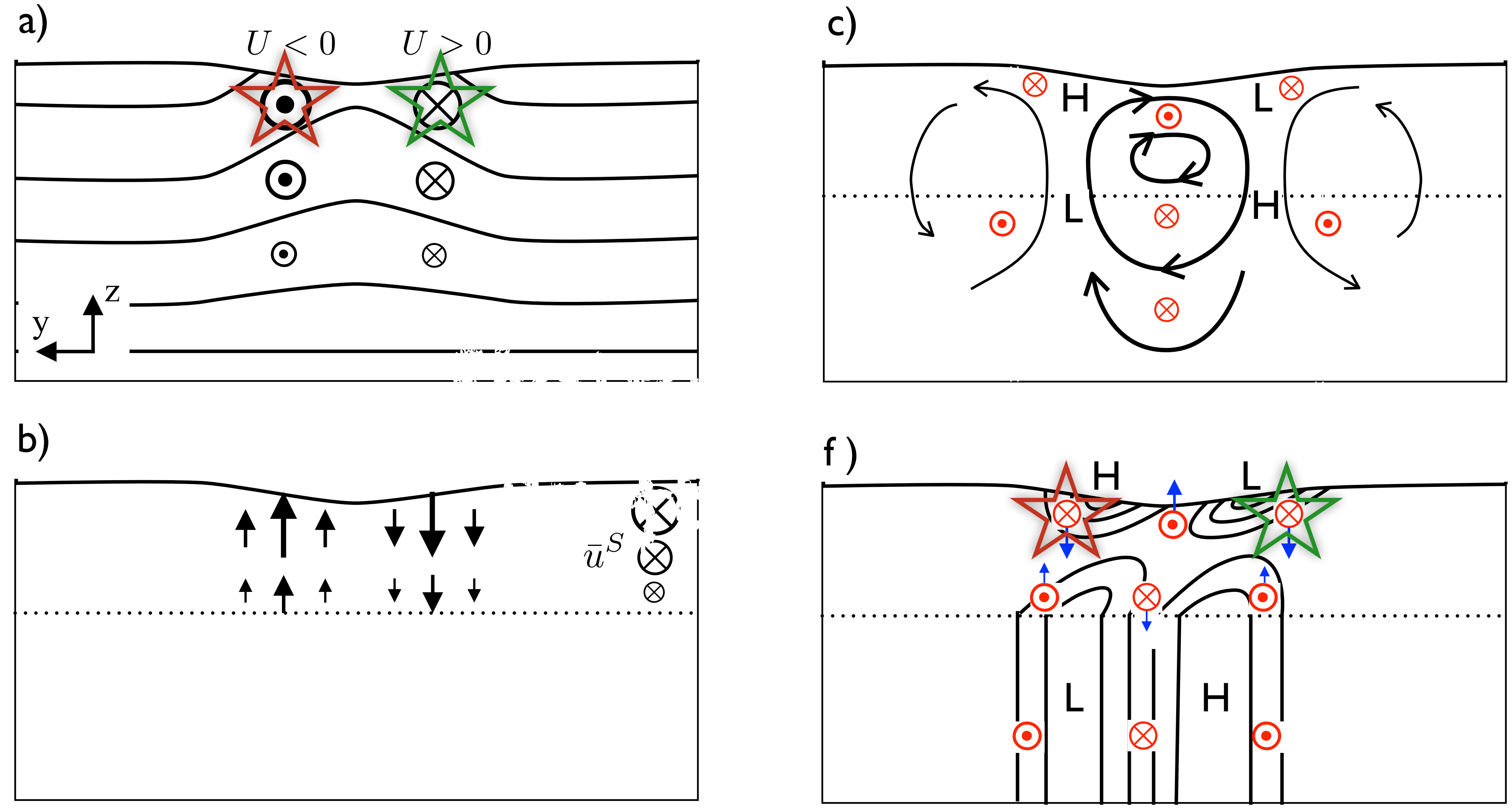
$$\varepsilon = \frac{V^s H}{fLH_s}$$

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

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

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, 2014.

Enhances Fronts for Down-Front Stokes

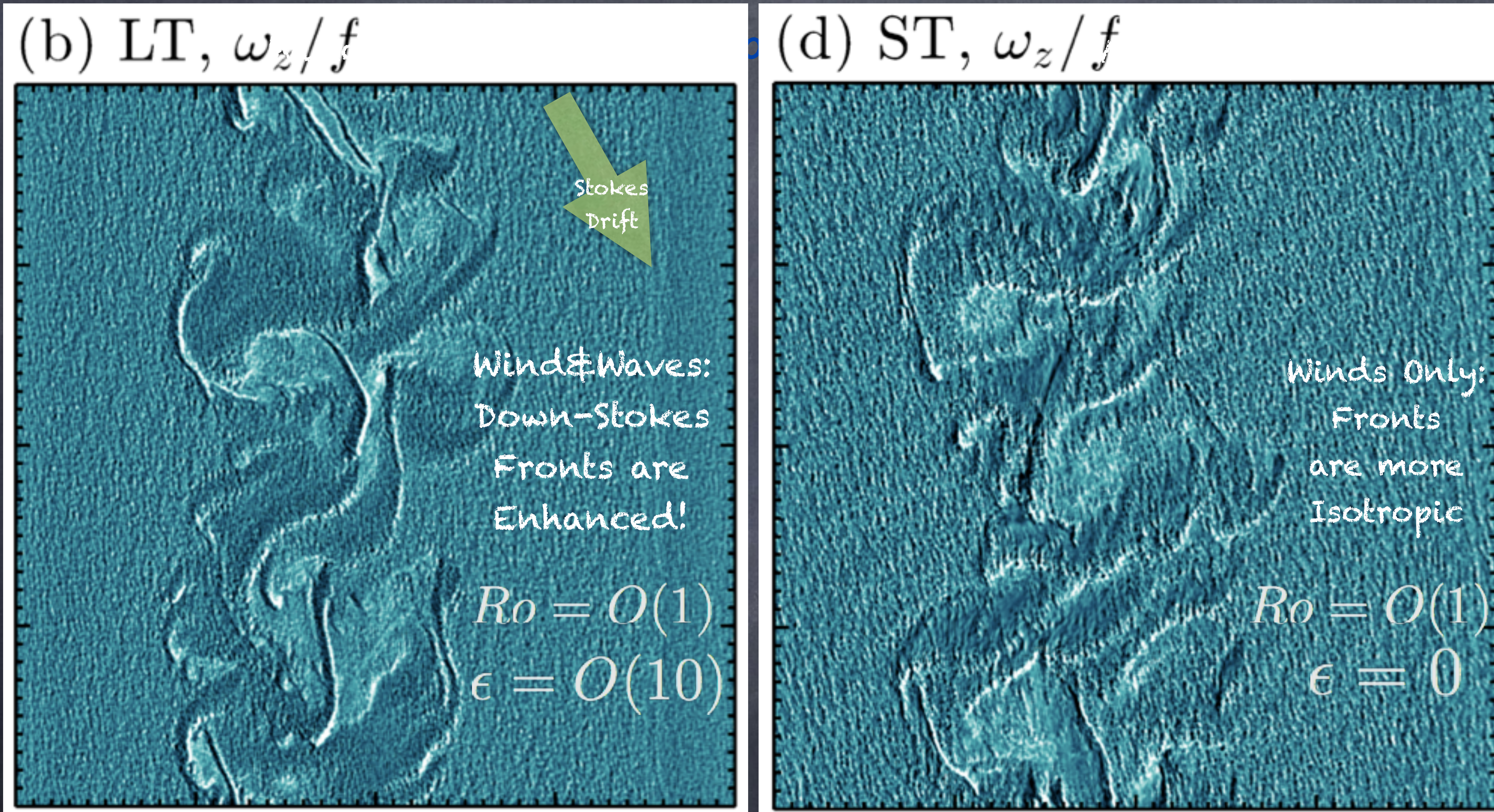
Opposes Fronts for Up-Front Stokes

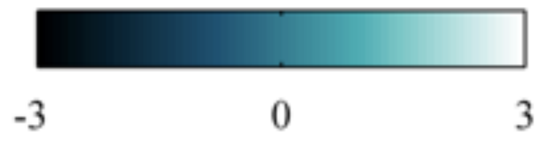
$$\frac{\alpha^2}{Ri}\left[w_{,t} + v_j^L w_{,j} + \frac{M_{Ro}}{RoRi} w w_{,z}\right] = -\pi_{,z} + b - \varepsilon v_j^L v^s_{j,z} + \frac{\alpha^2}{ReRi} w_{,jj}$$

Waves Give 30-40% of Power Produced at Front

Are Fronts and Filaments different with Stokes shear force?

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





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

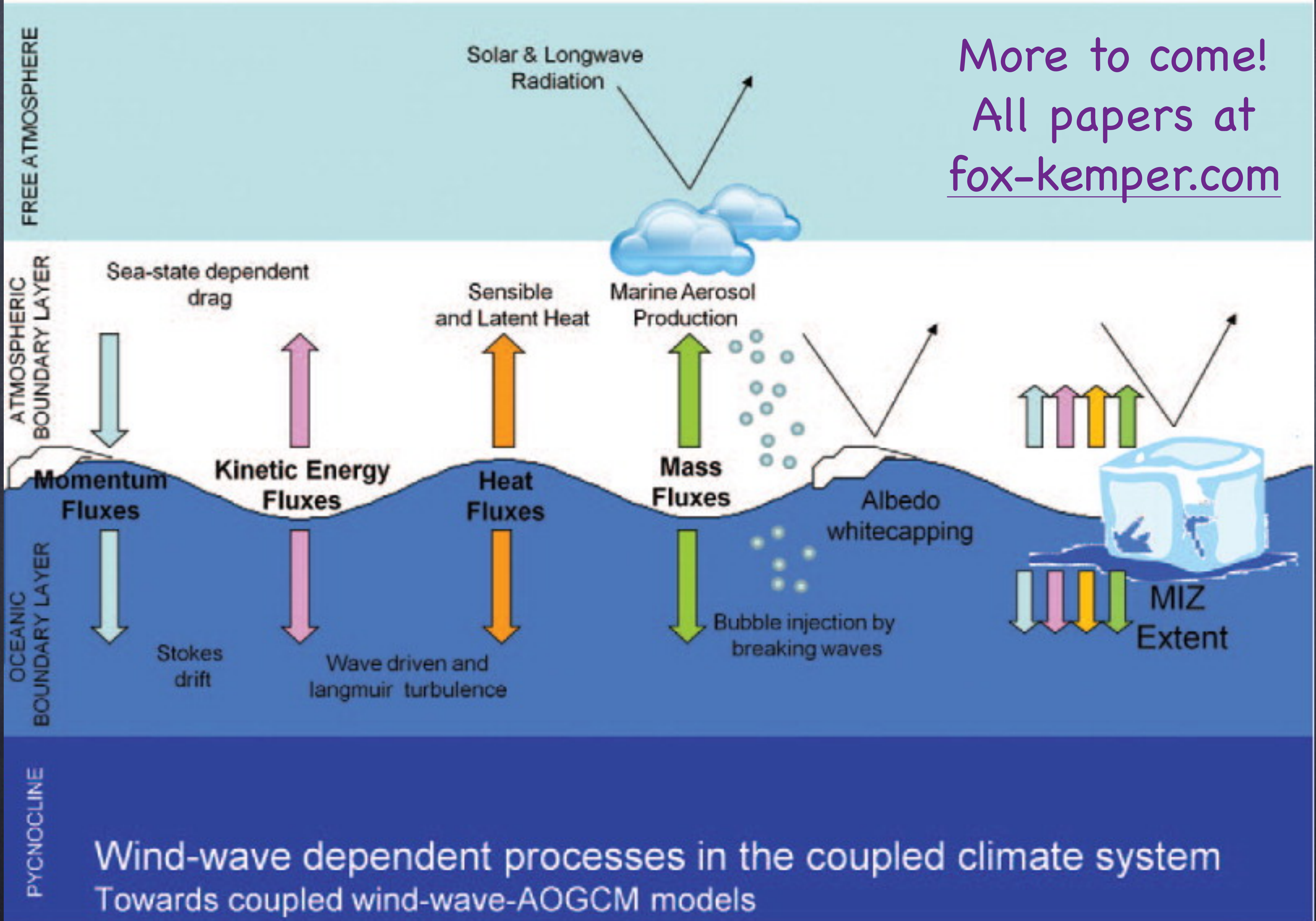
N. Suzuki, BFK, Hamlington, Van Roekel, Sullivan. Stokes Forces Affect Frontogenesis, JGR, in prep, 2015.

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.

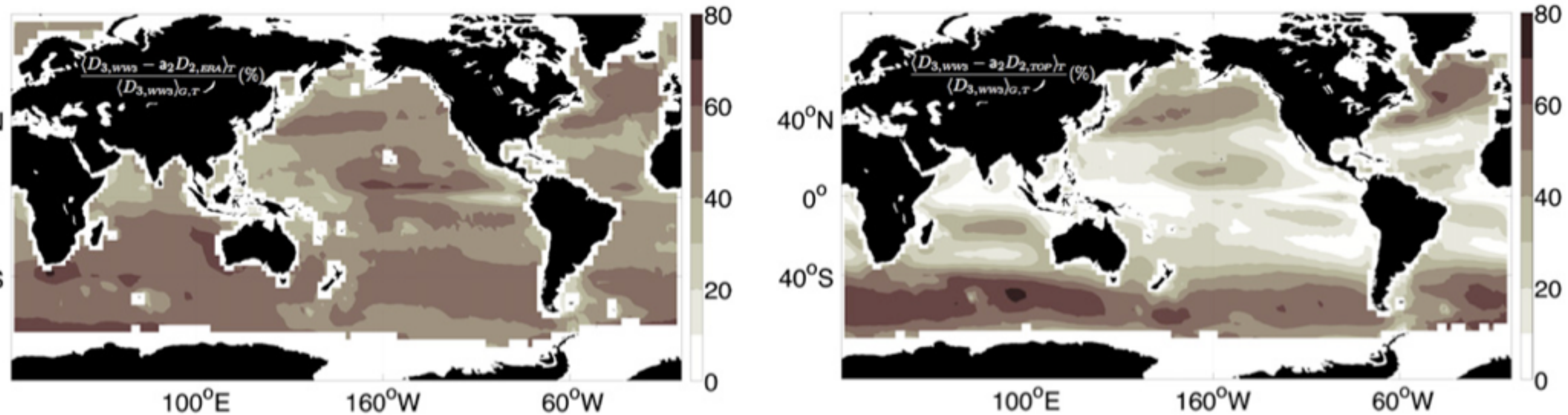
Conclusions

- 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
- Interesting transition occurs on the Submeso to Langmuir scale boundary, as nonhydro. & ageostrophic effects begin to dominate
- The effects of the Stokes forces on boundary layer and submesoscale dynamics are under-appreciated.
- All papers at: fox-kemper.com/pubs



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

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

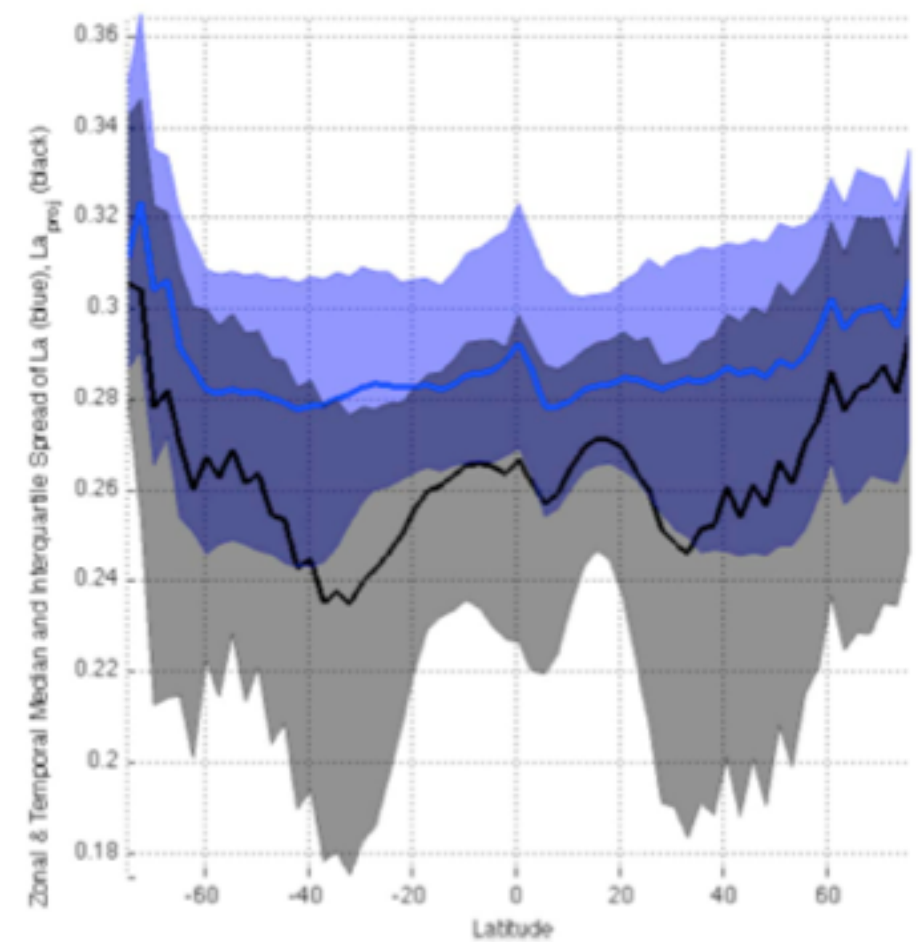


Figure 17. Temporal and zonal median and interquartile range of La_t and La_{proj} for a realistic simulation of 1994–2002 using Wave Watch III.

image: Thorpe, 04

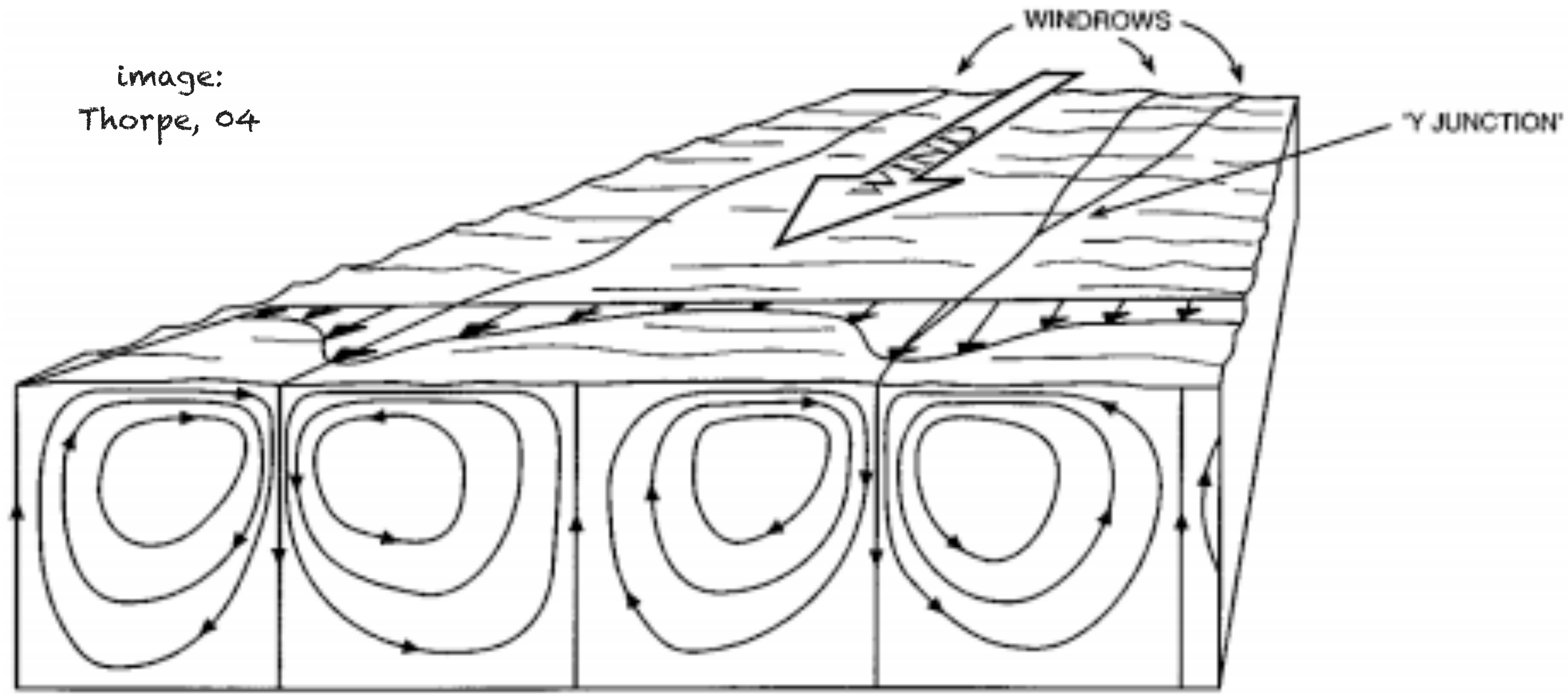


Figure 1 Sketch showing the pattern of mean flow in idealized Langmuir circulation. The windrows may be 2 m to 300 m apart, and the cell form is roughly square (as shown). In practice the flow is turbulent, especially near the water surface, and the windrows (Figure 2) amalgamate and meander in space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