Wind waves in the coupled climate system

Baylor Fox-Kemper (Brown)

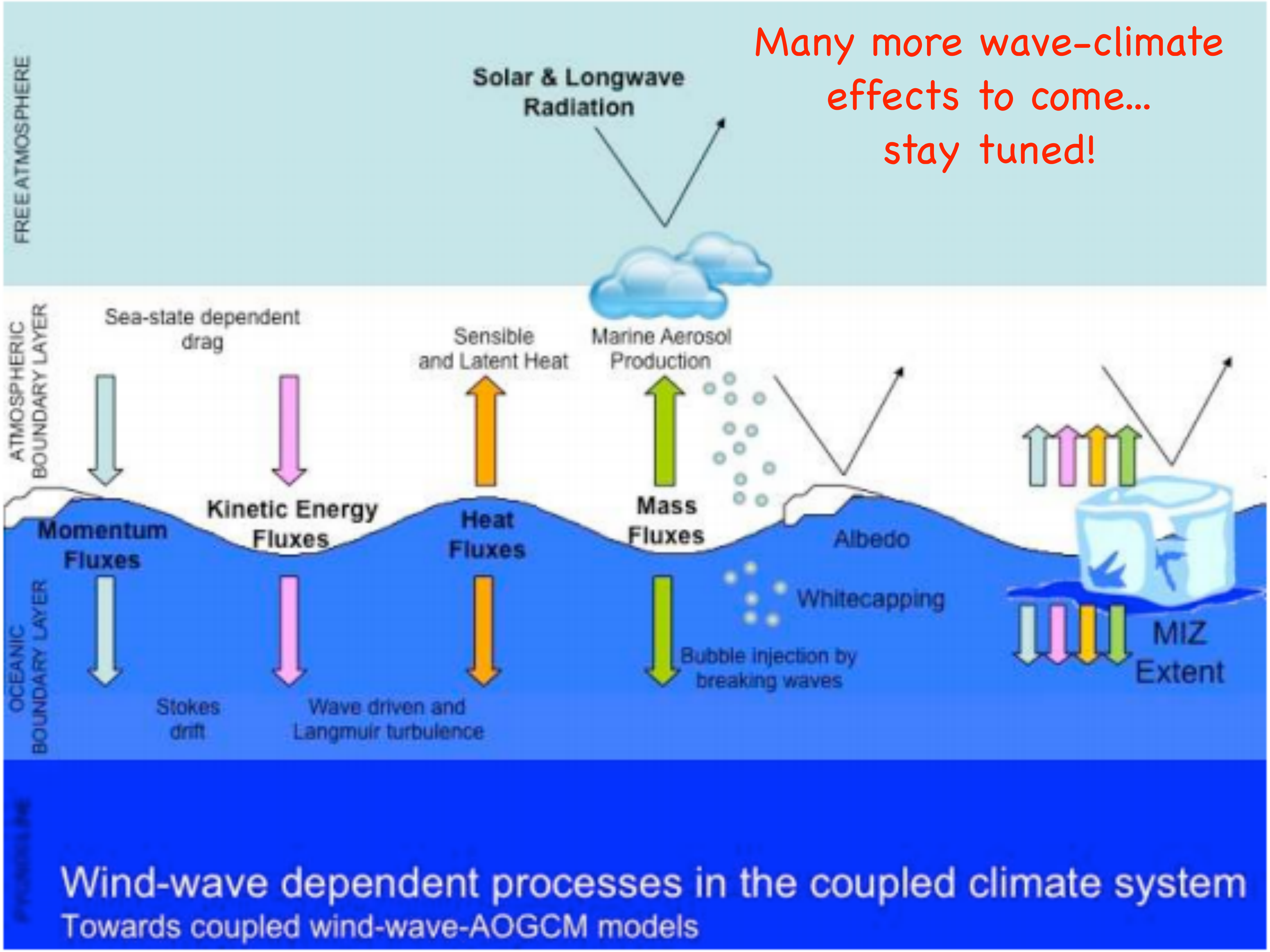
with Jim McWilliams (UCLA), Nobu Suzuki (Brown), Sean Haney (CU), and Qing Li (Brown)

Expanding on past work with:
Peter Hamlington (CU-Boulder), Luke Van Roekel (Northland College),
Adrean Webb (TUMST), Keith Julien (CU-APPM), Greg Chini (UNH),
Peter Sullivan (NCAR), Mark Hemer (CSIRO)

GFD Cottage, July 21, 2014, 10:30-12PM, Woods Hole, MA

Sponsors: NSF 1258907, 0934737, NASA NNX09AF38G

http://hvo.wr.usgs.gov/multimedia/archive/2007/2007_Jan-May.html

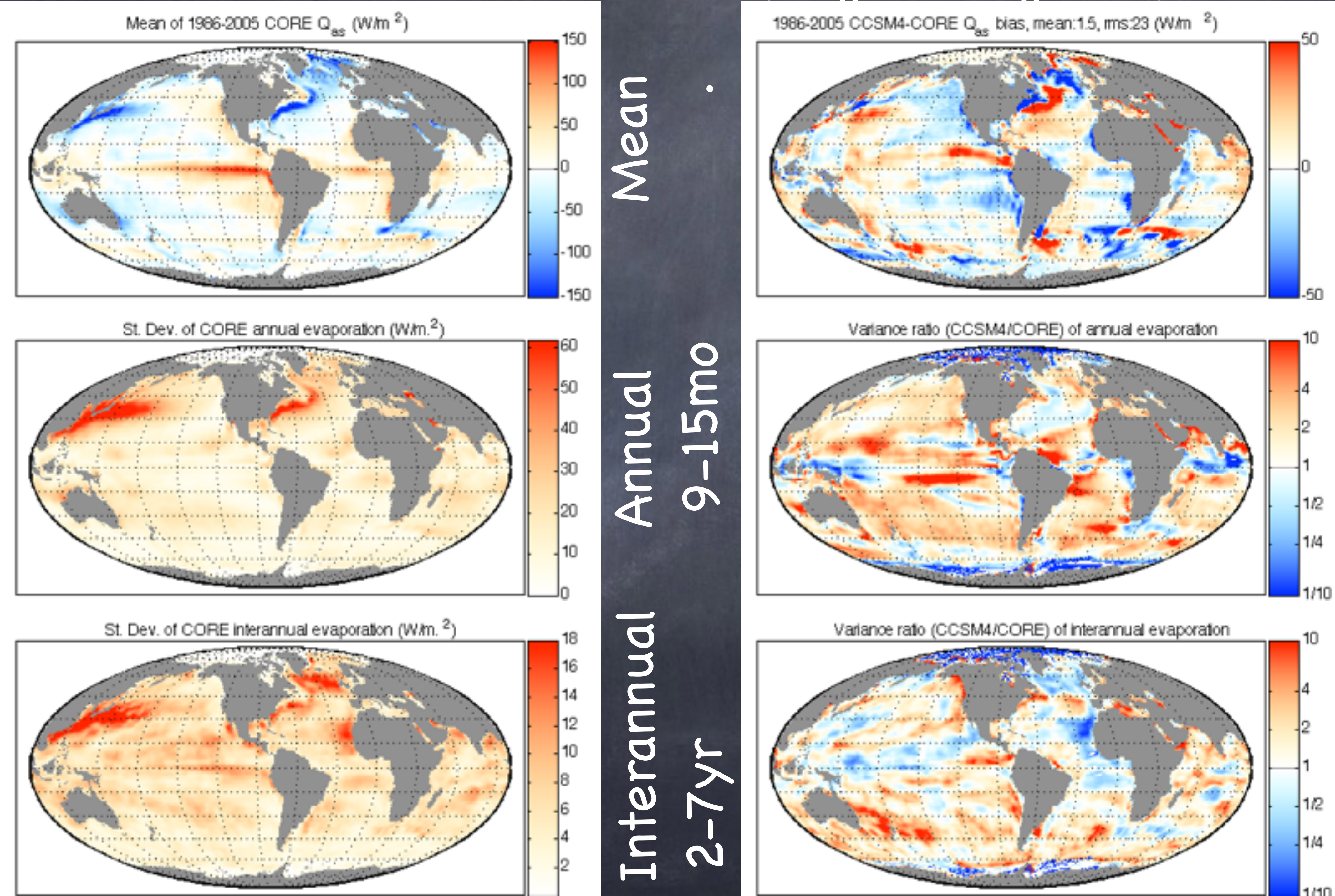


Many more wave-climate
effects to come…
stay tuned!

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, November 2012.

S. C. Bates, B. Fox-Kemper, 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, November 2012.

Air-Sea Flux Errors vs. Data (Large & Yeager 09)



Mean

Annual
9-15mo

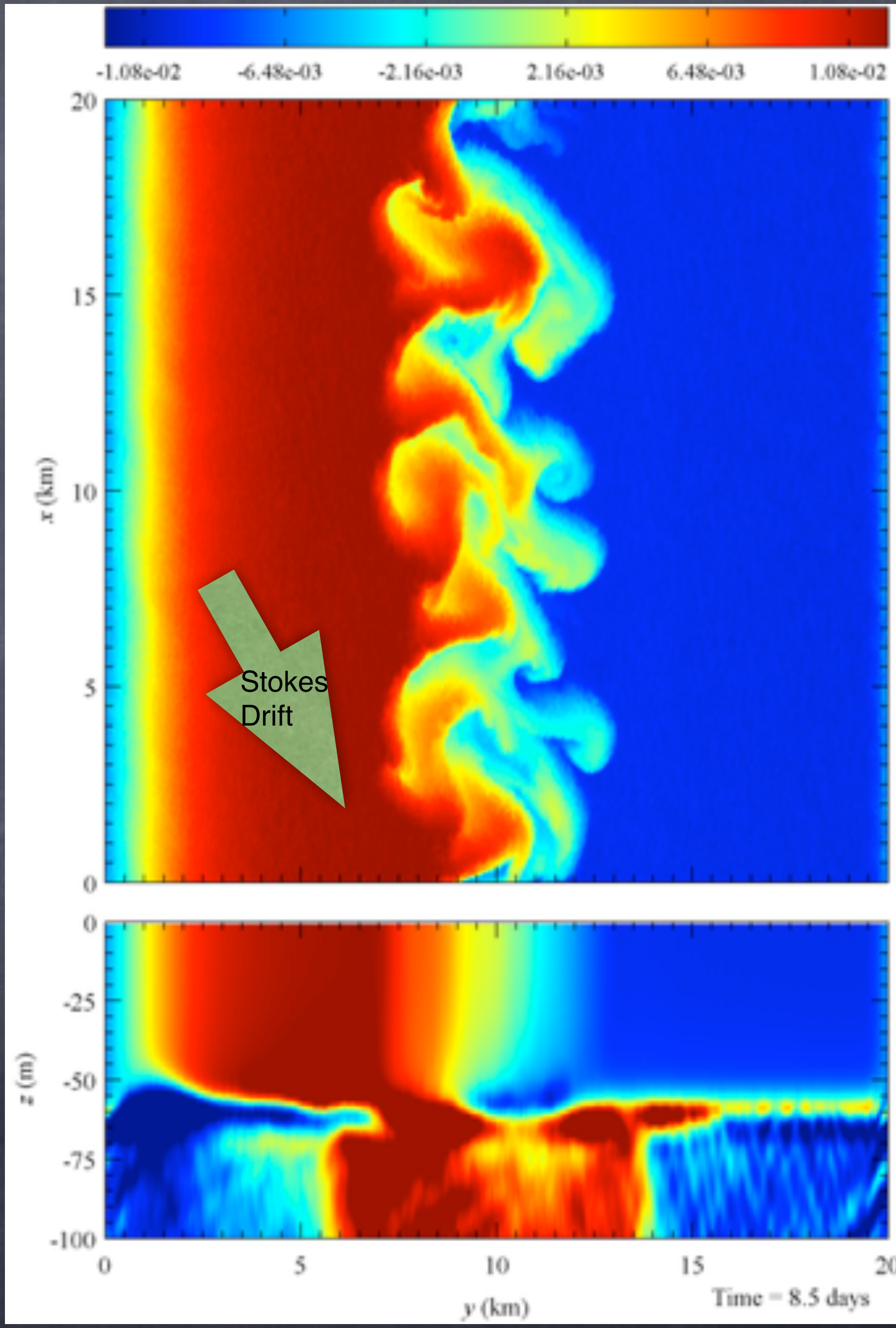
Interannual
2-7yr

LES of Langmuir-Submeso Interactions?

Perform large eddy simulations (LES) of Langmuir turbulence with a submesoscale temperature front using wave-averaged equations

2 Expts: 1 with Stokes forcing
1 without

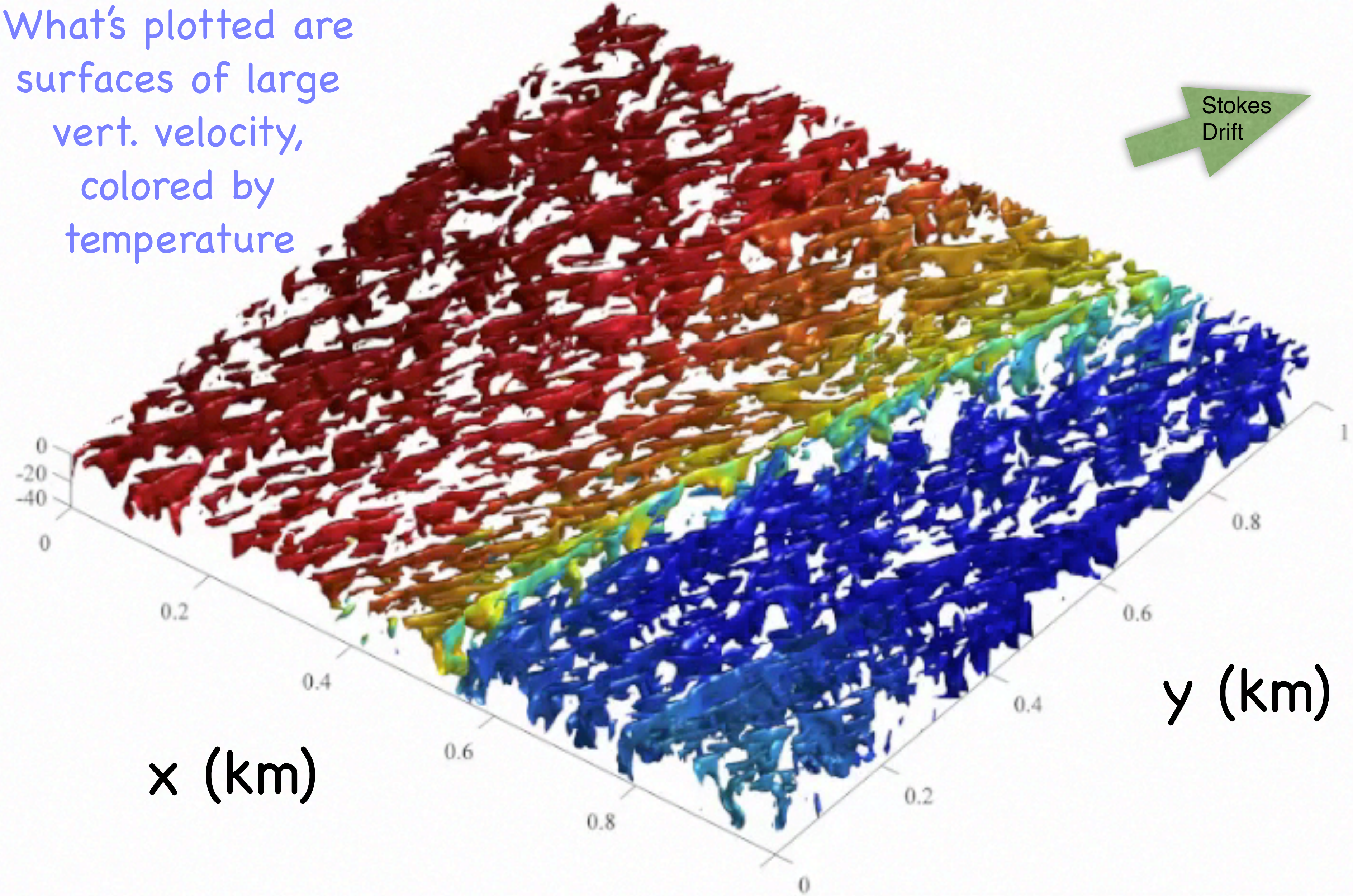
Computational parameters:
Domain size: 20km x 20km x -160m
Grid points: 4096 x 4096 x 128
Resolution: 5m x 5m x -1.25m
1000x more gridpoints than CESM



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

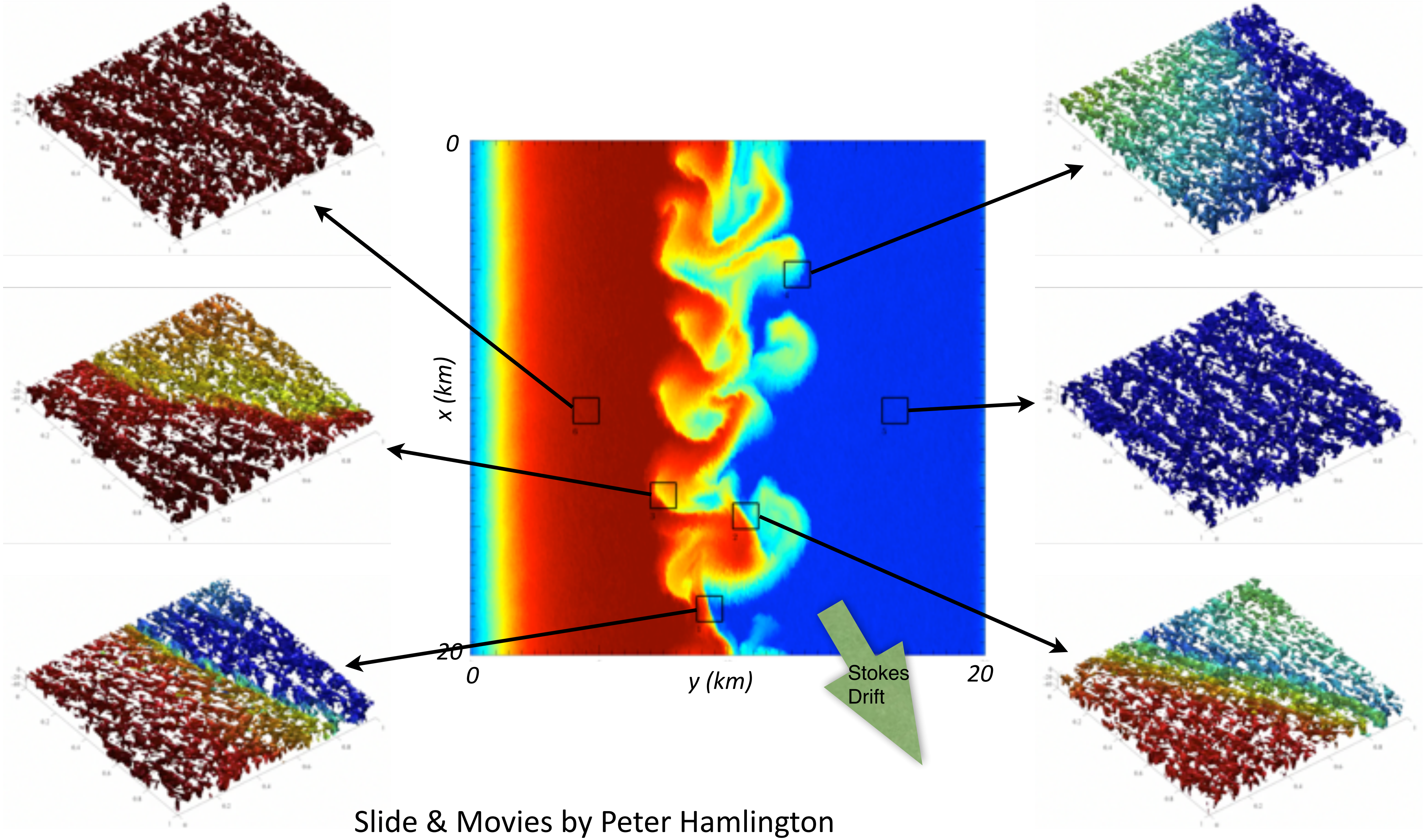
Zoom: Submeso-Langmuir Interaction!

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



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

Diverse types of interaction

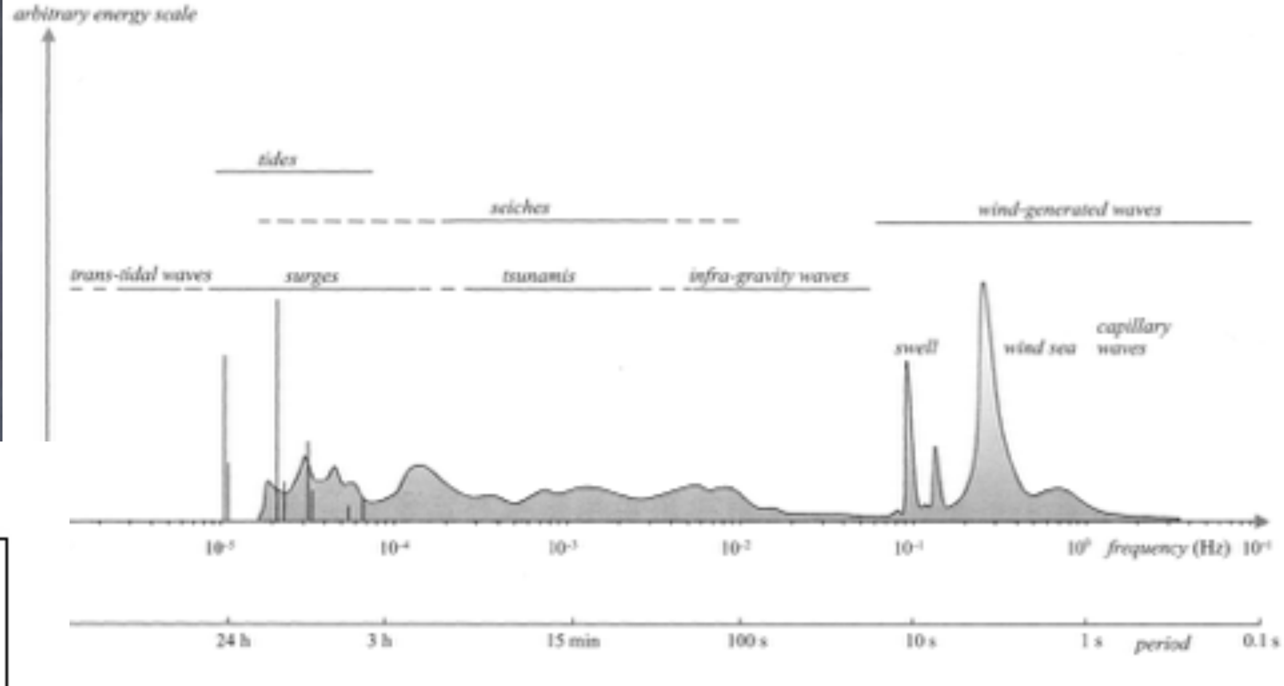


Slide & Movies by Peter Hamlington

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

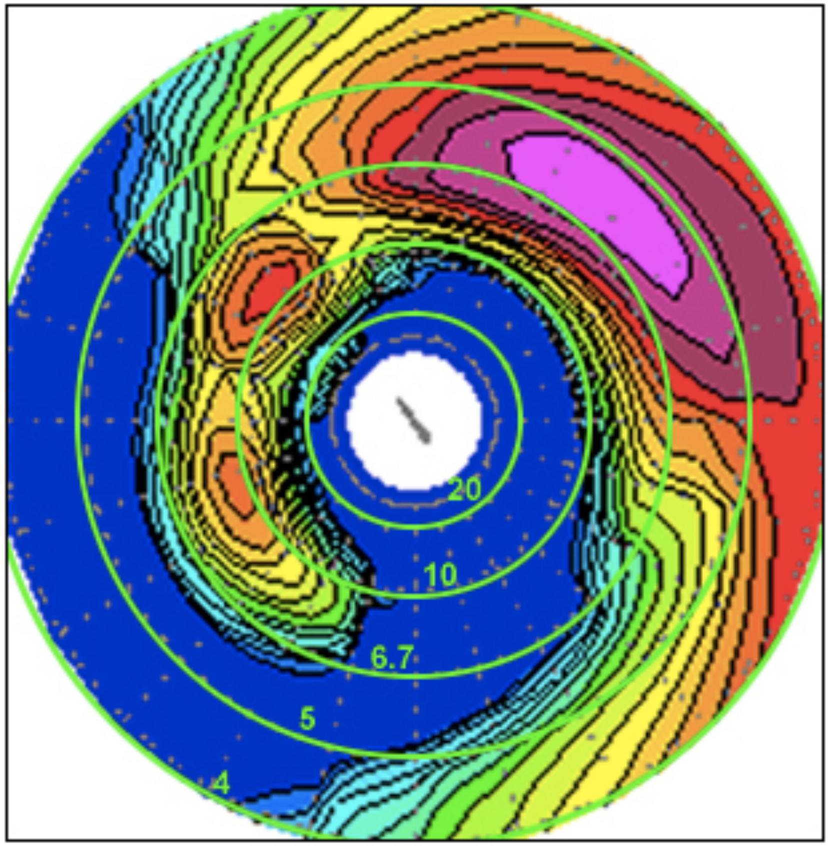
Surface Waves are...

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



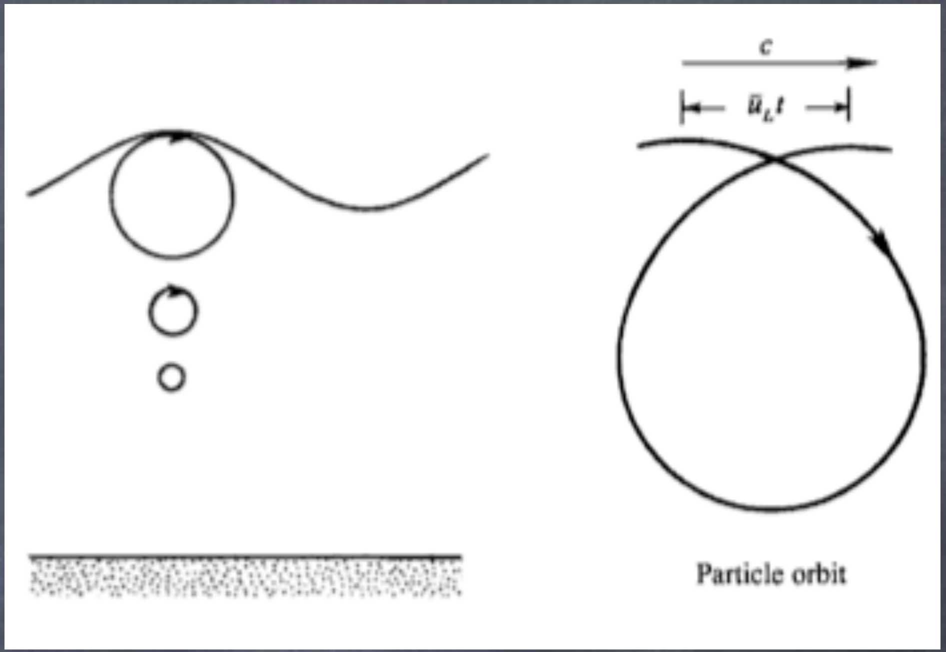
24 hr fcst Valid 0000 UTC 26 Apr 2002

NOAA / NWS / NCEP / MMAB

Stokes driftin' away

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

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



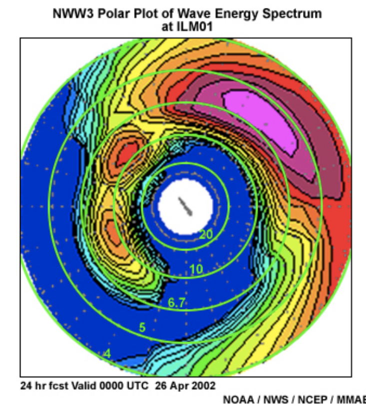
Monochromatic: $$\boldsymbol{u}^S = \hat{\mathbf{e}}^w \frac{8\pi^3 a^2 f_p^3}{g} e^{\frac{8\pi^2 f_p^2}{g}z} = \hat{\mathbf{e}}^w a^2\sqrt{gk^3}e^{2kz}.$$

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

Depth-Integrated: $$\boldsymbol{u}_*^{S\text{-int}} = \int_{-\infty}^{0}\boldsymbol{u}_*^S(z)\,dz = 2\pi\int_0^\infty \boldsymbol{H}_*(f)fS_f(f)\,df$$

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

A. Webb and B. Fox-Kemper. Estimating Stokes drift for random seas. In prep.



Stokes forcing on the Langmuir Scale

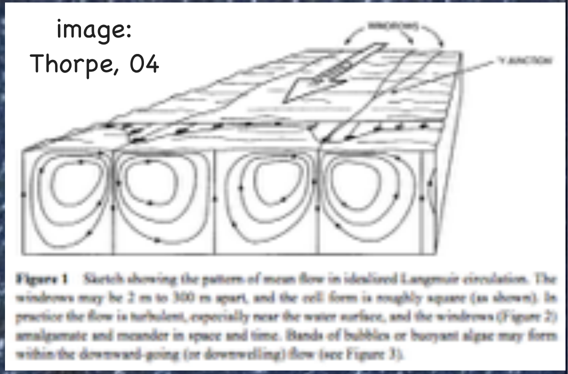
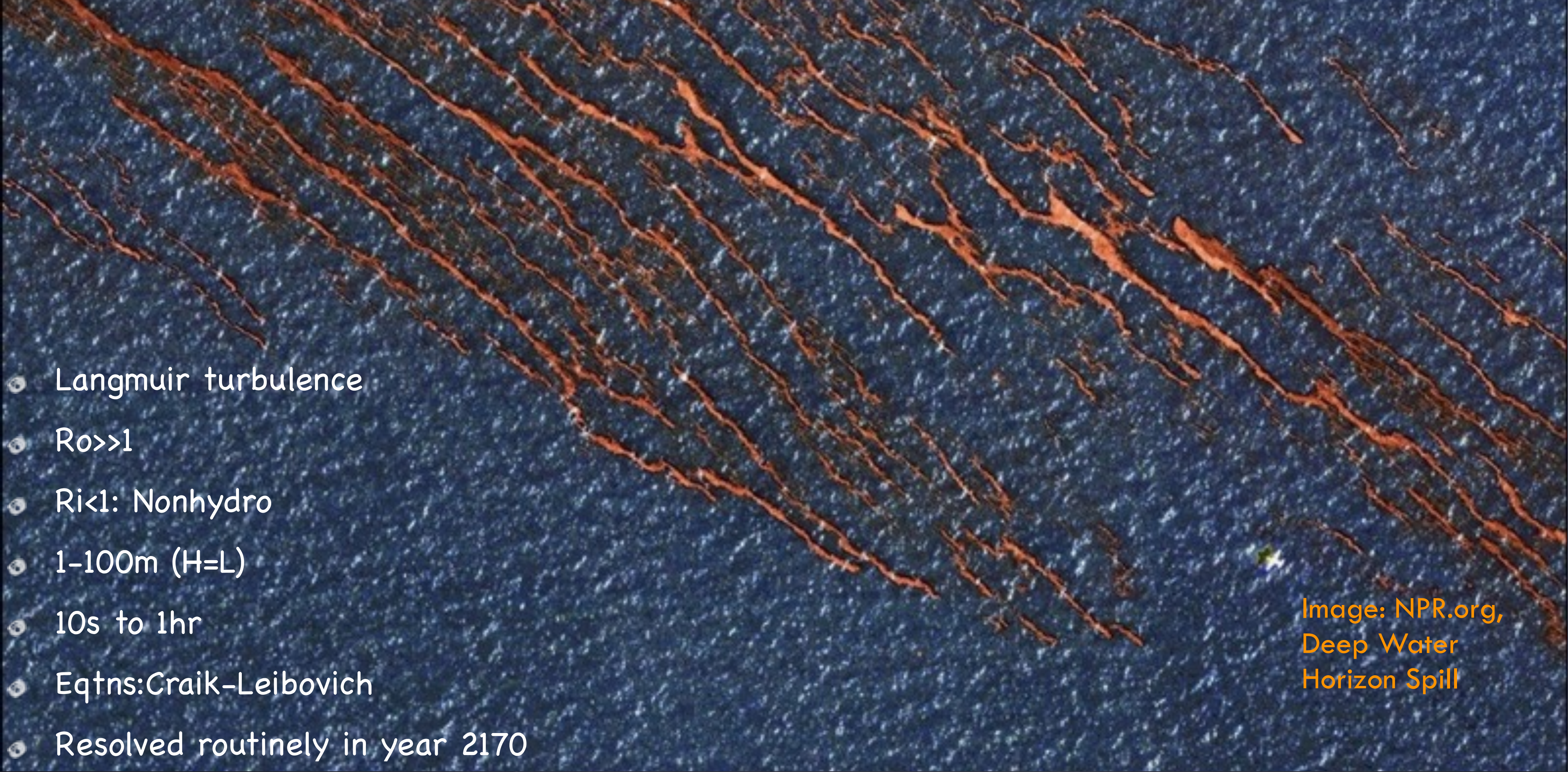


image: Thorpe, 04

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



- Langmuir turbulence
- Ro>>1
- Ri<1: Nonhydro
- 1-100m (H=L)
- 10s to 1hr
- Eqtns:Craik-Leibovich
- Resolved routinely in year 2170

Image: NPR.org, Deep Water Horizon Spill

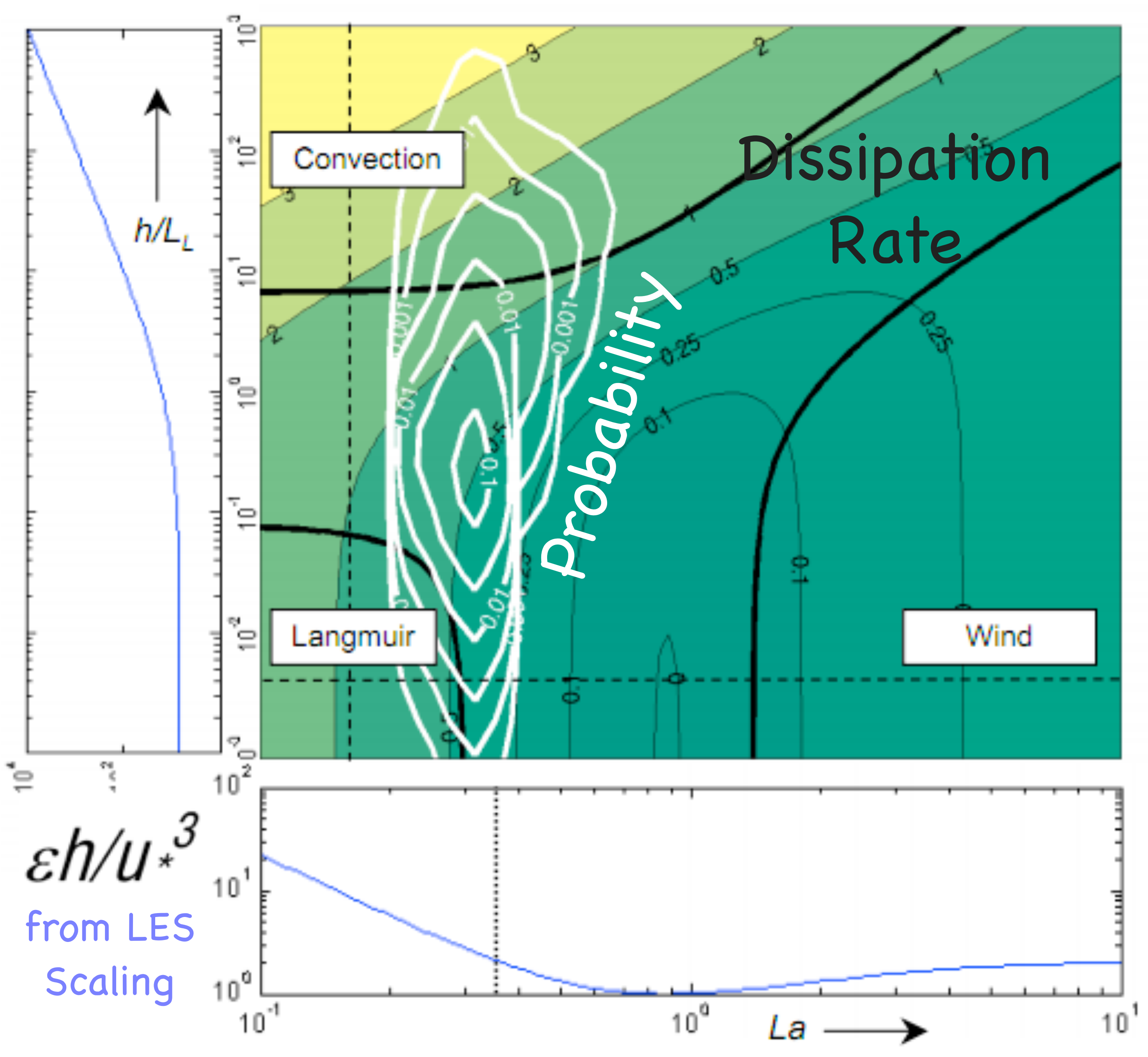
“Wave-forcing and hence Langmuir turbulence could be important over wide areas of the ocean and in all seasons in the Southern Ocean.”

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, September 2012.

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

$$\frac{B_s}{u_*^2 u_s/h} = \frac{w_*^3/h}{w_{*L}^3/h} = \frac{h}{L_L}.$$

$$\frac{u_*^2 u_*/h}{u_*^2 u_s/h} = \frac{u_*^3/h}{w_{*L}^3/h} = La^2.$$



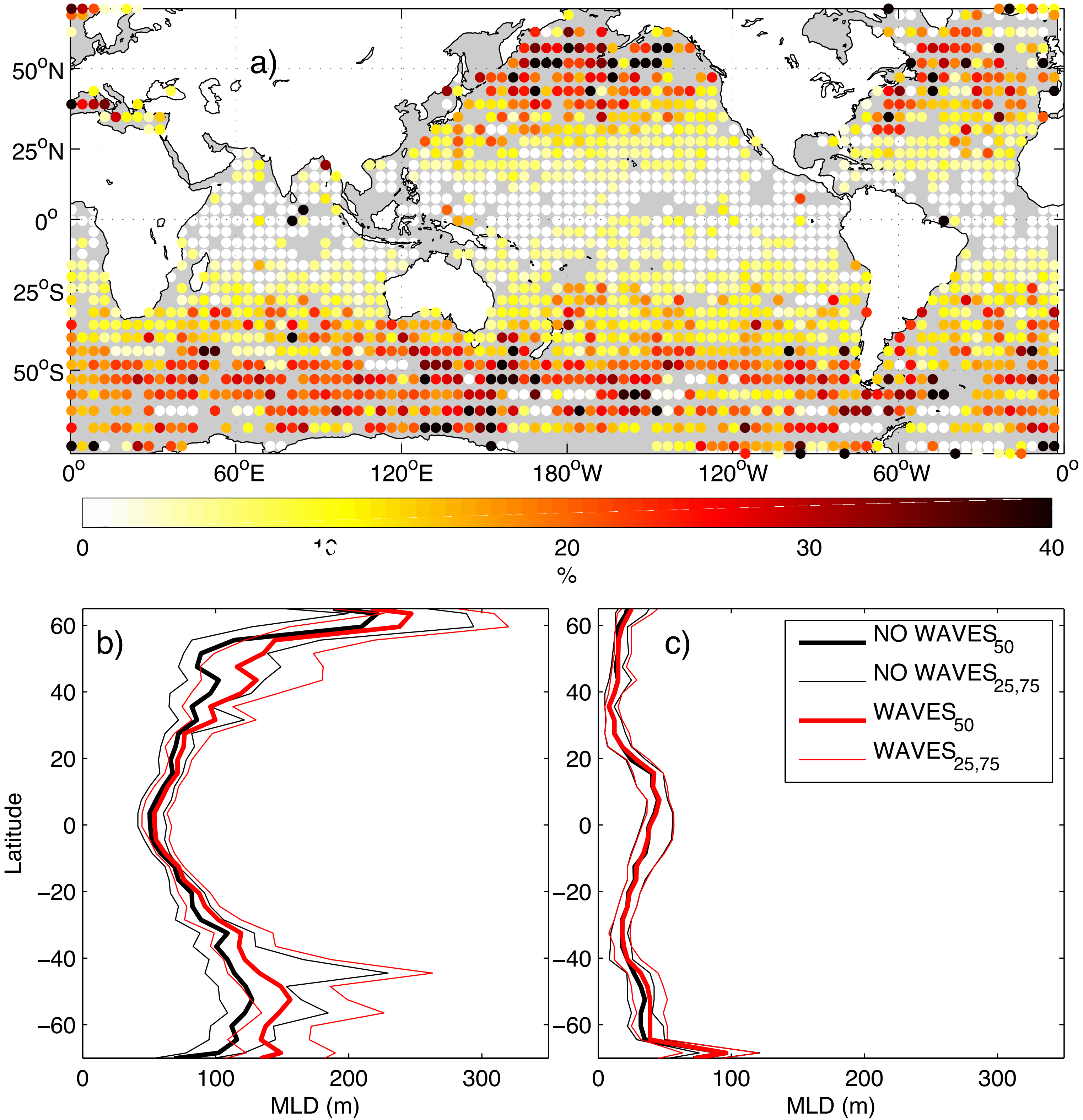
S. E. Belcher, A. A. L. M. Grant, K. E. Hanley, B. Fox-Kemper, L. Van Roekel, P. P. Sullivan, W. G. Large, A. Brown, A. Hines, D. Calvert, A. Rutgersson, H. Petterson, J. Bidlot, P. A. E. M. Janssen, and J. A. Polton. A global perspective on Langmuir turbulence in the ocean surface boundary layer. Geophysical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

Offline observation-driven parameterization:

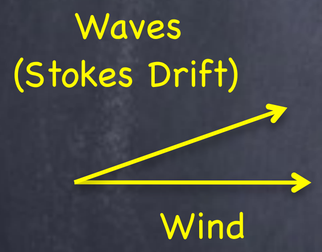
Including Stokes-driven Mixing (Harcourt 2013) Deepens the Mixed Layer!

See Also:
Fan & Griffies (2013)

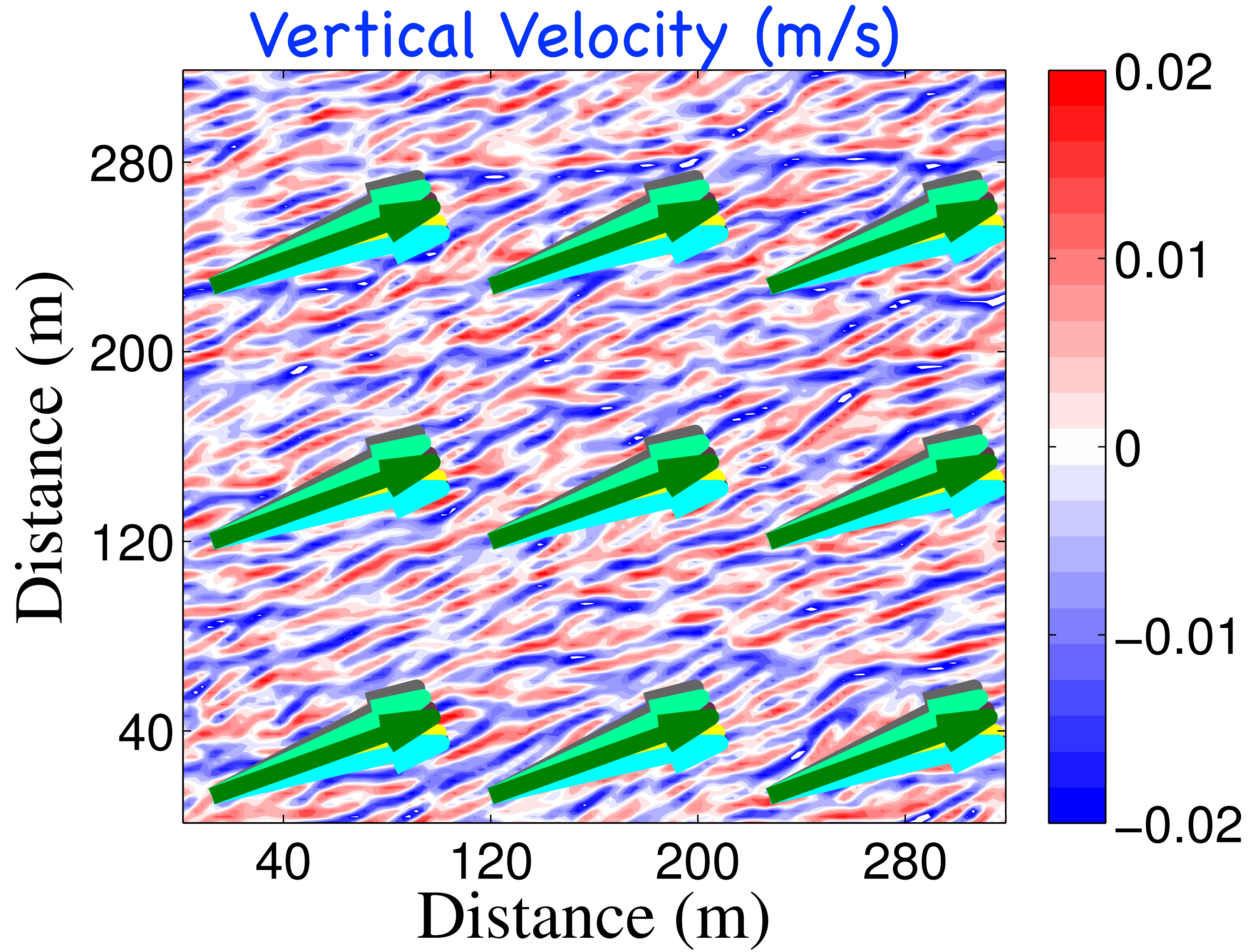
E. A. D'Asaro, J. Thomson, A. Y. Shcherbina, R. R. Harcourt, M. F. Cronin, M. A. Hemer, and B. Fox-Kemper. Quantifying upper ocean turbulence driven by surface waves. Geophysical Research Letters, 41(1): 102-107, January 2014.



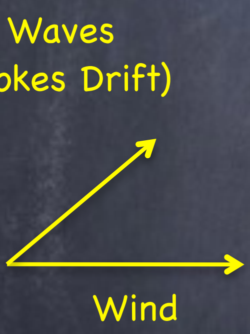
CLB as equations for Large Eddy Simulations: Tricky: Misaligned Wind & Waves

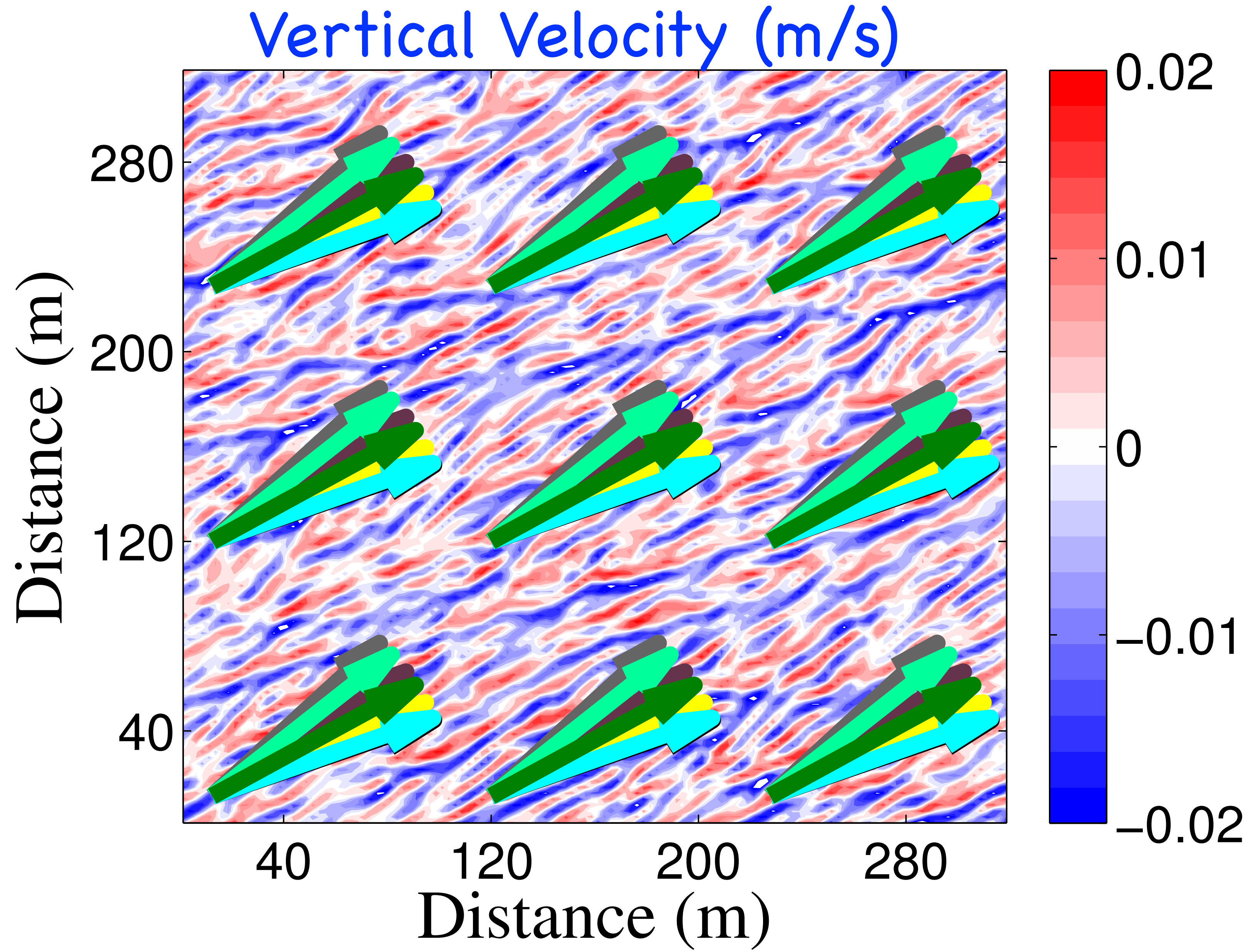


L. P. Van Roekel, B. Fox-Kemper, P. P. Sullivan, P. E. Hamlington, and S. R. Haney. The form and orientation of Langmuir cells for misaligned winds and waves. Journal of Geophysical Research-Oceans, 117:C05001, 22pp, May 2012.



Tricky: Misaligned Wind & Waves





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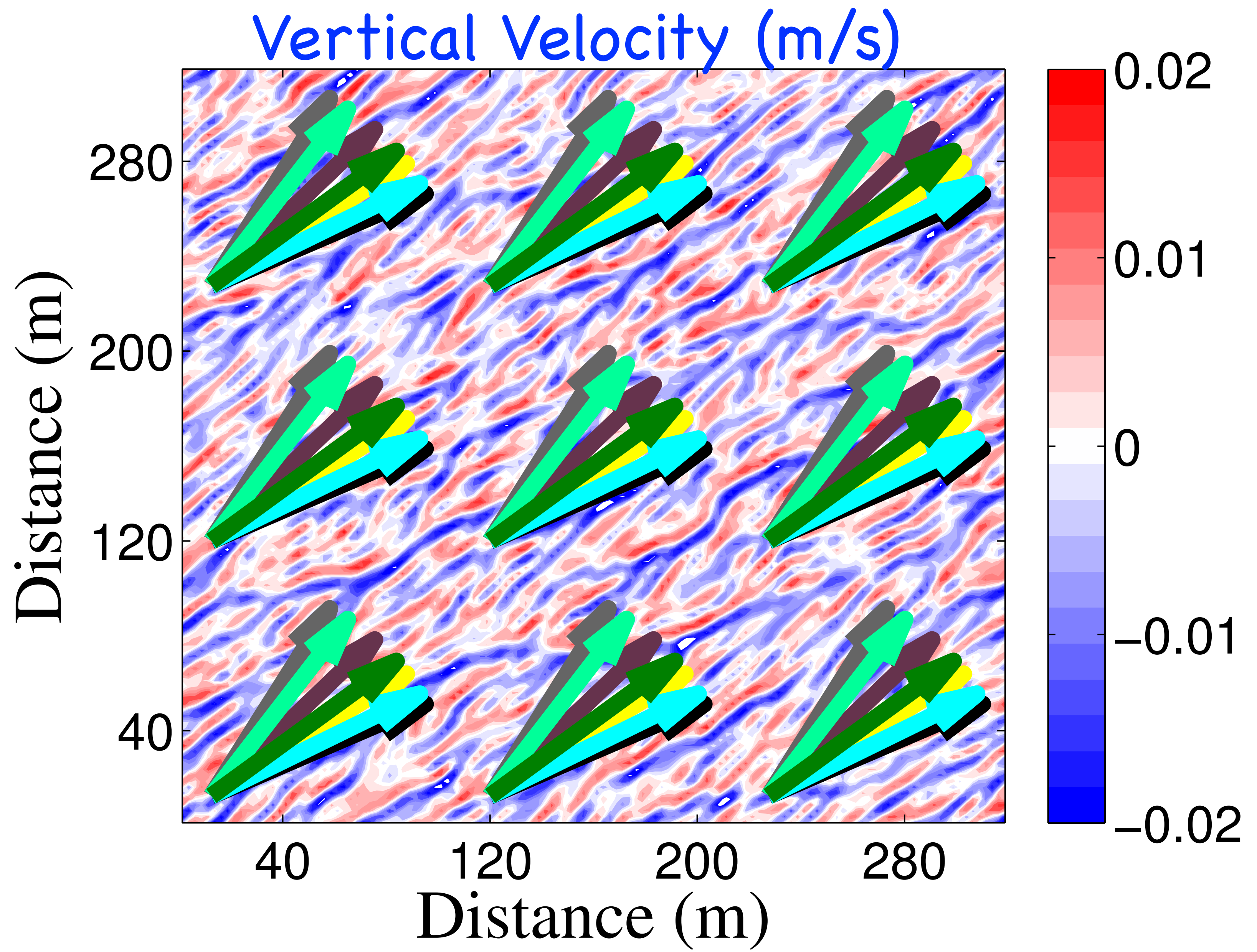

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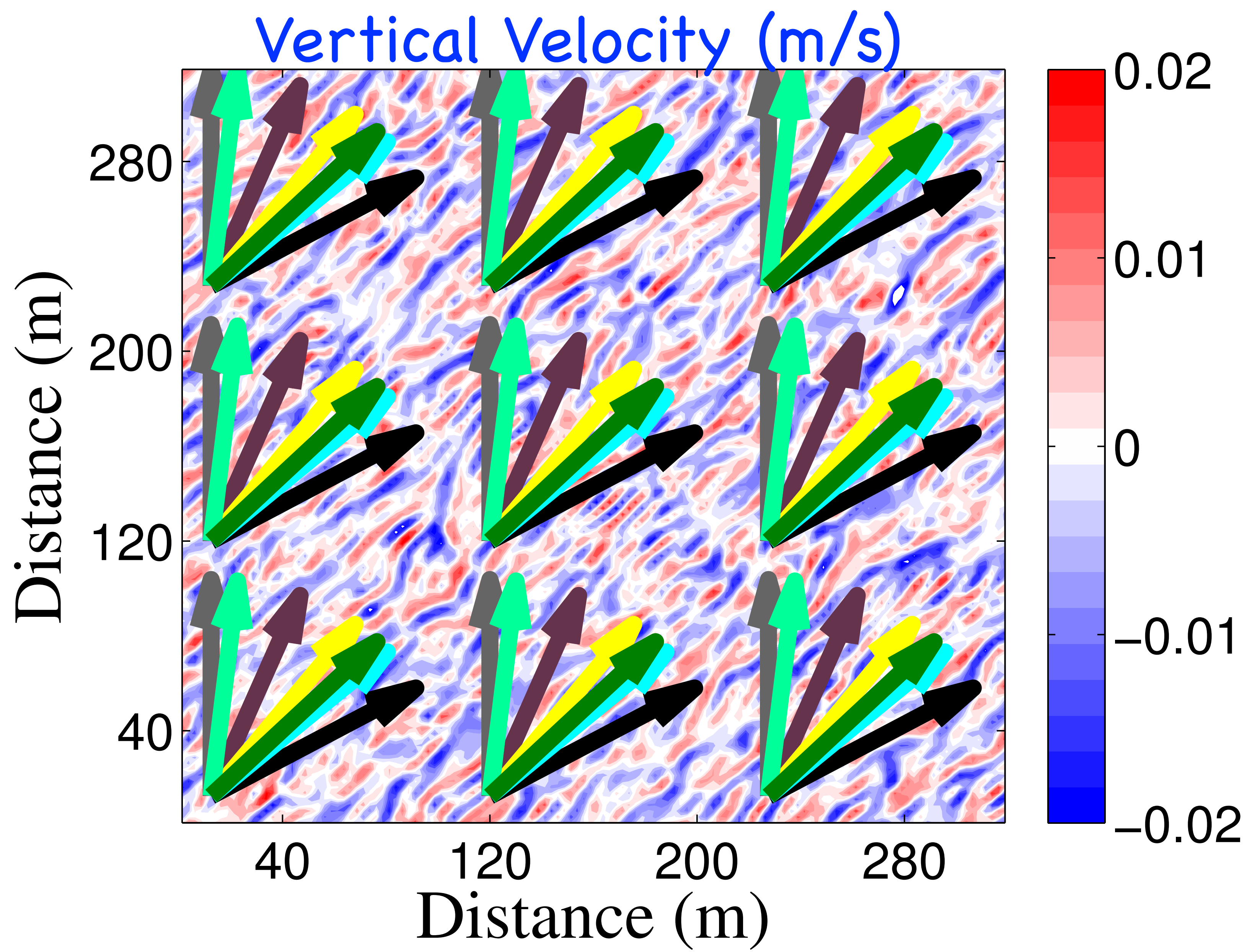


Stokes Depth vs. OSBL Depth

HARCOURT AND D'ASARO

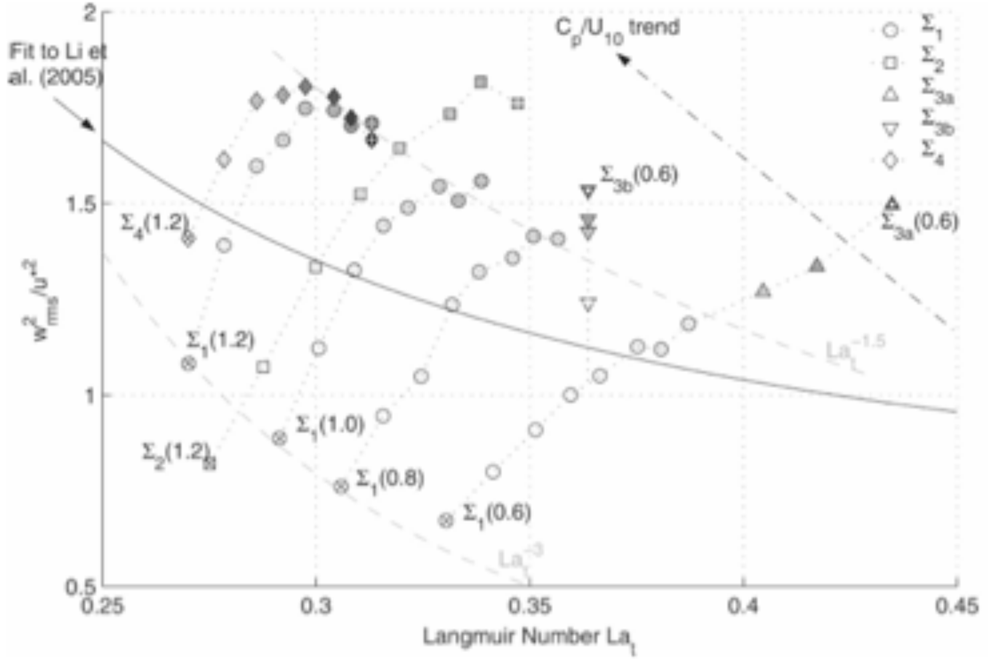


FIG. 6. Bulk u^*-scaled VKE $\langle w^2\rangle/u^{*2}$ vs turbulent Langmuir number La_t for all simulation sets Σ_{1-4}. The symbol type indicates the case number. Simulations within each case with the same wave ages are connected by dotted lines with the wave age in parentheses indicating the wave age for each subset. Relative Stokes depth D^*_S/H_{ML} is mapped in gray shades. Wind speed values are not shown for all cases, but upper and lower U_{10} values are indicated within each age subset "x" (8.3 m s^{-1}), "+" (32.6 m s^{-1}), or "·" (69.9 m s^{-1}). The apparent scaling of Li et al. (2005) from Fig. 1 is included (solid).

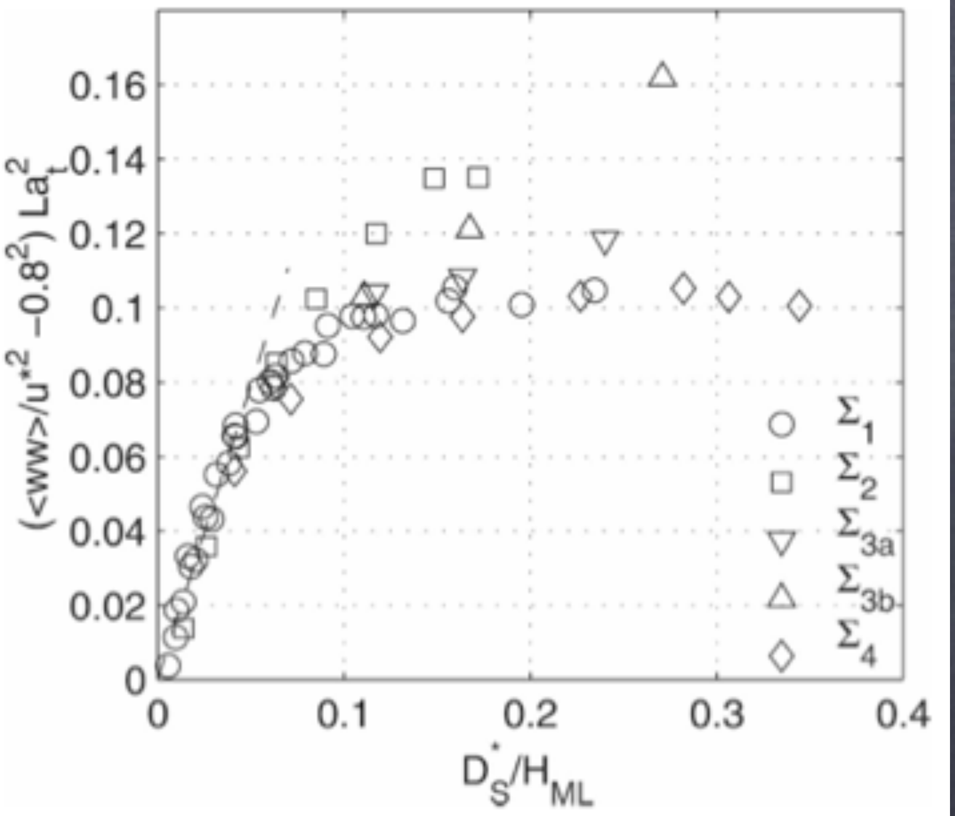


FIG. 7. Elevation of scaled bulk VKE $\langle w^2\rangle/u^{*2}$ above its zero-Stokes $La_t \to \infty$ limit (nominally at 0.8^2) by CL vortex-force production, rescaled by La_t^2, and plotted against nondimensional Stokes depth D^*_S/H_{ML}. The dashed reference line has a slope of 1.6.

R. Harcourt & E.A. D'Asaro, 2008. Large-Eddy Simulation of Langmuir Turbulence in Pure Wind Seas, J. Phys. Oceanogr. 38, 1542-1562.

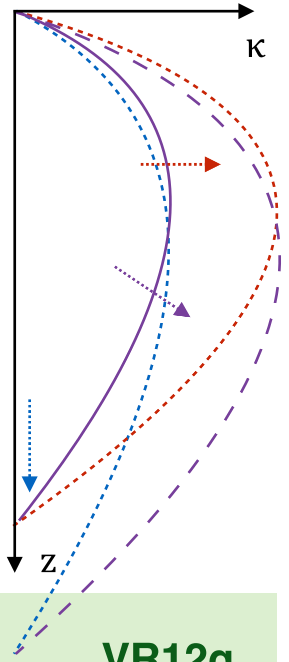
Q. Li, B. F-K, T. Arbetter, A. Webb , 2014. Assessing the Influence of Surface Wind Waves to the Global Climate by Incorporating WAVEWATCH III in CESM, 2014 AGU Ocean Sciences Meeting Poster, related paper in prep.

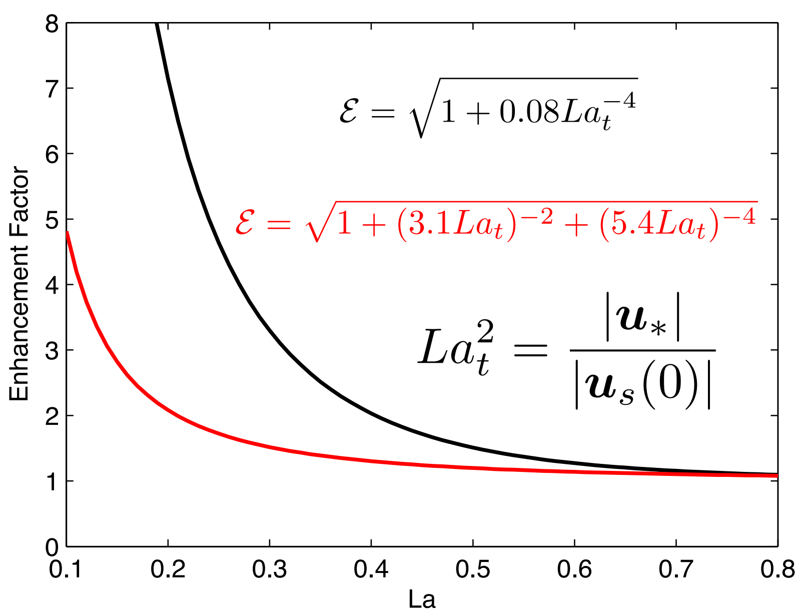
Langmuir Mixing in KPP

Slide Courtesy of Qing Li

- 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

$$W = \frac{kU_*}{\phi}\mathcal{E},$$
$$\kappa_v = W H_k G(-z/H_k).$$





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

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

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

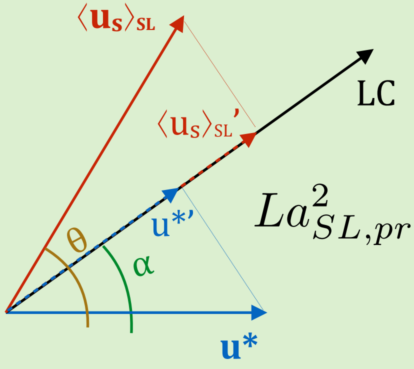
MS2K

VR12a

Enhancement factor to vertical velocity scale W

Aligned wind and waves

VR12g



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

Misaligned wind and waves; Stokes H vs. OSBL

VR12h

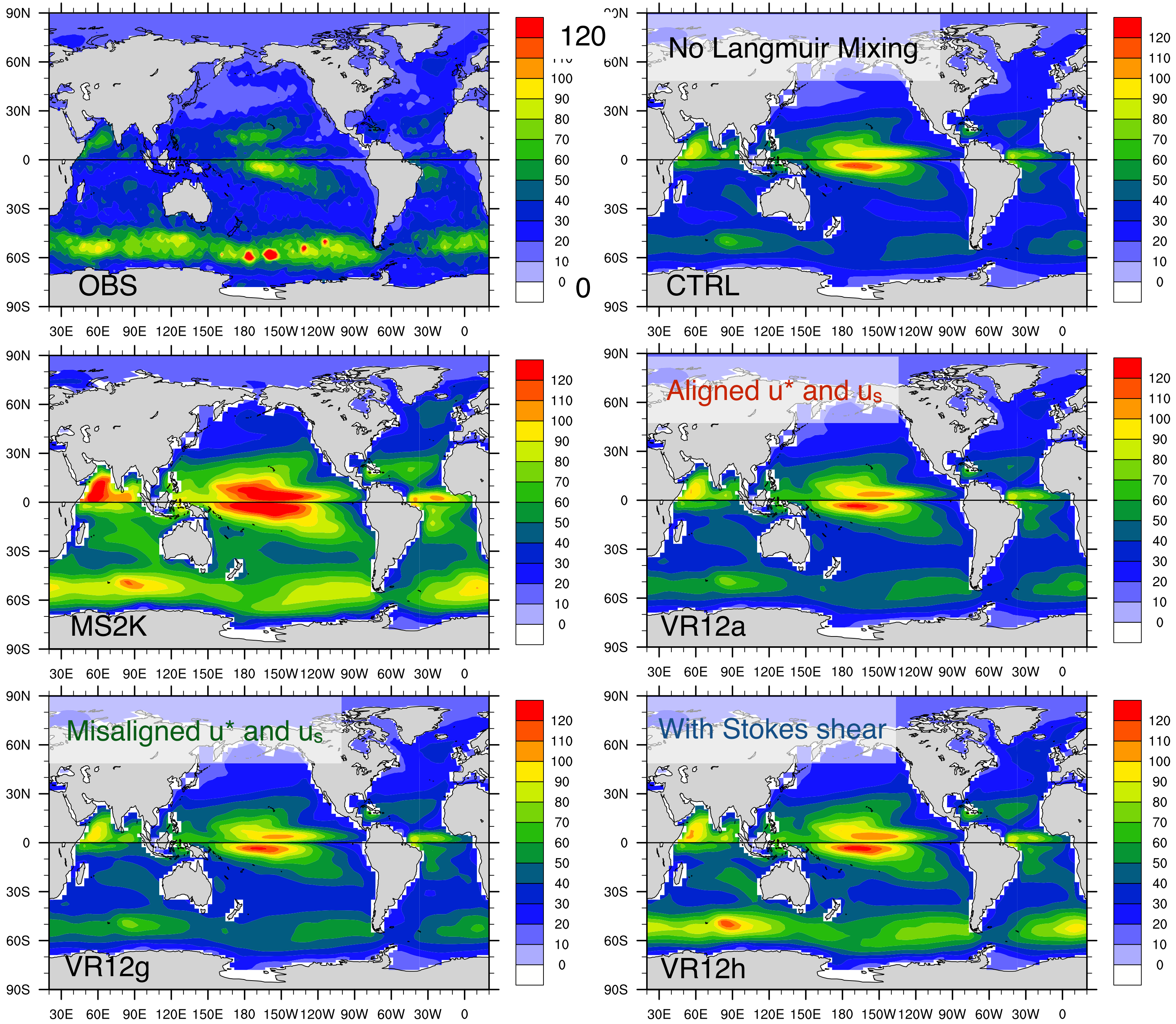
$$Ri_b = \frac{d\,[b_r - b(d)]}{|\langle \boldsymbol{u}_r \rangle - \langle \boldsymbol{u}(d) \rangle|^2 + U_t^2 + |\boldsymbol{u}_s(0)|^2}$$

Including Stokes shear

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

Summer Mixed Layer Depth (JAS for NH & JFM for SH)

Slide Courtesy of Qing Li



RMSE (m)

	CTRL	MS2K	VR12a	VR12g	VR12h
Global	15.63	30.62	16.92	16.36	18.11
20S-20N	17.89	43.56	22.74	21.36	24.97
South of 30S	**19.50**	**20.13**	**15.81**	**15.85**	**14.59**

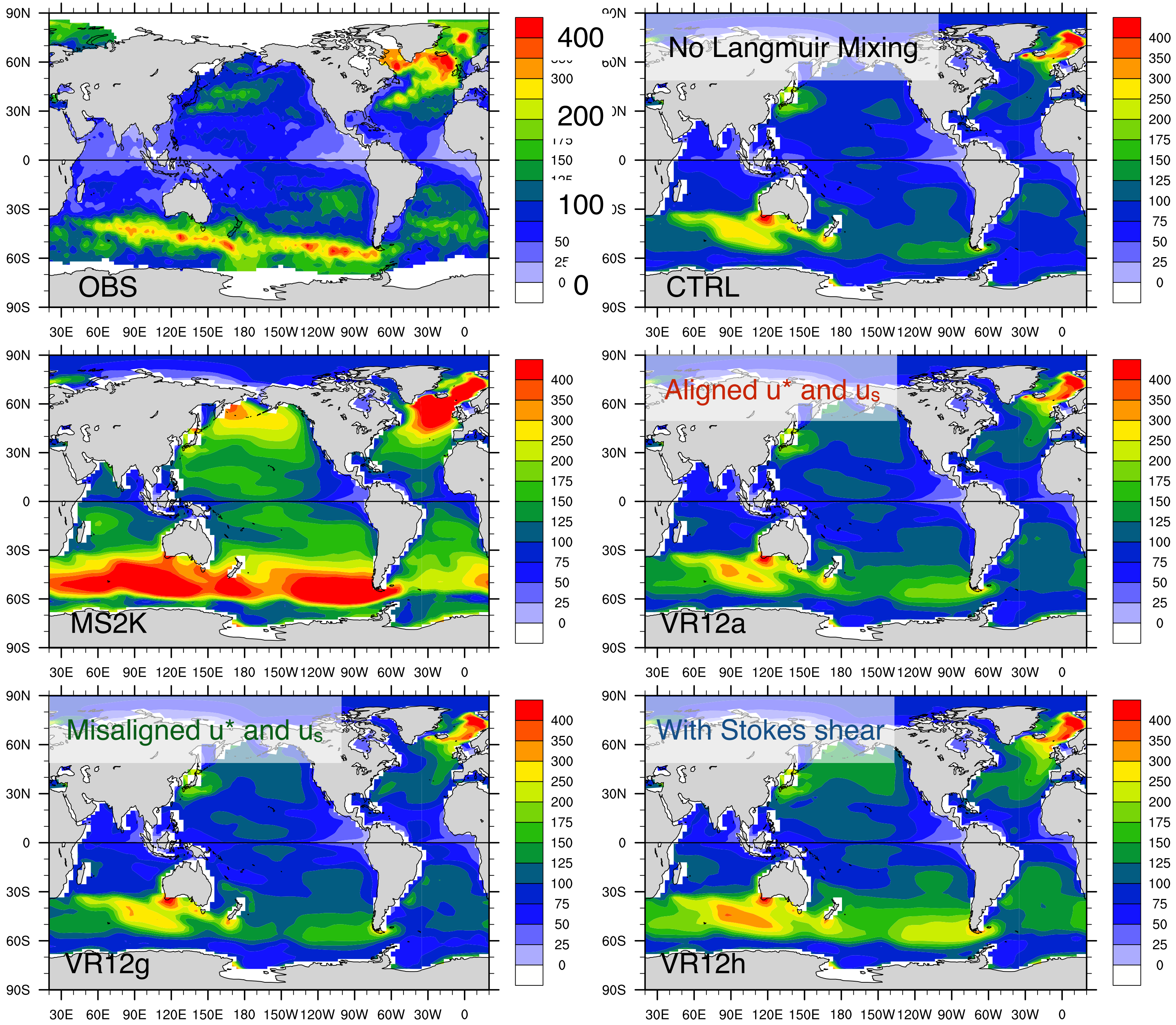
OBS: de Boyer Montégut et al. 2004

Winter Mixed Layer Depth (JFM for NH & JAS for SH)

Slide Courtesy of Qing Li

RMSE (m)

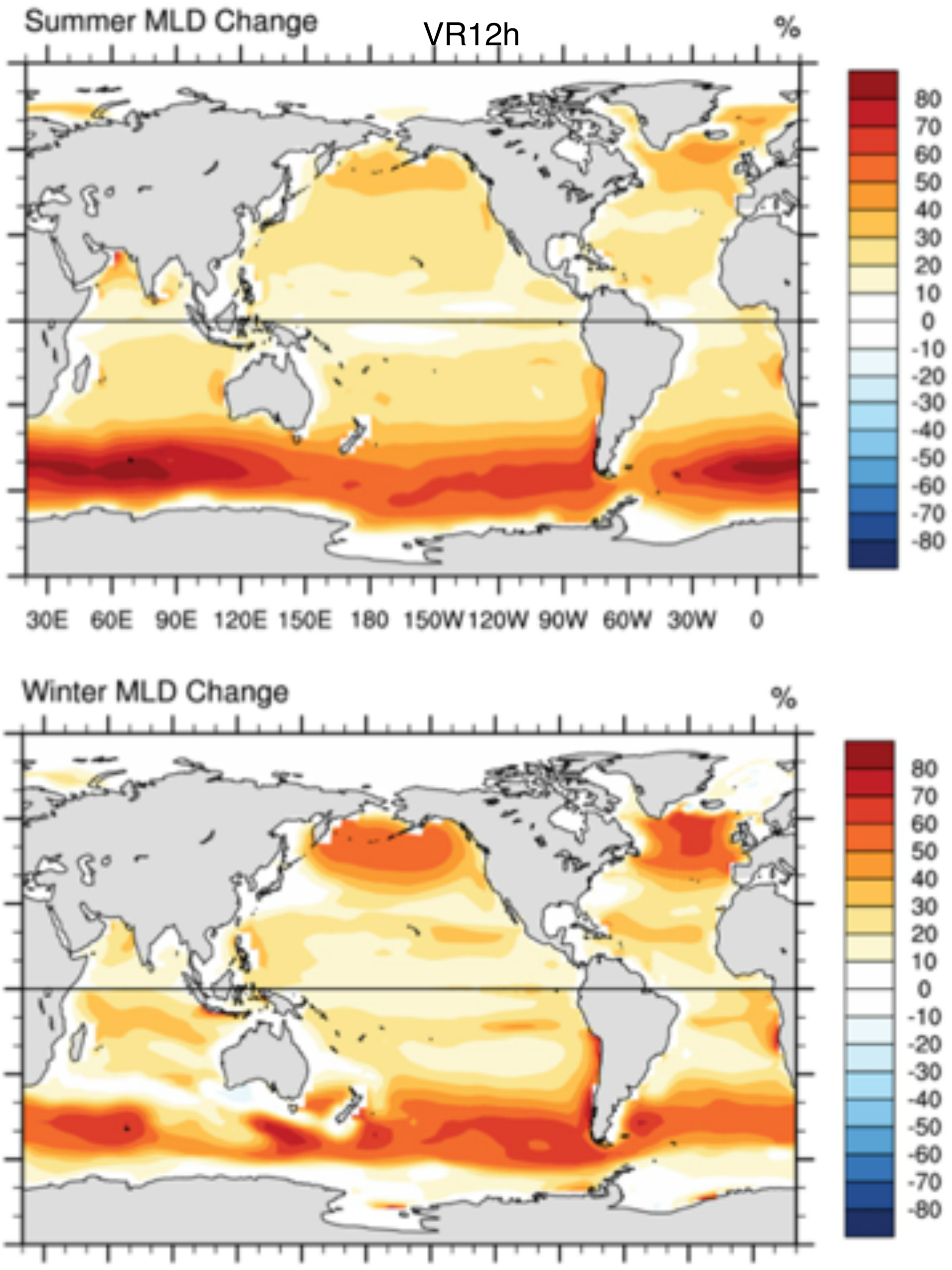
	Global	20S-20N	South of 30S
CTRL	49.70	19.24	62.59
MS2K	129.20	64.57	183.18
VR12a	46.80	26.78	54.36
VR12g	47.69	24.79	56.99
VR12h	48.46	31.24	56.08



OBS: de Boyer Montégut et al. 2004

Including Stokes-driven Mixing in CESM, too!

(with another param.: Harcourt & D'Asaro, 2008; Van Roekel et al, 2012)



LES-w^2

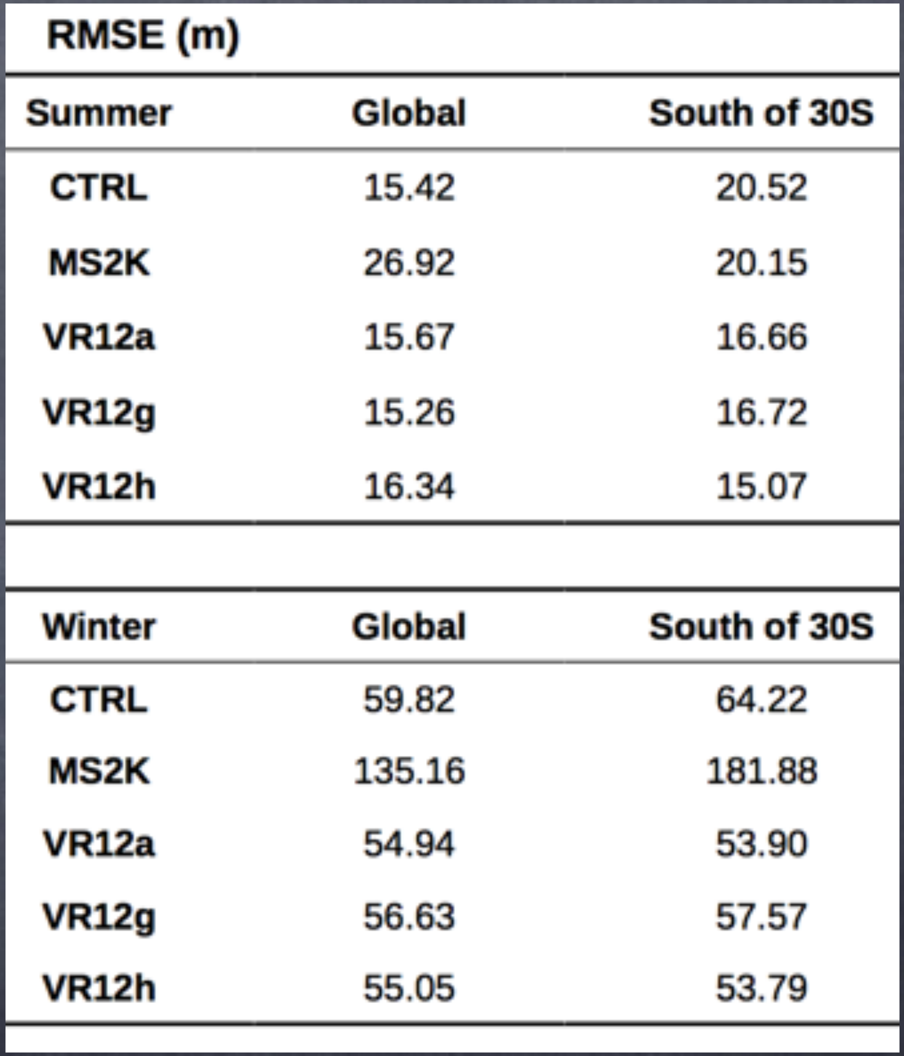
Depth & misaligned

& Crit. Ri

LES-w^2

Depth & misaligned

& Crit. Ri



RMSE (m)

Summer	Global	South of 30S
CTRL	15.42	20.52
MS2K	26.92	20.15
VR12a	15.67	16.66
VR12g	15.26	16.72
VR12h	16.34	15.07

Winter	Global	South of 30S
CTRL	59.82	64.22
MS2K	135.16	181.88
VR12a	54.94	53.90
VR12g	56.63	57.57
VR12h	55.05	53.79

Remains to be co-tuned with mixed layer eddy, mesoscale, and near-inertial mixing parameterizations

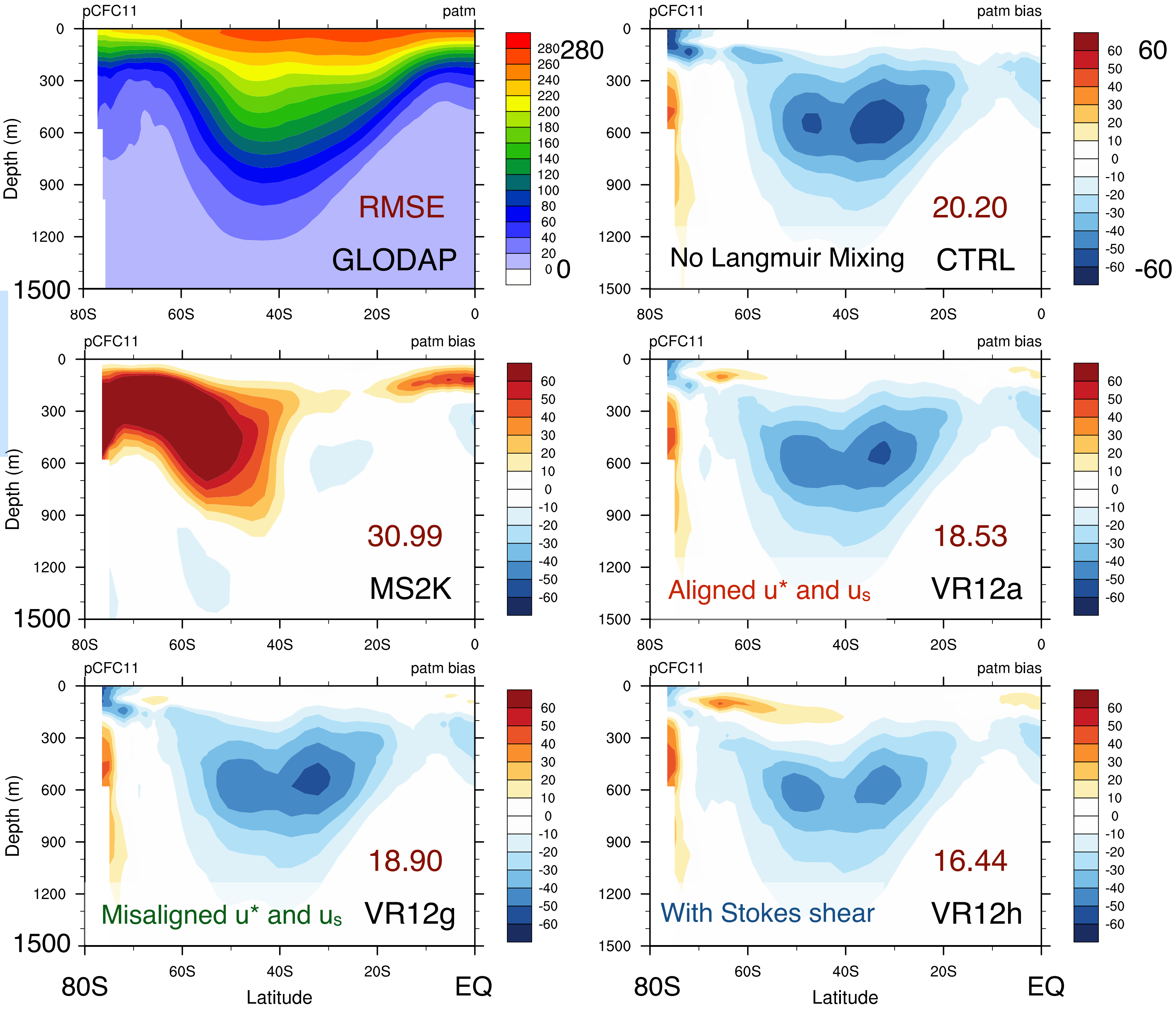
Q. Li, B. F-K, T. Arbetter, A. Webb , 2014. Assessing the Influence of Surface Wind Waves to the Global Climate by Incorporating WAVEWATCH III in CESM, 2014 AGU Ocean Sciences Meeting Poster, related paper in prep.

pCFC11 Bias

Slide Courtesy of Qing Li

Southern
Hemisphere

RMSEs are reduced by **6% ~ 18%**



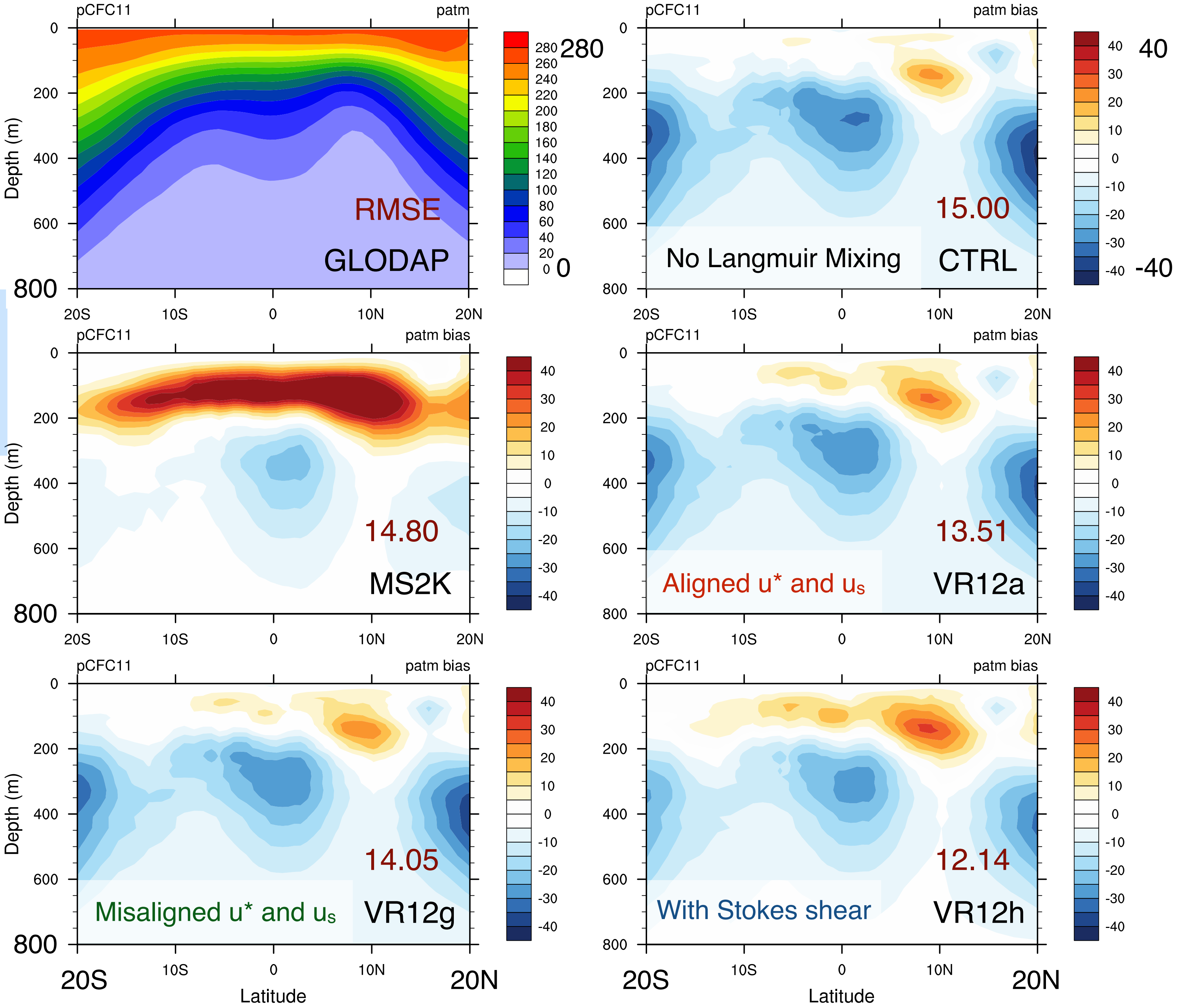
GLODAP: Key et al. 2004

pCFC11 Bias

Slide Courtesy of Qing Li

Equatorial Region

RMSEs are reduced by **6% ~ 19%**



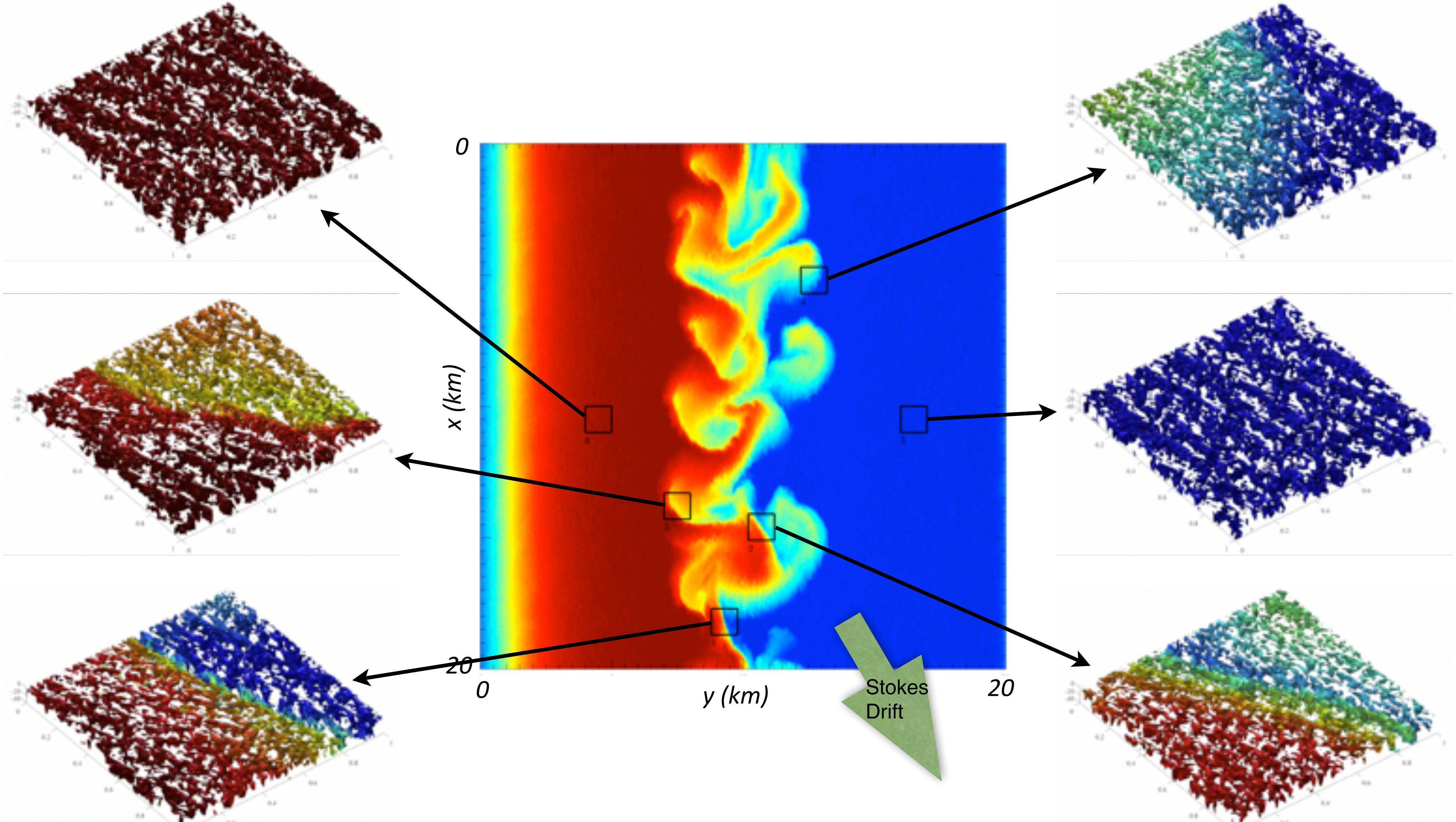
GLODAP: Key et al. 2004

1/2 Conclusions

All papers at: fox-kemper.com/pubs

- Stokes forces affect OSBL turbulence, enchancing W by up to a factor of 2.
- A number of similar parameterizations are now in testing for next generation of CMIP models.
- OSBL is deepened *consistently in all cases* in the S. Ocean especially, in both summer and winter.
- Bias vs. observations is reduced, with RMSE decreasing by roughly 20% south of 30S, and staying constant overall.
- CFC-11 bias is substantially reduced in both S. Hemisphere and equatorial region.
- Overall: Stokes-driven turbulence is important!!

Diverse types of interaction



Slide & Movies by Peter Hamlington

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

Dimensionless Boussinesq

Spanning Mesoscale to Stratified Turbulence

following McWilliams (85)

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

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

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

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

Plus boundary conditions

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

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

Wave-Averaged Equations

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

following Lane et al. (07), McWilliams & F-K (13)
and Suzuki & F-K (14)

(for horizontally uniform Stokes drift)

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

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

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

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

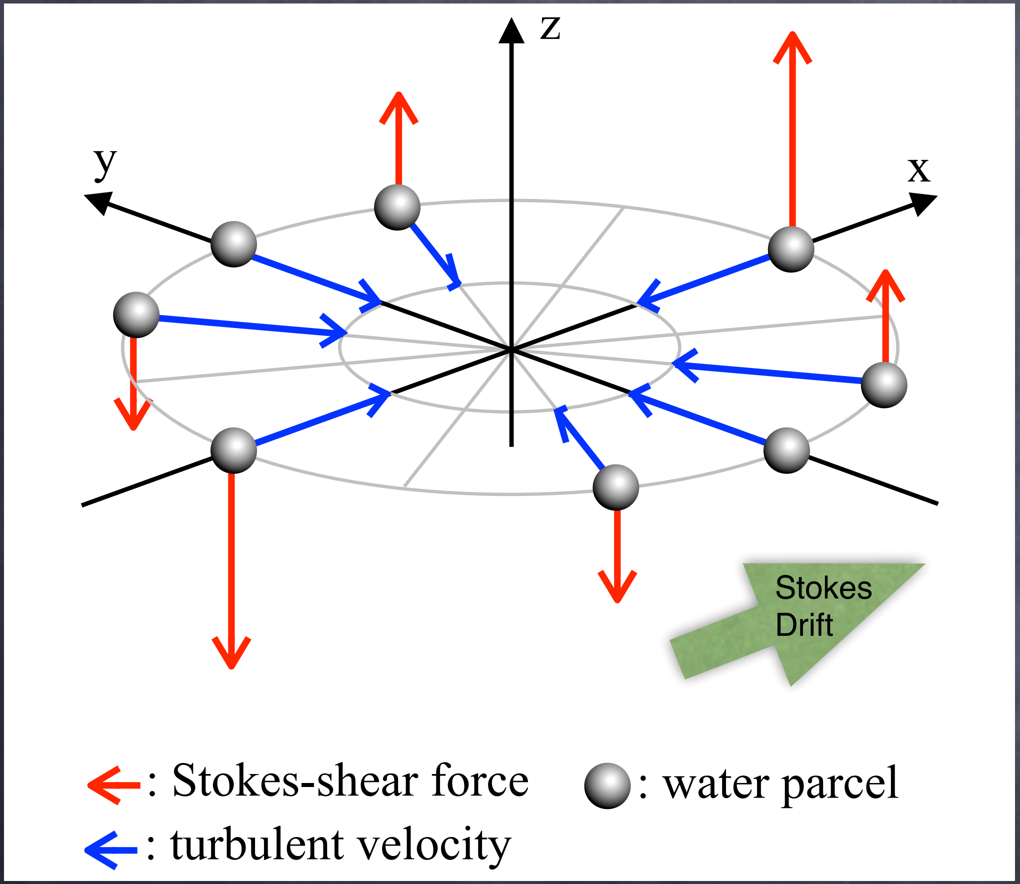
Plus boundary
conditions

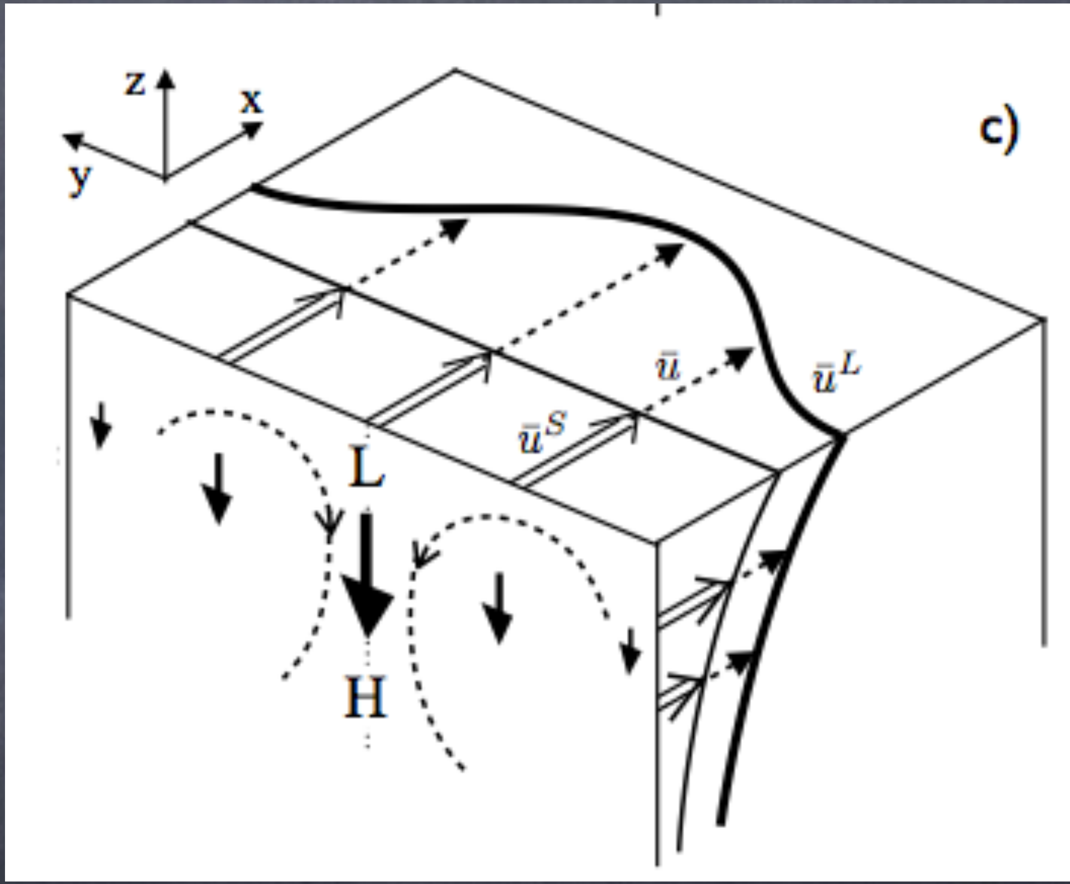
LAGRANGIAN (Eulerian+Stokes) advection & Coriolis

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

Stokes Shear Force
and the CL2 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 B. F-K. Understanding Stokes Forces in the Wave-Averaged Equations, JPO, in prep, 2014.

Stokes forcing of the (Sub)mesoscale

(Capet et al., 2008)

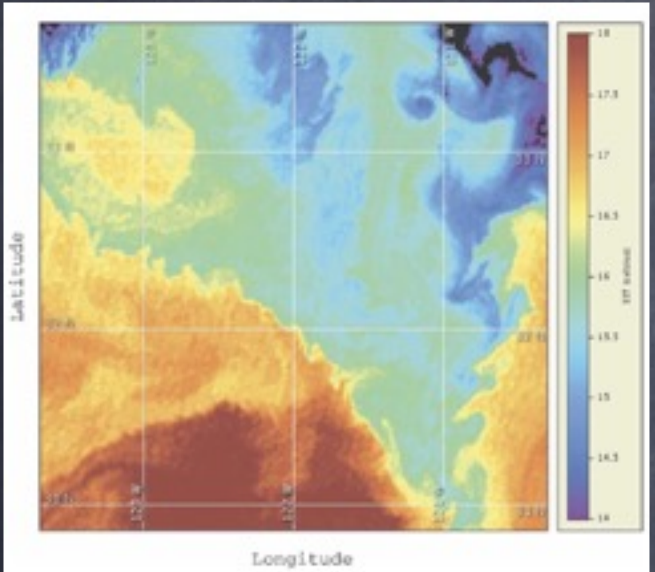
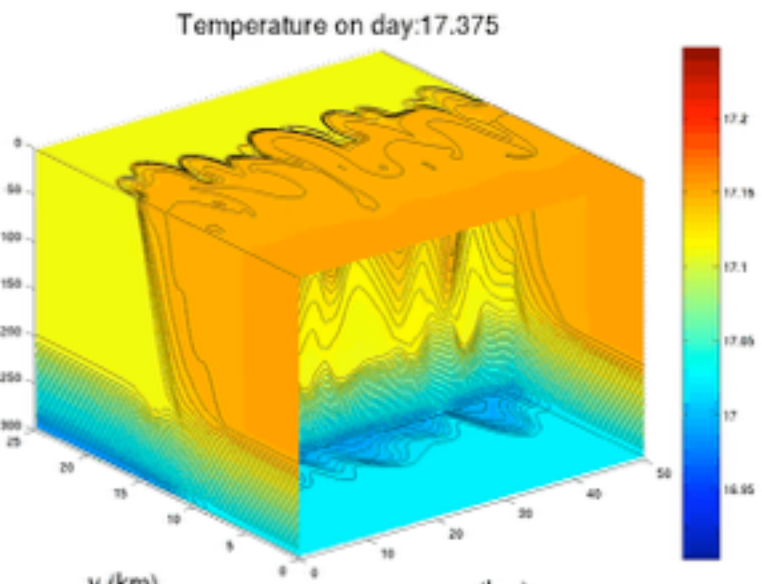
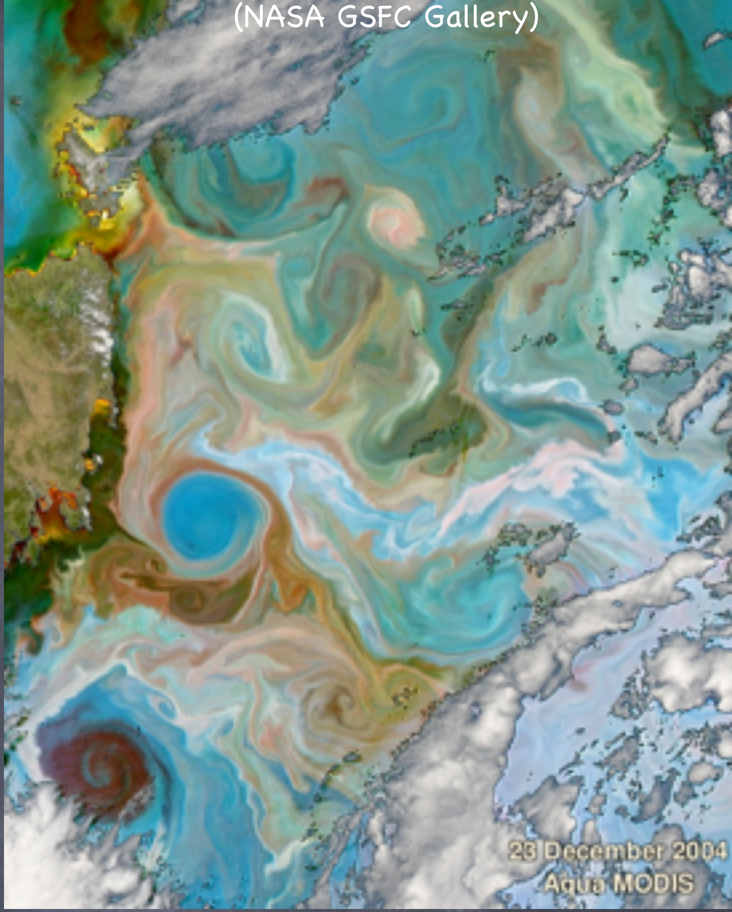


FIG. 16. Sea surface temperature measured at 1832 UTC 3 Jan 2006 off Point Conception in the California Current from CoastWatch (http://coastwatch.pfeg.noaa.gov). The fronts between recently



- Fronts (mesoscale & submesoscale)
- Eddies
- Ro=O(1)
- Ri=O(1)
- near-surface
- 1-10km, days
- Resolved: yr 2050 to 2100

← 10 km



(NASA GSFC Gallery)

B. F-K, 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. F-K. Eddy parameterization challenge suite. I: Eady spindown. Ocean Modelling, 64:12-28, 2013

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

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

- Isopycnal slope is O(0.1—0.01) for submesoscale
- Isopycnal slope is O(0.0001) for mesoscale

Consider perturbing from geostrophic, hydrostatic soln:

$$\phi = \phi_{00000} + \varepsilon\phi_{10000} + Ro\,\phi_{01000} + \frac{1}{\sqrt{Ri}}\,\phi_{00100} + \frac{\alpha^2}{\sqrt{Ri}}\,\phi_{00010} + \frac{1}{Re}\,\phi_{00001}$$

$$+\,\varepsilon^2\phi_{20000} + \varepsilon Ro\,\phi_{11000} + Ro^2\,\phi_{02000} + \frac{Ro}{\sqrt{Ri}}\,\phi_{01100} + \ldots$$

$$+\,O(Ro^3)$$

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

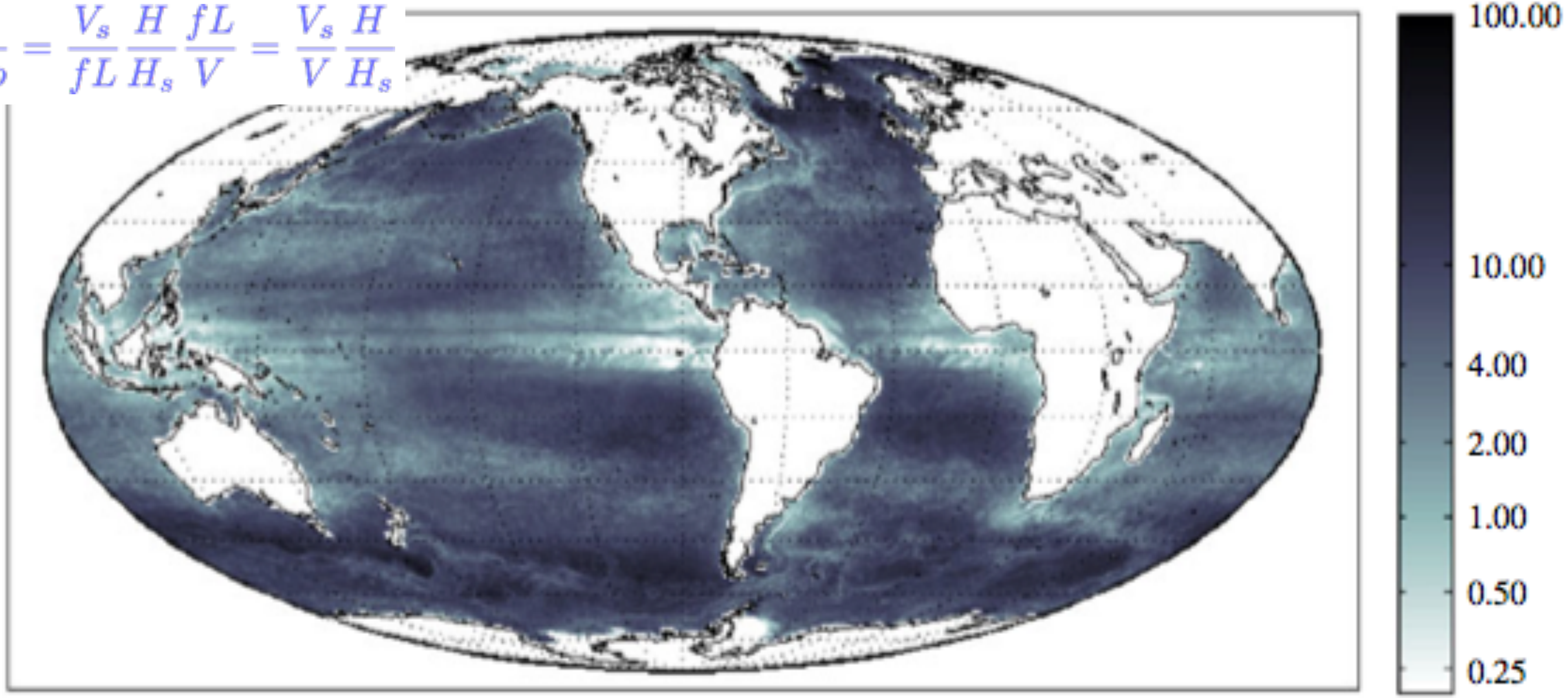
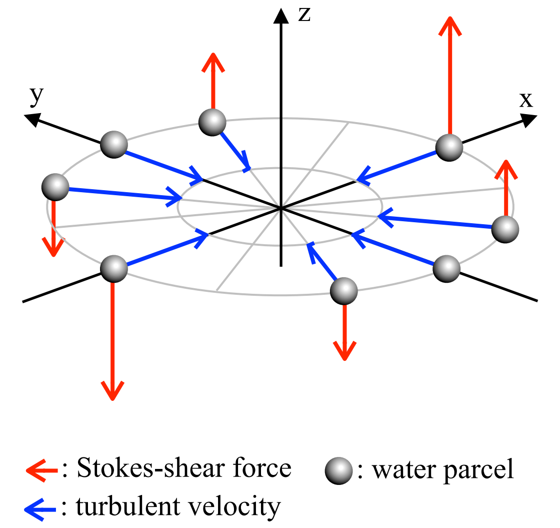
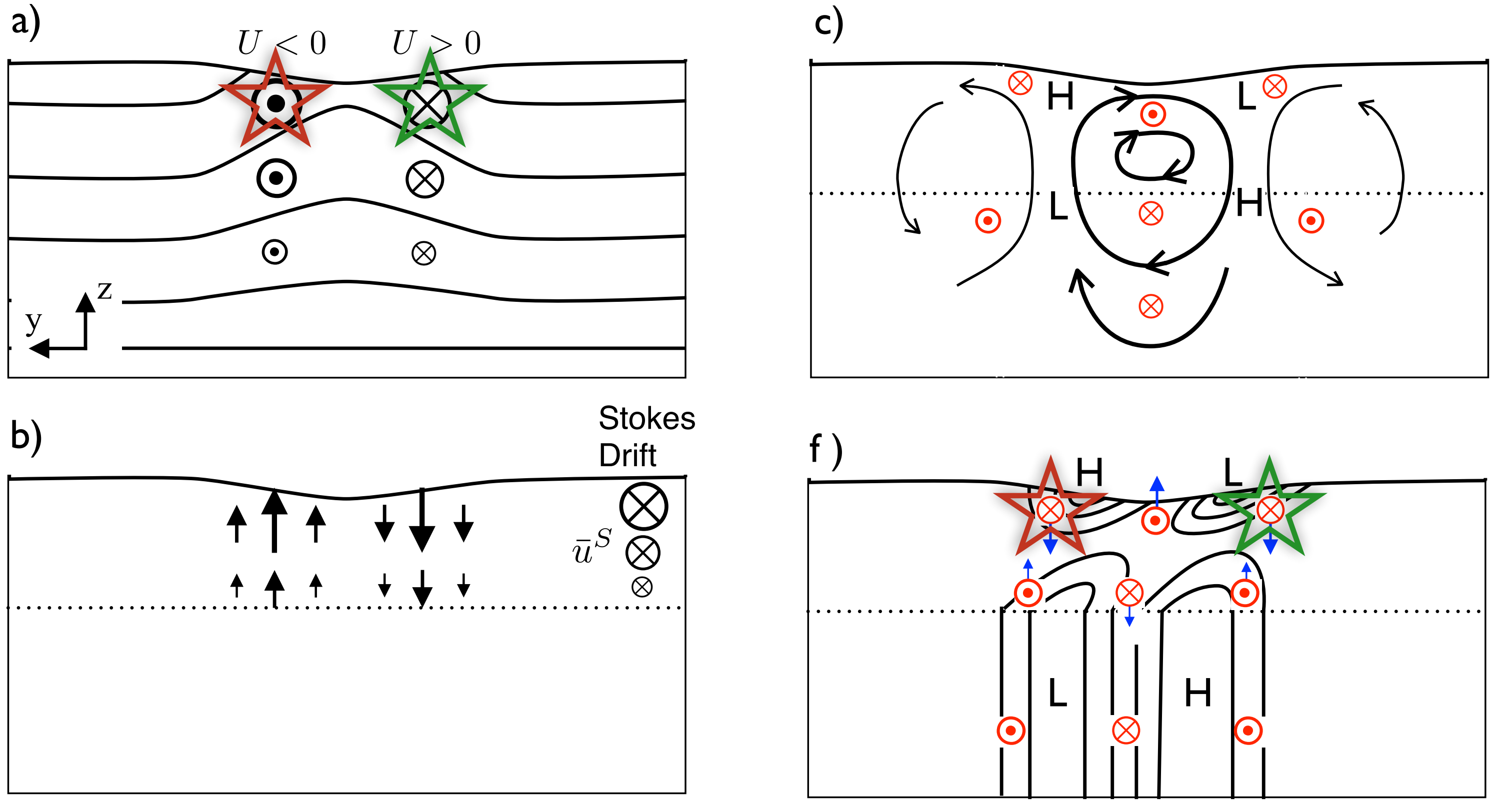


FIGURE 1. (Colour online) Estimated ratio $\epsilon/\mathscr{R} \approx (|\boldsymbol{u}_s \cdot \boldsymbol{u}|h)/(|\boldsymbol{u}|^2 h_s)$ governing the relative importance of Stokes effects versus nonlinearity. Eulerian velocity ($\boldsymbol{u}$) is taken as the

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 on Submesoscale Cold Filament





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

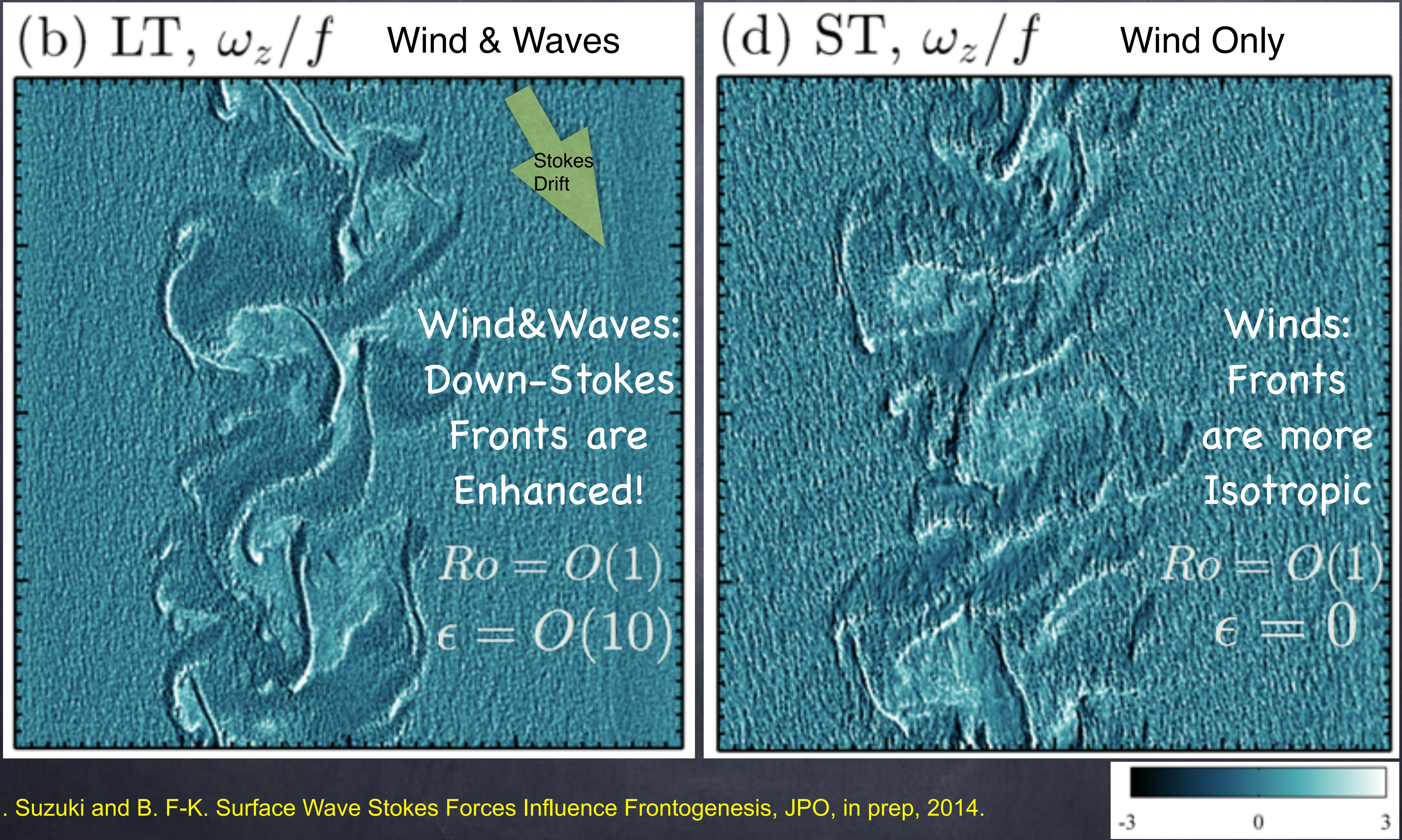
N. Suzuki and B. F-K. Understanding Stokes Forces in the Wave-Averaged Equations, In prep, 2014.

Enhances Fronts for Down-Front Stokes

Opposes Fronts for Up-Front Stokes

Are Fronts and Filaments different with Stokes shear force?

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



Wind&Waves: Down-Stokes Fronts are Enhanced!

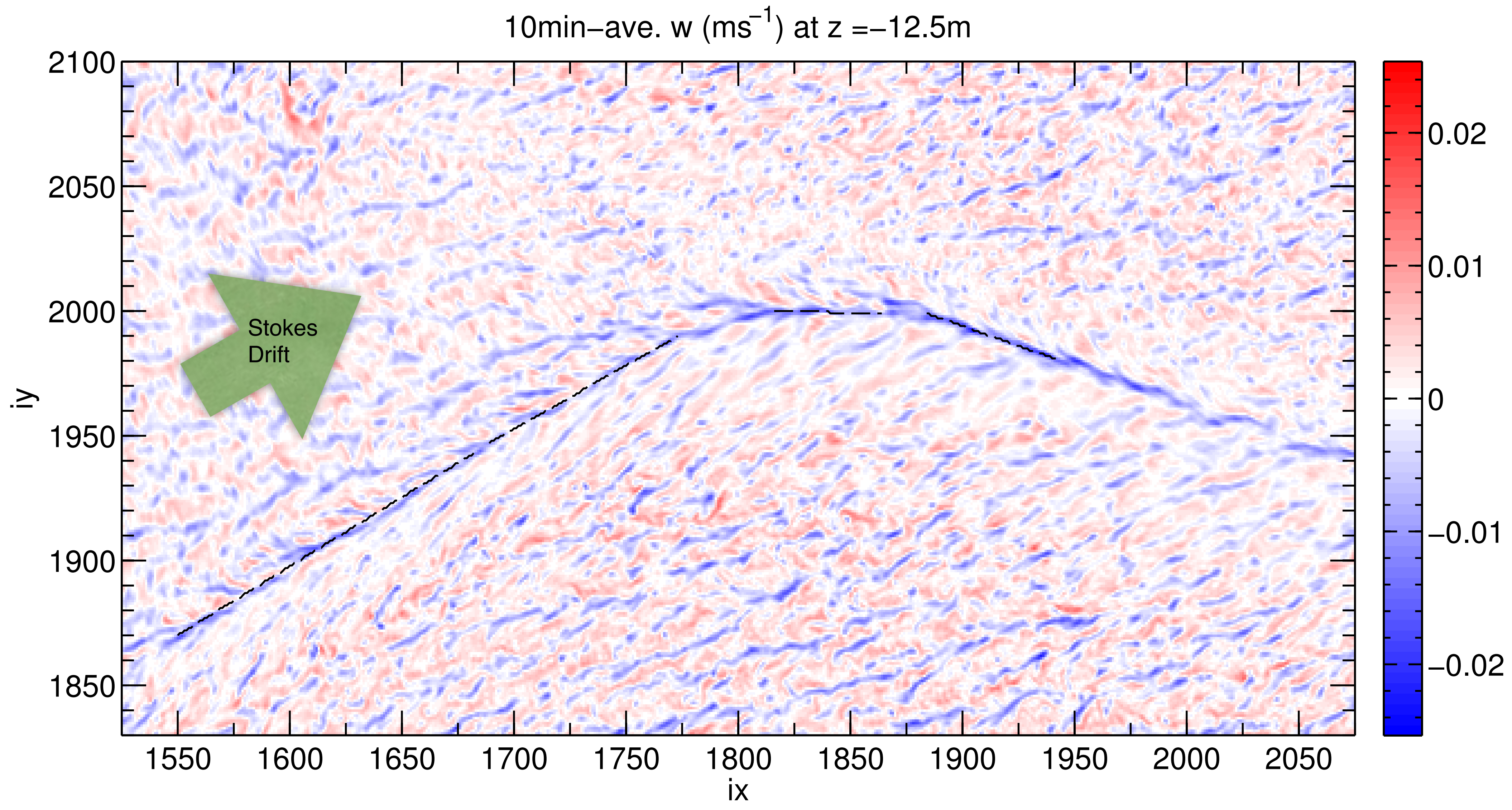
Winds: Fronts are more Isotropic

N. Suzuki and B. F-K. Surface Wave Stokes Forces Influence Frontogenesis, JPO, in prep, 2014.

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

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

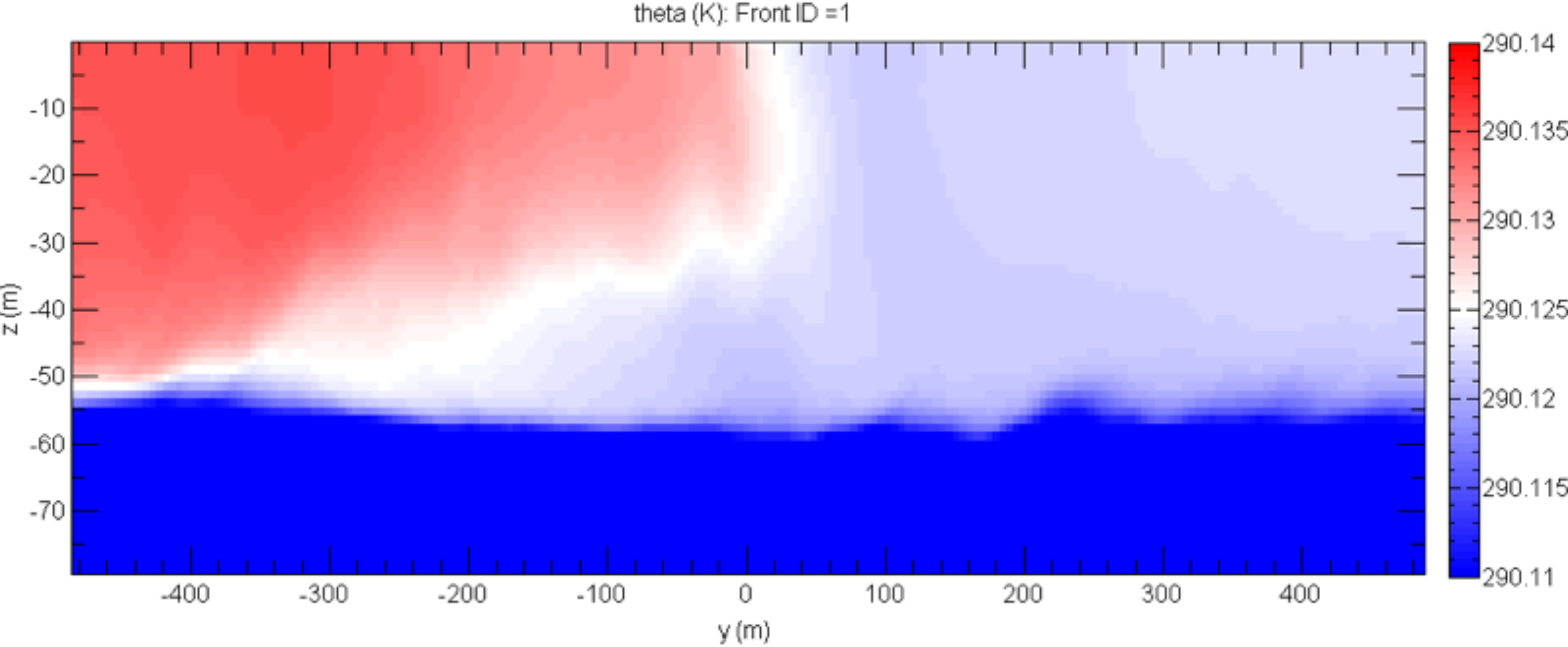
Let's examine a particular front with $\varepsilon = \dfrac{V^s H}{f L H_s} \approx 20$

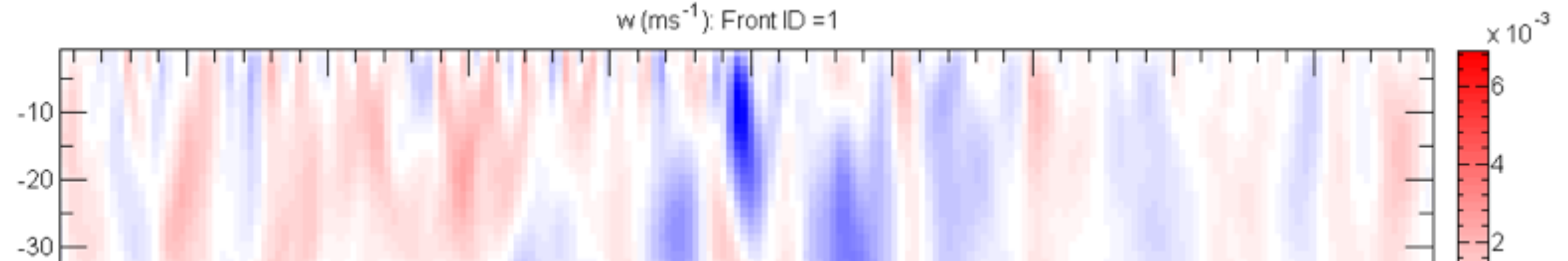


N. Suzuki and B. F-K. Stokes Drift of Surface Waves Influences Frontogenesis, JPO, in prep, 2014.

Along-Front and 10min Average

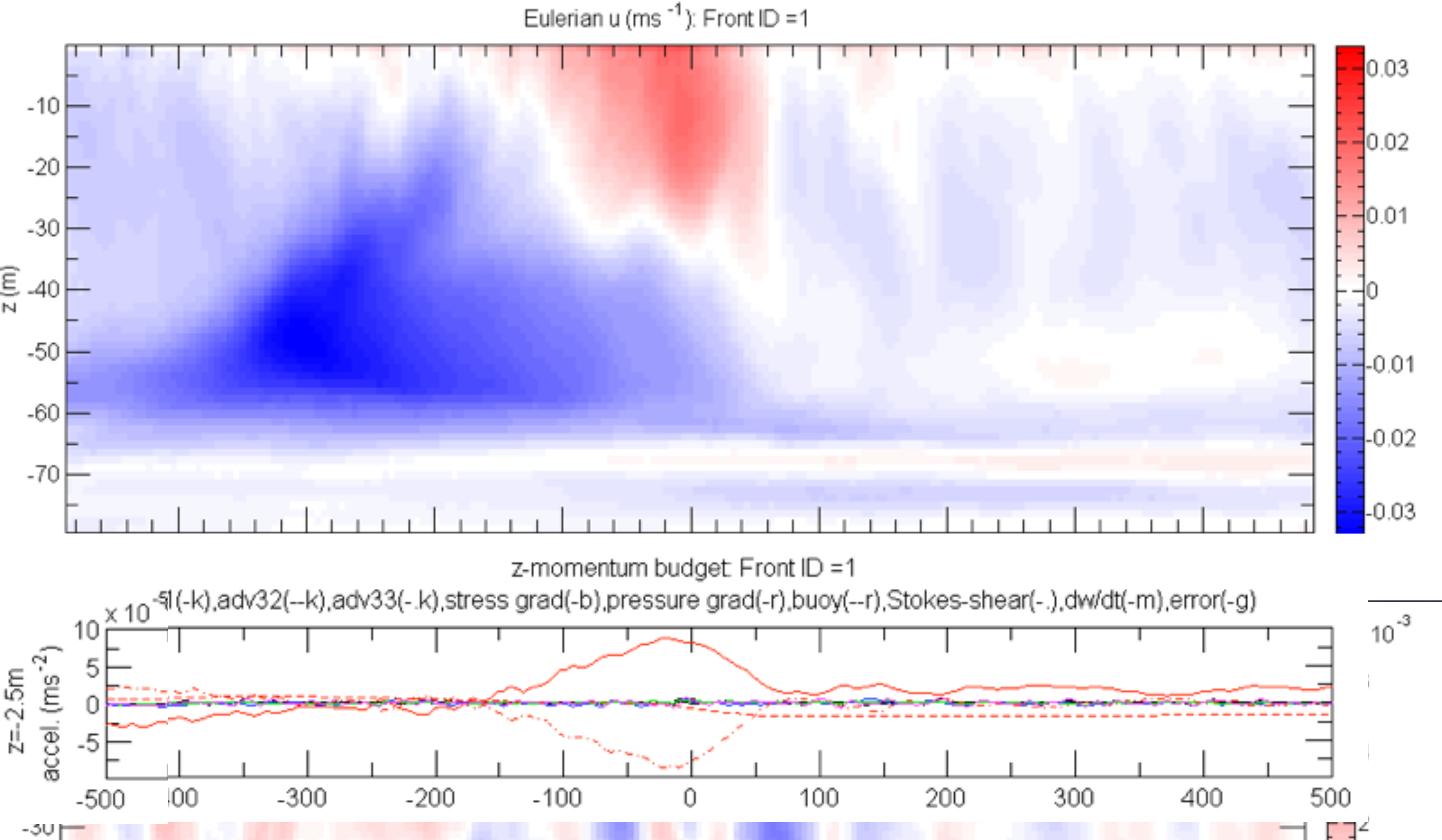
$$\varepsilon = \frac{V^s H}{f L H_s} \approx 20$$





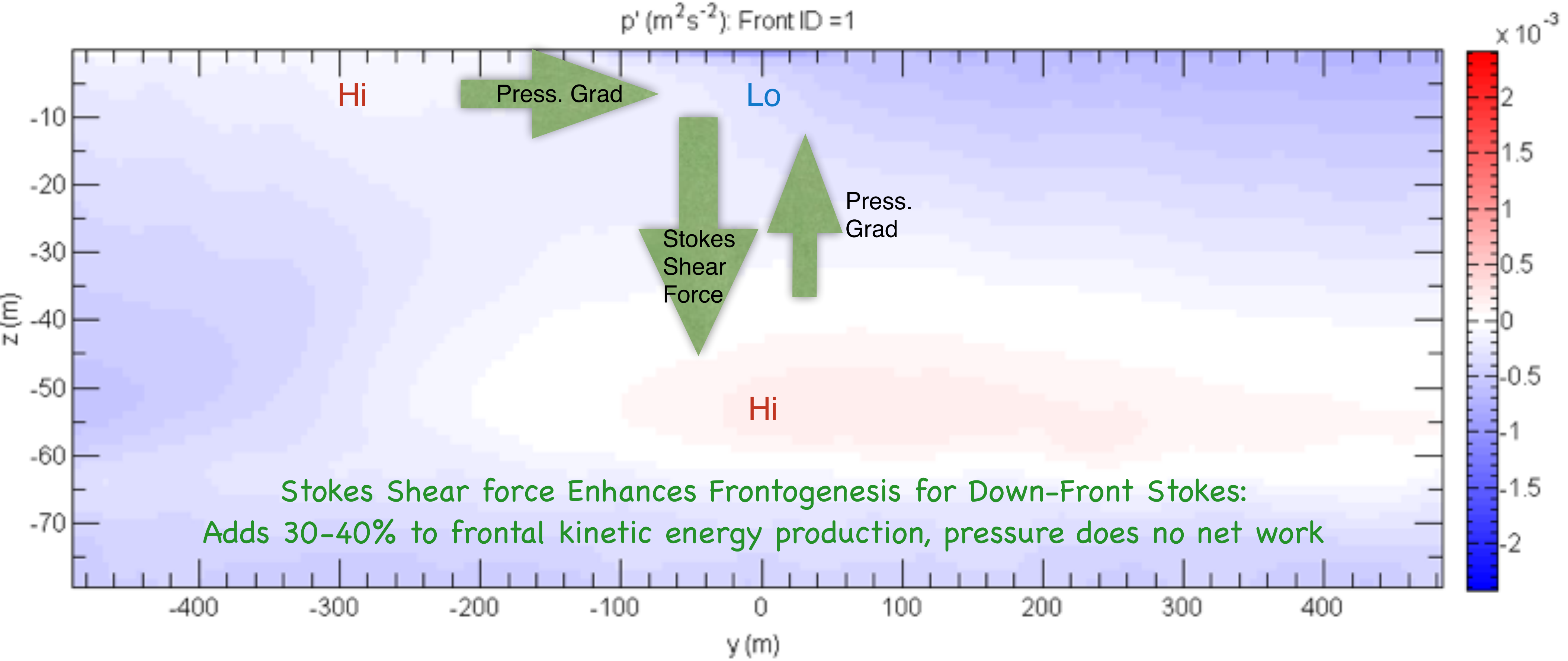
Along-Front and 10min Average

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

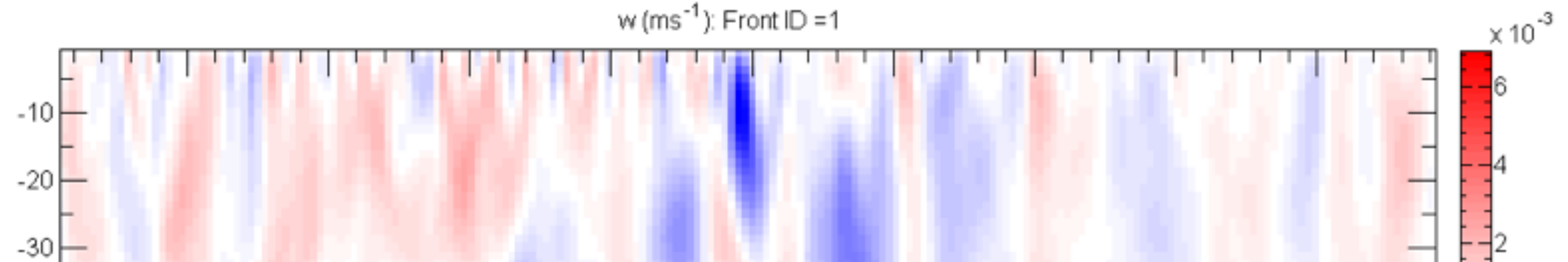


Along-Front and 10min Average

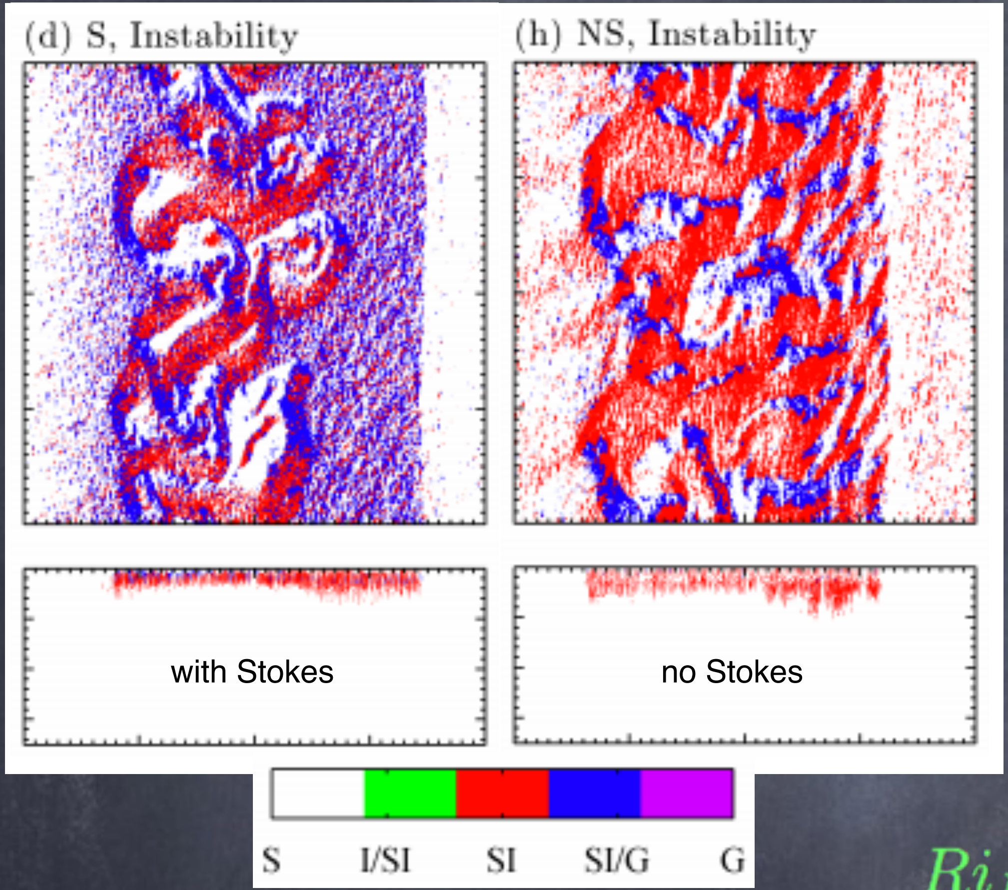
$$\varepsilon = \frac{V^s H}{f L H_s} \approx 20$$

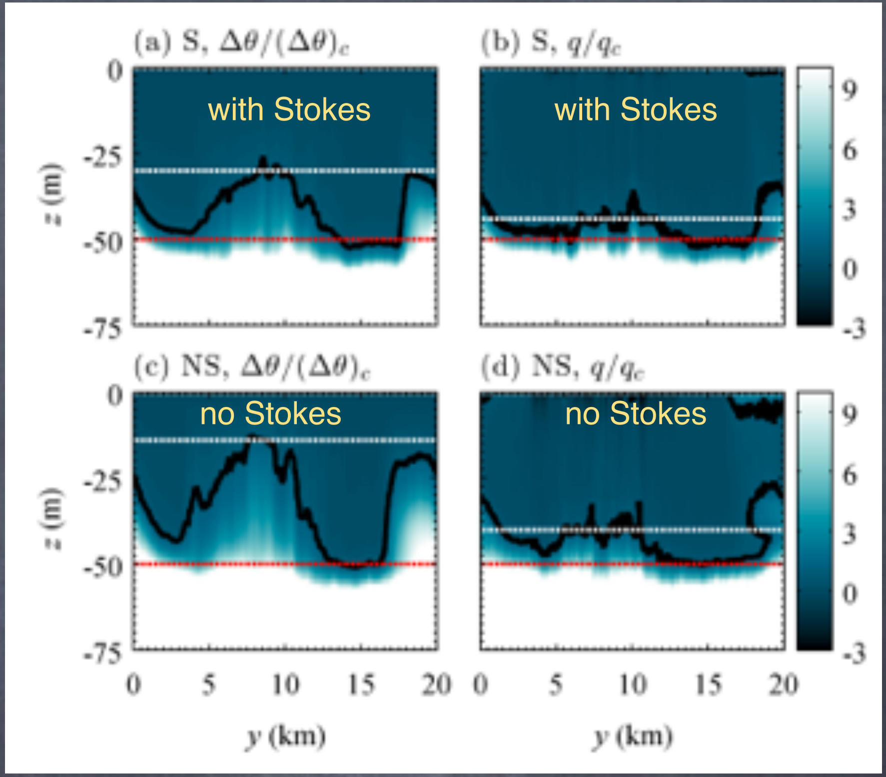


Stokes Shear force Enhances Frontogenesis for Down-Front Stokes:
Adds 30-40% to frontal kinetic energy production, pressure does no net work



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





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

So, $q < 0$

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

$$q = (f + \nabla \times u) \cdot \nabla b \approx [f + \nabla \times (u^L - u^s)] \cdot \nabla b$$

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

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

S. Haney, B. Fox-Kemper, 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.

Conclusion:

KH win if $Ri_L < \frac{1}{4}$

SI win if $\frac{1}{4} < Ri_L$ and $fq < 0$

BCI win if $\frac{1}{4} < Ri_L$ and $fq > 0$

$fq < 0$

$Ri_E > 1$

$\frac{1}{4} < Ri_L < 1$

SI win

$fq < 0$

$Ri_E < 1$

$Ri_L > 1$

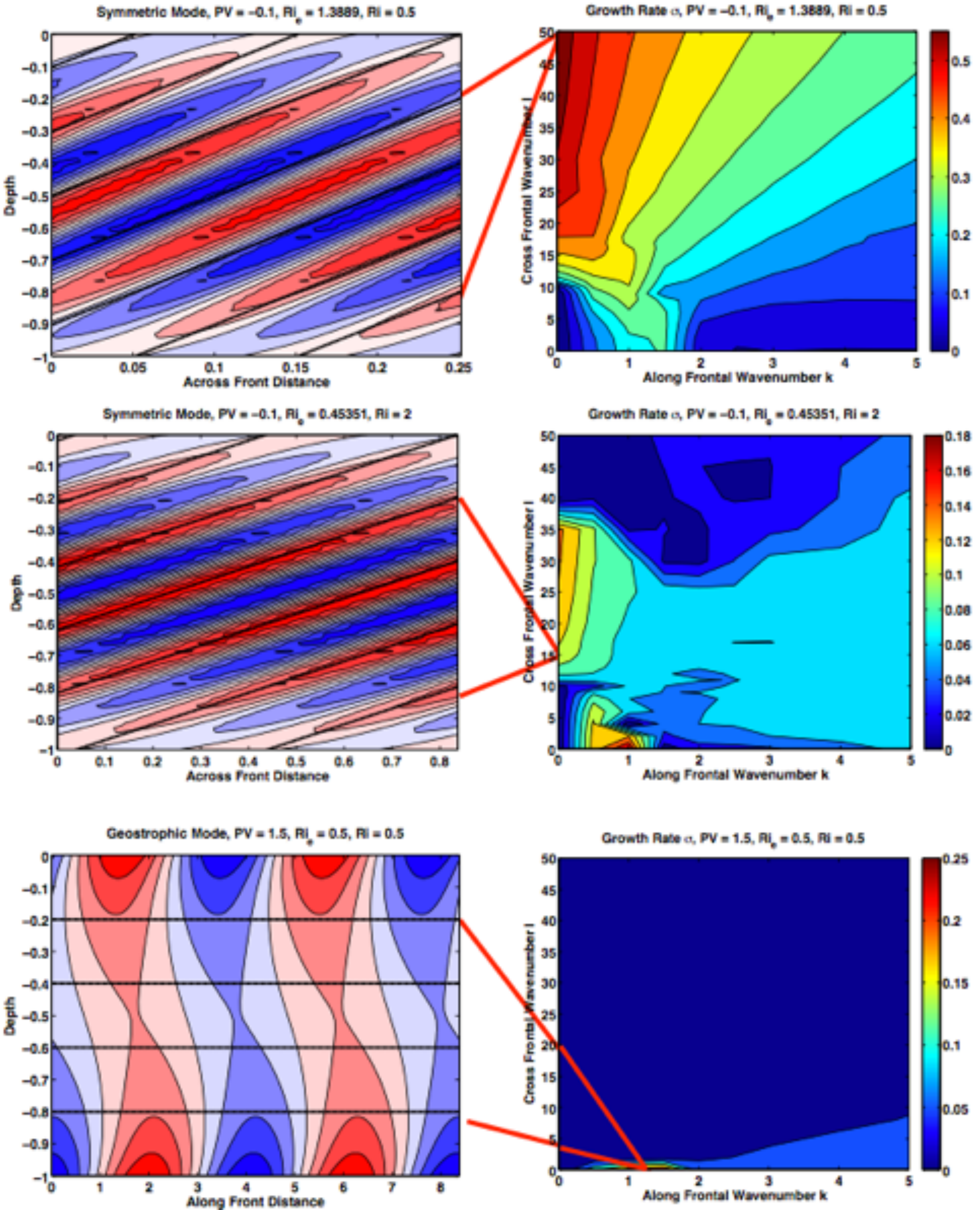
SI win

$fq > 0$

$Ri_E < 1$

$\frac{1}{4} < Ri_L < 1$

BCI win



S. Haney, B. F-K, 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.

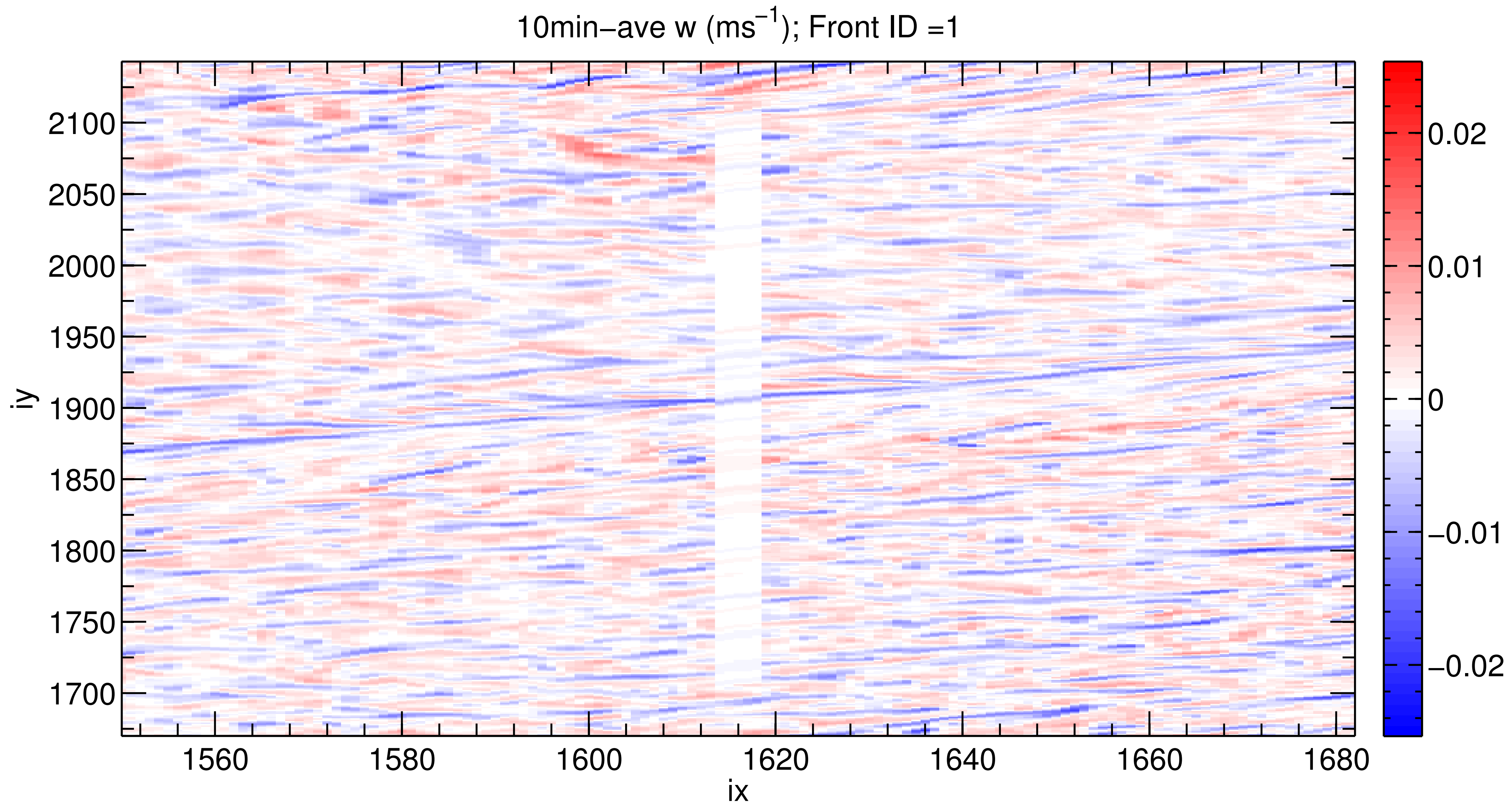
2/2 Conclusions

All papers at: fox-kemper.com/

- Stokes shear force affects frontogenesis. Add/subtract 30-40% of frontal KE production for downfront/upfront Stokes drift
- The controlling parameter, $\mathcal{E}$, measures nonhydrostatic frontal effects. It can dominate other nonlinear effects, such as O(1) Rossby, and is O(20) in these simulated submesoscale fronts.
- Down-Stokes fronts are sharper than those directed across or esp. against Stokes and have horizontal velocity and pressures that are not antisymmetric about the max w.
- Future/Present: Cross-frontal transport pathways, wave-mean 2-way interaction, and Stokes effects on frontal instabilities
- Overall: Stokes force can affect submesoscale dynamics as well as Langmuir turbulence.

Along-Front and 10min Average

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



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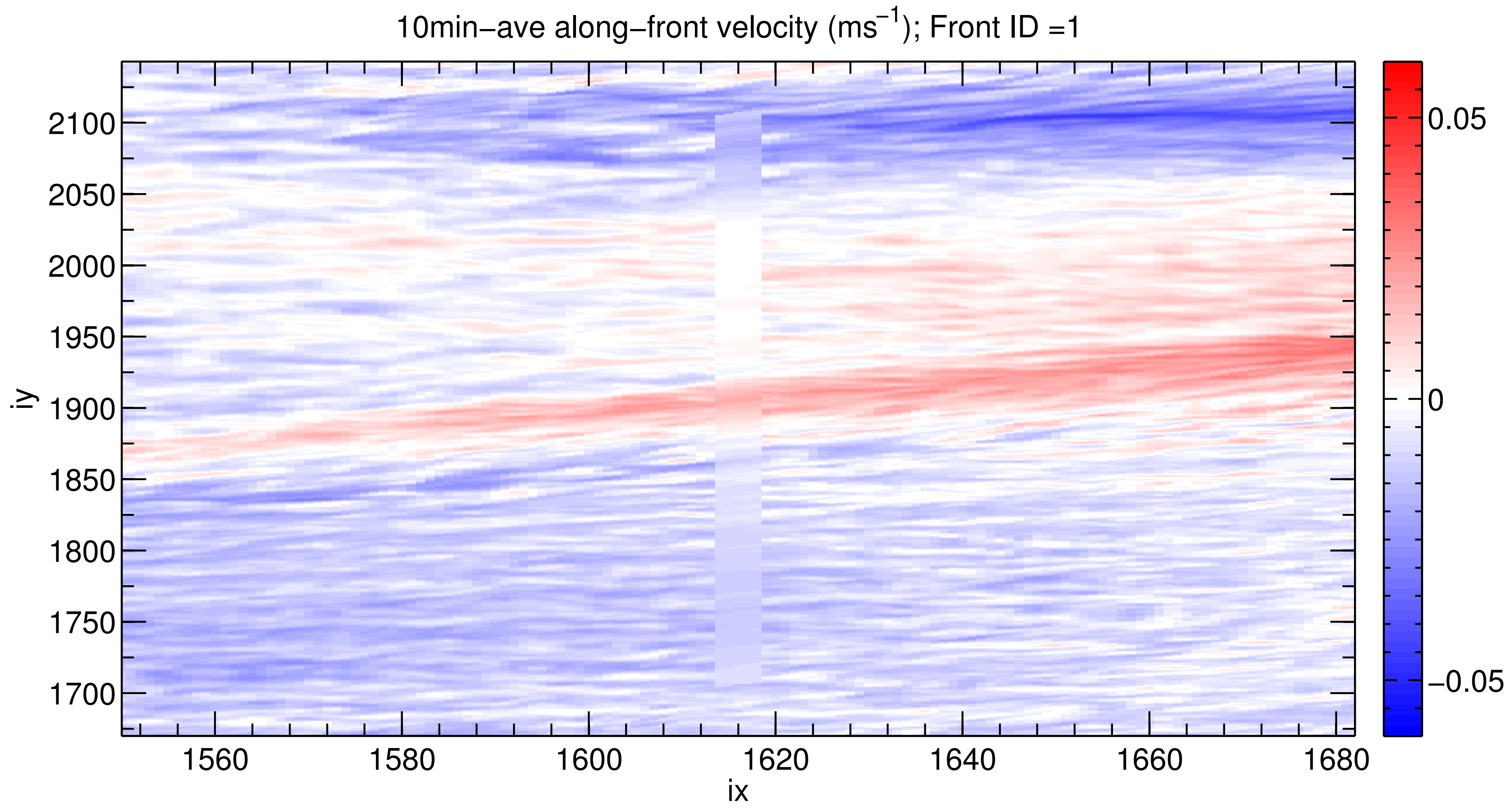

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