Surface Waves in Turbulent and Laminar Submesoscale Flow

Baylor Fox-Kemper (Brown U., Geo.)

with Peter Hamlington (CU-Boulder), Luke Van Roekel (Northland College), Sean Haney (CU-ATOC), Adrean Webb (CU-APPM), Keith Julien (CU-APPM), Greg Chini (UNH), Peter Sullivan (NCAR), Jim McWilliams (UCLA), Mark Hemer (CSIRO)

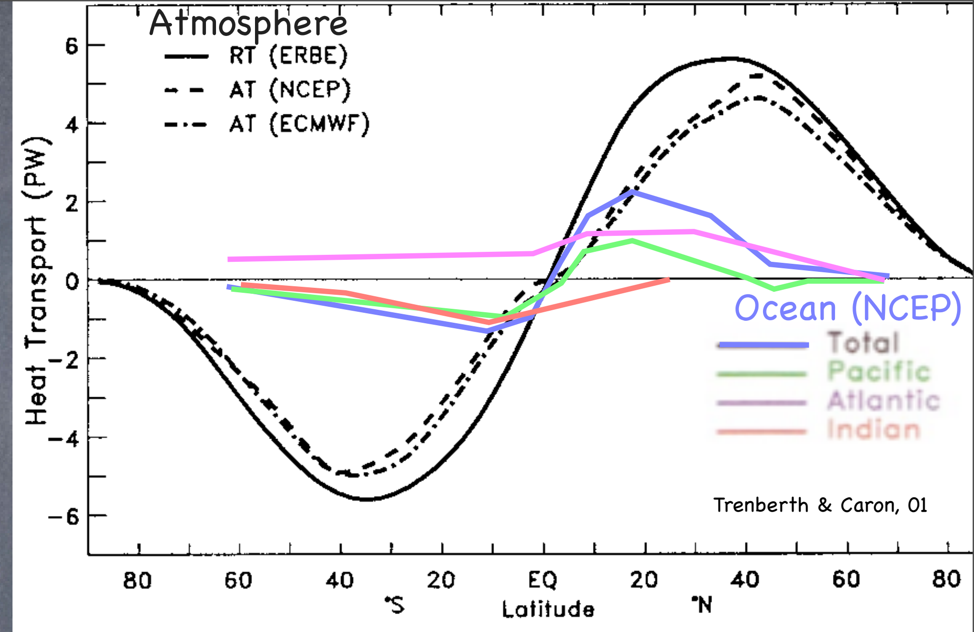
LANL's Center for Nonlinear Studies 33rd Meeting
Ocean Turbulence

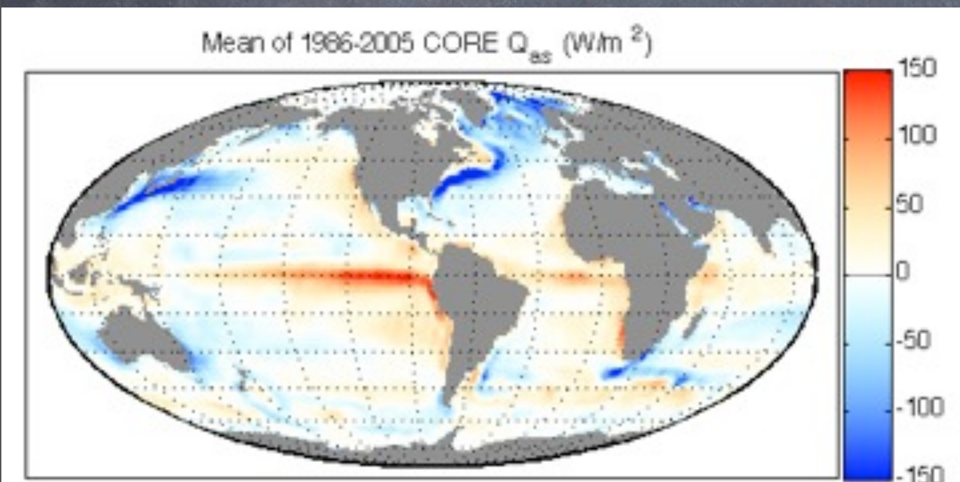
Sponsors: NSF 1245944, 0934737, 0825614, NASA NNX09AF38G

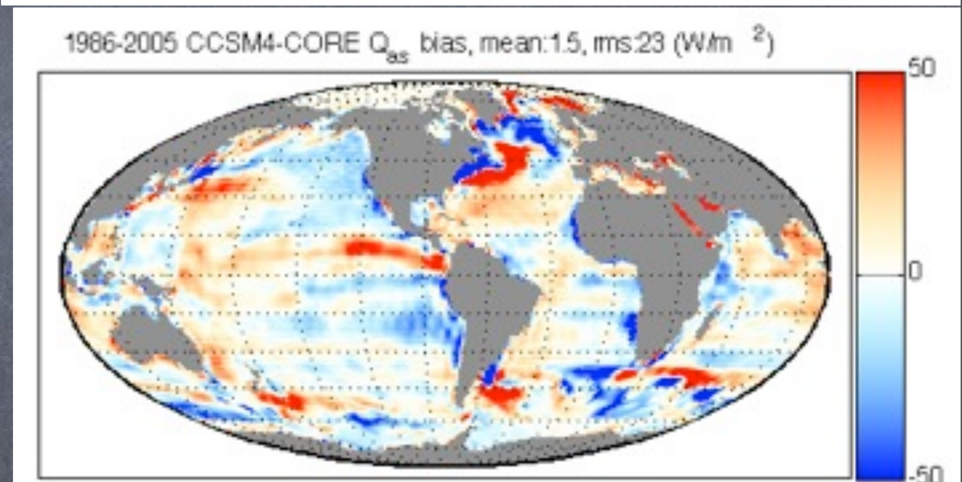
Air-Sea Flux Errors vs. Data

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

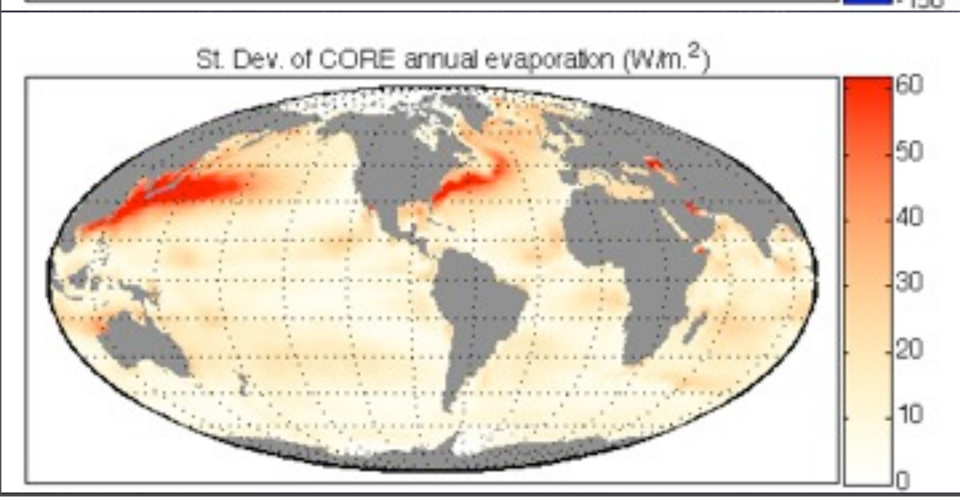
S. C. Bates, BFK, S. R. Jayne, W. G. Large, S. Stevenson, and S. G. Yeager. Mean biases, variability, and trends in air-sea fluxes and SST in the CCSM4.Journal of Climate, 25(22):7781-7801, 2012.

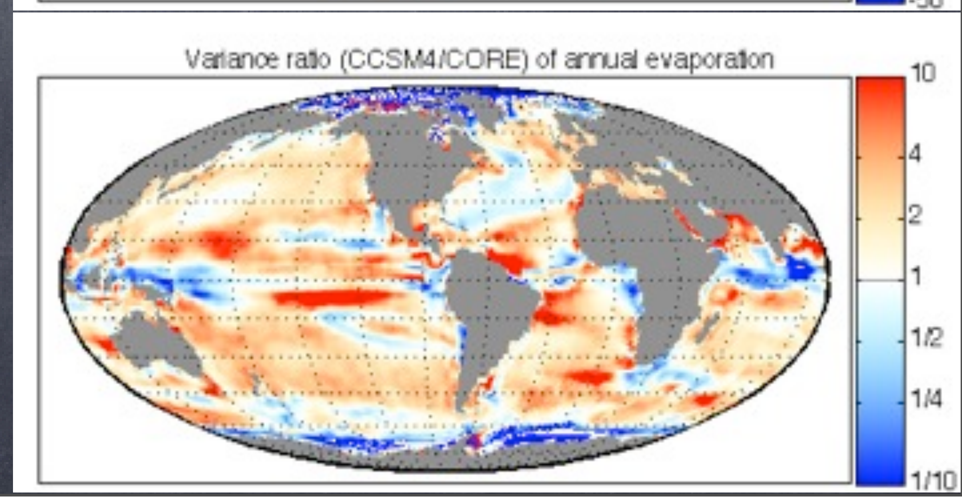






Mean





Annual
9-15mo

With nearly incompressible (small density variations) approximation & approximated rotating Earth:

A simple(?) set of 5 vars

Summary of Boussinesq Equations

$$\frac{D?}{Dt} \equiv \frac{\partial ?}{\partial t} + \mathbf{v} \cdot \nabla ?$$

The simple Boussinesq equations are, for an inviscid fluid:

momentum equations:
$$\frac{\mathrm{D}\boldsymbol{v}}{\mathrm{D}t} + \boldsymbol{f} \times \boldsymbol{v} = -\nabla \phi + b\mathbf{k}, \tag{B.1}$$

mass conservation:
$$\nabla \cdot \boldsymbol{v} = 0, \tag{B.2}$$

buoyancy equation:
$$\frac{\mathrm{D}b}{\mathrm{D}t} = \dot{b}. \tag{B.3}$$

Vallis, 06

If you want, it's easy to distinguish buoyancy into contributions from Temperature and from Salinity (since we are near surface--linear EOS is OK)

Geostrophy, Hydrostasy, & Thermal Wind

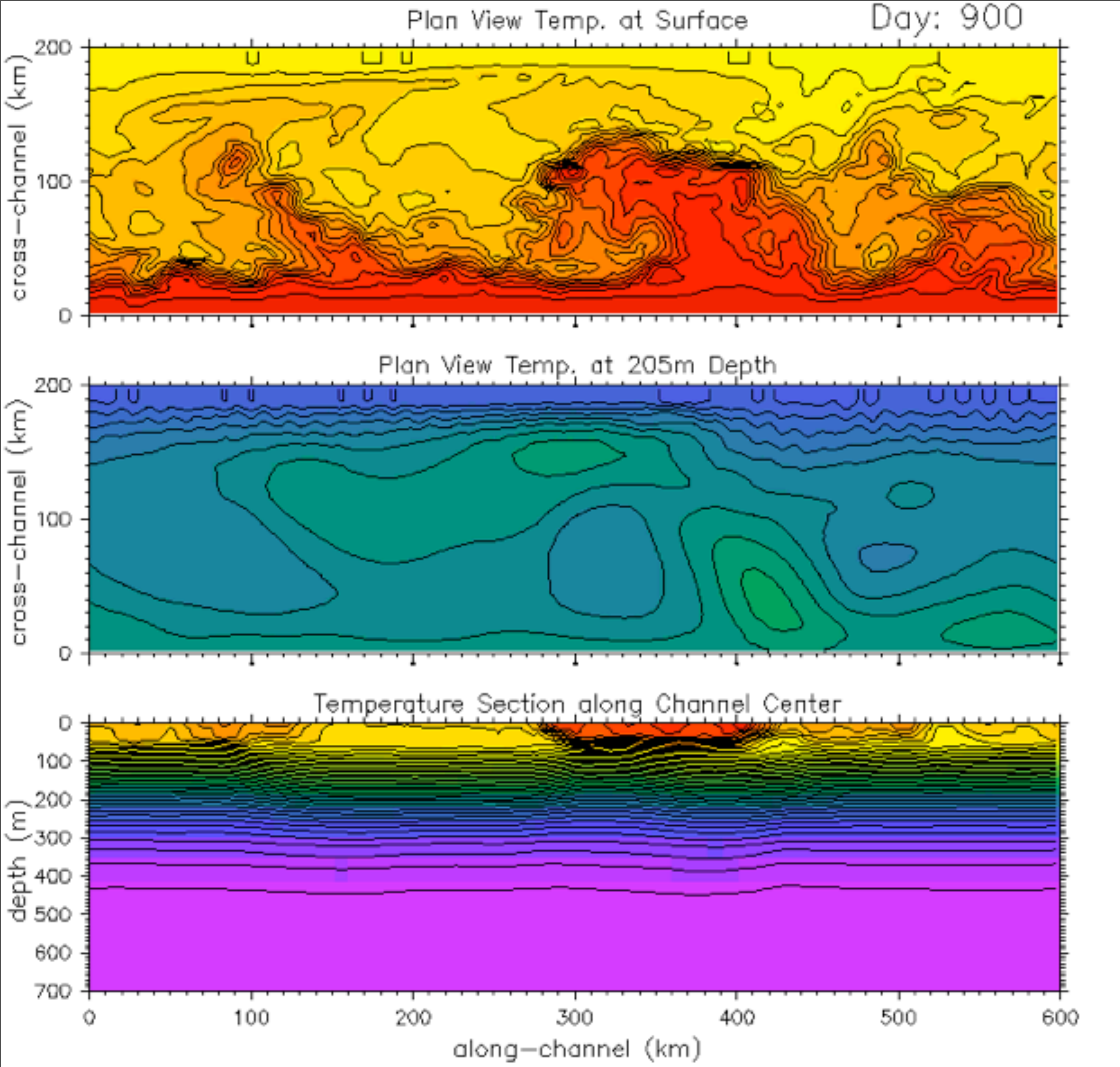
Traditional Oceanography & Resolved Flow in IPCC models inhabits a special distinguished limit:

Inviscid (Re>>1), rapidly rotating (Ro<<1), and thin (L>>H)

(Combined) Thermal Wind Balance

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

Adding forcing (air-sea) and advection of buoyancy by this flow--you have (nearly) all large-scale ocean physics!



Big, Deep (mesoscale)

interact with

Little, Shallow (submeso)

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.

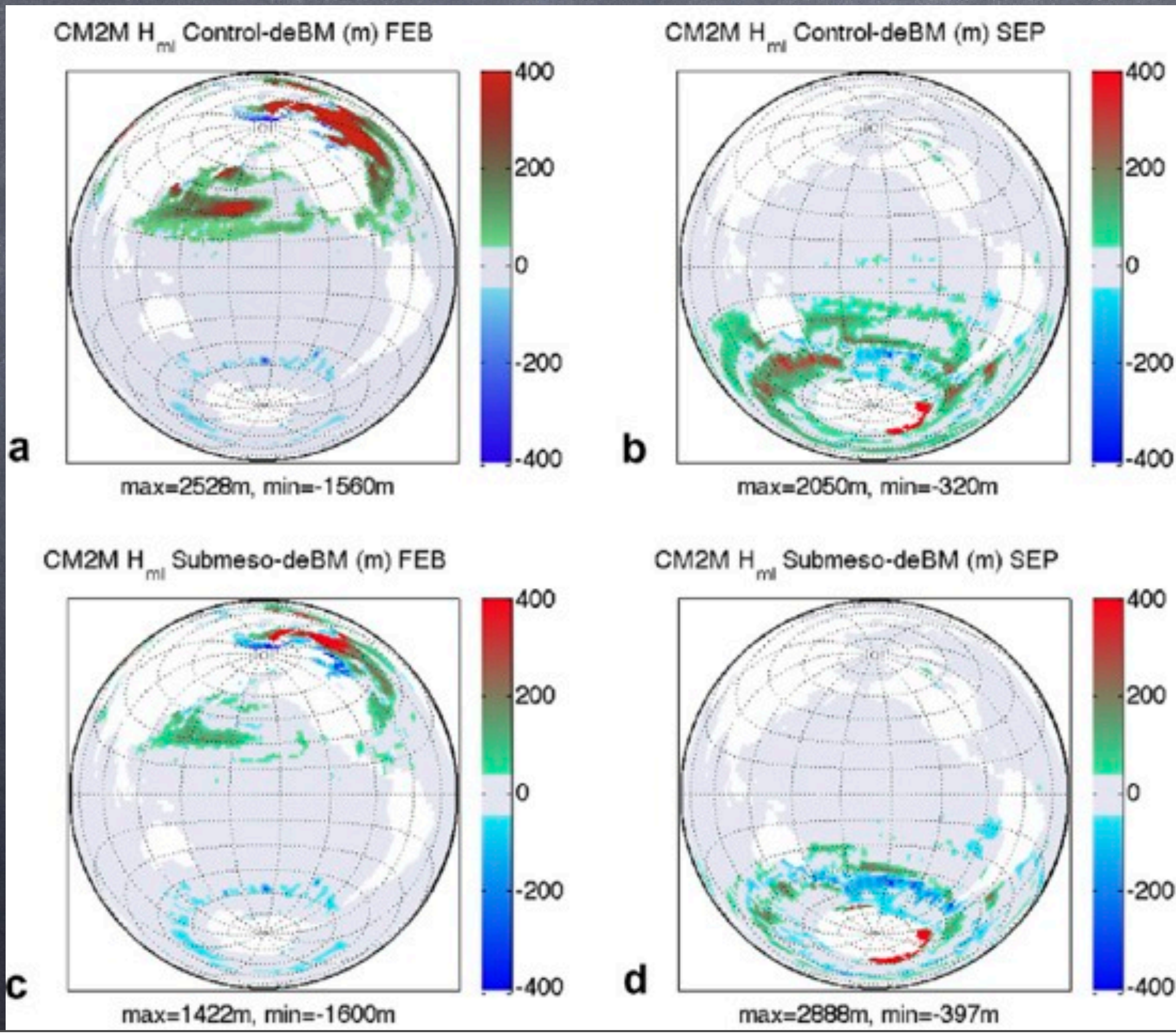
Climate affected by (Submeso) Mixed Layer Eddy Restratification

Affects AMOC, Sea Ice, SST, SSS, CFCs, Water Masses, Air-Sea, etc.

February | September

Error w/o MLE

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

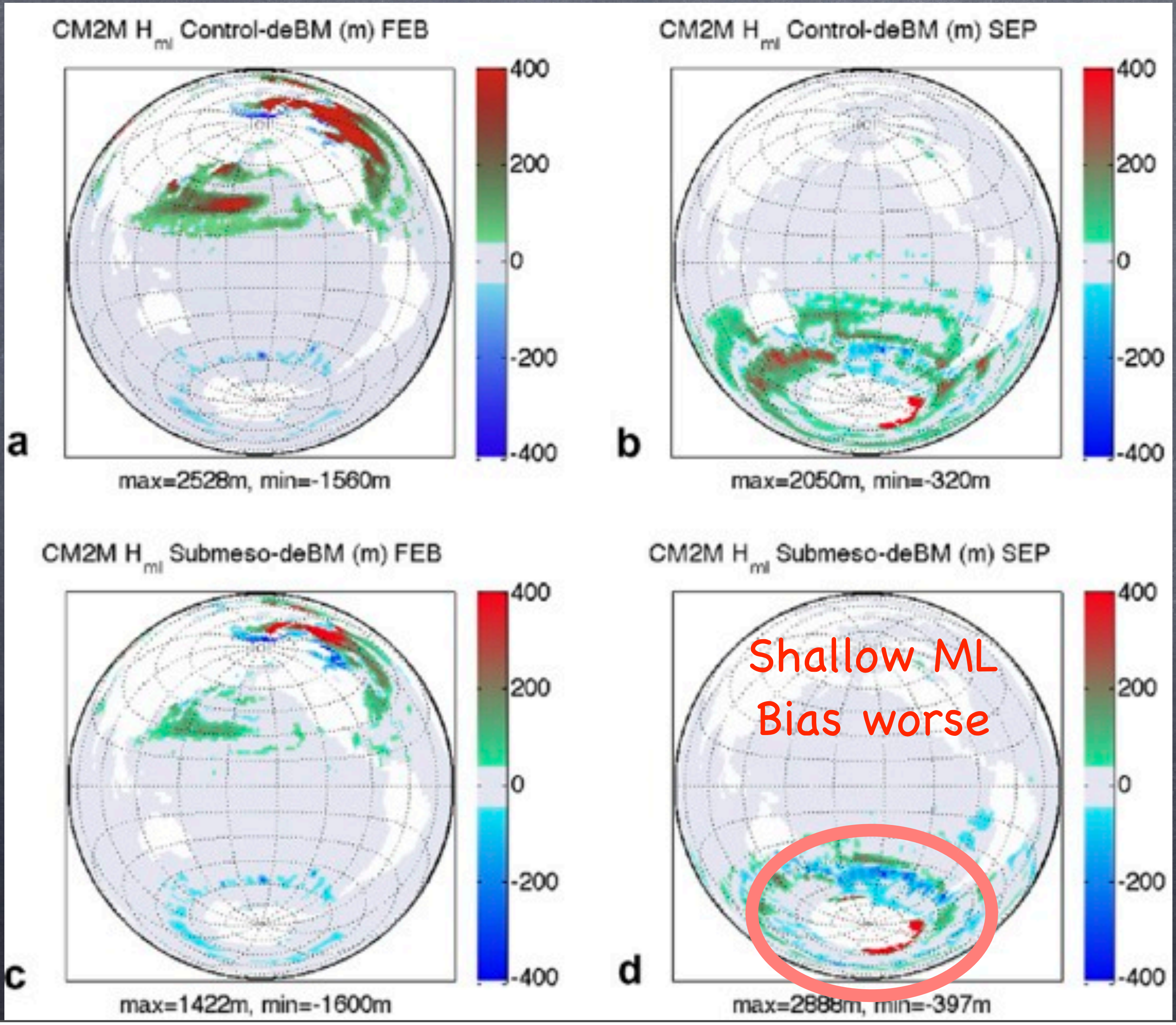
Climate affected by (Submeso) Mixed Layer Eddy Restratification

Affects AMOC, Sea Ice, SST, SSS, CFCs, Water Masses, Air-Sea, etc.

February September

Error w/o MLE

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

- Method: Study a small-scale phenomenon (100m-10km submeso mixed layer fronts & eddies), parameterize, assess impact globally, and improve climate models
    - In submeso, we relied heavily on thermal wind
- Problem with models: they are only slightly smarter than we are (they don't do what we don't put in!)
- But, what about the effects of things that aren't geostrophic & hydrostatic?
    - For example, waves and near-surface 3d turbulence

Surface Waves

Look for fast, small solutions of the Boussinesq Equations:

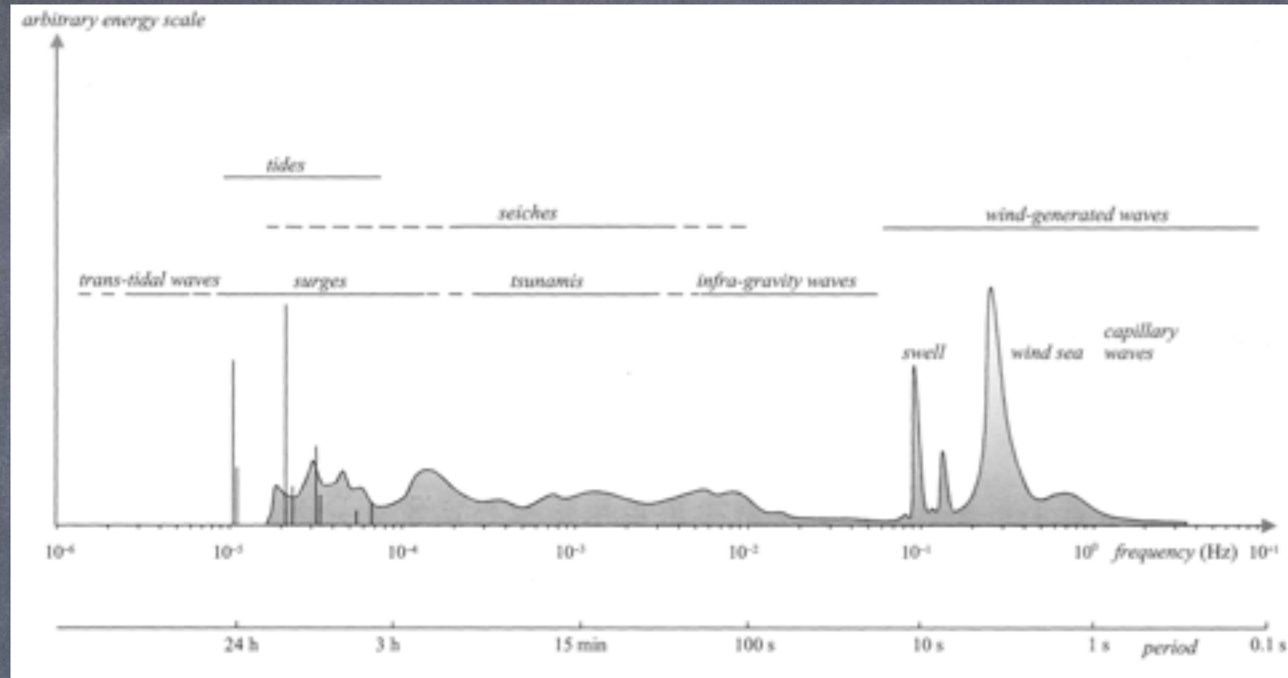


Illustration of wave spectra from different types of ocean surface waves (Holthuijsen, 2007)

The irrotational, incompressible flow obeys

$$\frac{\partial^2 \phi}{\partial x^2}+\frac{\partial^2 \phi}{\partial z^2}=0$$

$$u=\frac{\partial \phi}{\partial x} \qquad w=\frac{\partial \phi}{\partial z}$$

The boundary conditions are:

Solid Bottom: $w=\frac{\partial \phi}{\partial z}=0 \quad \text{at} \quad z=-H$

Pressure Matching (dynamic): $p=0 \quad \text{at} \quad z=\eta$

Velocity Matching (kinematic): $\frac{D\eta}{Dt}=w_\eta \quad \text{at} \quad z=\eta$

Surface Waves

Look for fast, small solutions of the Boussinesq Equations:

Linearized for not steep waves

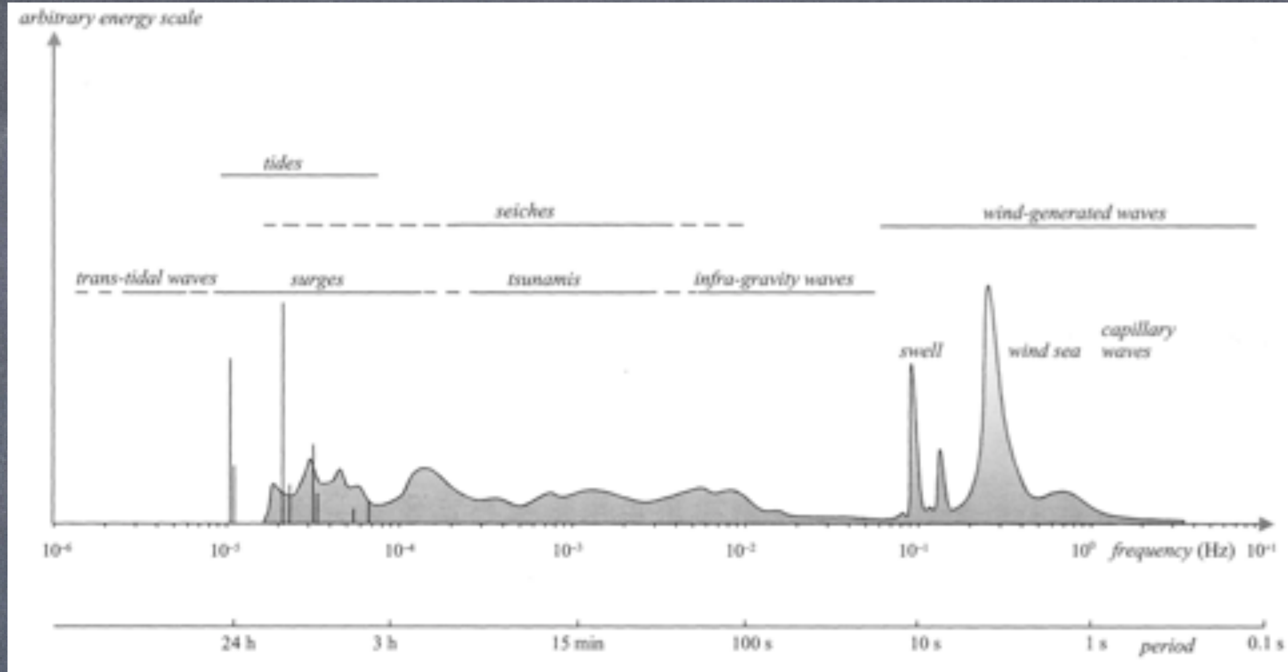


Illustration of wave spectra from different types of ocean surface waves (Holthuijsen, 2007)

The irrotational, incompressible flow obeys

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial z^2} = 0$$

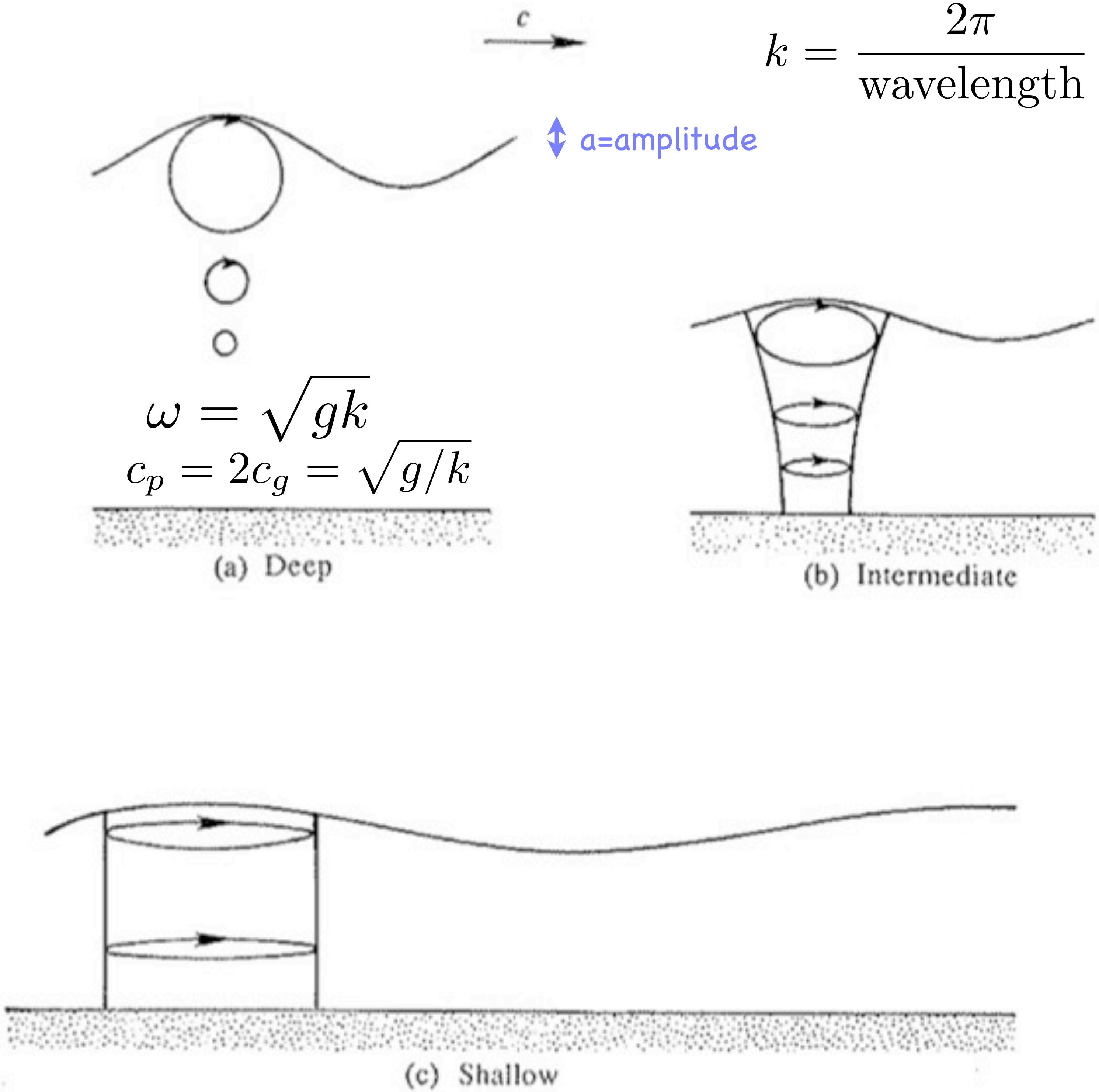
$$u = \frac{\partial \phi}{\partial x} \qquad w = \frac{\partial \phi}{\partial z}$$

The boundary conditions are (small steepness):

Solid Bottom	$w = \frac{\partial \phi}{\partial z} = 0 \quad \text{at} \quad z = -H$
Pressure Matching (dynamic)	$\frac{\partial \phi}{\partial t} = -g\eta \quad \text{at} \quad z = 0$
Velocity Matching (kinematic)	$\frac{\partial \eta}{\partial t} = \frac{\partial \phi}{\partial z} \quad \text{at} \quad z = 0$

Particle motions

$$k = \frac{2\pi}{\text{wavelength}}$$



$$\omega = \sqrt{gk}$$

$$c_p = 2c_g = \sqrt{g/k}$$

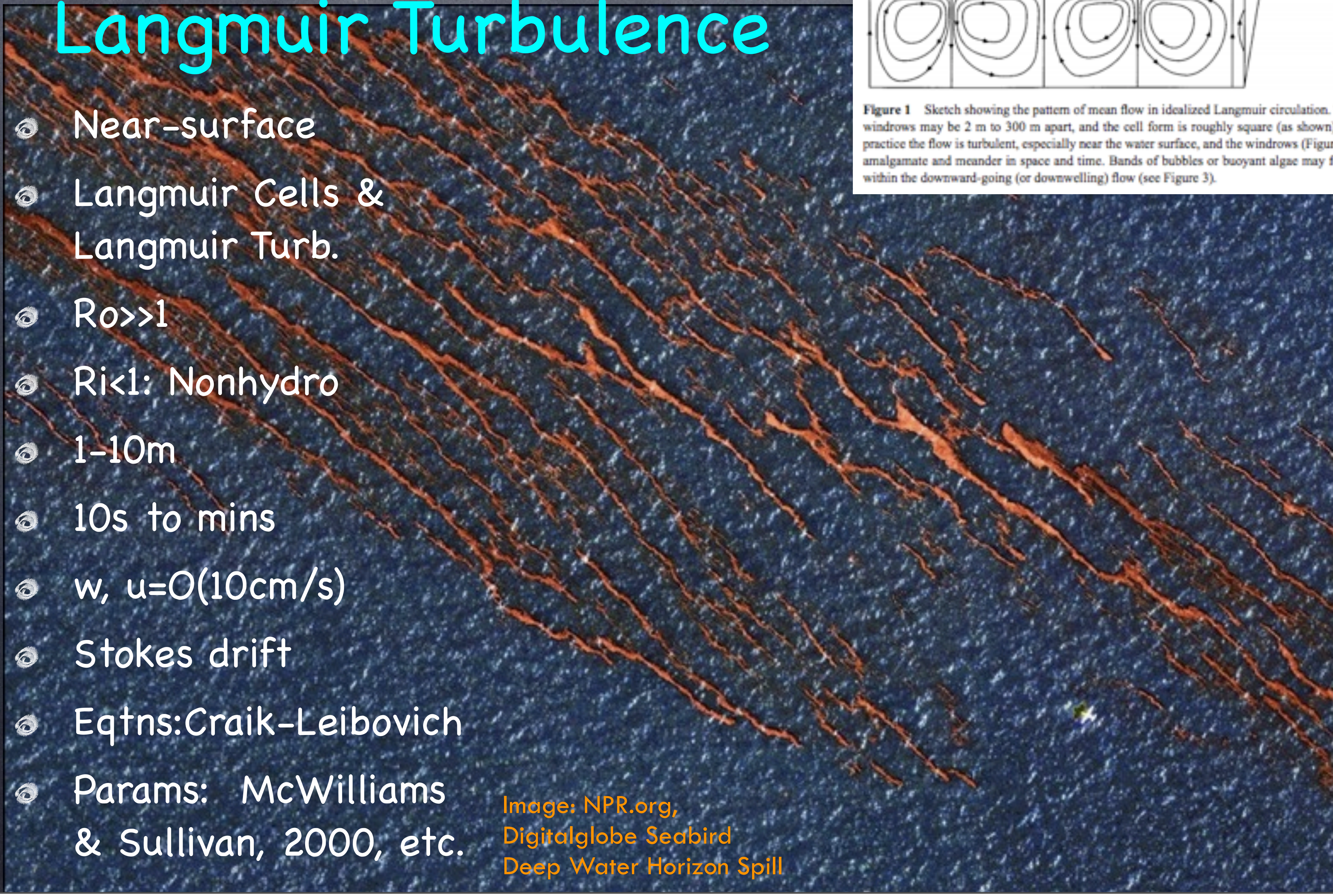
The u, v, decay exponentially toward the bottom with decay scale proportional to the wavelength.

Thus, kH is a measure of depth

ka is a measure of steepness

Deep water waves don't "feel" the bottom. Implies nonhydrostatic ($H \approx L$) & fast timescale (Ro>>1)

The Character of the Langmuir Turbulence



- Near-surface
- Langmuir Cells & Langmuir Turb.
- Ro>>1
- Ri<1: Nonhydro
- 1-10m
- 10s to mins
- w, u=O(10cm/s)
- Stokes drift
- Eqtns:Craik-Leibovich
- Params: McWilliams & Sullivan, 2000, etc.

Image: NPR.org, Digitalglobe Seabird Deep Water Horizon Spill

image: Thorpe, 04

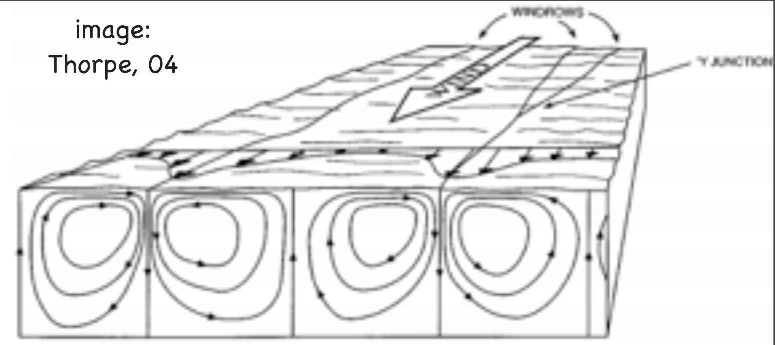


Figure 1 Sketch showing the pattern of mean flow in idealized Langmuir circulation. Th windrows may be 2 m to 300 m apart, and the cell form is roughly square (as shown). I practice the flow is turbulent, especially near the water surface, and the windrows (Figure 2 amalgamate and meander in space and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

Call for Papers: Gulf of Mexico Modelling: Lessons learned from the spill

The Gulf of Mexico (GoM) is a complex, semi-enclosed basin of great environmental and economic importance. On 20 April 2010, the Deepwater Horizon drilling rig experienced a catastrophic failure, which claimed 11 lives and set off an 87 day oil spill in the GoM. Academic, governmental and private sector research has contributed to mitigation efforts, and the GoM has received unprecedented attention over the last three years. At present, no single ocean model is capable of handling the wide range of scales and complex dynamics necessary to understand the GoM circulation and dispersion of the oil spill. Instead, different model configurations have been used to capture a subset of the GoM dynamics.

Ocean Modelling will host a Virtual Special Issue (VSI): **"Gulf of Mexico Modelling: Lessons learned from the spill"** to collect the last three years of intense research concerning GoM modelling. The VSI will serve as a standard and influence for future GoM modelling efforts and development. While the VSI will focus on the GoM, submissions that address the modelling advances required to understand this basin's circulation and dispersion of pollutants but also have broader applicability are encouraged.

This VSI would be open to all modelling efforts related to GoM, as well as studies of processes or observations found to be important or needed for GoM modelling. Submissions which address oil spill related science in the following areas are encouraged:

1. GoM basin or shelf scale physical/biological/chemical processes
2. GoM open-coastal ocean connectivity and cross-topography transport
3. Bubble/droplet scale dynamics including biological and chemical degradation and dispersant application effects
4. Air-sea and boundary layer processes
5. Surfactant or emulsion dispersion processes

Contributions should address: Why does the particular method of investigation appropriately model the physical process of interest? How does the particular method advance GoM modelling? What are the future implications of the work to GoM modelling and related modelling worldwide?

As a Virtual Special Issue, accepted papers will appear in *Ocean Modelling* as per a normal submission, but designated as part of the **"Gulf of Mexico Ocean Modelling: Lessons learned from the spill"** Special Issue. All papers will be linked online to other "Gulf of Mexico Modelling: Lessons learned from the spill." The first papers are expected to appear late in 2013 or early 2014.

Special Issue Editor(s):
Dr. Baylor Fox-Kemper
Dr. Joseph Kuehl (assistant)

Craik-Leibovich Boussinesq

- 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!
  - Must also assume slowly-varying wave packets
  - Average over deep water waves in space & time,
  - Arrive at Large, Slow equation set:

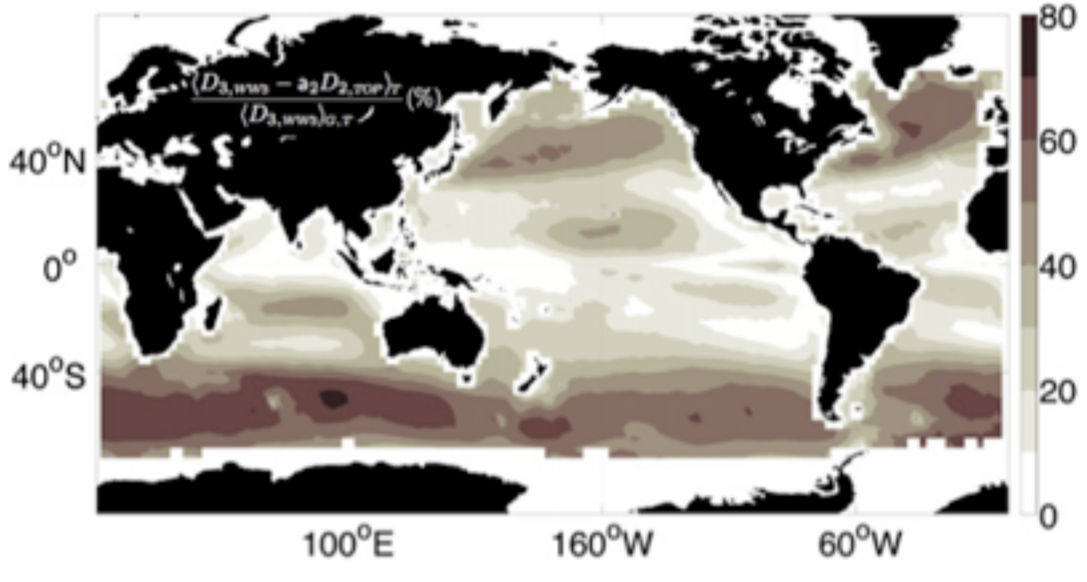
$$\frac{\partial \mathbf{v}}{\partial t} + [\mathbf{f} + \nabla \times \mathbf{v}] \times (\mathbf{v} + \mathbf{v}_s) = -\nabla \pi^\dagger + b\mathbf{k} + \nu \nabla^2 \mathbf{v}$$

$$\frac{\partial b}{\partial t} + (\mathbf{v} + \mathbf{v}_s) \cdot \nabla b = 0 \qquad \nabla \cdot \mathbf{v} = 0$$

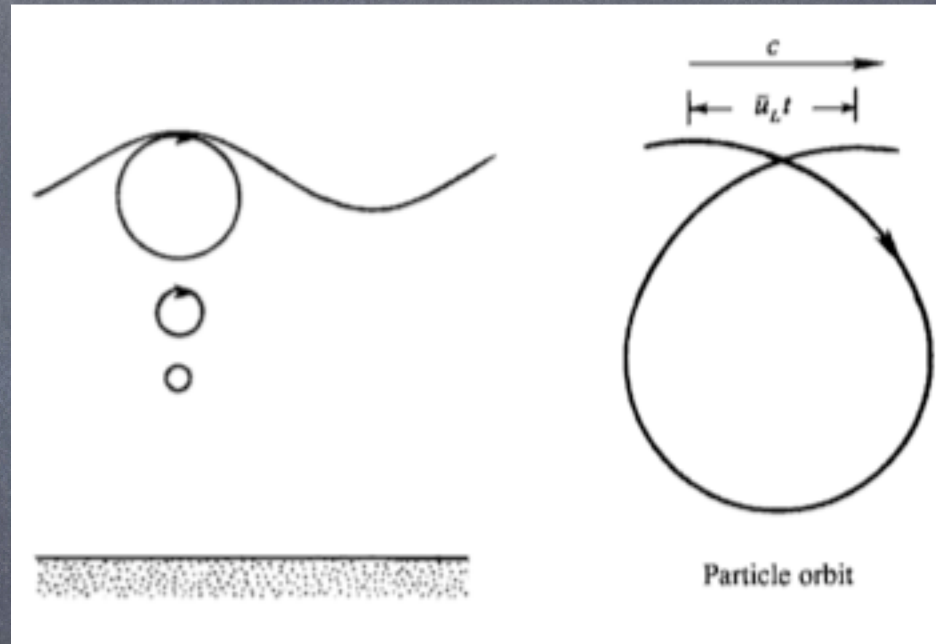
$$\mathbf{v}_s = \text{Stokes Drift}$$

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

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



(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,
between wave models (not shown)
or model vs. altimeter (shown)

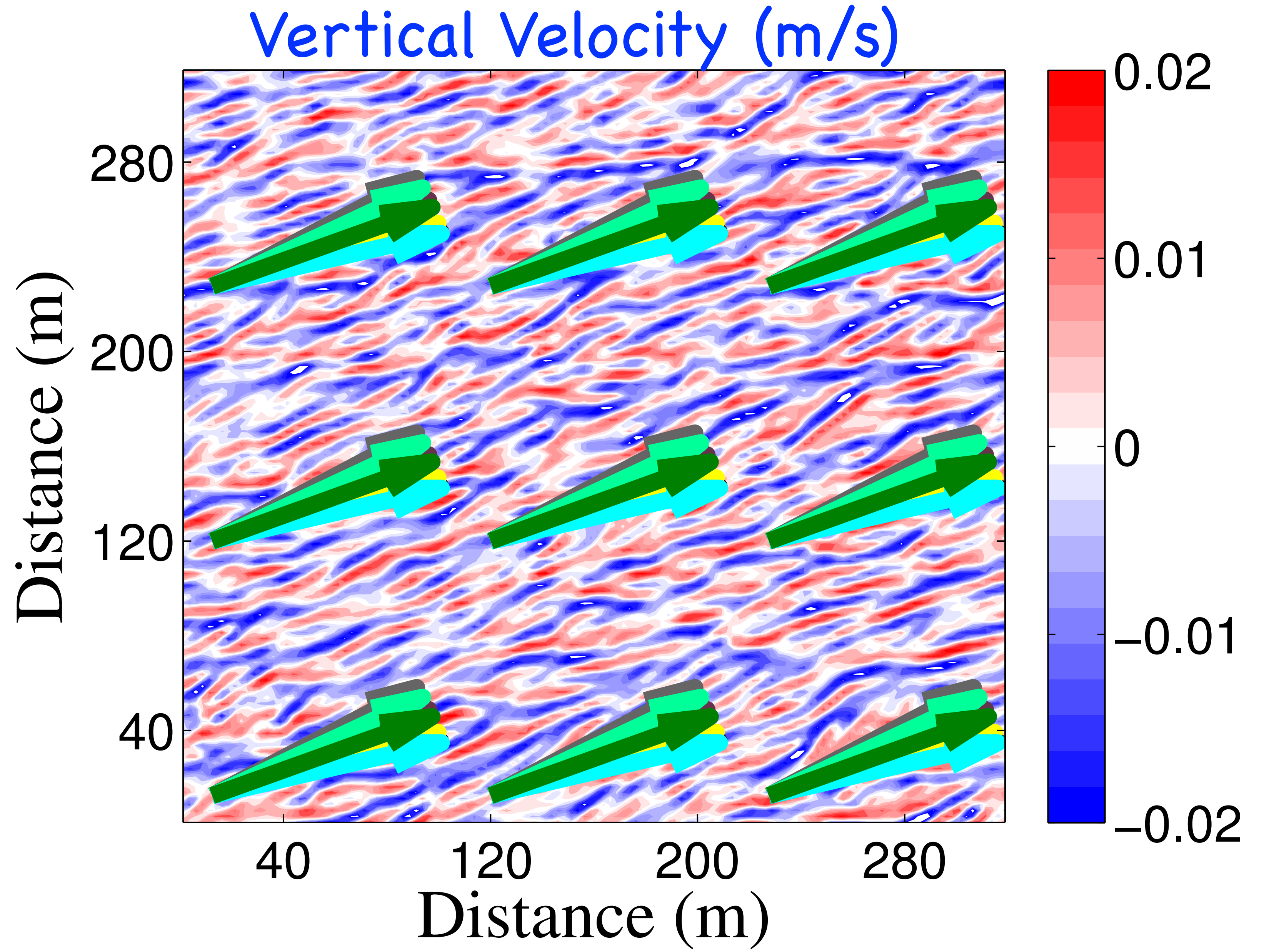
A. Webb and BFK. Wave spectral moments and Stokes drift estimation. *Ocean Modelling*, 40(3-4):273-288, 2011.

Now, we've got the CLB equations & estimated global Stokes, what to do?

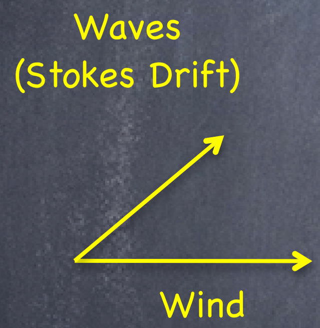
- 1) Stokes-driven small-scale turbulence (Large Eddy Simulations of CLB)
- 2) Laminar submesoscale flow with Stokes Coriolis & Stokes Vortex forces (Analytic Solns of CLB)
- 3) Wave-driven turbulence interacting with submesoscale flow (Multiscale LES of CLB)

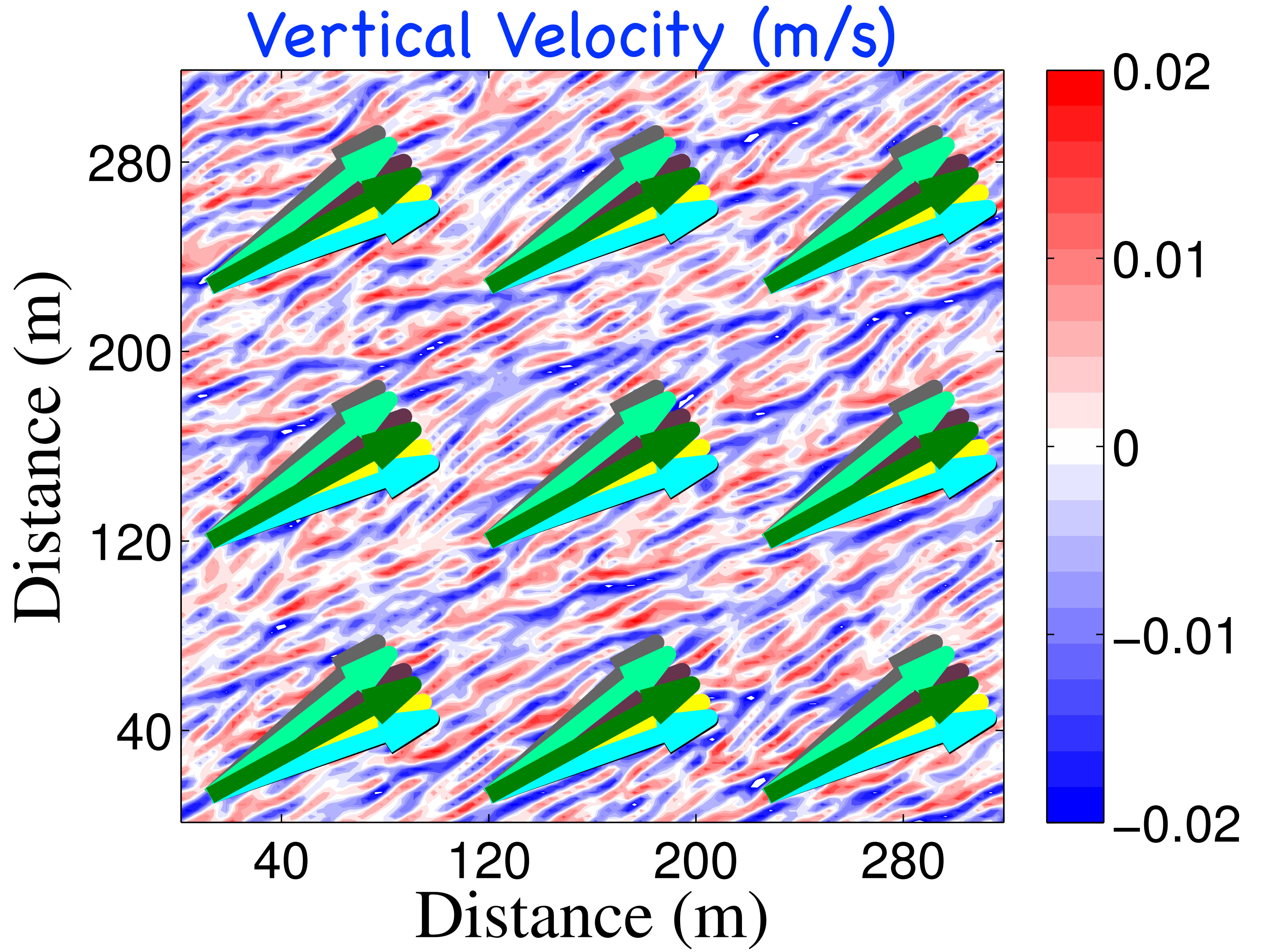
CLB as equations for Large Eddy Simulations:
Interesting in Data: Misaligned Wind & Waves

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.



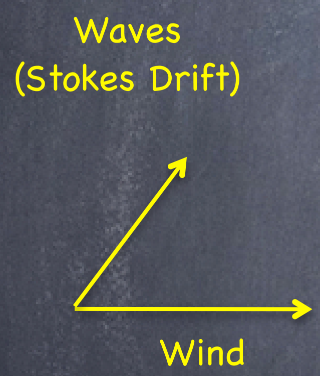
CLB as equations for Large Eddy Simulations:
Interesting in Data: Misaligned Wind & Waves



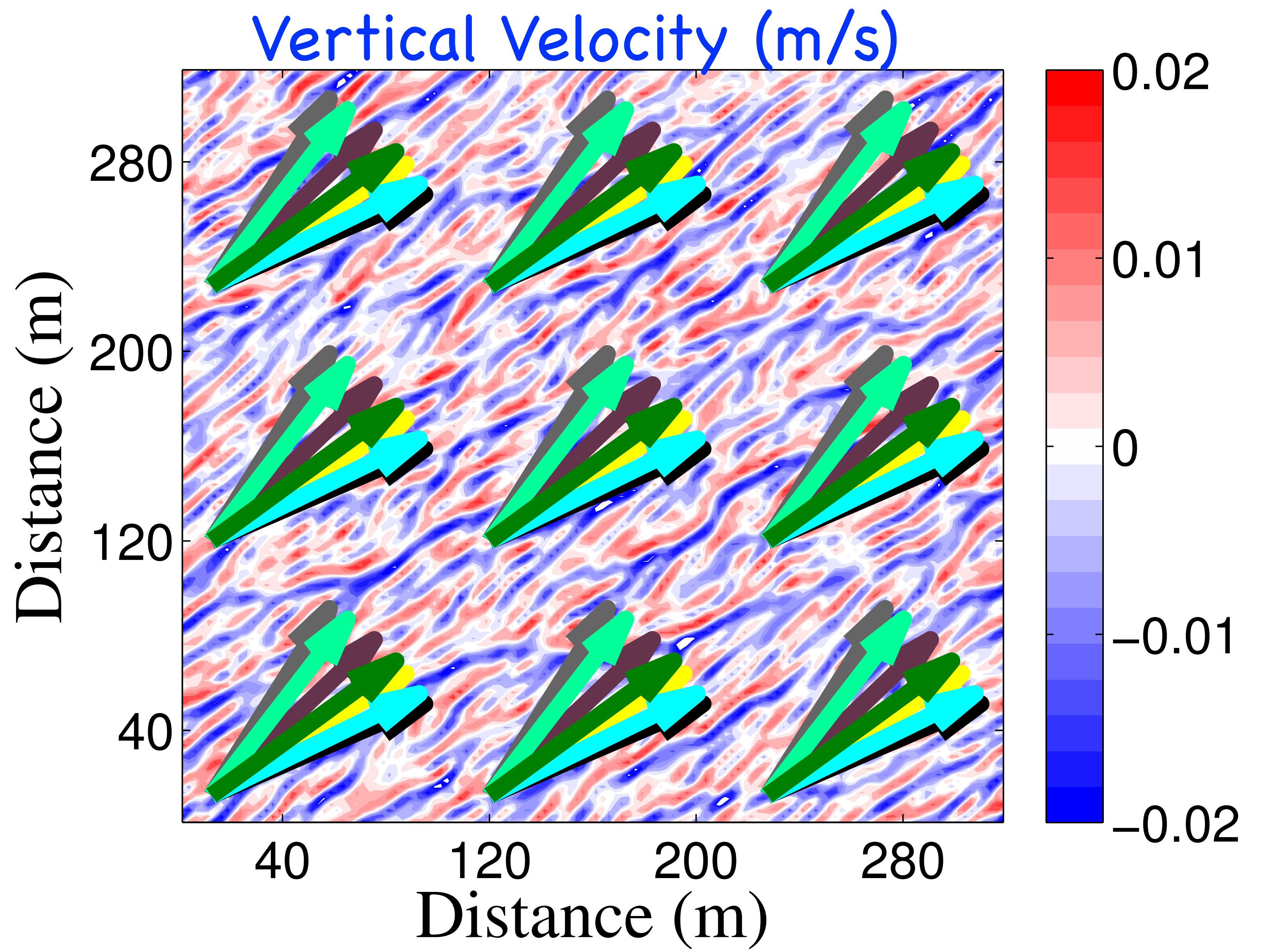


L. P. Van Roekel, BFK, P. P. Sullivan, P. E. Hamlington, and S. R. Haney. The form and orientation of Langmuir cells for misaligned winds and waves. Journal of Geophysical Research-Oceans, 117:C05001, 22pp, May 2012.

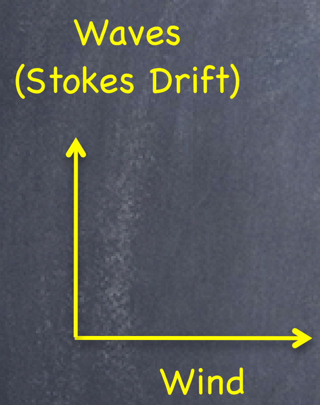
CLB as equations for Large Eddy Simulations:
Interesting in Data: Misaligned Wind & Waves

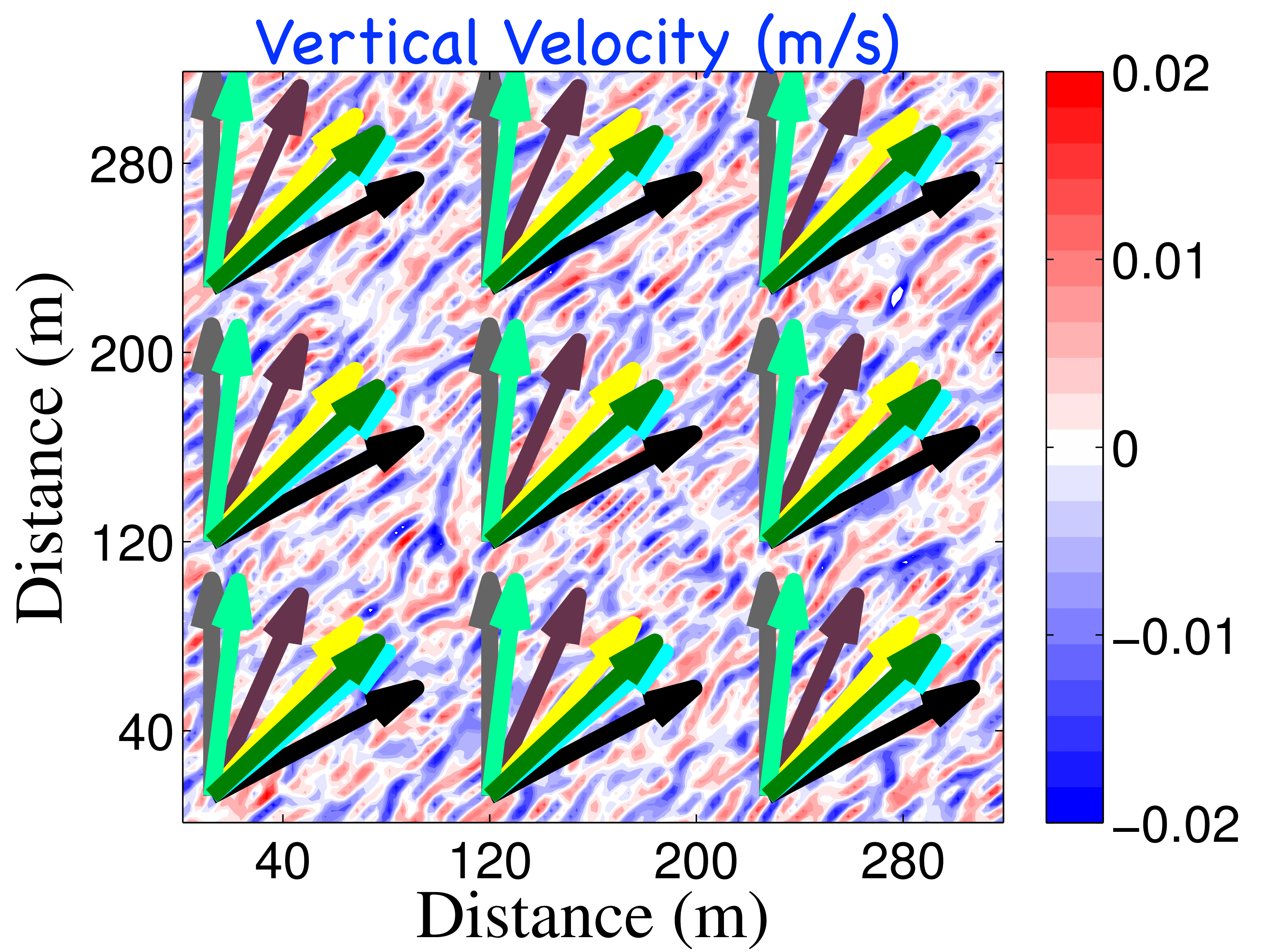


L. P. Van Roekel, BFK, P. P. Sullivan, P. E. Hamlington, and S. R. Haney. The form and orientation of Langmuir cells for misaligned winds and waves. Journal of Geophysical Research-Oceans, 117:C05001, 22pp, May 2012.



CLB as equations for Large Eddy Simulations:
Interesting in Data: Misaligned Wind & Waves





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.

Why? Vortex Tilting Mechanism

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

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

image:
Thorpe, 04

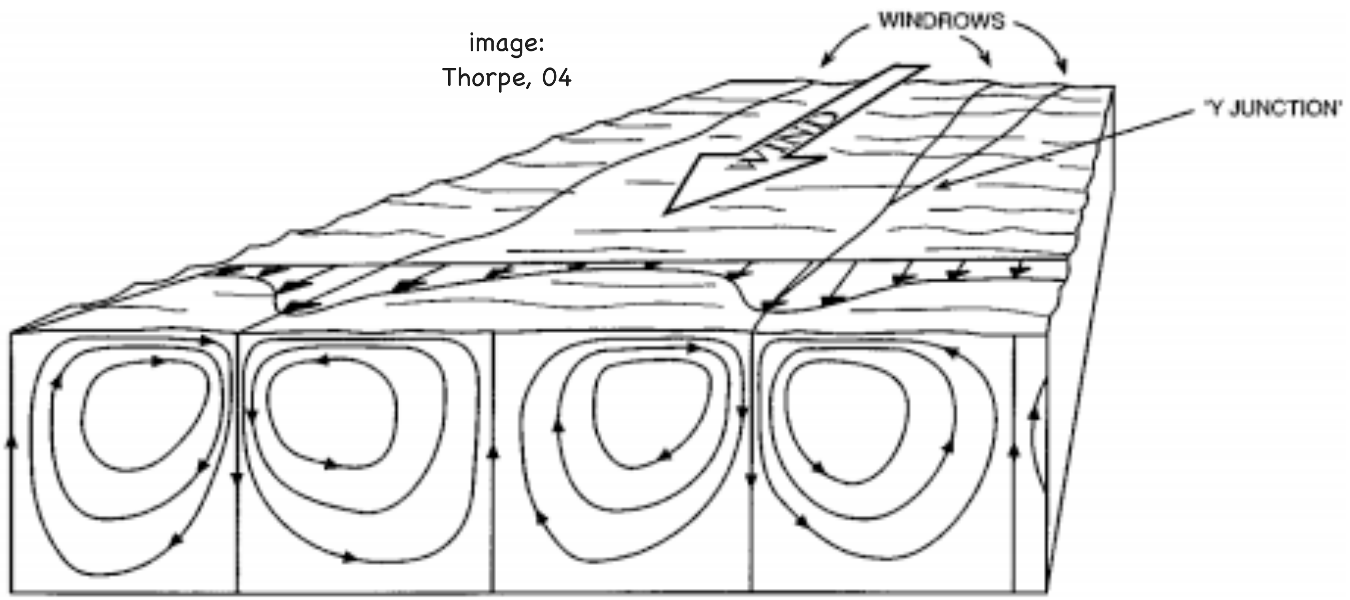
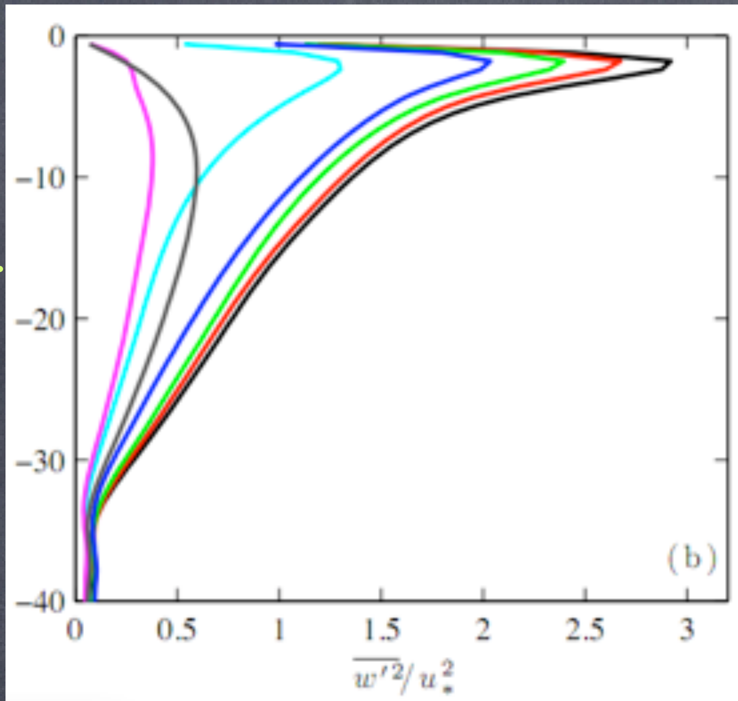


Figure 1 Sketch showing the pattern of mean flow in idealized Langmuir circulation. The windrows may be 2 m to 300 m apart, and the cell form is roughly square (as shown). In practice the flow is turbulent, especially near the water surface, and the windrows (Figure 2) amalgamate and meander in space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

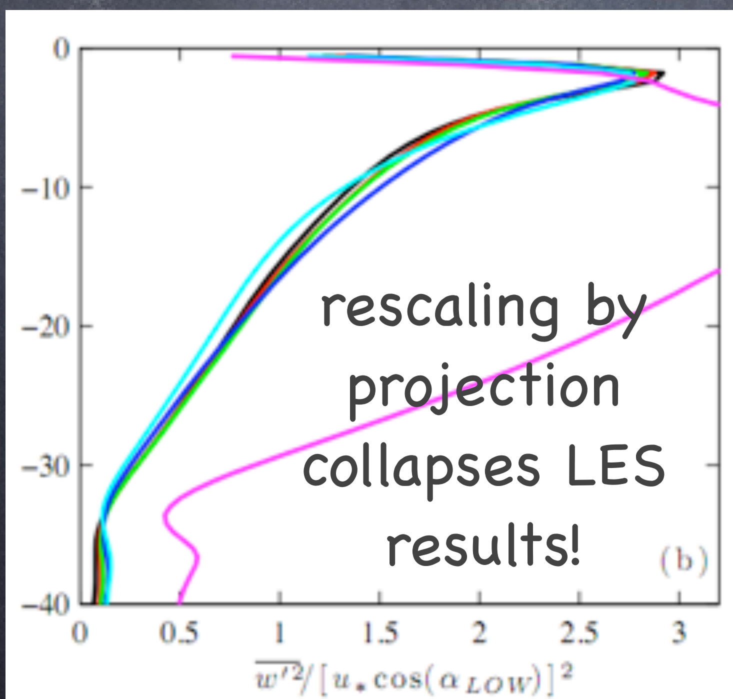
<w^2>

depth



rescaled <w^2>

depth



Generalized Parameters: Predict & Project into Lagrangian Shear Direction

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

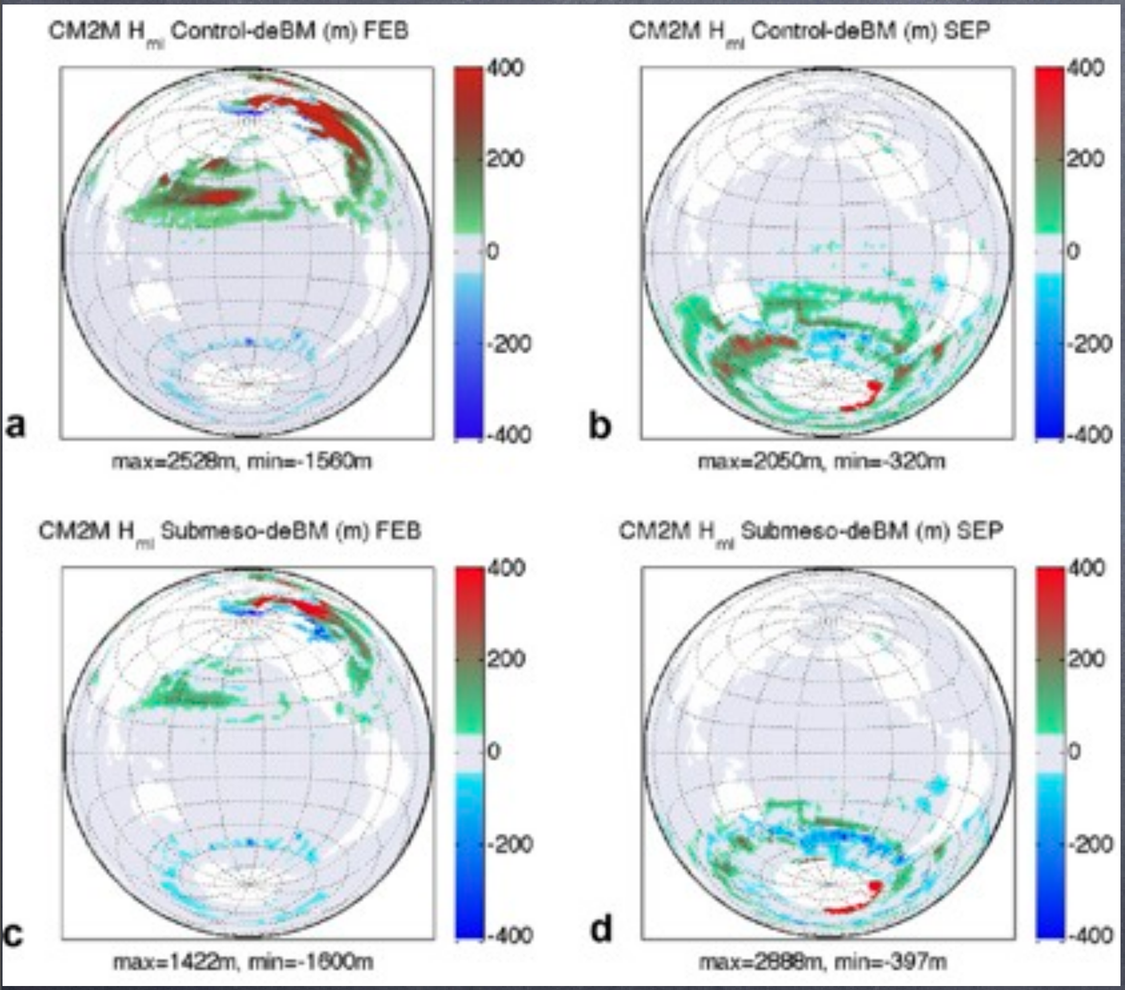
$$La_{proj}^2 = \frac{|u_*|\cos(\alpha_{LOW})}{|u_s|\cos(\theta_{ww}-\alpha_{LOW})},$$

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

= parameterization for LC strength!

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.

Recall our problem with the (submeso) Mixed Layer Eddy Restratification--Southern Ocean too shallow!



Bias w/o MLE

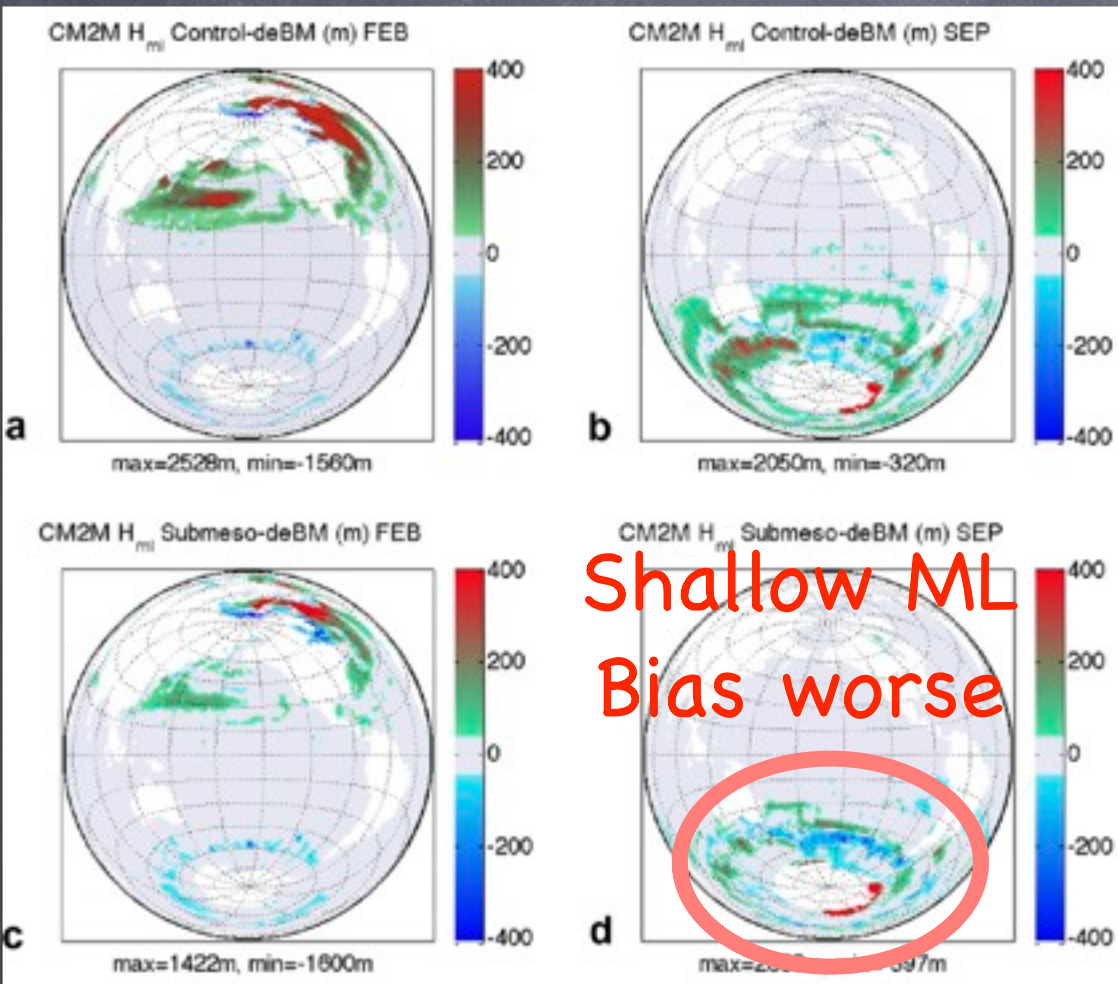
Sallee et al. (2013) have shown that a too shallow S. Ocean MLD is true of most* present climate models

salinity forcing or ocean physics?

*true for CMIP5 multi-model 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.

Recall our problem with the (submeso) Mixed Layer Eddy Restratification--Southern Ocean too shallow!



Bias w/o MLE

Sallee et al. (2013) have shown that a too shallow S. Ocean MLD is true of most* present climate models

salinity forcing or ocean physics?

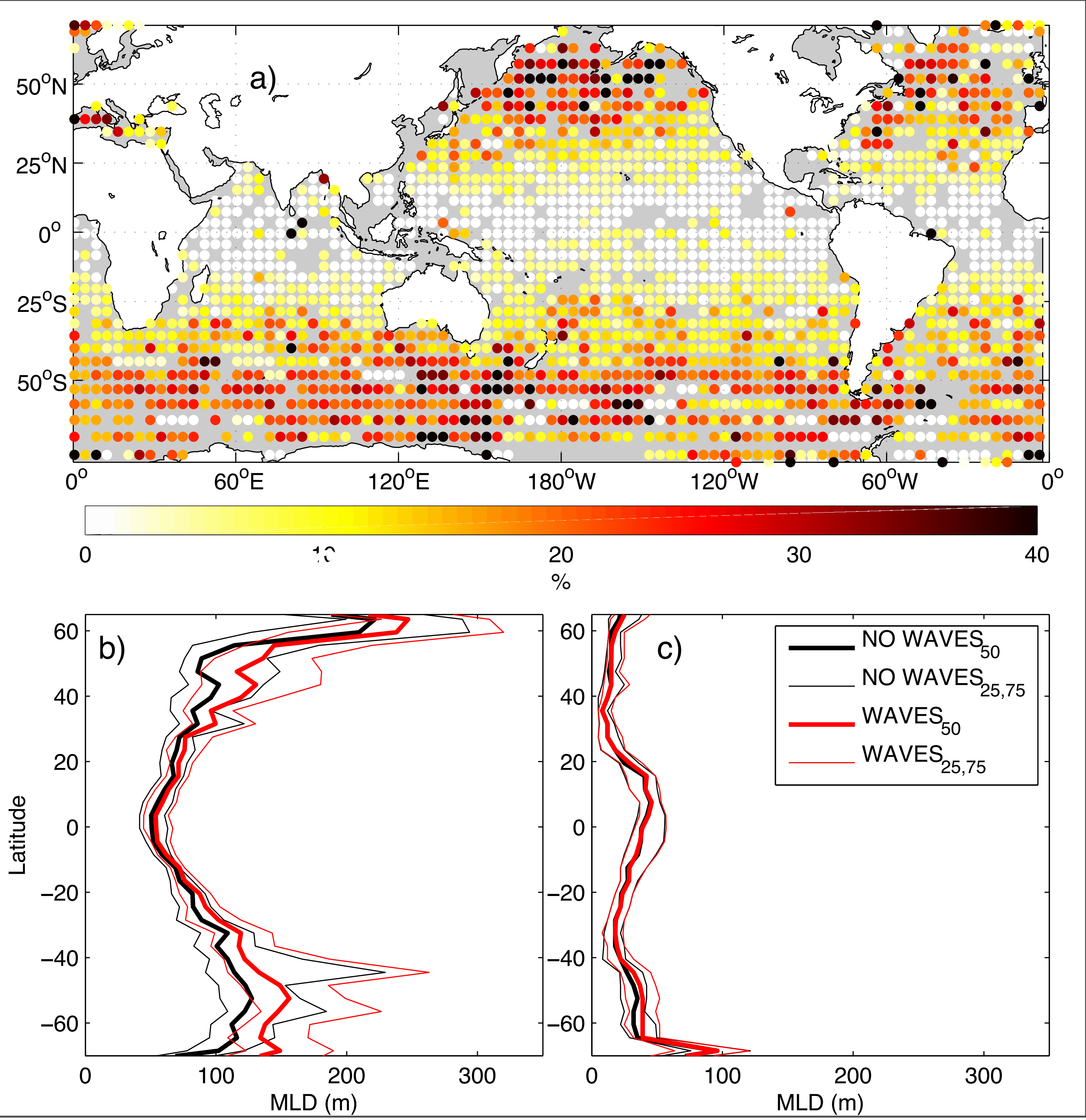
*true for CMIP5 multi-model ensemble

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.

Including Wave-driven Mixing
(Harcourt 2013 parameterization shown)

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

M. A. Hemer, BFK, & R. R. Harcourt. Quantifying the effects of wind waves the the coupled climate system, in prep. 2013.



So, Waves can Drive turbulence that affects large scale:

What about direct effects of waves on larger scales?

Stokes Coriolis & Stokes Vortex Forces on Submesoscales

Recall, Subinertial Boussinesq Equations Dominated by:

(Combined) Thermal Wind Balance

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

So, Waves can Drive turbulence that affects large scale:

What about direct effects of waves on larger scales?
Stokes Coriolis & Stokes Vortex Forces on Submesoscales

Craik-Leibovich Boussinesq Subinertial Dominated By:

(Combined) 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 buoyancy gradients govern the Lagrangian flow, not the not the Eulerian!

J. C. McWilliams and BFK. Oceanic wave-balanced surface fronts and filaments. *Journal of Fluid Mechanics*, 2013. Submitted.

Craik-Leibovich Boussinesq Subinertial Dominated By:

(Combined) Lagrangian Thermal Wind Balance

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

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

Buoyancy & PV also advected by Lagrangian Flow!

All GFD is for the Lagrangian Flow??

J. C. McWilliams and BFK. Oceanic wave-balanced surface fronts and filaments. *Journal of Fluid Mechanics*, 2013. Submitted.

Can we just forget the whole thing and interpret large scales as Lagrangian velocities?

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

No, because vortex force is different!

The "Rossby #" for waves, is big *more often* than Ro is

See Haney's Poster for more!!!

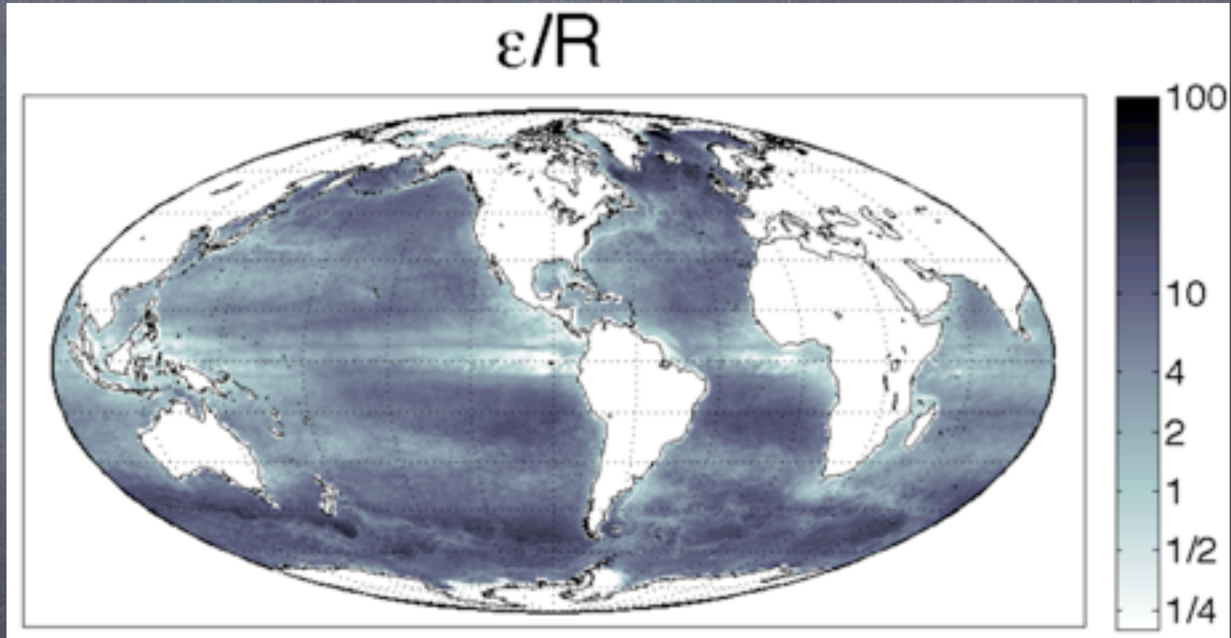
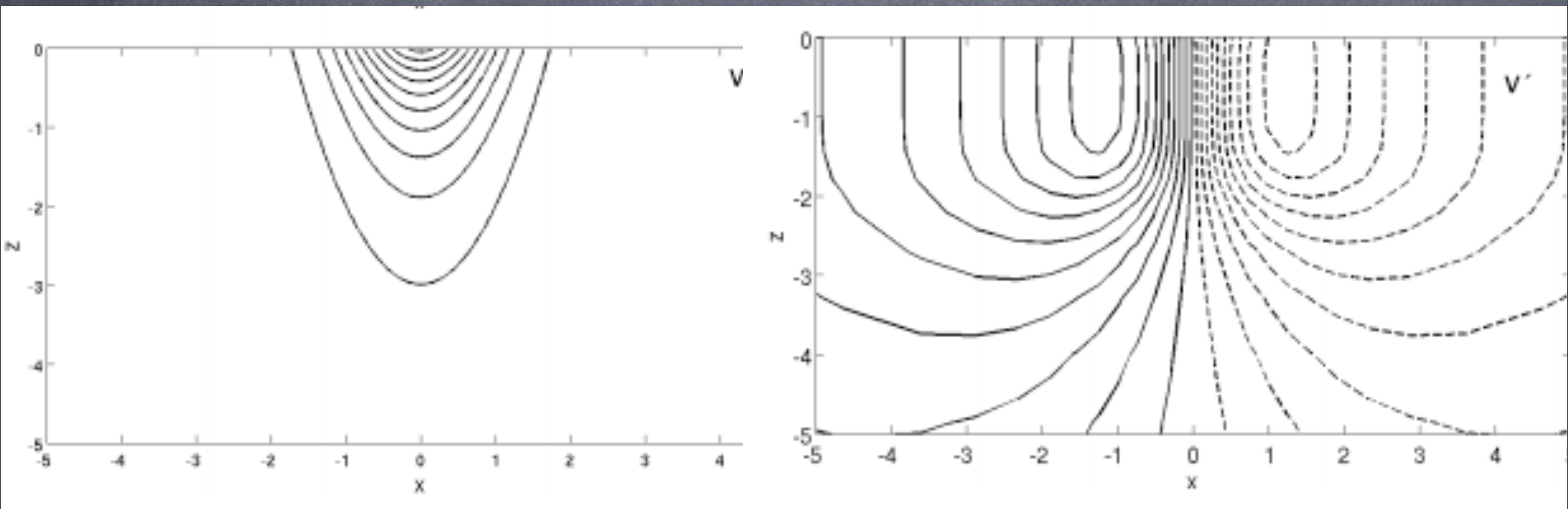


FIGURE 1. Estimated ratio $\epsilon/\mathcal{R} \approx (|\mathbf{u}_s \cdot \mathbf{u}|h)/(|\mathbf{u}|^2 h_s)$ governing the relative importance of Stokes effects versus nonlinearity. Eulerian velocity ($\mathbf{u}$) is taken as the AVISO weekly satellite geostrophic velocity or $-\mathbf{u}_s$ (for anti-Stokes flow) if $|\mathbf{u}_s| > |\mathbf{u}|$. The front/filament depth (h) is estimated as the mixed layer depth from the de Boyer Montégut *et al.* (2004) climatology. An exponential fit to the Stokes drift of the upper 9m projected onto the AVISO geostrophic velocity provides $\mathbf{u}_s \cdot \mathbf{u}$ and h_s. Stokes drift is taken from the WaveWatch-3 simulation described in Webb & Fox-Kemper (2011). $\mathbf{u}$, $\mathbf{u}_s$, and h_s are all for the year 2000, while h is from a climatology of observations over 1961-2008. The year 2000 average of $\epsilon/\mathcal{R}$ is shown.

J. C. McWilliams and BFK. Oceanic wave-balanced surface fronts and filaments. *Journal of Fluid Mechanics*, 2013. Submitted.

Waves (Stokes Vortex Force) example of wave-balancing Submeso flow



Initial Submeso Front

Contours: 0.1

Perturbation on that scale due to waves

Contours: 0.014

J. C. McWilliams and BFK. Oceanic wave-balanced surface fronts and filaments. *Journal of Fluid Mechanics*, 2013. Submitted.

What about Langmuir-Submeso Interactions?

Movie: P. Hamlington

See his poster for more!!

Perform large eddy simulations (LES) of CLB with a submesoscale temperature front with winds-- with and without Stokes drift

$$\frac{\partial \rho}{\partial t} + \mathbf{u}_L \cdot \nabla \rho = \mathrm{SGS}$$

$$\nabla \cdot \mathbf{u} = 0$$

$$\frac{\partial \mathbf{u}}{\partial t} + (\boldsymbol{\omega} + f\hat{\mathbf{z}}) \times \mathbf{u}_L = -\nabla \pi - \frac{g\rho\hat{\mathbf{z}}}{\rho_0} + \mathrm{SGS}$$

Wave & Wind Dir.

Computational parameters:

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

Grid points: 4096 x 4096 x 128

Resolution: 5m x 5m x -1.25m

What about Langmuir-Submeso Interactions?

Movie: P. Hamlington

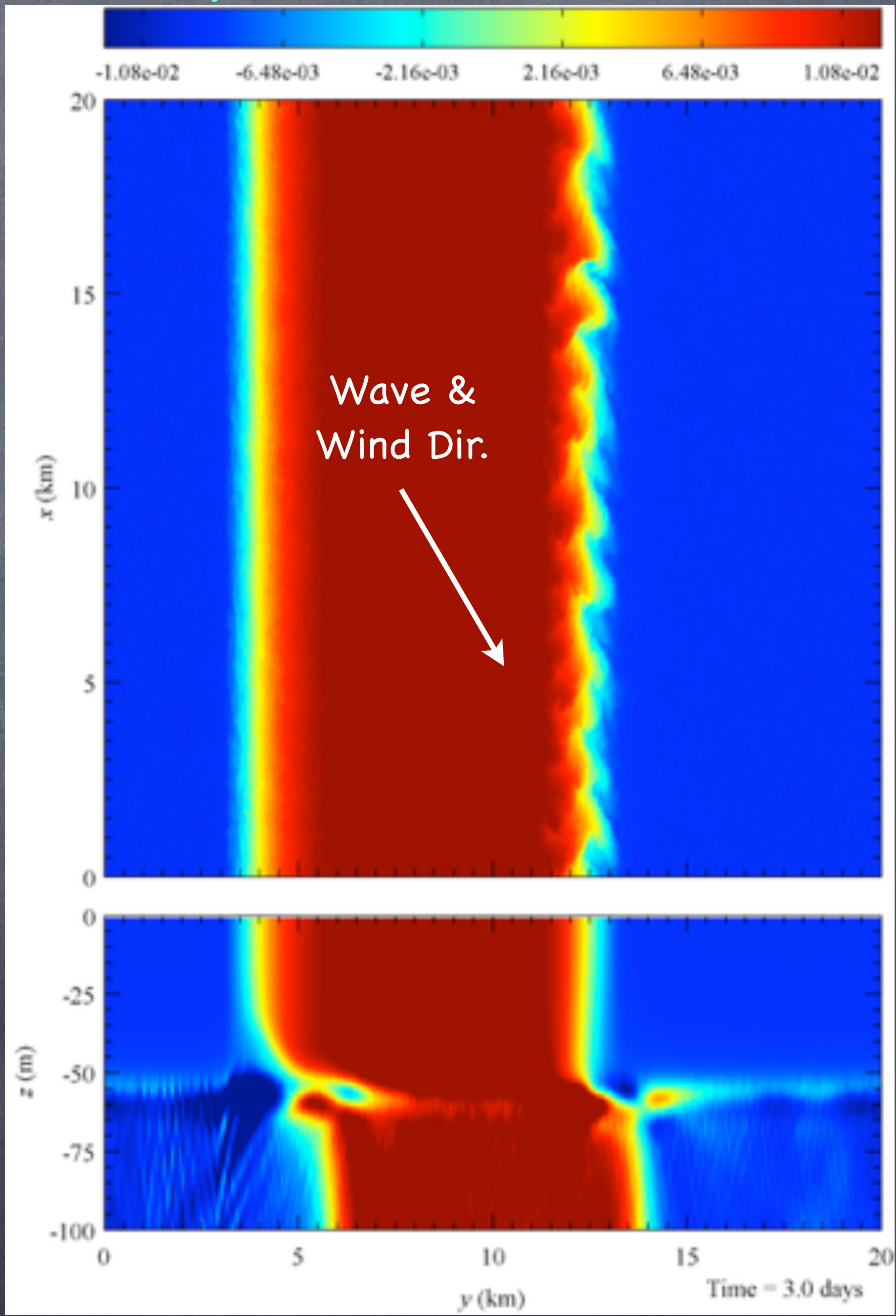
See his poster for more!!

Perform large eddy simulations (LES) of CLB with a submesoscale temperature front with winds-- with and without Stokes drift

$$\frac{\partial \rho}{\partial t} + \mathbf{u}_L \cdot \nabla \rho = \mathrm{SGS}$$

$$\nabla \cdot \mathbf{u} = 0$$

$$\frac{\partial \mathbf{u}}{\partial t} + (\boldsymbol{\omega} + f\hat{\mathbf{z}}) \times \mathbf{u}_L = -\nabla \pi - \frac{g\rho\hat{\mathbf{z}}}{\rho_0} + \mathrm{SGS}$$



Computational parameters:

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

Grid points: 4096 x 4096 x 128

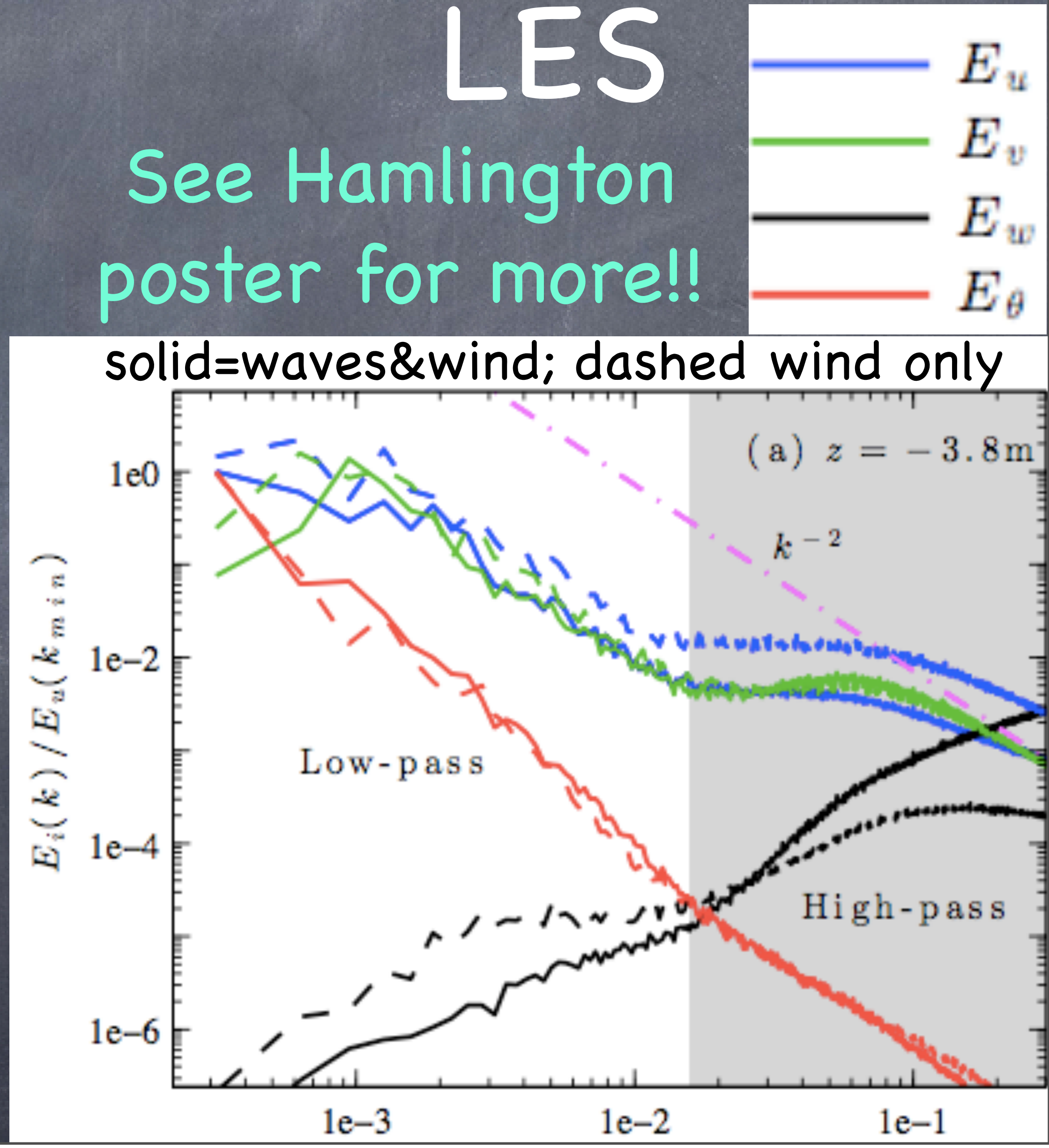
Resolution: 5m x 5m x -1.25m

Overall results from multiscale LES

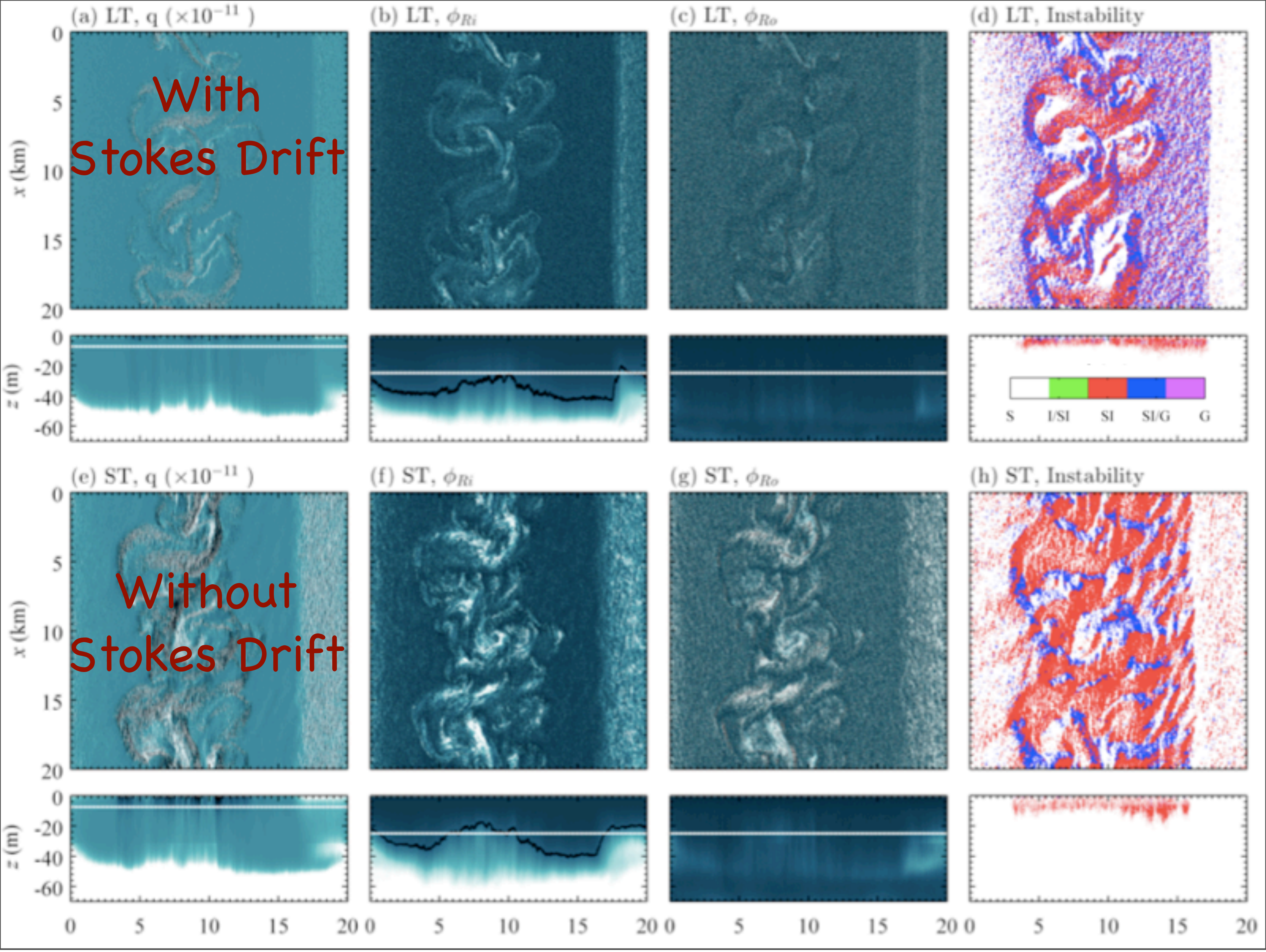
- Submesoscale flow is affected by wave-balance and enhanced <u'w'> (weaker surf. w/ Stokes)
- Strong two-way turbulent interactions are rare for this configuration
- Two turbulent cascades.
- Presence of waves greatly changes small scale from symmetric instability to gravitational

See Hamlington poster for more!!

solid=waves&wind; dashed wind only



P. E. Hamlington, L. P. Van Roekel, BFK, K. Julien, G. P. Chini. Langmuir-Submesoscale Interactions: Descriptive Analysis of Multiscale Frontal Spin-down Simulations, *JGR-Oceans*, 2013. In prep.

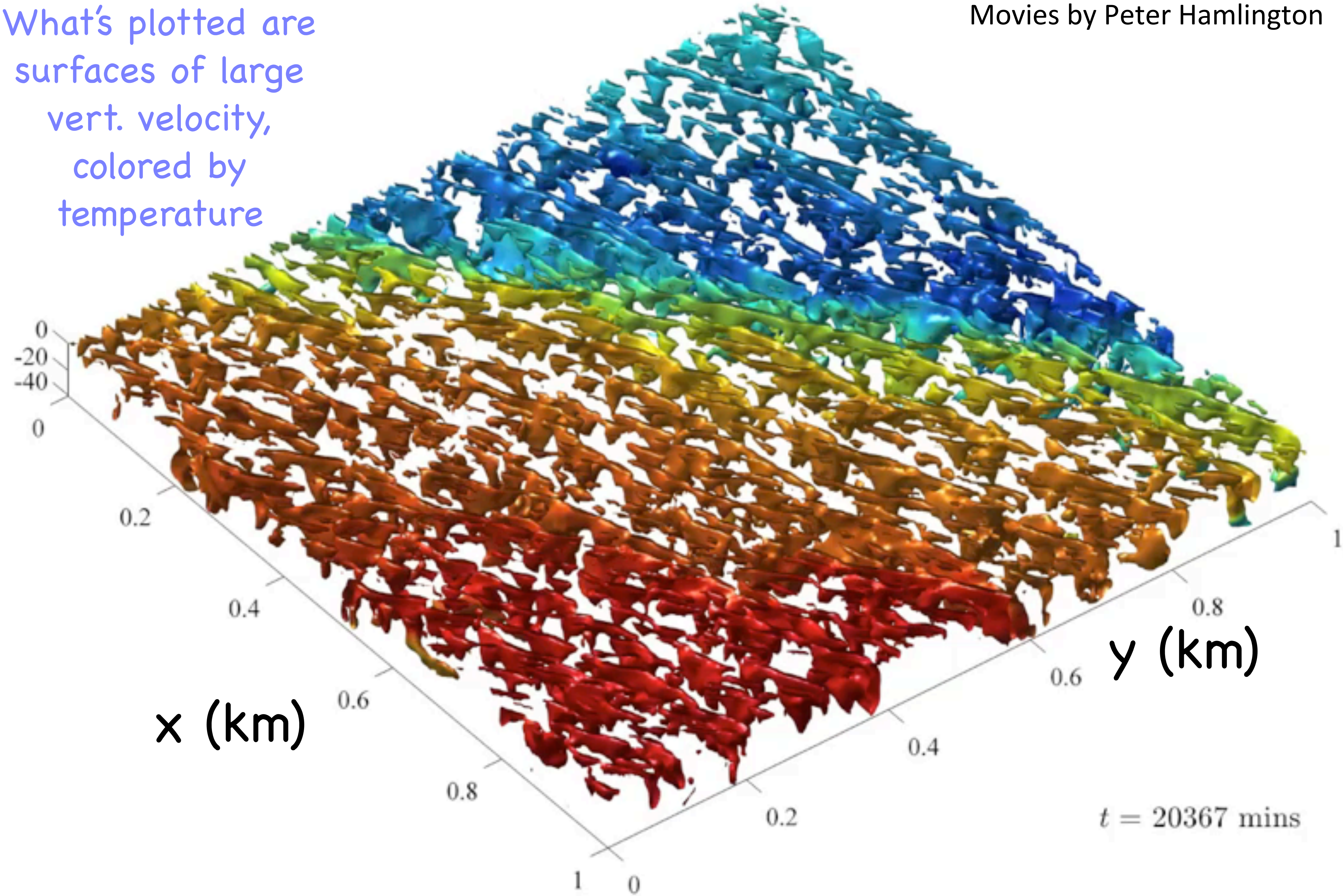


(a) LT, q (×10⁻¹¹)
(b) LT, ϕ_{Ri}
(c) LT, ϕ_{Ro}
(d) LT, Instability
With Stokes Drift
x (km)
z (m)
S
I/SI
SI
SI/G
G
(e) ST, q (×10⁻¹¹)
(f) ST, ϕ_{Ri}
(g) ST, ϕ_{Ro}
(h) ST, Instability
Without Stokes Drift

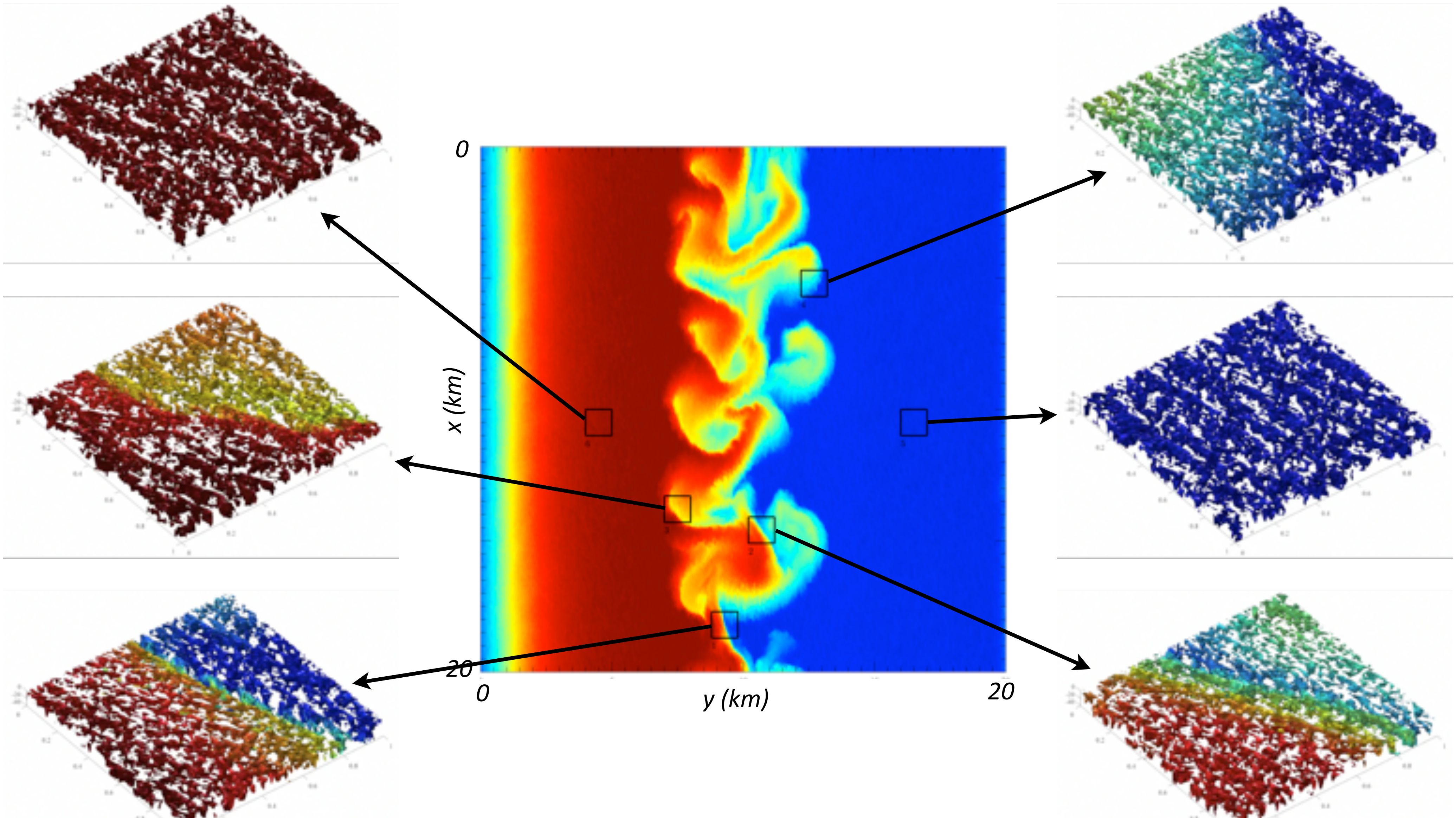
Zoom: Submeso-Langmuir Interaction!

What's plotted are surfaces of large vert. velocity, colored by temperature

Movies by Peter Hamlington



Diverse types of interaction

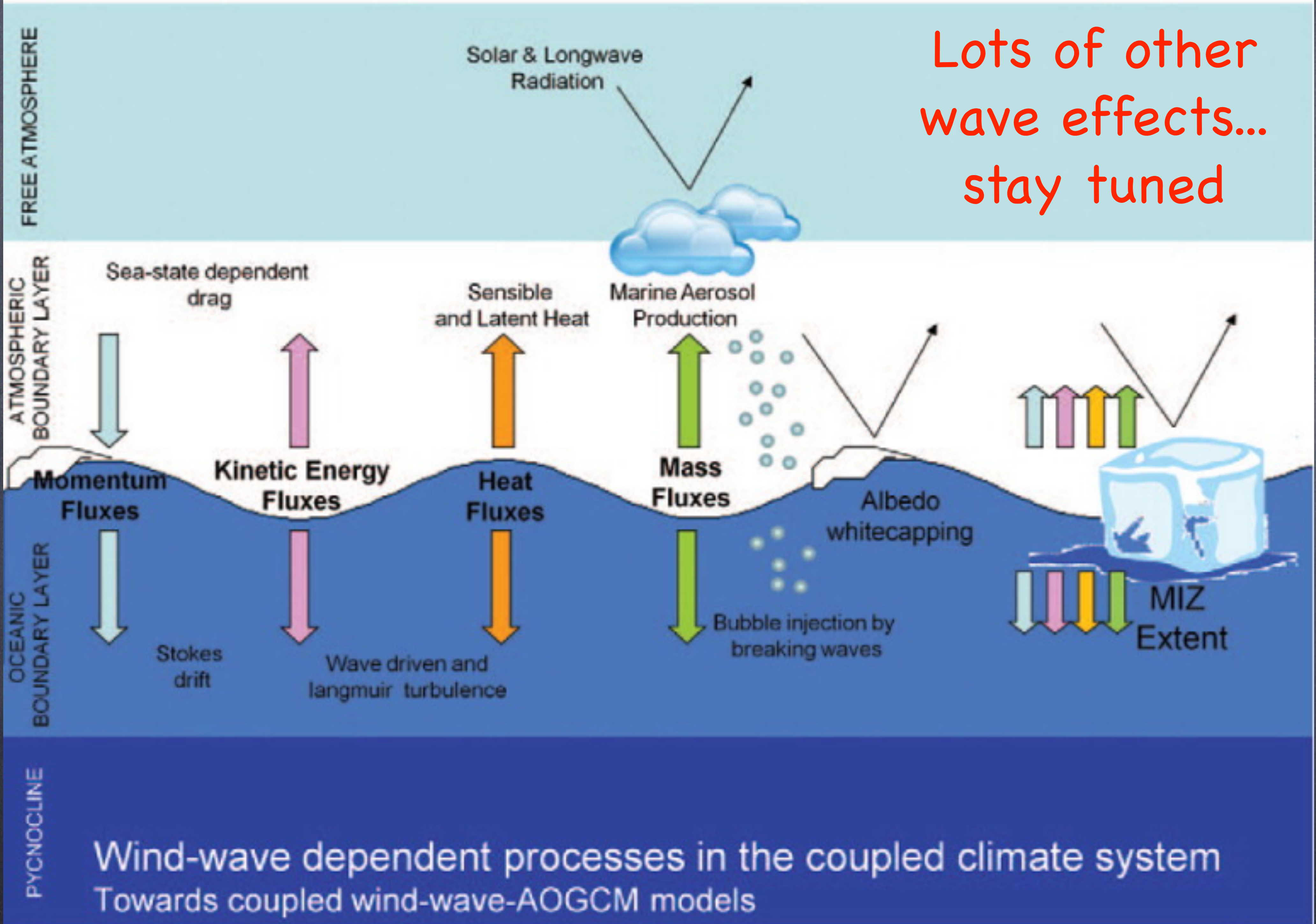


Slide & Movies by Peter Hamlington

P. E. Hamlington, L. P. Van Roekel, BFK, K. Julien, and G. P. Chini. Langmuir-submesoscale interactions: Descriptive analysis of multiscale simulations. In preparation, 2013.

CLB Conclusions

- Waves are a dominant feature of the upper ocean on short timescales
- On longer timescales, rectified effects of waves--in CLB the Stokes drift--changes boundary layer and submesoscale dynamics
- Critical concept: Lagrangian shear takes over for Eulerian--except for a different *vortex force*
- Wave, convective, & wind effects are particularly important when transient
  - e.g., waves *not fully developed* which is most of the time for long fetch (i.e., open ocean)



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

Big Picture 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 centimeters contribute non-negligibly
- Process models are needed to study these connections and improve subgrid models.
- Interesting are the submeso to Langmuir scales, as nonhydro. & ageostrophic effects become dominant
- The CLB are good for LES & analysis in this range, but cannot capture some effects of small, steep waves (breaking, spray, nearshore, etc.)

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!

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

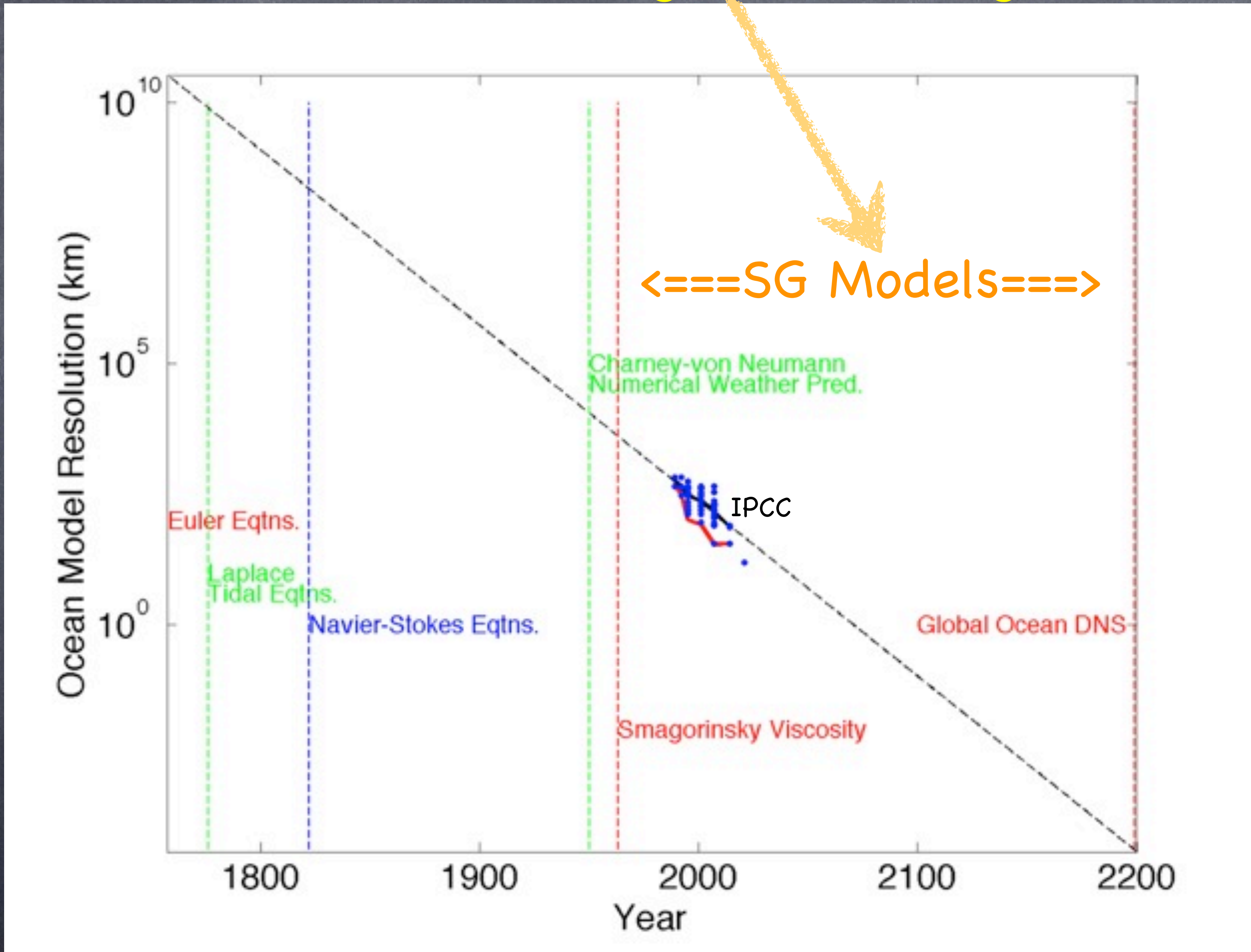
Steep waves break->vortex motion & small scale turbulence!

So, no problems?
Just crunch away with CLB?

- Let's revisit our assumptions for scale separation:
  - Also, what about finite wave packets?
  - What about co-evolution of the submesoscale flow and wave packets?
  - What about steep wave effects? Breaking?
  - Are there other ways for waves to drive turbulence?

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

Extrapolate for historical perspective: The Golden Era of Subgrid Modeling is Now!

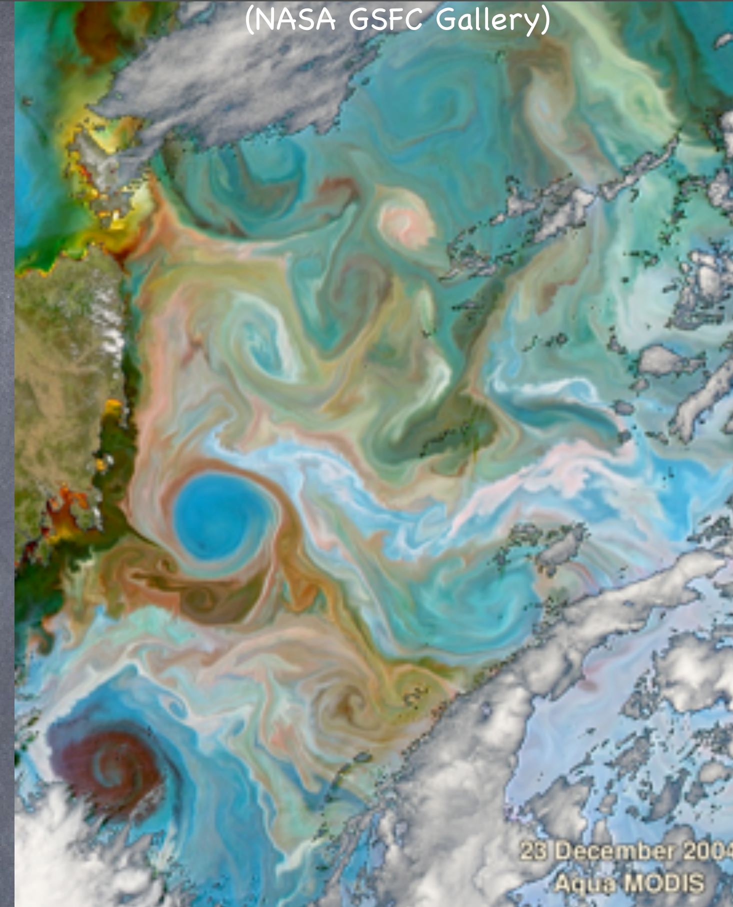


All papers at: fox-kemper.com/research

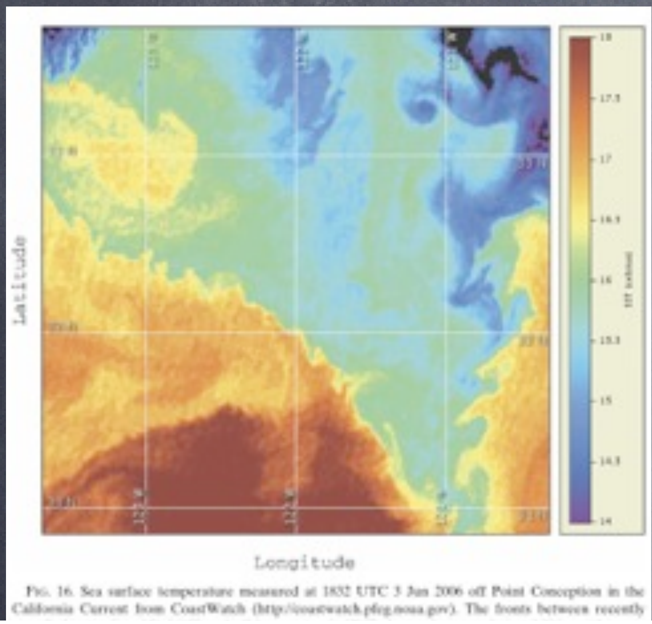
The Character of the Submesoscale

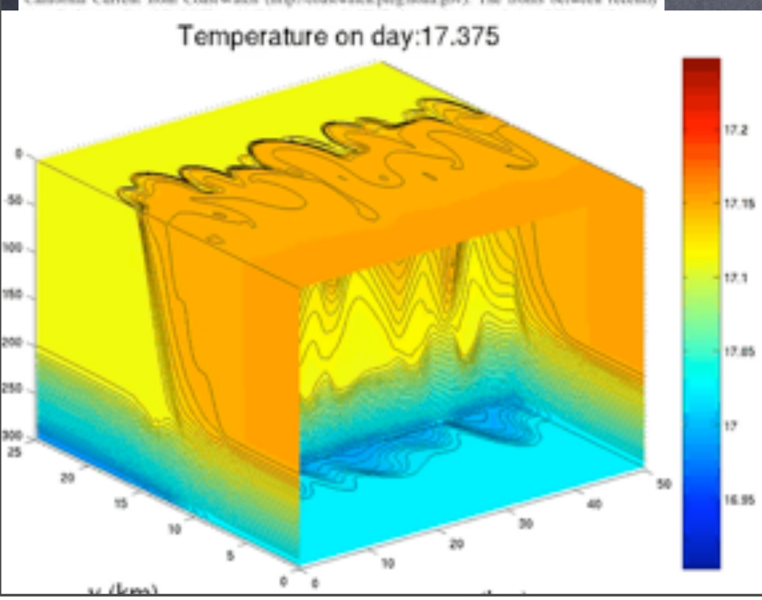
← 10 km

(NASA GSFC Gallery)



(Capet et al., 2008)





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

Eddy processes often baroclinic instability

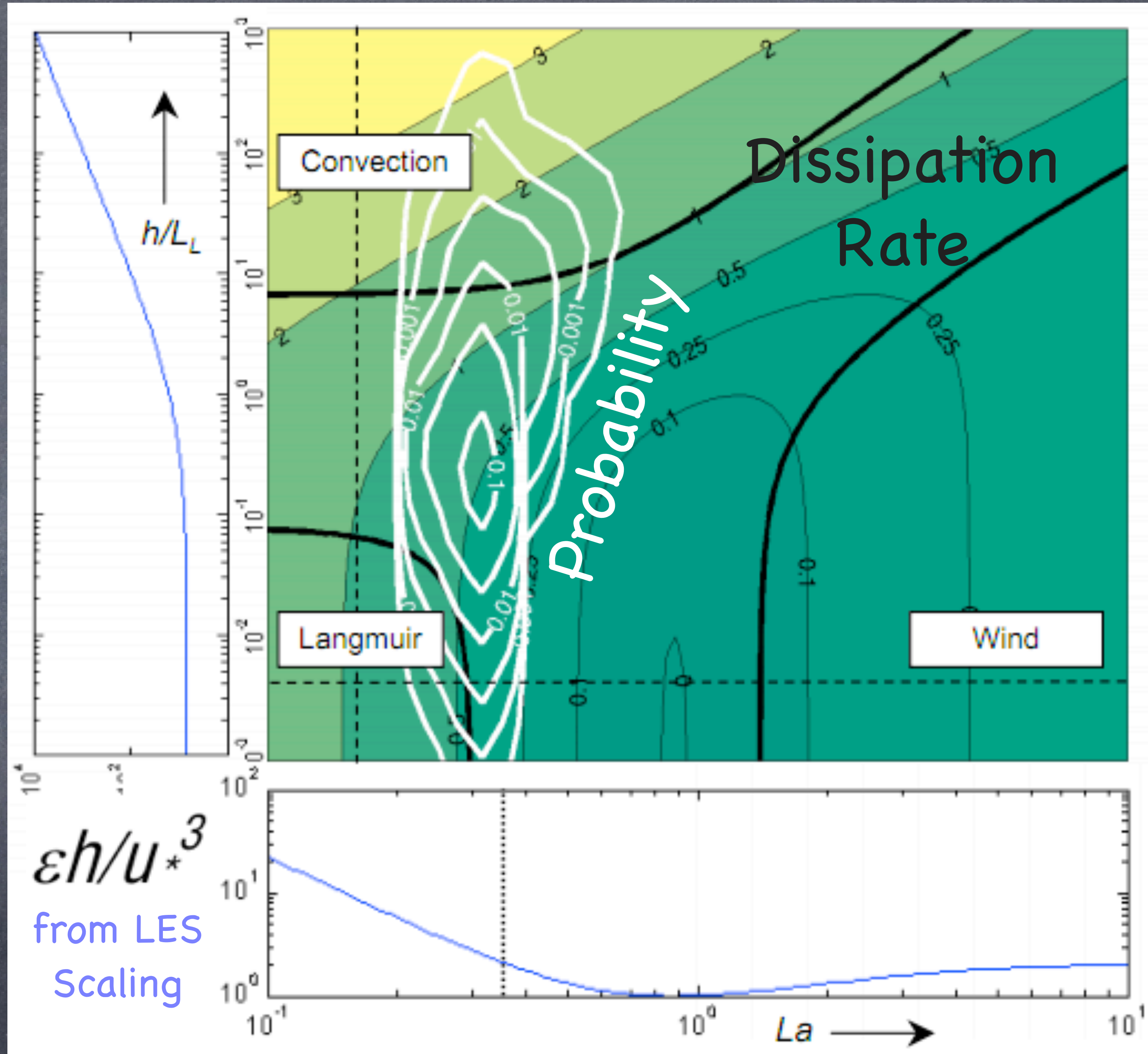
Parameterizations of submesoscale baroclinic instability?

B. Fox-Kemper, 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

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

Data + LES, Southern Ocean mixing energy: Langmuir (Stokes-drift-driven) and Convective

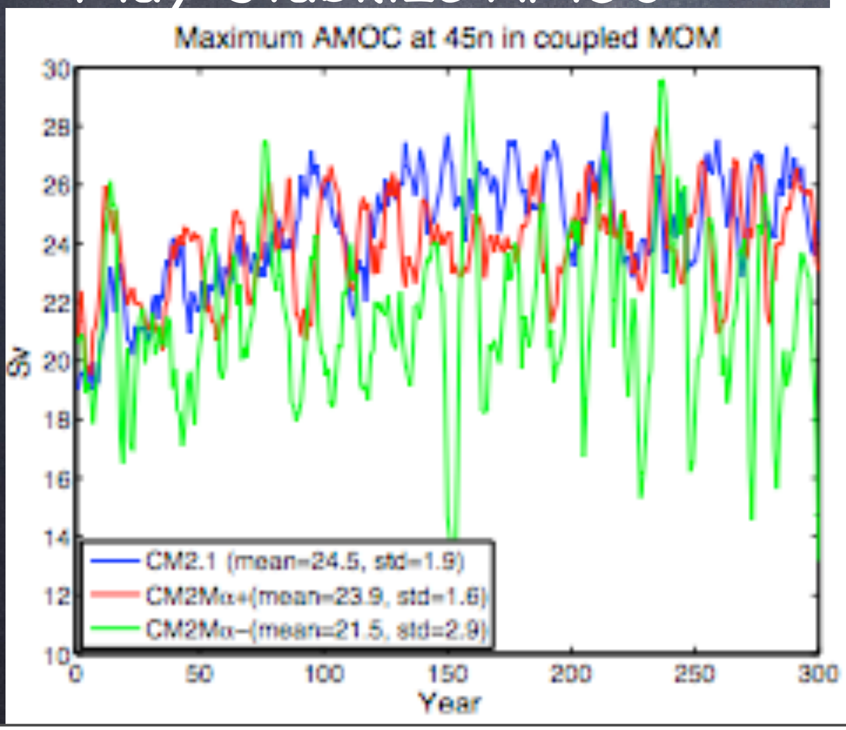
So, waves can drive mixing via Stokes drift (combines with cooling & winds)



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.

Sensitivity of Climate to Submeso: AMOC & Cryosphere Impacts

May Stabilize AMOC



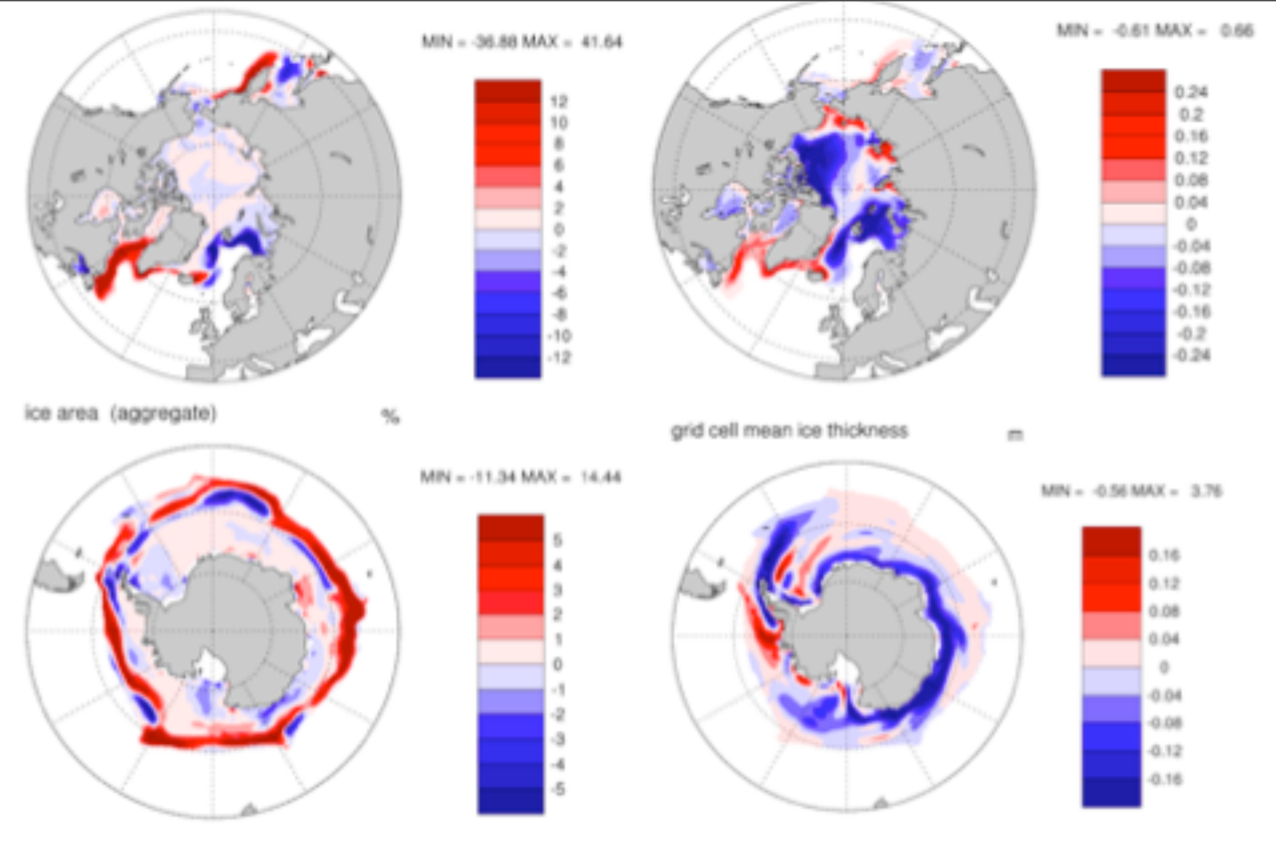


Figure 10: Wintertime sea ice sensitivity to introduction of MLE parameterization ($CCSM^+$ minus $CCSM^-$): January to March Northern Hemisphere a) ice area and b) thickness and July to September Southern Hemisphere c) ice area and d) thickness.

Affects sea ice

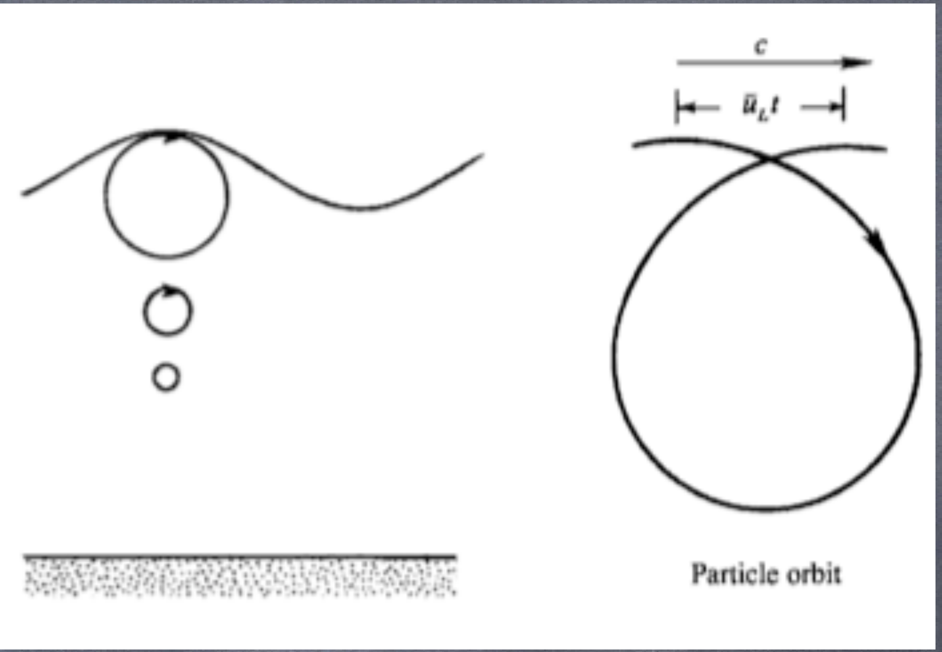
NO RETUNING NEEDED!!!

These are impacts: bias change unknown

What is Stokes Drift?

Take wave solns, compare the velocity of trajectories vs. Eulerian velocity, Taylor Expand, calculate:

$$\mathbf{u}^L(\mathbf{x}_p(t_0),t) - \mathbf{u}^E(\mathbf{x}_p(t_0),t) \approx [\mathbf{x}_p(t) - \mathbf{x}_p(t_0)] \cdot \nabla \mathbf{u}^E(\mathbf{x}_p(t_0),t)$$
$$\approx \left[\int_{t_0}^{t} \mathbf{u}^E(\mathbf{x}_p(t_0),s')ds'\right] \cdot \nabla \mathbf{u}^E(\mathbf{x}_p(t_0),t)\,.$$



Examples:

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

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

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

Craik-Leibovich Boussinesq

Old Boussinesq (written in vortex force form)

$$\frac{\partial \mathbf{v}}{\partial t} + [\mathbf{f} + \nabla \times \mathbf{v}] \times \mathbf{v} = -\nabla \pi + b\mathbf{k} + \nu \nabla^2 \mathbf{v}$$

$$\frac{\partial b}{\partial t} + \mathbf{v} \cdot \nabla b = 0 \qquad \nabla \cdot \mathbf{v} = 0$$

Craik-Leibovich Boussinesq $\quad \mathbf{v}_s = \text{Stokes Drift}$

$$\frac{\partial \mathbf{v}}{\partial t} + [\mathbf{f} + \nabla \times \mathbf{v}] \times (\mathbf{v} + \mathbf{v}_s) = -\nabla \pi^\dagger + b\mathbf{k} + \nu \nabla^2 \mathbf{v}$$

$$\frac{\partial b}{\partial t} + (\mathbf{v} + \mathbf{v}_s) \cdot \nabla b = 0$$

$$\nabla \cdot \mathbf{v} = 0$$

Global Picture: Misalignment enhances degree to which we expect wave-driven turbulence in Boundary layer

Wind-Driven

Wave-Driven

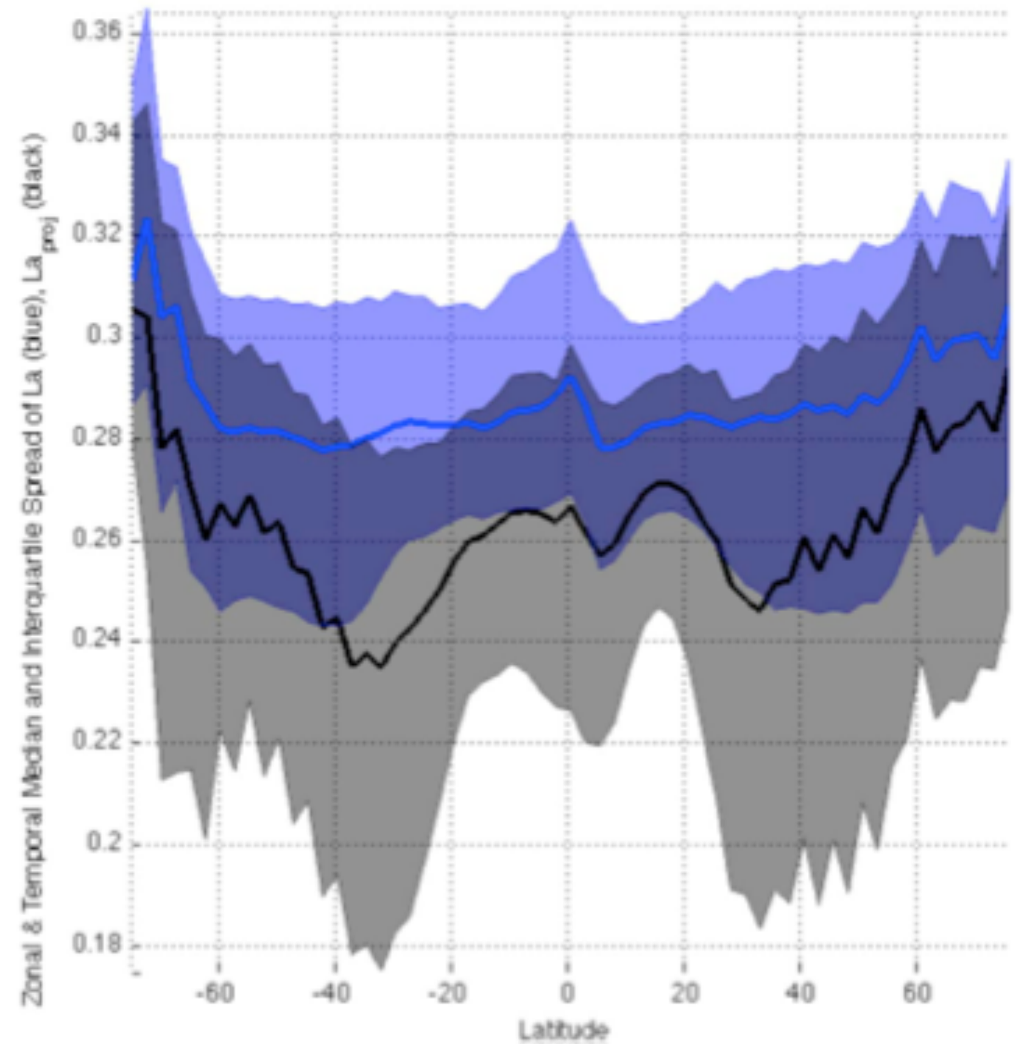


Figure 17. Temporal and zonal median and interquartile range of La_t and La_{proj} for a realistic simulation of 1994–2002 using Wave Watch III.