Eddies, Mixing and all that: Ocean Parameterization Developments from 4m to 400km

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Balance, Boundaries, and Mixing in the Climate Problem
13:40 - 14:20, September 19, 2011; Montreal, Canada

Sponsors:
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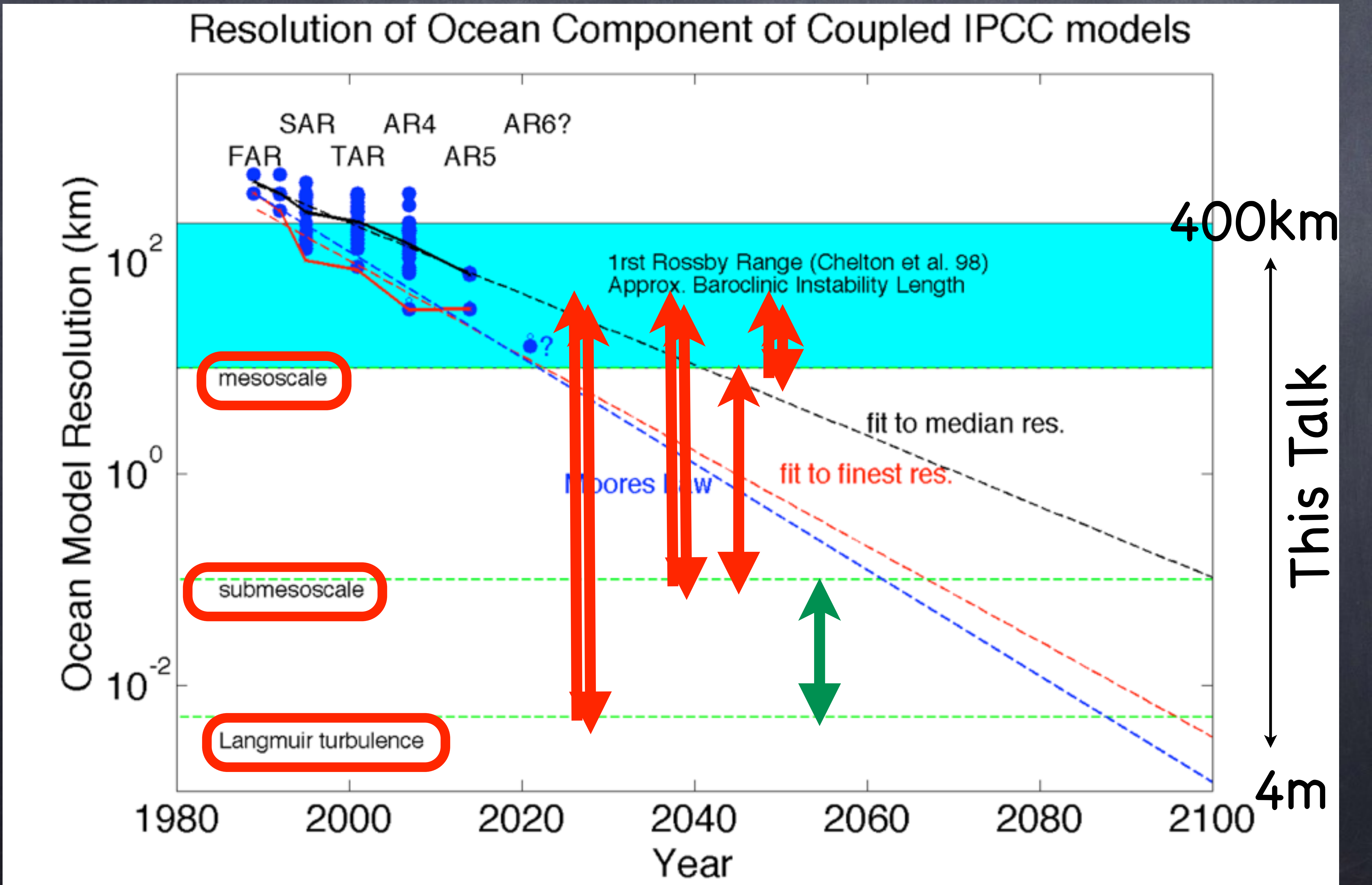
TeraGRID, IBM, UCAR, CIRES, CU-Boulder

Climate Forecasts (IPCC/CMIP Runs) have a very coarse ocean gridscale (>100km)



Parameterization Questions:

- How will we use them?
- Will the largest features be resolved?
- What needs parameterization?
- What dynamics dominate the resolved and parameterized scales?

Different Uses, Different Needs

- MORANS (e.g., typical IPCC/CMIP; >50km)
- Mesoscale Ocean Reynolds-Averaged Navier-Stokes
- No instabilities resolved, all instabilities to be parameterized
- MOLES = SMORANS (e.g., grid 5-50km)
- Mesoscale Ocean Large Eddy Simulation
- Submesoscale Ocean Reynolds-Averaged Navier-Stokes
- Same Resolution, Different Parameterizations!
- SMOLES = BLORANS (e.g., grid 100m-1km)
- Submesoscale Ocean Reynolds-Averaged Navier-Stokes
- Boundary Layer Ocean Reynolds-Averaged Navier-Stokes
- BLOLES (e.g., grid 1-5m)
- Boundary Layer Ocean Large Eddy Simulation

Sub-Mesoscale Parameterizations

- Anyone who doesn't take truth seriously in small matters cannot be trusted in large ones either.

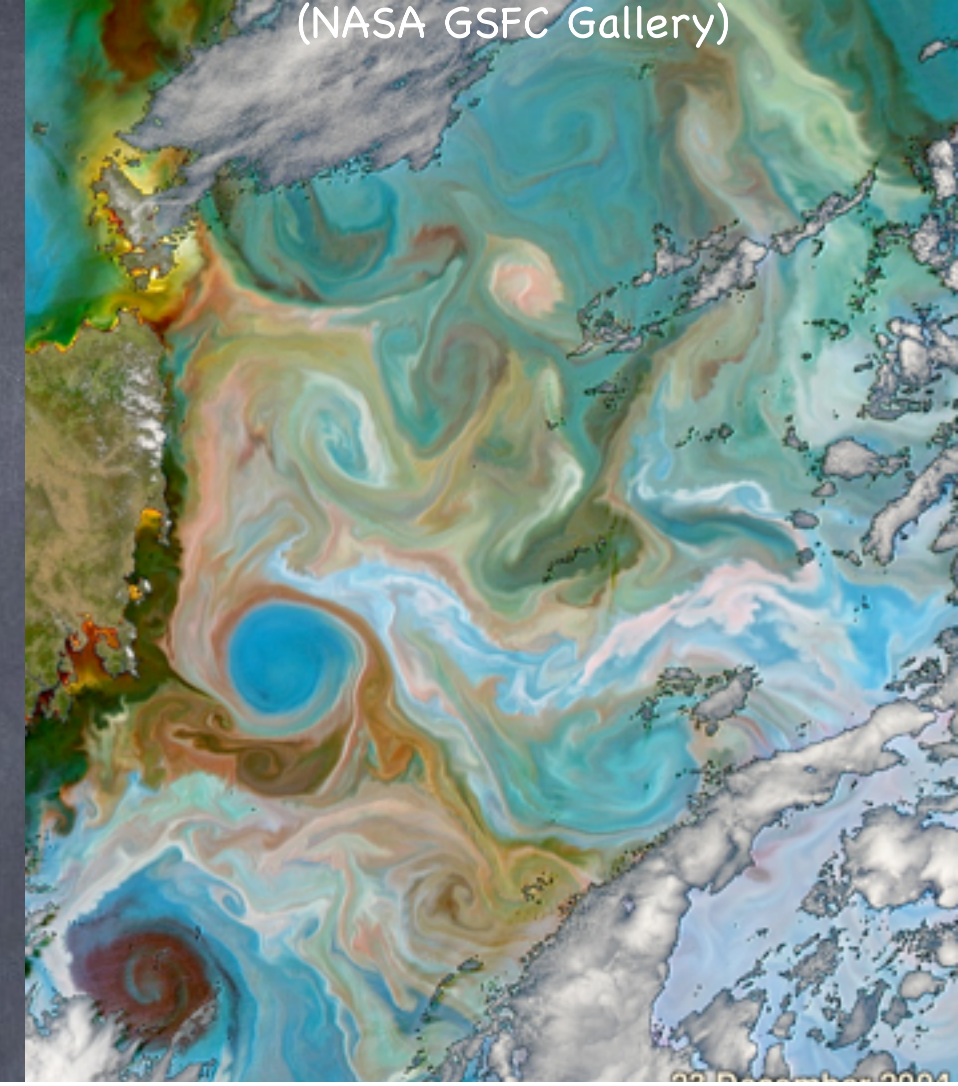
  - --Albert Einstein

B. Fox-Kemper, 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.

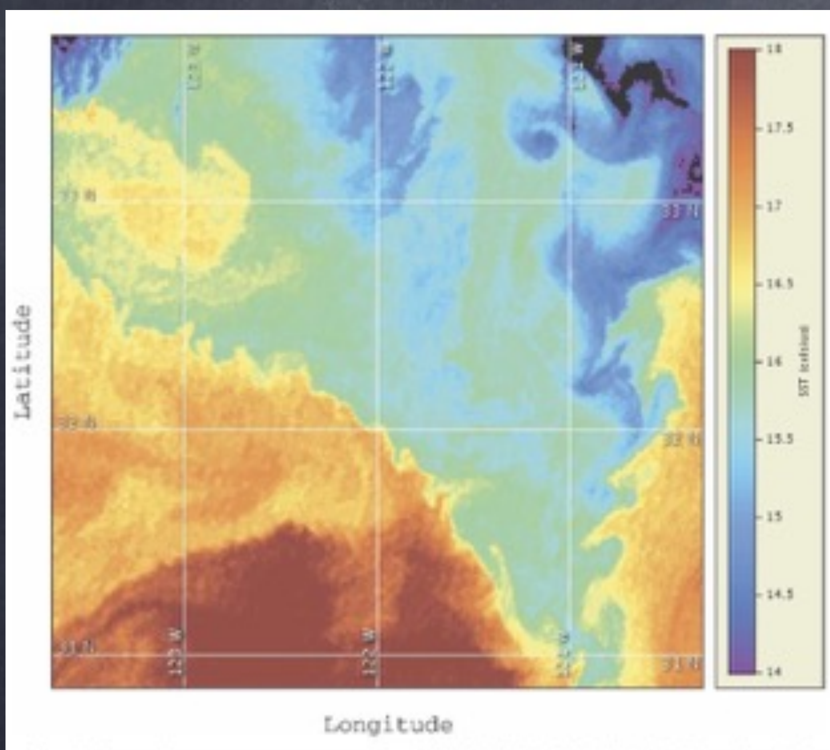
The Character of the Submesoscale

10 km

(NASA GSFC Gallery)



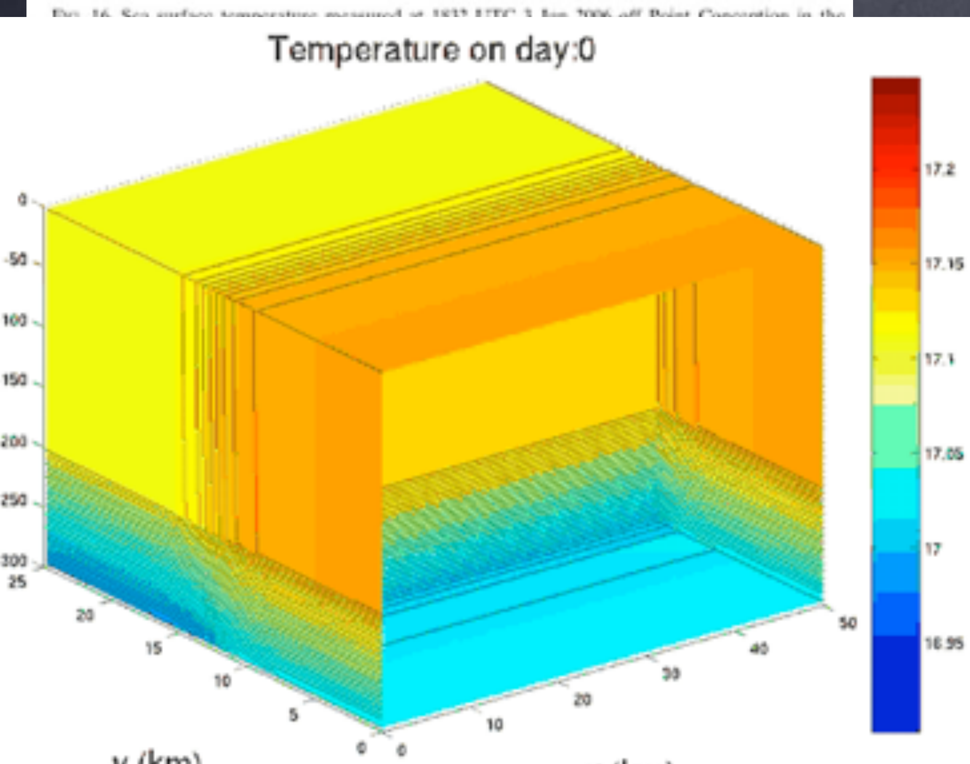
(Capet et al., 2008)

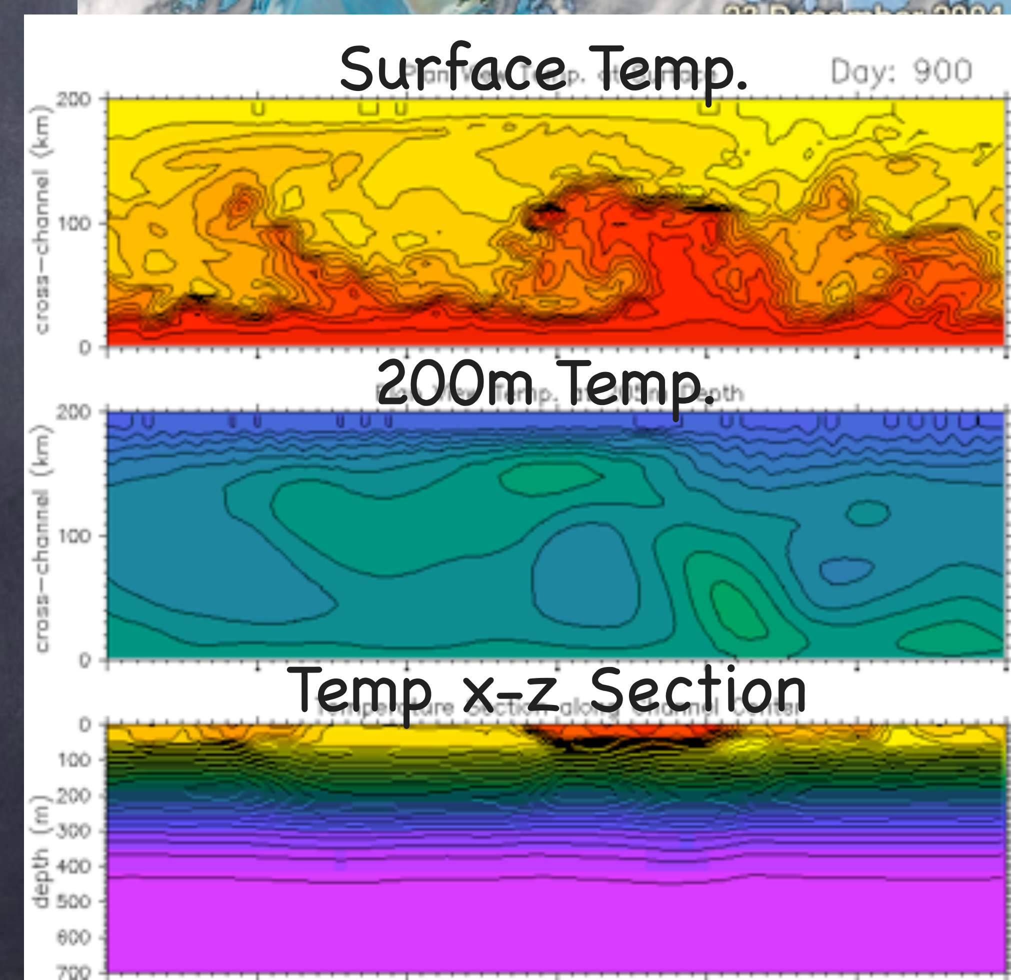


- Fronts
- Eddies
- Ro=O(1)
- Ri=O(1)
- near-surface
- 1-10km, days

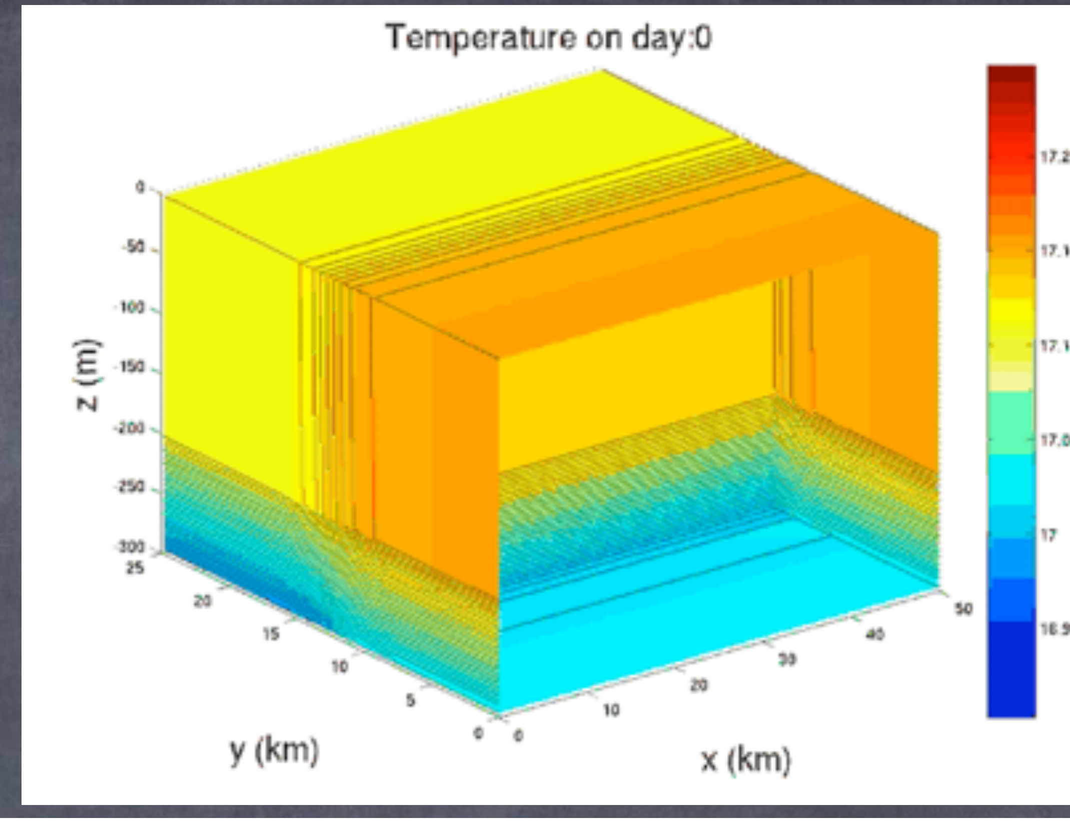
Eddy processes often baroclinic instability (Boccaletti et al '07, Haine & Marshall '98).

Parameterizations of baroclinic instability?





Mixed Layer Eddy Restratification



Estimating eddy buoyancy/density fluxes:

$$\overline{\mathbf{u}'b'} \equiv \mathbf{\Psi} \times \nabla \bar{b}$$

A submeso eddy-induced overturning:

$$\mathbf{\Psi} = \frac{C_e H^2 \mu(z)}{|f|} \nabla \bar{b} \times \hat{\mathbf{z}}$$

in ML only:

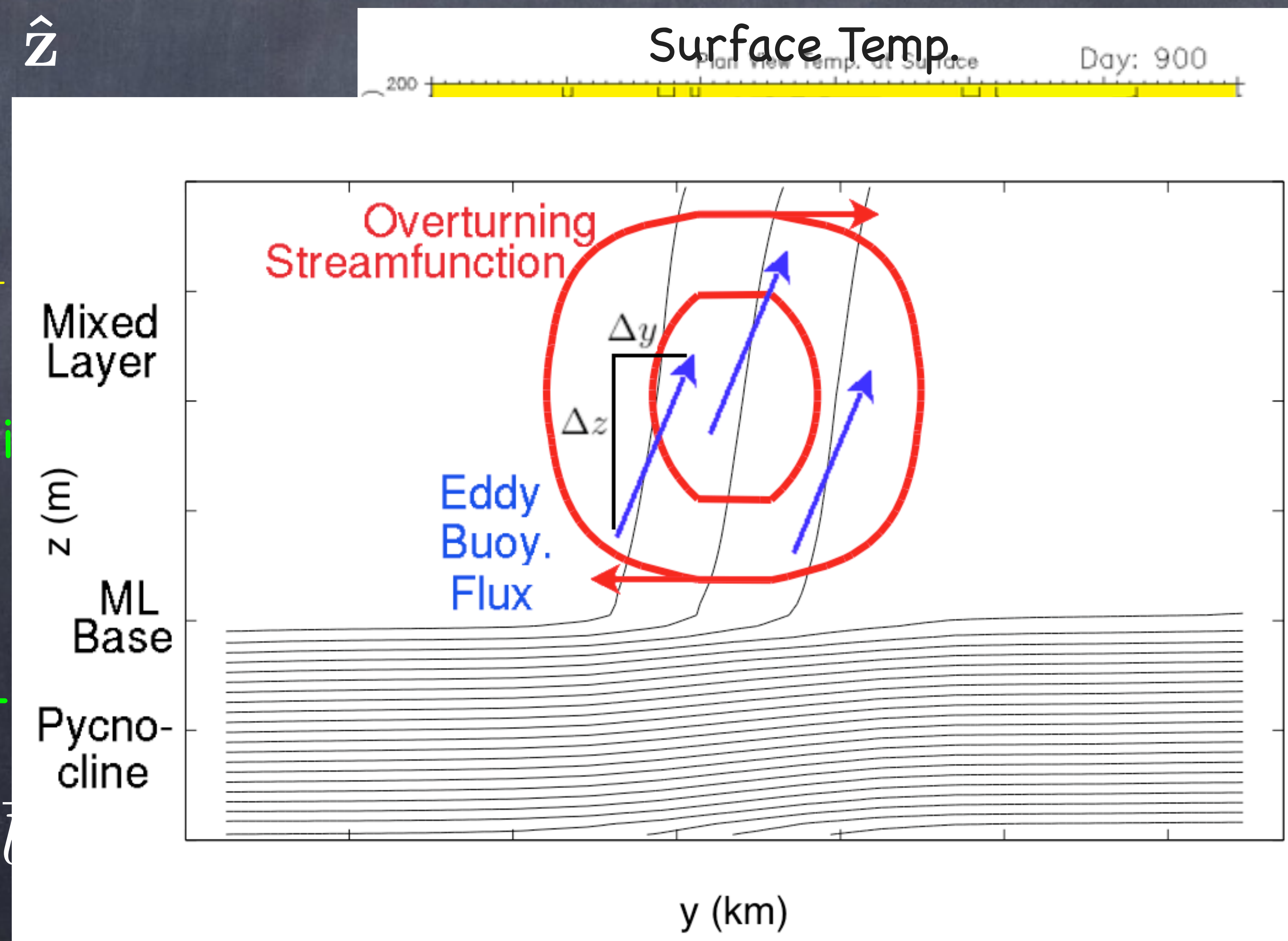
$$\mu(z) = 0 \text{ if } z < -H$$

For a consistently restratifyi

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

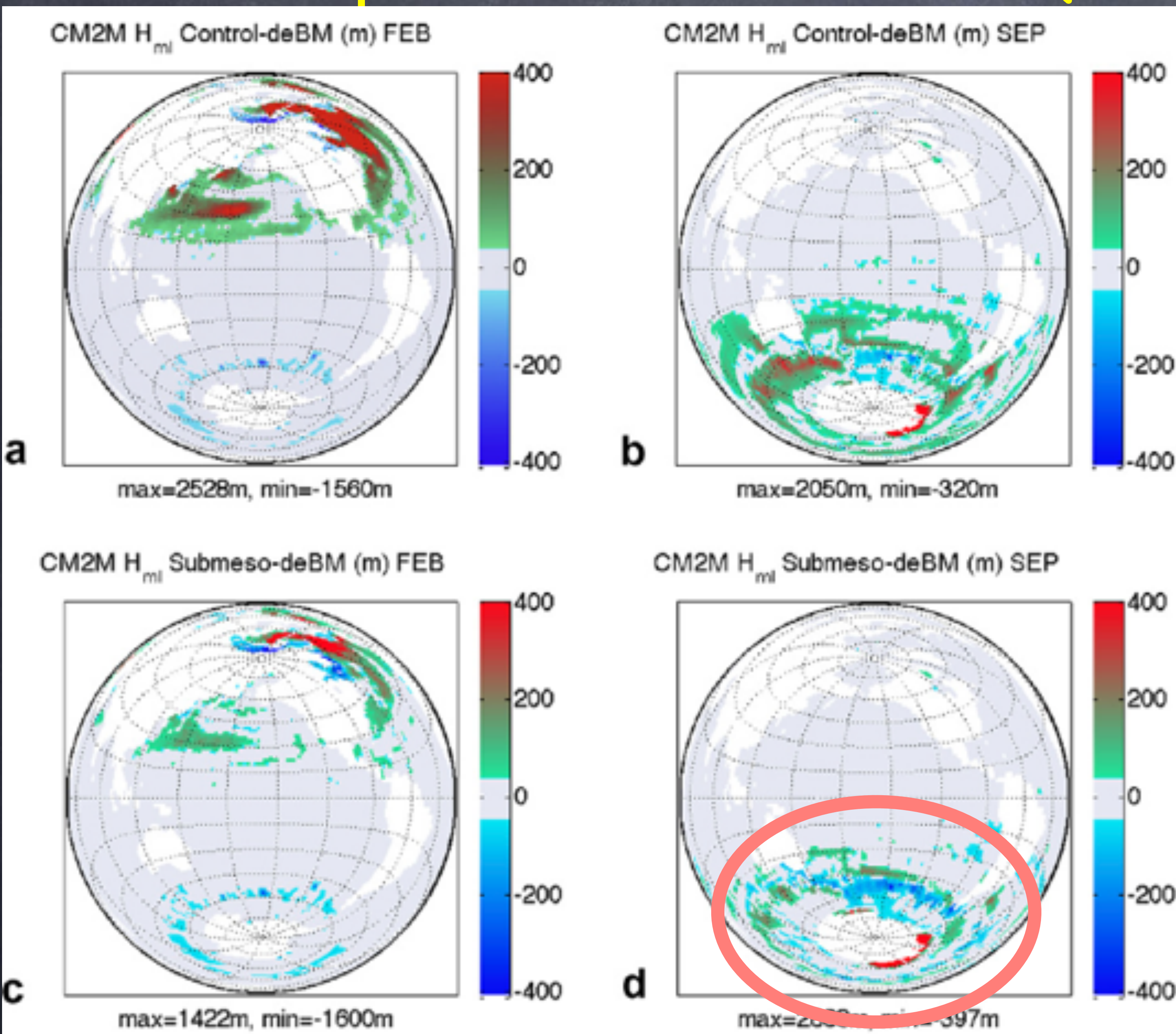
and horizontally downgradient

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



Physical Sensitivity of Ocean Climate to Submesoscale Eddy Restratification:

MLE implemented in CCSM (NCAR), CM2M & CM2G (GFDL)



Bias w/o MLE

NO RETUNING NEEDED!!!

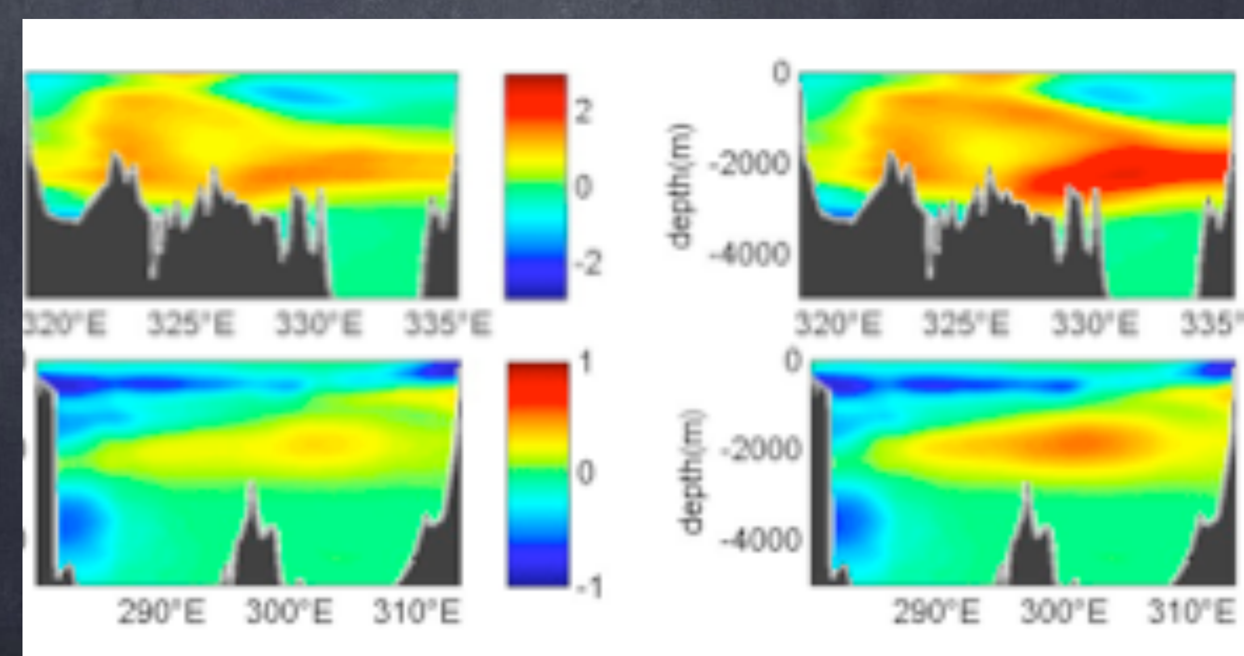
Deep ML Bias reduced

From Fox-Kemper et al., 2011

Improves CFCs Passive tracer

Bias with MLE

Bias w/o MLE



Sensitivity of Climate to Submeso: AMOC & Cryosphere Impacts

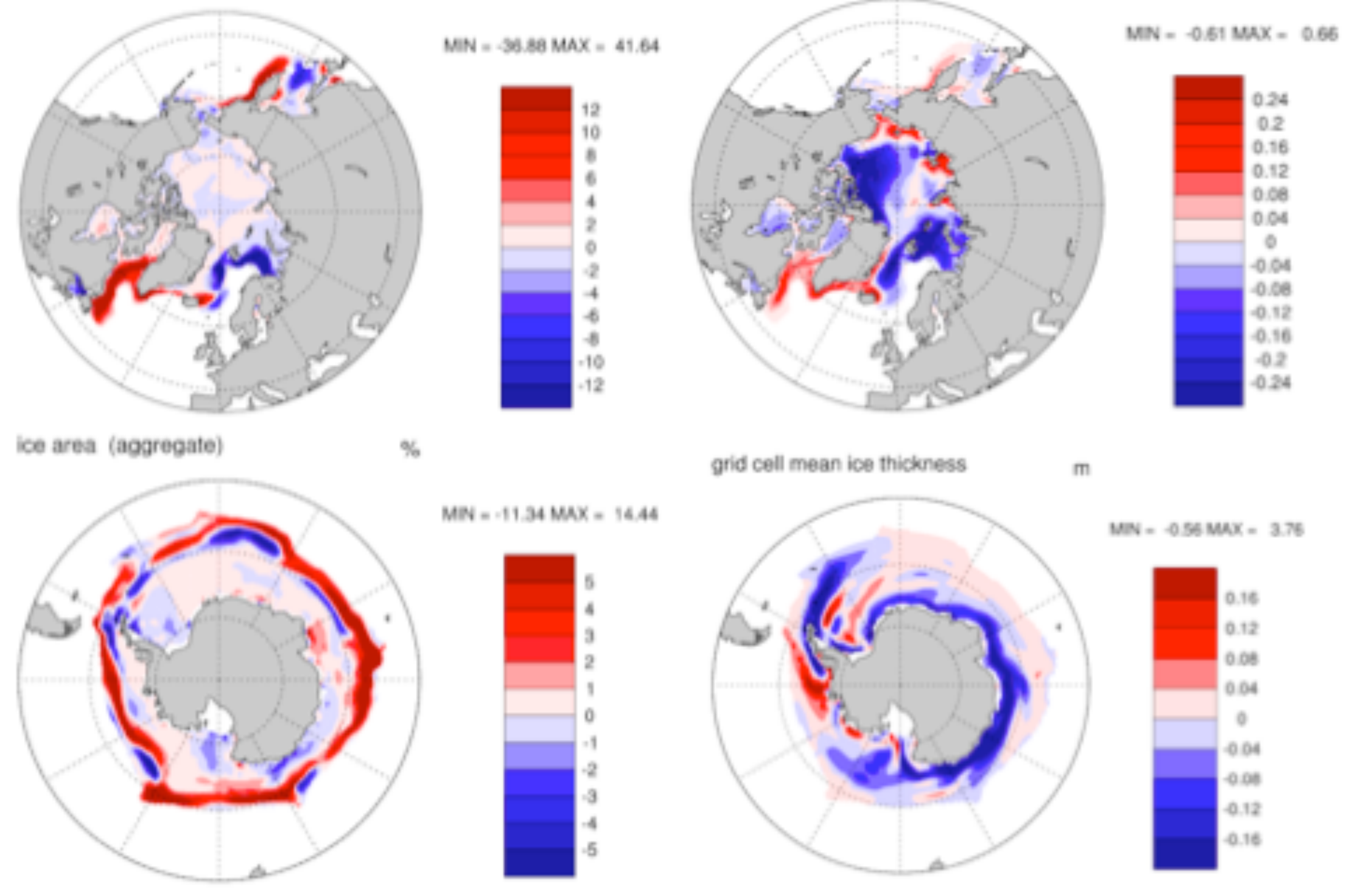
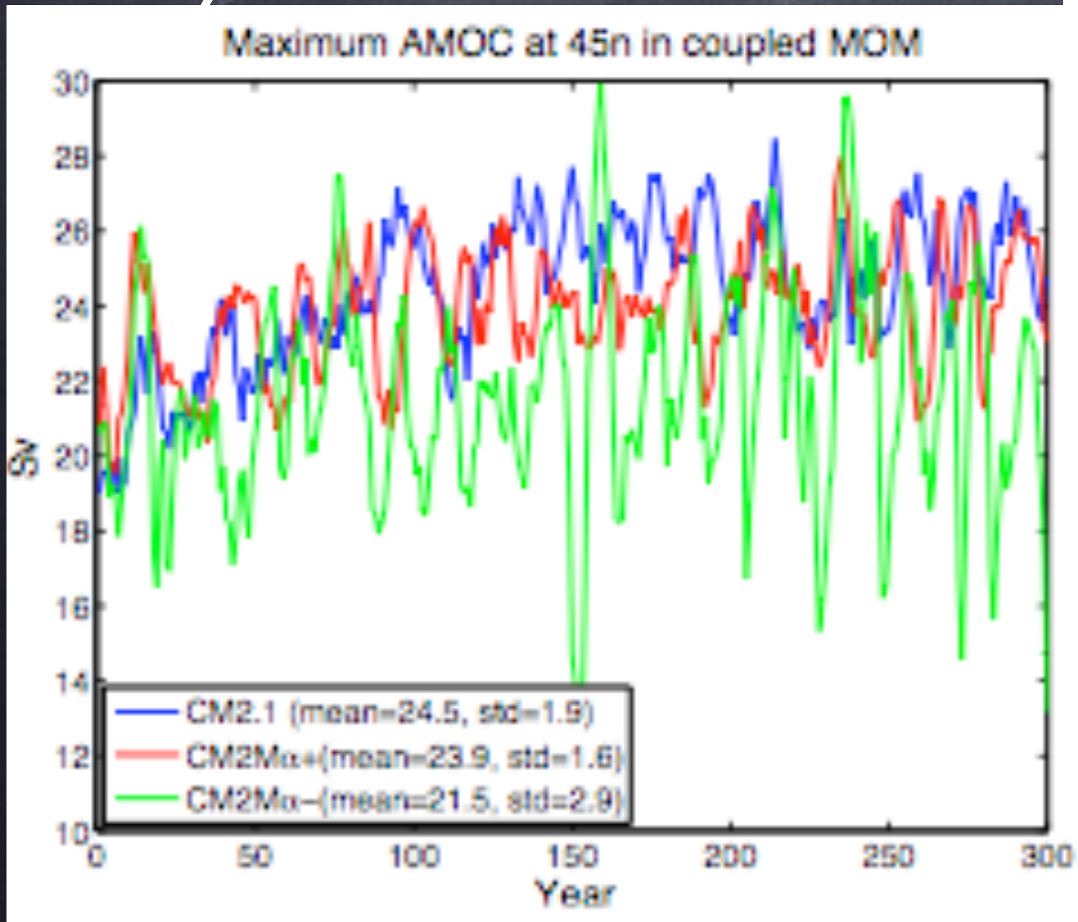


Figure 10: Wintertime sea ice sensitivity to introduction of MLE parameterization ($CCSM^+$ minus $CCSM^-$): January to March Northern Hemisphere a) ice area and b) thickness and July to September Southern Hemisphere c) ice area and d) thickness.

May Stabilize AMOC



Affects sea ice

NO RETUNING NEEDED!!!

These are impacts: bias change unknown

Langmuir Turbulence Parameterizations

- On a list of the 50 most important things to fix in the ocean model, Langmuir is number 51.
    - --Bill Large

The Character of the Langmuir Scale

- Near-surface
- Langmuir Cells & Langmuir Turb.
- Ro>>1
- Ri<1: Nonhydro
- 10-100m
- mins, hours
- w, u=O(10cm/s)
- Stokes drift
- Eqtns: Craik-Leibovich
- unused params exist

image: Leibovich, 83

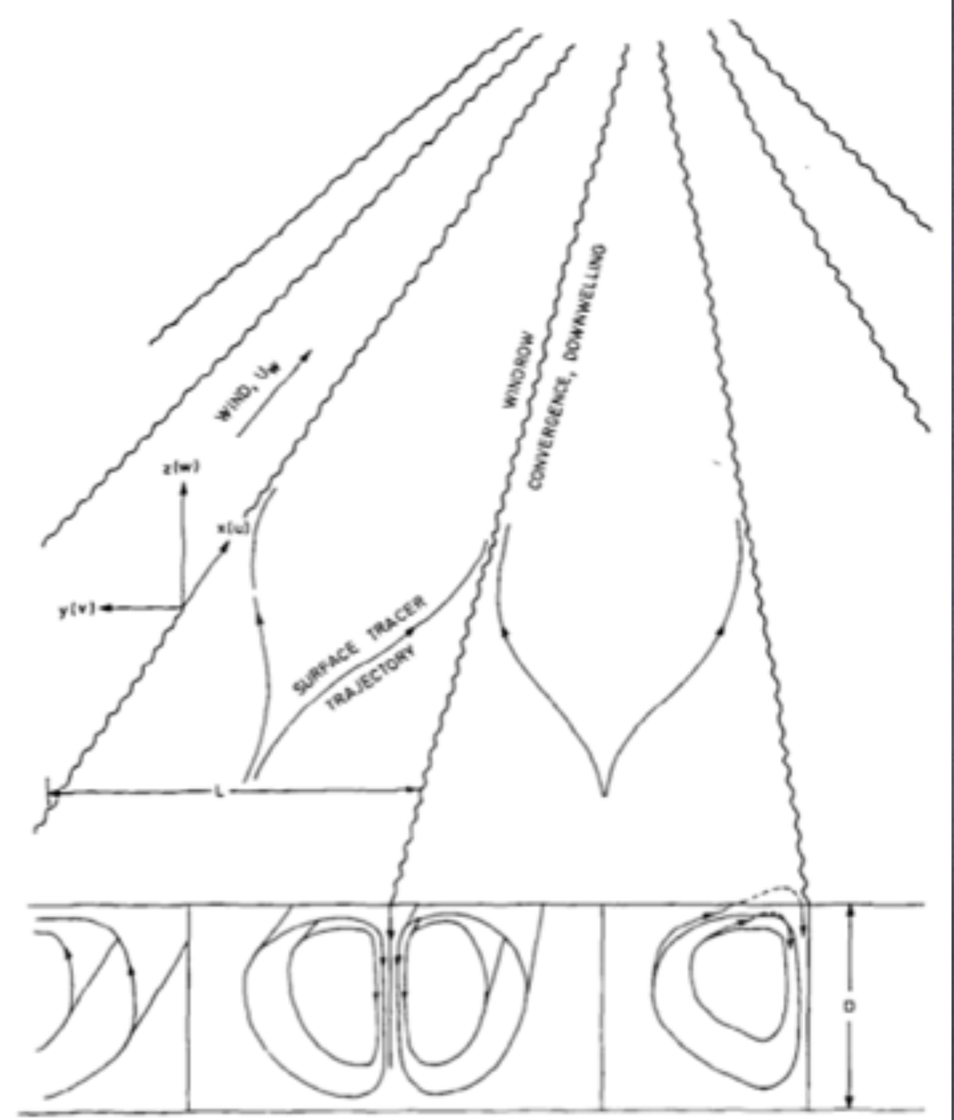


Figure 1a Illustration of Langmuir circulations showing notation used in this review and surface and subsurface motions.

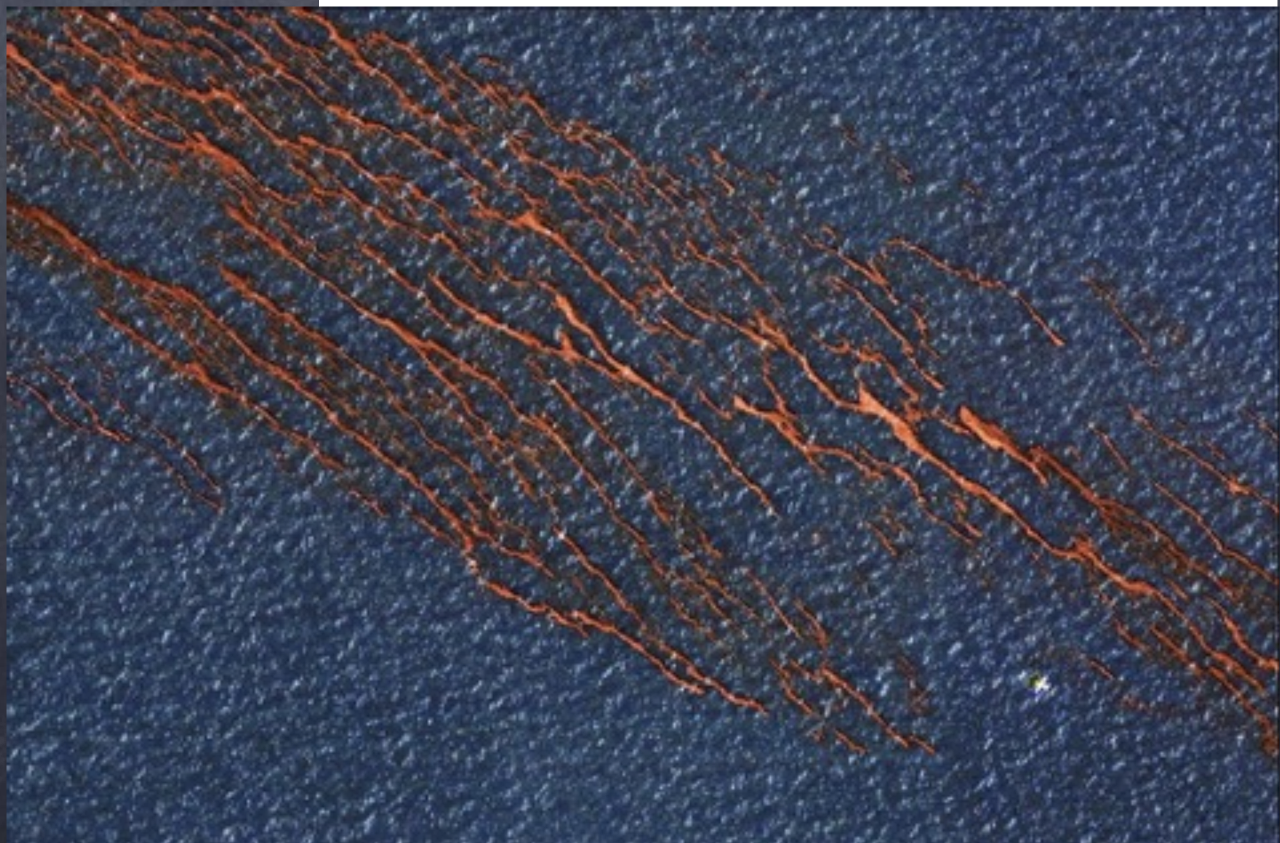


Image: NPR.org, Deep Water Horizon Spill

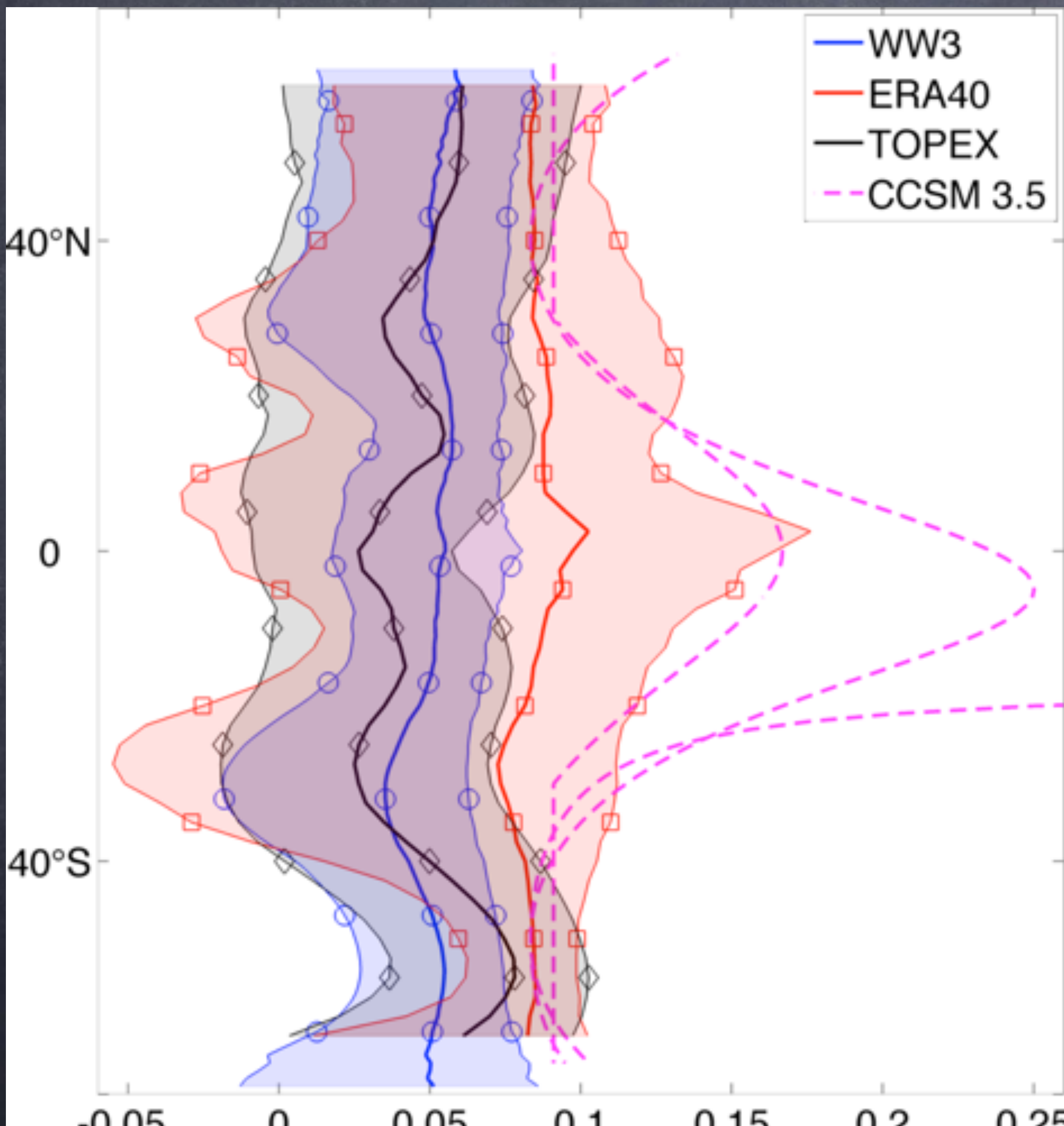
Shuga Ice
Image: aspect.aq

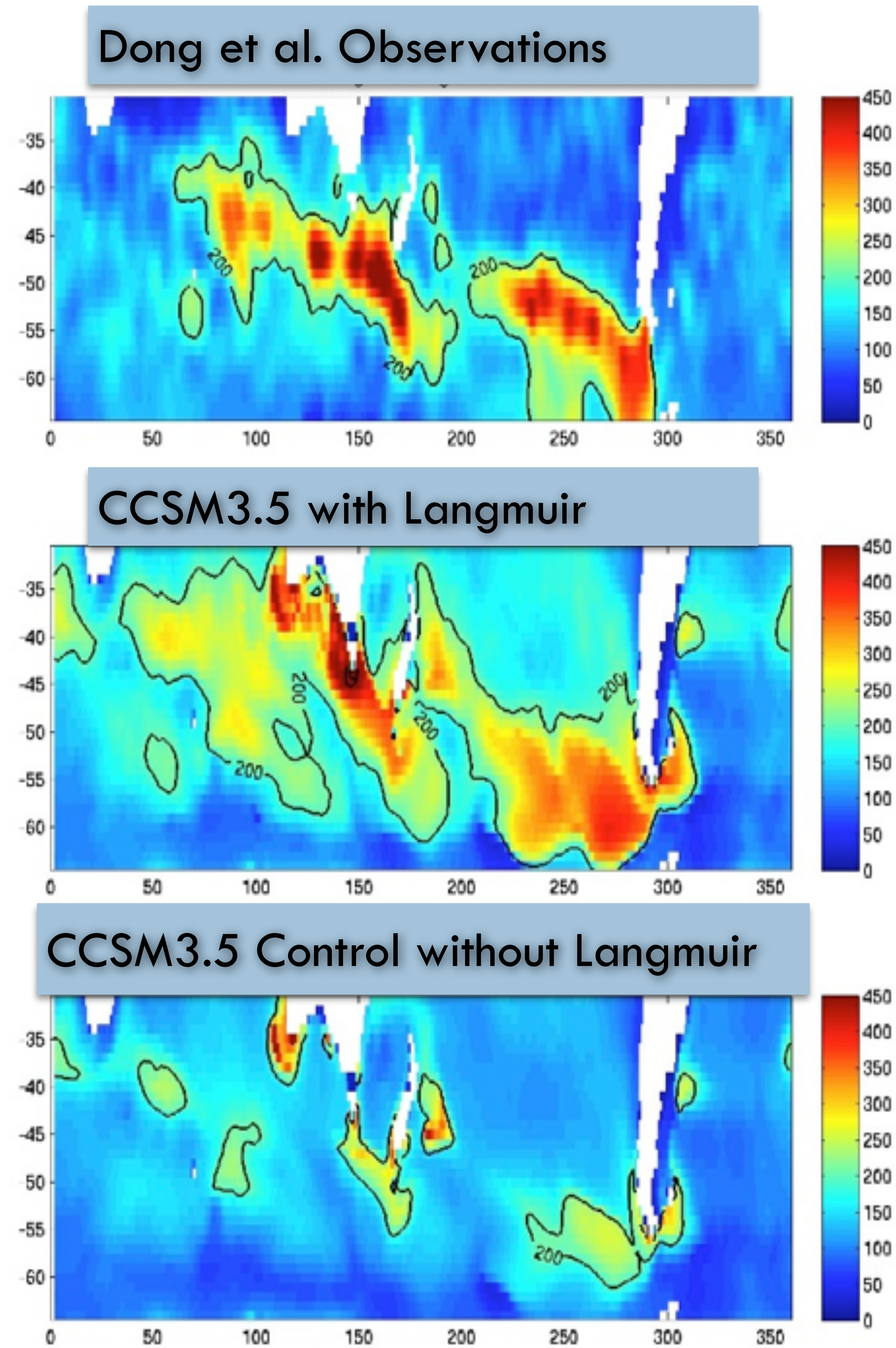
An Immature Improvement to Air-Sea BL

Image: NPR.org, Deep Water Horizon Spill

- Mixing by Langmuir Turbulence
  - Forced by wind and waves
    - i.e., Stokes drift & Eulerian Shear
  - Scalings from LES, Observations disagree
- We used a 2-part approximation
  - 1) McWilliams & Sullivan (01) additional OBL mixing (within mixed layer)
  - 2) Li & Garrett (98) Langmuir mixing depth (entrainment)
  - Roughly comparable to other schemes, but crude & incompletely validated
  - Needs only u^*, u_s to work

Langmuir Mixing Forced by Climatology

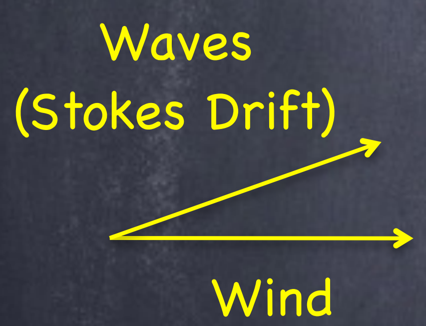


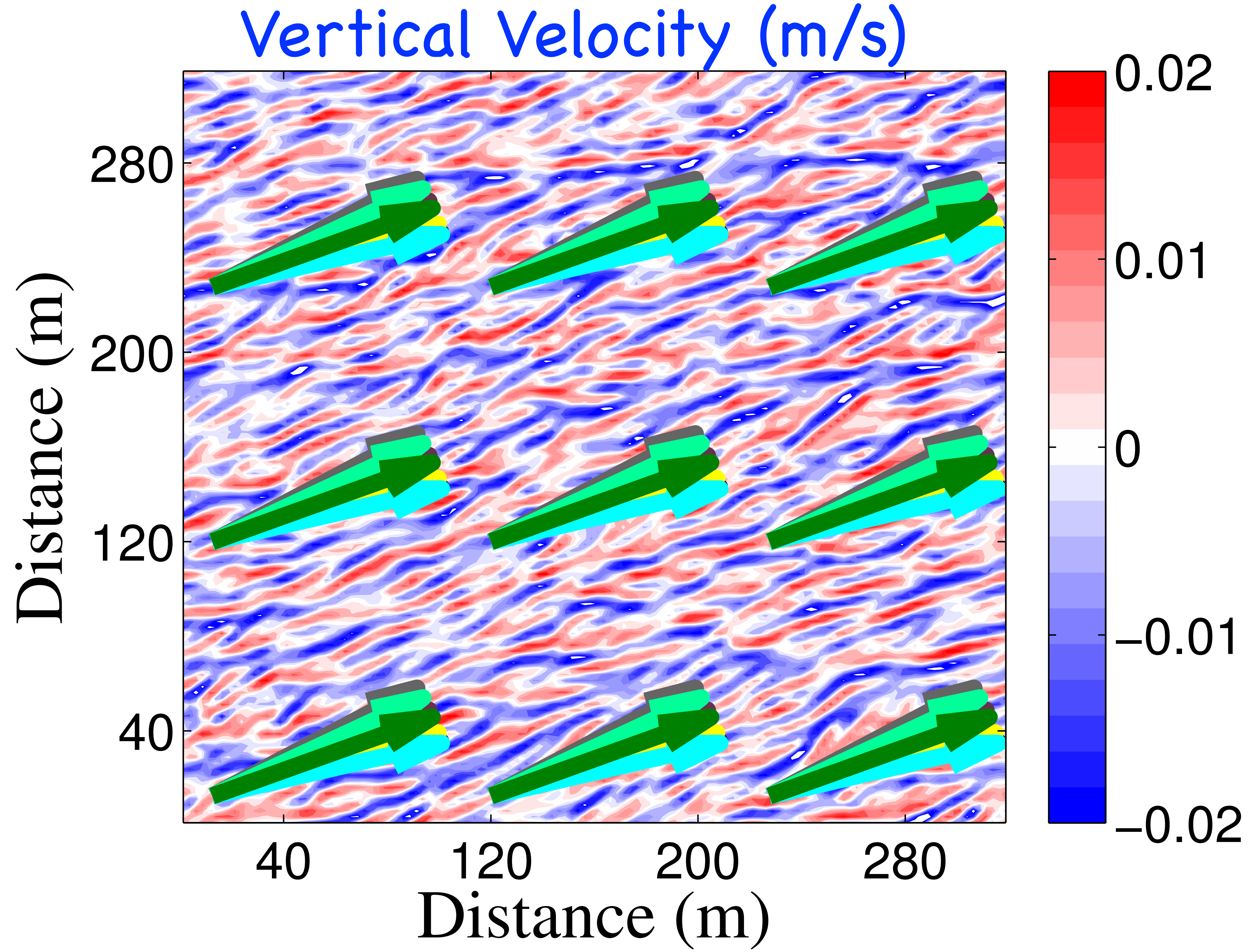


(Generalized Turbulent Langmuir)²
Projection of u*, u_s into Langmuir Direction

$$La_t^2 = \frac{|u^*|}{|u_s|}\left[\frac{|u^*| + |u_s|\cos\theta}{|u_s| + |u^*|\cos\theta}\right]$$

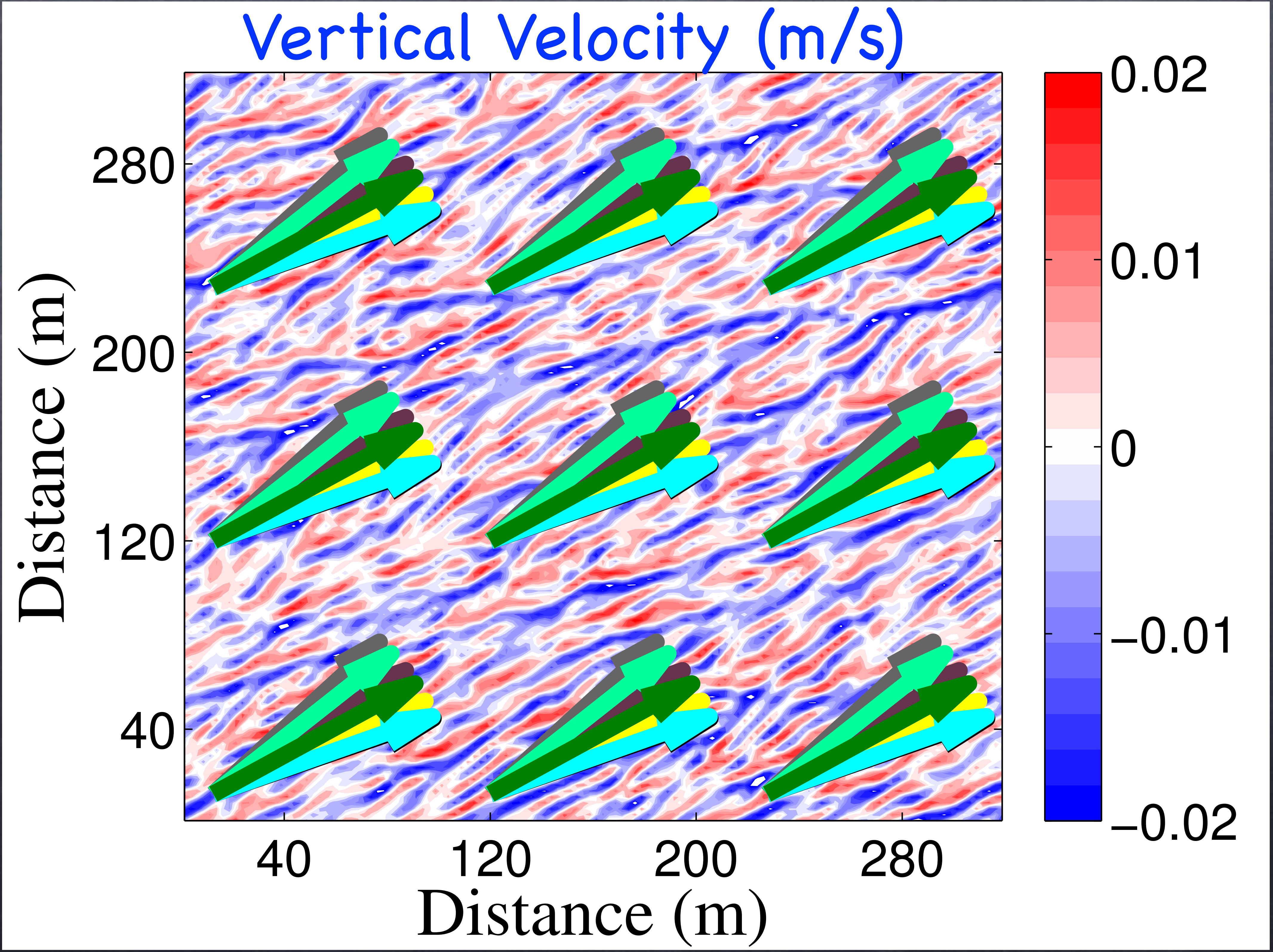
Tricky: Misaligned Wind & Waves





Van Roekel et al. 2011
(submitted)

Tricky: Misaligned Wind & Waves



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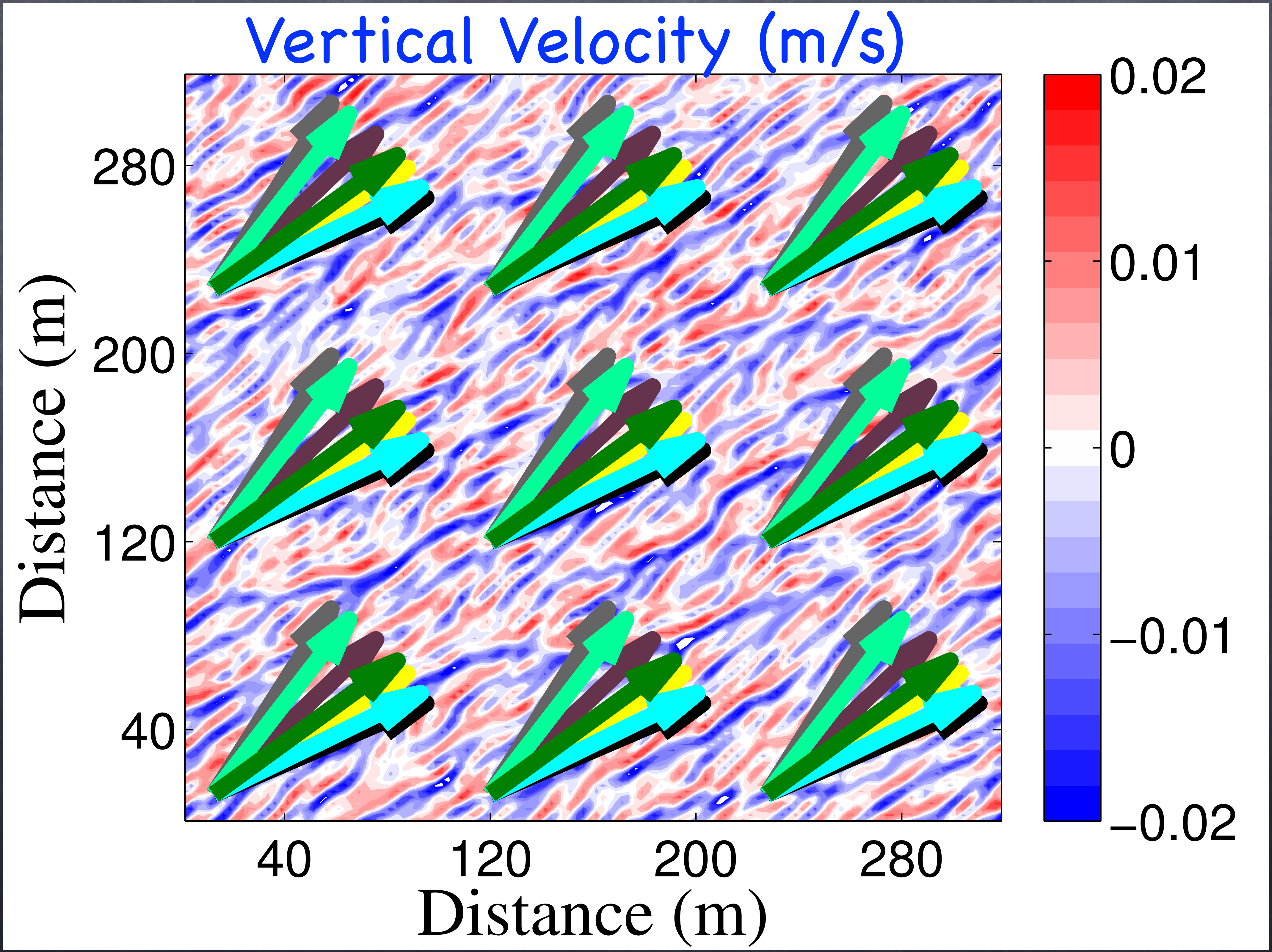

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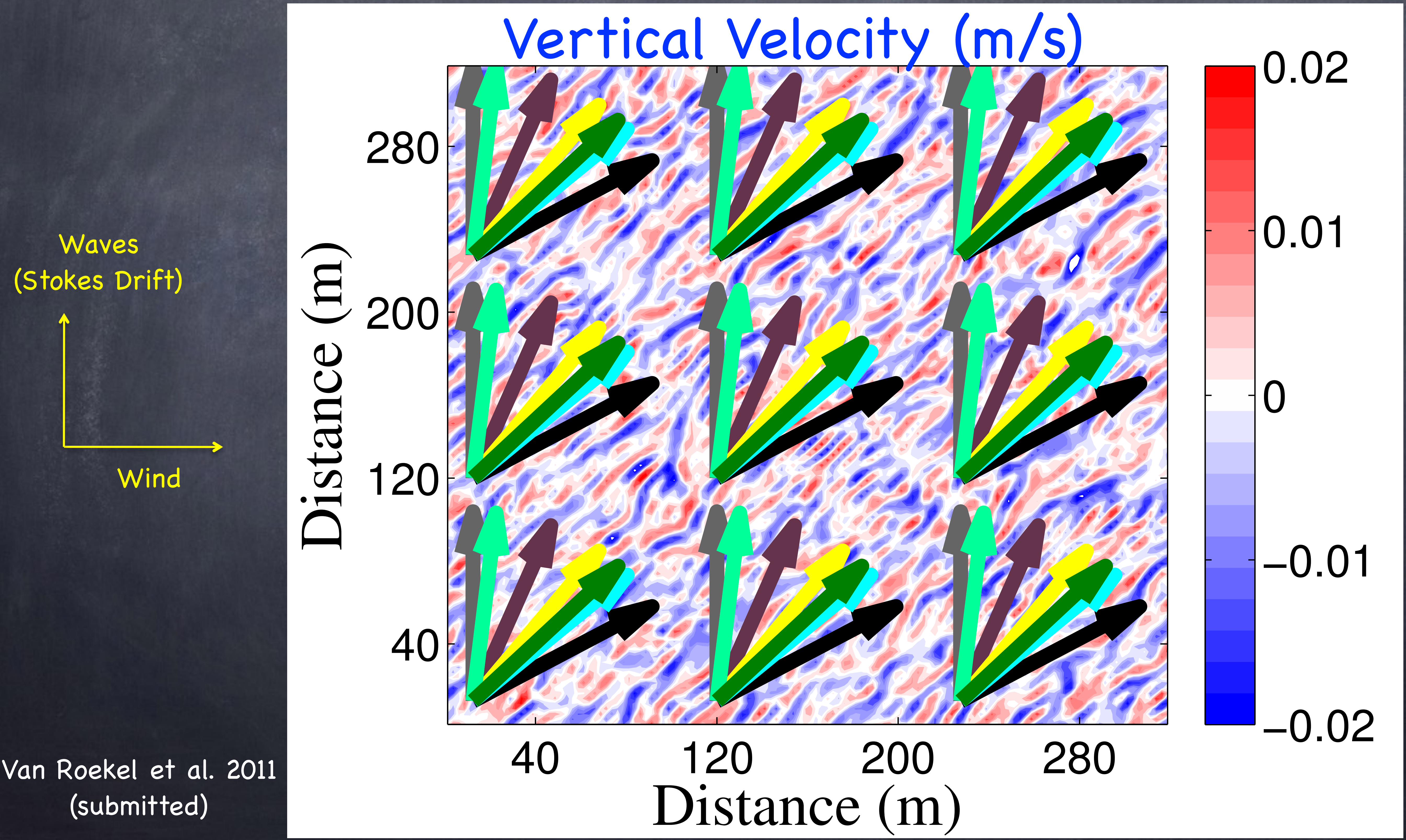
(submitted)

Tricky: Misaligned Wind & Waves



Van Roekel et al. 2011
(submitted)

Van Roekel, Fox-Kemper, Sullivan, Haney & Hamlington (2011)

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

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

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

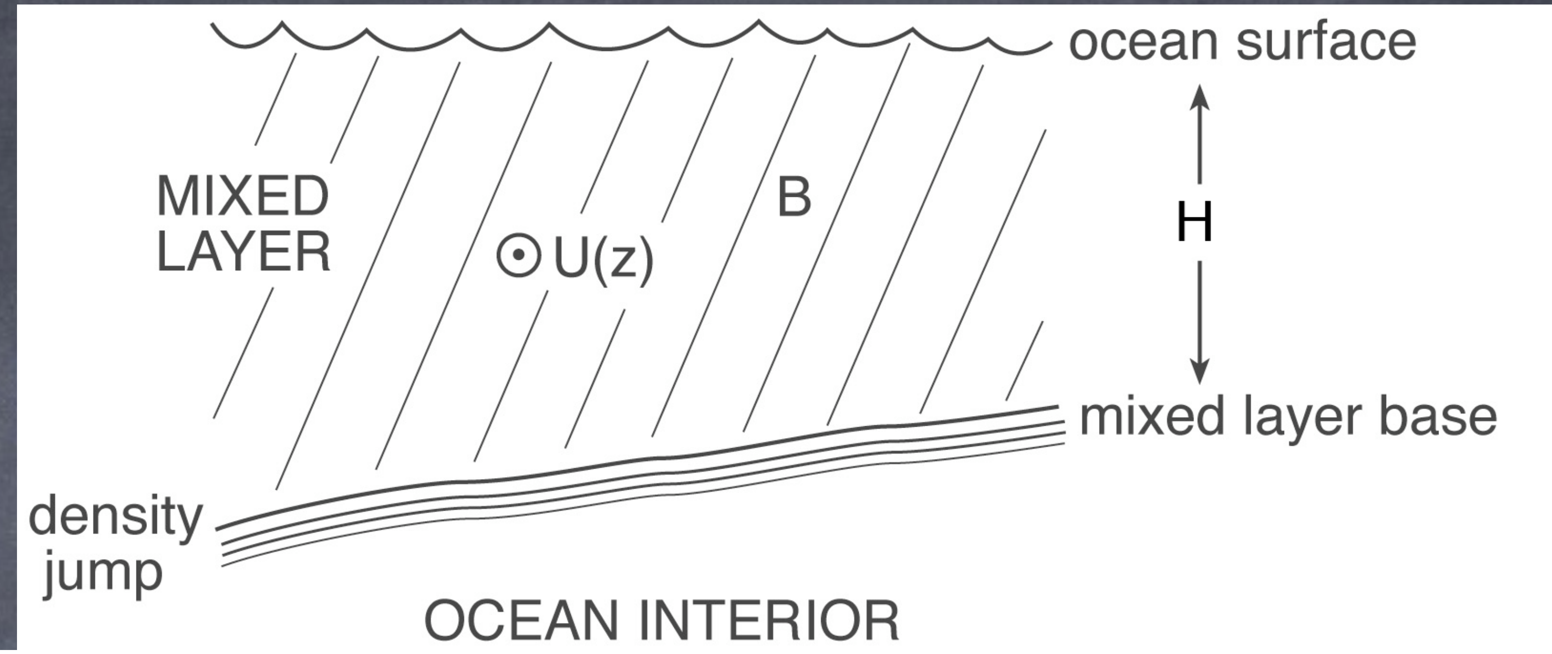
Coupling between Langmuir and Submeso?

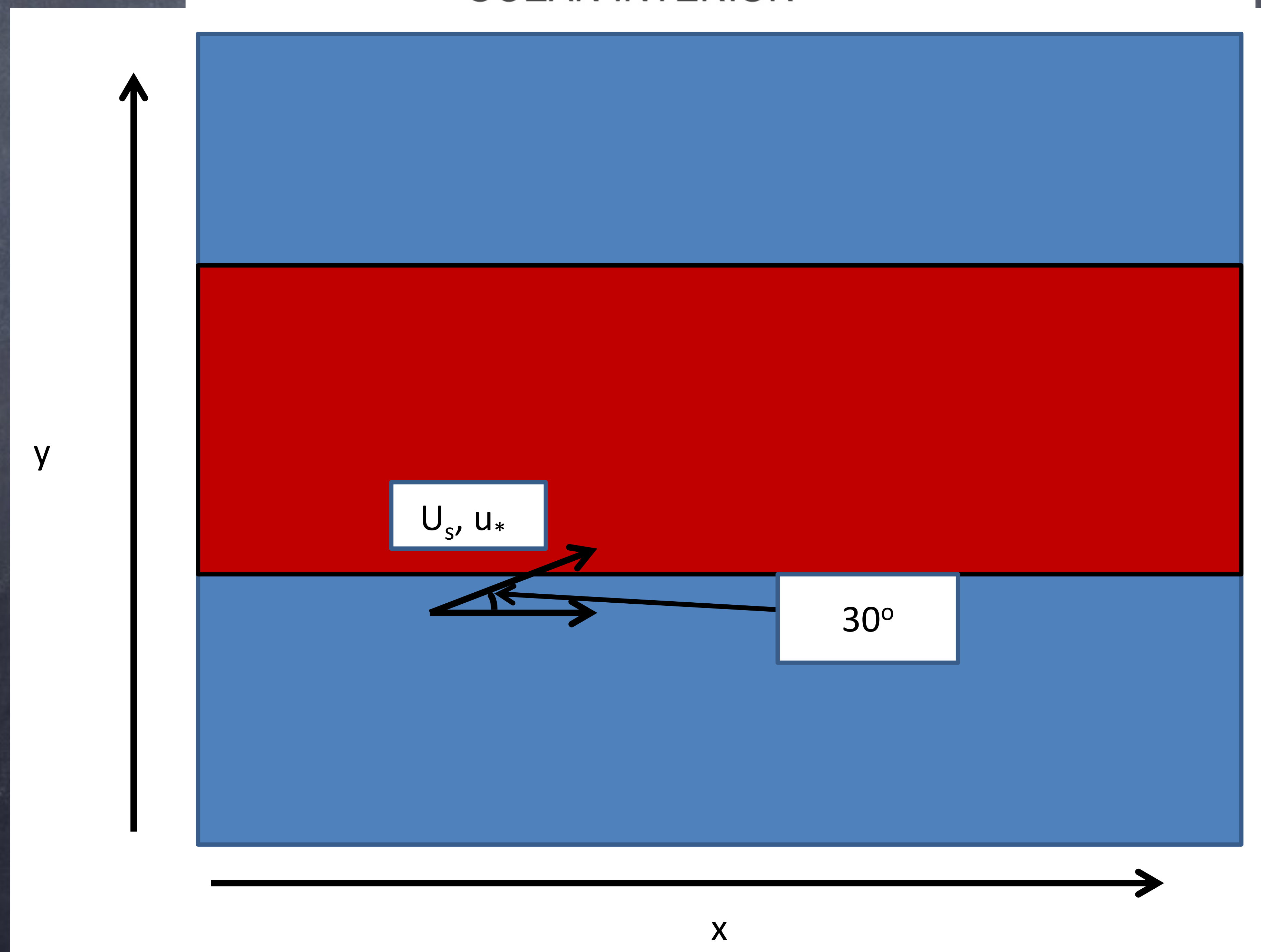
- Together?
- Separate?

Multiscale

- Langmuir & Submeso resolving LES
- 20kmx20kmx0.3km
- Grid 4096x4096x128
- 5x5x<1m resolution
- Compromises--wind, front, wave, size, etc

km



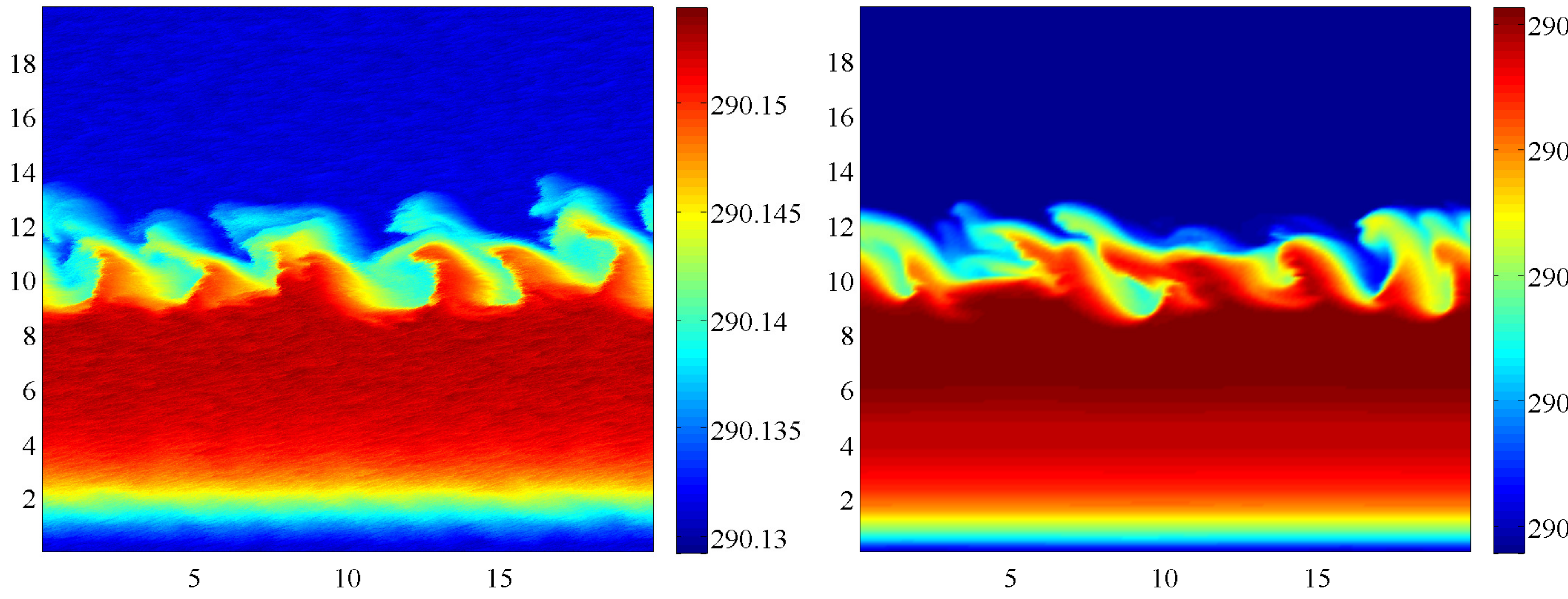


Coupling Langmuir to Submesoscale?

From Scratch... No interpolation!

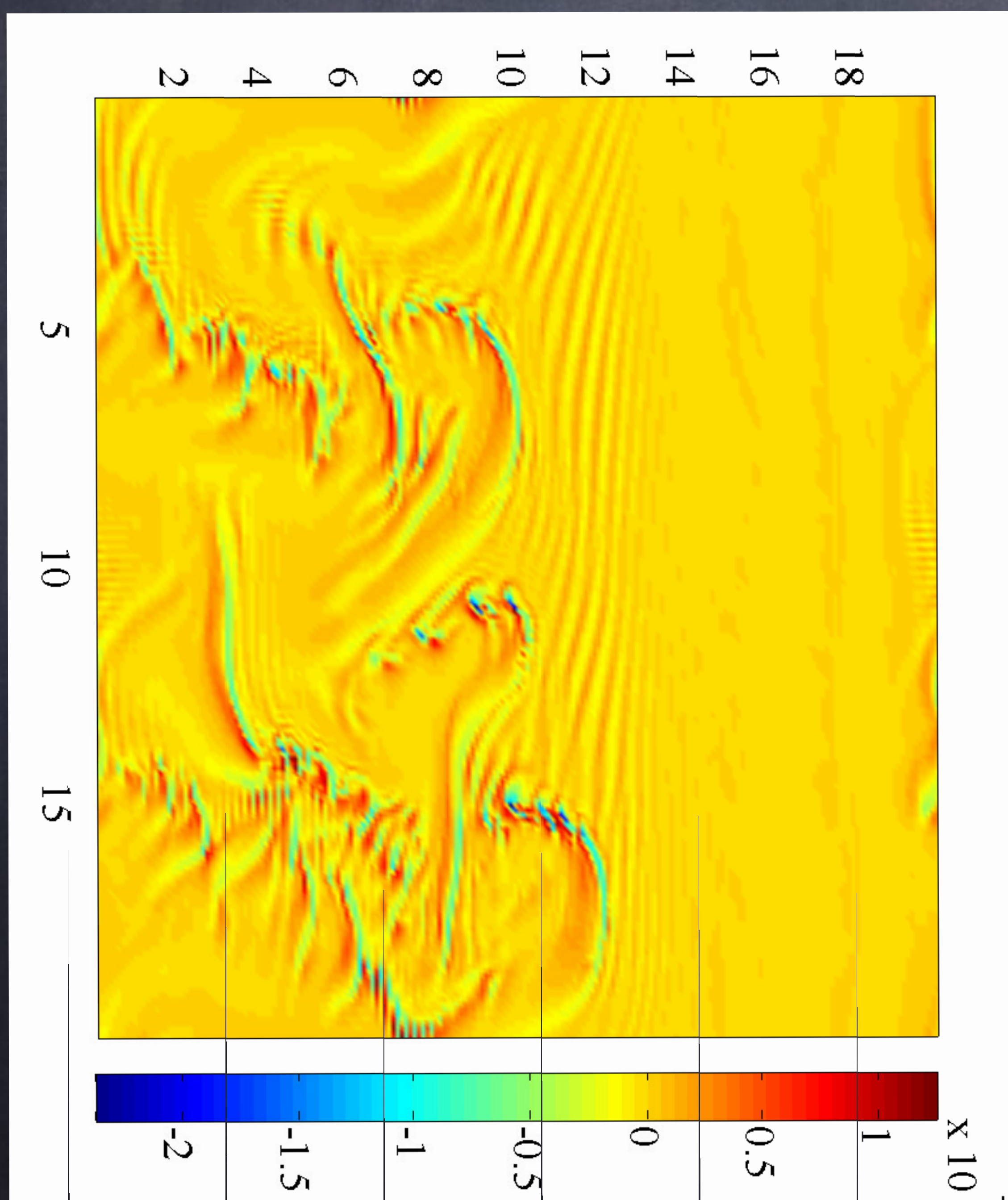
LES, Near-Surf. Temp. No Stokes Drift

MITgcm Near-Surf. Temp. Submeso-Only Res.

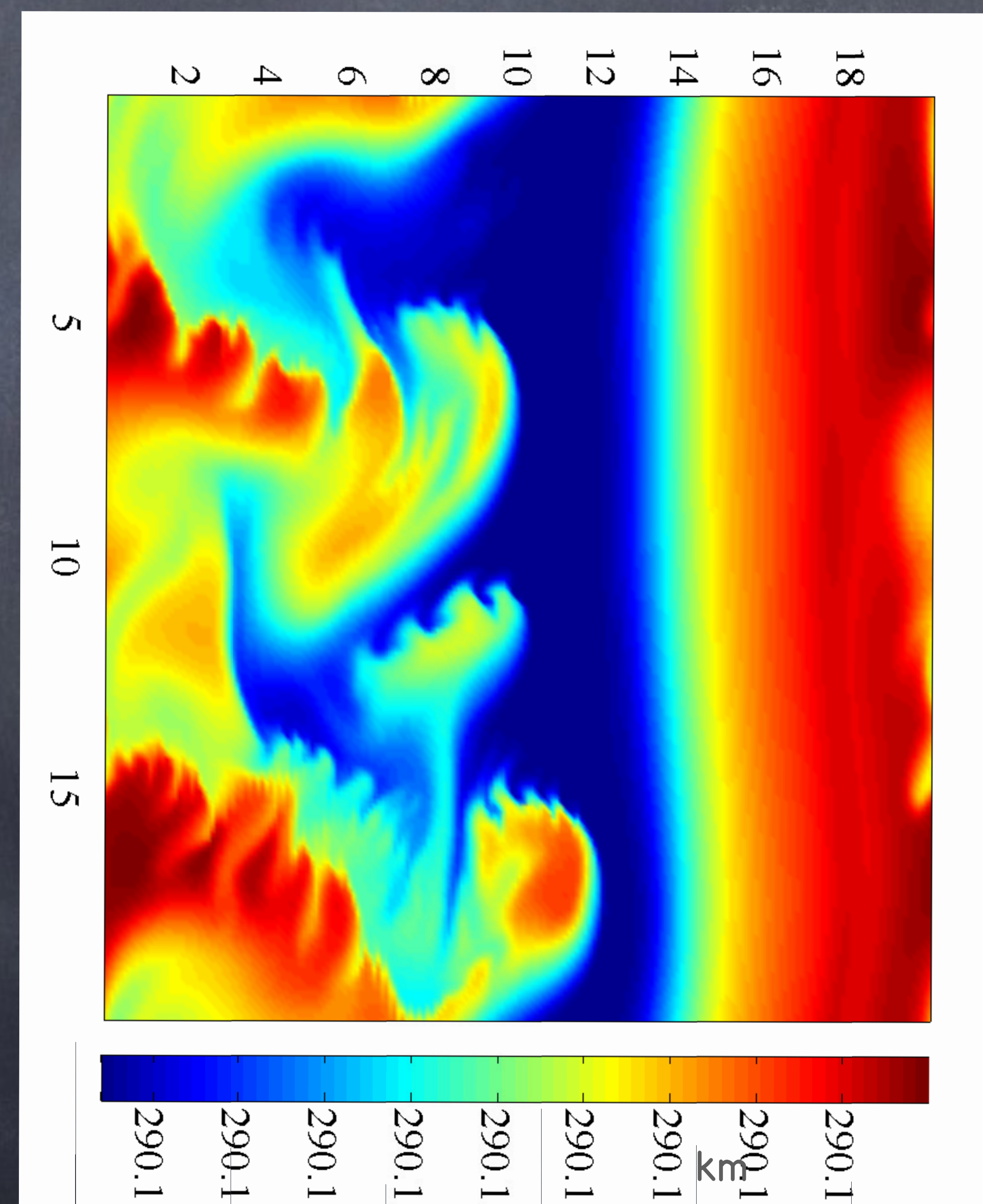


The Scales, and the Sim

Day 6.5 of a Submeso Resolving run Vert. Velocity=w



Day 6.5 of a Submeso Resolving run Near Surf. Temp



The Scales, and the Sim

$$f^2 < \left| f \frac{\partial \overline{v}}{\partial z} \right| = M^2 < (3f)^2$$

$$\overline{Ro} \approx 0.1$$

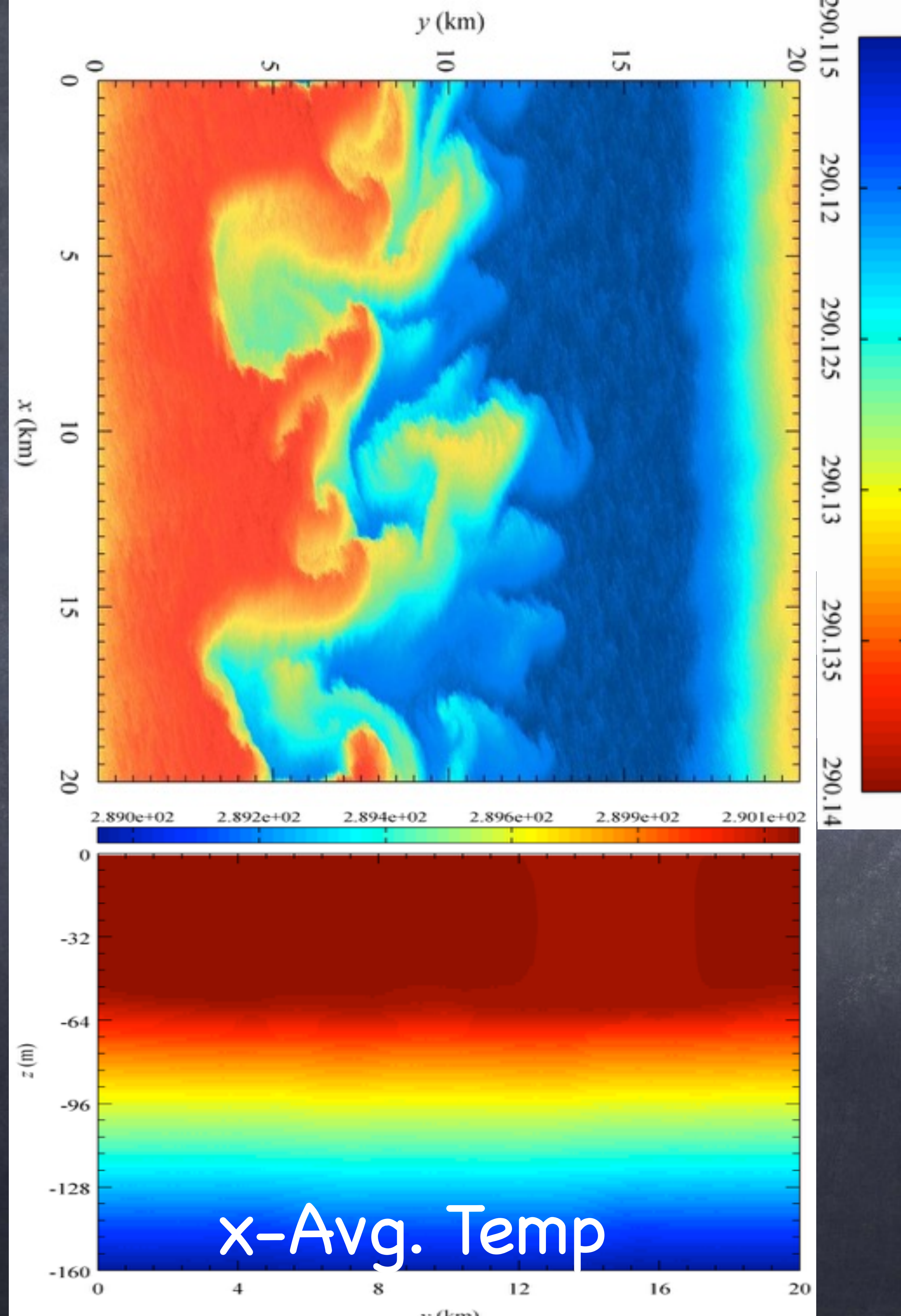
km

$$\overline{Ri} < 1$$

km

Wind & Fronts Only

No Stokes Drift



-0.015

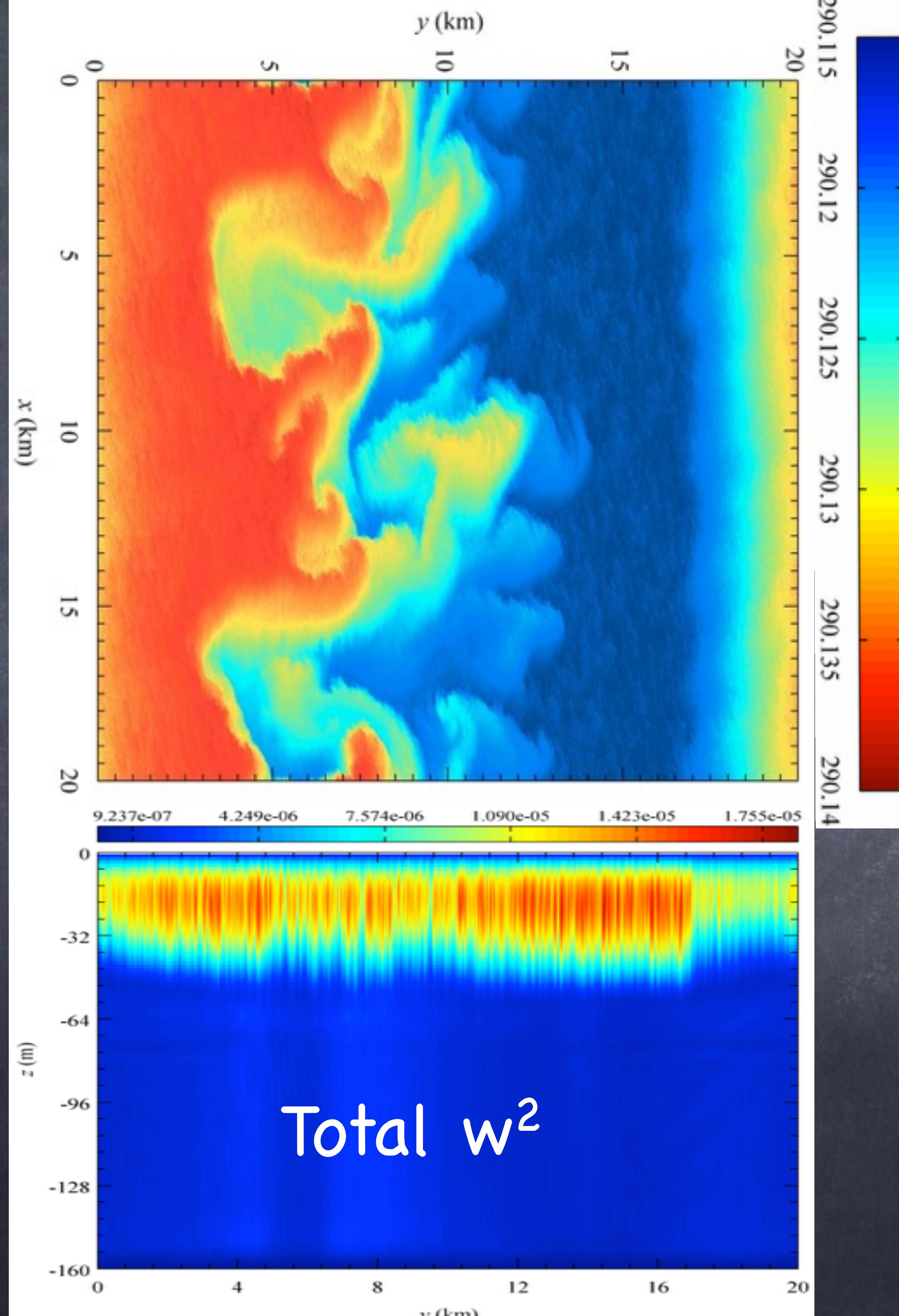
Surf. Temp (K)

+0.015

Temp (K)

Wind & Fronts Only

No Stokes Drift



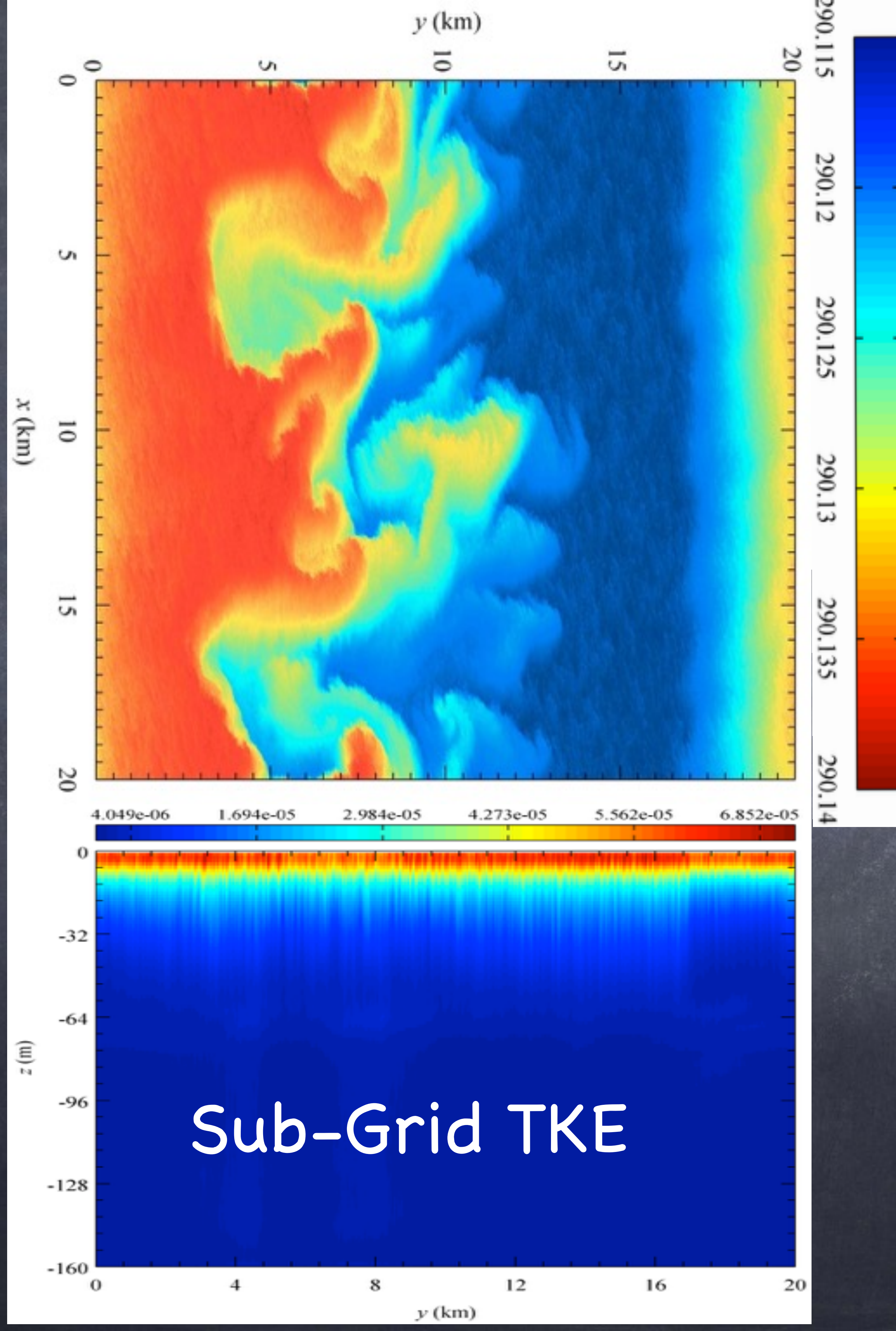
Surf. Temp (K)

w^2 (m^2/s^2)

$< (400m/d)^2$

Wind & Fronts Only

No Stokes Drift

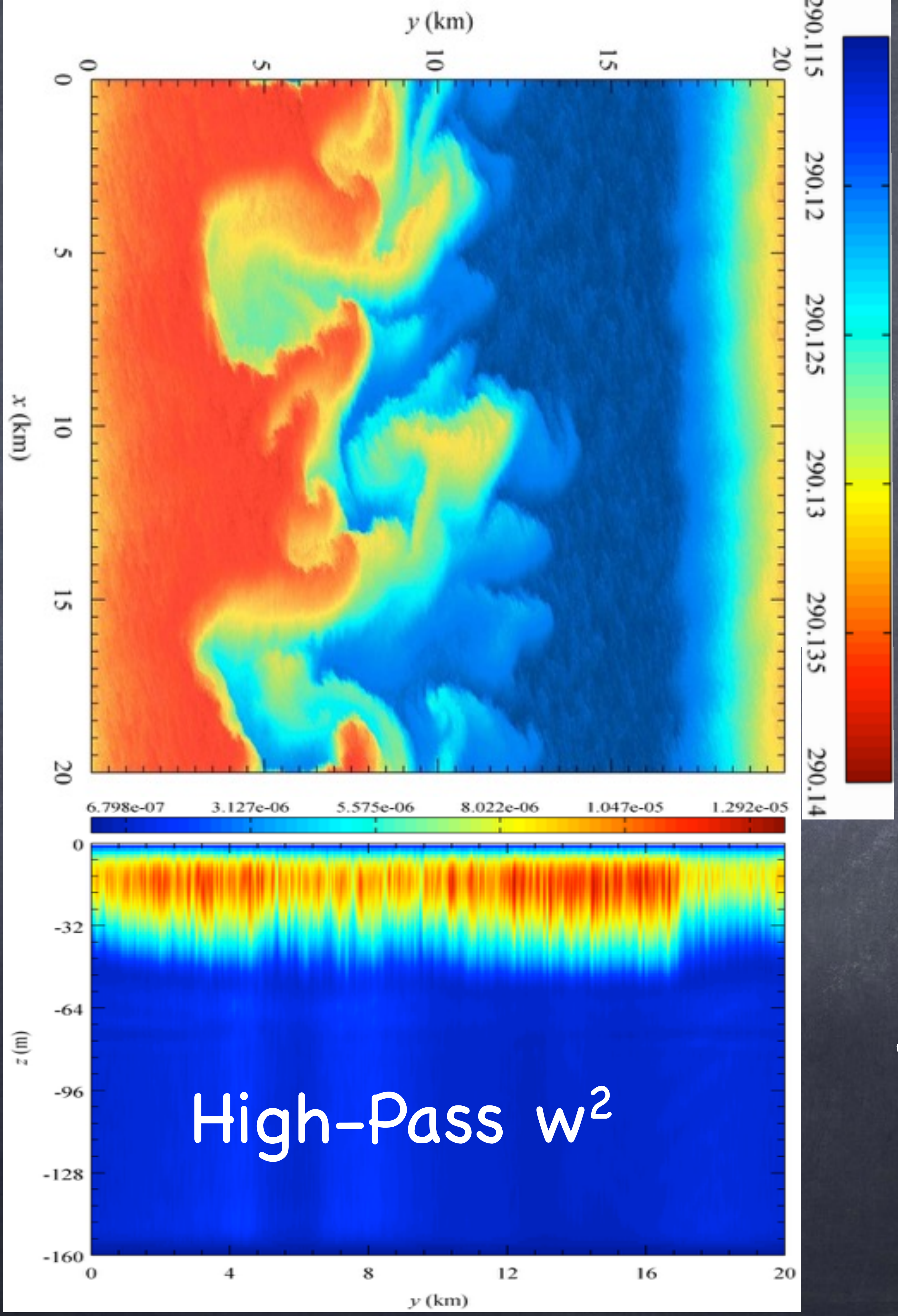


Surf. Temp (K)

w^2 (m^2/s^2)

Wind & Fronts Only

No Stokes Drift



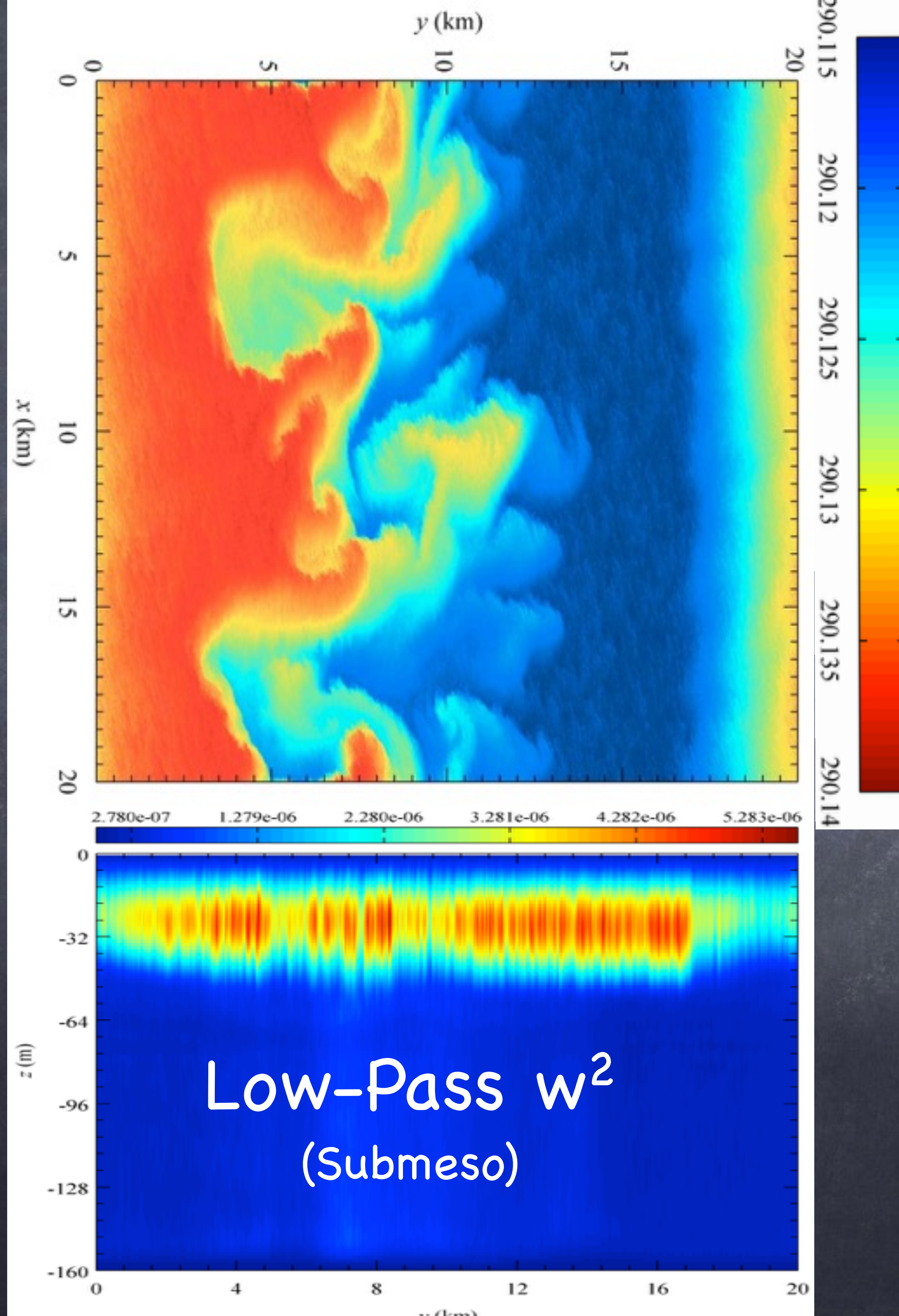
Surf. Temp (K)

w^2 (m^2/s^2)

$< (300m/d)^2$

Wind & Fronts Only

No Stokes Drift

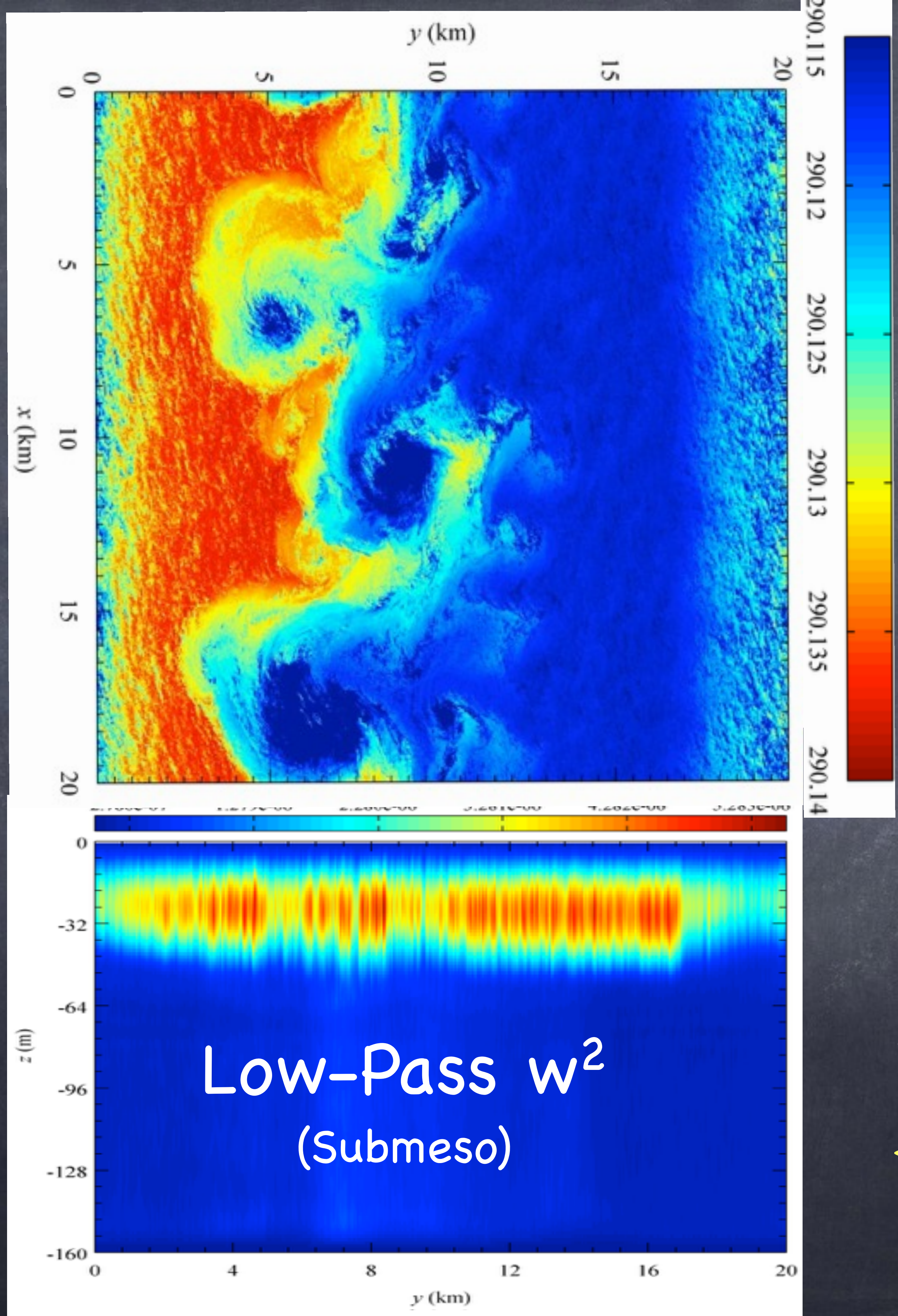


Surf. Temp (K)

w^2 (m^2/s^2)
$< (200m/d)^2$

Wind & Fronts Only

No Stokes Drift



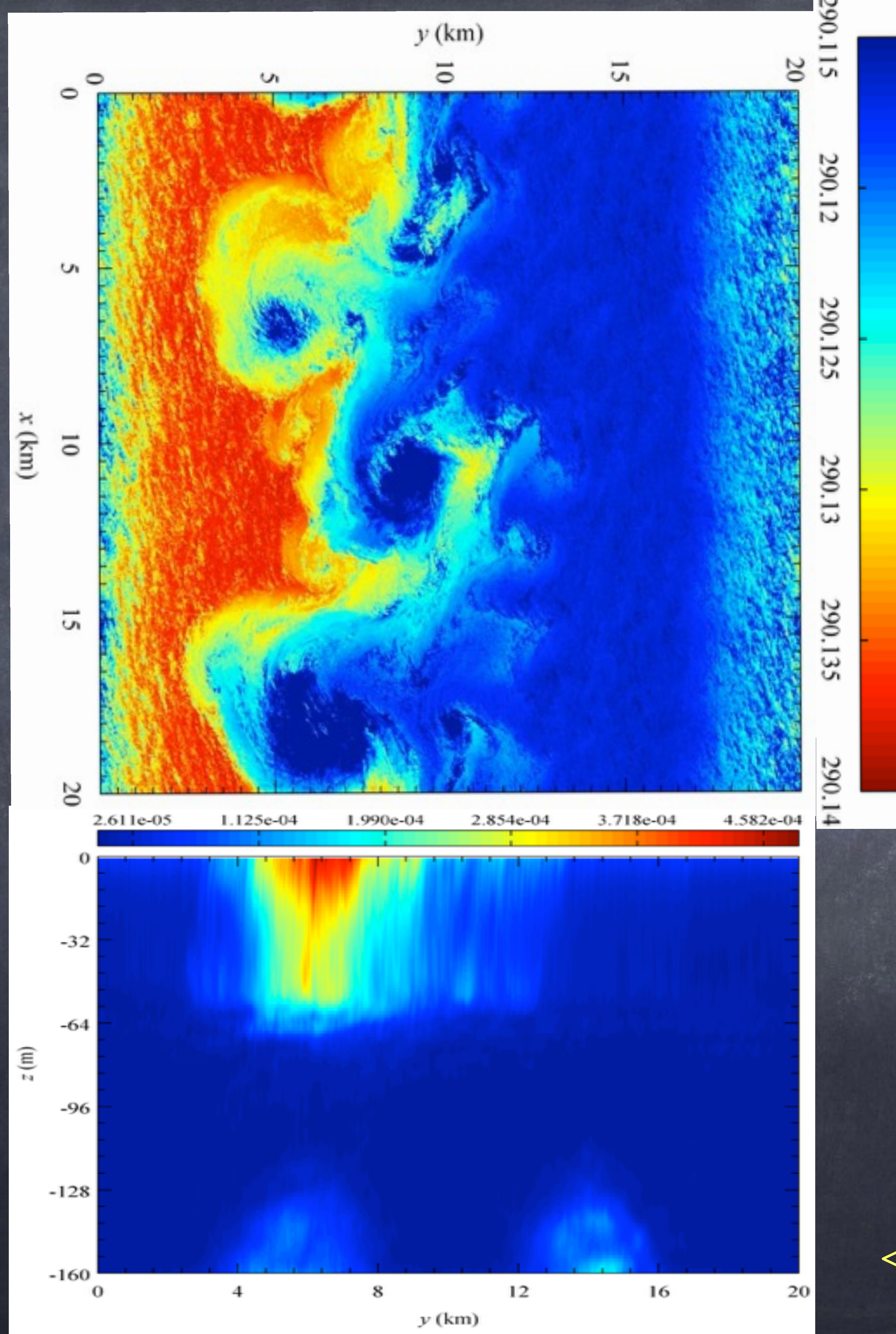
Mid-ML Temp (K)

w^2 (m^2/s^2)

$< (200m/d)^2$

Wind & Fronts Only

No Stokes Drift



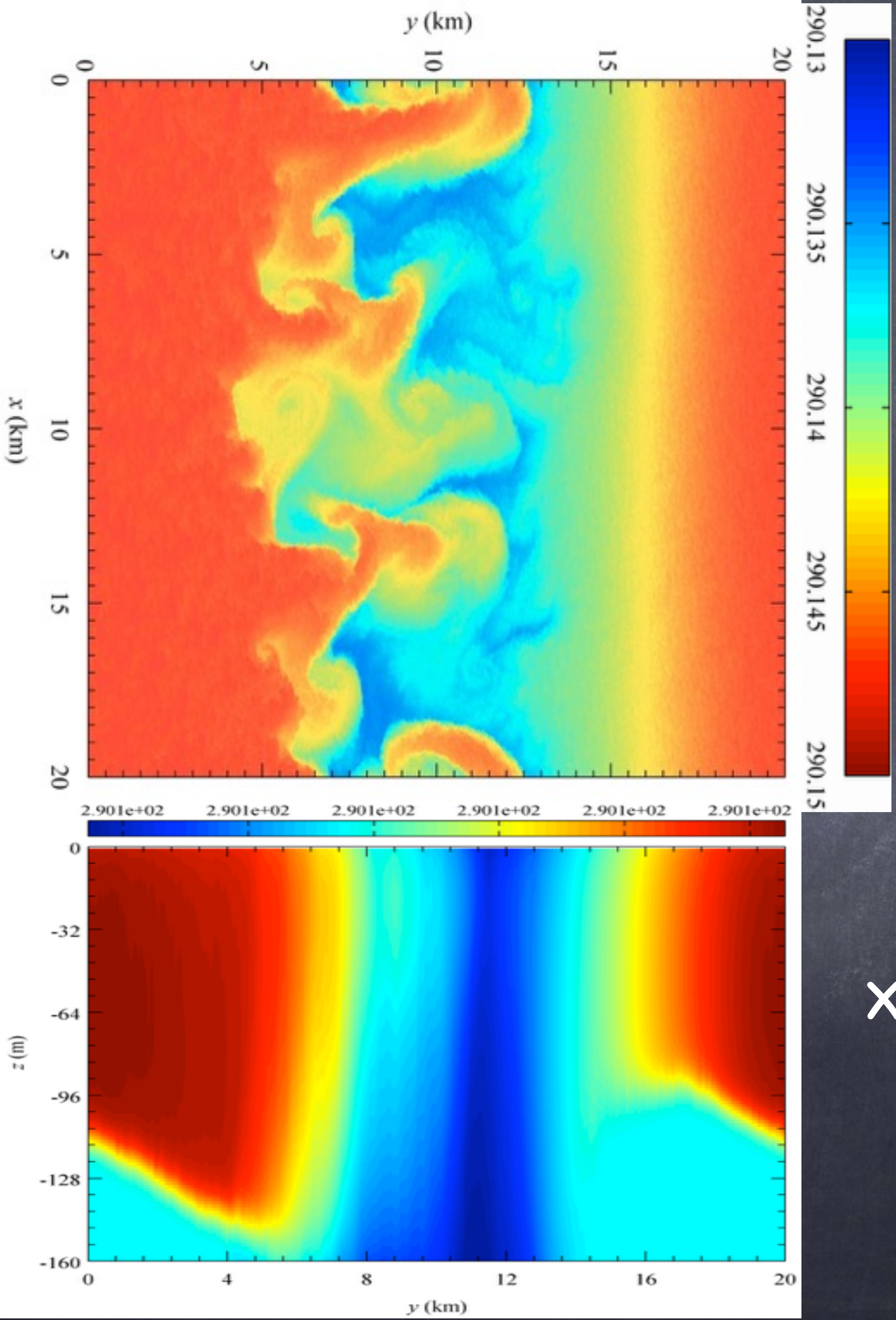
Mid-ML Temp (K)

v^2 (m^2/s^2)

$< (2cm/s)^2$

$< (2000m/d)^2$

Wind, Fronts, & Stokes Drift



-0.01

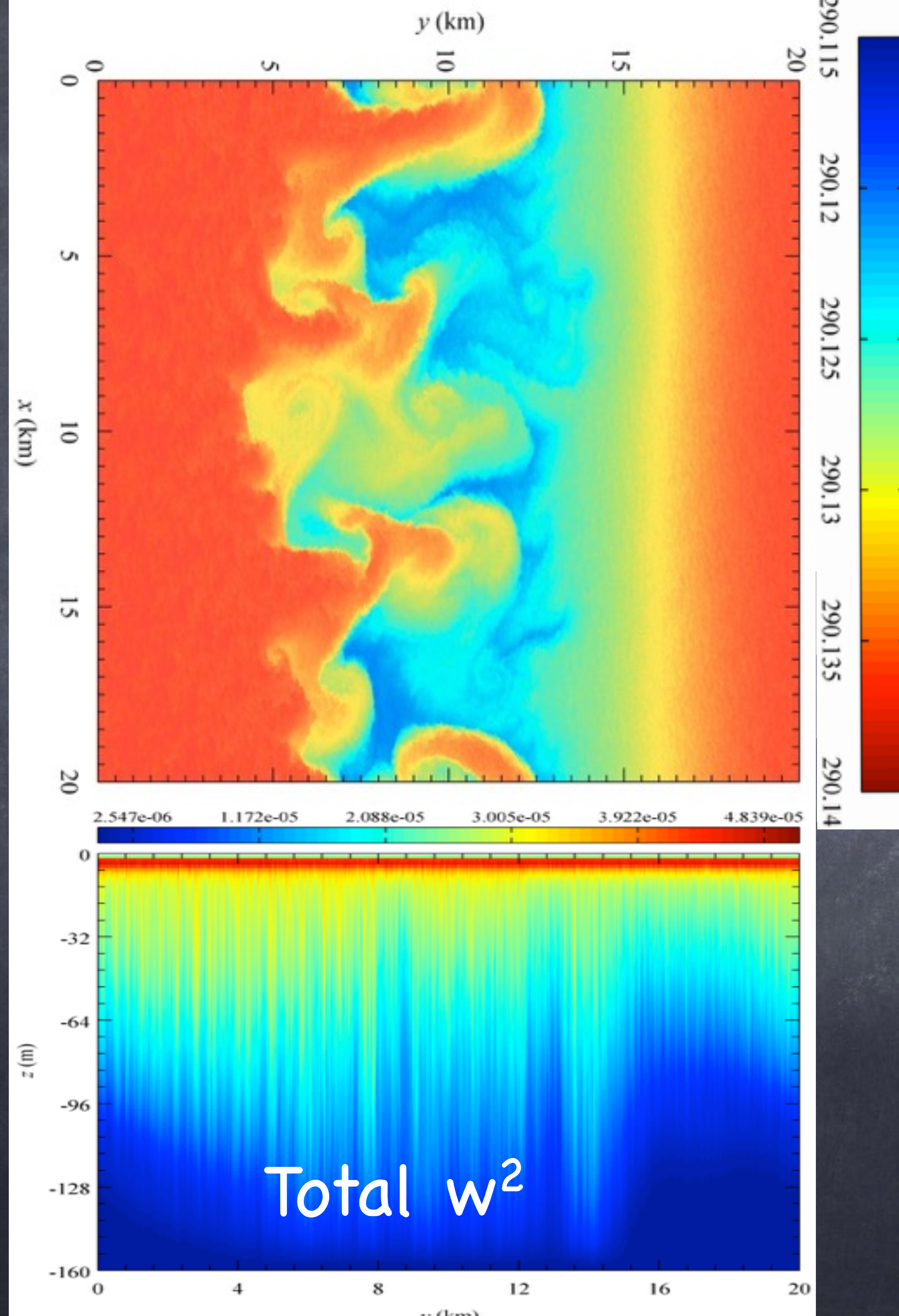
Surf. Temp (K)

+0.01

x-Avg. Temp

Temp (K)

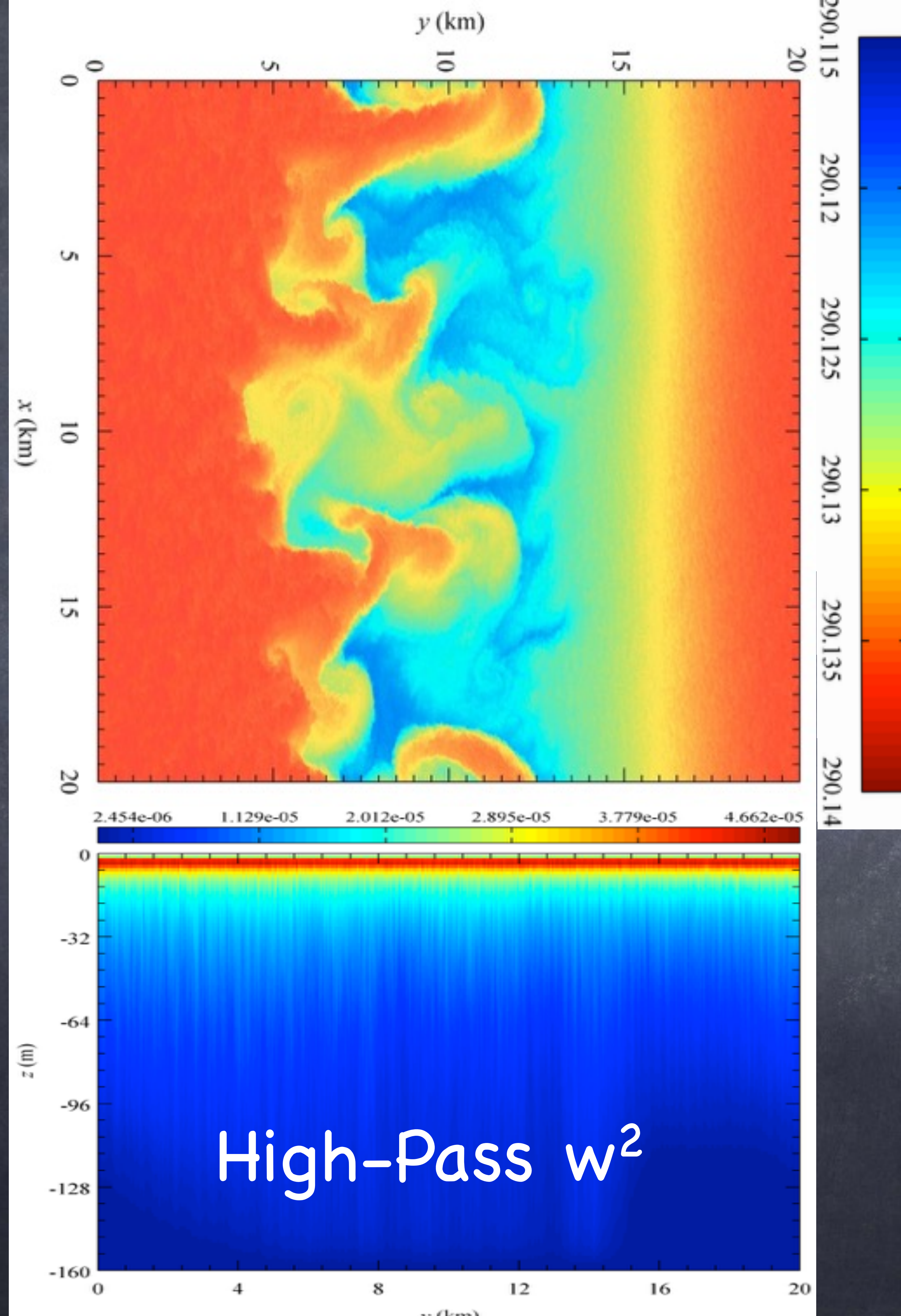
Wind, Fronts, & Stokes Drift



Surf. Temp (K)

w^2 (m^2/s^2)
$< (600m/d)^2$

Wind, Fronts, & Stokes Drift

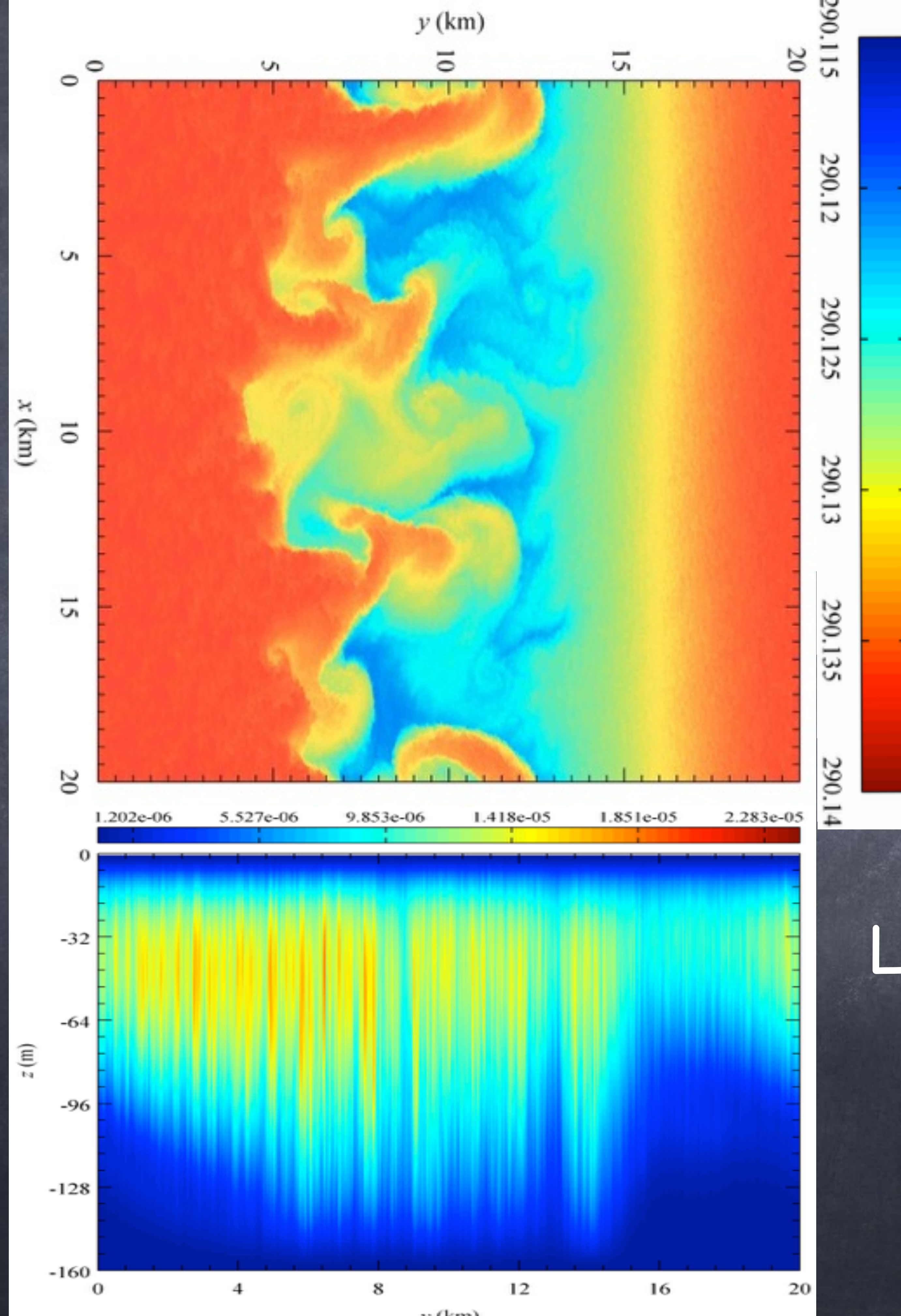


Surf. Temp (K)

w^2 (m^2/s^2)

$< (600m/d)^2$

Wind, Fronts, & Stokes Drift



Surf. Temp (K)

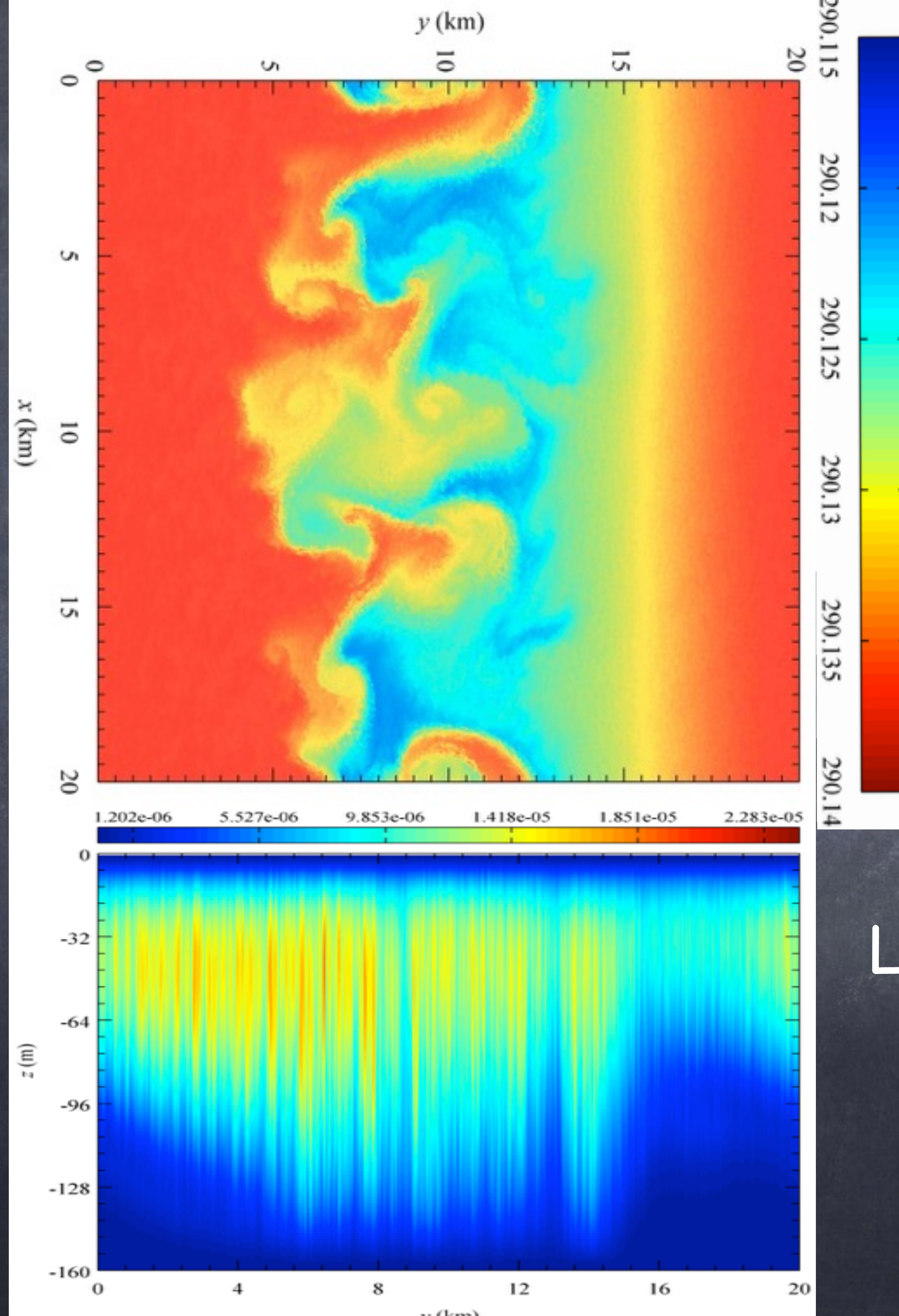
Low-Pass w^2

(Submeso)

w^2 (m^2/s^2)

$< (400m/d)^2$

Wind, Fronts, & Stokes Drift

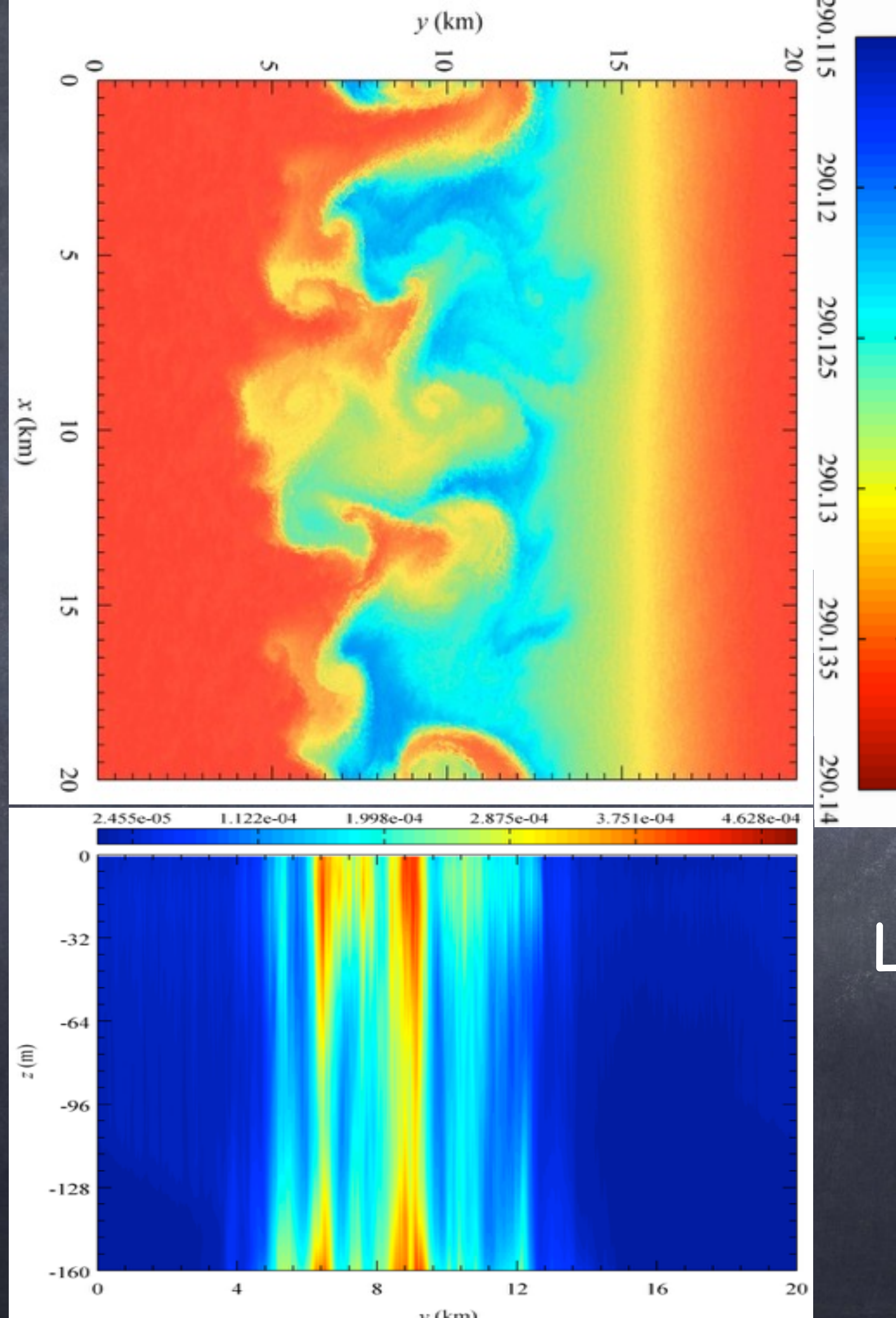


Mid-ML Temp (K)

Low-Pass w^2 (Submeso)

w^2 (m^2/s^2)

Wind, Fronts, & Stokes Drift



Mid-ML Temp (K)

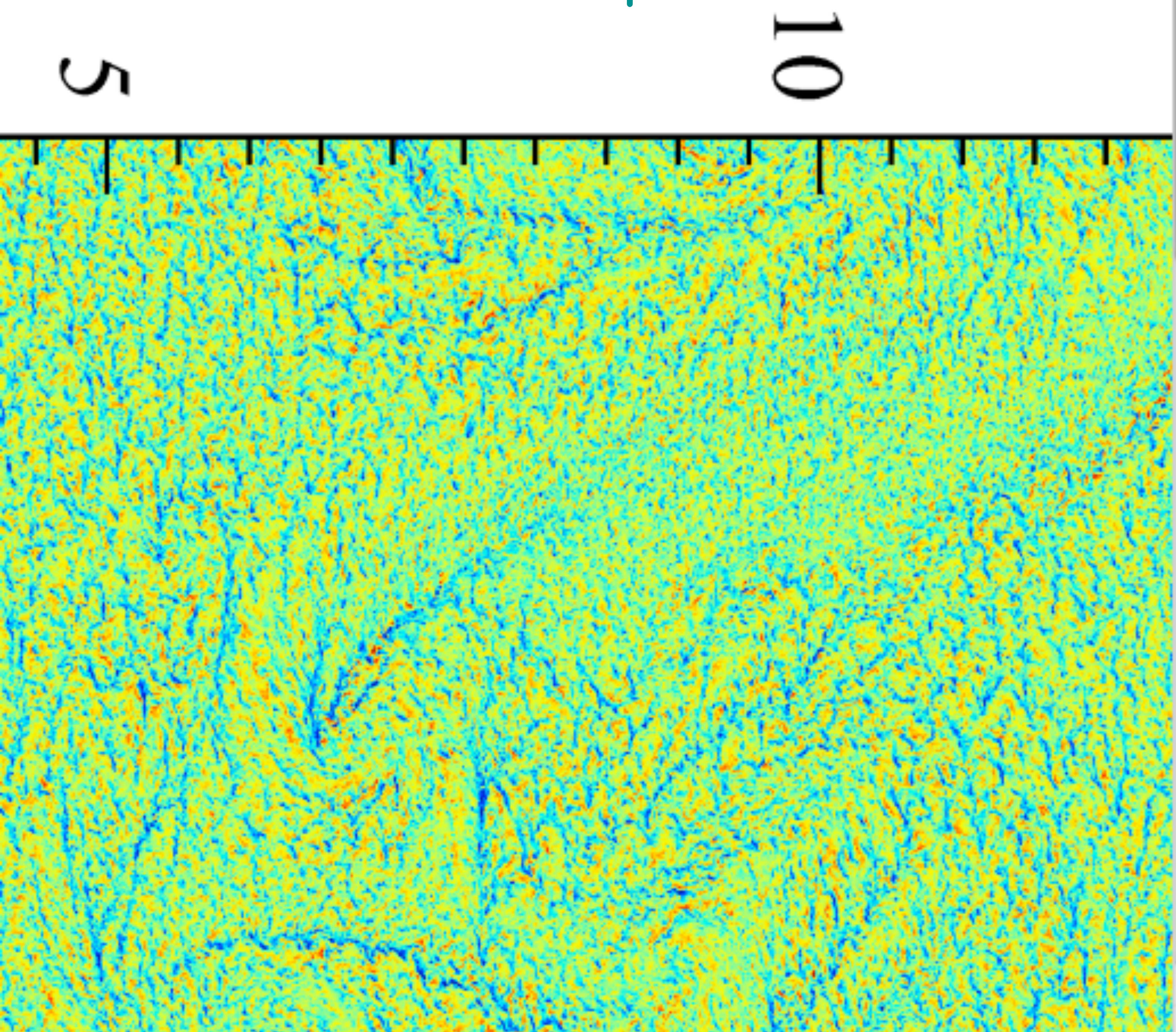
Low-Pass u^2

(Submeso)

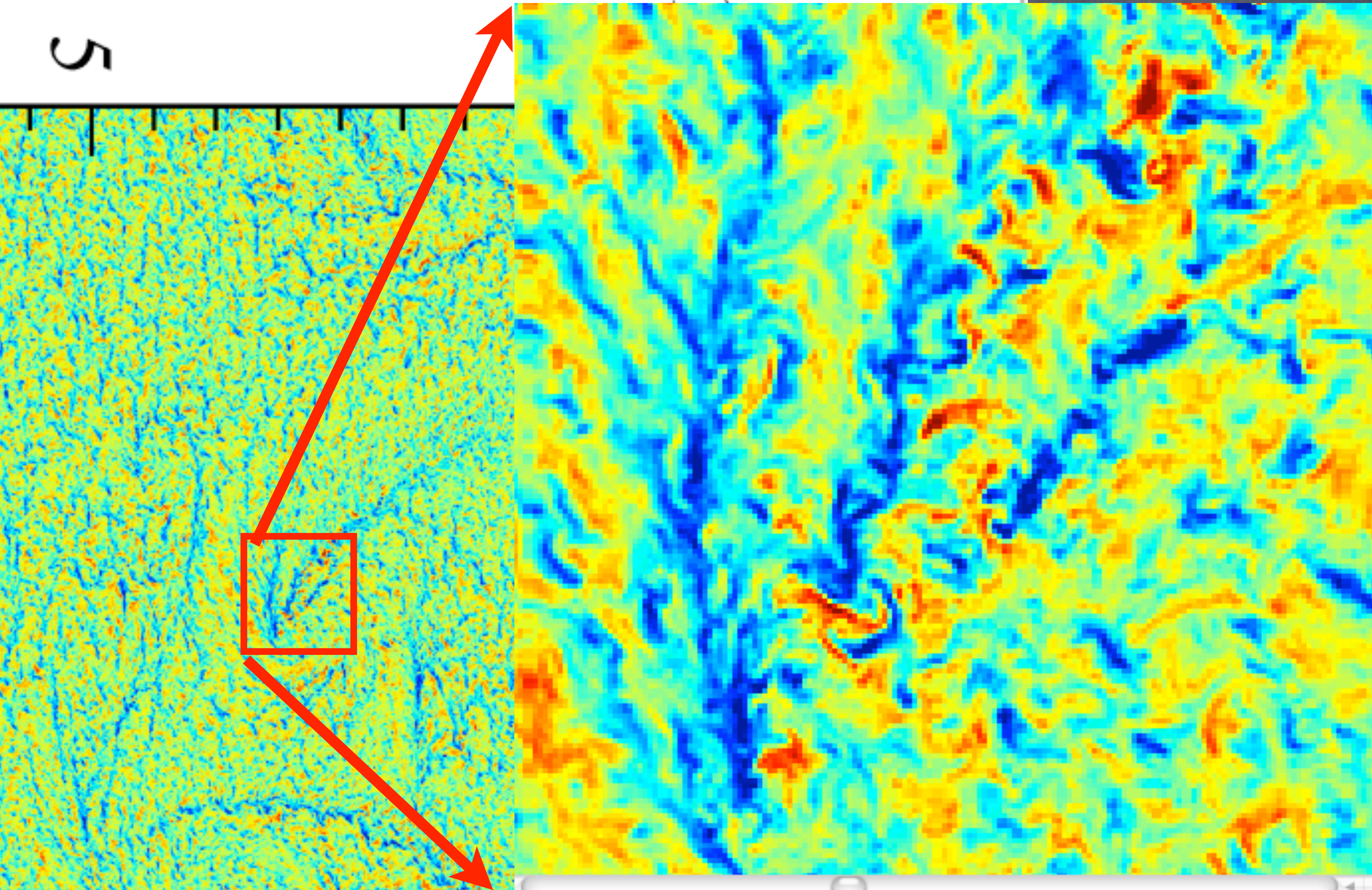
u^2 (m^2/s^2)

$< (2000m/d)^2$

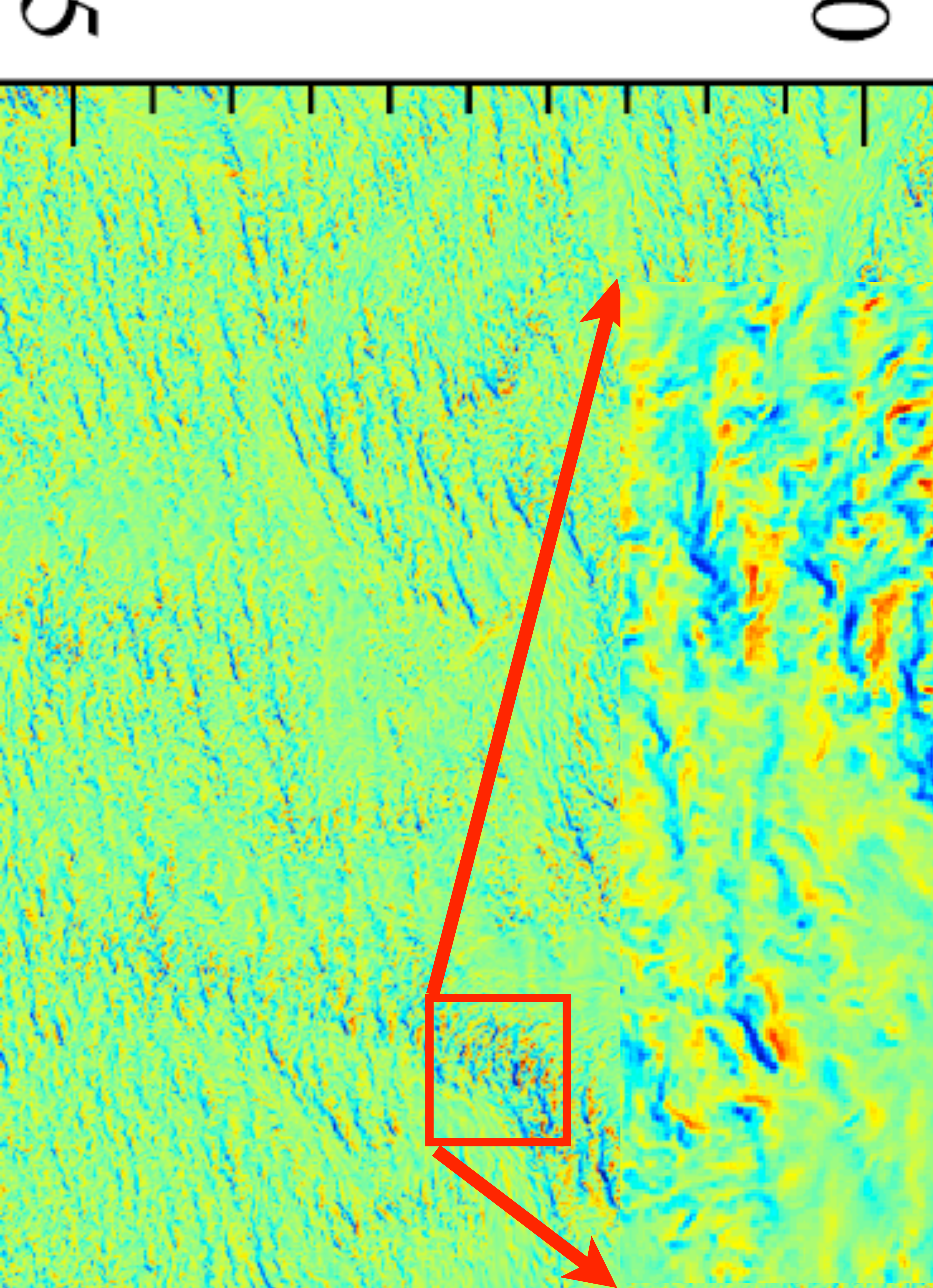
Filaments are hard to see!
even at mid-ML depth

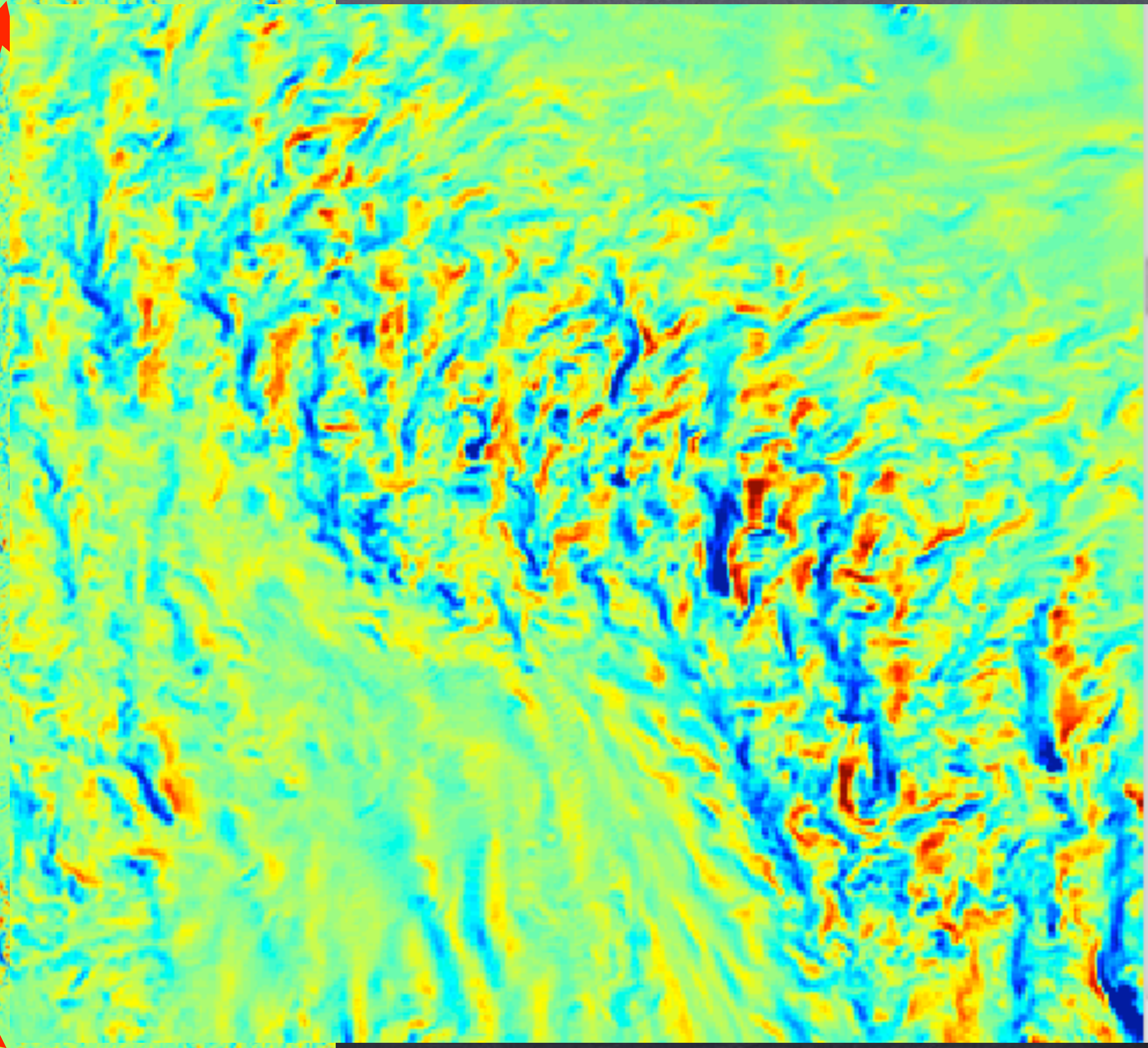


Filaments are hard to see!
even at mid-ML depth



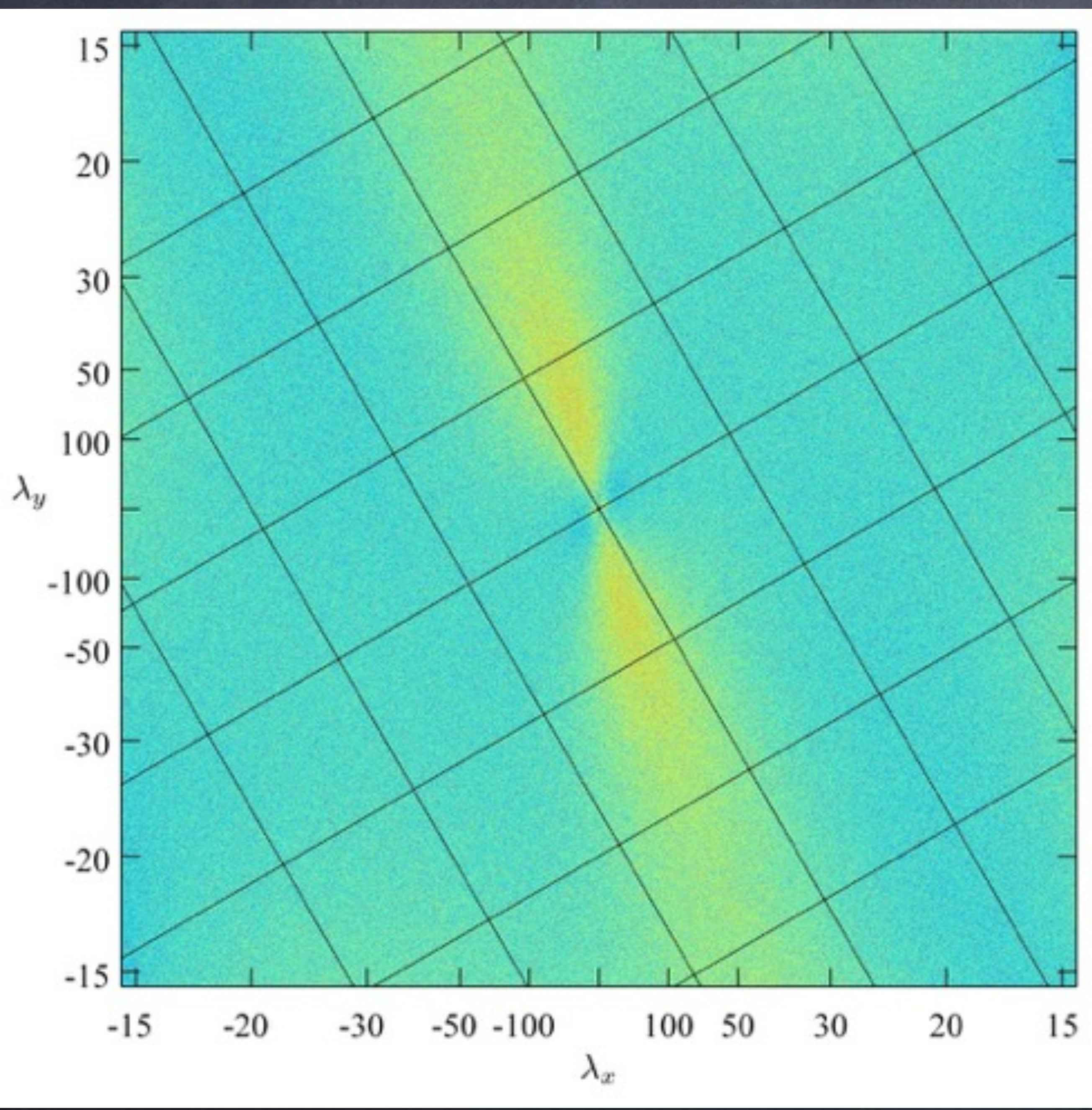
Different Scales in filaments without Stokes



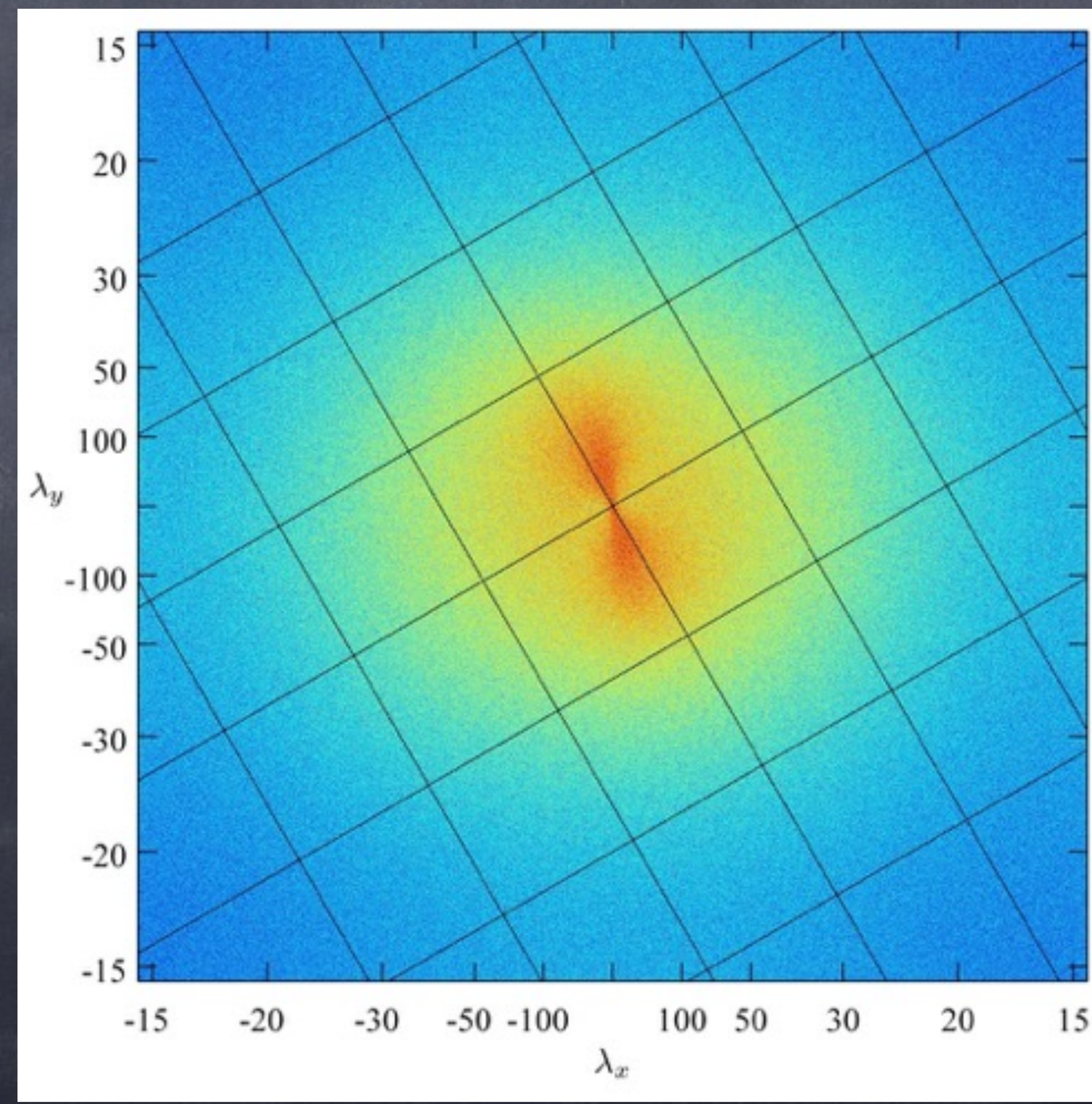


Power Spectral Density of w^2: No Stokes

Near Surface

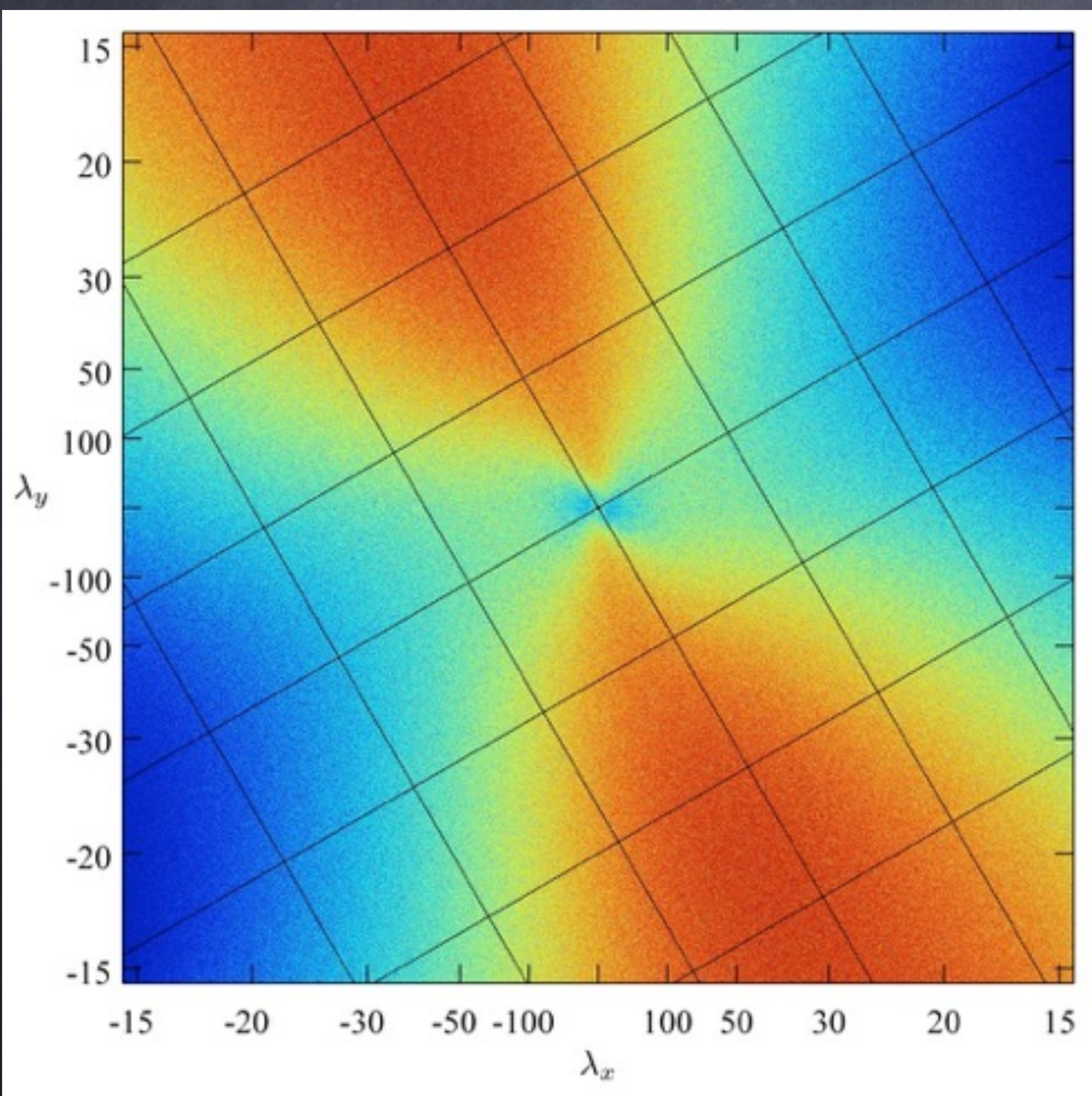


Mid Mixed Layer

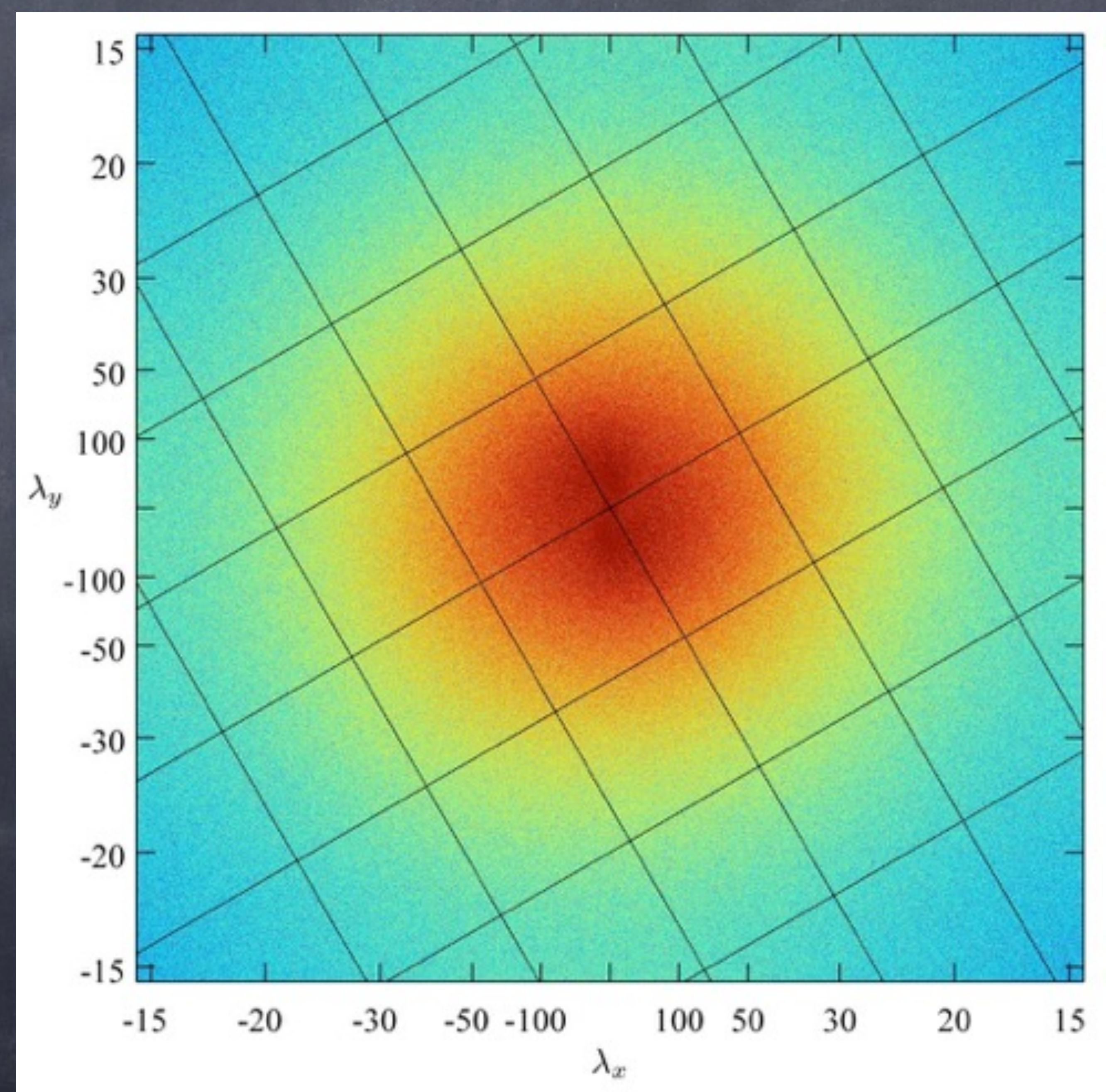


Power Spectral Density of w^2: With Stokes

Near Surface



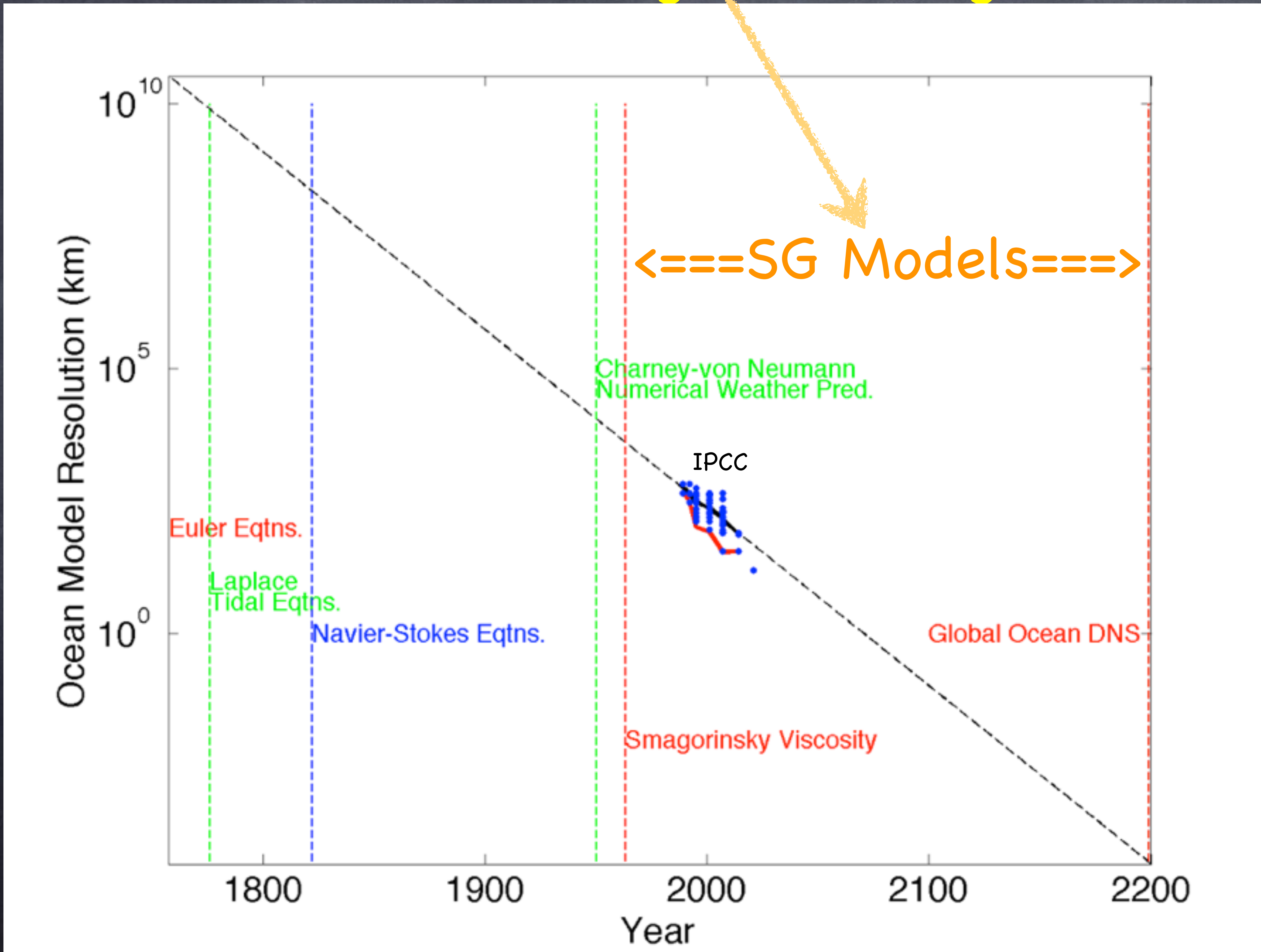
Mid Mixed Layer



Conclusions

- Mesoscale, Submesoscale, and Langmuir scale phenomena all have a nontrivial affect on the global climate, thus need accurate parameterizations
- Parameterizations are developed by comparison to higher-resolution models, with careful diagnosis of interesting couplings
- These high resolution models not only reveal loss of balance (if it's there), but also random coupling/mixing of disparate

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



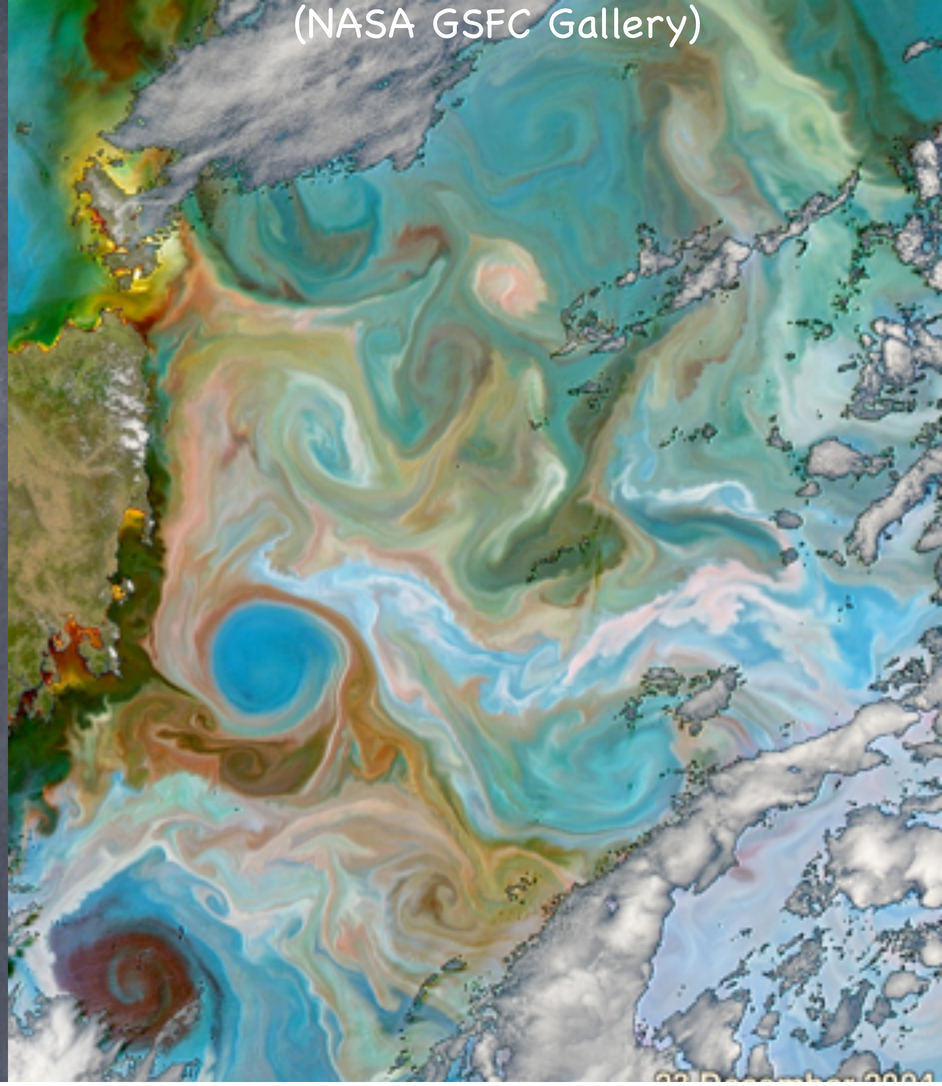
Mesoscale Parameterizations

- Researchers have already cast much darkness on this subject and if they continue their investigations we shall soon know nothing at all about it.
  - --Mark Twain

The Character of the Mesoscale

100 km

(NASA GSFC Gallery)



(Capet et al., 2008)

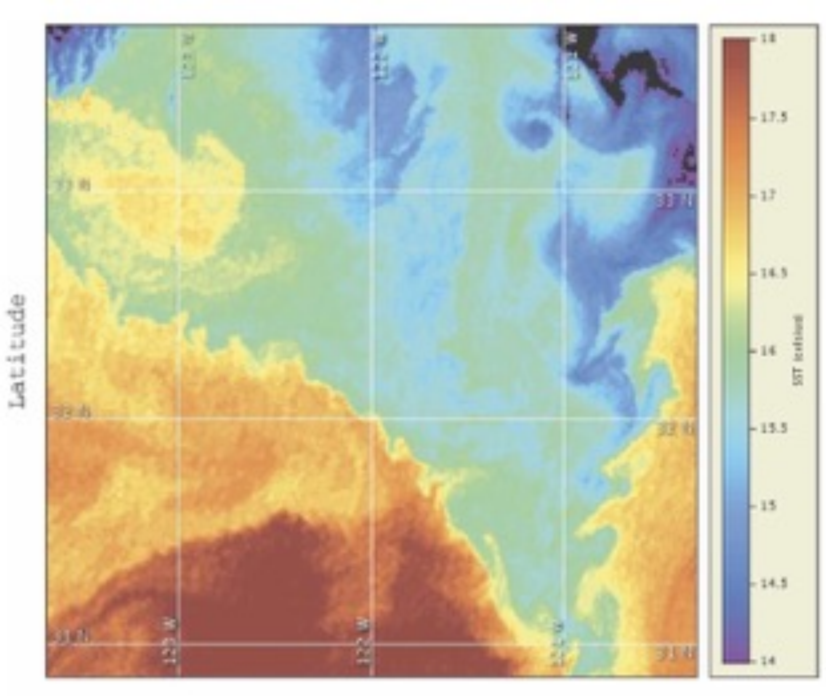
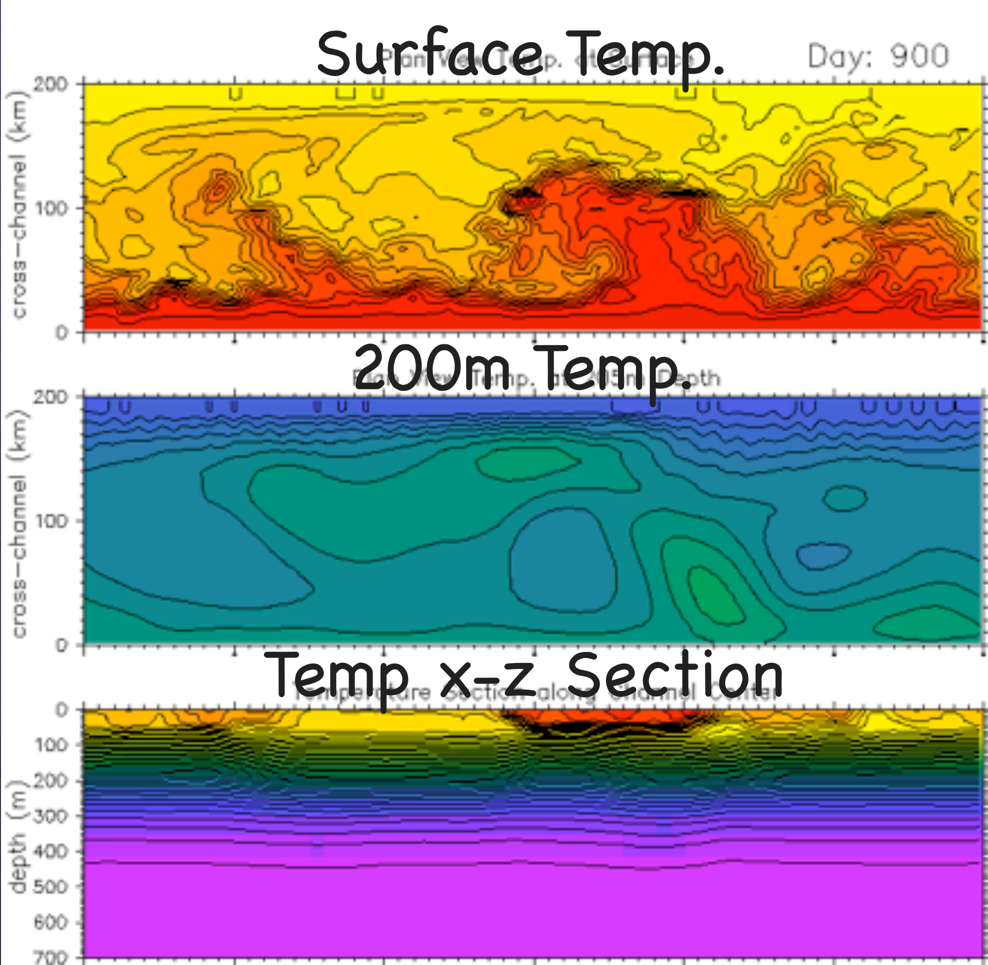


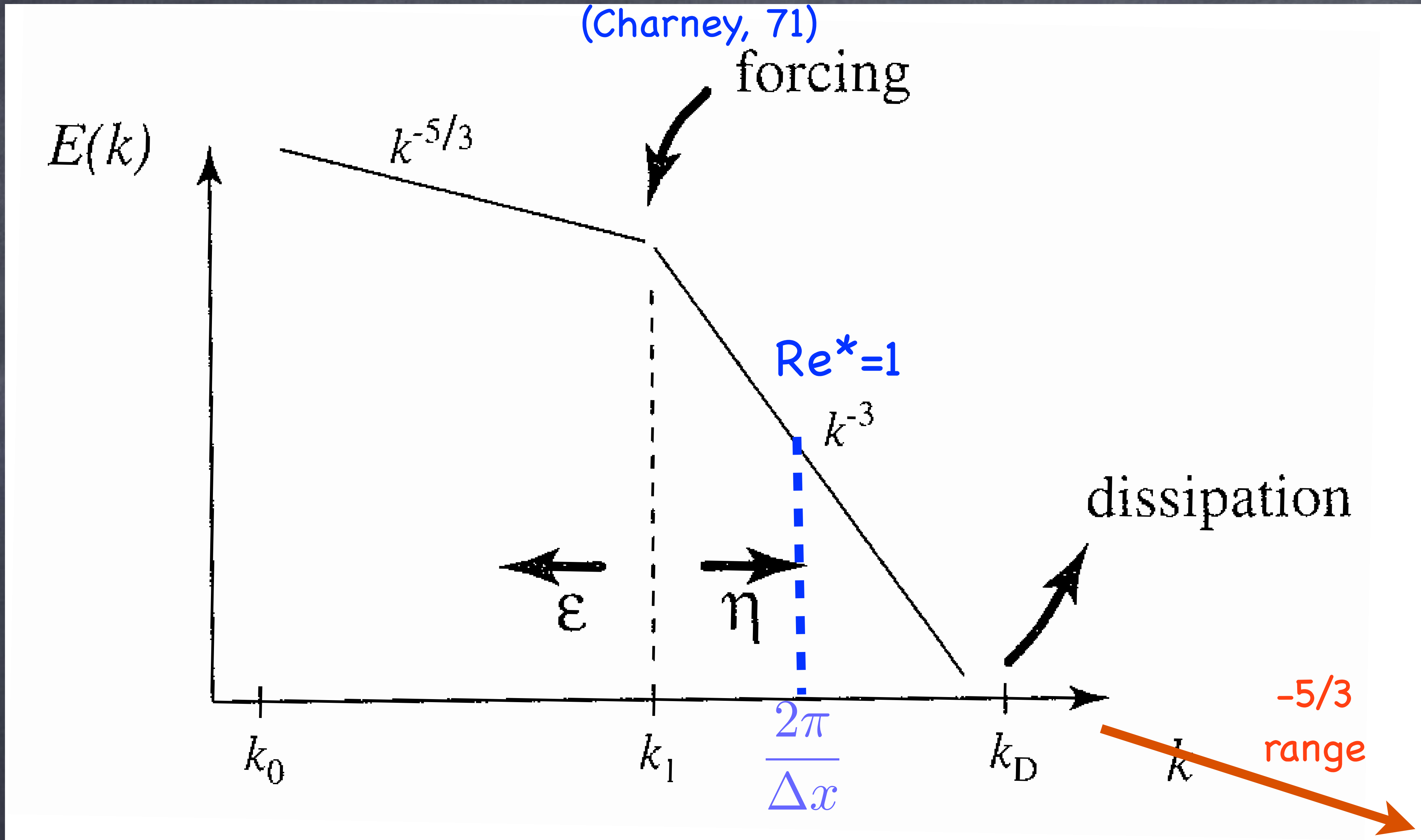
FIG. 16. Sea surface temperature measured at 1832 UTC 3 Jan 2006 off Point Conception in the California Current from CoastWatch (http://coastwatch.pfeg.noaa.gov). The fronts between recently upwelled water (i.e., 15°–16°C) and offshore water (≥17°C) show submesoscale instabilities with wavelengths around 30 km (right front) or 15 km (left front). Images for 1 day earlier and 4 days later show persistence of the instability events.

- Boundary Currents
- Eddies
- Ro=O(0.1)
- Ri=O(1000)
- Full Depth
- Eddies strain to produce Fronts
- 100km, months



Eddy processes mainly baroclinic & barotropic instability. Parameterizations of baroclinic instability (GM, Visbeck...).

MOLES Turbulence Like Pot'l Enstrophy cascade, but divergent



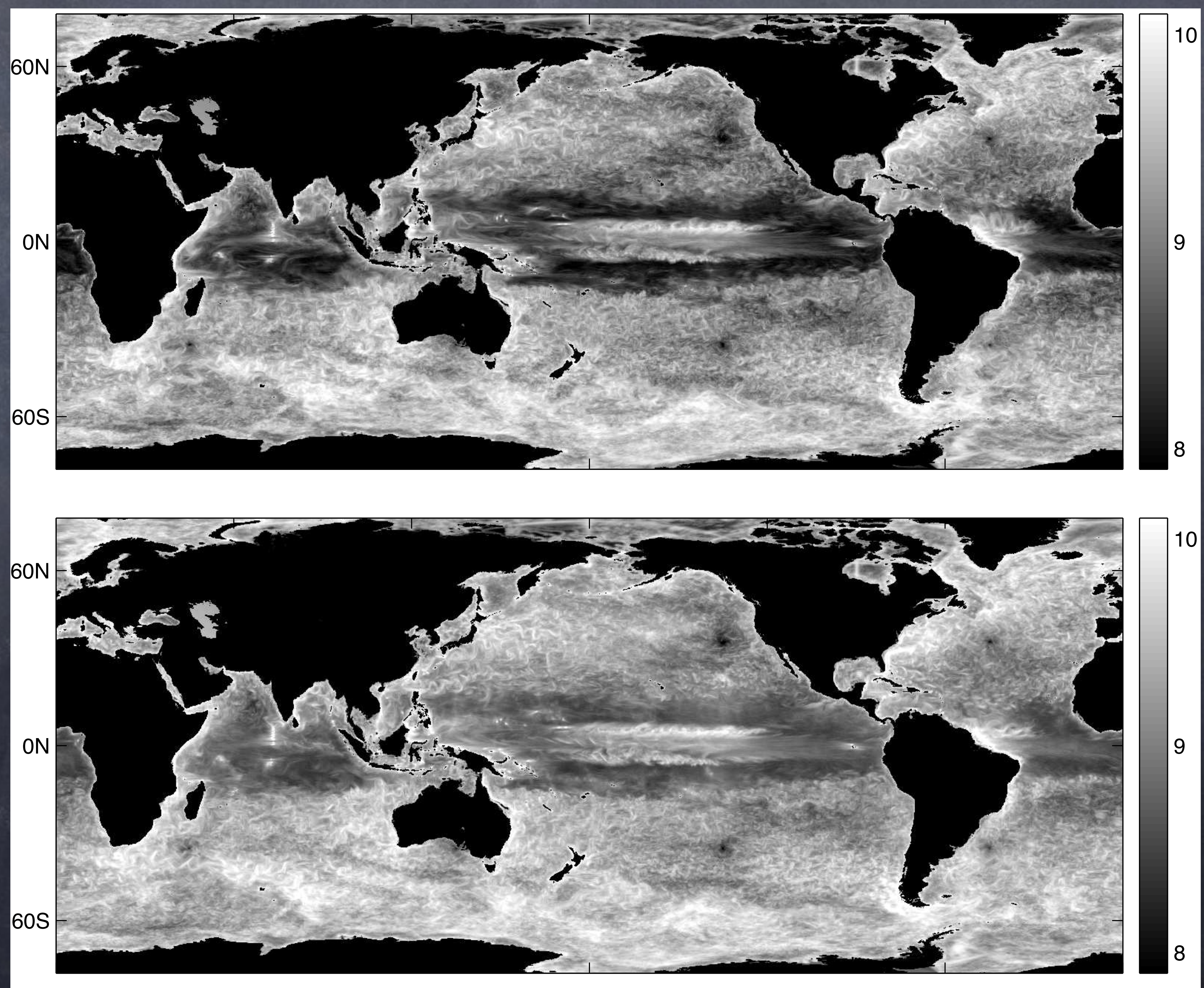
2008: F-K & Menemenlis Revise Leith Viscosity Scaling,
So that diverging, vorticity-free, modes are also damped

$$\nu_* = \left(\frac{\Delta x}{\pi}\right)^3 \sqrt{\Lambda^6 |\nabla_h q_{2d}|^2 + \Lambda_d^6 |\nabla_h (\nabla_h \cdot \mathbf{u}_*)|^2}.$$

Makes viscosity a bit bigger, especially near Eq.

Leith

F-K&M



But matters a lot for stability!

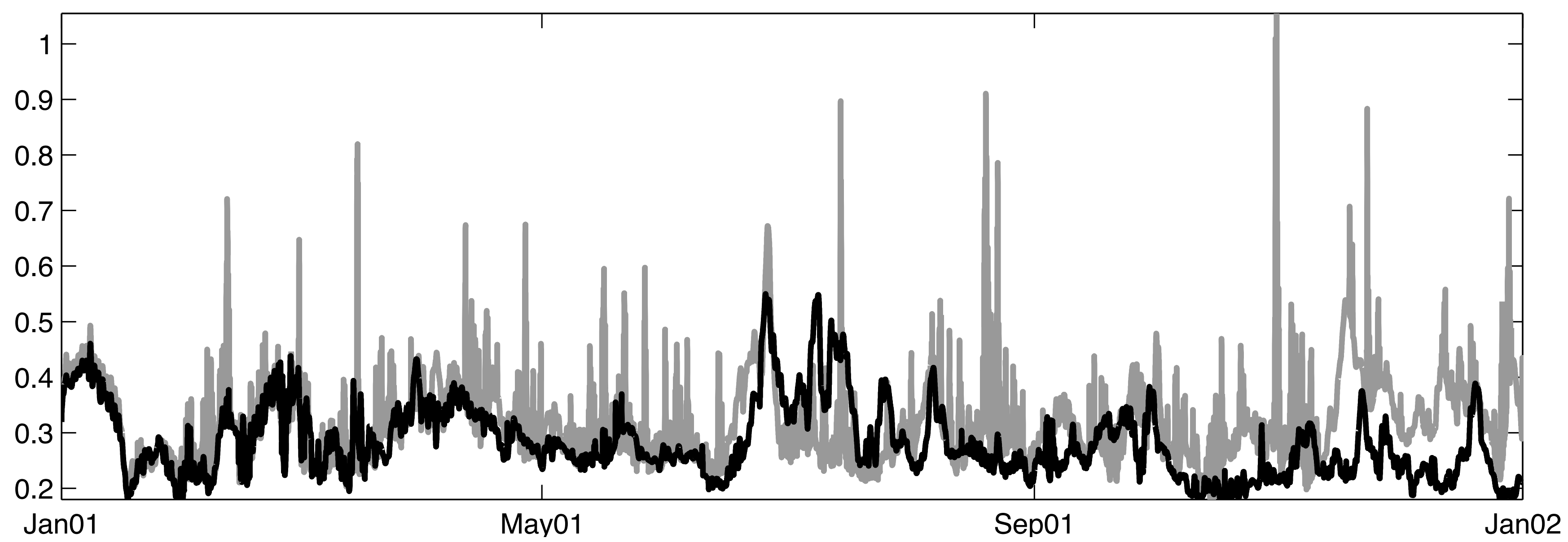
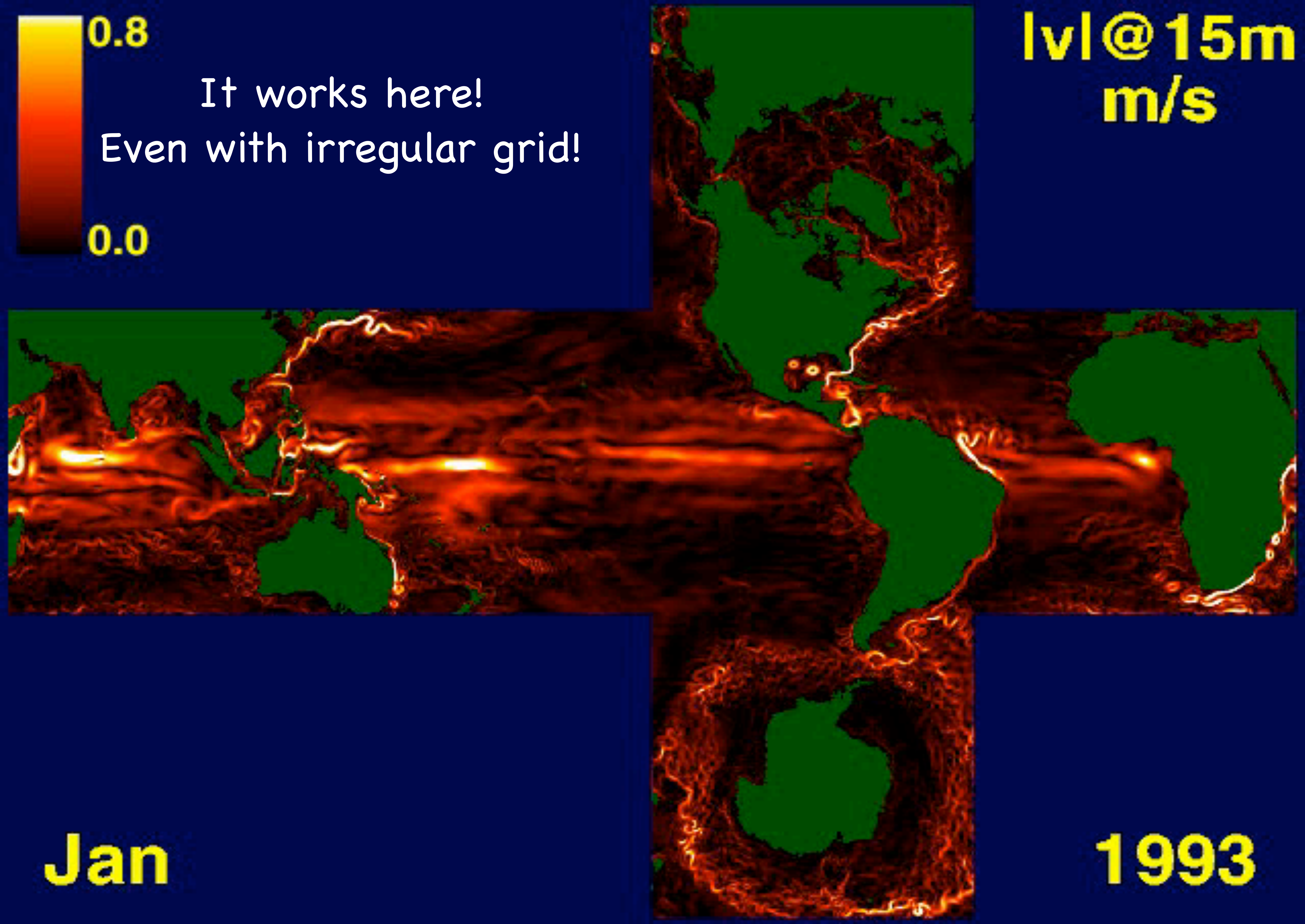


Figure 4. Maximum Courant number, $w\Delta t/\Delta z$, for vertical advection. Gray line is from the *LeithOnly* integration and black line is from the *LeithPlus* integration.

Fox-Kemper & Menemenlis, 2008



ECCO2 (Estimating the Circulation & Climate of the Ocean, Phase 2, www.ecco2.org)

Mesoscale Eddy Parameterizations all have the form:

$$\overline{\mathbf{u}'\tau'} = -\mathbf{M}\nabla\overline{\tau}$$

$$\begin{bmatrix} \overline{u'\tau'} \\ \overline{v'\tau'} \\ \overline{w'\tau'} \end{bmatrix} = - \begin{bmatrix} M_{xx} & M_{xy} & M_{xz} \\ M_{yx} & M_{yy} & M_{yz} \\ M_{zx} & M_{zy} & M_{zz} \end{bmatrix} \begin{bmatrix} \overline{\tau}_x \\ \overline{\tau}_y \\ \overline{\tau}_z \end{bmatrix}$$

With John Dennis & Frank Bryan, we took a POP0.1° Normal-Year forced model (yrs 16-20)

Added 9 Passive tracers--restored x,y,z @ 3 rates

Kept all the eddy fluxes for passive & active

Coarse-grained to 2°, transient eddies, tracers to $\mathbf{M}$

$$\overline{\mathbf{u}'\tau'} = -\mathbf{M}\nabla\overline{\tau}$$

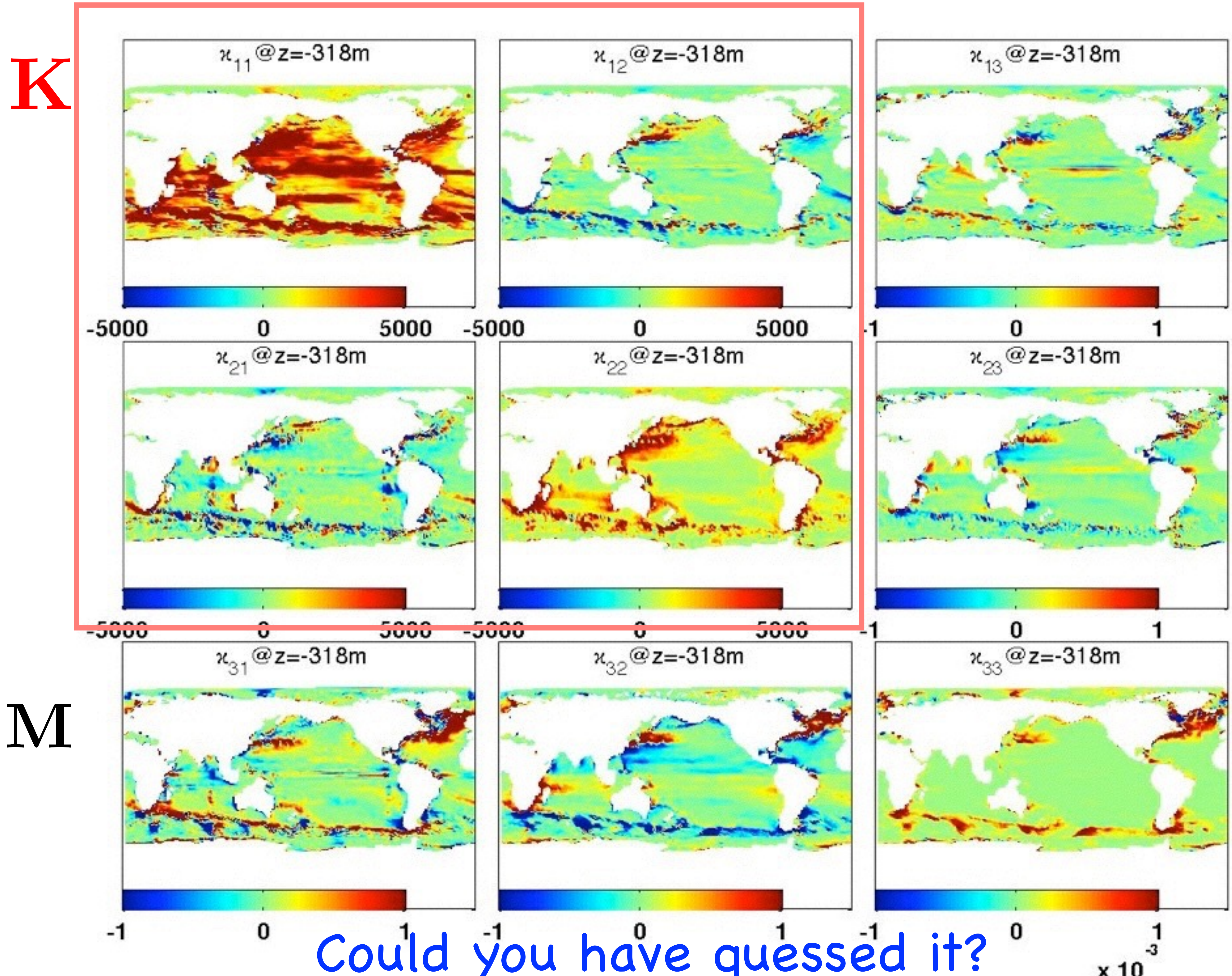
Sym Part=Anisotropic* Redi

$$\begin{bmatrix} \overline{u'\tau'} \\ \overline{v'\tau'} \\ \overline{w'\tau'} \end{bmatrix} = - \begin{bmatrix} K_{xx} & K_{xy} & \hat{\mathbf{x}}\cdot\mathbf{K}\cdot\tilde{\nabla}\mathbf{z} \\ K_{yx} & K_{yy} & \hat{\mathbf{y}}\cdot\mathbf{K}\cdot\tilde{\nabla}\mathbf{z} \\ \hat{\mathbf{x}}\cdot\mathbf{K}\cdot\tilde{\nabla}\mathbf{z} & \hat{\mathbf{y}}\cdot\mathbf{K}\cdot\tilde{\nabla}\mathbf{z} & \tilde{\nabla}z\cdot\mathbf{K}\cdot\tilde{\nabla}\mathbf{z} \end{bmatrix} \begin{bmatrix} \overline{\tau}_x \\ \overline{\tau}_y \\ \overline{\tau}_z \end{bmatrix}$$

AntiSym Part=Anisotropic* GM

$$\begin{bmatrix} \overline{u'\tau'} \\ \overline{v'\tau'} \\ \overline{w'\tau'} \end{bmatrix} = - \begin{bmatrix} 0 & 0 & -\hat{\mathbf{x}}\cdot\mathbf{K}\cdot\tilde{\nabla}\mathbf{z} \\ 0 & 0 & -\hat{\mathbf{y}}\cdot\mathbf{K}\cdot\tilde{\nabla}\mathbf{z} \\ \hat{\mathbf{x}}\cdot\mathbf{K}\cdot\tilde{\nabla}\mathbf{z} & \hat{\mathbf{y}}\cdot\mathbf{K}\cdot\tilde{\nabla}\mathbf{z} & 0 \end{bmatrix} \begin{bmatrix} \overline{\tau}_x \\ \overline{\tau}_y \\ \overline{\tau}_z \end{bmatrix}$$

Yellow $\mathbf{K}$ ‘are‘ horizontal stirring & mixing



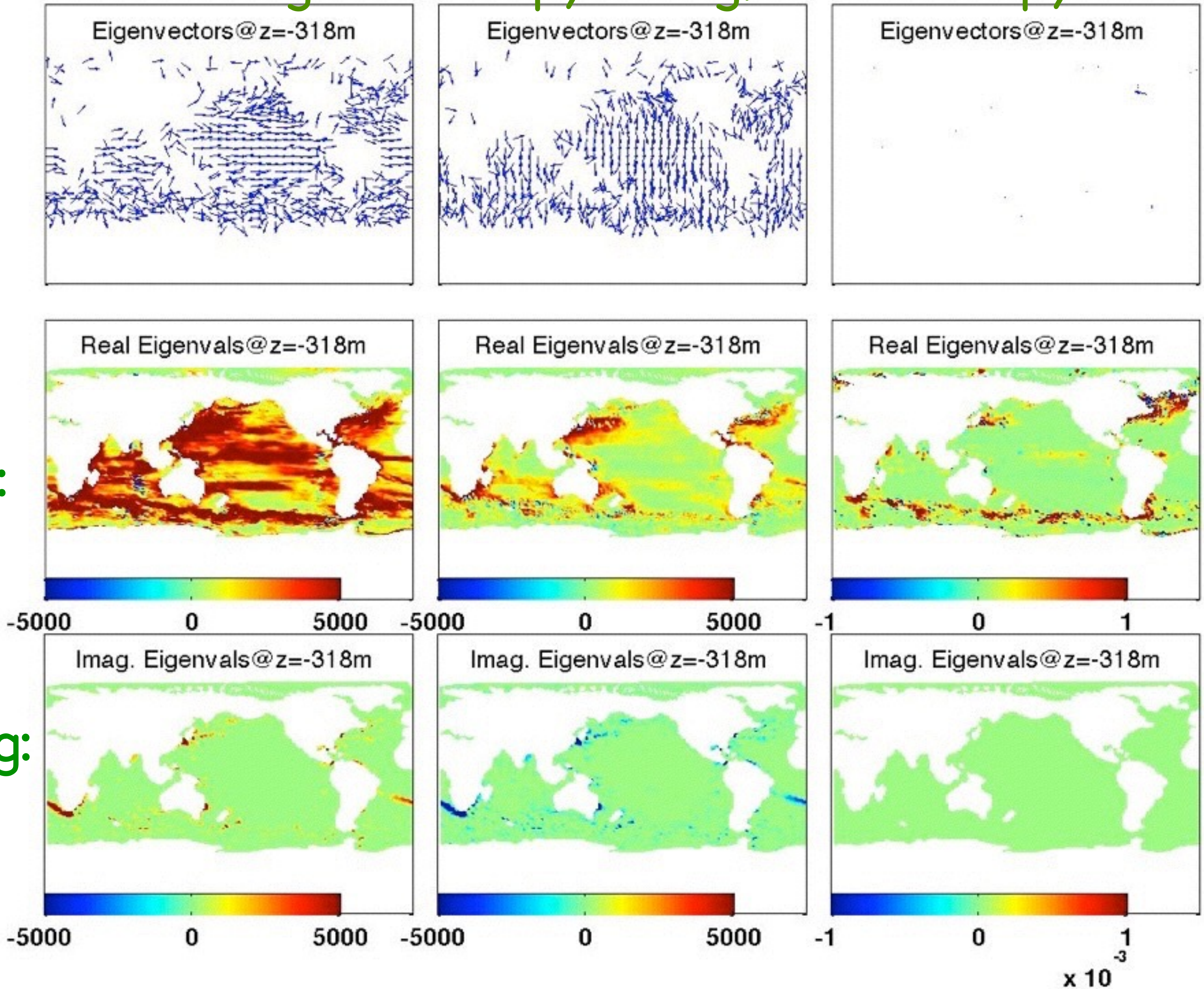
Could you have guessed it?

Result: Strong Anisotropy Along/Across Isopycnals

Mixing direction

Mixing:

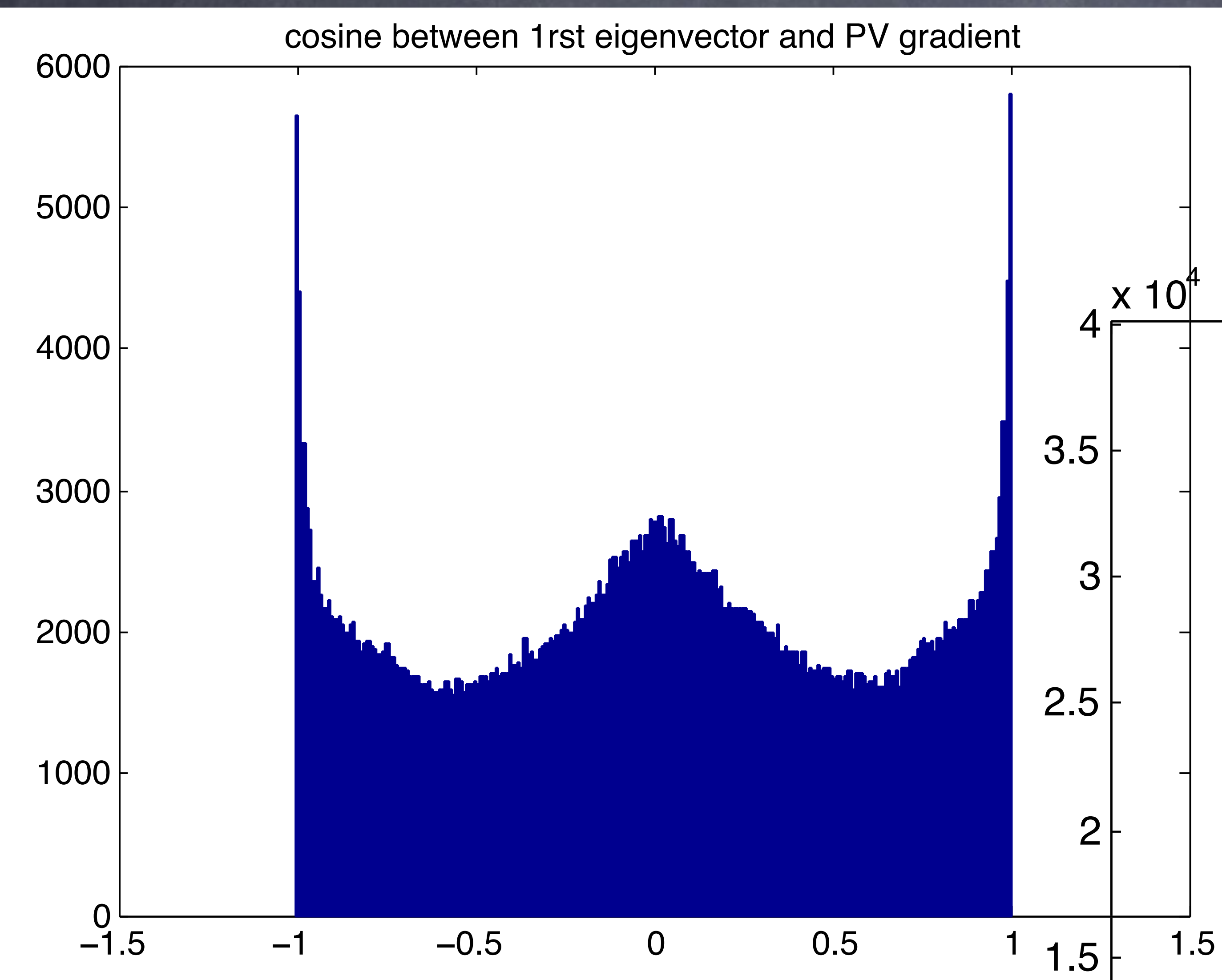
Stirring:



Result: Strong Anisotropy Along/Across PV Grads.

Mixing direction

Either along PV contours or across



1rst Eigenvector

2nd Eigenvector Across PV contours