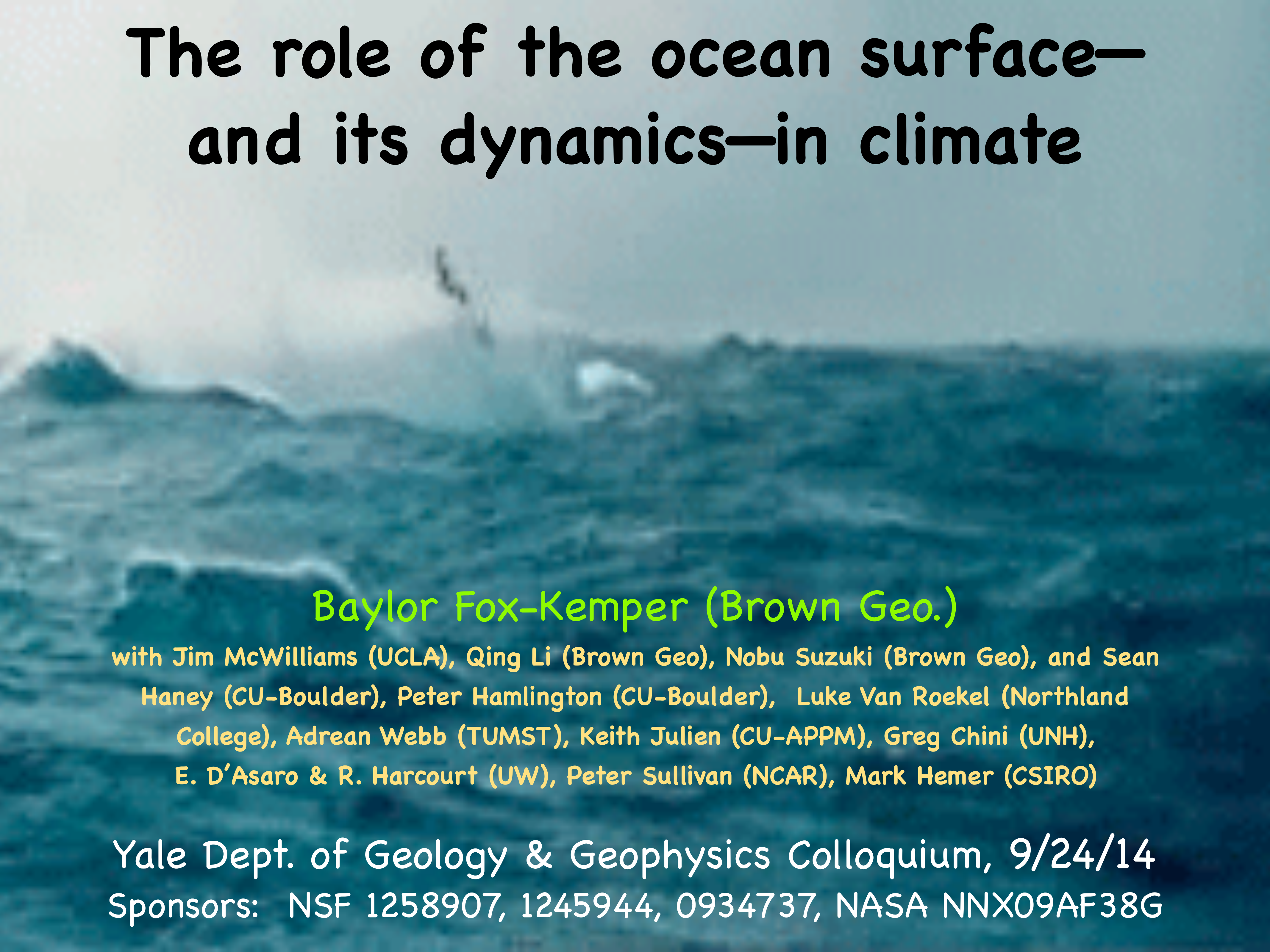


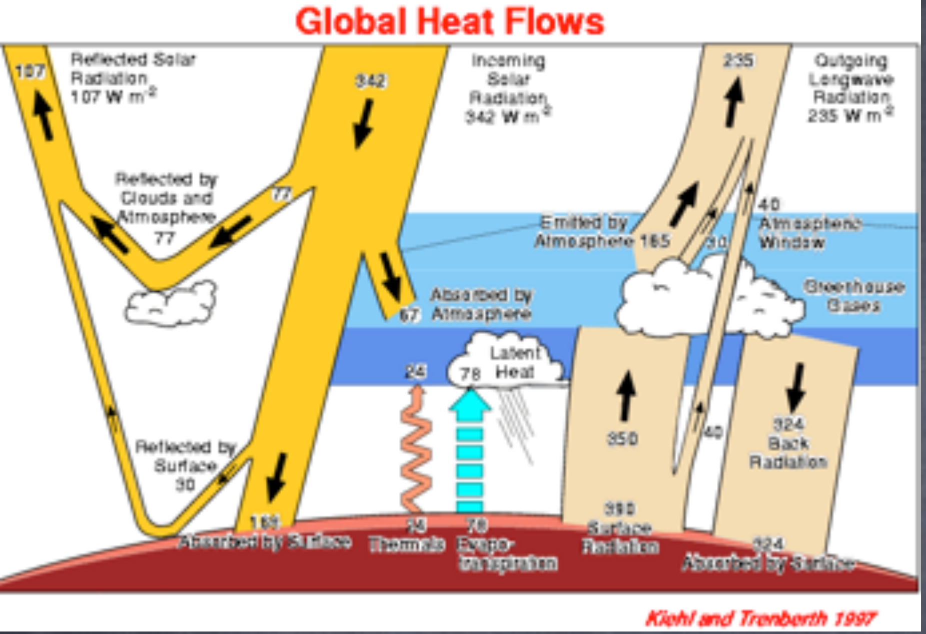
The role of the ocean surface—and its dynamics—in climate

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)

Yale Dept. of Geology & Geophysics Colloquium, 9/24/14

Sponsors: NSF 1258907, 1245944, 0934737, NASA NNX09AF38G

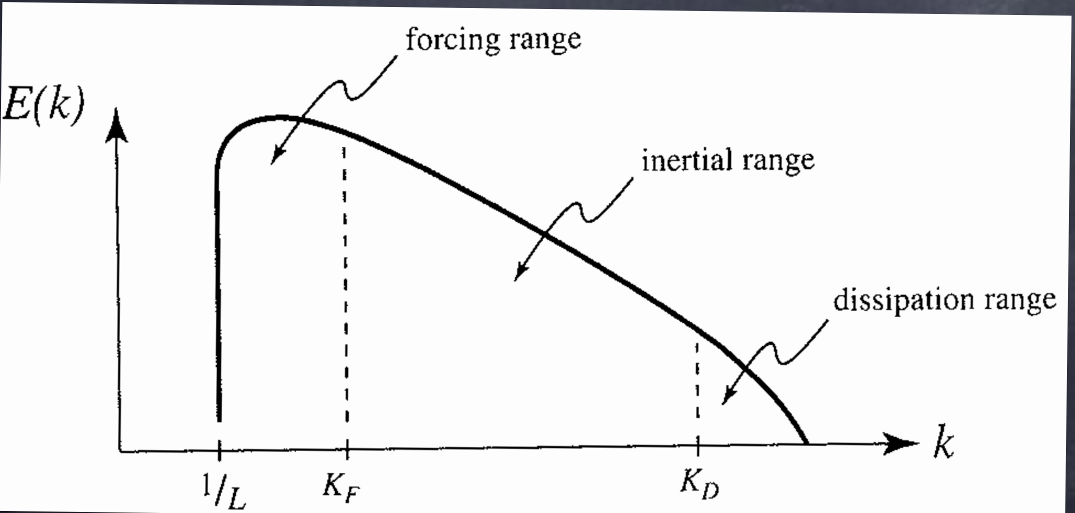


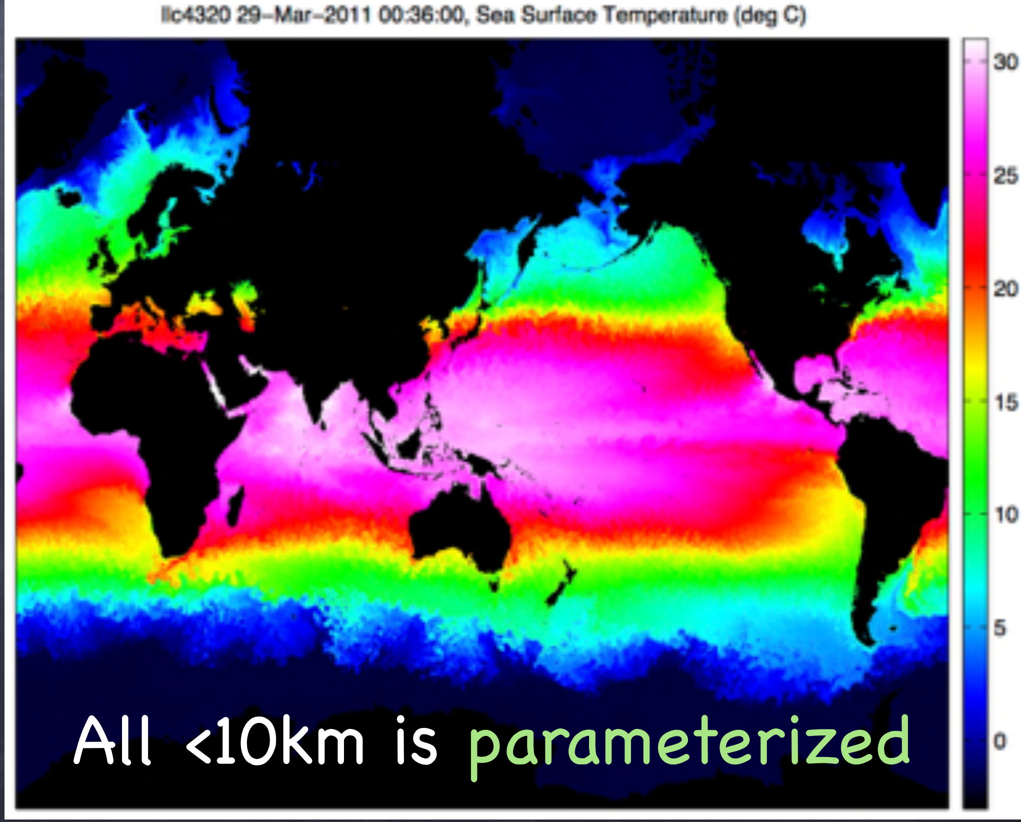
Kiehl and Trenberth 1997

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

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

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





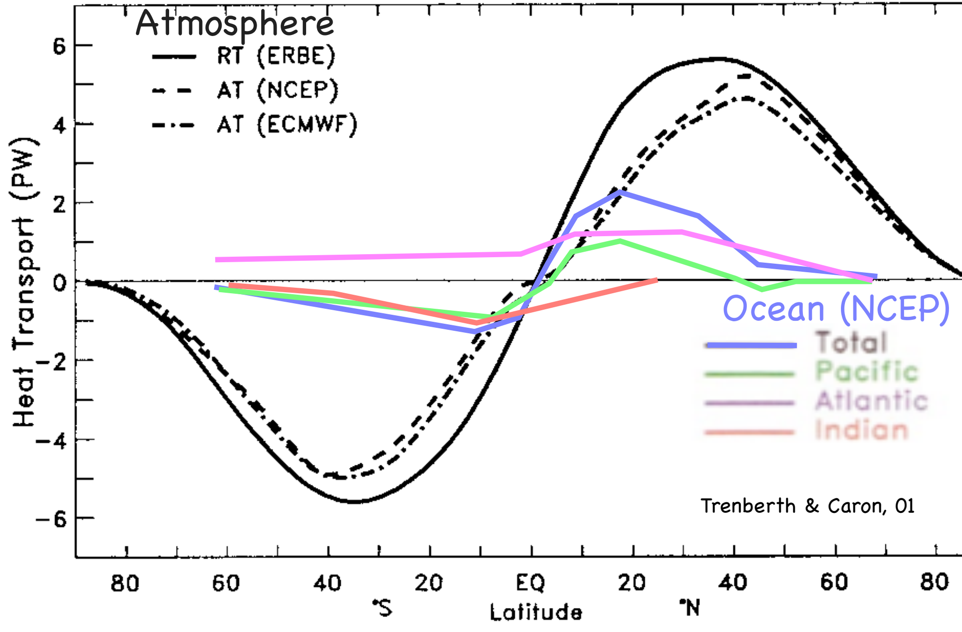
All <10km is parameterized

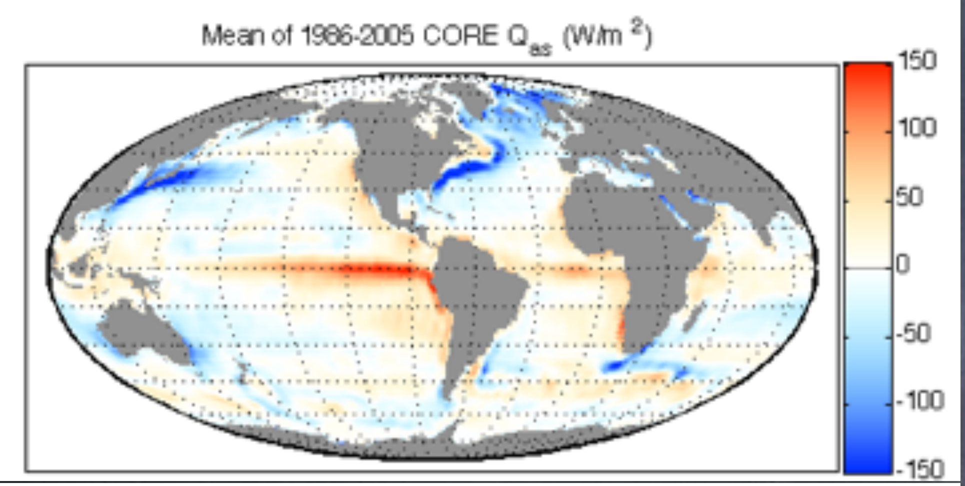
Air-Sea Flux Errors vs. Data

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

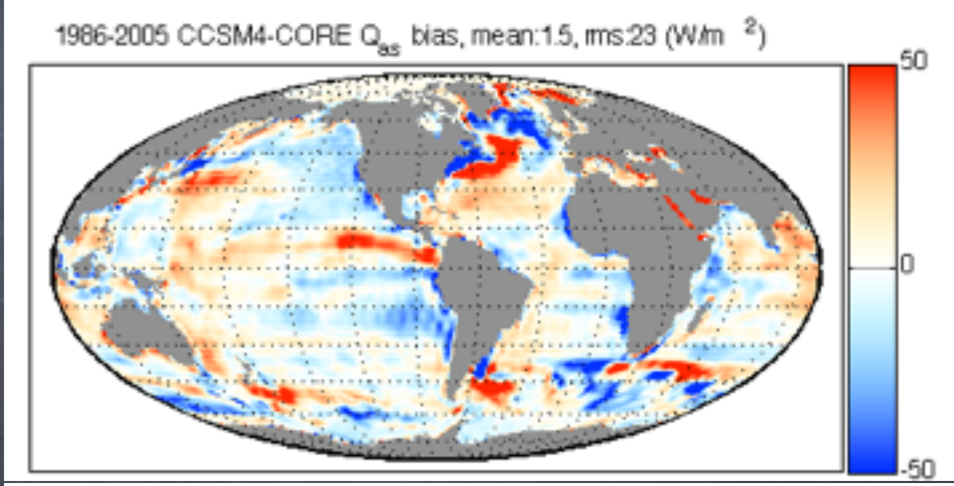
>90% of GW is oceanic, 10m O=whole A

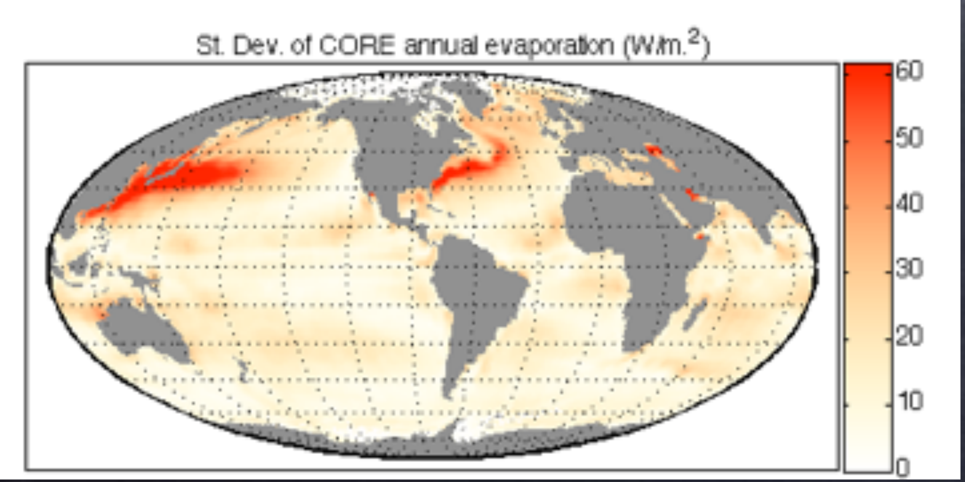
S. C. Bates, BFK, S. R. Jayne, W. G. Large, S. Stevenson, and S. G. Yeager. Mean biases, variability, and trends in air-sea fluxes and SST in the CCSM4.Journal of Climate, 25(22):7781-7801, 2012.



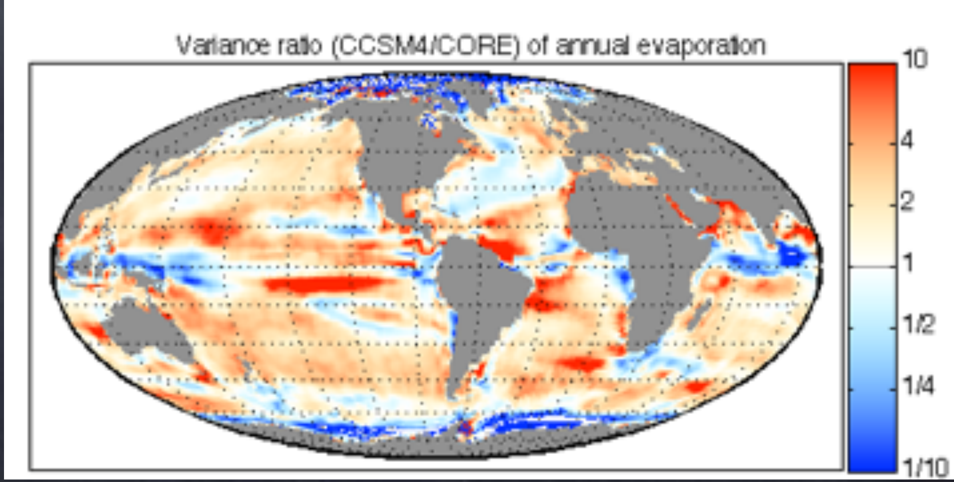

Mean of 1986-2005 CORE Q_{as} (W/m ^{2})

Mean

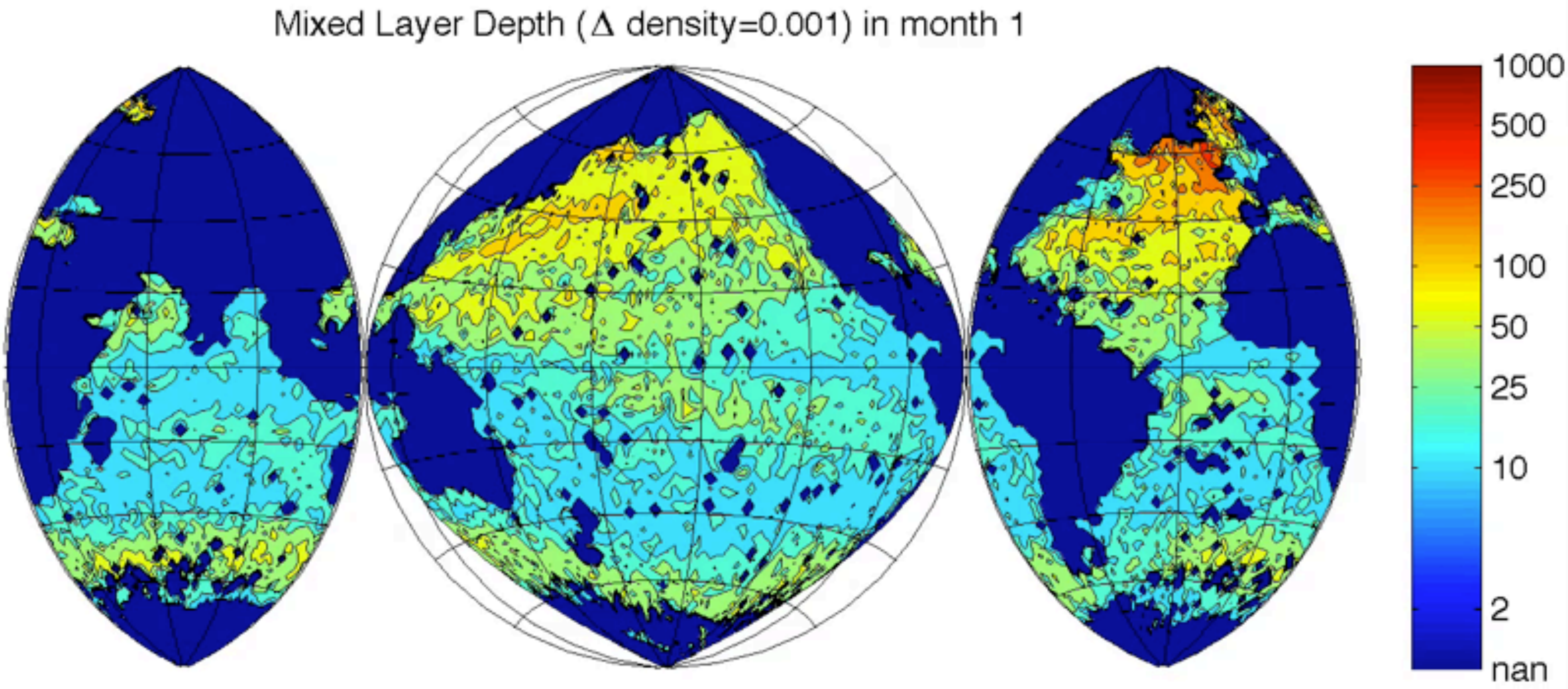

1986-2005 CCSM4-CORE Q_{as} bias, mean:1.5, rms:23 (W/m ^{2})


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

Annual
9-15mo


Variance ratio (CCSM4/CORE) of annual evaporation

The Ocean Mixed Layer



Mixed Layer Depth (Δ density=0.001) in month 1

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)

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

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

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

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

Plus boundary conditions

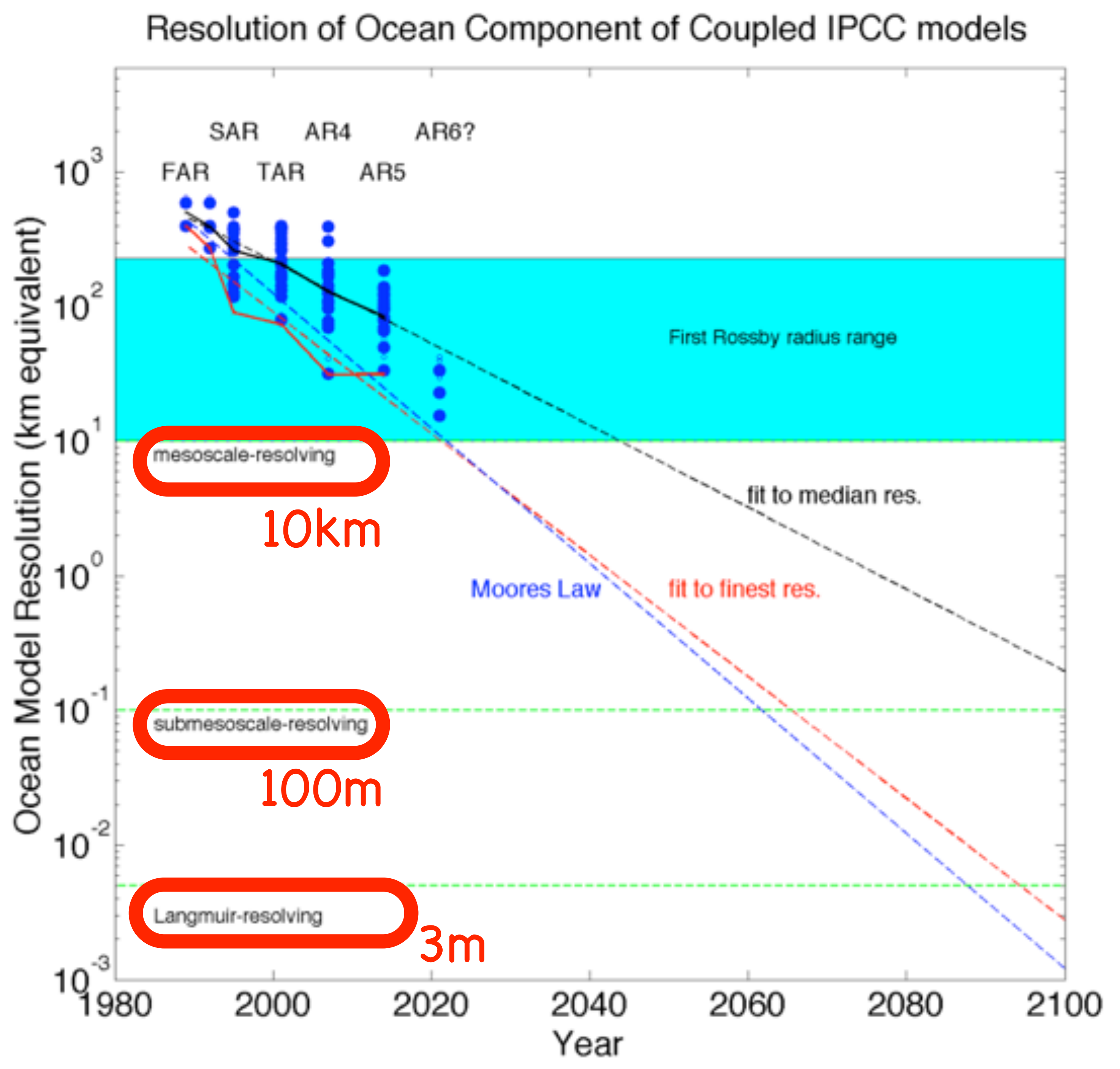
$$Re = \frac{UL}{\nu} \qquad Ro = \frac{U}{fL} \qquad Ri = \frac{N^2}{(U_{,z})^2} \qquad \alpha = H/L$$

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

So, climate models aren't perfect. Now what?

- Resolve more!
- Make existing parameterizations better! (Not today)
- Look for important neglected physics!
  - Submesoscale Eddies
  - Langmuir (Wave-Driven) Mixing
  - Combinations?

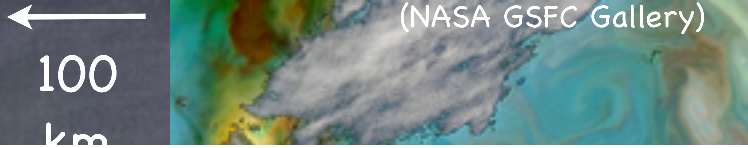
Resolution will be an issue for centuries to come!



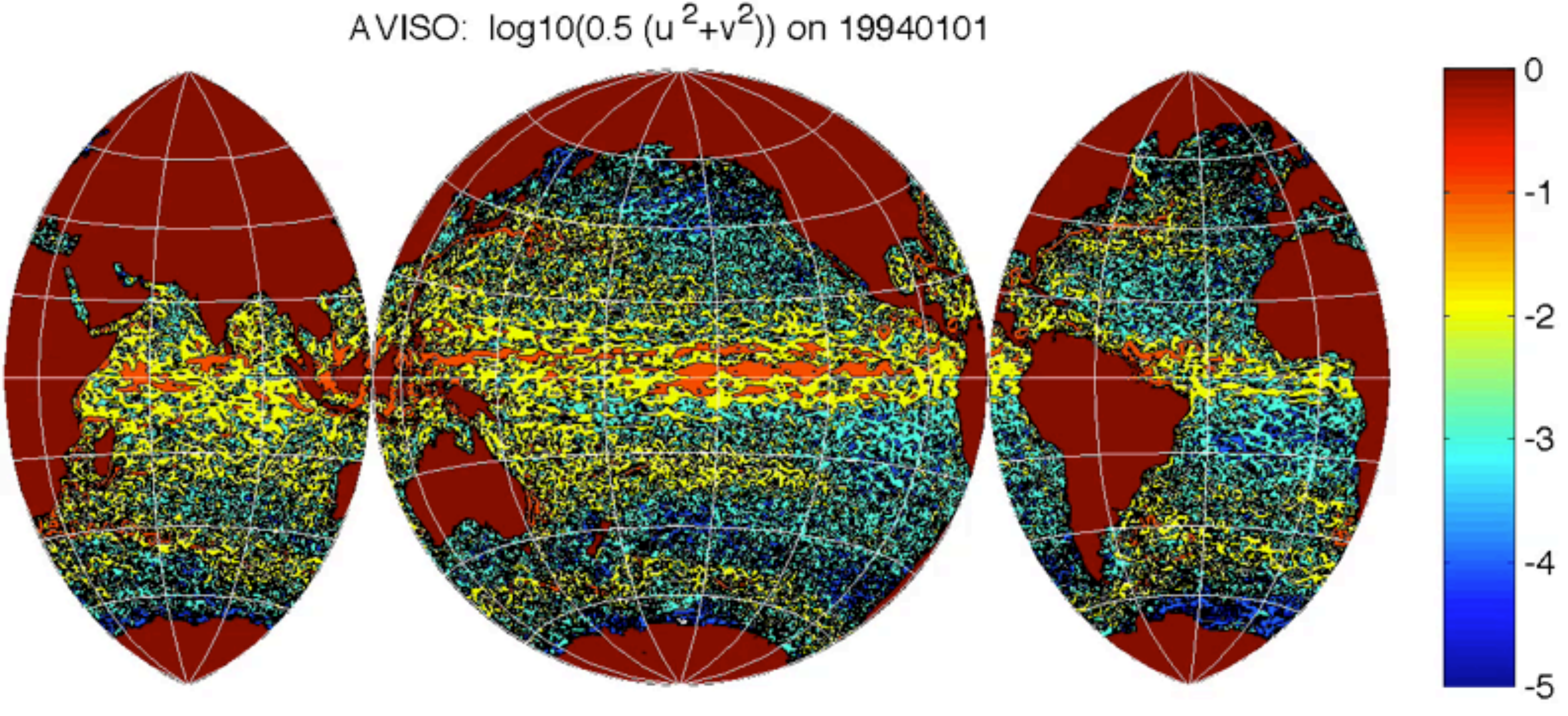
Here are the collection of IPCC models...

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

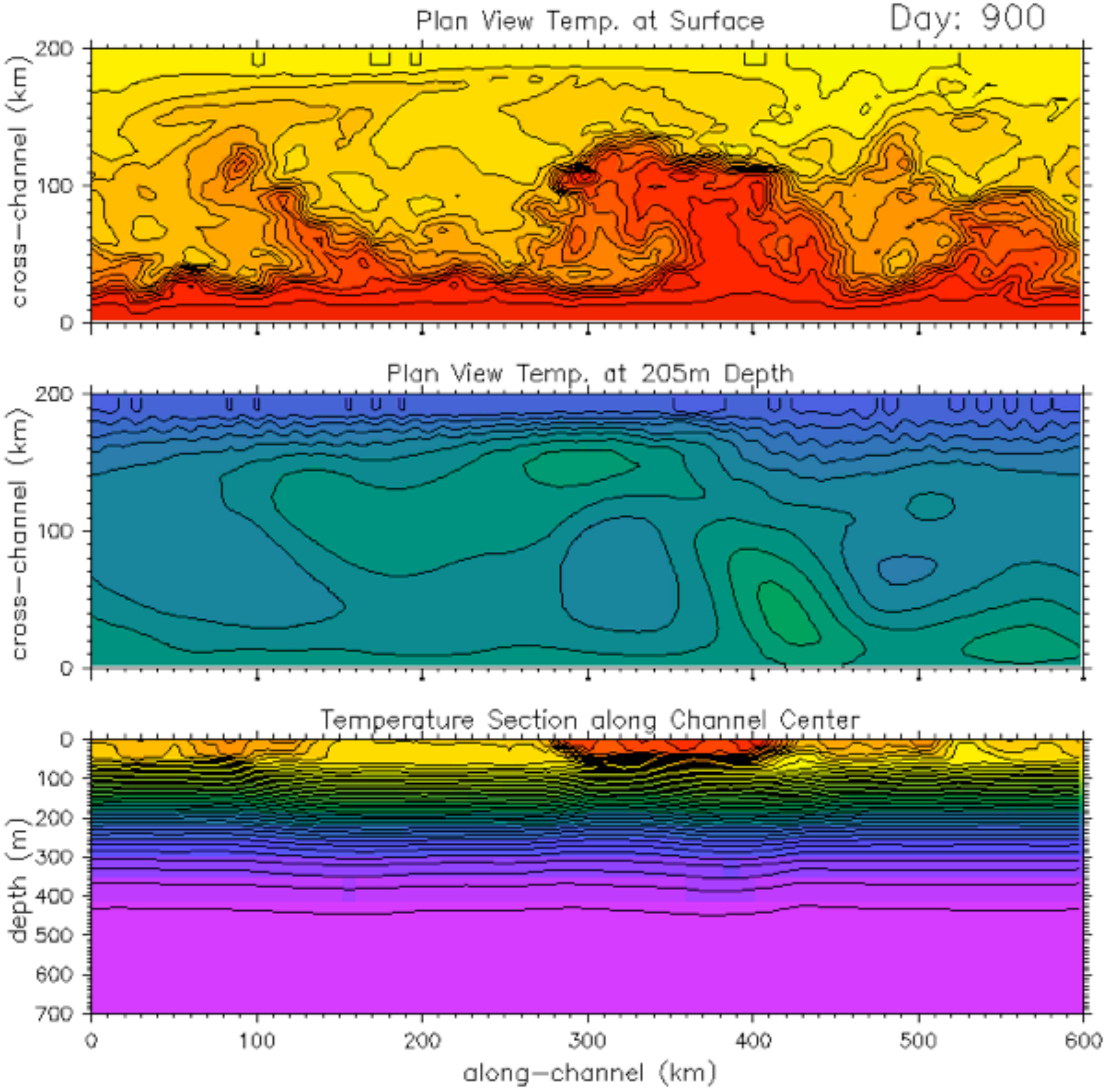
The Character of the



(NASA GSFC Gallery)


AVISO: $\log10(0.5\,(u^2+v^2))$ on 19940101

Eddy processes mainly baroclinic & barotropic instability. Parameterized (e.g., Gent-McWilliams), will be routinely resolved in climate models in 2040 —not today's talk!



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.

The Character of the Submesoscale

← 10 km

(Capet et al., 2008)

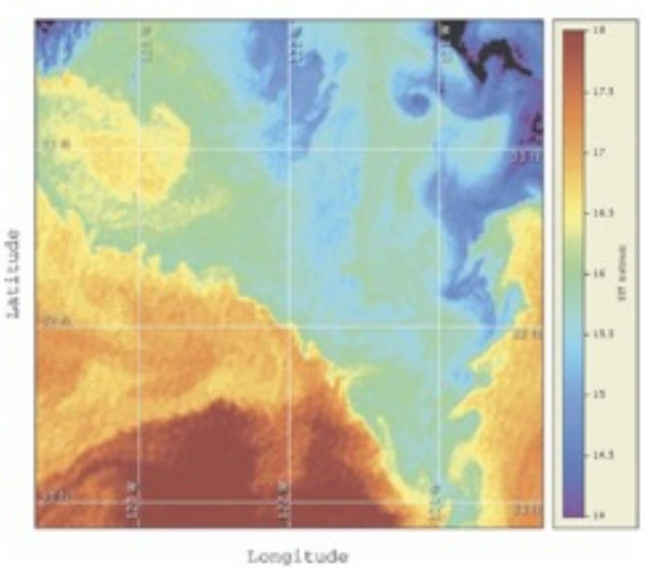
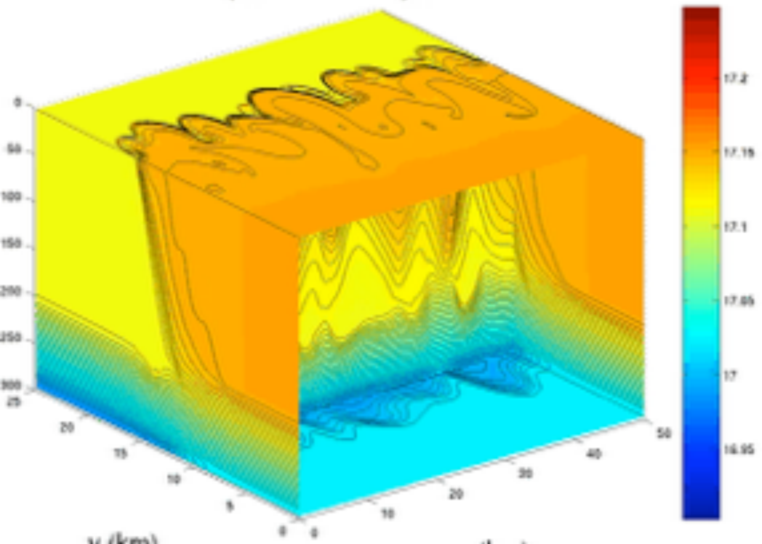


Fig. 16. Sea surface temperature measured at 1832 UTC 3 Jan 2006 off Point Conception in the California Current from CoastWatch (http://coastwatch.pfeg.noaa.gov). The fronts between recently

Temperature on day:17.375



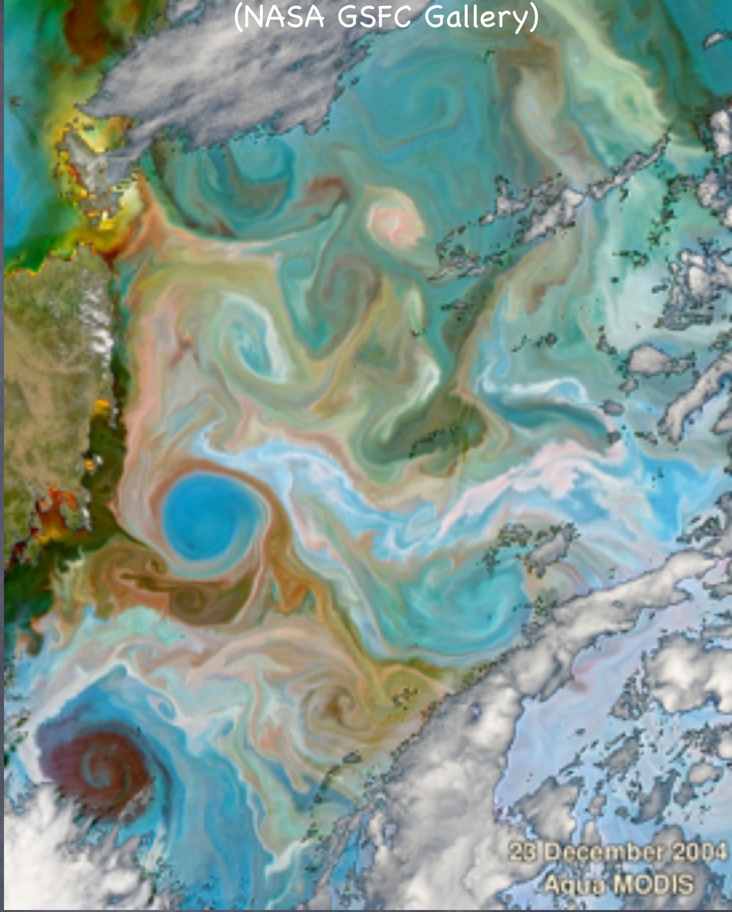
- Fronts
- Eddies
- $Ro=O(1)$
- $Ri=O(1)$
- near-surface ($H=100m$)
- 1-10km, days

Eddy processes often baroclinic instability

Parameterizations = F-K 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

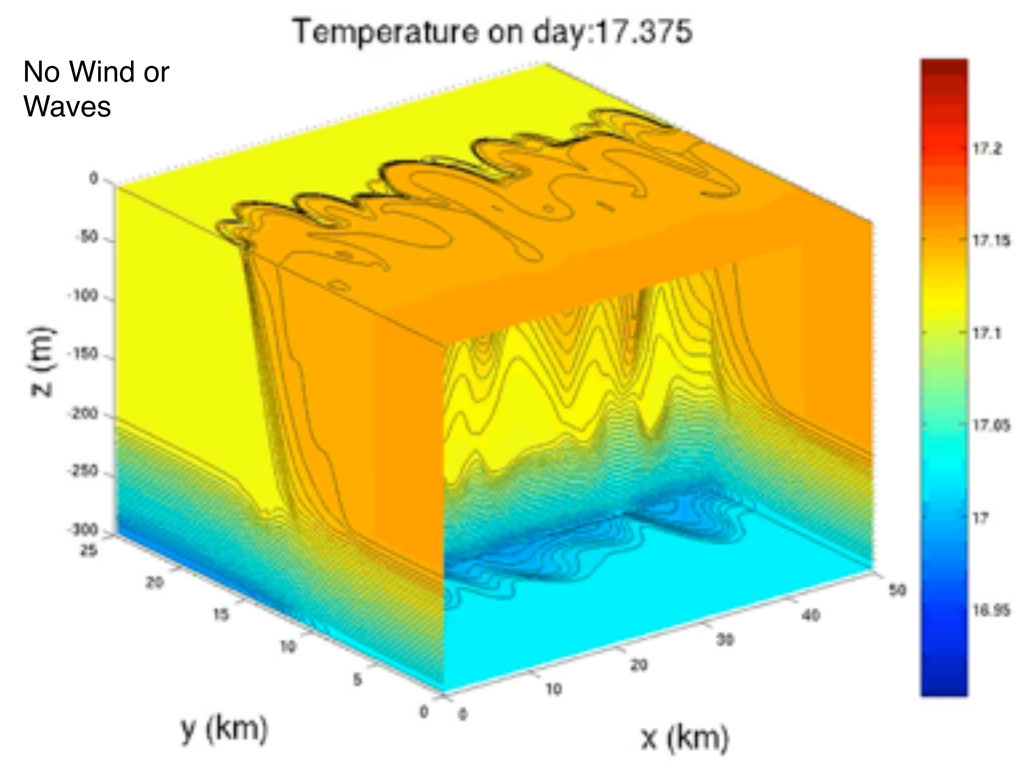
BFK, G. Danabasoglu, R. Ferrari, S. M. Griffies, R. W. Hallberg, M. M. Holland, M. E. Maltrud, S. Peacock, and B. L. Samuels. Parameterization of mixed layer eddies. III: Implementation and impact in global ocean climate simulations. Ocean Modelling, 39:61-78, 2011.

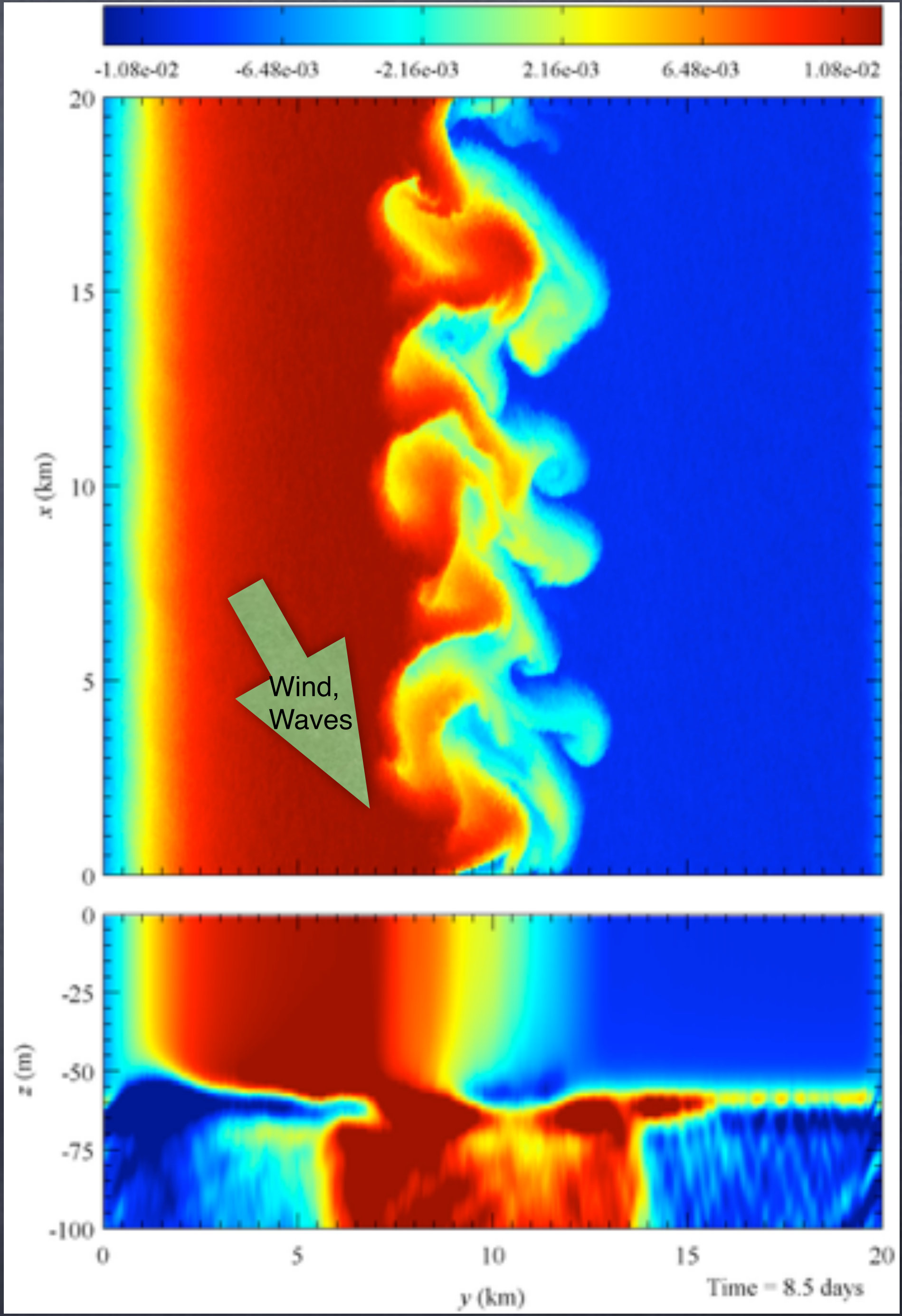
S. Bachman and BFK. Eddy parameterization challenge suite. I: Eady spindown. Ocean Modelling, 64:12-28, 2013

Submesoscale?

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

Mixing balances restratification



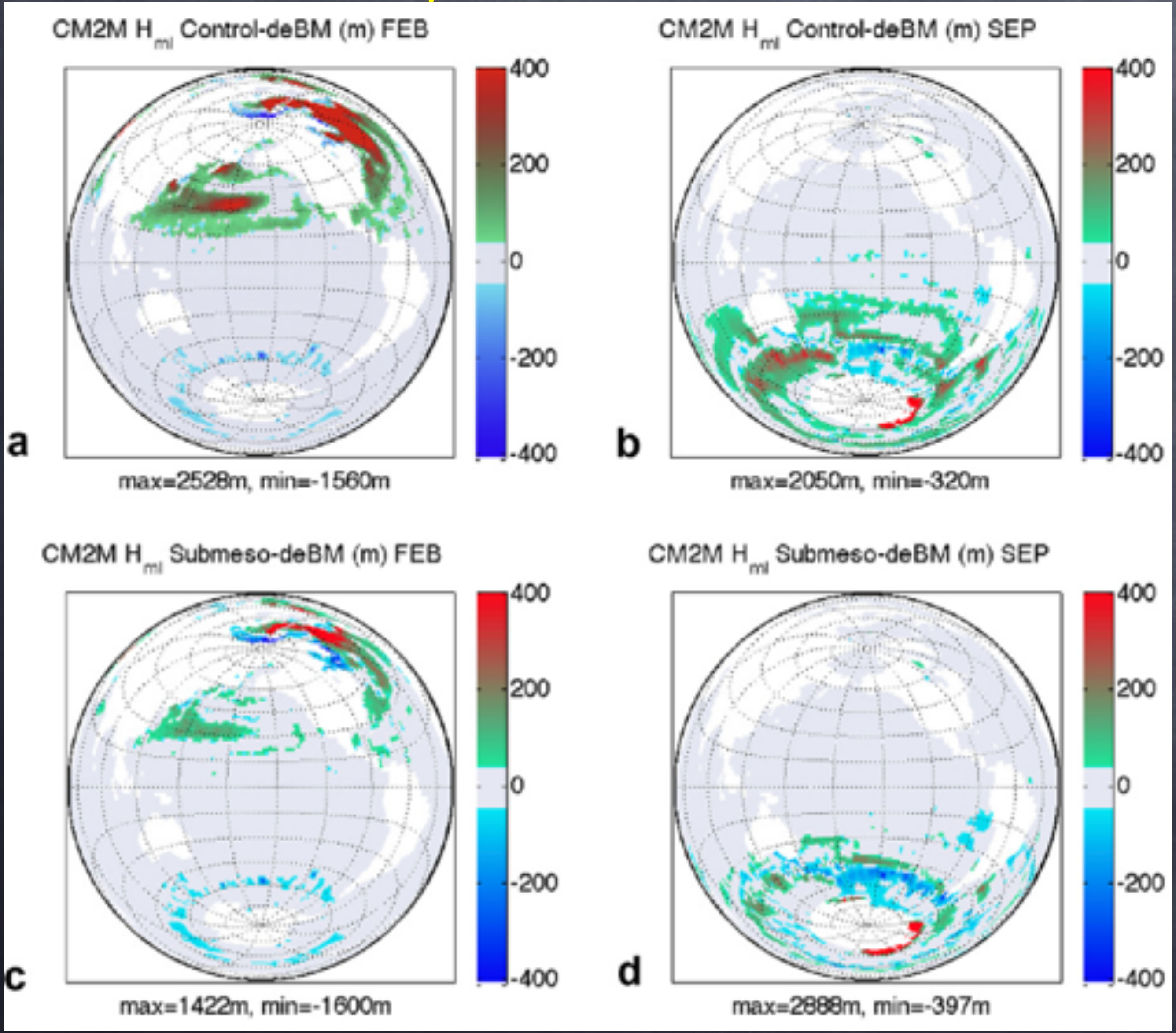


Movie: P. Hamlington

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

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.

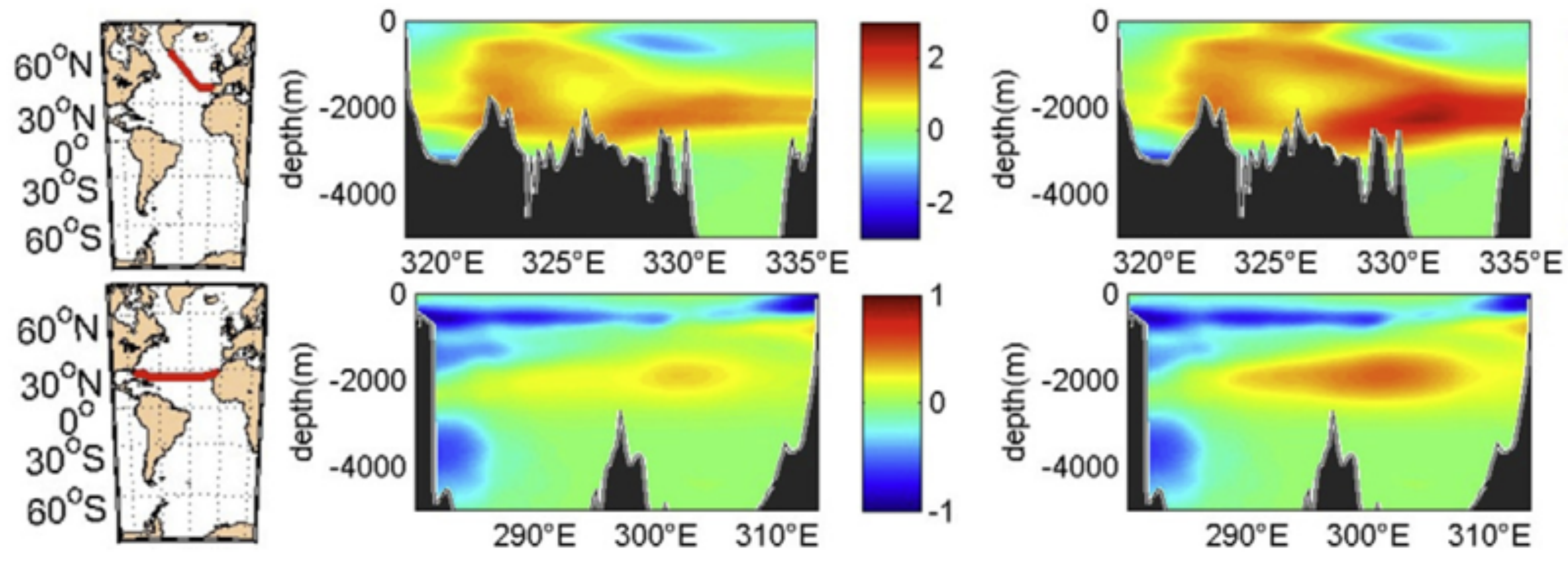
Physical Sensitivity of Ocean Climate to Submesoscale Mixed Layer Eddy Restratification:

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

Improves CFC uptake (water masses)

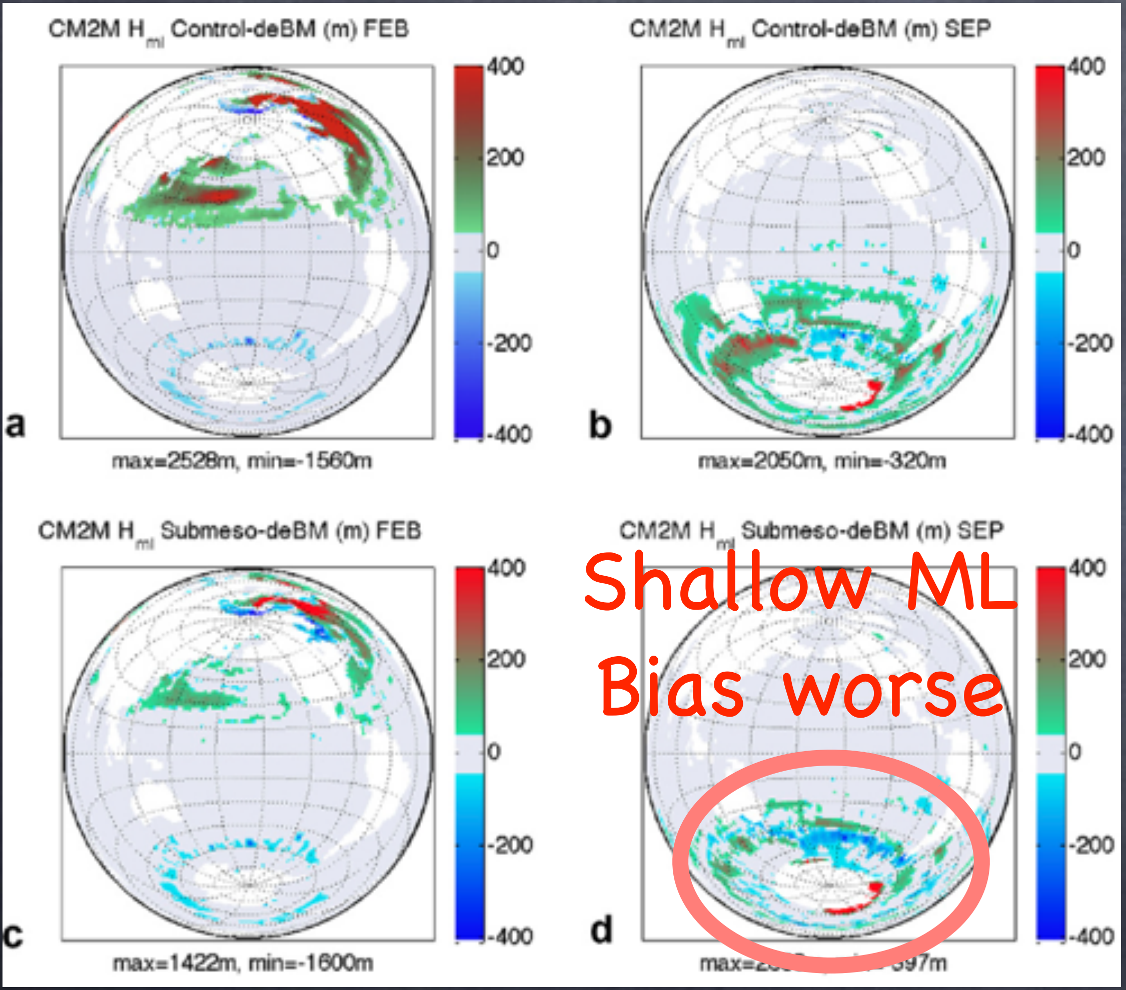
With MLE Parameterization

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.

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



Shallow ML Bias worse

Bias w/o MLE

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

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.

Are the MLE to blame?

Or is something else missing?

A hint:

The Character of the Langmuir Scale

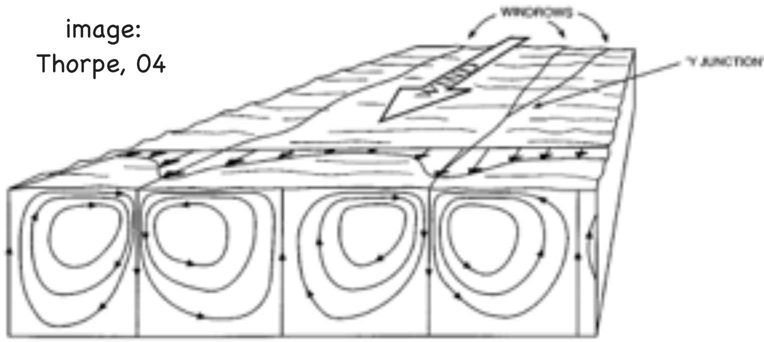


image:
Thorpe, 04

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).

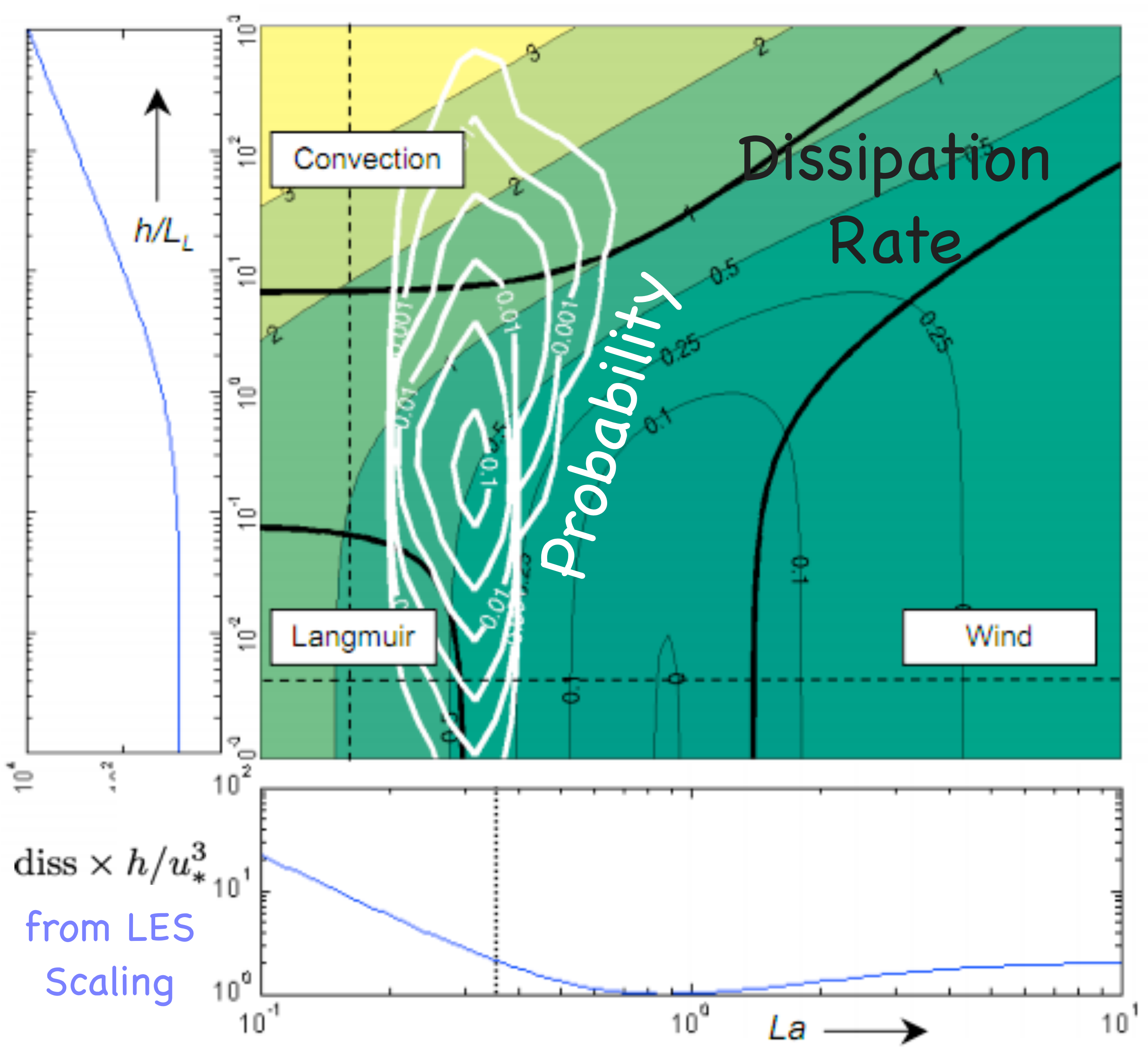
- Near-surface
- Langmuir Cells & Langmuir Turb.
- Ro>>1
- Ri<1: Nonhydro
- 1-100m (H=L)
- 10s to 1hr
- w, u=O(10cm/s)
- Stokes drift
- Eqtns:Craik-Leibovich
- Params: McWilliams & Sullivan, 2000, Van Roekel et al. 2011
- Resolved routinely in 2170

Image: NPR.org, Deep Water Horizon Spill

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

One way to estimate

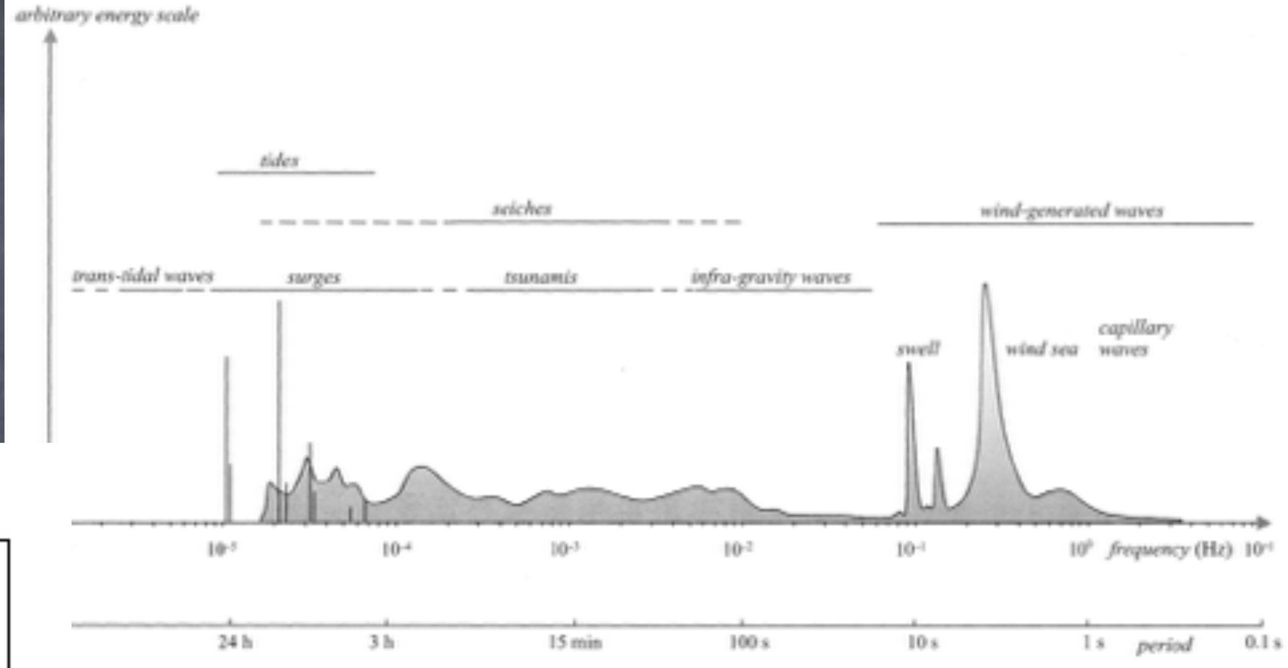
So, waves can drive mixing via Stokes drift (combines with cooling & winds)



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.

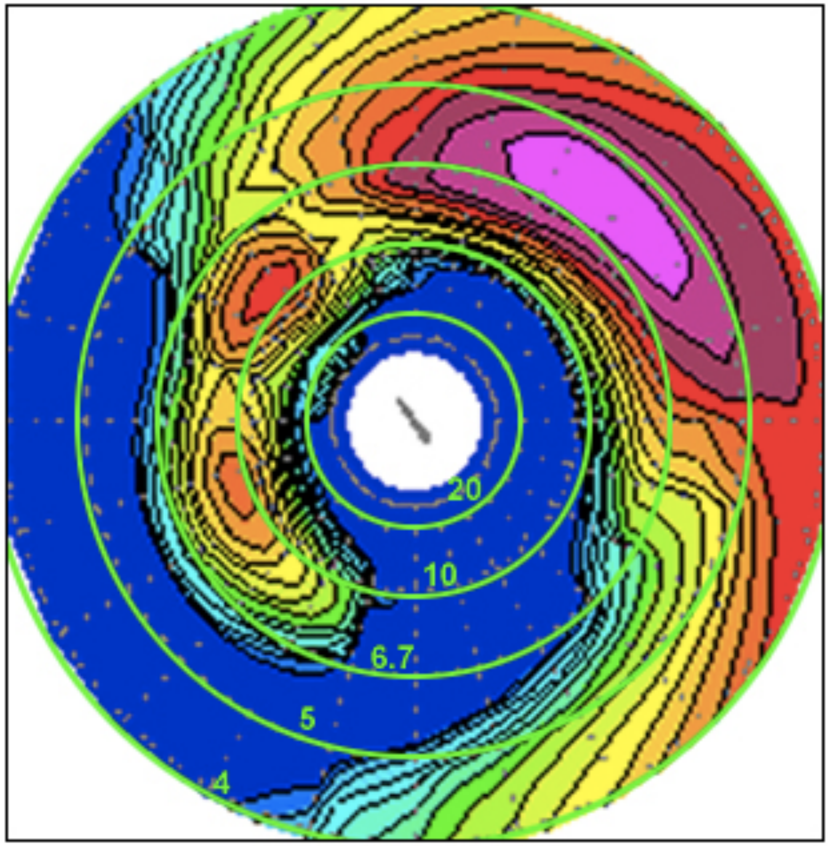
Surface Waves are...

fast, small, irrotational solutions of the Boussinesq Equations



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

NWW3 Polar Plot of Wave Energy Spectrum at ILM01

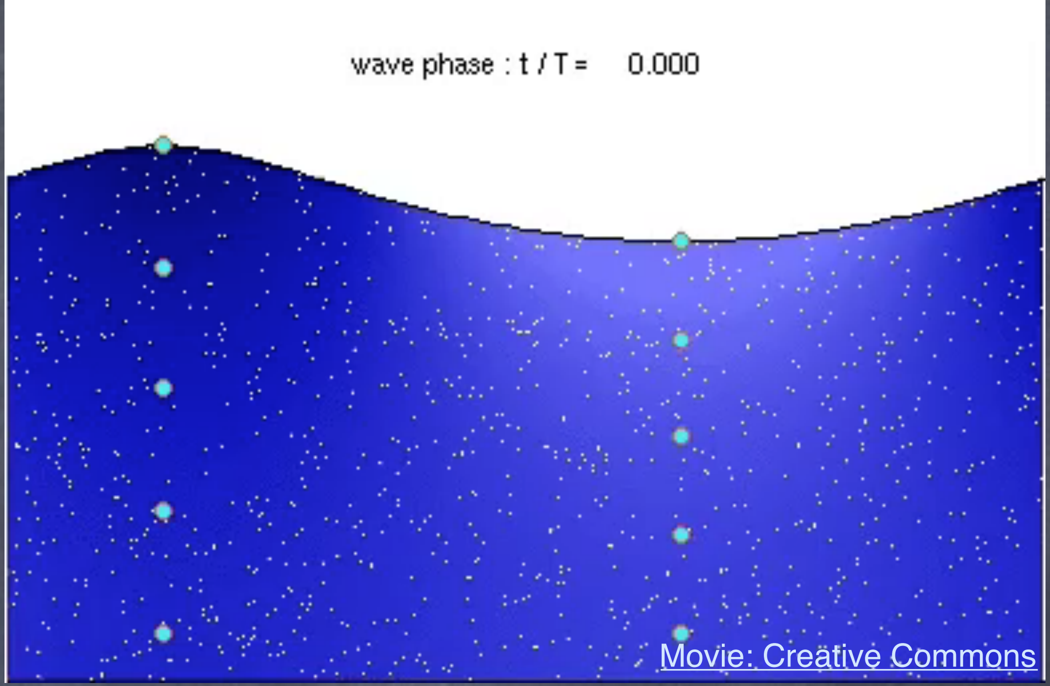


24 hr fcst Valid 0000 UTC 26 Apr 2002

NOAA / NWS / NCEP / MMAB

Waves Provide Stokes Drift

Take wave solns, compare the velocity of trajectories vs. Eulerian velocity, leading difference=Stokes:



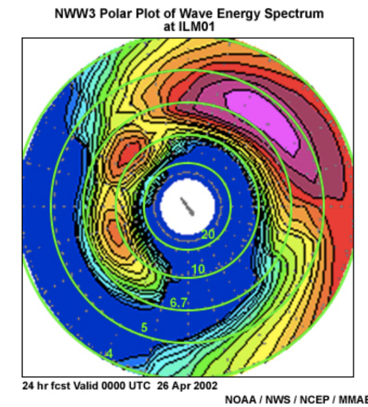
Movie: Creative Commons

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 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 (14)

(for horizontally uniform Stokes drift)

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

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

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

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

Plus boundary conditions

LAGRANGIAN (Eulerian+Stokes) advection & Coriolis

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

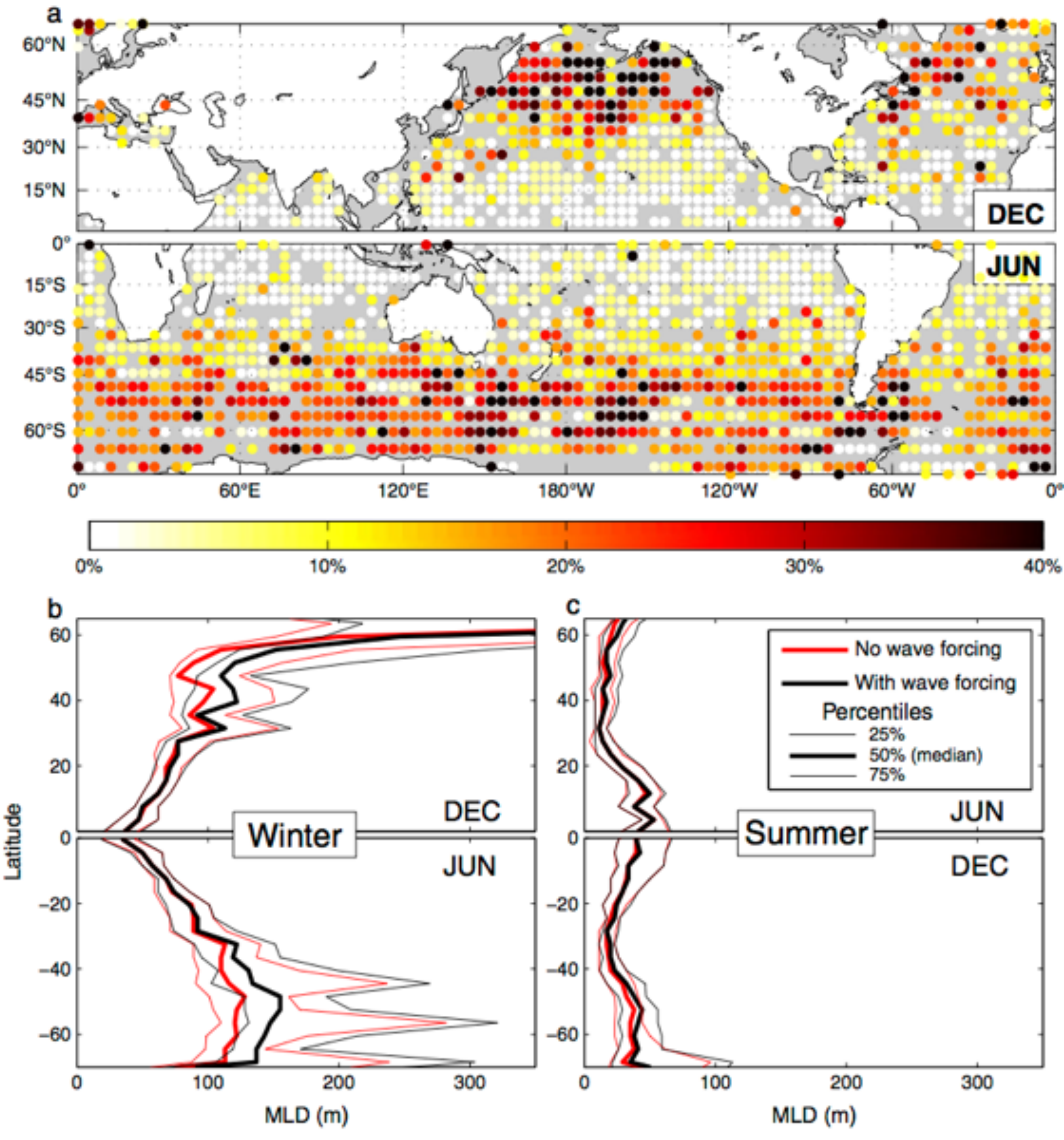
J. C. McWilliams and BFK. Oceanic wave-balanced surface fronts and filaments. Journal of Fluid Mechanics, 730:464-490, 2013.

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

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.



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

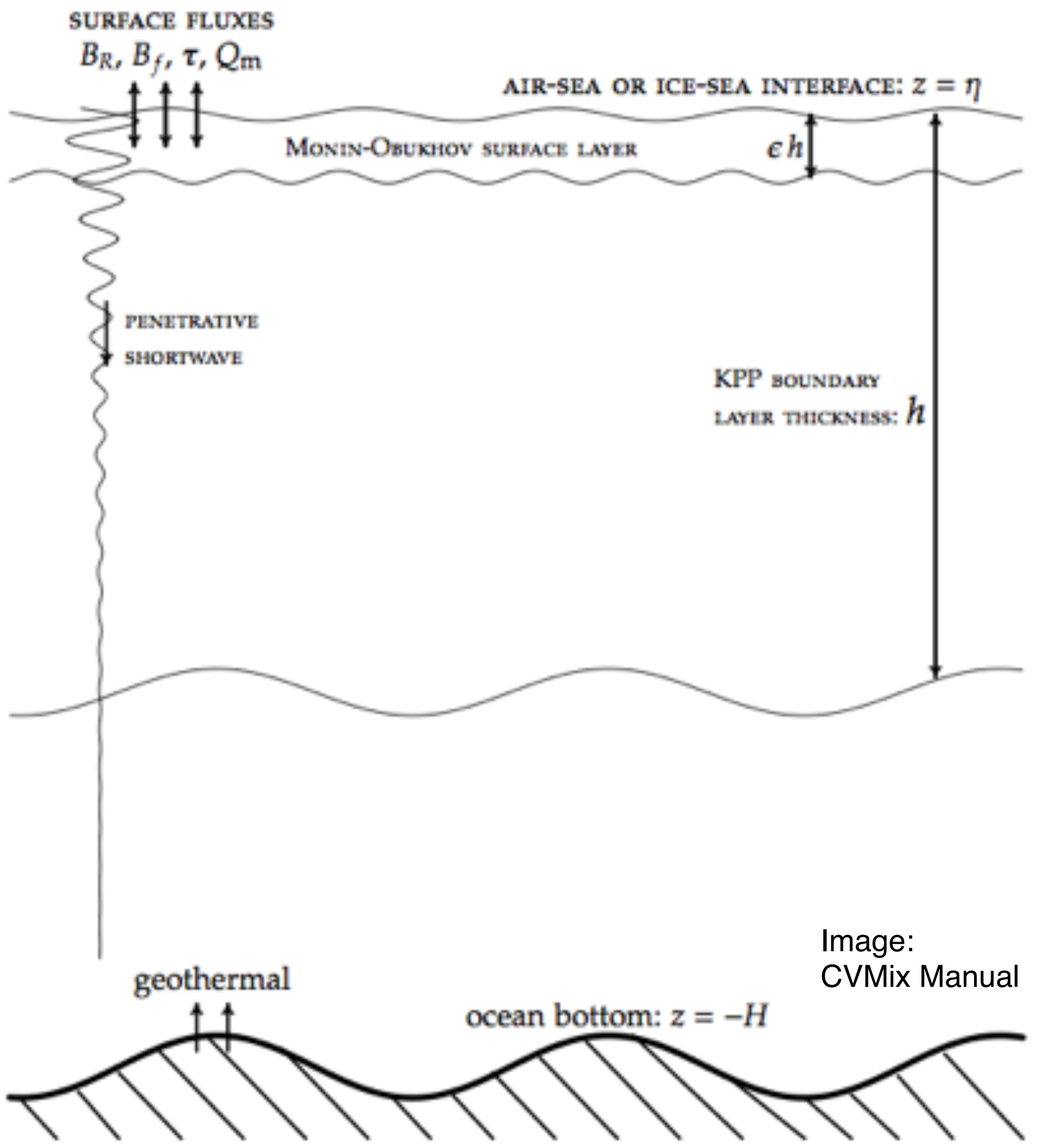
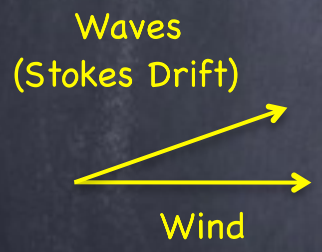
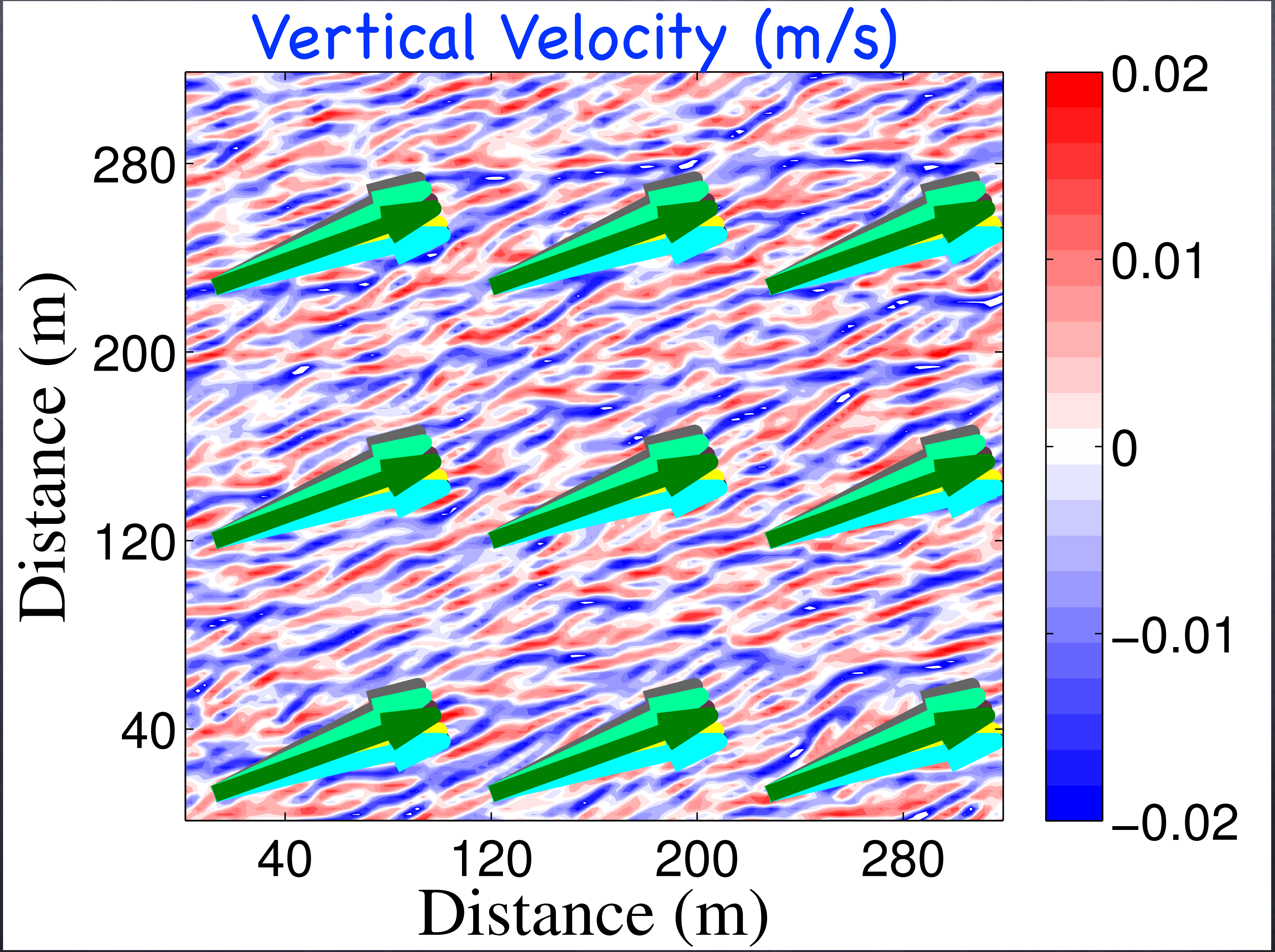


Image: CVMix Manual

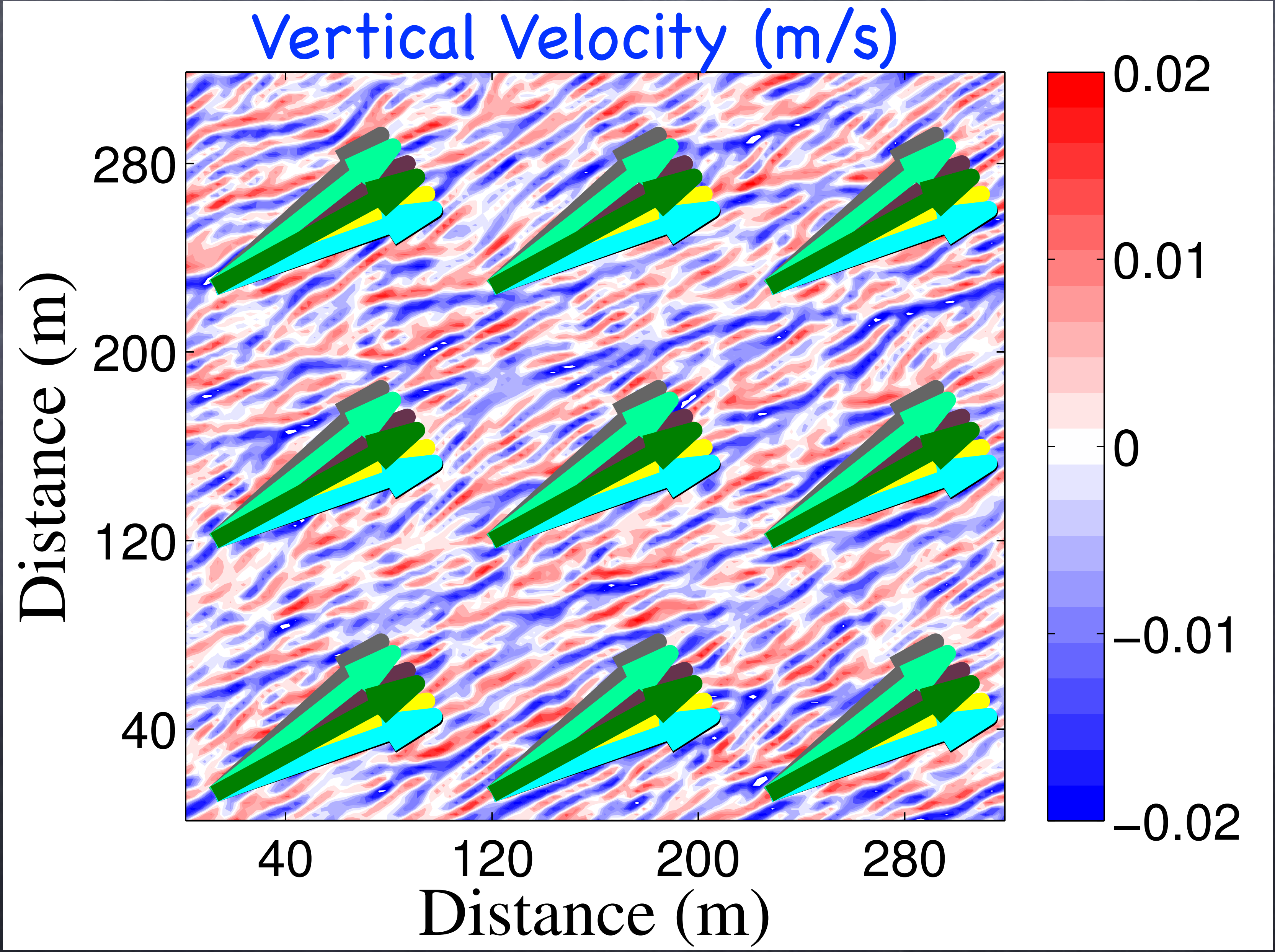
CLB as equations for Large Eddy Simulations: Tricky: Misaligned Wind & Waves



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



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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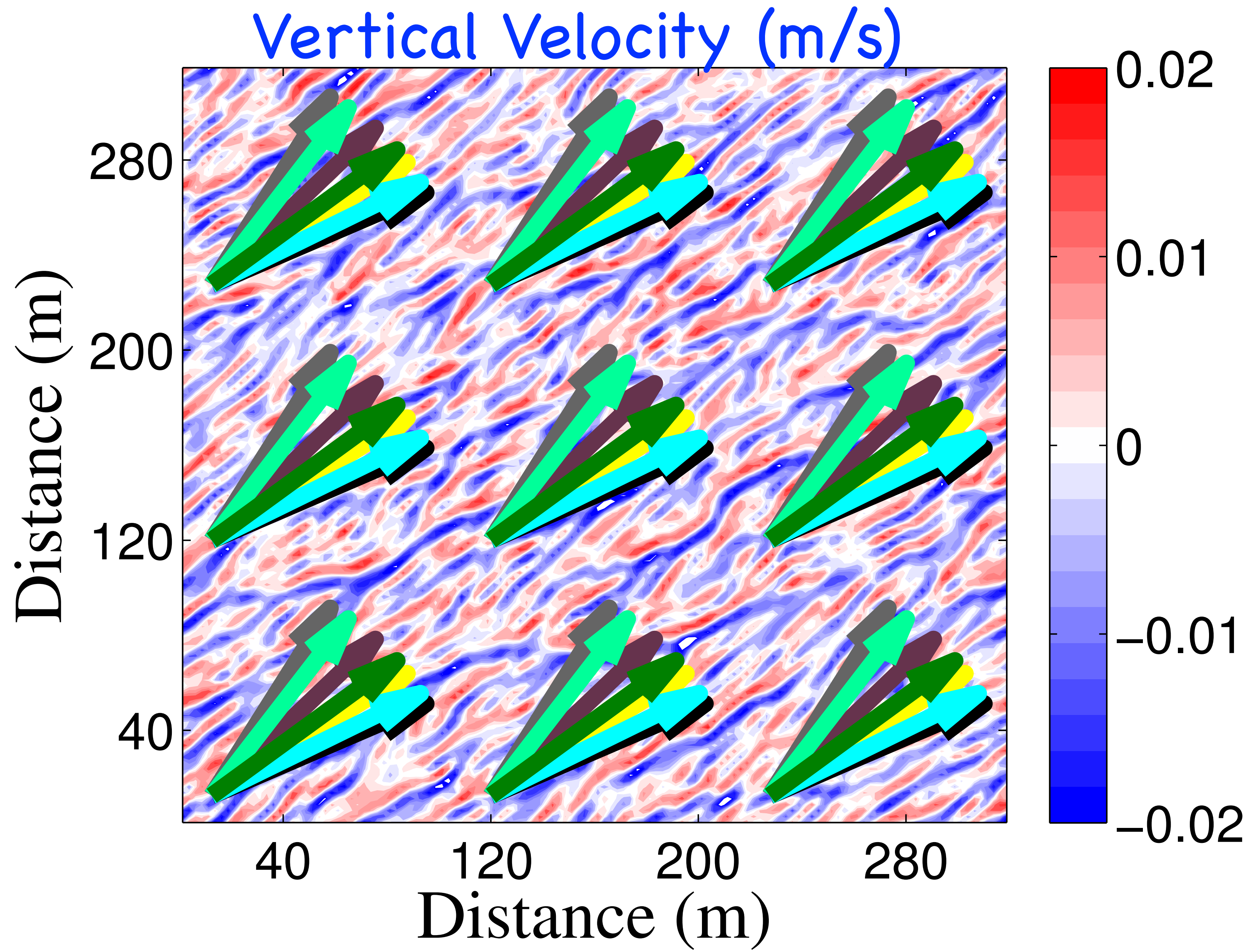
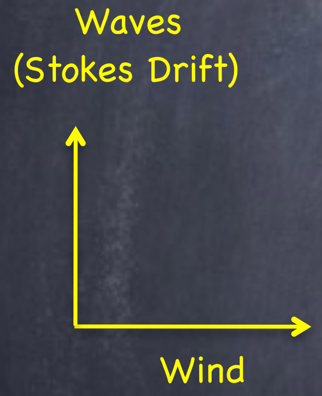
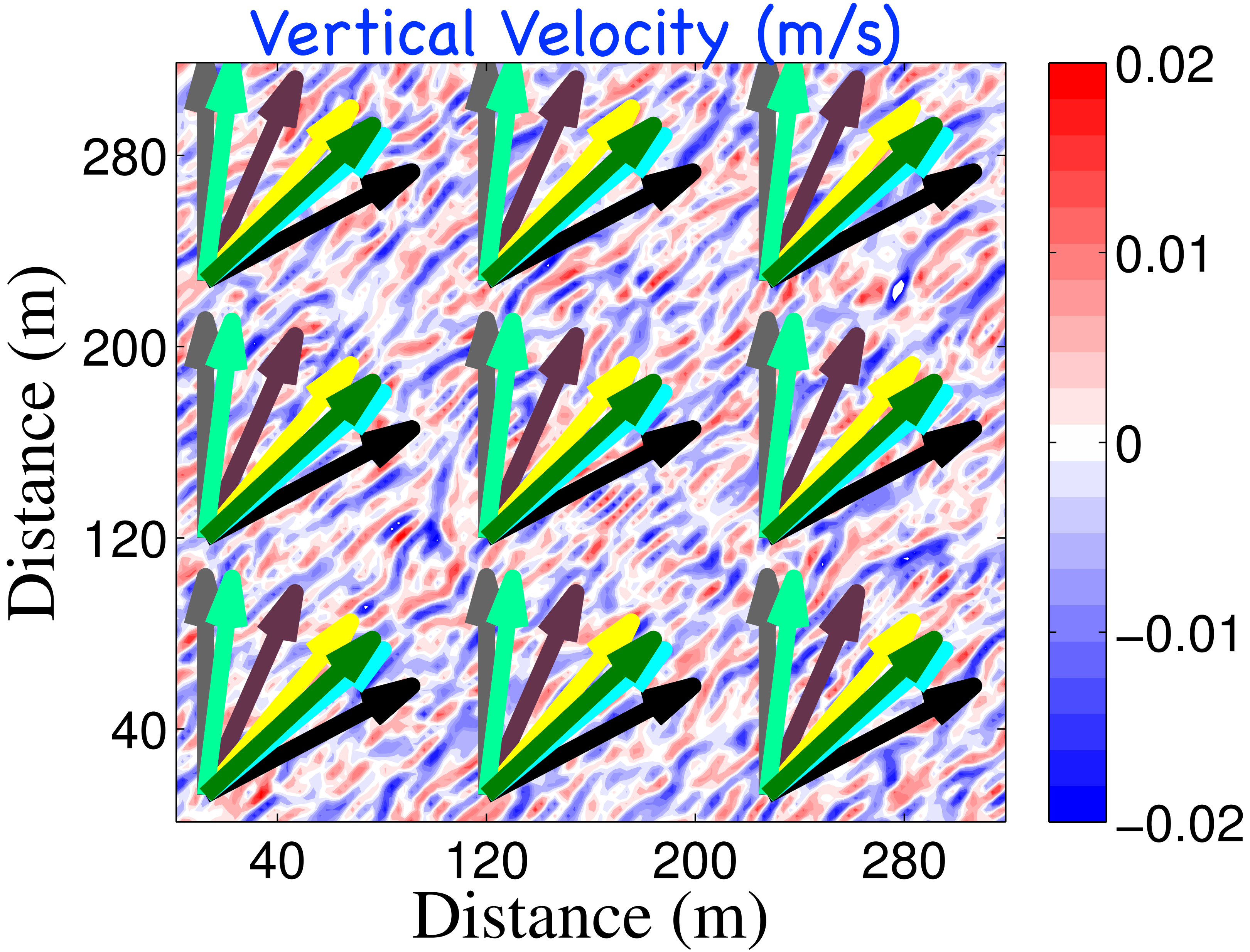


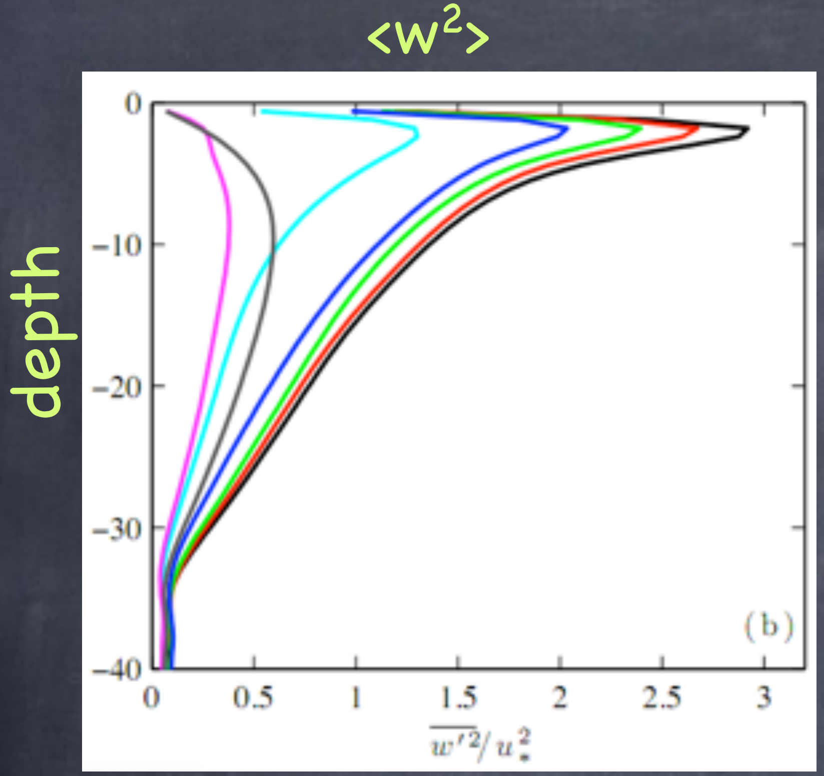
Tricky: Misaligned Wind & Waves





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.

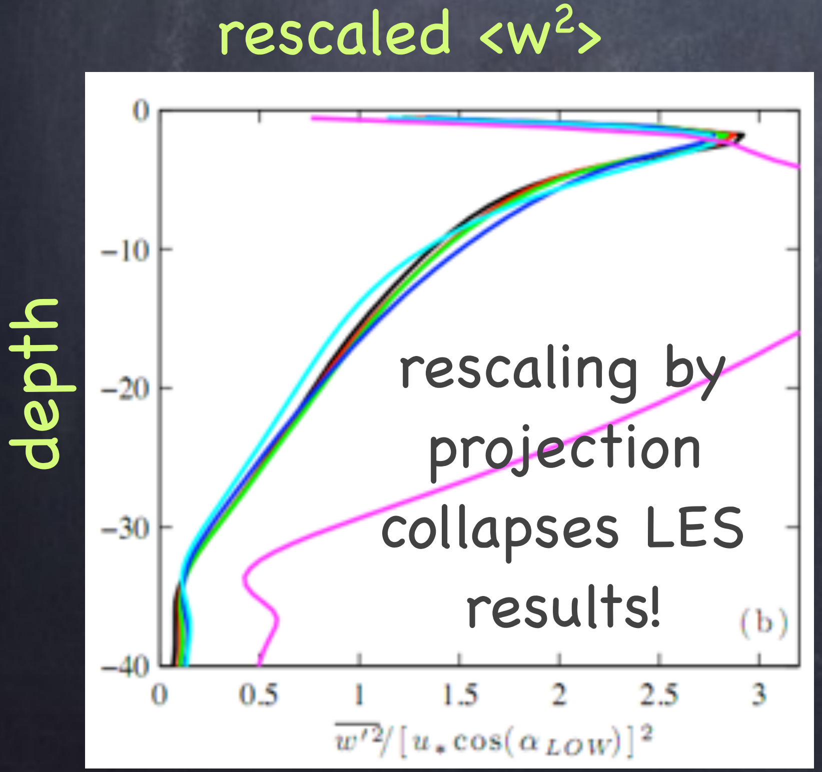
Generalized Turbulent Langmuir No., Projection of u^*, u_s into Langmuir Direction



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

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

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



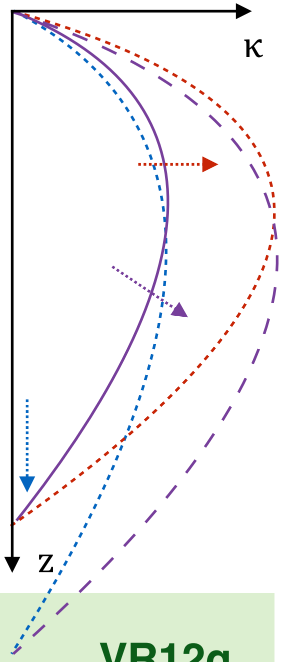
rescaling by projection collapses LES results!

A scaling for LC strength & direction!

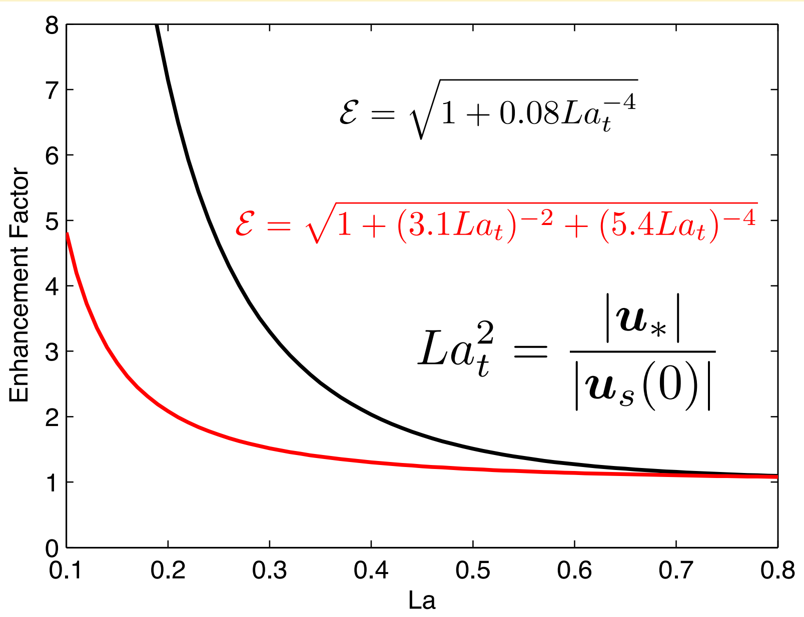
L. P. Van Roekel, BFK, P. P. Sullivan, P. E. Hamlington, and S. R. Haney. The form and orientation of Langmuir cells for misaligned winds and waves. Journal of Geophysical Research-Oceans, 117:C05001, 22pp, 2012.

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



$$\mathcal{E} = \sqrt{1 + 0.08 La_t^{-4}}$$

$$\mathcal{E} = \sqrt{1 + (3.1 La_t)^{-2} + (5.4 La_t)^{-4}}$$

$$La_t^2 = \frac{|\boldsymbol{u}_*|}{|\boldsymbol{u}_s(0)|}$$

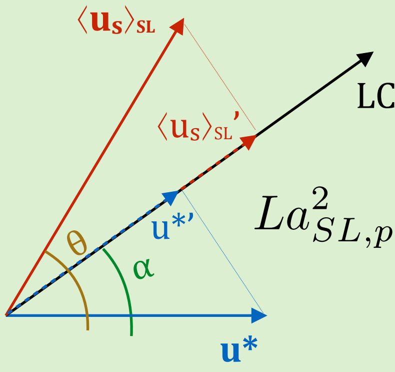
MS2K

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

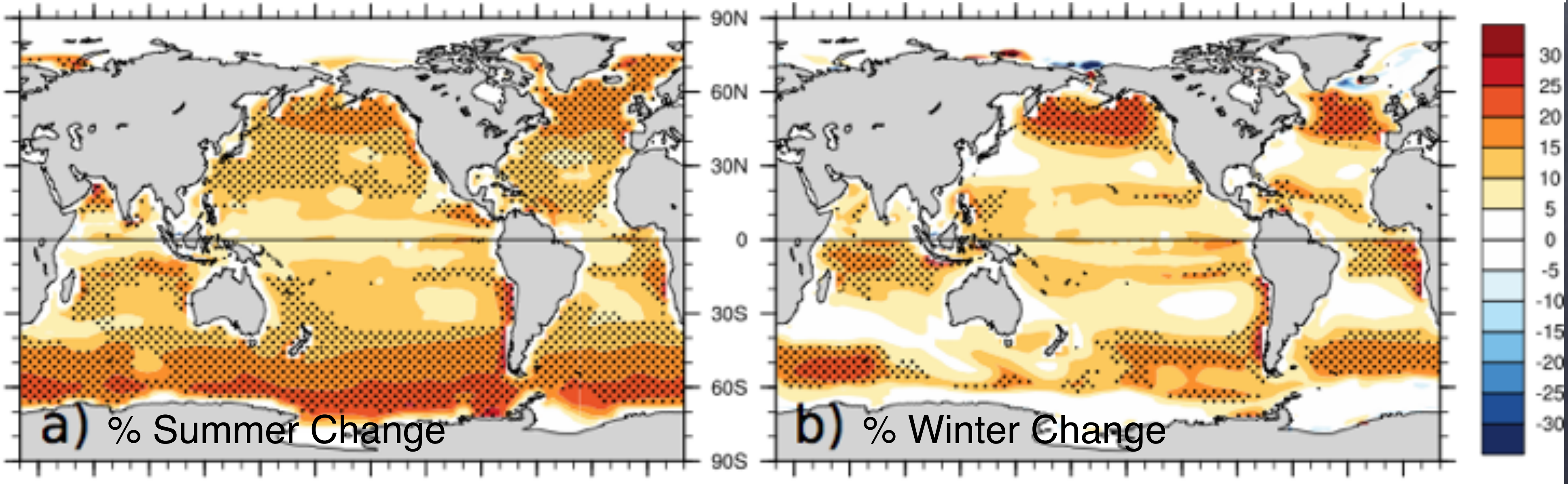
McWilliams and Sullivan, 2000; Van Roekel et al., 2012

Wave Mixing in CESM: Reduces Errors

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



a) % Summer Change

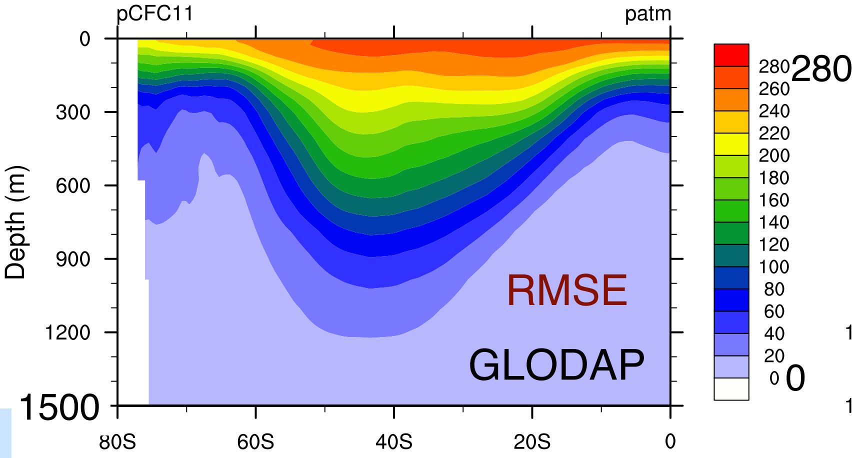
b) % Winter Change

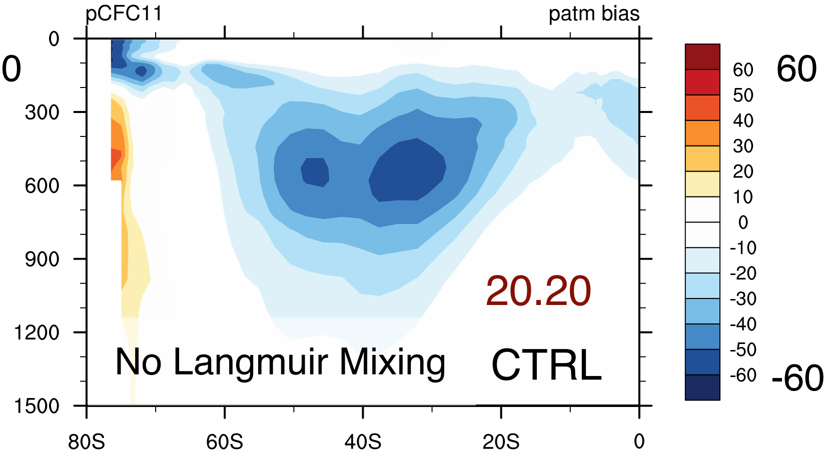
L. P. Van Roekel, BFK, P. P. Sullivan, P. E. Hamlington, and S. R. Haney. The form and orientation of Langmuir cells for misaligned winds and waves. Journal of Geophysical Research-Oceans, 117:C05001, 22pp, May 2012.

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.

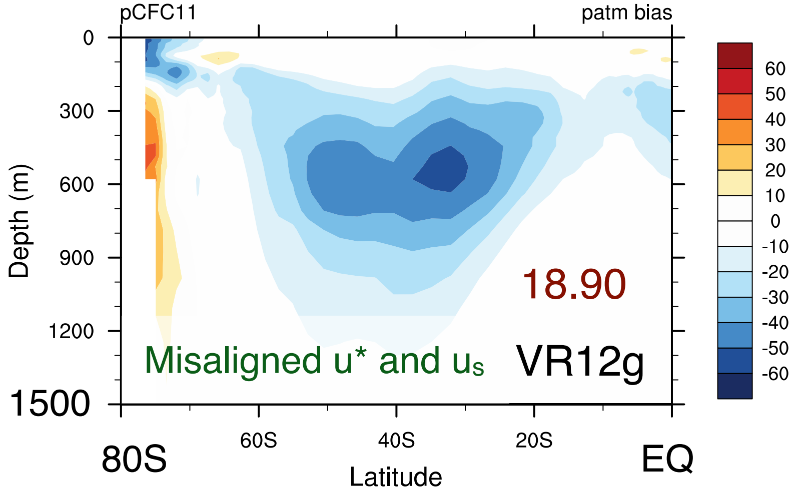
pCFC11 Bias

Southern Hemisphere





RMSEs are reduced by **6%**

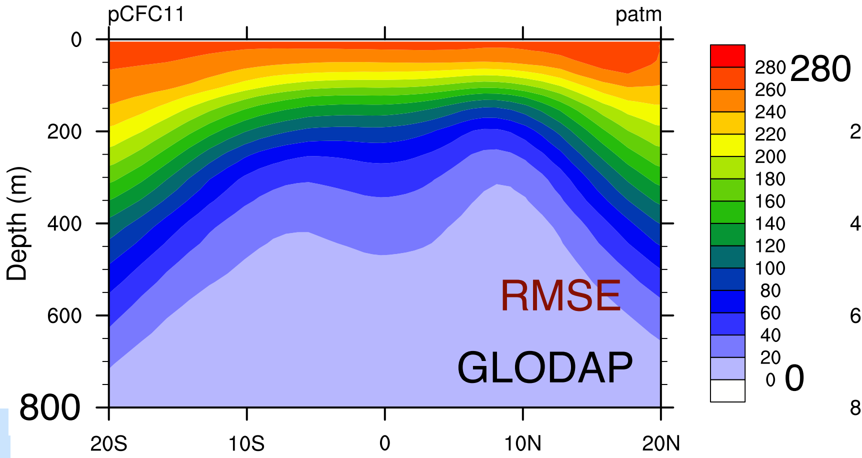


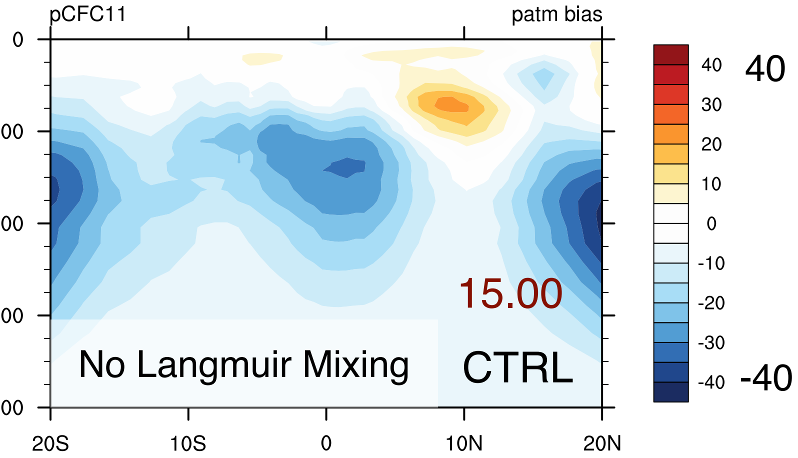
Versus observations from GLODAP: Key et al. 2004

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.

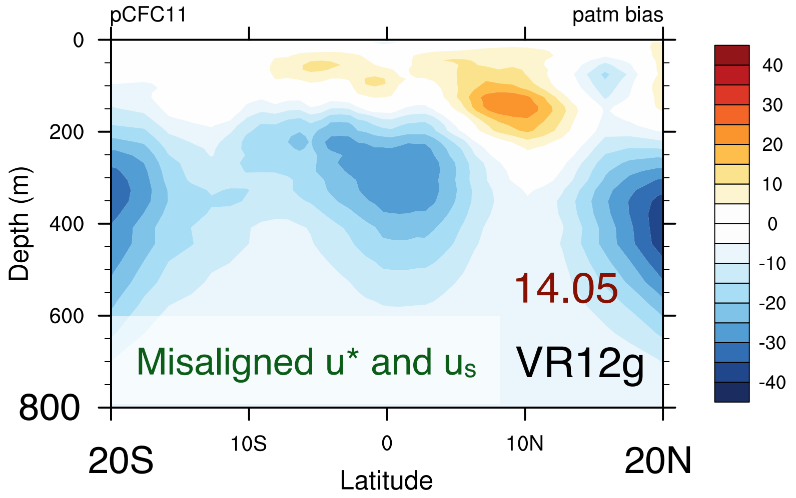
pCFC11 Bias

Equatorial Region





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.

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, a fundamental physics question:
  - What if these are combined? What interactions?

LES of Langmuir-Submeso Interactions?

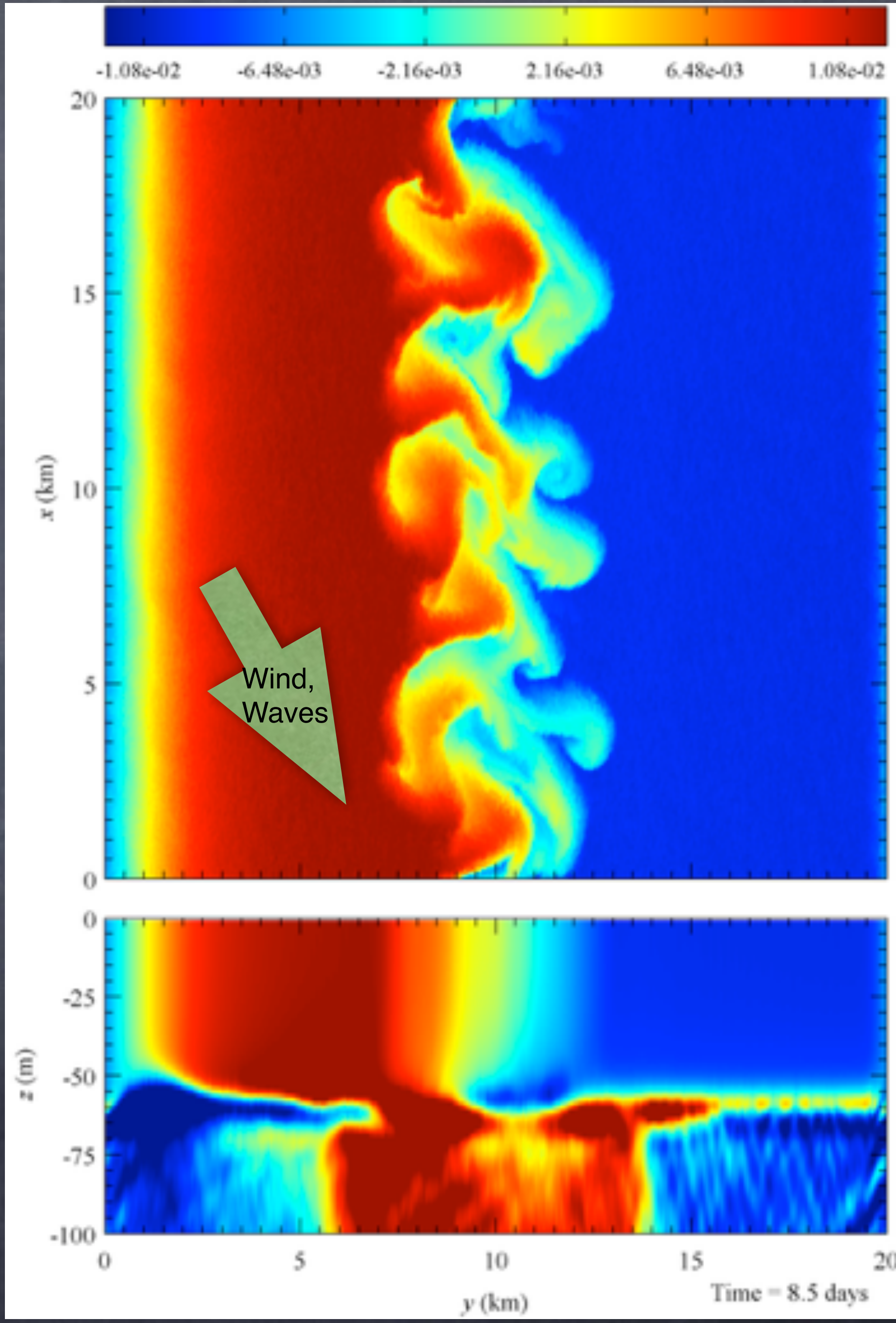
Perform large eddy simulations (LES) of Langmuir turbulence with a submesoscale temperature front

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

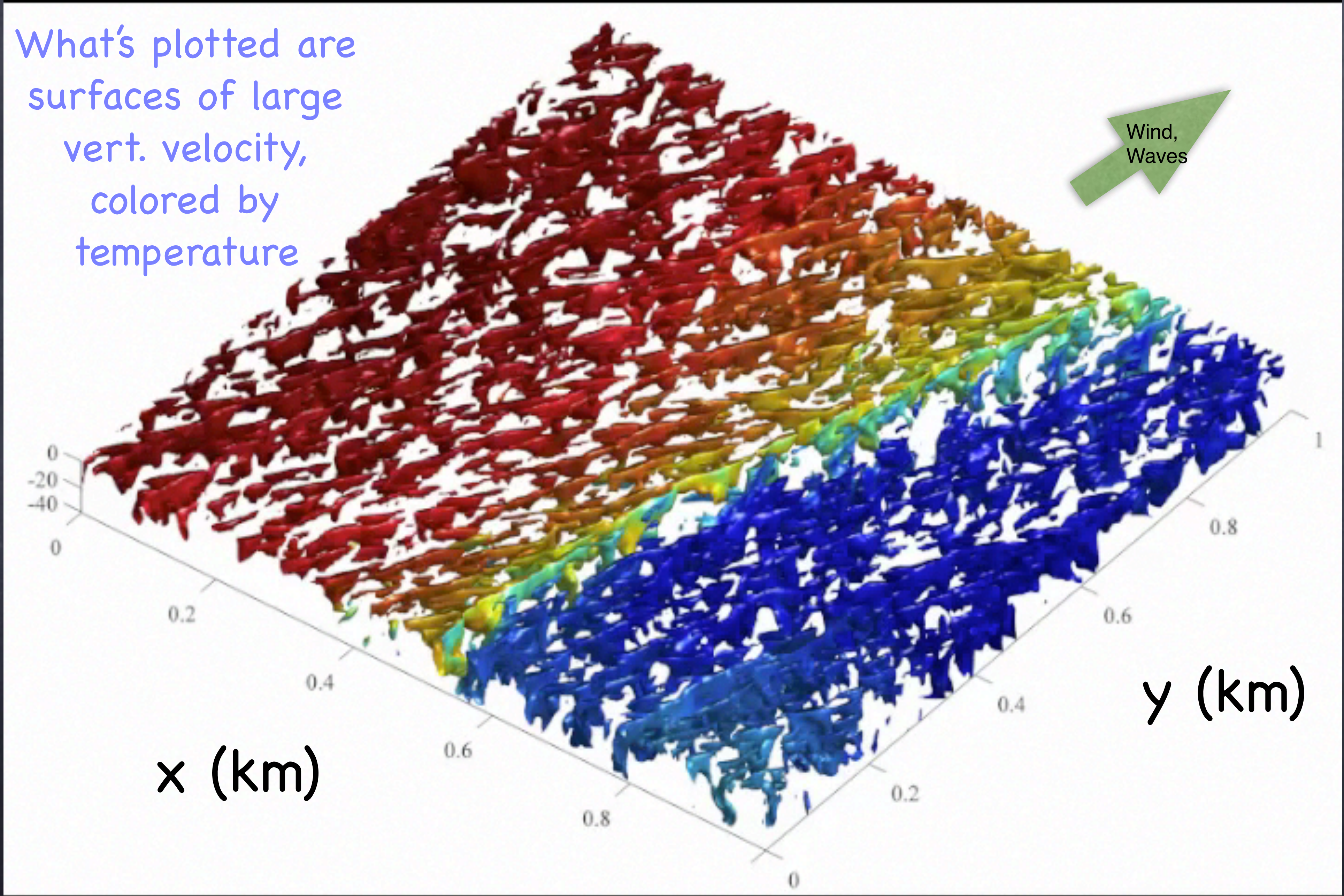
1000x more gridpoints than CESM

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.

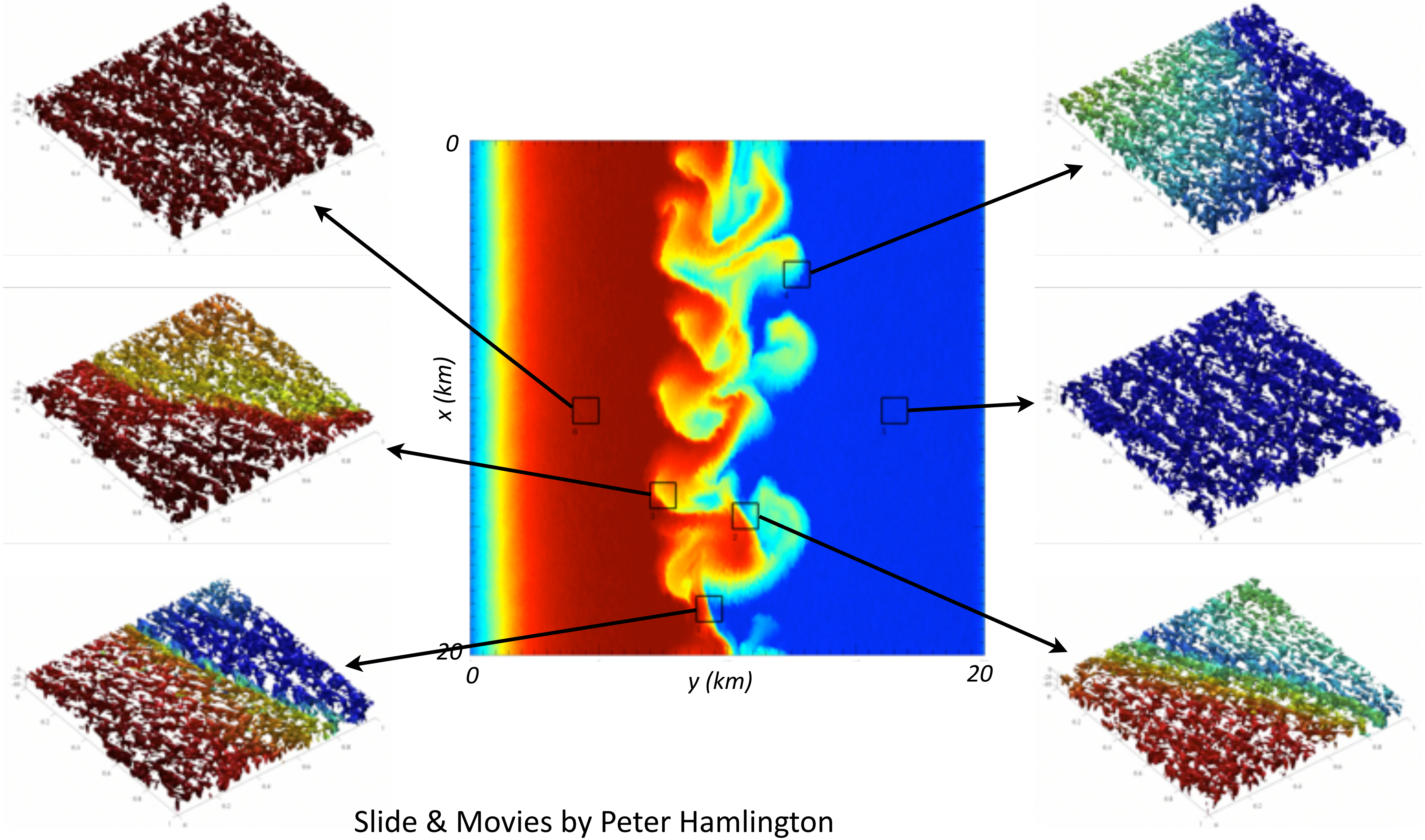
Zoom: Submeso-Langmuir Interaction!



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

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

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 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

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

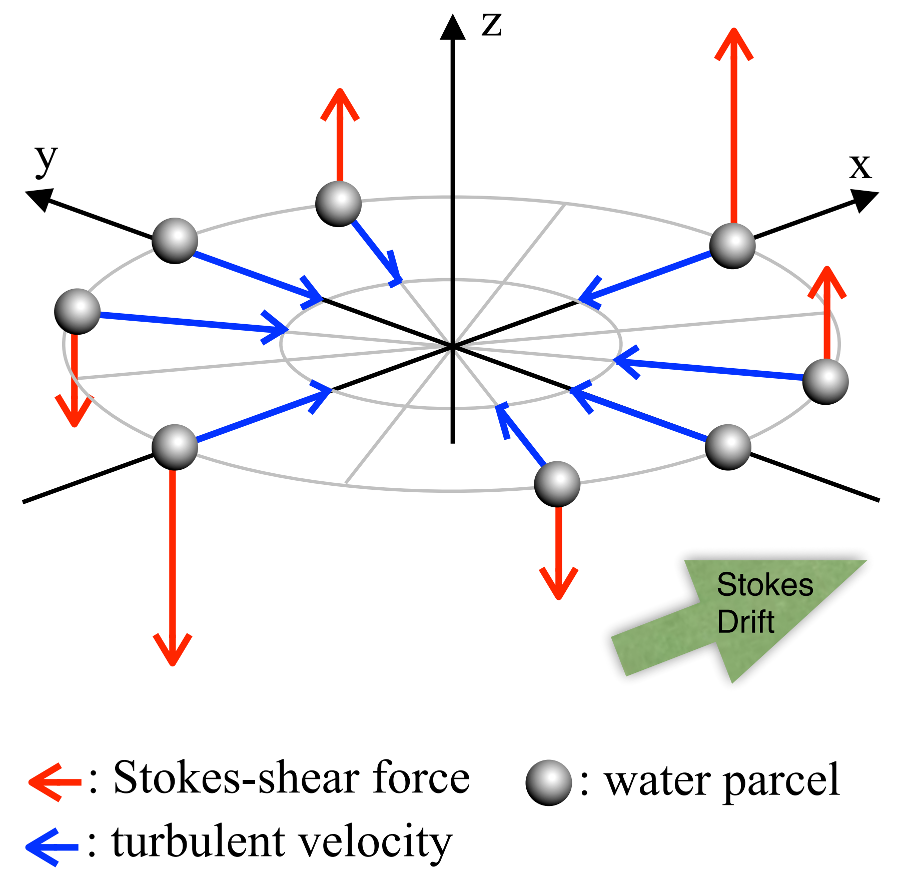
Now the temperature gradients govern the Lagrangian flow, not the not the Eulerian!

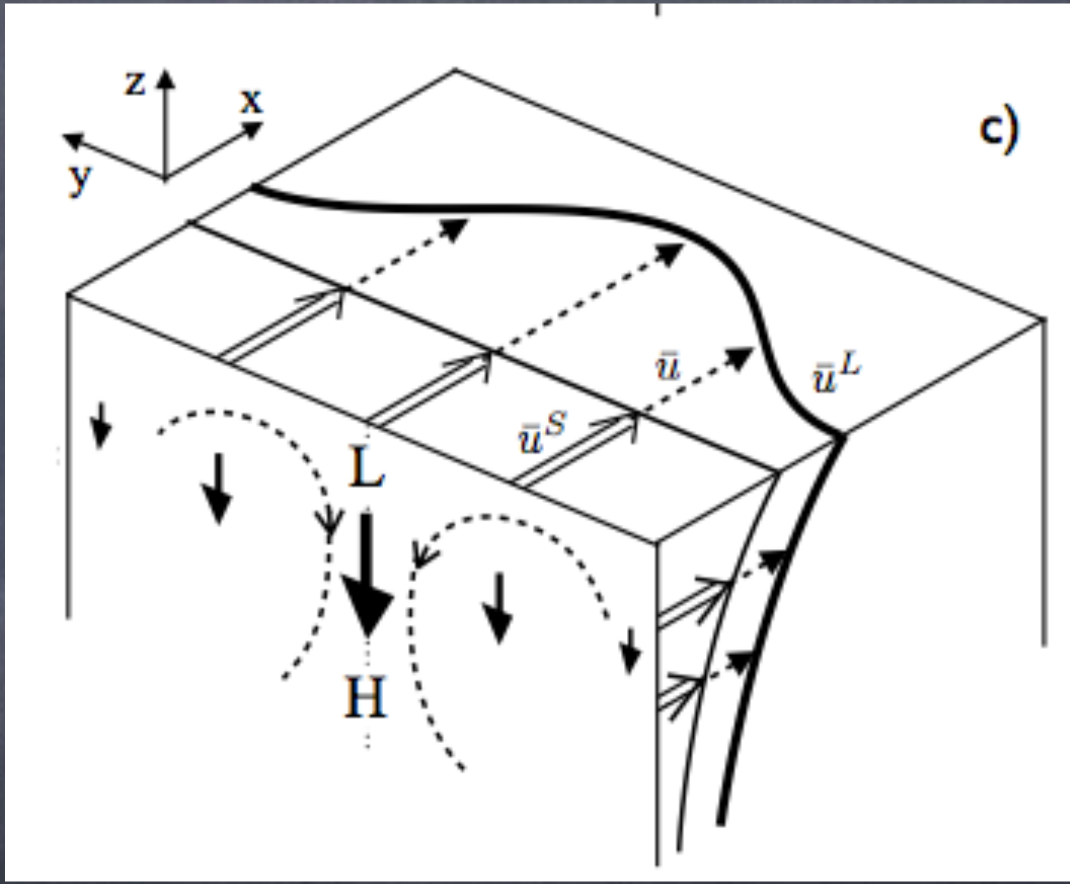
J. C. McWilliams and B. F-K. Oceanic wave-balanced surface fronts and filaments. Journal of Fluid Mechanics, 730:464-490, 2013.

Stokes Shear Force:

Craik-Leibovich mechanism for Langmuir circulations

Flow directed along Stokes shear=downward force

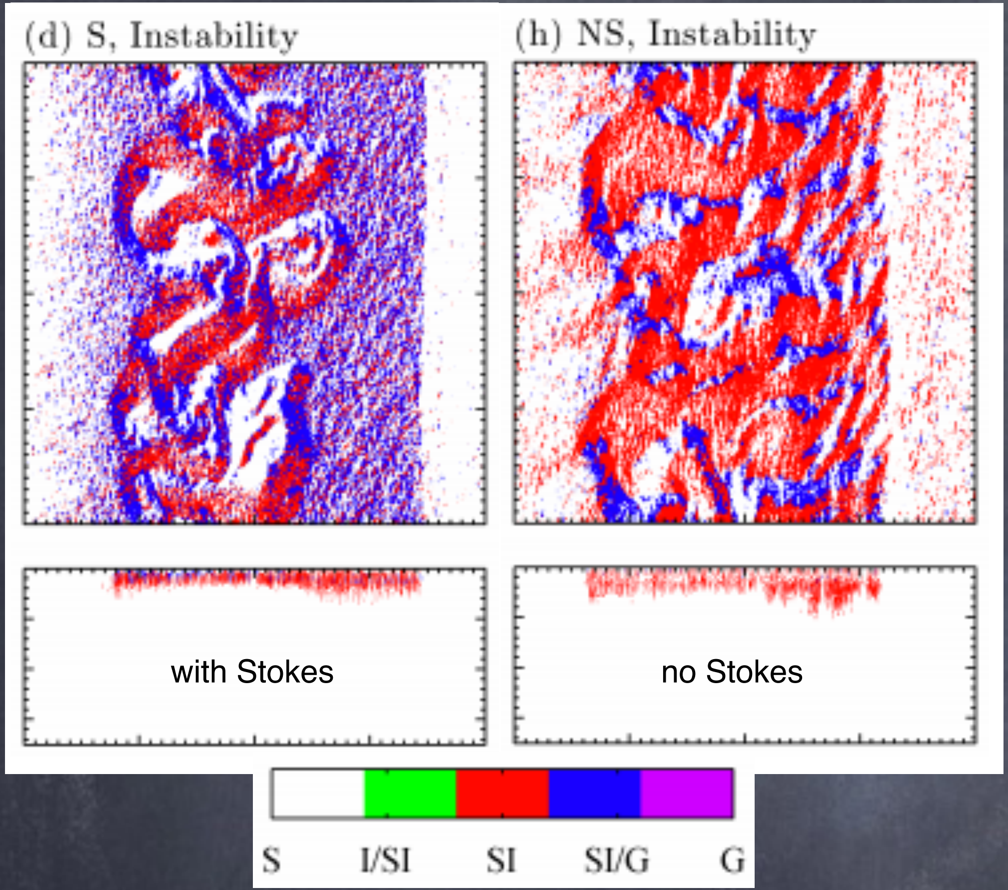


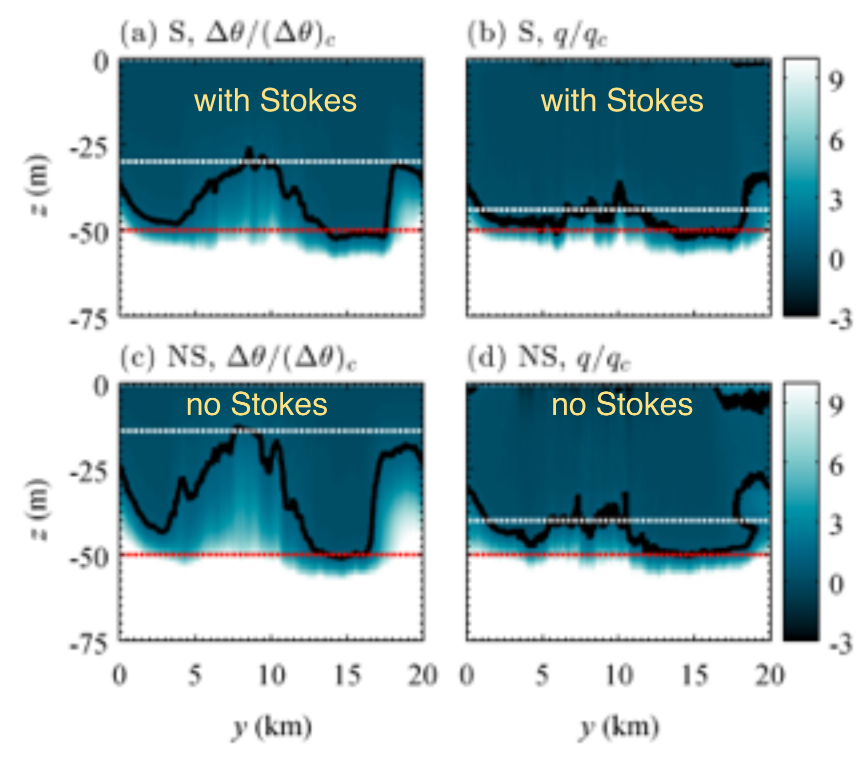


$$\frac{\alpha^2}{Ri}\left[w_{,t}+v_j^L w_{,j}+\frac{M_{Ro}}{RoRi}ww_{,z}\right]=-\pi_{,z}+b-\varepsilon v_j^L v^s_{j,z}+\frac{\alpha^2}{ReRi}w_{,jj}$$

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

Stokes influences Submesoscale & Langmuir-scale Instabilities through Lagrangian shear (Holm ’96) & Lagrangian Thermal Wind





$$Ri_L = \frac{N^2}{(dv^L/dz)^2} \approx \frac{N^2 f^2}{|\nabla_h b|^2}$$

So, $q < 0$

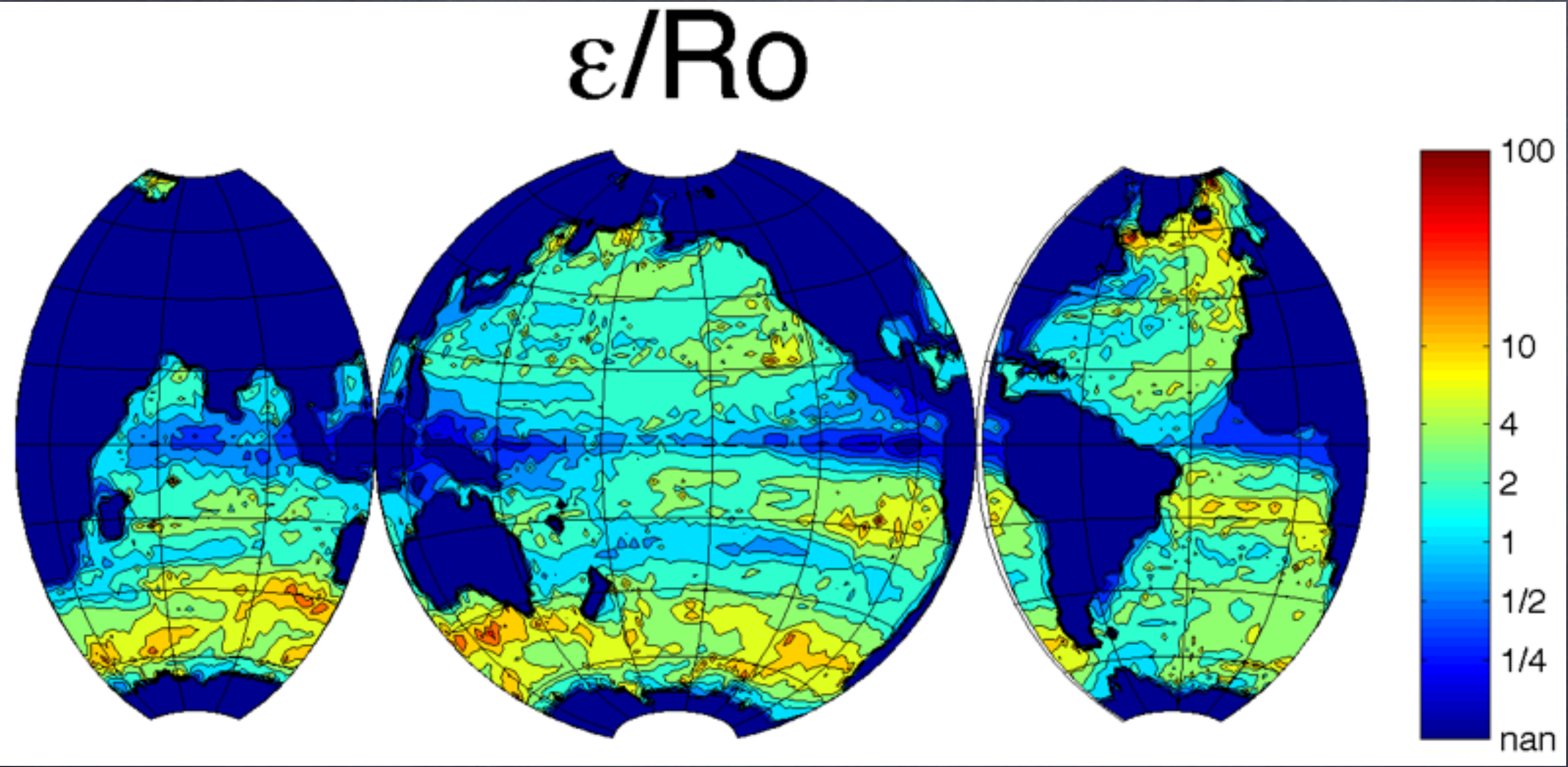
Is not the same as $Ri < \frac{f}{\zeta}$

Reinterpret Hoskins, Stone, & Charney-Stern-Pedlosky with care!

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.

S. Haney, BFK, and K. Julien. Stability of the ocean mixed layer in the presence of surface gravity wave forcing. In TOS/ALSO/AGU 2014 Ocean Sciences Meeting. American Geophysical Union, 2014. Paper in prep.

Stokes force directly affects the (sub)mesoscale!!



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

$$\varepsilon = \frac{V^s H}{fLH_s} \qquad Ro = \frac{U}{fL}$$

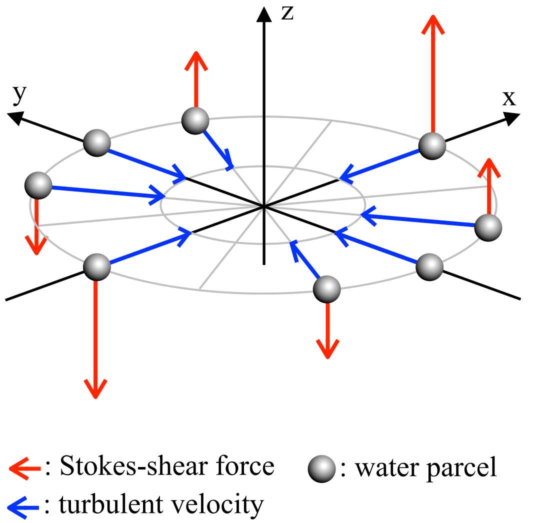
J. C. McWilliams and BFK. Oceanic wave-balanced surface fronts and filaments. Journal of Fluid Mechanics, 730:464-490, 2013.

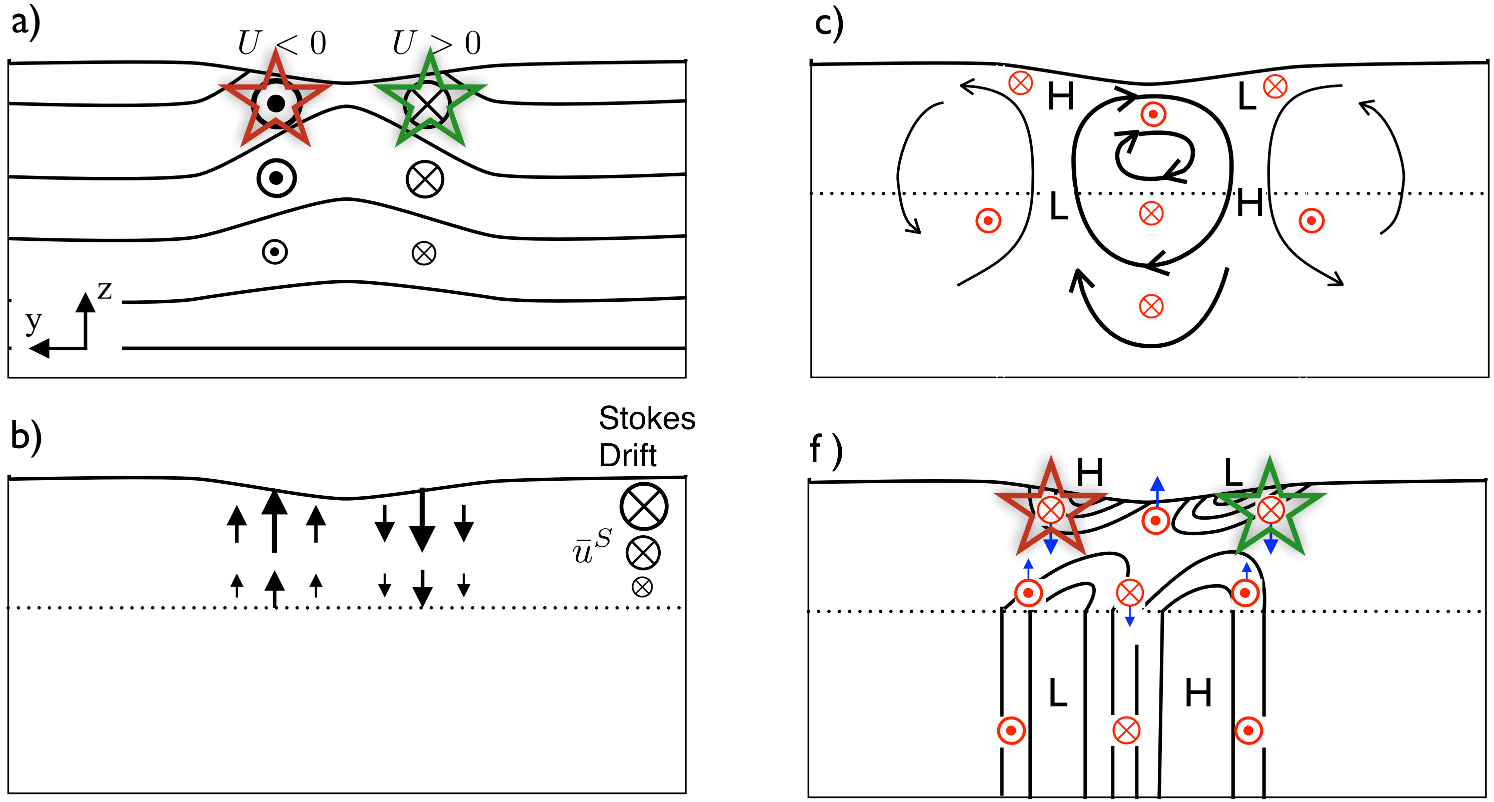
When is $\varepsilon = \frac{V^s H}{f L H_s}$ big?

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

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

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

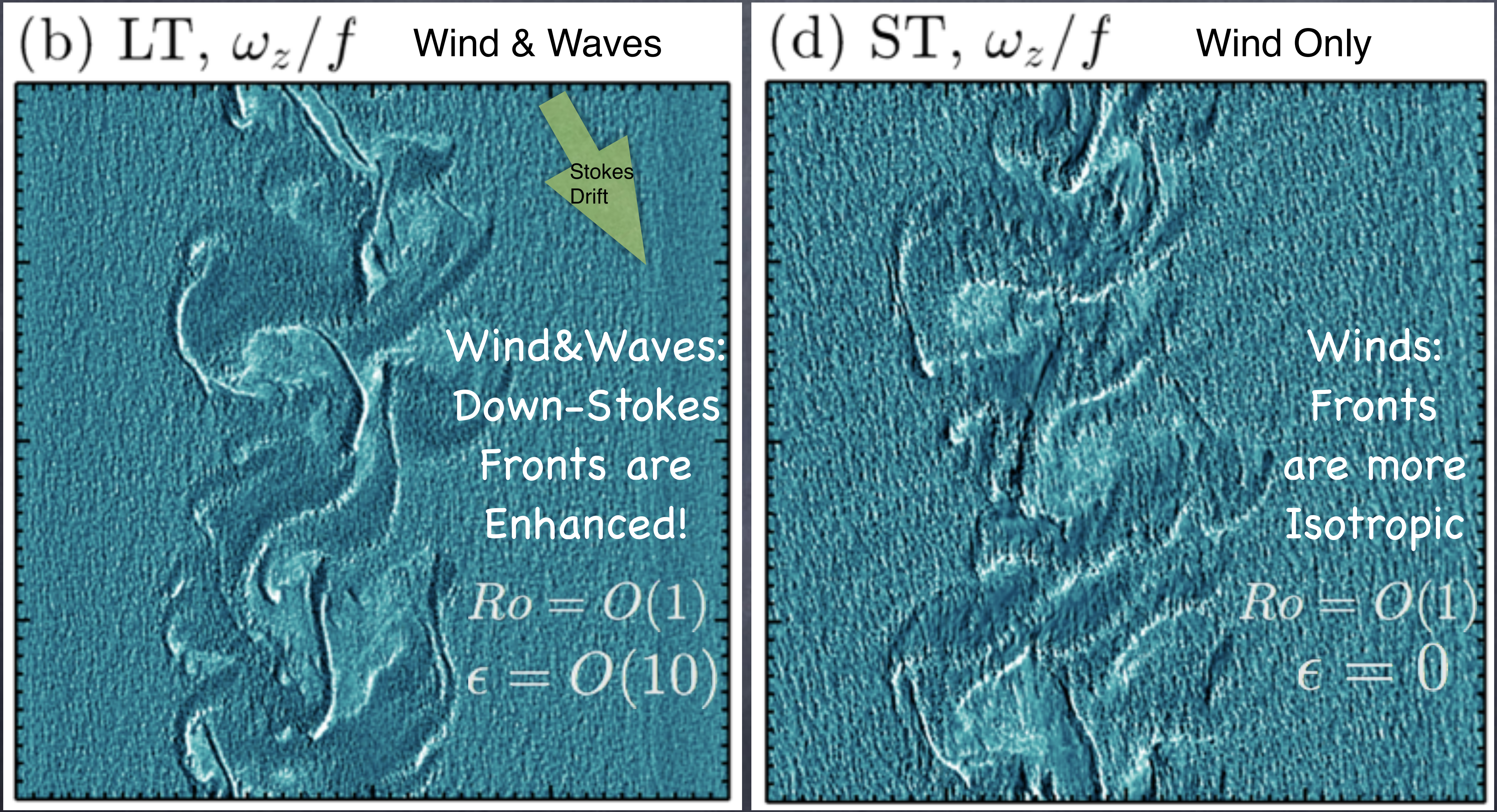
Opposes Fronts for Up-Front Stokes

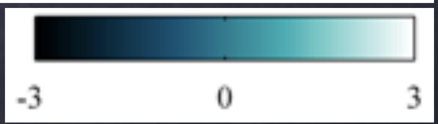
$$\frac{\alpha^2}{Ri}\left[w_{,t} + v_j^L w_{,j} + \frac{M_{Ro}}{RoRi} w w_{,z}\right] = -\pi_{,z} + b - \varepsilon v_j^L v^s_{j,z} + \frac{\alpha^2}{ReRi} w_{,jj}$$

Waves Give 30-40% of Power Produced at Front

Are Fronts and Filaments different with Stokes shear force?

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





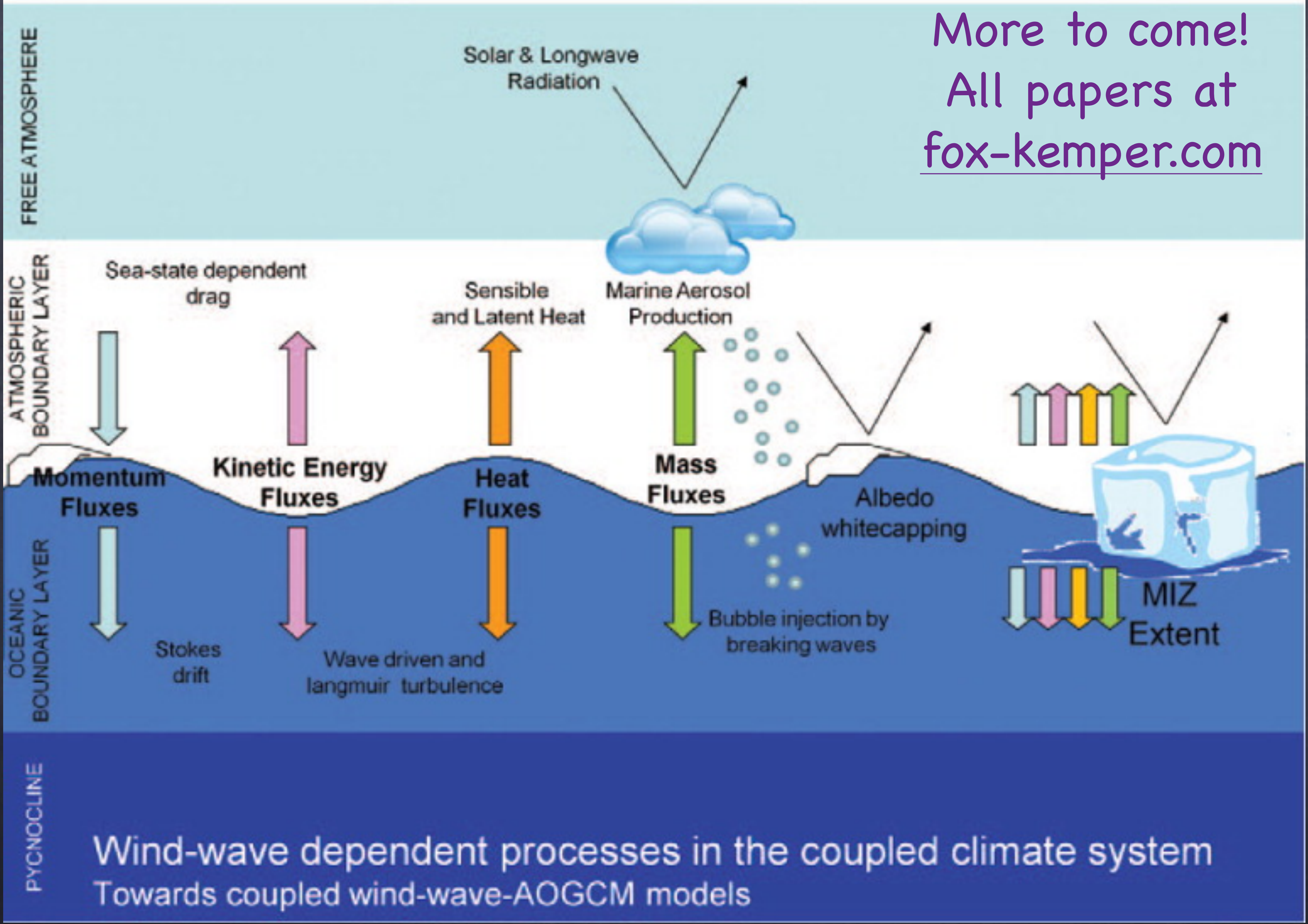
N. Suzuki and BFK. Surface Wave Stokes Forces Influence Frontogenesis, JPO, in prep, 2014.

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.

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



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

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

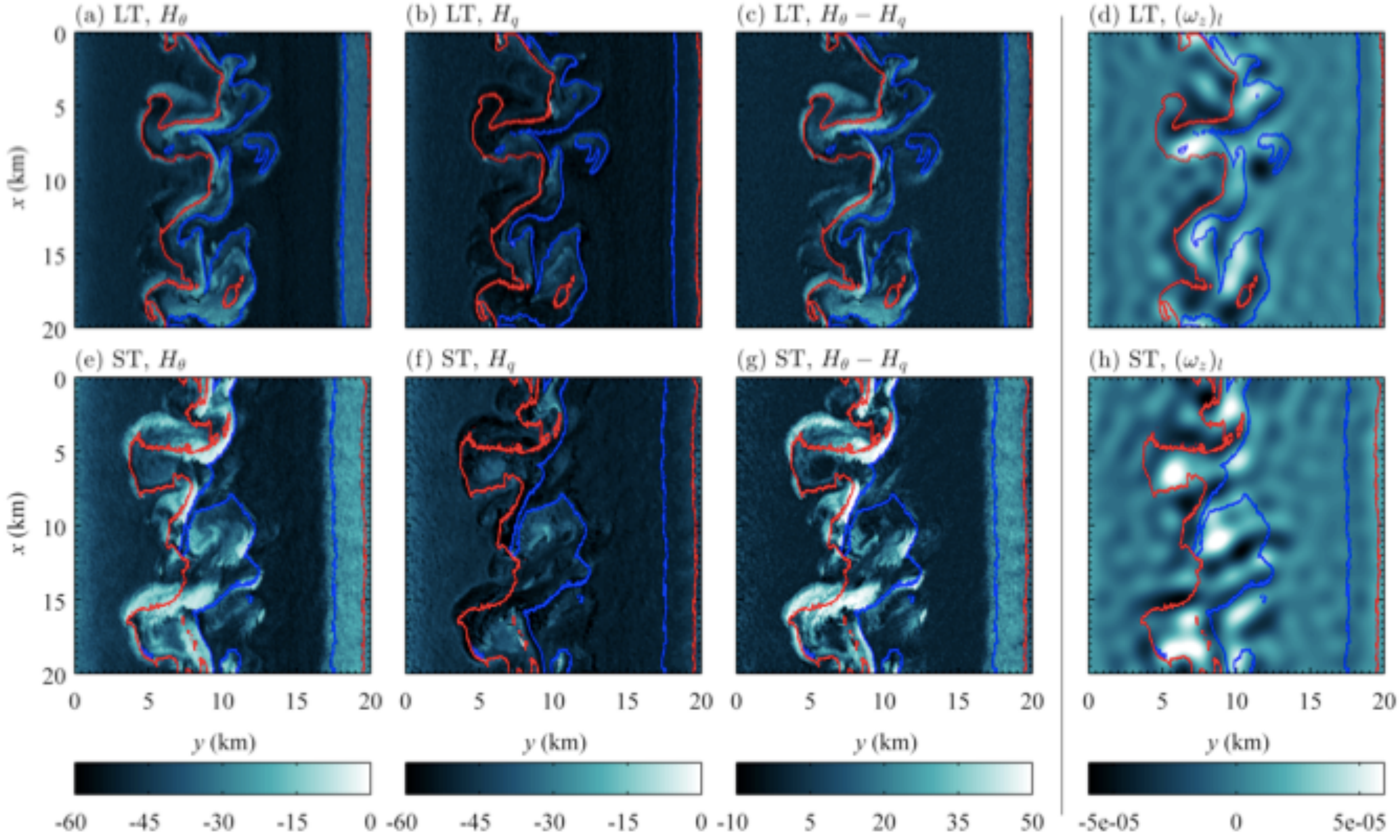


FIG. 13. Fields of the mixed layer depth (in m) based on temperature, denoted H_θ, (a,e) and on potential vorticity, denoted H_q, (b,f) for the LT (a,b) and ST (e,f) cases. The difference $H_\theta - H_q$ is shown in (c,g) and low-pass (submesoscale) vertical vorticity fields are shown in (d,h), where 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:

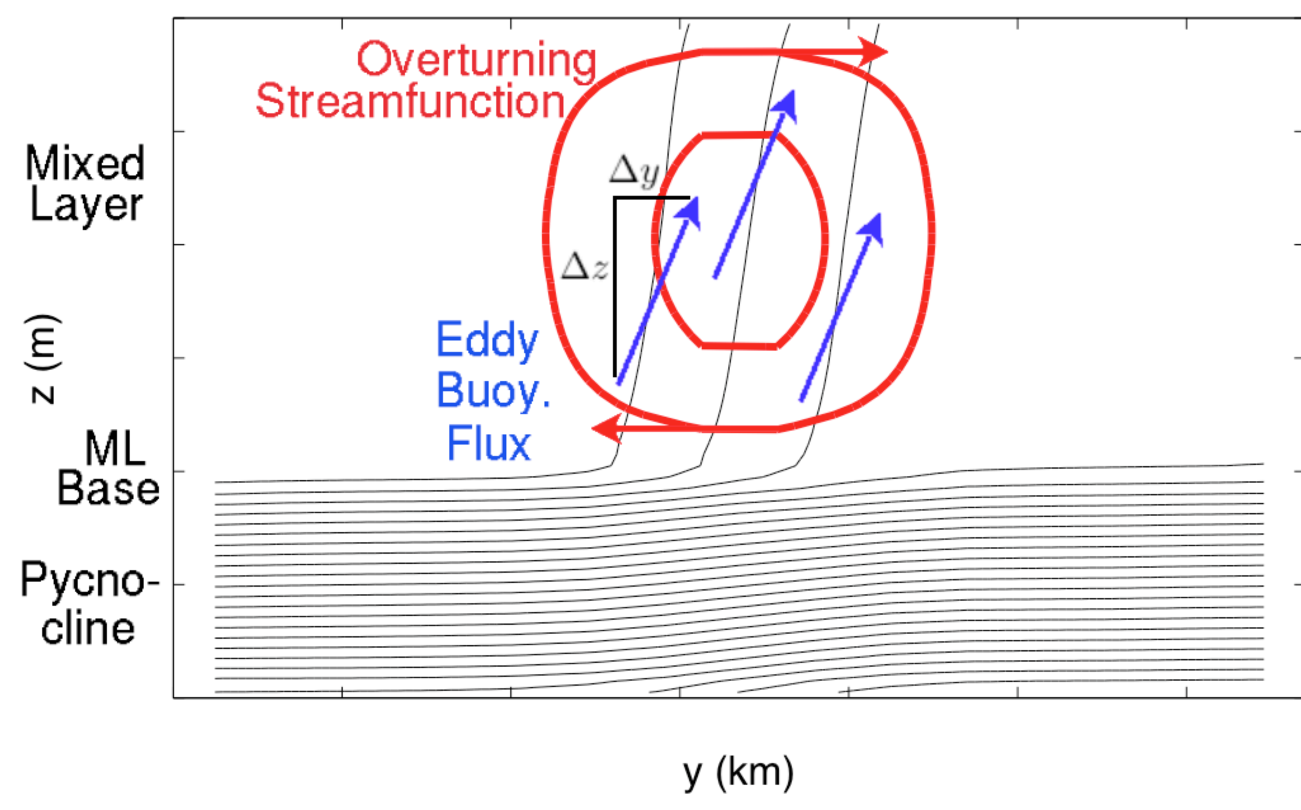
$$\mu(z) = 0 \text{ if } z < -H$$

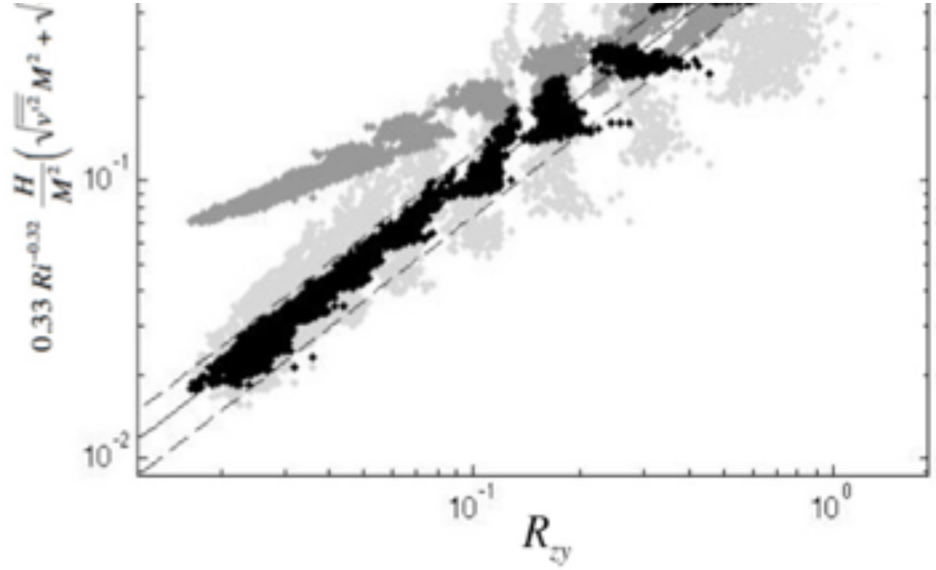
For a consistently restratifying,

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

and horizontally downgradient flux.

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

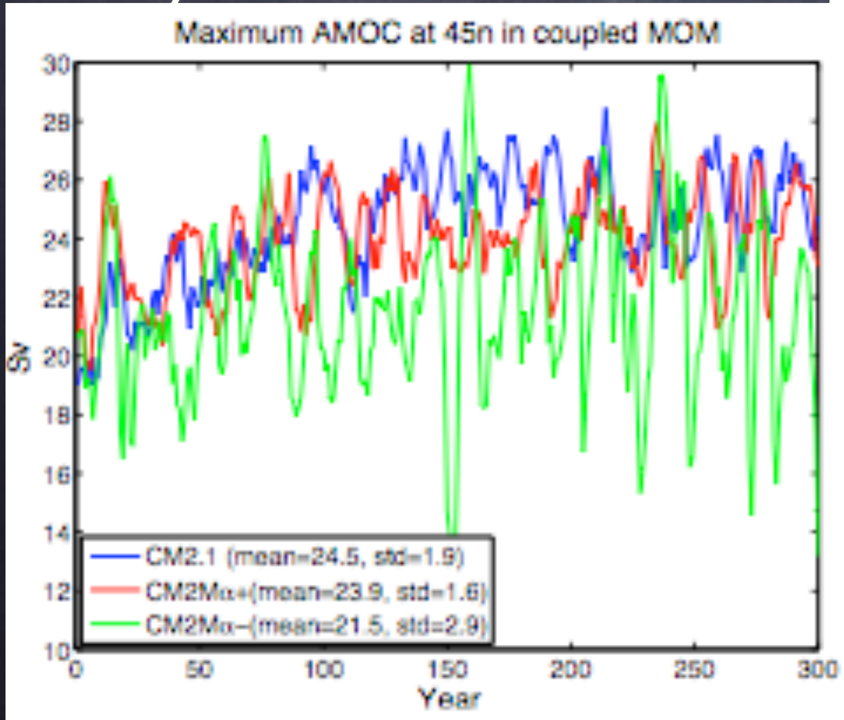




S. Bachman and B. Fox-Kemper. Eddy parameterization challenge suite. I: Eady spindown. Ocean Modelling, 64:12-28, 2013

Sensitivity of Climate to Submeso: AMOC & Cryosphere Impacts

May Stabilize AMOC



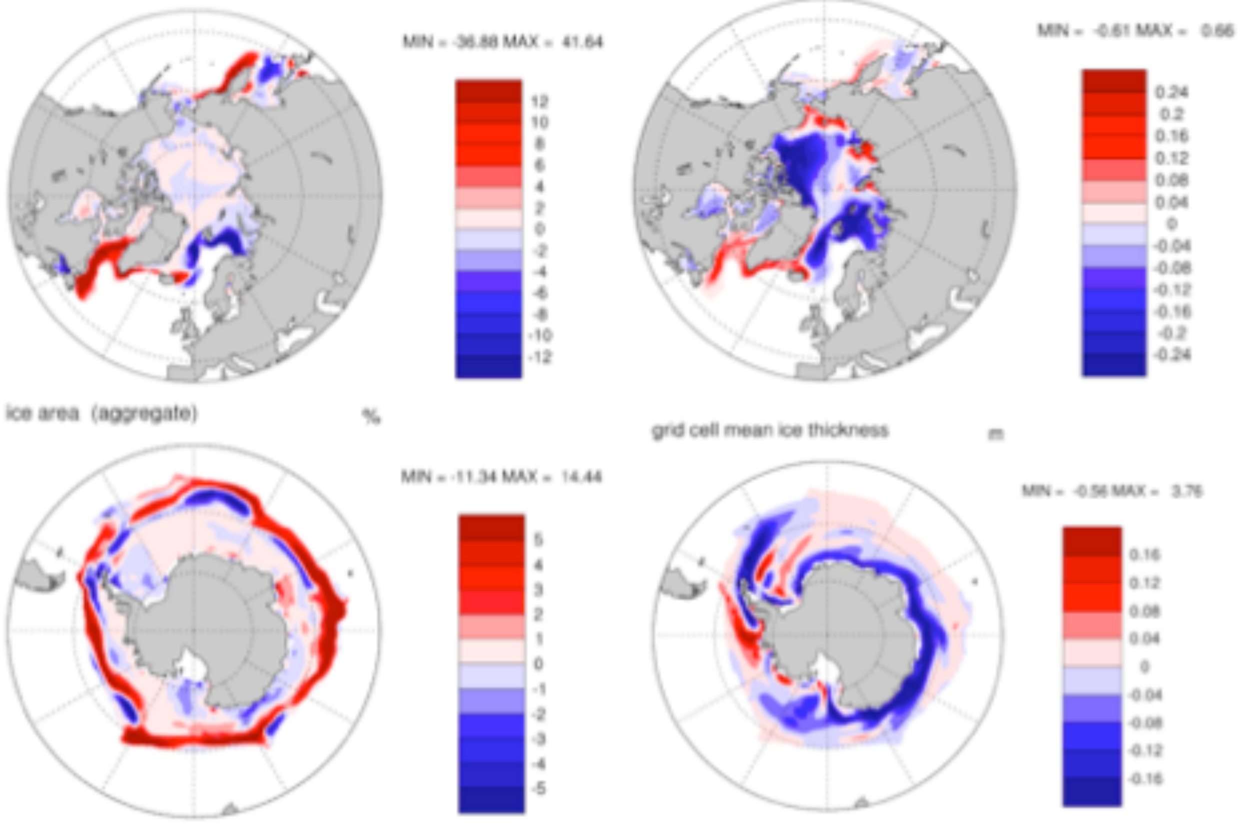


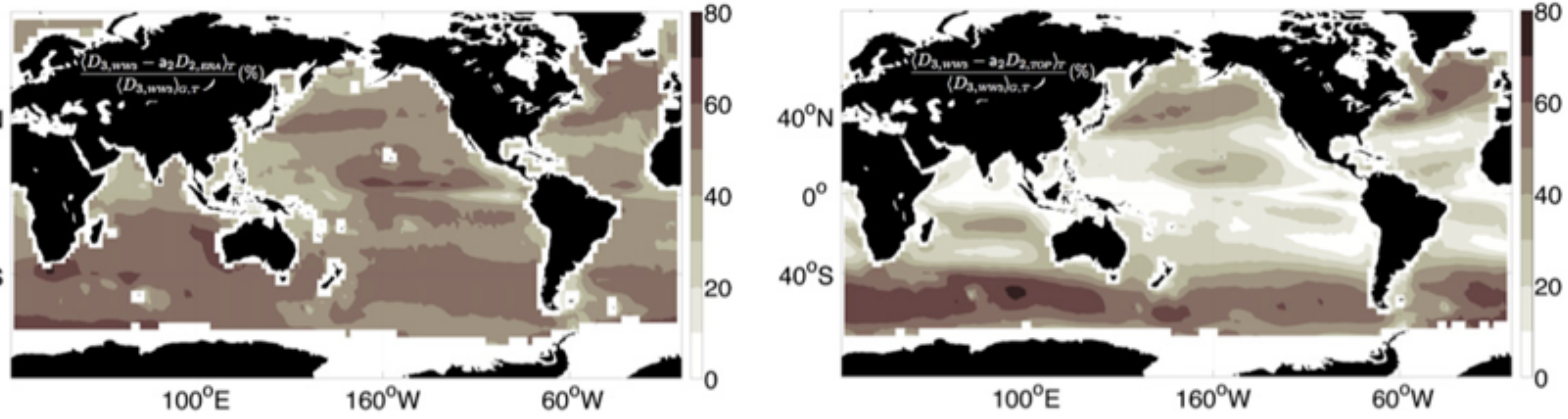
Figure 10: Wintertime sea ice sensitivity to introduction of MLE parameterization (CCSM$^+$ minus CCSM$^-$): January to March Northern Hemisphere a) ice area and b) thickness and July to September Southern Hemisphere c) ice area and d) thickness.

Affects sea ice

NO RETUNING NEEDED!!!

These are impacts:
bias change unknown

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



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

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

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

Year 2000 data & models

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

Why? Vortex Tilting Mechanism

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

Misalignment enhances degree of wave-driven LT

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

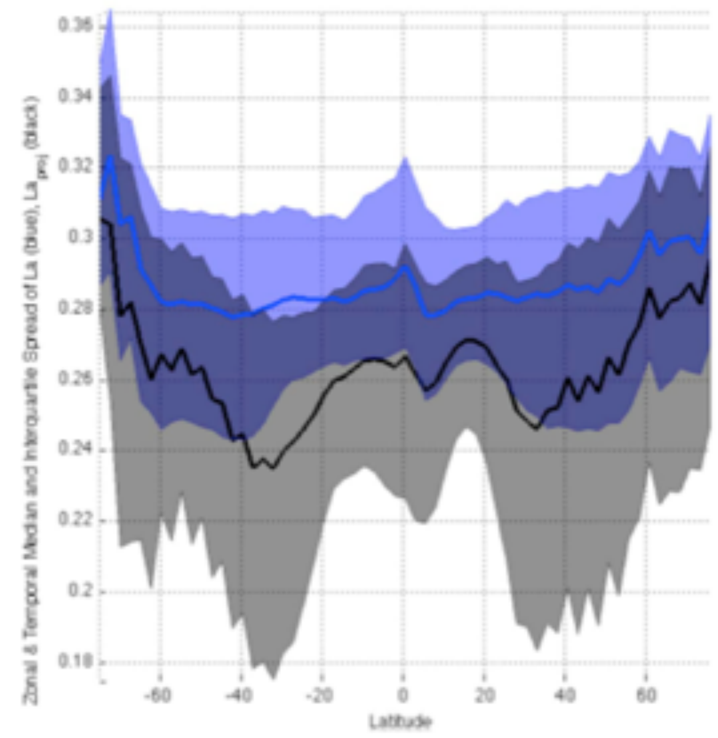


Figure 17. Temporal and zonal median and interquartile range of La_t and La_{proj} for a realistic simulation of 1994–2002 using Wave Watch III.

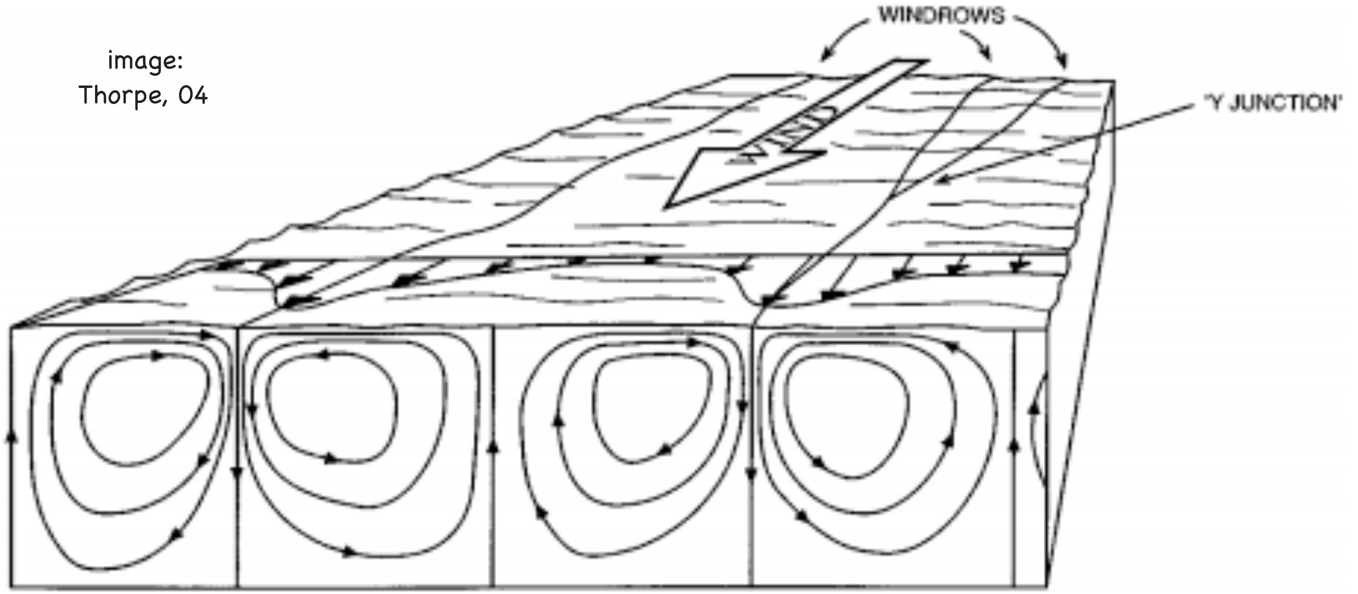


image: Thorpe, 04

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

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!