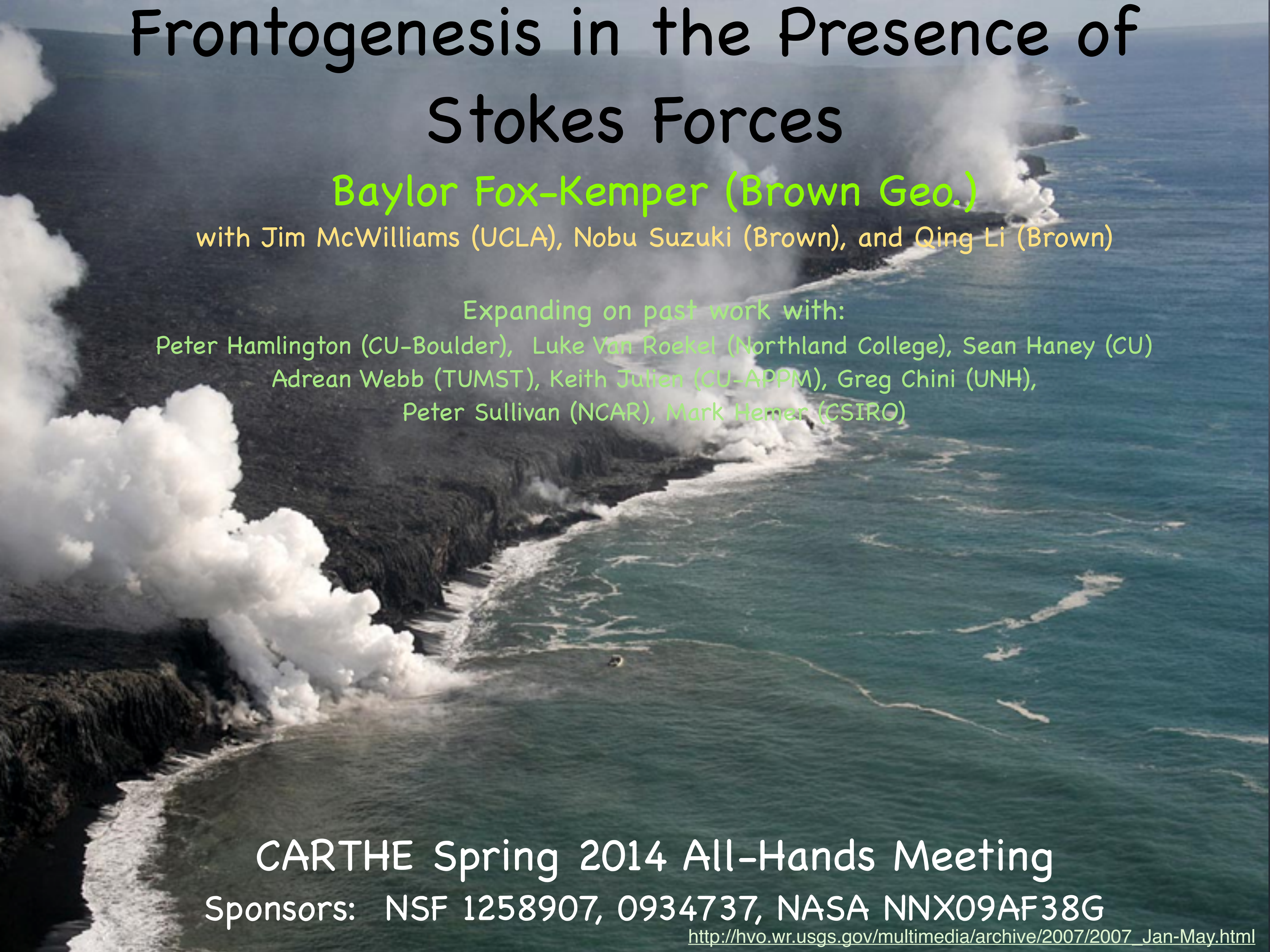
Frontogenesis in the Presence of Stokes Forces

Baylor Fox-Kemper (Brown Geo.)

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

Expanding on past work with:

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



CARTHE Spring 2014 All-Hands Meeting

Sponsors: NSF 1258907, 0934737, NASA NNX09AF38G

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

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

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

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

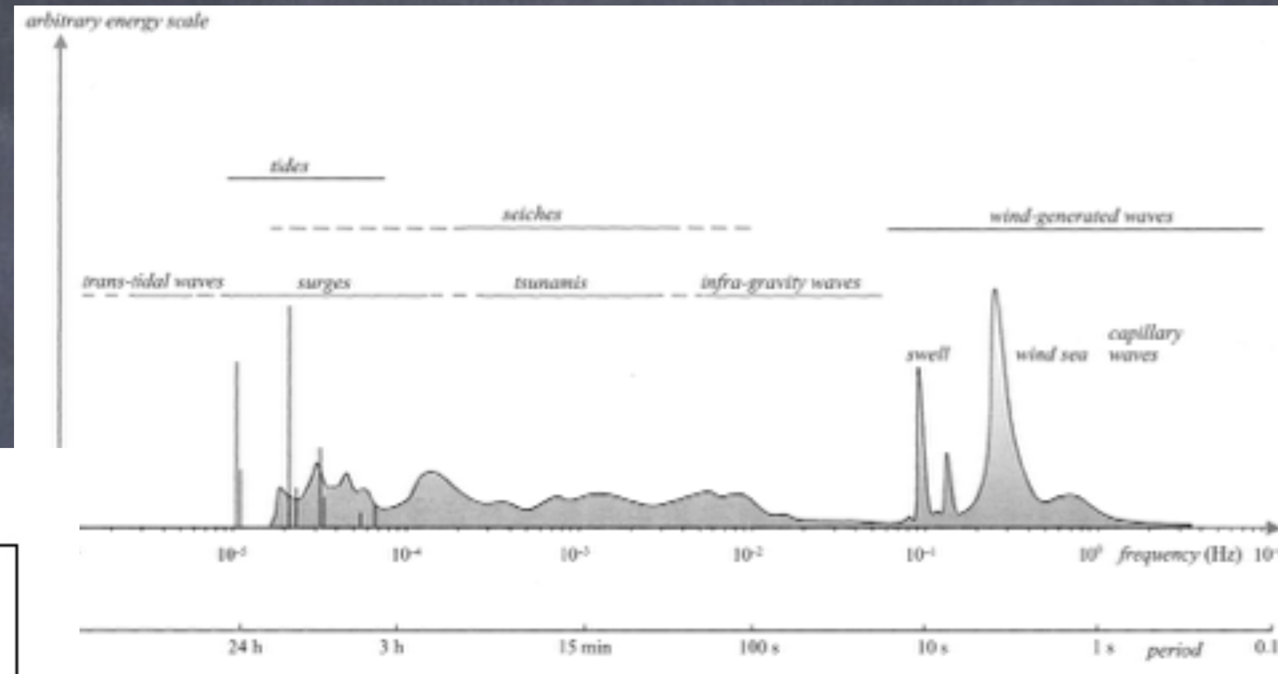
Plus boundary conditions

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

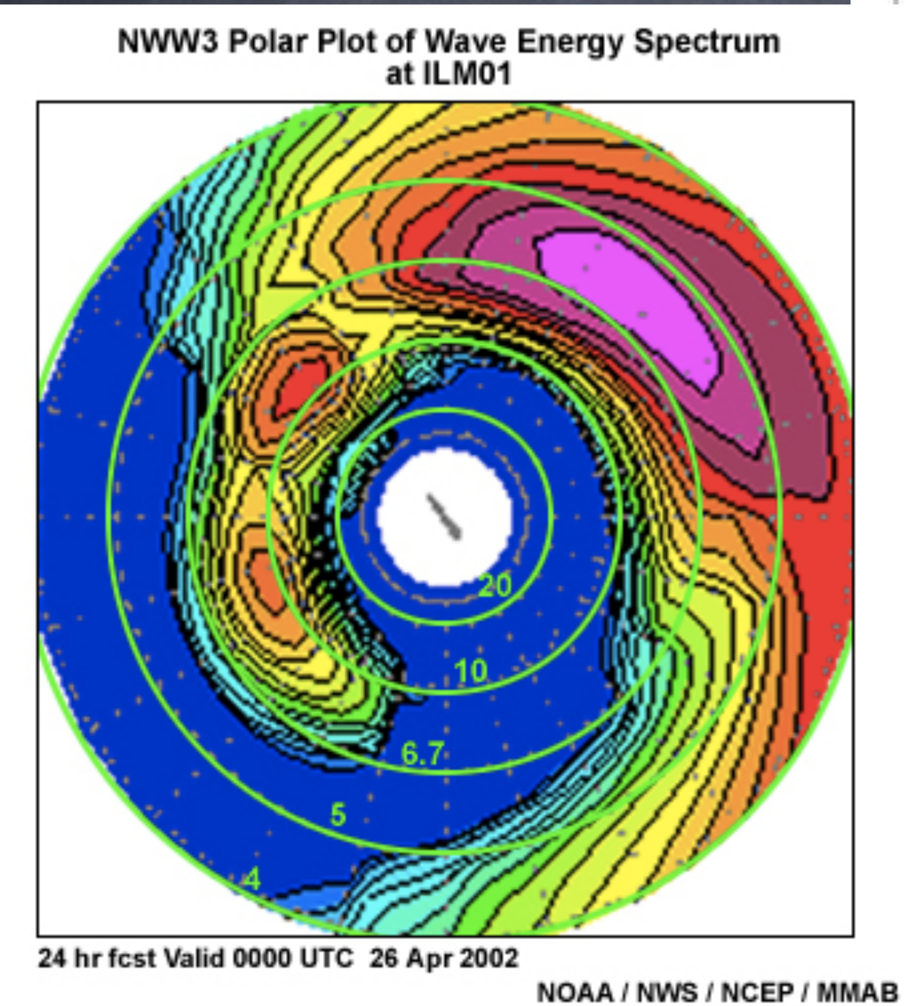
$$M_{Ro} \equiv \max(1, Ro) \quad v = \text{horiz. vel.} \quad w = \text{vert. vel.}$$

Surface Waves are...

fast, small, irrotational solutions of the Boussinesq Equations



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



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)

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

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

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

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

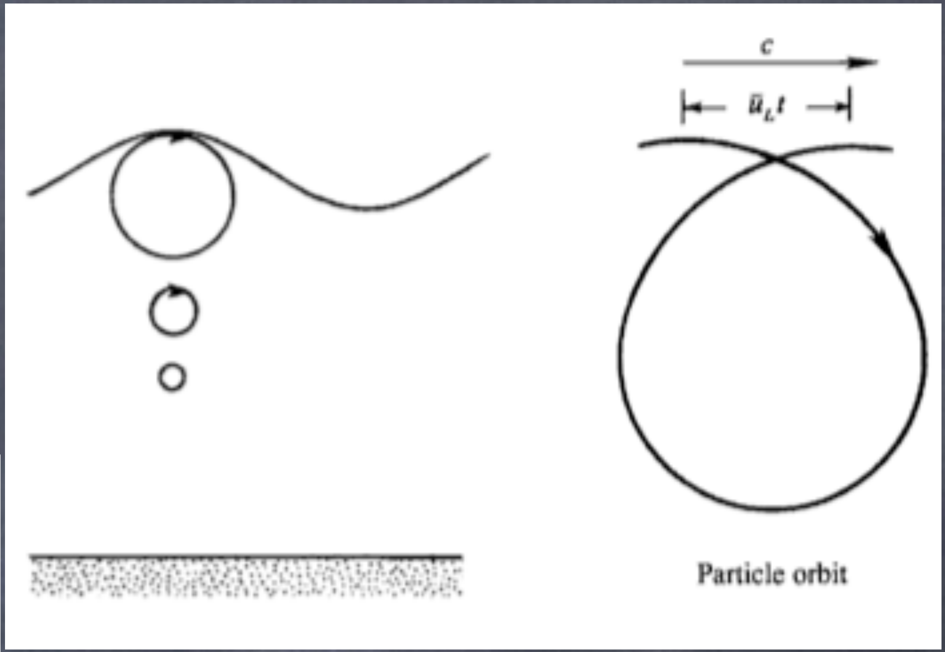
Plus boundary conditions

LAGRANGIAN (Eulerian+Stokes) advection & Coriolis

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

Stokes driftin' away

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

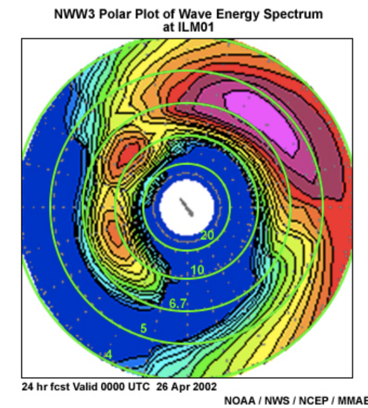


$$\boldsymbol{u}^L(\boldsymbol{x}_p(t_0),t) - \boldsymbol{u}^E(\boldsymbol{x}_p(t_0),t) \approx [\boldsymbol{x}_p(t) - \boldsymbol{x}_p(t_0)] \cdot \nabla \boldsymbol{u}^E(\boldsymbol{x}_p(t_0),t)$$
$$\approx \left[\int_{t_0}^{t} \boldsymbol{u}^E(\boldsymbol{x}_p(t_0),s')ds'\right] \cdot \nabla \boldsymbol{u}^E(\boldsymbol{x}_p(t_0),t).$$

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

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



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

The Character of the Langmuir Scale

- 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: Thorpe, 04

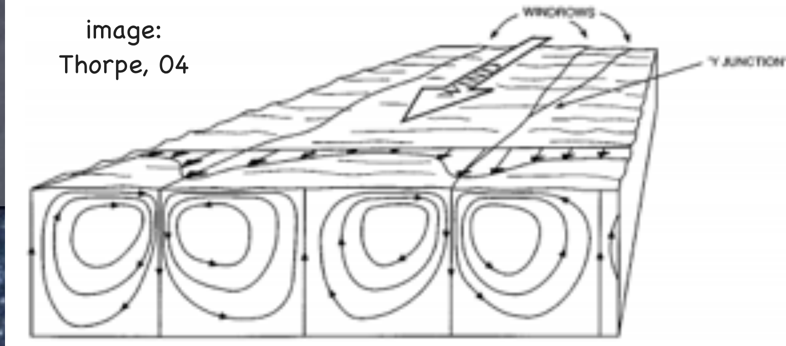


Figure 1 Sketch showing the pattern of mean flow in idealized Langmuir circulation. Th windrows may be 2 m to 300 m apart, and the cell form is roughly square (as shown). I practice the flow is turbulent, especially near the water surface, and the windrows (Figure 2 amalgamate and meander in space and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

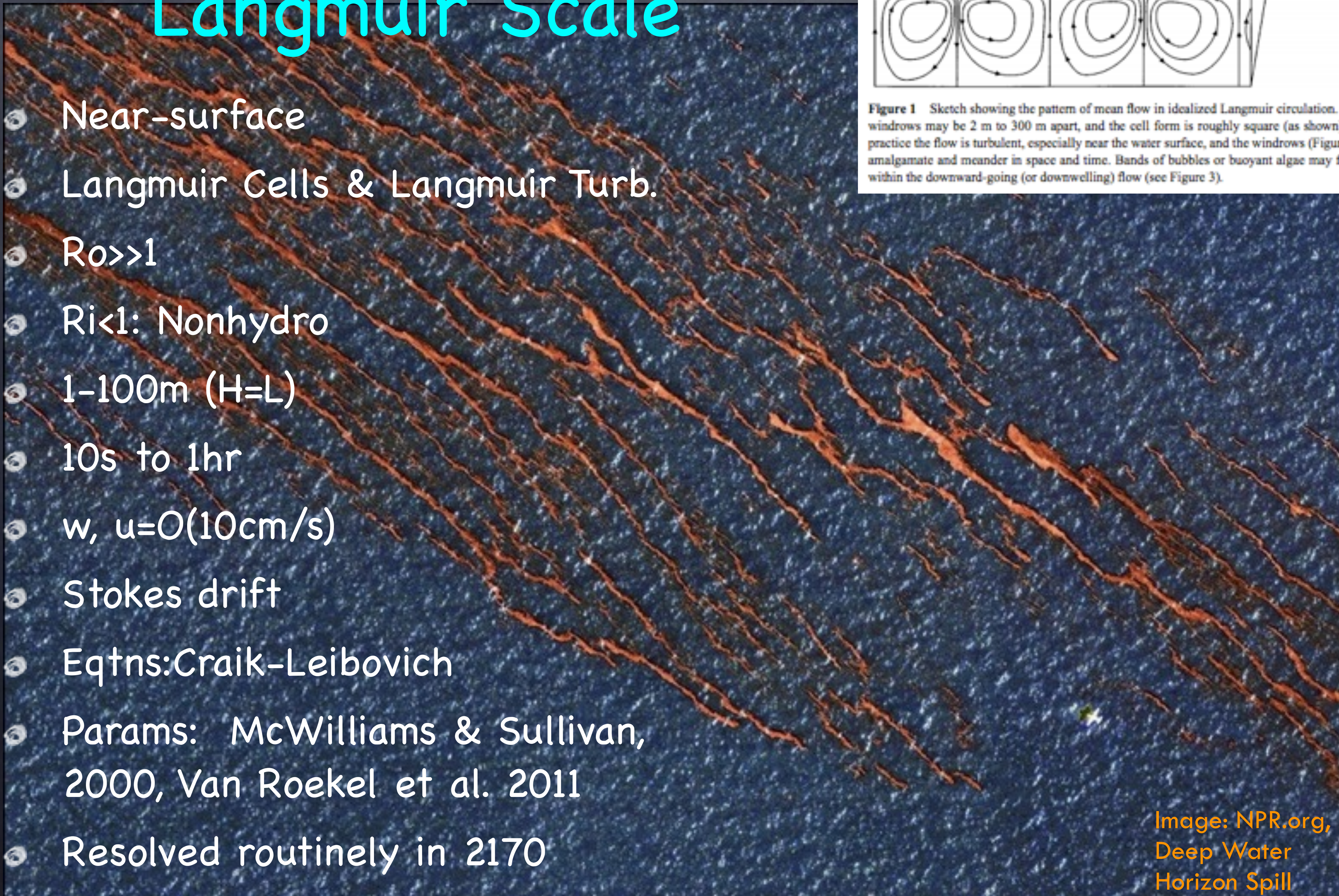
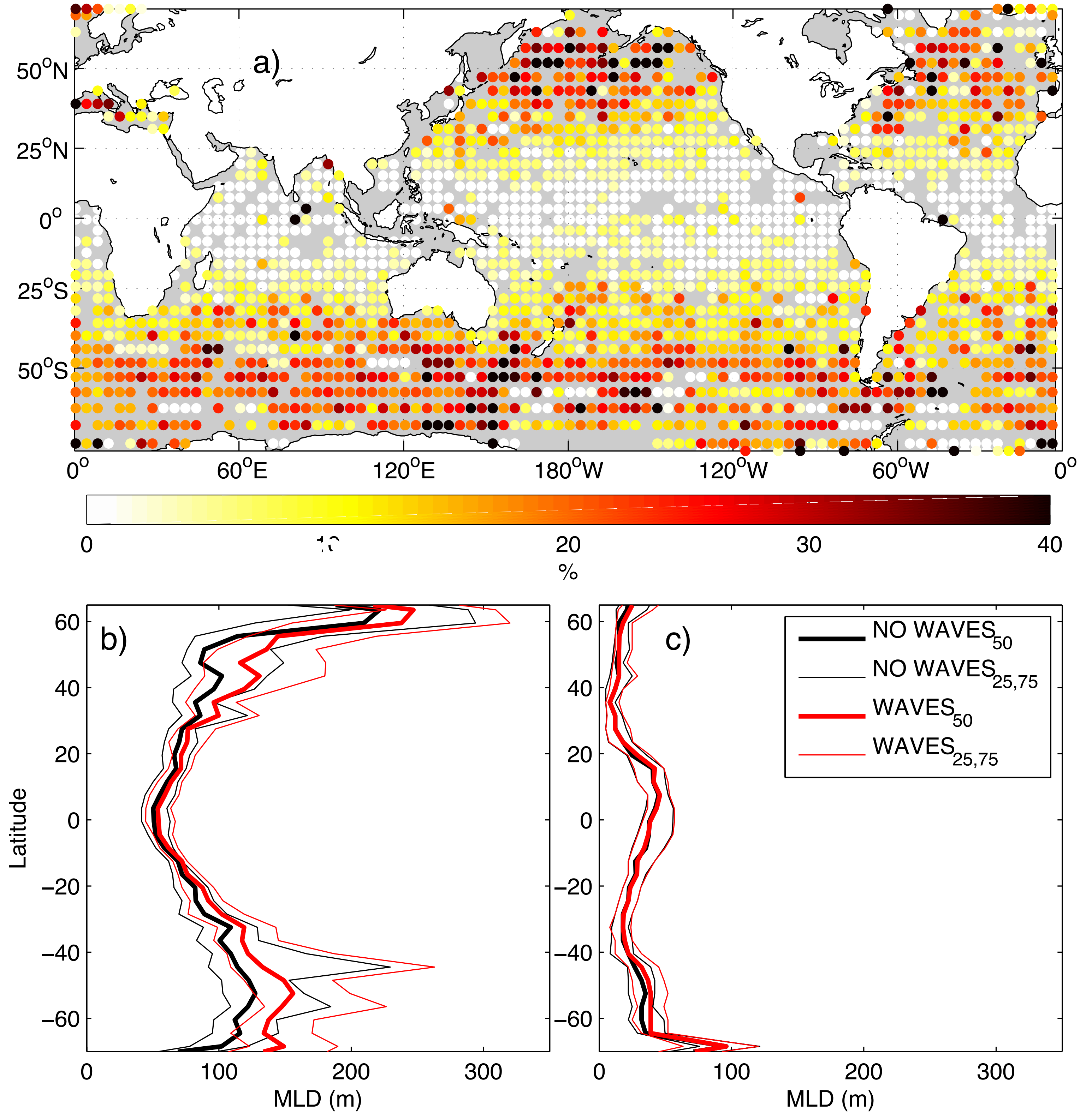


Image: NPR.org, Deep Water Horizon Spill

Offline obs-driven parameterization:

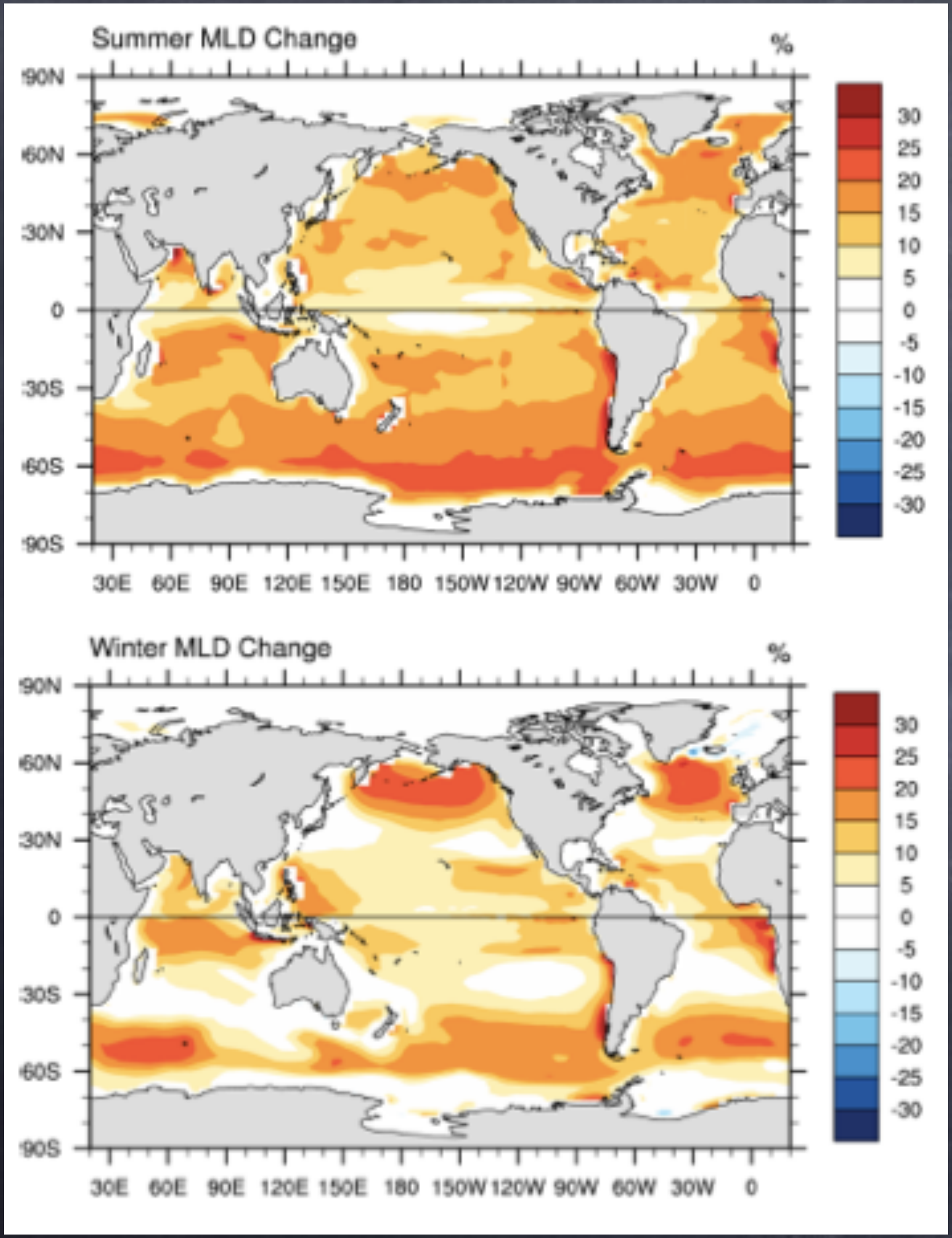
Including Stokes-driven Mixing (Harcourt 2013) Deepens the Mixed Layer!



E. A. D'Asaro, J. Thomson, A. Y. Shcherbina, R. R. Harcourt, M. F. Cronin, M. A. Hemer, and 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!

(Harcourt & D'Asaro, 2008; Van Roekel et al, 2012)



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

Depth & misaligned

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

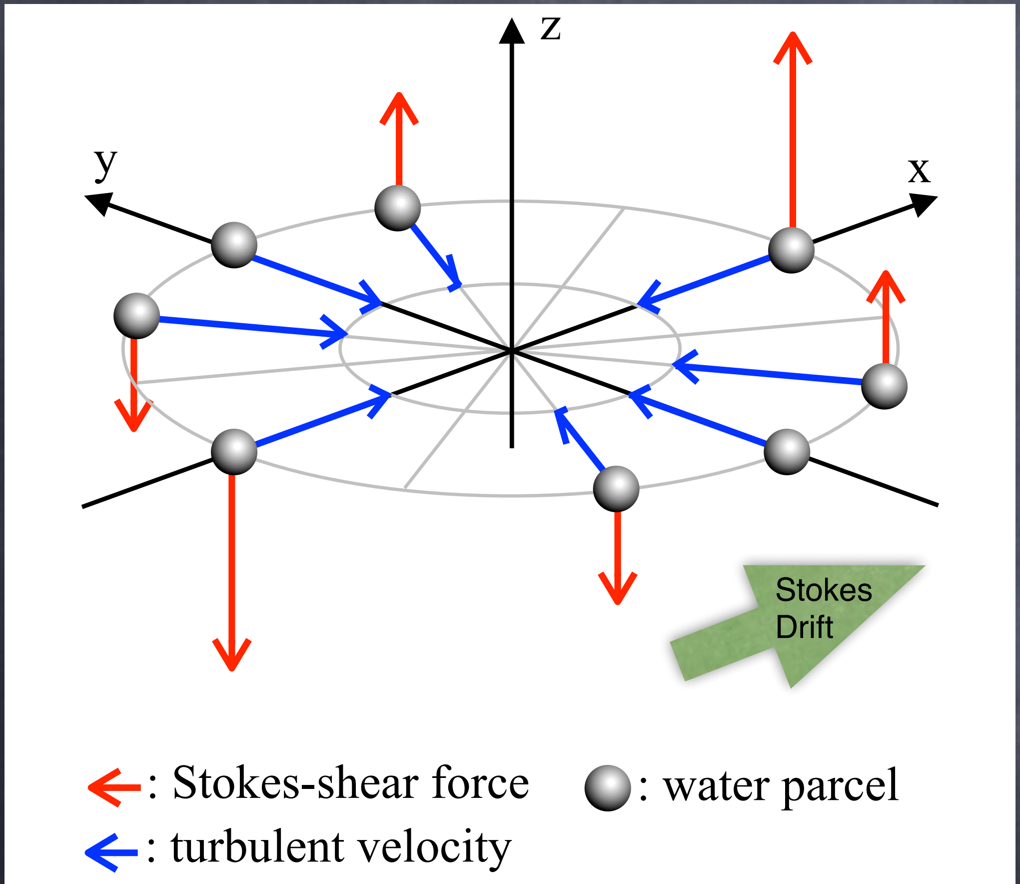
Depth & misaligned

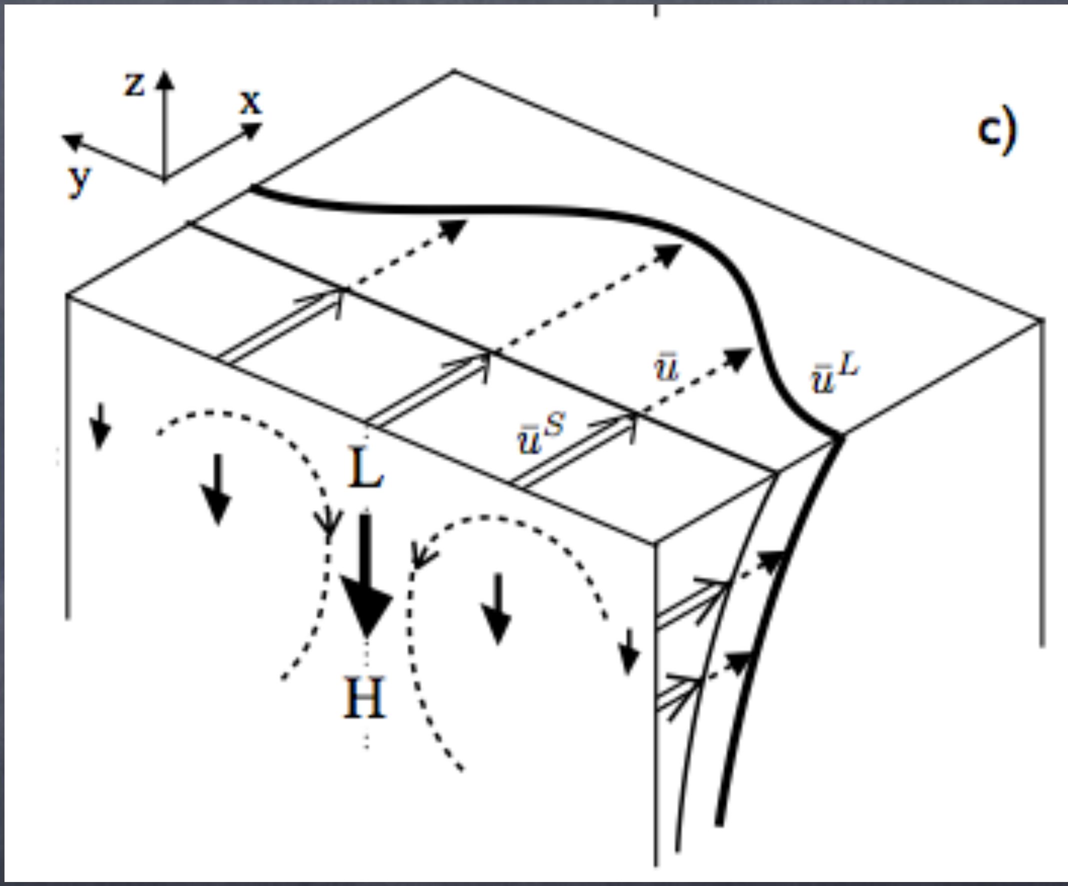
Remains to be co-tuned with mixed layer eddy, mesoscale, and near-inertial mixing parameterizations

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.

Stokes Shear Force
and the CL2 mechanism for Langmuir circulations

Flow directed along Stokes shear=downward force

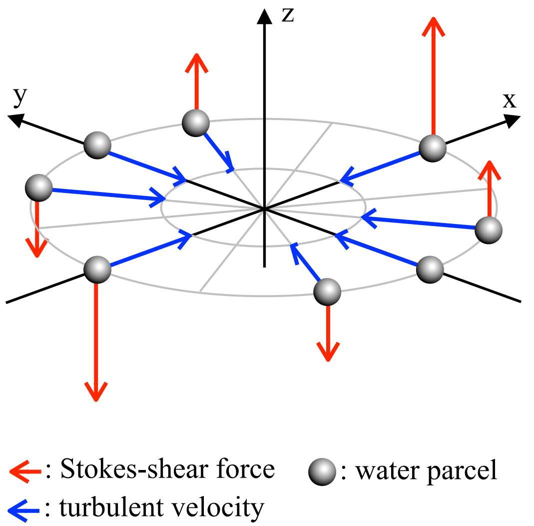


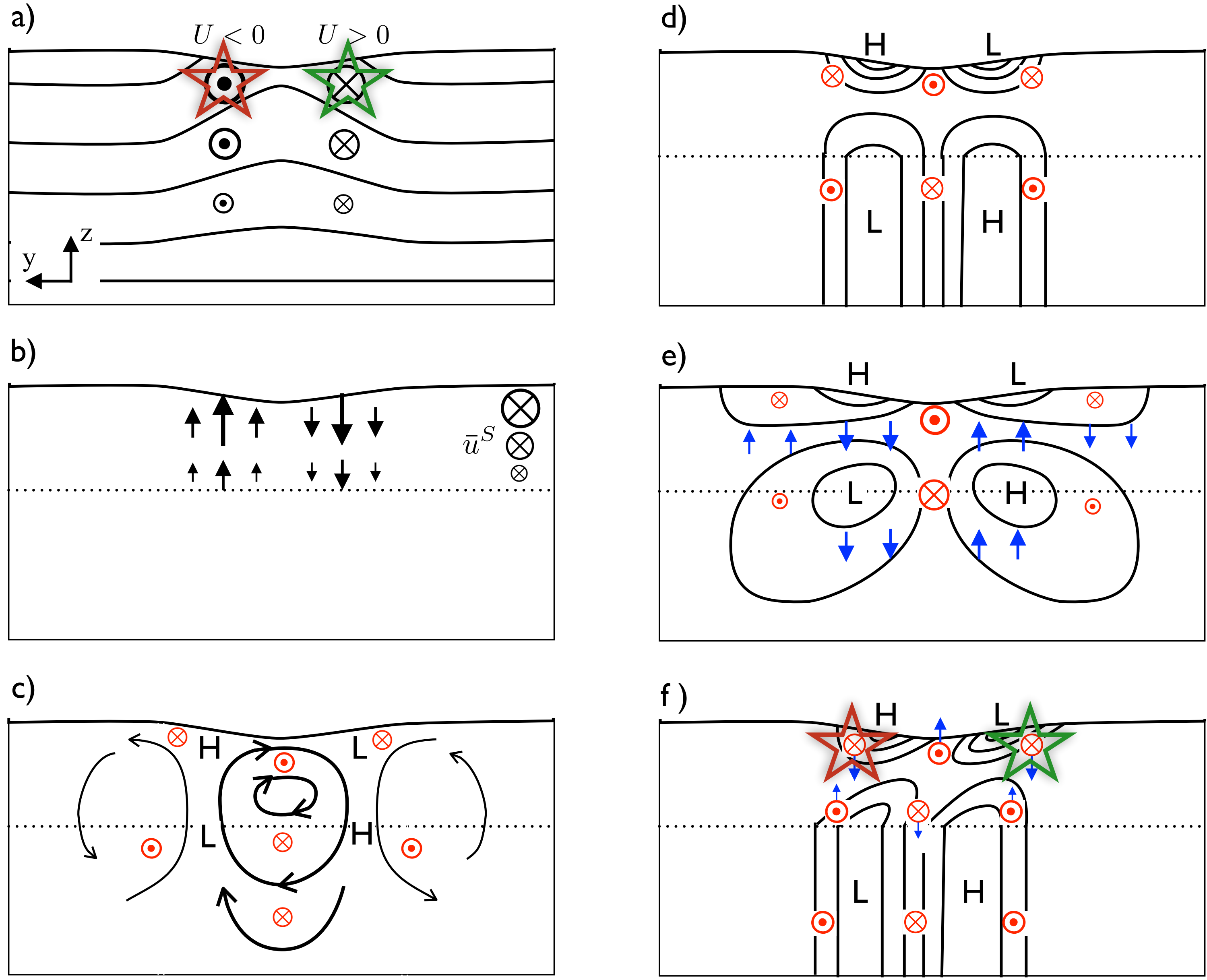


$$\frac{\alpha^2}{Ri}\left[w_{,t} + v_j^L w_{,j} + \frac{M_{Ro}}{RoRi}\right] = -\pi_{,z} + b + \varepsilon v_j^L v_{j,z}^s + \frac{\alpha^2}{ReRi} w_{,jj}$$

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

Stokes 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, JPO, in prep, 2014.

Enhances Frontogenesis for Down-Front Stokes

Opposes Frontogenesis for Up-Front Stokes

Importance of Stokes shear force versus finite Rossby on (sub)mesoscale: McWilliams & F-K (13)

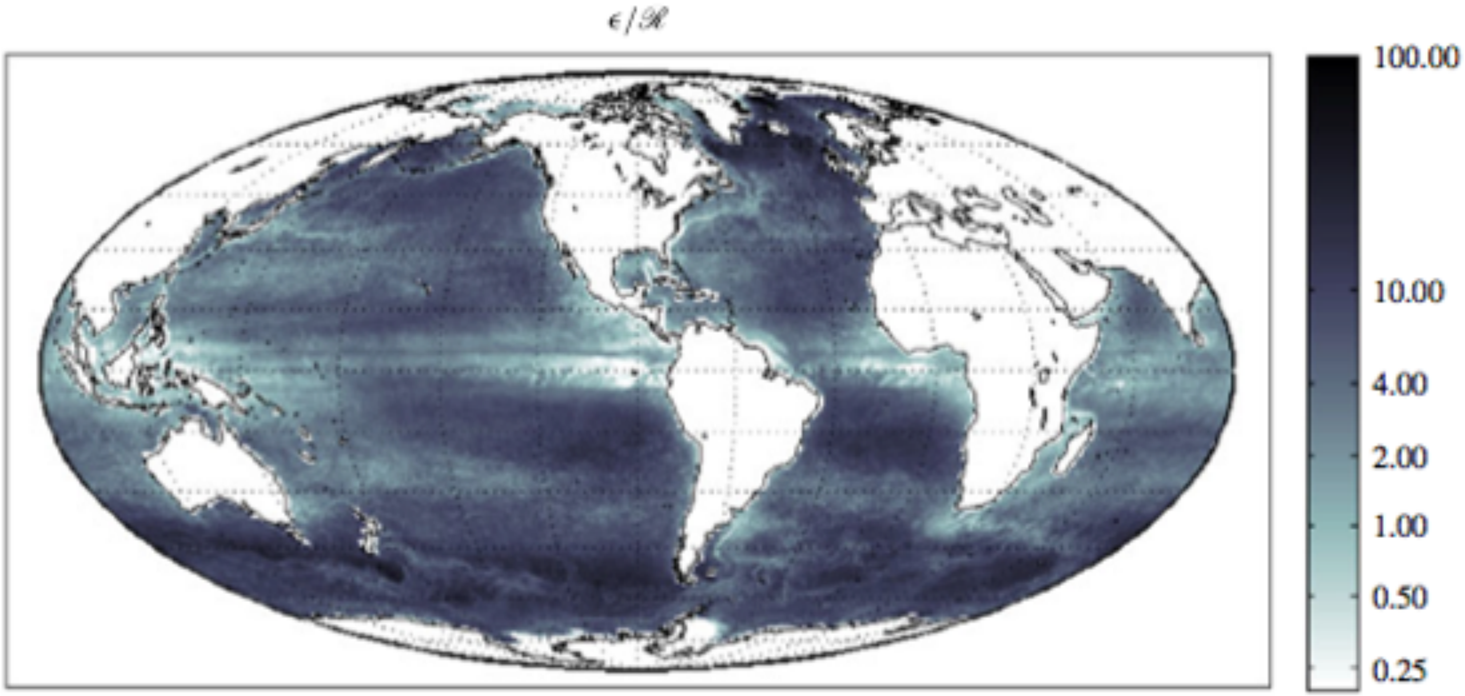


FIGURE 1. (Colour online) Estimated ratio $\epsilon/\mathscr{R} \approx (|\boldsymbol{u}_s \cdot \boldsymbol{u}| h)/(|\boldsymbol{u}|^2 h_s)$ governing the relative importance of Stokes effects versus nonlinearity. Eulerian velocity ($\boldsymbol{u}$) is taken as the AVISO weekly satellite geostrophic velocity or $-\boldsymbol{u}_s$ (for anti-Stokes flow) if $|\boldsymbol{u}_s| > |\boldsymbol{u}|$. 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 9 m projected onto the AVISO geostrophic velocity provides $\boldsymbol{u}_s \cdot \boldsymbol{u}$ and h_s. Stokes drift is taken from the Wave Watch 3 simulation described in Webb & Fox-Kemper (2011). $\boldsymbol{u}, \boldsymbol{u}_s$, 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 $\epsilon/\mathscr{R}$ is shown.

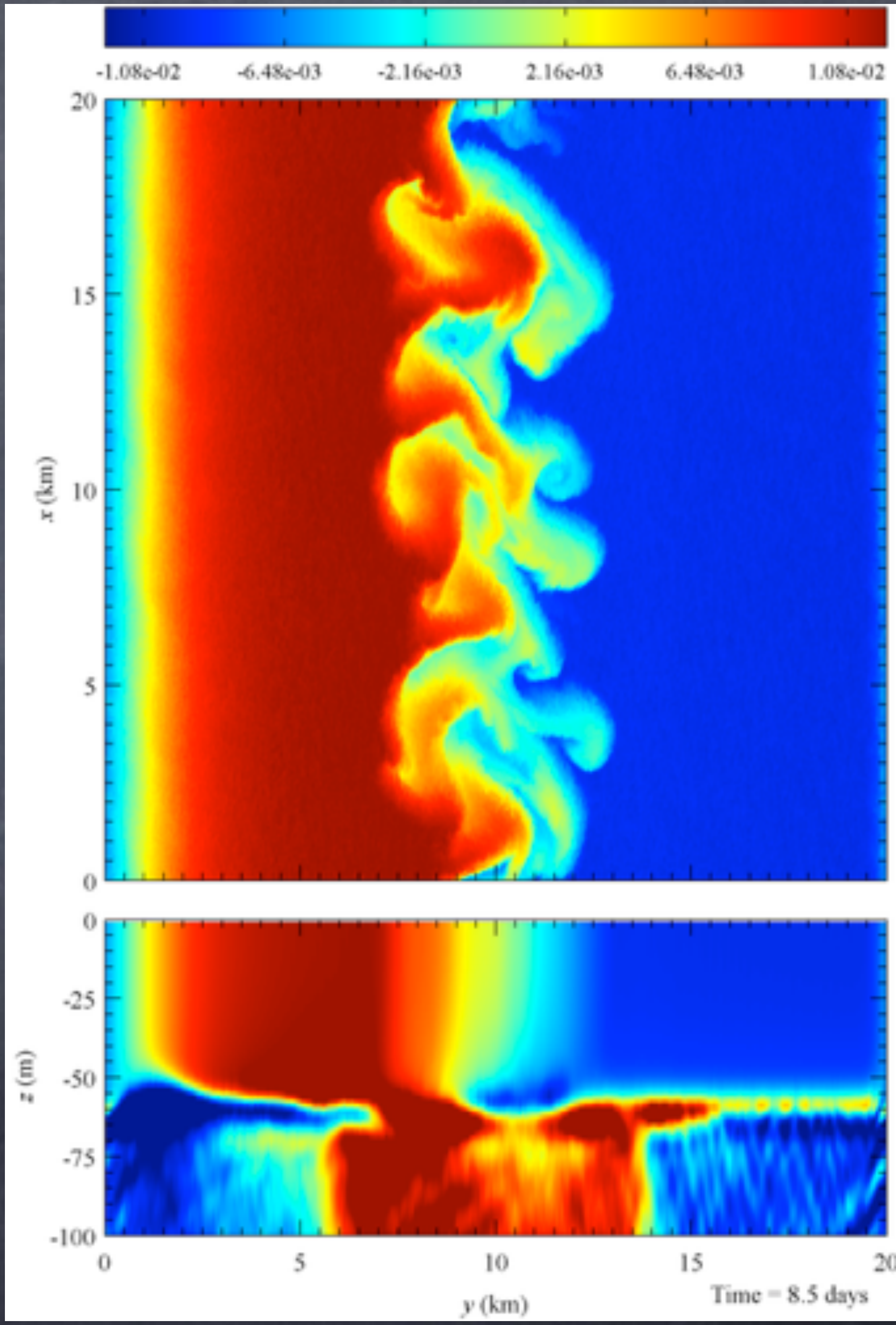
$$\varepsilon = \frac{V^s H}{f L H_s}$$

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

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

LES of Langmuir-Submeso Interactions?

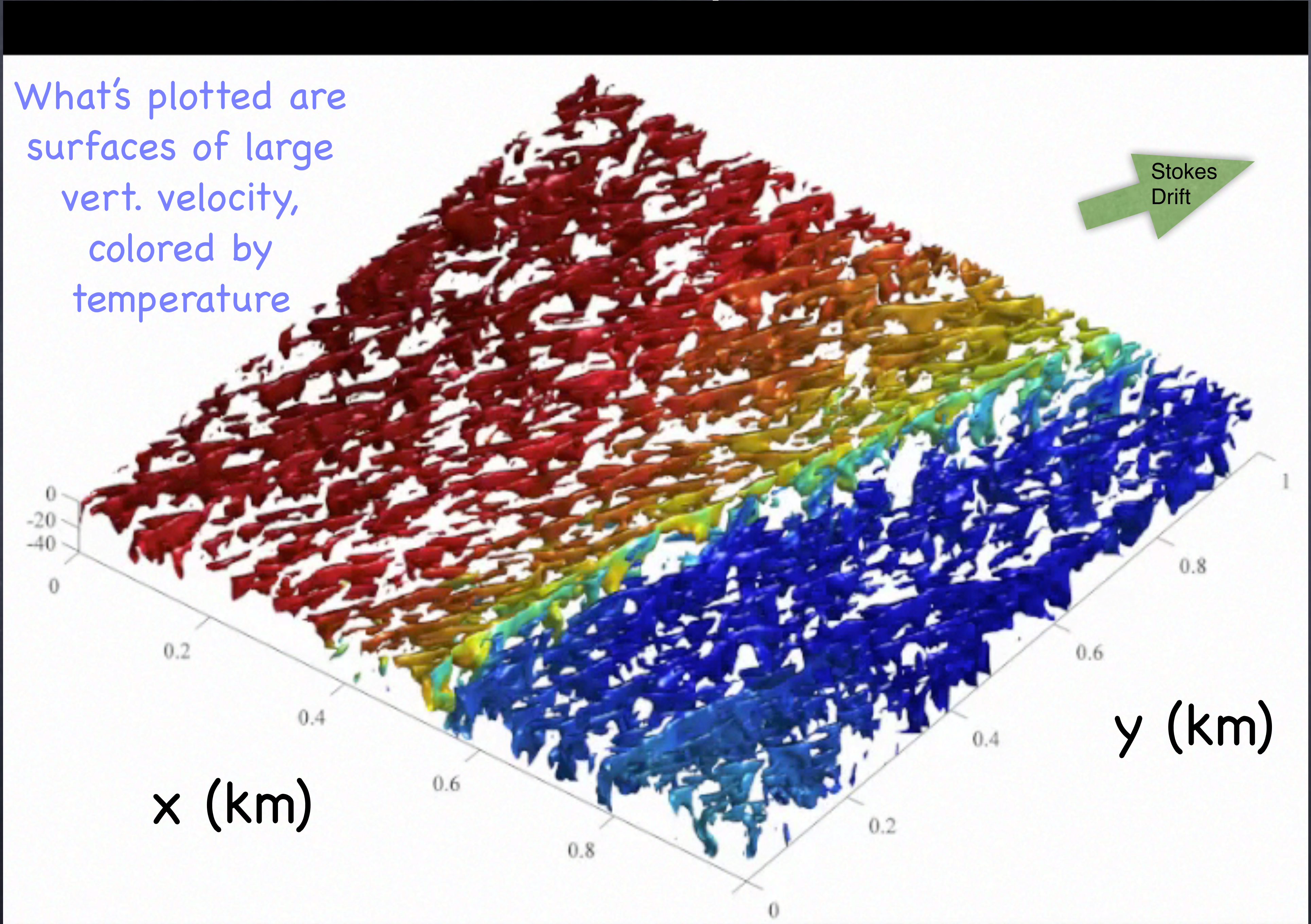
Perform large eddy simulations (LES) of Langmuir turbulence with a submesoscale temperature front using wave-averaged equations



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!



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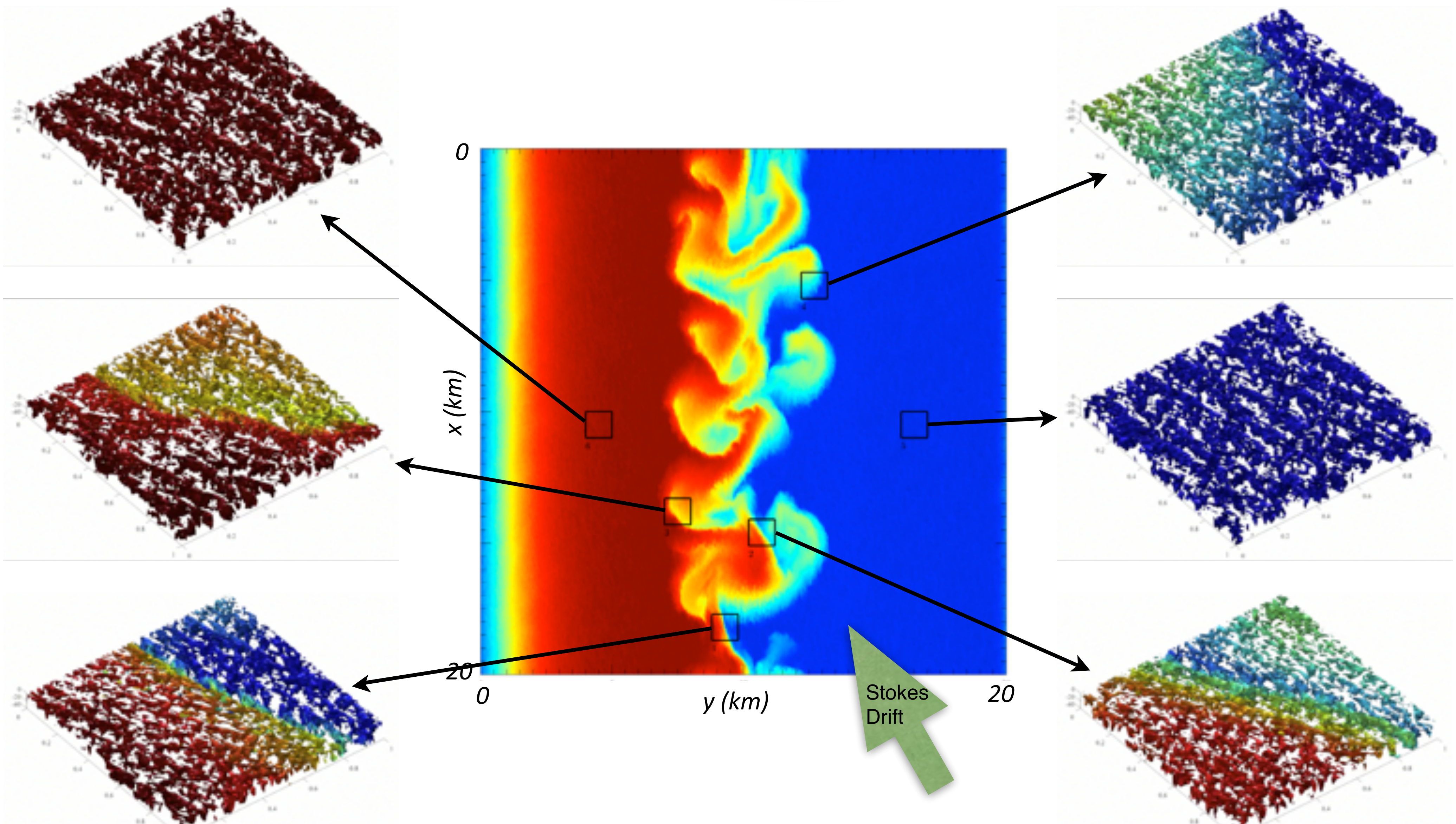
Diverse types of interaction



Slide & Movies by Peter Hamlington

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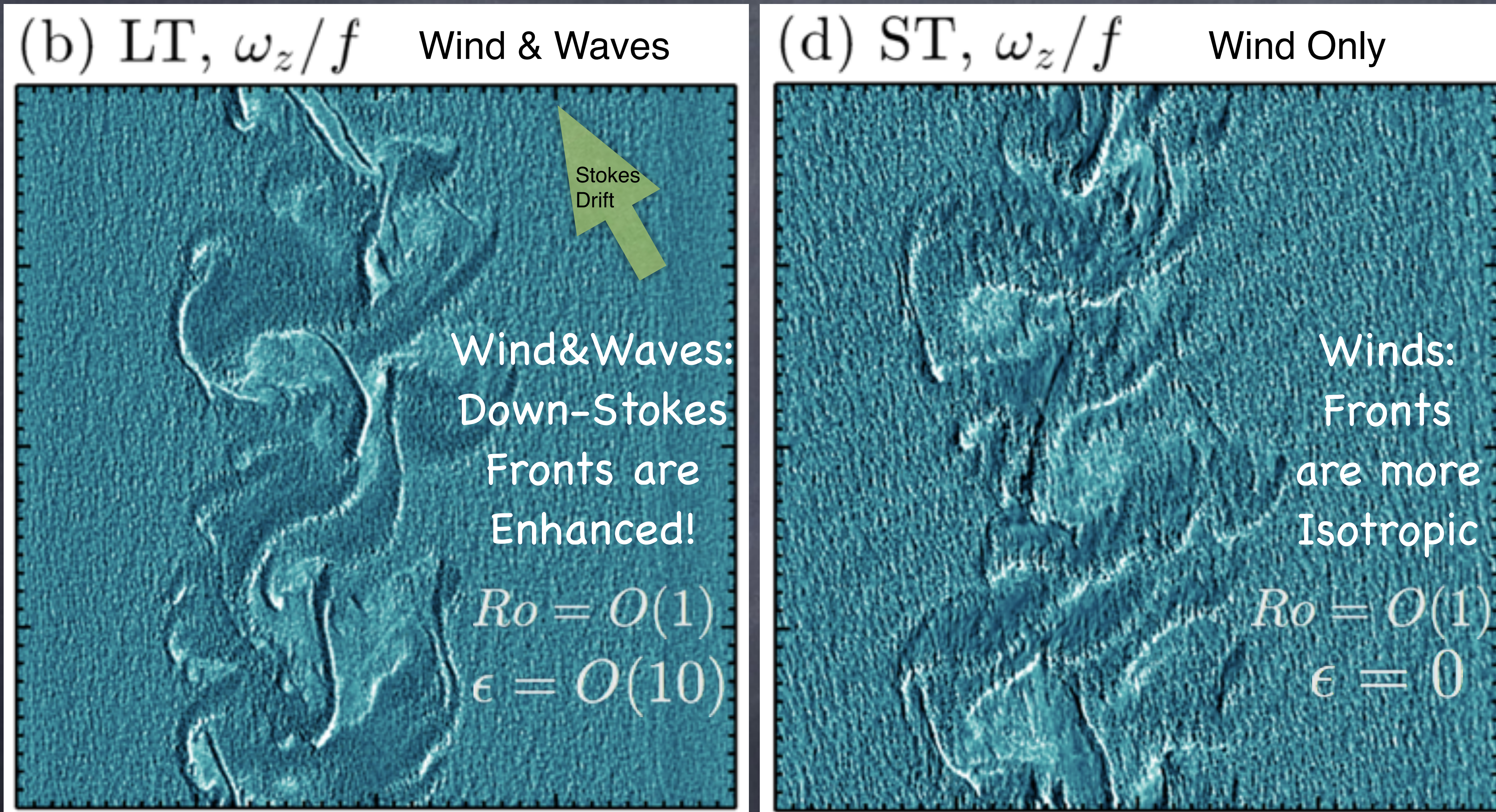
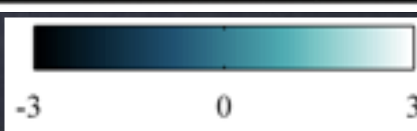
Are Fronts and Filaments different with Stokes shear force?

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





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

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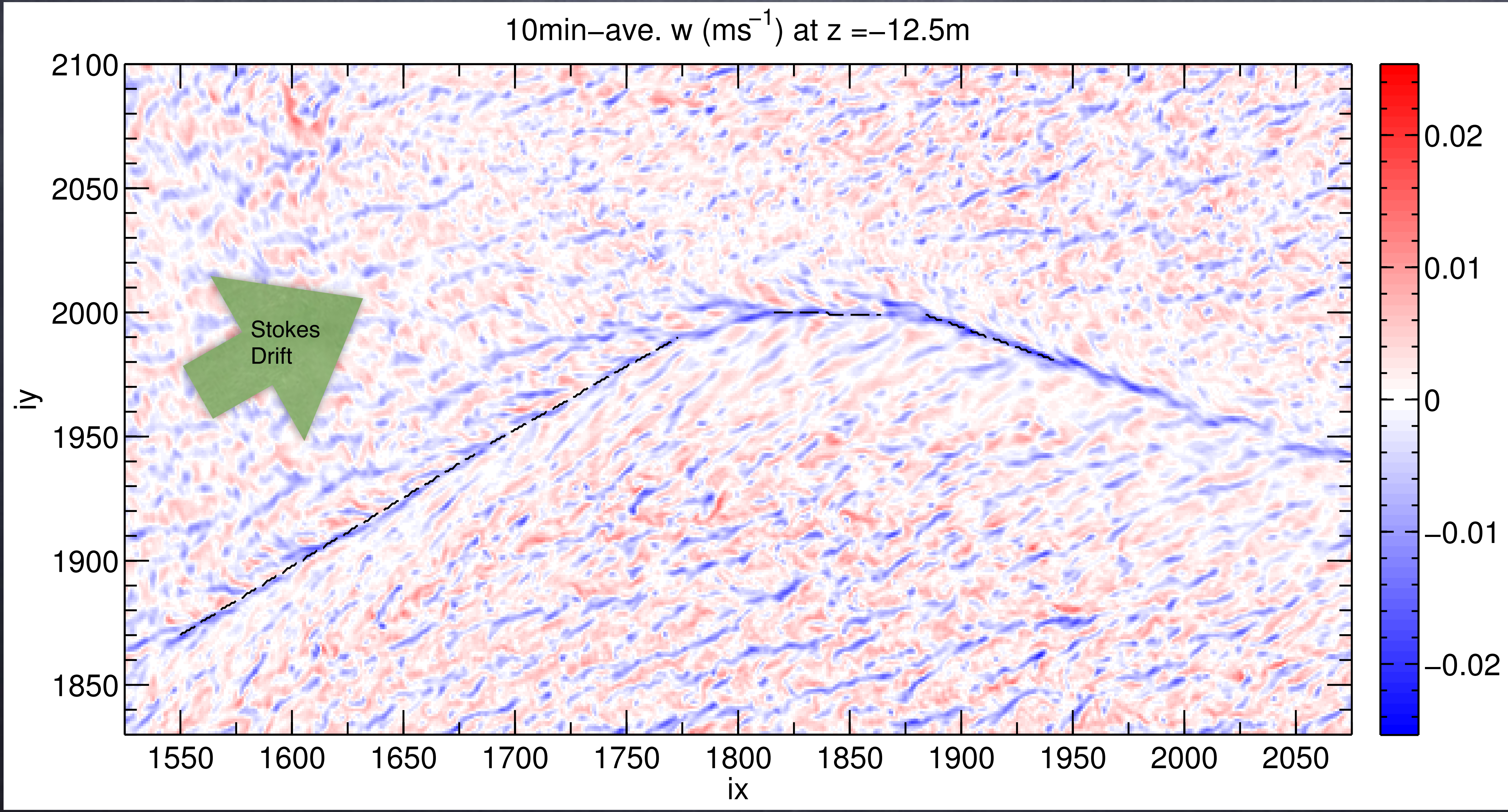
Let's examine 1 particular front

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



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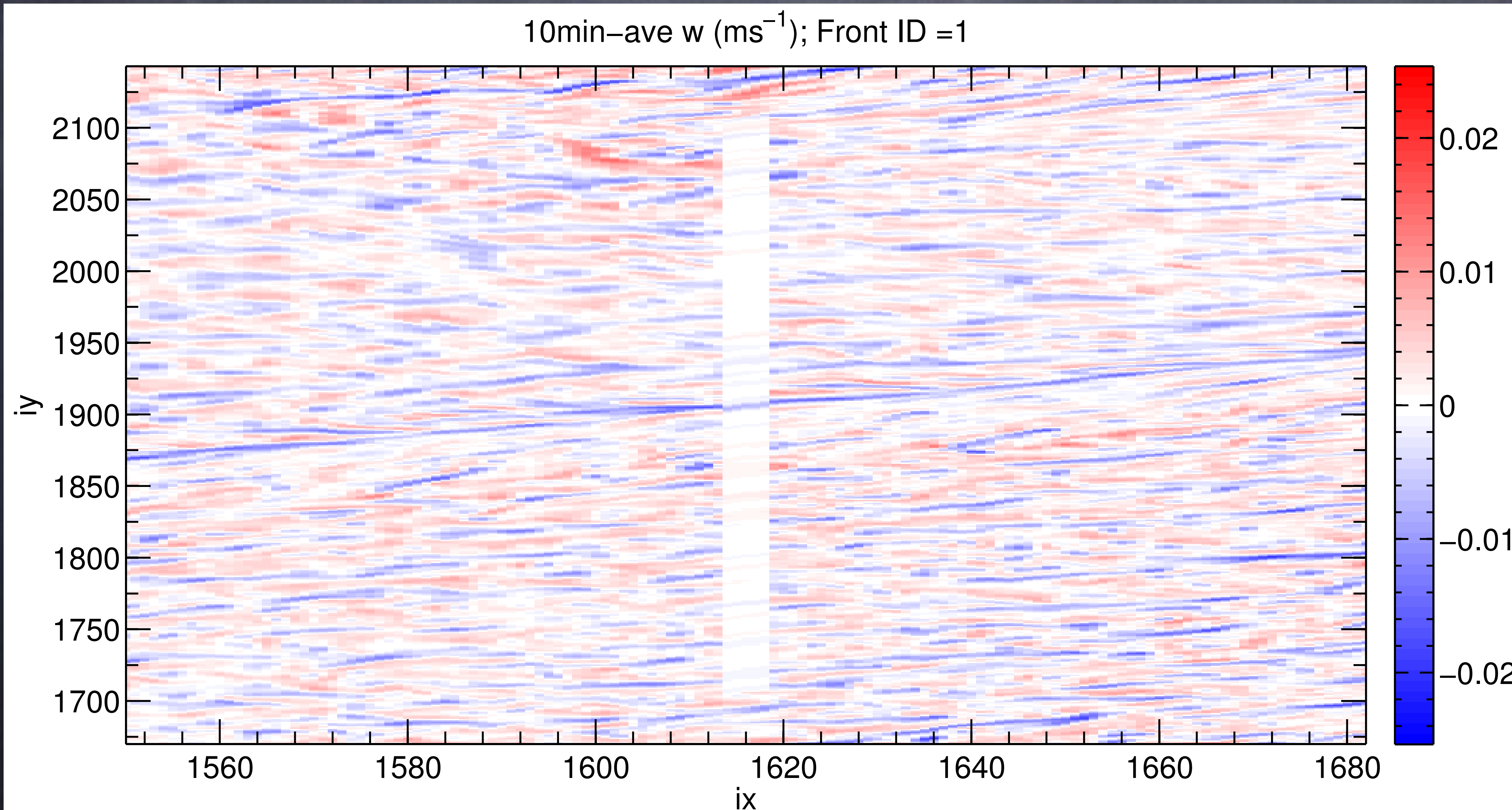
Along-Front and 10min Average

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



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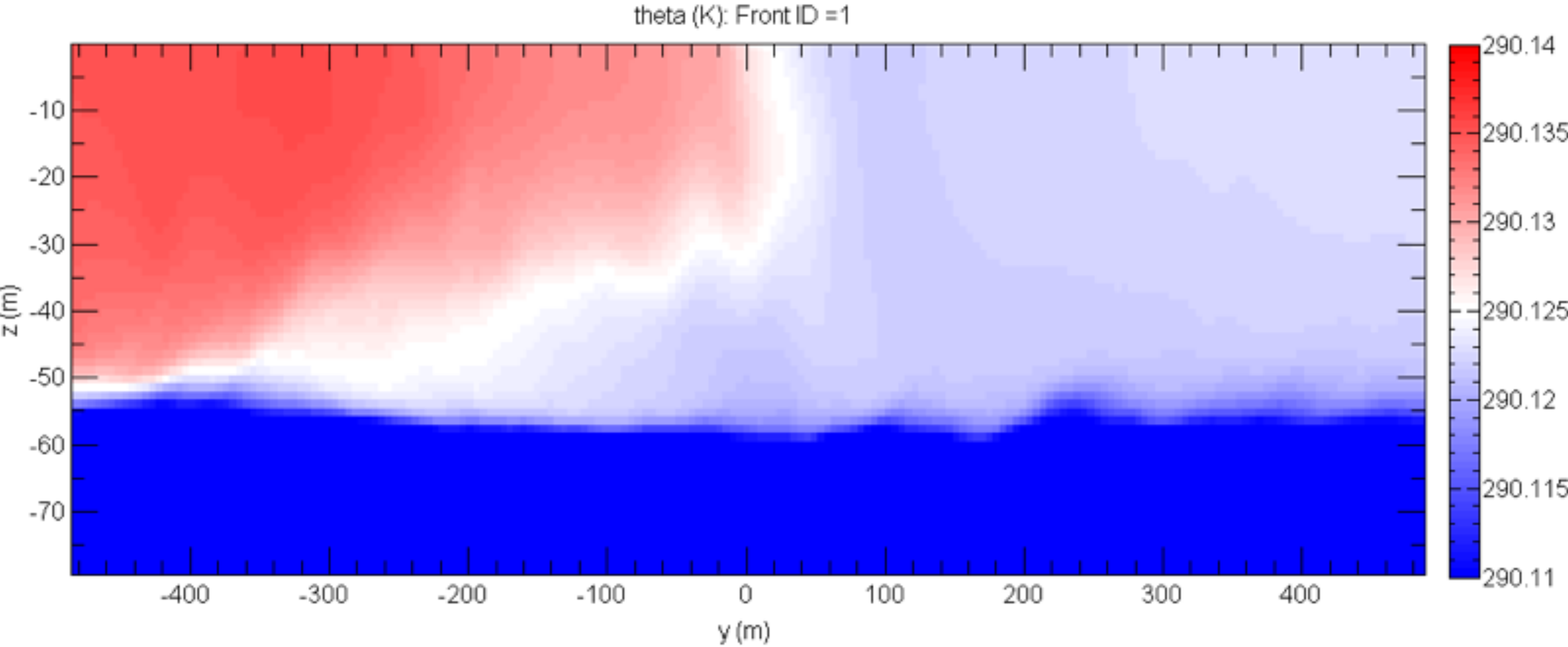

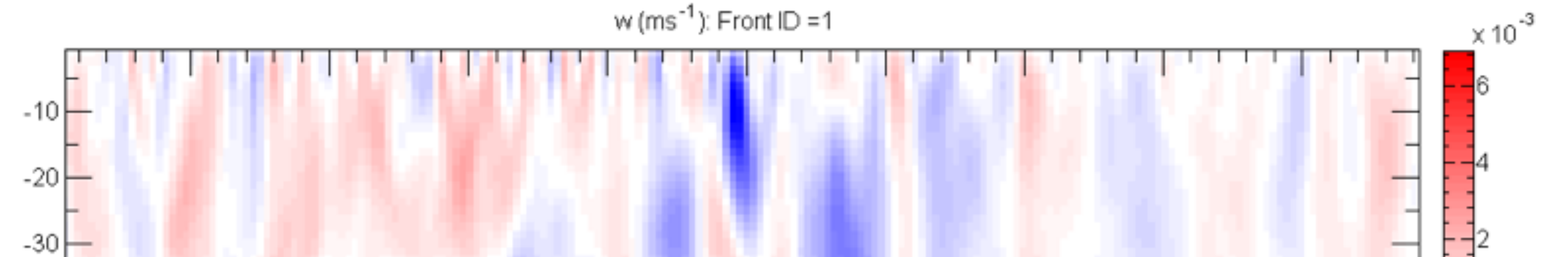

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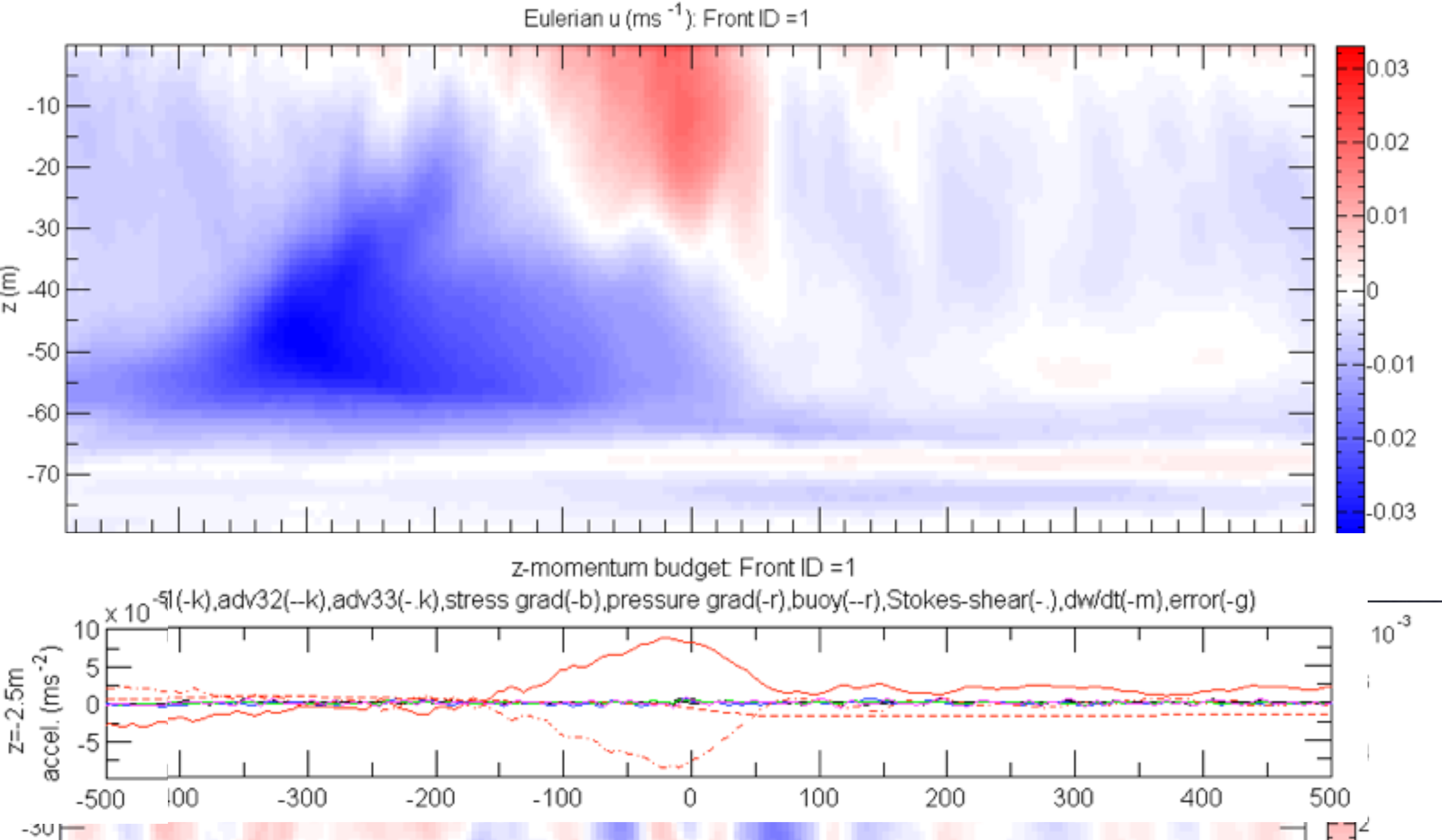

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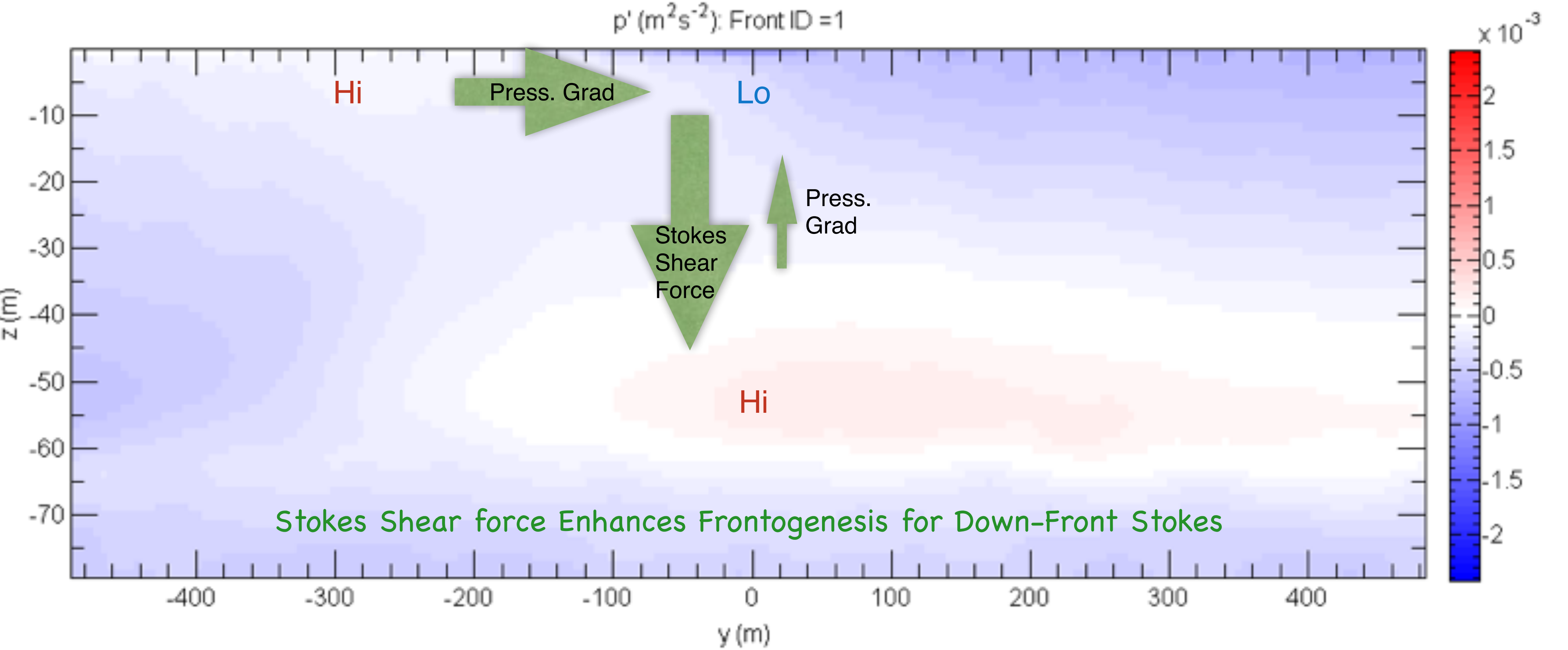
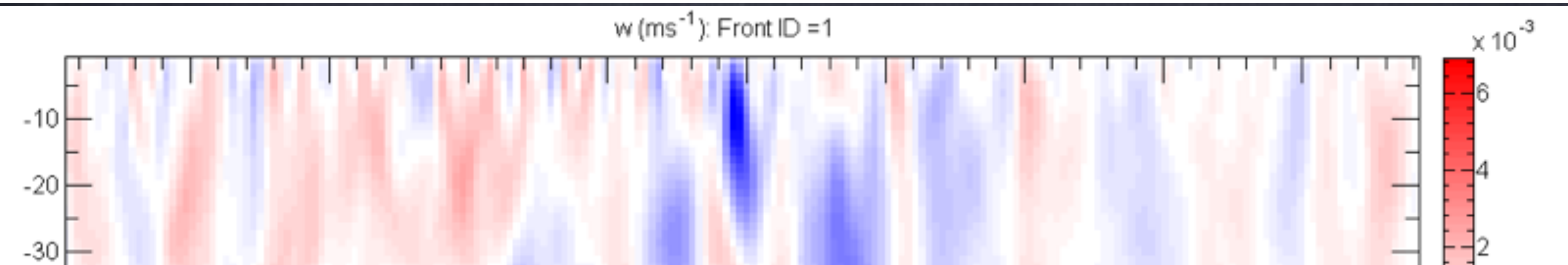




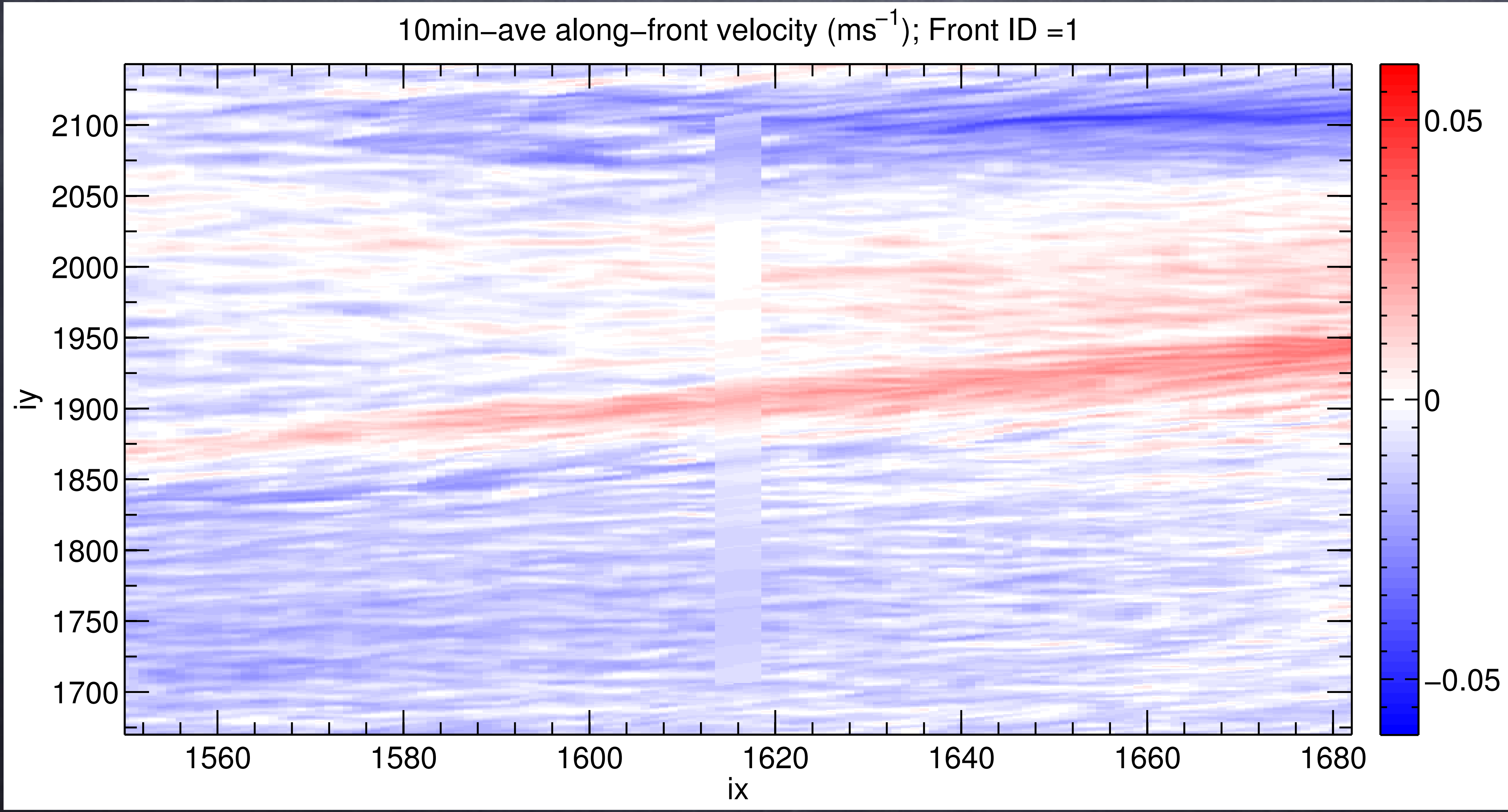
Conclusions

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, ϵ , 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 interaction, and frontal instabilities will be different
- 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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