Mixed Layer Restratification

Baylor Fox-Kemper

Collaborators:
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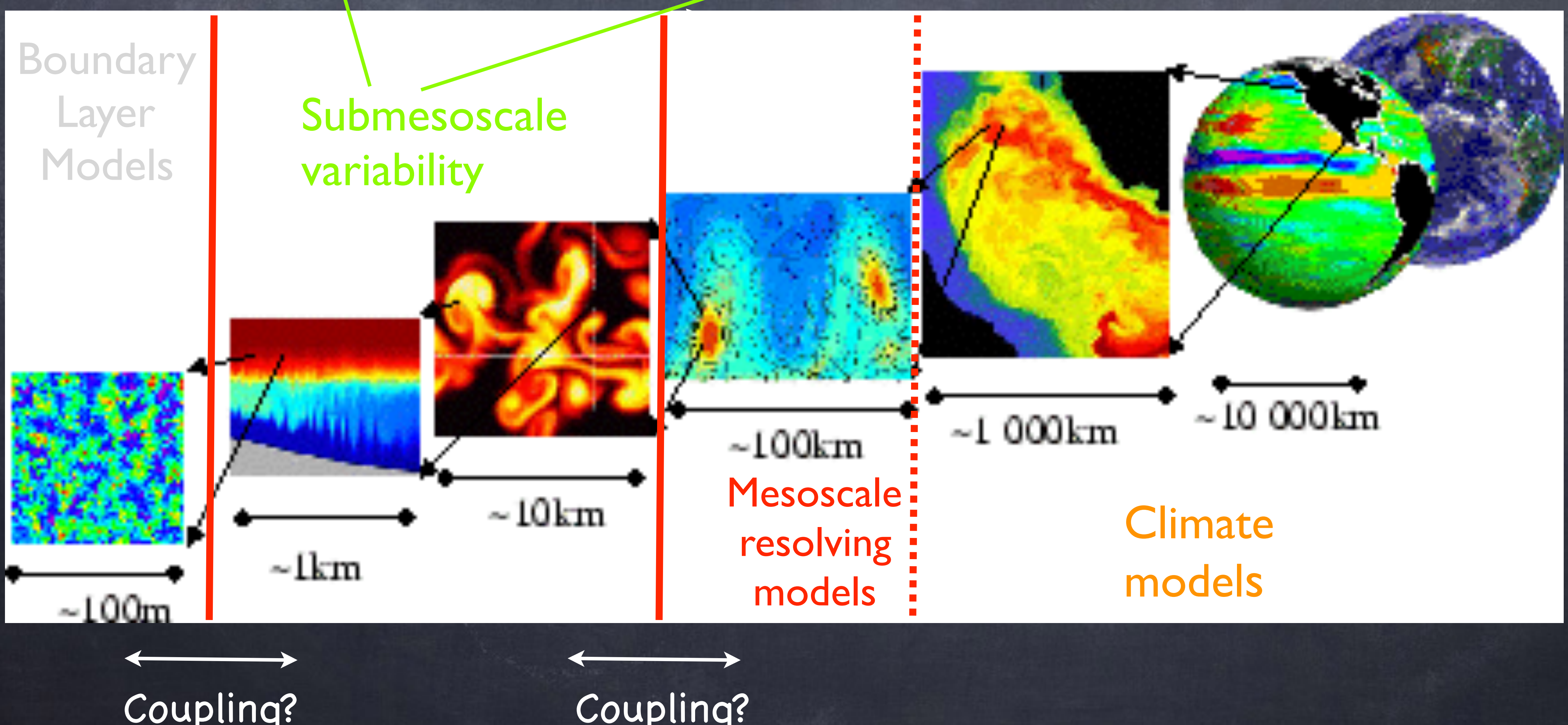
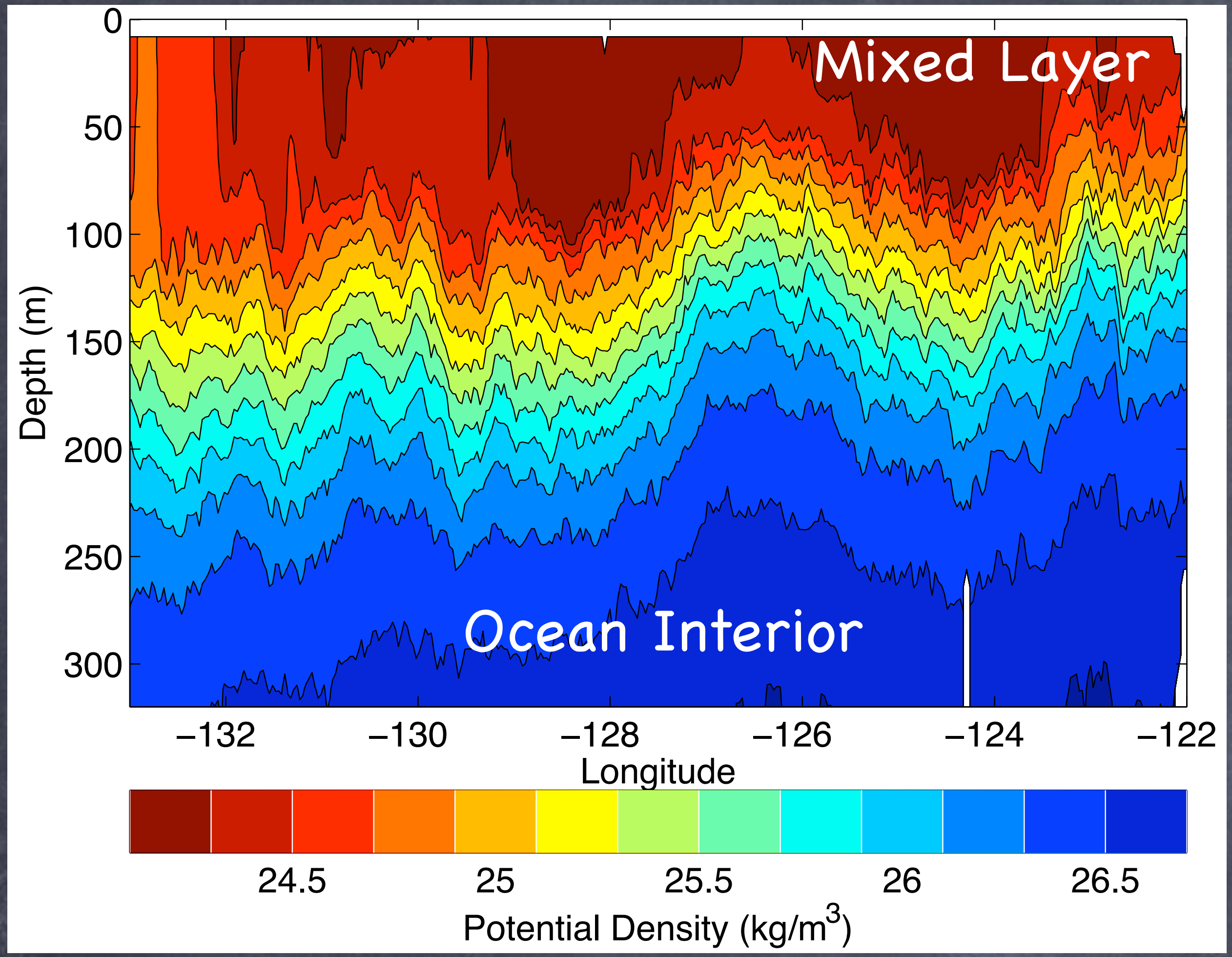
LDEO DOCP Seminar
Friday 12/1/06, 11:00-12:00

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



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.

(Ferrari & Rudnick, 2000)

The mixed layer is not TOTALLY mixed.

Lateral density gradients are common.

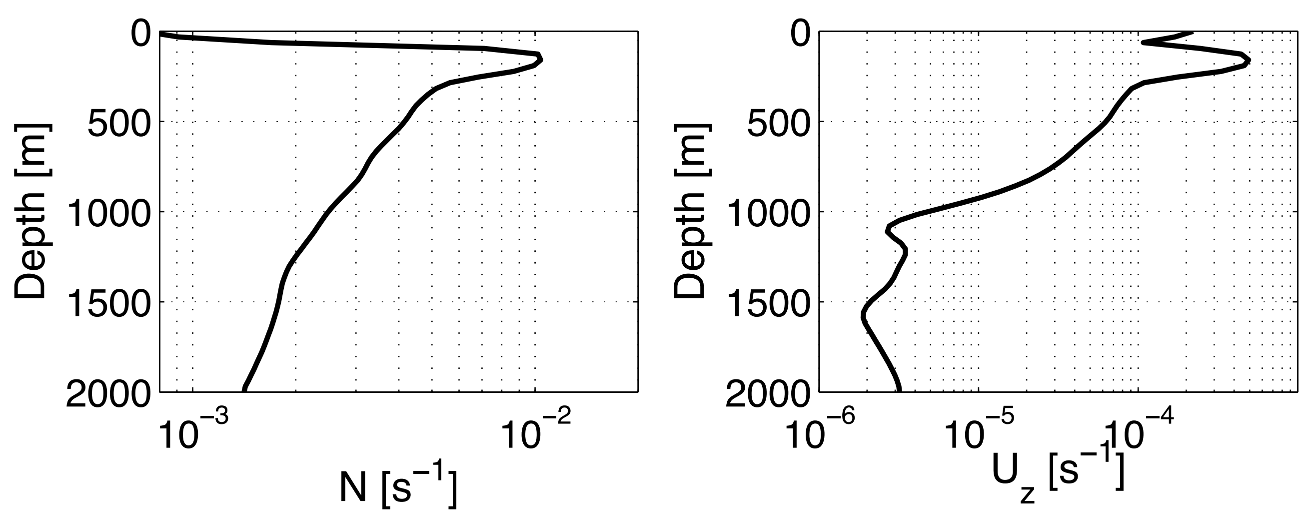
1) What does its stratification imply?

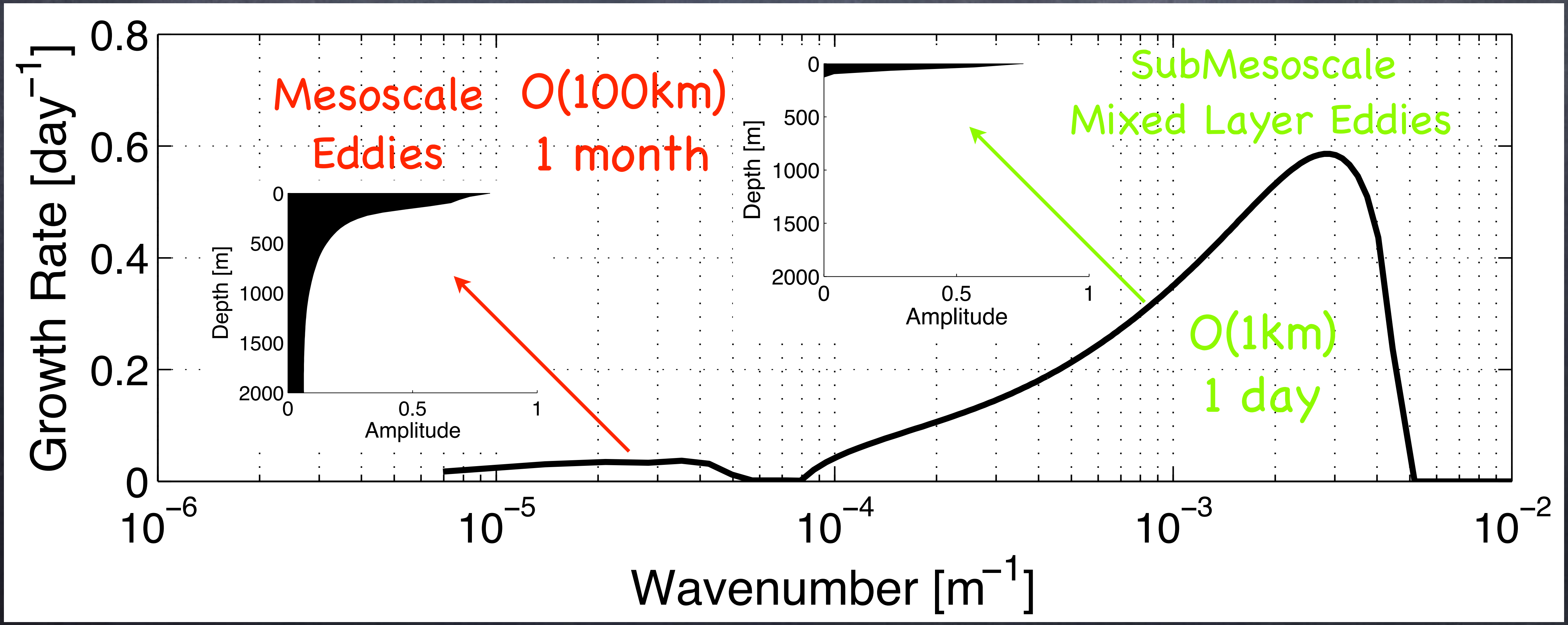
2) How does the stratification get set?

3) Why do we care?

The Stratification Permits Two Types of Baroclinic Instability:

Mesoscale and SubMesoscale (Boccaletti et al., 2006)

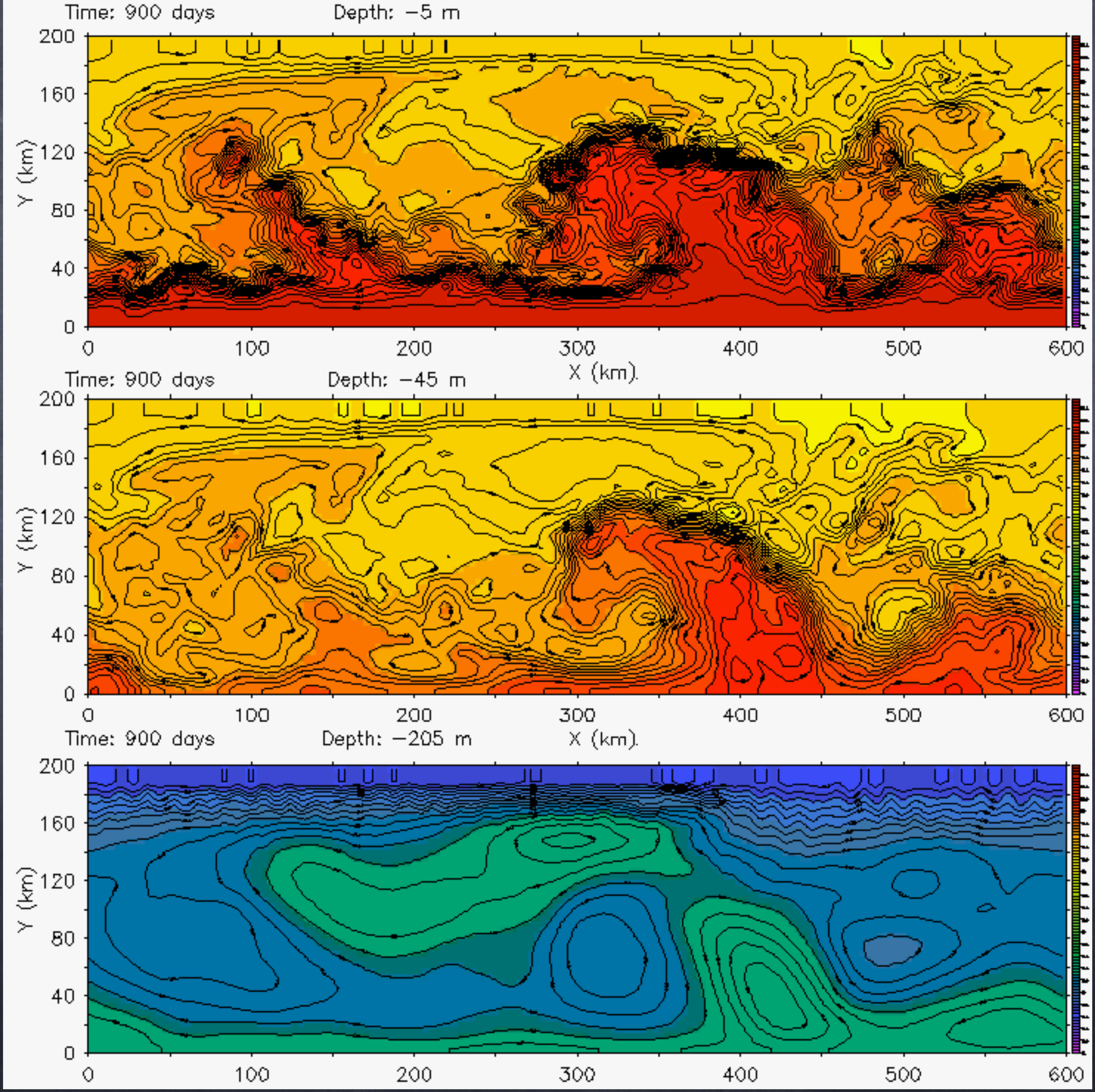




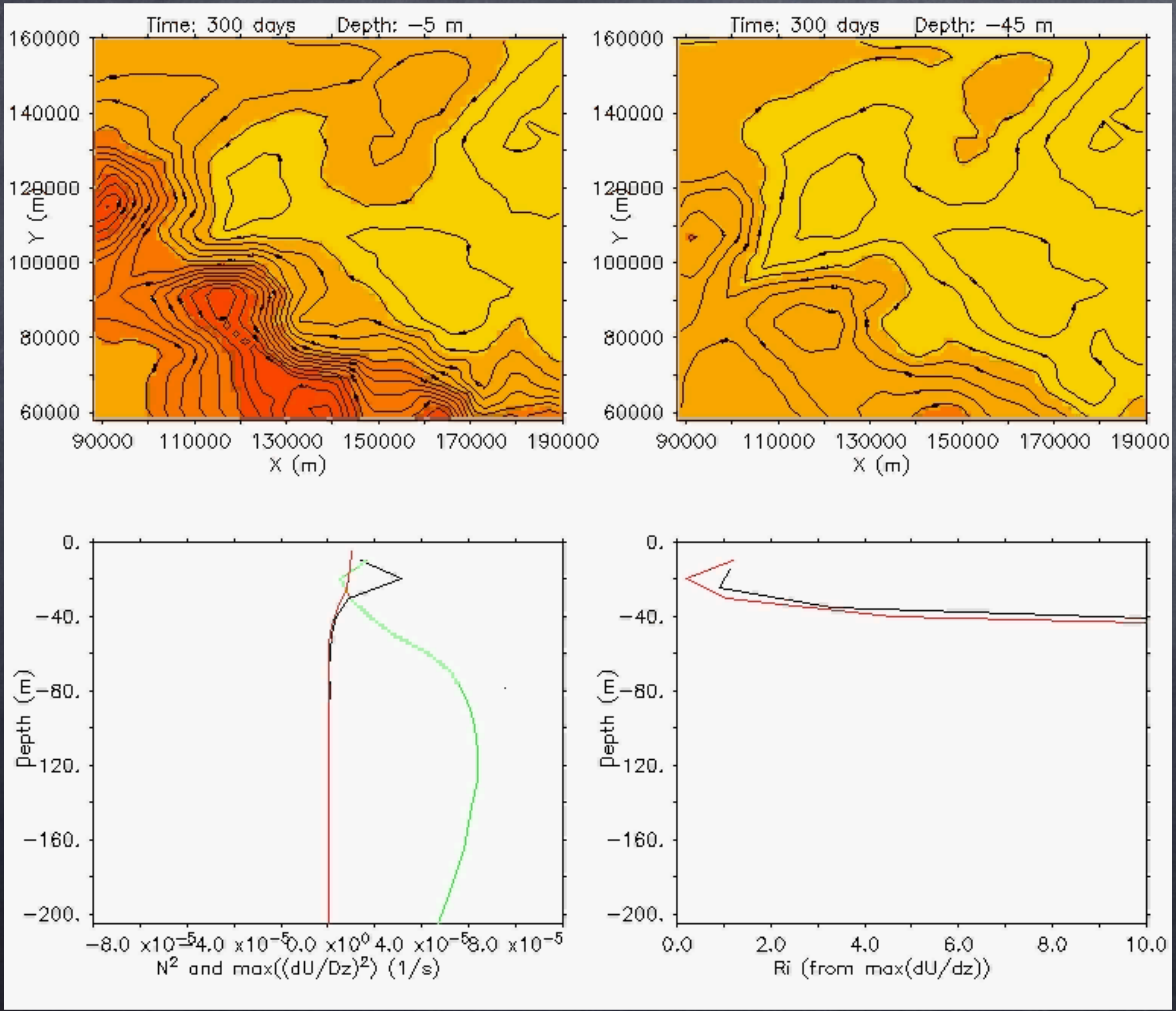
Mesoscale and SubMesoscale are Coupled Together:

ML Fronts are formed by Mesoscale Straining.

Submesoscale eddies remove PE from those fronts.



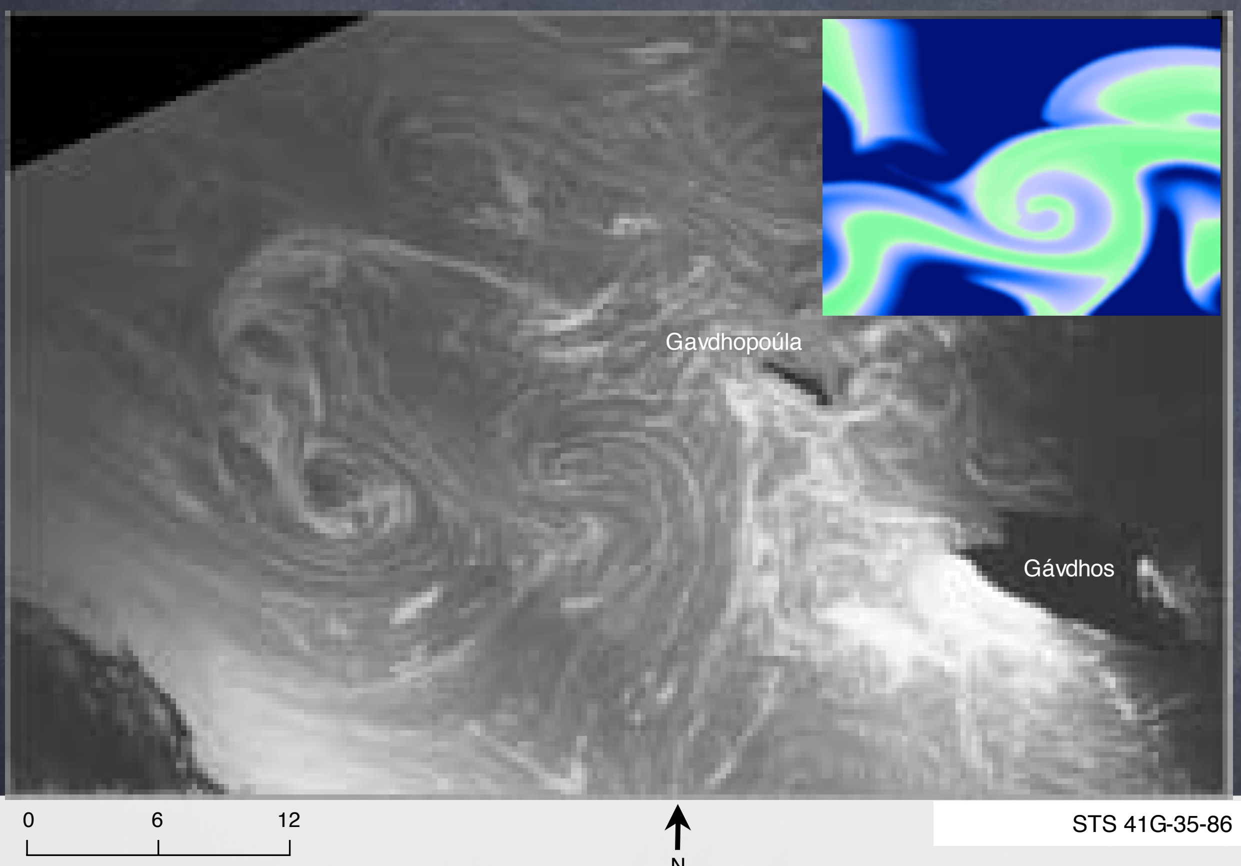
Zooming In



Time: 300 days
Depth: −5 m
Time: 300 days
Depth: −45 m
Y (m)
X (m)
Depth (m)
N^2 and max((dU/Dz)^2) (1/s)
Ri (from max(dU/dz))

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.

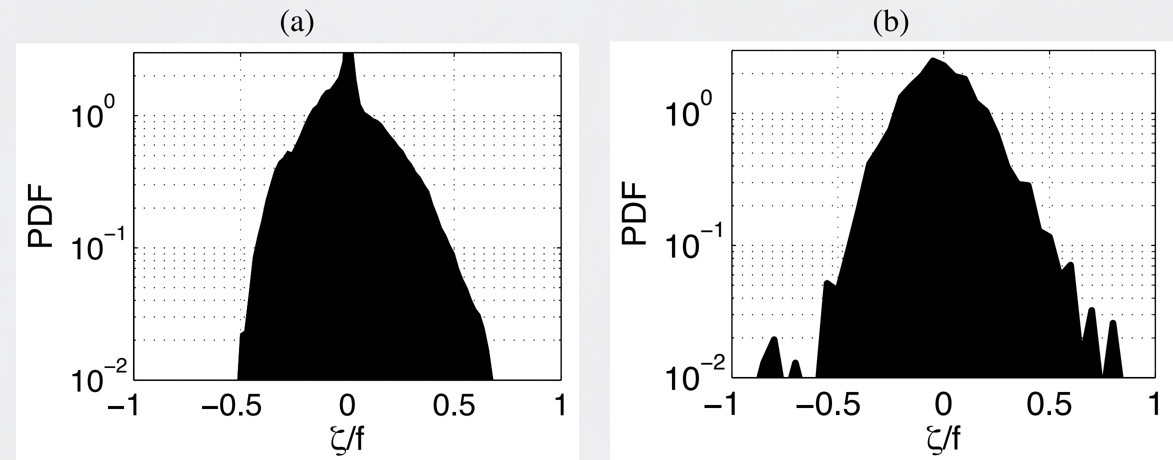
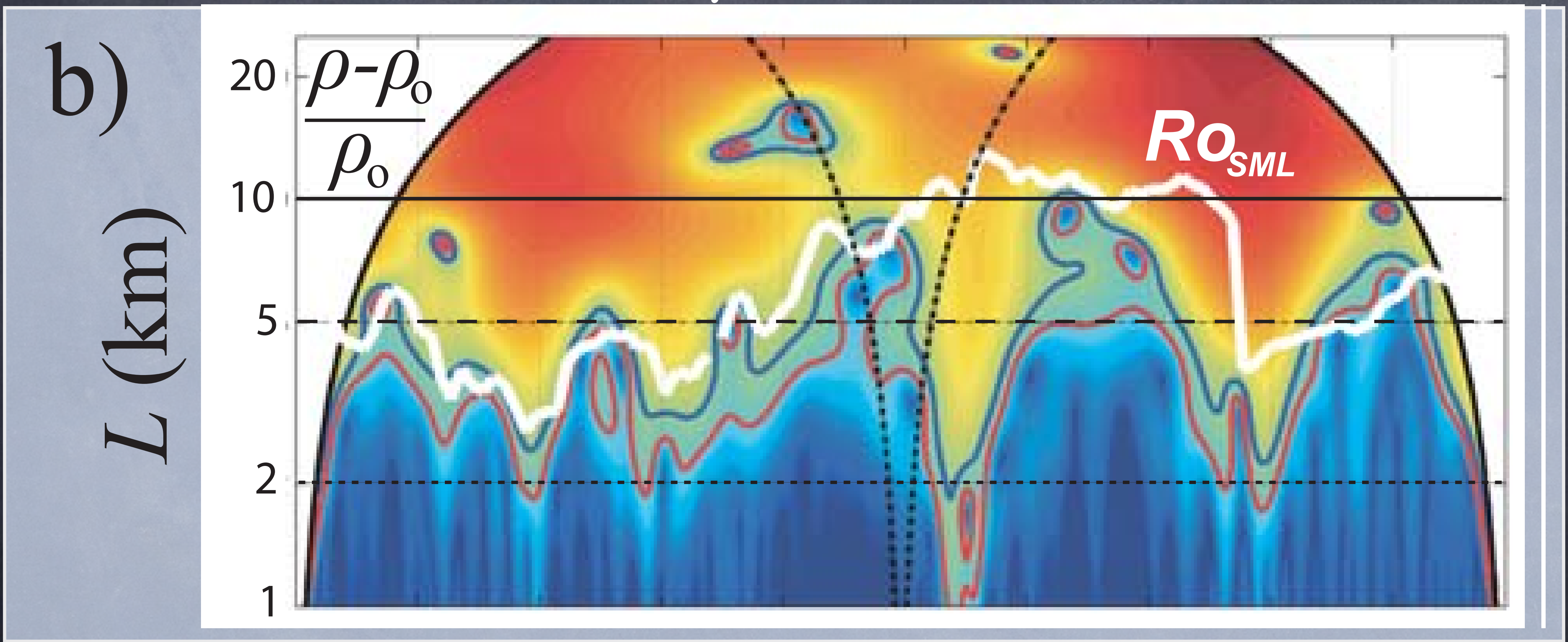


Figure 12: Probability density function of relative vorticity divided by Coriolis parameter. (a) Results from the numerical simulation of a slumping horizontal density front. ($z > 100$ only to exclude bottom Ekman layer.) The PDF is estimated using surface velocity measurements at day 25 (see also Fig. 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.
S & T vary at all scales.



Midlatitude Pacific near Hawaii: Hosegood et al. 06

Vertical fluxes are Submesoscale

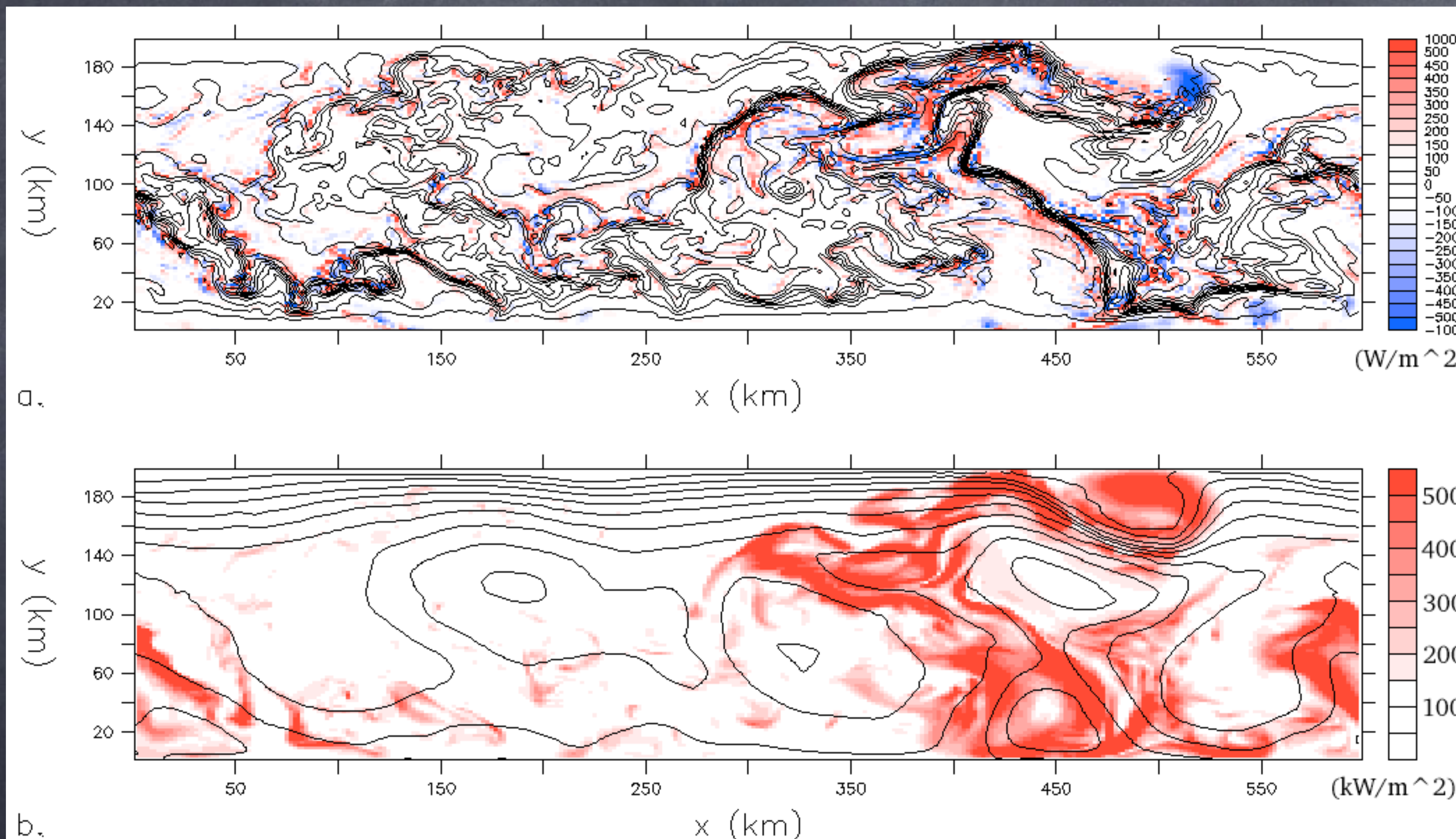


FIGURE 1: Contours of temperature at the a) surface and b) below the mixed layer base in a simulation with both mesoscale eddies and MLEs ($0.2°C$ contour intervals). Shading indicates the value at the depth where $\overline{w'b'}$ (upper panel) and $|\overline{\mathbf{u}'_H b'}|$ (lower panel) take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

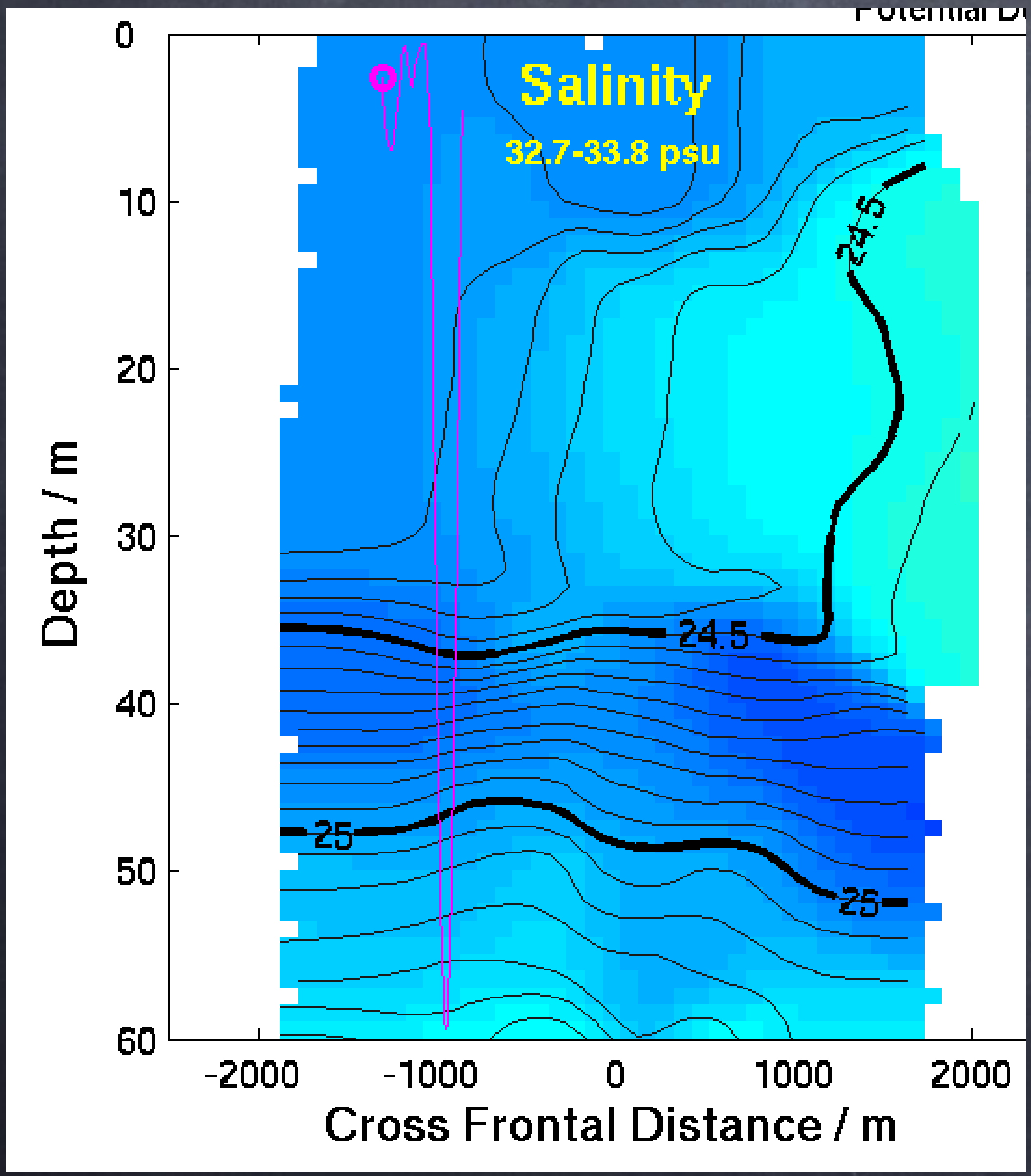
Horizontal fluxes are Mesoscale

Vertical Buoyancy Fluxes at Different Resolutions

- Comparison of vertical buoyancy fluxes at two different resolutions
- Threefold enhancement of fluxes critically depends on presence of a mixed layer
- The fluxes are such as to rapidly restratify the surface mixed layer

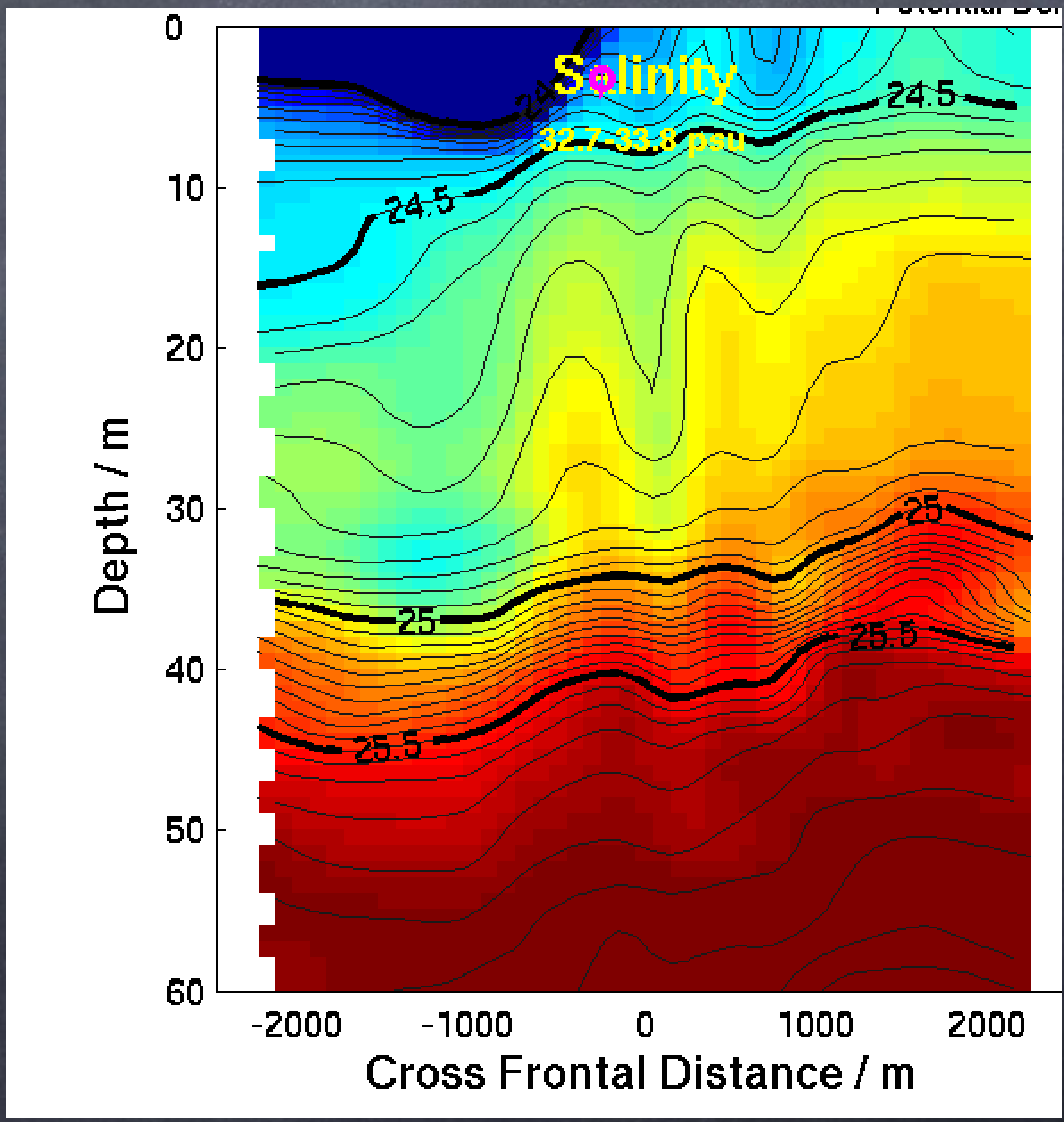
AESOP Observations of Rapid Restratification near Monterey Bay

- 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

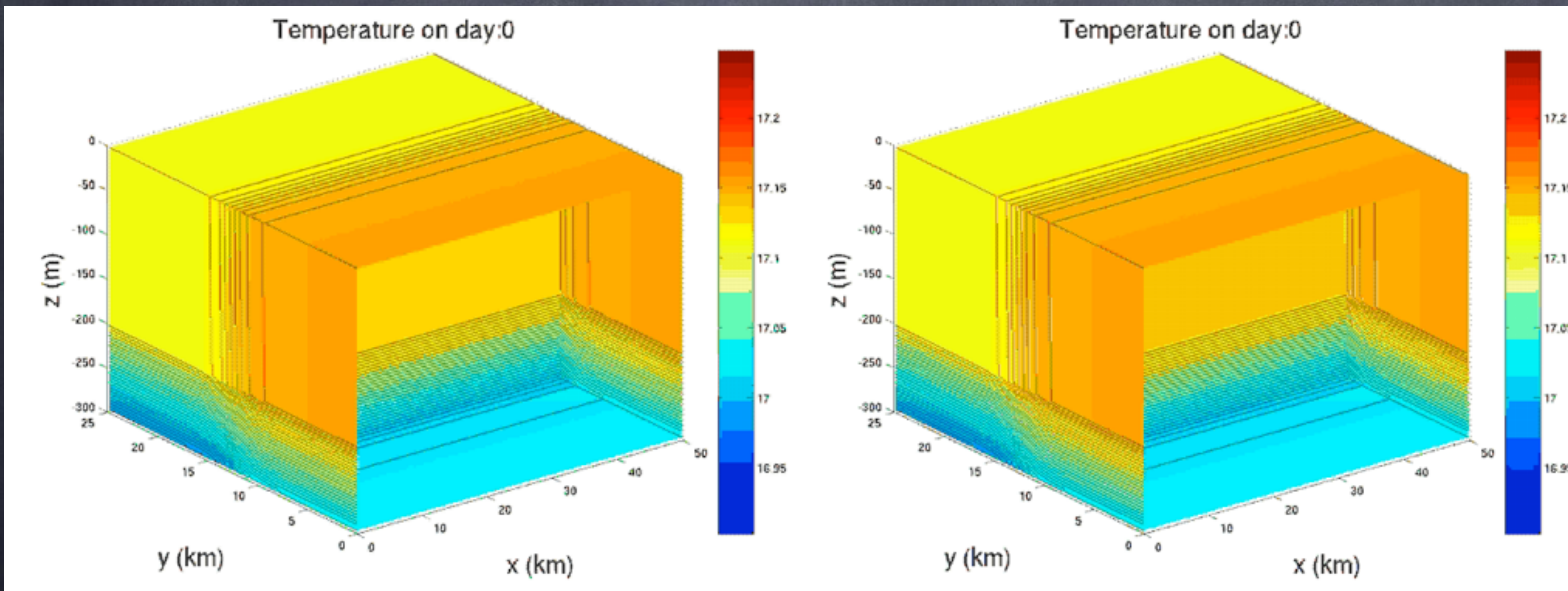
After one day



10 kt wind

Courtesy E. D'Asaro

Prototype: Mixed Layer Front Adjustment

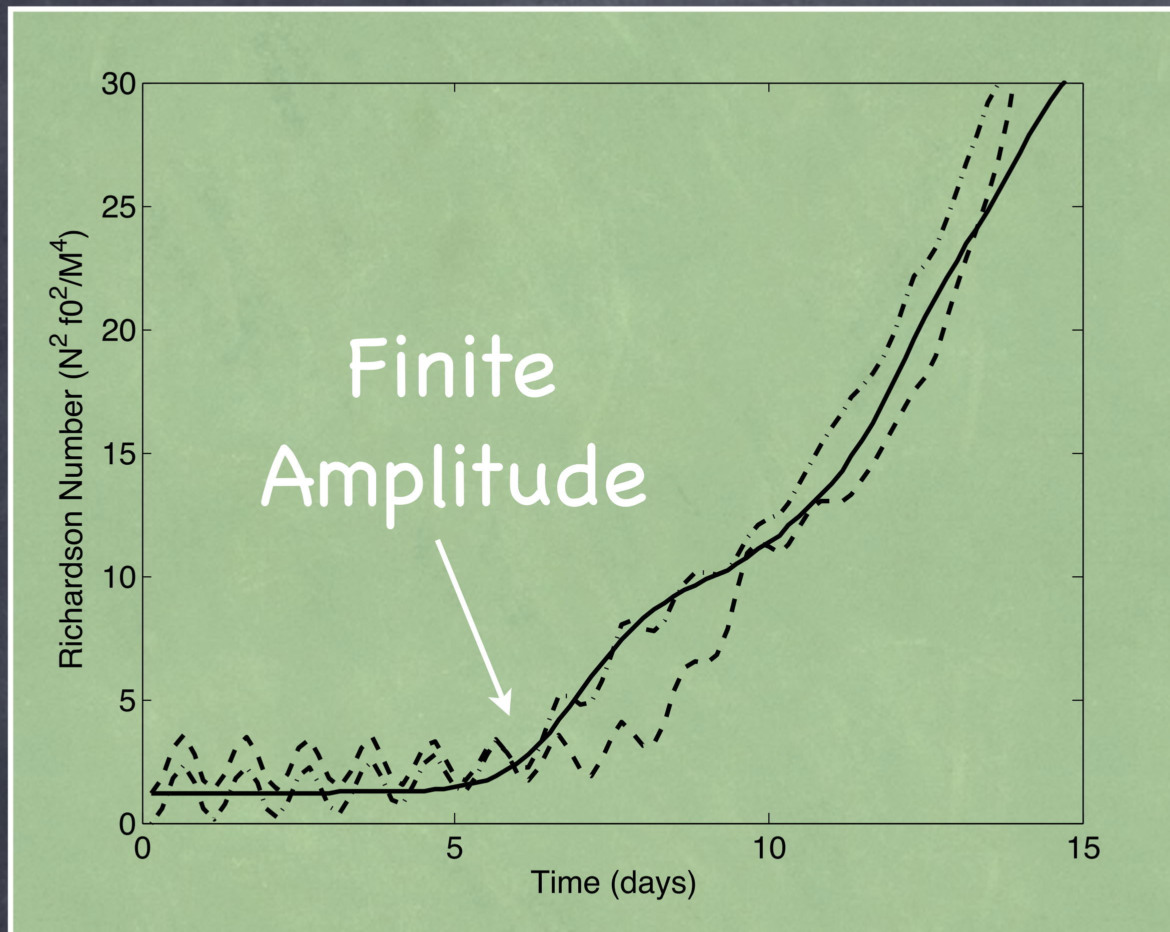


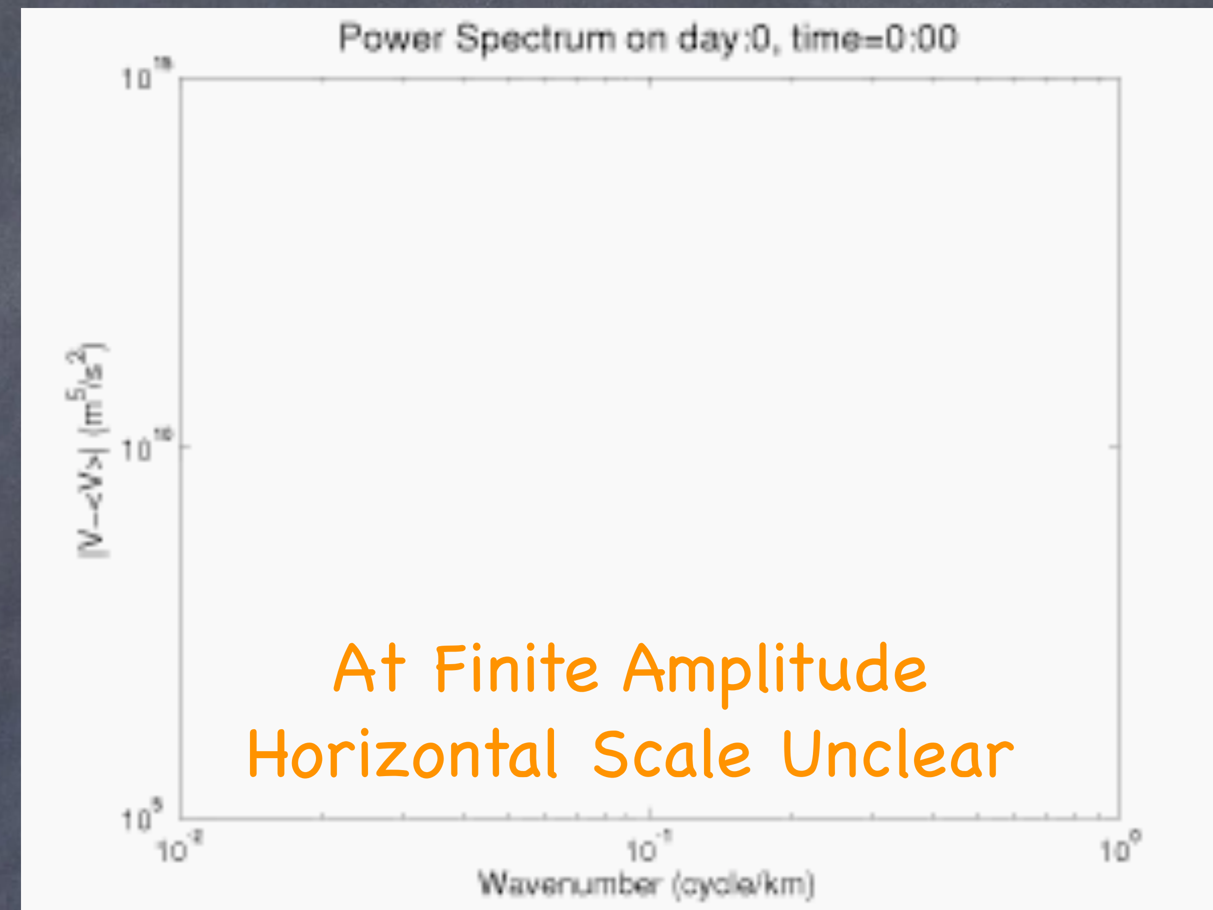
Simple Adjustment

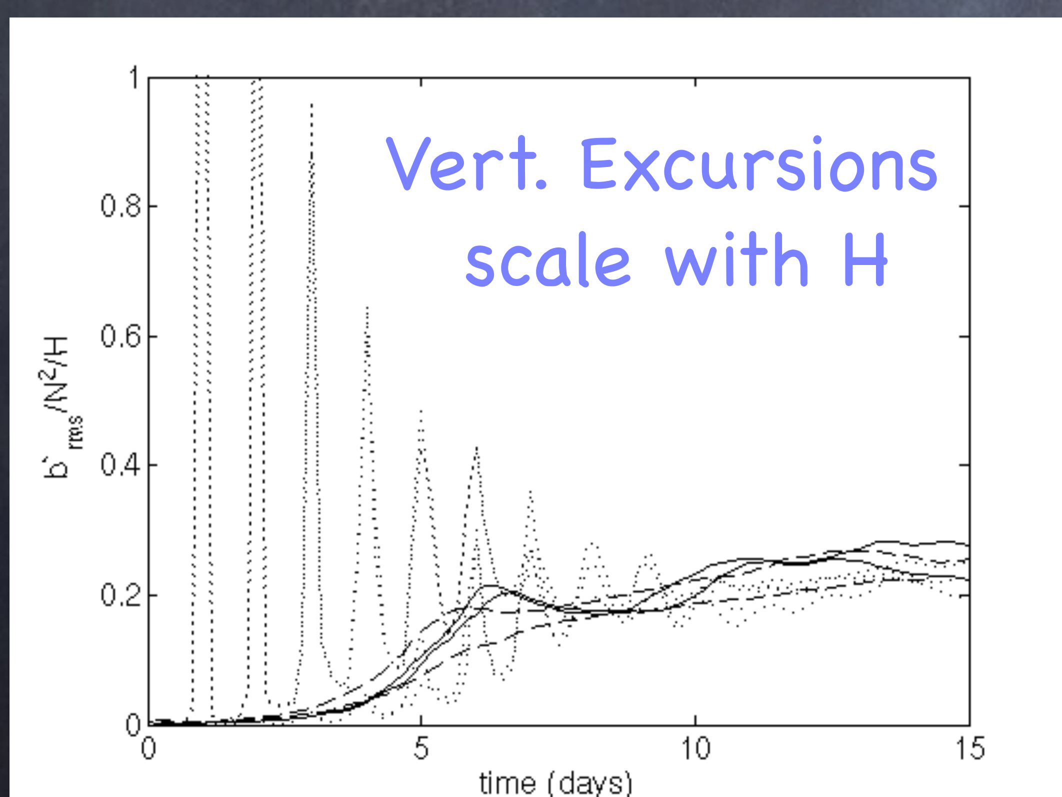
Diurnal Cycle and KPP Adjustment

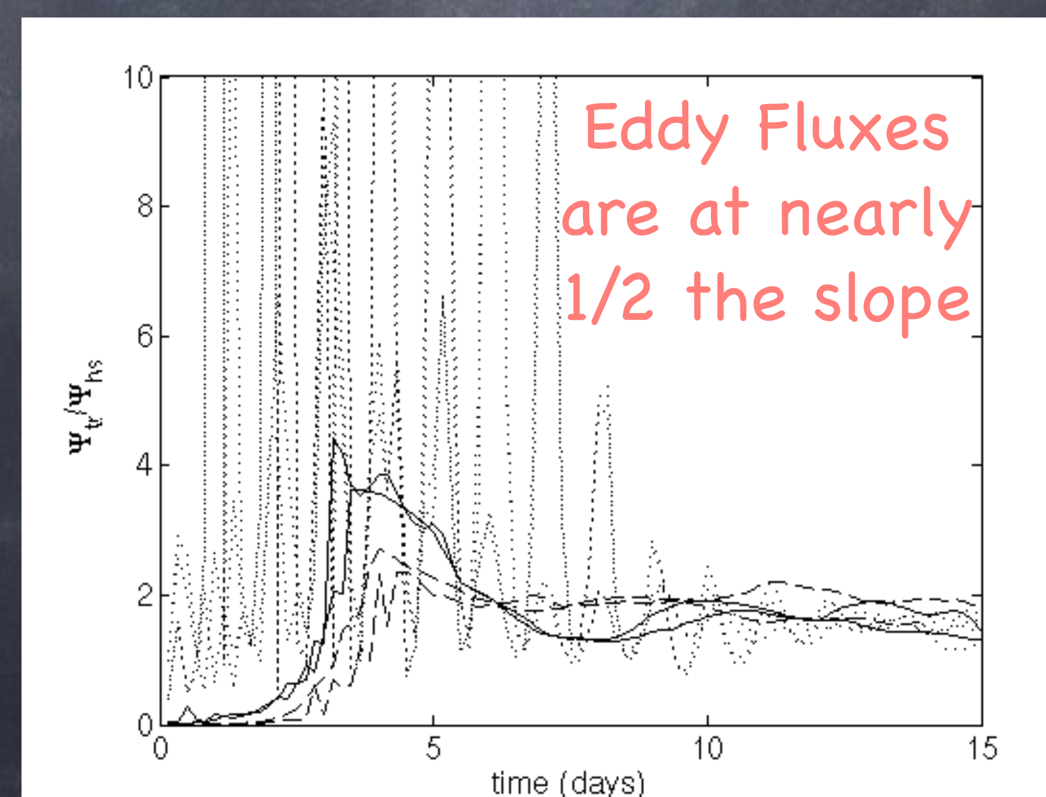
Note: initial geostrophic adjustment overwhelmed by eddy restratification

Parameterization of Finite Amp. Eddies: Ingredients

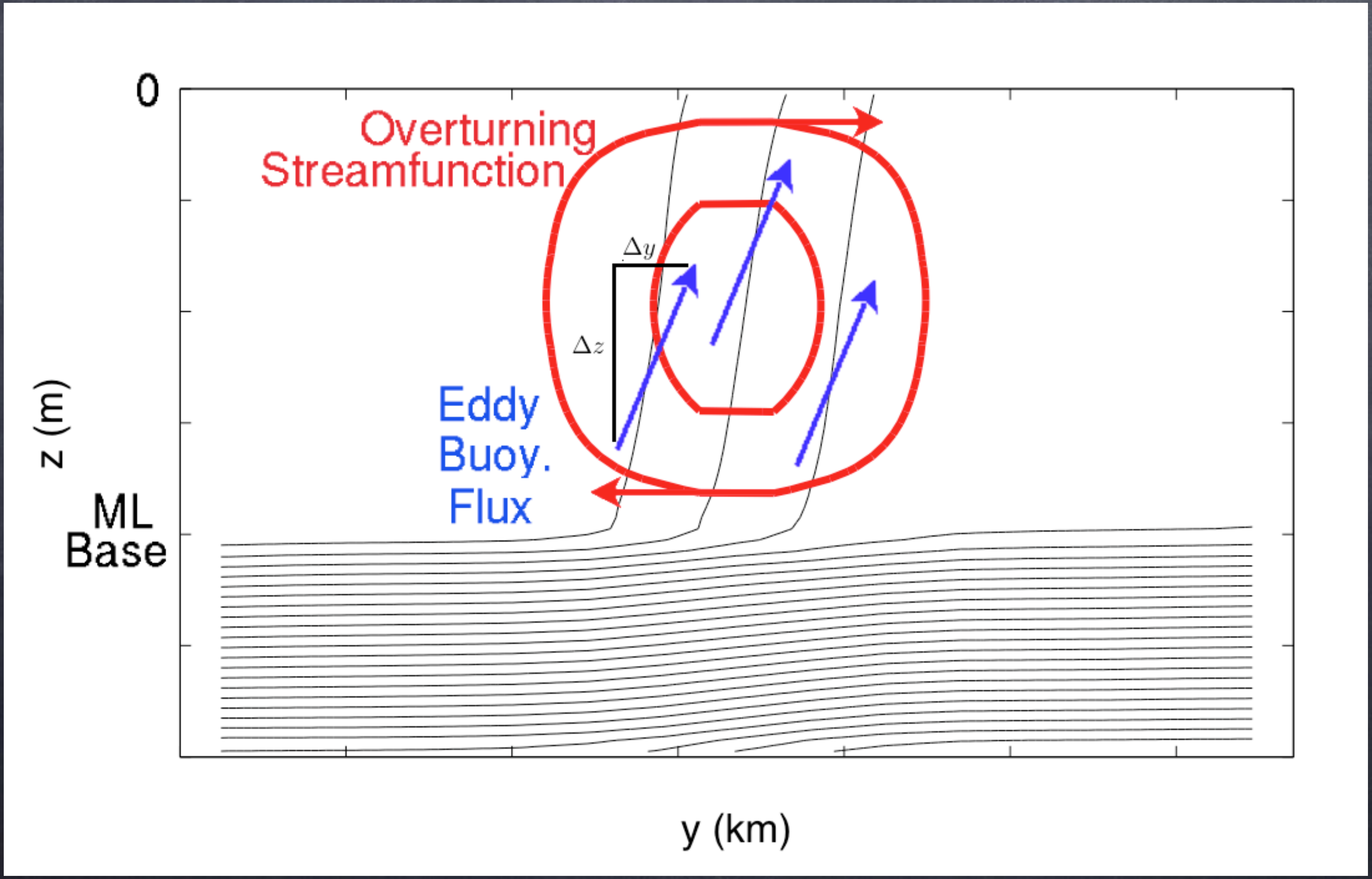








Schematic of the overturning



Magnitude Analysis: Vert. Fluxes

Extraction of potential energy by submesoscale eddies:

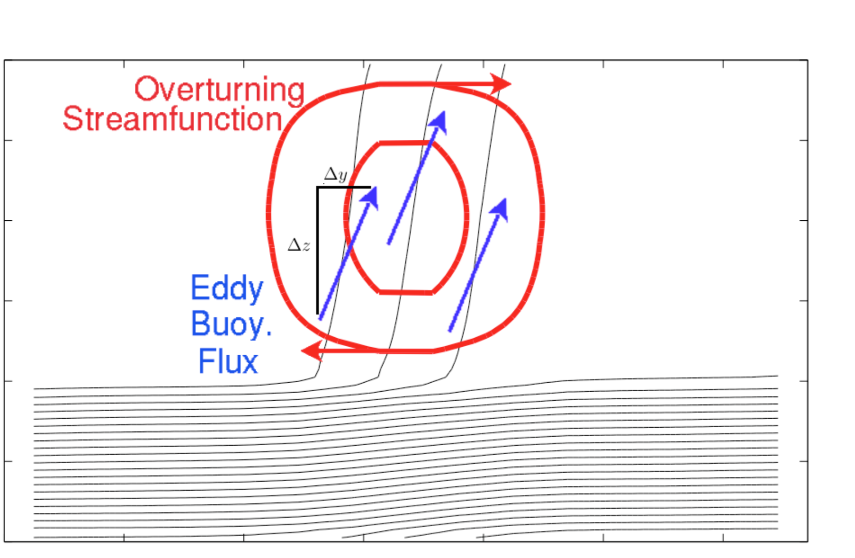
$$-\langle wb\rangle = \frac{\partial \langle PE\rangle}{\partial t} \approx \frac{\Delta PE}{\Delta t} \propto \frac{\Delta z \Delta b}{\Delta t}$$

Buoy. diff just parcel exchange of large-scale buoy.

Flux slope scales with the buoy. slope: $\frac{\Delta y}{\Delta z} \propto \frac{-\frac{\partial \bar b}{\partial z}}{\frac{\partial \bar b}{\partial y}}$

Time scale is turnover time of thermal wind:

Vertical scale known: $\Delta z \propto H$



$$\langle wb\rangle \propto \frac{\Delta z\left(\Delta y\frac{\partial \bar b}{\partial y} + \Delta z\frac{\partial \bar b}{\partial z}\right)}{\Delta t} \qquad \langle wb\rangle \propto \frac{H^2}{|f|}\left[\frac{\partial \bar b}{\partial y}\right]^2$$

Fox-Kemper et al., 2007

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

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

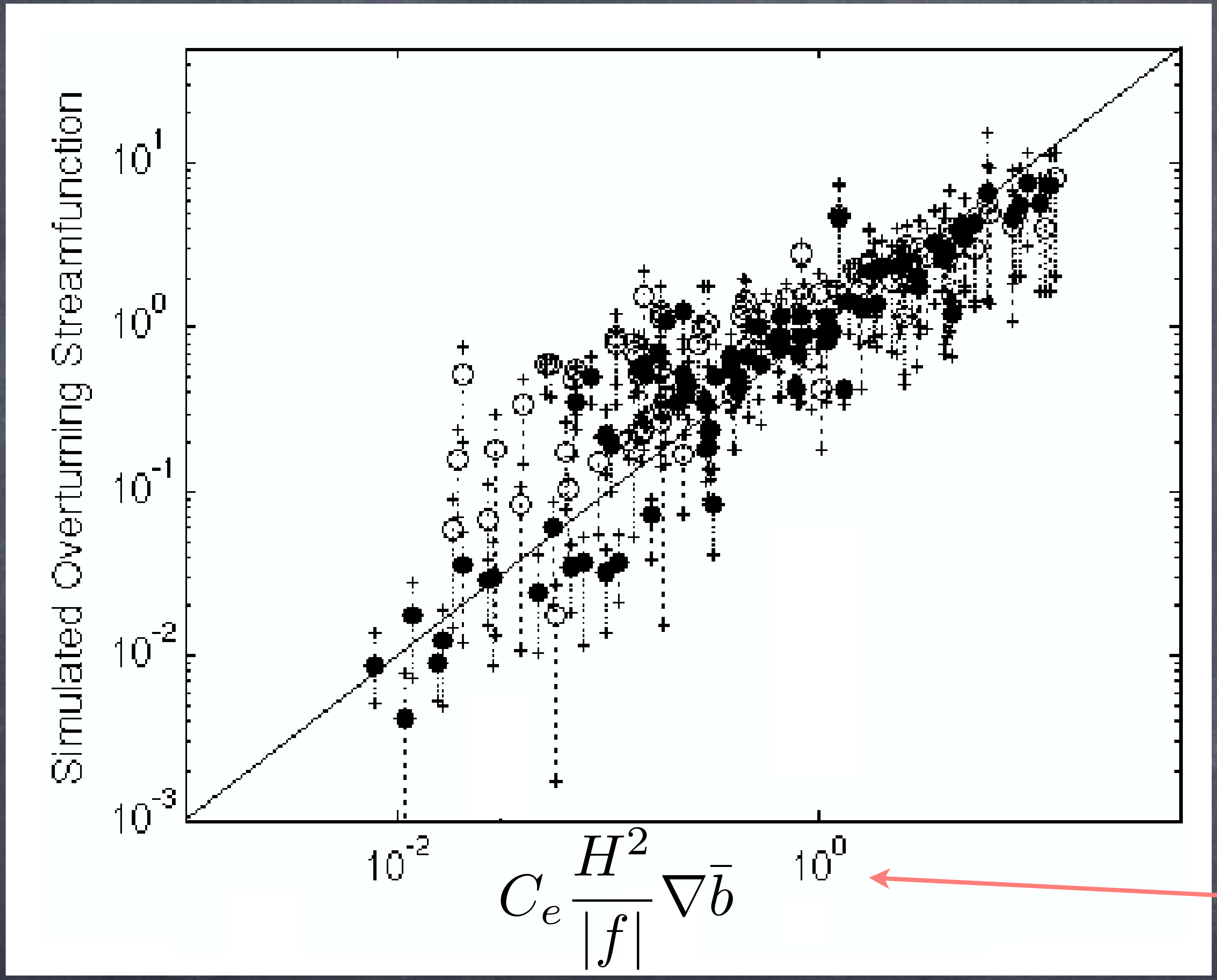
For a consistently upward,

$$\langle w' b' \rangle \propto \frac{H^2}{|f|} |\nabla \bar{b}|^2$$

And horizontally downgradient flux.

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

It works for Prototype:

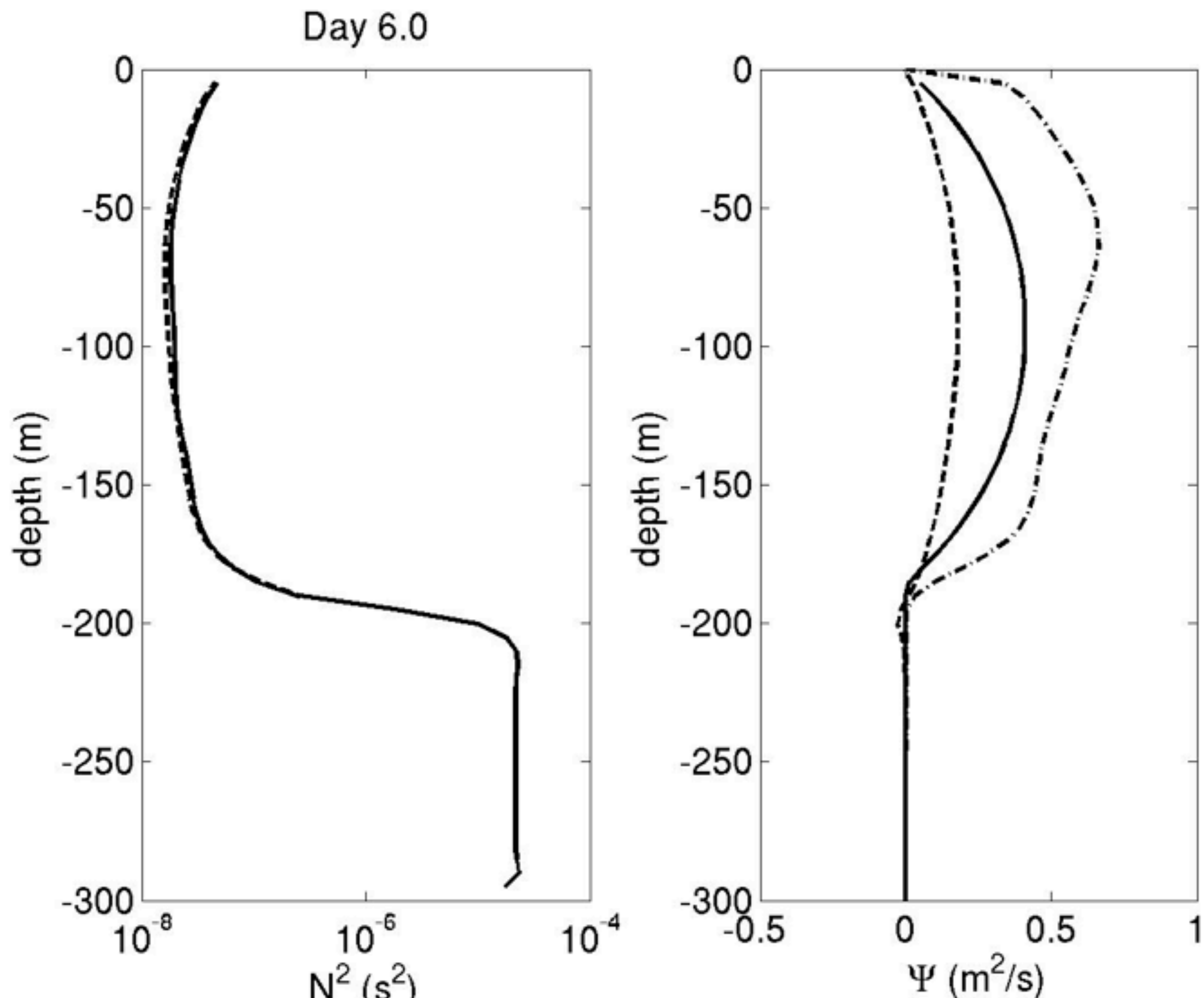


>2 orders of magnitude!

Closed Circles: No Diurnal

Open Circles: With Diurnal

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



Eady Solution

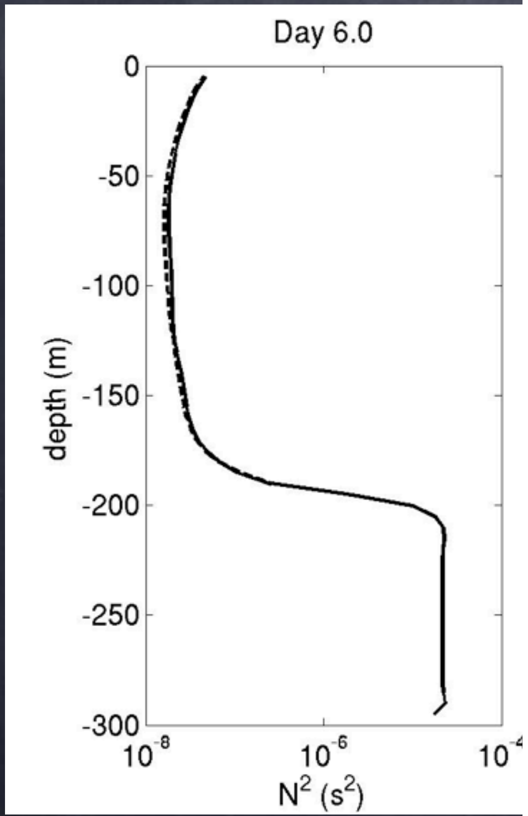
$$\frac{\sinh\left(\frac{-2z}{H\sqrt{\mathrm{Bu}_\kappa}}\right)\sinh\left(\frac{2(H+z)}{H\sqrt{\mathrm{Bu}_\kappa}}\right)}{\sinh^2\left(\frac{1}{\sqrt{\mathrm{Bu}_\kappa}}\right)}$$

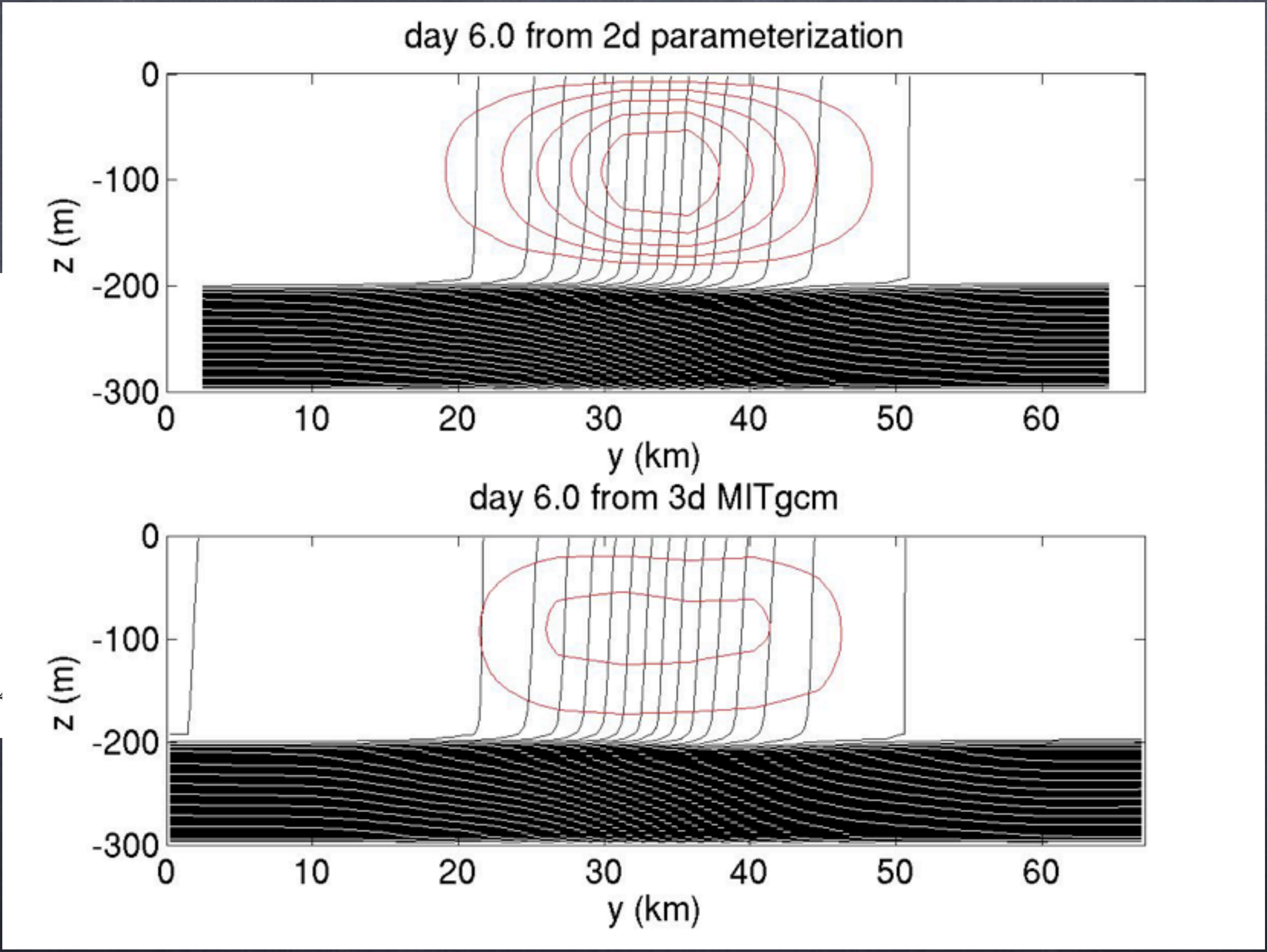
Simplified Form:

$$\frac{-4z(z+H)}{H^2}$$

What does it look like?

N^2





Summary so far:

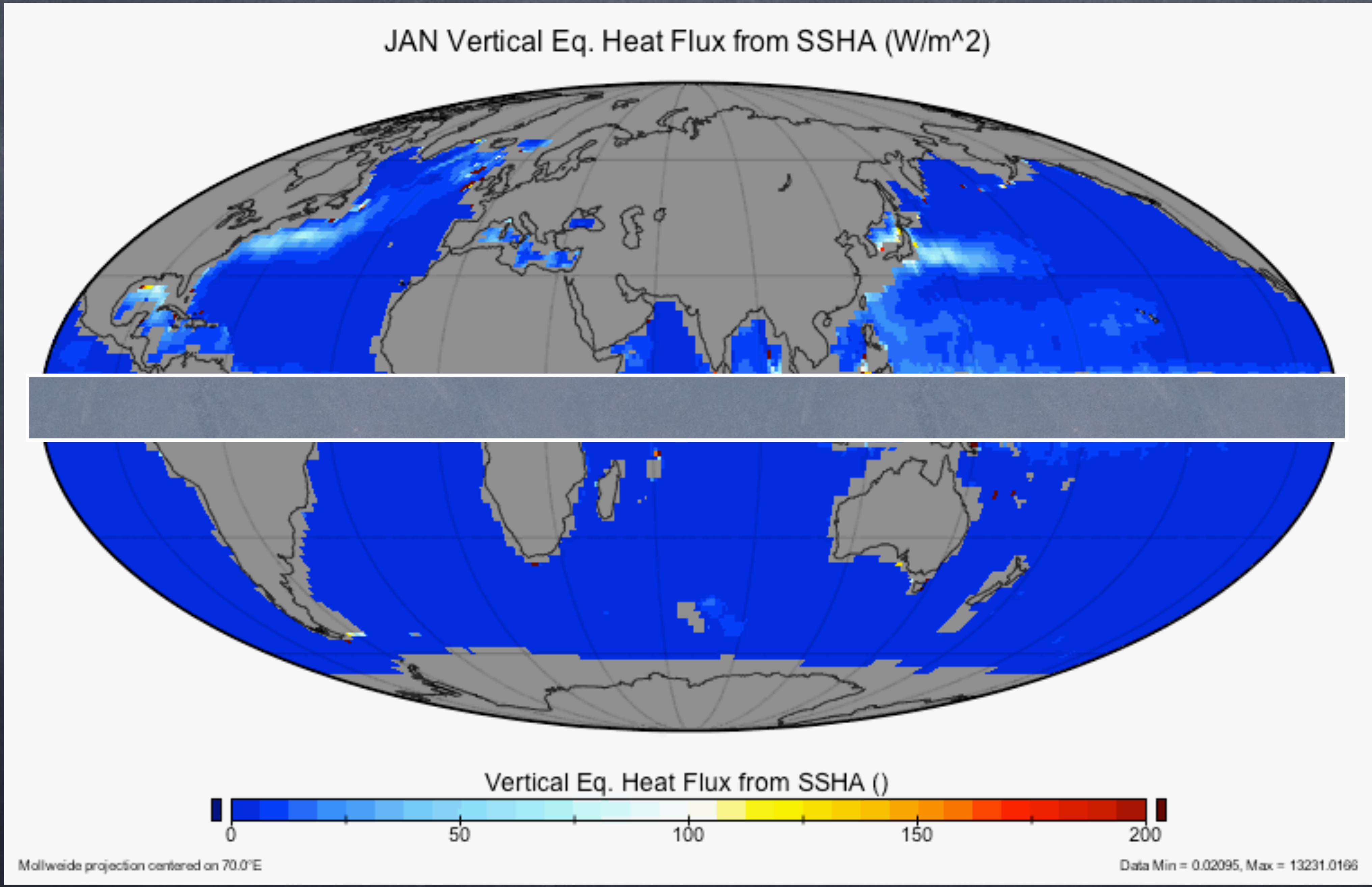
- Ocean mixed layer isn't totally mixed
- Submesoscale vertical fluxes are important in setting mixed layer stratification
- Weak mixed layer stratification makes for submesoscale eddies by baroclinic instability
- Their overturning can be parameterized

Now we turn to their impact

Where in the world are the fluxes?

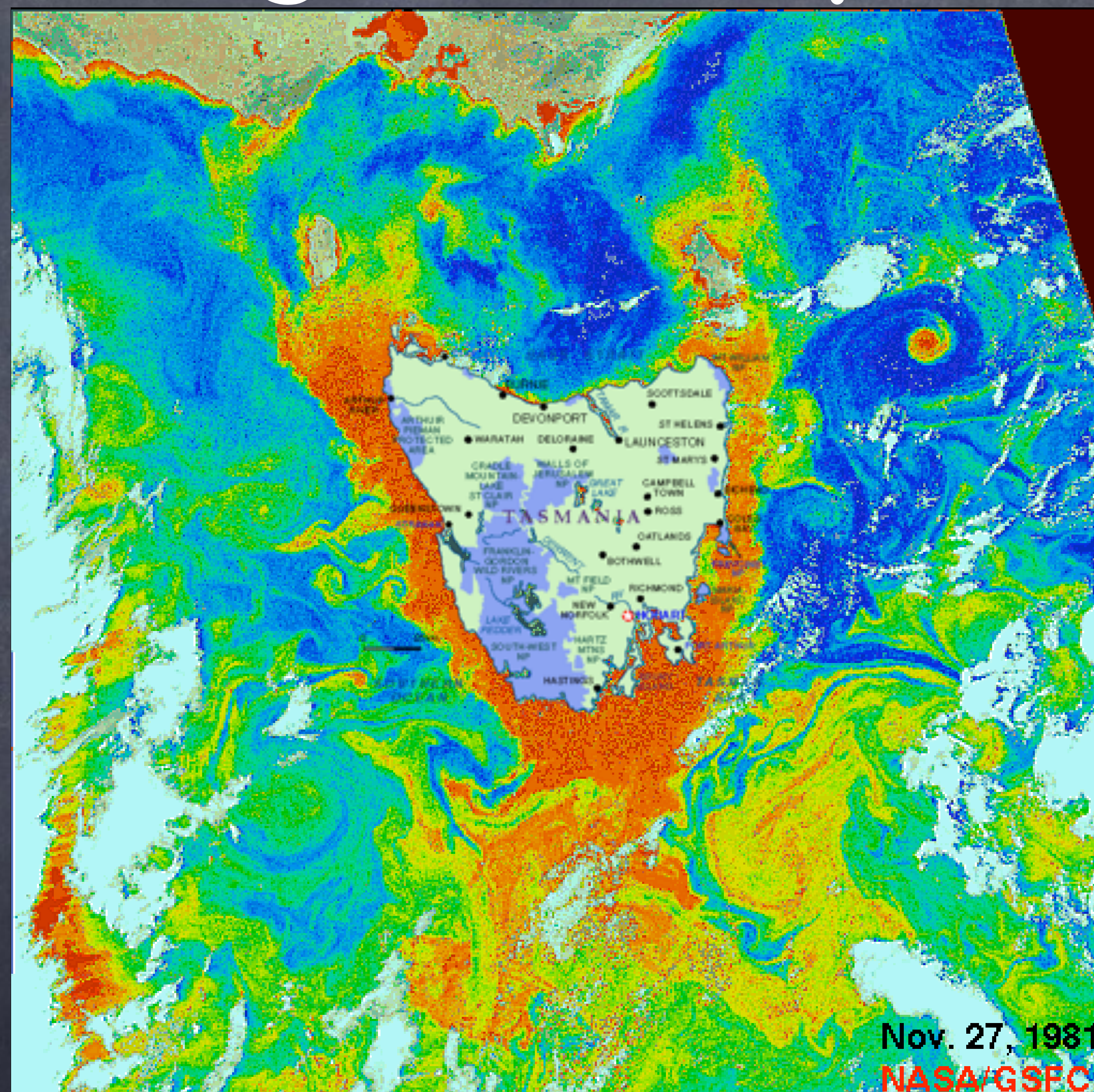
(Equiv. Vert. Heat Flux from Satellite SSHA)

Where convection makes ML deep.



Biological Impact?

Ocean color image showing submesoscale structure in chlorophyll concentration near Tasmania



100 km

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

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 fluxes, but elsewhere surface fluxes are weaker, too.

Overall, MLE estimates exceed:

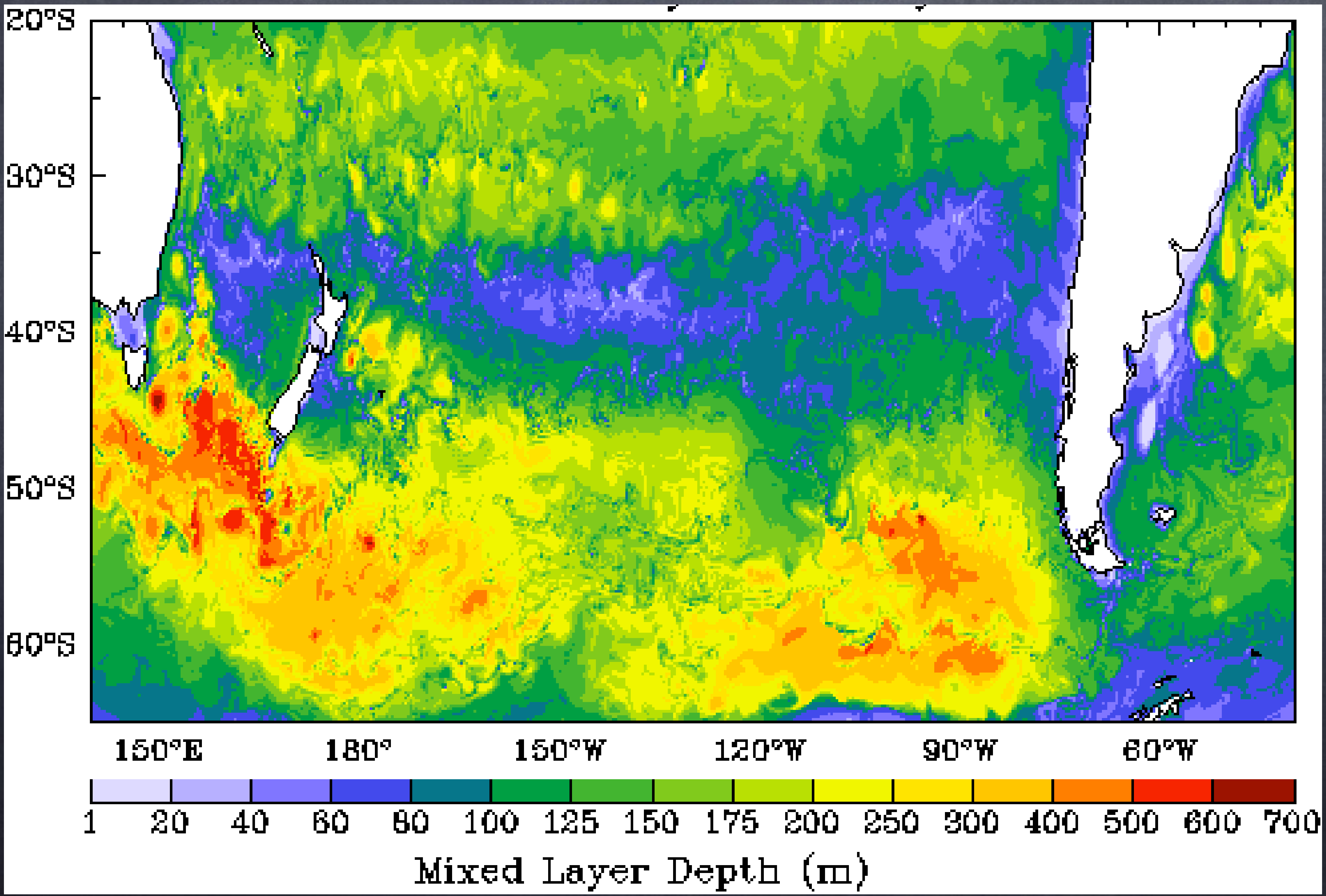
50% of monthly-mean surface flux climatology 25% of the time,

and

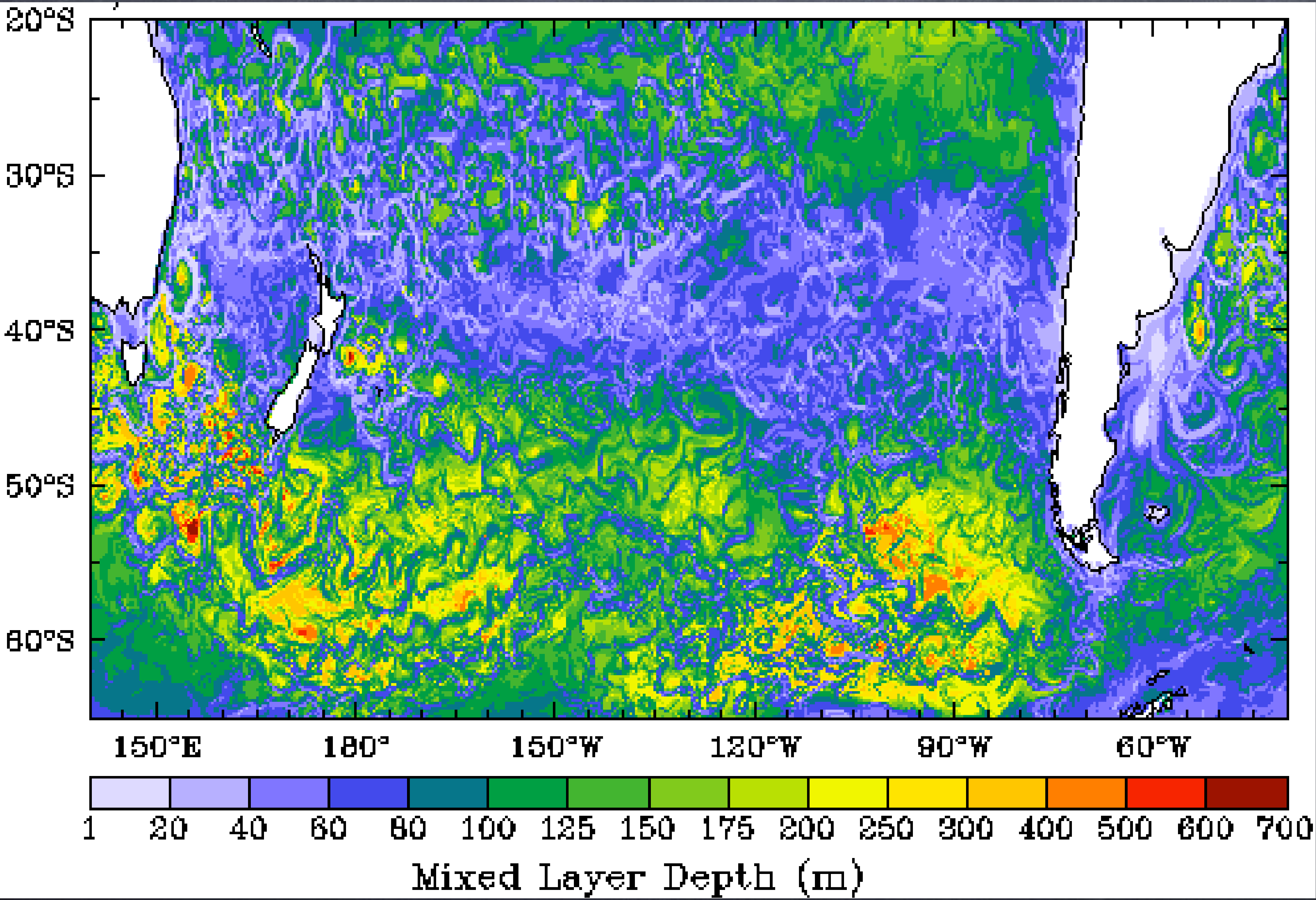
5% of monthly-mean surface flux climatology 50% of the time.

(compared to Grist & Josey 2003)

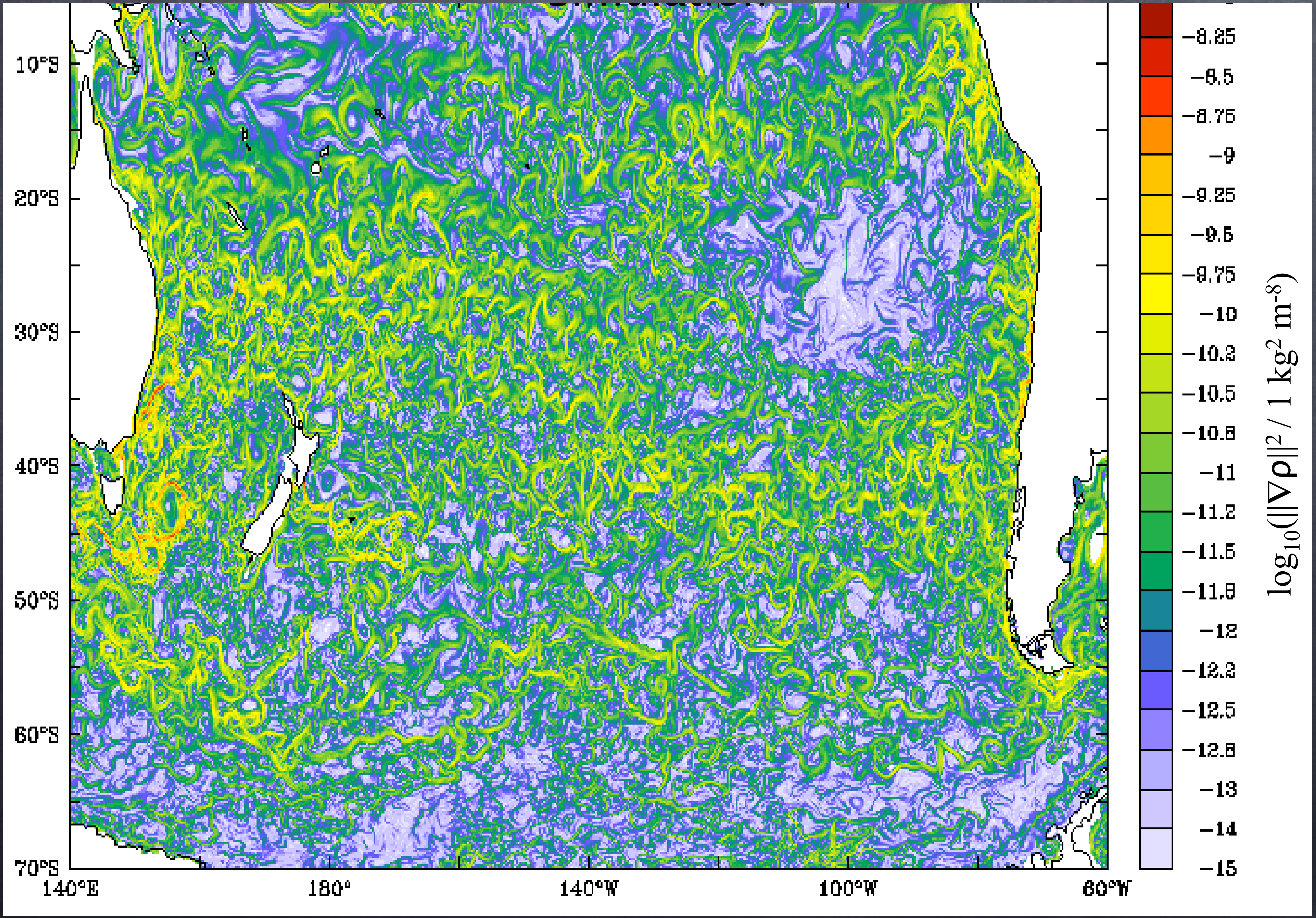
Changes To Mixing Layer Depth in Eddy-Resolving Southern Ocean Model



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

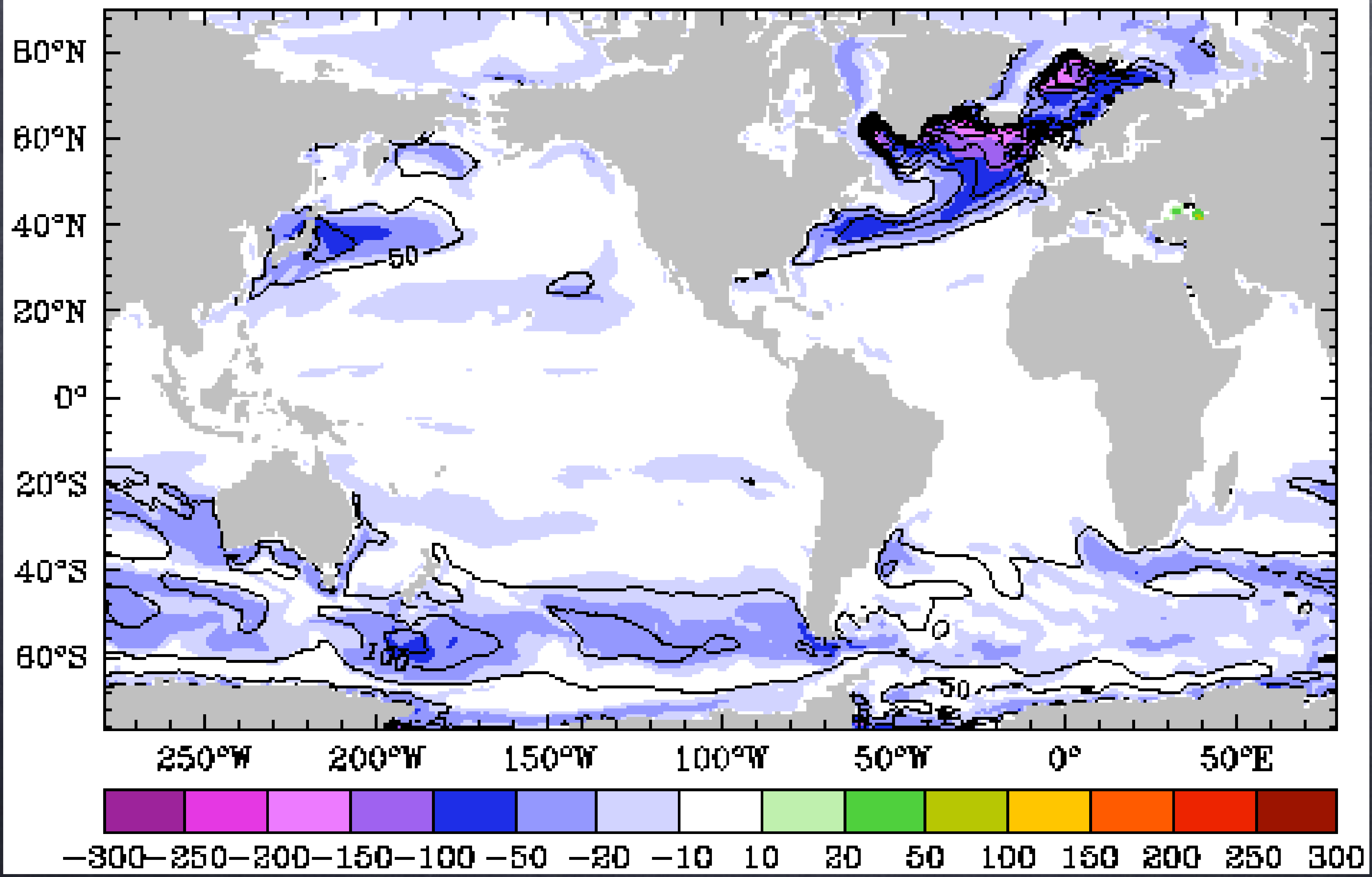


Surf. Buoy. Gradients



Improves Restratification after Deep Convection

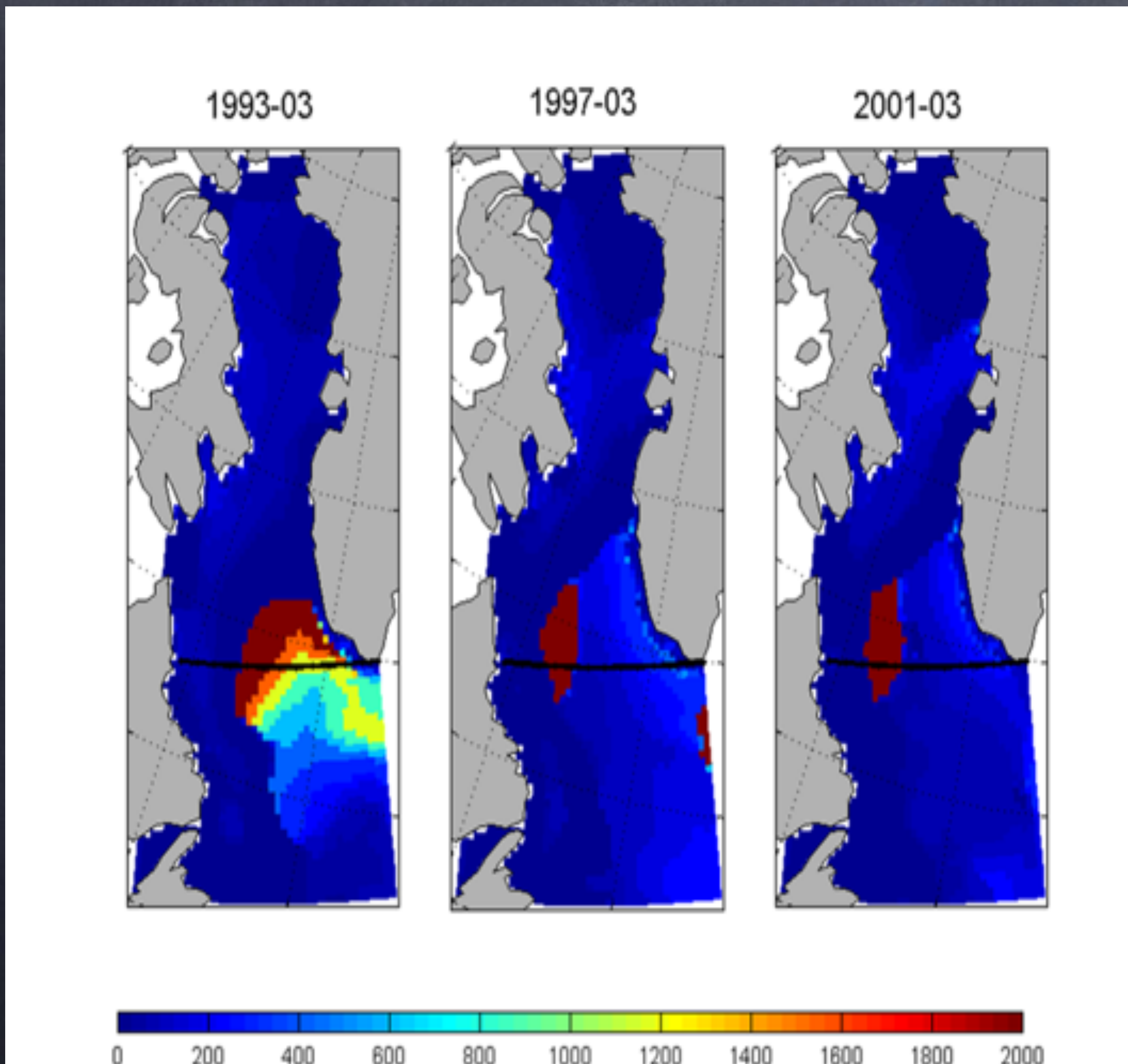
Note: scaling agrees with Haine&Marshall (98) and Jones&Marshall (93,97)



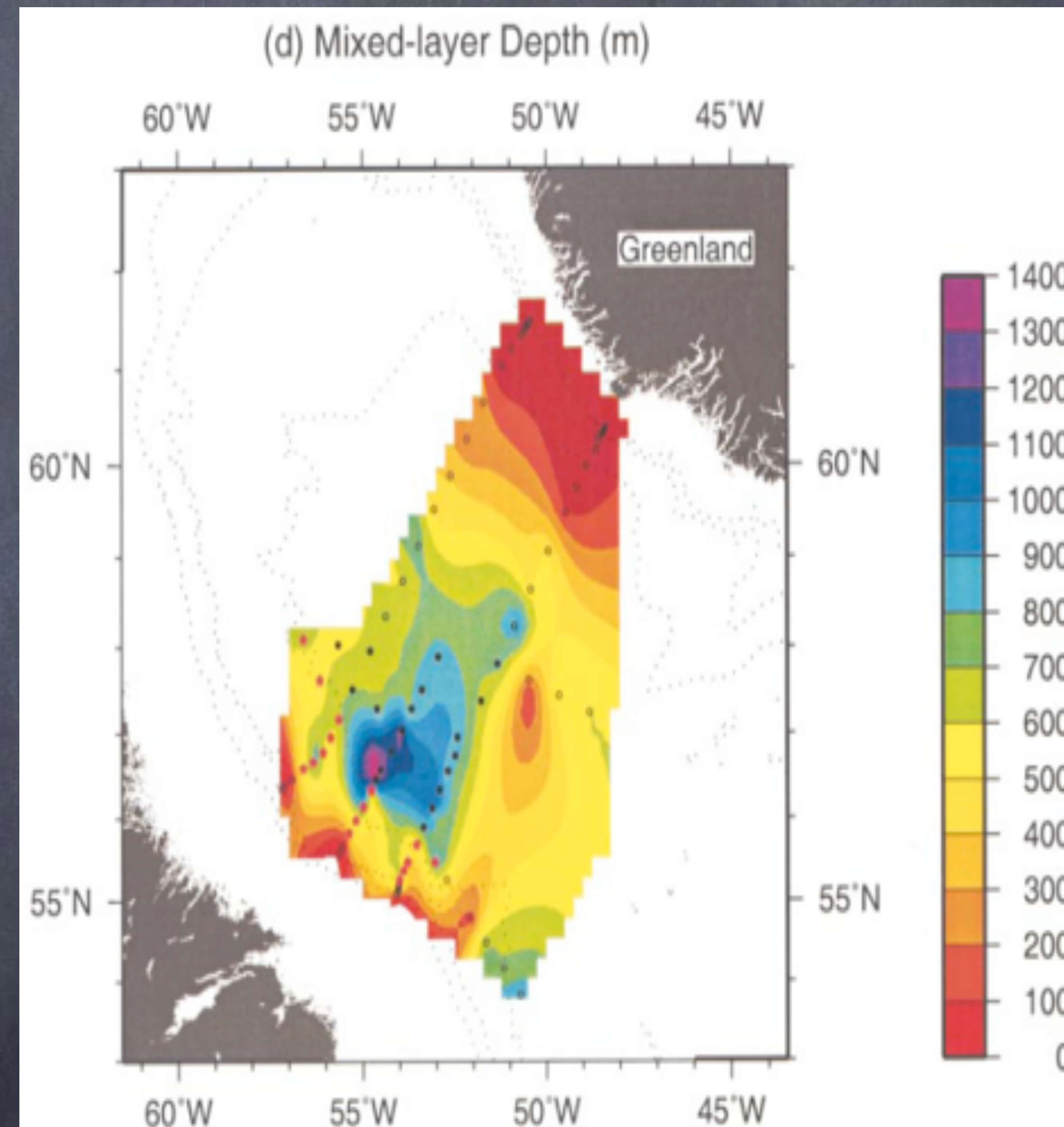
Equator (f->0) and coarse resolution (up to 1 deg) are manageable

Known Deep Bias in Other Models

MLD from MITgcm/ECCO



MLD from Obs.



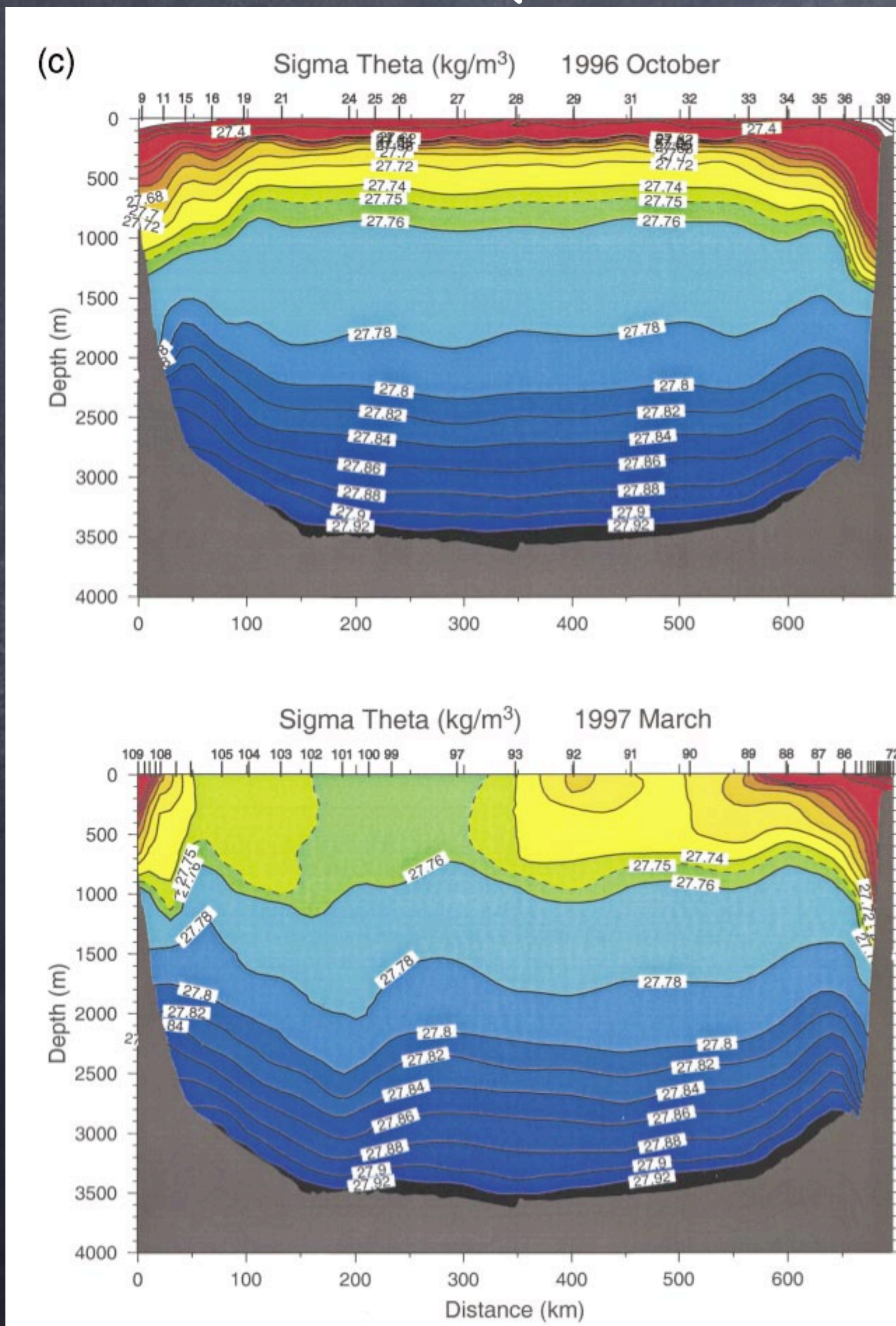
Hydrography of the Labrador Sea during Active Convection

ROBERT S. PICKART AND DANIEL J. TORRES

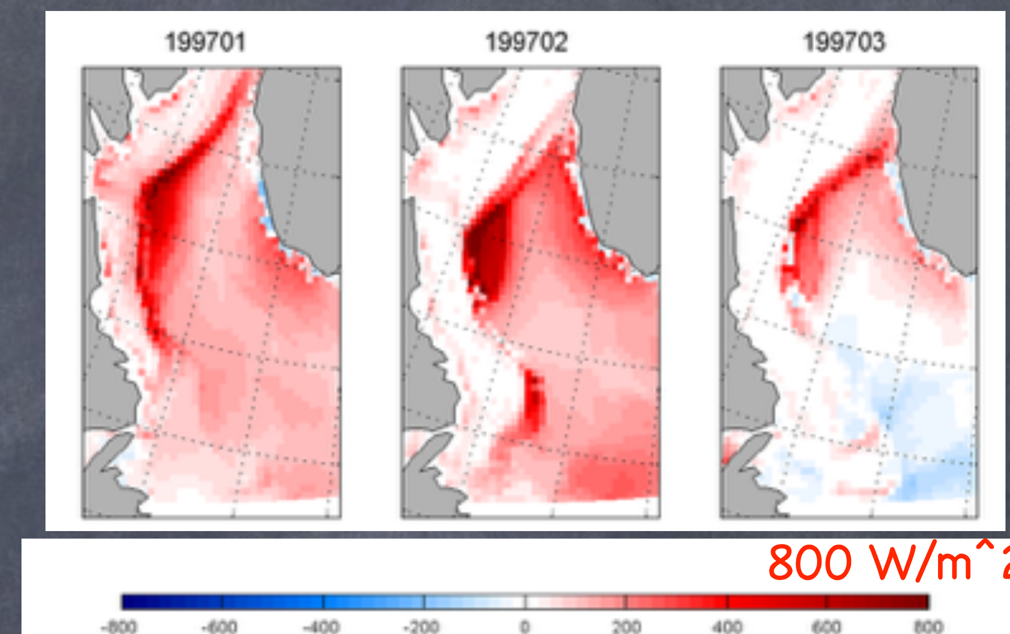
Courtesy I. G. Fenty

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

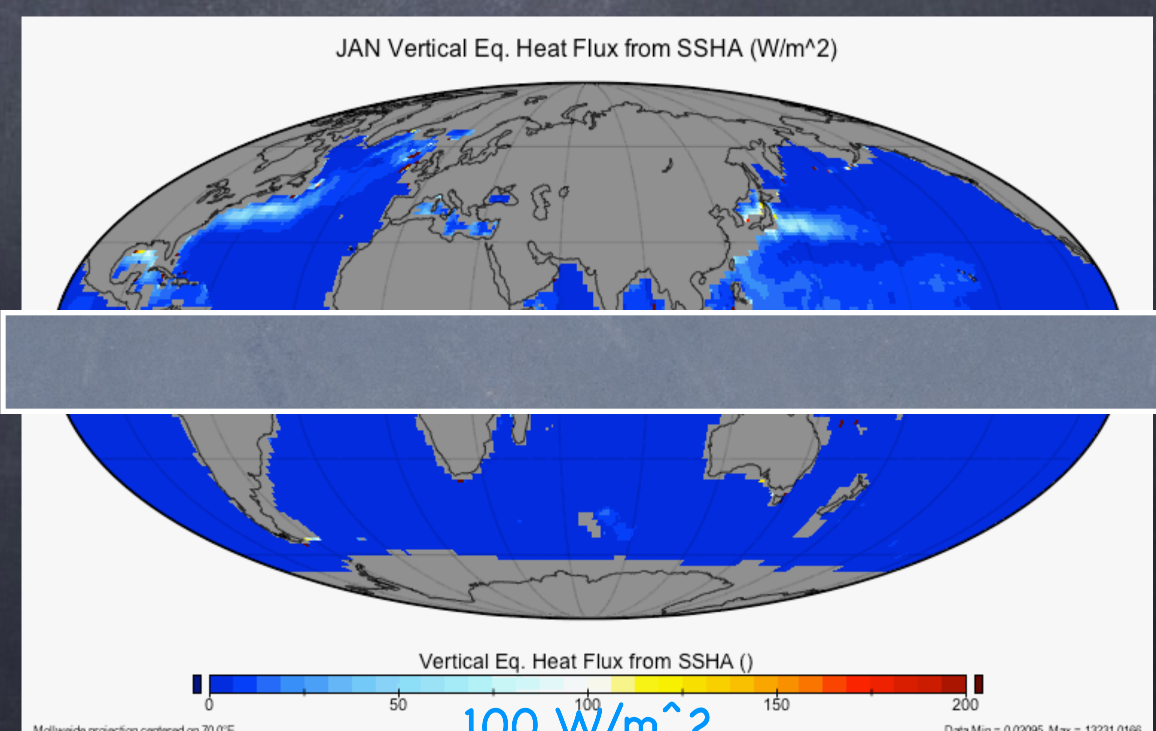
(GM can't do it because of tapering)



Pickart et al 02.



Fenty/MITgcm



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.
- Eddies' main effect is restratification of ML with sizeable equivalent vertical heat fluxes. Many observations are consistent, and model biases are reduced. Biogeochemical effects are likely, as vertical fluxes and mixed layer depth are changed.
- How to separate effects of frontogenesis??

The Parameterization:

- Thus, the Streamfunction:

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

- 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:

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

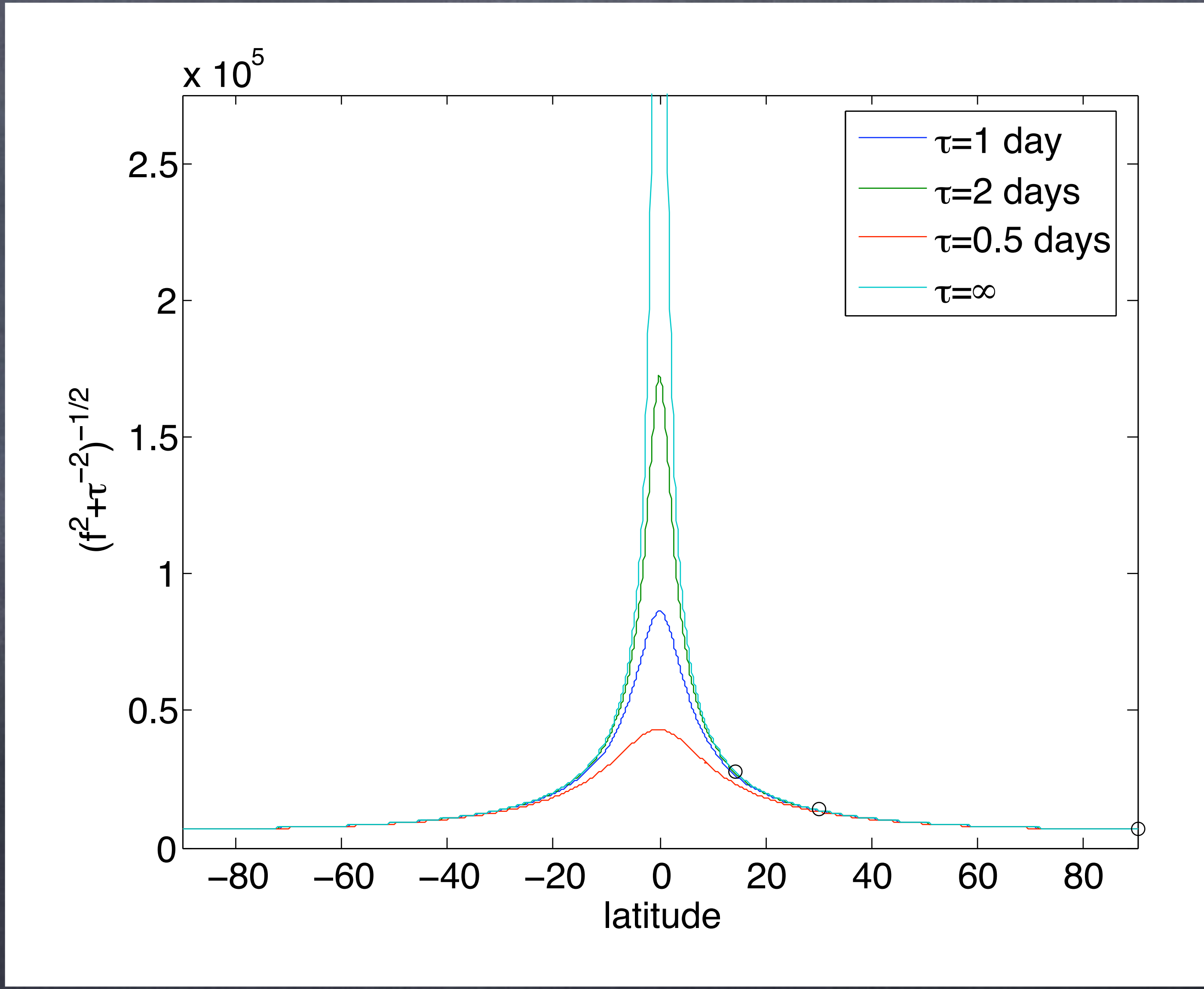
- Adjustments for coarse resolution and f->0 are known

Taper to SML at Equator

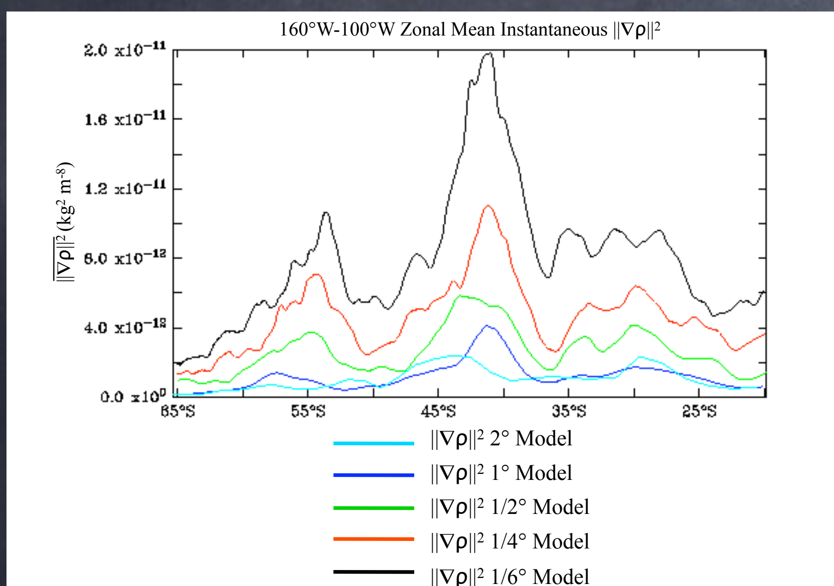
$$\boldsymbol{\Psi} = \frac{C_e H^2 \mu(z)}{|f|} \nabla \bar{b} \times \hat{\mathbf{z}}$$

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

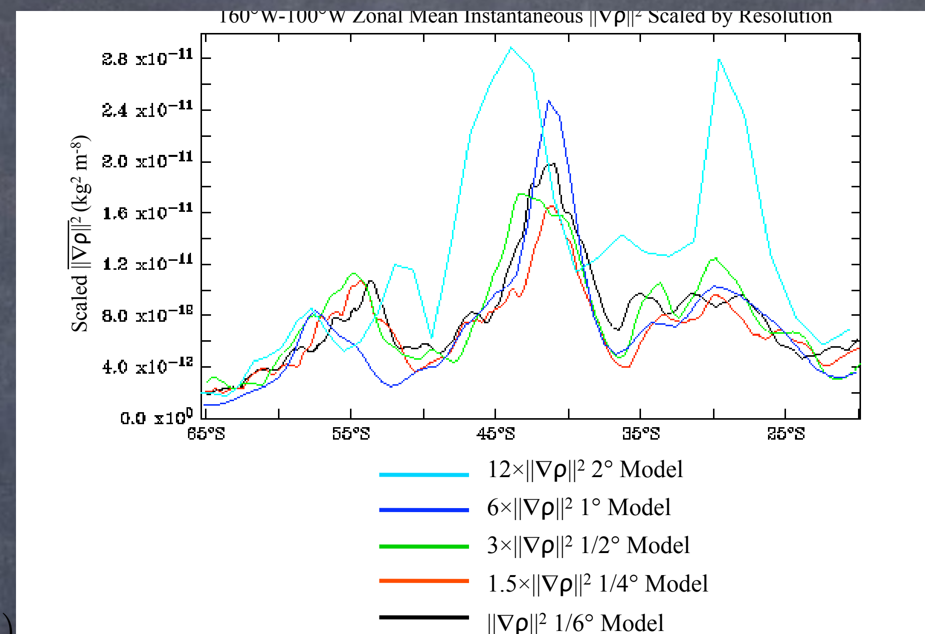
Converges to Young (1994) Subinertial ML Approx. at equator, which is gravity waves interrupted by mixing

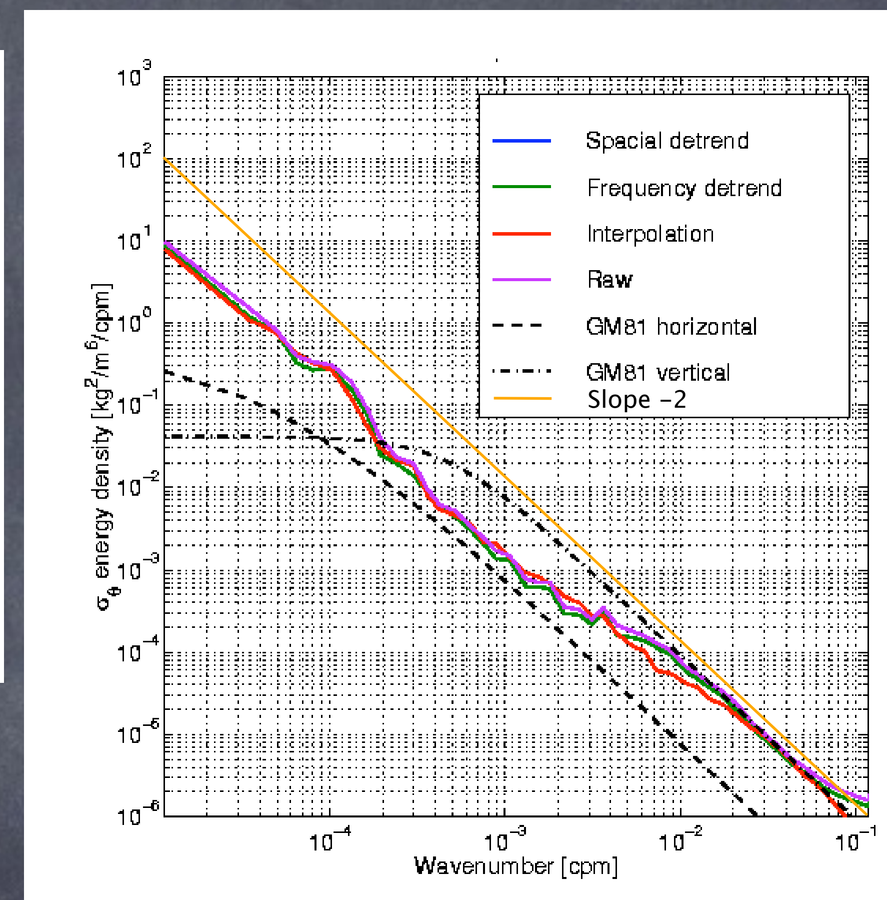


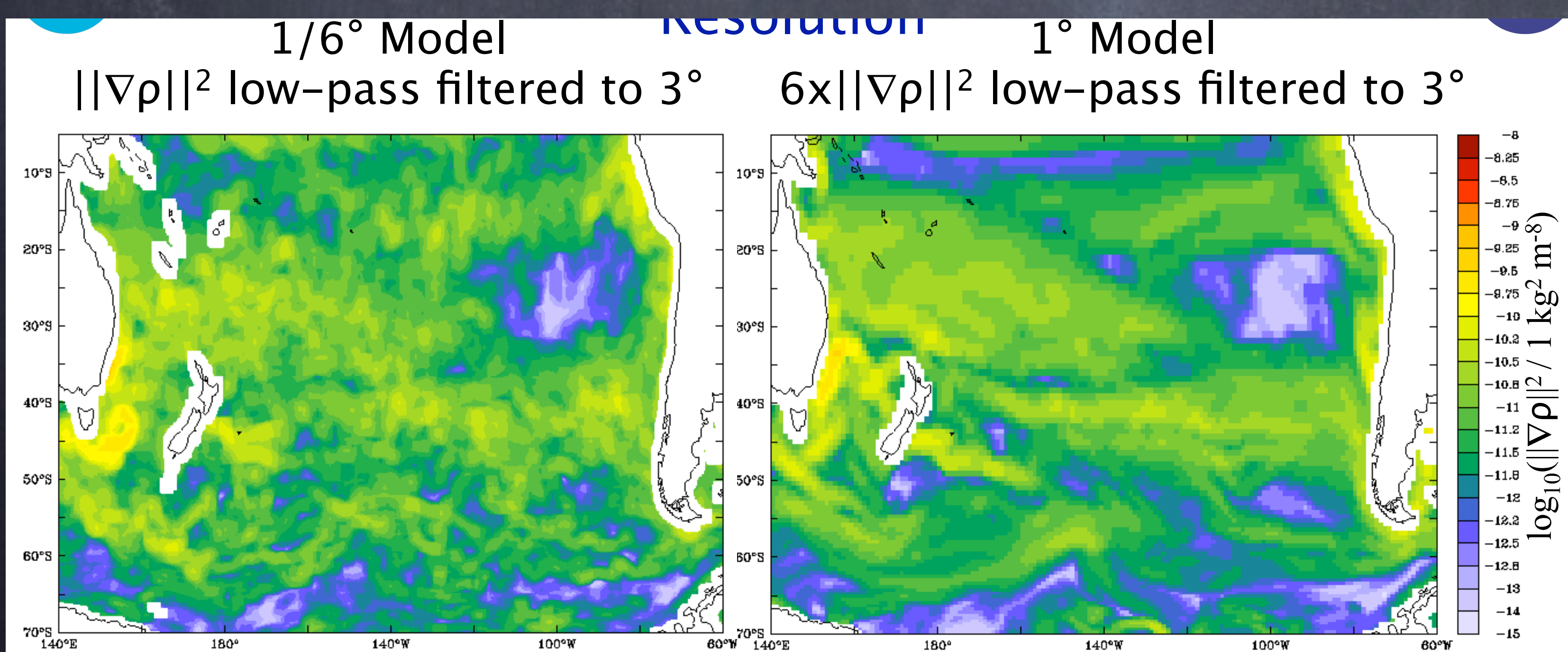
Coarse Resolution Adjustment



b)



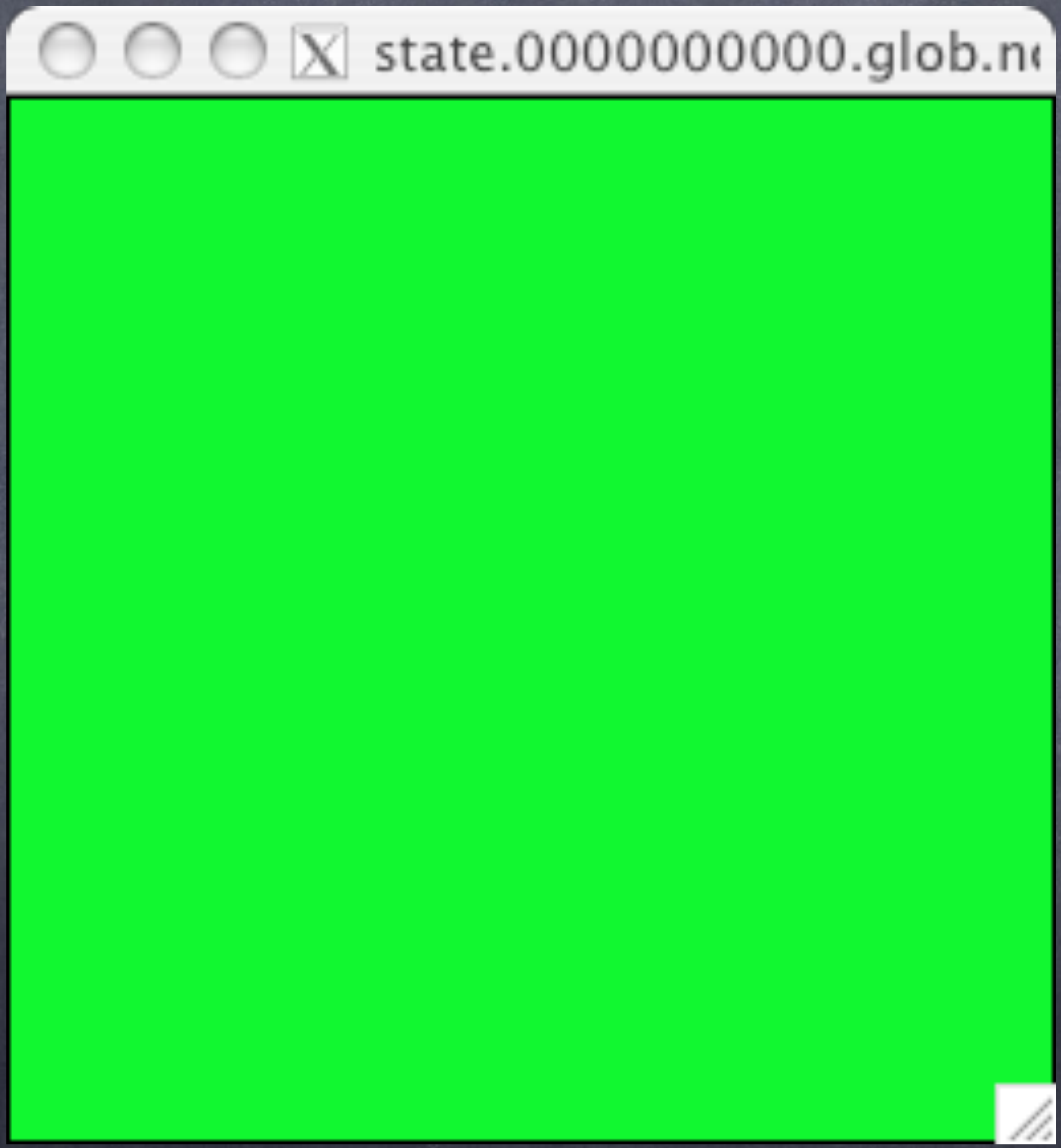




$$\overline{w'b'} = \frac{C_e H^2 \mu(z)}{|f|} |\nabla \bar{b}|^2$$

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

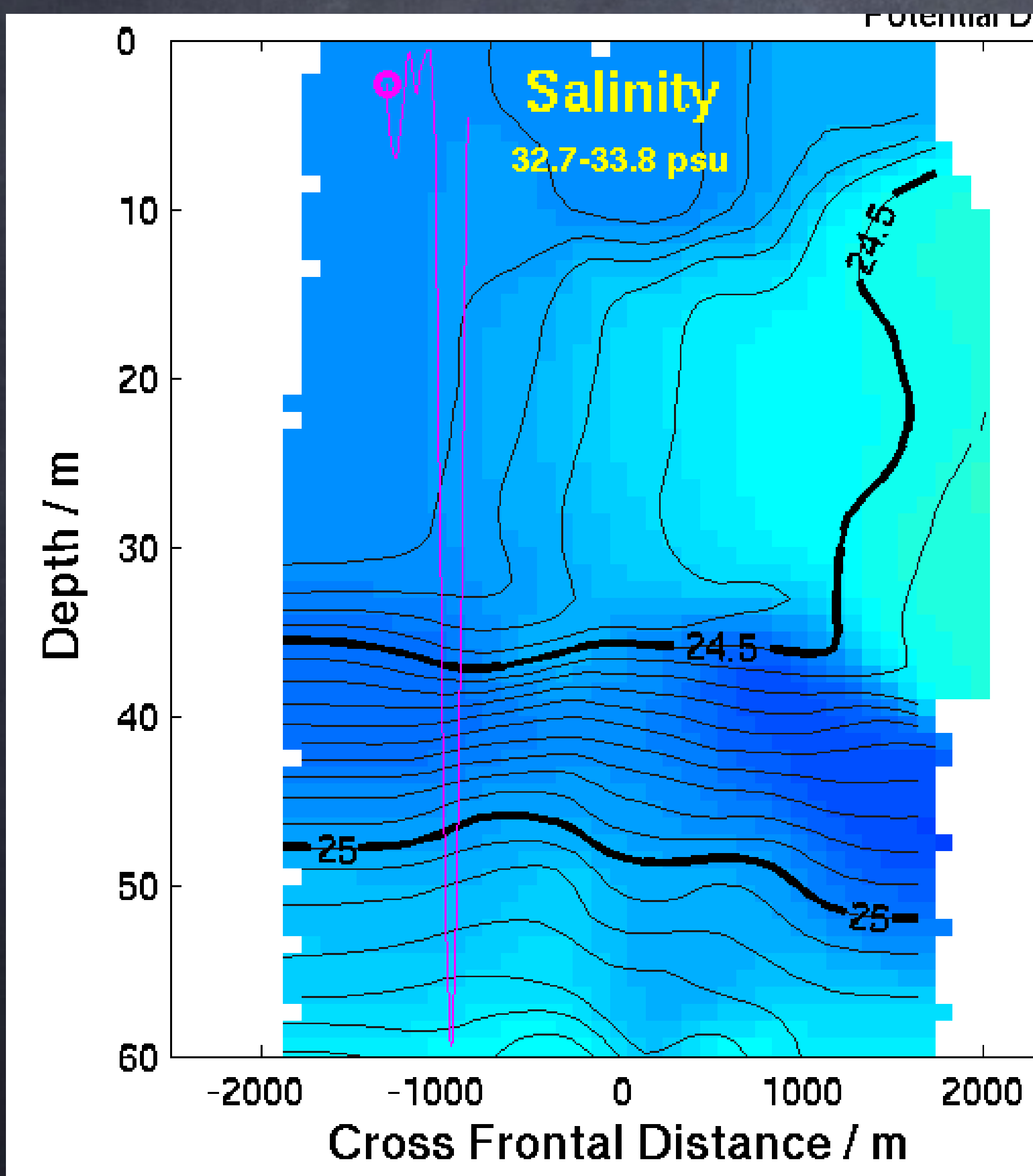
Coupling to turbulence?



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

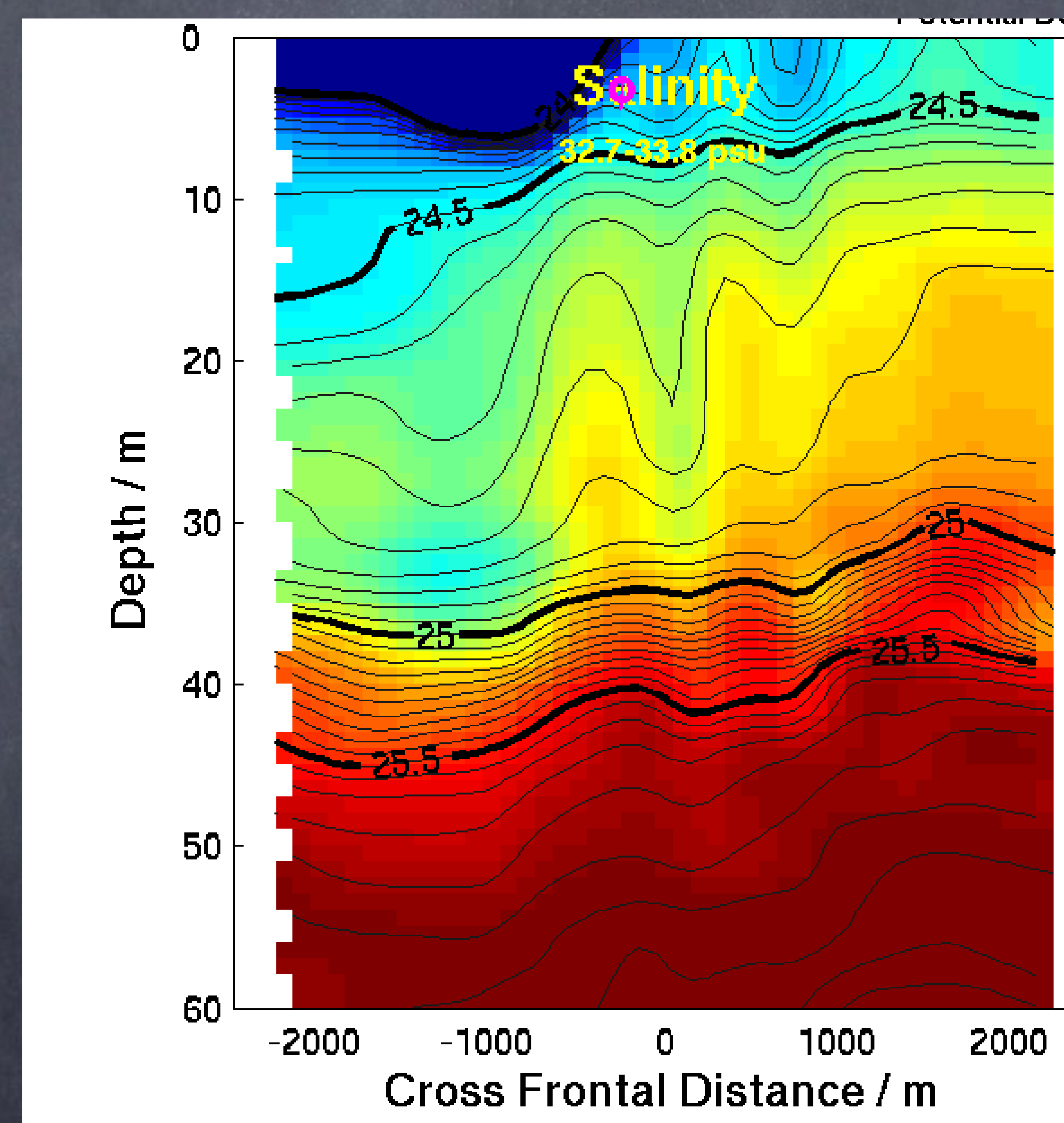
- 1.5 days, 5-6 Aug 2006
- Mixed layer restratifies under weakening wind forcing
- Characterized mixed layer evolution in Lagrangian (float-following) frame.

AESOP Observations of Rapid Restratification



30 kt wind

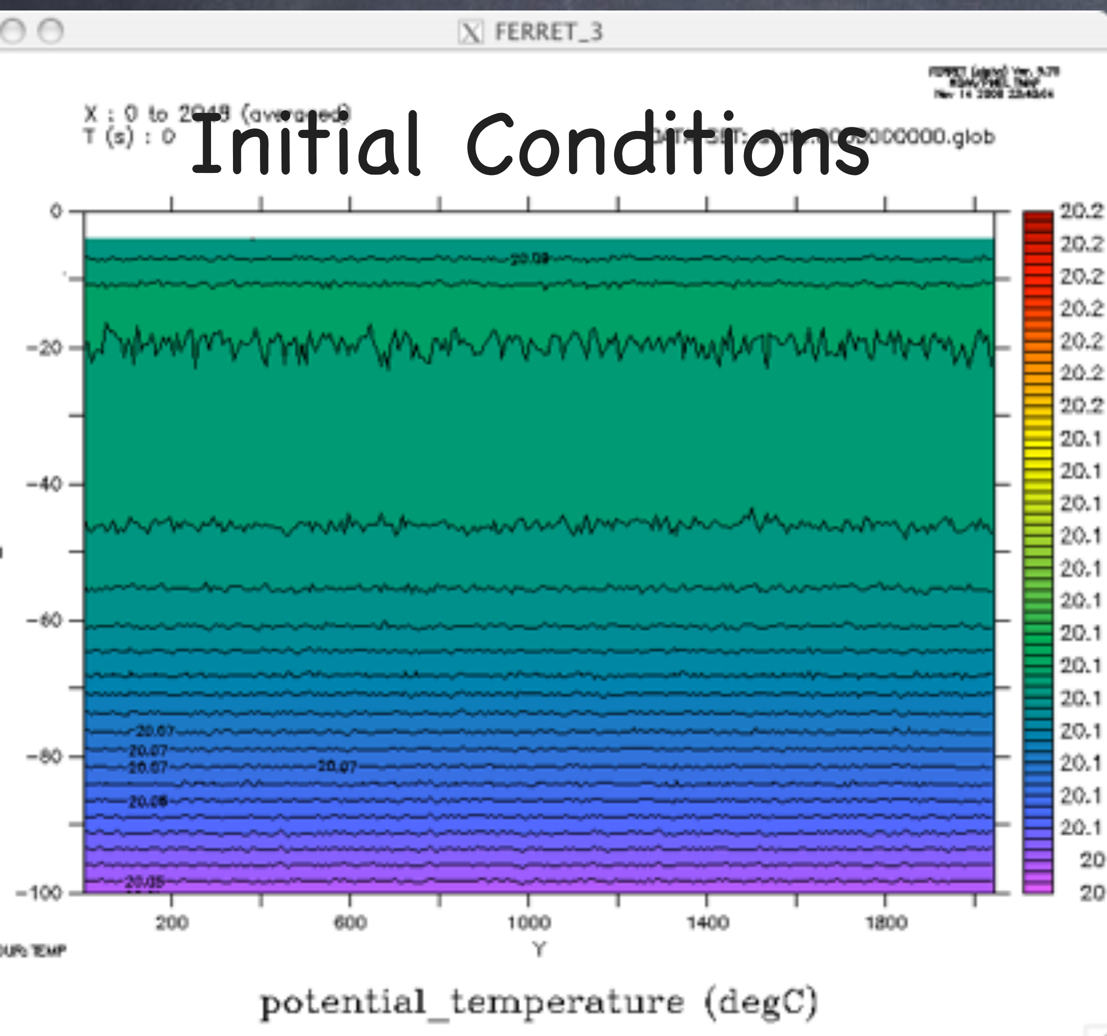
After one day



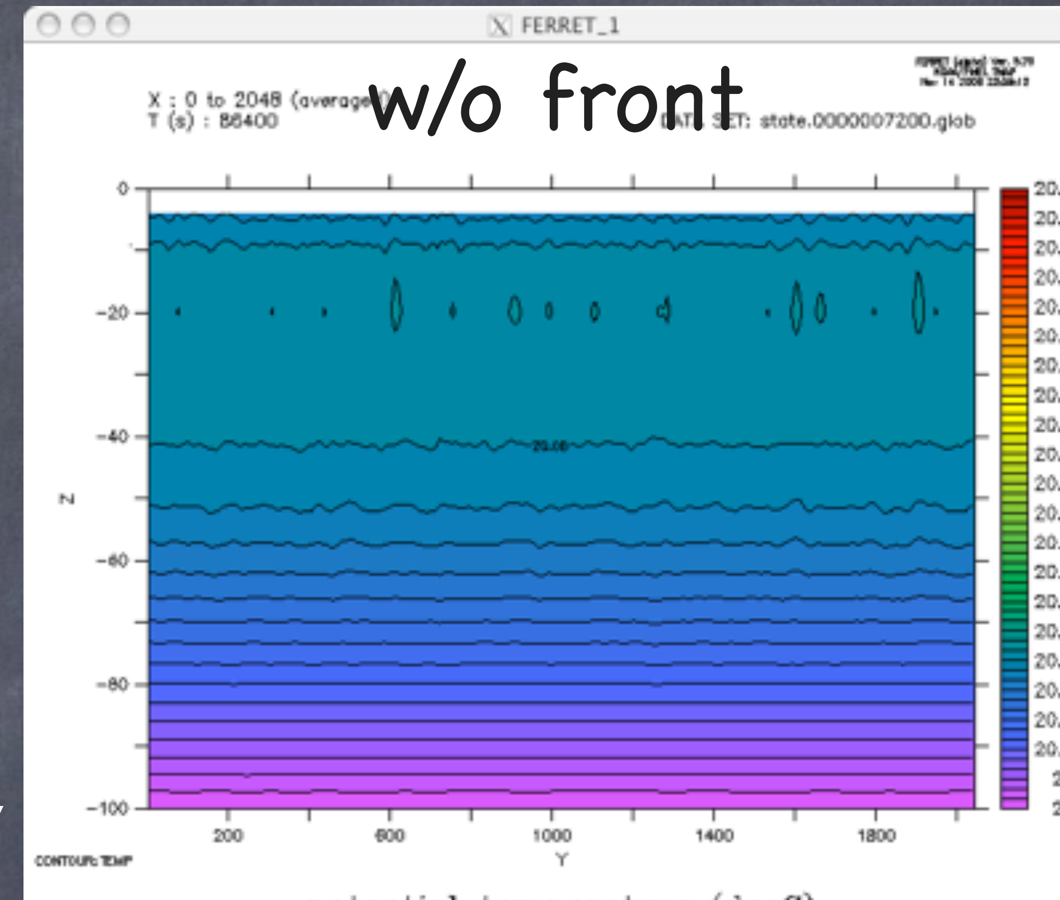
10 kt wind

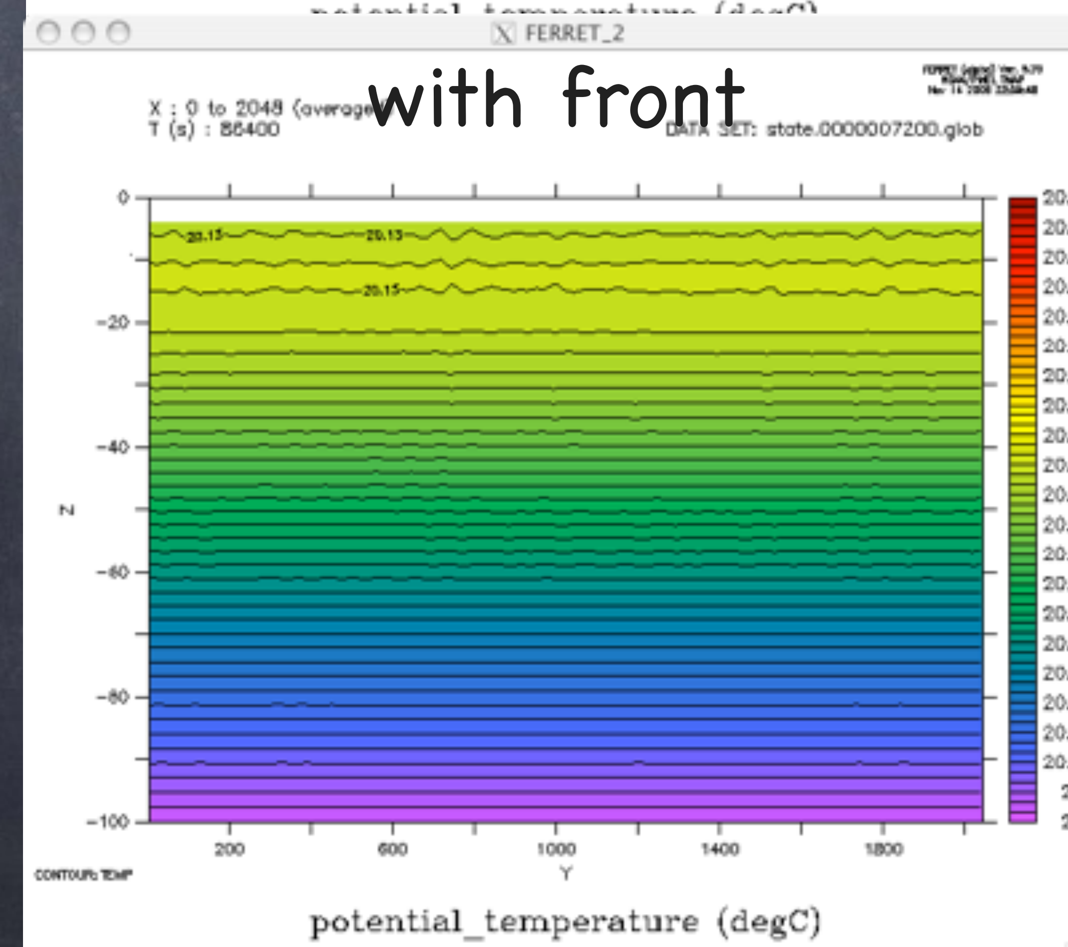
Courtesy E. D'Asaro

GRF/MLE Rapid Restratification



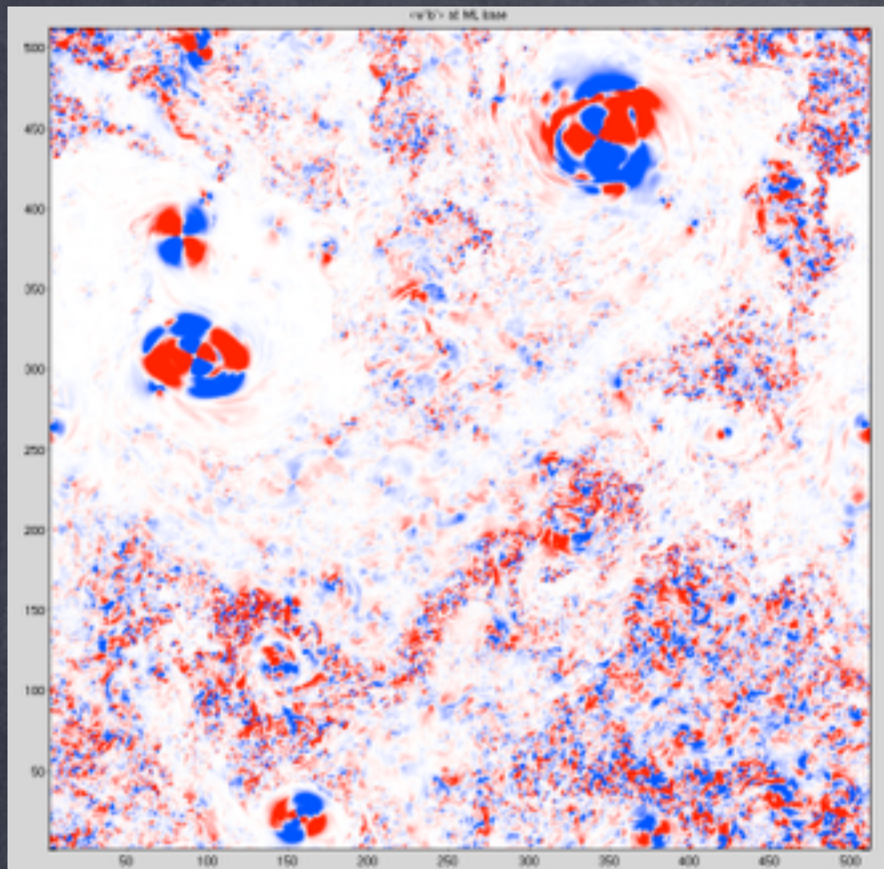
After one day



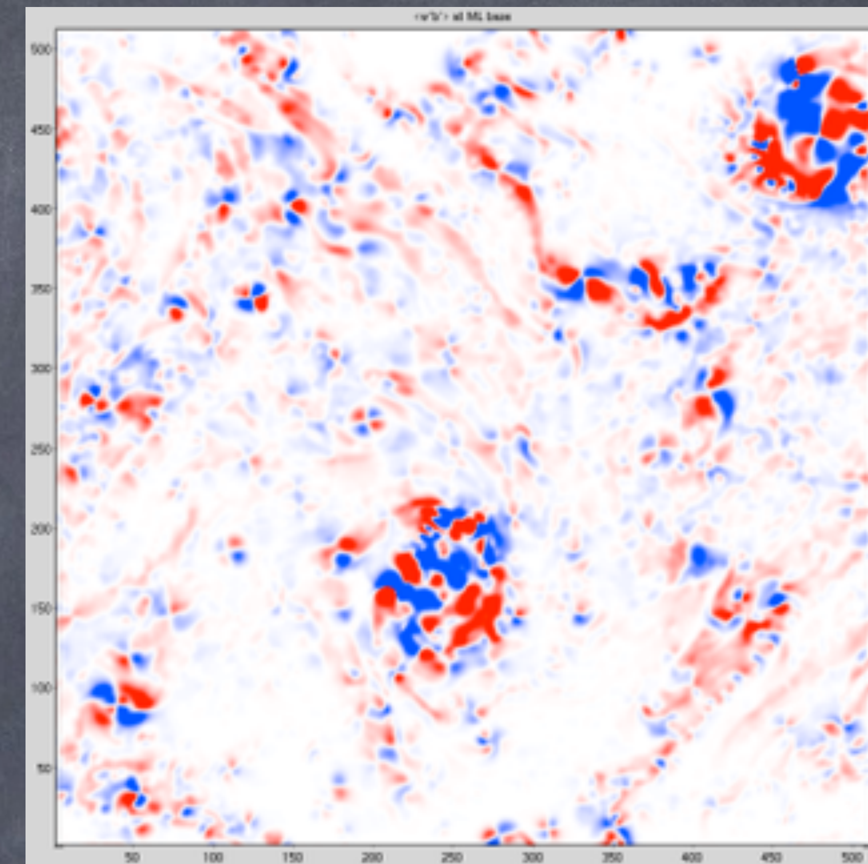


Flierl, Fox-Kemper, Ferrari

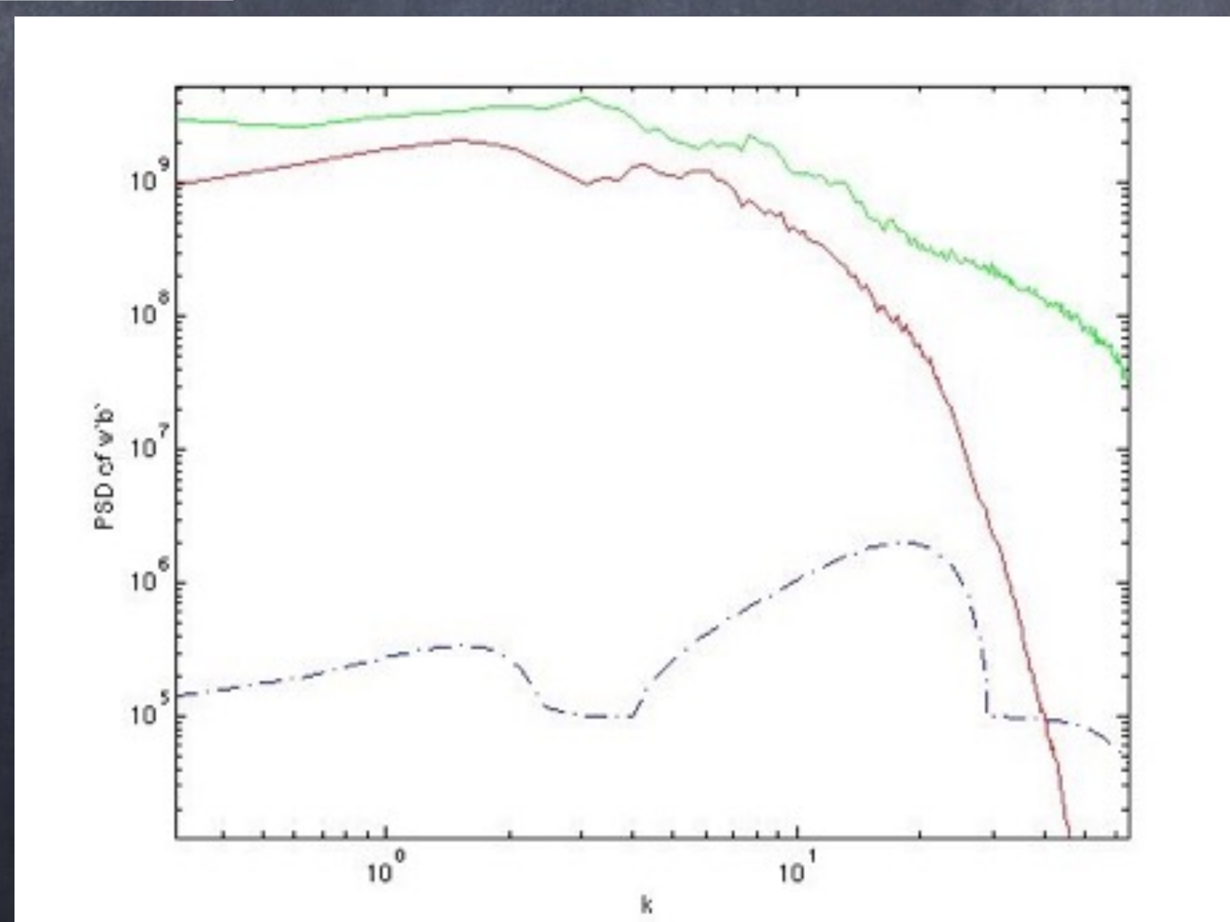
WB With a ML

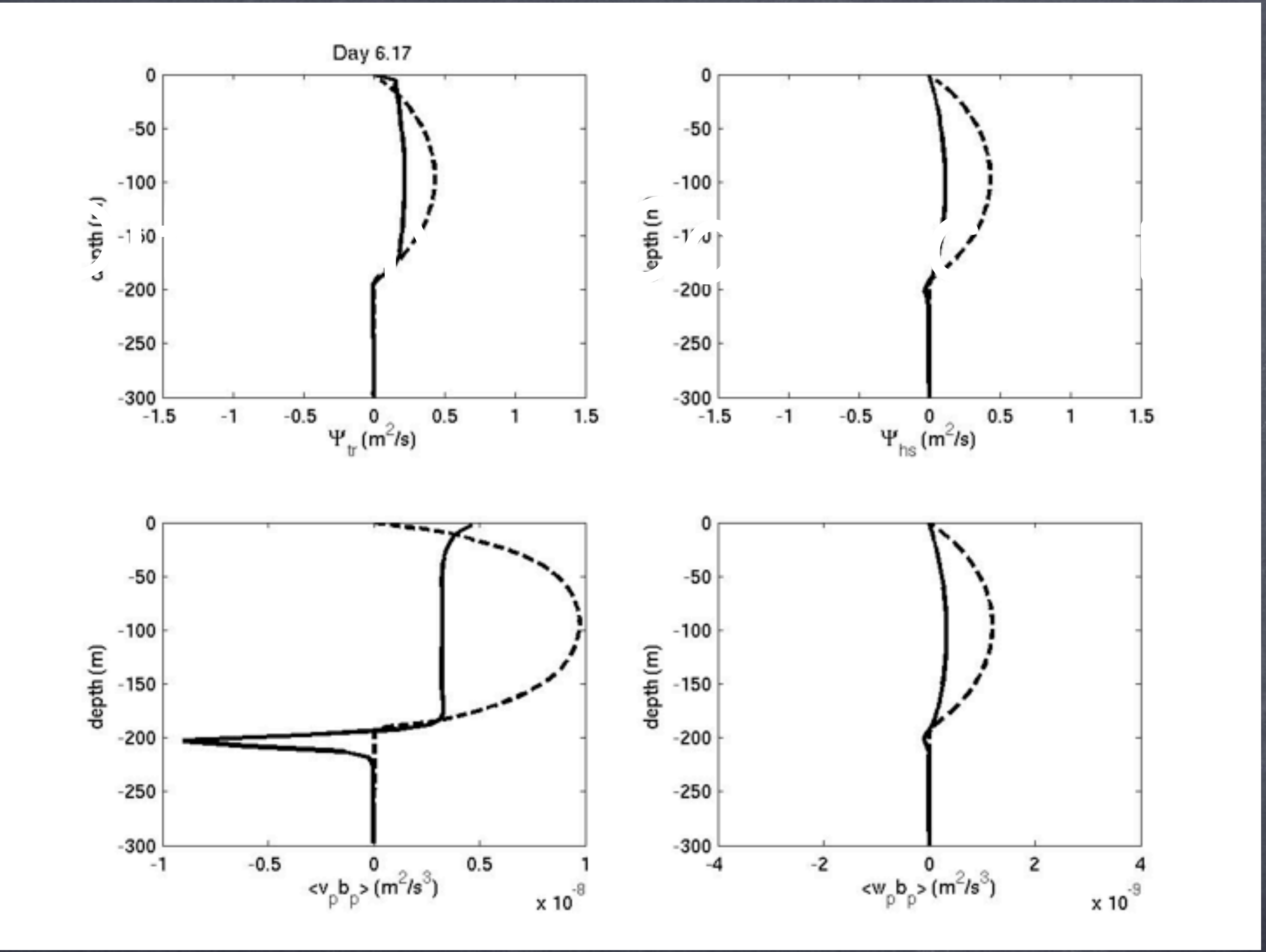


WB Without a ML



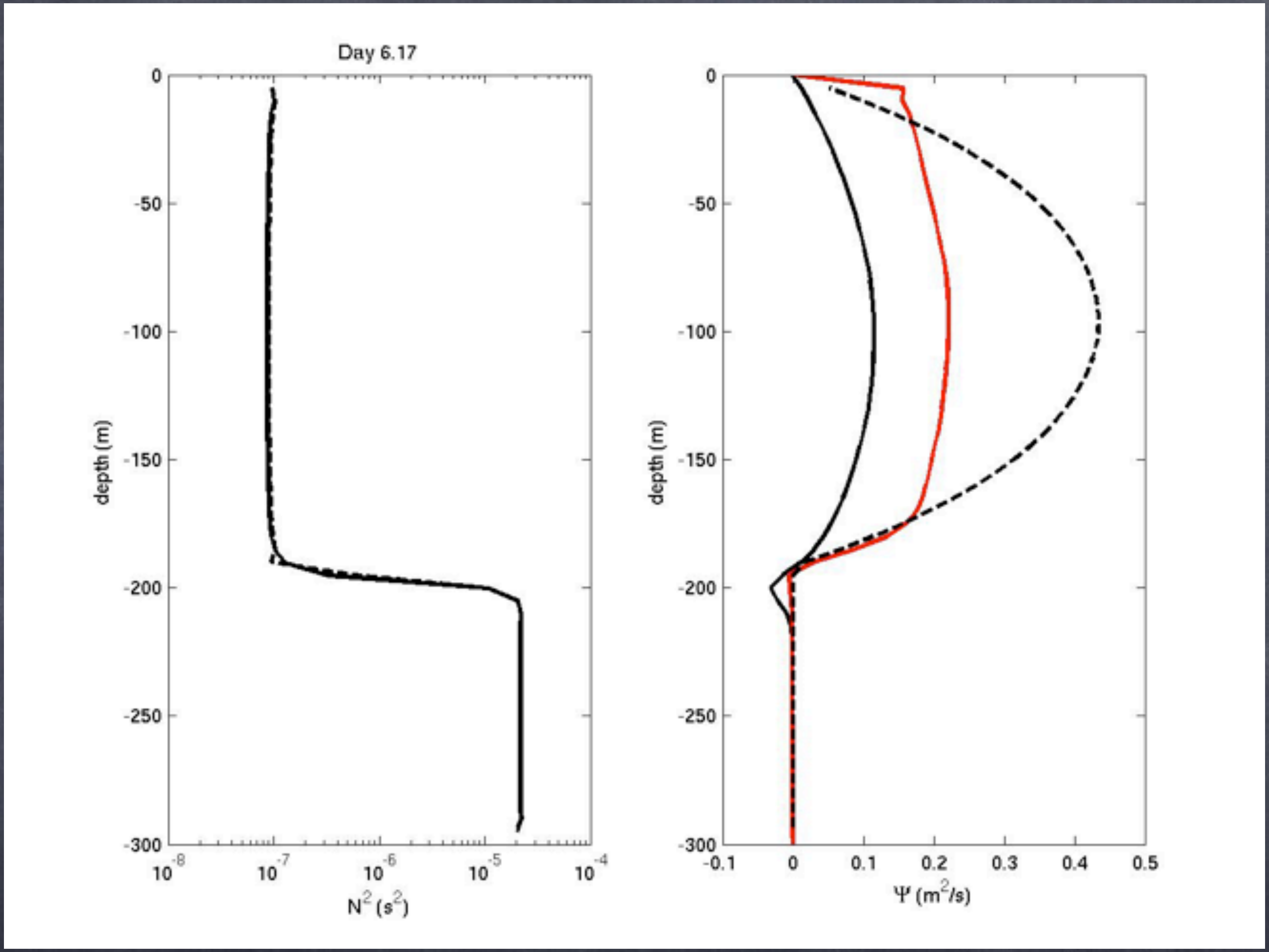
Spectra





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

‘Diffusive’ Corrections



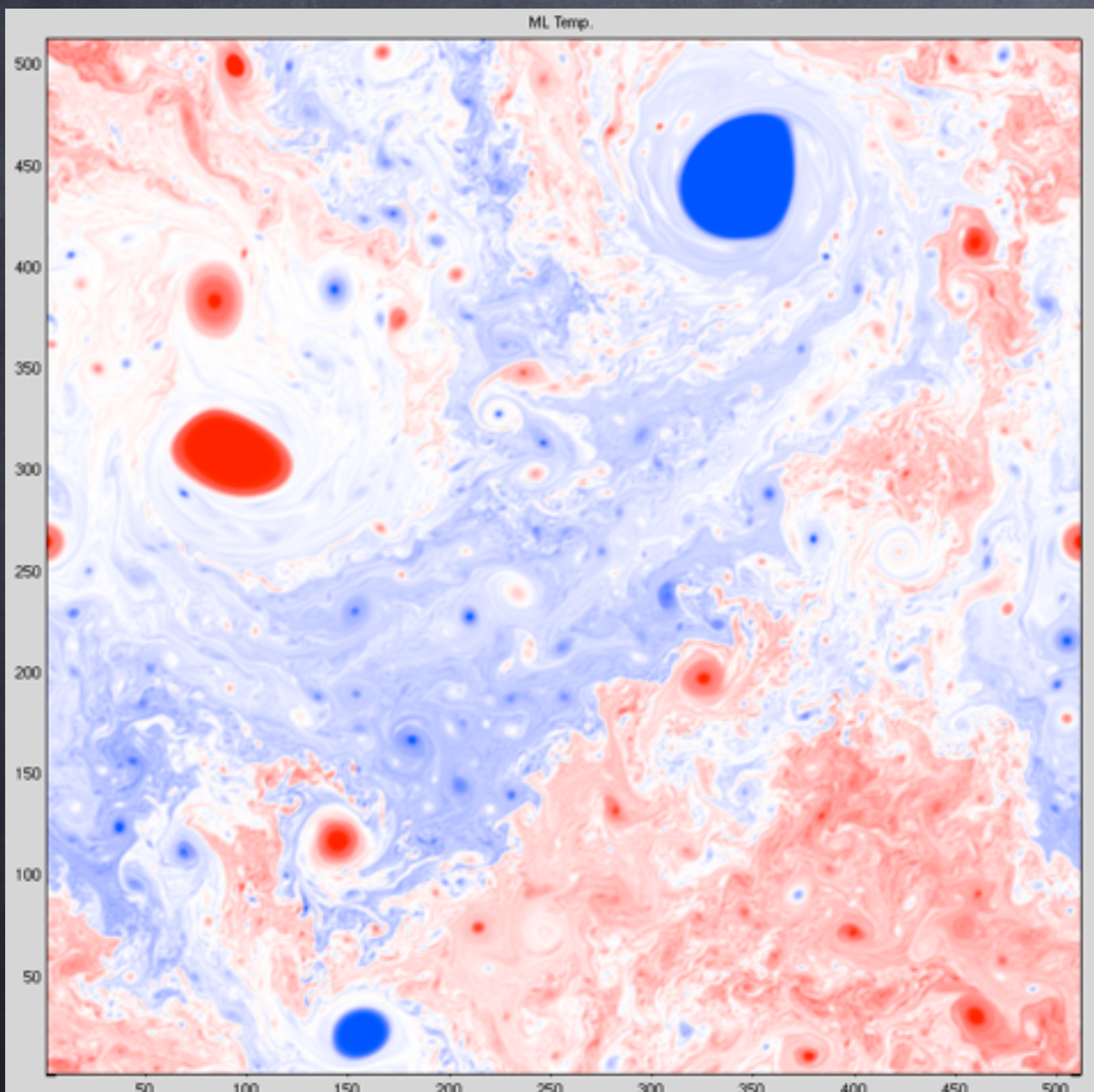
- Horiz. gives difference in Streamfcts (vb only).

Magnitude Analysis 2: Horizontal Fluxes

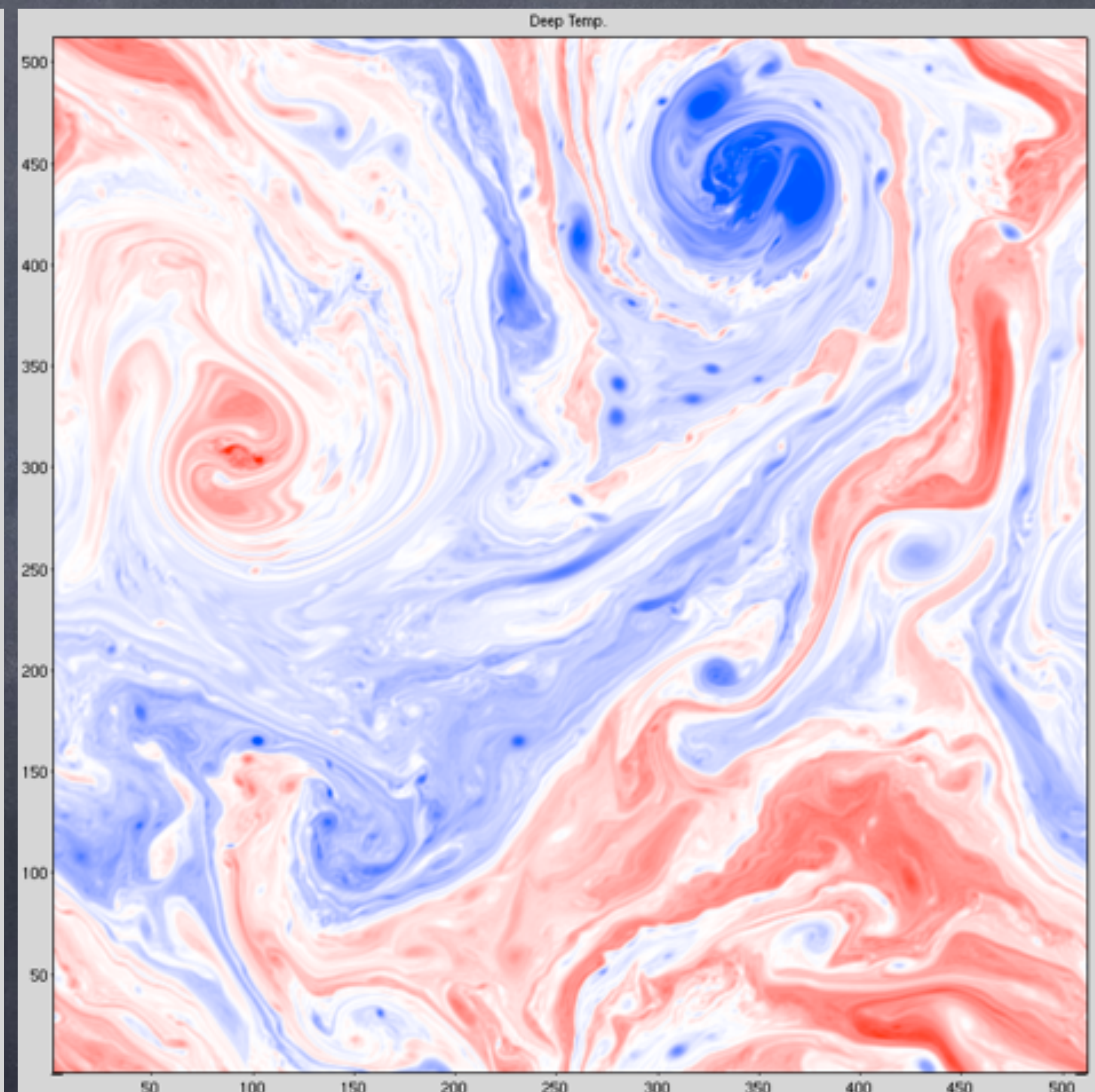
- Scaling for the Horizontal Buoyancy Flux
- Growing Baroclinic Instab. Fluxes near 1/2 the slope
- Vertical Scale is H
- Velocity scale is thermal wind

$$
\begin{aligned}
\overline{v'b'} &\propto V(N^2\Delta z + M^2\Delta y), \\
&\propto \frac{-N^2 M^2 H^2}{f}.
\end{aligned}
$$

A Blumen multi-SQG model allows an approximate coupled run to equilibrate.

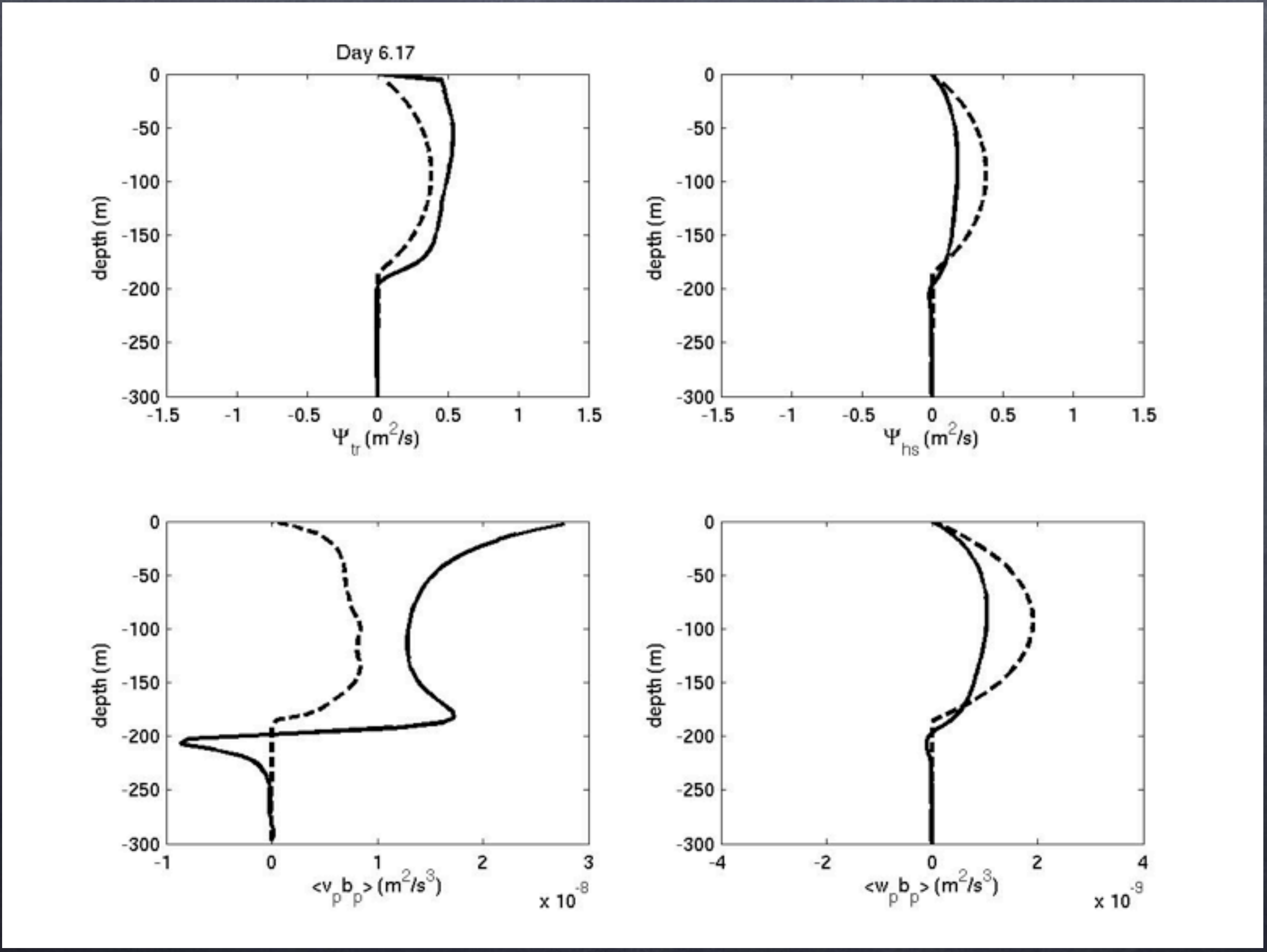


Surface Temp

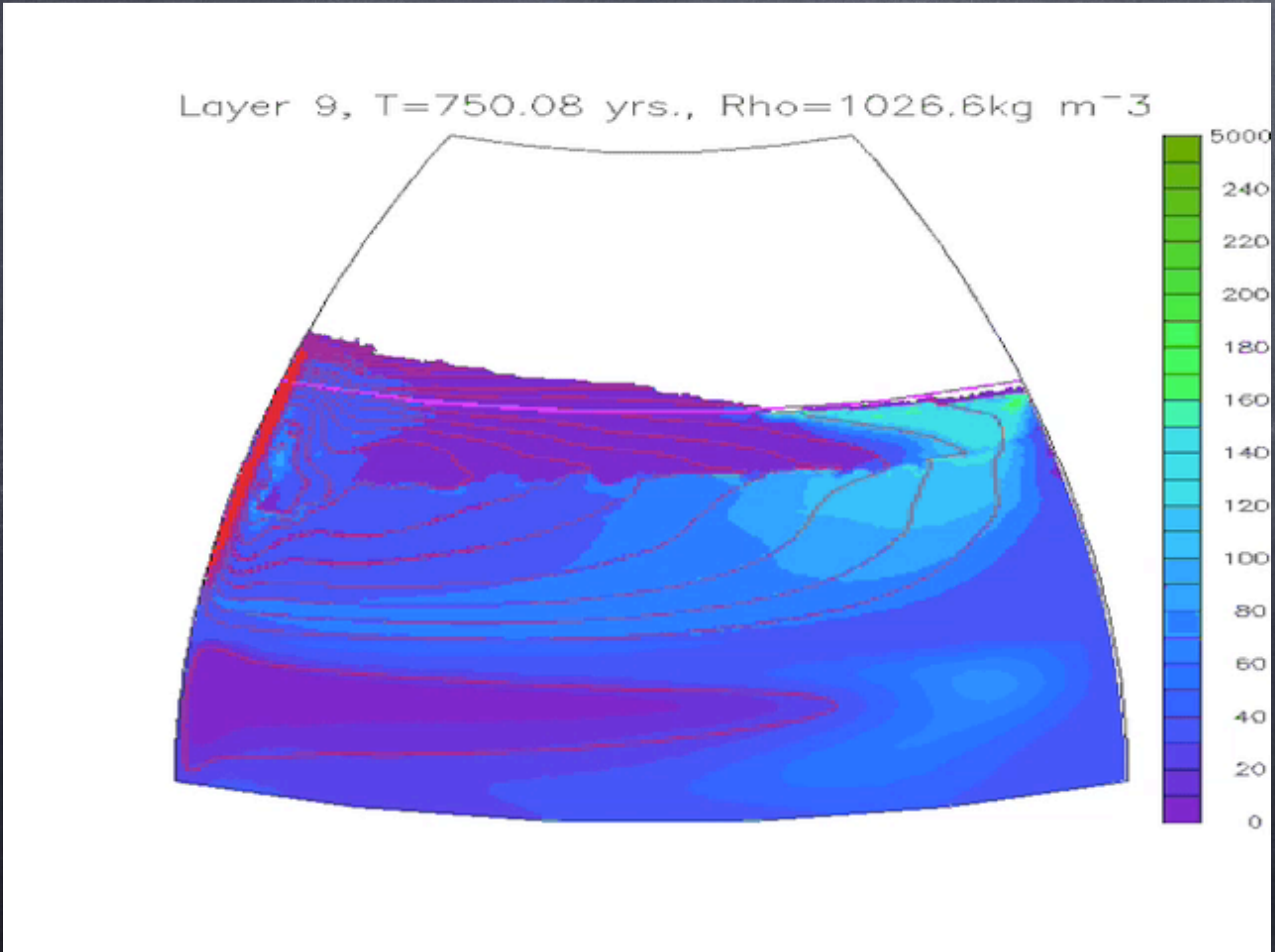


Bottom Temp

Fluxes due to Psi



How I got into ML Stuff



How I got into ML Stuff