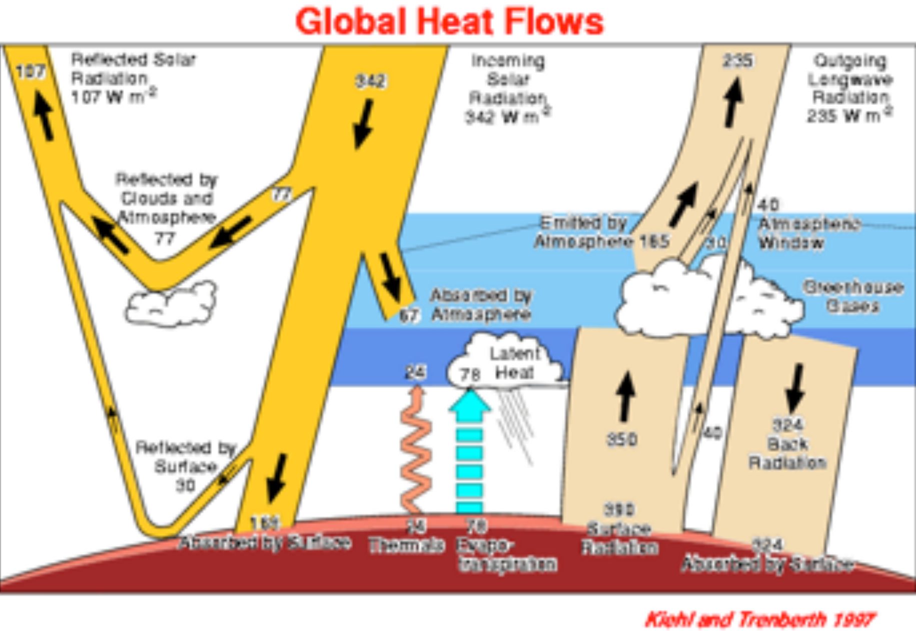
What's Waves Got to Do with It? Stokes Effects on Turbulence, Fronts, and Instabilities of the Upper Ocean

Baylor Fox-Kemper (Brown Geo.)

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

IPAM Mathematics of Turbulence, 10/27/14: 9-9:40

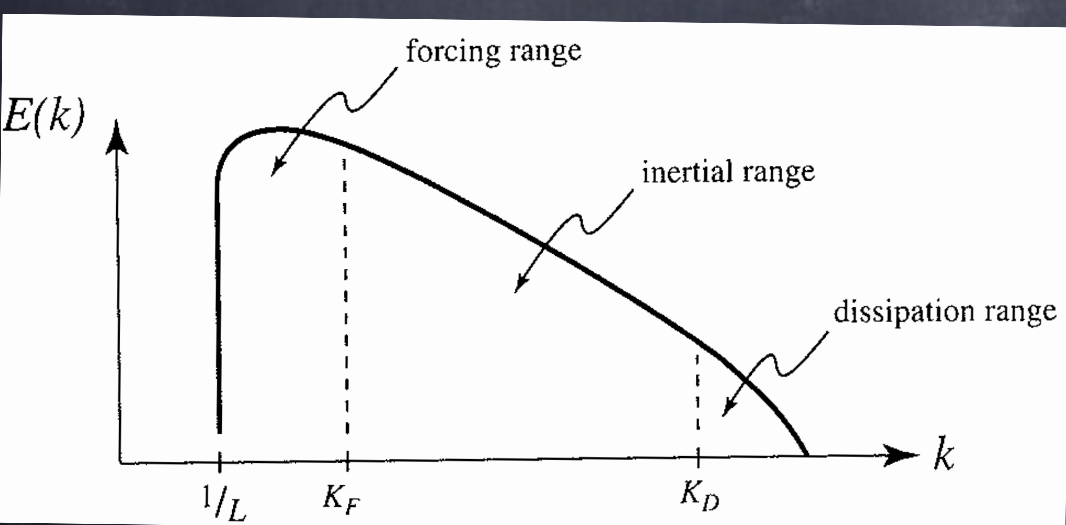
Sponsors: NSF 1258907, 1245944, 0934737, NASA NNX09AF38G

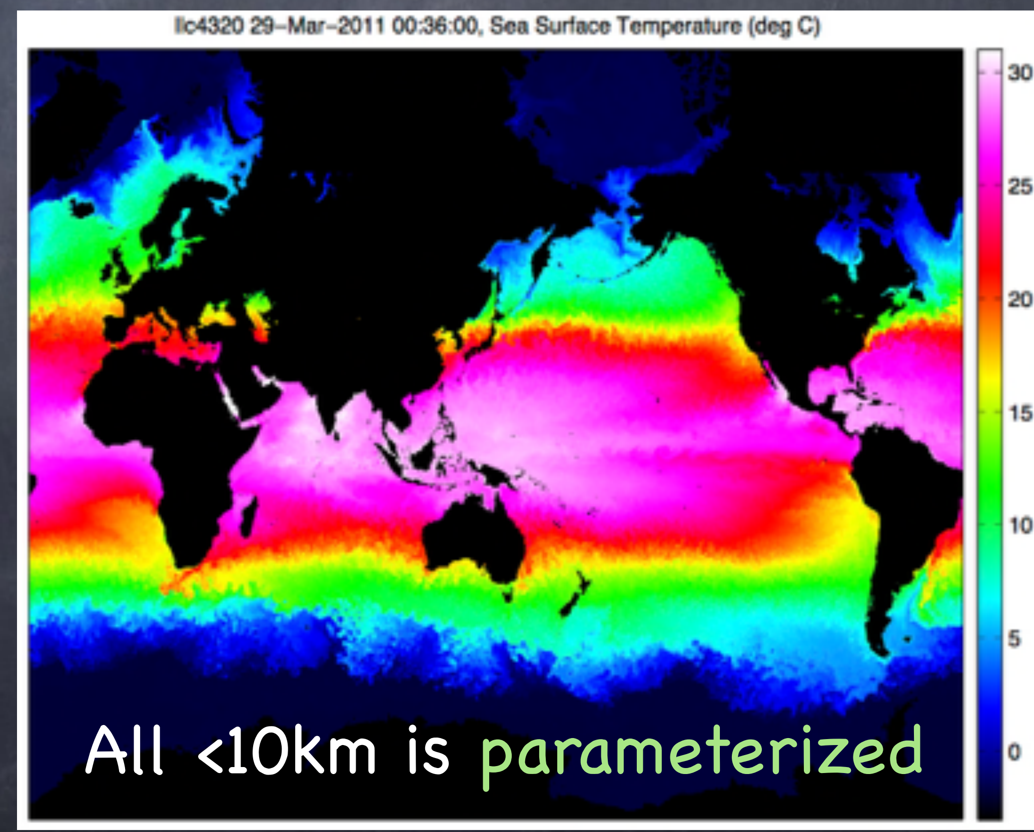


The Earth's Climate System is forced by the Sun on a global scale (20,000-40,000km)

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

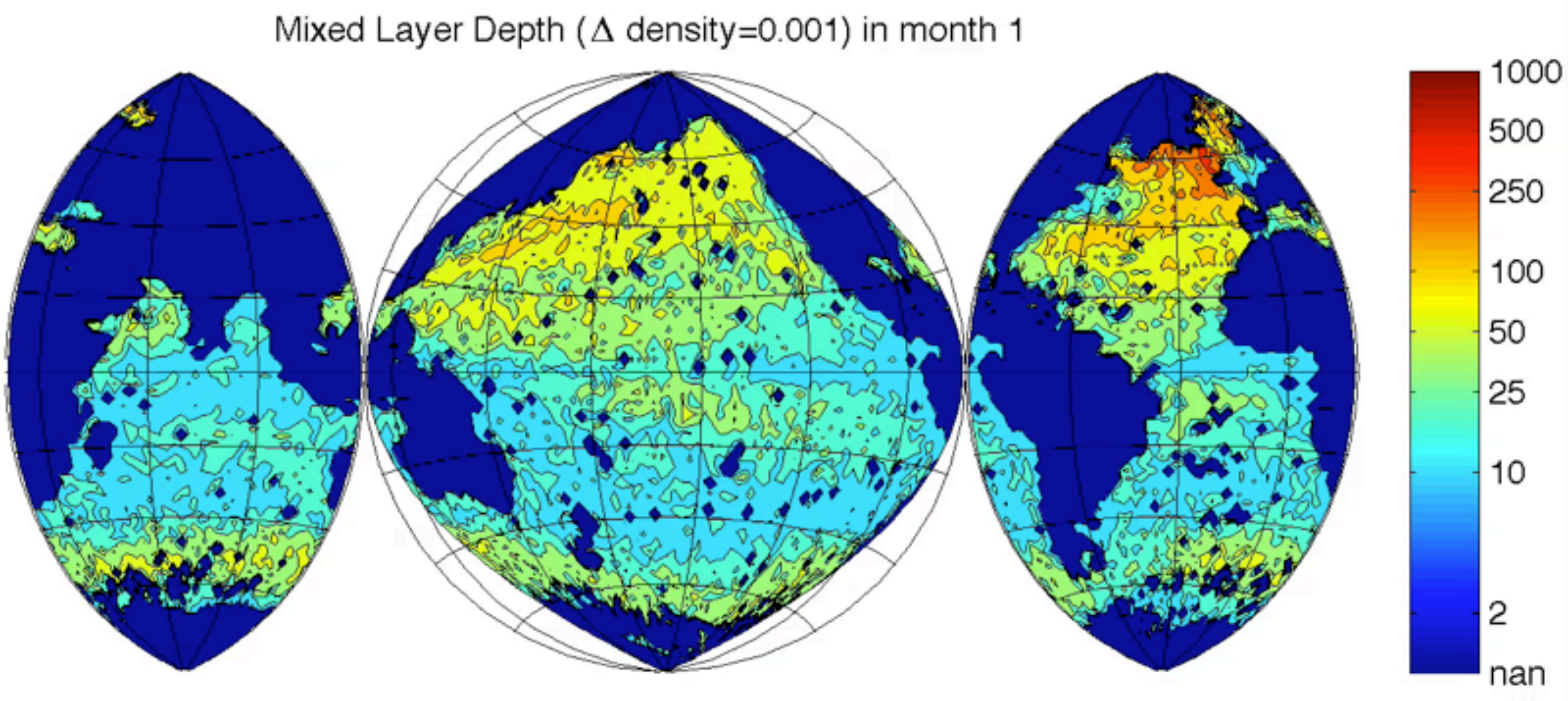
Turbulence cascades to scales about 10 billion times smaller O(1mm)





All <10km is parameterized

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

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

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

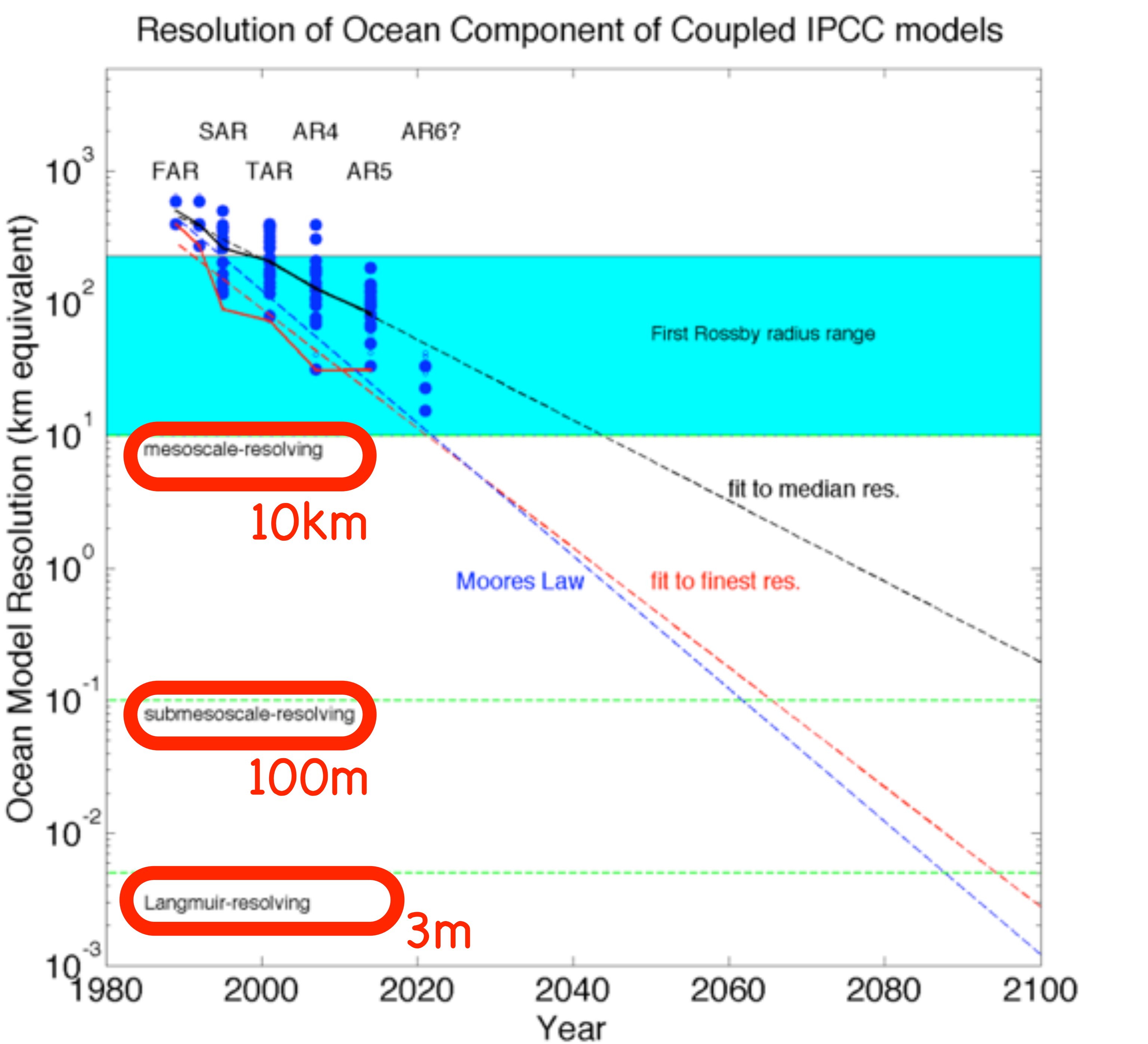
$$v_{j,j} + \frac{M_{Ro}}{RoRi} w_z = 0$$

Plus boundary conditions

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

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

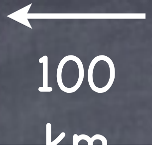
Resolution will be an issue for centuries to come!

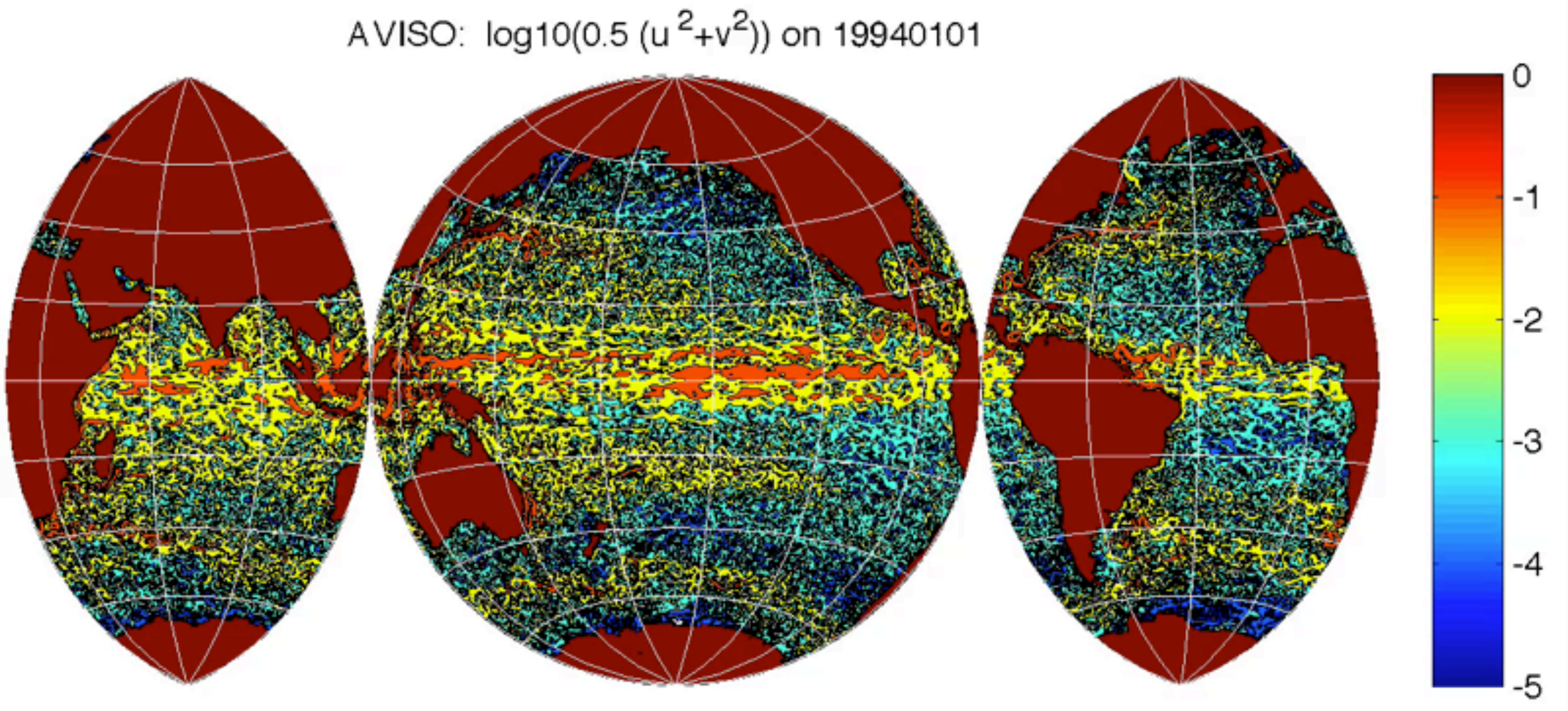


Here are the collection of IPCC models...

If we can't resolve a process, we need to develop a parameterization or subgrid model of its effect

The Character of the

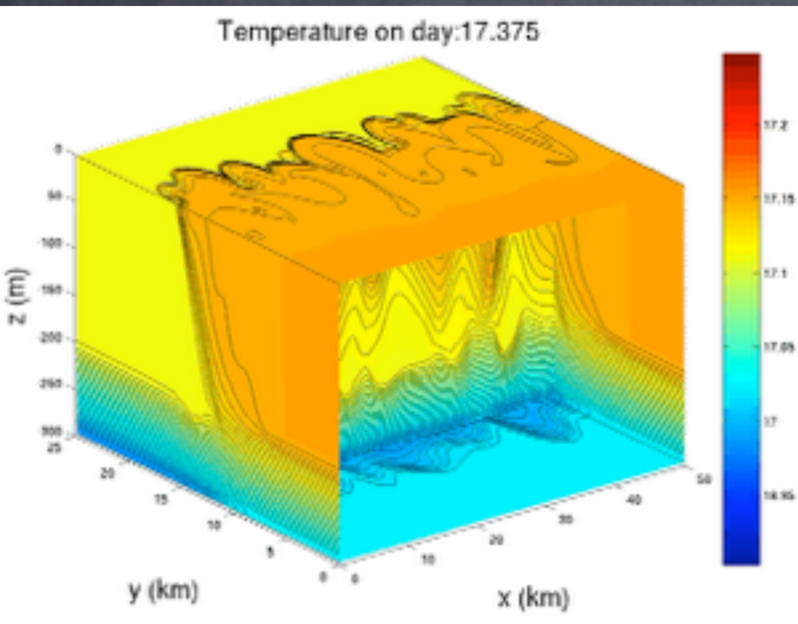




Eddy processes mainly baroclinic & barotropic instability. Parameterized (e.g., Gent-McWilliams), will be routinely resolved in climate models in 2040

The Character of the Submesoscale

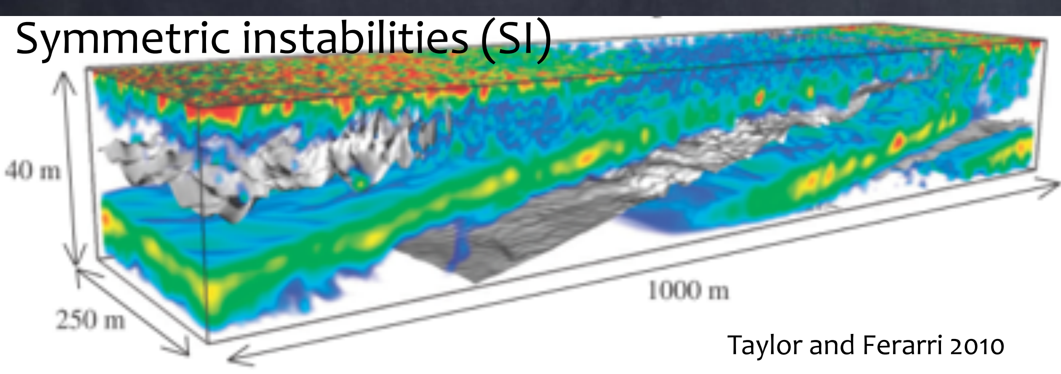
← 10 km



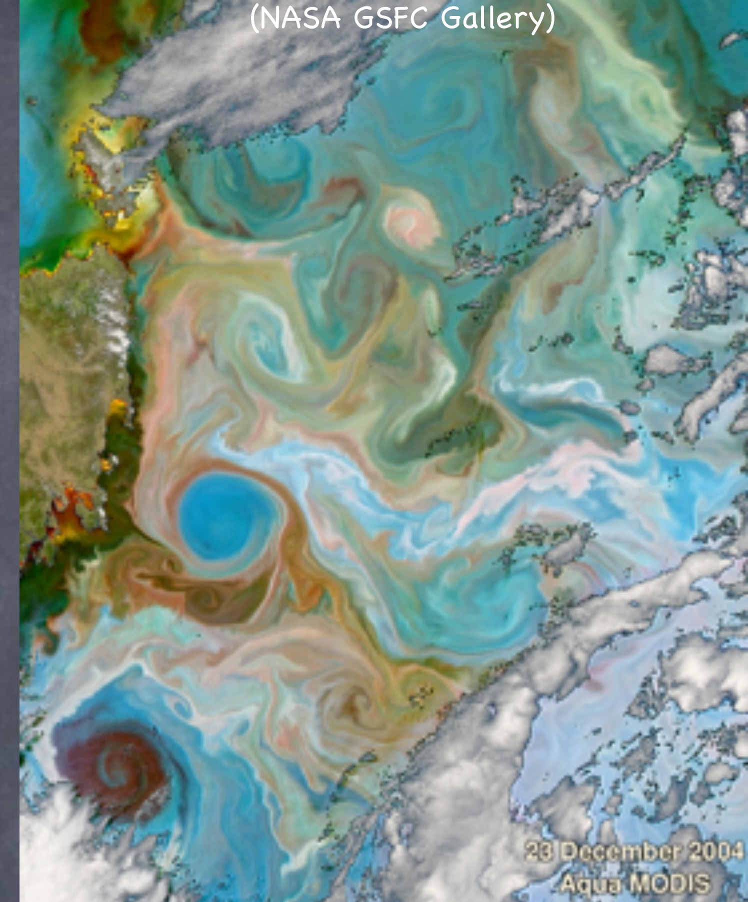
- Fronts
- Eddies
- Ro=O(1)
- Ri=O(1)
- near-surface (H=100m)
- 1-10km, days

Instability processes often
baroclinic instability
symmetric instability

Routinely resolved in 2100



Taylor and Ferarri 2010



(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

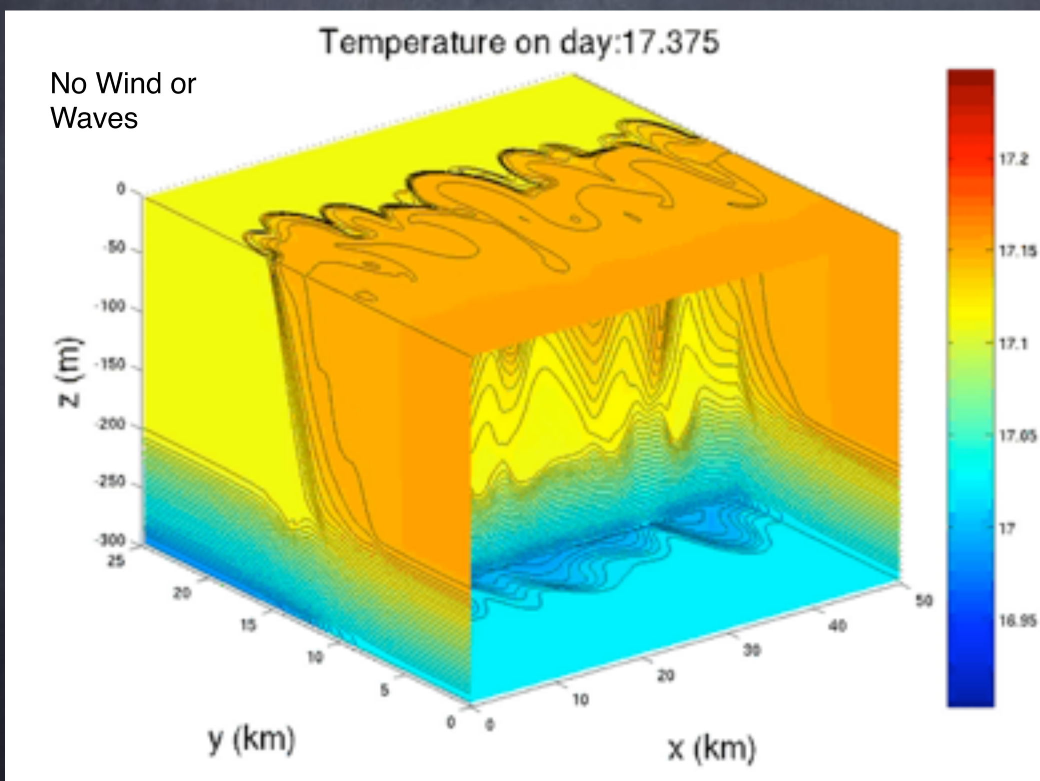
BFK, G. Danabasoglu, R. Ferrari, S. M. Griffies, R. W. Hallberg, M. M. Holland, M. E. Maltrud, S. Peacock, and B. L. Samuels. Parameterization of mixed layer eddies. III: Implementation and impact in global ocean climate simulations. Ocean Modelling, 39:61-78, 2011.

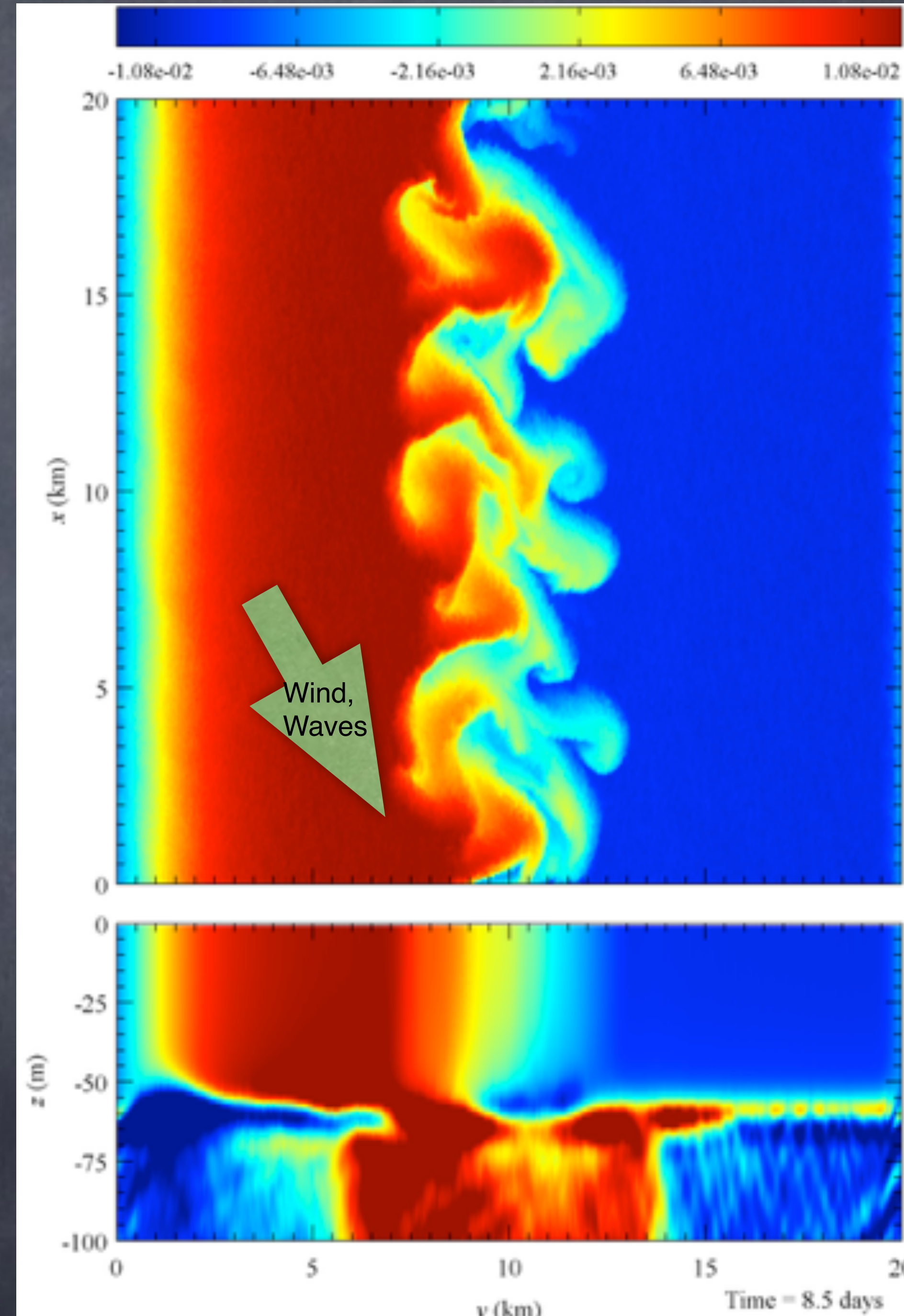
S. Bachman and BFK. Eddy parameterization challenge suite. I: Eady spindown. Ocean Modelling, 64:12-28, 2013

Submesoscale?

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

Mixing balances restratification



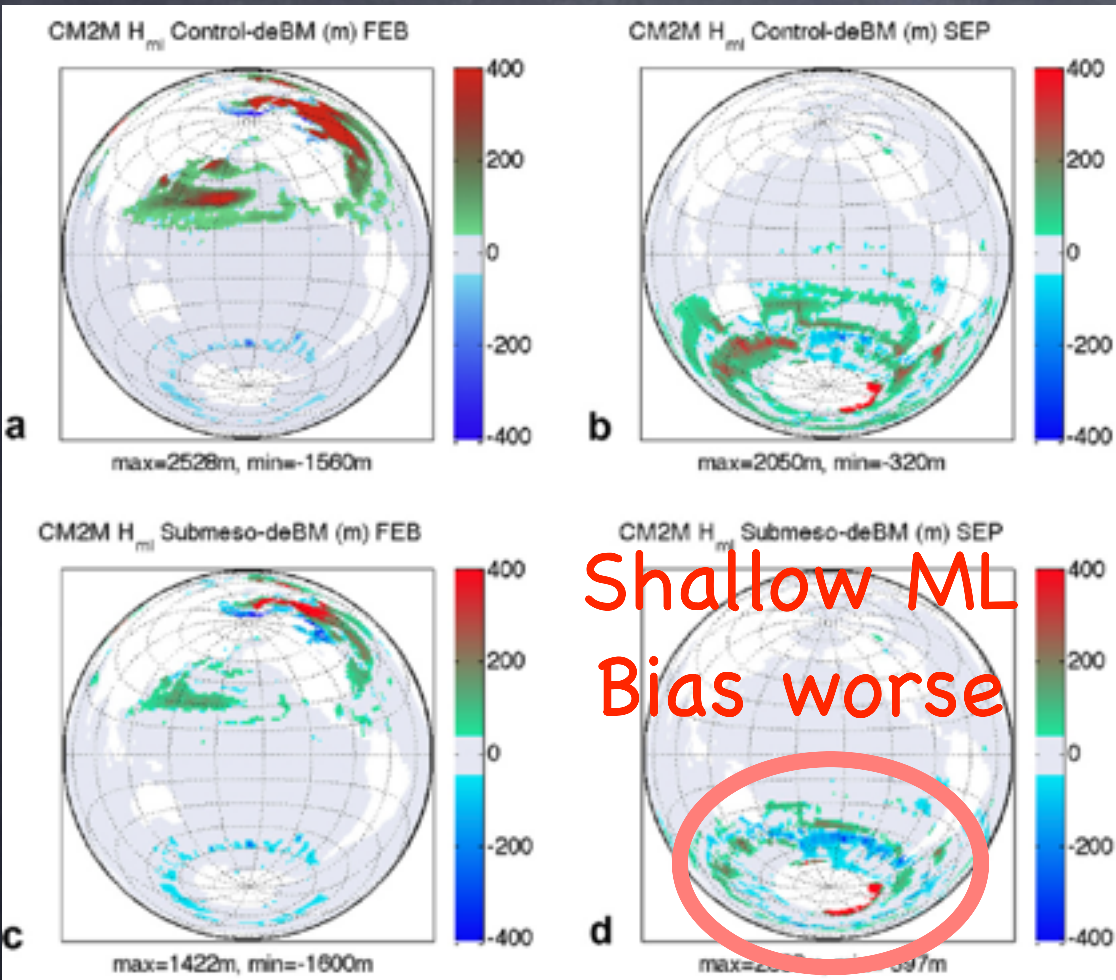


Movie: P. Hamlington

P. E. Hamlington, L. P. Van Roekel, BFK, K. Julien, and G. P. Chini. Langmuir-submesoscale interactions: Descriptive analysis of multisca
frontal spin-down simulations. Journal of Physical Oceanography, 2013. Submitted.

A problem with Mixed Layer Eddy Restratification?

Southern Ocean already too shallow!



Bias w/o MLE

Sallee et al. (2013) have shown that a too shallow S. Ocean MLD is true of most* climate models even without MLE parameterization

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.

MLE not only to blame, so is something else missing?

The Character of the Langmuir Scale

image: Thorpe, 04

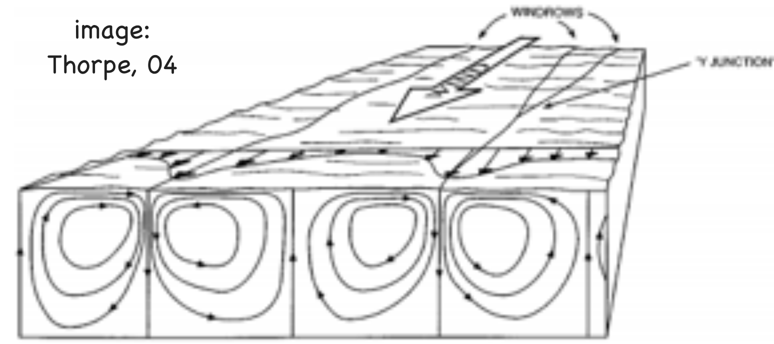


Figure 1 Sketch showing the pattern of mean flow in idealized Langmuir circulation. Th windrows may be 2 m to 300 m apart, and the cell form is roughly square (as shown). I practice the flow is turbulent, especially near the water surface, and the windrows (Figure 2 amalgamate and meander in space and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

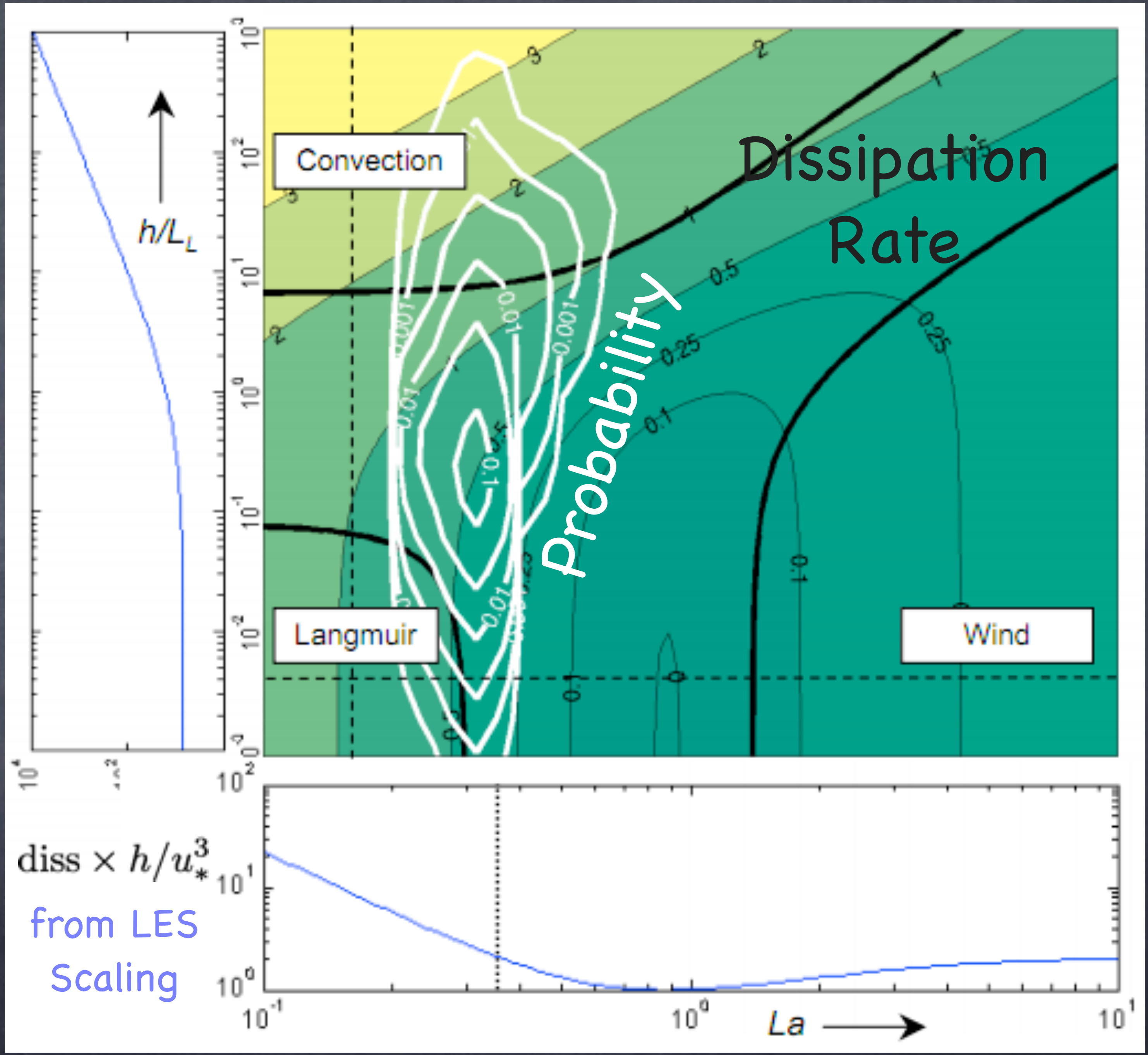
- Near-surface
- Langmuir Cells & Langmuir Turb.
- Ro>>1
- Ri<1: Nonhydro
- 1-100m (H=L)
- 10s to 1hr
- w, u=O(10cm/s)
- Stokes drift
- Eqtns:Wave-Avg, Craik-Leibovich
- Params: McWilliams & Sullivan, 2000, Van Roekel et al. 2011
- Resolved routinely in 2170

Image: NPR.org, Deep Water Horizon Spill

Data + Large Eddy Simulation scaling, Southern Ocean mixing energy:

One way to estimate

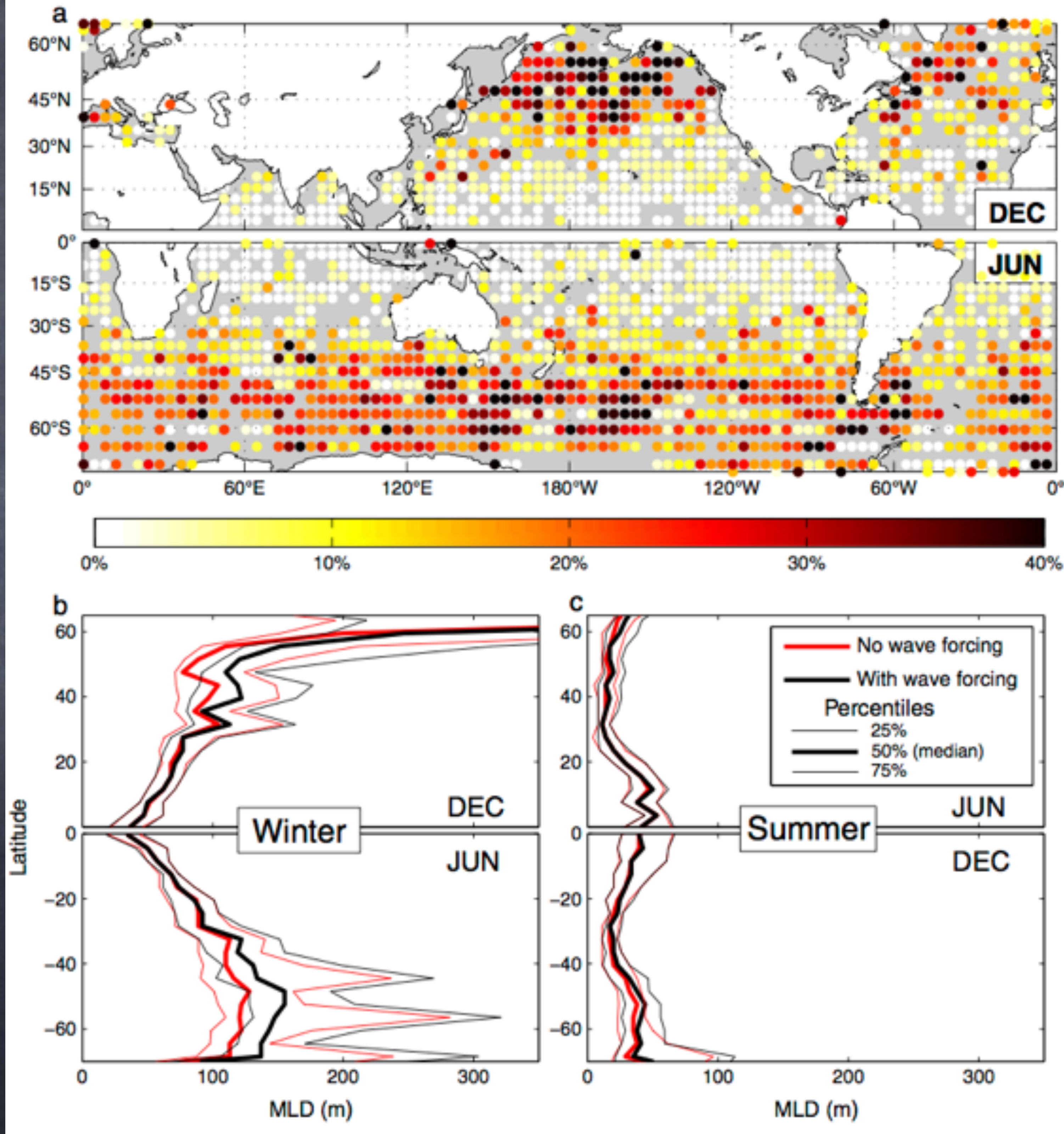
So, waves can drive mixing via Stokes drift (combines with cooling & winds)



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.

Offline obs-driven parameterization:

Including Stokes-driven Mixing (Harcourt 2013) Deepens the Mixed Layer!



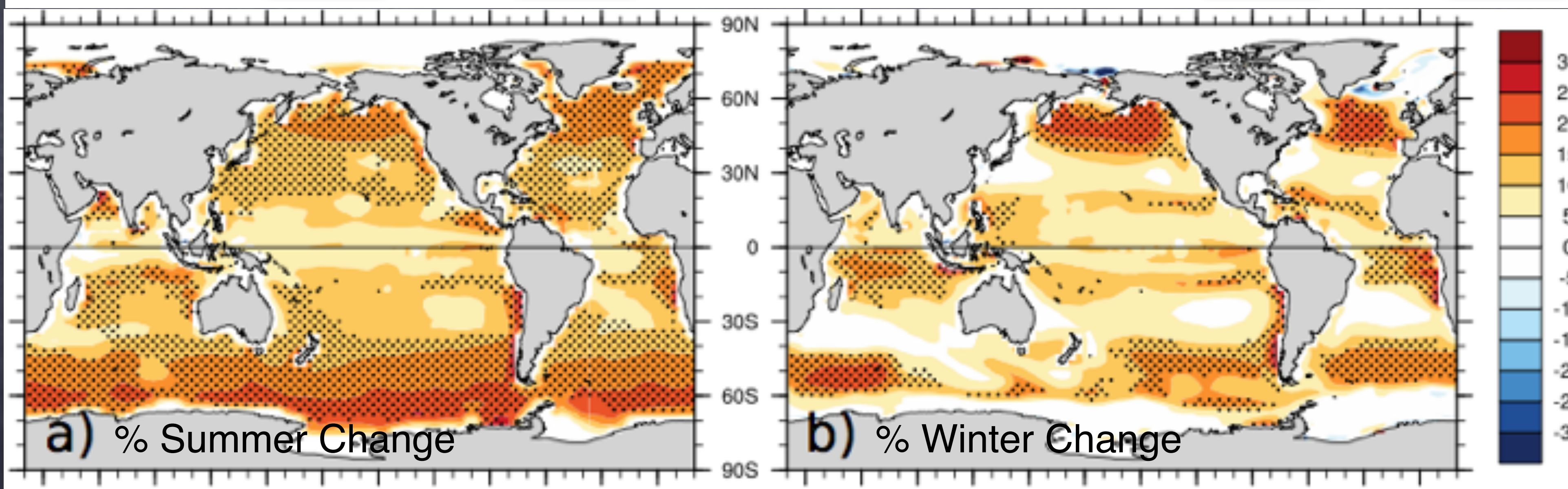
E. A. D'Asaro, J. Thomson, A. Y. Shcherbina, R. R. Harcourt, M. F. Cronin, M. A. Hemer, and BFK. Quantifying upper ocean turbulence driven by surface waves. Geophysical Research Letters, 41(1): 102-107, January 2014.

Wave-Driven Mixing in CESM Climate Model

RMS Error vs. Obs.

Forced Ocean-Ice

	Case	Summer			Winter		
		Global	South of 30S	20S-20N	Global	South of 30S	20S-20N
	CTRL	11.85	18.24	6.84	39.46	52.84	10.51
Basic Waves	*VR12a*	10.21	14.29	8.31	39.41	50.48	14.37
Depth & misaligned	*VR12g*	9.83	13.40	8.39	38.42	50.07	13.88



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, BFK, T. Arbetter, A. Webb , 2014. Assessing the Influence of Surface Wind Waves to the Global Climate by Incorporating WAVEWATCH III in CESM, 2014 AGU Ocean Sciences Meeting Poster, related paper in prep.

Enough with Climate Models: Let's work on the dynamics!

- Including submesoscale restratification in climate models improves the boundary layer.
- Including wave-driven (Langmuir) mixing in climate models improves the boundary layer.
- But, fundamental questions remain:
  - What if these are combined? What dynamics? What interactions?

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. (McWilliams et al, 1997)

Computational parameters:

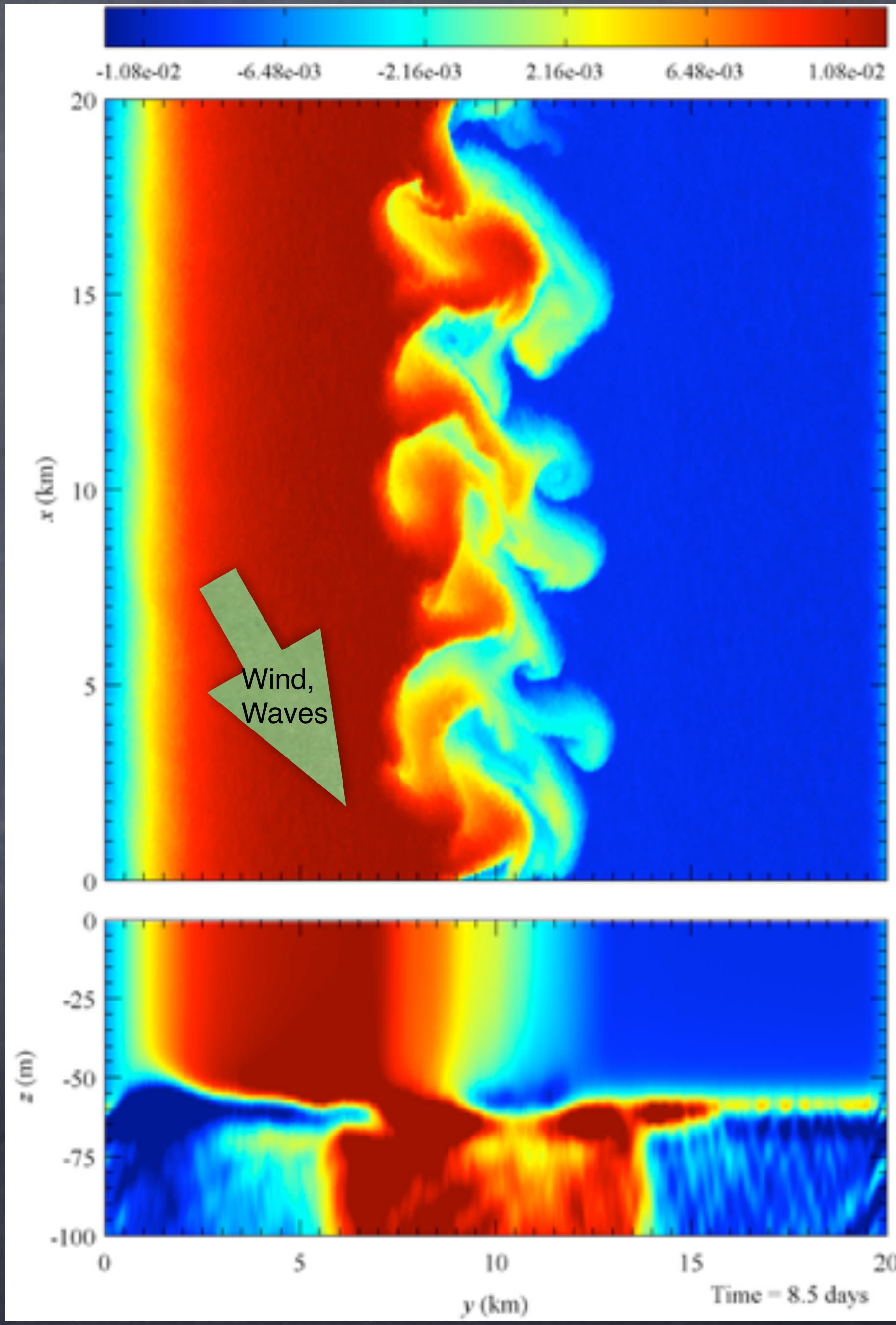
Domain size: 20km x 20km x -160m

Grid points: 4096 x 4096 x 128

Resolution: 5m x 5m x -1.25m

1000x more gridpoints than CESM

Movie: P. Hamlington



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

Surface Waves are...

fast, small, irrotational solutions of the Boussinesq Equations

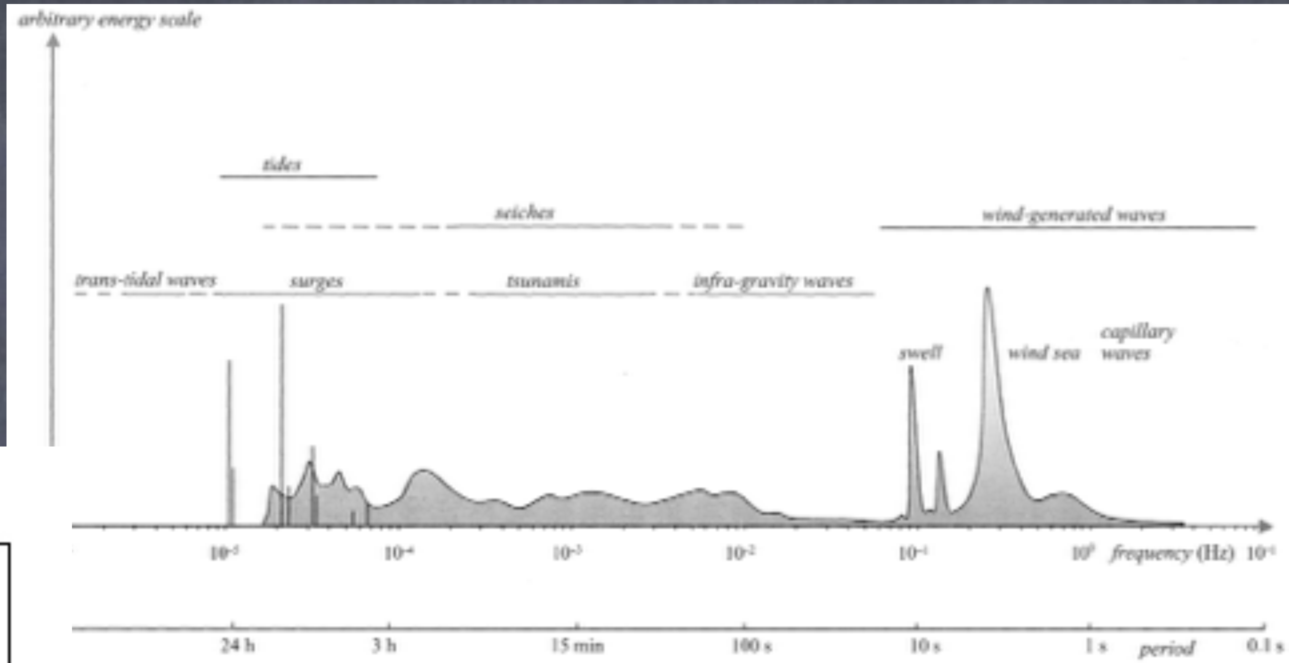
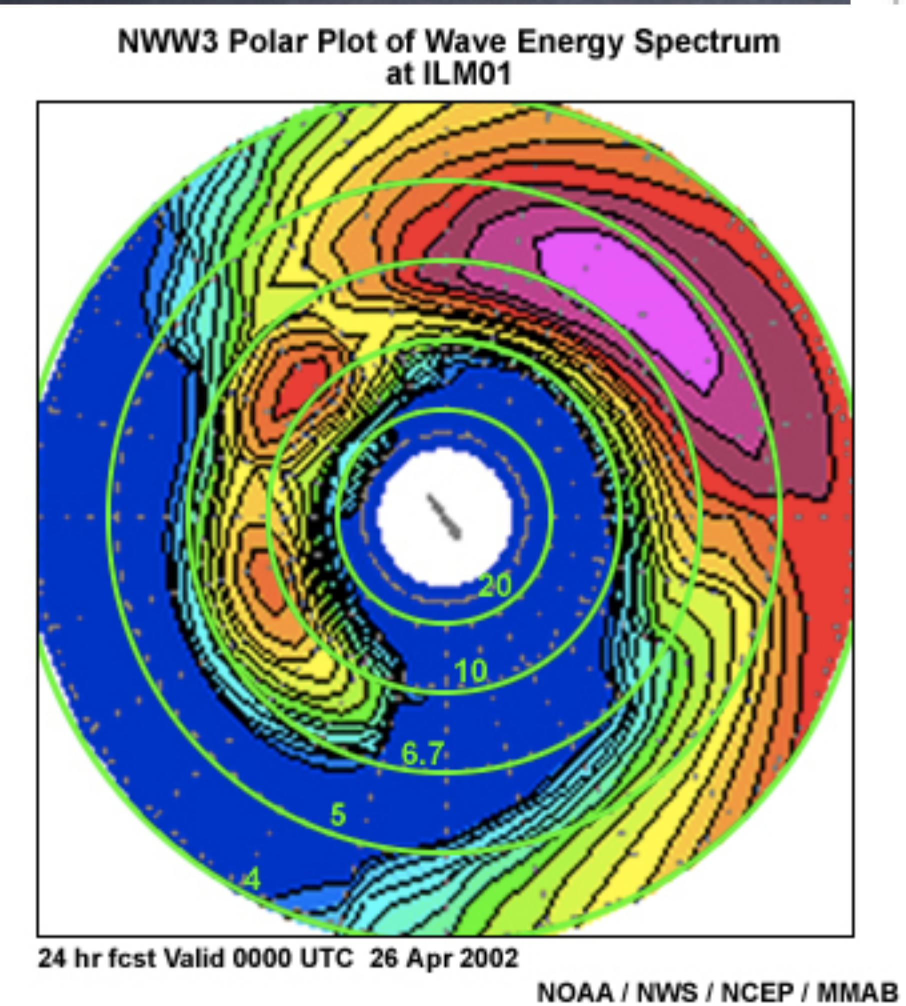


Illustration of wave spectra from different types of ocean surface waves (Holthuijsen, 2007)



Wave-Averaged Eqtns:

Stokes Drift Affects Slower Phenomena

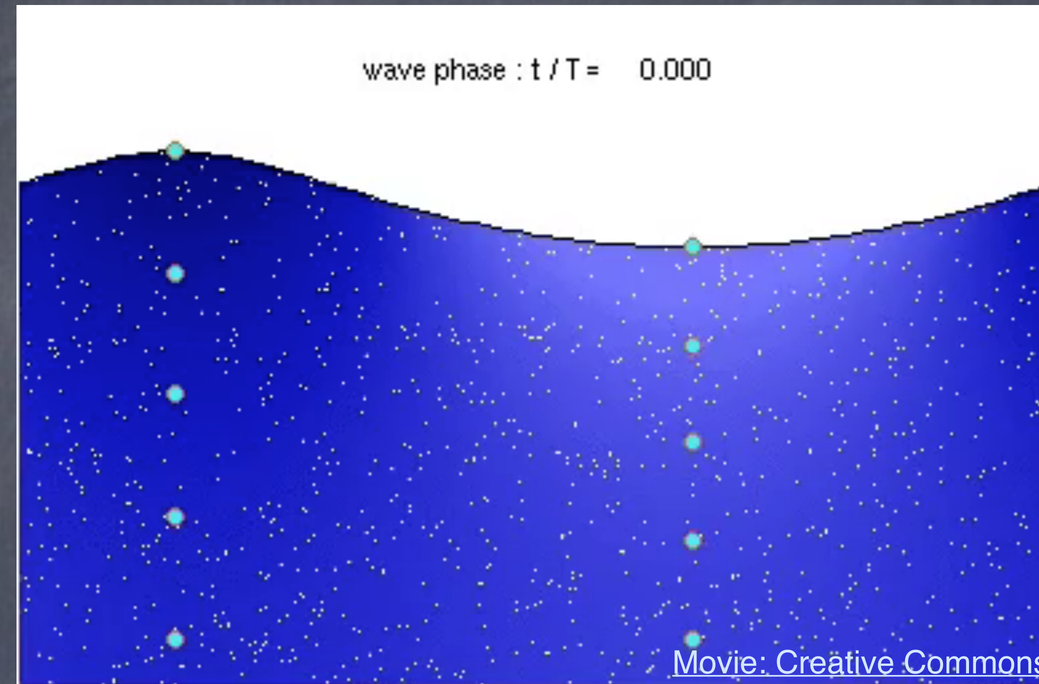
- Formally a multiscale asymptotic equation set:
  - 3 classes: Small, Fast; Large, Fast; Large, Slow
  - Solve first 2 types of motion in the case of limited slope (ka), irrotational --> Deep Water Waves!
  - Average over deep water waves in space & time,
  - Arrive at Large, Slow equation set.

All Wave-Mean coupling terms involve the Stokes Drift

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

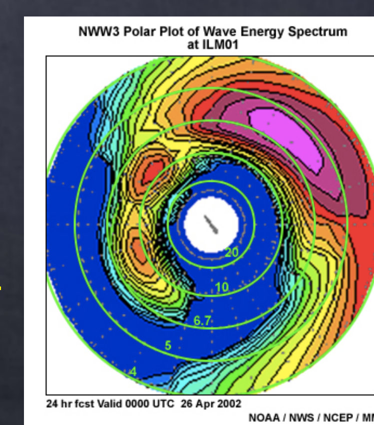
Waves Provide Stokes Drift

Take wave solns, compare the velocity of 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: $$\boldsymbol{u}^S = \frac{16\pi^3}{g} \int_0^\infty \int_{-\pi}^{\pi} (\cos\theta, \sin\theta, 0) f^3 S_{f\theta}(f,\theta) e^{\frac{8\pi^2 f^2}{g} z} d\theta df.$$



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

A. Webb and BFK. Estimating Stokes drift for directional random seas. Ocean Modelling, June 2014. Submitted.

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 (14)

(for horizontally uniform Stokes drift)

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

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

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

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

Plus boundary conditions

LAGRANGIAN (Eulerian+Stokes) advection & Coriolis

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, 2014.

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

Stokes 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 shear, not the not the Eulerian!

Lagrangian=Eulerian+Stokes

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

Plus, it is the Lagrangian Flow that transports tracers

(salinity, temperature, density, etc.)

Analytic Stability Criteria: Geostrophic Modes

- Charney, Stern, and Pedlosky showed, that geostrophic instability exists only if one of the following is true:

1. Q_y changes sign in the interior of the domain.
2. Q_y is the opposite sign to U^L_z at the surface.
3. Q_y is the same sign to U^L_z at the bottom.
4. U^L_z has the same sign at the surface and bottom.

Where Q is the quasi-geostrophic potential vorticity:

$$\bar{Q} = \nabla_H^2 \bar{\psi} + \beta Y + \partial_z \left(\frac{f_0^2}{N^2} \bar{\psi}_z^L \right)$$

Charney, Stern, & Pedlosky gets a tweak—> U is Lagrangian sometimes!

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 (14)

(for horizontally uniform Stokes drift)

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

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

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

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

Plus boundary conditions

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

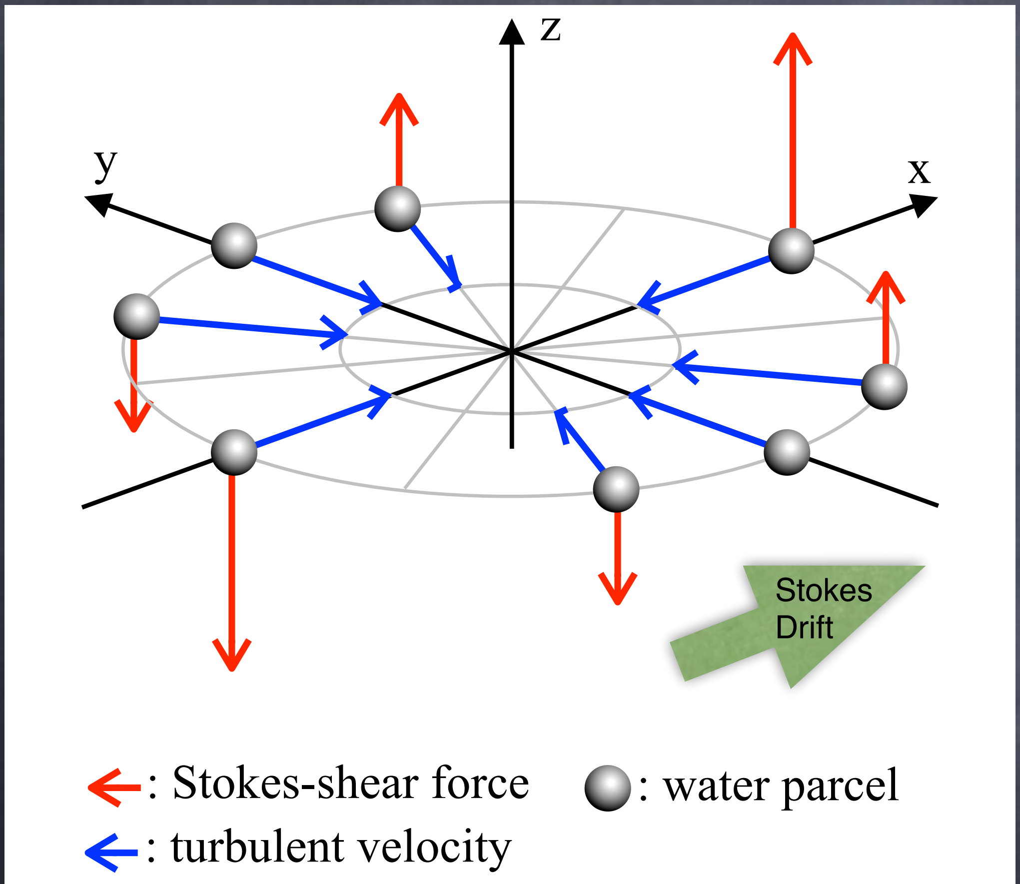
J. C. McWilliams and BFK. Oceanic wave-balanced surface fronts and filaments. Journal of Fluid Mechanics, 730:464-490, 2013.

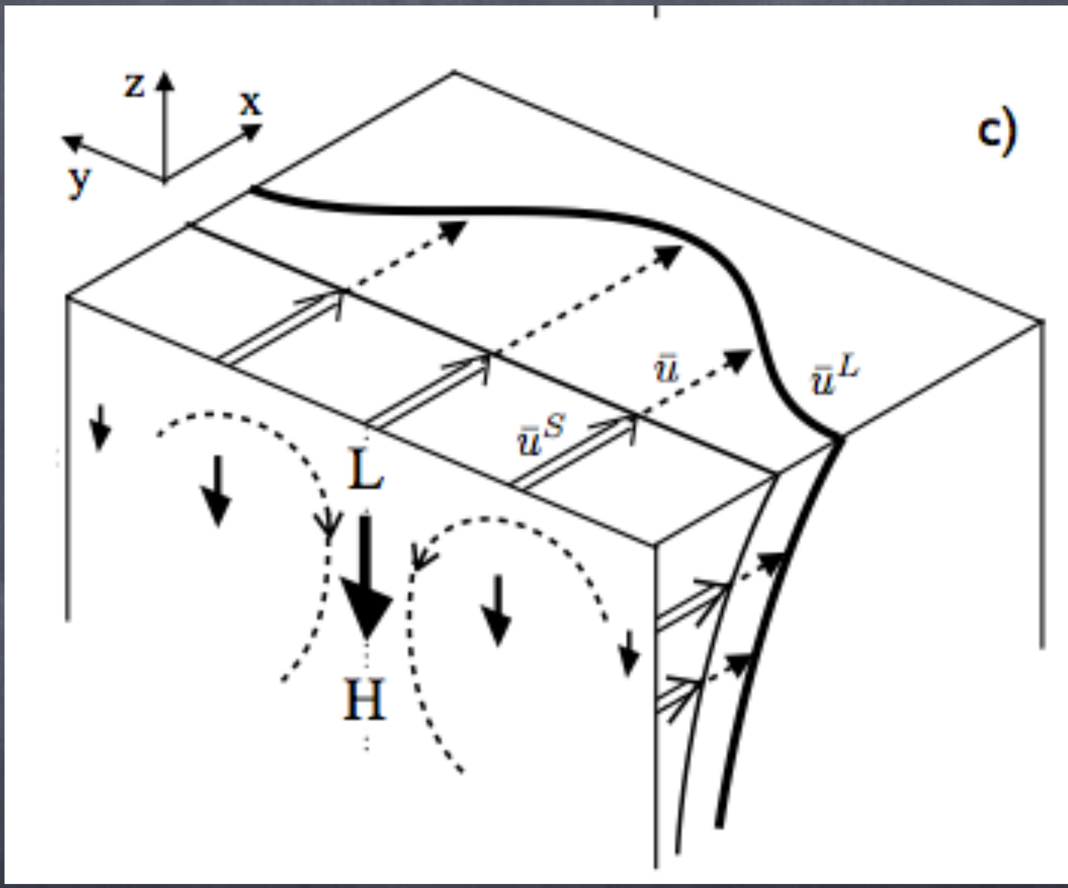
N. Suzuki and BFK. Understanding Stokes Forces in the Wave-Averaged Equations, JPO, in prep, 2014.

Stokes Shear Force:

Craik-Leibovich mechanism for Langmuir circulations

Flow directed along Stokes shear=downward force





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

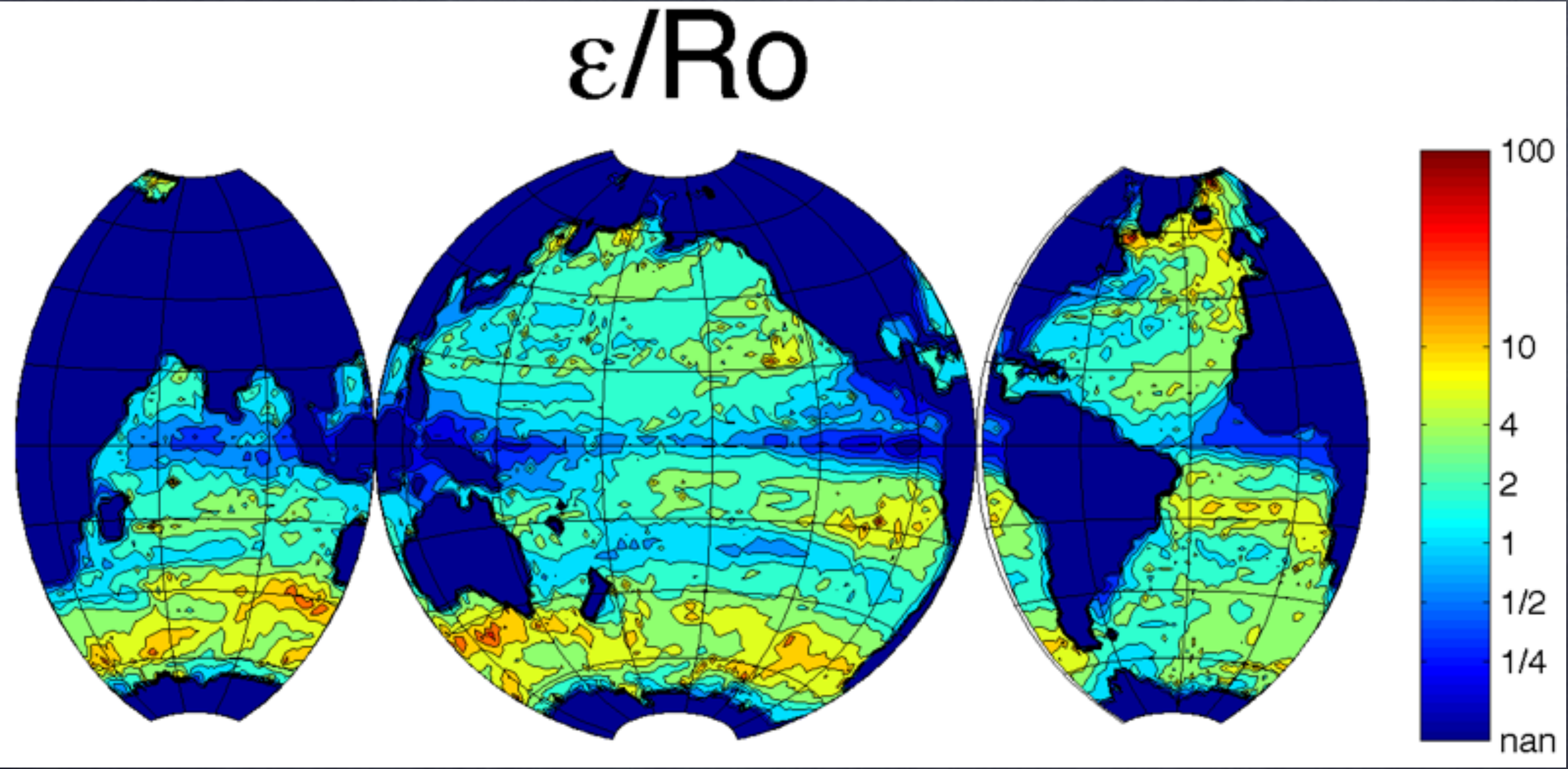
N. Suzuki and BFK. Understanding Stokes Forces in the Wave-Averaged Equations, JPO, in prep, 2014.

When is $\varepsilon = \dfrac{V^s H}{f L H_s}$ big?

$$\varepsilon = \frac{V_s}{fL}\frac{H}{H_s} = \underbrace{\frac{V_s}{fH_s}}_{O(10-100)} \overbrace{\frac{H}{L}}^{\text{slope}}$$

- Isopycnal slope (H/L) is O(0.1—0.01) for submesoscale
- Isopycnal slope (H/L) is $O(10^{-4})$ for mesoscale

Potential Stokes effect at the (sub)mesoscale!!



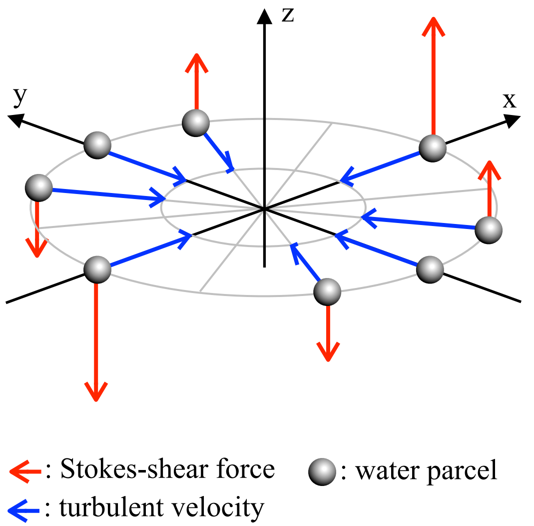
$$\frac{\varepsilon}{Ro} = \frac{V_s}{fL}\frac{H}{H_s}\frac{fL}{V} = \frac{V_s}{V}\frac{H}{H_s}$$

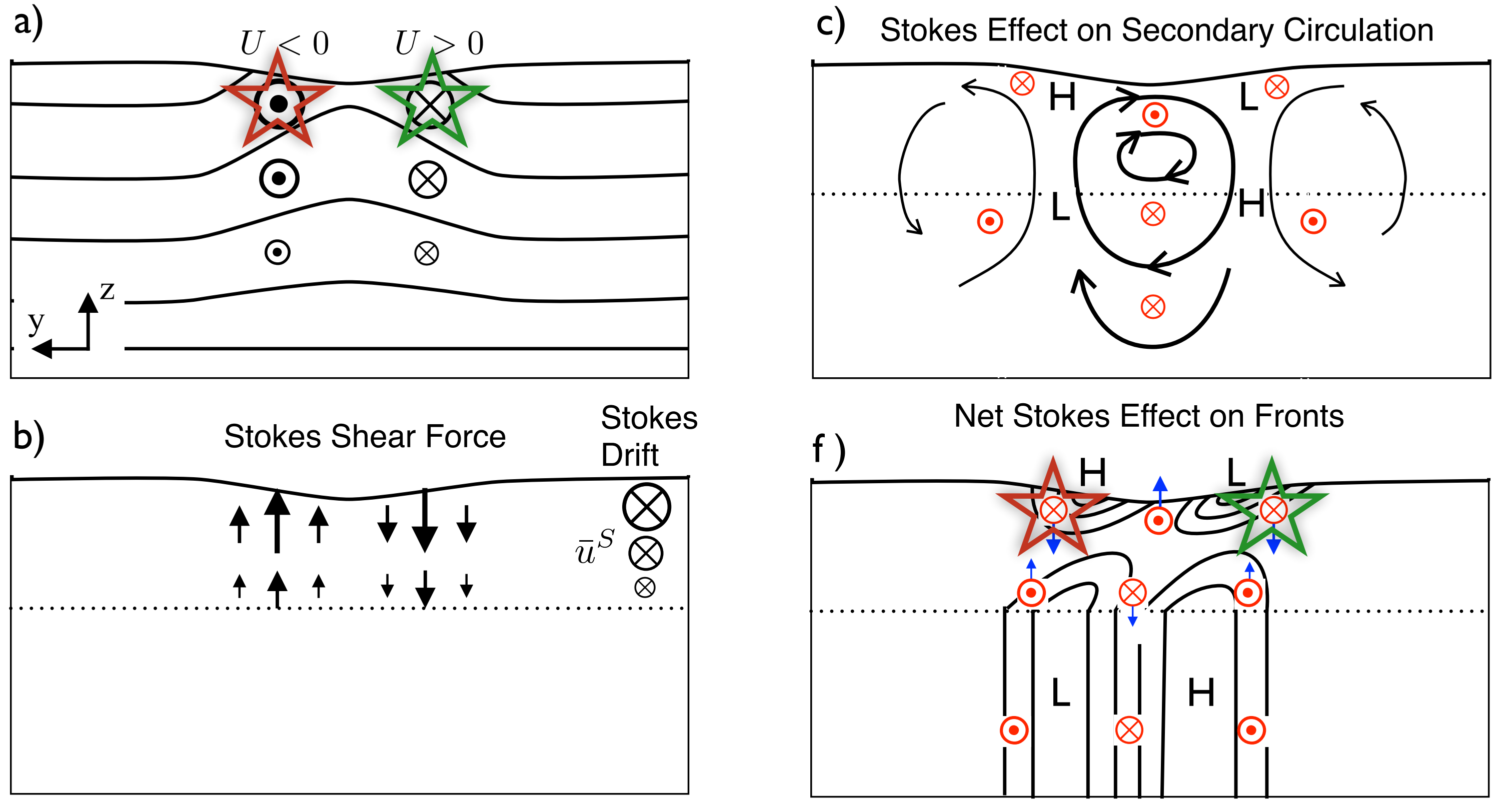
$$\varepsilon = \frac{V^s H}{f L H_s}$$

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

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

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.

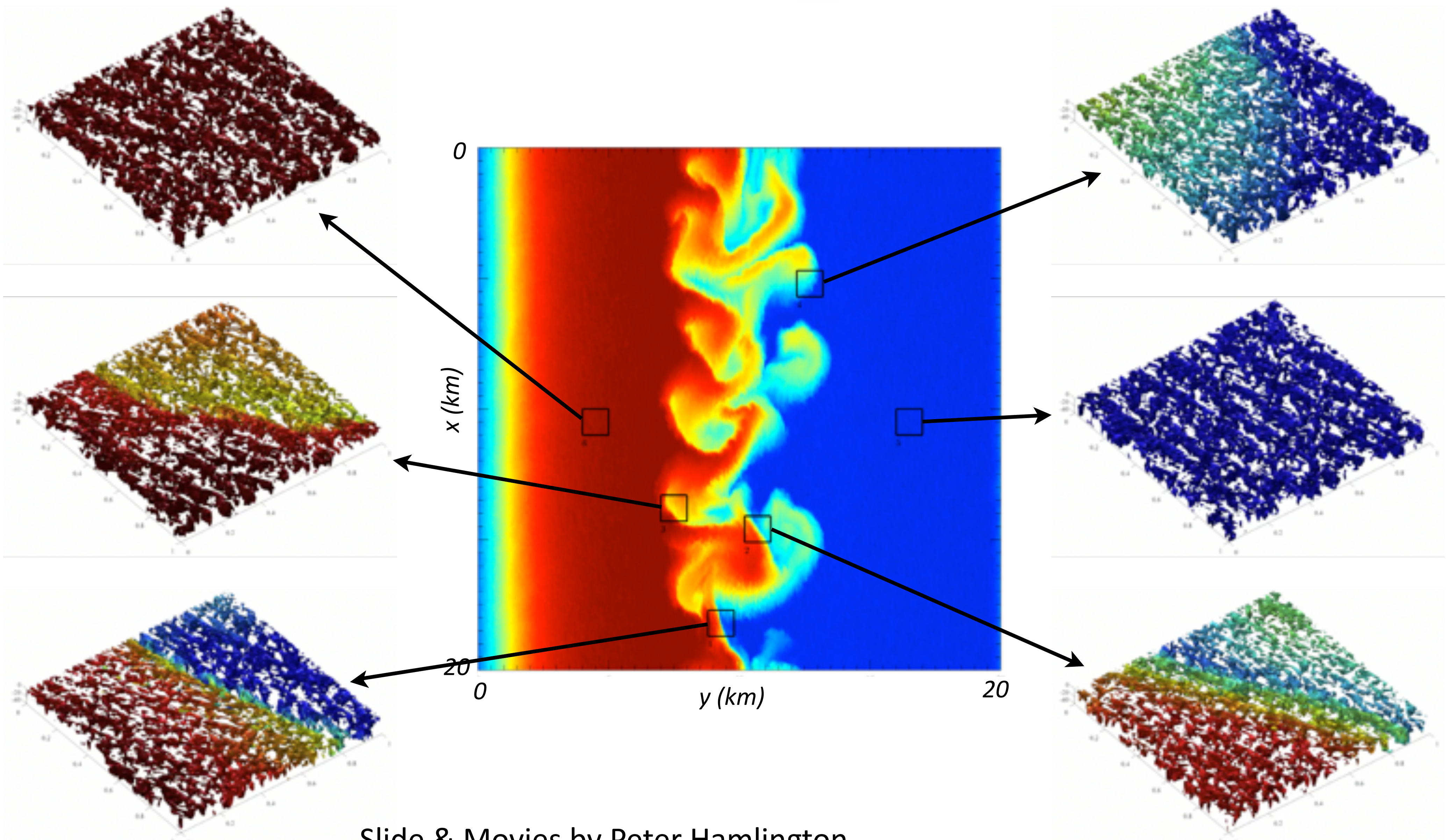
Enhances Fronts for Down-Front Stokes

Opposes Fronts for Up-Front Stokes

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

Waves Give 30-40% of Power Produced at Front

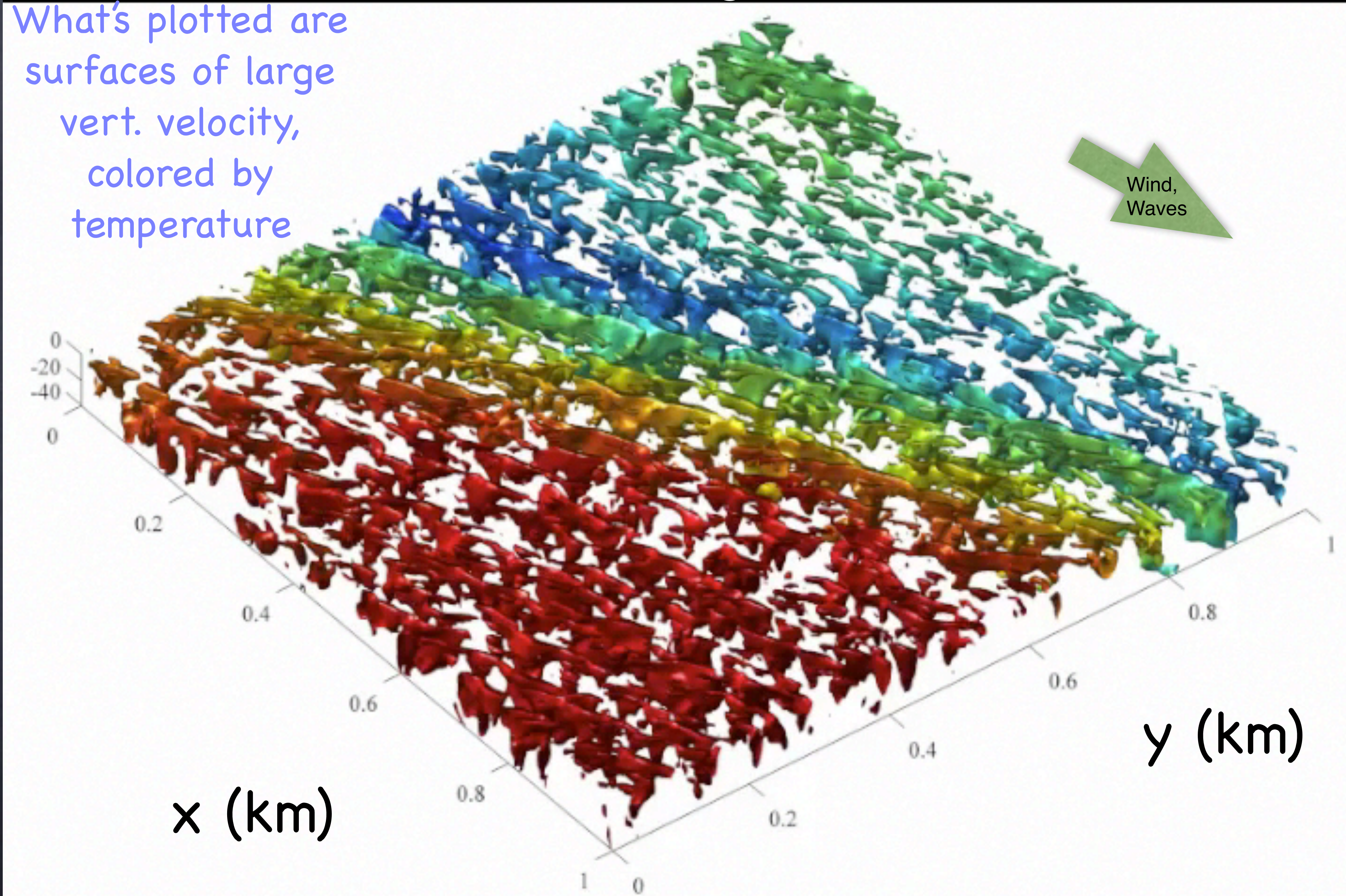
Diverse types of interaction in multiscale simulation.



Slide & Movies by Peter 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.

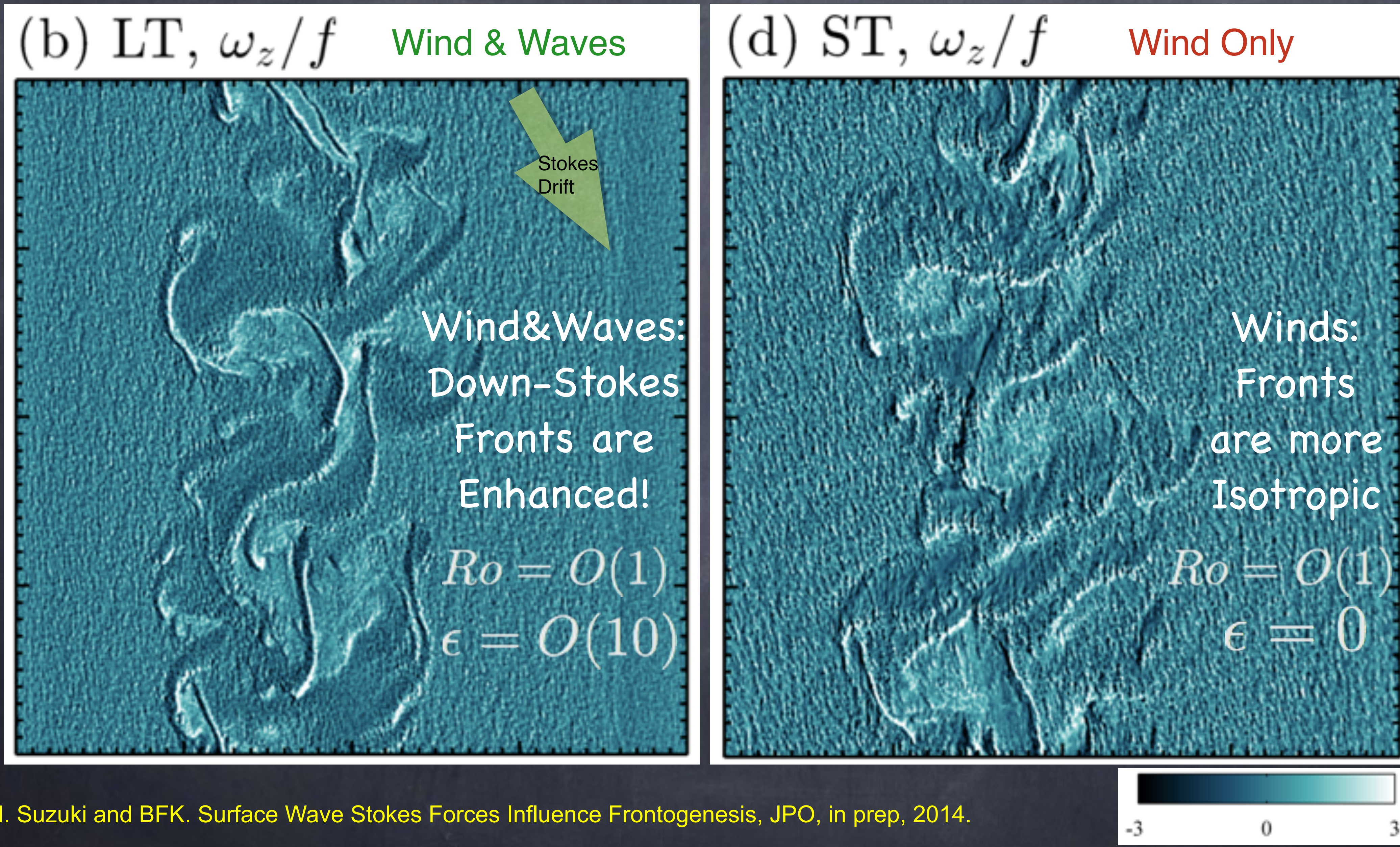
Zoom: Submeso-Langmuir Interaction!



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

Are Fronts and Filaments different with Stokes shear force?

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

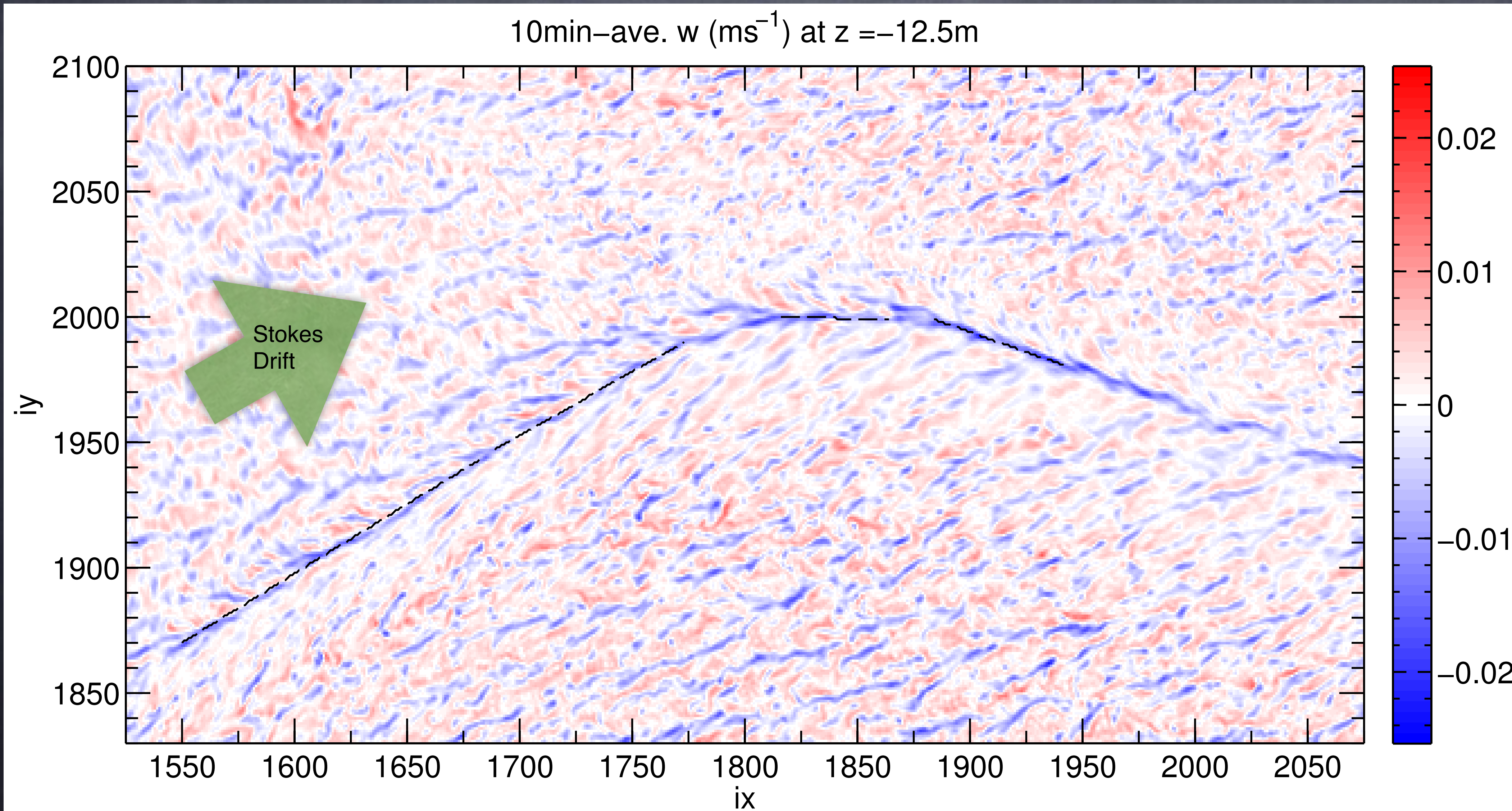


N. Suzuki and BFK. Surface Wave Stokes Forces Influence Frontogenesis, JPO, in prep, 2014.

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.

Let's examine a particular front with $\varepsilon = \frac{V^s H}{f L H_s} \approx 20$ (Nobu Suzuki)

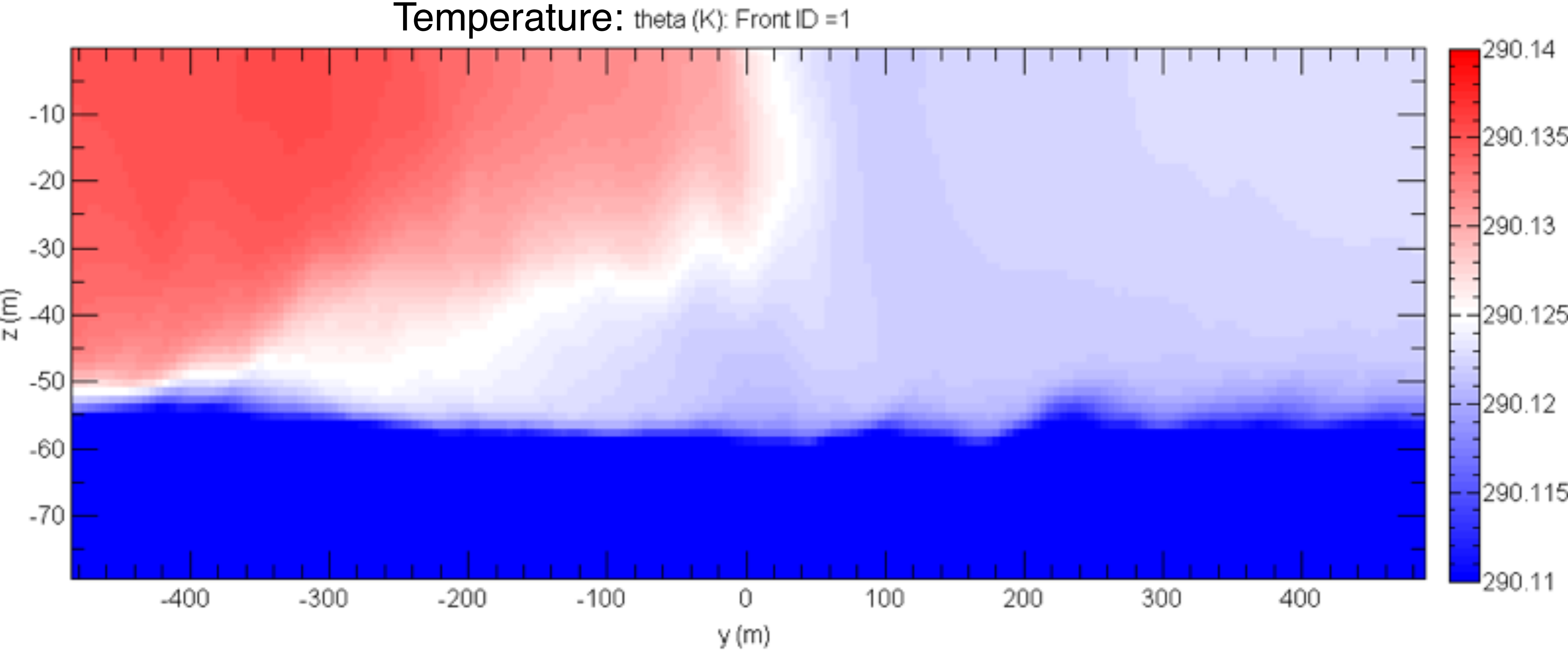


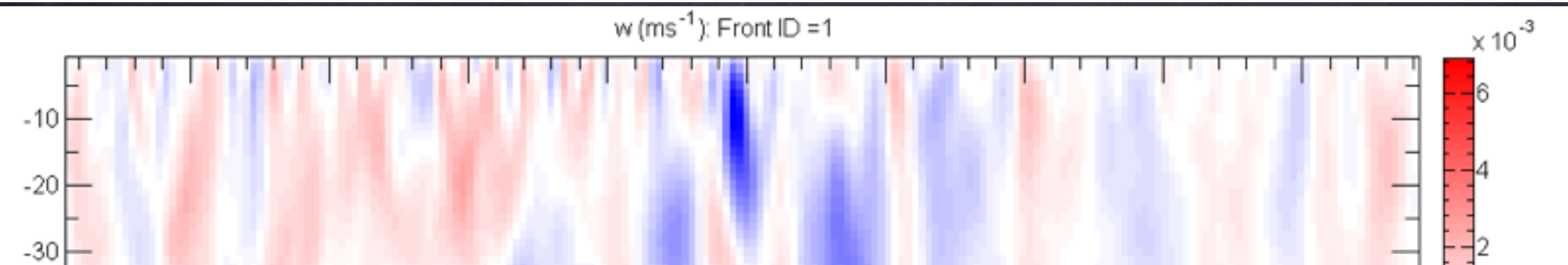
N. Suzuki and B. Fox-Kemper. Stokes Drift of Surface Waves Influences Frontogenesis, JPO, in prep, 2014.

Along-Front and 10min Average

$$\varepsilon = \frac{V^s H}{f L H_s} \approx 20$$

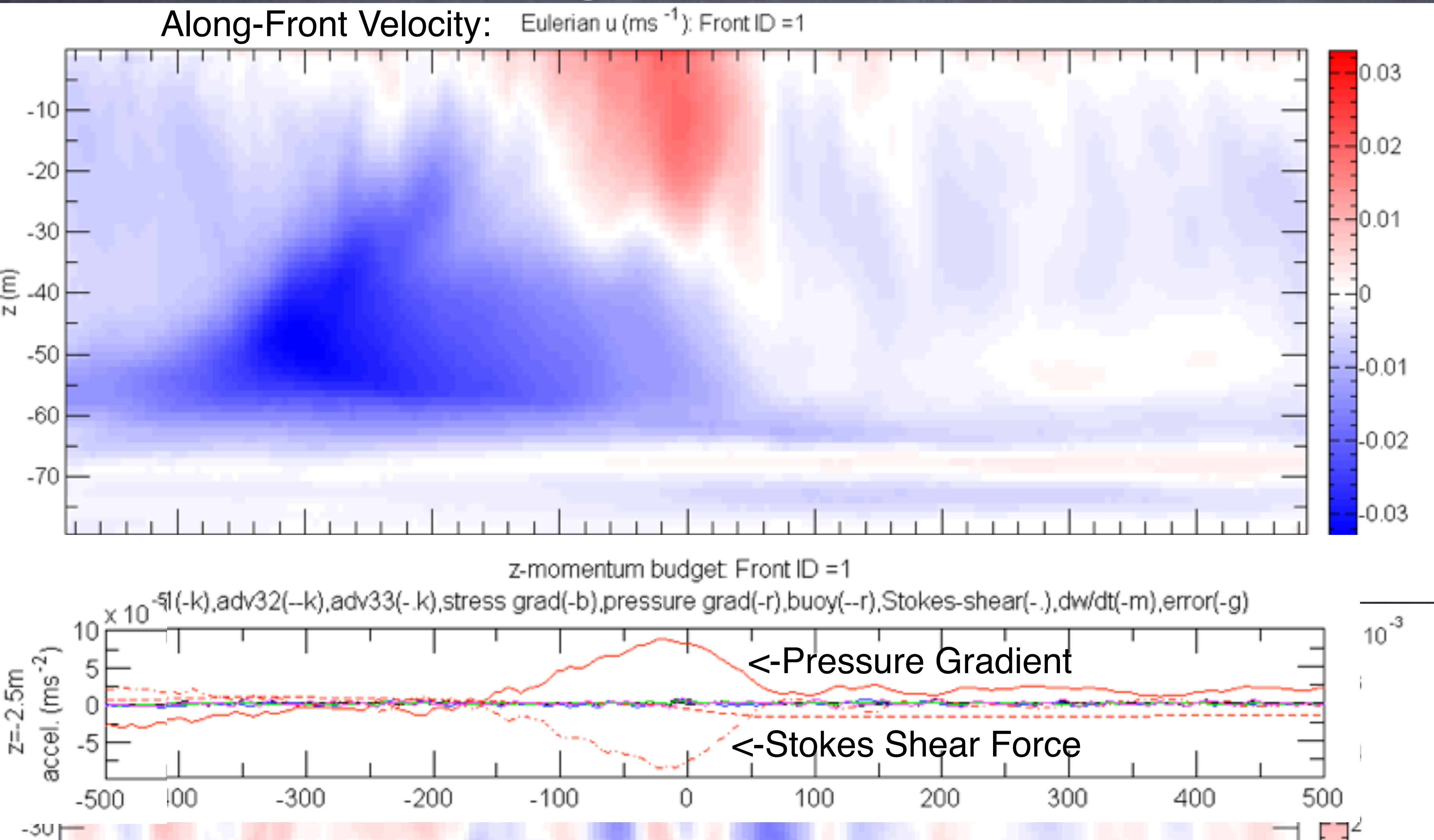
Temperature:





Along-Front and 10min Average

$$\varepsilon = \frac{V^s H}{f L H_s} \approx 20$$



Along-Front and 10min Average

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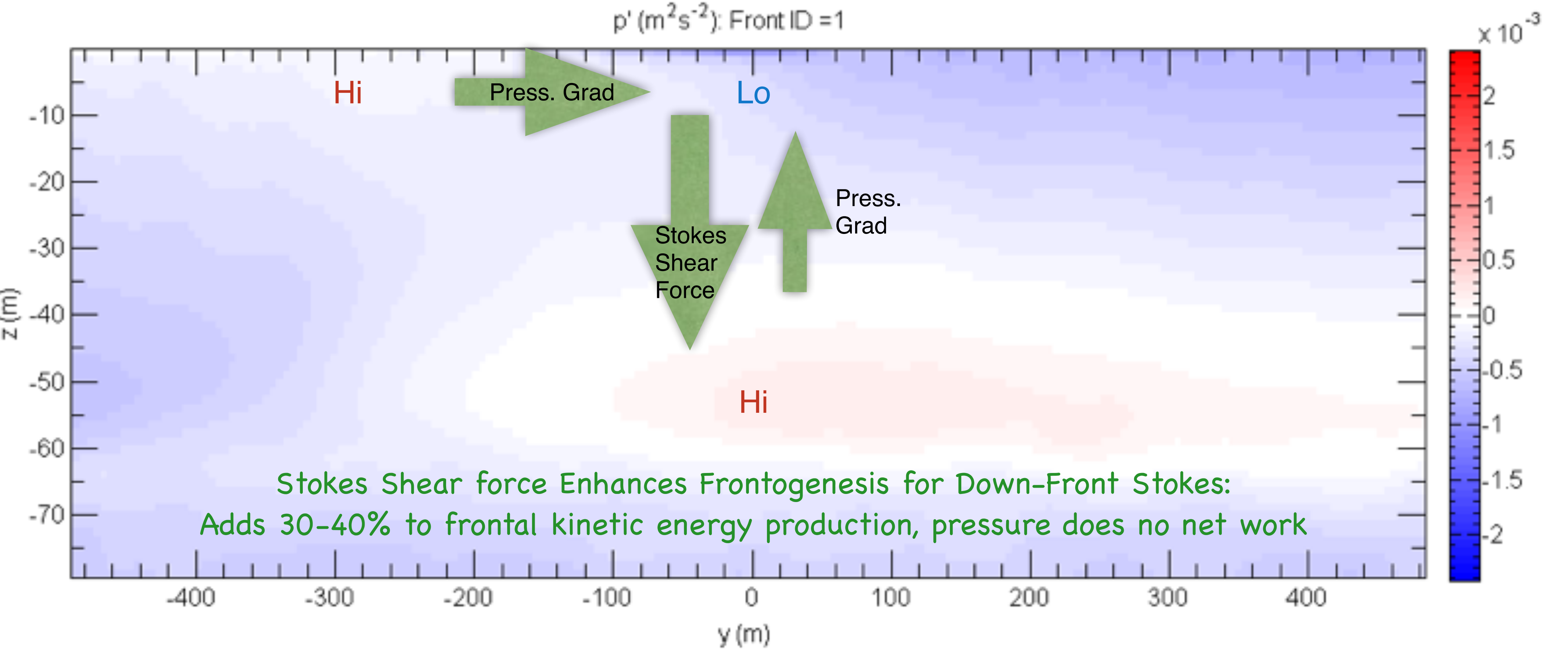
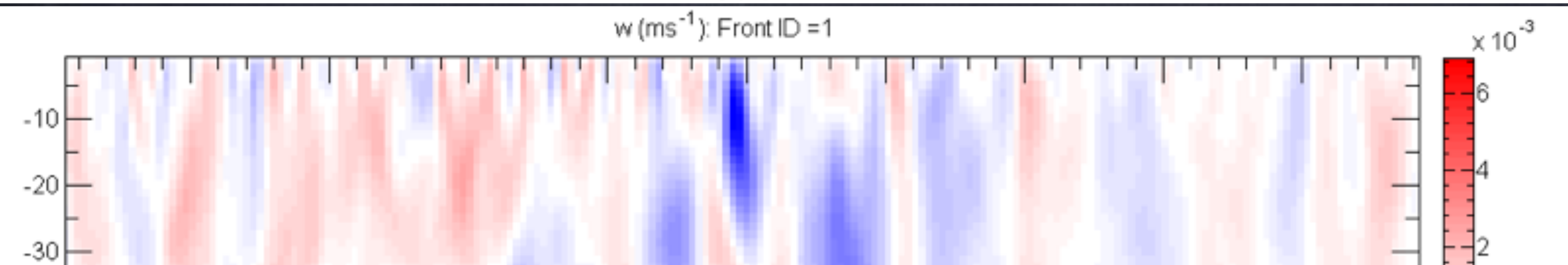




Are Instabilities different with Stokes shear force?

top=Stokes
bot=no Stokes

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.

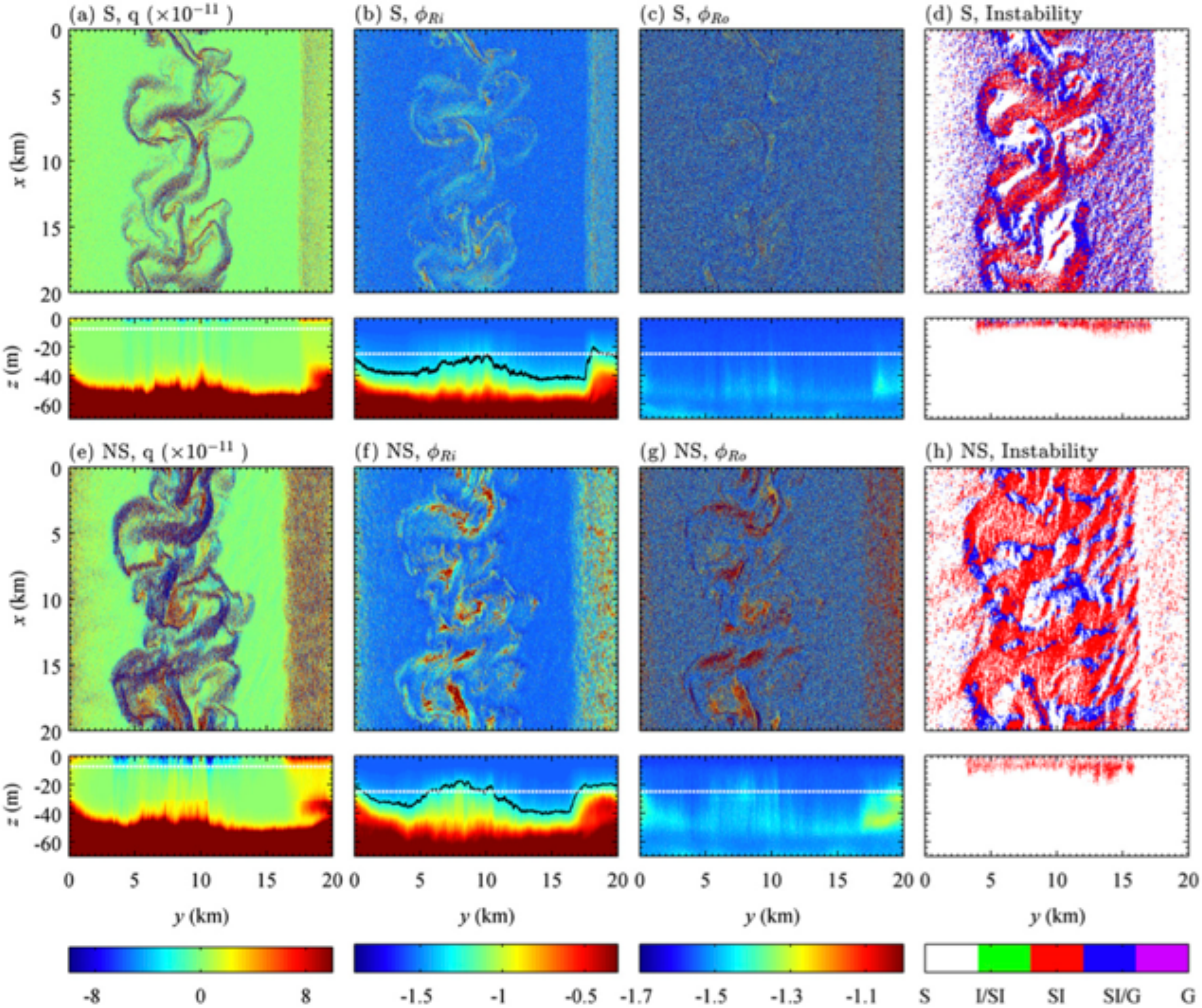
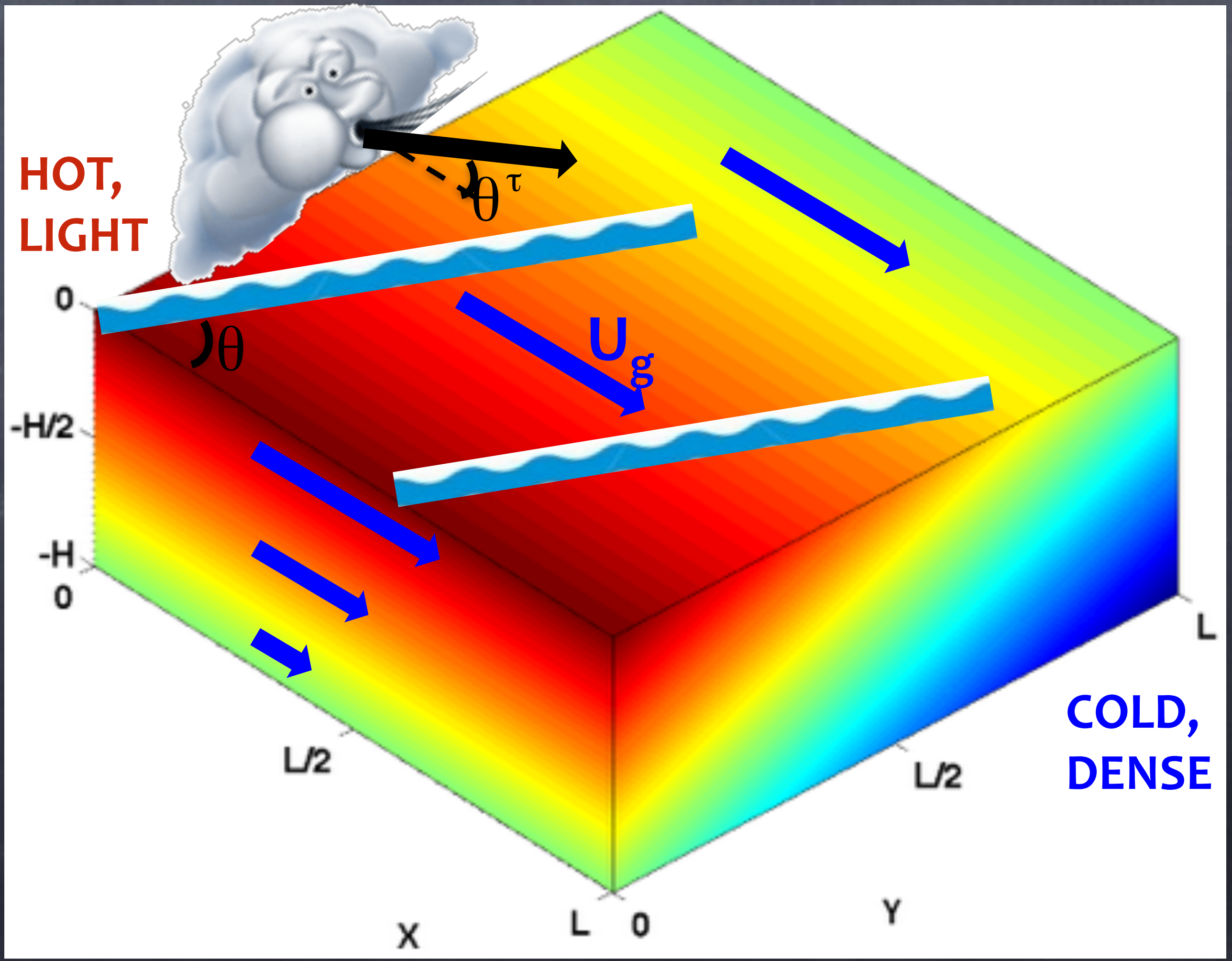


FIG. 12. (a),(e) Potential vorticity q, (b),(f) modified Richardson number ϕ_{Ri}, (c),(g) modified Rossby number ϕ_{Ro}, and (d),(h) instability maps in x–y planes (top panels) and as a function of y and z using x averages (bottom panels) for the (a)–(d) Stokes and (e)–(h) no-Stokes simulations. Instability maps in (d) and (h) are calculated using the criteria in Table 2, and on the color axis "S" corresponds to stable regions, "I" denotes inertial instabilities, "SI" denotes symmetric instability, and "G" denotes gravitational instability.

Stokes effects on Ocean Instabilities (Sean Haney's PhD)

- Which dynamical mixing and restratifying mechanisms, are important and under what combination of winds, waves, and fronts?
- How do the winds and waves stabilize or destabilize the typical the front?
- How does the front stabilize or destabilize the windy/wavy layer?



Analytic Stability Criteria: Geostrophic Modes

* Charney, Stern, and Pedlosky showed, that geostrophic instability exists only if one of the following is true:

1. Q_y changes sign in the interior of the domain.
2. Q_y is the opposite sign to $U^L{}_z$ at the surface.
3. Q_y is the same sign to $U^L{}_z$ at the bottom.
4. $U^L{}_z$ has the same sign at the surface and bottom.

Where Q is the quasi-geostrophic potential vorticity:

$$\bar{Q} = \nabla_H^2 \bar{\psi} + \beta Y + \partial_z \left(\frac{f_0^2}{N^2} \bar{\psi}_z^L \right)$$

Charney, Stern, & Pedlosky gets a tweak—> U is Lagrangian sometimes!

Analytic Stability Criteria: Geostrophic Modes

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Charney, Stern, & Pedlosky gets a tweak—> U is Lagrangian sometimes!

Analytic Stability Criteria: Symmetric Modes

* Hoskins (1974) showed that symmetric instability exists only if the Ertel potential vorticity (PV) is negative.

$$PV = \left(\nabla \times \bar{\mathbf{U}} + f\hat{\mathbf{k}}\right) \bullet \nabla \bar{B} < 0 \Rightarrow SI$$

* Proven for constant shear Stokes drift profiles as well.
* The Stokes drift modifies the PV by changing the Eulerian flow that balances the pressure gradient:

Lagrangian Thermal Wind:

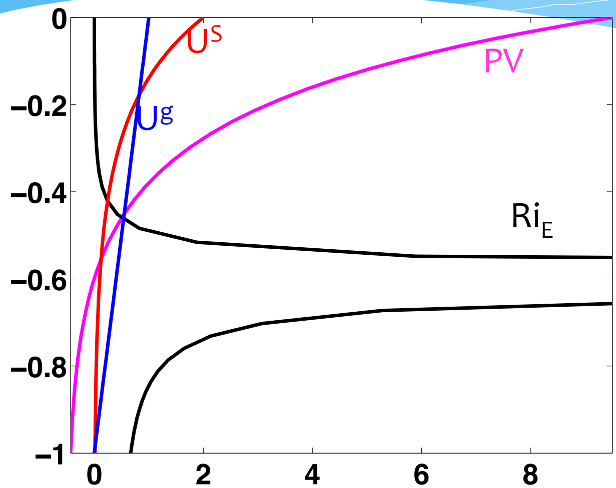
$$\bar{\mathbf{U}}_z = -\frac{\nabla_H \bar{B}}{f} - \mathbf{U}_z^S$$

* The Stokes drift does not contribute directly to Ertel PV
* Be careful! Can't use tracer diagnosis to find Eulerian shear!

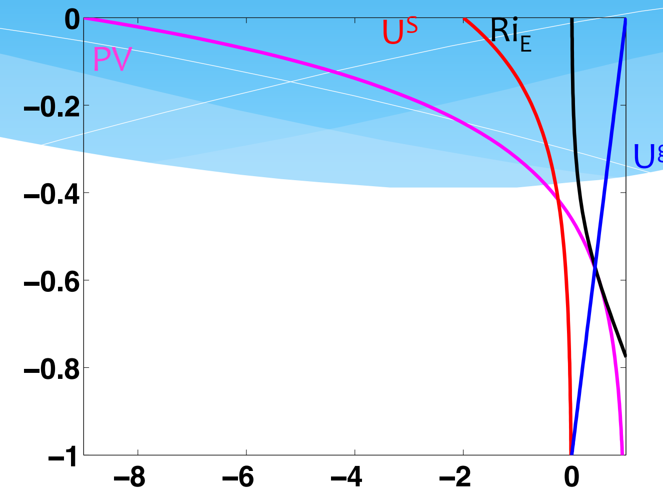
~~Ri < 1 ⇒ SI~~

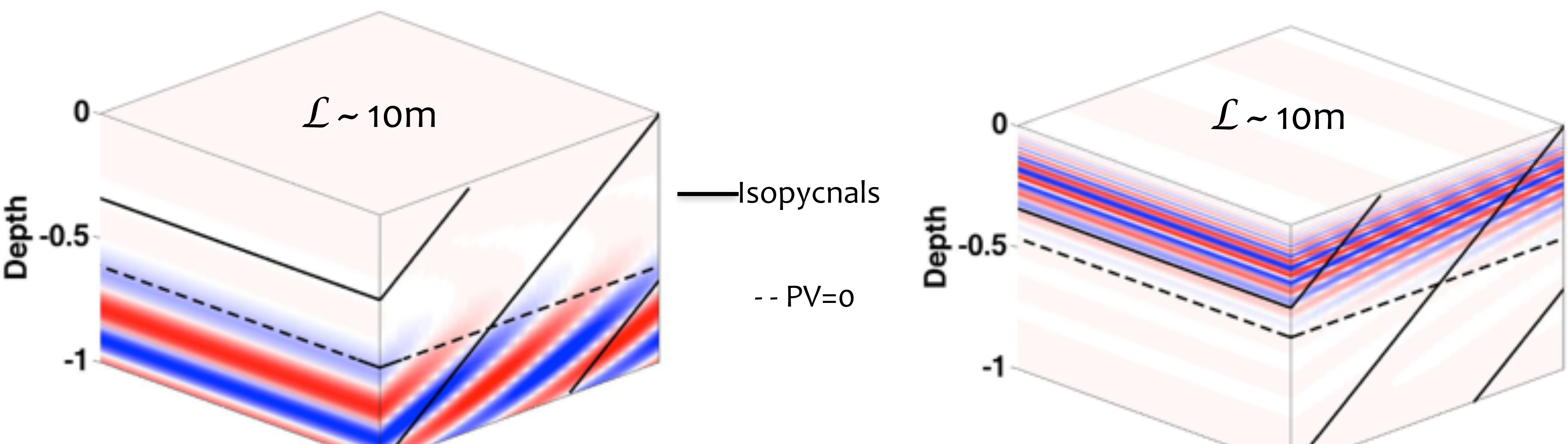
PV<0 ⇒ SI ✓

Ri = 0.5



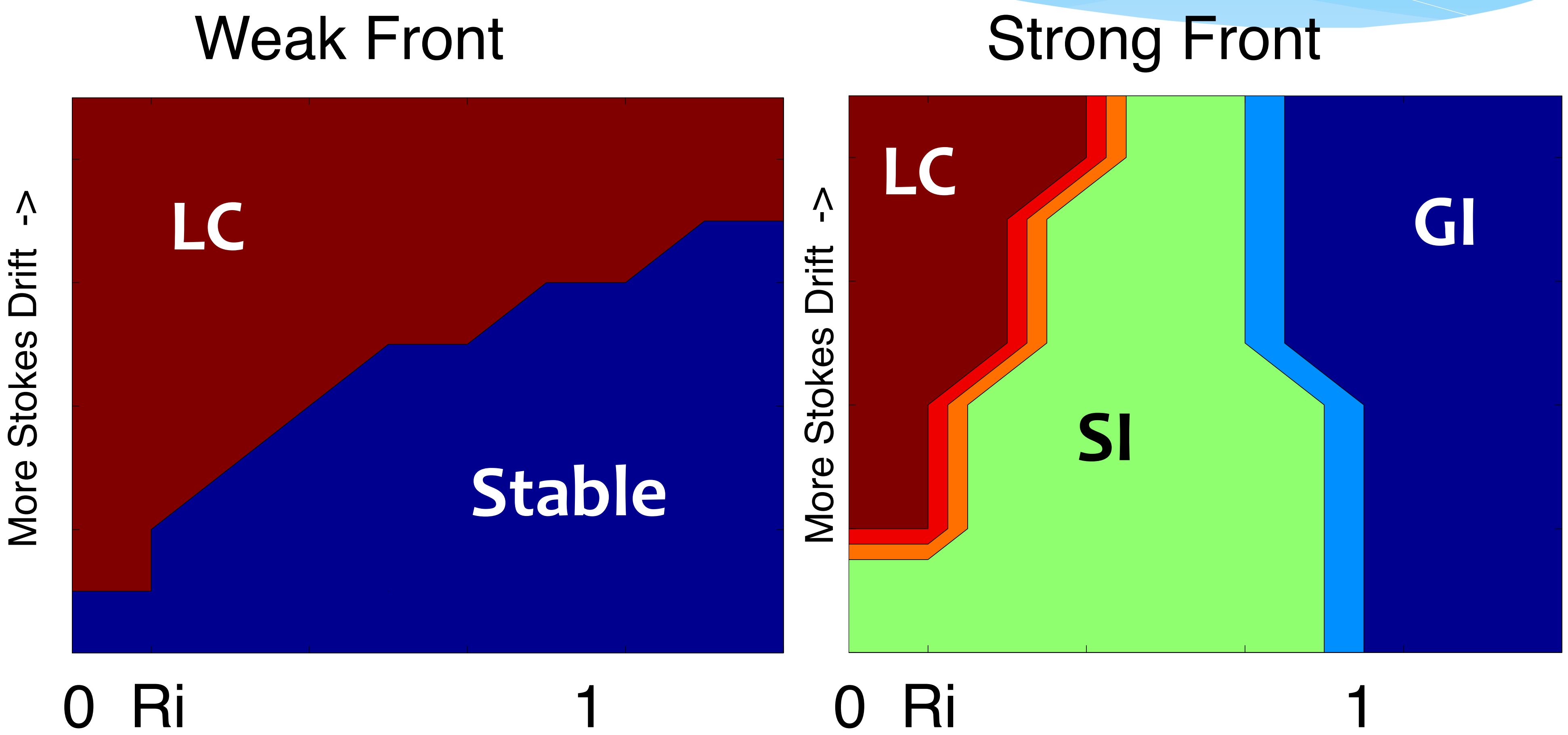
Ri = 2

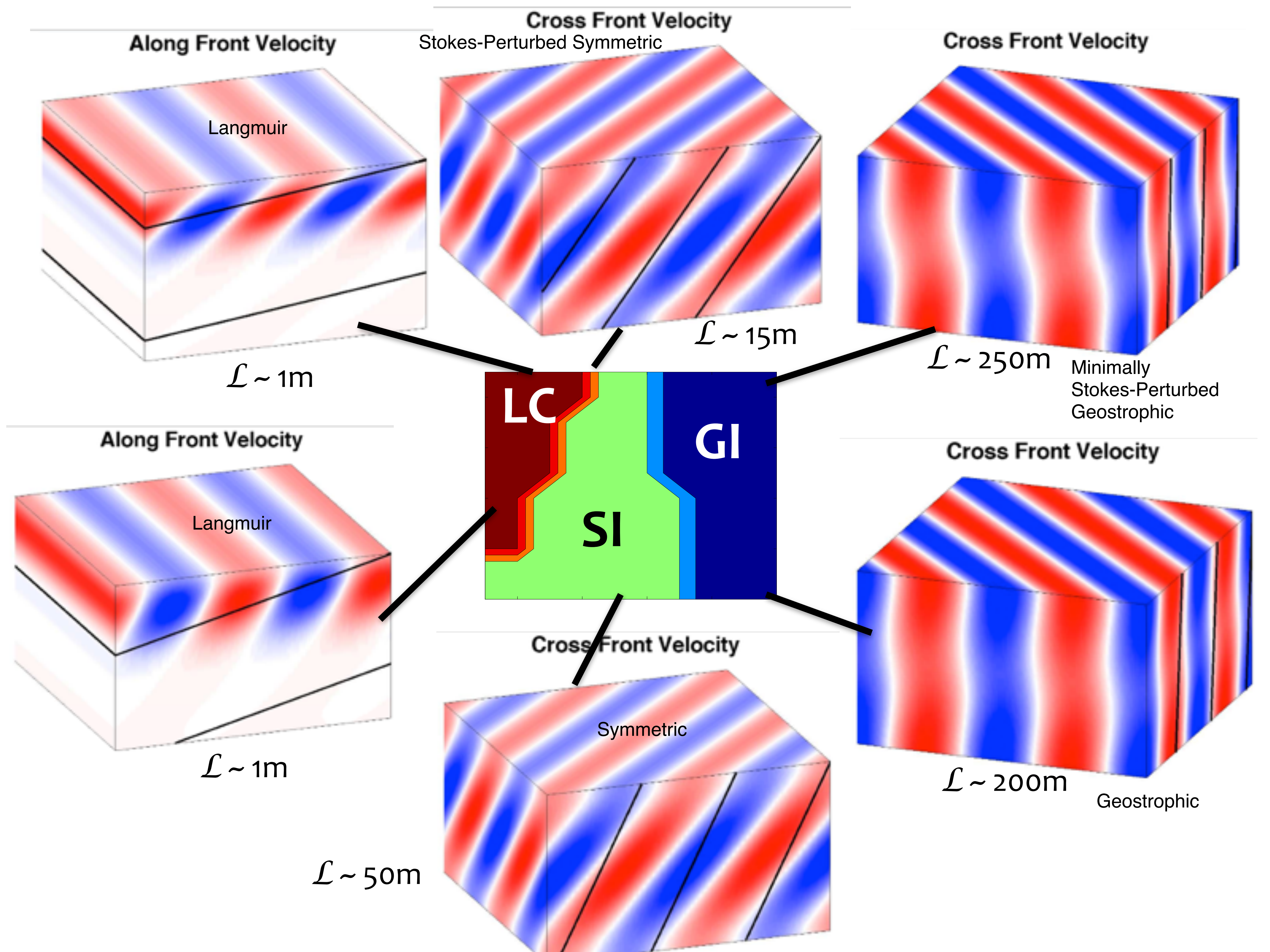




Cross front velocity for the fastest growing mode

Linear Instability Regimes for Fastest Growing Mode





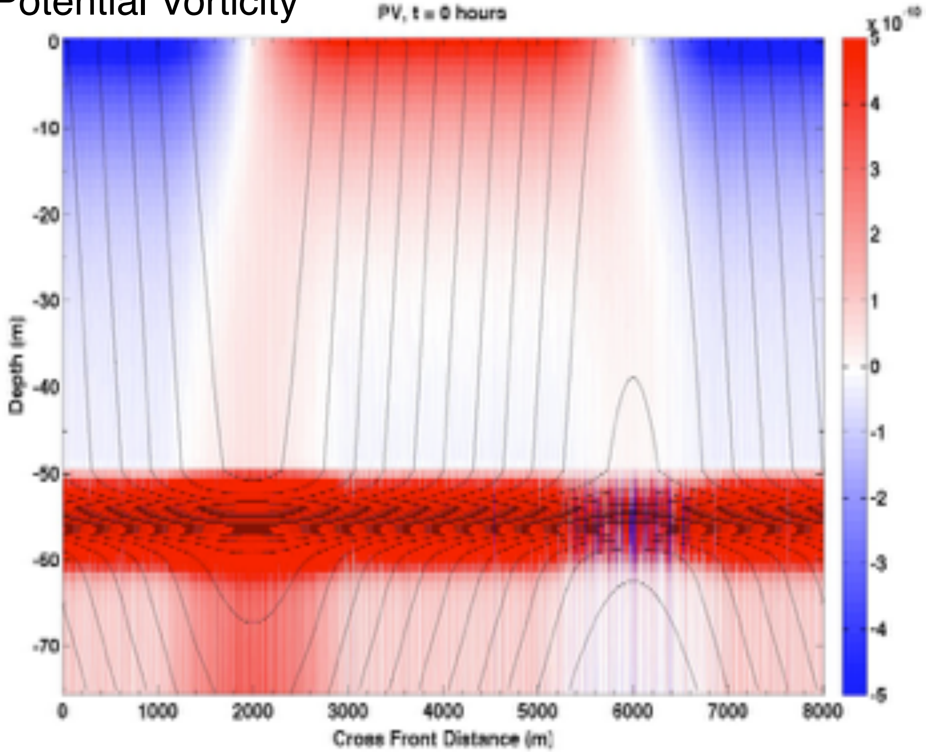
Along Front Velocity
Langmuir
$\mathcal{L}$ ~ 1m
Cross Front Velocity
Stokes-Perturbed Symmetric
$\mathcal{L}$ ~ 15m
Cross Front Velocity
$\mathcal{L}$ ~ 250m
Minimally
Stokes-Perturbed
Geostrophic
LC
GI
SI
Along Front Velocity
Langmuir
$\mathcal{L}$ ~ 1m
Cross Front Velocity
Symmetric
$\mathcal{L}$ ~ 50m
Cross Front Velocity
$\mathcal{L}$ ~ 200m
Geostrophic

What's What?

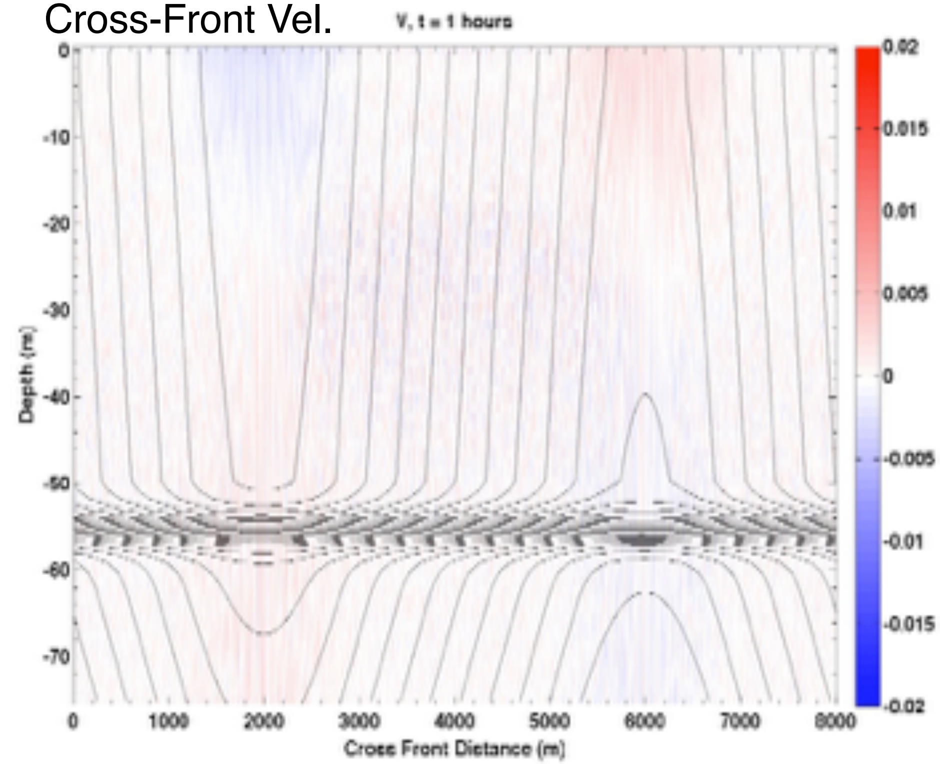
- We have linear & nonlinear sims. with Geostrophic, Langmuir, Kelvin-Helmholtz, and Symmetric Instabilities
- How do we distinguish them?
  - Energy Source (e.g., PE->baroclinic, Stokes shear->LC)
  - By Scale & Orientation (vs. Stokes, shear, etc.)
  - By Dependence on Parameters of Growth & Scale

PV<0 ⇒ SI

Potential Vorticity



Cross-Front Vel.



- A “no [wind] stress” Ekman layer develops due the the surface geostrophic stress.
- SI develop only in regions of negative PV, and are stronger for more negative PV.
- SI restore the PV to zero by exchanging negative PV for positive PV in the pycnocline.

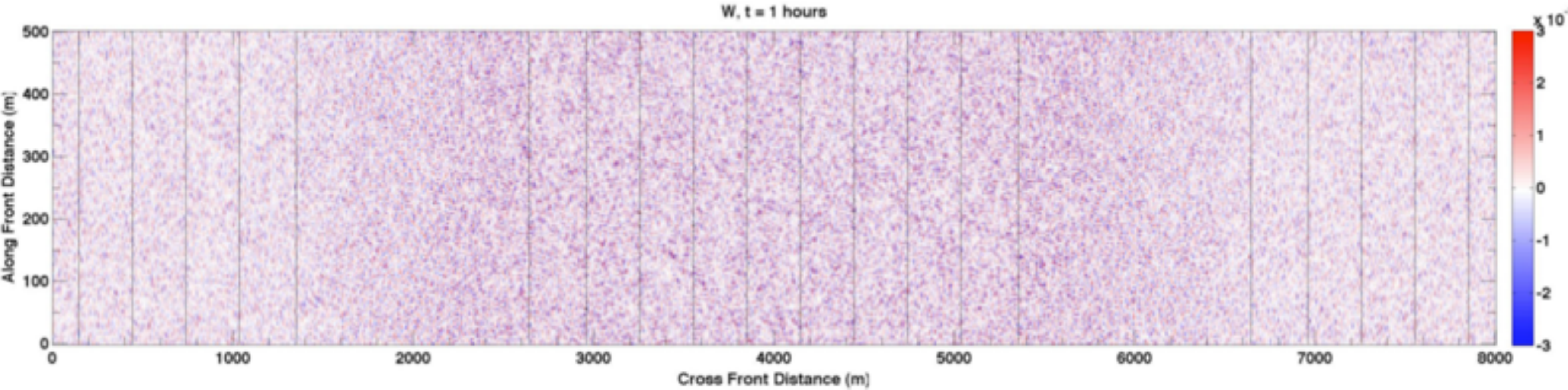
Simulation with no wind, but waves & fronts. Domain too small for mixed layer eddies.
It is SI, not LC that restratify. SI are strongly affected by Stokes drift.
Compare to Taylor & Ferrari (2010) & Li, Chini, Flierl (2012).

Near-Surface: No SI, Fronts Slow LC & Make KH rolls

Horizontal slice of vert. vel. at ~ 5m deep.

HOT, LIGHT

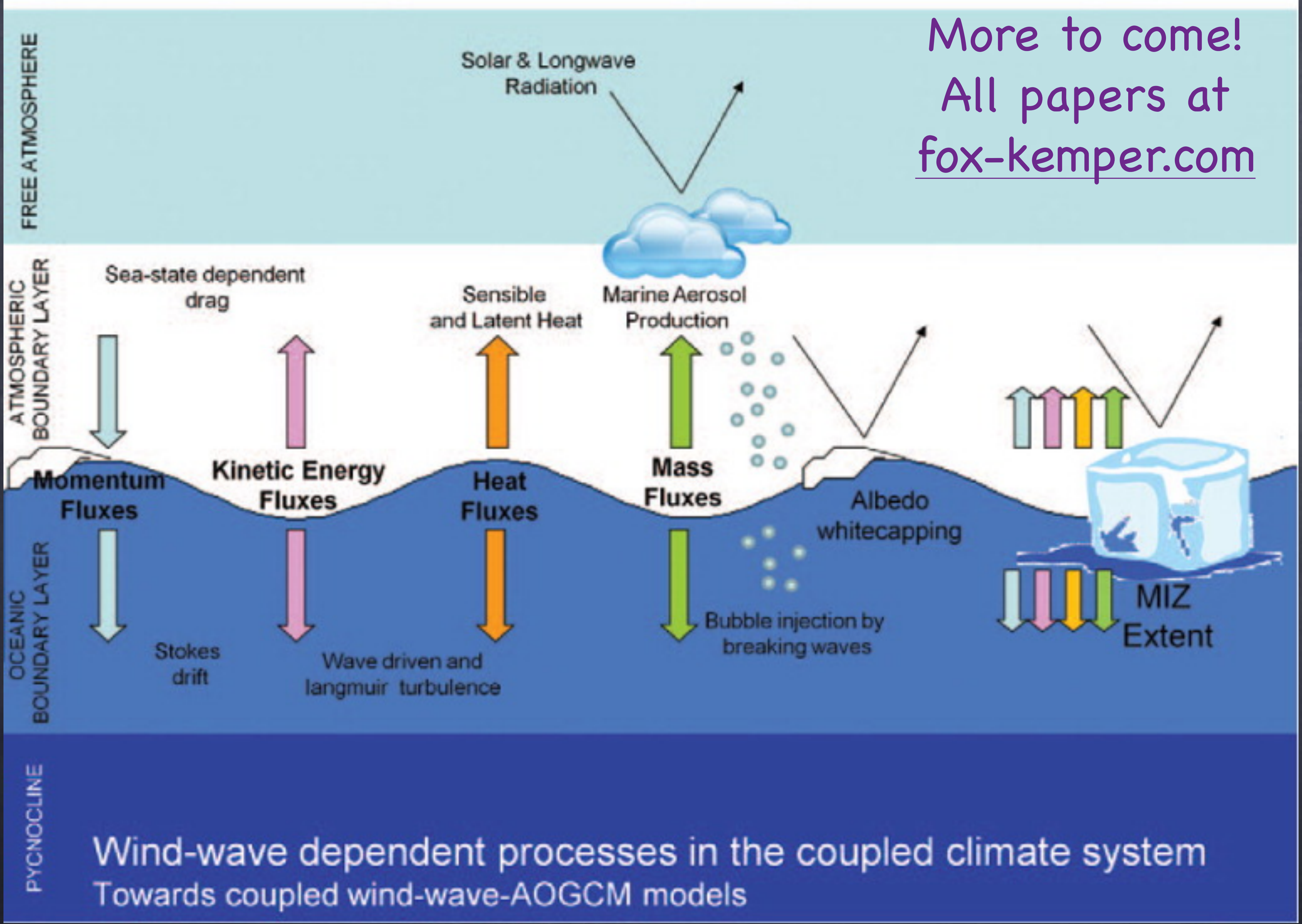
COLD, DENSE



- LC develop in regions without horizontal stratification, align with Lagrangian shear direction
- Unstable stratification in central front yields convective KH rolls, perp to shear.

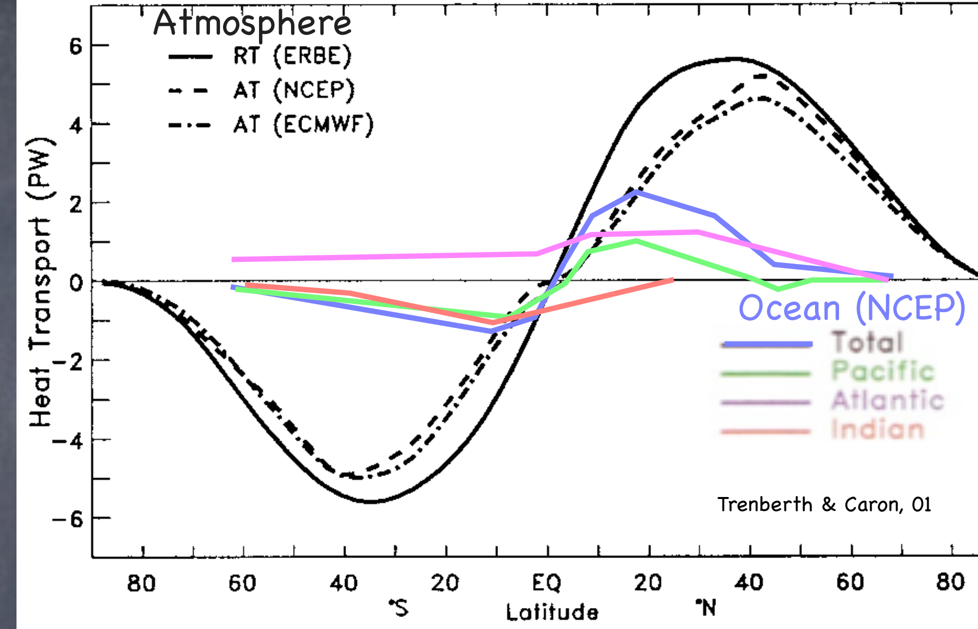
Conclusions

- 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.

Air-Sea Flux Errors vs. Data

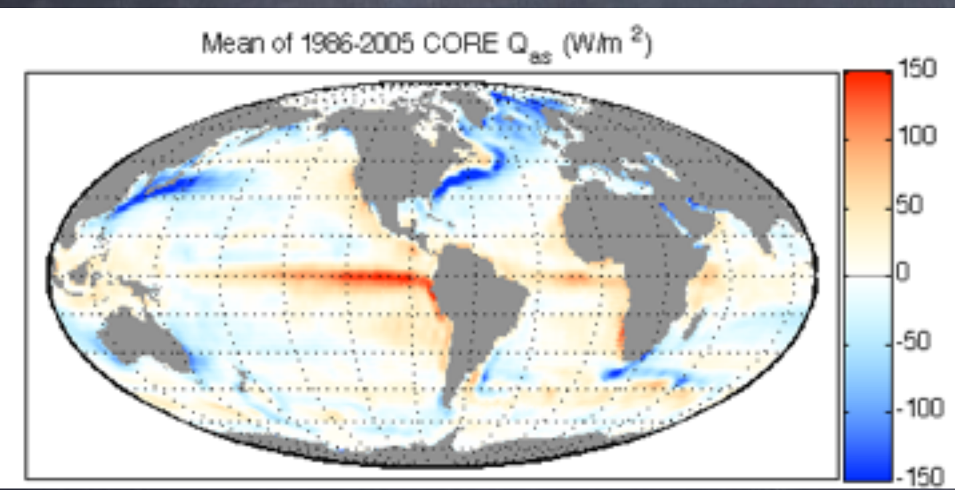


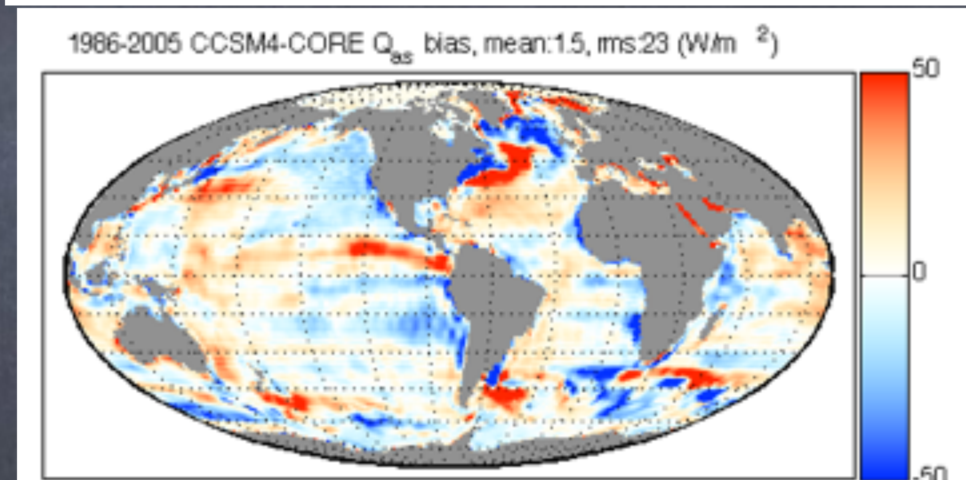
Heat capacity & mode of transport is different in A vs. O

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

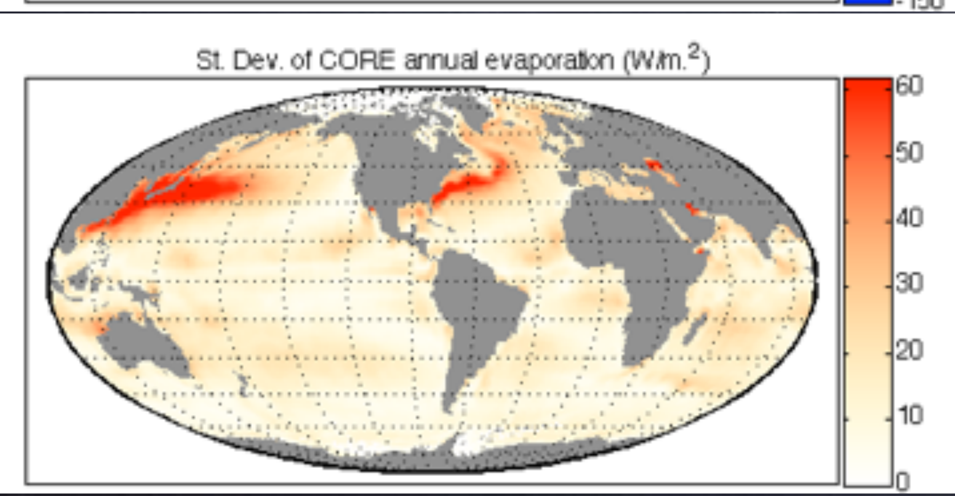
S. C. Bates, BFK, S. R. Jayne, W. G. Large, S. Stevenson, and S. G. Yeager. Mean biases, variability, and trends in air-sea fluxes and SST in the CCSM4.Journal of Climate, 25(22):7781-7801, 2012.

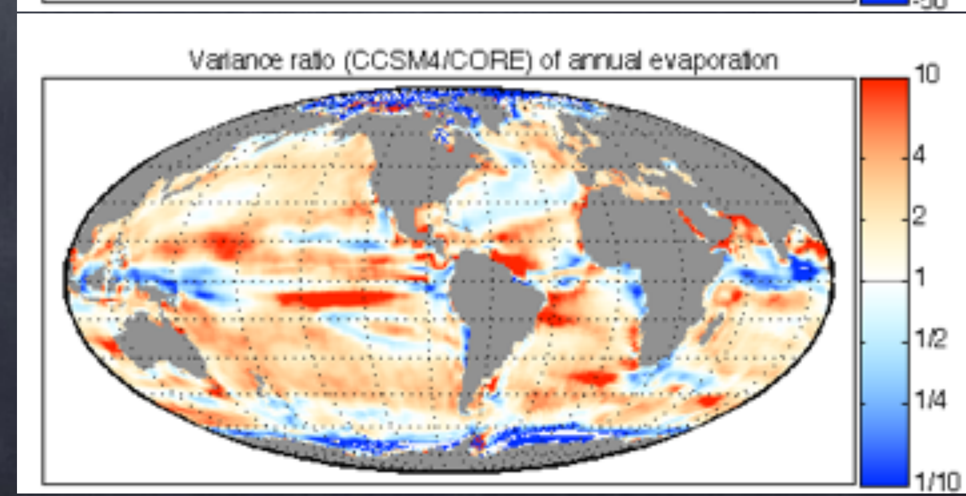
Mean





Annual 9-15mo





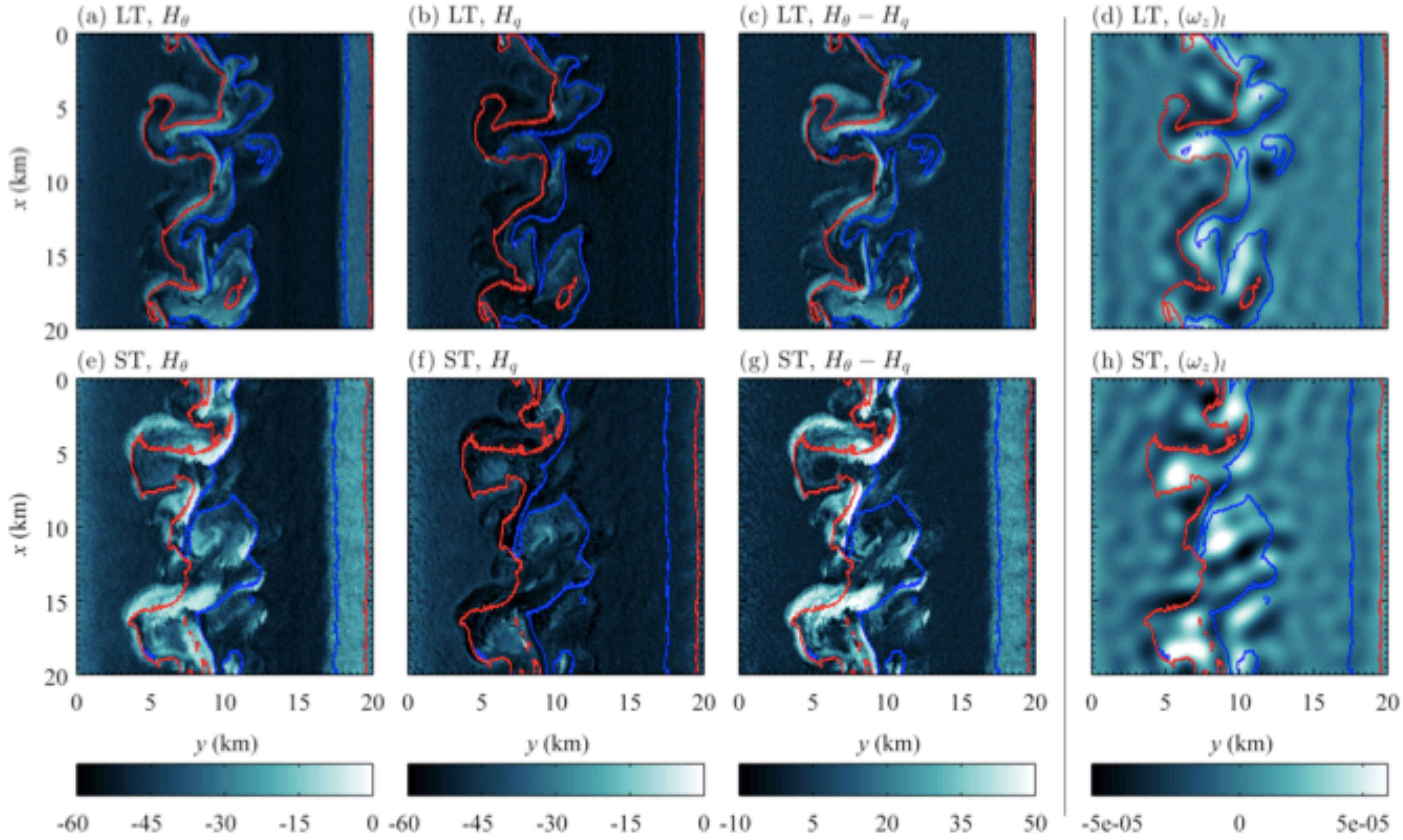


FIG. 13. Fields of the mixed layer depth (in m) based on temperature, denoted H_θ, (a,e) and on potential vorticity, denoted H_q, (b,f) for the LT (a,b) and ST (e,f) cases. The difference $H_\theta - H_q$ is shown in (c,g) and low-pass (submesoscale) vertical vorticity fields are shown in (d,h), where the filter cutoff for the vorticity fields is at 2km. Contour lines correspond to temperature contours taken from Figure 2.

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, 2013. Submitted.

Mixed Layer Eddy Res

Estimating eddy buoyancy/c

$$\overline{\mathbf{u}'b'} \equiv \mathbf{\Psi} \times \nabla \bar{b}$$

A submeso eddy-induced

$$\mathbf{\Psi} = \frac{C_e H^2 \mu(z)}{|f|} \nabla \bar{b} \times$$

in ML only:

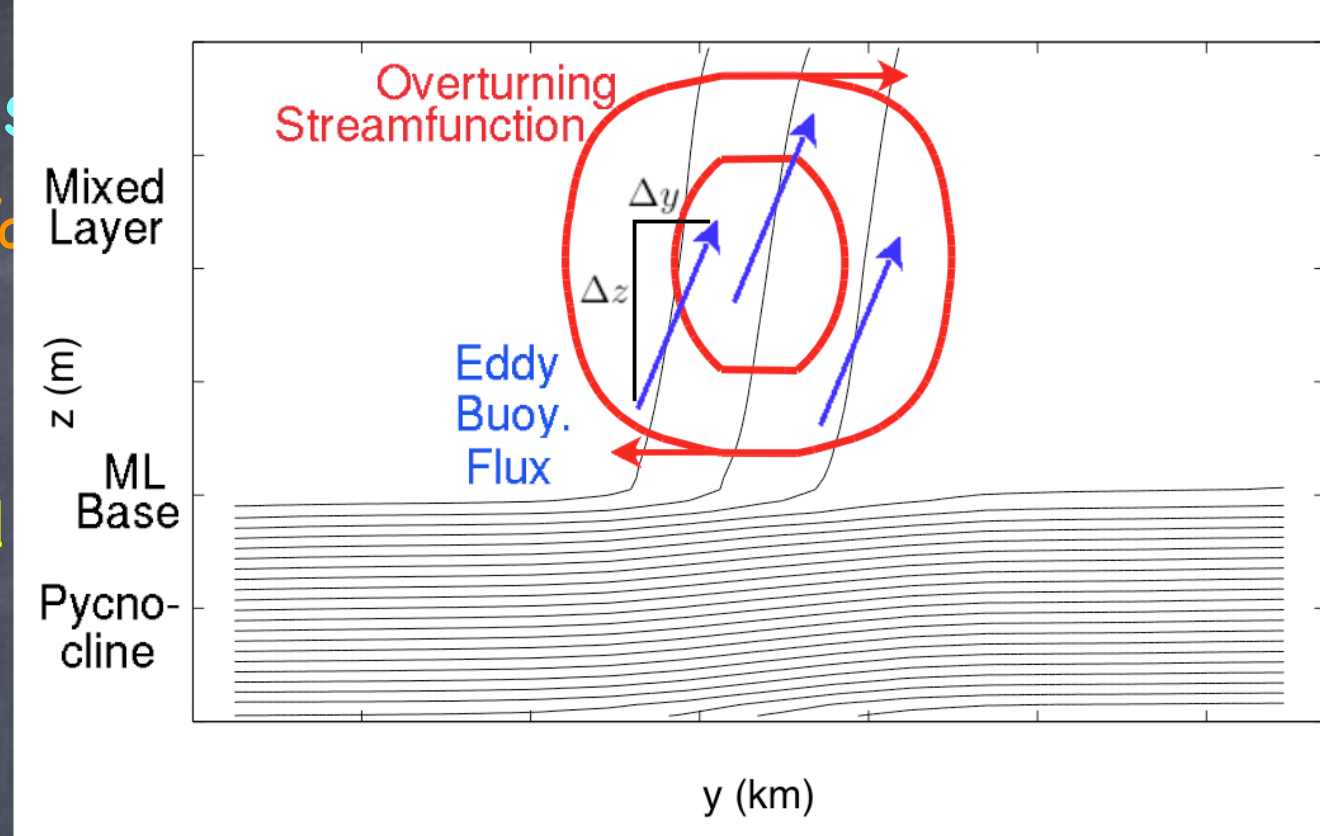
$$\mu(z) = 0 \text{ if } z < -H$$

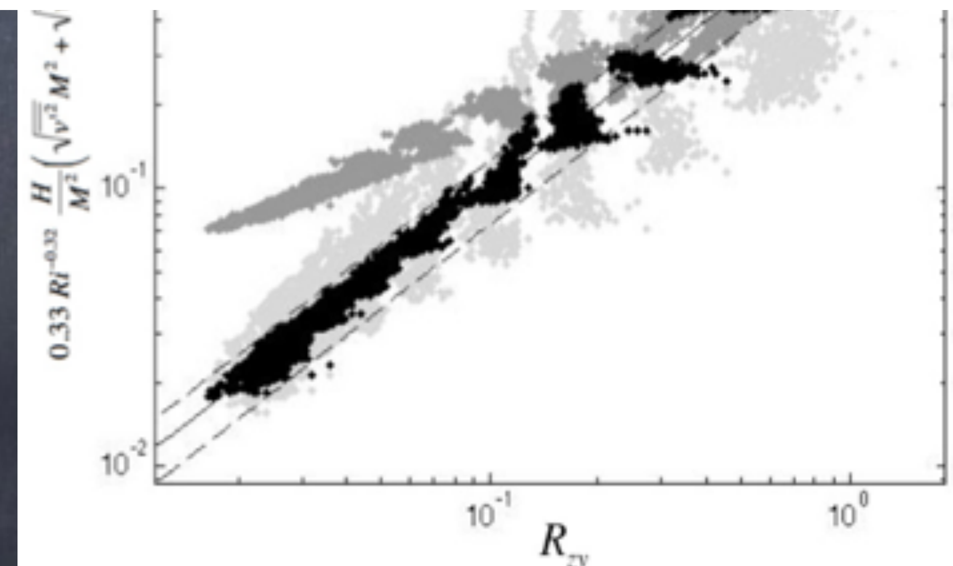
For a consistently restratifying,

$$\overline{w'b'} \propto \frac{H^2}{|f|} \left|\nabla_H \bar{b}\right|^2$$

and horizontally downgradient flux.

$$\overline{\mathbf{u}'_H b'} \propto \frac{-H^2 \frac{\partial \bar{b}}{\partial z}}{|f|} \nabla_H \bar{b}$$

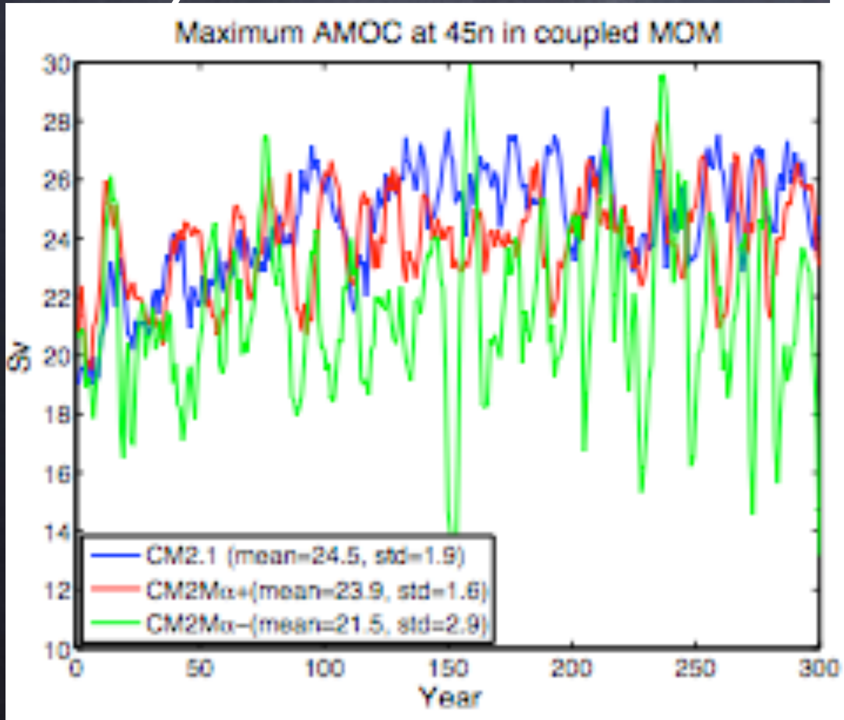




S. Bachman and B. Fox-Kemper. Eddy parameterization challenge suite. I: Eady spindown. Ocean Modelling, 64:12-28, 2013

Sensitivity of Climate to Submeso: AMOC & Cryosphere Impacts

May Stabilize AMOC



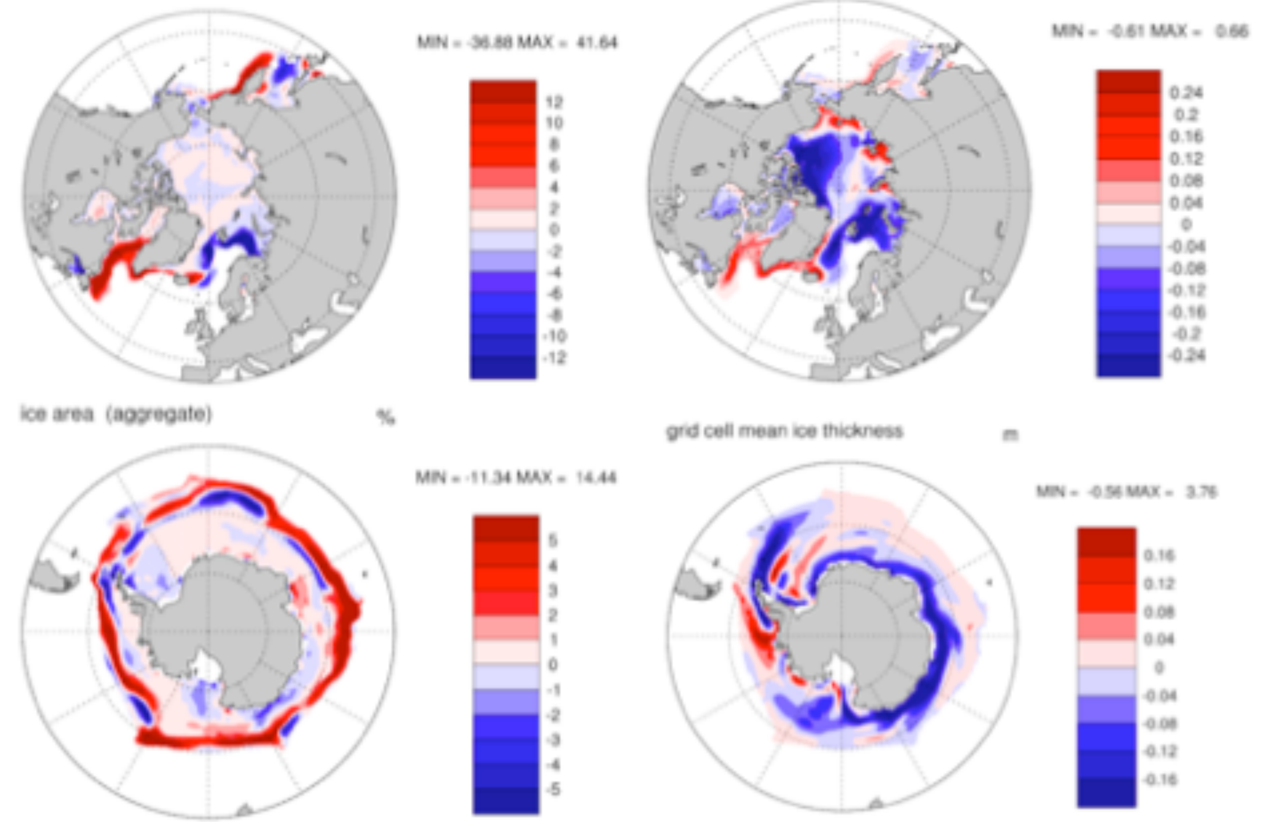


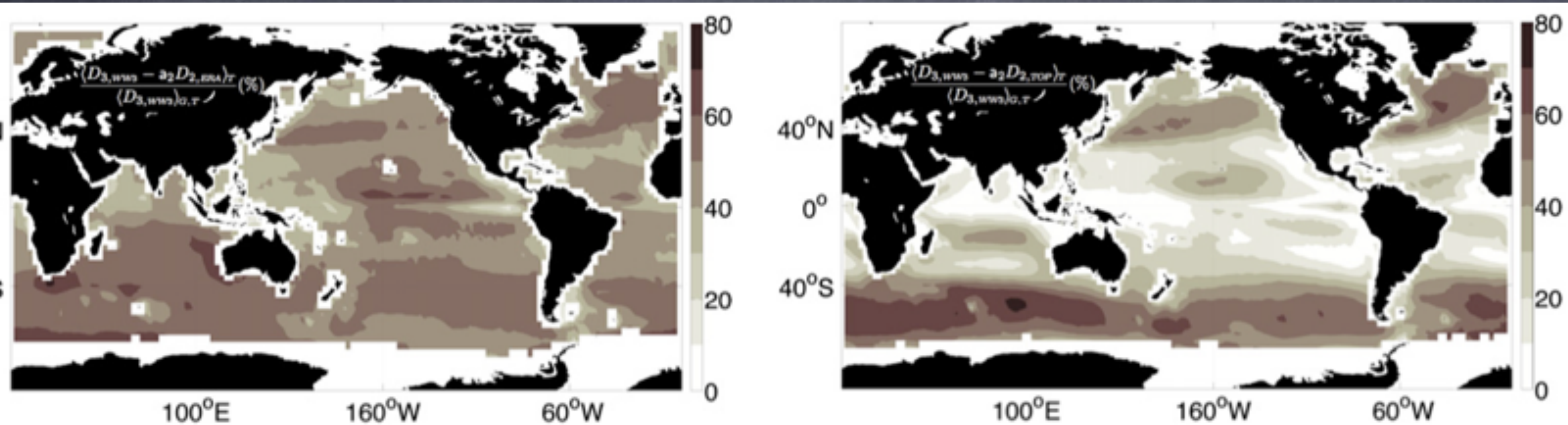
Figure 10: Wintertime sea ice sensitivity to introduction of MLE parameterization ($CCSM^+$ minus $CCSM^-$): January to March Northern Hemisphere a) ice area and b) thickness and July to September Southern Hemisphere c) ice area and d) thickness.

Affects sea ice

NO RETUNING NEEDED!!!

These are impacts: bias change unknown

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



(e) $\langle D_{3,WW3} - \mathrm{a}_2 D_{2,ERA} \rangle_T / \langle D_{3,WW3} \rangle_{G,T}$ (%)

(f) $\langle D_{3,WW3} - \mathrm{a}_2 D_{2,TOP} \rangle_T / \langle D_{3,WW3} \rangle_{G,T}$ (%)

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

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

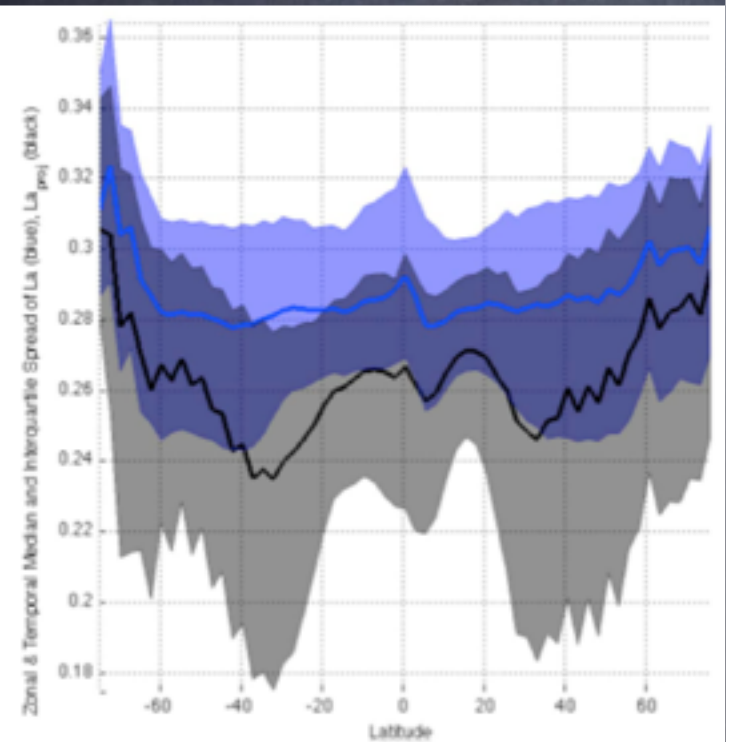


Figure 17. Temporal and zonal median and interquartile range of La_t and La_{proj} for a realistic simulation of 1994–2002 using Wave Watch III.

image: Thorpe, 04

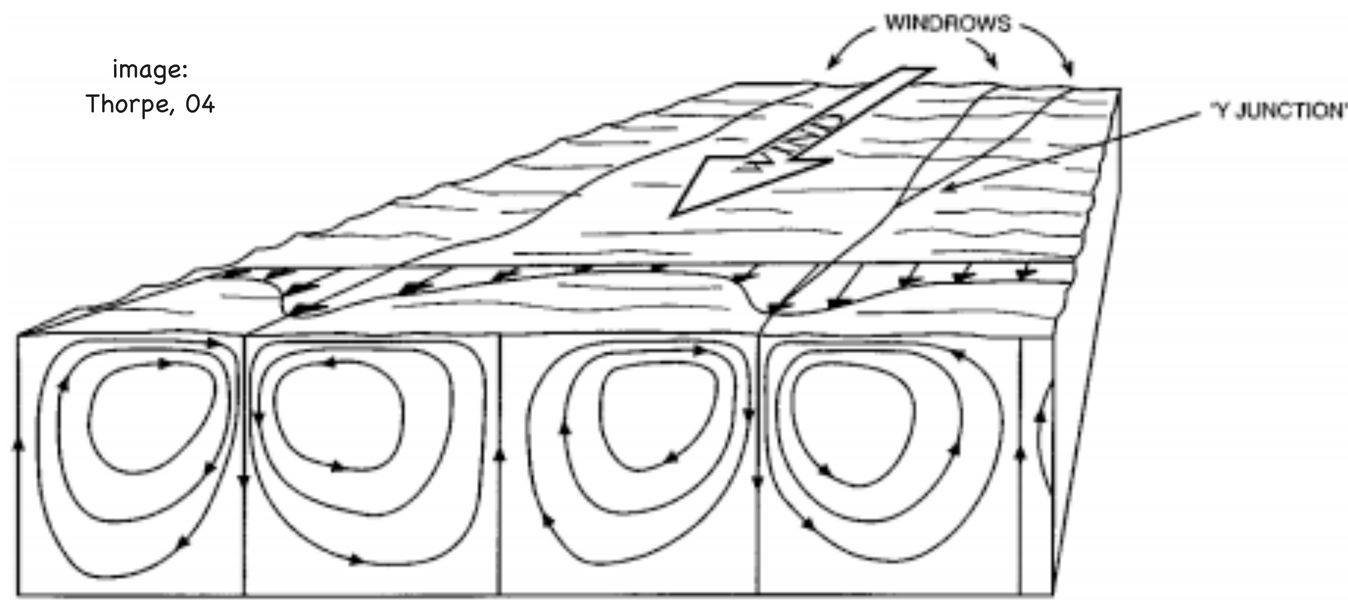


Figure 1 Sketch showing the pattern of mean flow in idealized Langmuir circulation. The windrows may be 2 m to 300 m apart, and the cell form is roughly square (as shown). In practice the flow is turbulent, especially near the water surface, and the windrows (Figure 2) amalgamate and meander in space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

So, no problems? Just crunch away with CLB?

- Let's revisit our assumptions for scale separation:
  - CLB wave equations require limited *wave steepness* and irrotational flow
  - Real wind-waves are not monochromatic, but incorporate a spectrum of waves, and…

Power Spectrum of wave height

$$\langle \eta^2 \rangle = \int_0^\infty E(k)dk = C_0 + \int_{k_h}^\infty C_1 k^{-2} dk$$

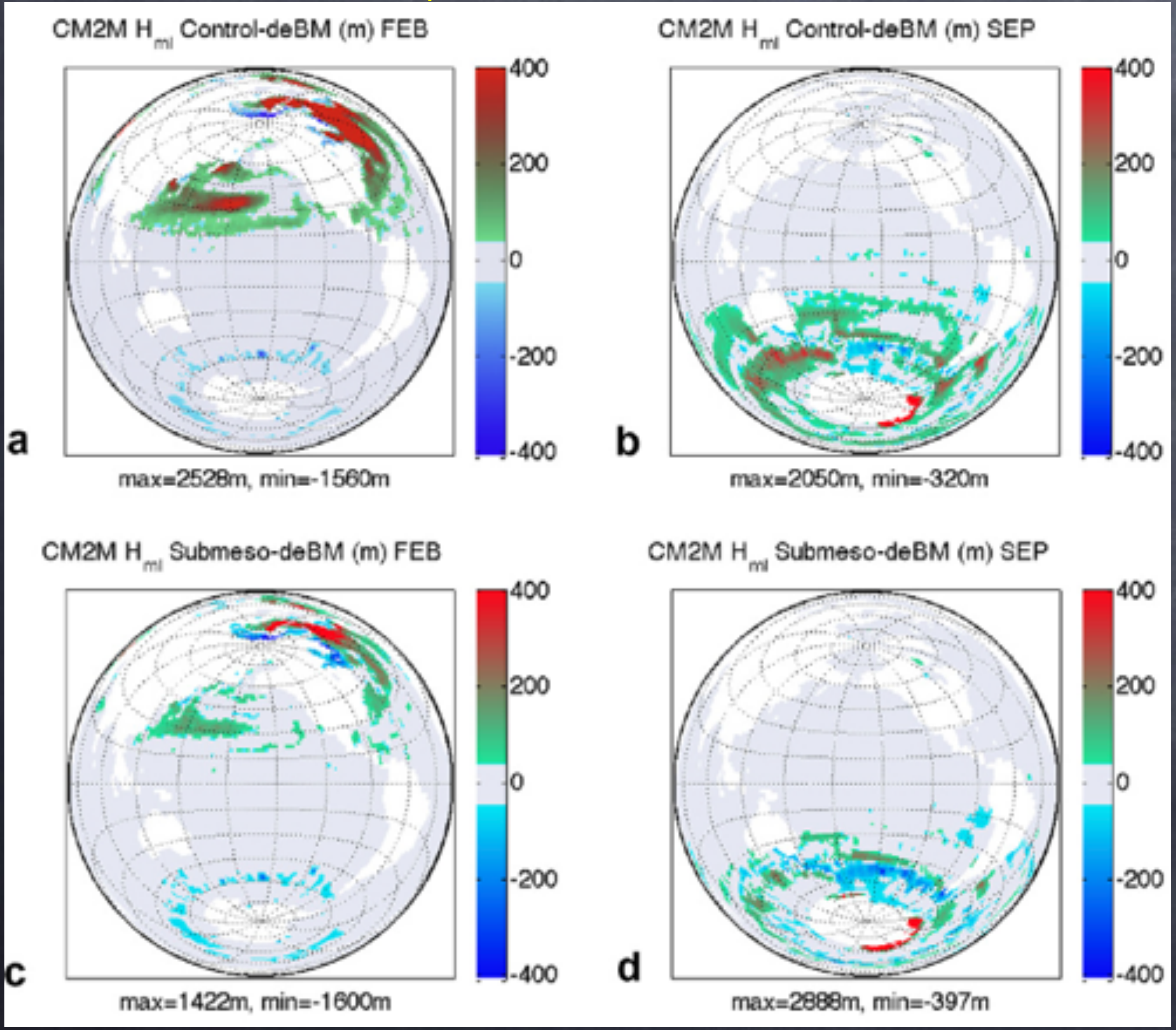
Power Spectrum of wave steepness: INFINITE!

$$\langle k^2 \eta^2 \rangle = \int_0^\infty k^2 E(k)dk = D_0 + \int_{k_h}^\infty D_1 dk$$

Steep waves break->vortex motion & small scale turbulence!

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

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



Bias w/o MLE

Deep ML Bias reduced

With MLE Parameterization

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

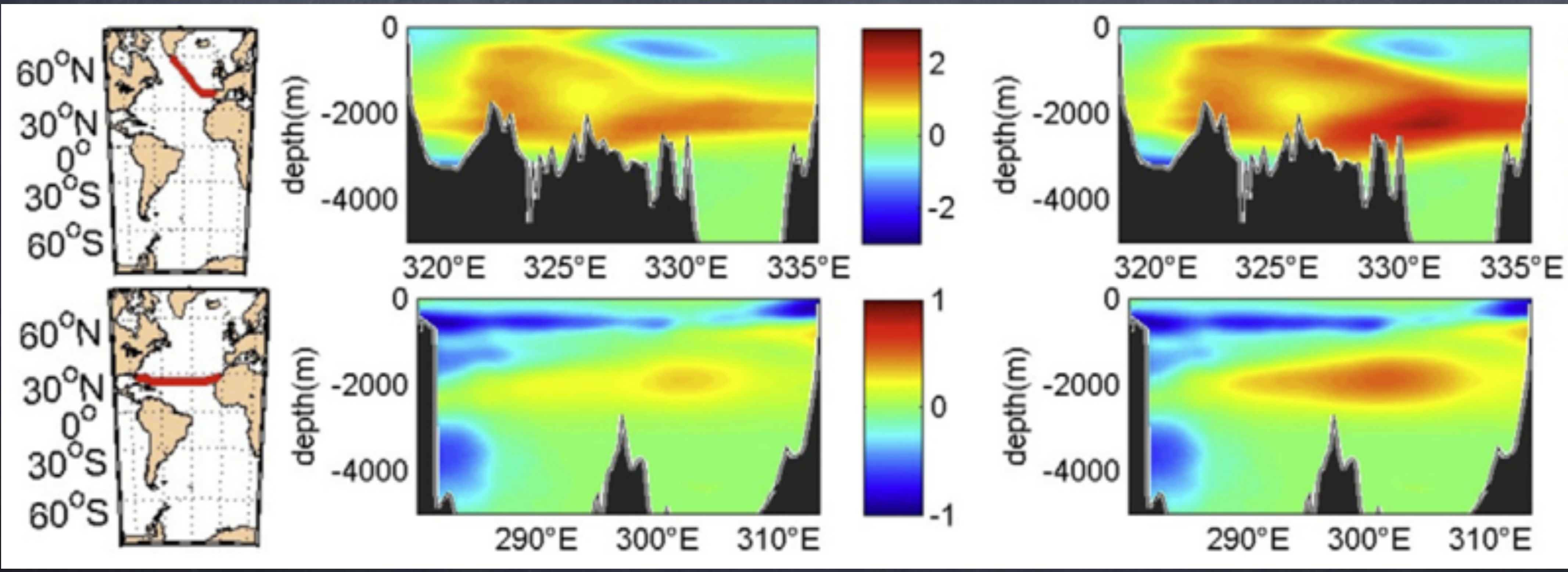
Physical Sensitivity of Ocean Climate to Submesoscale Mixed Layer Eddy Restratification:

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

Improves CFC uptake (water masses)

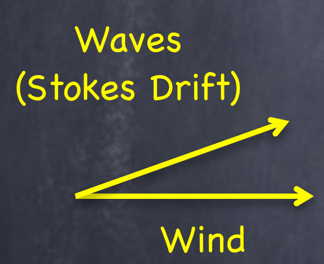
With MLE Parameterization

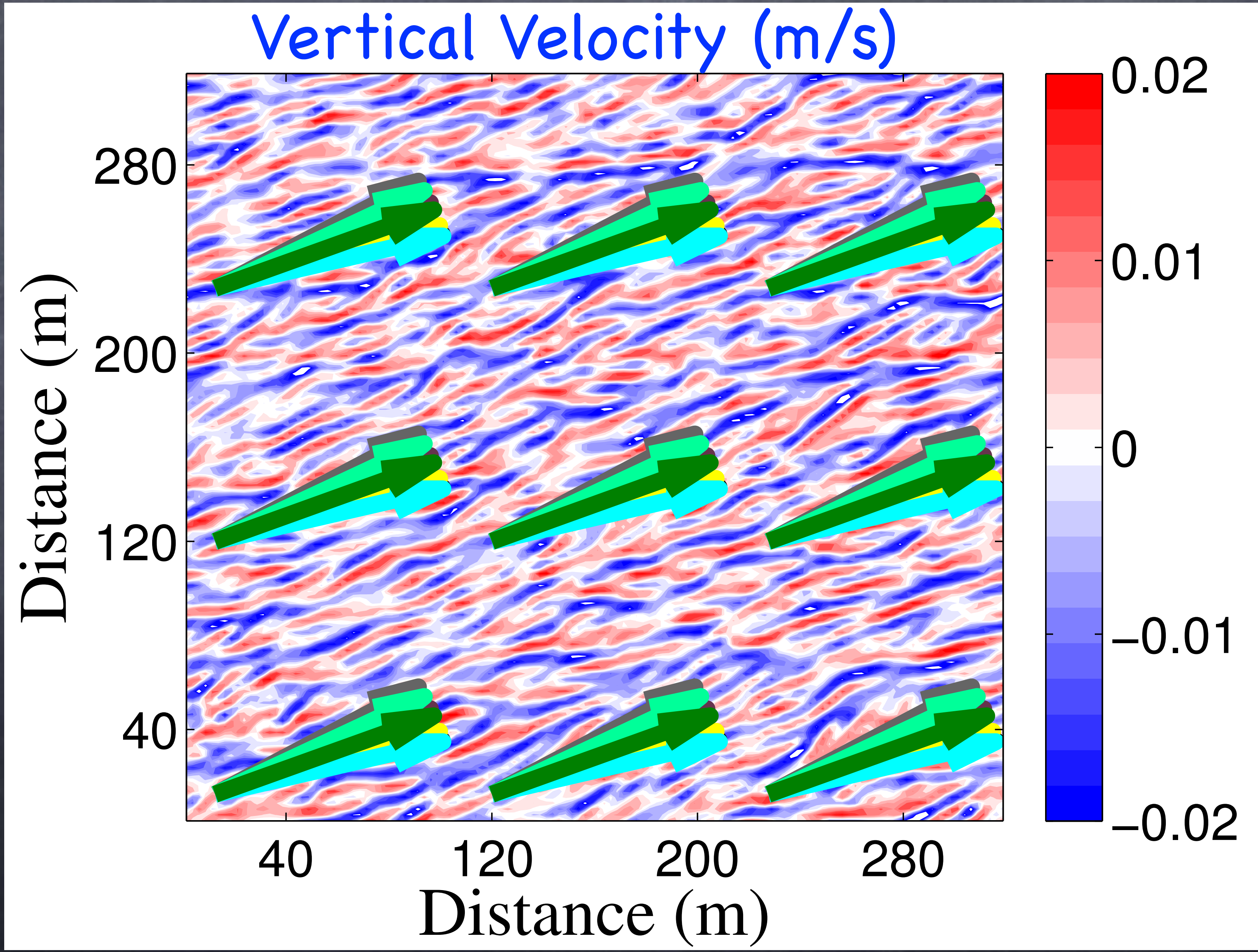
Bias w/o MLE



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

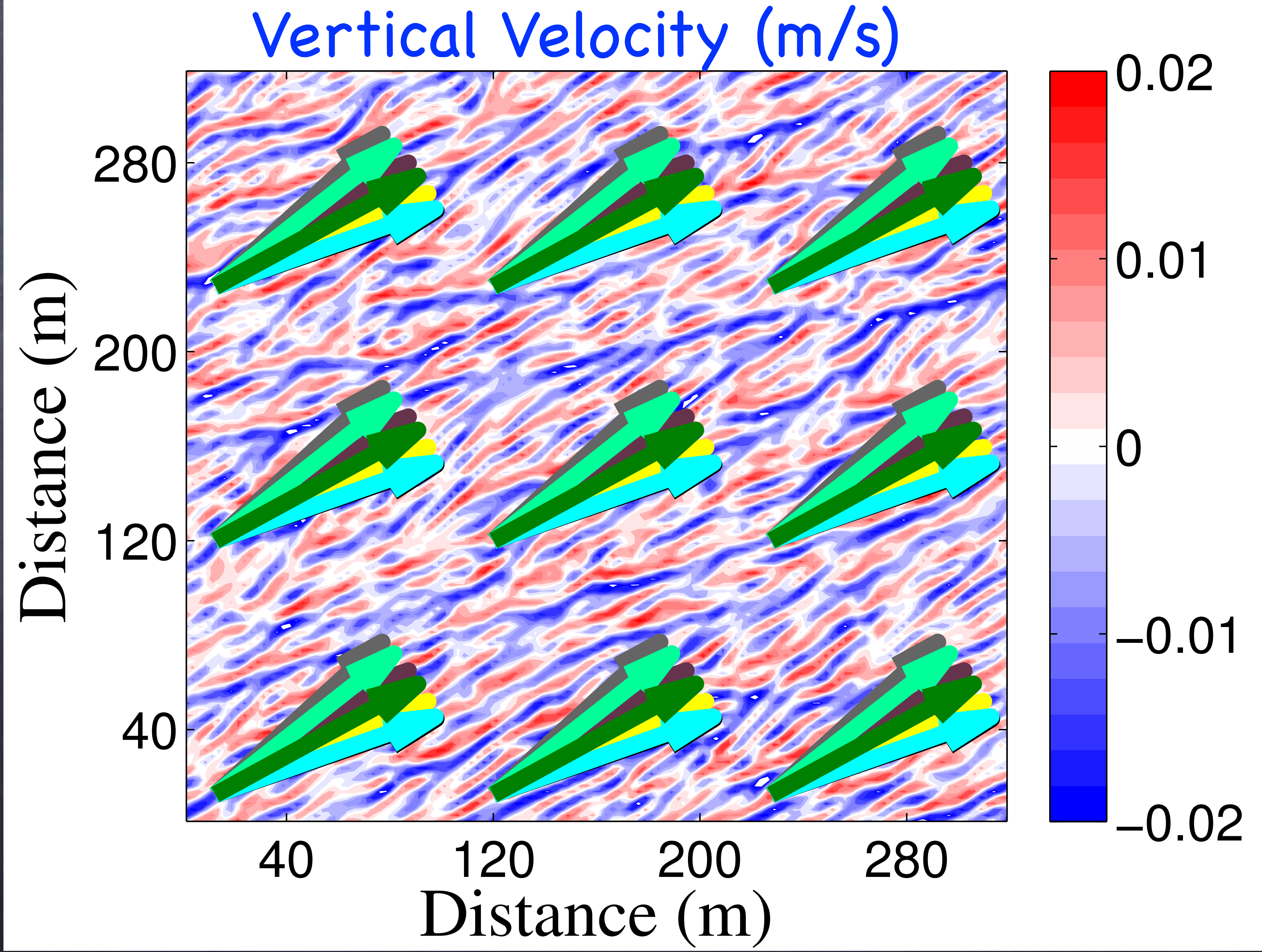
CLB as equations for Large Eddy Simulations: Tricky: Misaligned Wind & Waves





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

Tricky: Misaligned Wind & Waves



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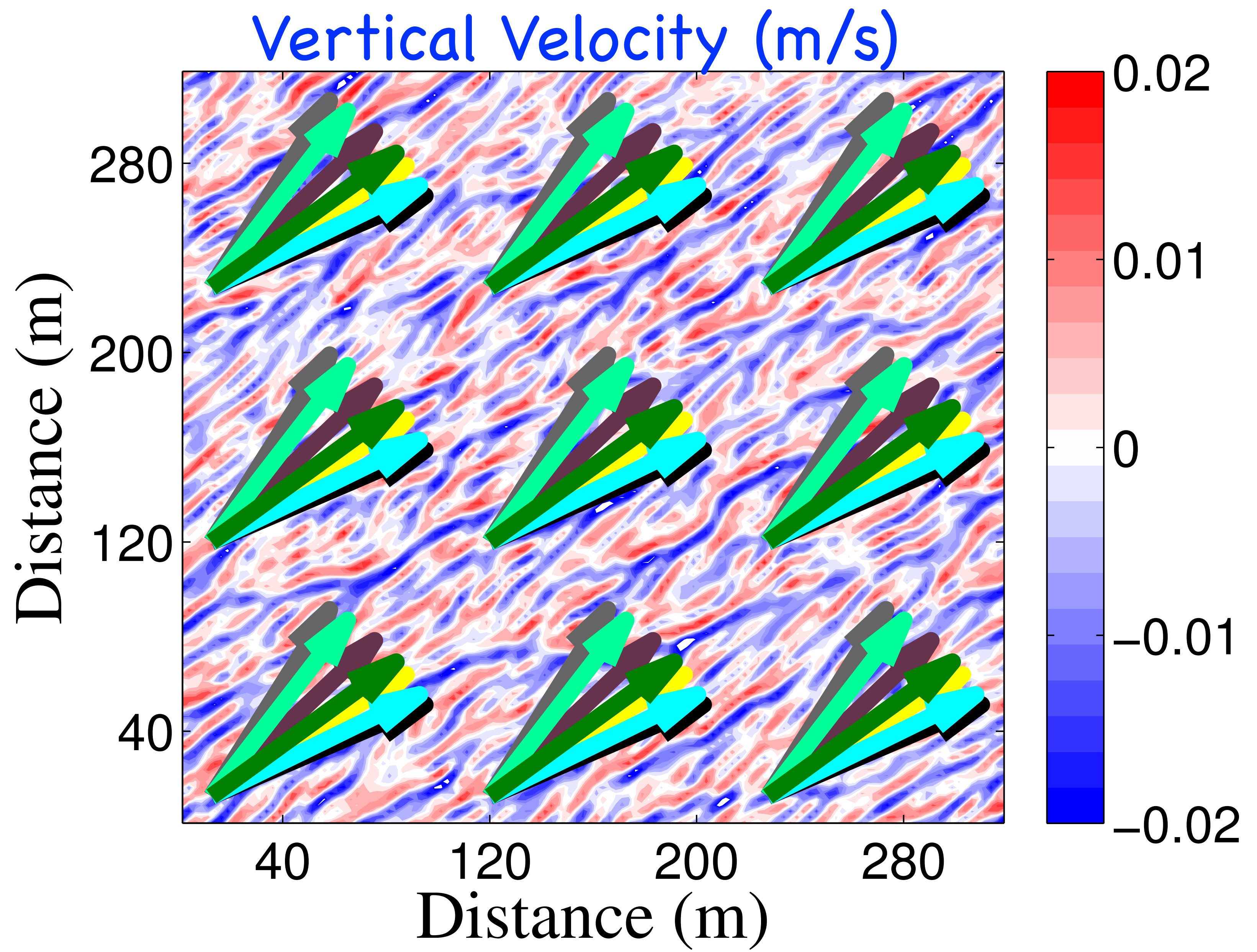
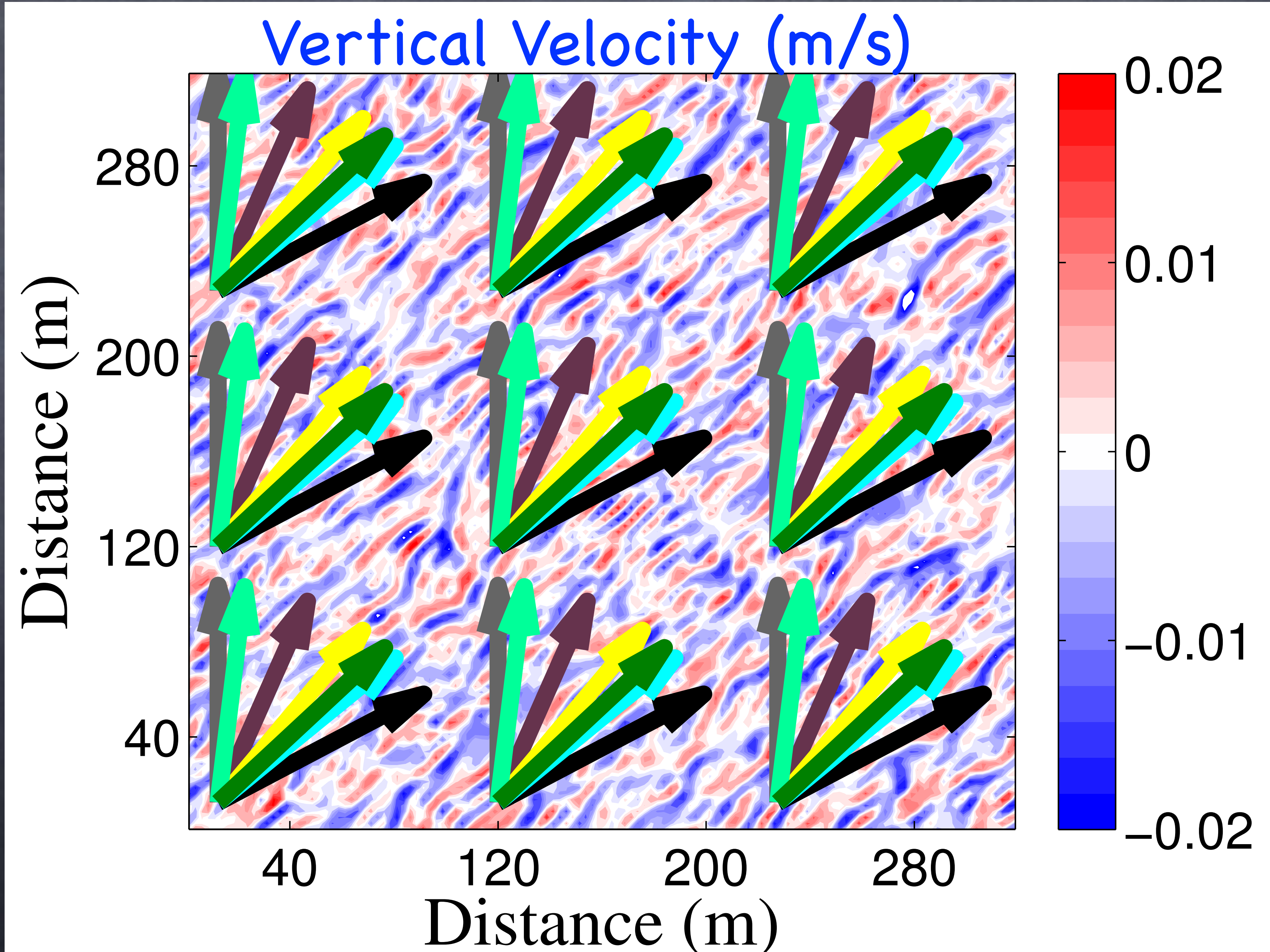


Tricky: Misaligned Wind & Waves



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.

What's in a boundary mixing parameterization?

- Wind Driven vertical mixing, key: κu^*
- Convectively Driven vertical mixing, key: $w_* = (-B_f h)^{1/3}$
- Boundary layer thickness, e.g.: Ri<0.3
- Non-local fluxes, etc.
- Love
- Usually not waves

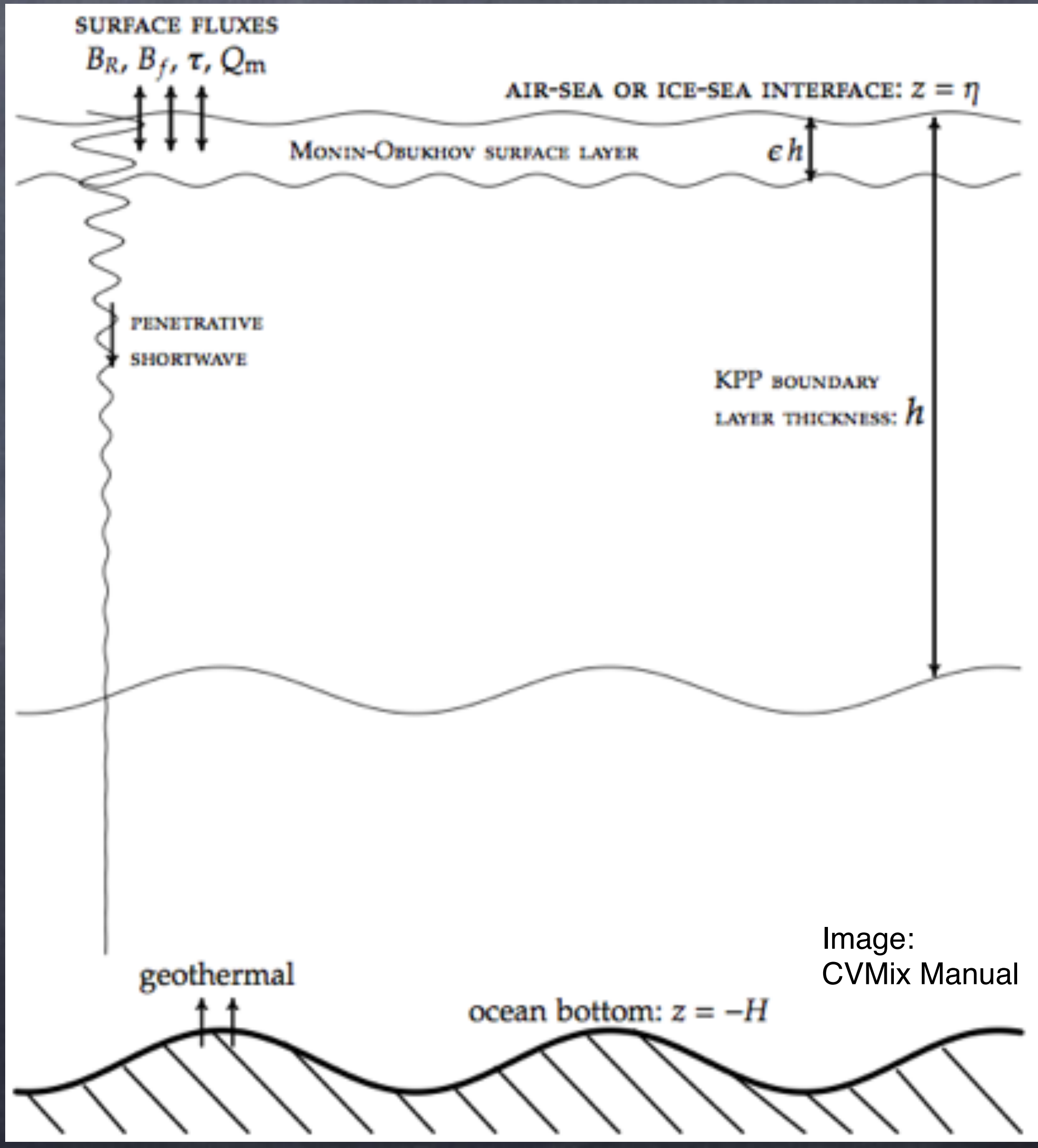
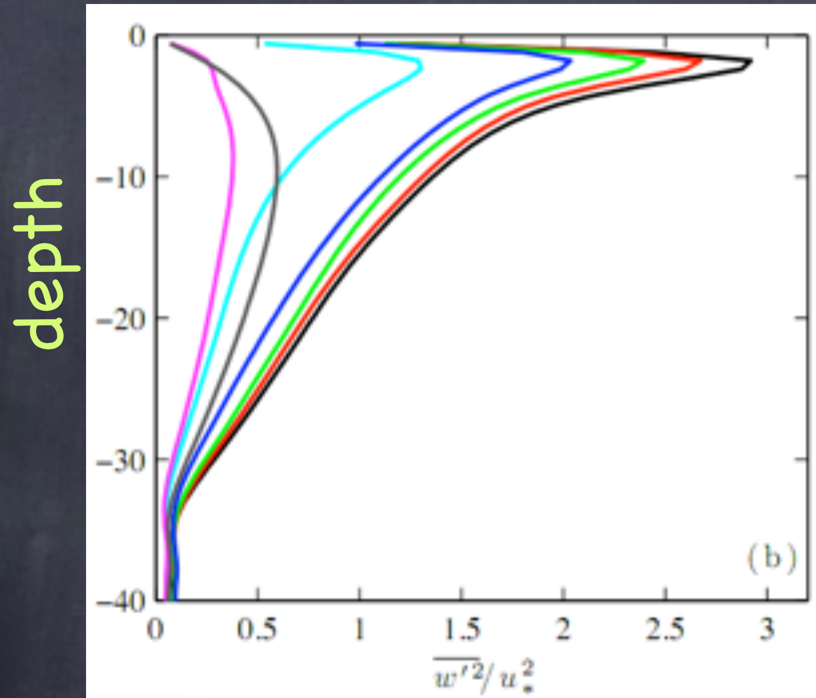
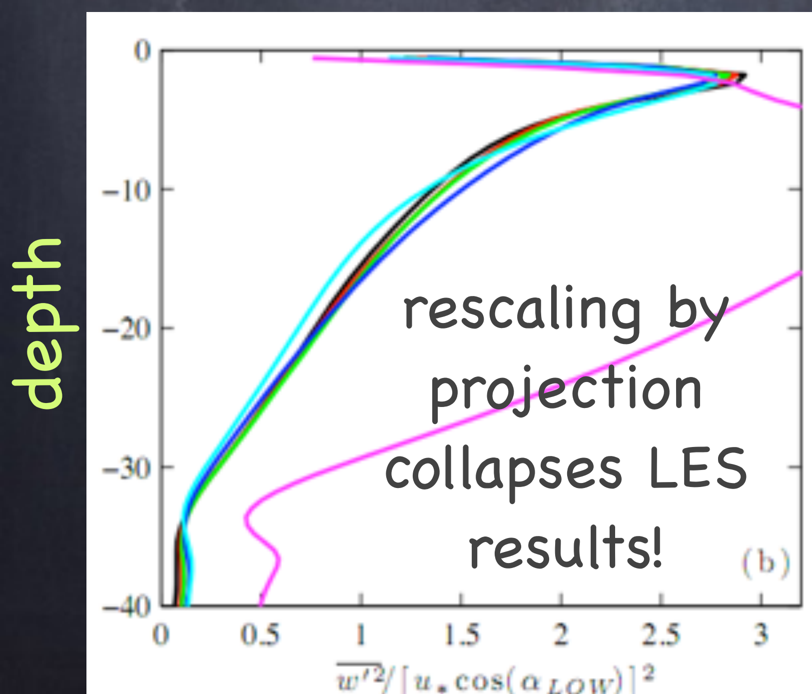


Image: CVMix Manual

<w^2>



rescaled <w^2>



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

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

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

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

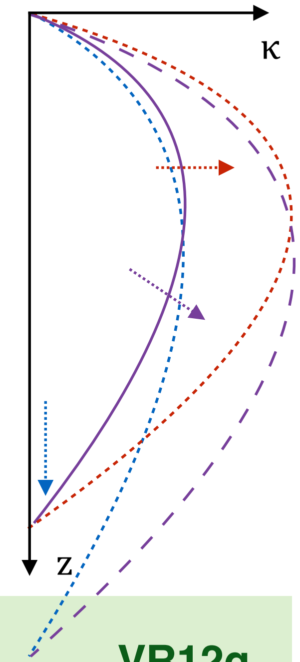
A scaling for LC strength & direction!

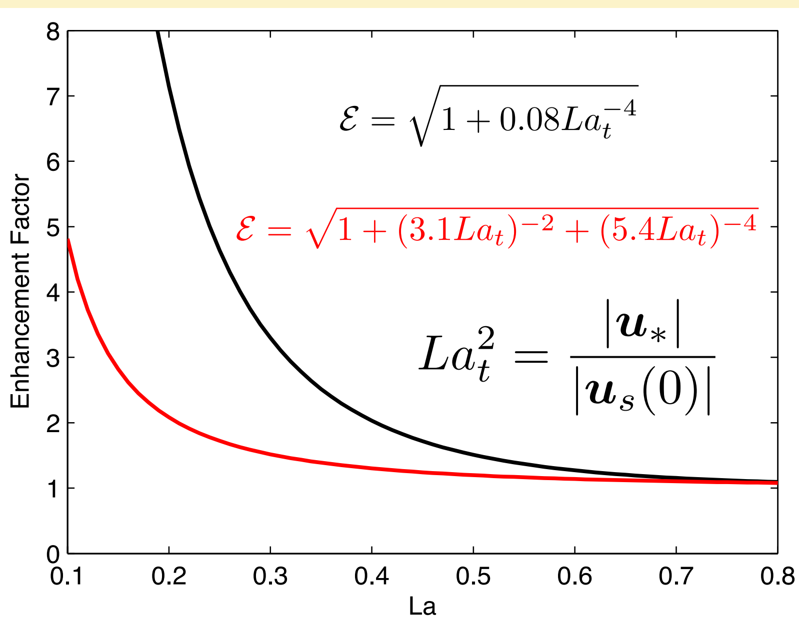
L. P. Van Roekel, BFK, P. P. Sullivan, P. E. Hamlington, and S. R. Haney. The form and orientation of Langmuir cells for misaligned winds and waves. Journal of Geophysical Research-Oceans, 117:C05001, 22pp, 2012.

Langmuir Mixing in KPP

Q. Li, BFK, T. Arbetter, A. Webb , 2014. Assessing the Influence of Surface Wind Waves to the Global Climate by Incorporating WAVEWATCH III in CESM, 2014 AGU Ocean Sciences Meeting Poster, related paper in prep.

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





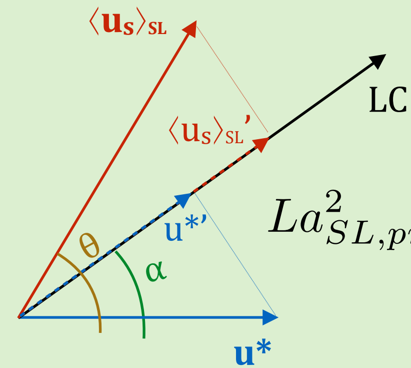
MS2K

VR12a

Enhancement factor to vertical velocity scale W

Aligned wind and waves

VR12g



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

Misaligned wind and waves

VR12h

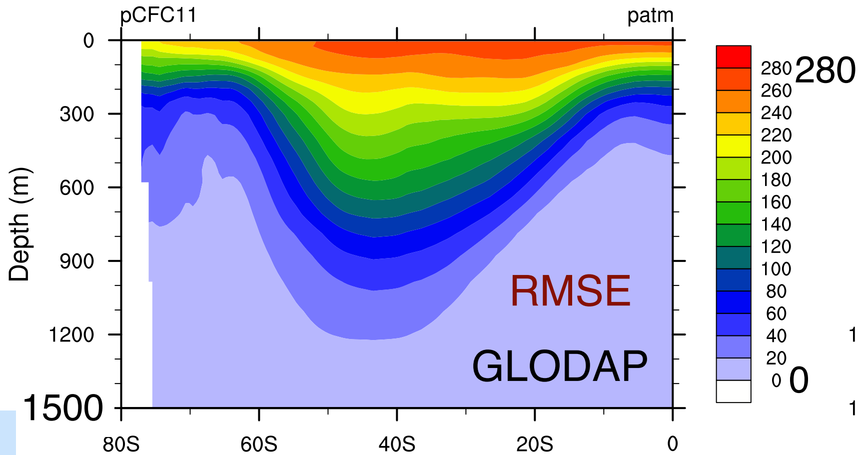
$$Ri_b = \frac{d\,[b_r - b(d)]}{|\langle \boldsymbol{u}_r \rangle - \langle \boldsymbol{u}(d) \rangle|^2 + U_t^2 + |\boldsymbol{u}_s(0)|^2}$$

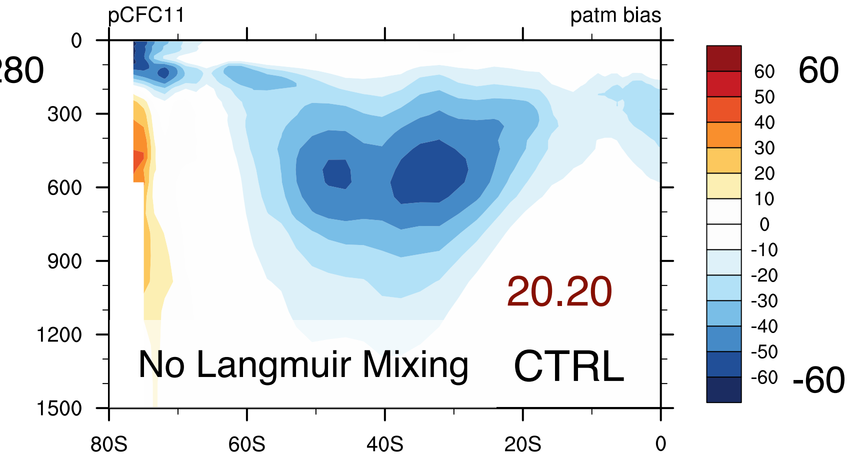
Including Stokes shear

McWilliams and Sullivan, 2000; Van Roekel et al., 2012

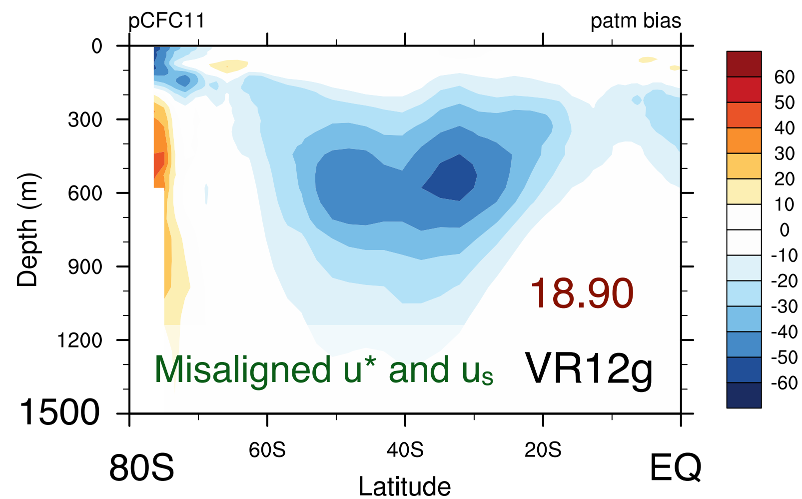
pCFC11 Bias

Southern Hemisphere





RMSEs are reduced by **6%**

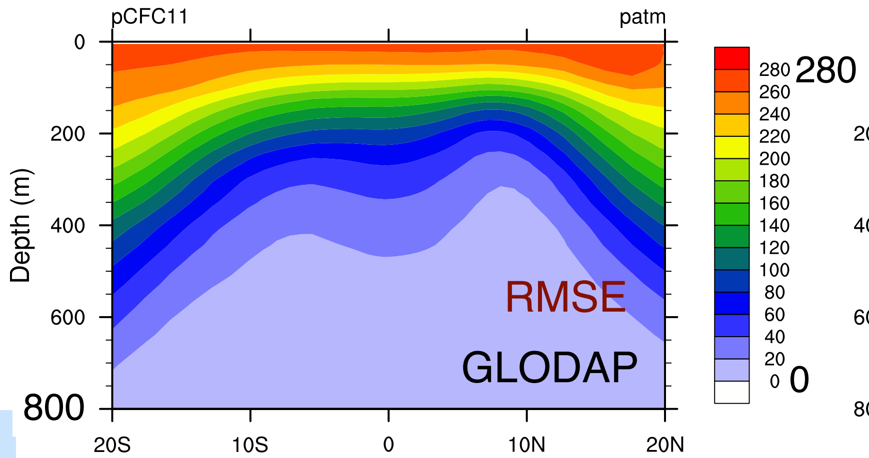


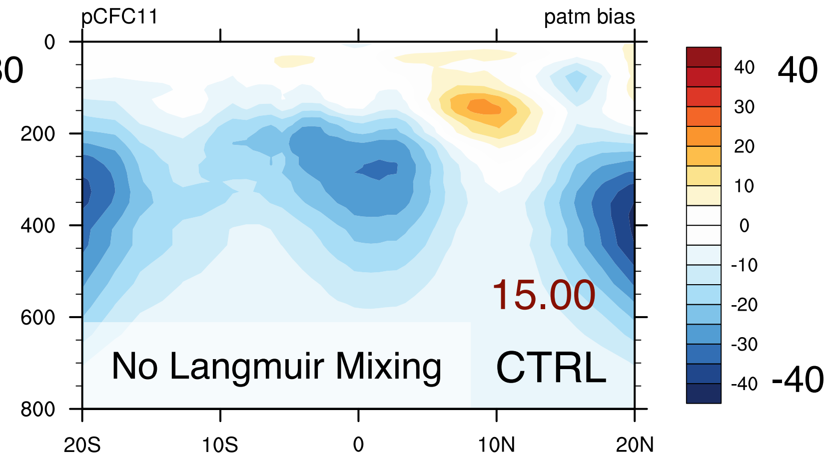
Versus observations from GLODAP: Key et al. 2004

Q. Li, BFK, T. Arbetter, A. Webb , 2014. Assessing the Influence of Surface Wind Waves to the Global Climate by Incorporating WAVEWATCH III in CESM, 2014 AGU Ocean Sciences Meeting Poster, related paper in prep.

pCFC11 Bias

Equatorial Region





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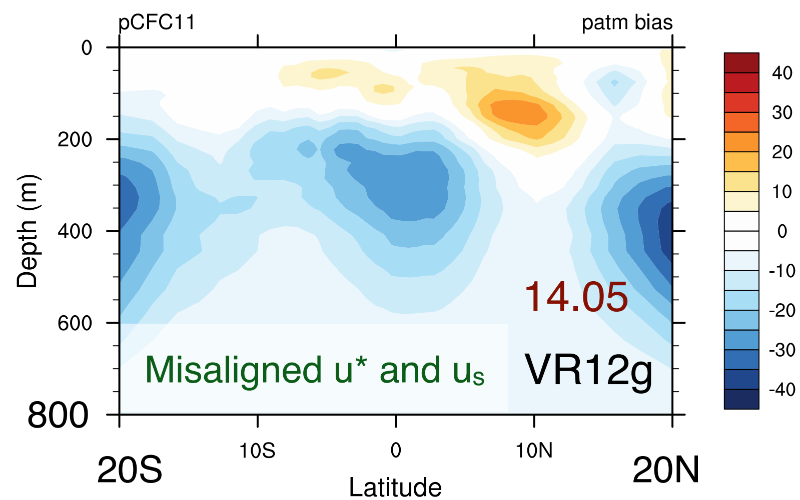

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The Steady Background State

$Ro >> 1, Ek > 0, \gamma = 0$

Weak Coriolis | Viscid | No front

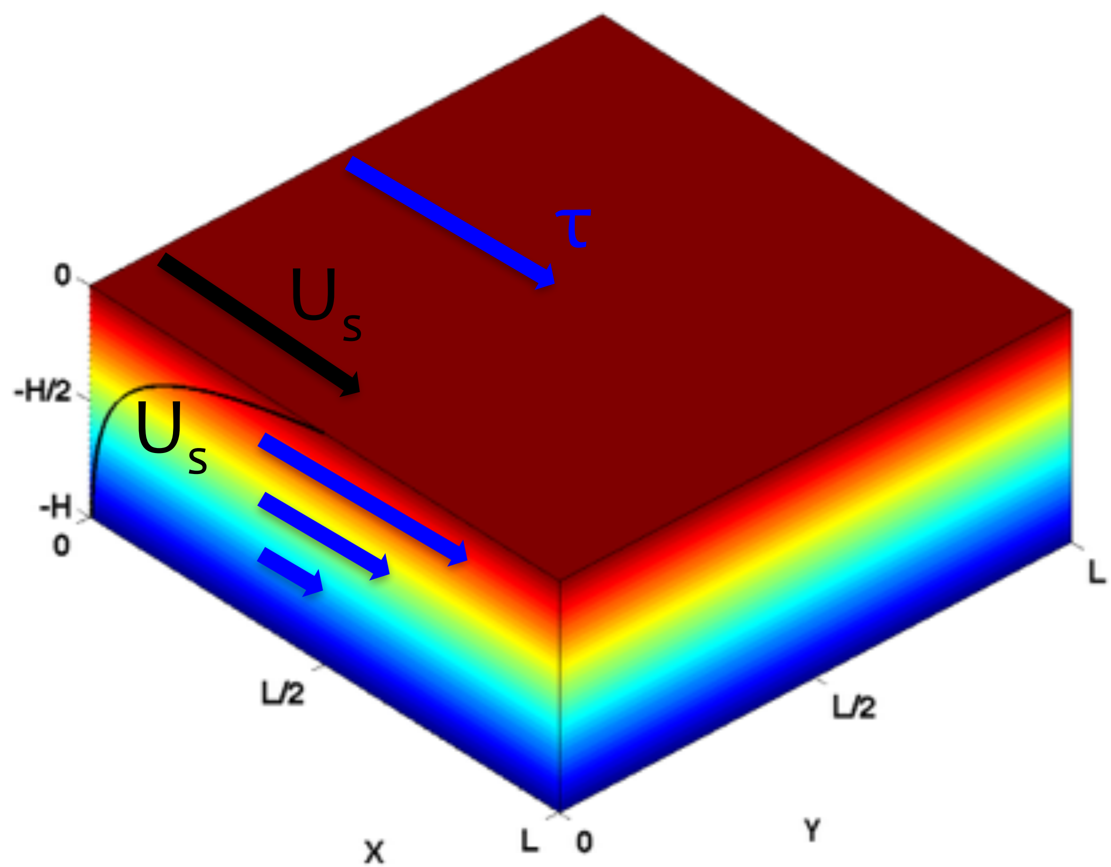
Background Flow

$$\bar{\mathbf{U}} = z \quad \bar{W} = 0$$

$$\bar{P}_z = \bar{B}$$ Hydrostatic

$$\bar{W} = 0$$

Reproduces "Classic" LC regime:
Leibovich and Paolucci, 1980



The Steady Background State

$Ro << 1, Ek = 0, \gamma = 1$

Stong Coriolis — INviscid — Strong front

Background Flow

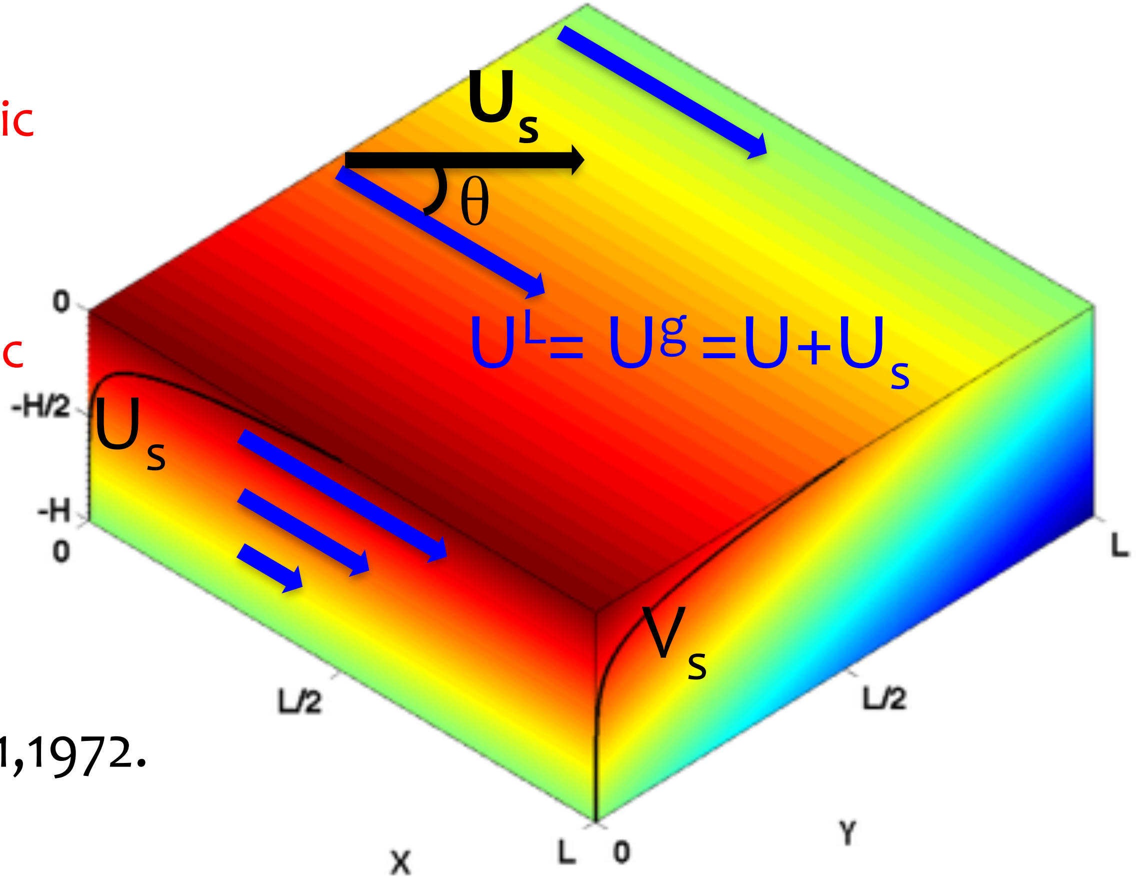
$$f(\hat{\mathbf{k}} \times \bar{\mathbf{U}}^L) = -\frac{\nabla \bar{P}}{\rho_0}$$ Geostrophic

$$\bar{P}_z = \bar{B}$$ Hydrostatic

$$f\bar{\mathbf{U}}^L_z = -\bar{B}_Y$$ Thermal Wind

$$\bar{W} = 0$$

$\mathbf{U}^S \to 0 \Rightarrow$ Stone, 1966,1970,1971,1972.



The Steady Background State

$Ro << 1, Ek > 0, \gamma \sim O(1)$

Stong Coriolis — Viscid — Strong front

Background Flow

$$f(\hat{\mathbf{k}} \times \bar{\mathbf{U}}^L) + \frac{\nabla \bar{P}}{\rho_0} = \nu \bar{\mathbf{U}}_{zz}$$

Ekman-Stokes-Front Layer

$$\bar{P}_z = \bar{B}$$ Hydrostatic

$$\bar{W} = 0$$

$\nabla \bar{B} \rightarrow 0 \Rightarrow$ Gnanadesikan and Weller, 1995