Other Submesoscale Processes: Frontogenesis & Stokes Effects

Baylor Fox-Kemper (Brown)

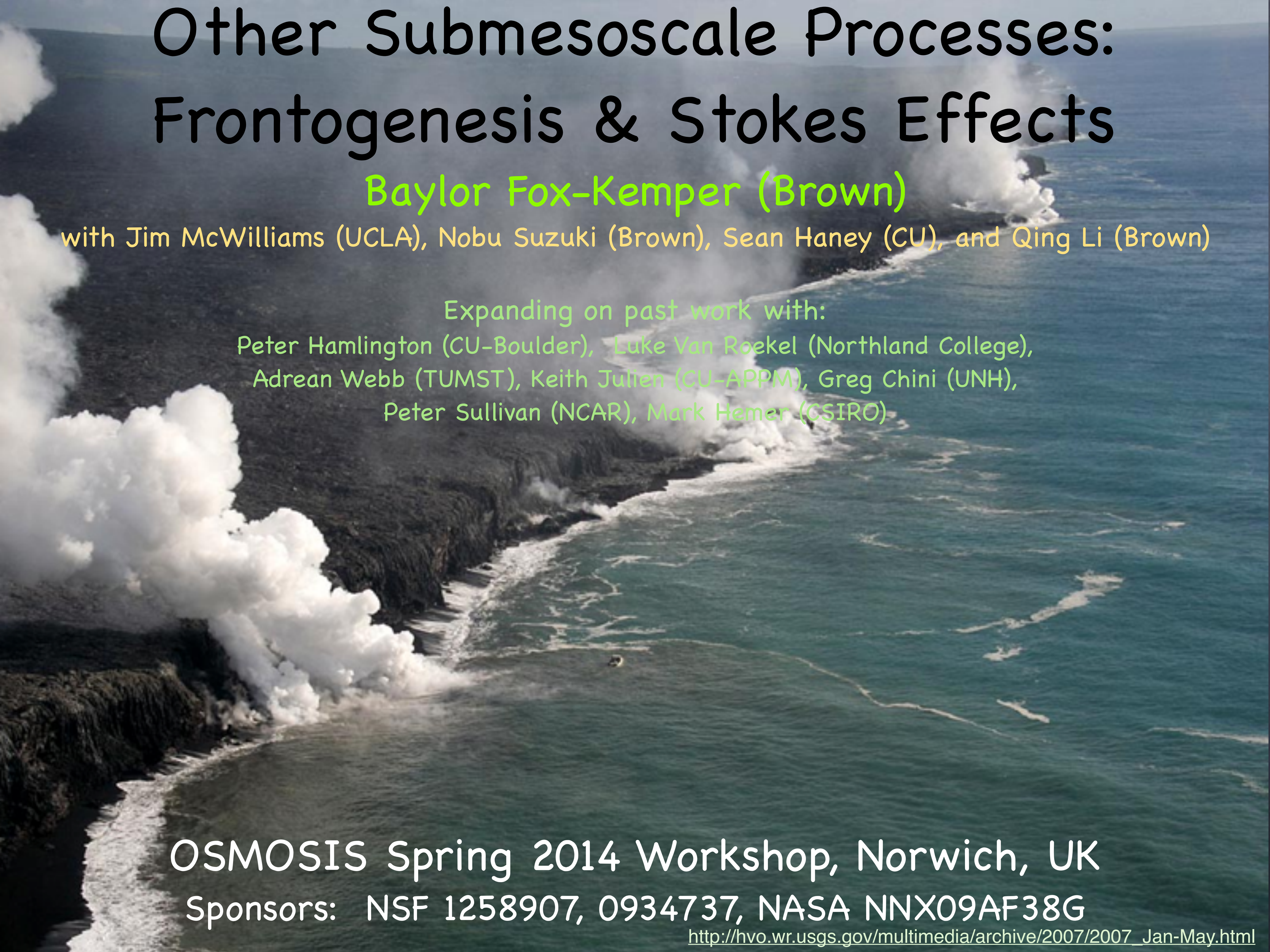
with Jim McWilliams (UCLA), Nobu Suzuki (Brown), Sean Haney (CU), and Qing Li (Brown)

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)

OSMOSIS Spring 2014 Workshop, Norwich, UK

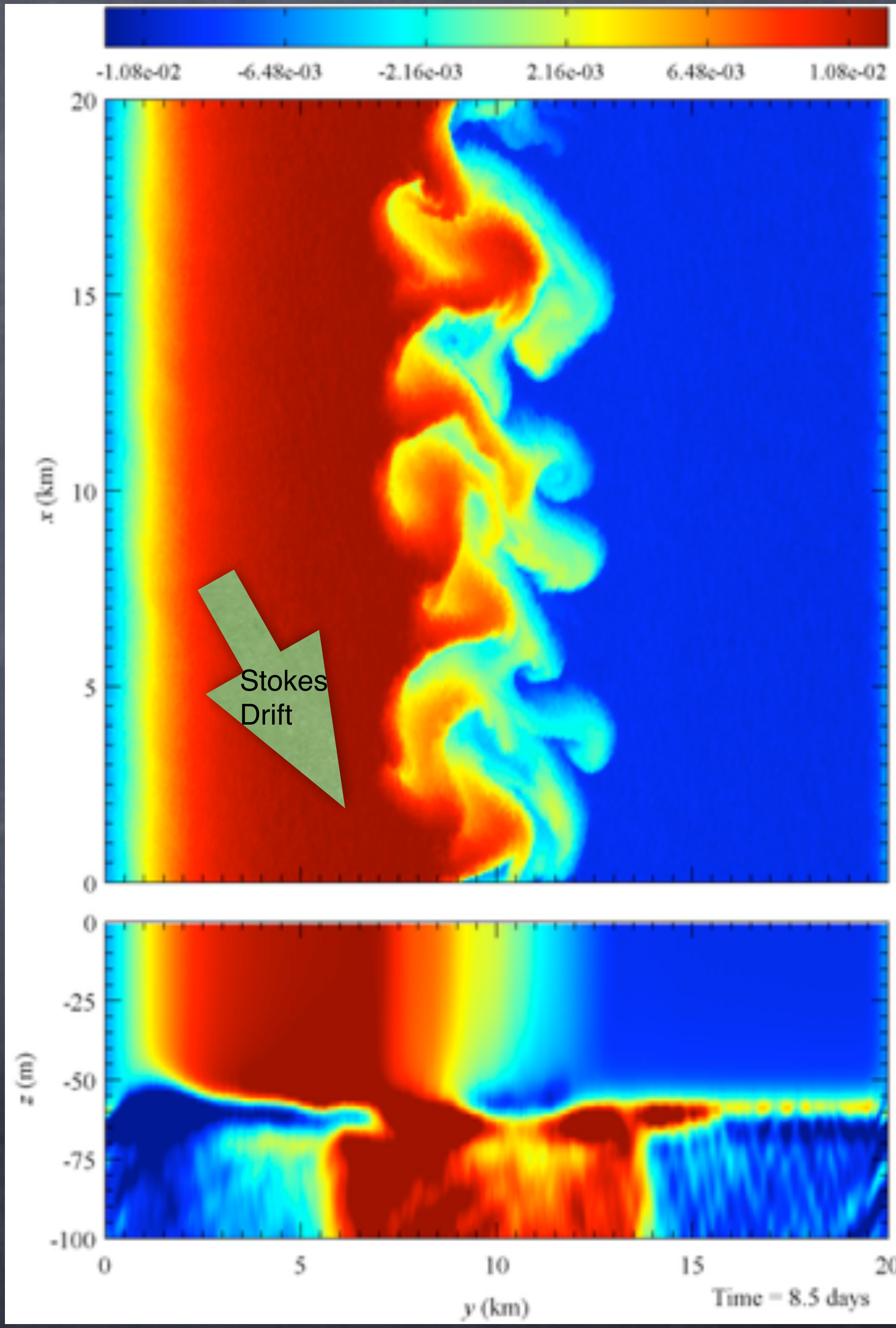
Sponsors: NSF 1258907, 0934737, NASA NNX09AF38G



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

LES of Langmuir-Submeso Interactions?

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



Computational parameters:

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

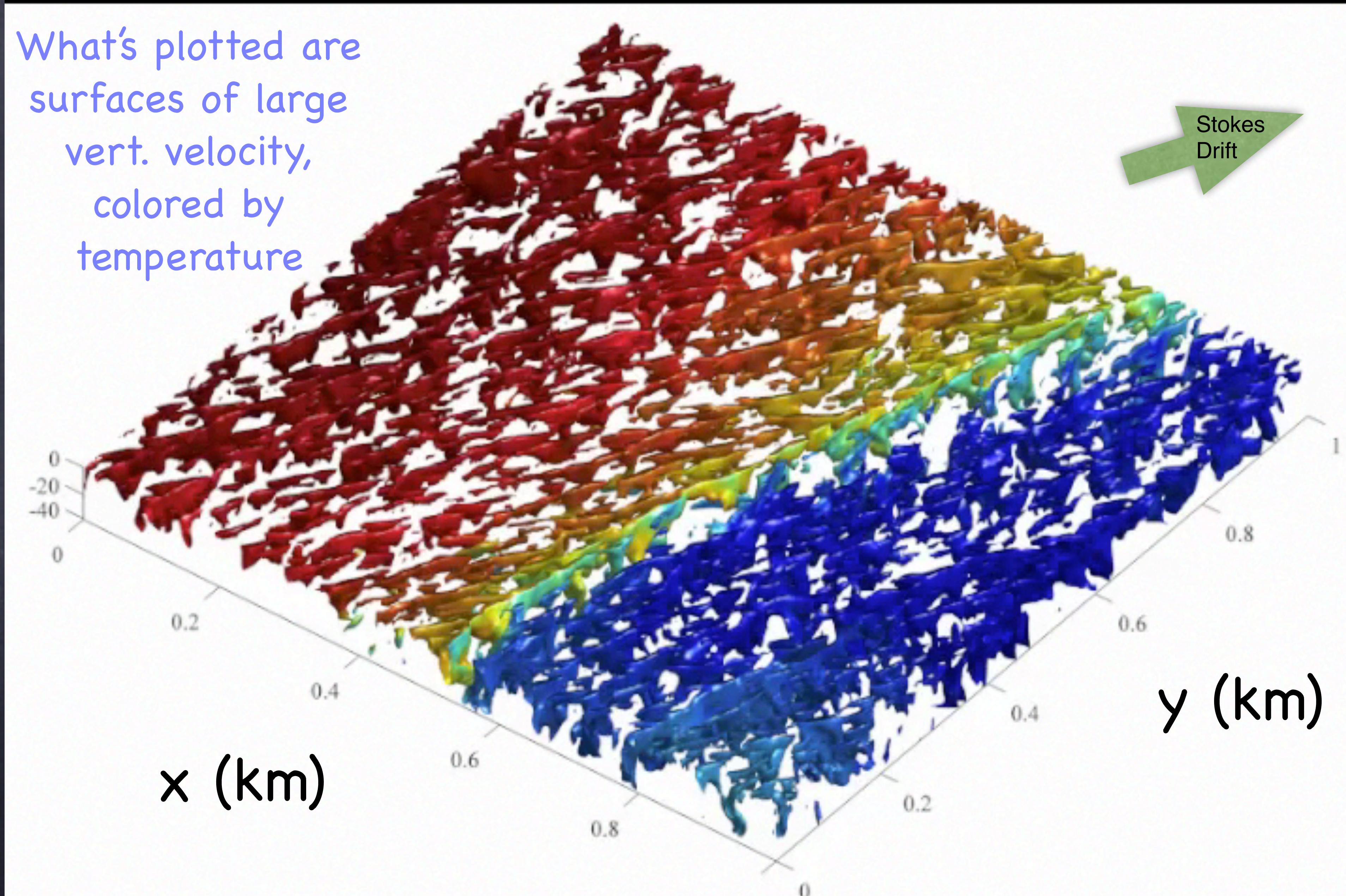
Grid points: 4096 x 4096 x 128

Resolution: 5m x 5m x -1.25m

1000x more gridpoints than CESM

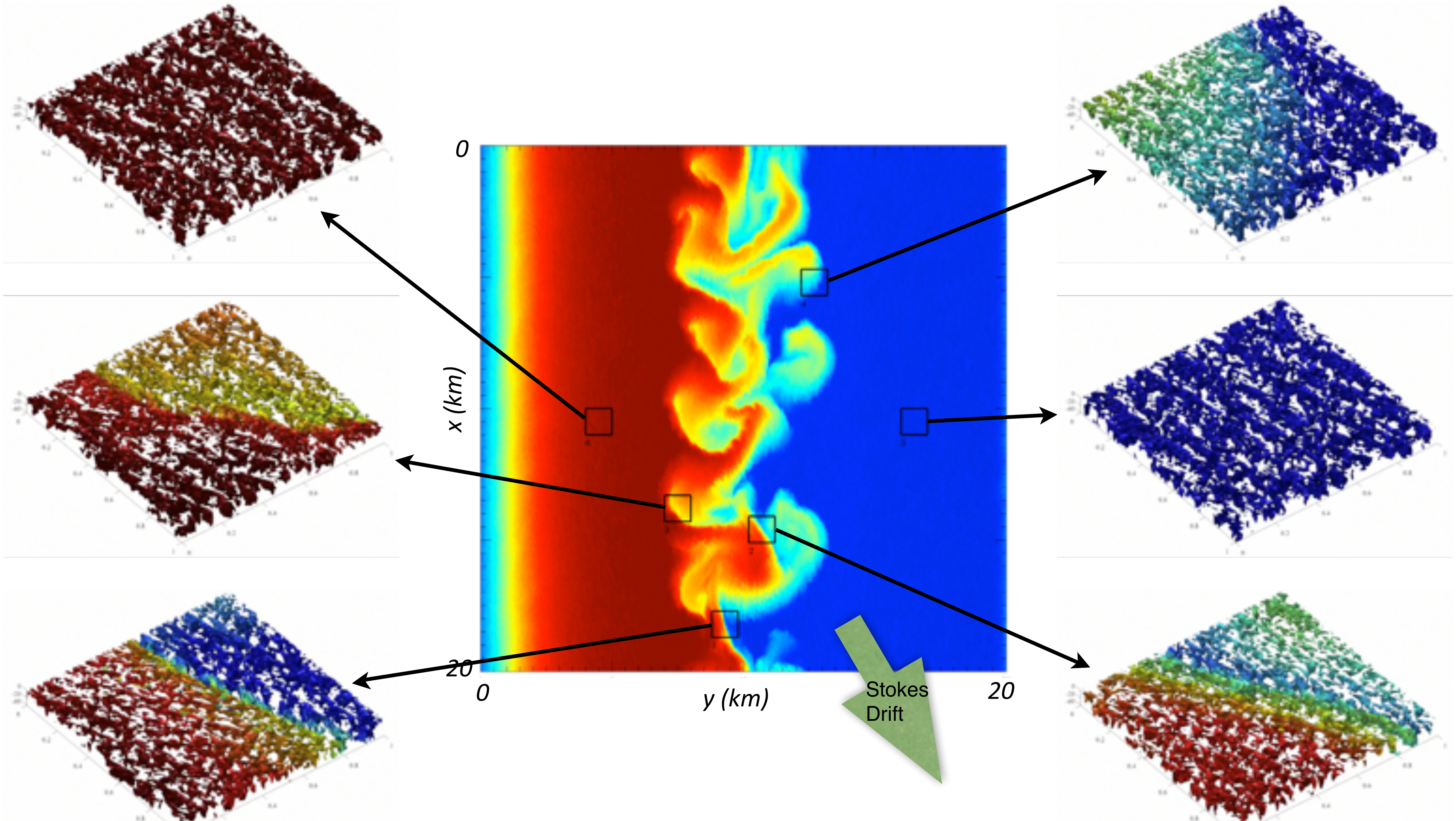
P. E. Hamlington, L. P. Van Roekel, B. Fox-Kemper, K. Julien, and G. P. Chini. Langmuir-submesoscale interactions: Descriptive analysis of multiscale frontal spin-down simulations. Journal of Physical Oceanography, 2014. In press.

Zoom: Submeso-Langmuir Interaction!



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

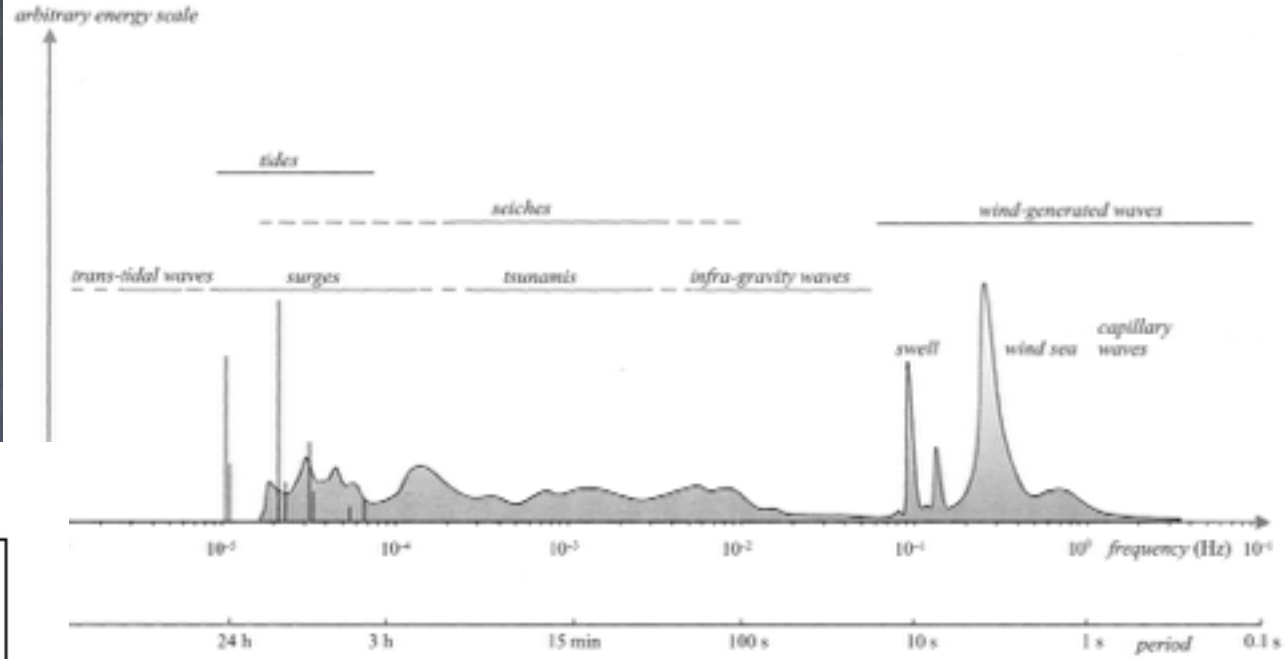


Slide & Movies by Peter Hamlington

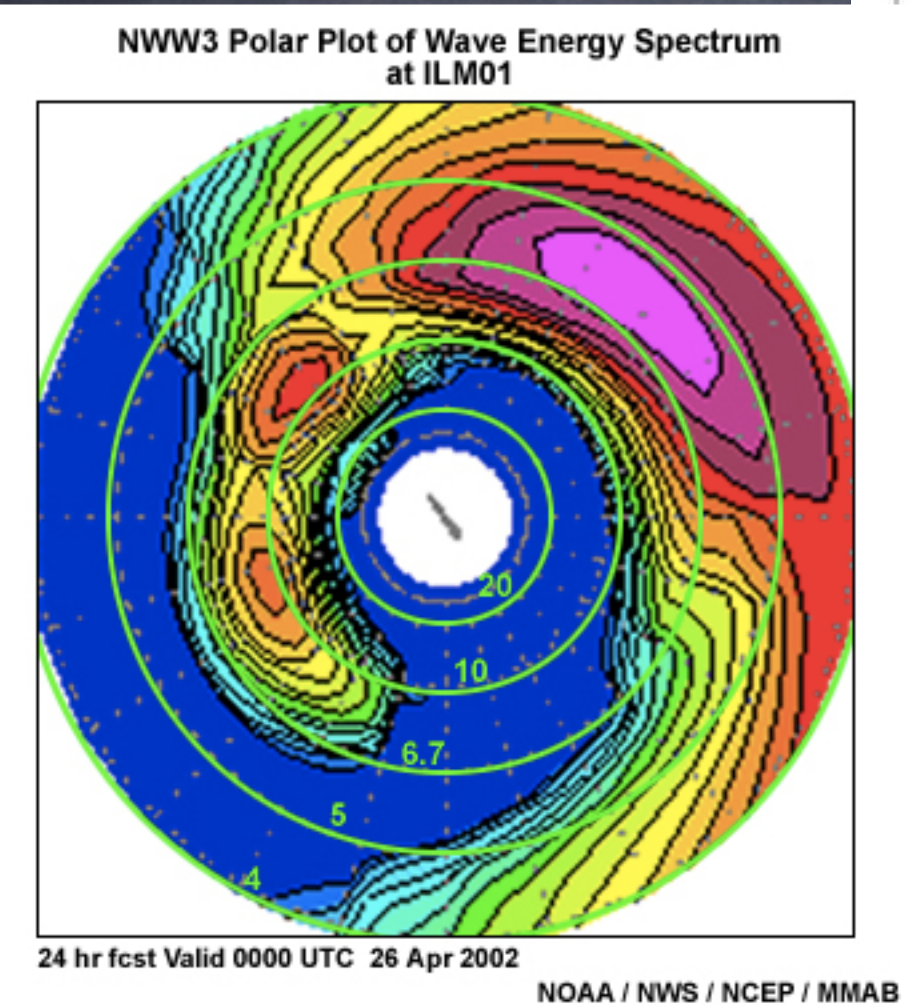
P. E. Hamlington, L. P. Van Roekel, B. Fox-Kemper, K. Julien, and G. P. Chini. Langmuir-submesoscale interactions: Descriptive analysis of multiscale frontal spin-down simulations. Journal of Physical Oceanography, 2014. In press.

Surface Waves are...

fast, small, irrotational solutions of the Boussinesq Equations



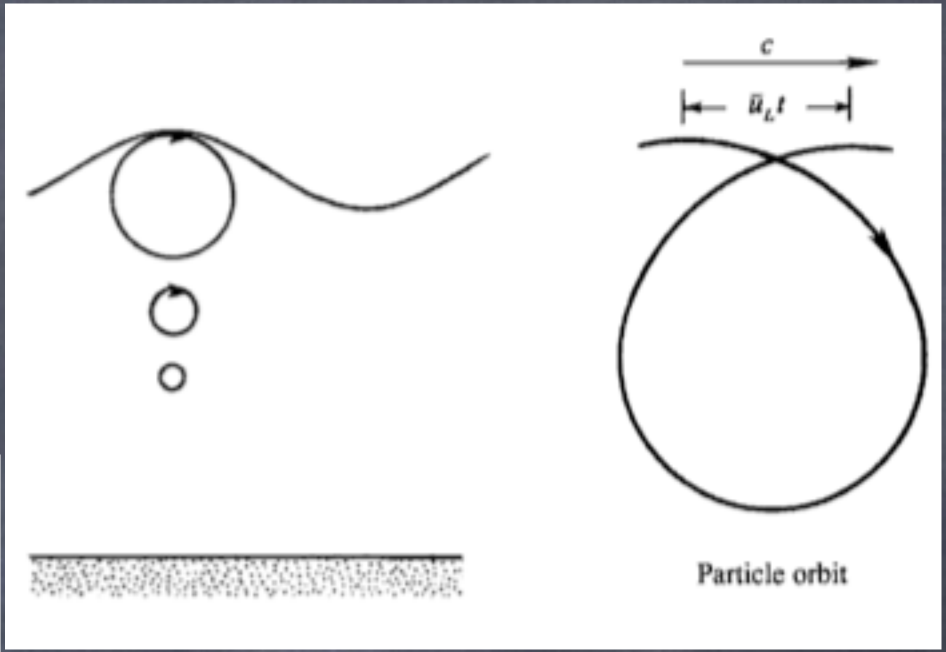
llustration of wave spectra from different types of ocean surface waves (Holthuijsen, 2007)



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:

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

Spectrum:

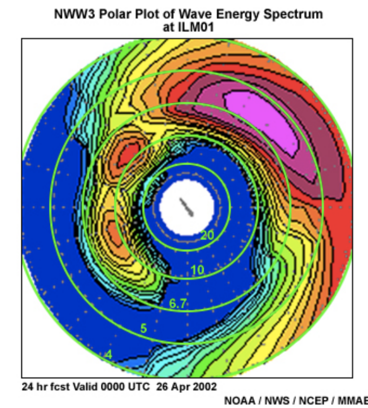
$$\boldsymbol{u}^S = \frac{16\pi^3}{g} \int_0^\infty \int_{-\pi}^{\pi} (\cos\theta, \sin\theta, 0) f^3 S_{f\theta}(f,\theta) e^{\frac{8\pi^2 f^2}{g} z} d\theta df.$$

Depth-Integrated:

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

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

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

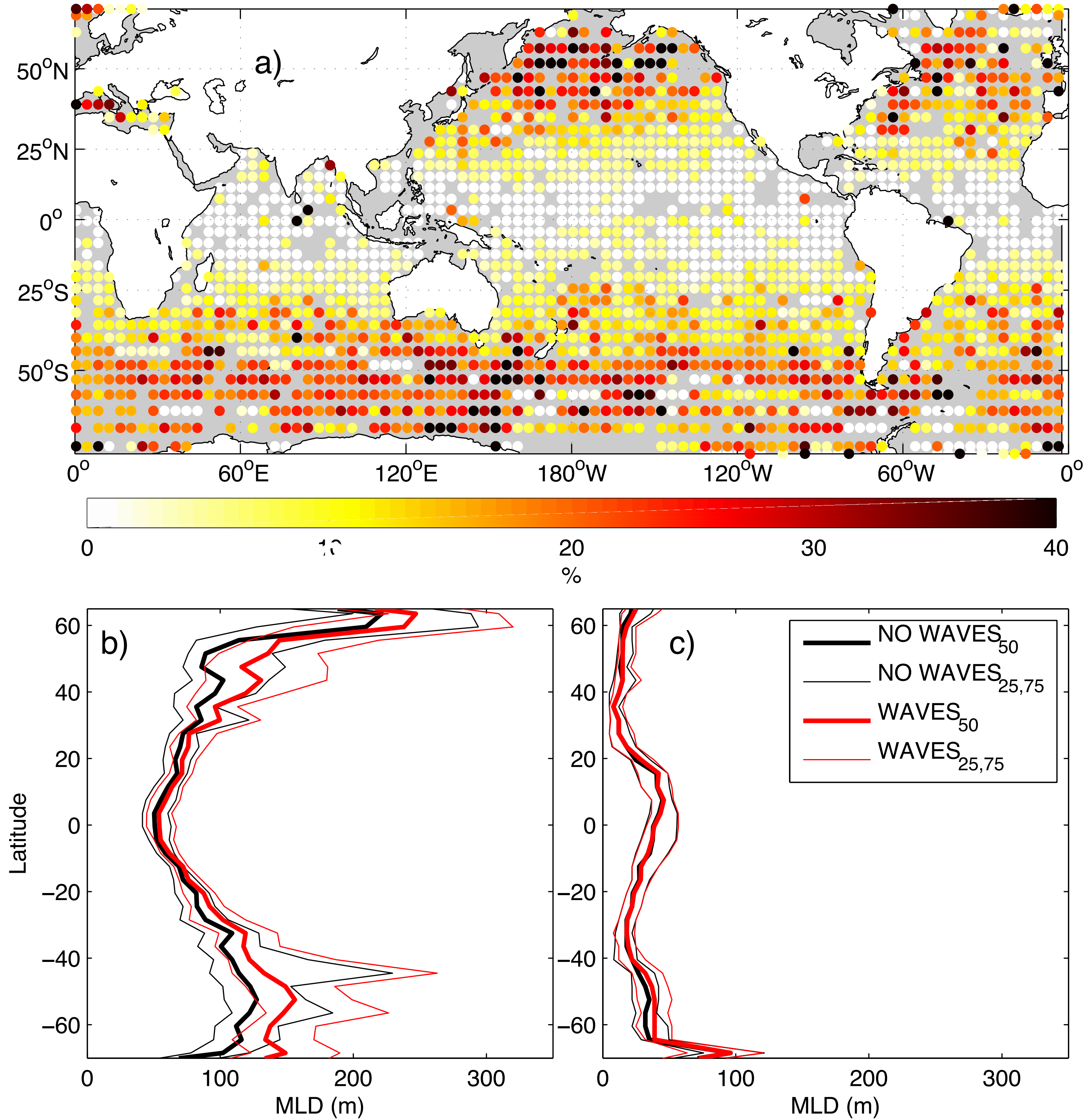
Image: NPR.org, Deep Water Horizon Spill

"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.

Offline observation-driven parameterization:

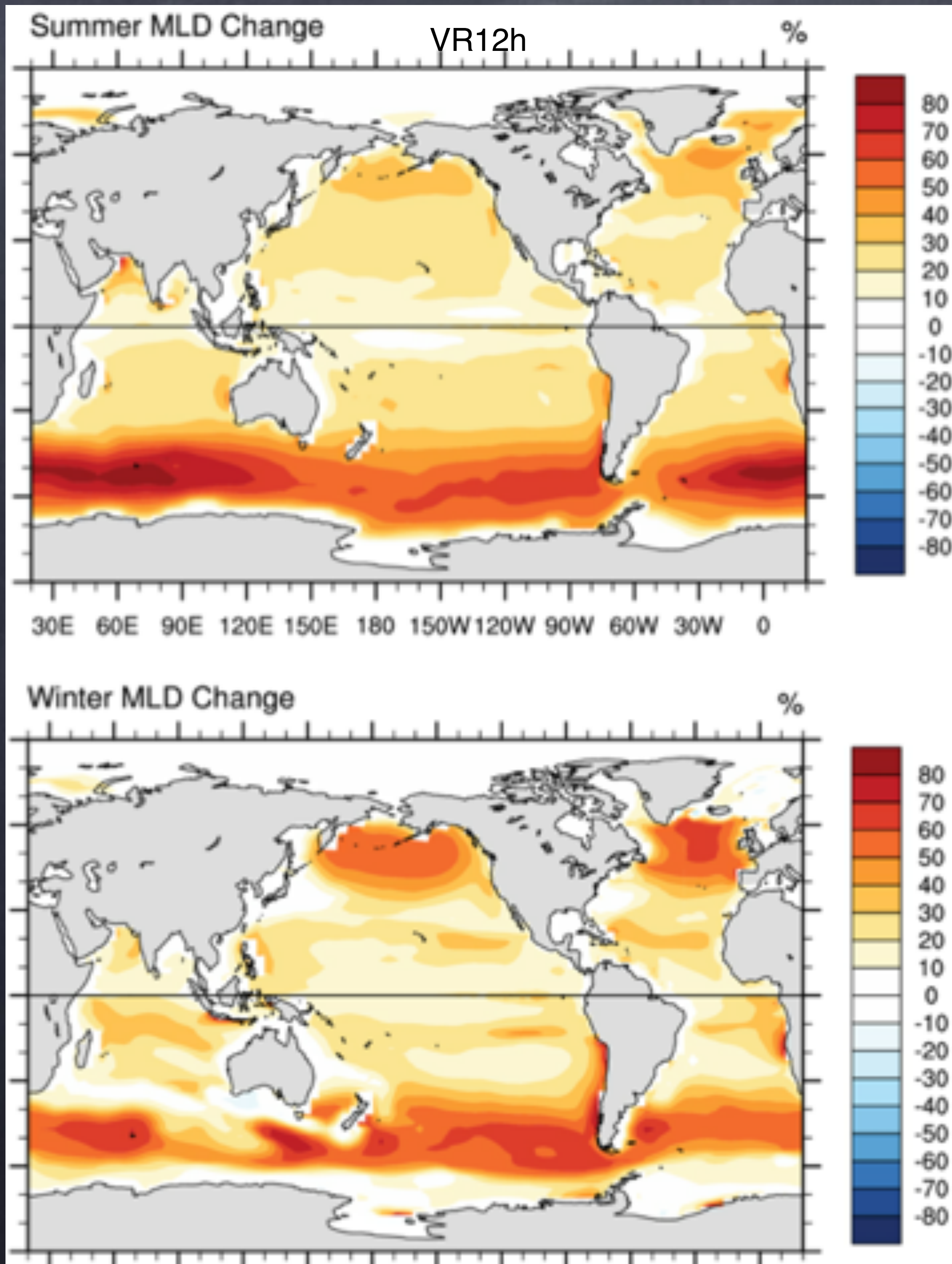
Including Stokes-driven Mixing (Harcourt 2013) Deepens the Mixed Layer!



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

Including Stokes-driven Mixing in CESM, too!

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



LES-w^2

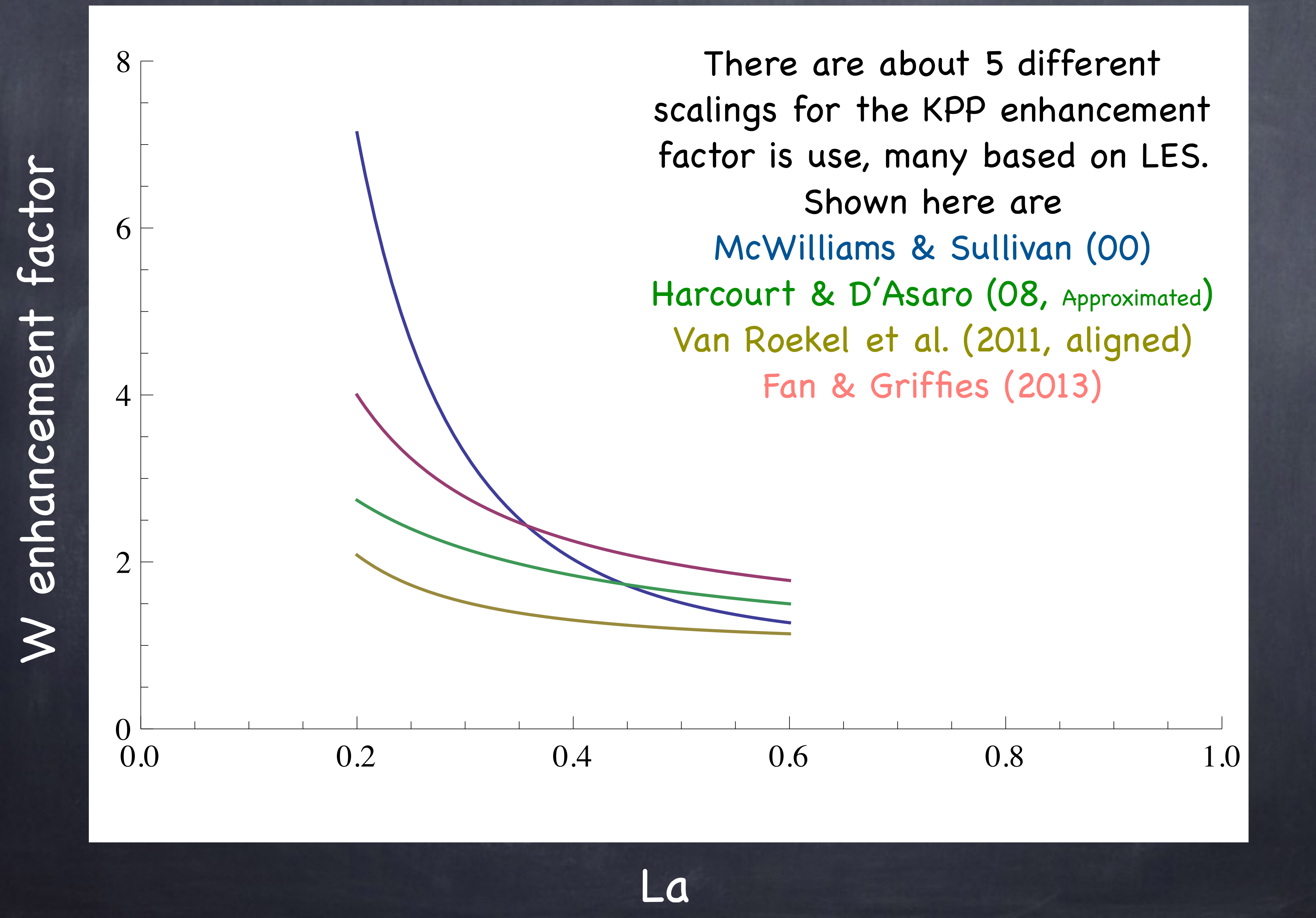
Depth & misaligned

& Crit. Ri

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.



W enhancement factor
La
0
2
4
6
8
0.0
0.2
0.4
0.6
0.8
1.0
There are about 5 different scalings for the KPP enhancement factor is use, many based on LES. Shown here are
McWilliams & Sullivan (00)
Harcourt & D'Asaro (08, Approximated)
Van Roekel et al. (2011, aligned)
Fan & Griffies (2013)

Dimensionless Boussinesq

Spanning Mesoscale to Stratified Turbulence

following McWilliams (85)

geostrophic

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

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

hydrostatic

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

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

Plus boundary conditions

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

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

Wave-Averaged Equations

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

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

(for horizontally uniform Stokes drift)

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

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

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

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

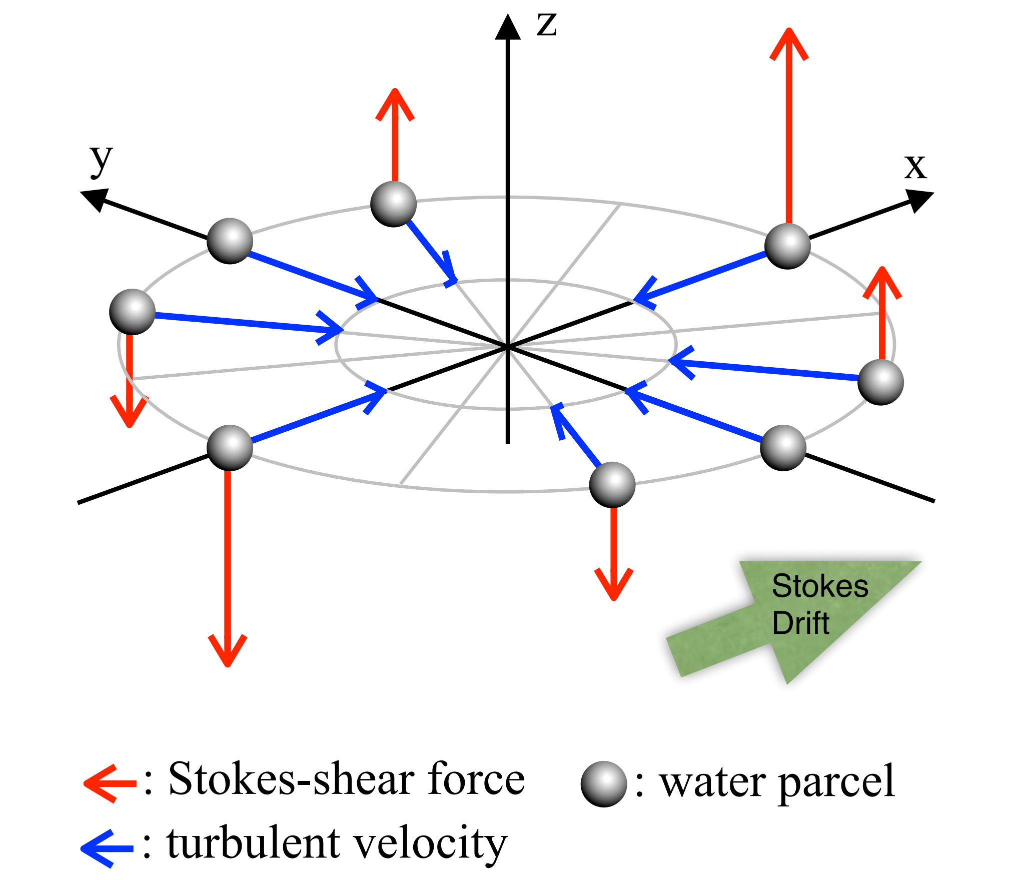
Plus boundary conditions

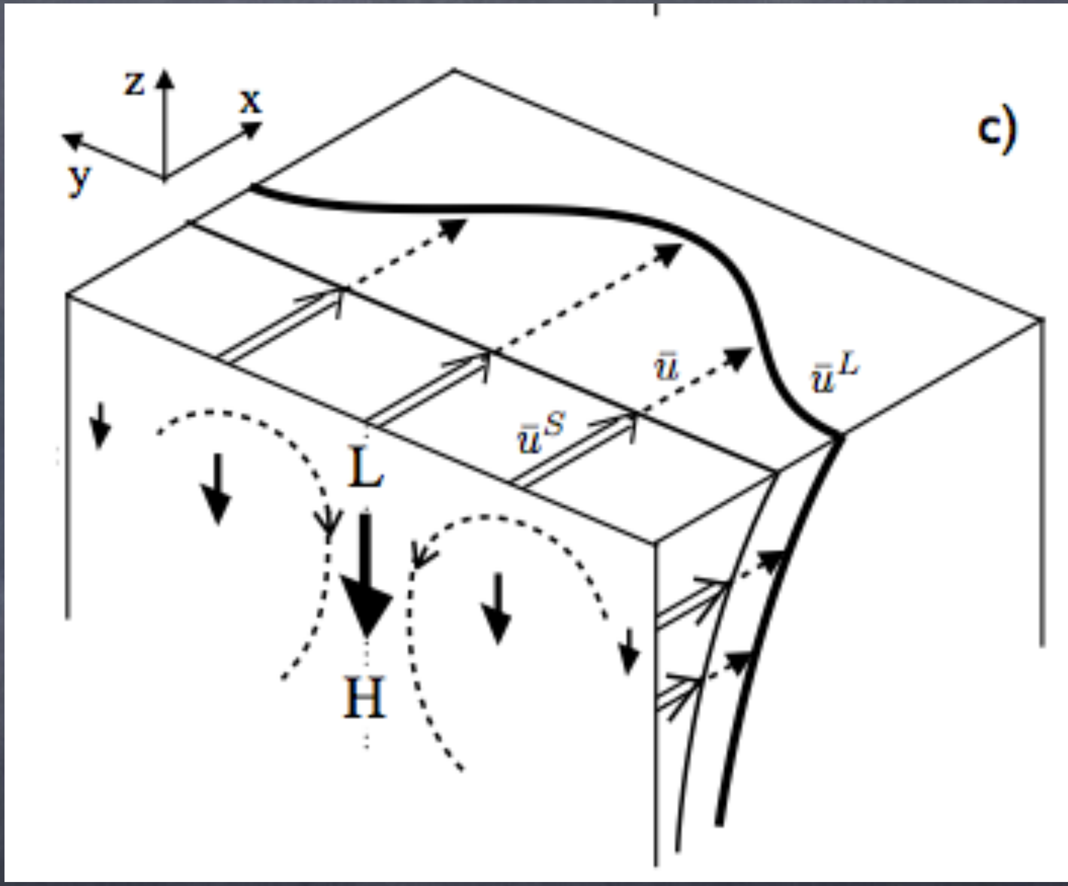
LAGRANGIAN (Eulerian+Stokes) advection & Coriolis

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





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

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

Stokes forcing of the (Sub)mesoscale

← 10 km

(Capet et al., 2008)

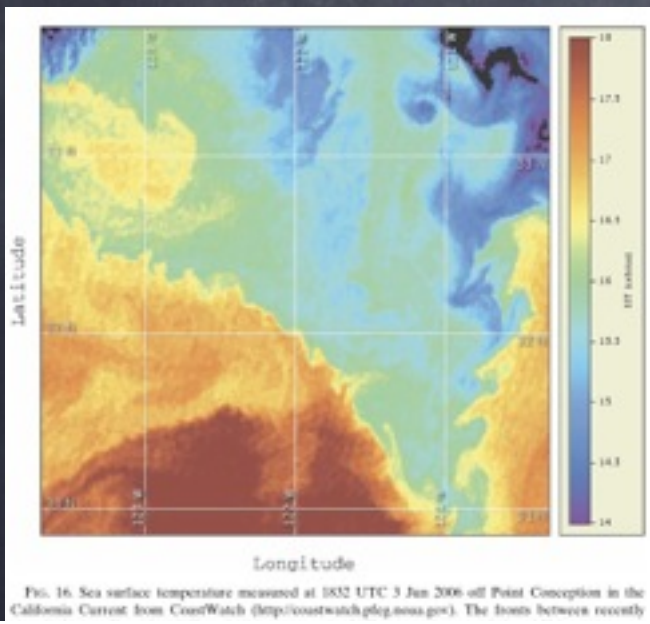
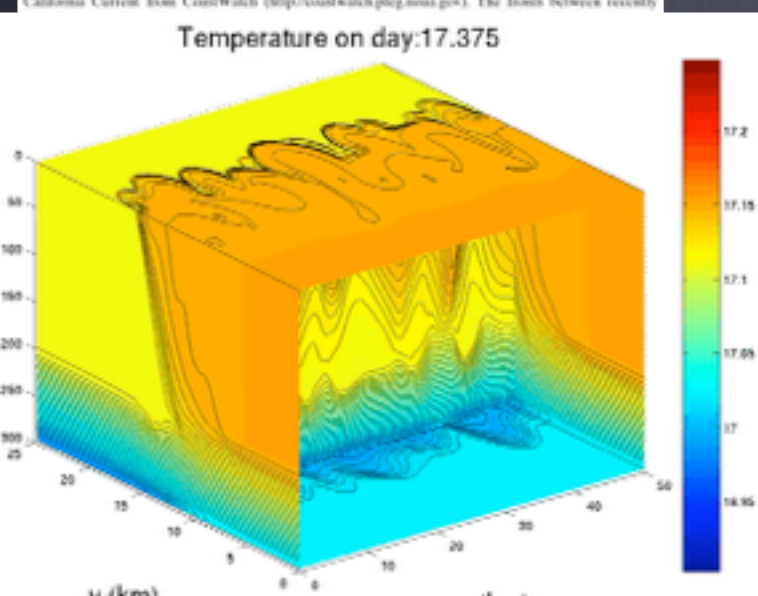
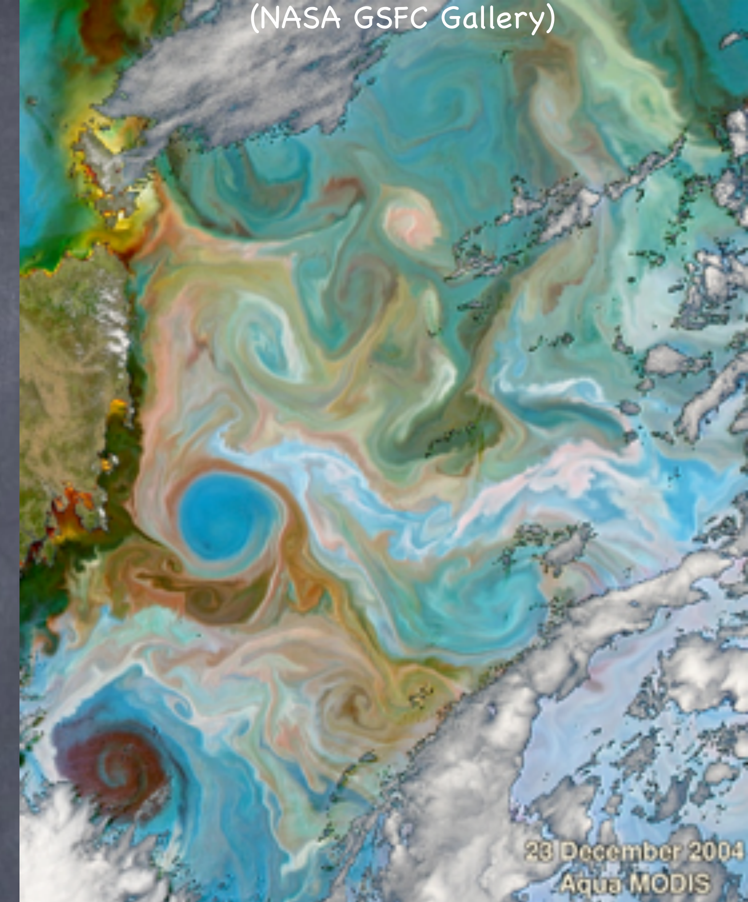


FIG. 16. Sea surface temperature measured at 1832 UTC 3 Jun 2006 off Point Conception in the California Current from CoastWatch (http://coastwatch.pfeg.noaa.gov). The fronts between recently



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

(NASA GSFC Gallery)



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

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

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

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

Consider perturbing from geostrophic, hydrostatic soln:

$$\phi = \phi_{00000} + \varepsilon\phi_{10000} + Ro\,\phi_{01000} + \frac{1}{\sqrt{Ri}}\,\phi_{00100} + \frac{\alpha^2}{\sqrt{Ri}}\,\phi_{00010} + \frac{1}{Re}\,\phi_{00001}$$
$$+ \varepsilon^2\phi_{20000} + \varepsilon Ro\,\phi_{11000} + Ro^2\,\phi_{02000} + \frac{Ro}{\sqrt{Ri}}\,\phi_{01100} + \ldots$$
$$+ O(Ro^3)$$

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

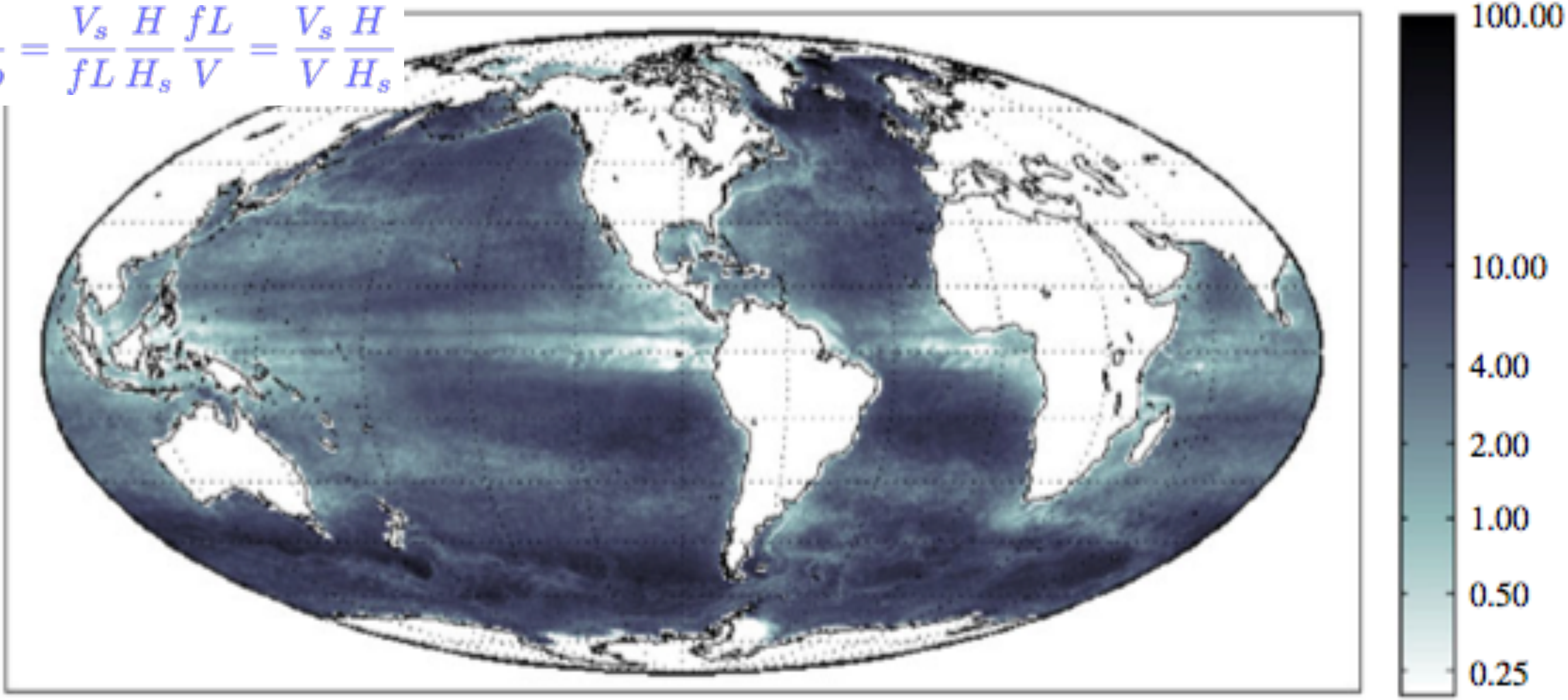
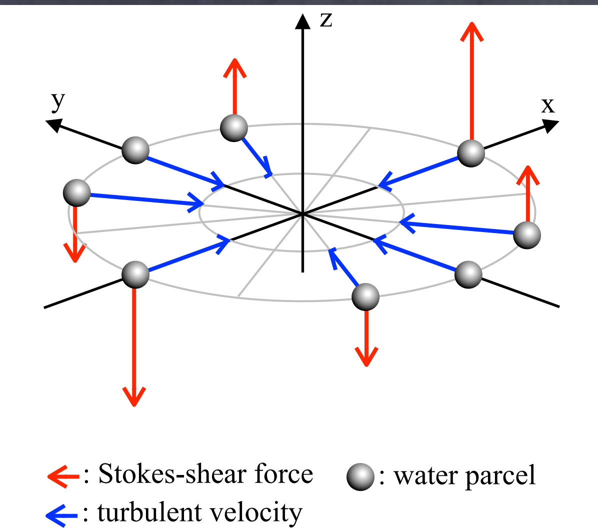
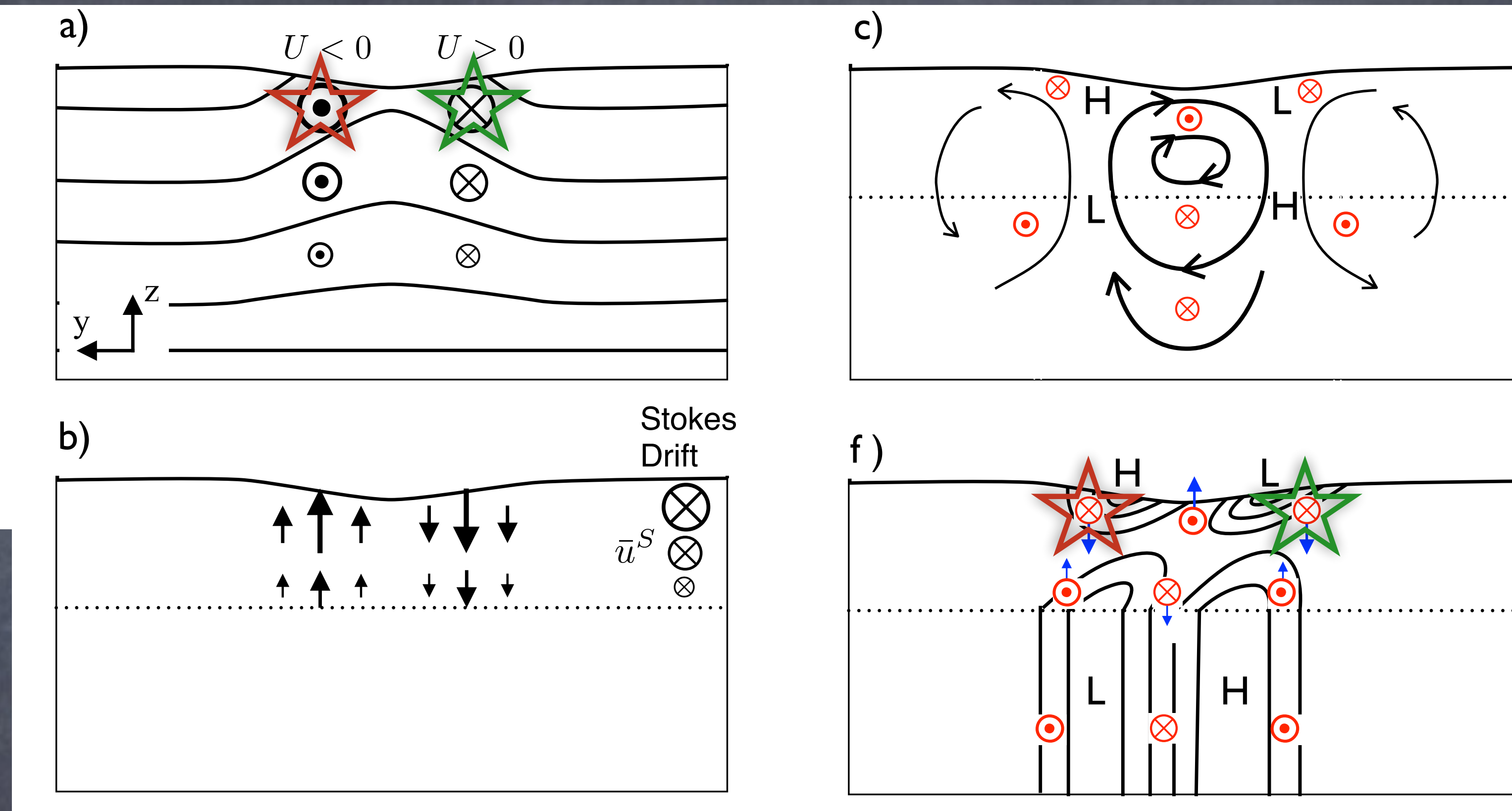


FIGURE 1. (Colour online) Estimated ratio $\epsilon/\mathscr{R} \approx (|\boldsymbol{u}_s \cdot \boldsymbol{u}|h)/(|\boldsymbol{u}|^2 h_s)$ governing the relative importance of Stokes effects versus nonlinearity. Eulerian velocity ($\boldsymbol{u}$) is taken as the

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.

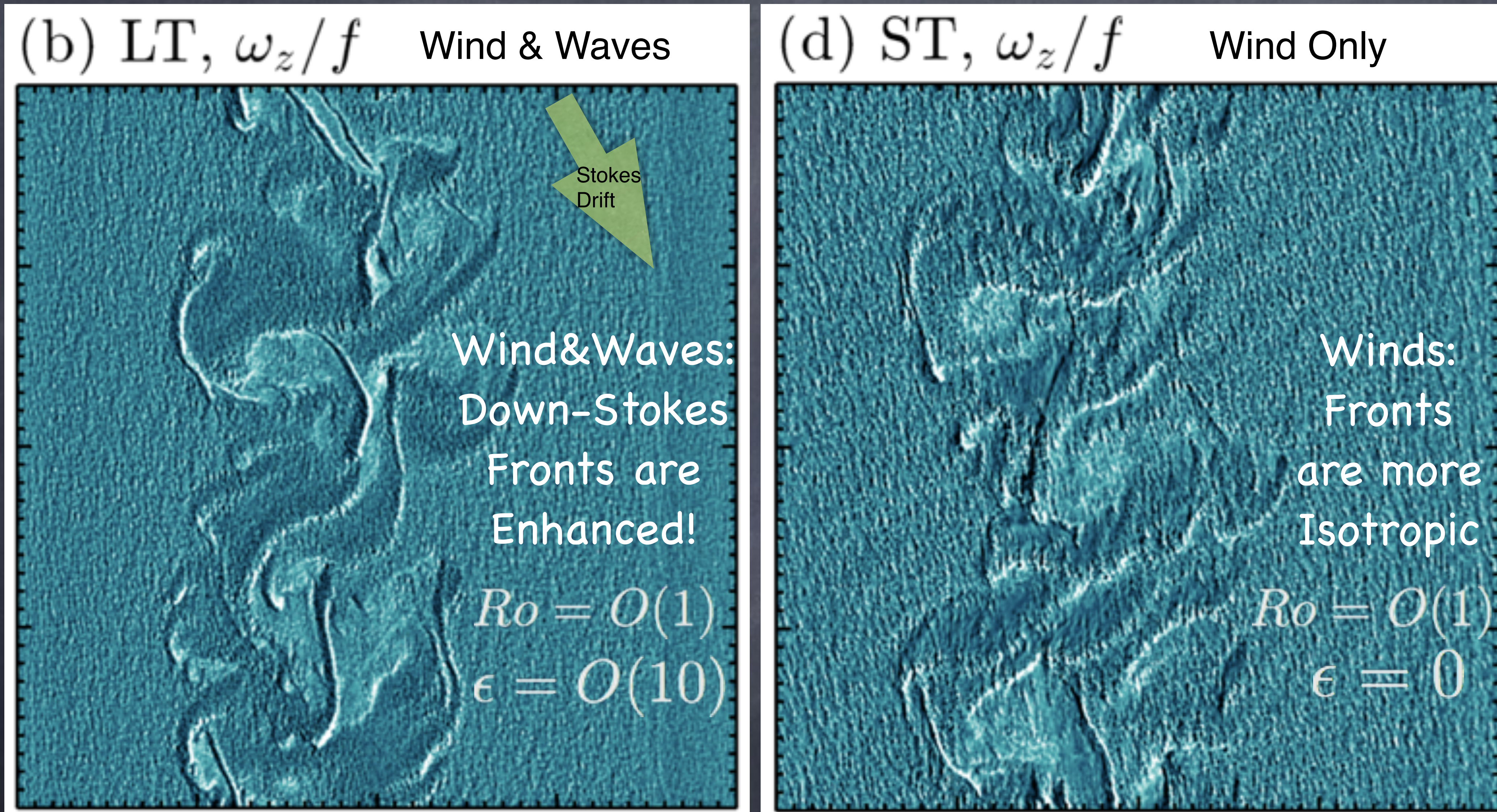
N. Suzuki and B. Fox-Kemper. Understanding Stokes Forces in the Wave-Averaged Equations, In prep, 2014.

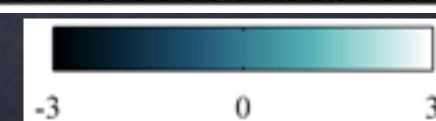
Enhances Fronts for Down-Front Stokes

Opposes Fronts for Up-Front Stokes

Are Fronts and Filaments different with Stokes shear force?

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



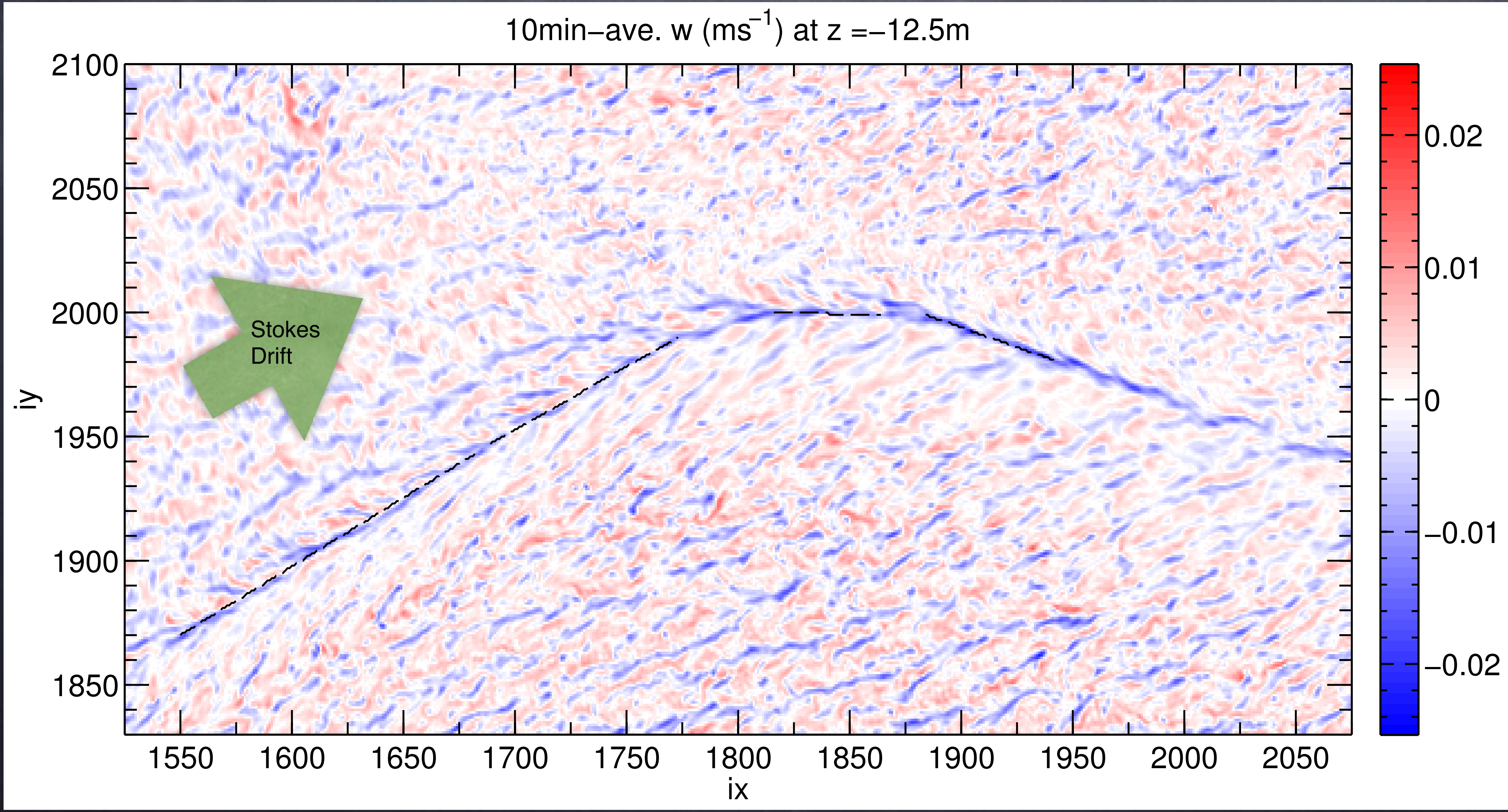


N. Suzuki and B. Fox-Kemper. Surface Wave Stokes Forces Influence Frontogenesis, JPO, in prep, 2014.

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. 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.

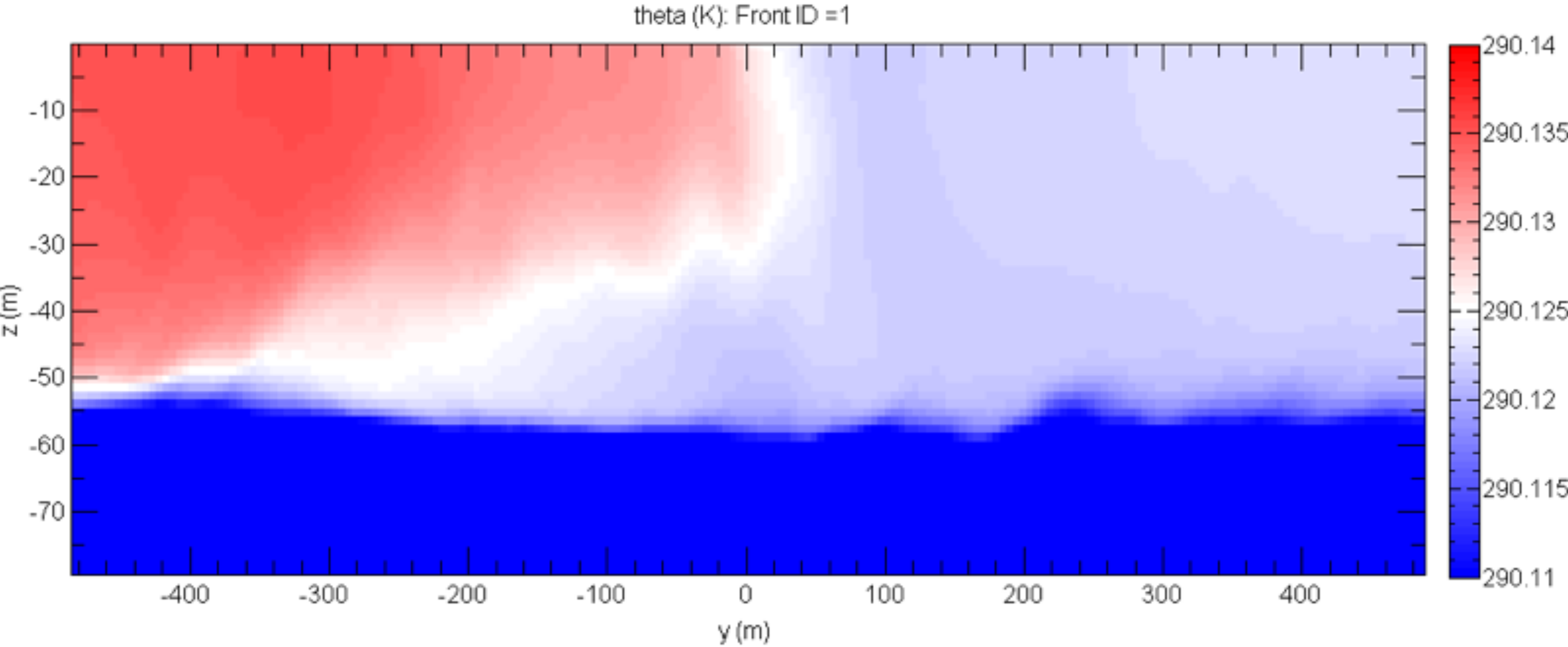
Let's examine a particular front with $\varepsilon = \frac{V^s H}{f L H_s} \approx 20$

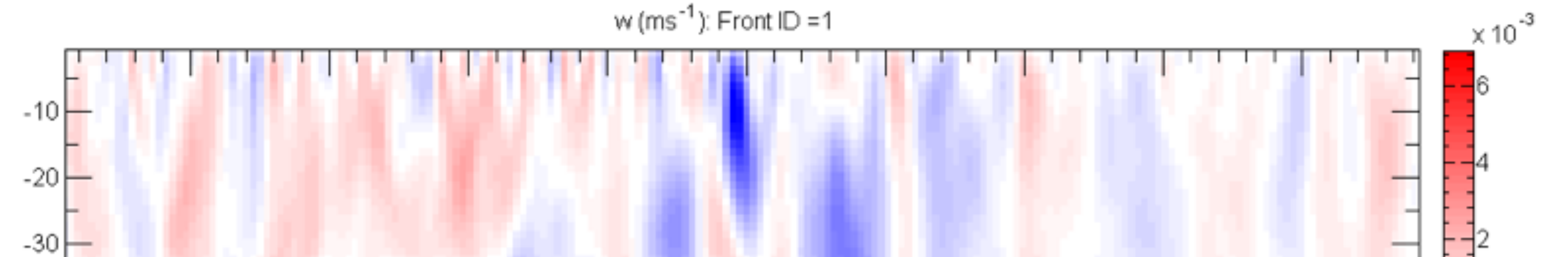


N. Suzuki and B. Fox-Kemper. Stokes Drift of Surface Waves Influences Frontogenesis, JPO, in prep, 2014.

Along-Front and 10min Average

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





Along-Front and 10min Average

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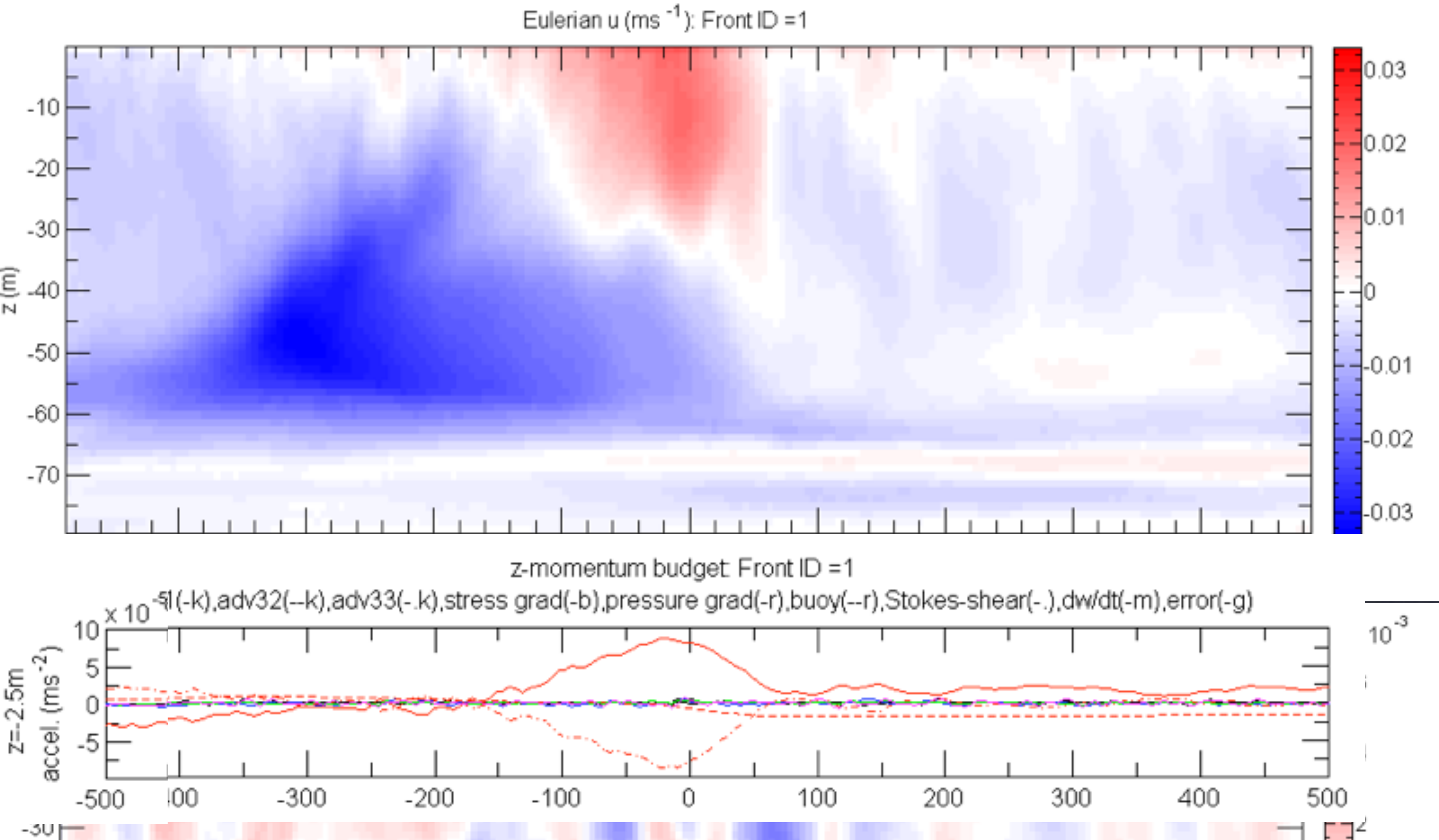

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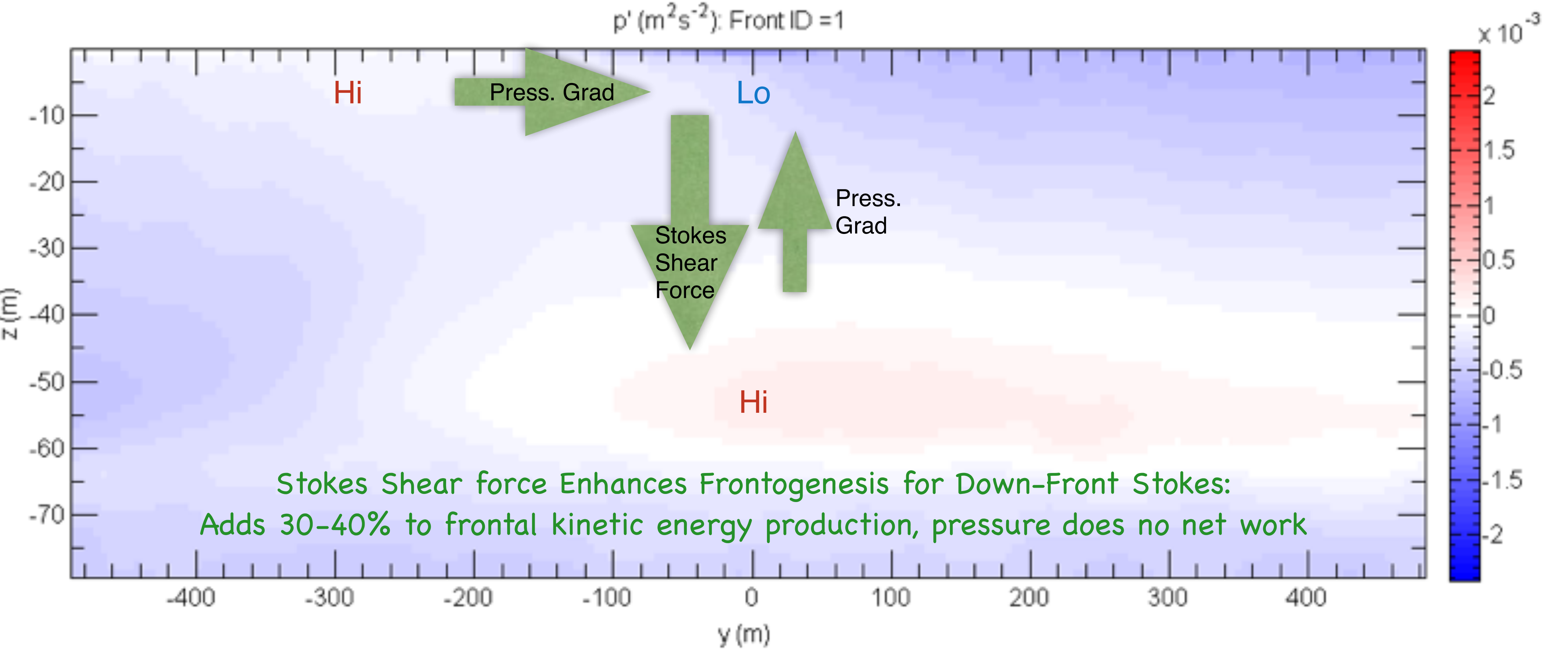
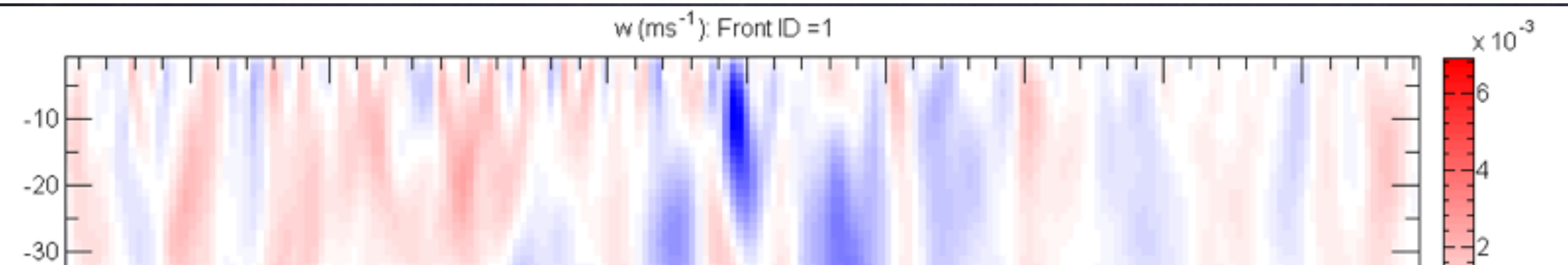
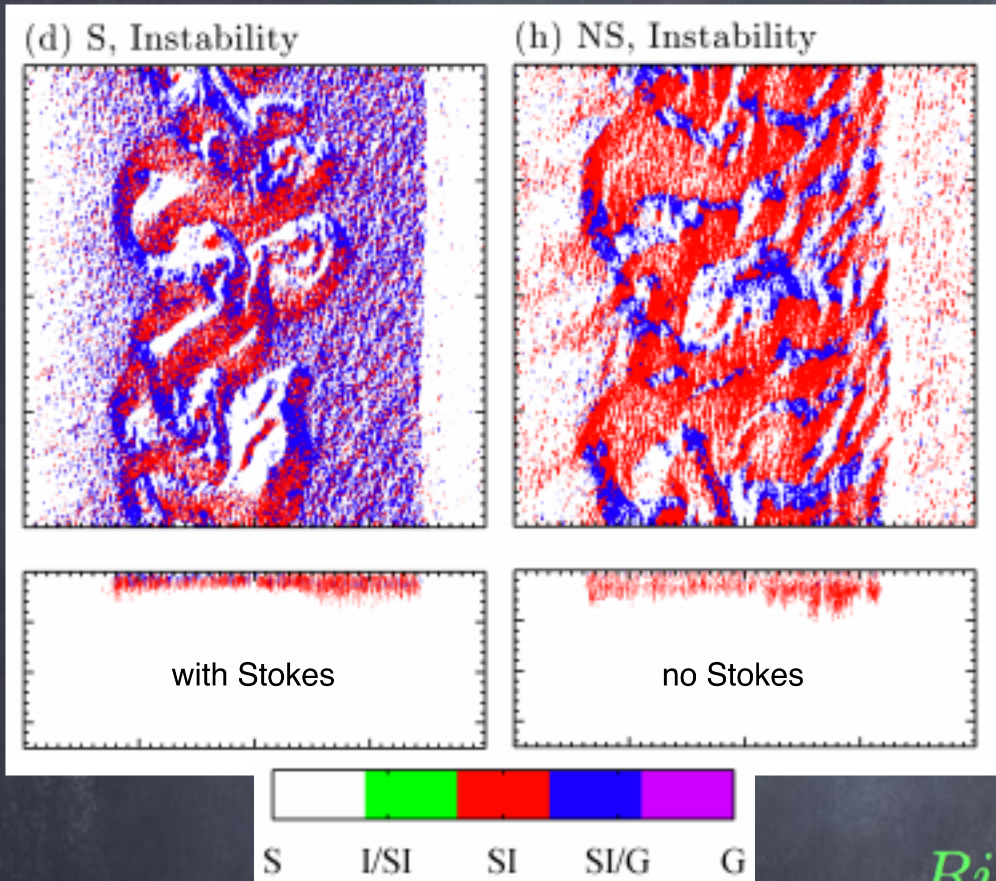
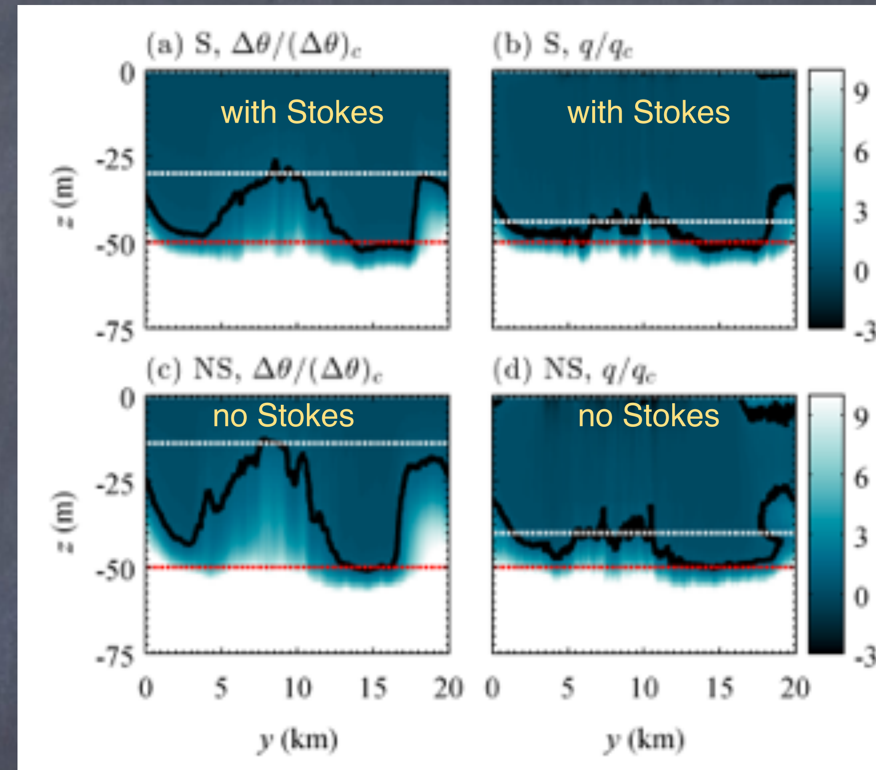




Stokes also influences Submesoscale & Langmuir-scale Instabilities through Lagrangian shear (Holm '96) & Lagrangian Thermal Wind





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

So, $q < 0$

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

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

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

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.

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 $q < 0$

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

$q < 0$

$Ri_E > 1$

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

SI win

$q < 0$

$Ri_E < 1$

$Ri_L > 1$

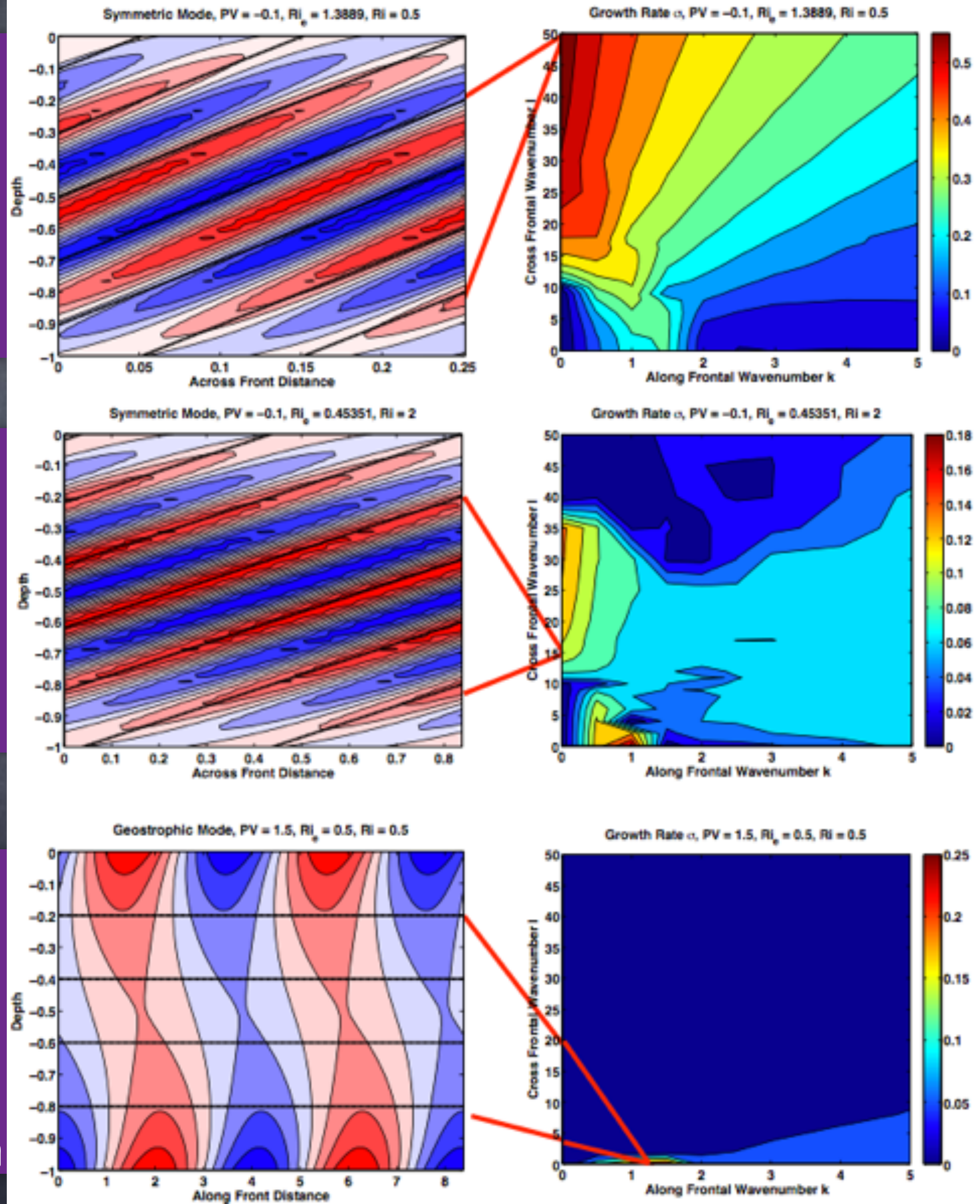
SI win

$q > 0$

$Ri_E < 1$

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

BCI win



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.

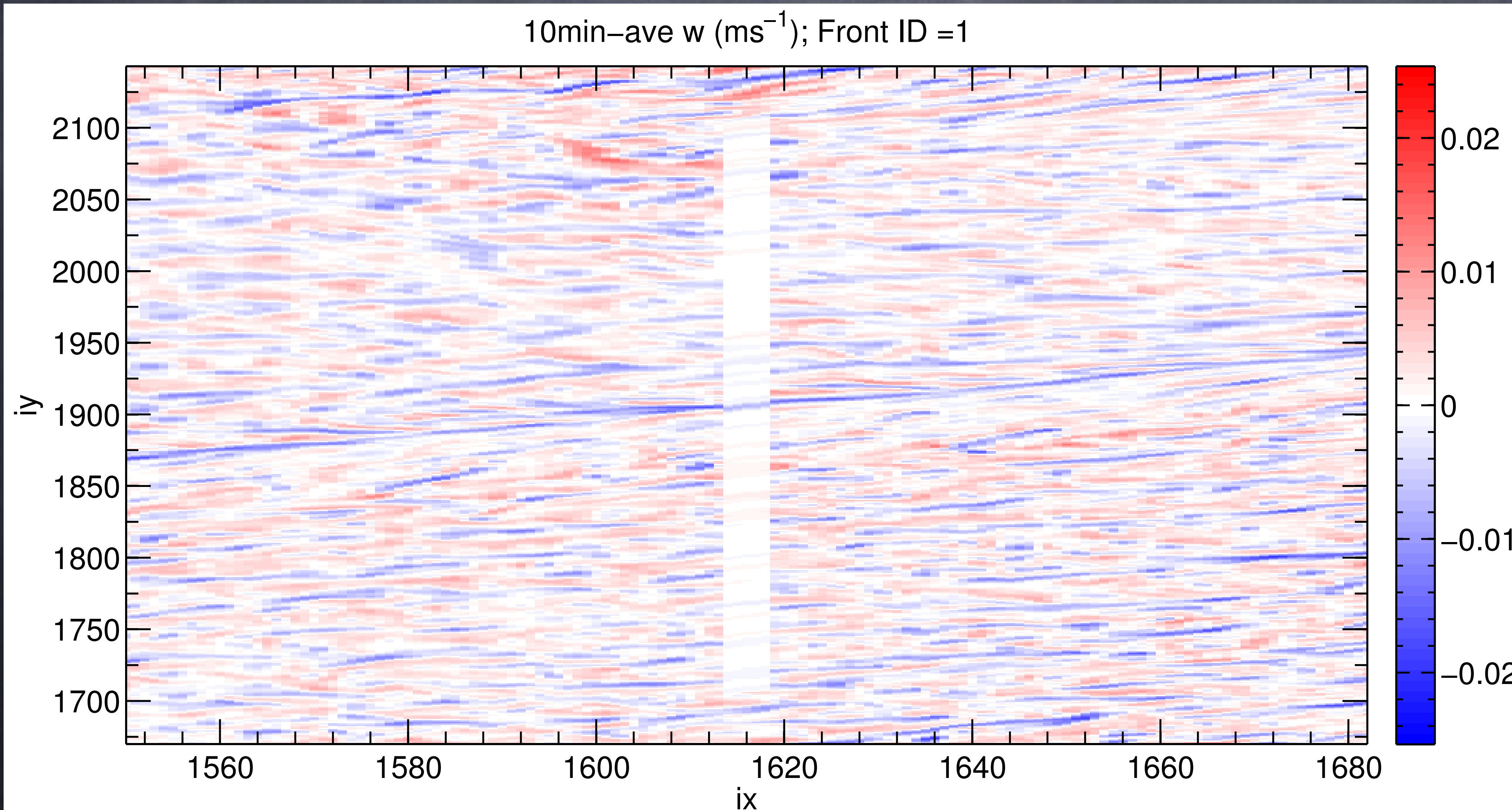
Conclusions

All papers at: fox-kemper.com/pubs

- 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

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



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

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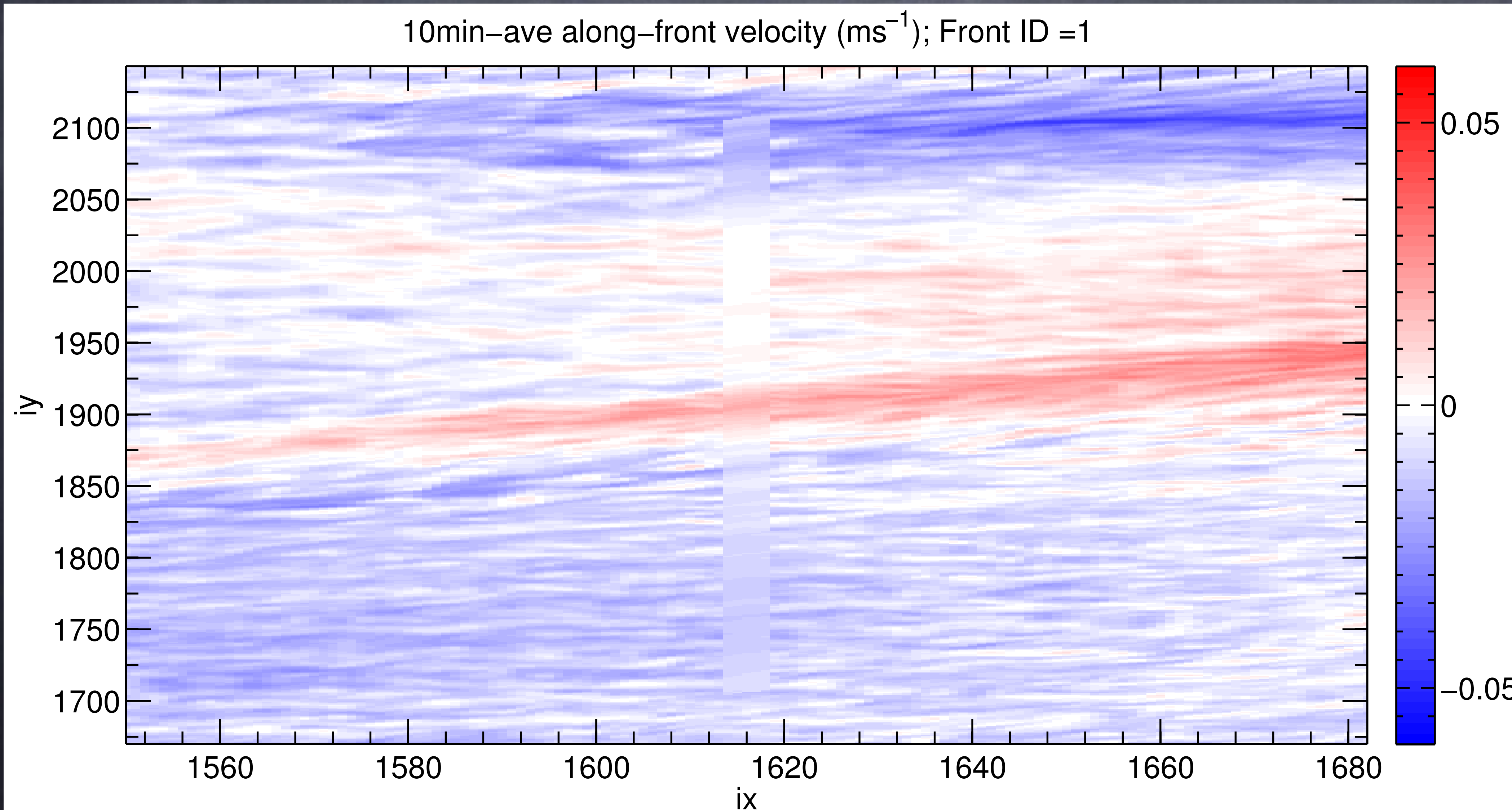

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