Mixed Layer Restratification

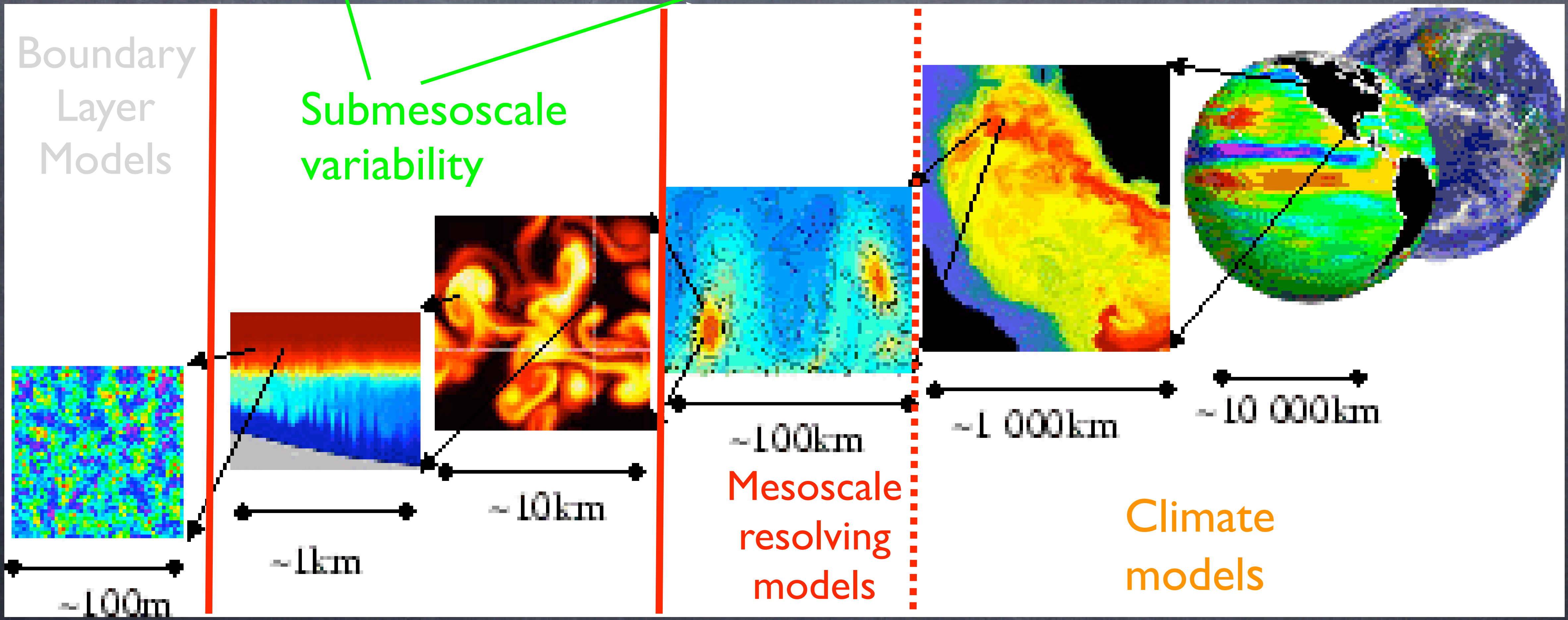
Baylor Fox-Kemper

Collaborators:
R. Ferrari, R. Hallberg, G. Flierl, G. Boccaletti and the CPT-EMiLIe team

CIRES/ATOC Seminar
Tuesday 3/21/07, 14:00-15:00

Upper Ocean in Climate Models

- Large-scale ocean circulation (100 - 10,000 km) => resolved
- Mesoscale variability (10 - 100 km) => resolved or parameterized
- Submesoscale variability (100 m - 10 km) => ignored
- Turbulent mixing (10 cm - 100 m) => parameterized



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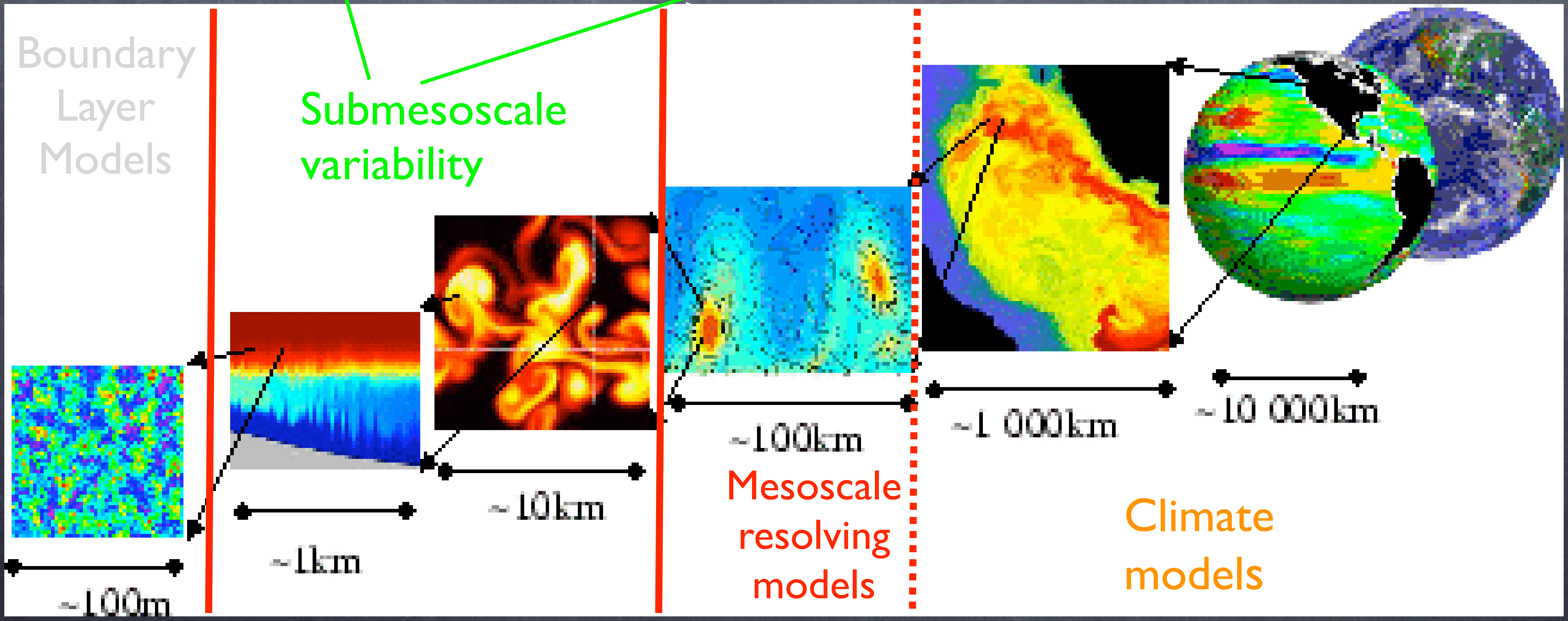
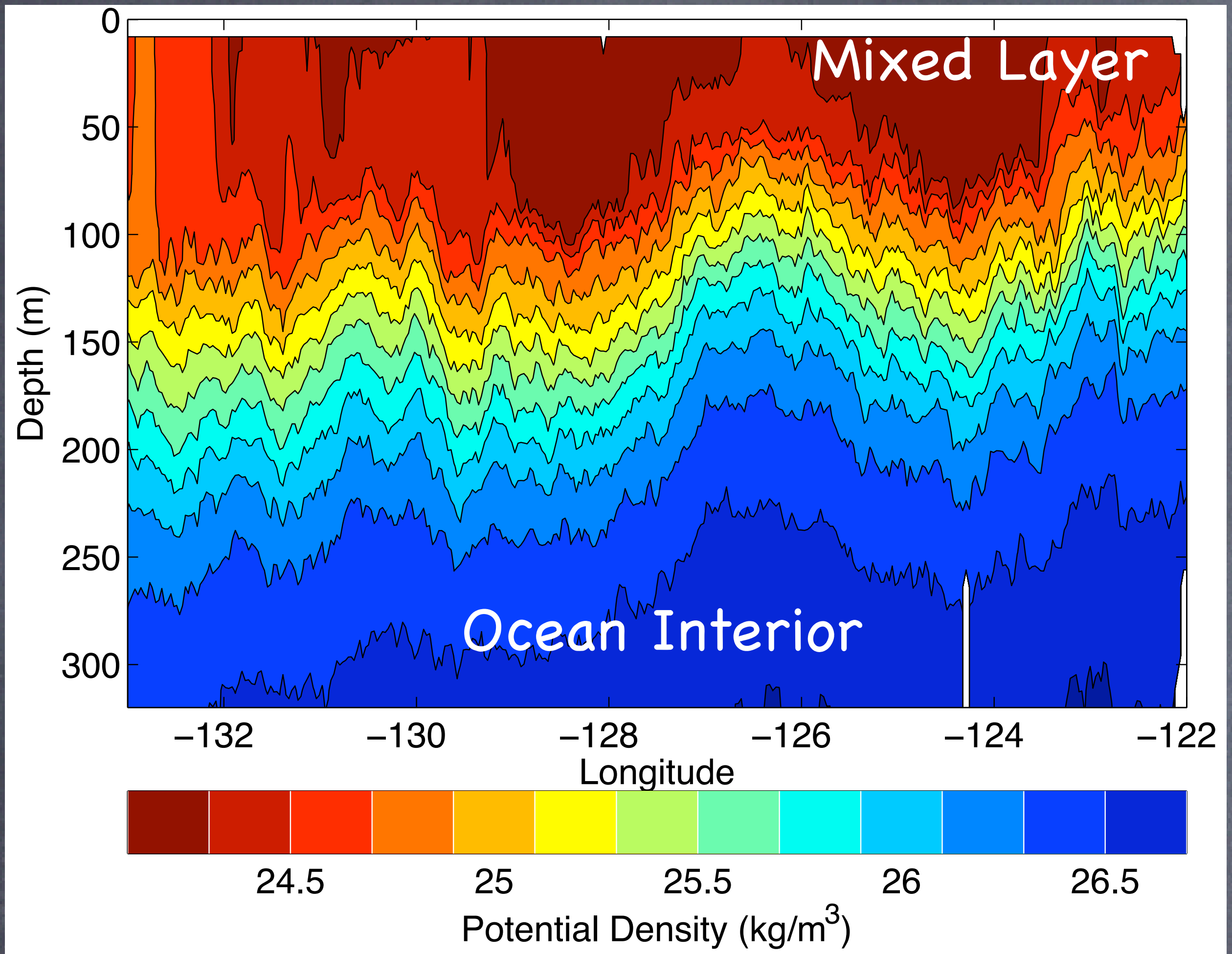


Coupling?

Coupling?

Ocean Mixed Layer



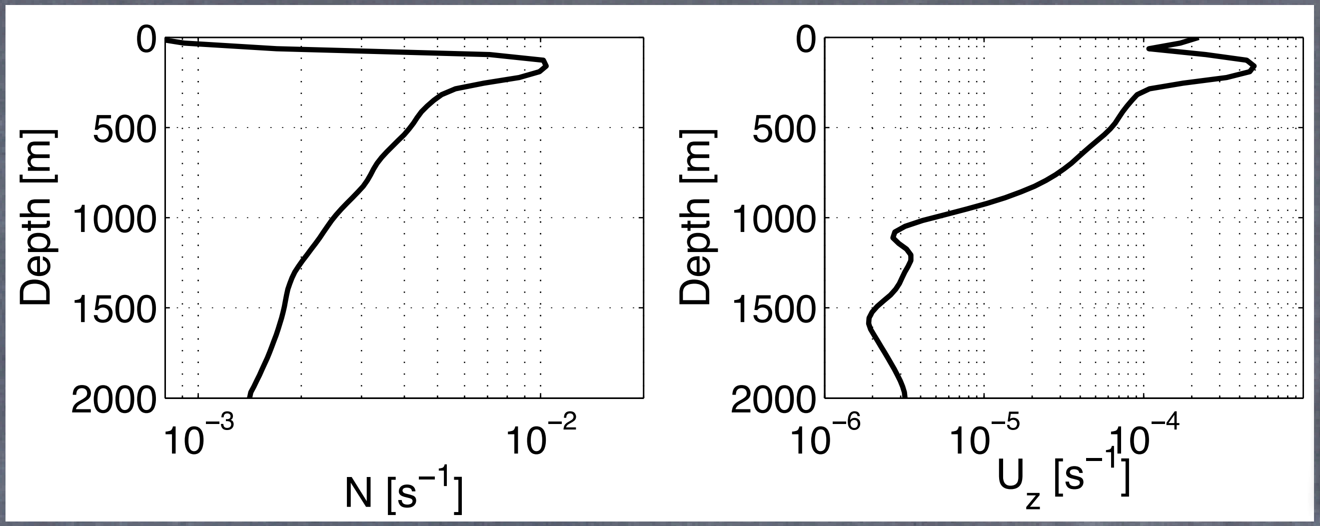
Pot'l Density measured by a Seasoar along a straight section from (32.5N, 122W) to (35N, 132W) between the CA current and the subtropical gyre.
(as in Ferrari & Rudnick, 2000)

The mixed layer is not TOTALLY mixed.
Horizontal density gradients are common.

1) What does its stratification imply?
2) How does the stratification get set?
3) Why do we care?

The Stratification Permits
Two Types of Baroclinic Instability:

Mesoscale and SubMesoscale (Boccaletti et al., 2006)



Note Def. Radius importance!

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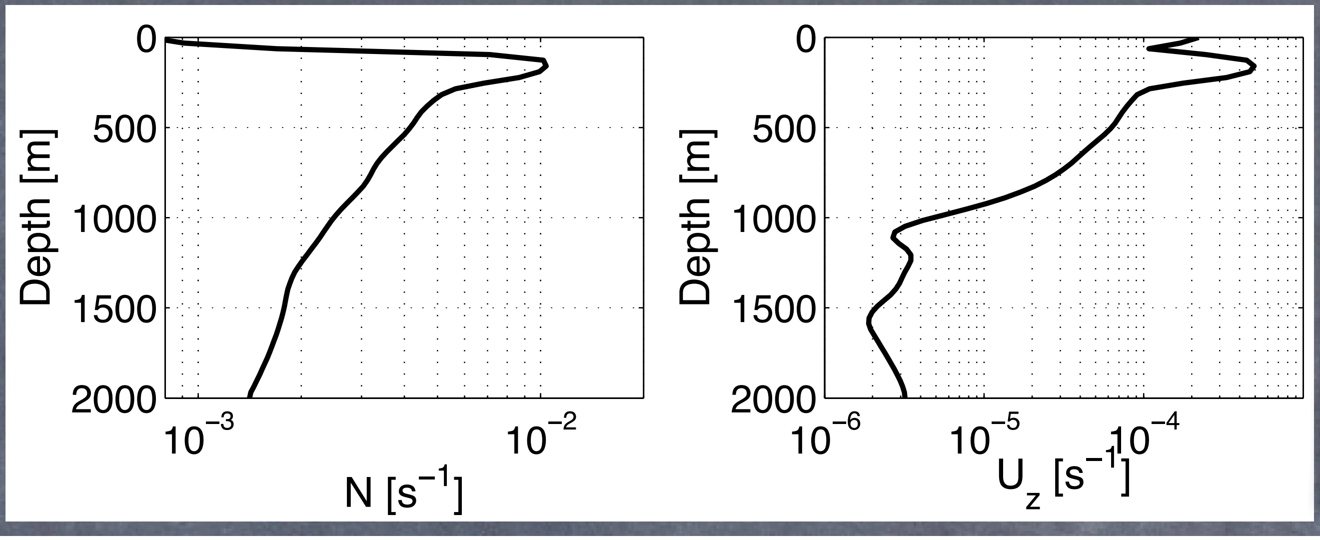

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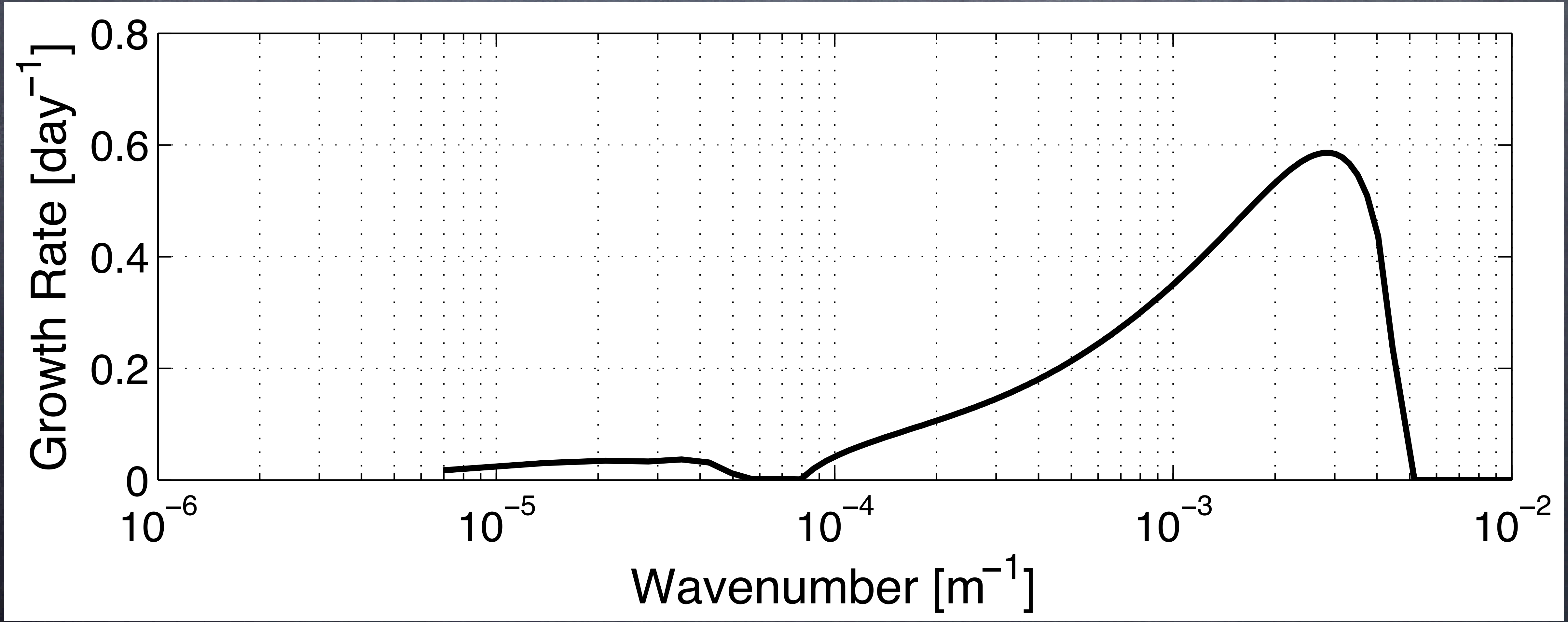

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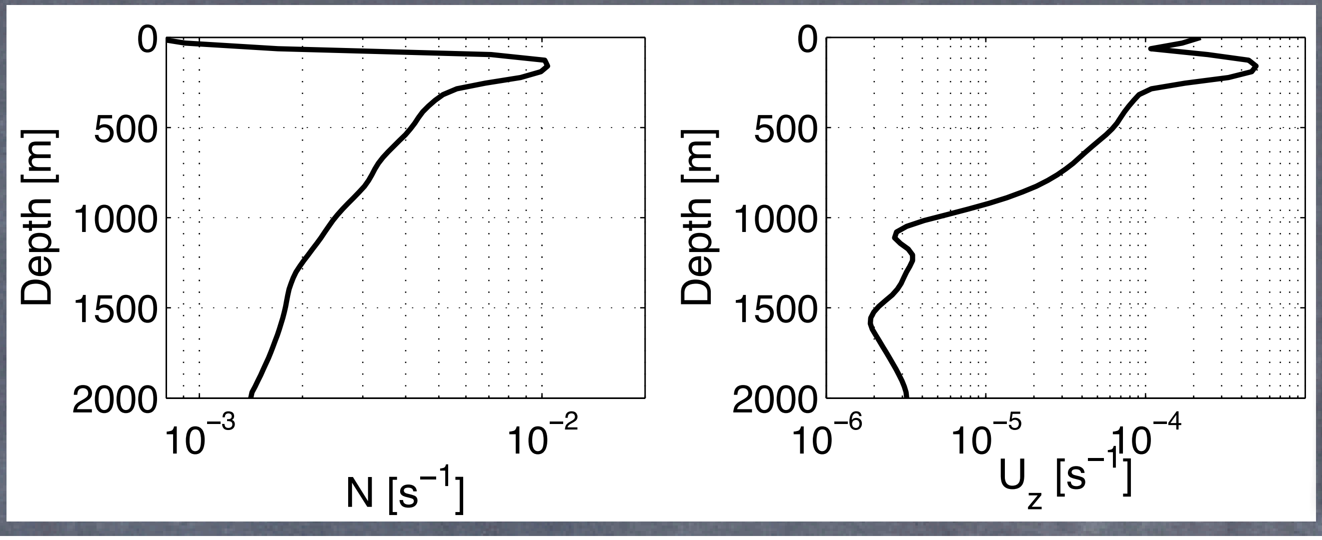

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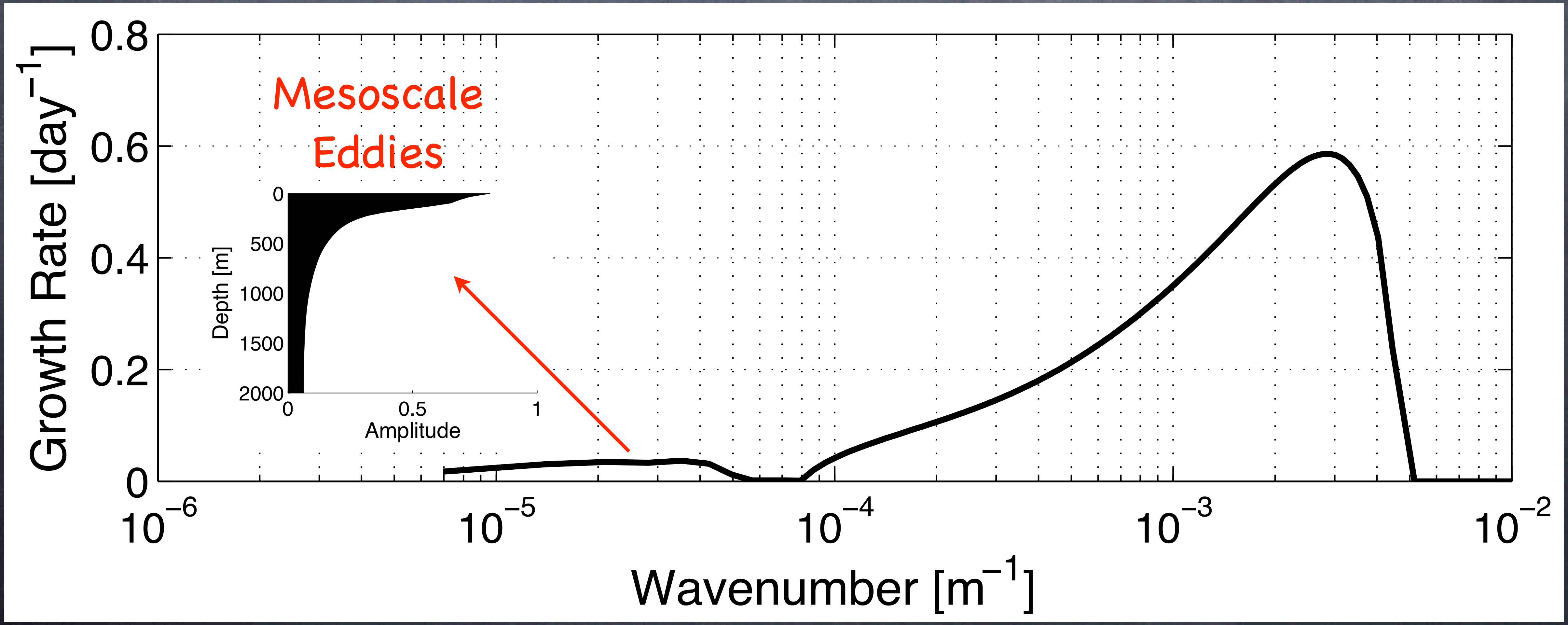

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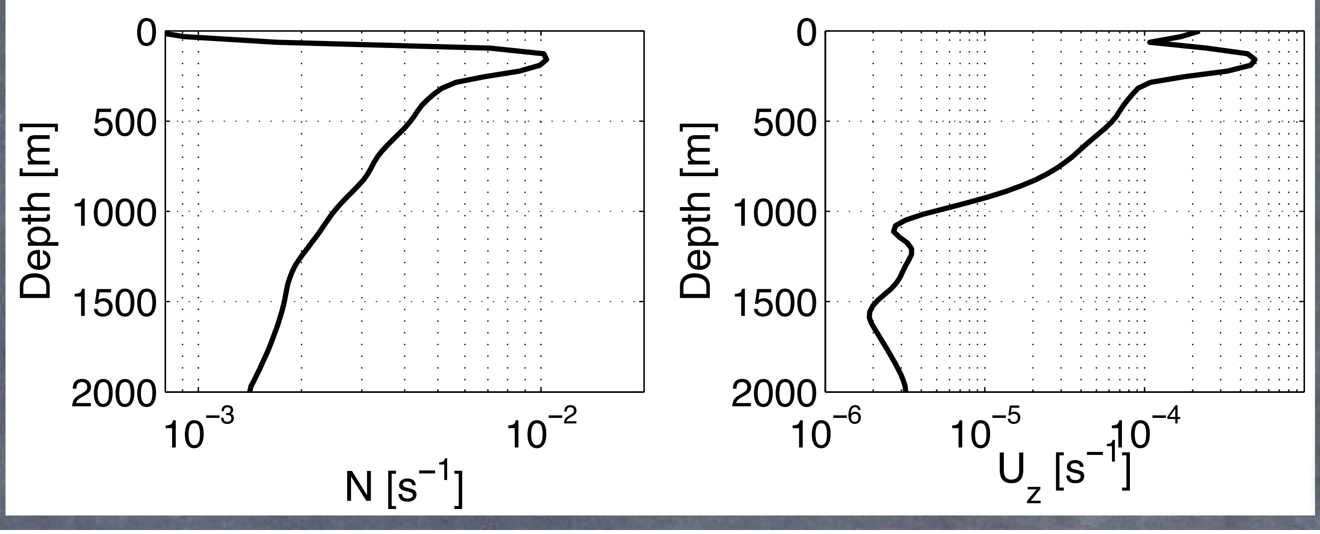

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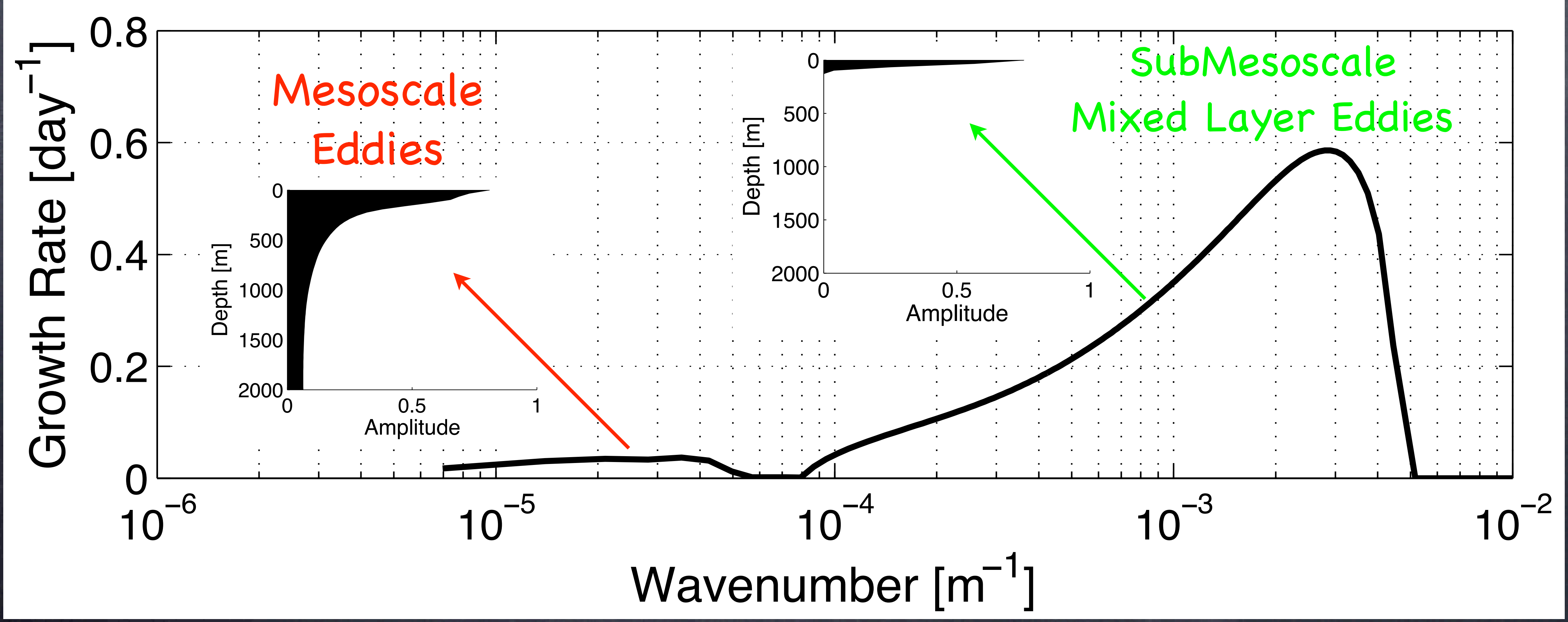

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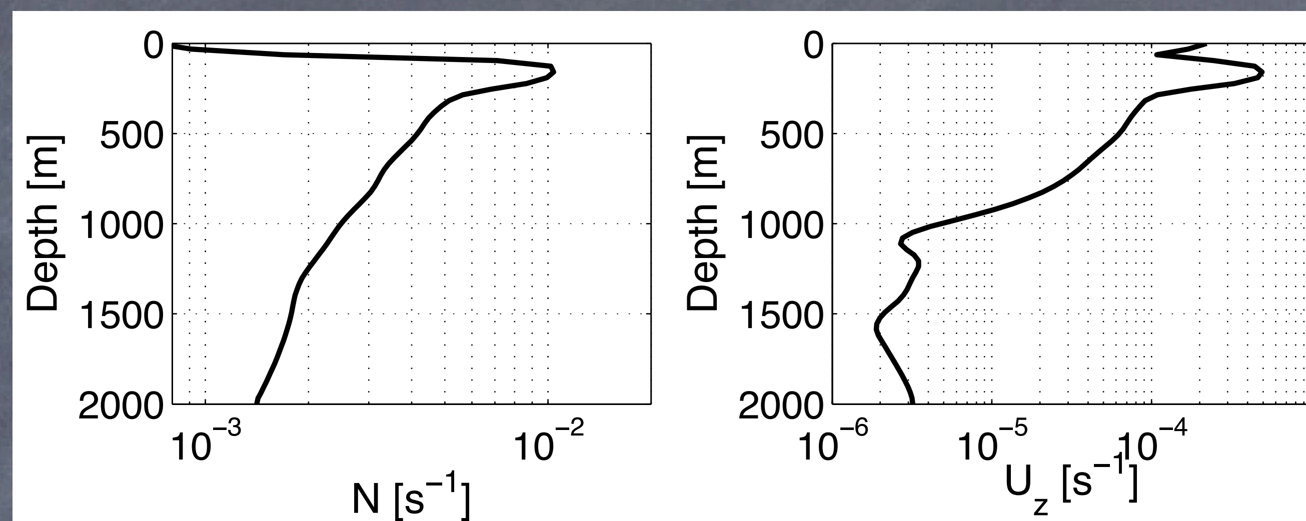

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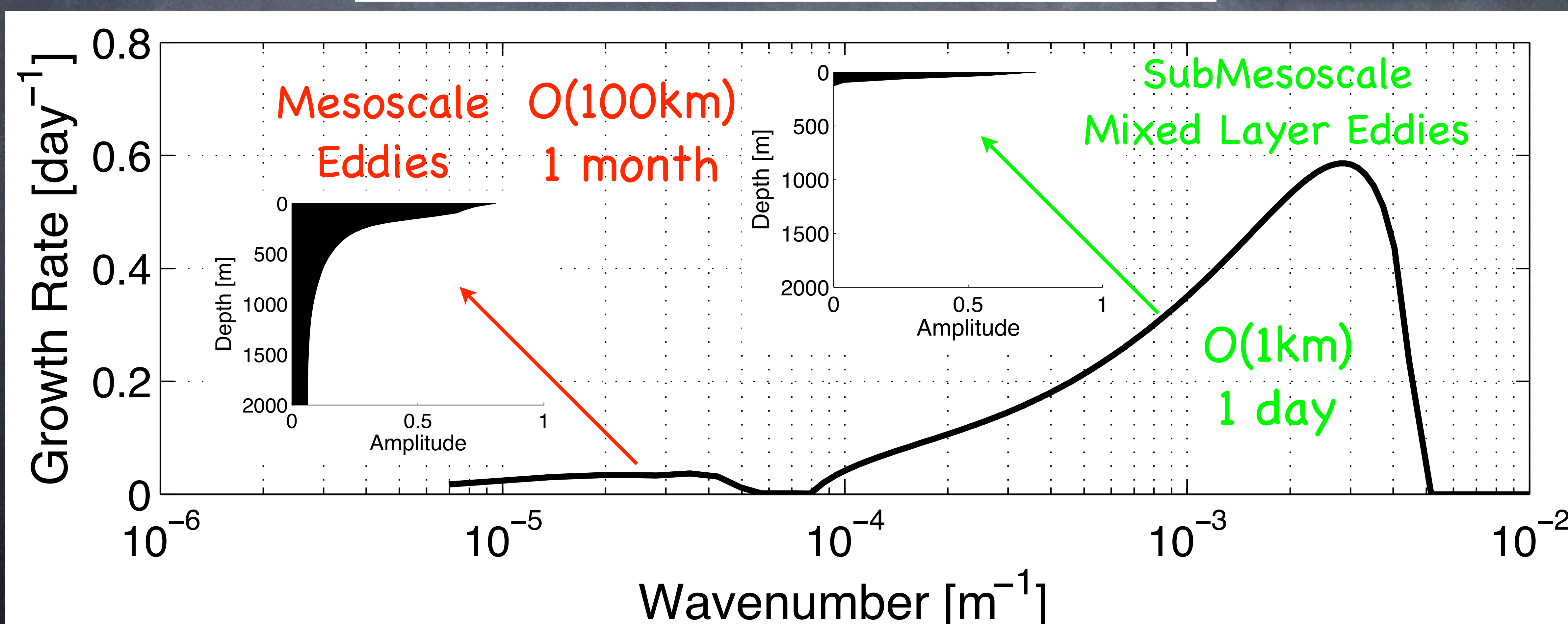
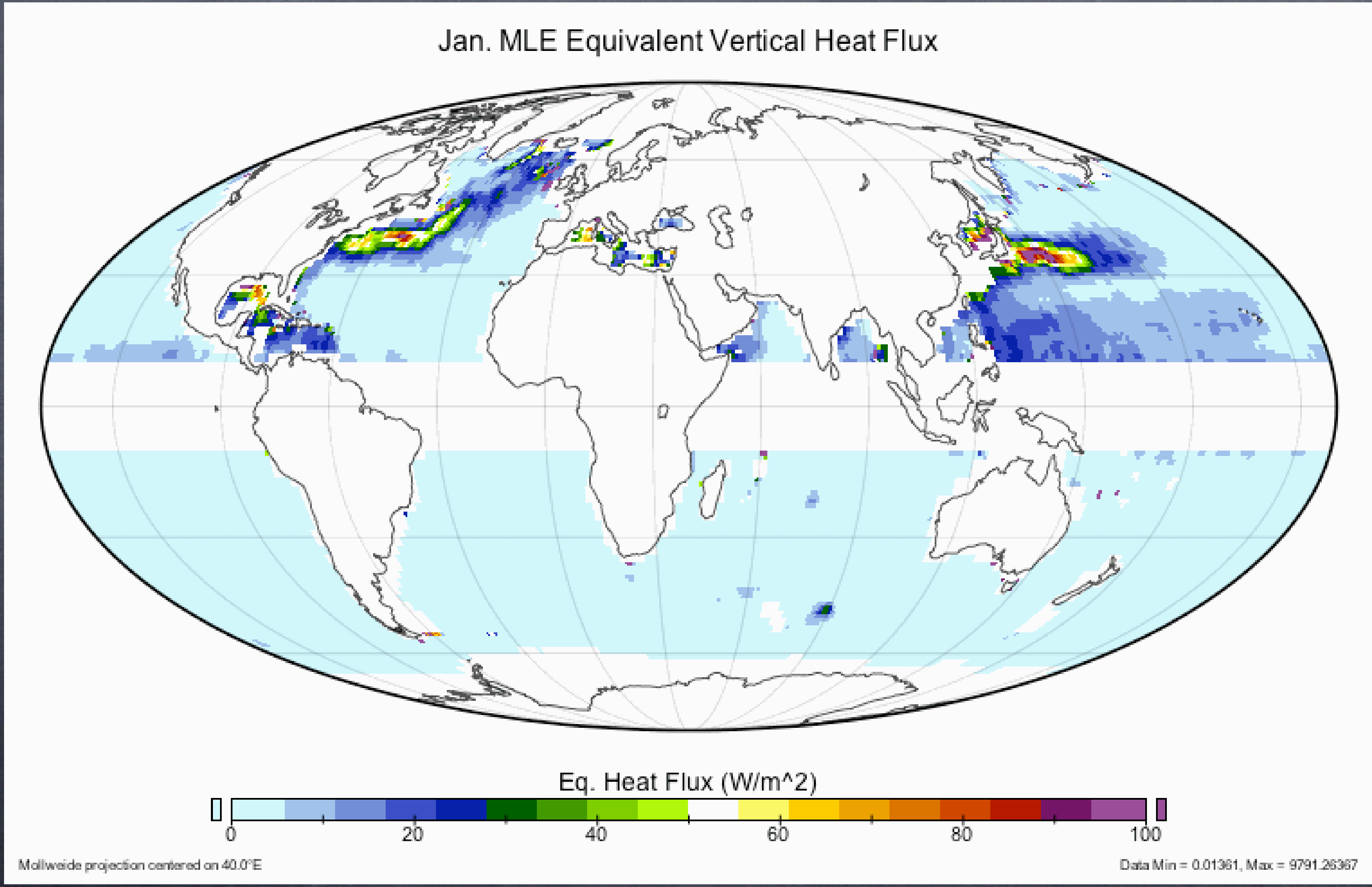


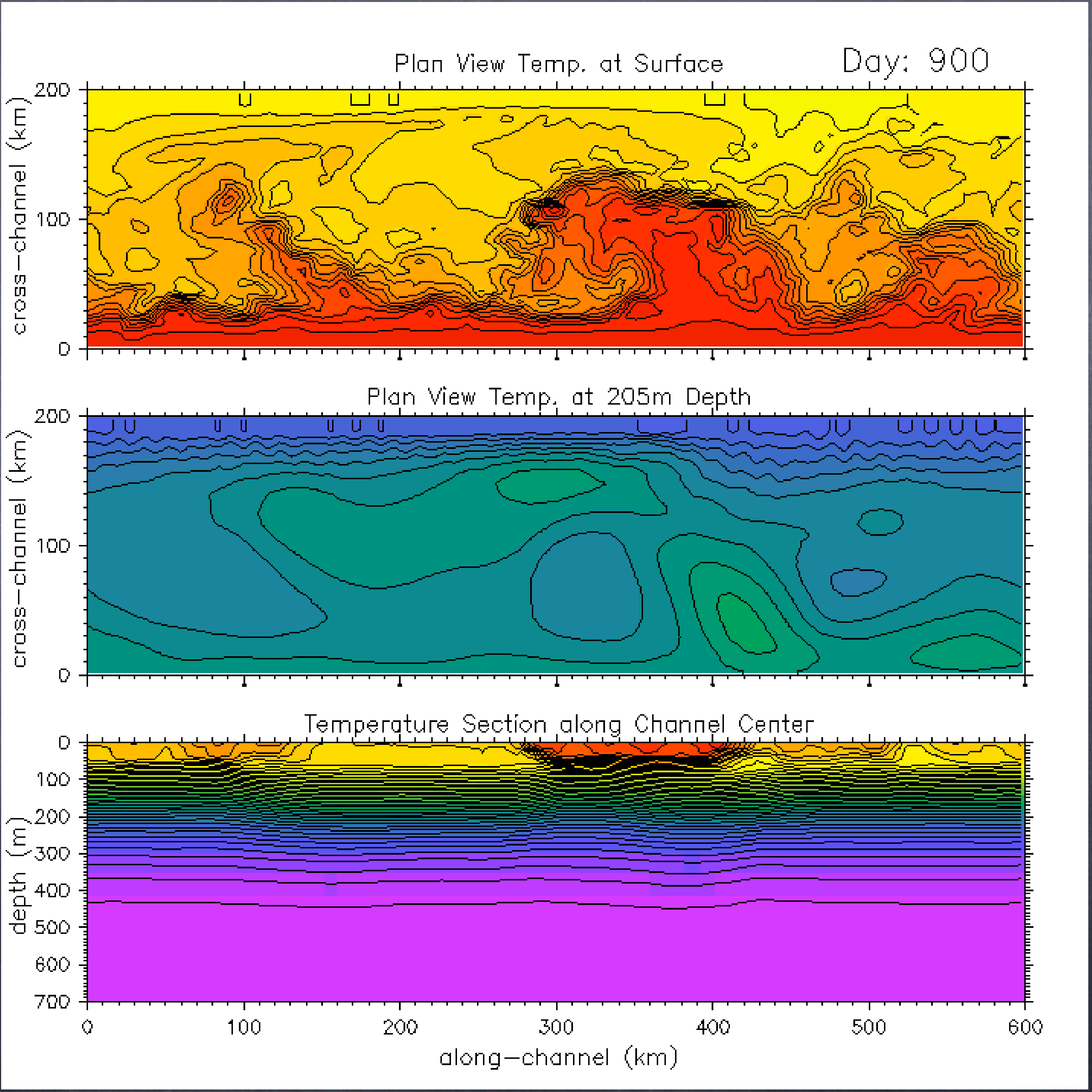
Preview:
Submeso. Eddy fluxes are important!
(Equiv. Vert. Heat Flux inferred from data)



Mesoscale and SubMesoscale are Coupled Together:

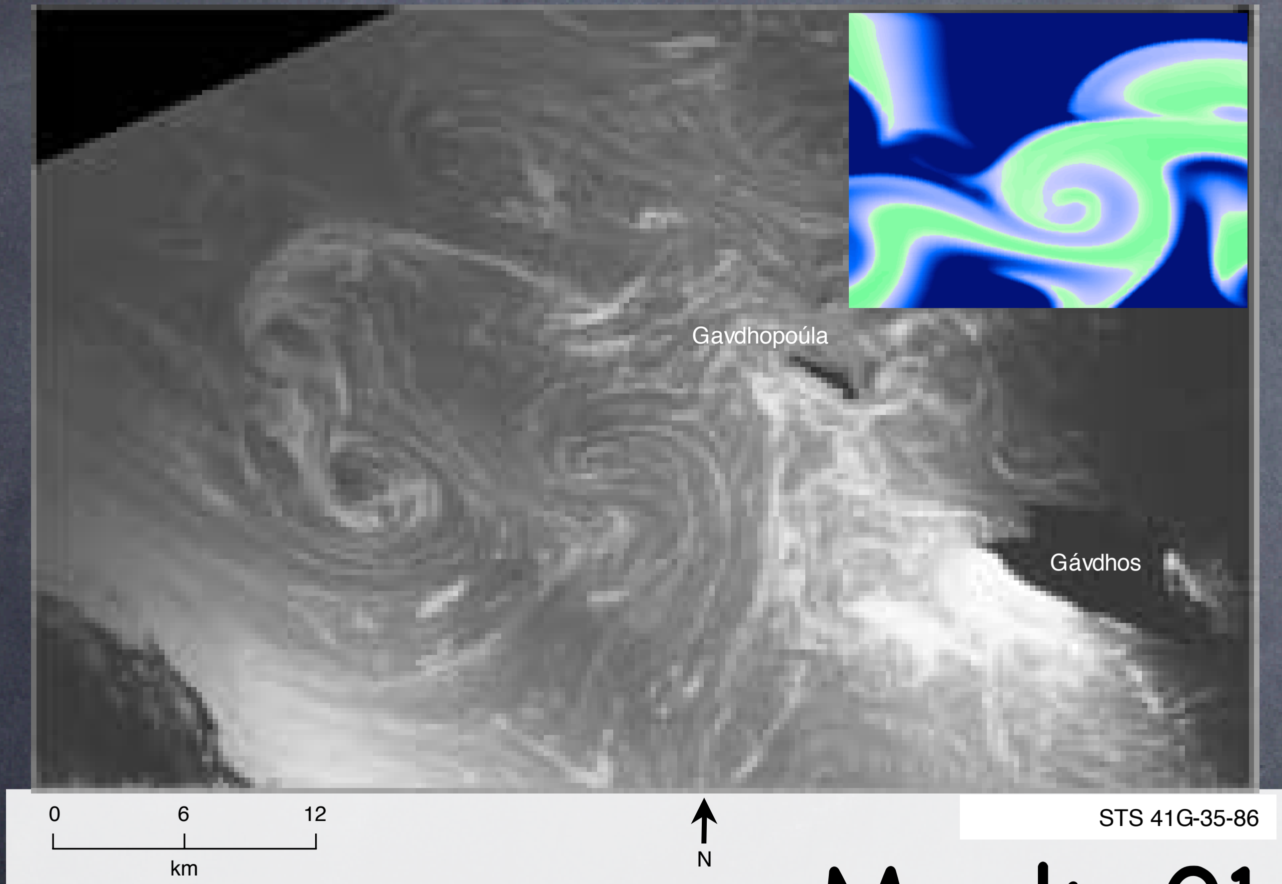
ML Fronts are formed by Mesoscale Straining.

Submesoscale eddies remove PE from those fronts.



Observed:

Strongest Surface Eddies= Spirals on the Sea?



Munk, 01

Figure 1. A pair of interconnected spirals in the Mediterranean Sea south of Crete. This vortex pair has a clearly visible stagnation point between the two spirals, the cores of which are aligned with the preconditioning wind field. 7 October 1984.

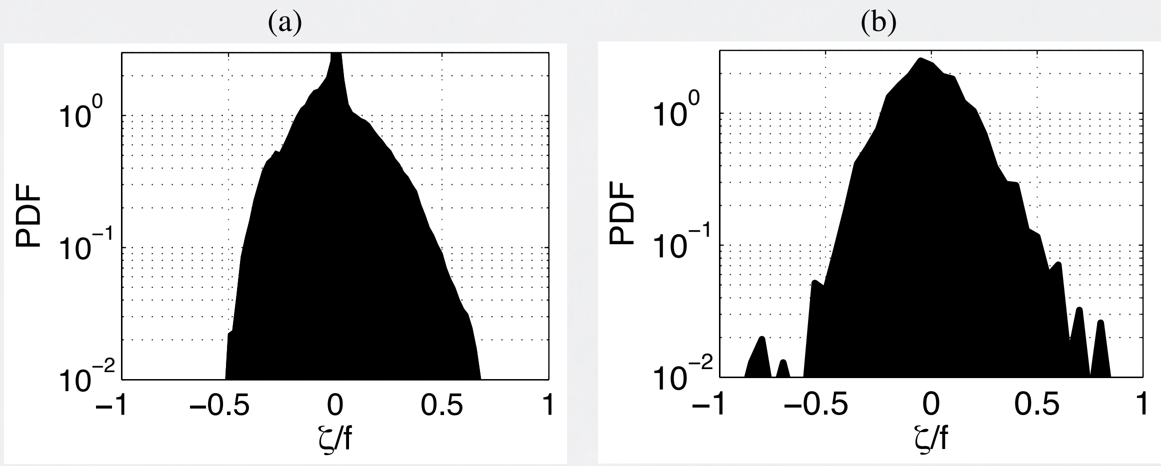
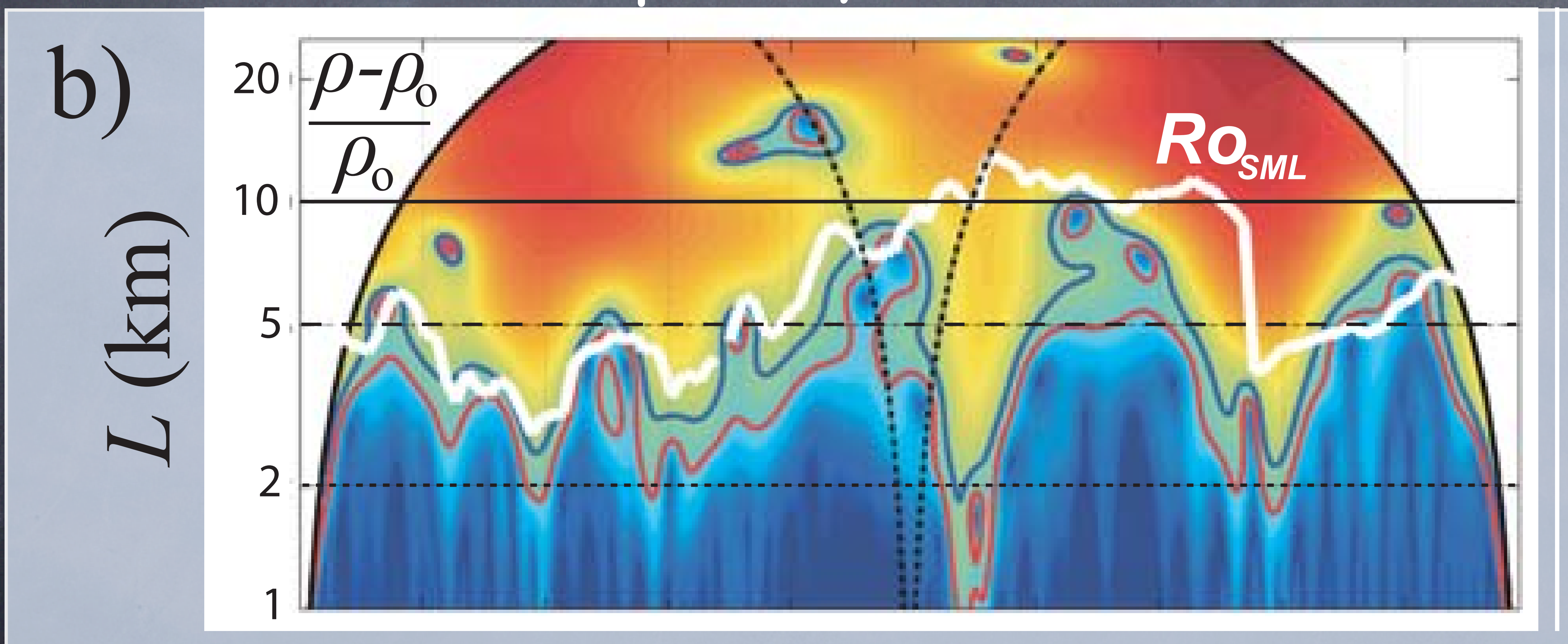


Figure 12: Probability density function of relative vorticity divided by Coriolis parameter. (a) Results from the numerical simulation of a slumping horizontal density front. ($z > 100$ only to exclude bottom Ekman layer.) The PDF is estimated using surface velocity measurements at day 25 (see also Fig. 11). A positive skewness appears as soon as the baroclinic instability enters in the nonlinear stage, and it continues to grow. Note that the peak at $\zeta/f = 0$ is due to the model's initial resting condition; that fluid has not yet been contacted by the MLI. (b) Results from ADCP measurements in the North Pacific. The PDF is calculated in bins of width 0.02.

Observed:

ML Density varies in horizontal, only at scales larger than ML Def. Rad. Salt & Temp. vary at all scales.



Midlatitude Pacific near Hawaii: Hosegood et al. 06

Vertical fluxes are Submesoscale and tend to restratify

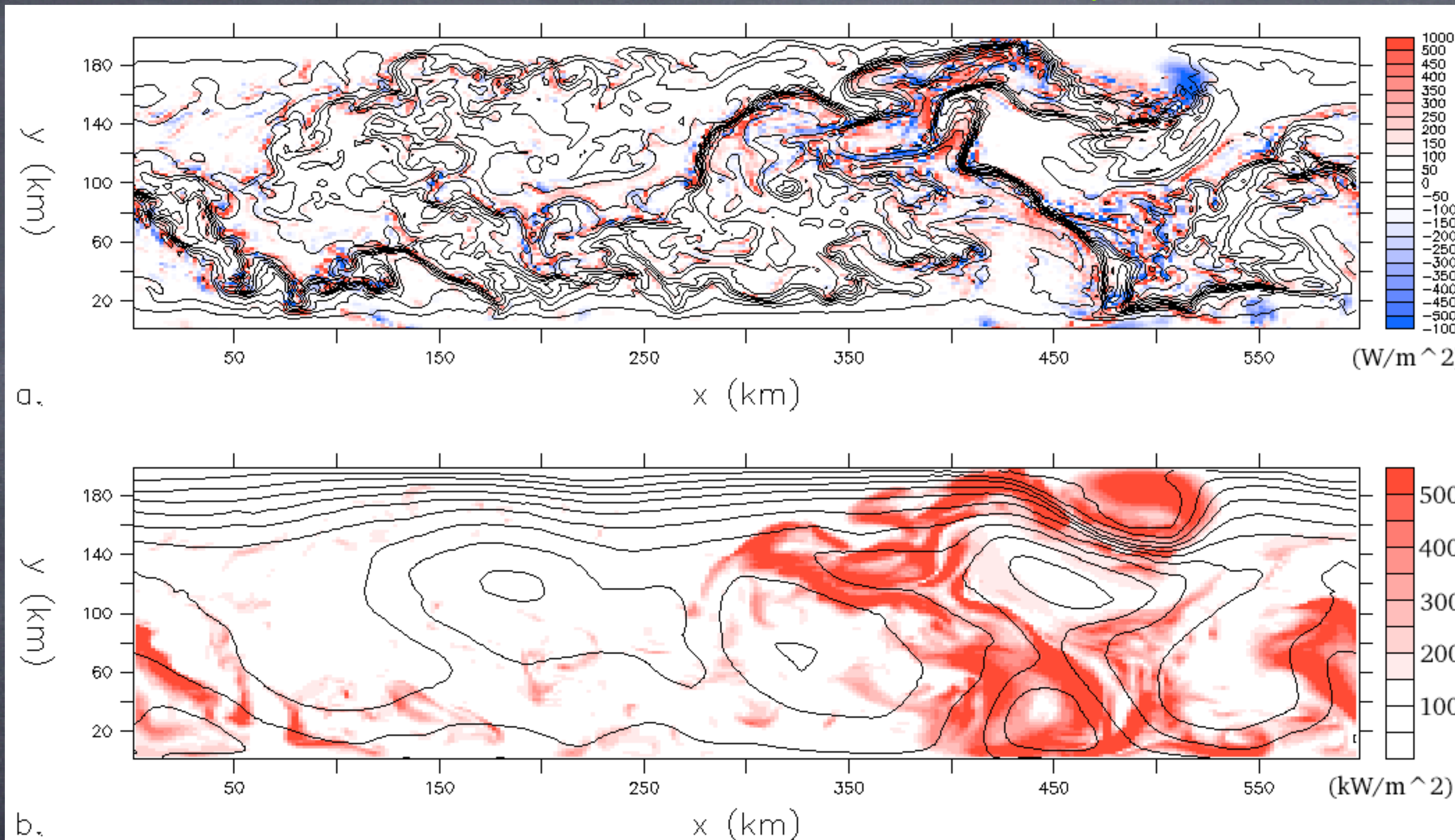
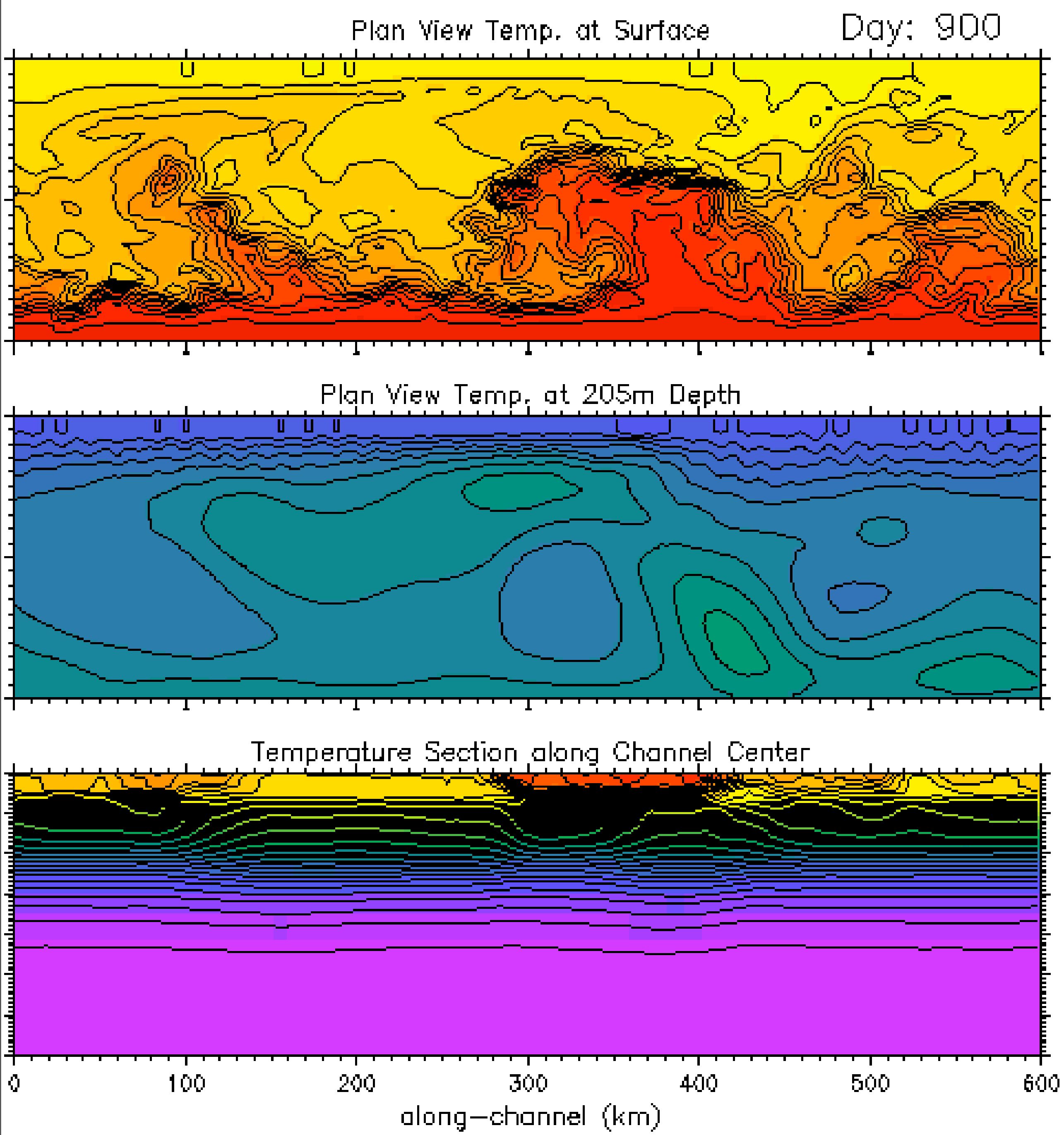


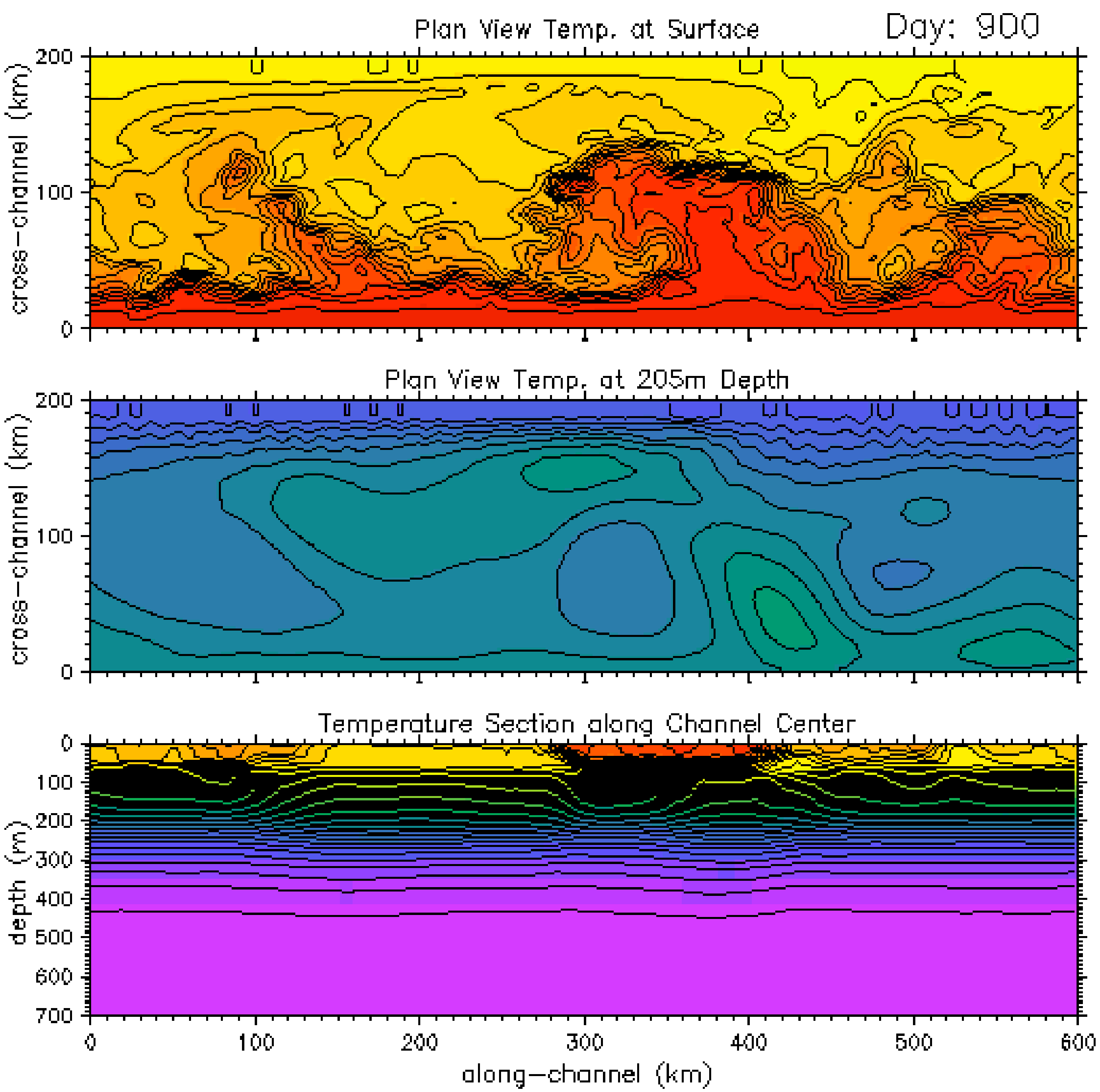
FIGURE 1: Contours of temperature at the a) surface and b) below the mixed layer base in a simulation with both mesoscale eddies and MLEs ($0.2°C$ contour intervals). Shading indicates the value at the depth where $\overline{w'b'}$ (upper panel) and $|\overline{\mathbf{u}'_H b'}|$ (lower panel) take the largest magnitude.

Horizontal fluxes are Mesoscale and tend to stir

Having a Mixed Layer Matters!

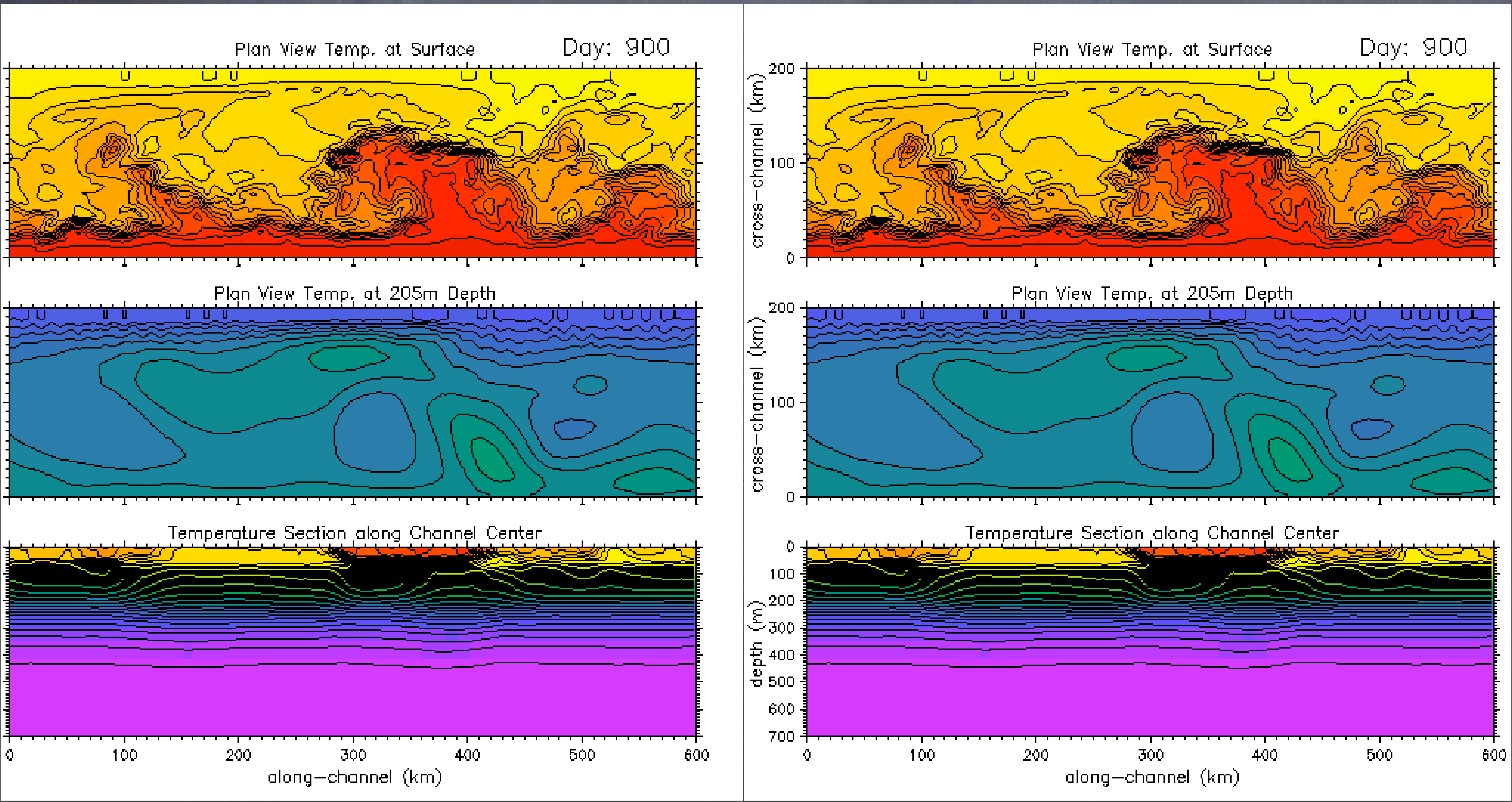
The vertical buoyancy flux in the ML (<w'b'>) without diurnal cycle is notless than with cycle (ML)





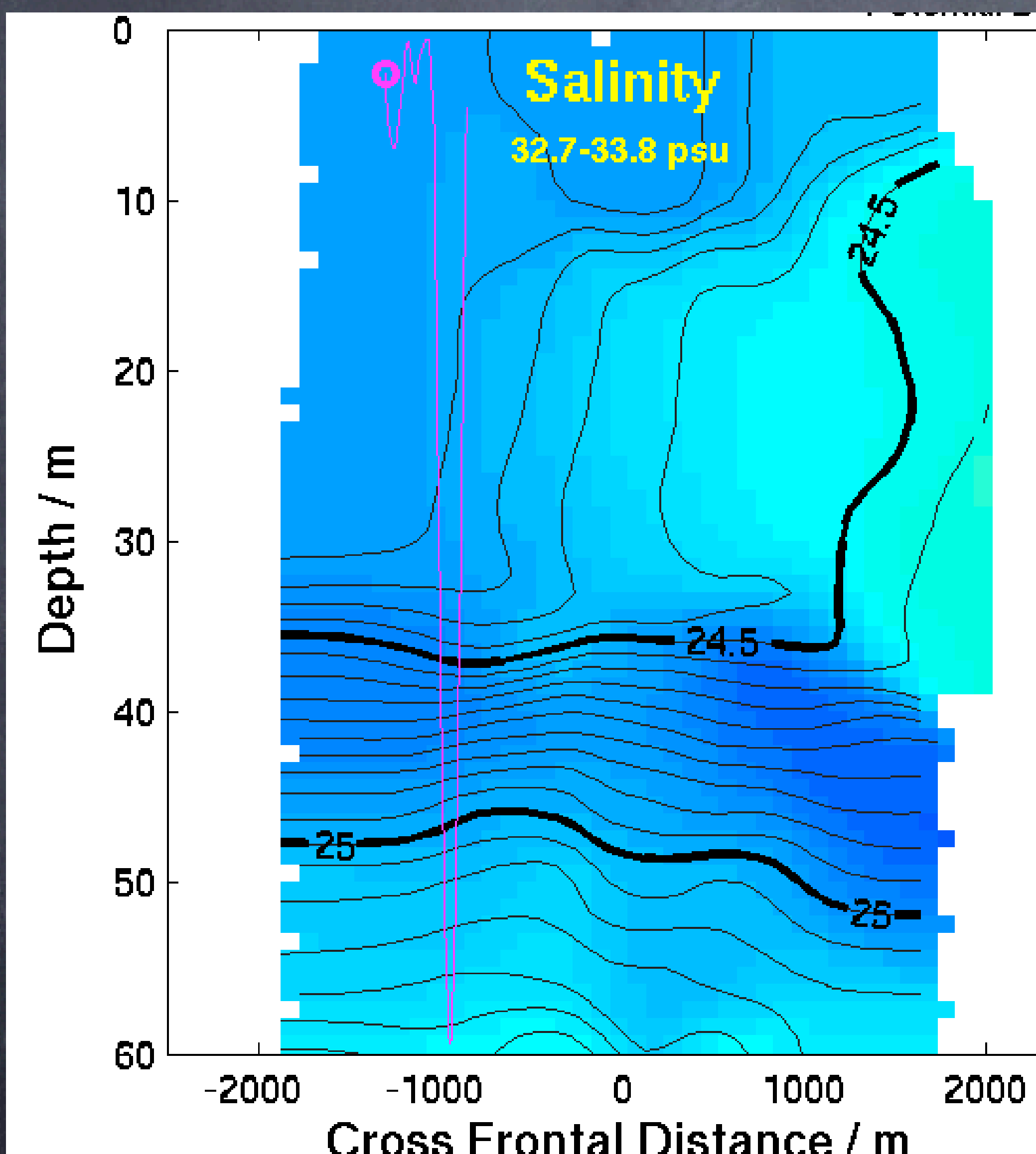
Having a Mixed Layer Matters!

The vertical buoyancy flux in the ML (<w'b'>) without diurnal cycle is 4x less than with cycle (ML)



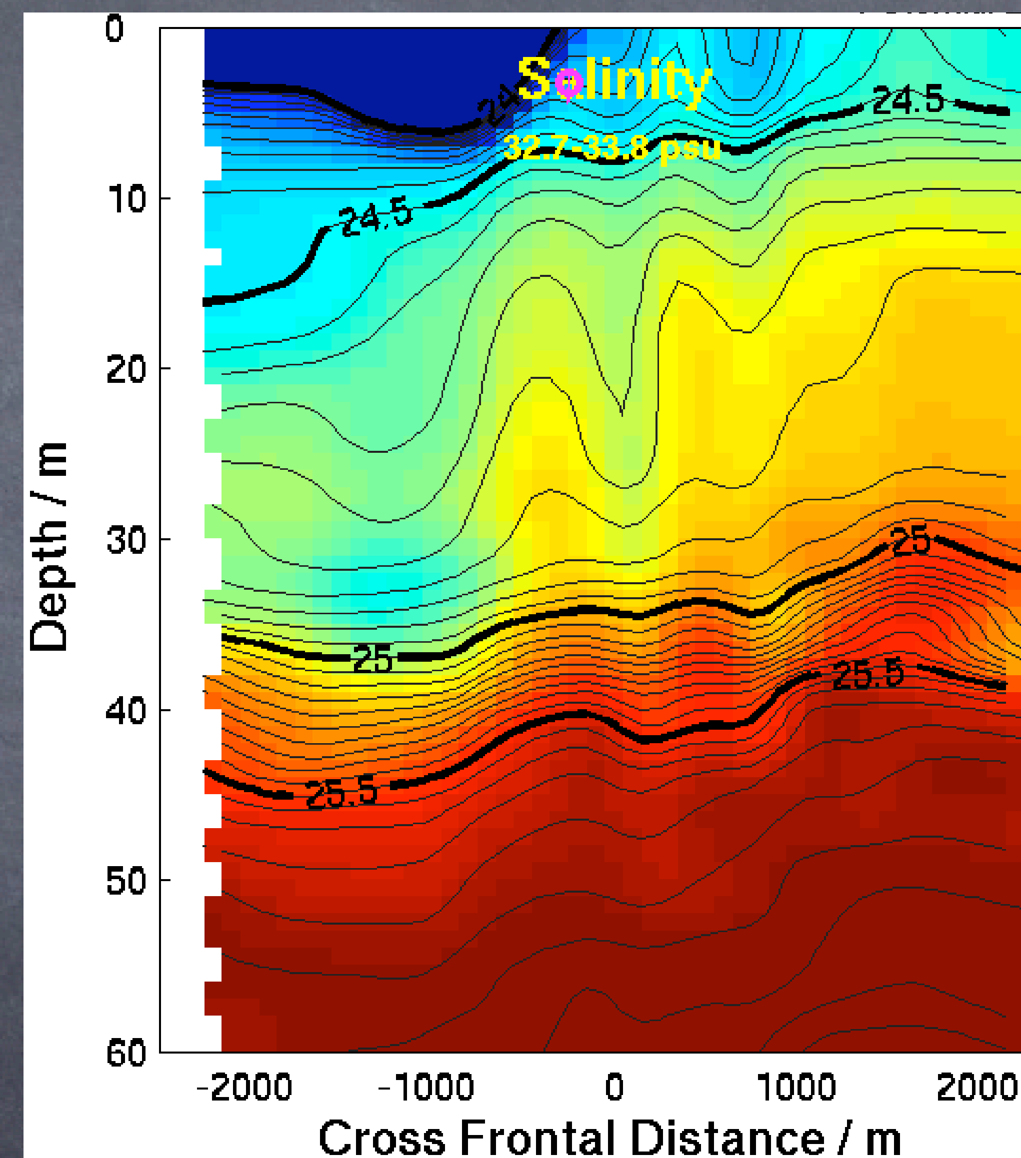
AESOP Observations of Rapid Restratification near Monterey Bay

- 1.5 days, 5-6 Aug 2006
- Mixed layer restratifies under weakening wind forcing
- Characterized mixed layer evolution in Lagrangian (float-following) frame.



30 kt wind

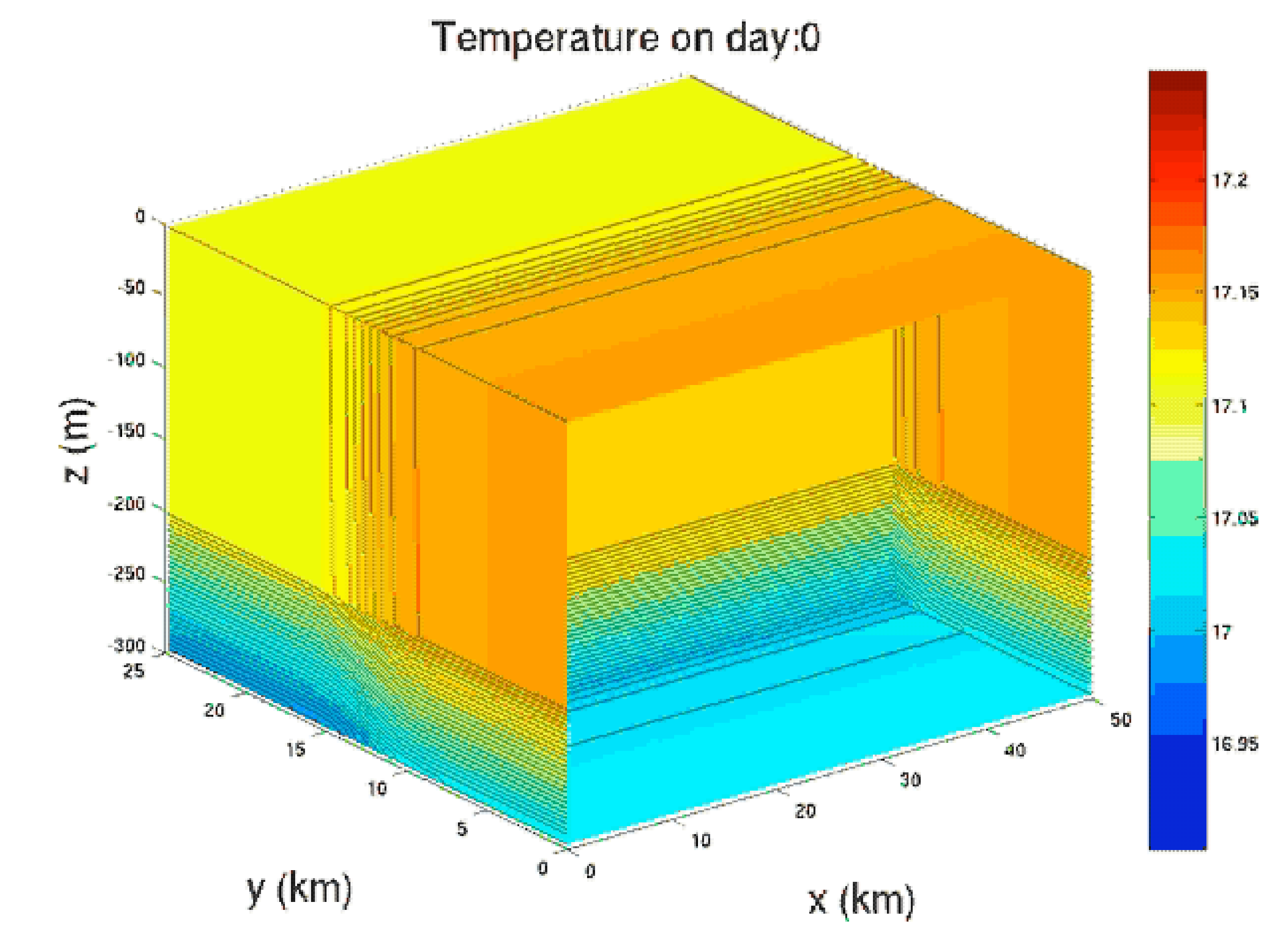
After one day

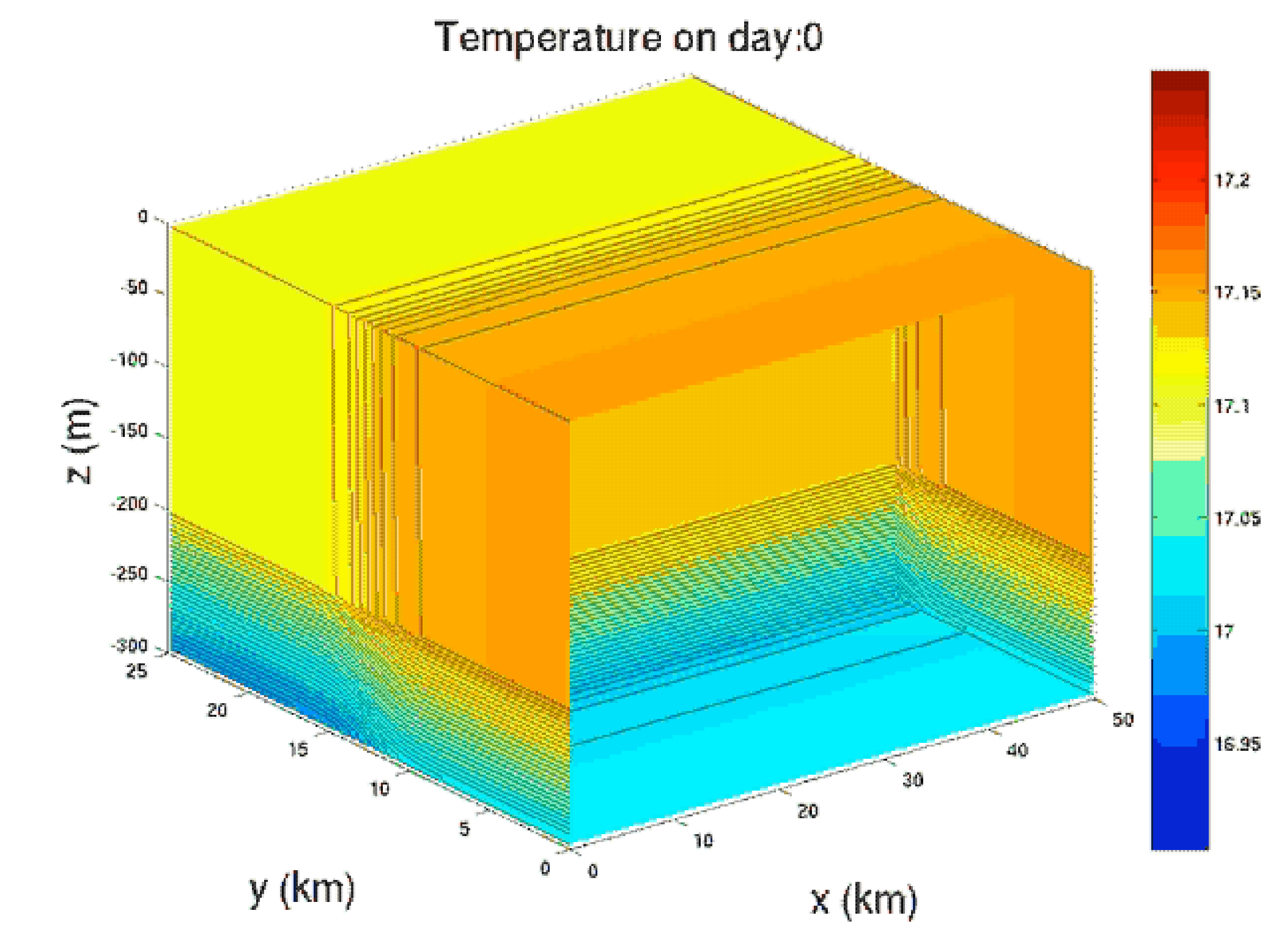


10 kt wind

Courtesy E. D'Asaro

Prototype: Mixed Layer Front Overturning



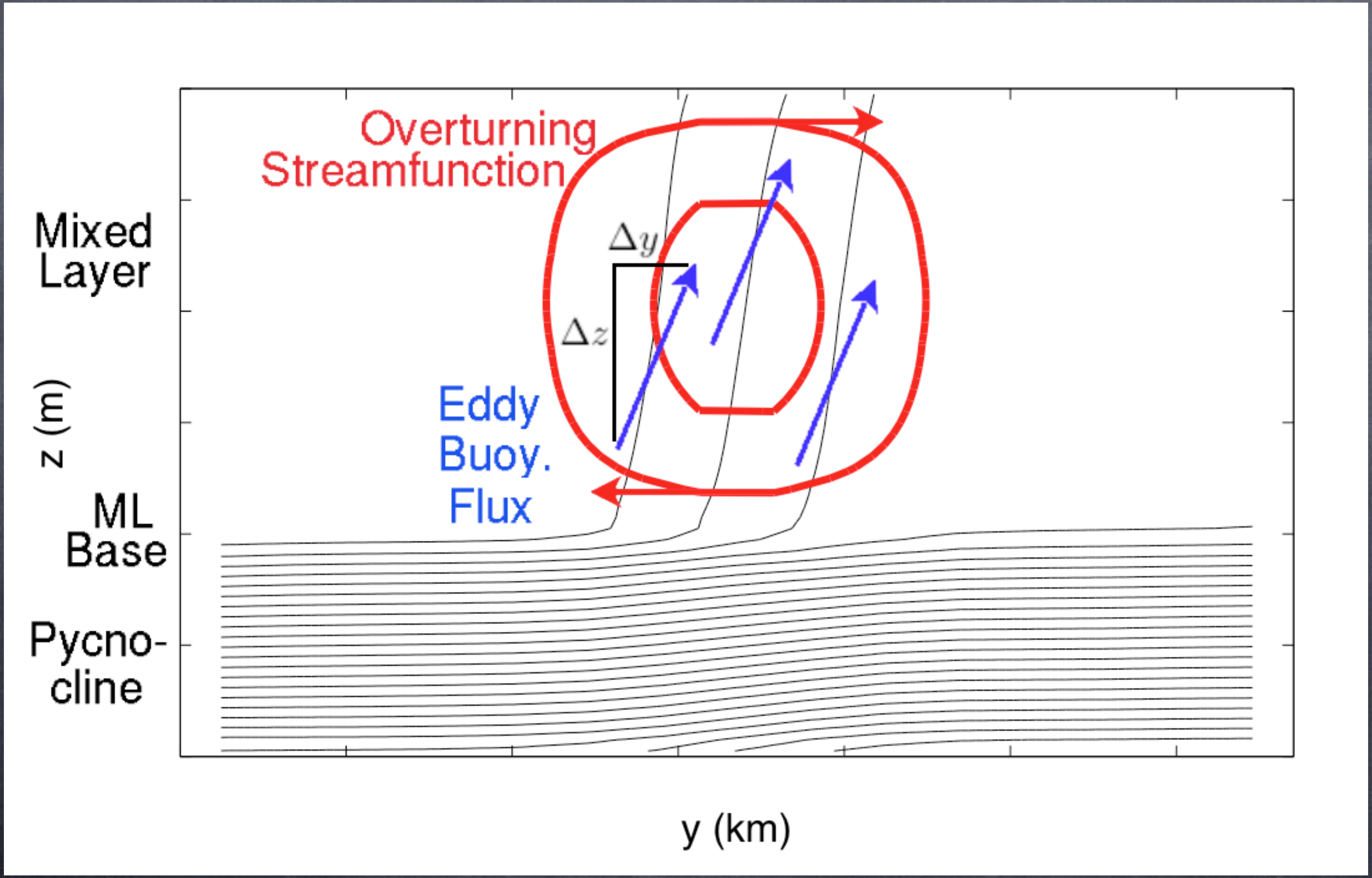


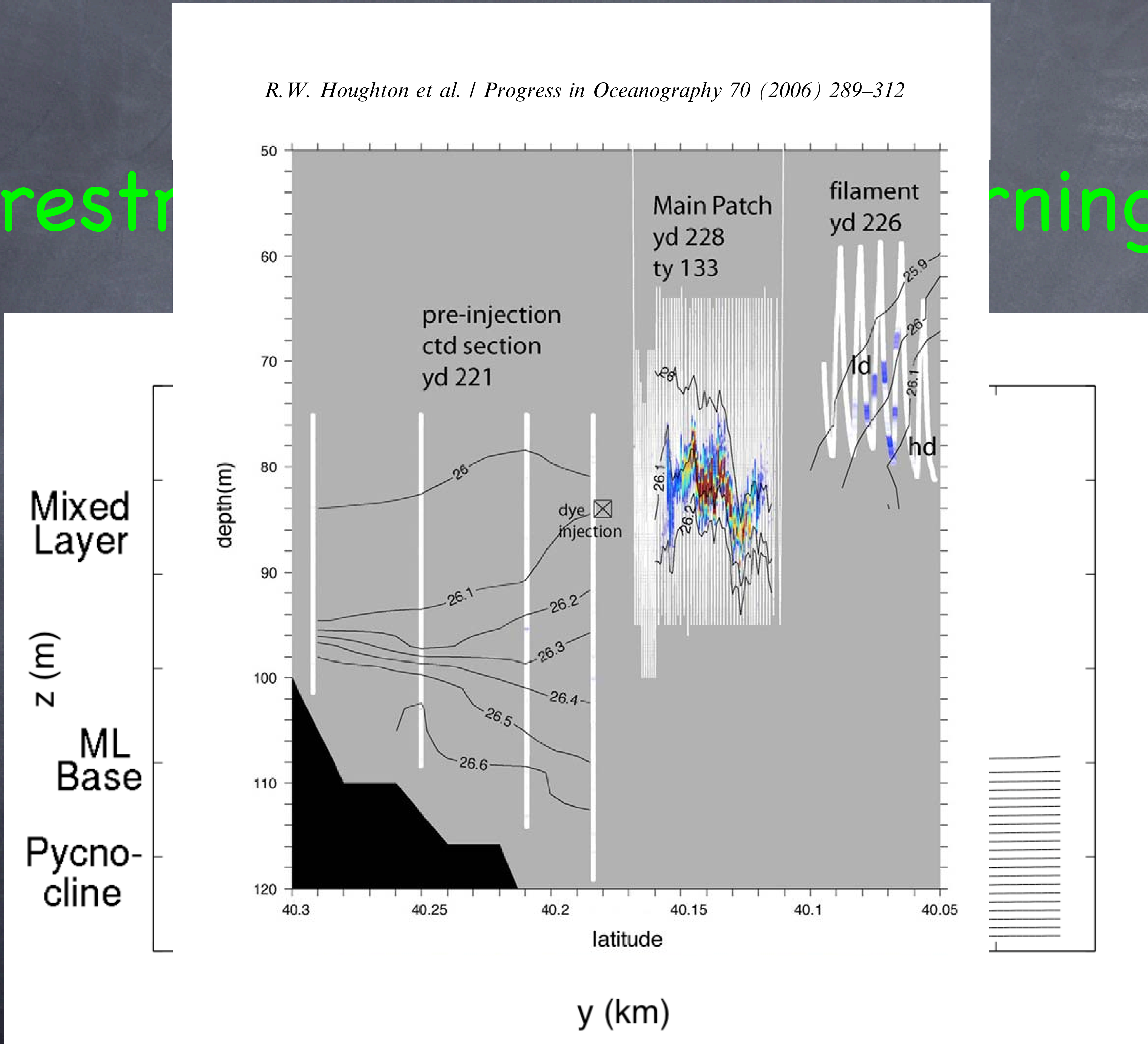
Simple Spindown

Plus, Diurnal Cycle and KPP

Note: initial geostrophic adjustment overwhelmed by eddy restratification

Schematic of the restratification by overturning

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R.W. Houghton et al. / Progress in Oceanography 70 (2006) 289–312
Main Patch
yd 228
ty 133
filament
yd 226
pre-injection
ctd section
yd 221
dye
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depth(m)
latitude
Mixed
Layer
z (m)
ML
Base
Pycno-
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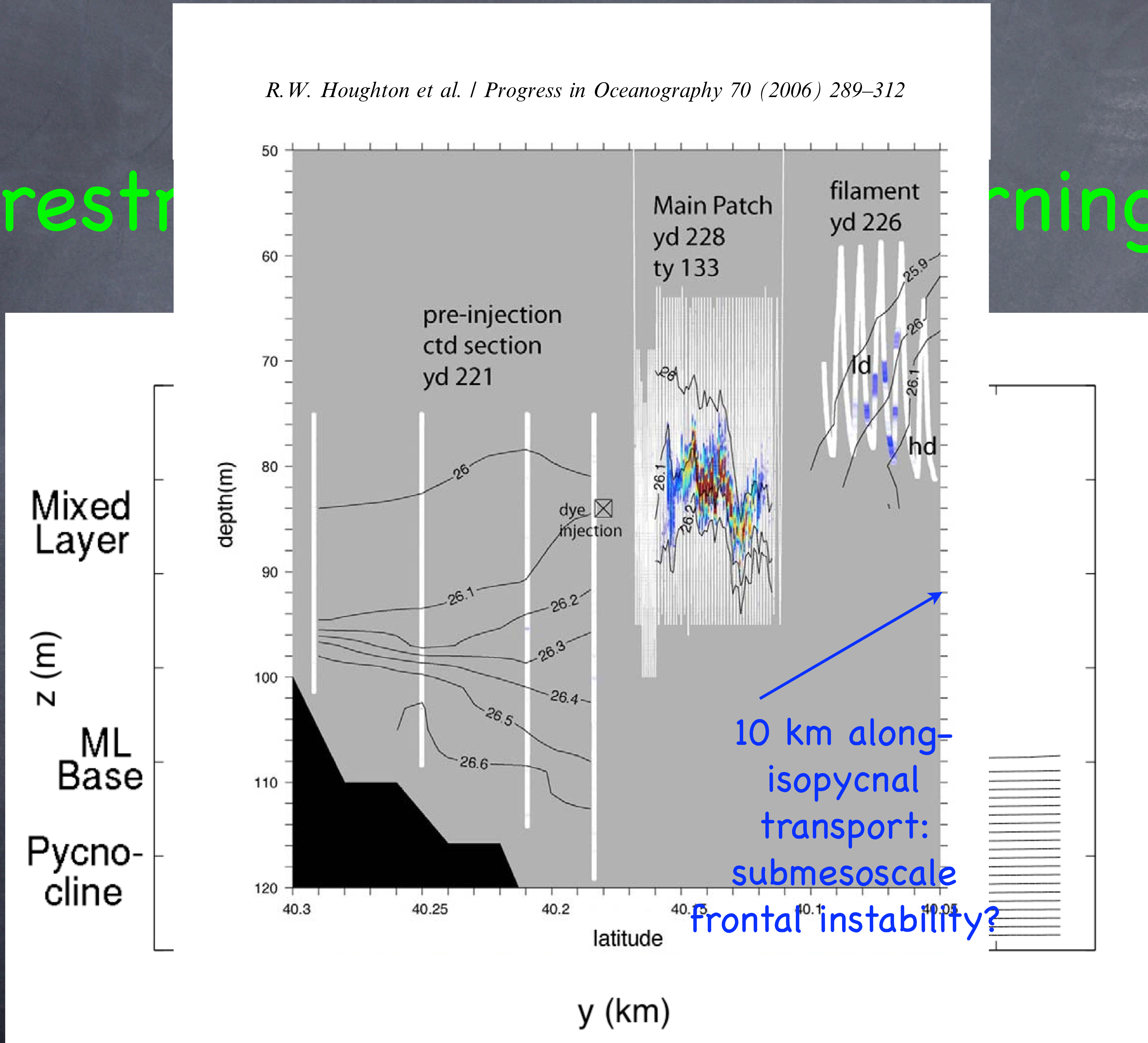
y (km)

restr… rning



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Main Patch
yd 228
ty 133
filament
yd 226
pre-injection
ctd section
yd 221
dye injection
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25.9
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26.1
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26.3
26.4
26.5
26.6
depth(m)
latitude
50
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90
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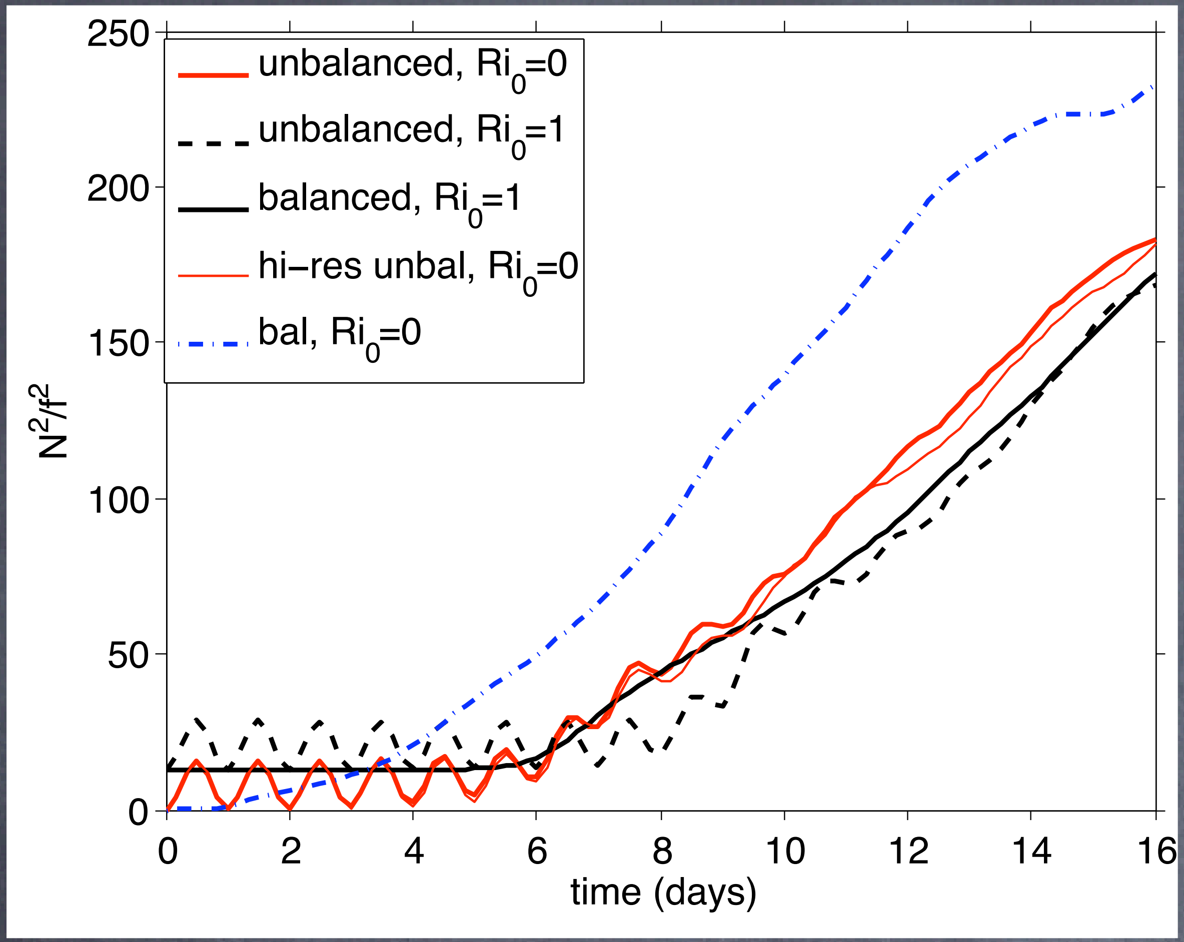
110
120
40.3
40.25
40.2
40.15
40.1
40.05
Mixed Layer
ML Base
Pycno-cline
z (m)
y (km)
10 km along-isopycnal transport: submesoscale frontal instability?

Parameterization of Finite Amp. Eddies: Ingredients



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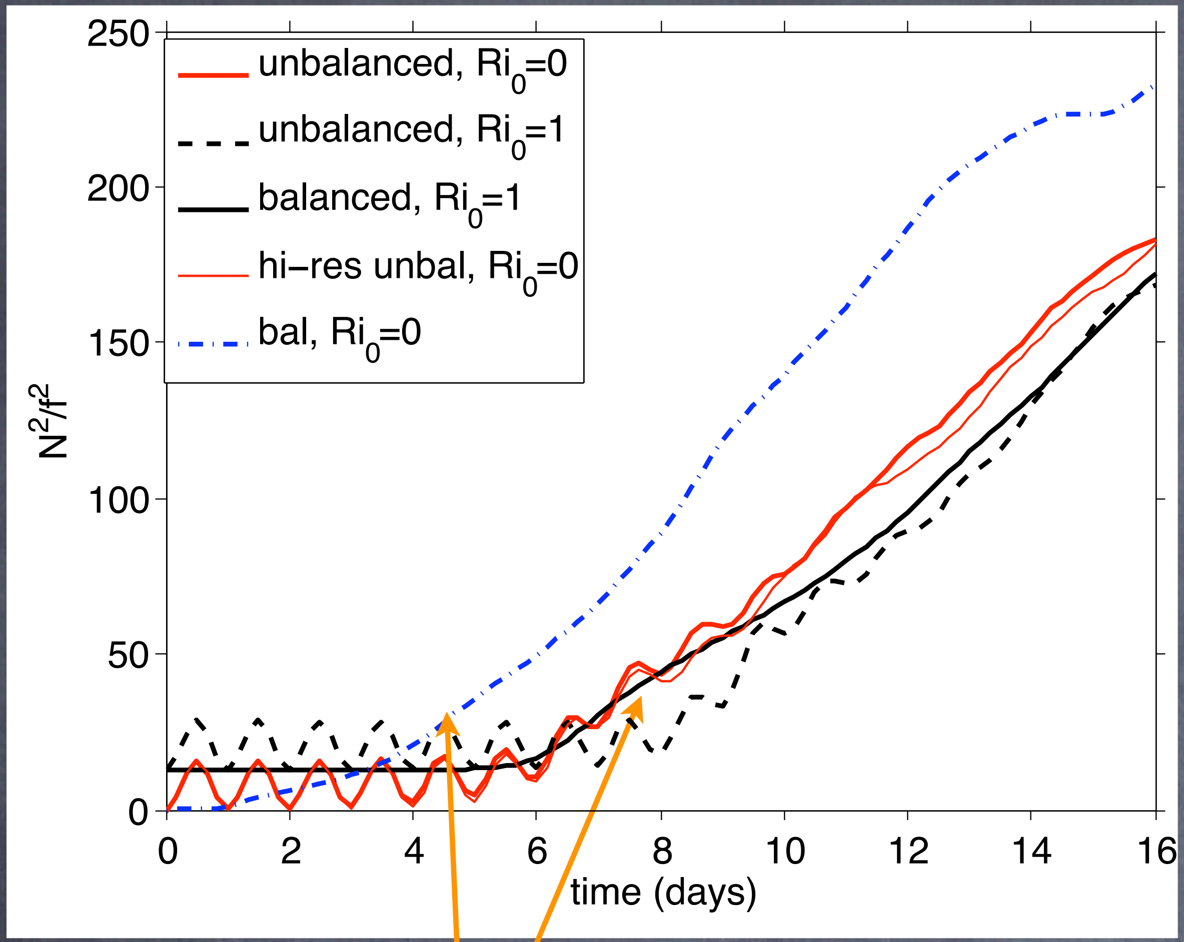

Eddies at Finite Amplitude

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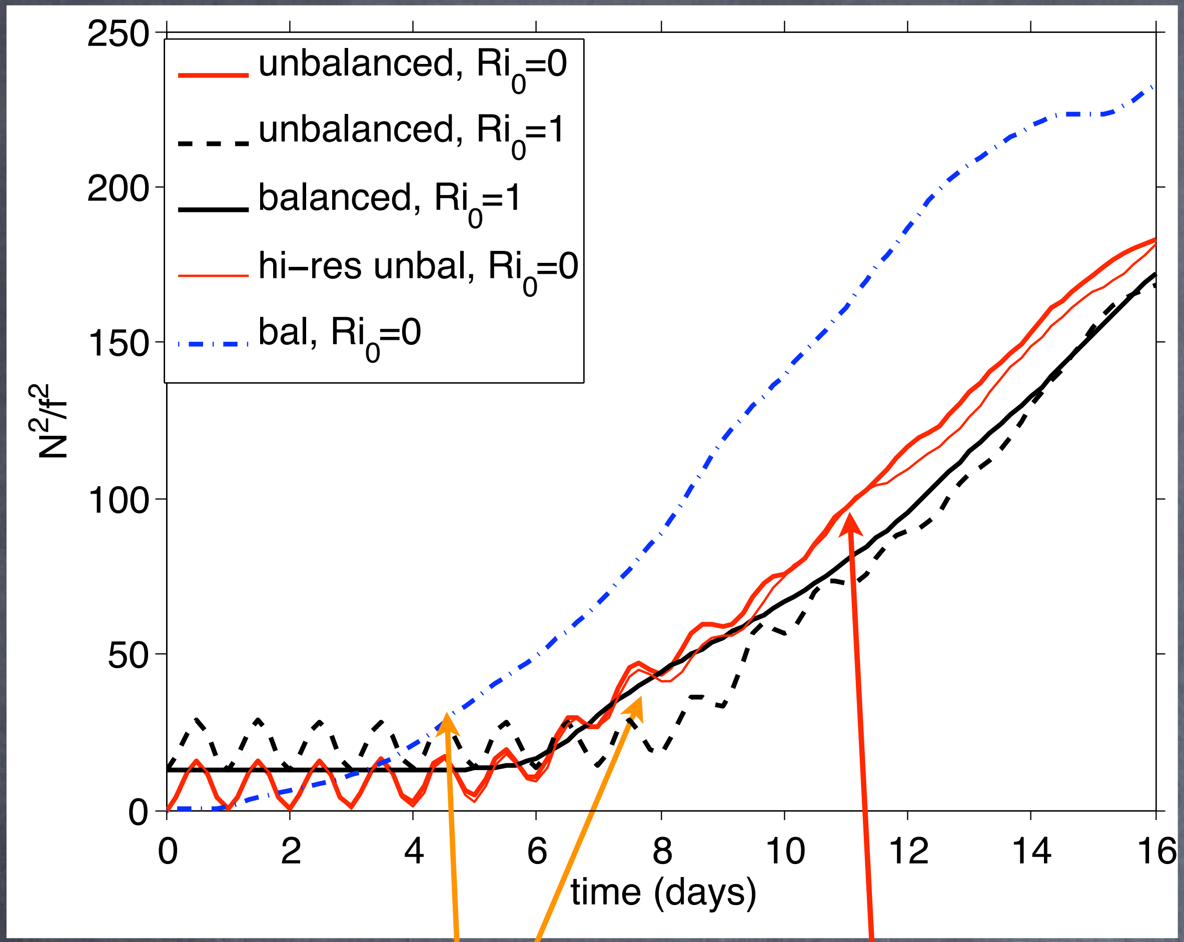
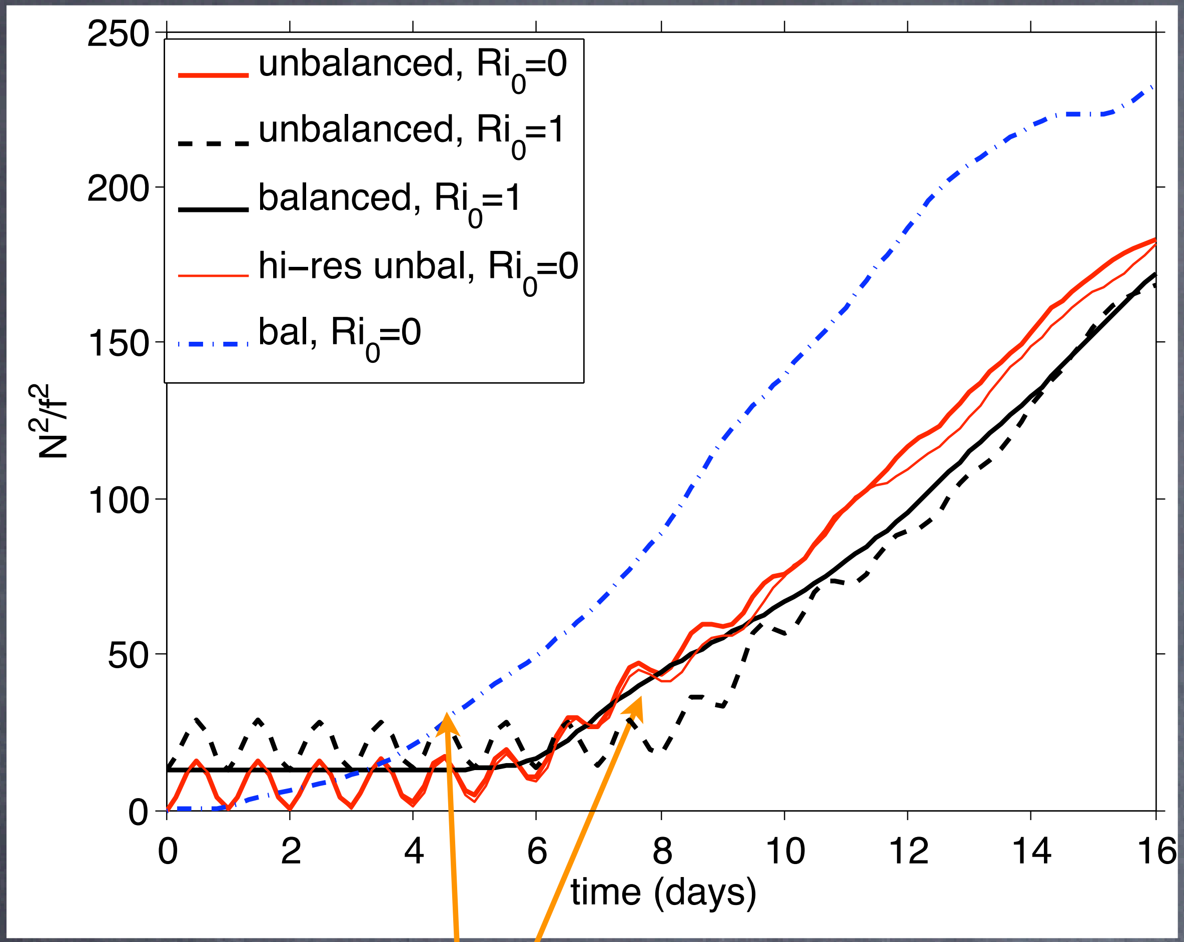


Eddies at Finite Amplitude

Resolution Convergence

Parameterization of Finite Amp. Eddies: Ingredients



Power Spectrum of KE

Eddies at Finite Amplitude

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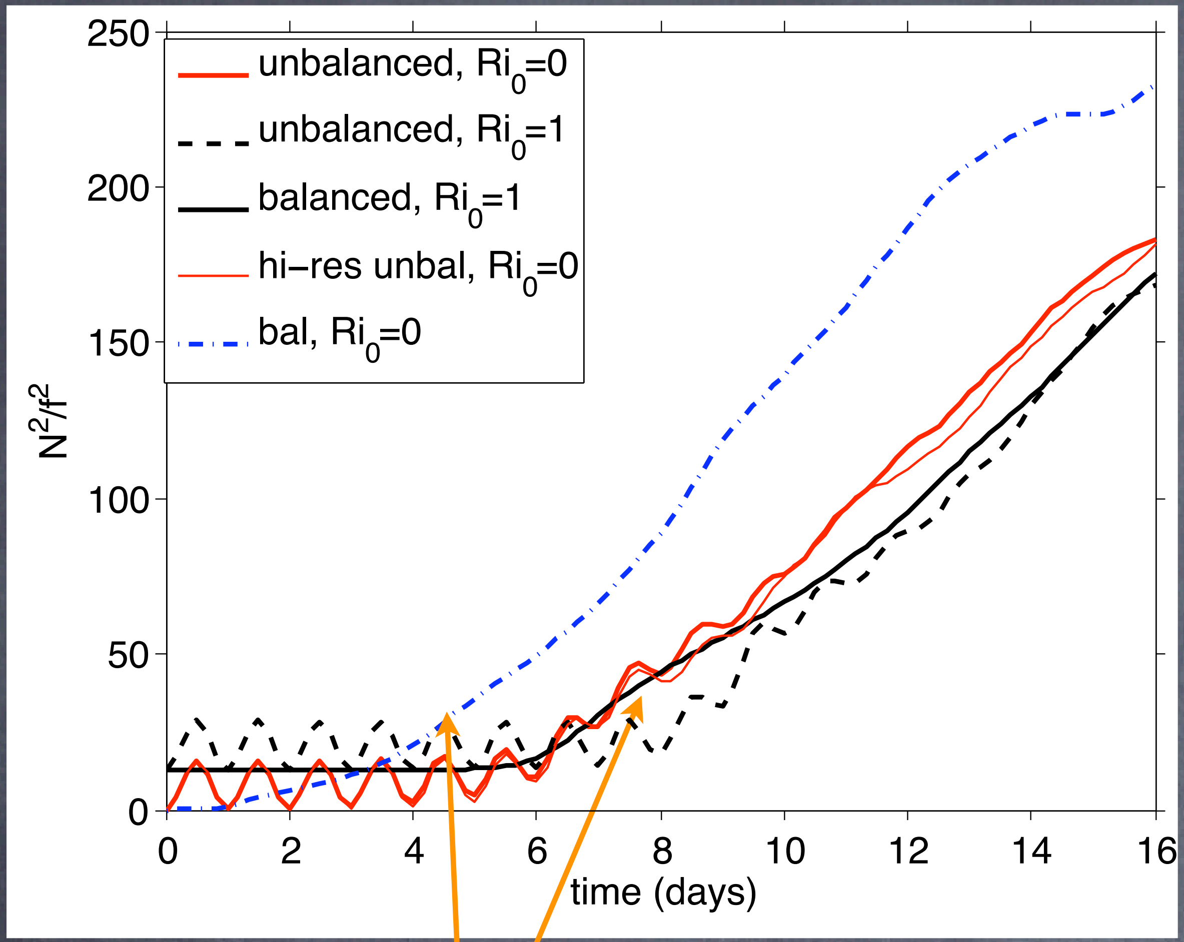
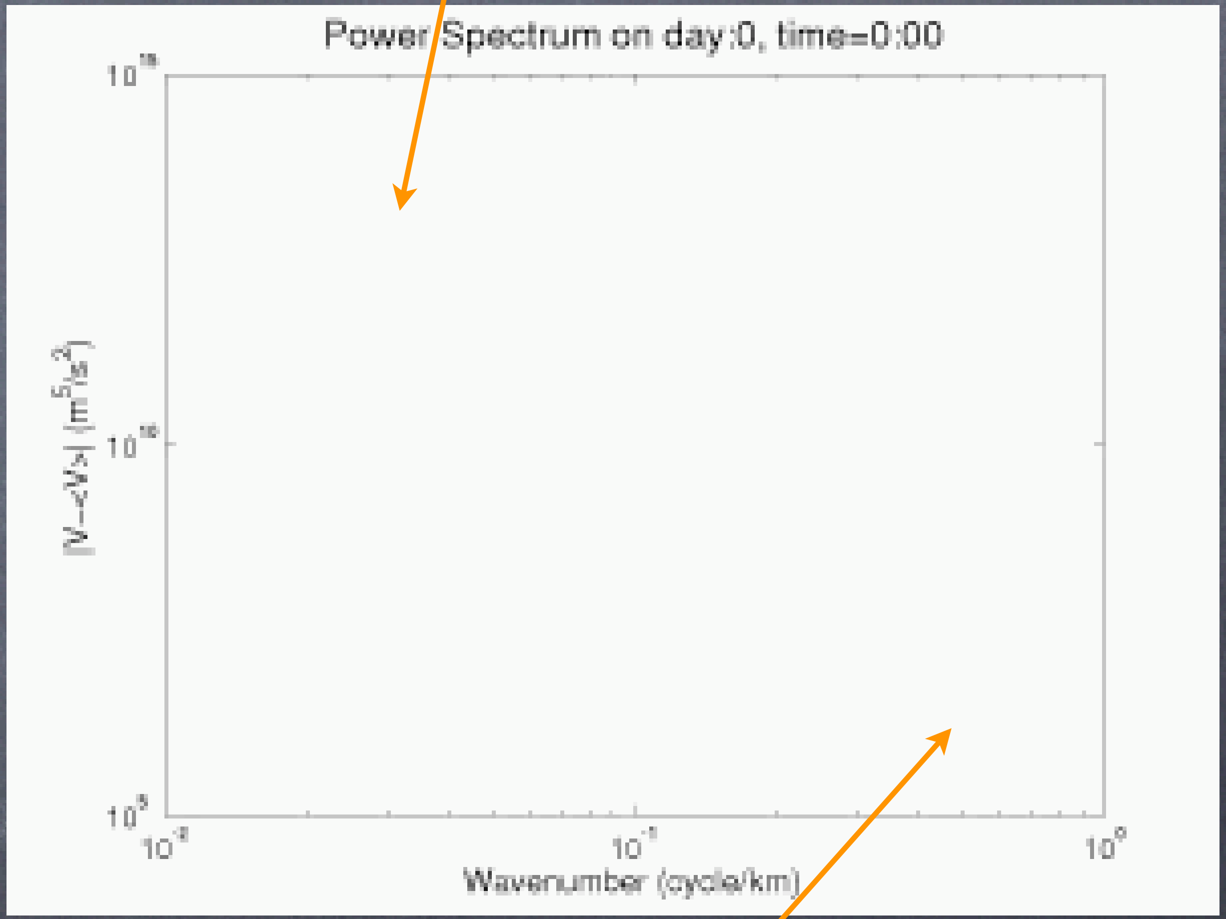


Eddies at Finite Amplitude

Power Spectrum of KE

At Finite Amplitude Horizontal Scale Unclear



Initially, Linear Prediction of Lengthscale good

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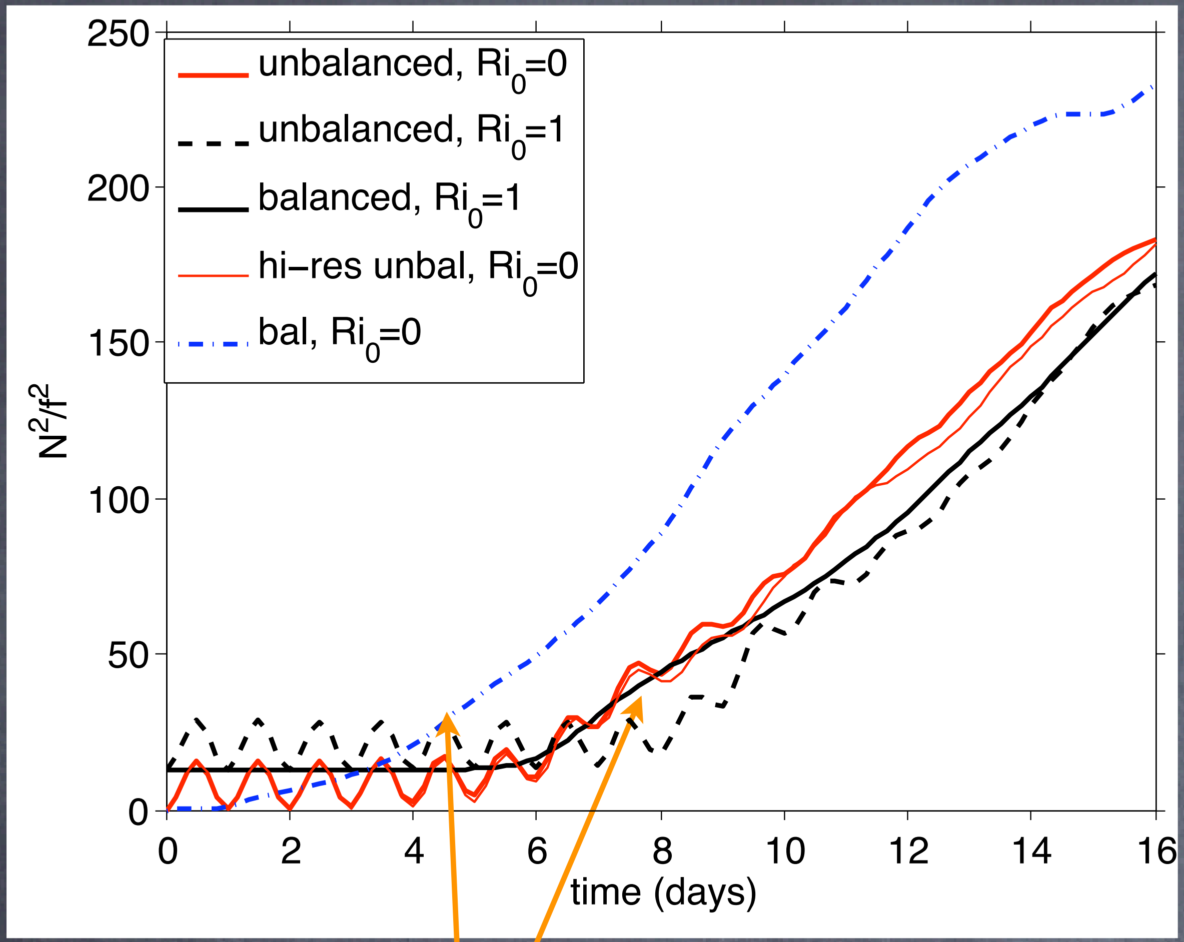

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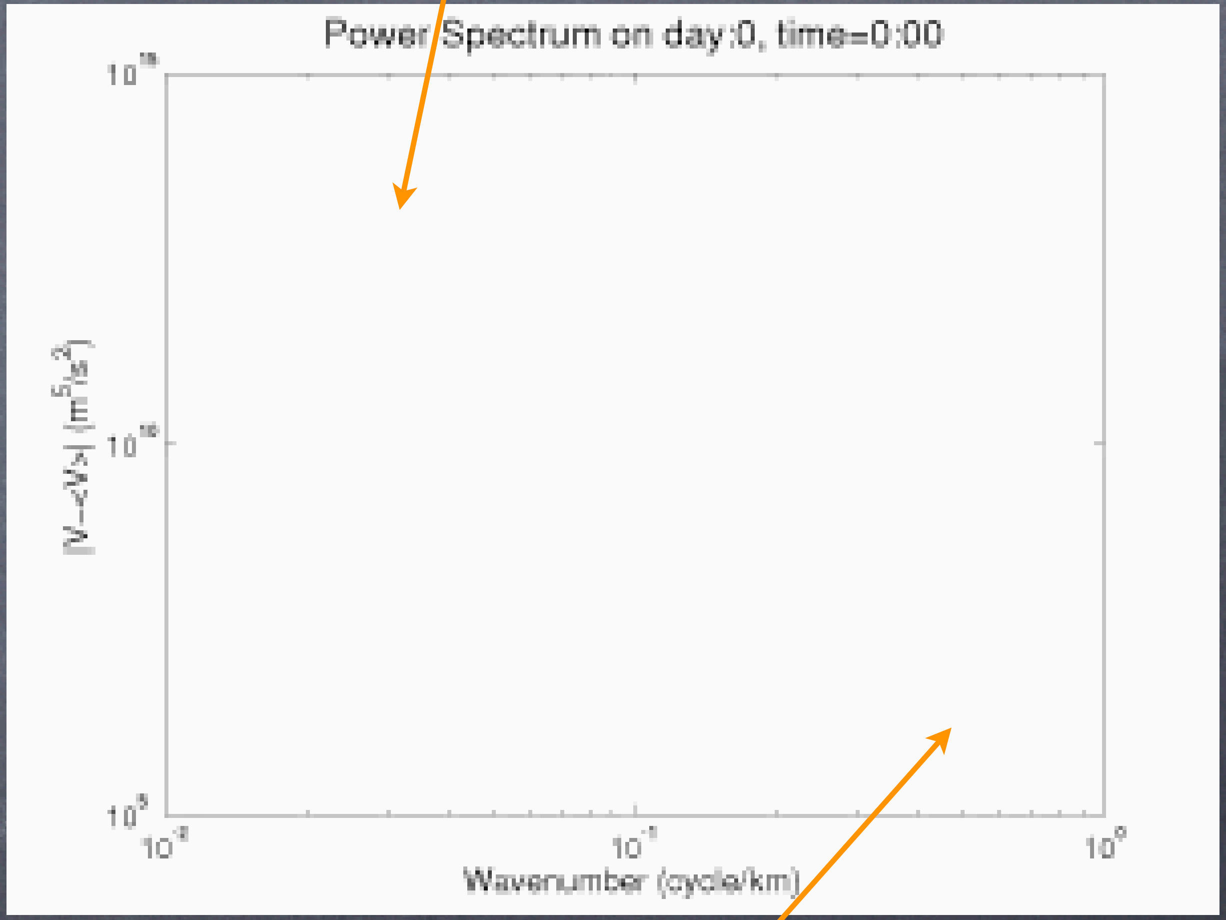

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Inverse Cascade => No Results from Linear Instability

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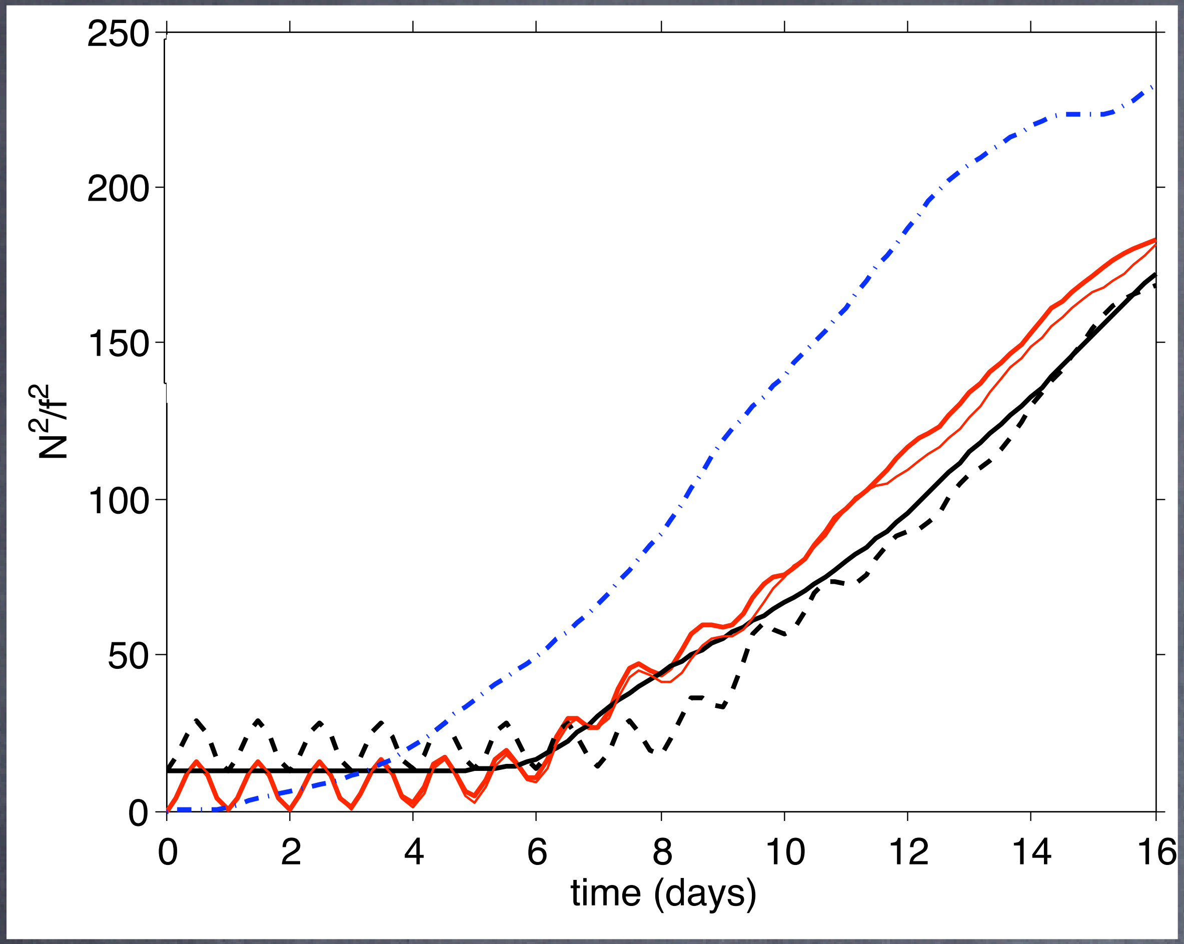

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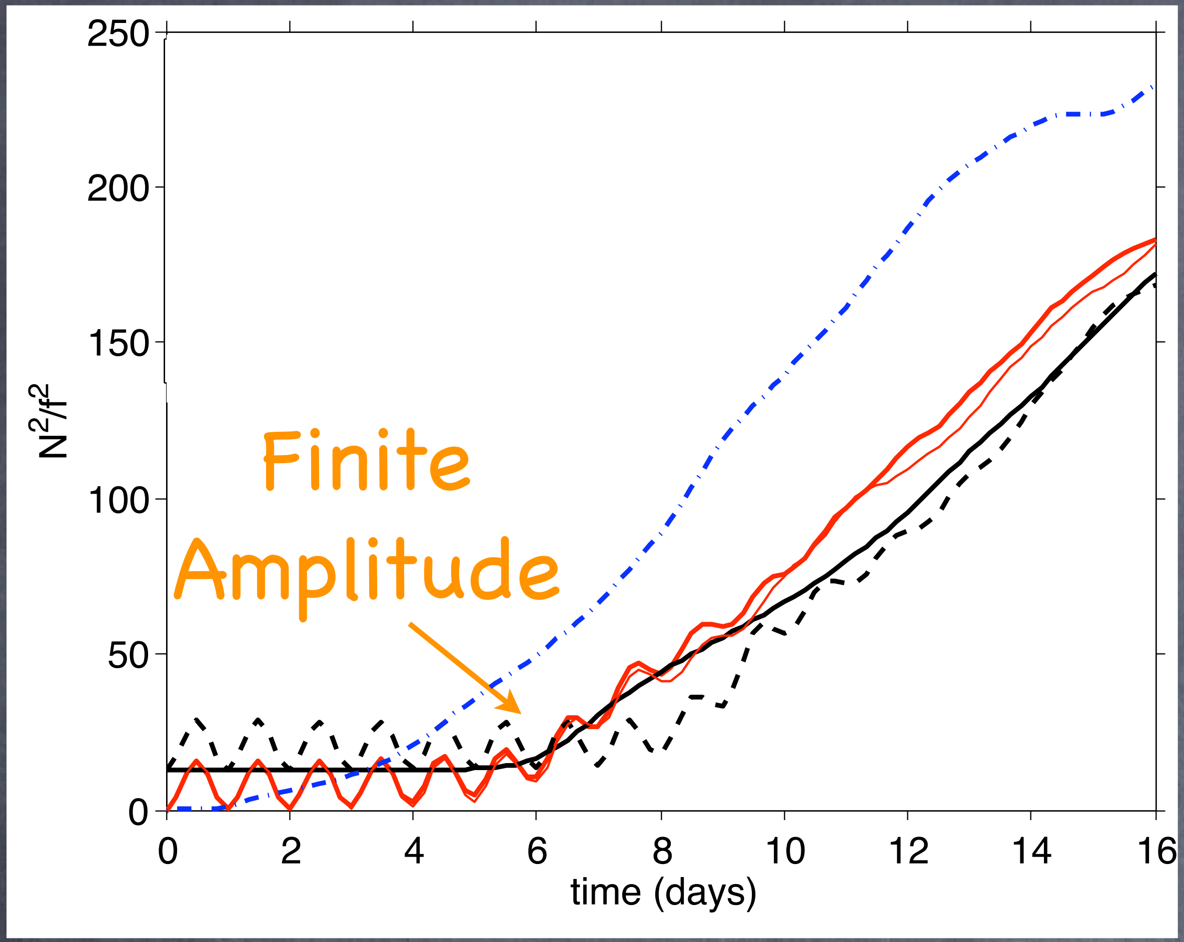

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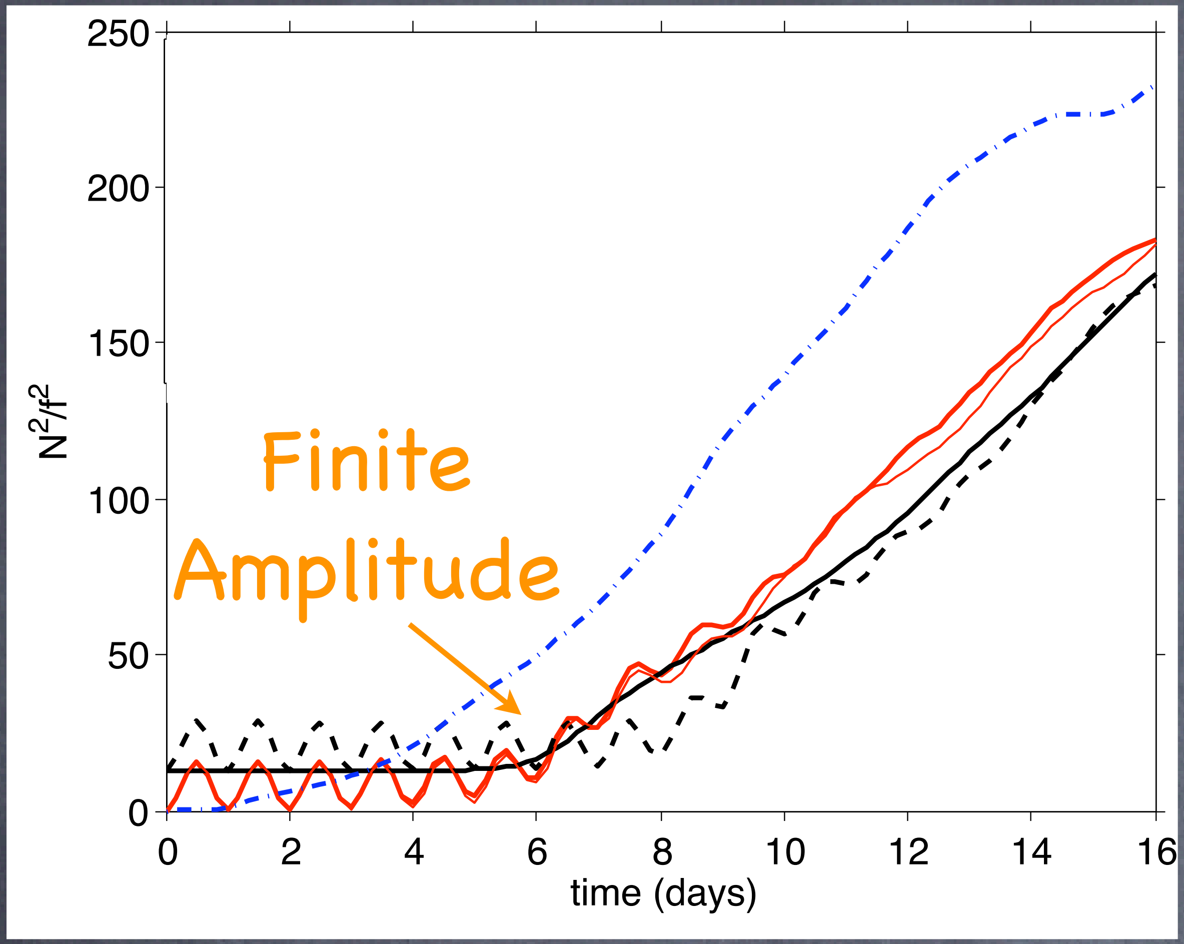

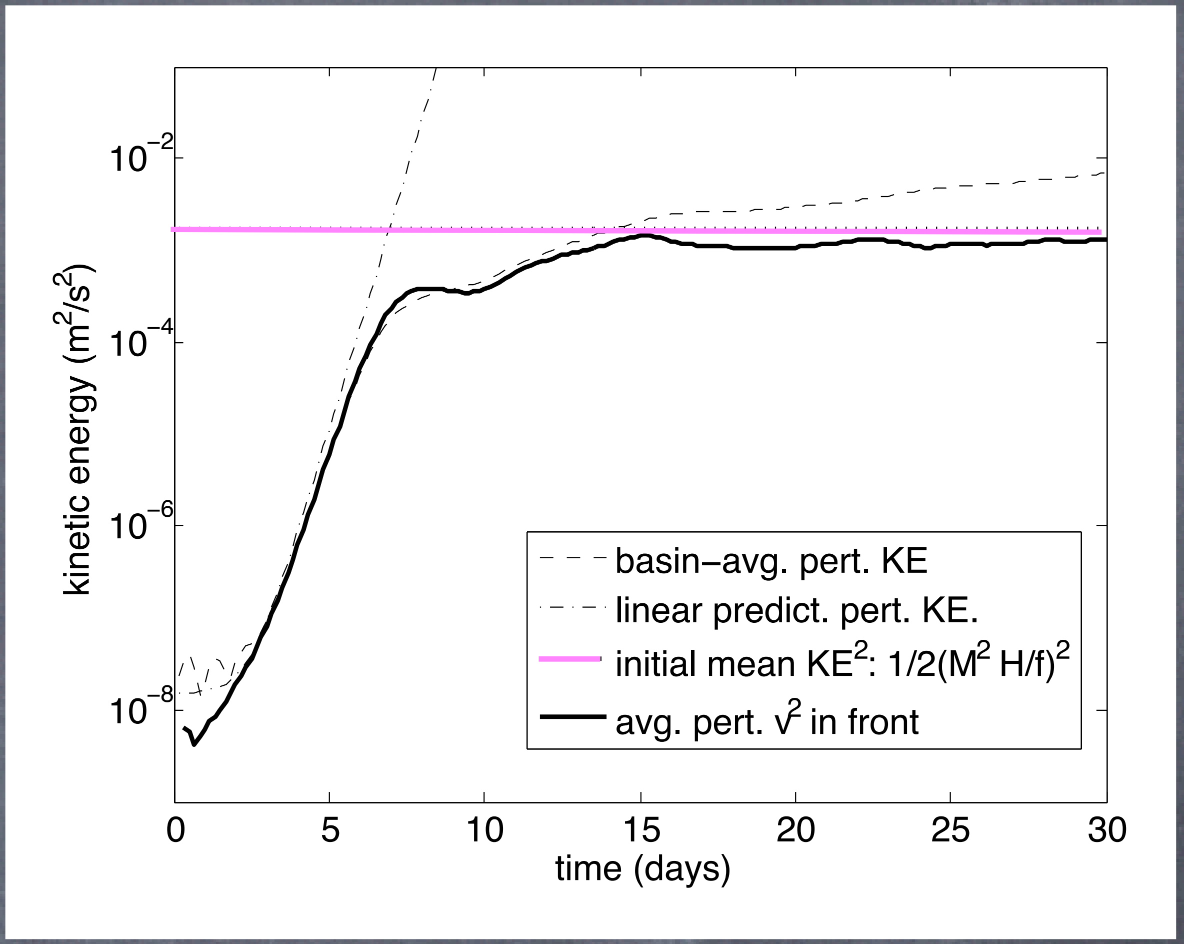

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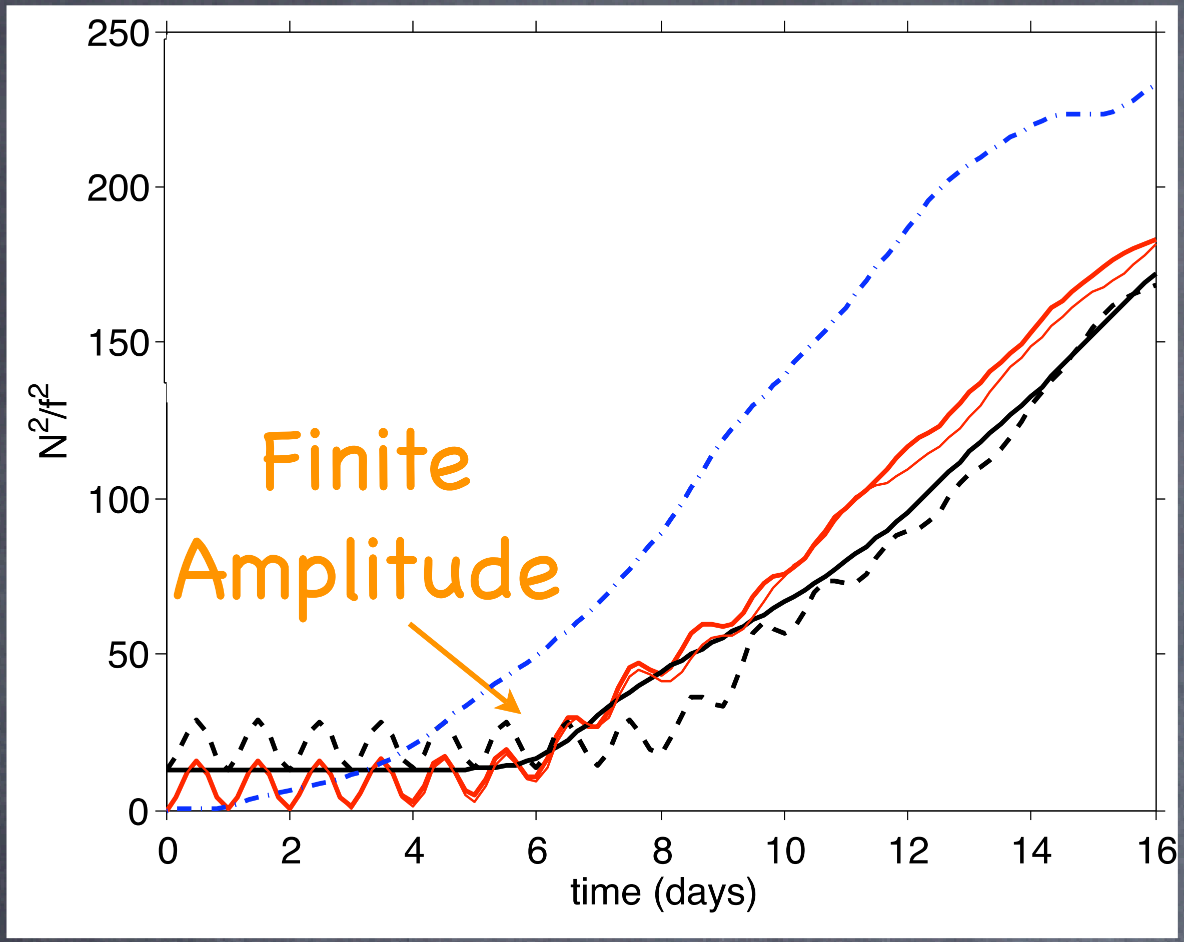

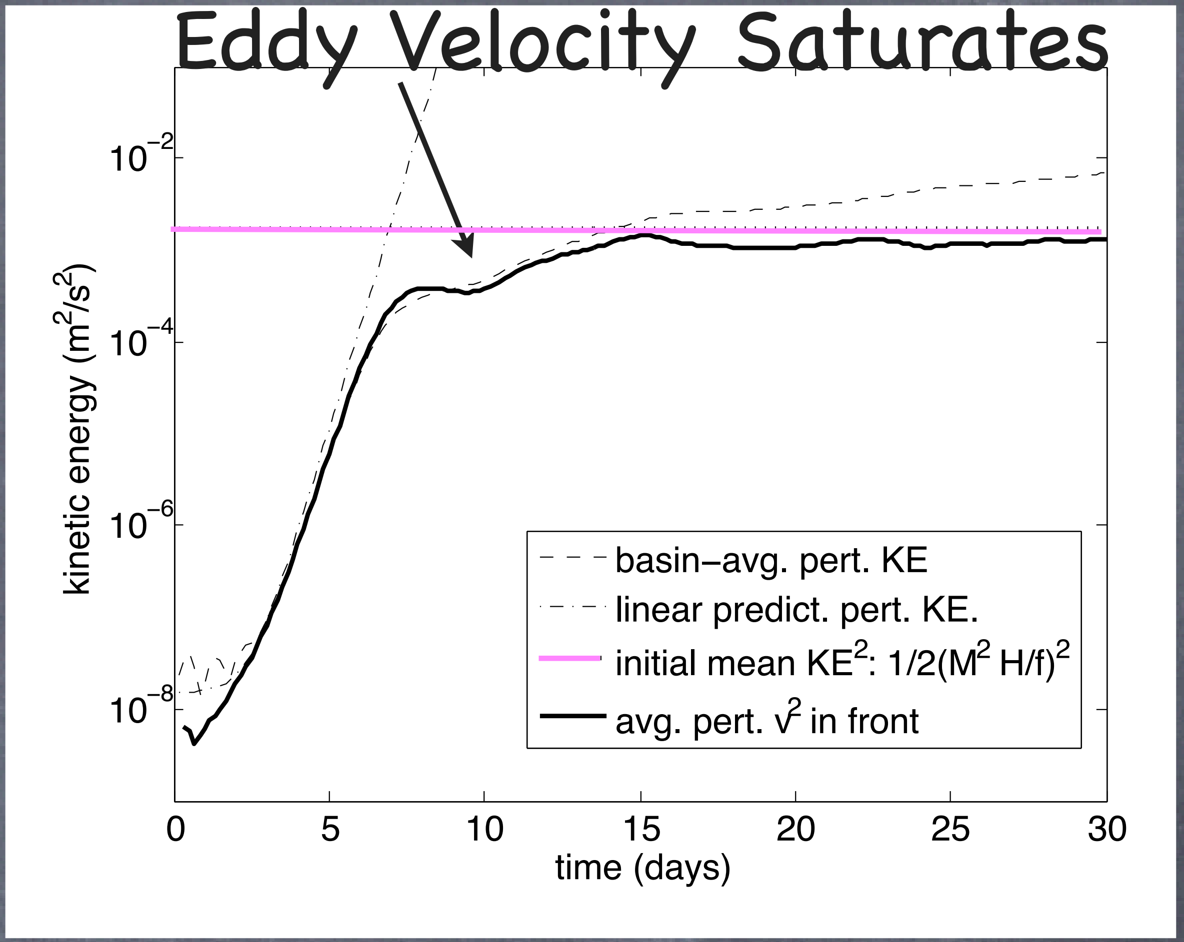

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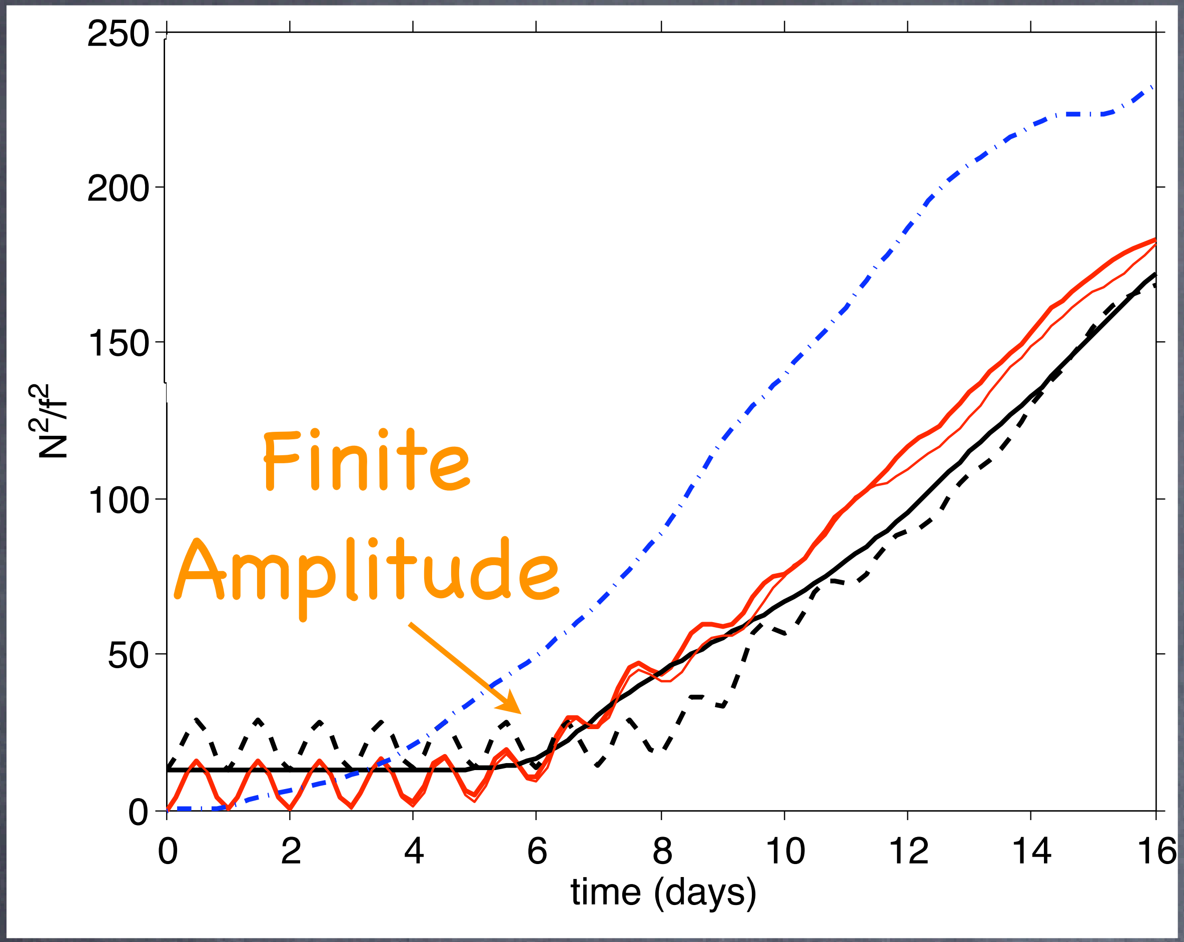

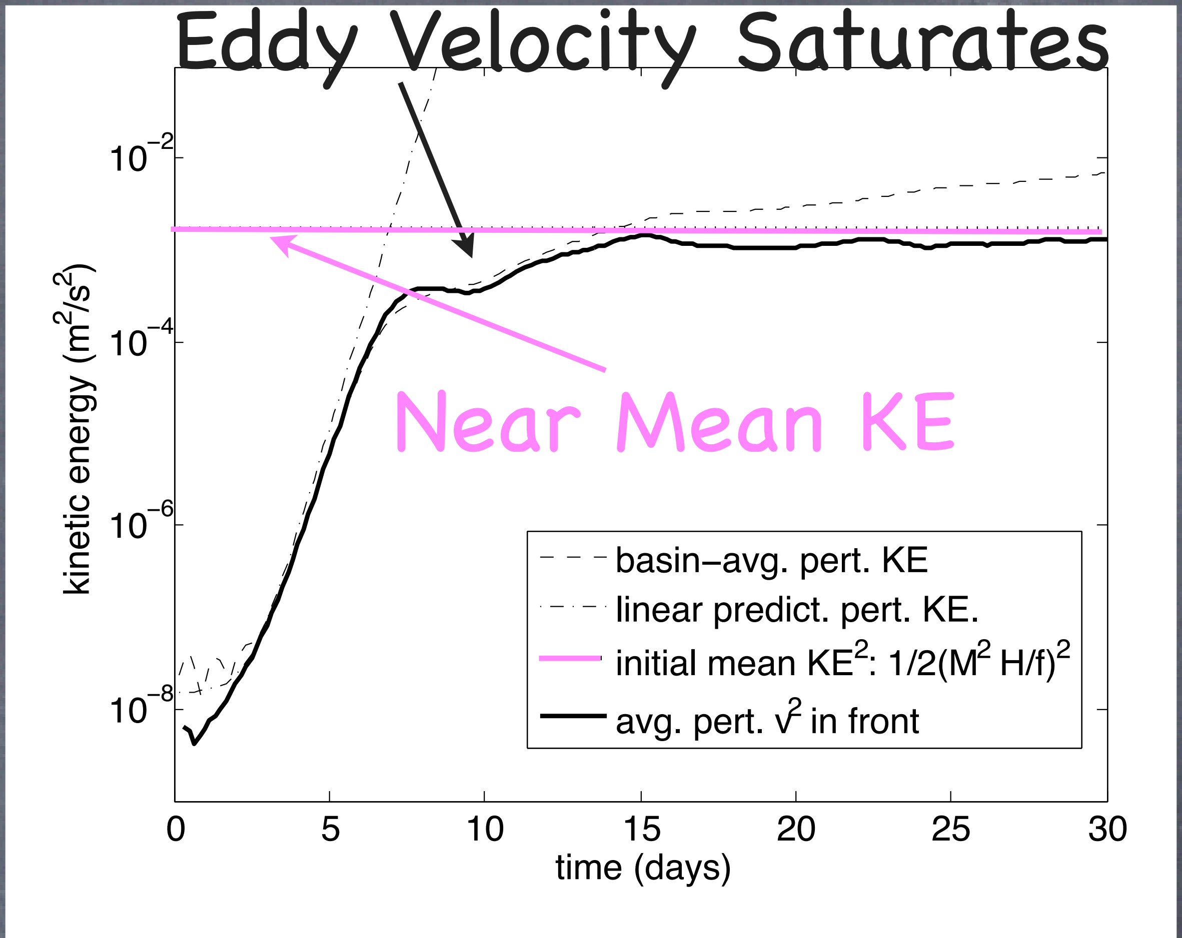

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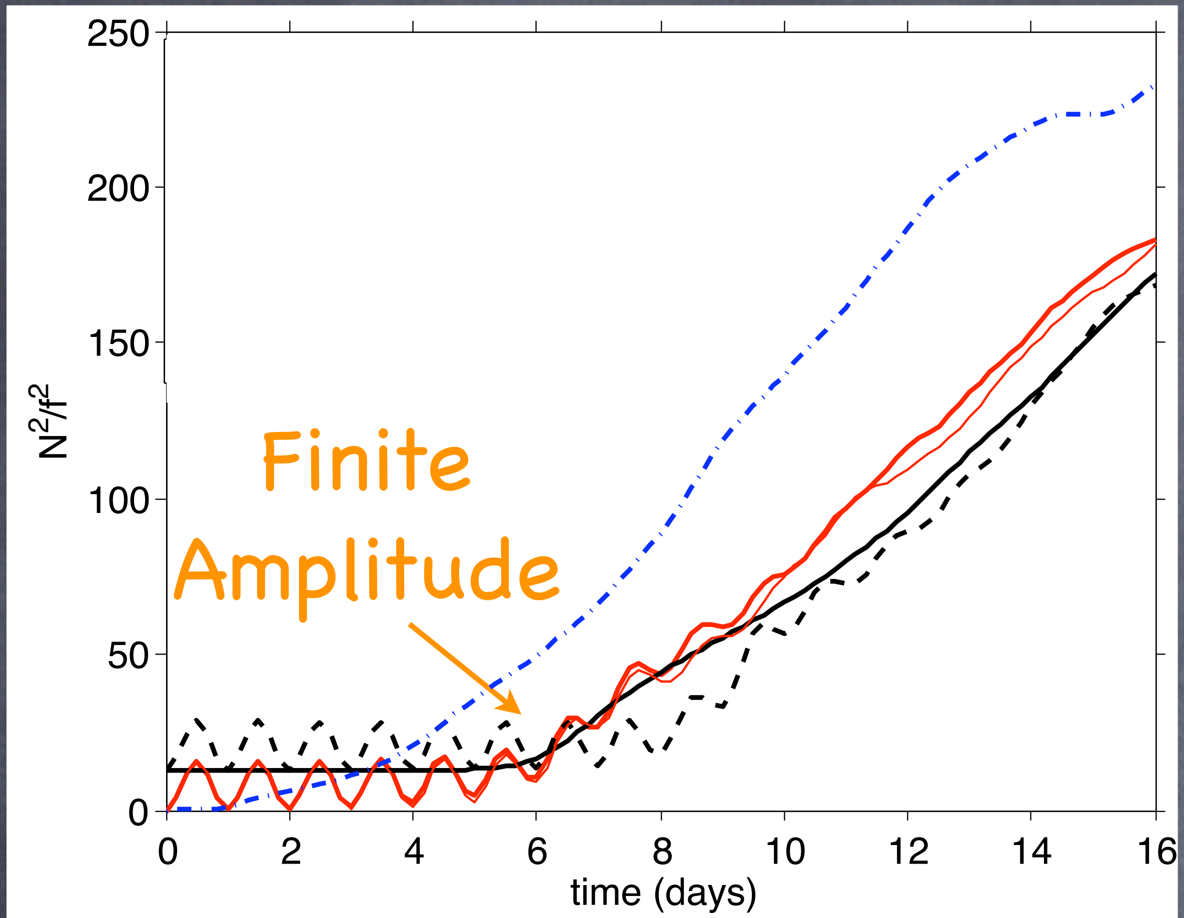

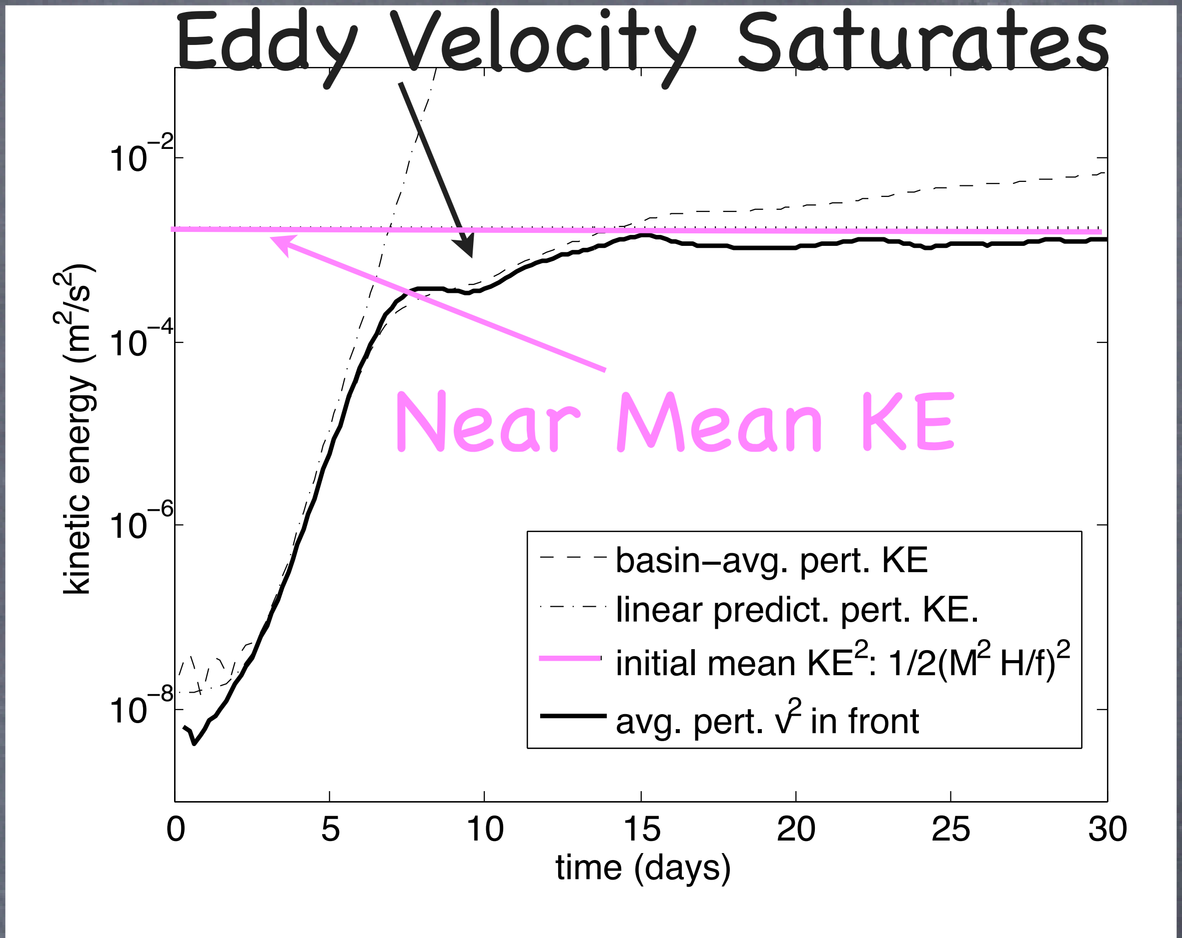

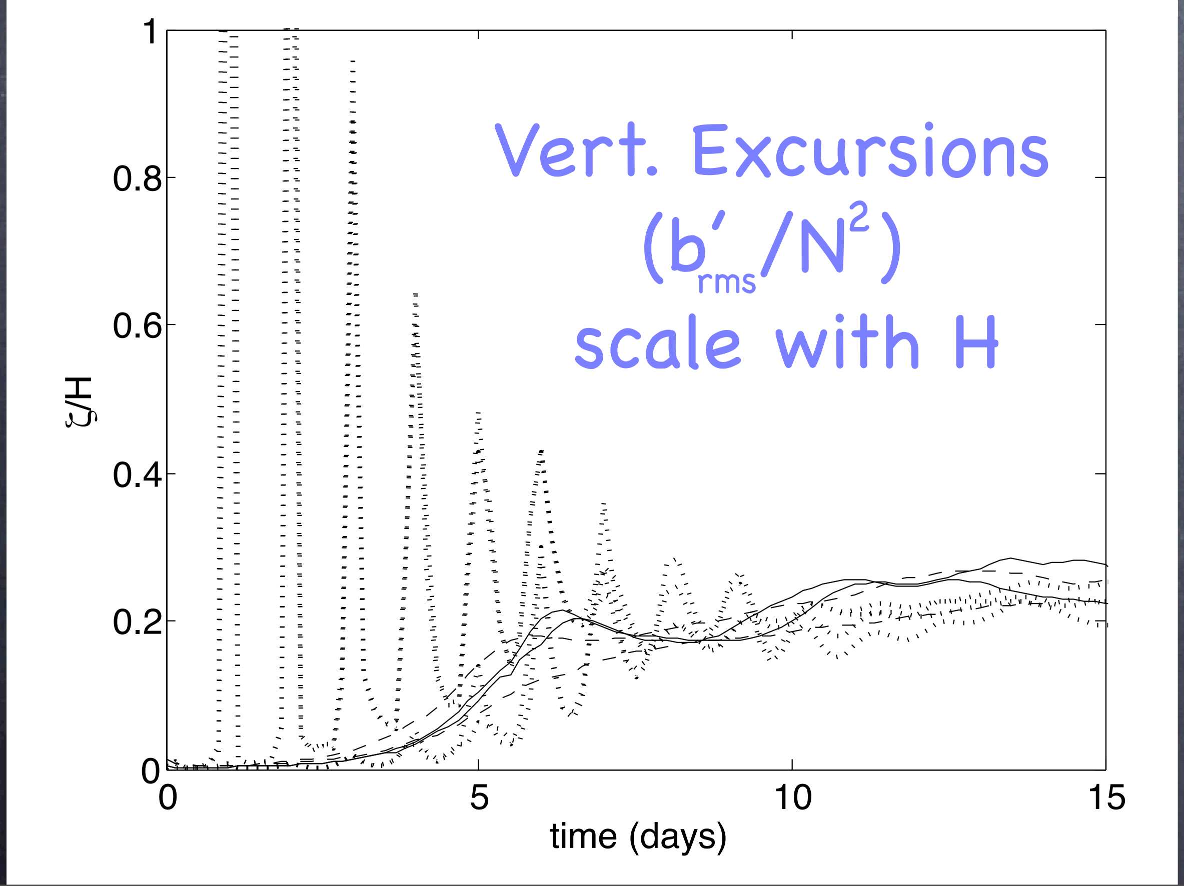

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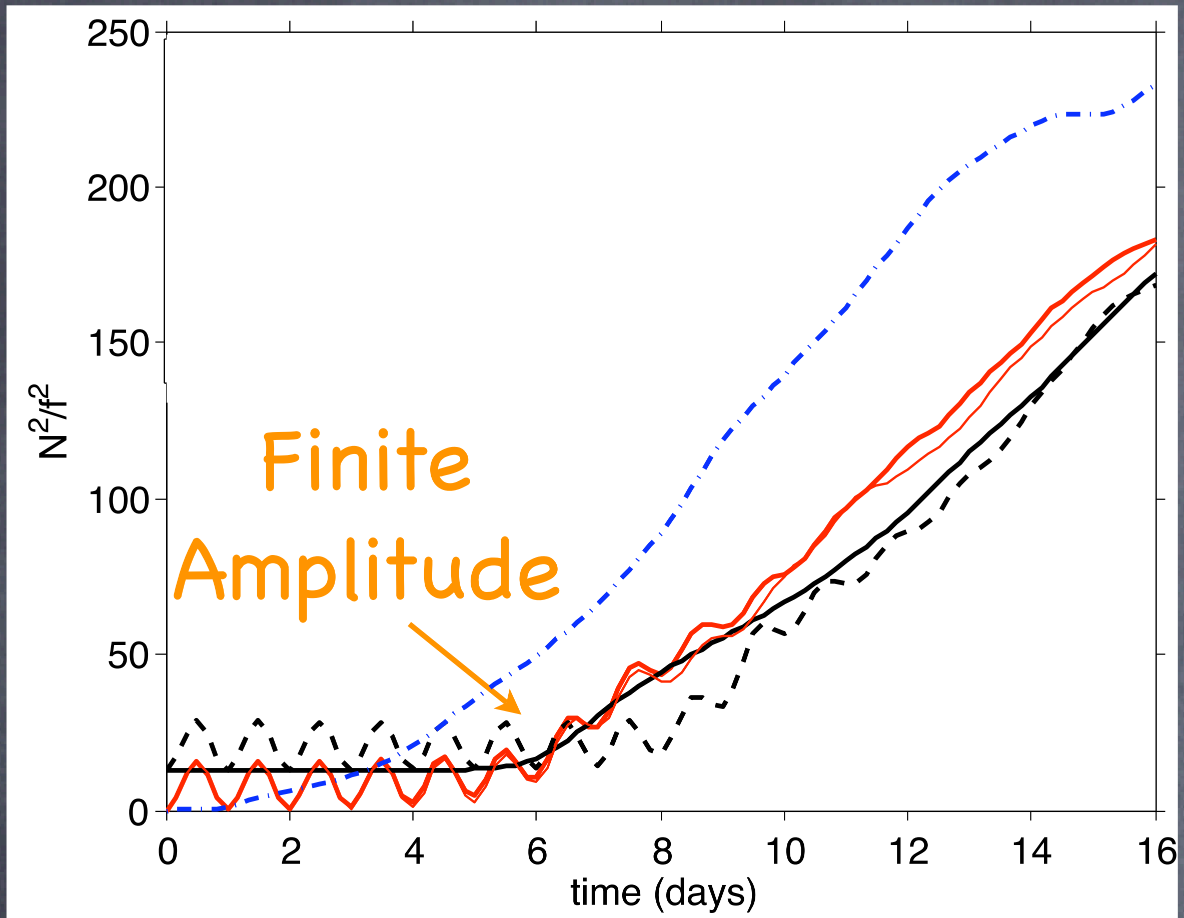
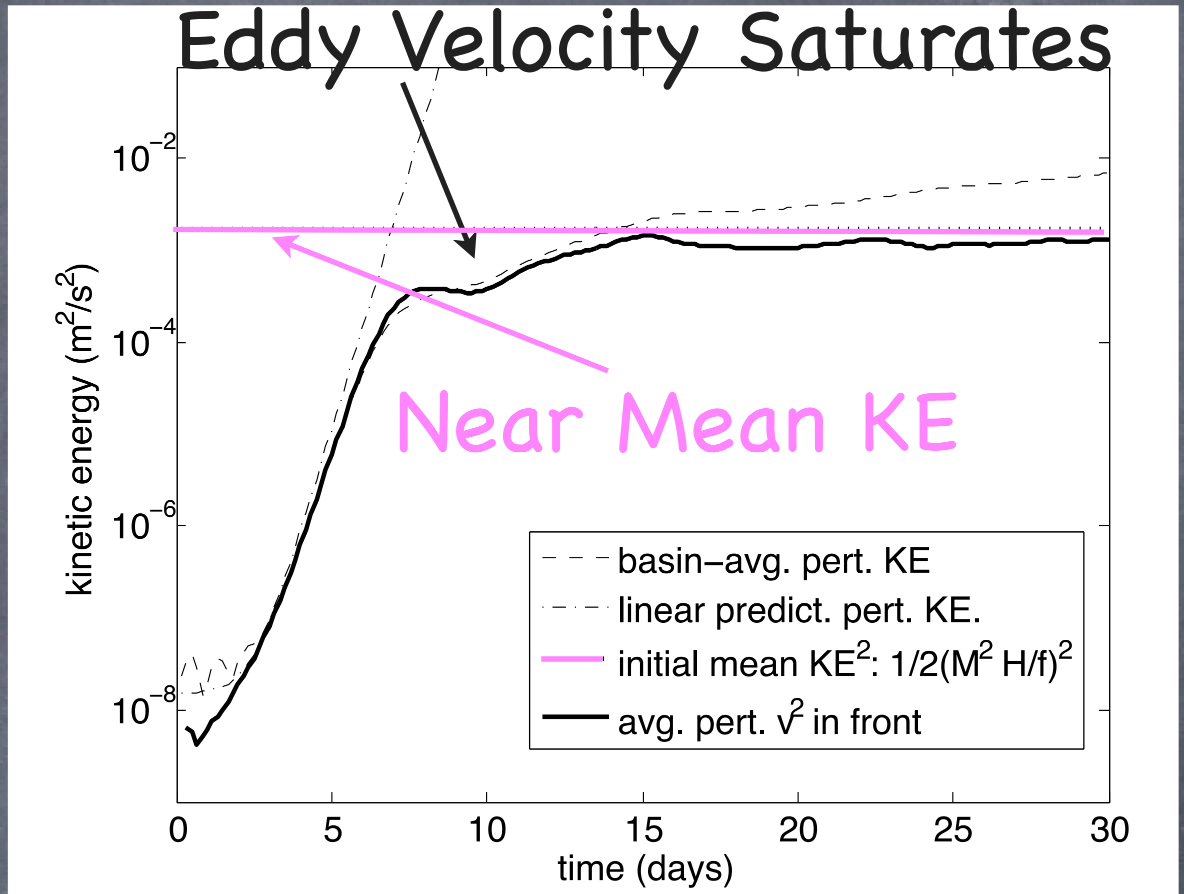
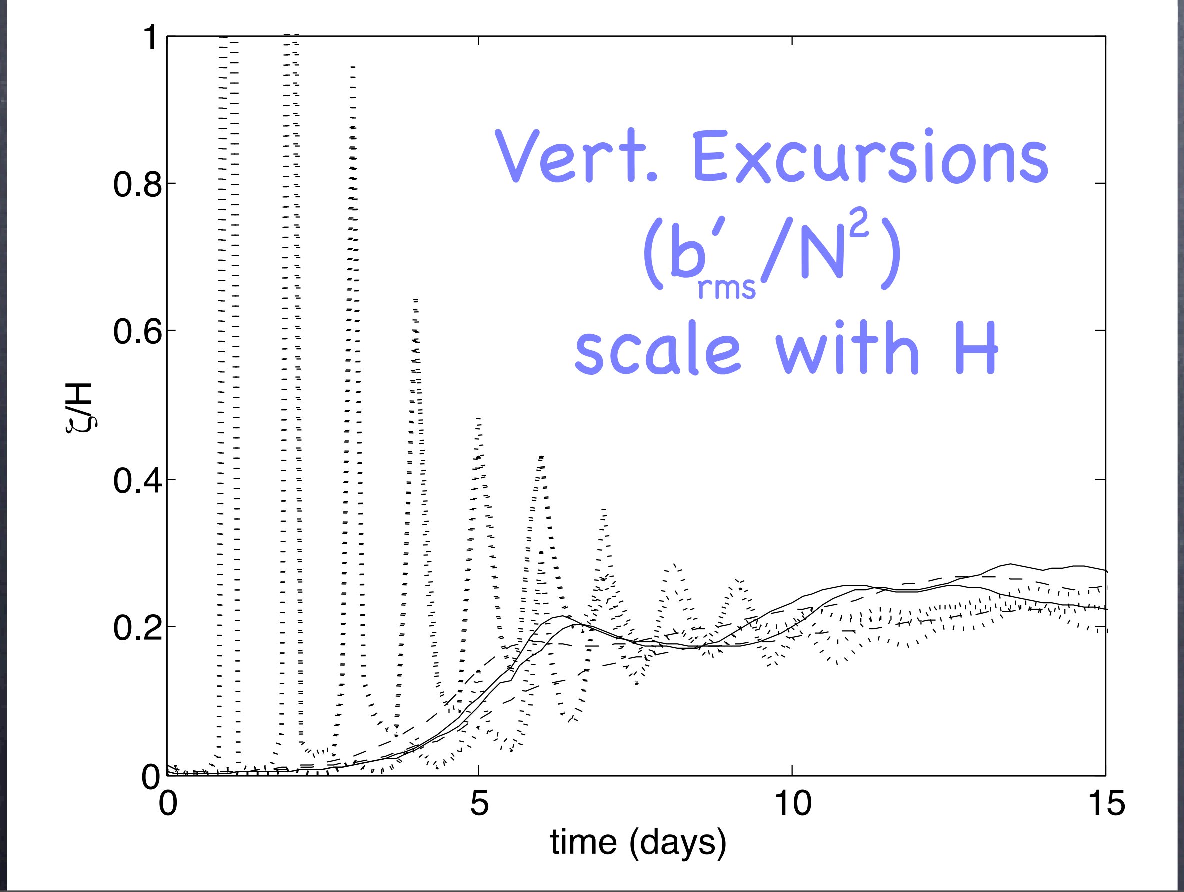
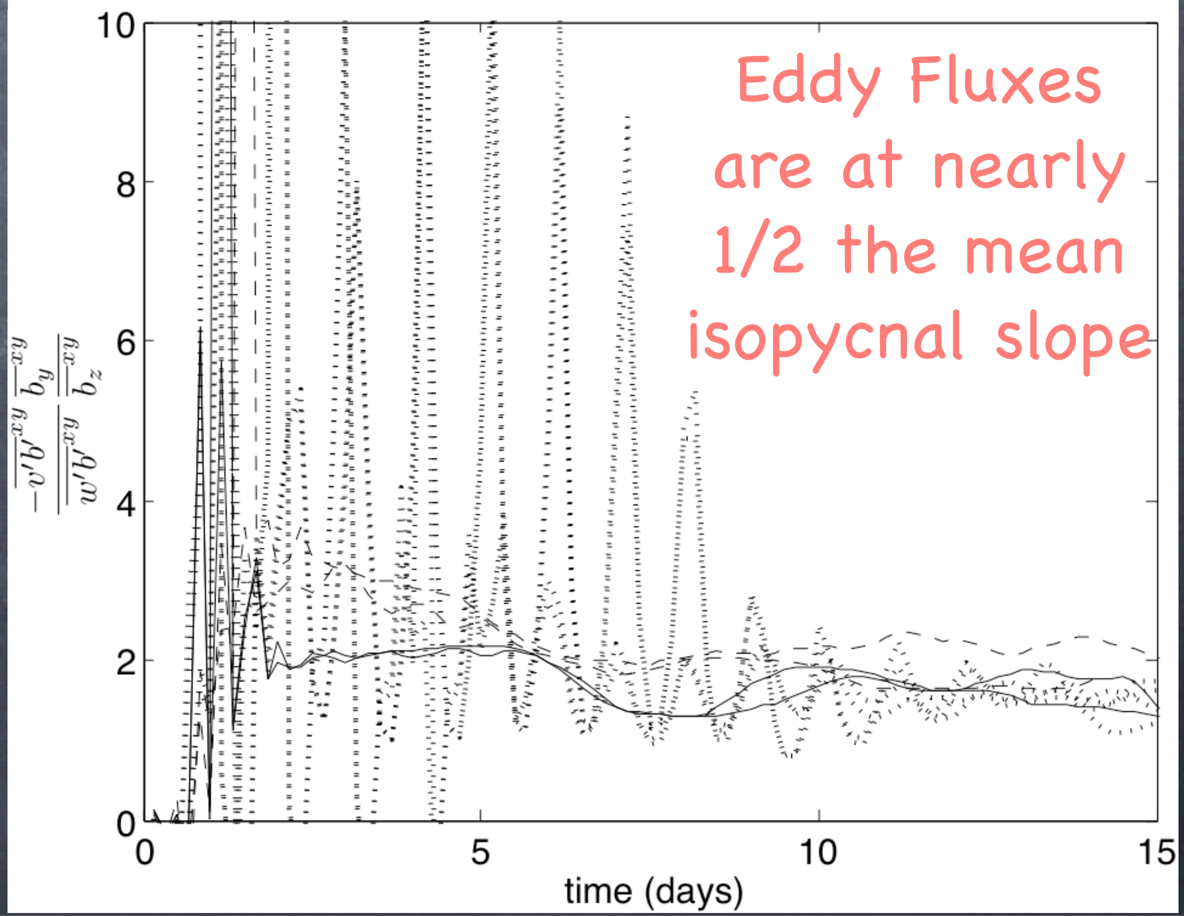




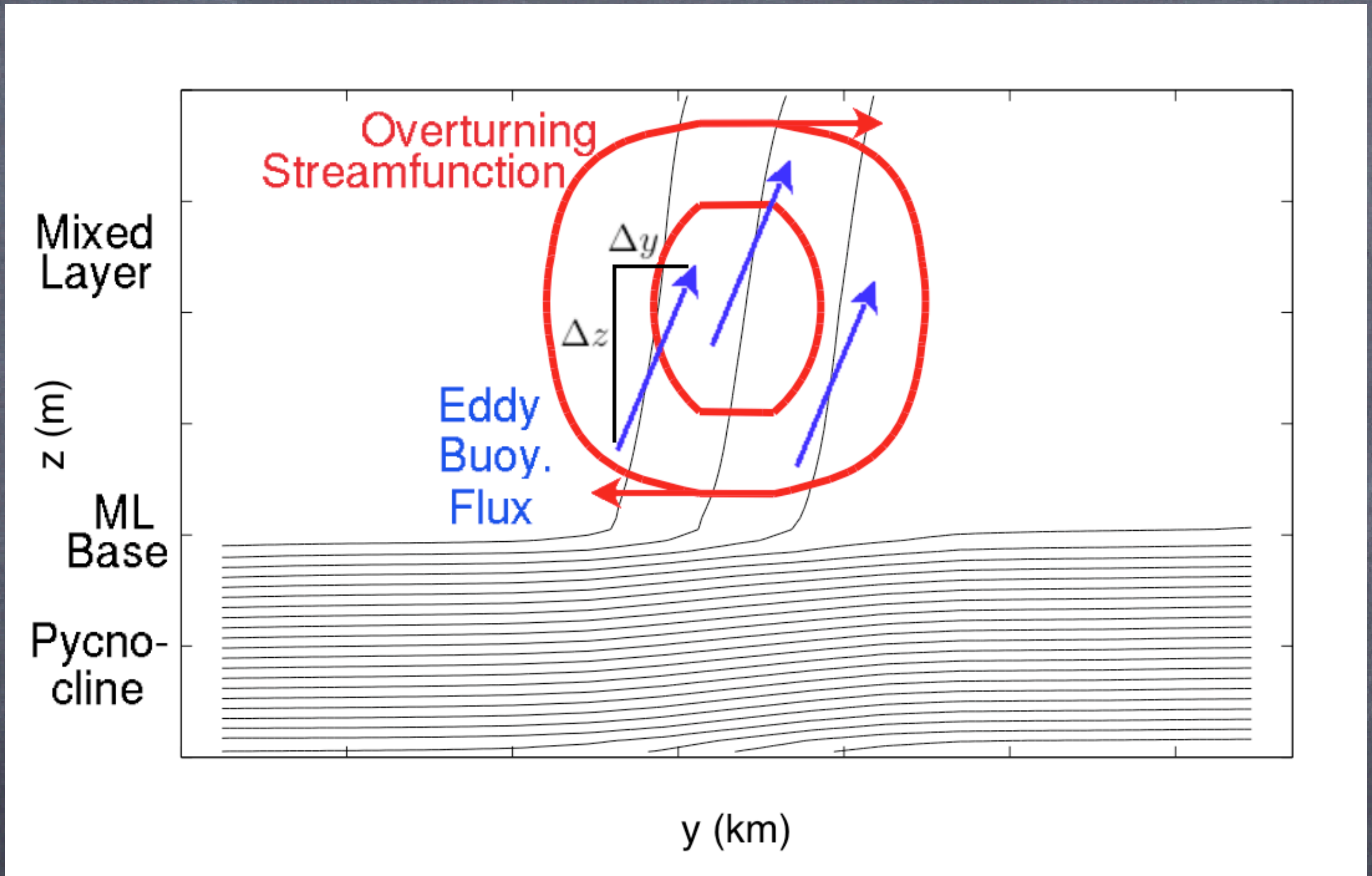




Magnitude Analysis: Vert. Fluxes

Extraction of potential energy by submesoscale eddies:

$$-\langle wb \rangle = \frac{\partial \langle PE \rangle}{\partial t}$$



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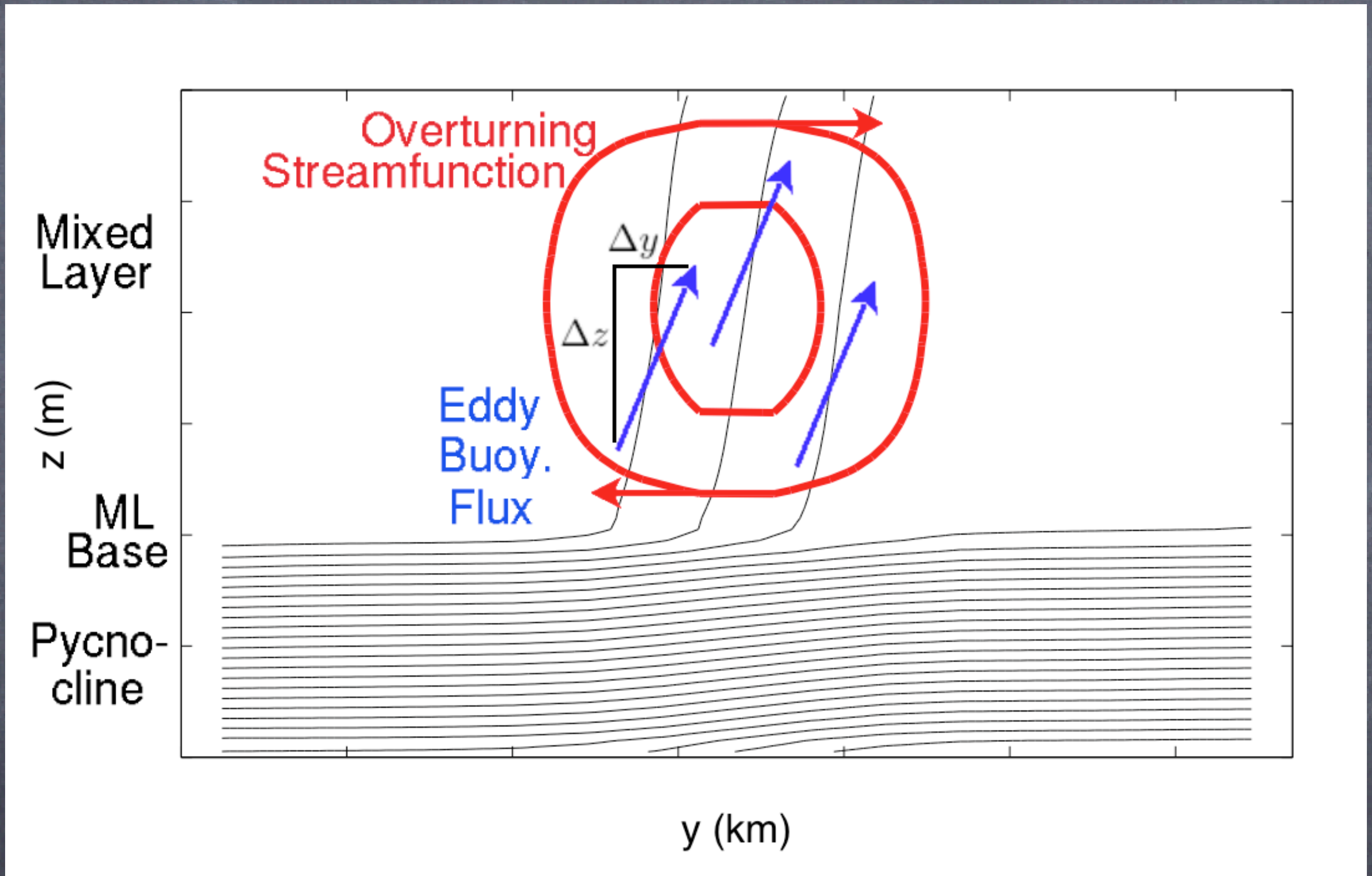
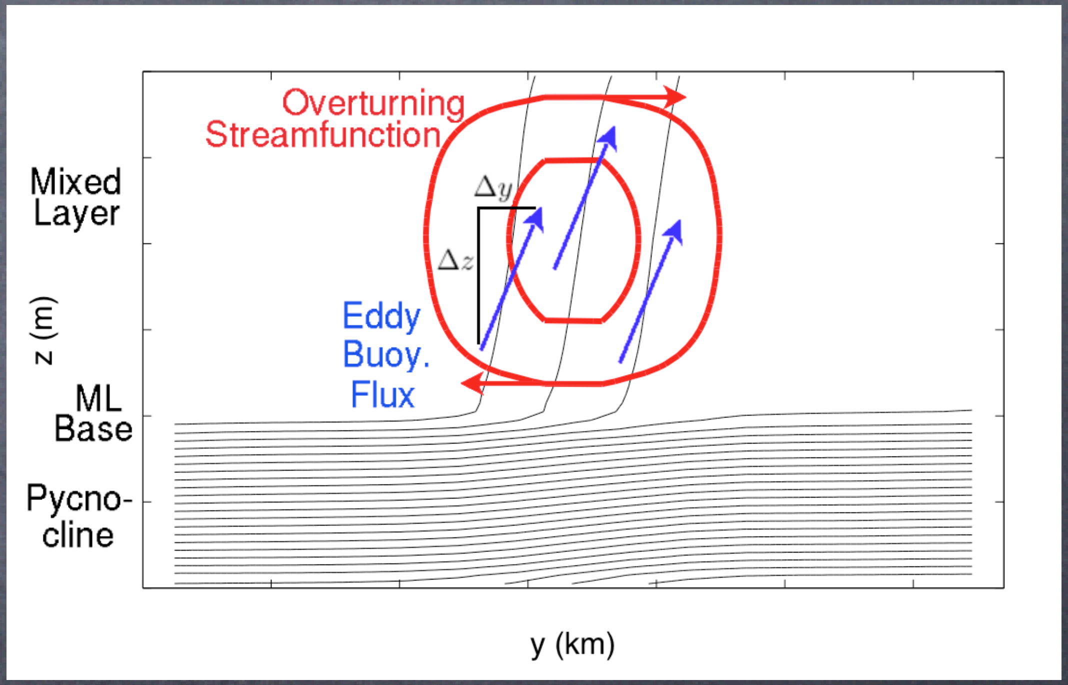


$$\langle wb \rangle \propto \frac{H^2}{|f|} \left[\frac{\partial \bar{b}}{\partial y} \right]^2$$

Fox-Kemper et al., 2007

Eddies effect a largely adiabatic transfer: thus representable by a streamfunction

$$\boldsymbol{\Psi} \propto \frac{H^2 \nabla \bar{b} \times \hat{\mathbf{z}}}{|f|} \longrightarrow \overline{\mathbf{u}'b'} \equiv \boldsymbol{\Psi} \times \nabla \bar{b}$$



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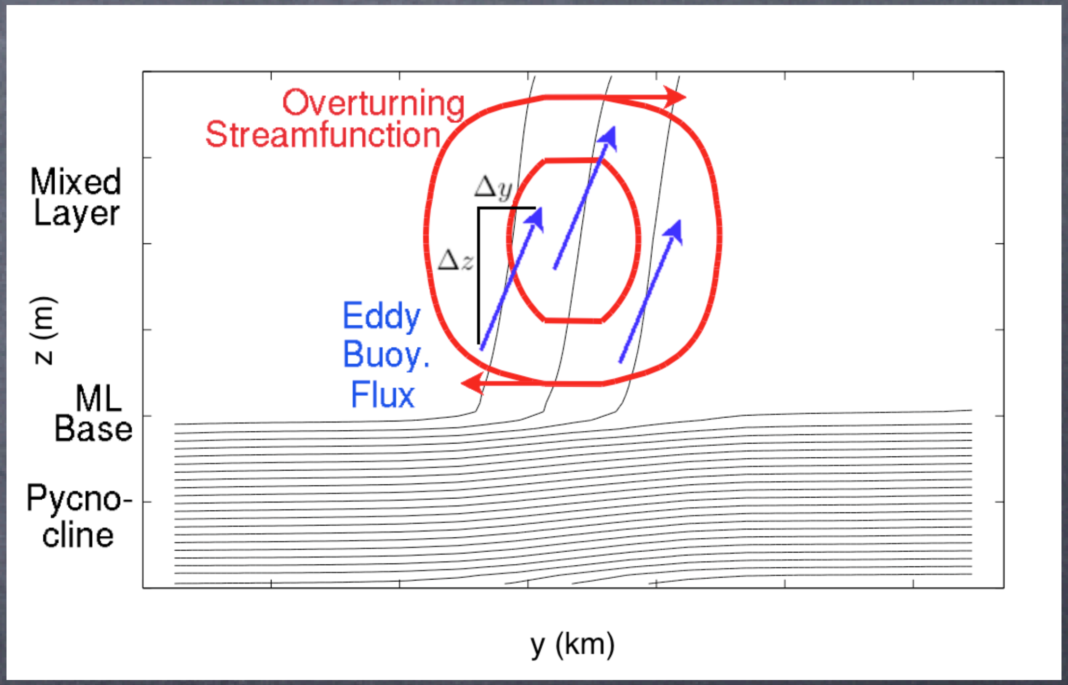
For a consistently upward,

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



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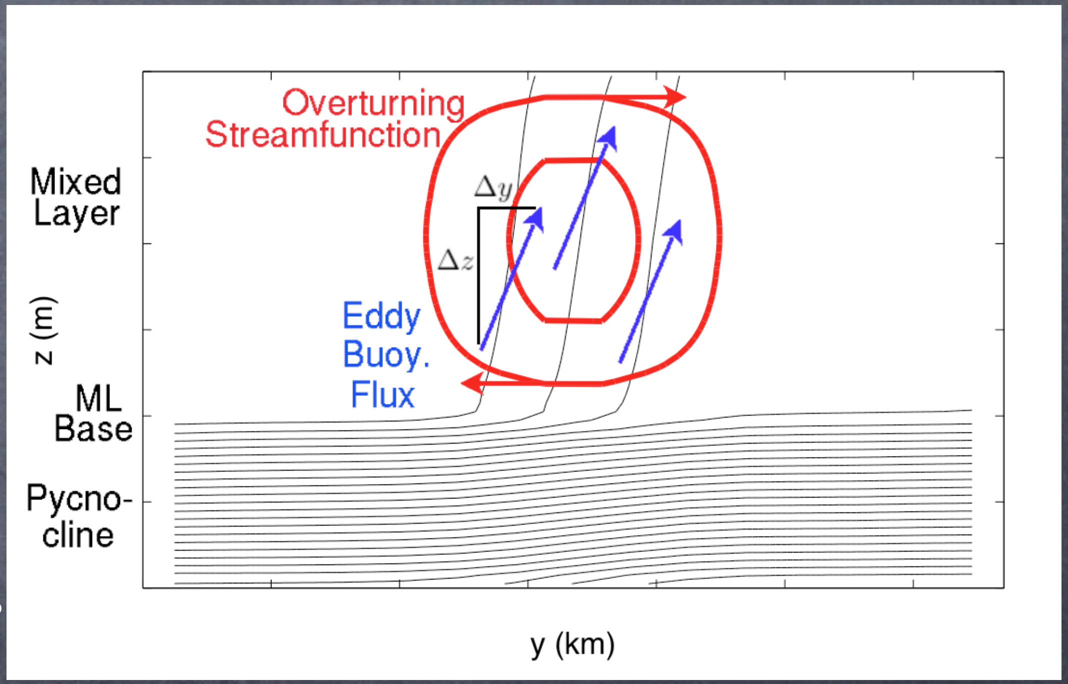

For a consistently upward,

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

horizontally downgradient flux.

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

Eddies effect a largely adiabatic transfer: thus representable by a streamfunction

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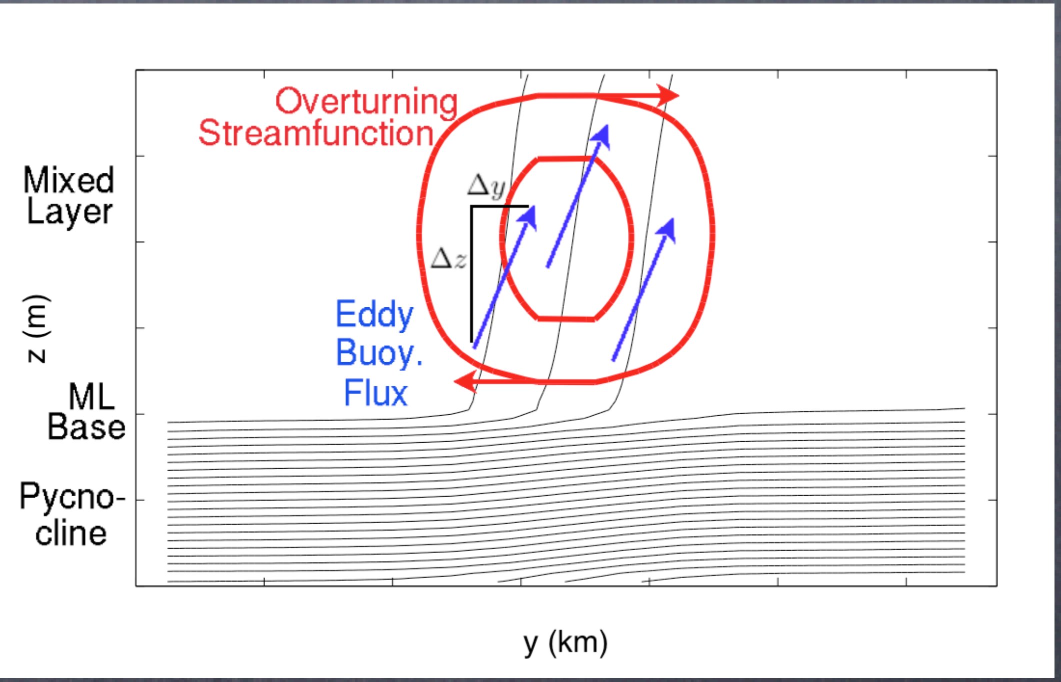
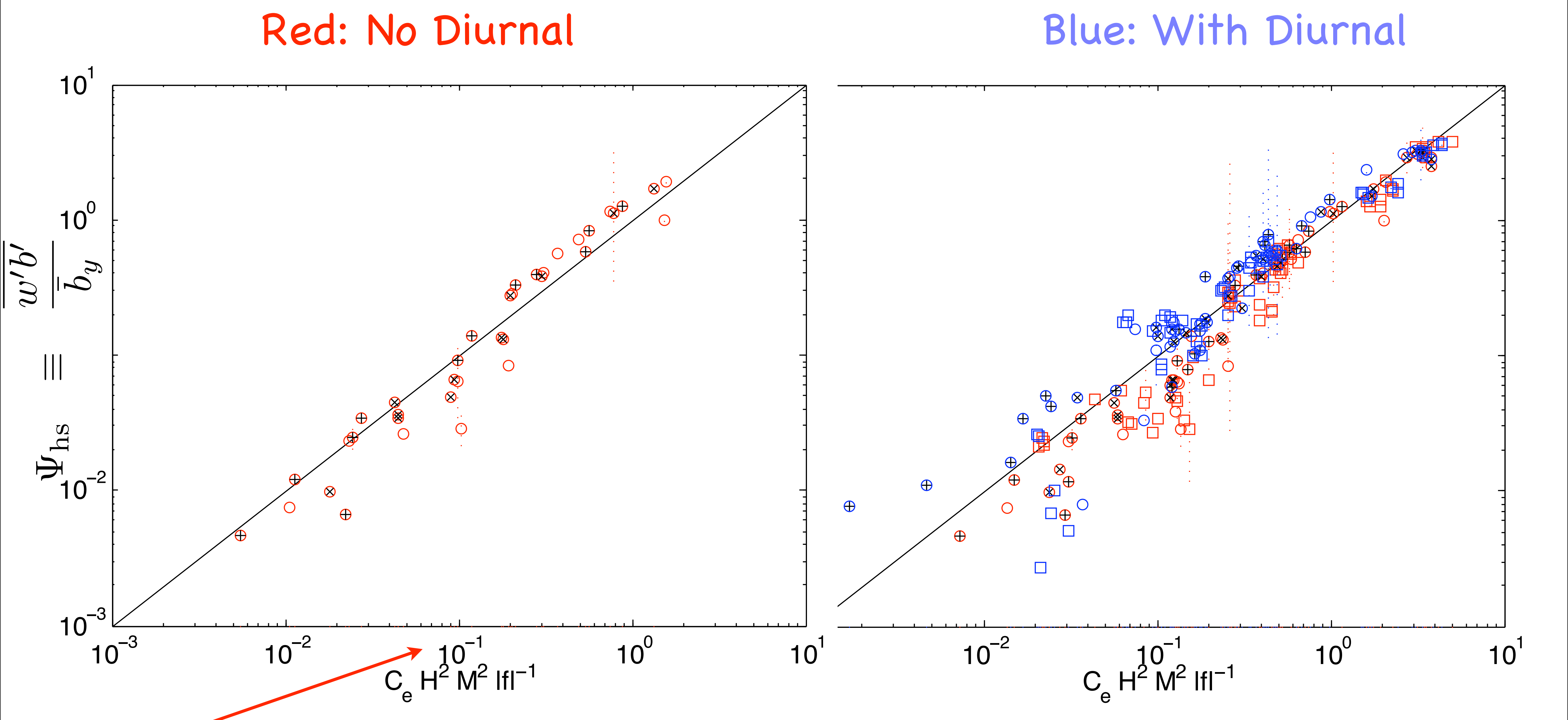


And, extends/agrees with Deep Convection Studies: Jones & Marshall (93,97), Haine & Marshall (98)

It works for Prototype Sims:

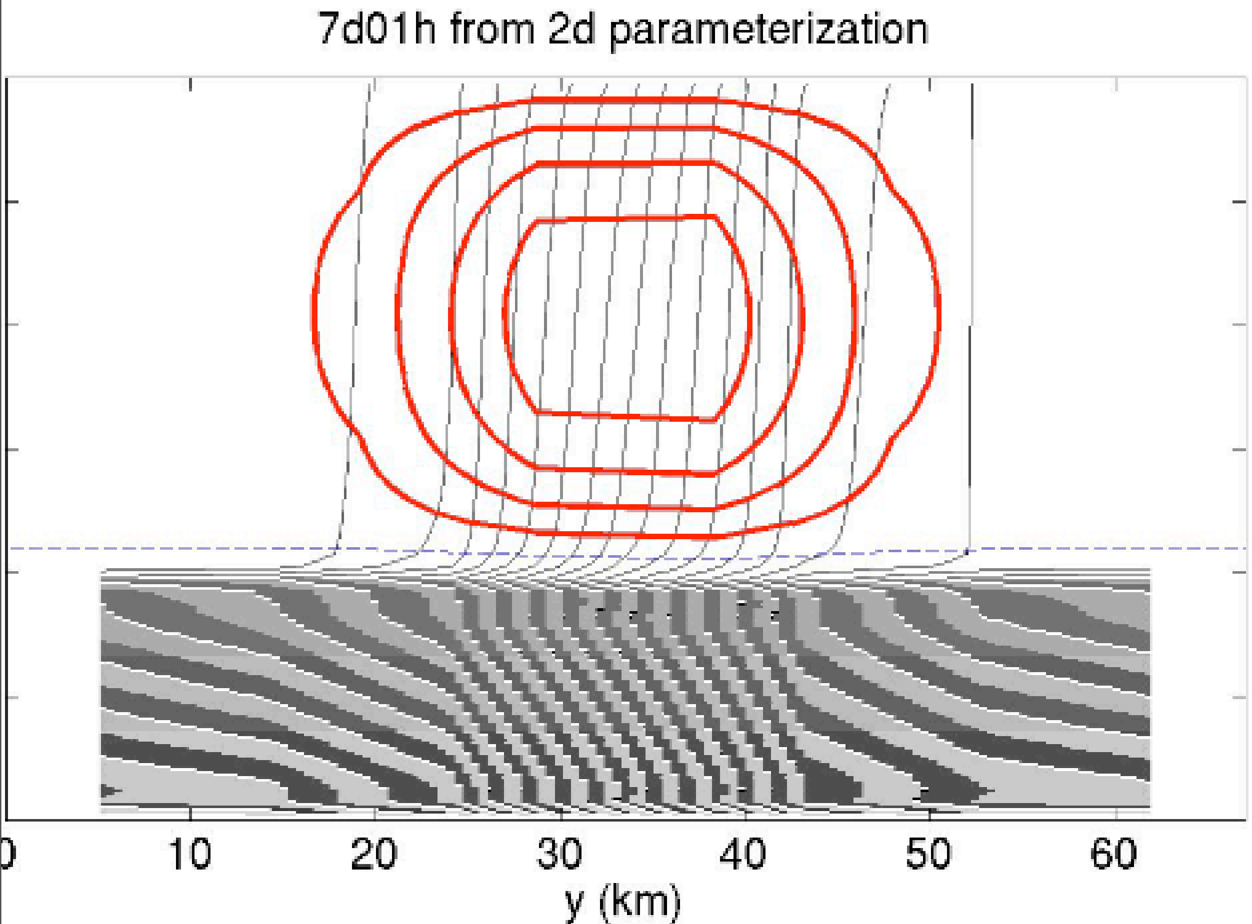


>2 orders of magnitude!

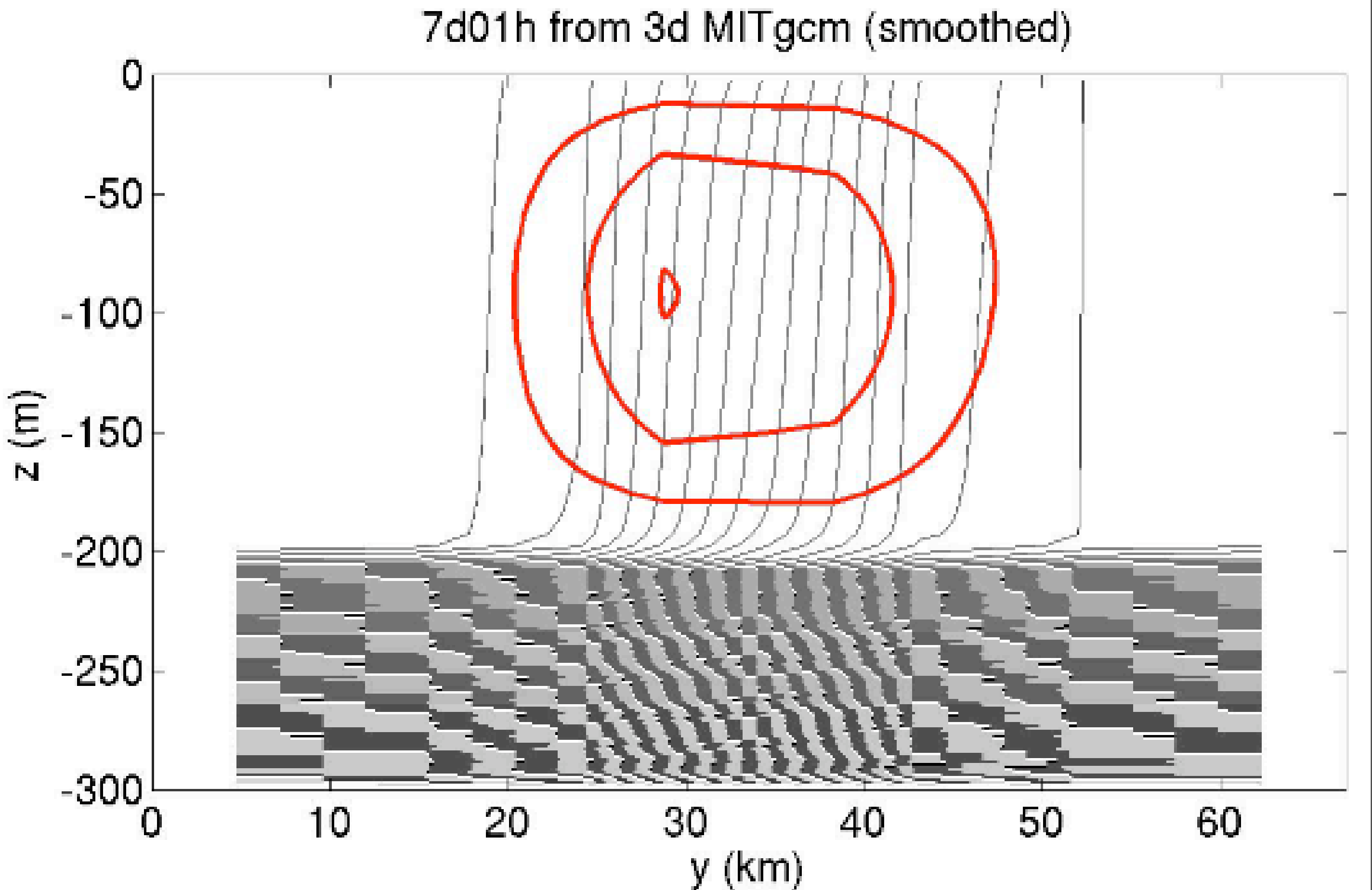
Circles: Balanced Initial Cond.
Squares: Unbalanced Initial Cond.

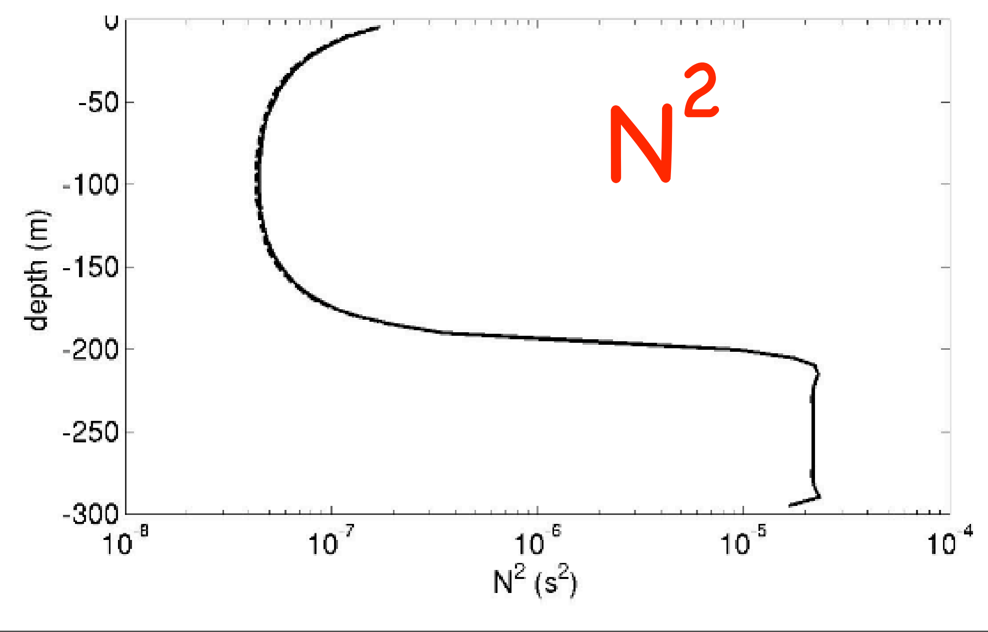
What does it look like?

Parameterization (2d, 10km grid)

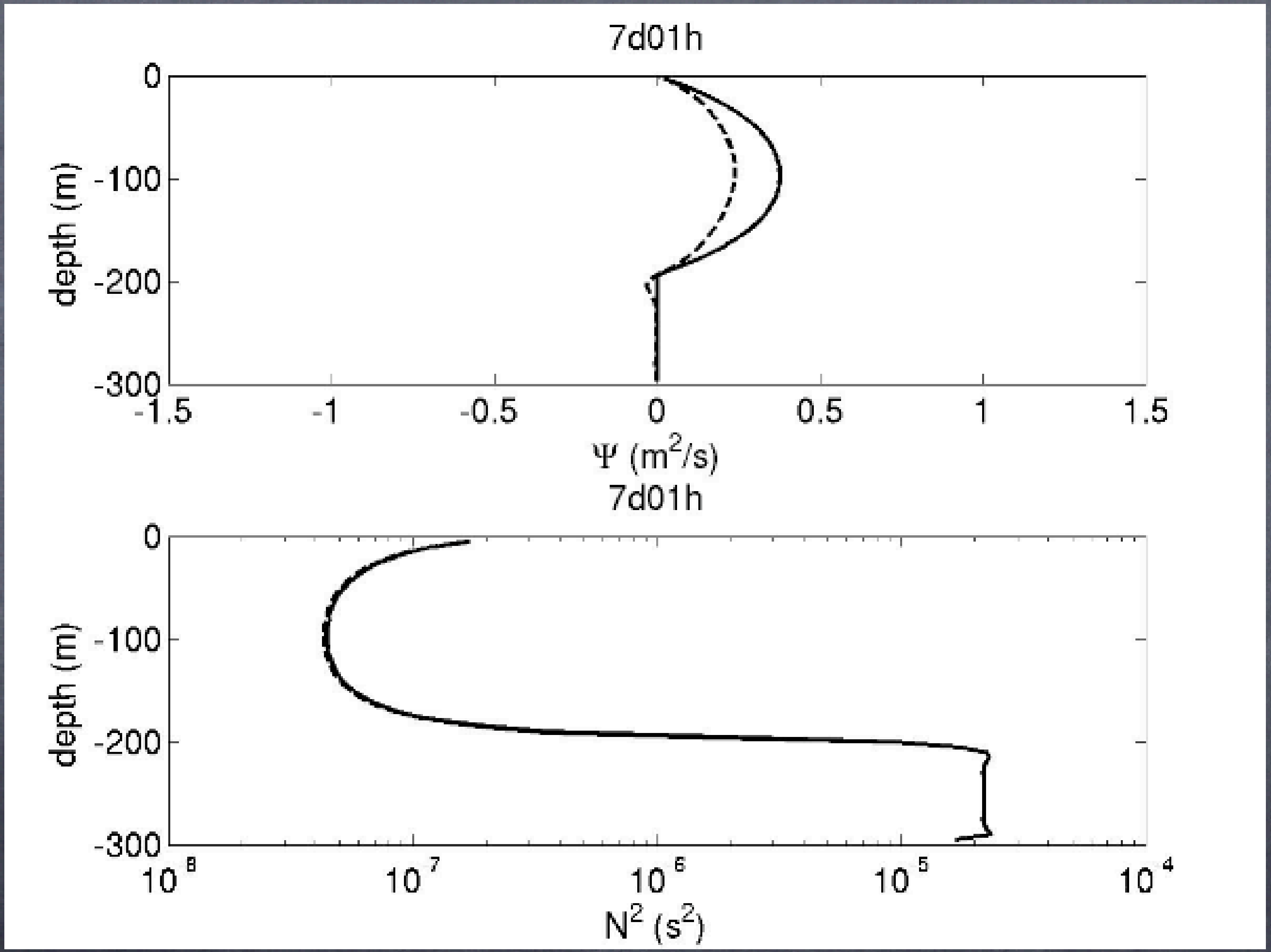


Submesoscale-Resolving (3d,500m grid





Vertical Structure:
like <w'b'> from linear instability solution.



Summary so far:

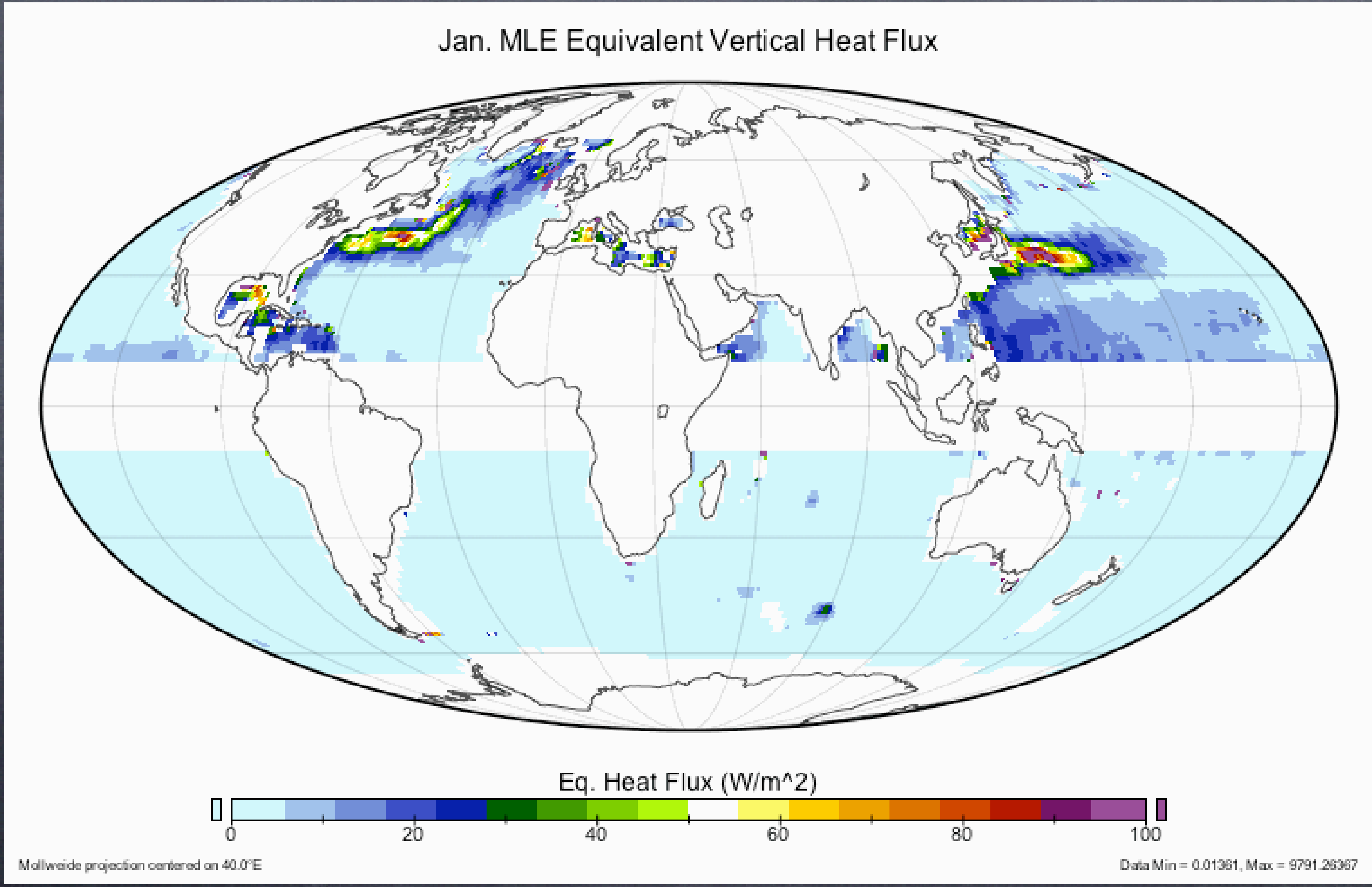
- Ocean mixed layer isn't totally mixed
- Submesoscale vertical fluxes are important in setting mixed layer stratification
- Weak mixed layer stratification makes for submesoscale eddies by baroclinic instability
- Their overturning can be parameterized

Now we turn to their impact

Where in the world are the fluxes?

(Equiv. Vert. Heat Flux from Satellite Altimetry)

Where convection makes ML deep.



Where in the world are the fluxes?

Where convection makes ML deep, which is where the ocean talks to the atmosphere

Those are the biggest MLE fluxes, but elsewhere surface fluxes are weaker, too.

Overall, MLE estimates exceed:

50% of monthly-mean surface flux climatology 25% of the time,

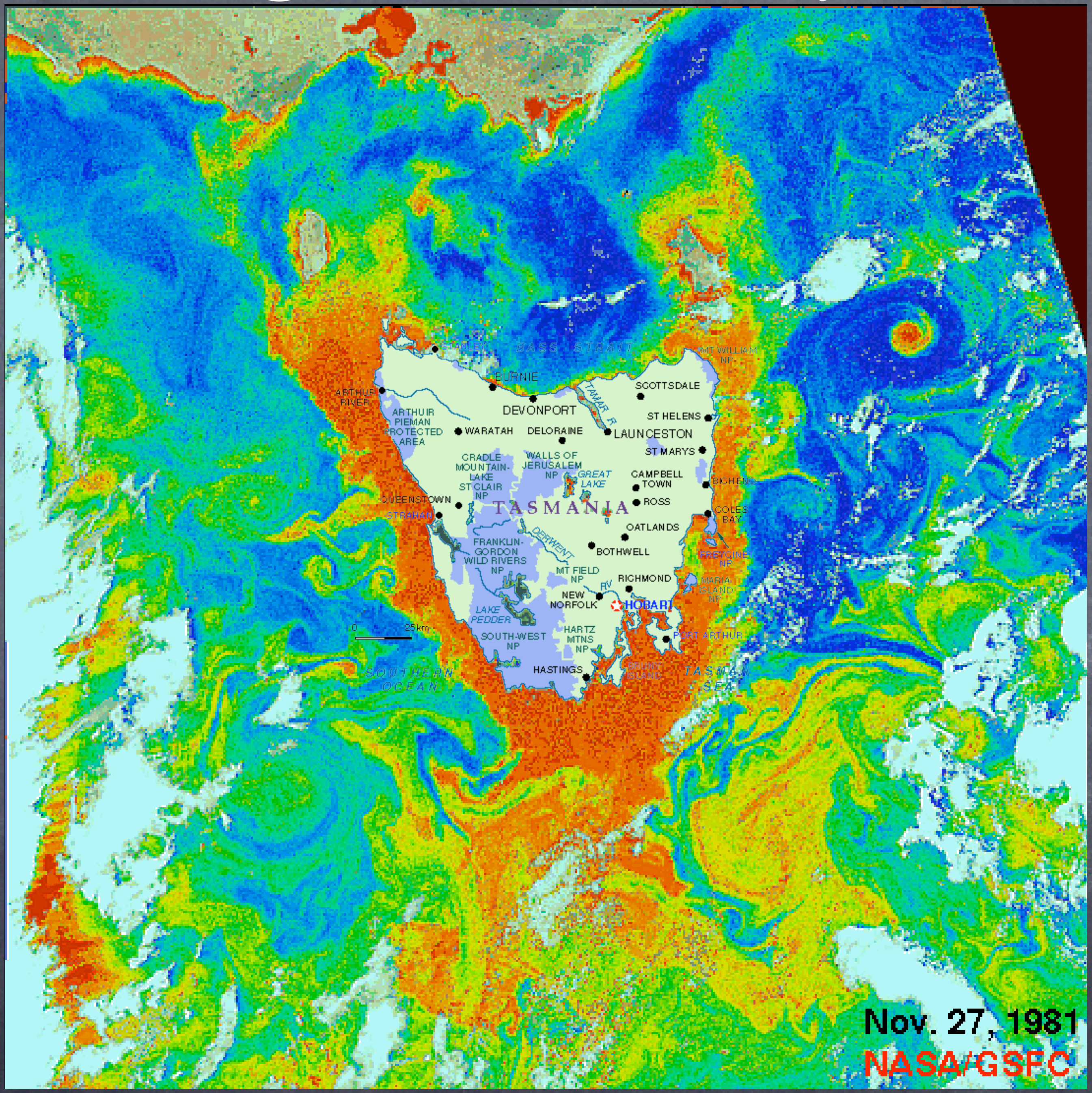
and

5% of monthly-mean surface flux climatology 50% of the time.

(compared to Grist & Josey 2003)

Biological Impact?

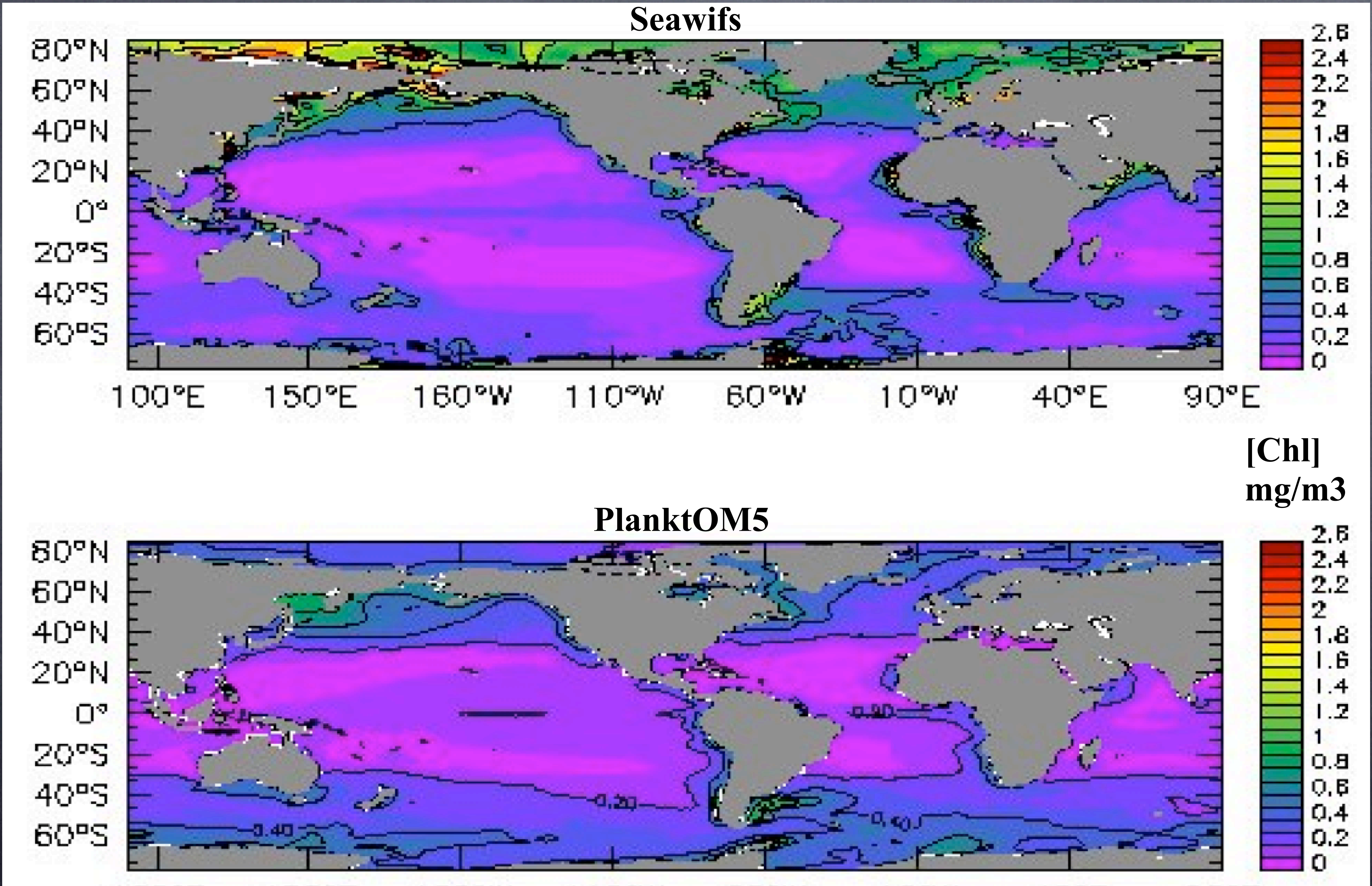
Ocean color image showing submesoscale structure in chlorophyll concentration near Tasmania



100 km

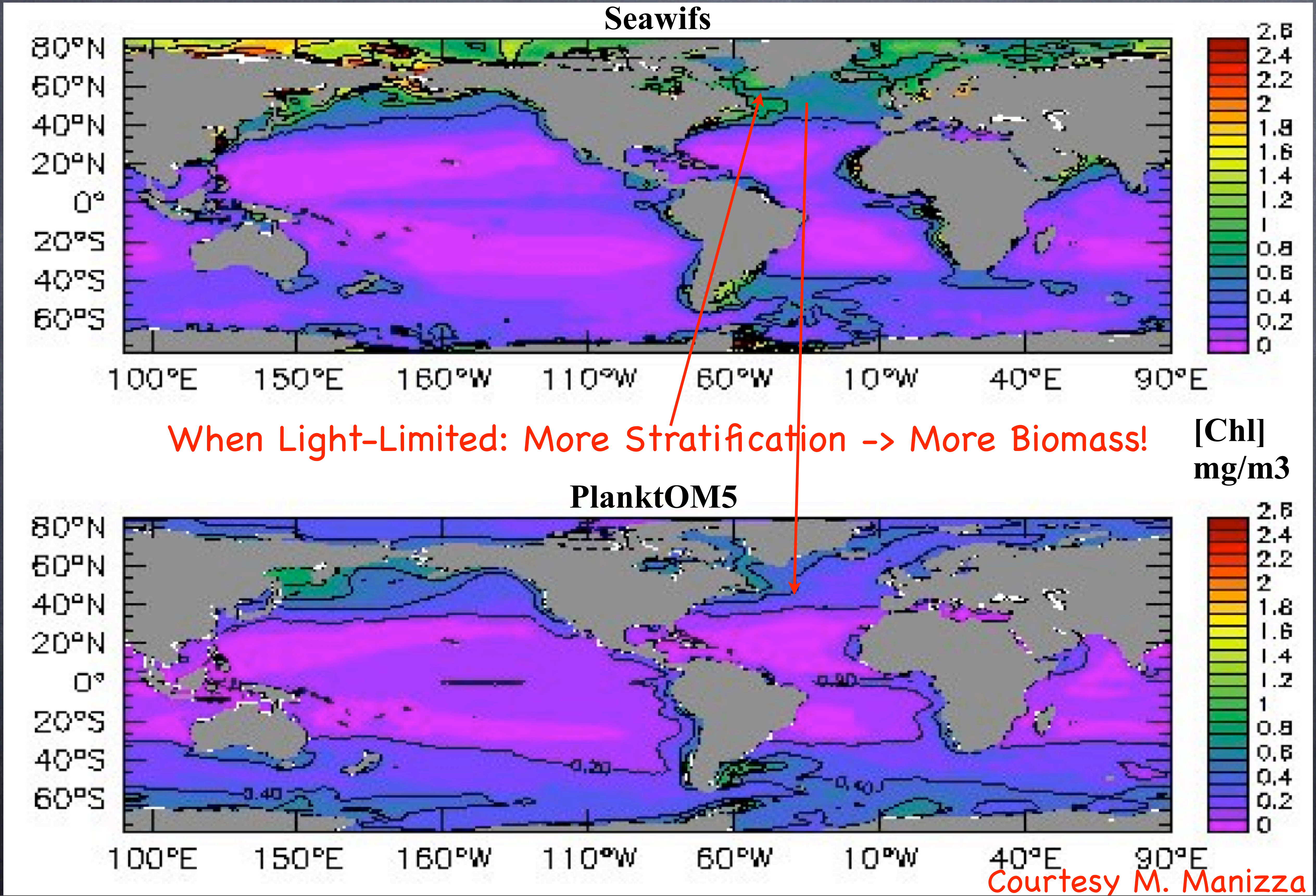
Vert. velocity of typical submesoscale eddies: > 20 m/day

Underprediction of Biology/Chlorophyll near deep convection



Courtesy M. Manizza

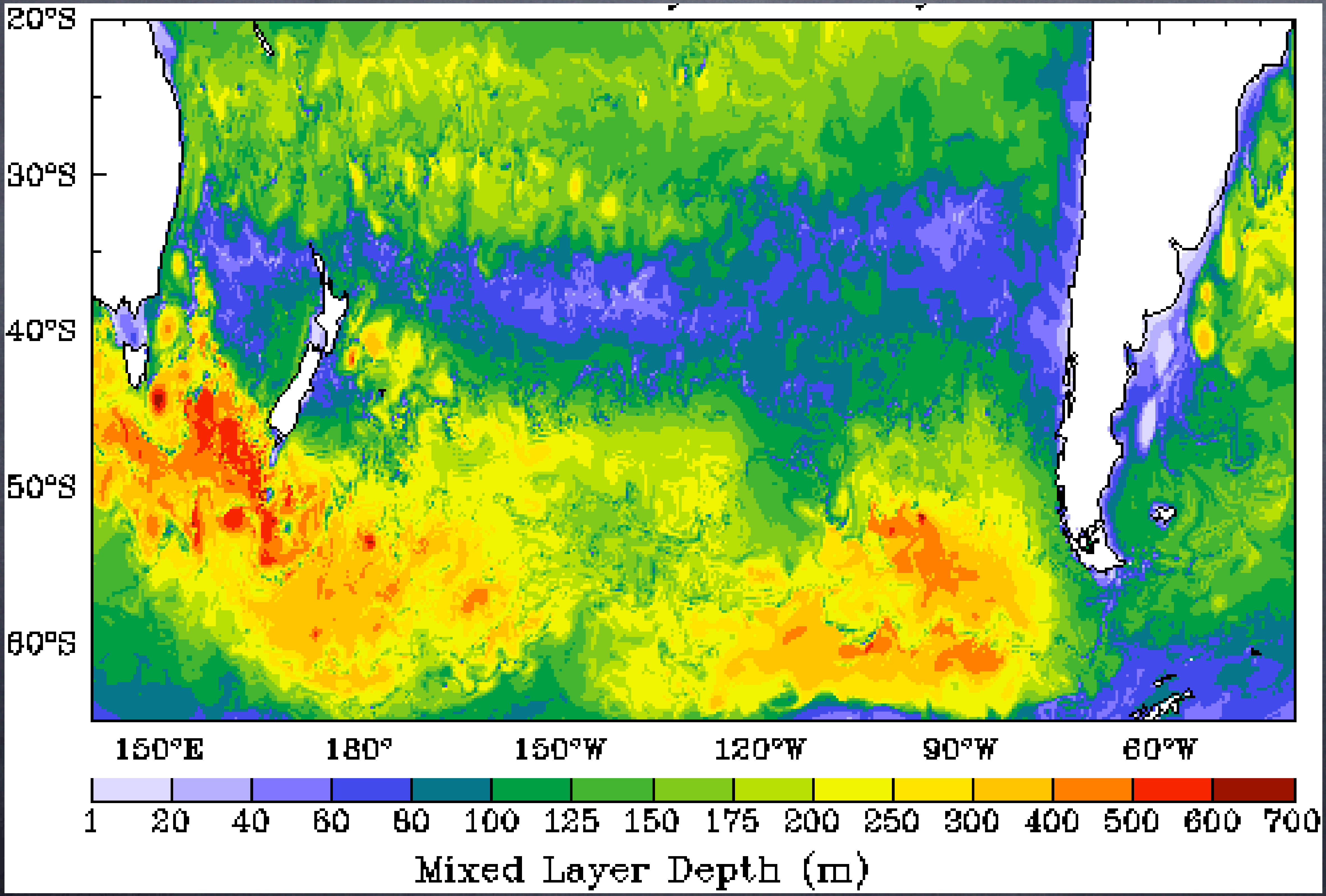
Underprediction of Biology/Chlorophyll near deep convection



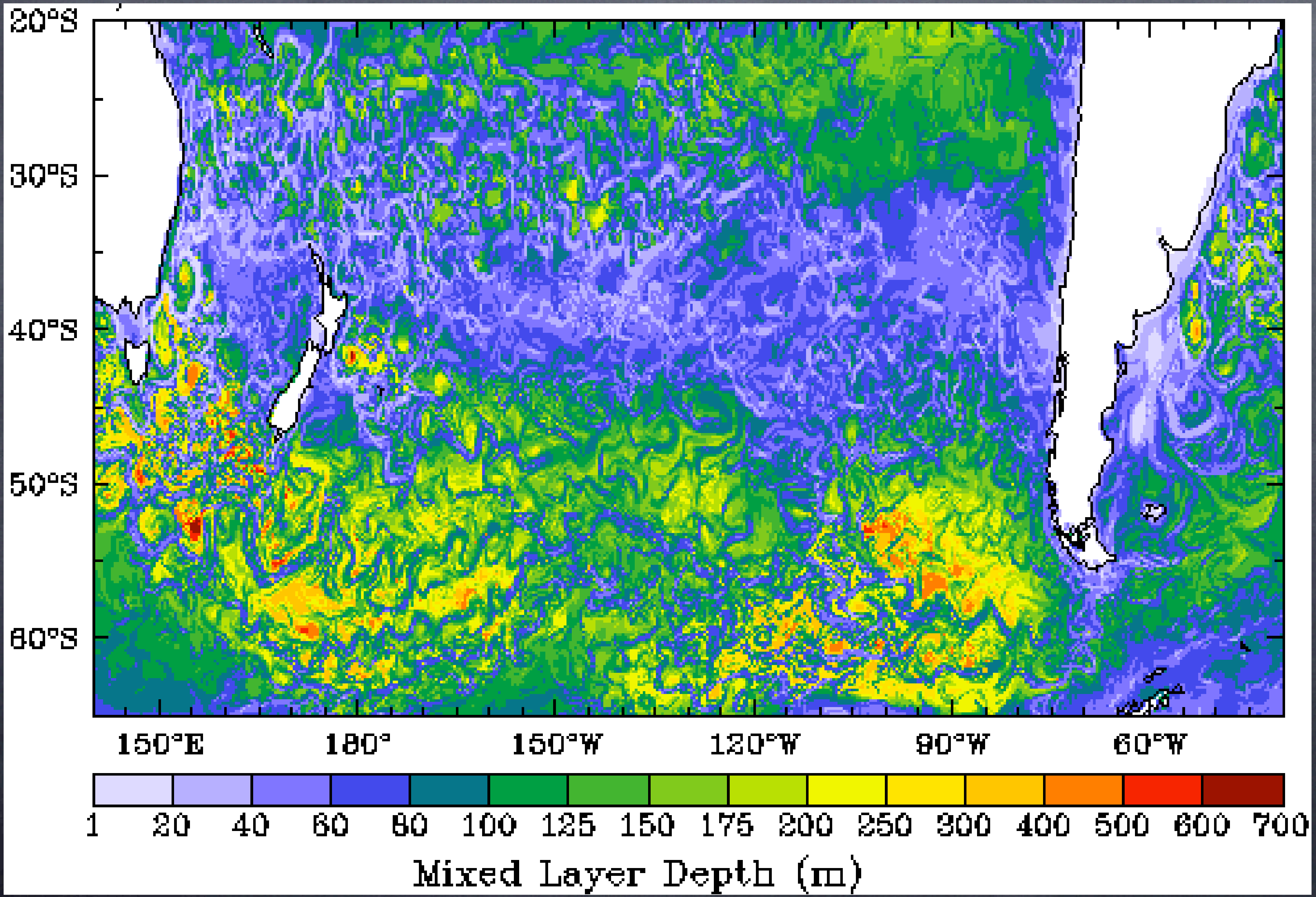
What does the new parameterization do in a GCM?

- It is already implemented in the Hallberg Isopycnal model.
- MITgcm, CCSM/POP are soon to come...

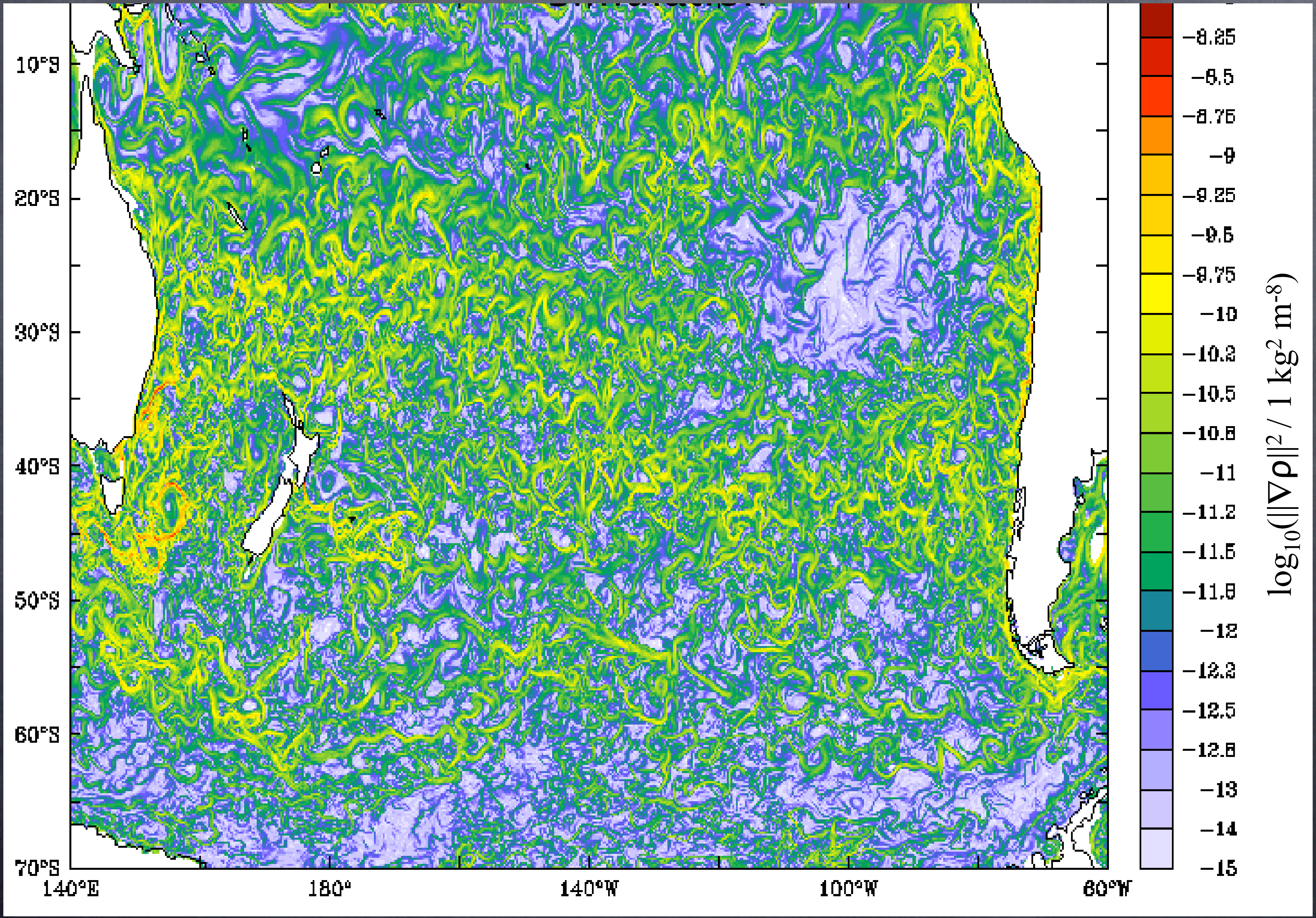
Changes To Mixing Layer Depth in Eddy-Resolving Southern Ocean Model



Changes To Mixing Layer Depth in Eddy-Resolving Southern Ocean Model



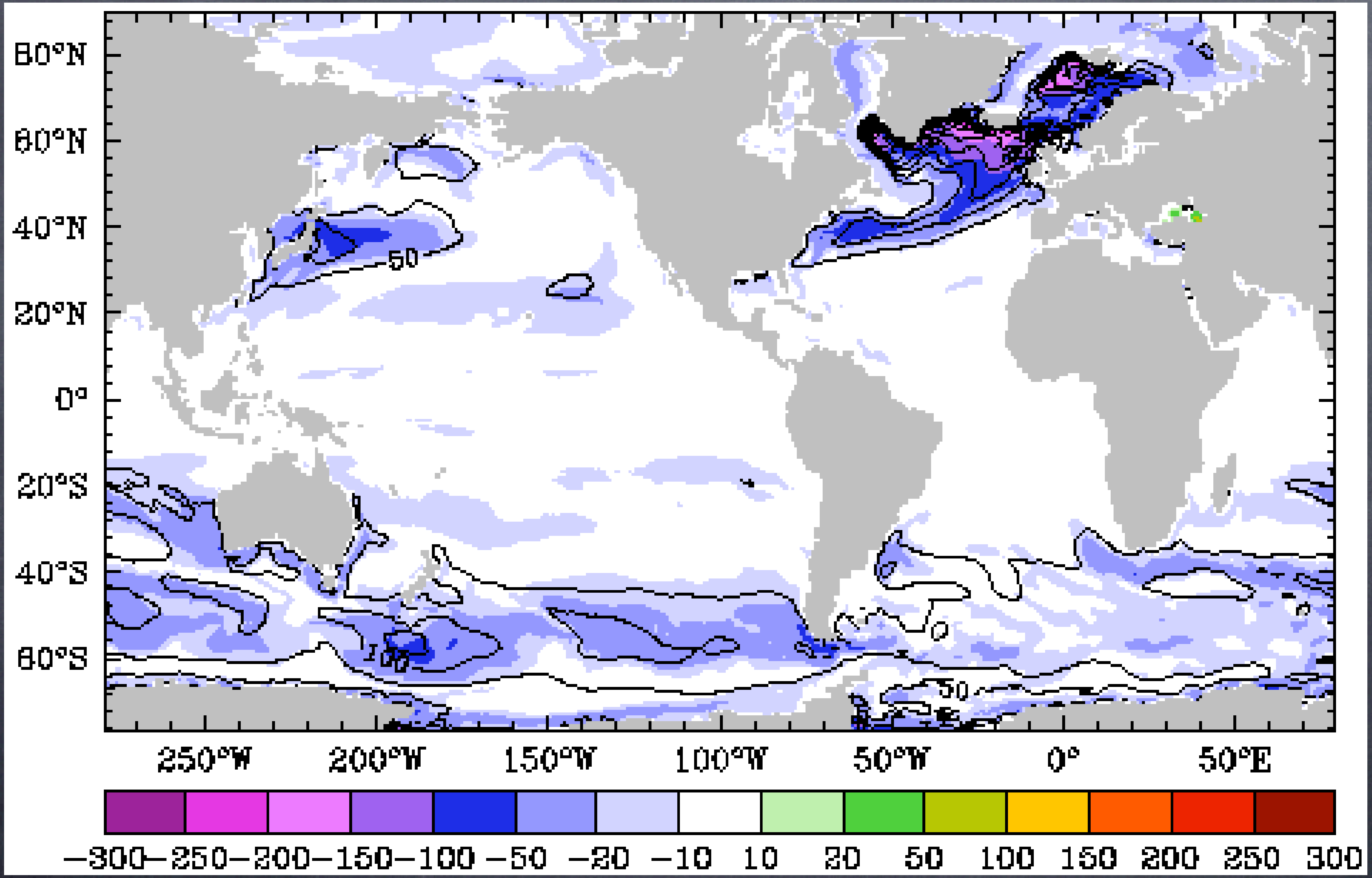
Surf. Buoy. Gradients



Equator (f->0) and coarse resolution (up to 1 deg) are manageable

Improves Restratification after Deep Convection

Note: param. reproduces Haine&Marshall (98) and Jones&Marshall (93,97)



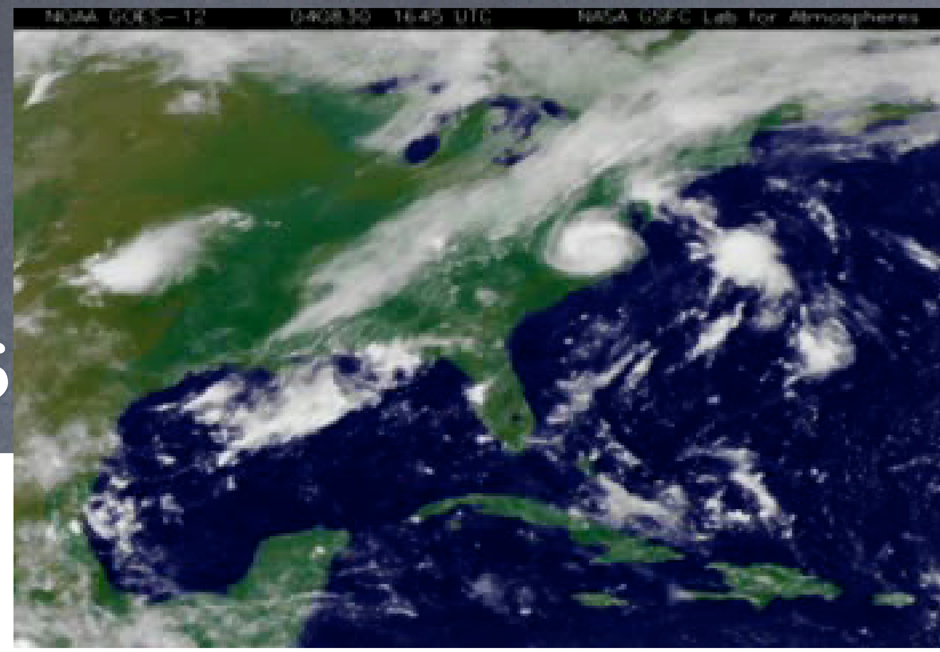
Contoured: 5-yr mean mixing layer depth (m) in HIM.
Shaded: change (m) with parameterization

Conclusion:

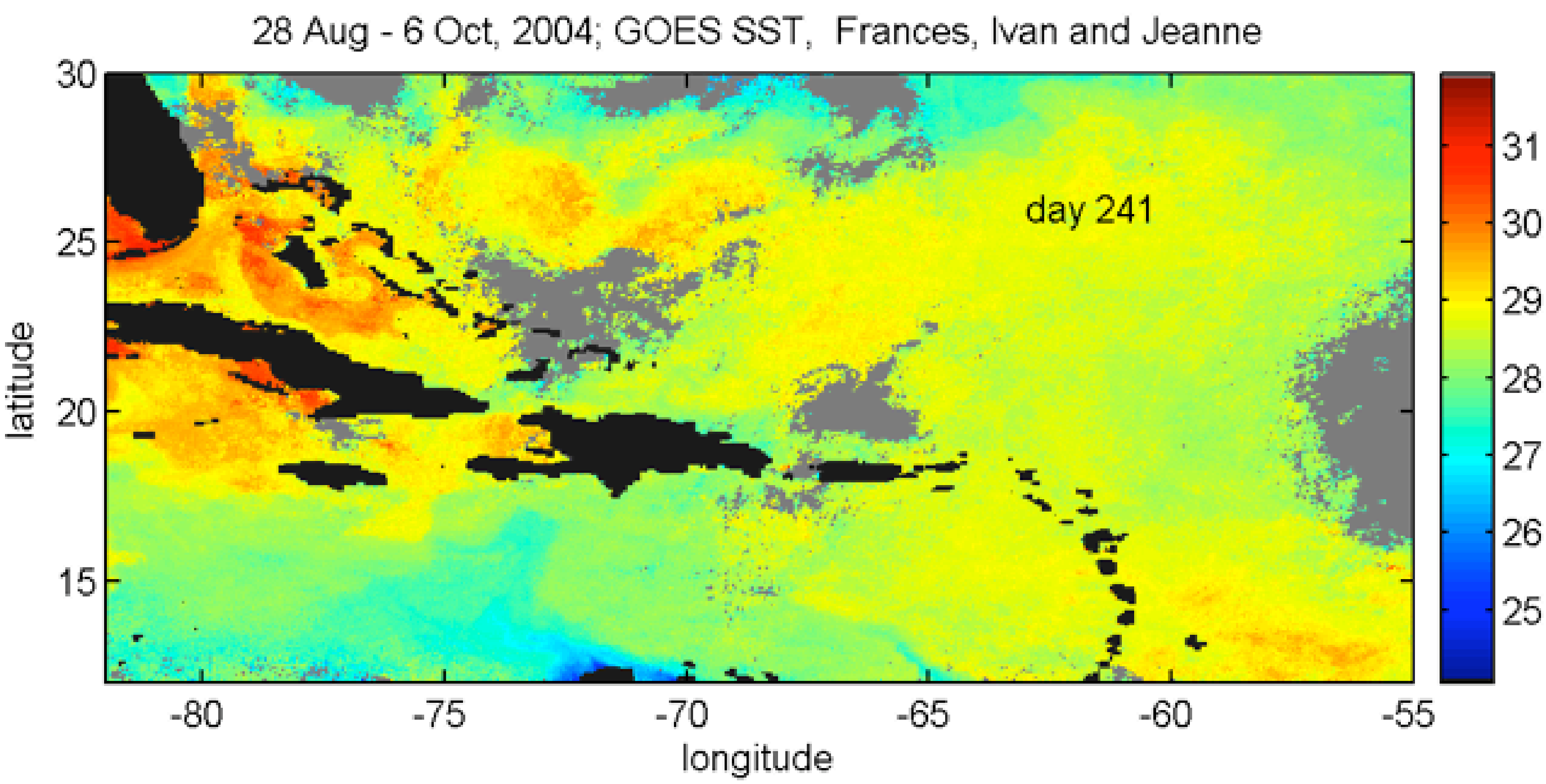
- Submesoscale features, and mixed layer eddies in particular, exhibit large vertical fluxes of buoyancy that are presently ignored in climate models.
- A parameterization of mixed layer eddy fluxes as an overturning streamfunction is proposed. The magnitude comes from extraction of potential energy, and the vertical structure resembles the linear Eady solution.
- Many observations are consistent, and model biases are reduced. Biogeochemical effects are likely, as vertical fluxes and mixed layer depth are changed.
- In HIM, soon to be in MITgcm and CCSM.
- 3 Papers so far... Just ask me for them.

More to come...

NASA: Seawifs

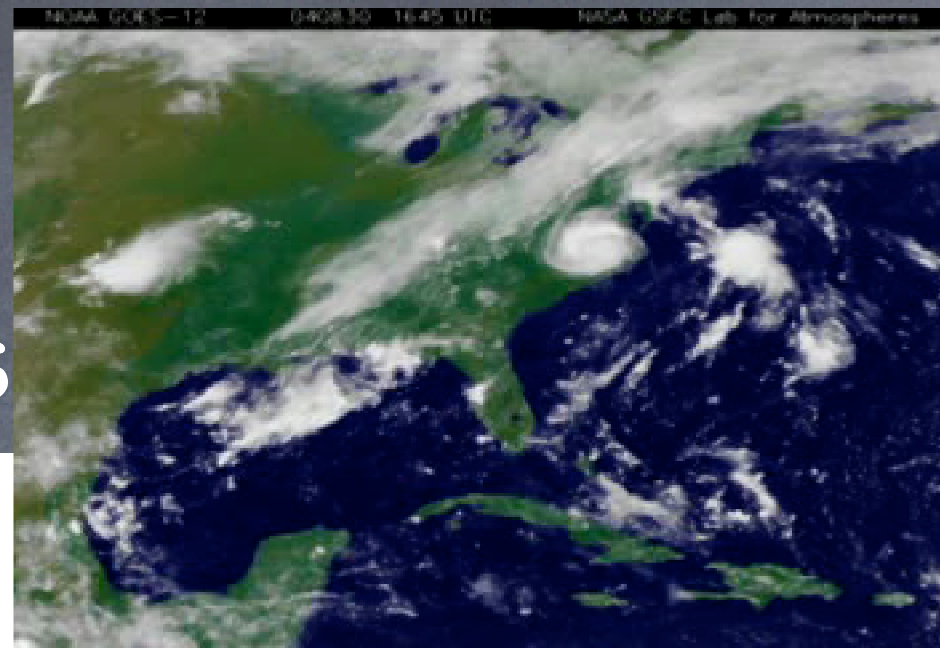


Hurricane Wake Recovery...



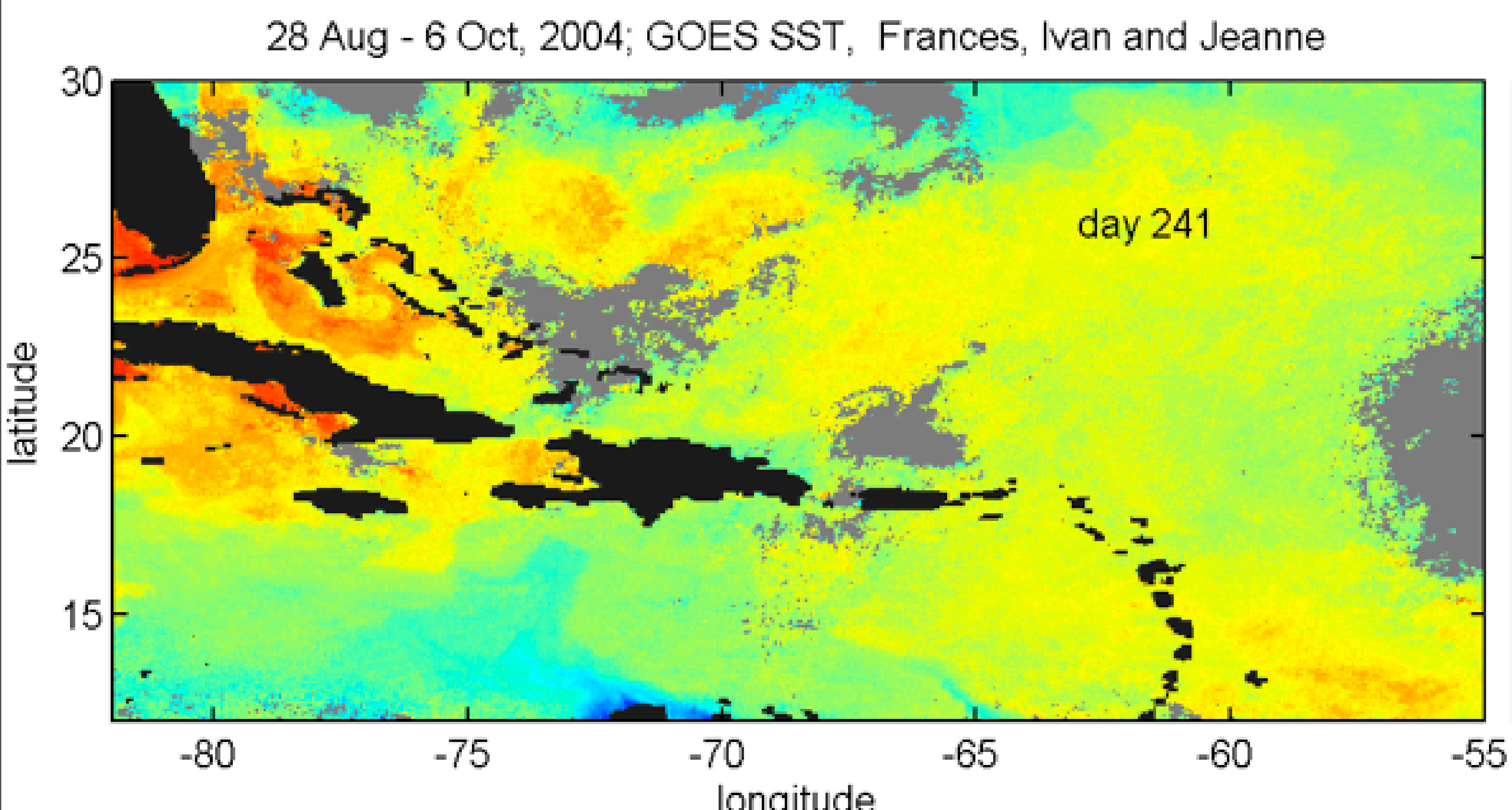
More to come...

NASA:
Seawifs



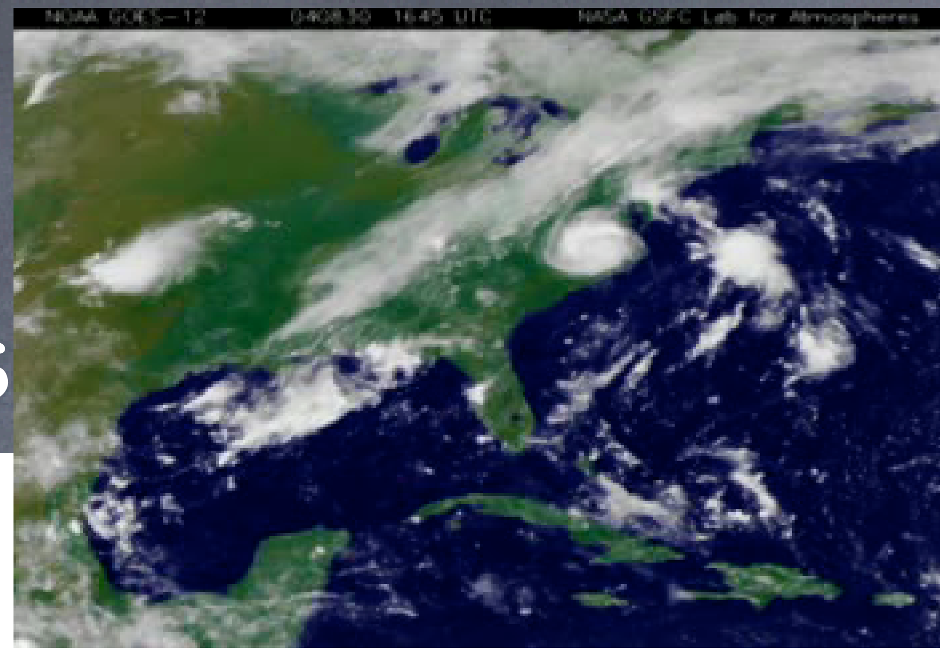
Lots of Data!
Satellites

Hurricane Wake Recovery...



More to come...

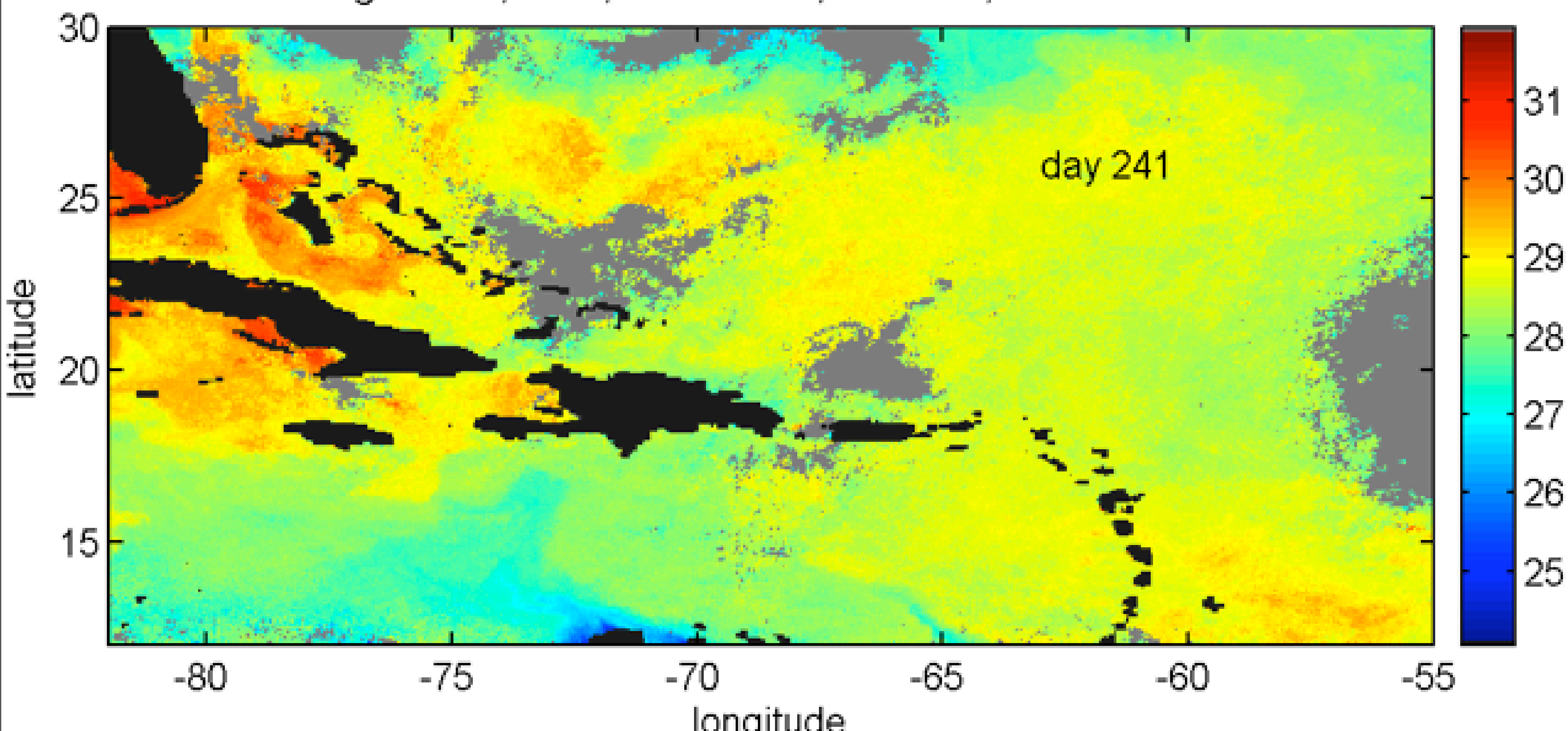
NASA: Seawifs



Lots of Data! Satellites with Chlorophyll

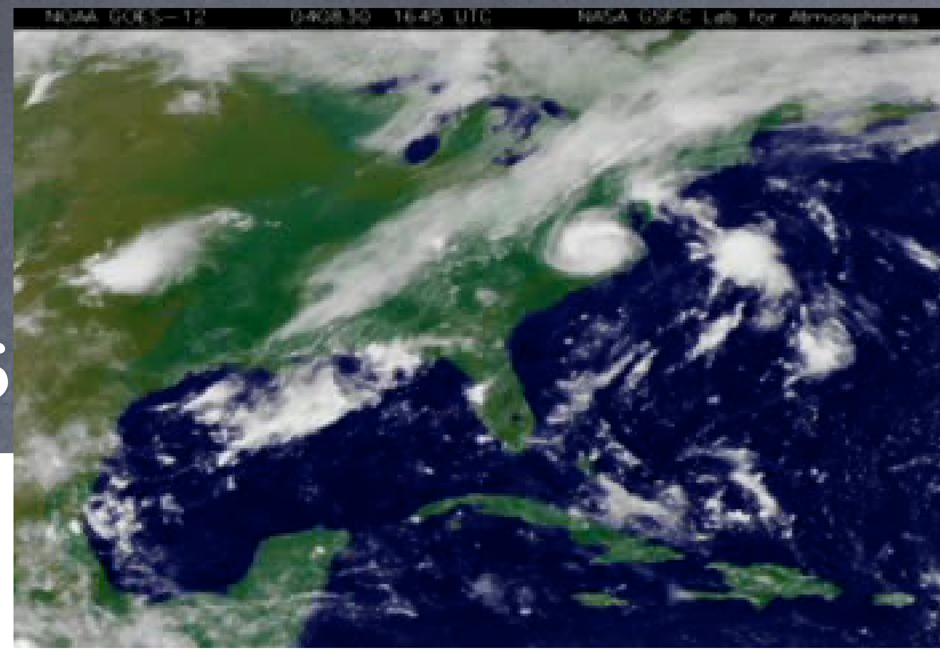
Hurricane Wake Recovery...

28 Aug - 6 Oct, 2004; GOES SST, Frances, Ivan and Jeanne



More to come...

NASA:
Seawifs



Lots of Data!
Satellites
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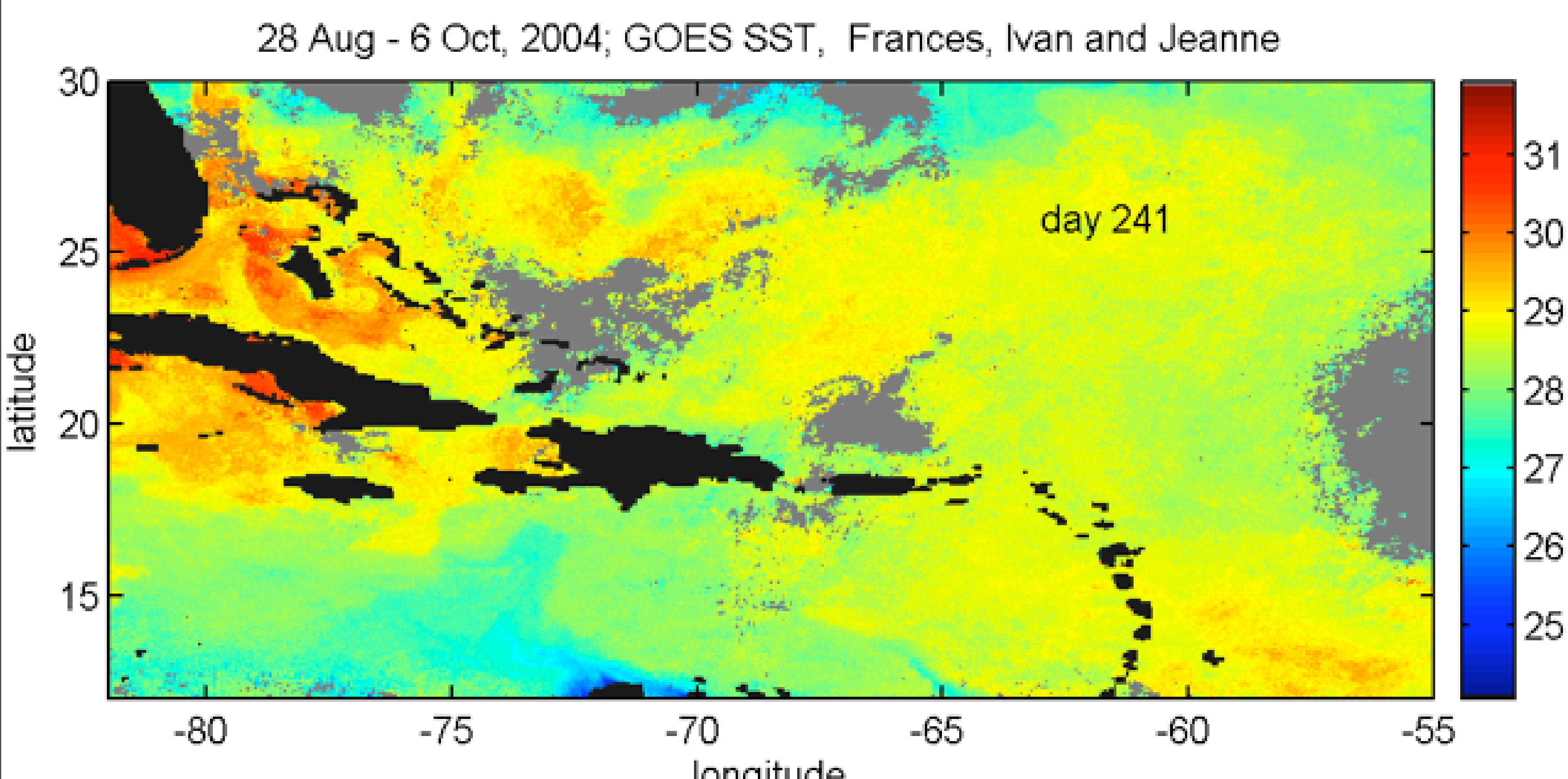
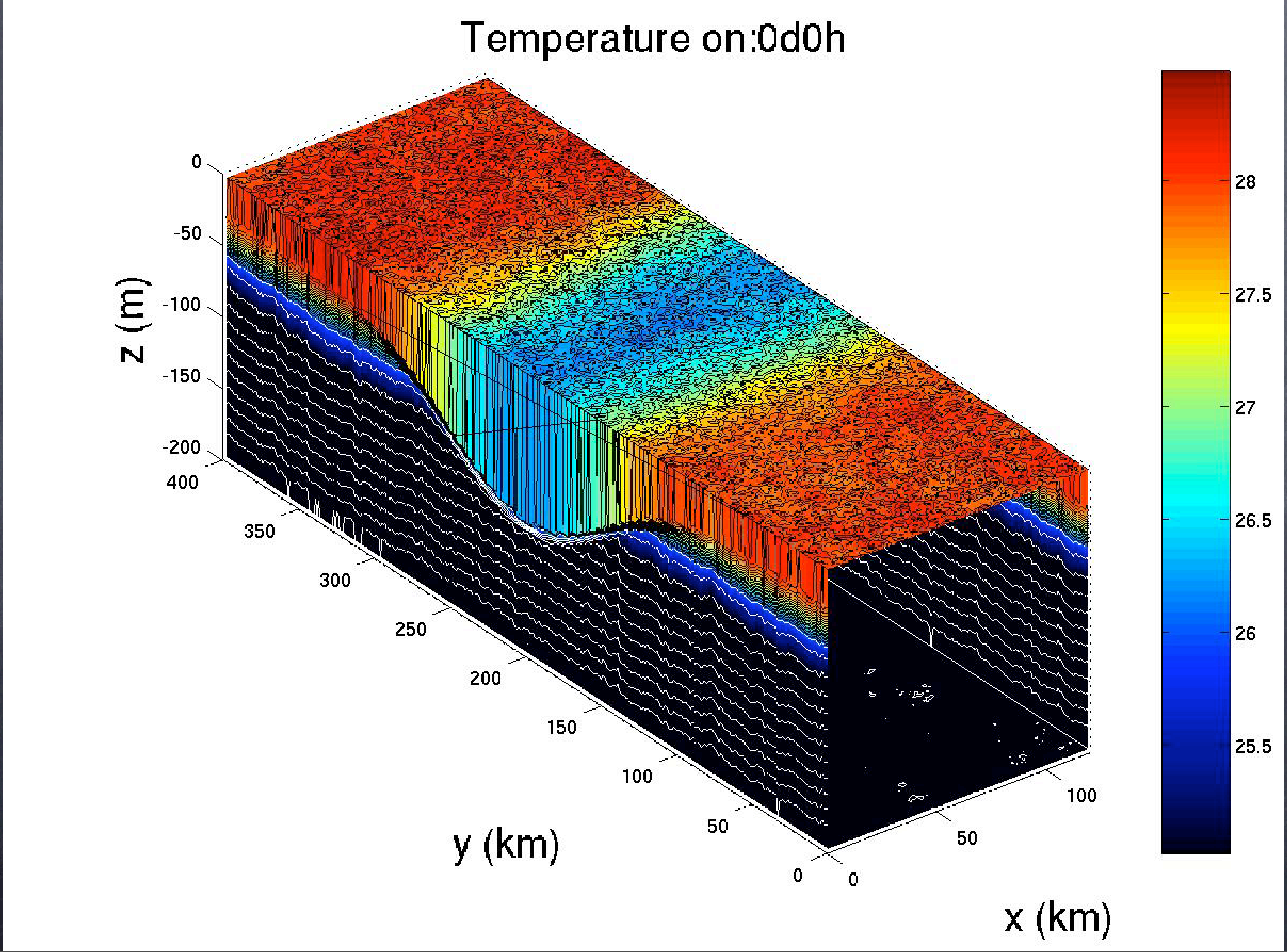
Chlorophyll

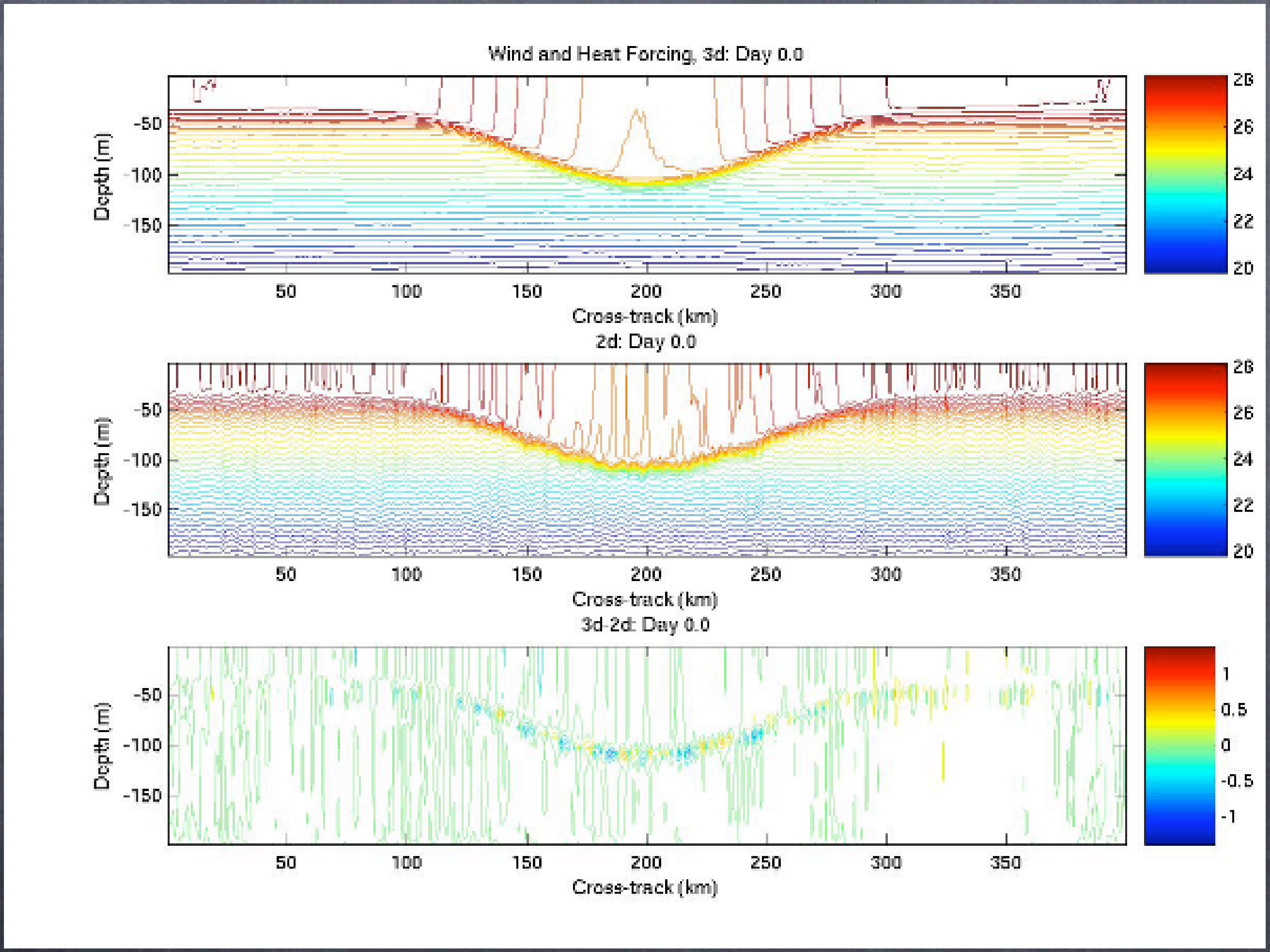
Hurricane Wake Recovery...



Preliminary Simulations

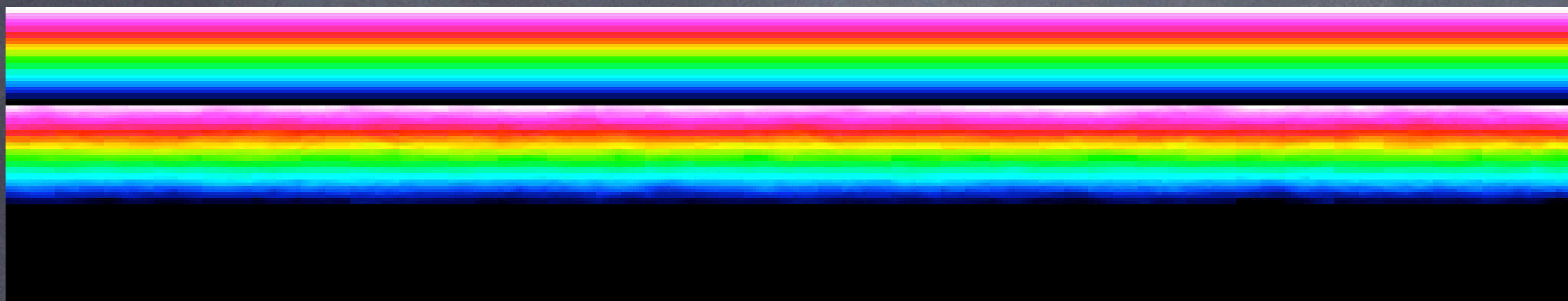


Compare with 2d (no eddies)



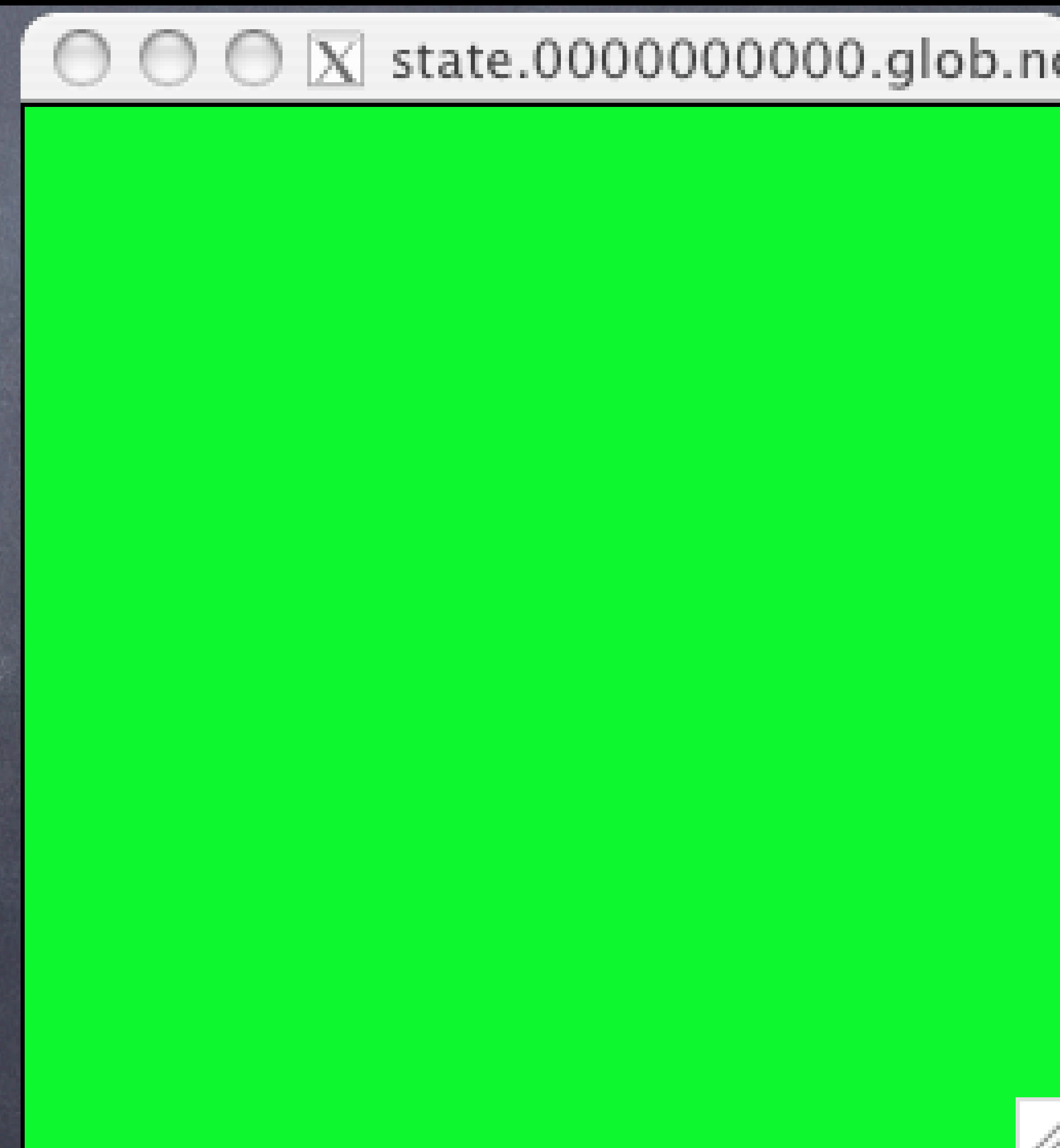
Coupling to 3d turbulence?

T
U
V

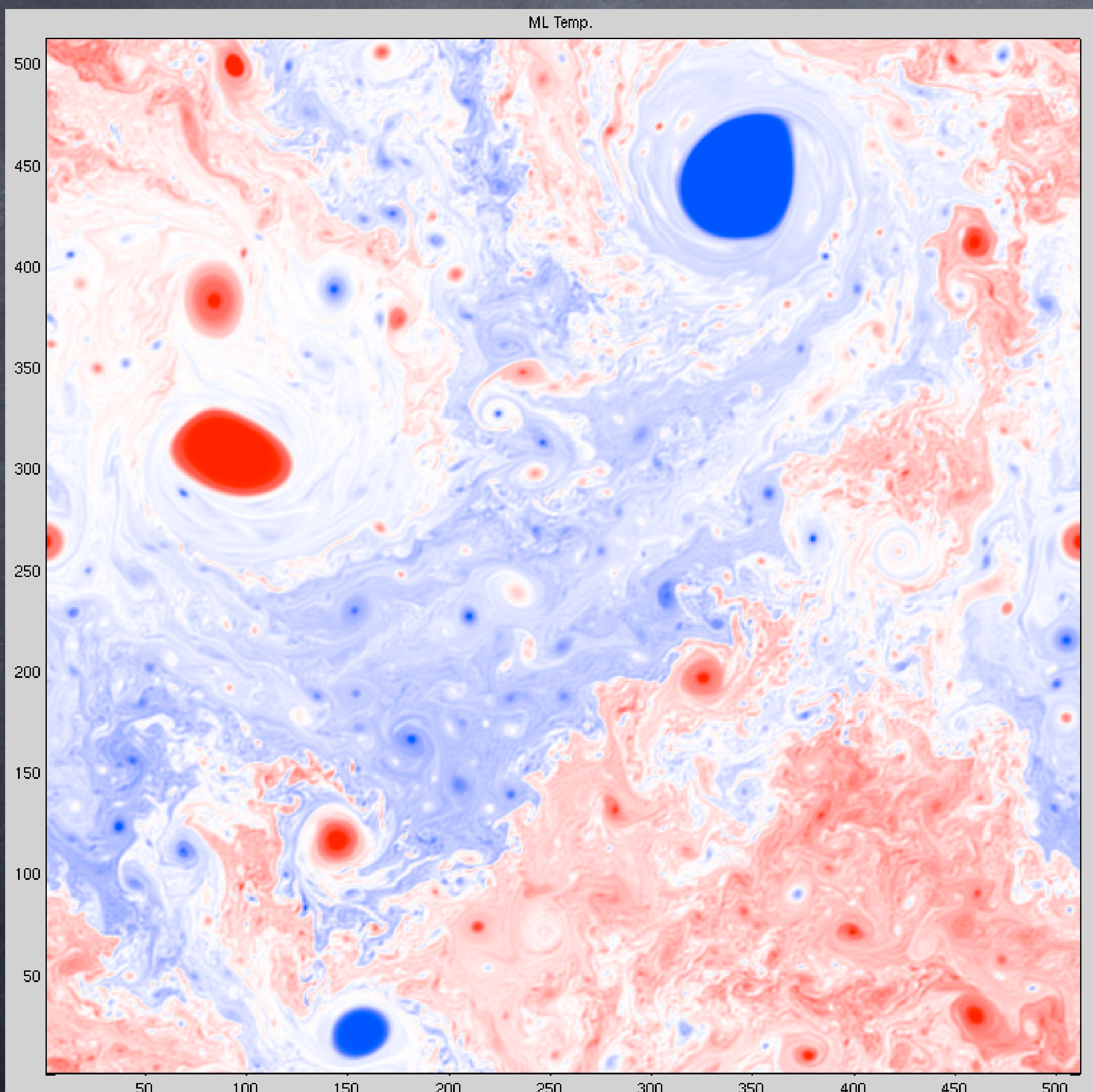


We saw little effect of KPP/diurnal on MLEs, but...

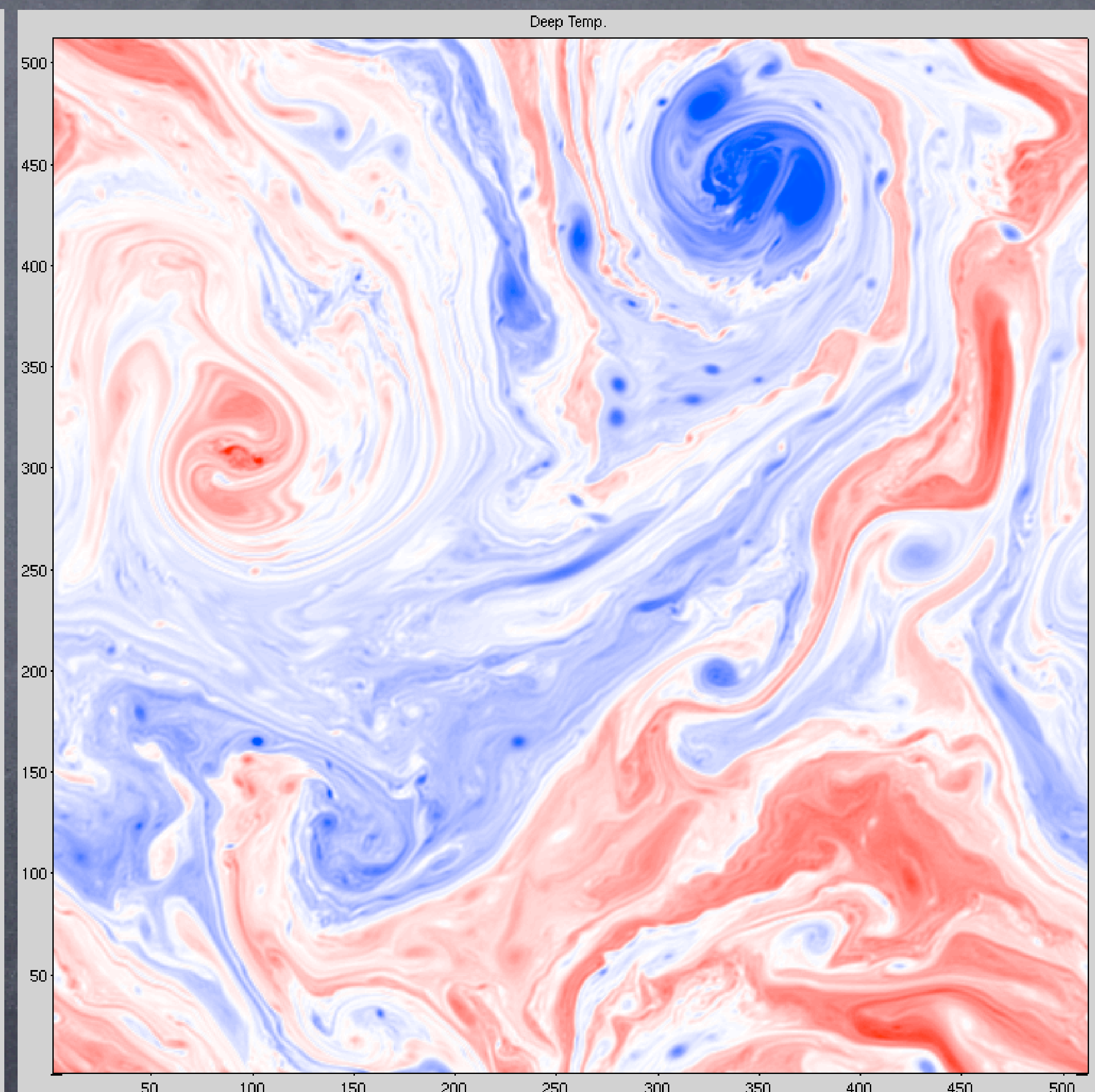
Plan View of W



Blumen Model: multiple layer Eady model (SQG) allows an approximate coupled run to equilibrate.



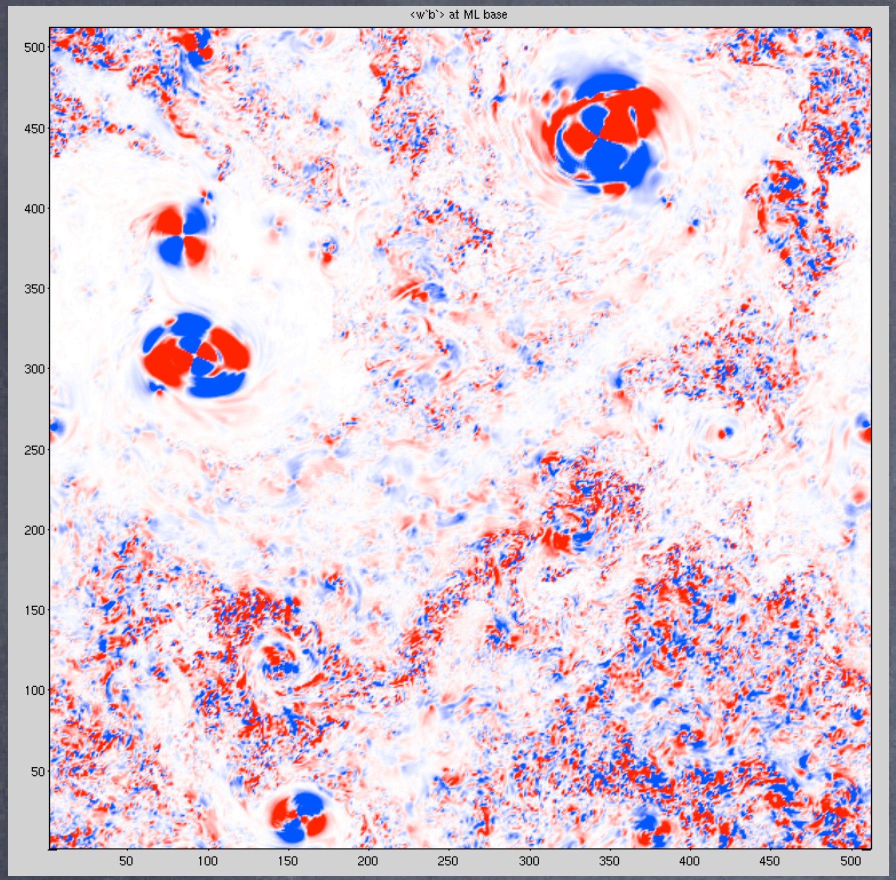
Surface Temp

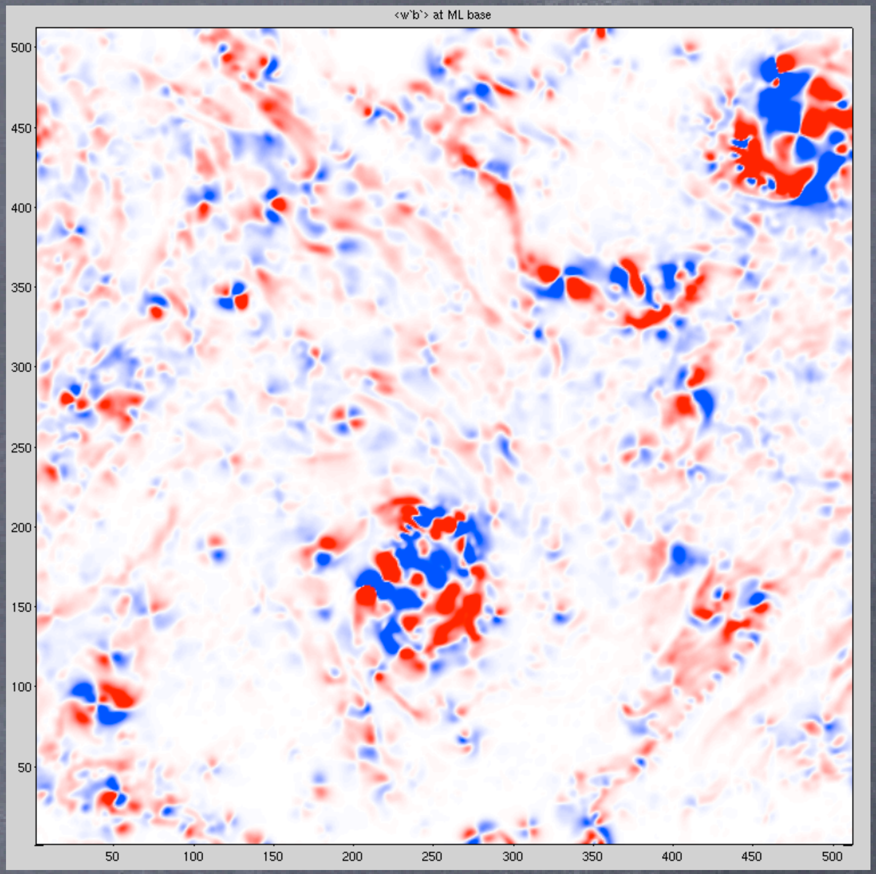


Bottom Temp

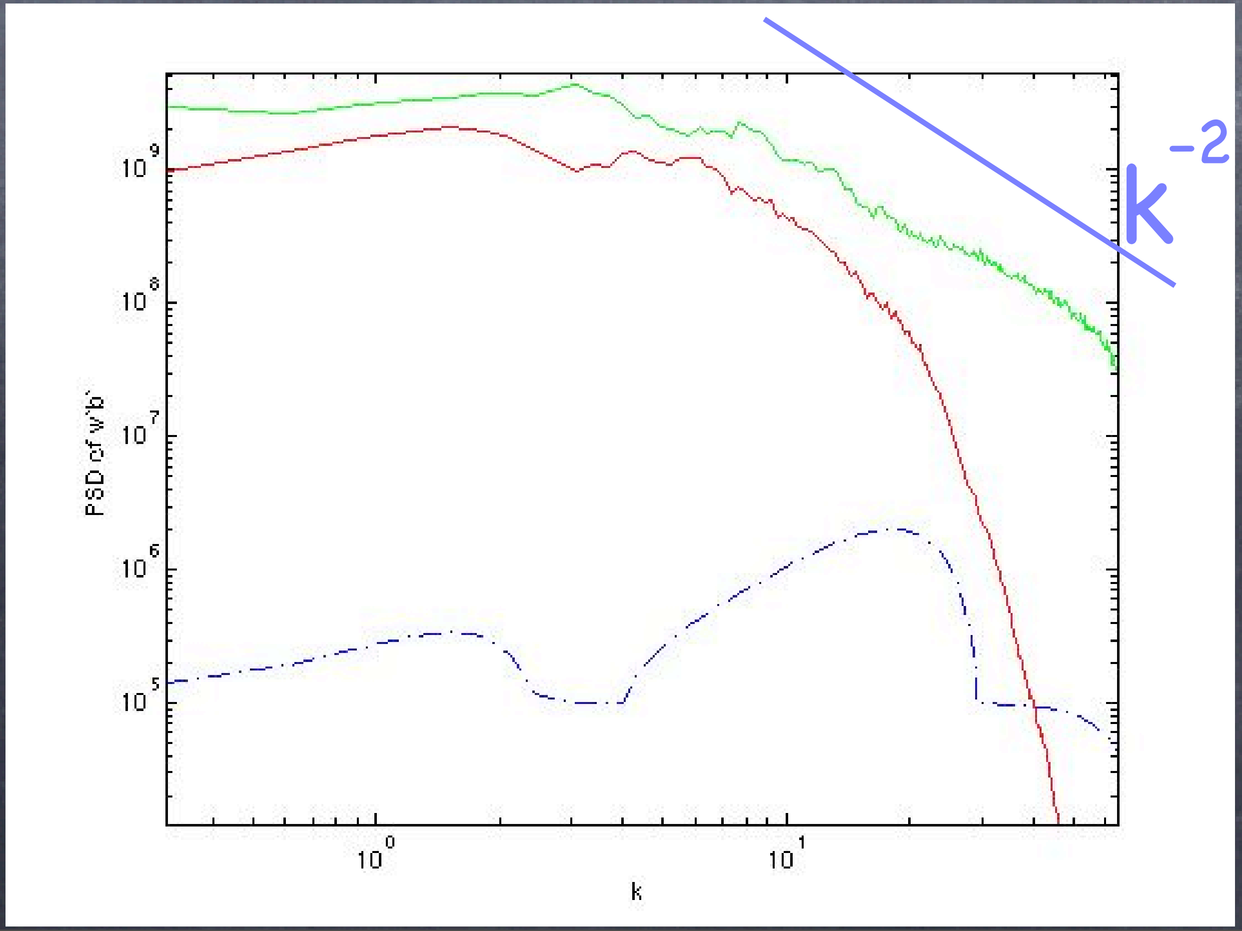
WB With a ML

WB Without a ML





Spectra



The Parameterization:

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

$$\mu(z) = \left[1 - \left(\frac{2z}{H} + 1\right)^2\right] \left[1 + \frac{5}{21}\left(\frac{2z}{H} + 1\right)^2\right]$$

- The horizontal fluxes are downgradient:

$$\overline{\mathbf{u}'_{\mathbf{H}} b'} = -\frac{C_e H^2 \mu(z) \frac{\partial b}{\partial z}}{|f|} \nabla_H \bar{b}$$

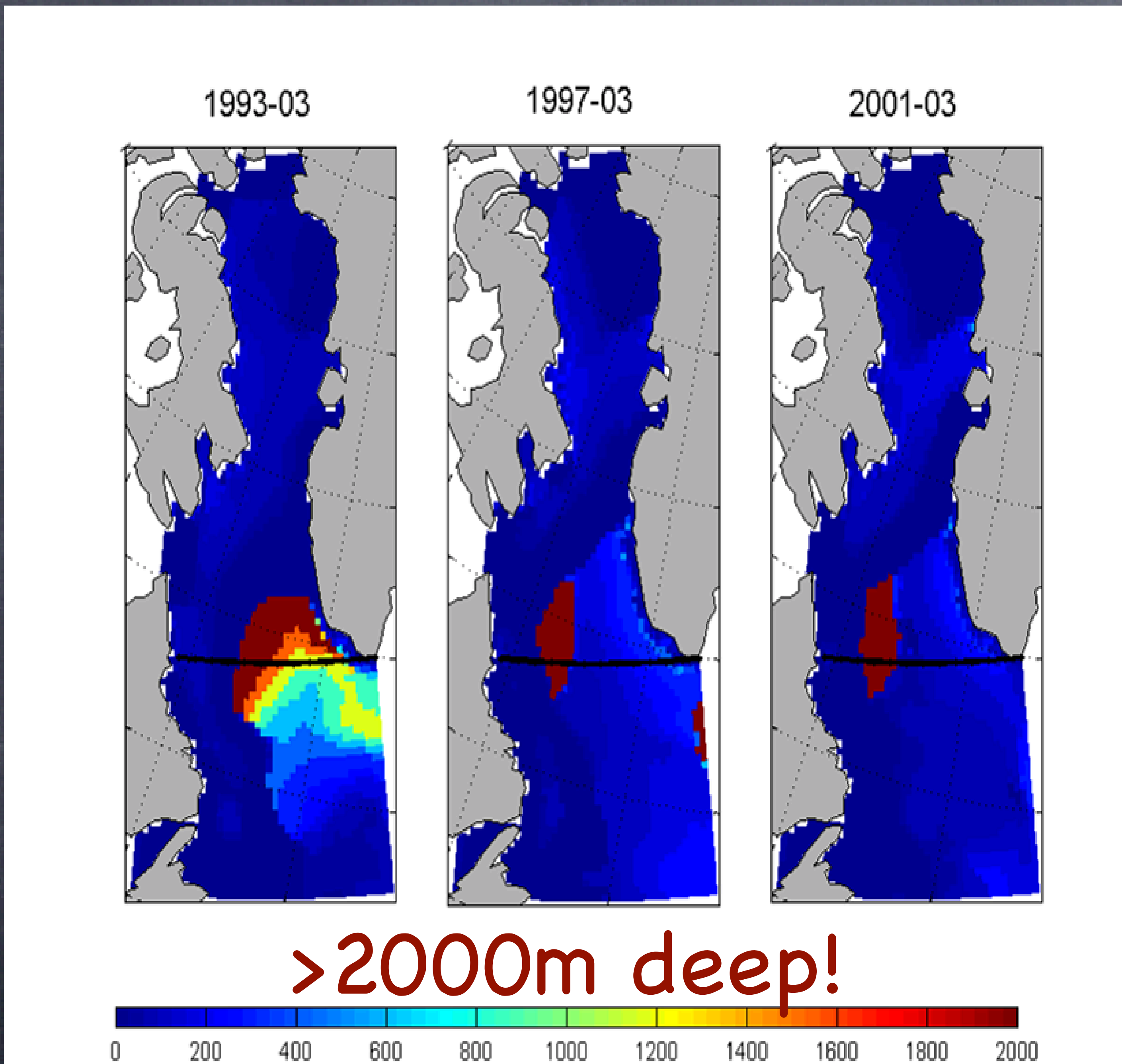
- Vertical fluxes always upward to restratify:

$$\overline{w' b'} = \frac{C_e H^2 \mu(z)}{|f|} |\nabla \bar{b}|^2$$

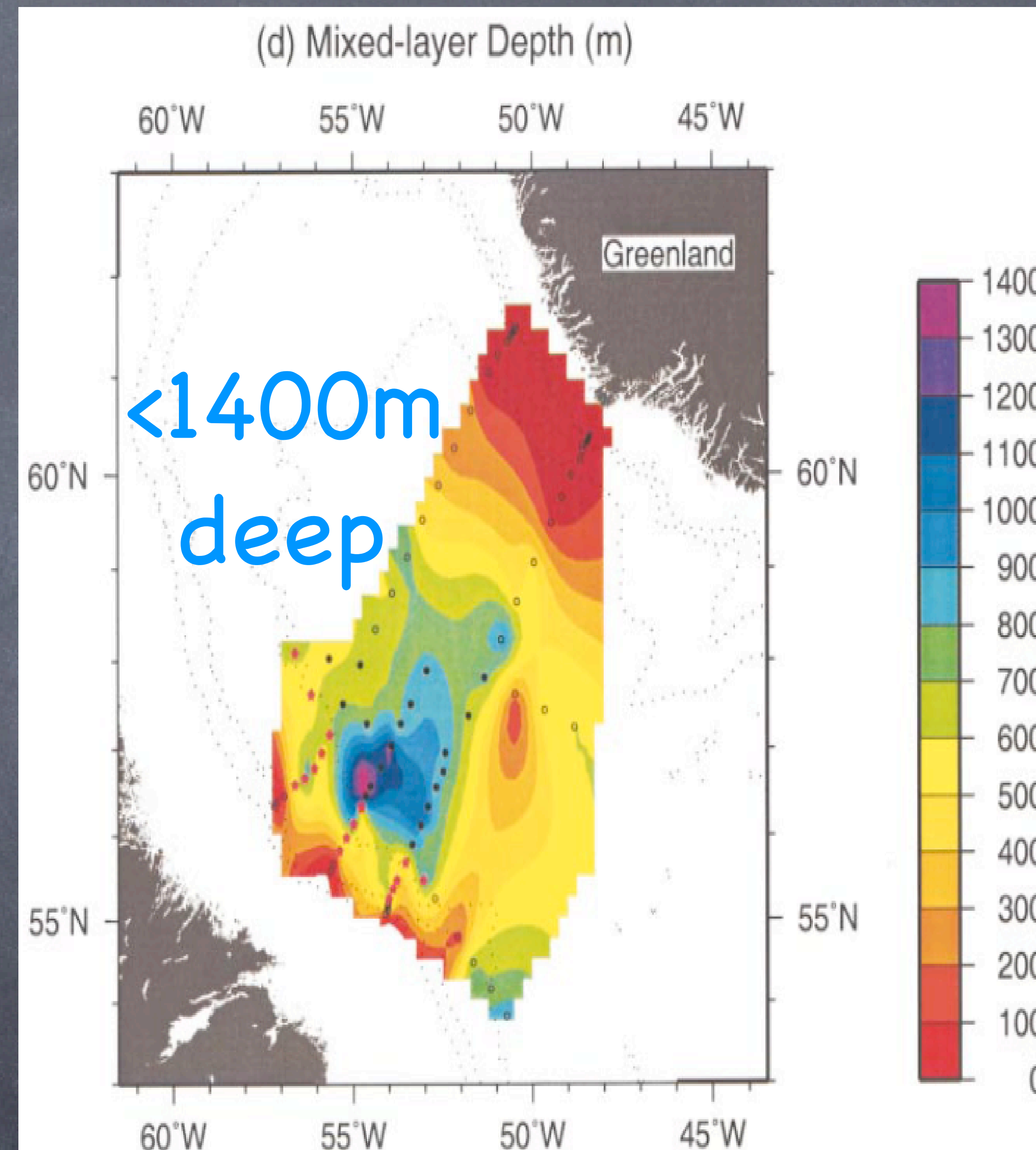
- Adjustments for coarse resolution and f->0 are known

Known Deep Bias in Models

MLD: MITgcm data assim



MLD from Obs.



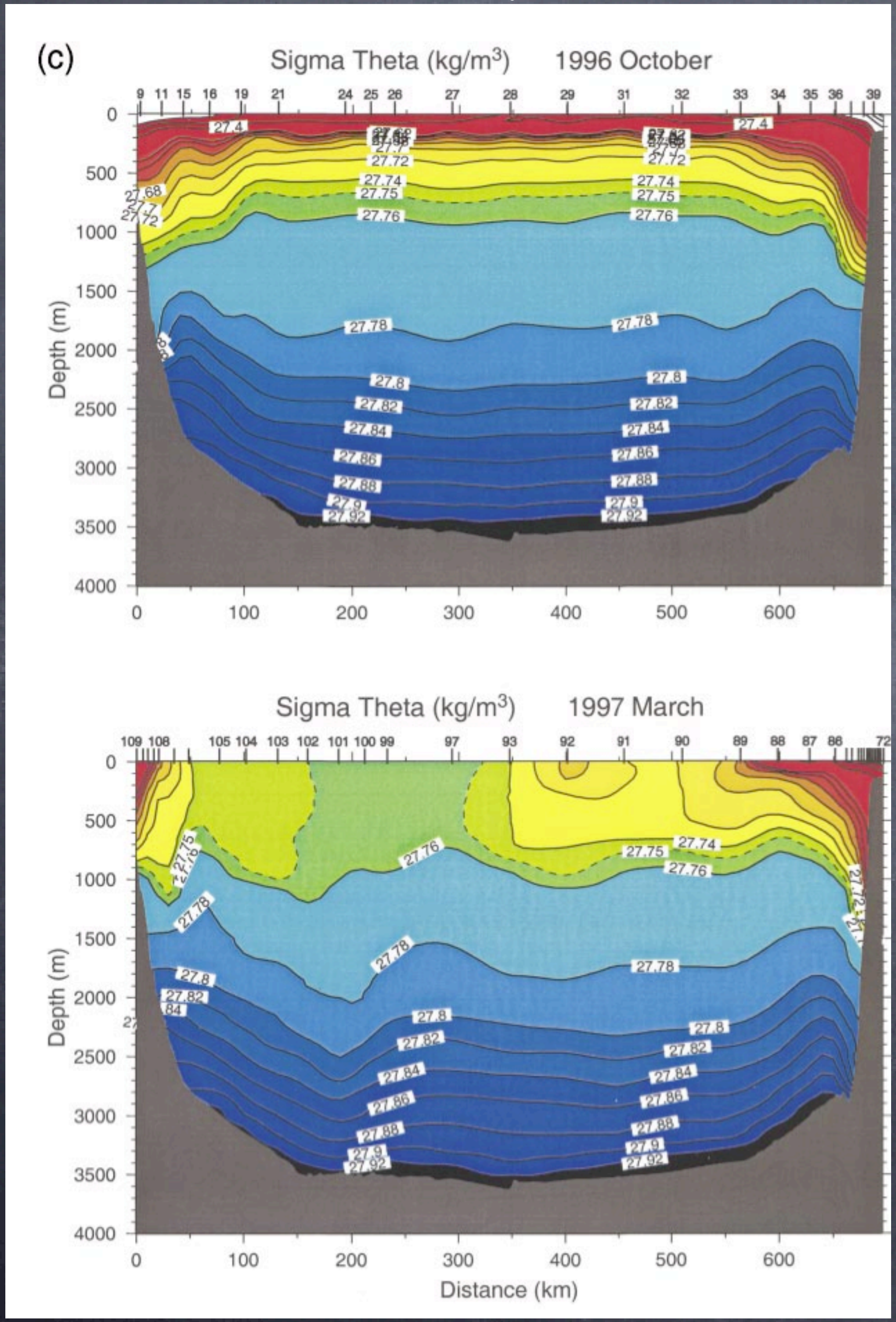
Courtesy I. G. Fenty

Hydrography of the Labrador Sea during Active Convection

Robert S. Pickart and Daniel J. Torres

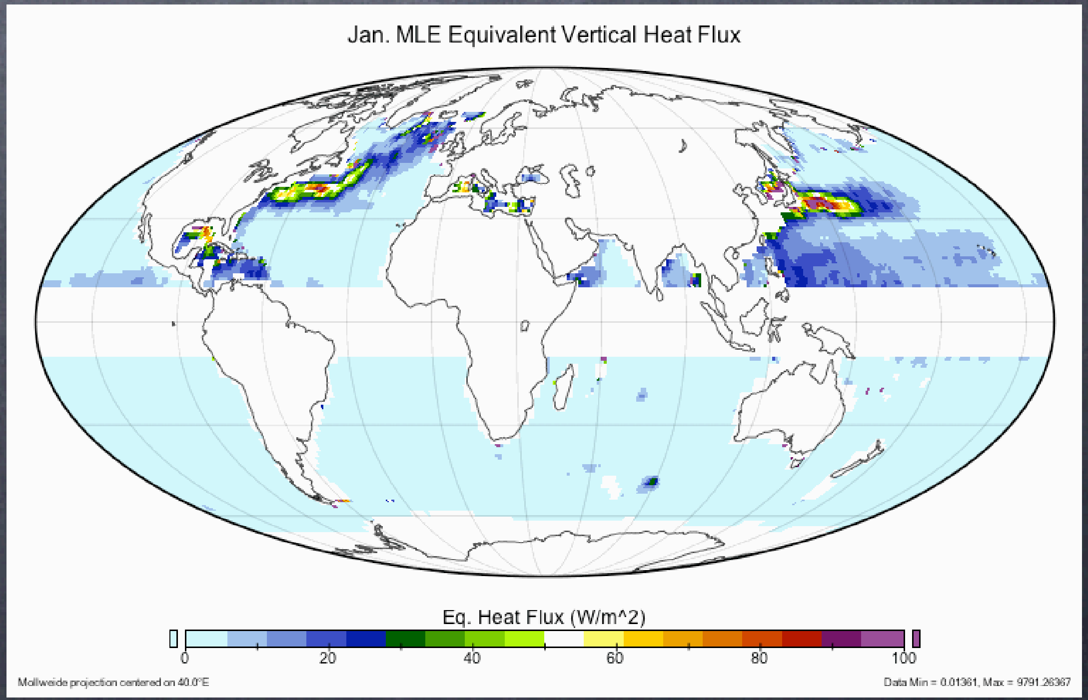
Deep Bias Partly Convection, but also total absence of restratification,

(GM can't do it because of tapering)



Pickart et al 02.

Fenty/MITgcm



Deep Bias Partly Convection, but also total absence of restratification,

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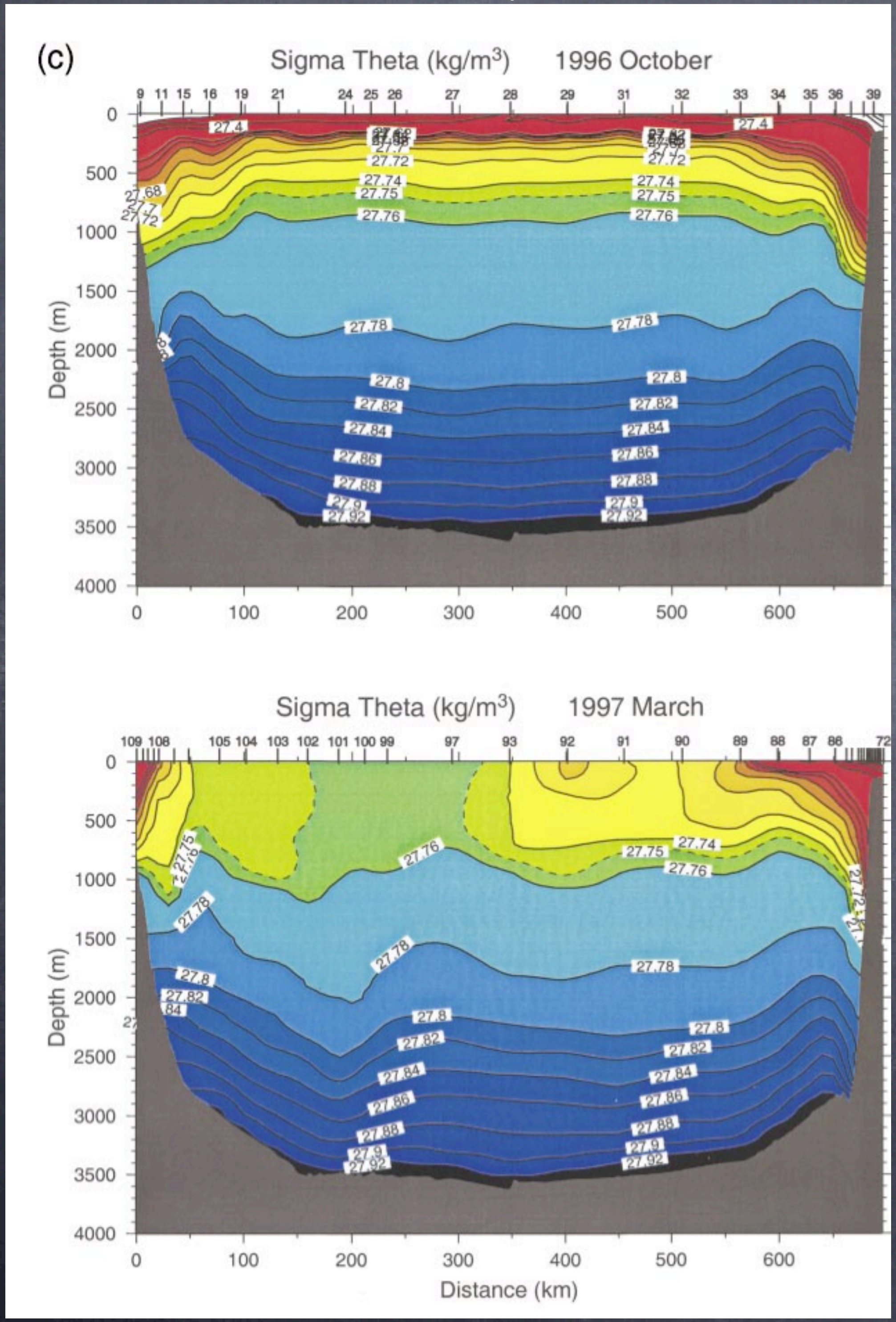
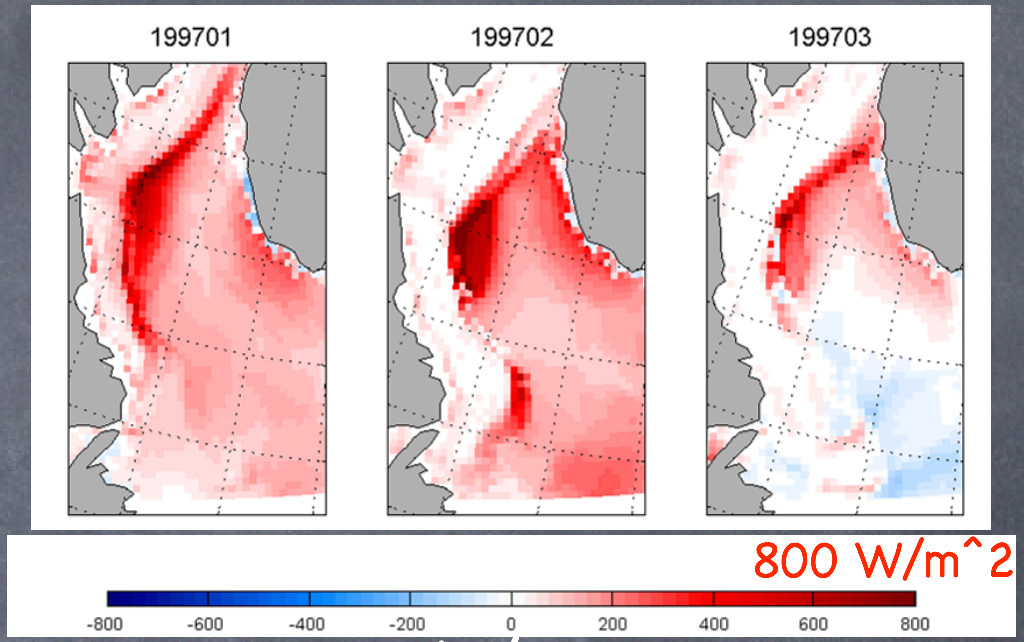
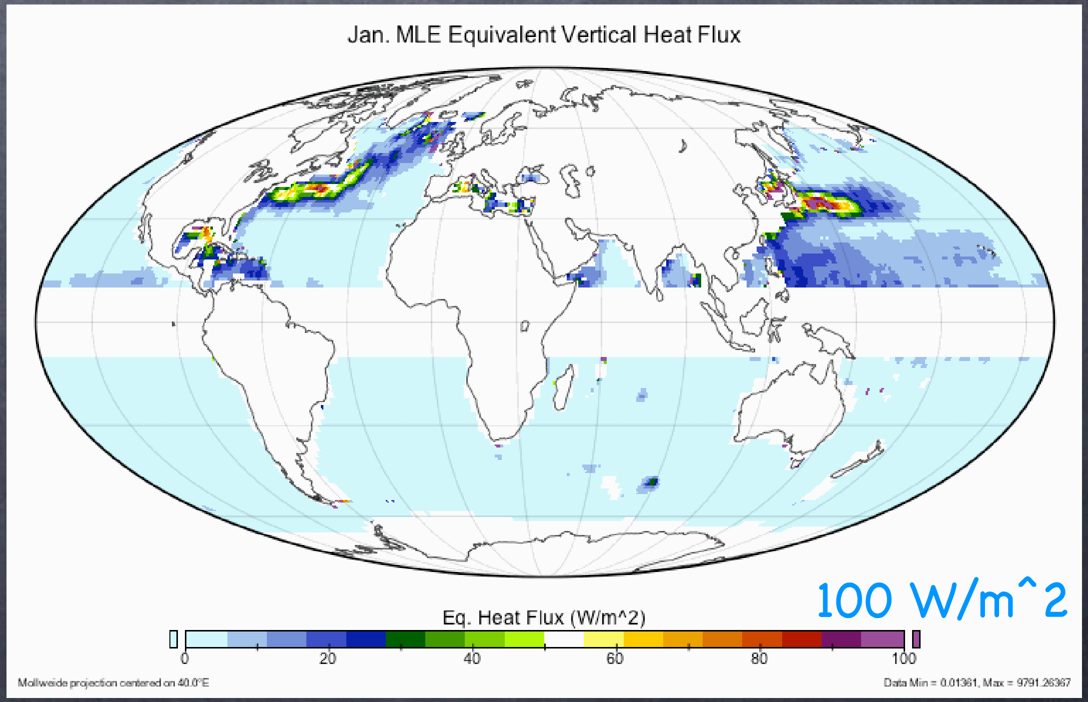


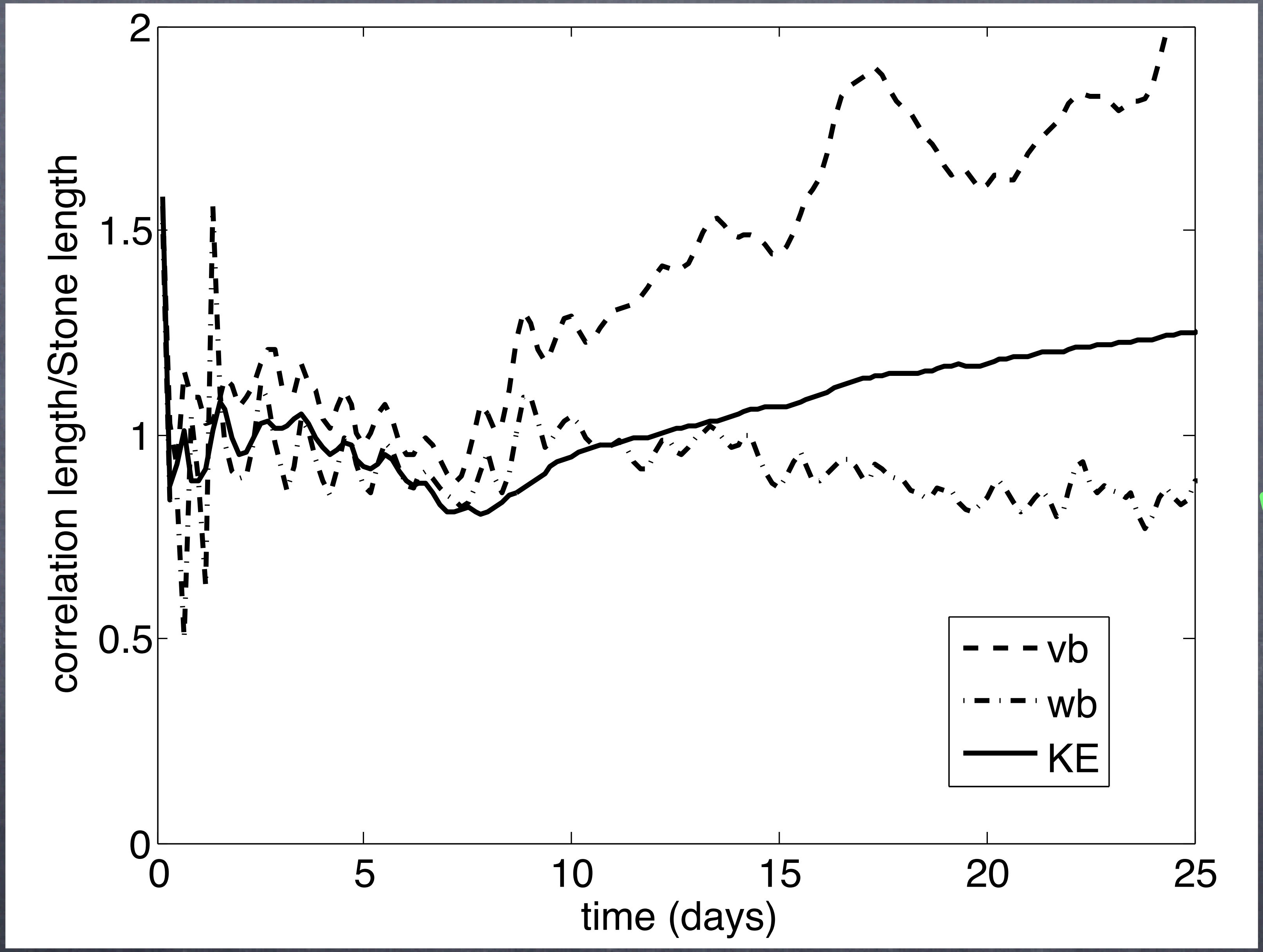
Pickart et al 02.



Fenty/MITgcm



What lengthscale dominates <w′b′>?

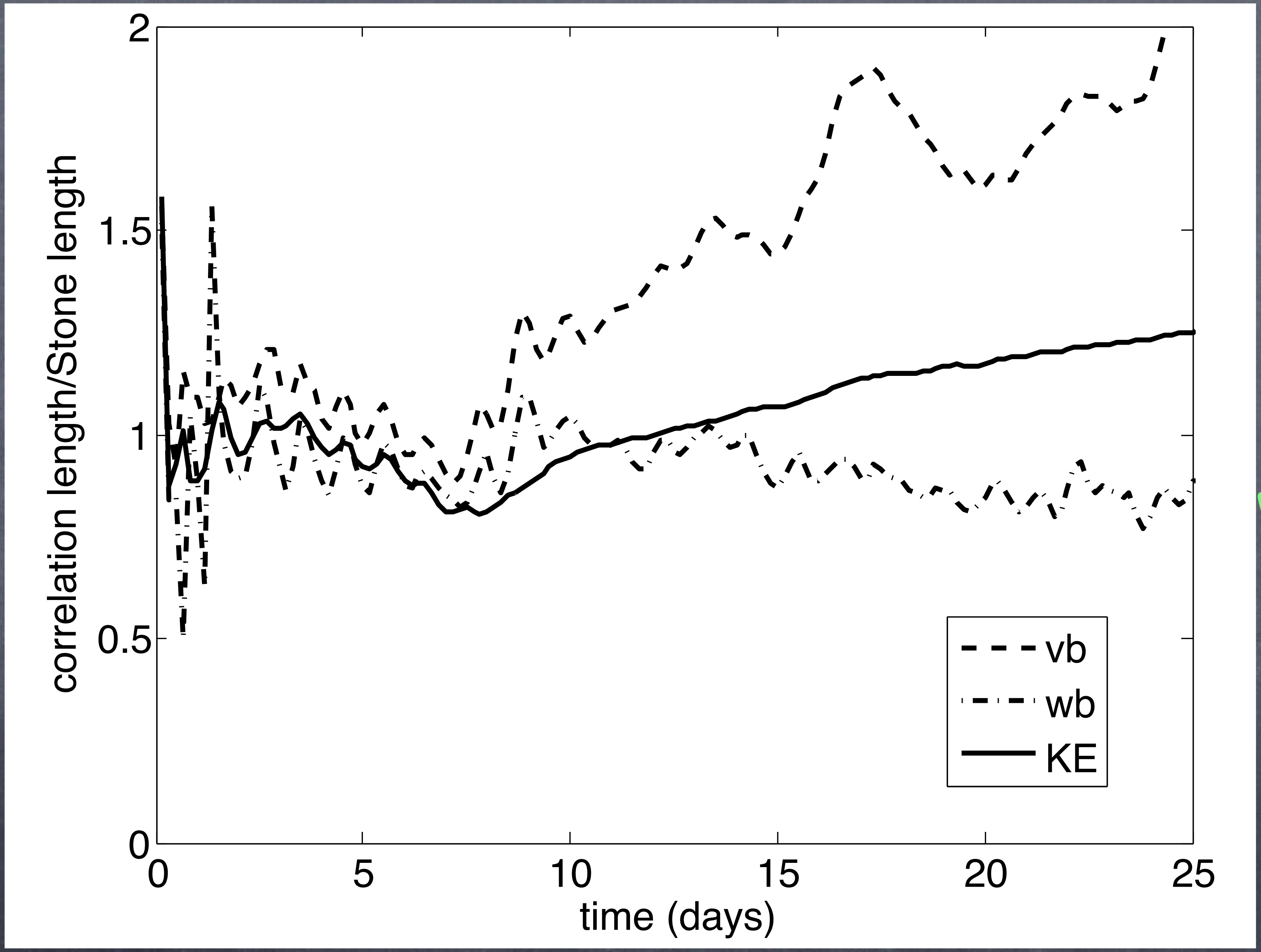


vb

KE

wb

What lengthscale dominates <w′b′>?



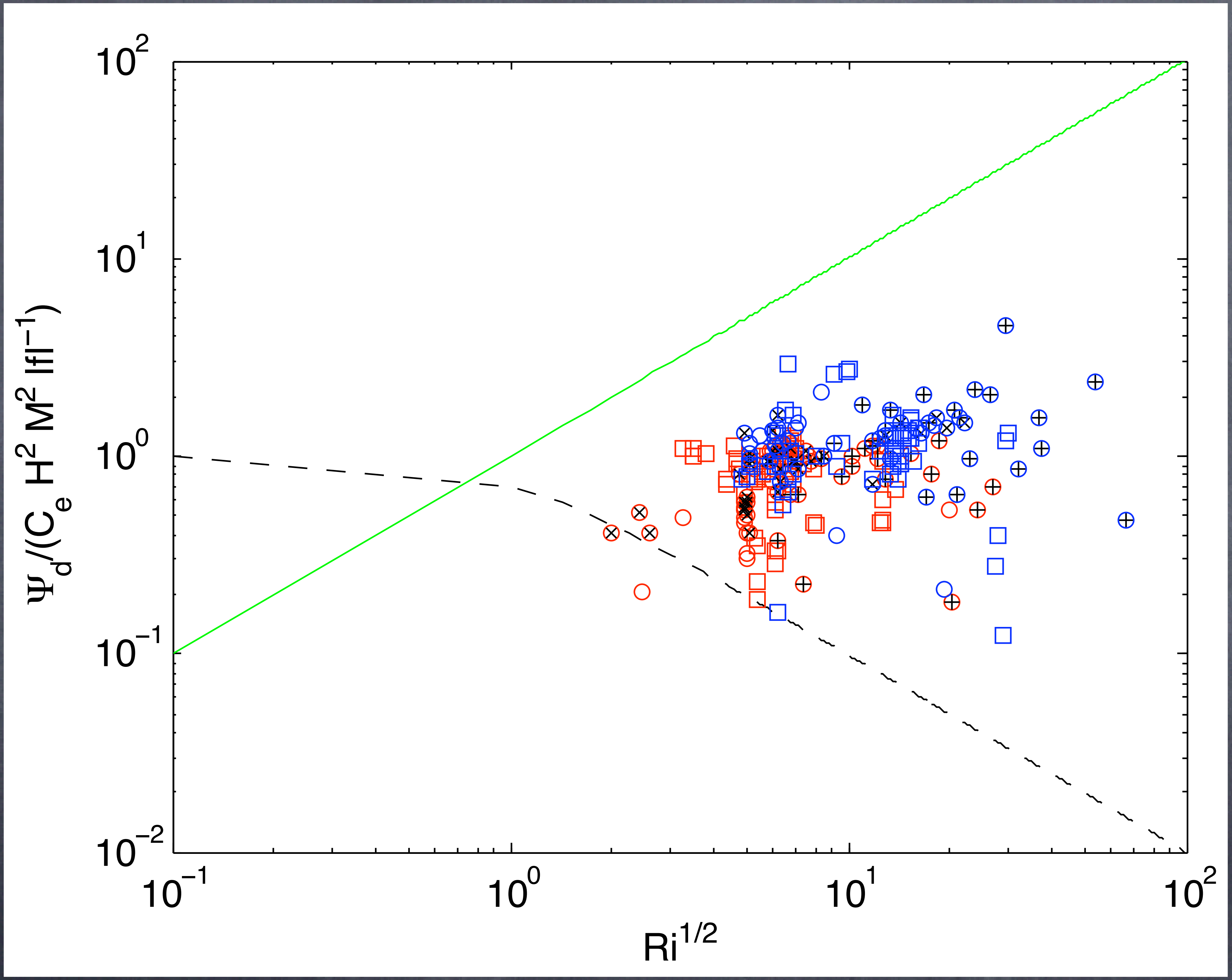
vb

KE

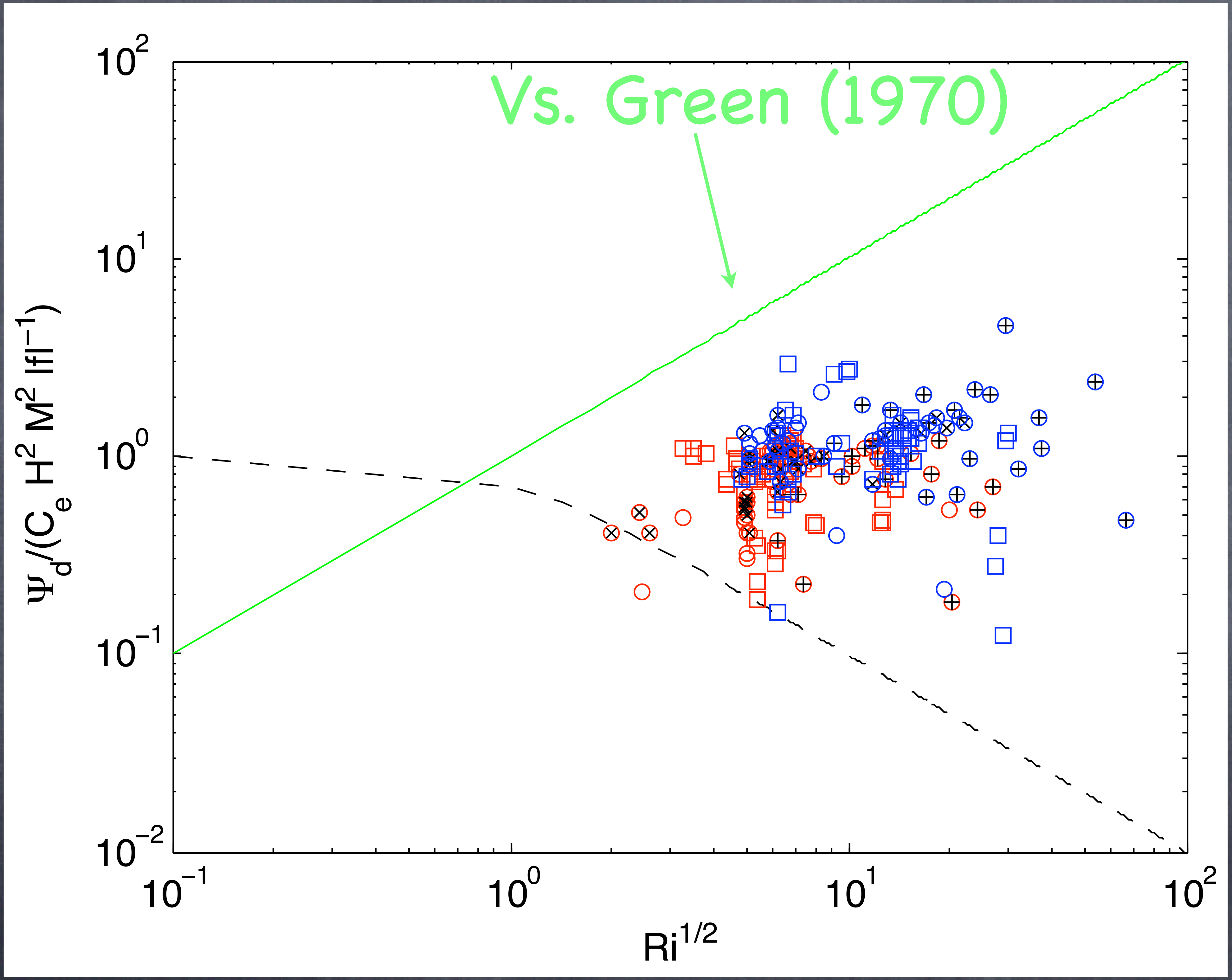
wb

Vertical Structure from linear Soln OK!

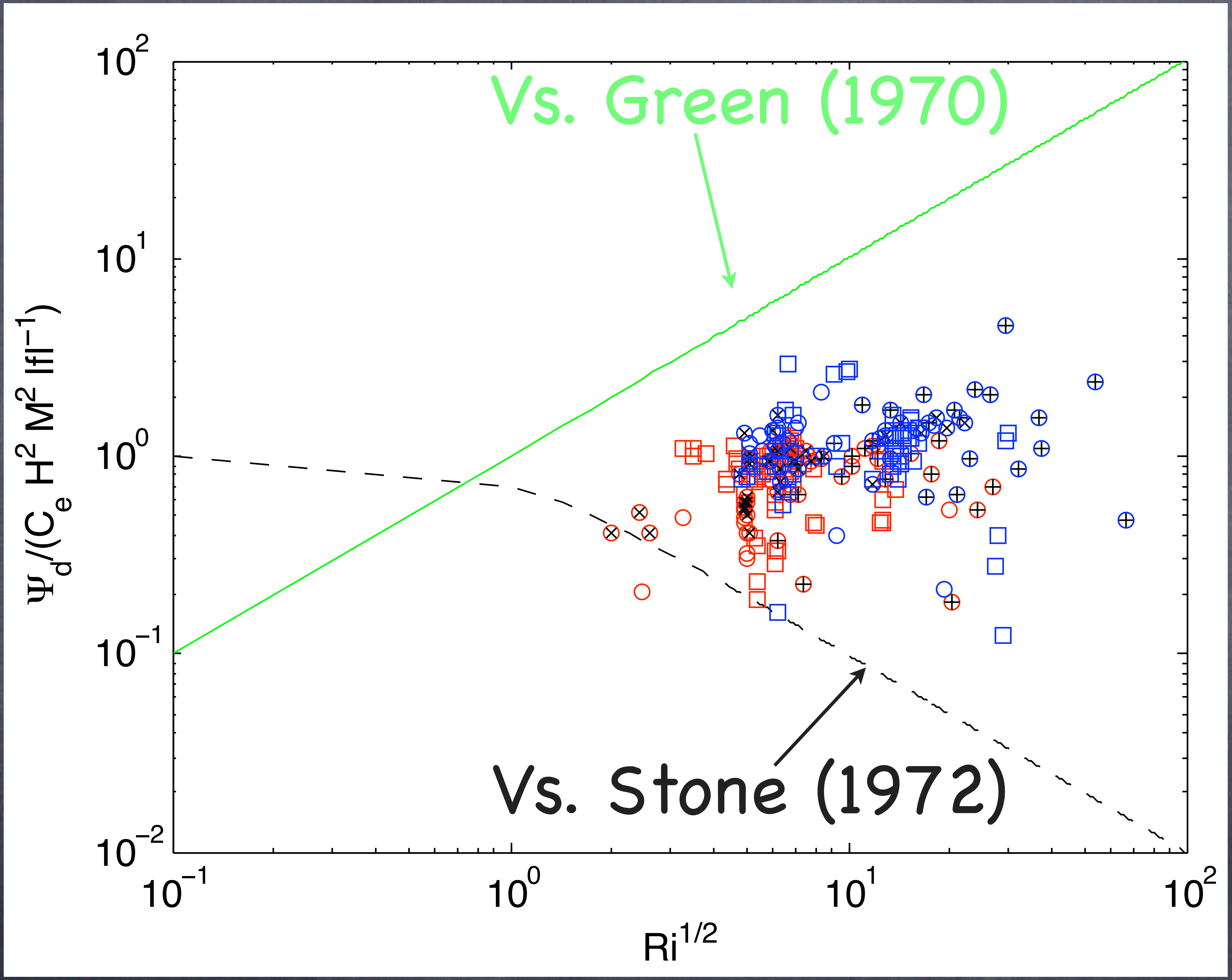
Better than the competition:



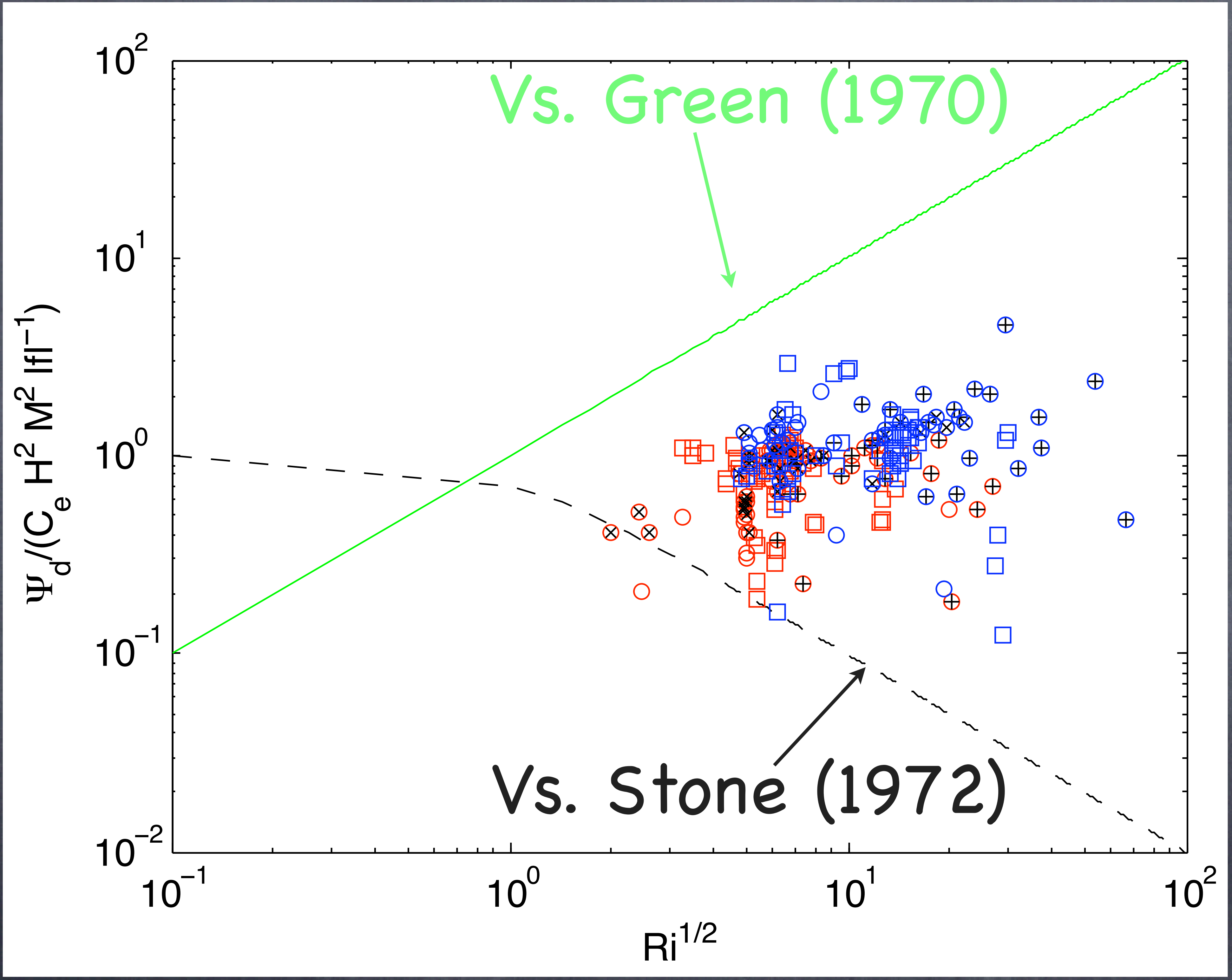
Better than the competition:



Better than the competition:



Better than the competition:



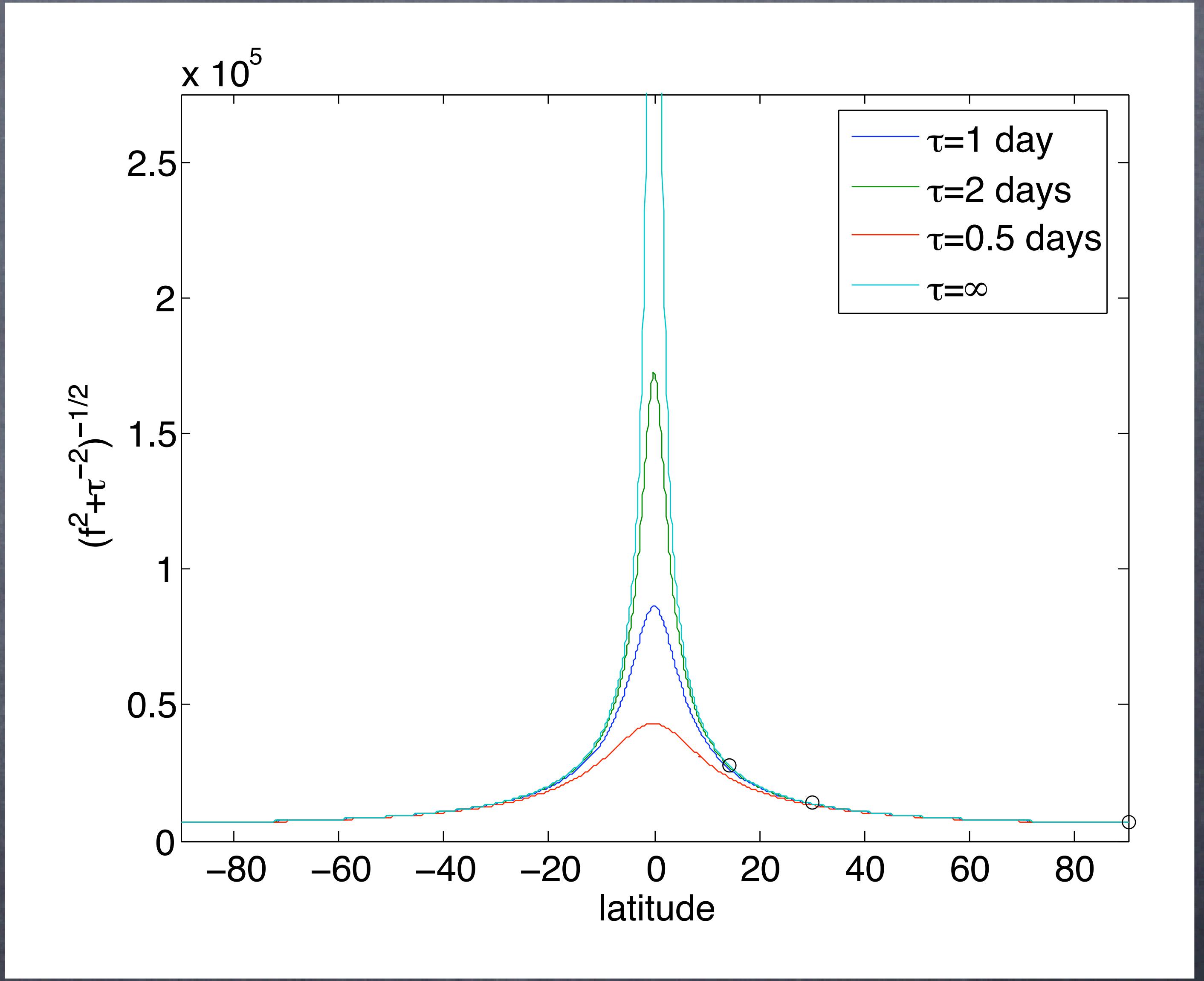
And, extends/agrees with Deep Convection Studies: Jones & Marshall (93,97), Haine & Marshall (98)

Taper to SML at Equator

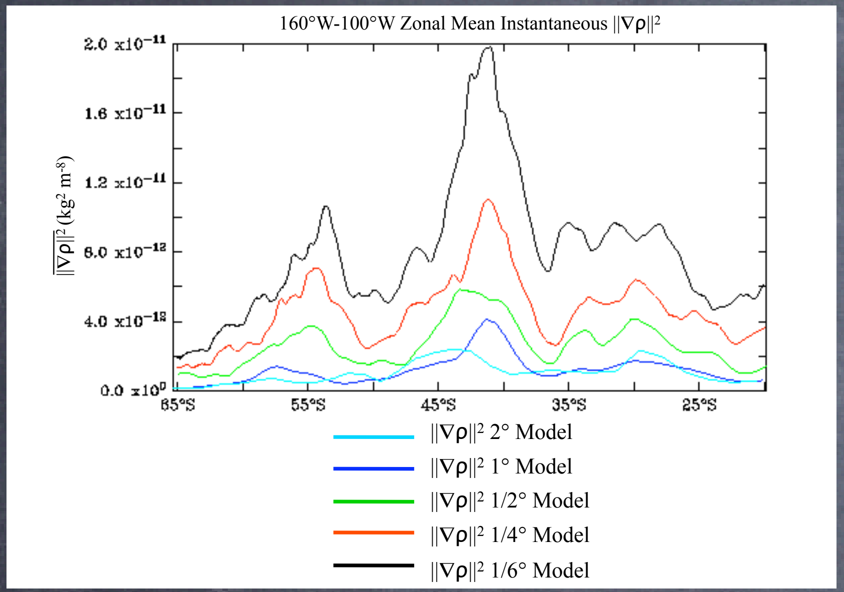
$$\Psi = \frac{C_e H^2 \mu(z)}{|f|} \nabla \bar{b} \times \hat{\mathbf{z}}$$

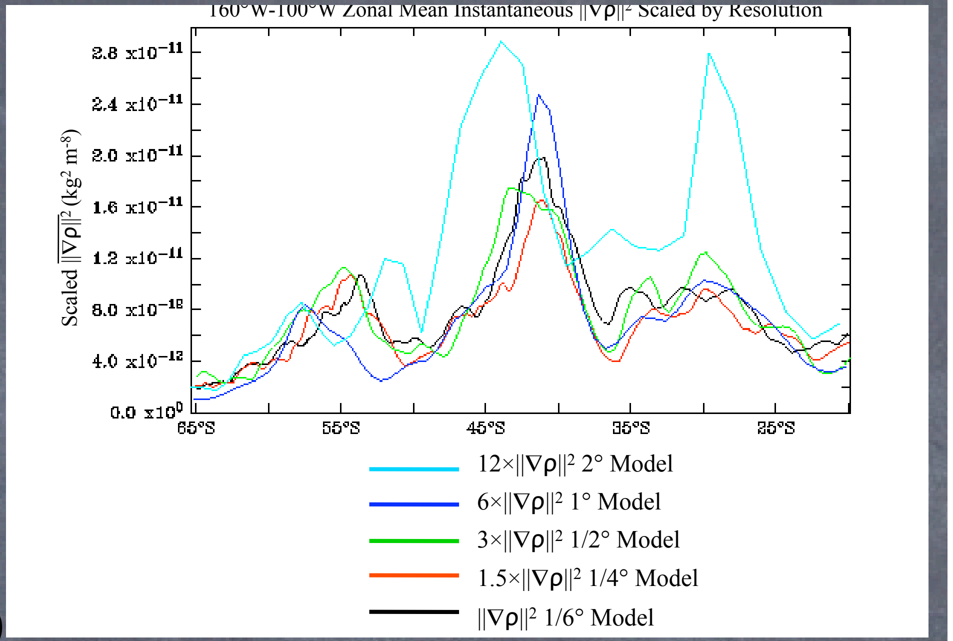
$$\Psi = \frac{C_e H^2 \mu(z)}{\sqrt{f^2 + \tau^{-2}}} \nabla \bar{b} \times \hat{\mathbf{z}}$$

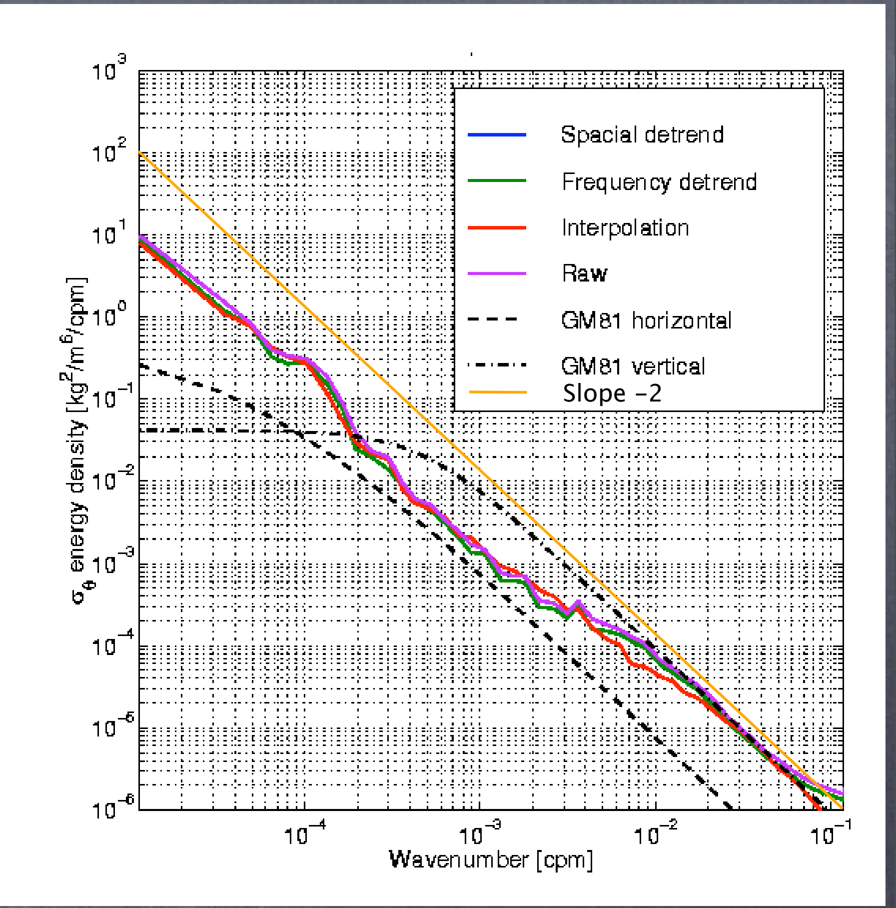
Converges to Young (1994) Subinertial ML Approx. at equator, which is gravity waves interrupted by mixing

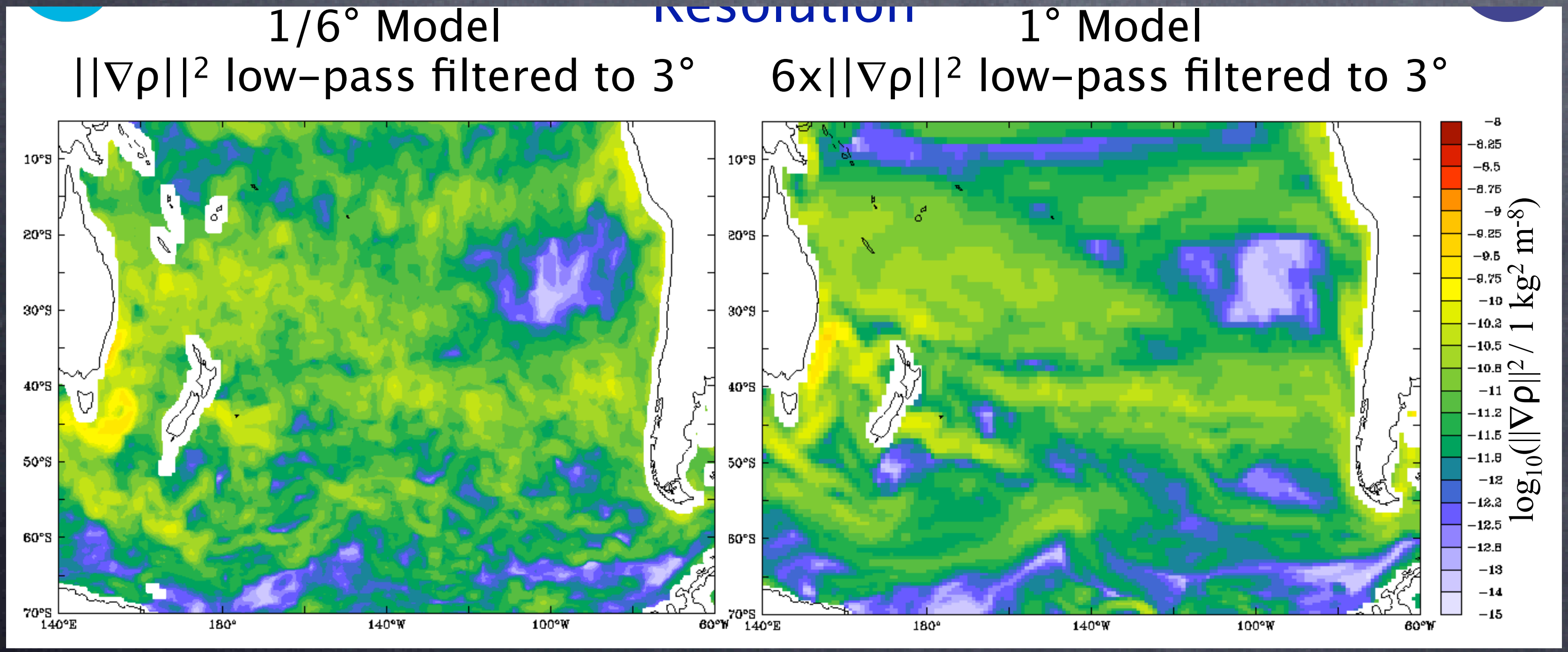


Coarse Resolution Adjustment









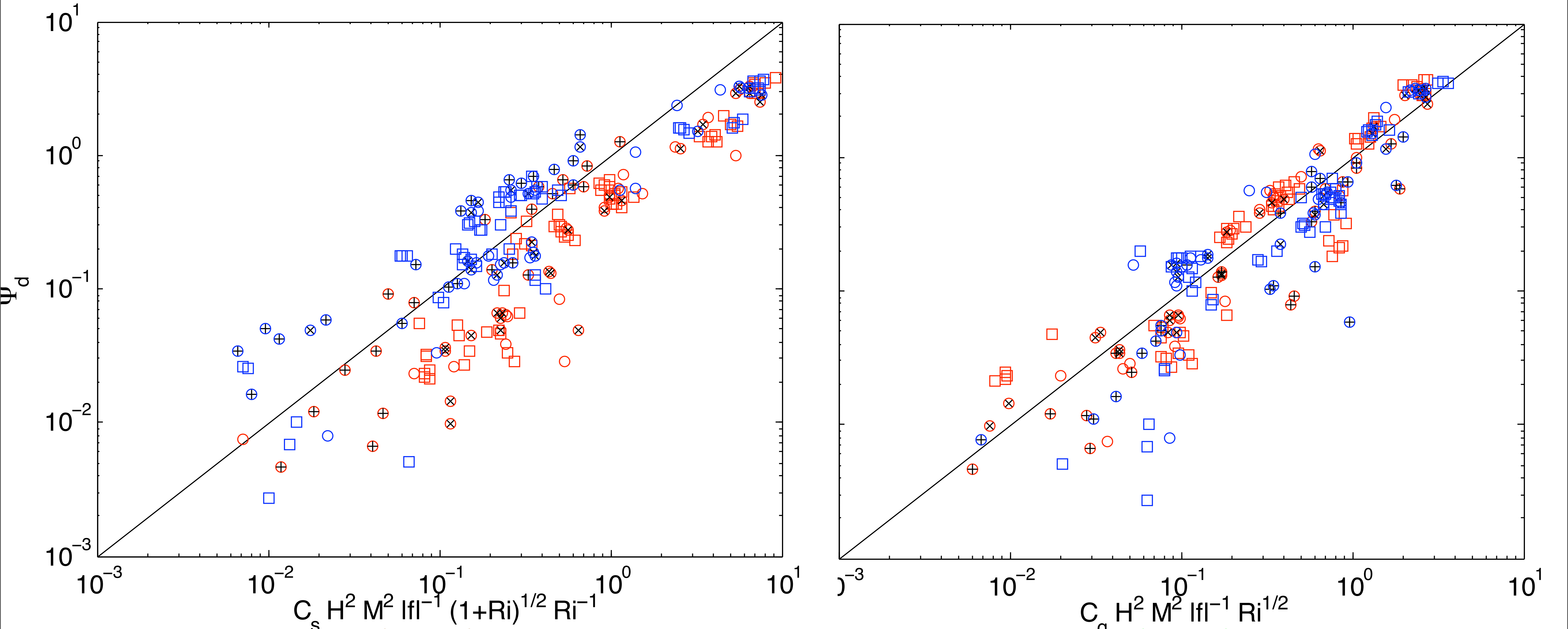
$$\overline{w'b'} = \frac{C_e H^2 \mu(z)}{|f|} |\nabla \bar{b}|^2$$

$$C_e \to C_e \frac{\Delta x}{L_d}$$

Better than the Competition:

Red: No Diurnal

Blue: With Diurnal



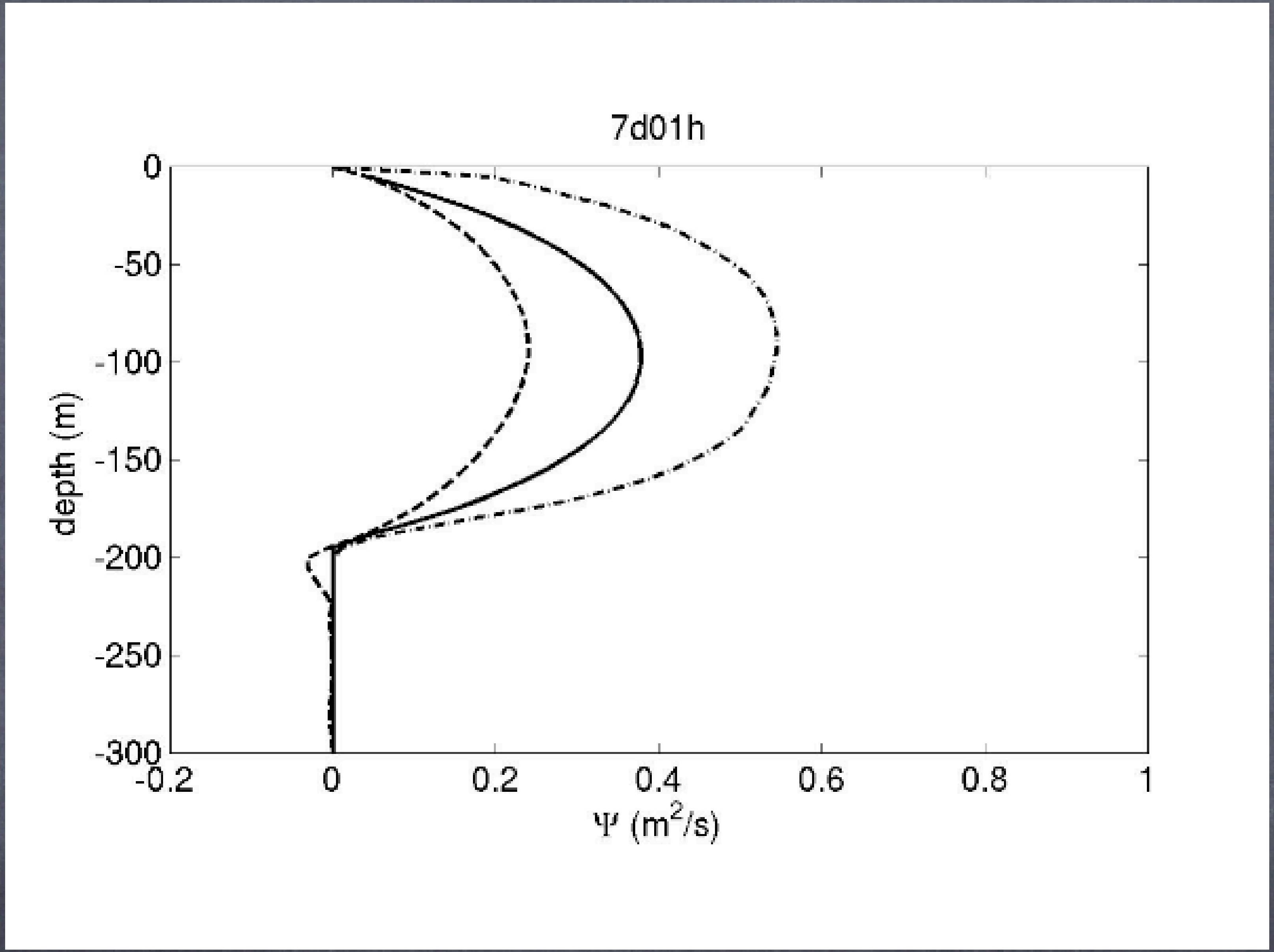
Stone (72) Scaling

Green (70) Scaling

But, Agrees with Deep Convection Studies:

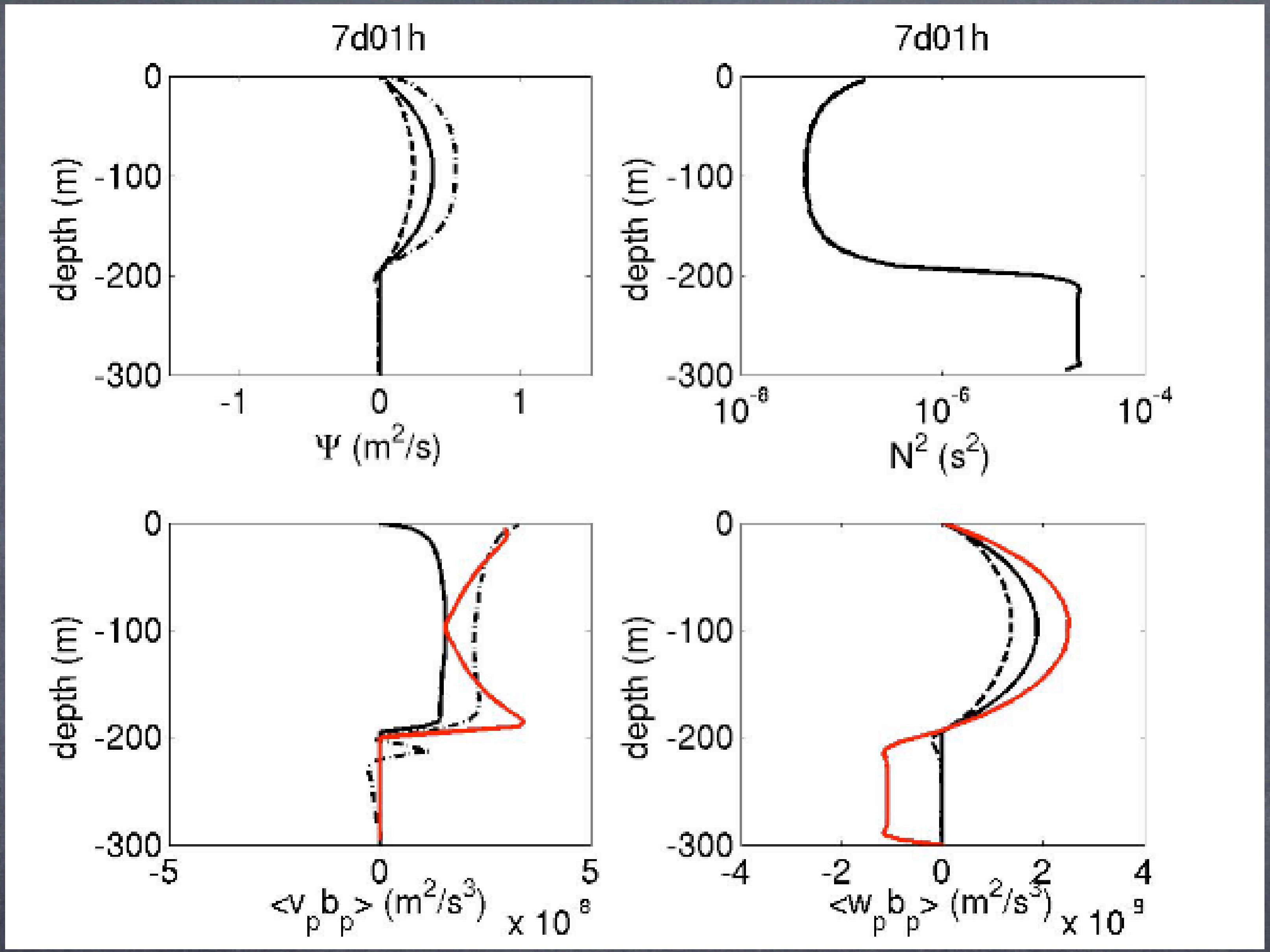
Jones & Marshall (93,97), Haine & Marshall (98)

‘Diffusive’ Corrections



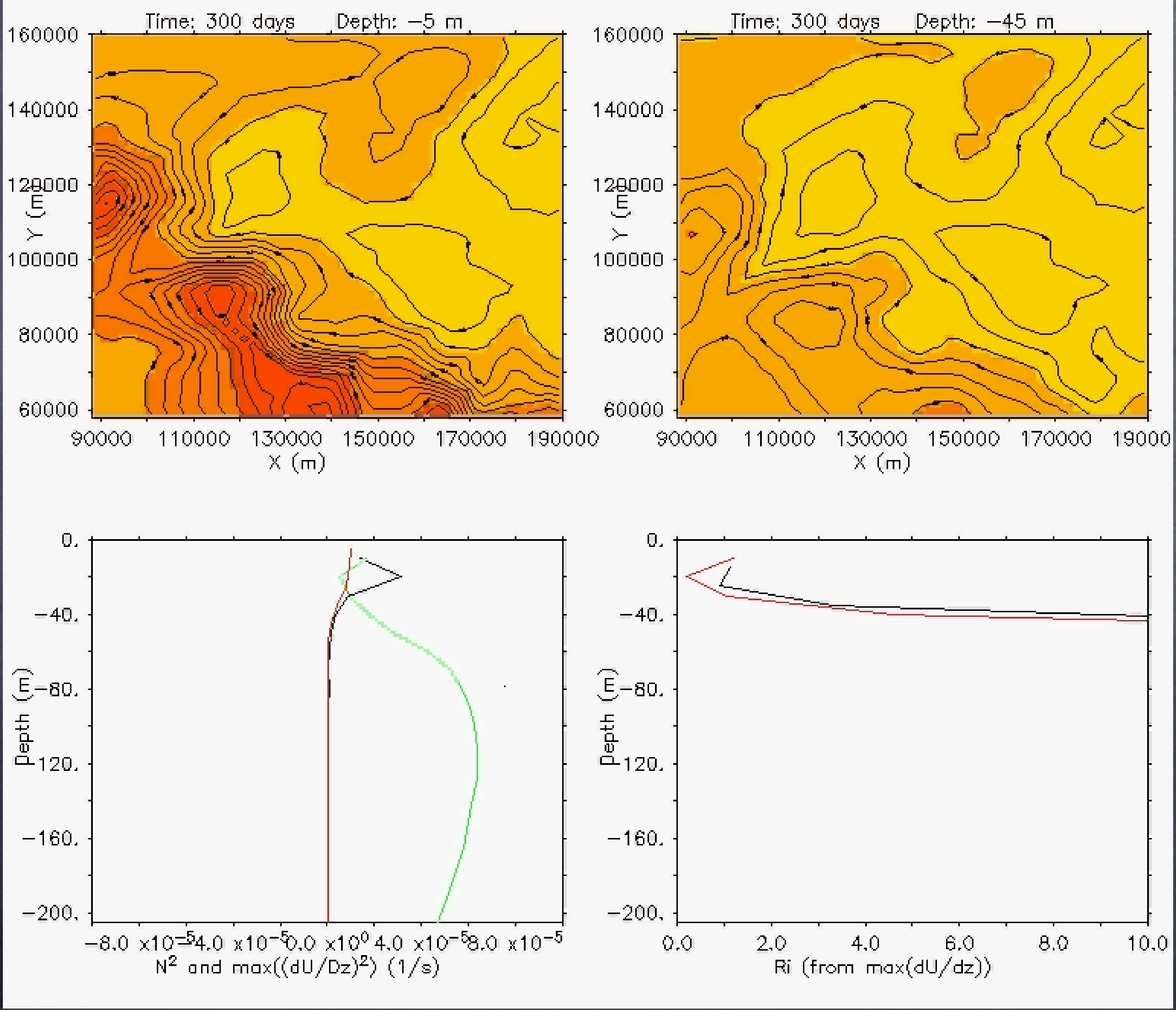
- Horiz. gives leftovers (vb only).
- Vert. reduces ML base density jump (mostly wb)

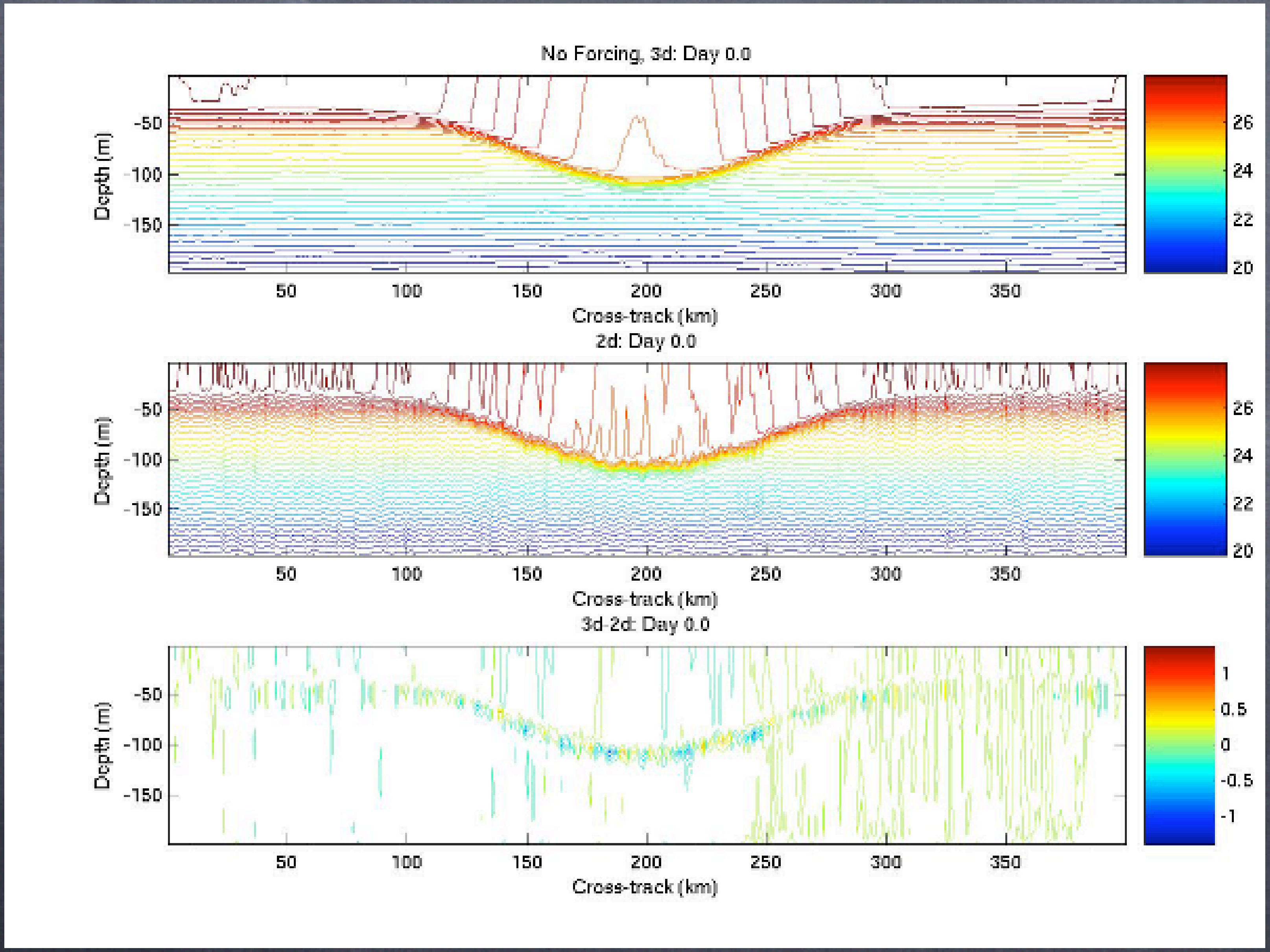
‘Diffusive’ Corrections



- Horiz. gives difference in Streamfcts (vb only).
- Vert. reduces ML base density jump (wb only).

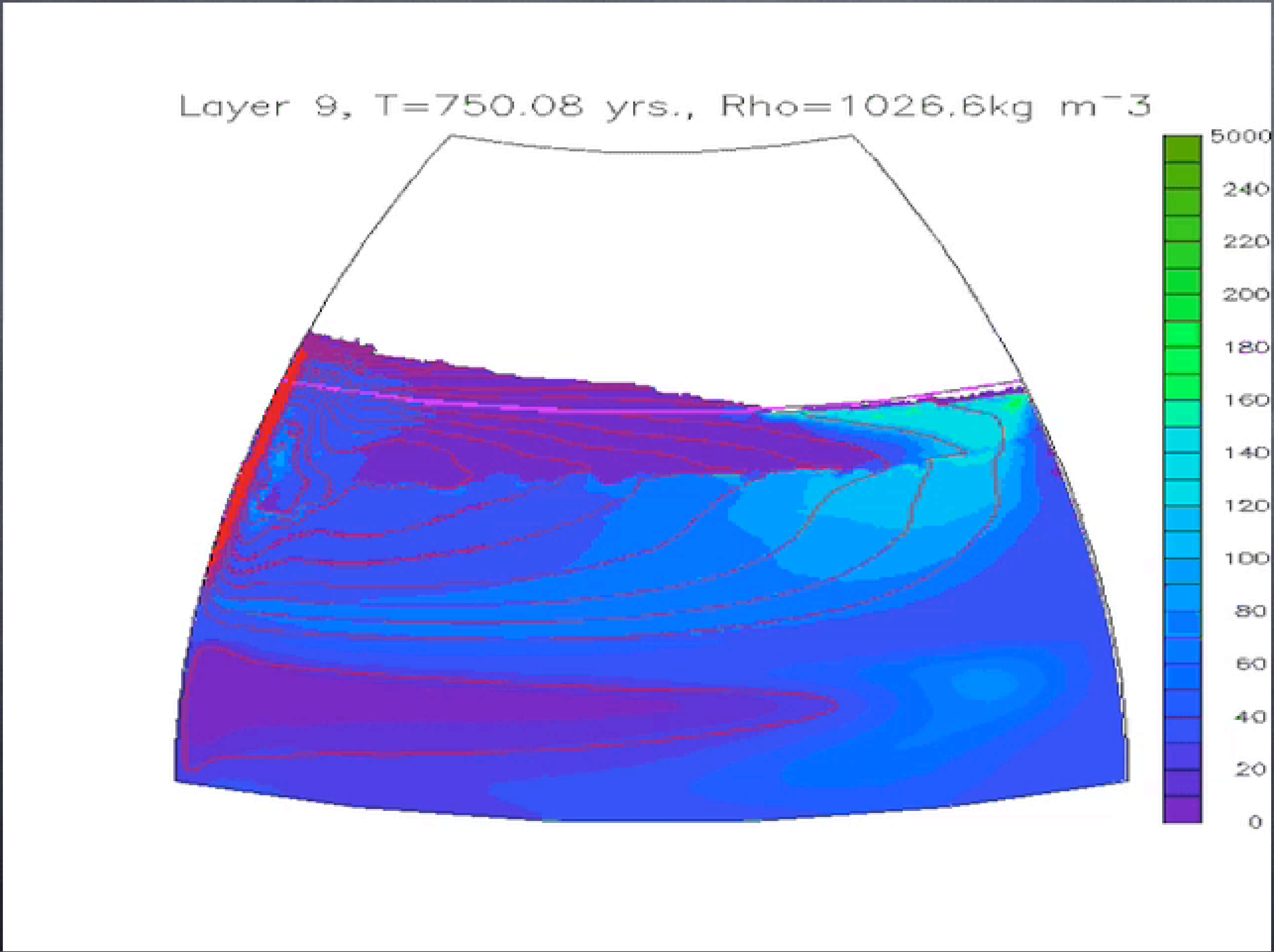
Zooming In


Time: 300 days
Depth: −5 m
Time: 300 days
Depth: −45 m
Y (m)
X (m)
160000
140000
120000
100000
80000
60000
90000
110000
130000
150000
170000
190000
Depth (m)
0.
−40.
−80.
−120.
−160.
−200.
−8.0 x10−5
−4.0 x10−5
0.0 x10^0
4.0 x10−5
8.0 x10−5
N² and max((dU/Dz)²) (1/s)
0.0
2.0
4.0
6.0
8.0
10.0
Ri (from max(dU/dz))



No Forcing, 3d: Day 0.0
Depth (m)
-50
-100
-150
50
100
150
200
250
300
350
Cross-track (km)
26
24
22
20
2d: Day 0.0
Depth (m)
-50
-100
-150
50
100
150
200
250
300
350
Cross-track (km)
26
24
22
20
3d-2d: Day 0.0
Depth (m)
-50
-100
-150
50
100
150
200
250
300
350
Cross-track (km)
1
0.5
0
-0.5
-1

How I got into ML Stuff



How I got into ML Stuff