Modeling and Parameterizing Mixed Layer Eddies

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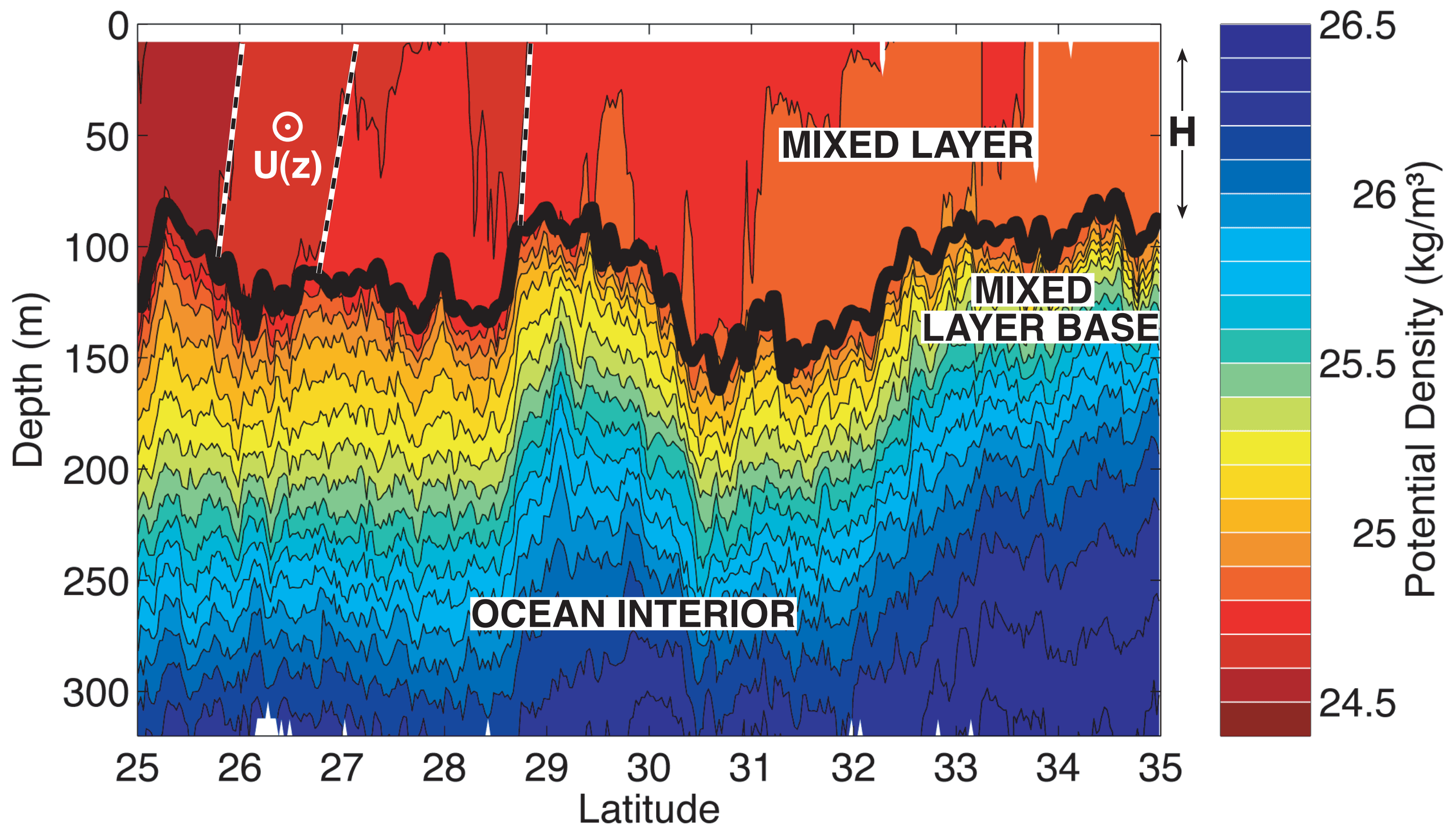
Mixed Layer Eddies

- Part I: Baroclinic Instabilities of the Ocean Interior and Mixed Layer
- Part II: Modeling and Parameterizing Mixed Layer Eddies
- Part III: Implementing the Parameterization in the Hallberg Isopycnal Model

Ocean Mixed Layer



Potential density section from towing a CTD following a saw-tooth pattern in the Subtropical Gyre of the North Pacific between 25N and 35N at 140W. (Ferrari and Rudnick, 2000).

The ocean mixed layer (ML) is a layer of weak stratification in the upper 100 m overlying the more stratified thermocline. The ML is not horizontally homogeneous: there are numerous lateral density gradients. ADCP measurements collected during the same campaign confirm that the lateral density gradients are in geostrophic balance with a sheared velocity U_z as schematized here.

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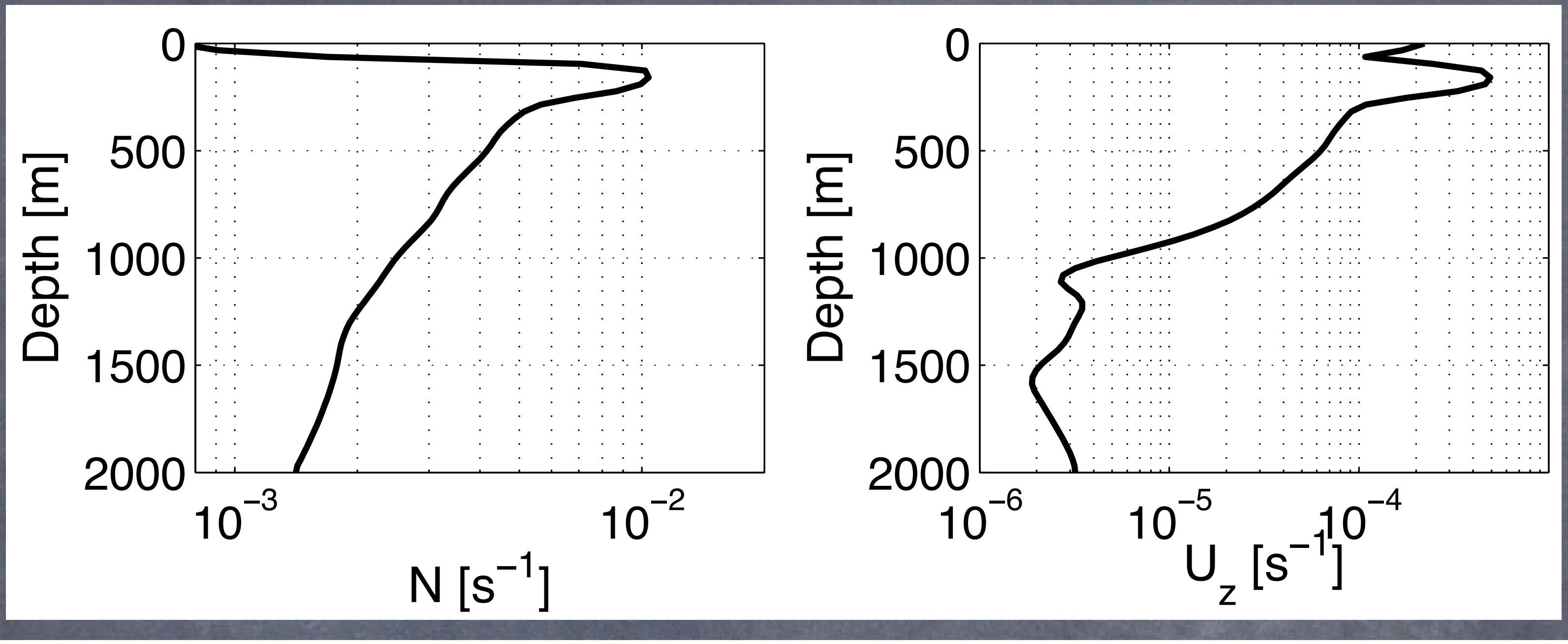
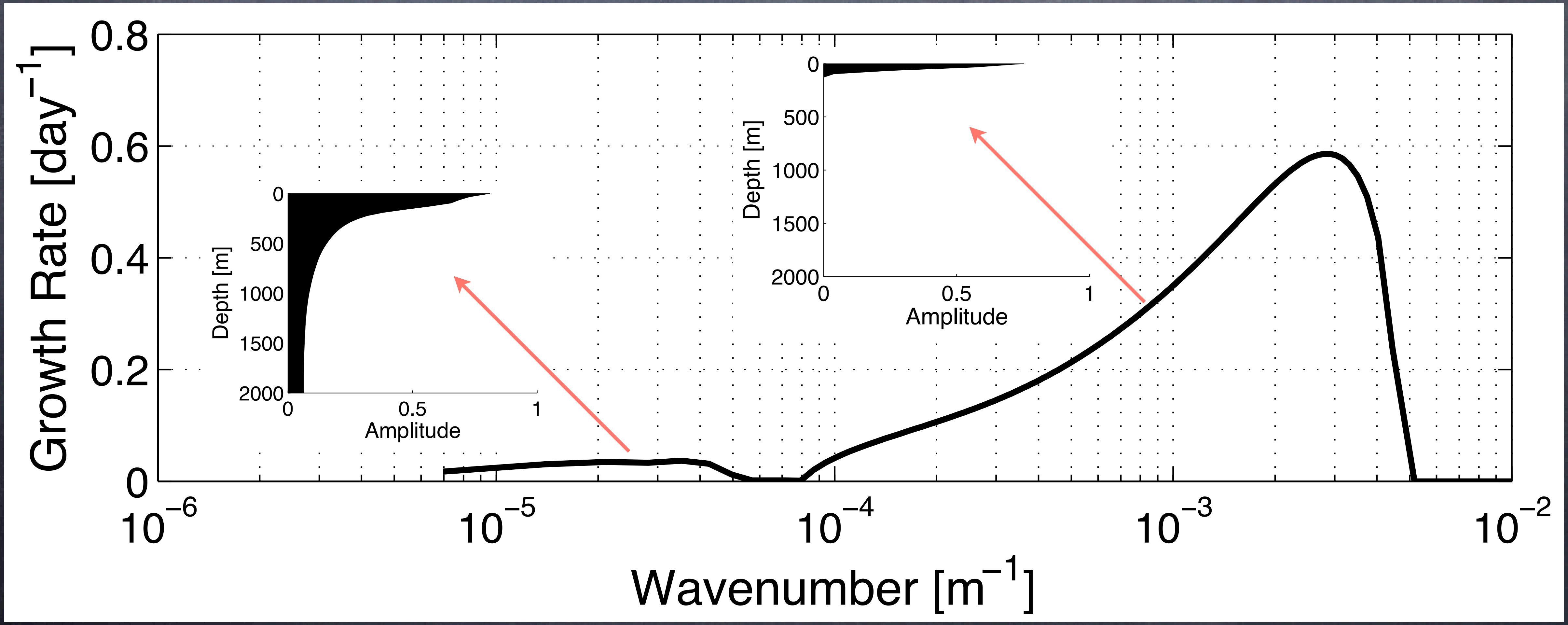
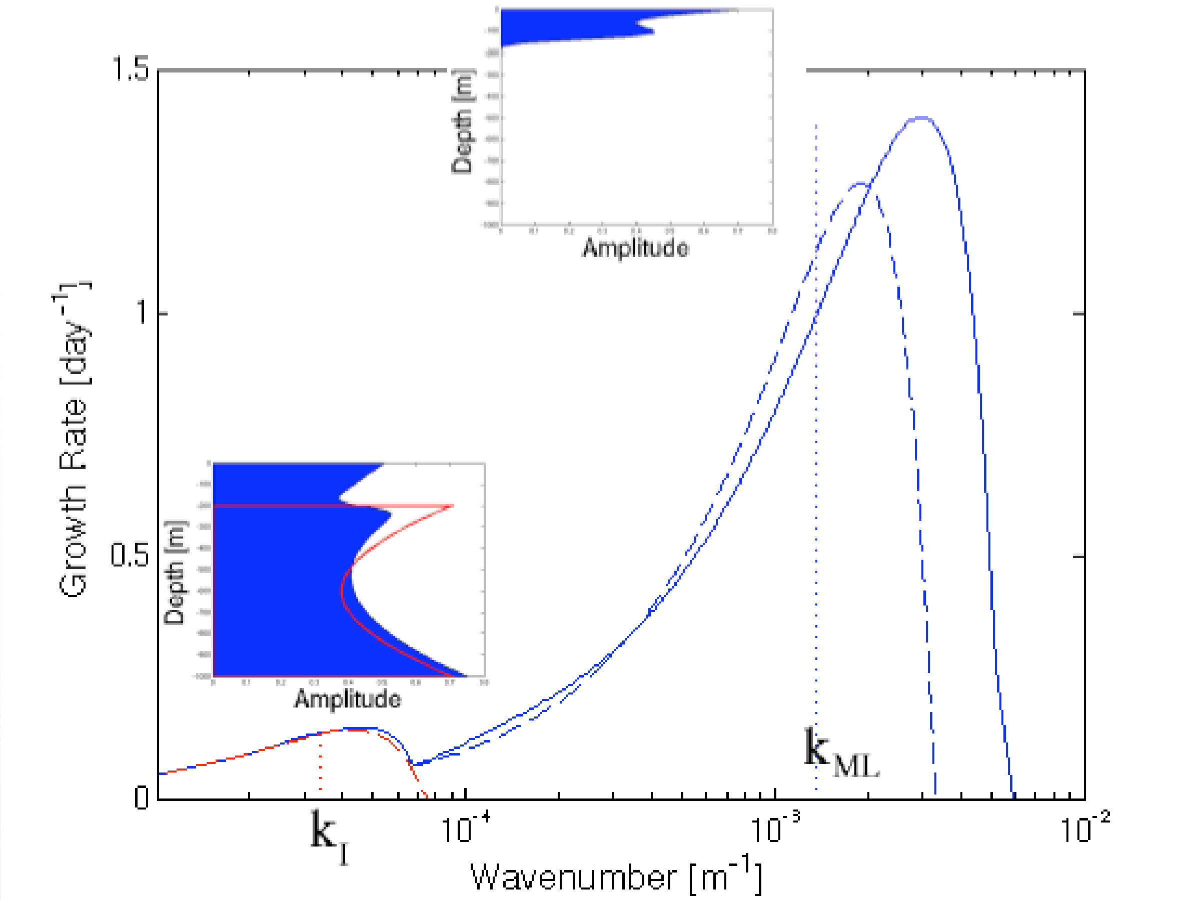
The Stratification of the Ocean Permits Two Classes of QG Baroclinic Instability: Mesoscale and SubMesoscale (in the Mixed Layer)





Geostrophic and Ageostrophic Baroclinic Instability



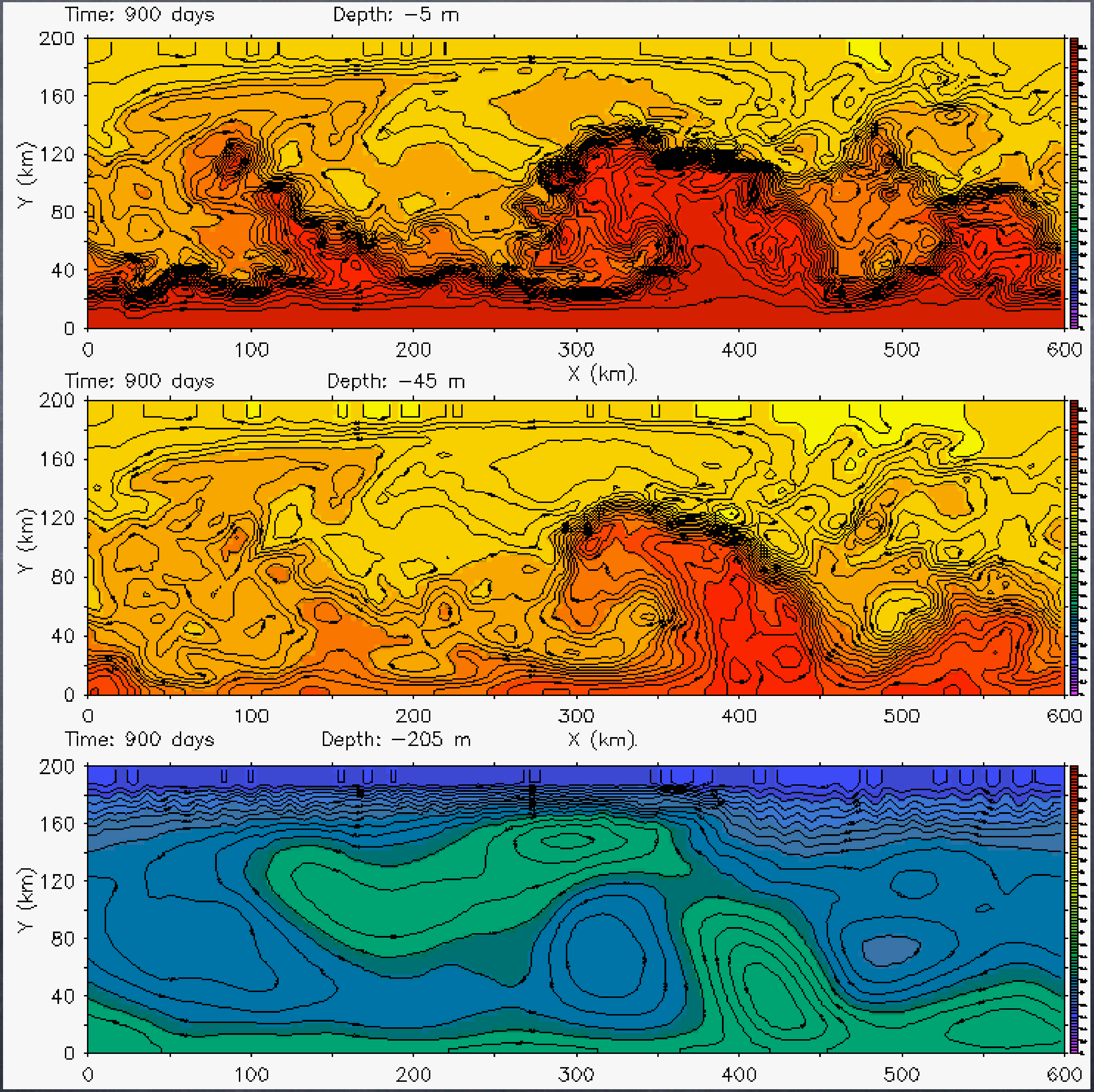
The linear instability of the upper 1000m of the ocean water column: a 200m deep ML with $N \approx 4 \times 10^{-4} s^{-1}$, $U_z = 2 \times 10^{-4} s^{-1}$, and Ri$= 3.6$ sits on a 800m thermocline with $N \approx 4 \times 10^{-3} s^{-1}$, $U_z = 2 \times 10^{-4} s^{-1}$ and $Ri = 360$. For comparison, shown in red is the instability of the 800m ocean interior alone with a rigid lid replacing the ML. Also shown are the inverse deformation radii and the fastest-growing modes of the ML and interior (inset). (solid = quasi-geostrophic, dashed = Stone (1971) ageostrophic estimate).

The baroclinic instability of the upper ocean water column is dominated by two distinct modes: interior instabilities with fastest-growing wavelengths close to the internal deformation radius (≈ 60km) and mixed-layer instabilities (MLI) with growth peaking near the ML deformation radius (≈ 1.5km). The former span the whole ocean depth. MLI are confined to the ML.

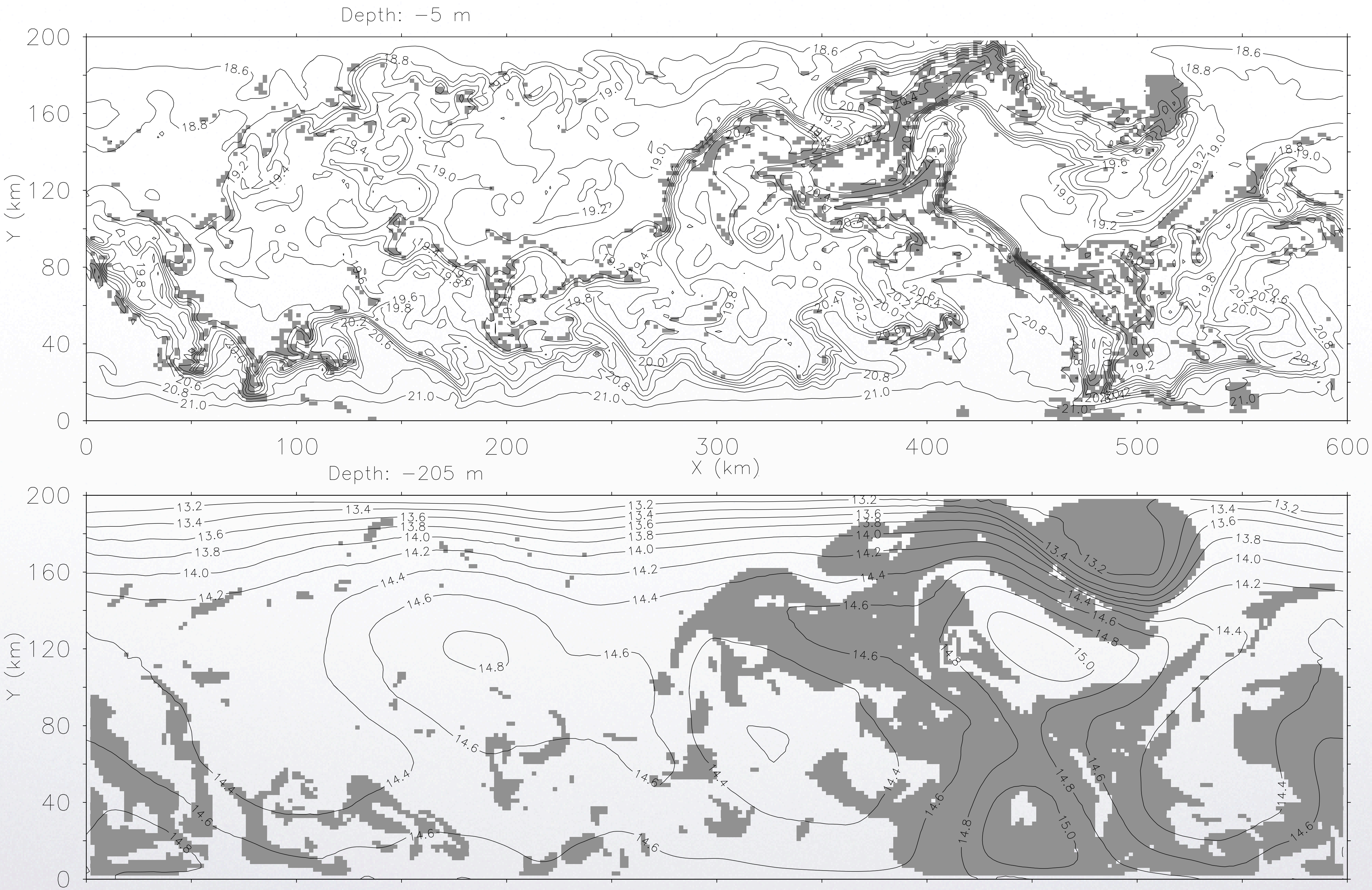
Mesoscale and SubMesoscale are Coupled Together:

ML Fronts are formed by Mesoscale Straining.

Submesoscale eddies remove APE from those fronts.



SubMesoscale Dominates Vertical Buoyancy Fluxes;

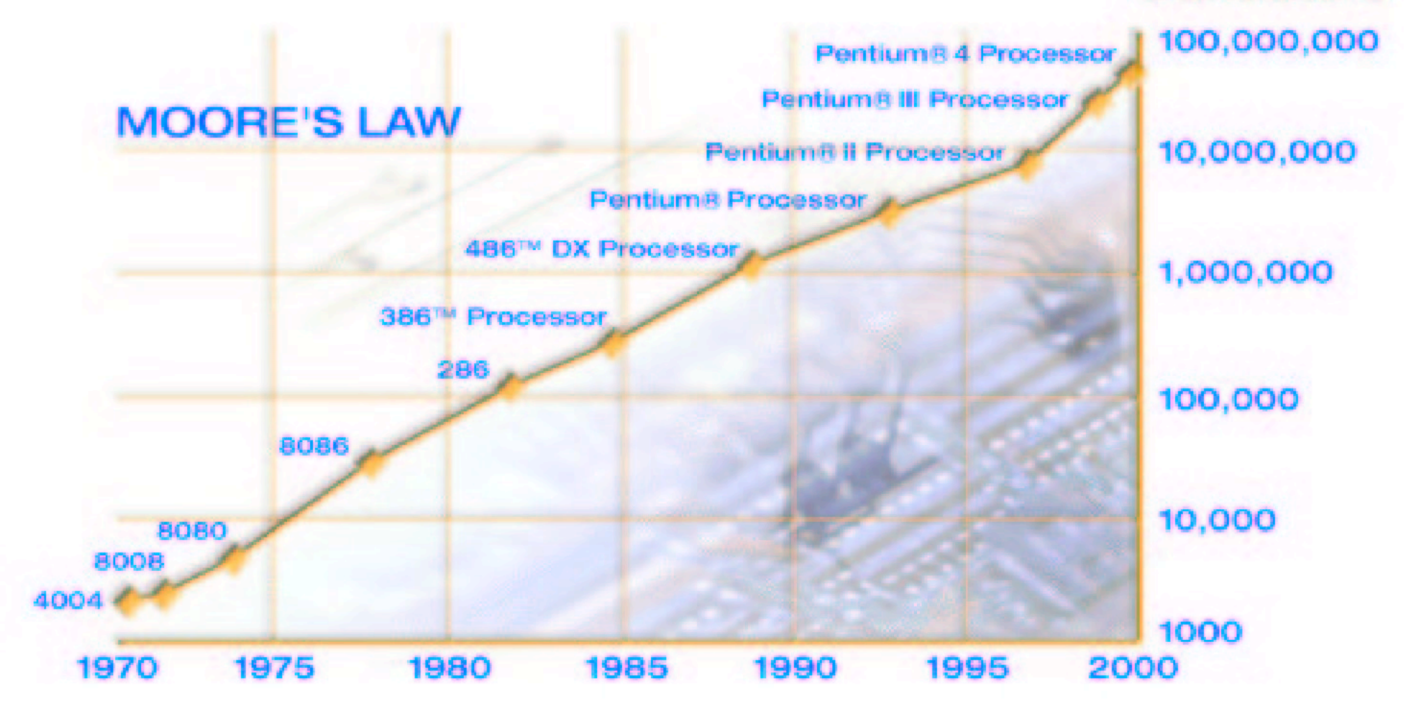


Mesoscale Dominates Horizontal Buoyancy Fluxes

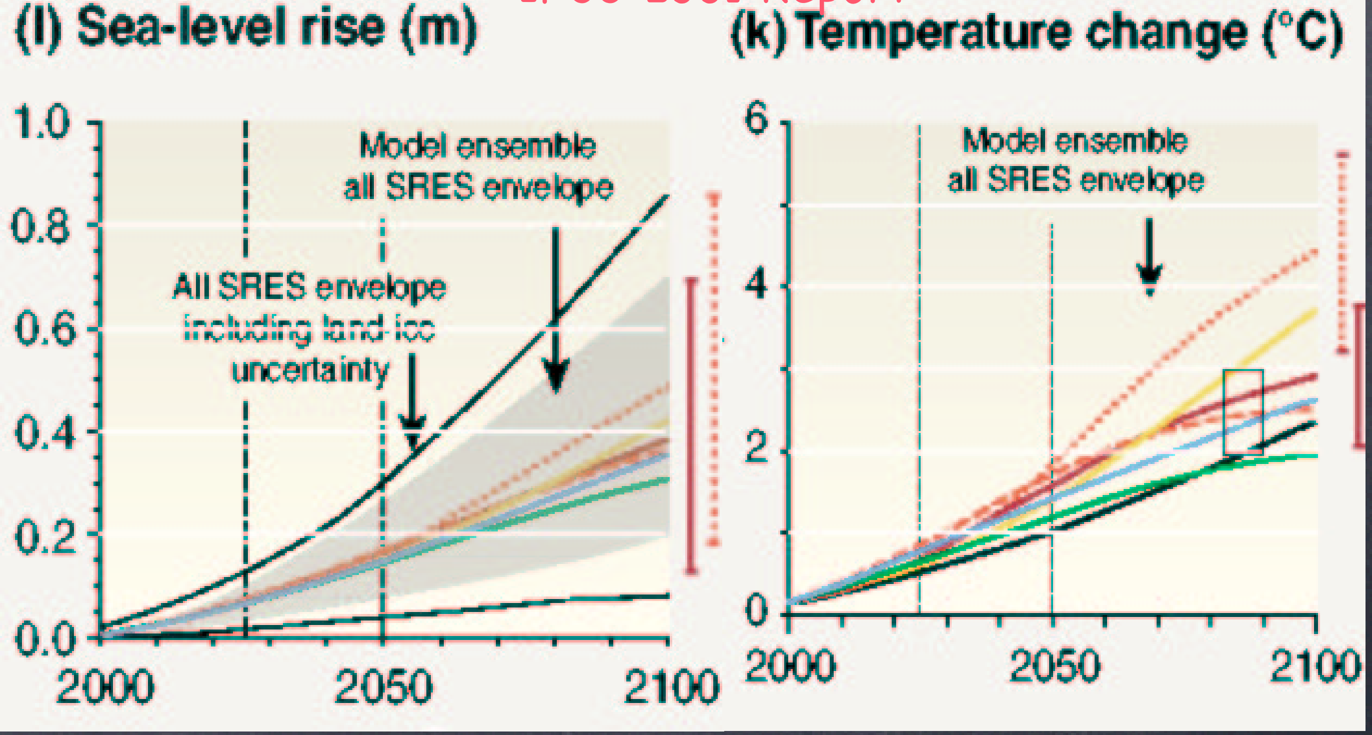
Parameterize? Why not Resolve?

- 2004 IPCC takes ~50% of GFDL's computing (4 in the top 250: 6/03).
- To make eddy-resolving IPCC forecasts with the same level of commitment and approach:
- Fair Resolution of Ocean Interior Eddies (global 10-20km): 10×10×2×5×(flops) = 1000×(cpu) ≈ 18yrs
  By Then ≈ 0.5K Global Temp, 5cm Sea Level
- Fair Resolution of Mixed Layer and Eddies (global 100m): 1000×1000×10×100×(flops) = 1 billion×(cpu) ≈ 54yrs
  By Then ≈ 1.5K Global Temp, 20cm Sea Level

Moore (1965) from Intel Website



IPCC 2001 Report



Conclusion Part I:

- 2 classes of Baroclinic Instability: Mesoscale and Submesoscale
- Submesoscale instabilities are trapped in the mixed layer
- Submesoscale instabilities have faster growth rates O(1/day) and smaller scales O(1 km).
- Submesoscale dominates vertical flux, Mesoscale dominates horizontal flux
- Mesoscale will soon be resolved in GCMs, submesoscale will not.

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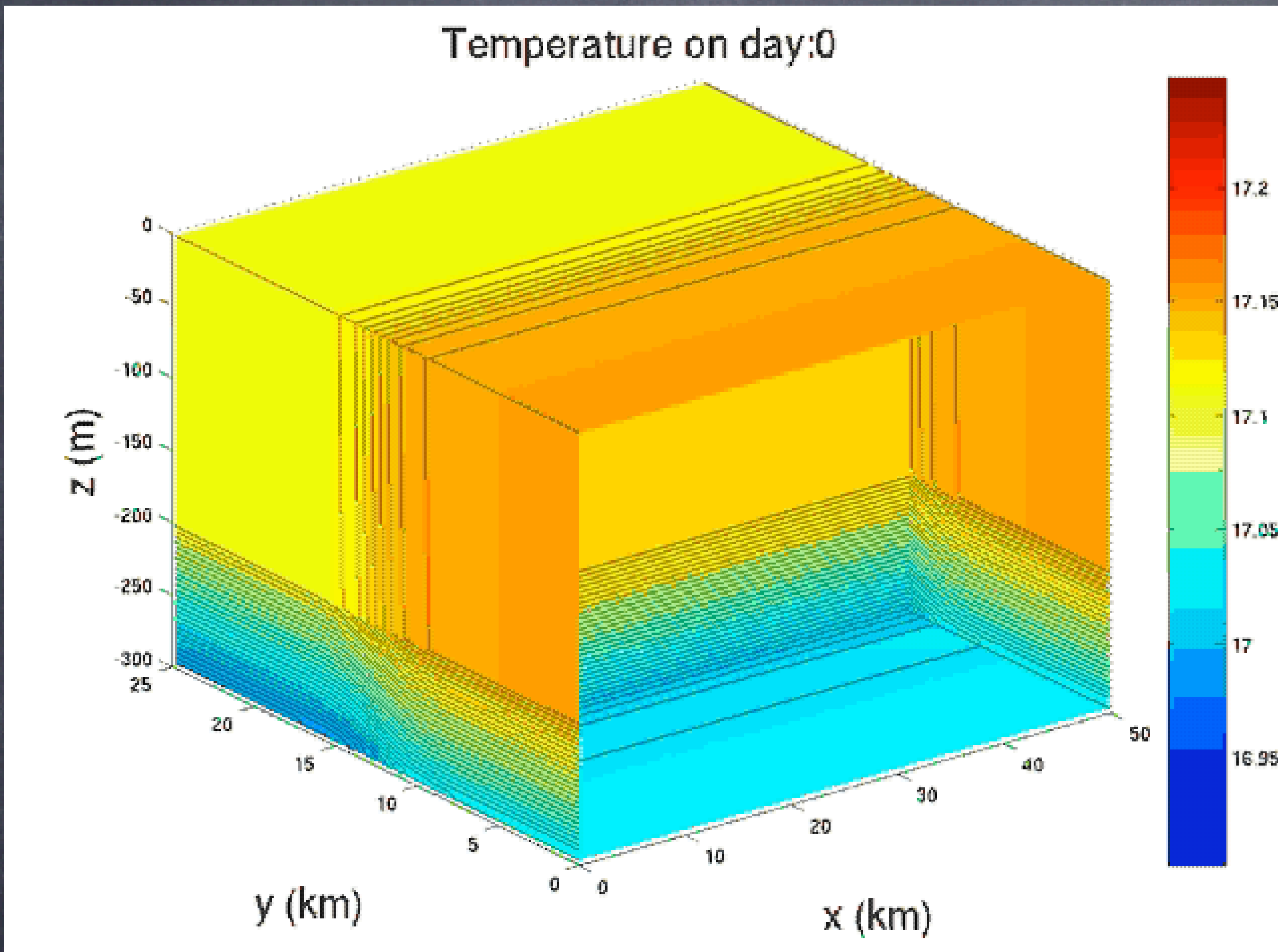
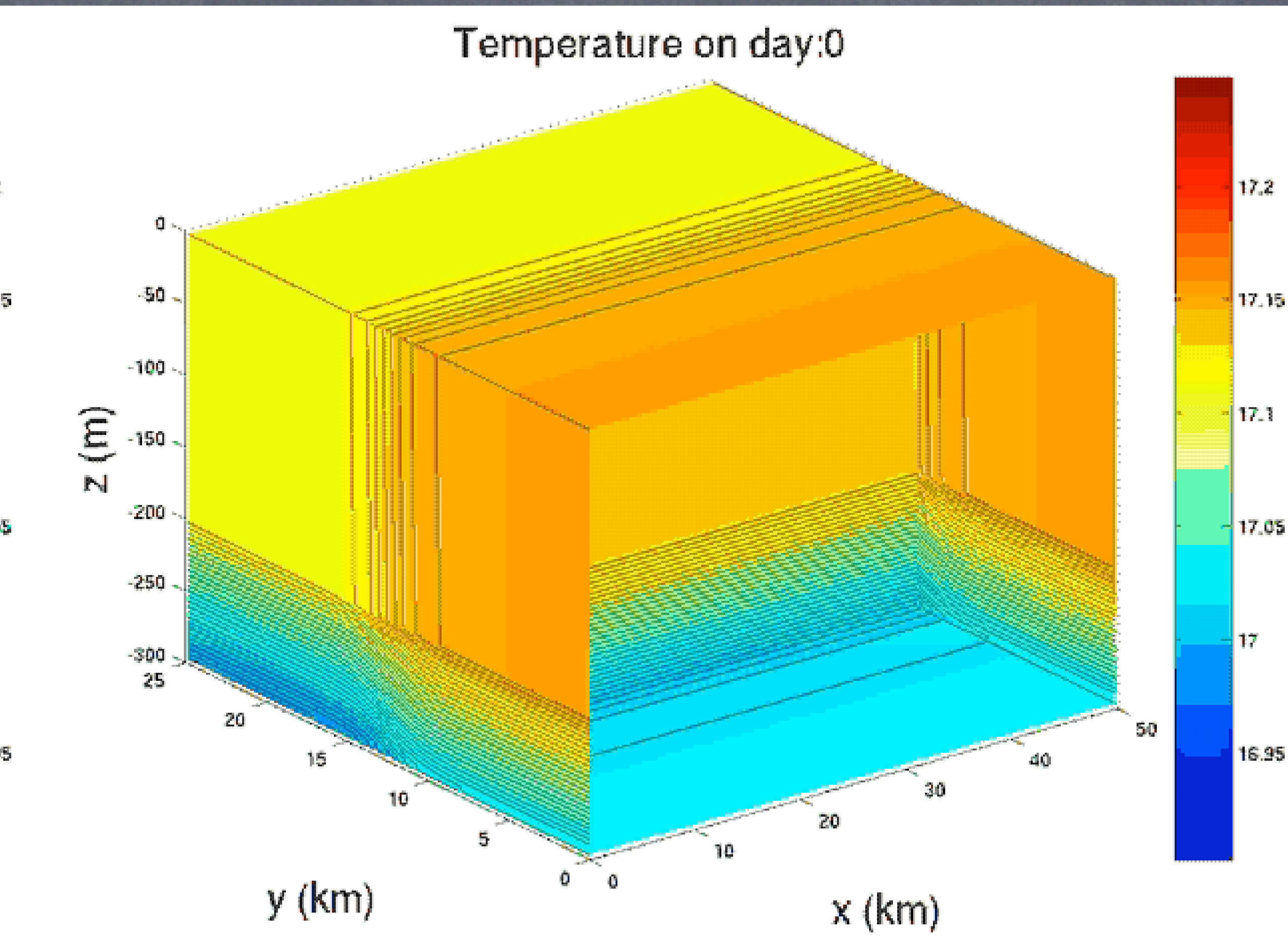
Prototype: Mixed Layer Front Adjustment





Simple Adjustment

Diurnal Cycle and KPP Adjustment

Analysis:

- Extraction of potential energy by SubMesoscale eddies:

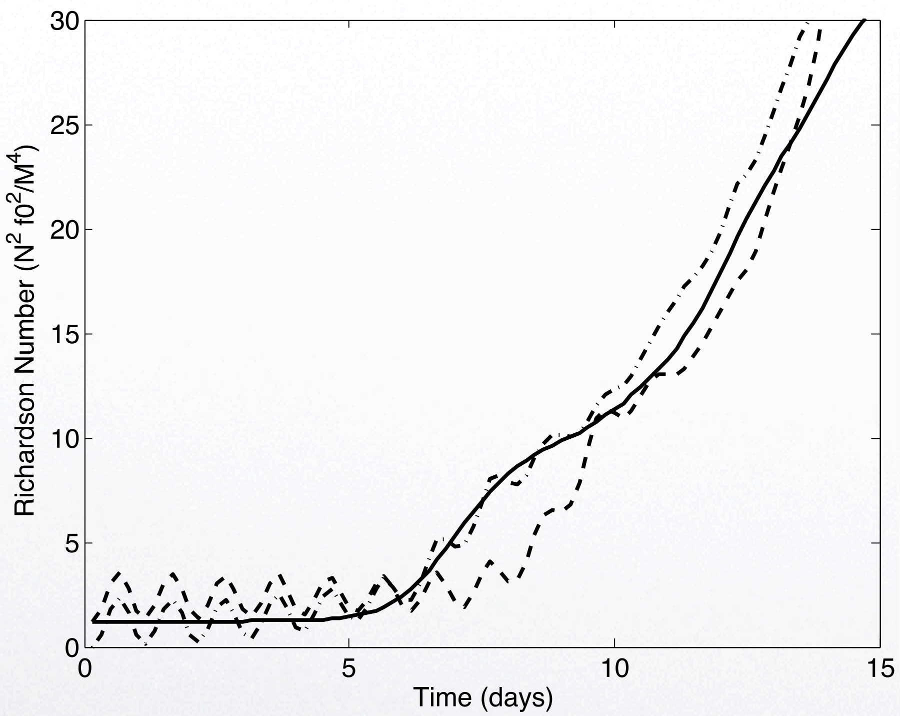
$$\frac{\partial[-z\bar{b}]}{\partial t} = -[\overline{wb}] \approx -[\overline{w'b'}]$$

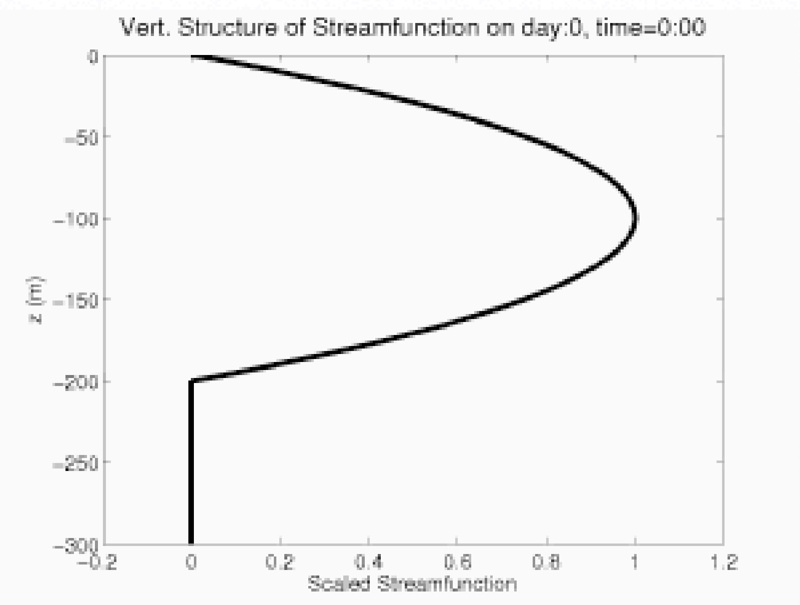
- Growing Baroclinic Instability Fluxes at 1/2 the slope; heuristically derived from maximal APE extraction.

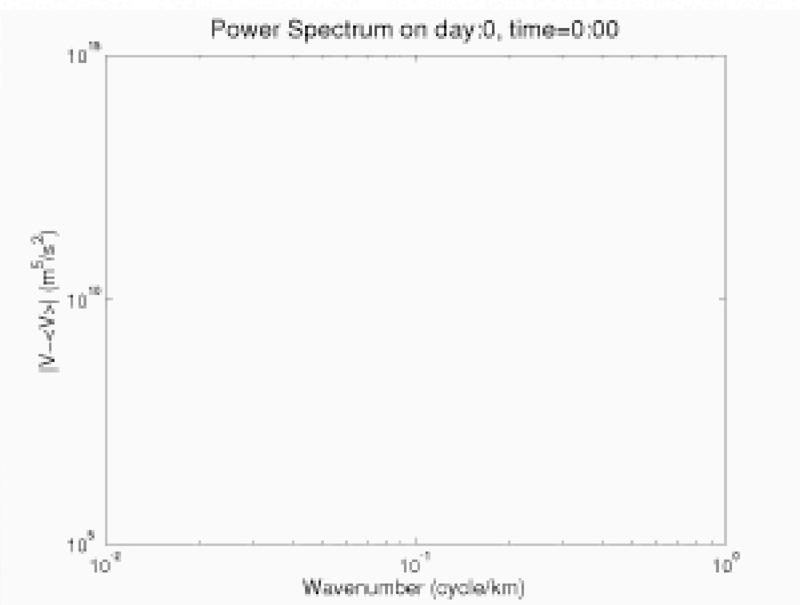
$$2\overline{w_h'b'} = -\frac{\overline{\mathbf{u}_h'b'}}{\bar{b}_z} \cdot \nabla\bar{b} = \mathbf{\Psi} \cdot \nabla\bar{b}$$

- This Ψ is the usual eddy-induced streamfunction as in Andrews and McIntyre, Gent and McWilliams, Visbeck et al., Treguier et al., etc.

Strongest Restratification Occurs with Finite Amplitude Eddies







Finite Amplitude Eddies have cascaded in horizontal: Front Width
Finite Amplitude Eddies have cascaded in vertical: ML Depth
Finite Amplitude Eddy Fluxes are at close to 1/2 the isopycnal slope

Parameterize Fluxes?

- We know how to parameterize horizontal fluxes using mixing length akin to Green:

$$\Psi = \kappa \frac{\nabla \bar{b}}{\bar{b}_z} = U_{eddy} L_{mix} \frac{\nabla \bar{b}}{\bar{b}_z}$$

- Eddies are at lowest mode in the vertical; We assume same velocity shear as mean:

$$U_{eddy} = \frac{H \nabla \bar{b}}{|f|}$$

- Since the fluxes are at 1/2 the slope

$$L_{mix} \frac{|\nabla \bar{b}|}{\bar{b}_z} = L_{mix} \frac{2H}{L_{mix}} = 2H$$

The Parameterization:

- Thus, the Streamfunction:

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

- The horizontal fluxes are downgradient:

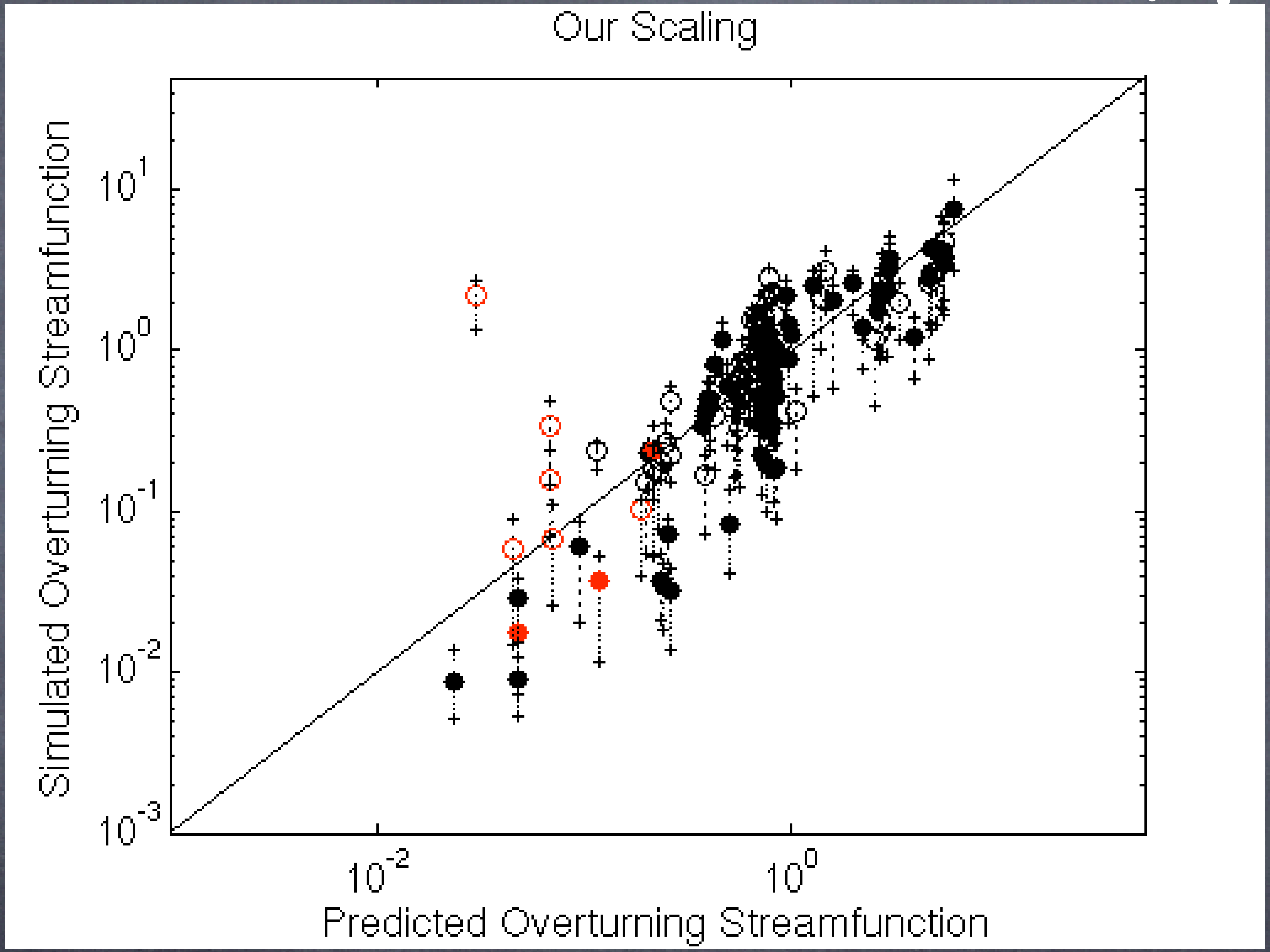
$$\overline{\mathbf{u}'_H b'} = -\mathbf{\Psi} \bar{b}_z = -C_e \mu(z) \frac{H^2 \nabla \bar{b}}{|f|} \bar{b}_z$$

- Vertical fluxes at 1/2 the slope and always restratify:

$$\overline{w' b'} = \frac{1}{2} \mathbf{\Psi} \cdot \nabla b = \frac{C_e \mu(z) H^2 |\nabla \bar{b}|^2}{2|f|}$$

- The potential energy equation is closed using this form.

It works for Prototype:

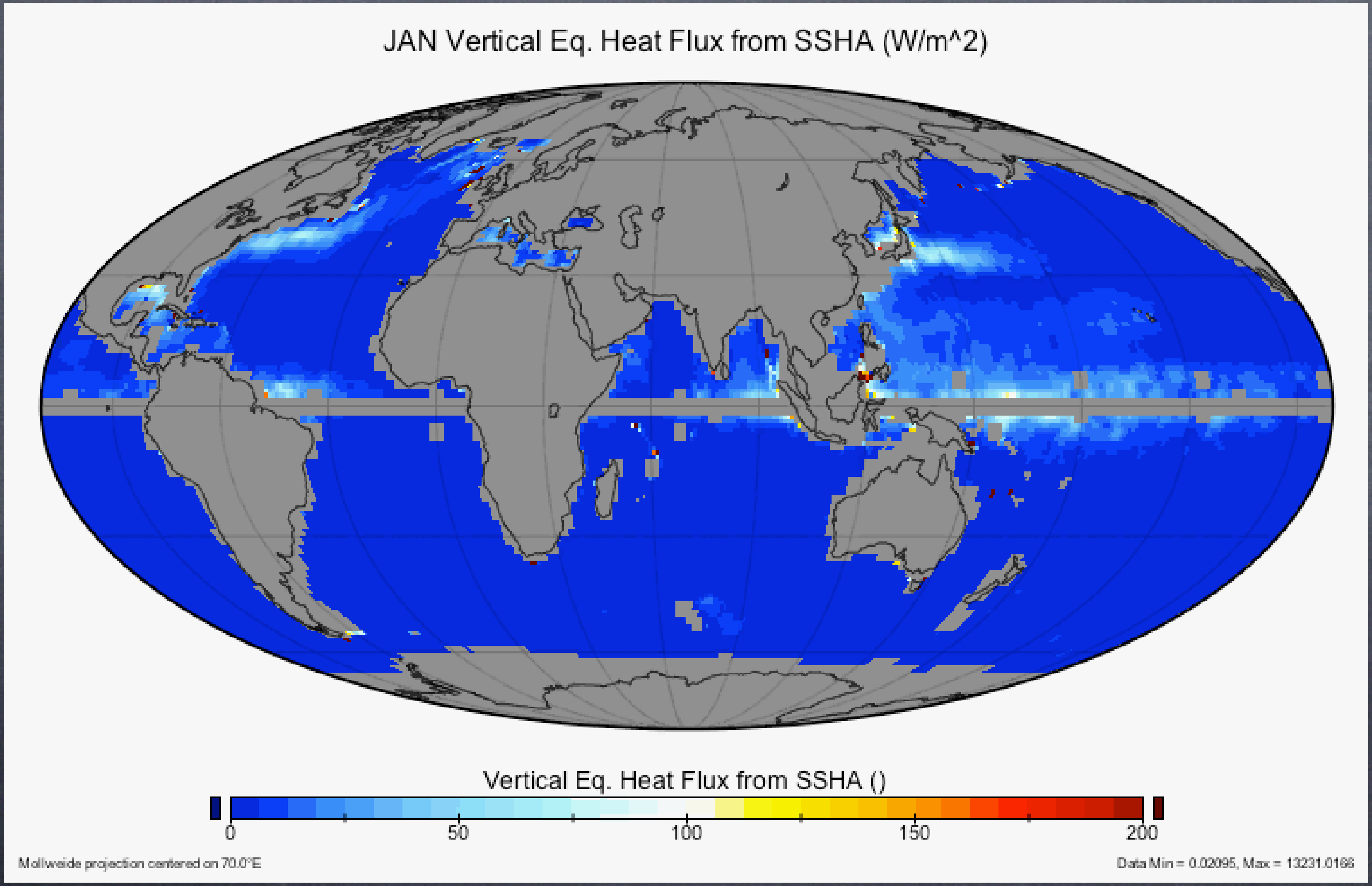


Closed Circles: No Diurnal

Open Circles: With Diurnal

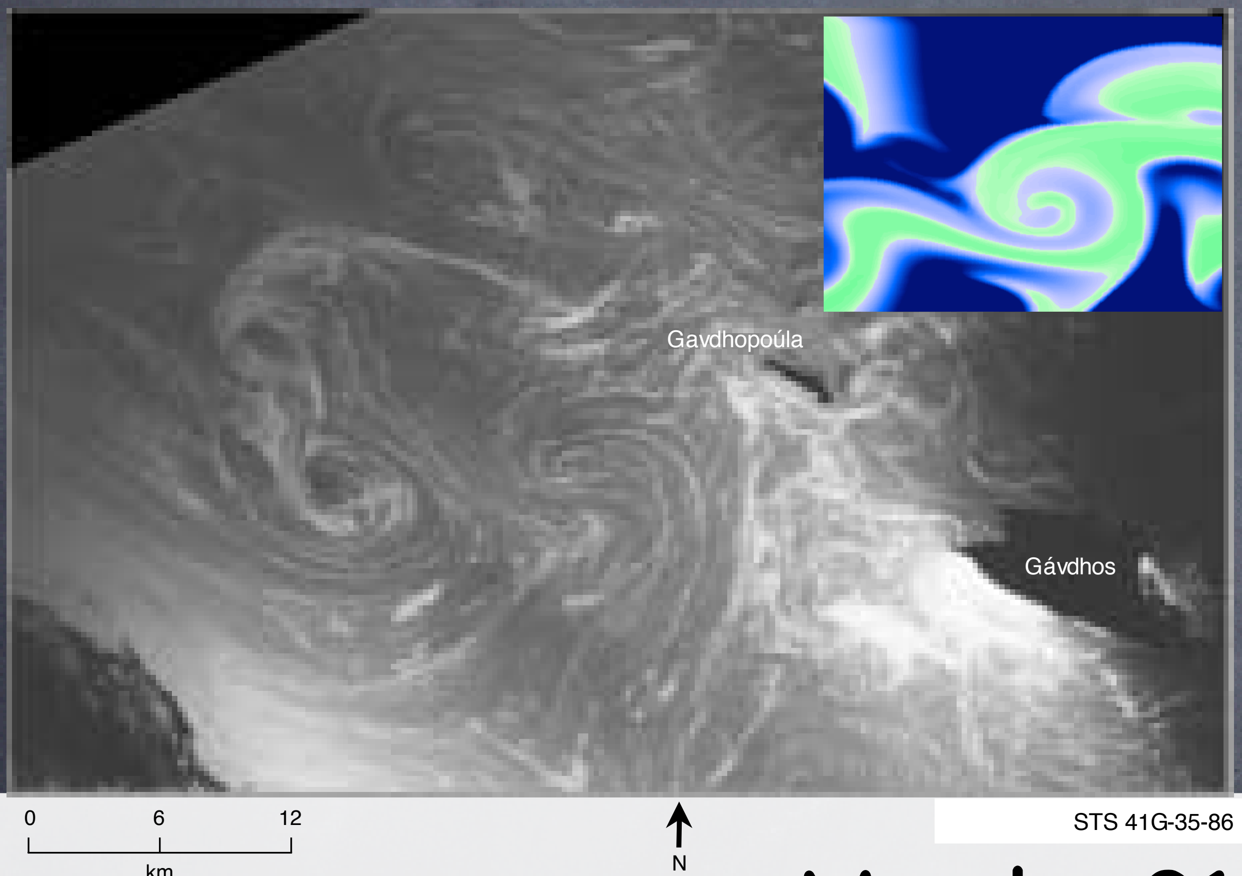
Red: Didn't restratify much

Impact: Equivalent Vertical Heat Flux from Satellite SSHA



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.

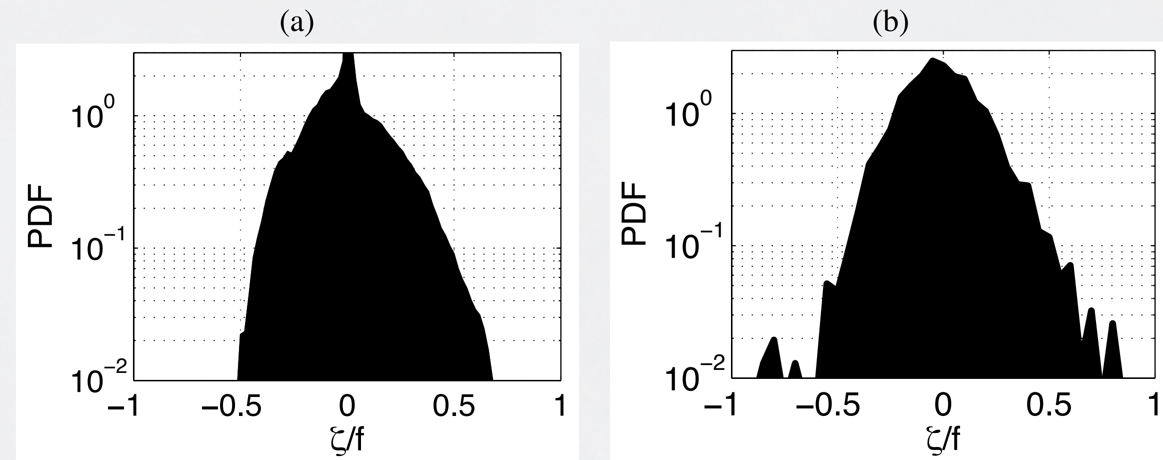


Figure 12: Probability density function of relative vorticity divided by Coriolis parameter. (a) Results from the numerical simulation of a slumping horizontal density front. ($z > 100$ only to exclude bottom Ekman layer.) The PDF is estimated using surface velocity measurements at day 25 (see also Fig.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

Conclusion Part II:

- Extraction of potential energy by SubMesoscale eddies:

$$\frac{\partial[-z\bar{b}]}{\partial t} = -[\overline{wb}] \approx -[\overline{w'b'}]$$

- They Flux at 1/2 the slope:

$$\overline{w'b'} = \frac{1}{2}\mathbf{\Psi} \cdot \nabla b = \frac{C_e \mu(z) H^2 |\nabla \bar{b}|^2}{2|f|}$$

- The Finite Amplitude horizontal flux scaling is via mixing length akin to Green (1970), assuming the gravest ML vertical mode.

- Eddies' Effect is restratification of ML after strong mixing with sizeable equivalent vertical heat fluxes.

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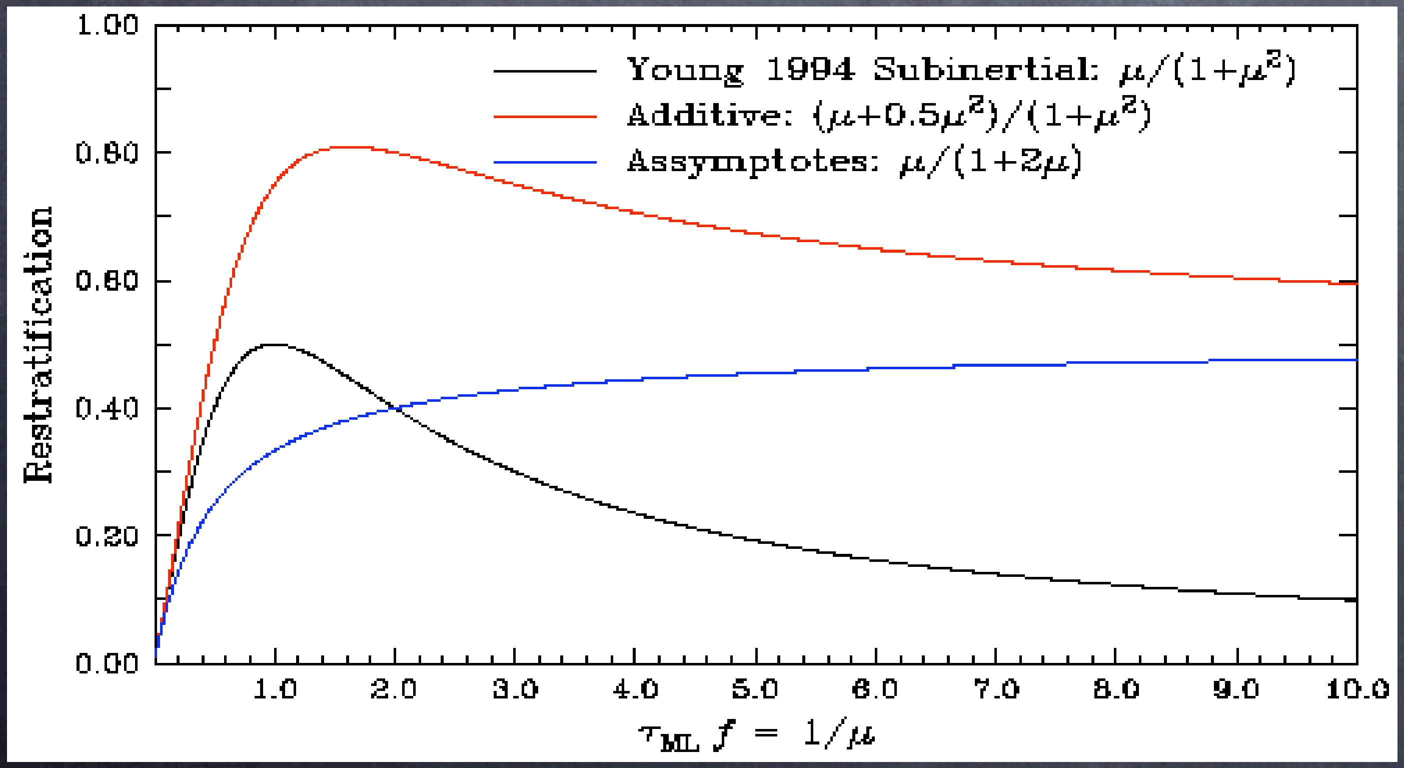
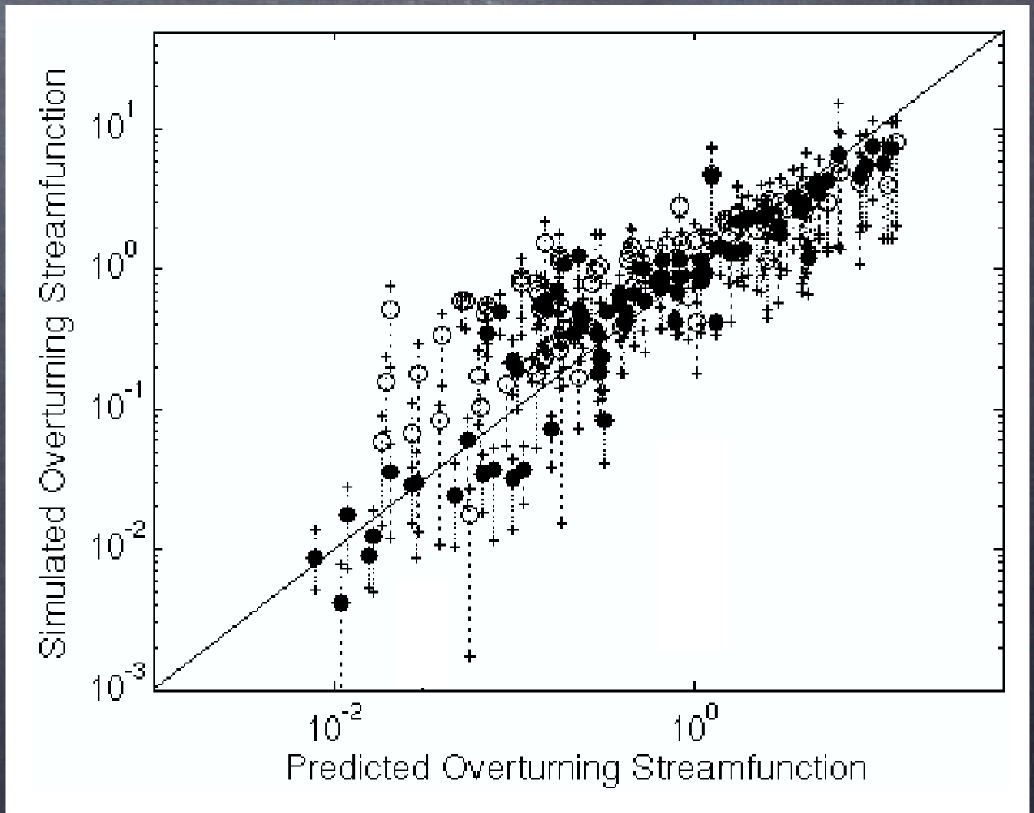
What about the Equator?

- Our parameterization relies on geostrophic eddies at finite amplitude, which take infinitely long to grow at the equator.
- One option: taper by matching Young (1994)

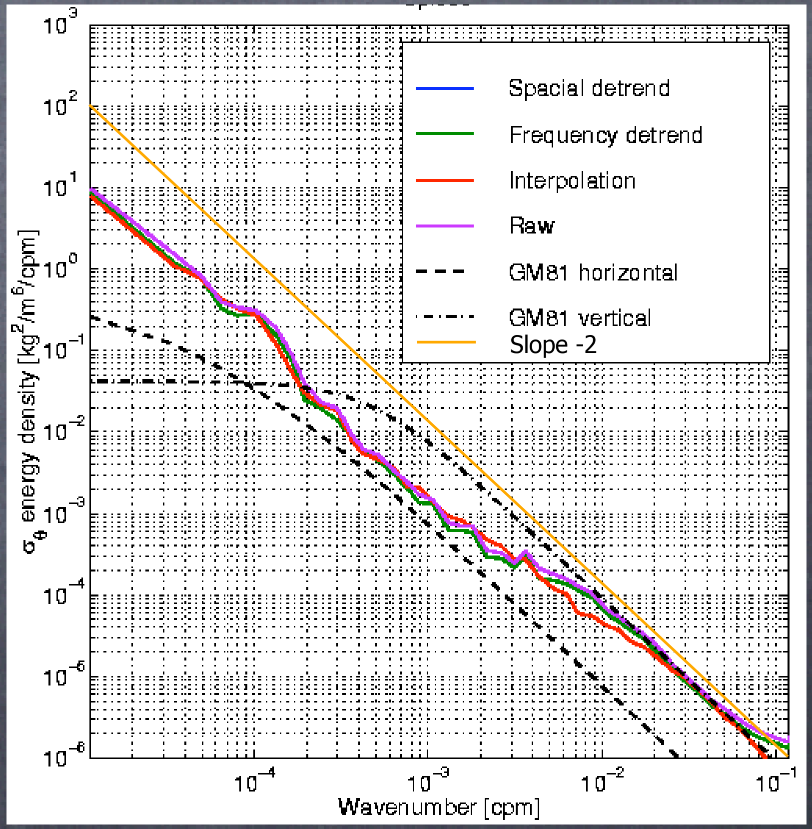




What about Coarse Resolution?

- Observed buoyancy gradient spectrum gives:

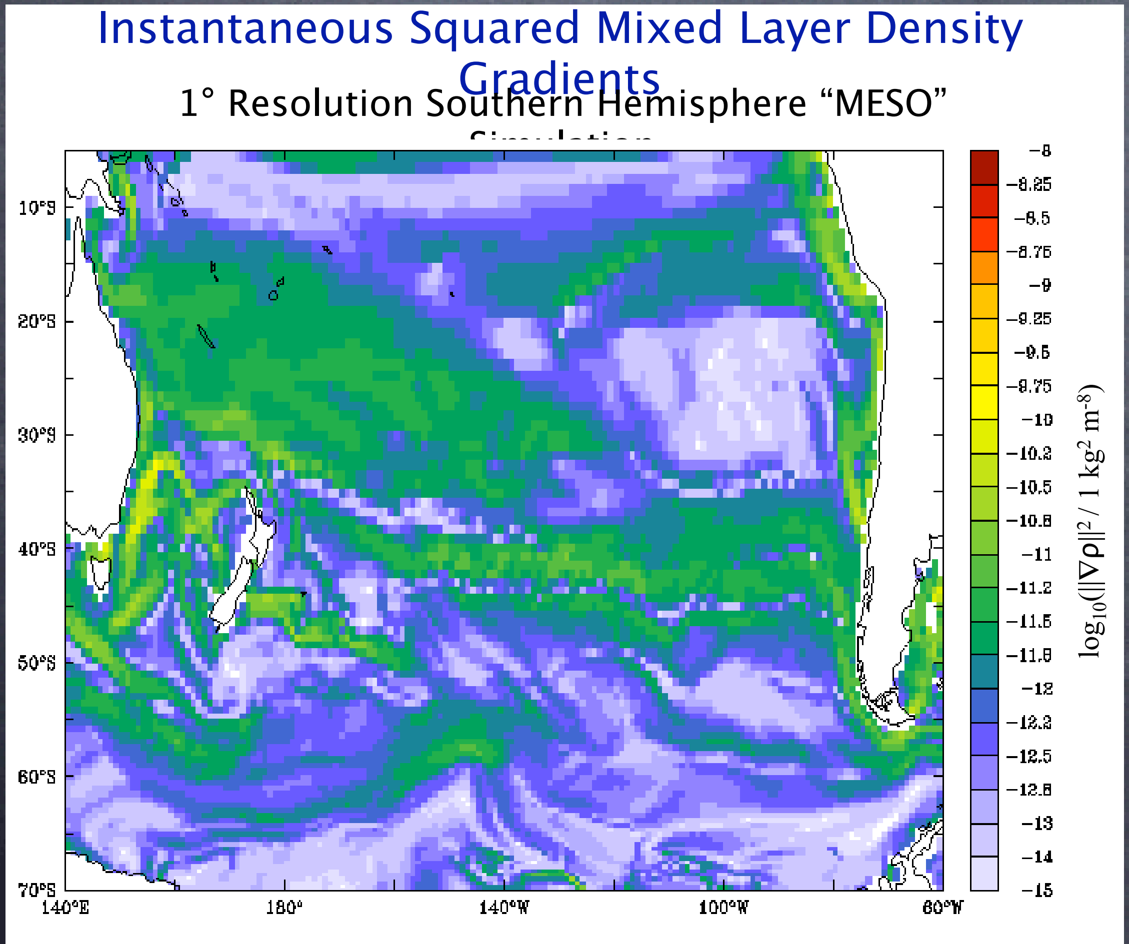
$$\frac{\overline{|\nabla b_{fine}|^2}}{|\nabla b_{coarse}|^2} \approx \frac{L_{coarse}}{L_{fine}}$$

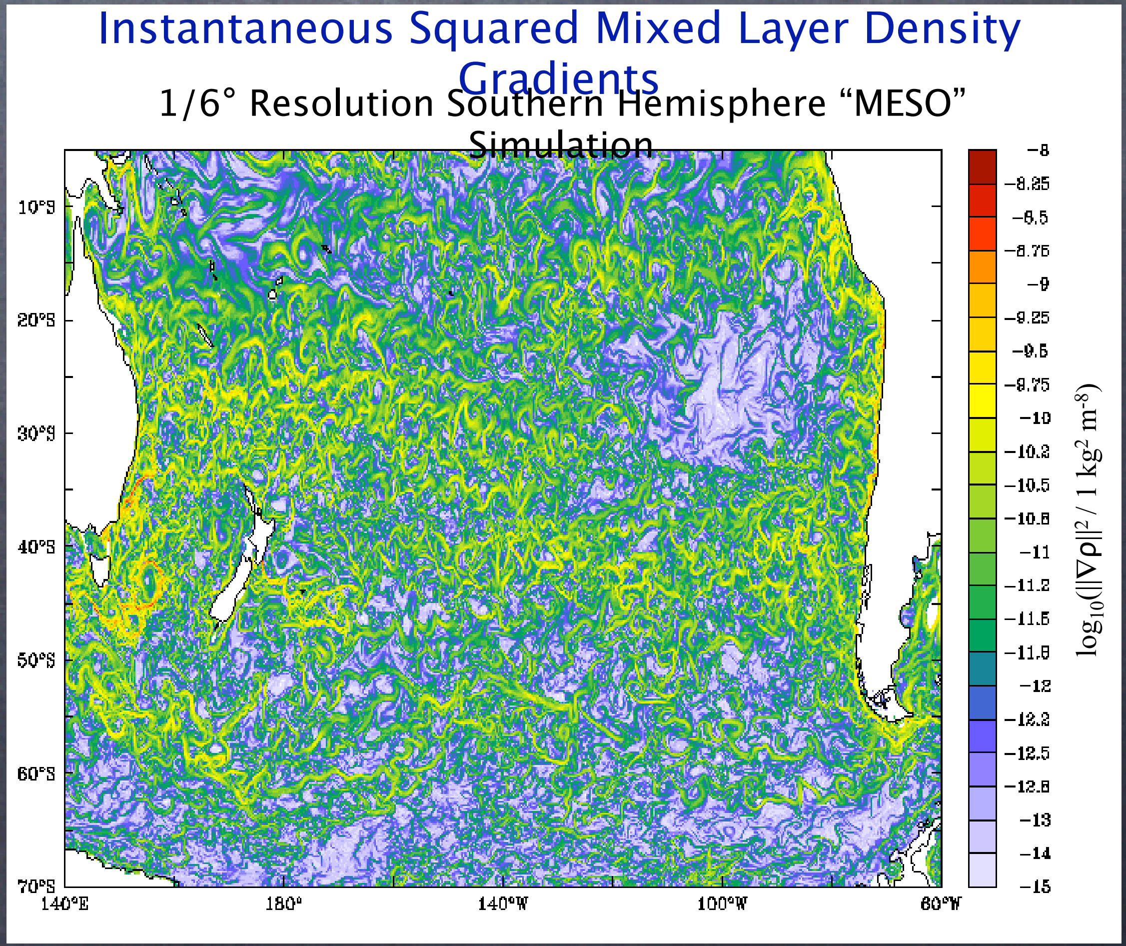


What about Coarse Resolution?

- Modeled buoyancy gradient gives:

$$\frac{\overline{|\nabla b_{fine}|^2}}{|\nabla b_{coarse}|^2} \approx \frac{L_{coarse}}{L_{fine}}$$





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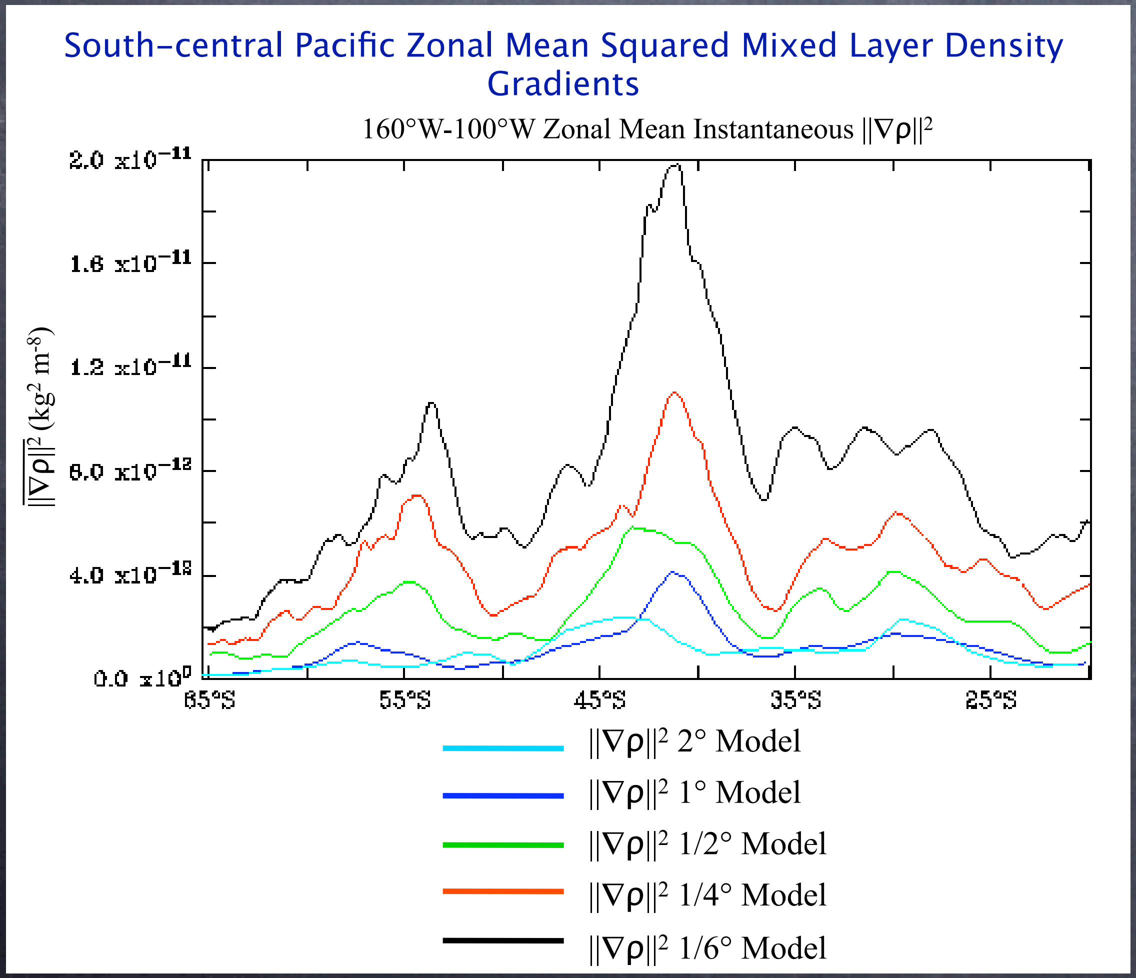
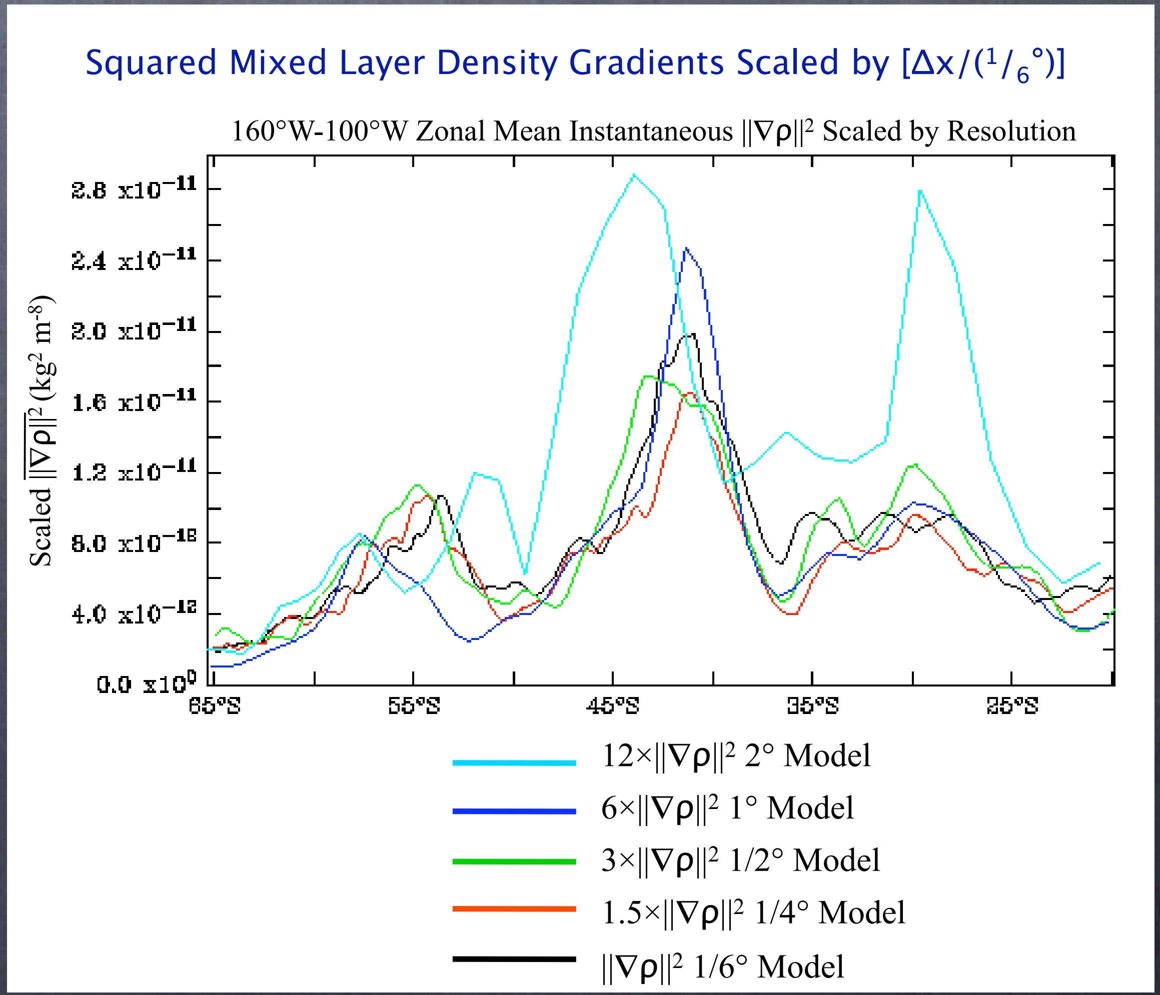


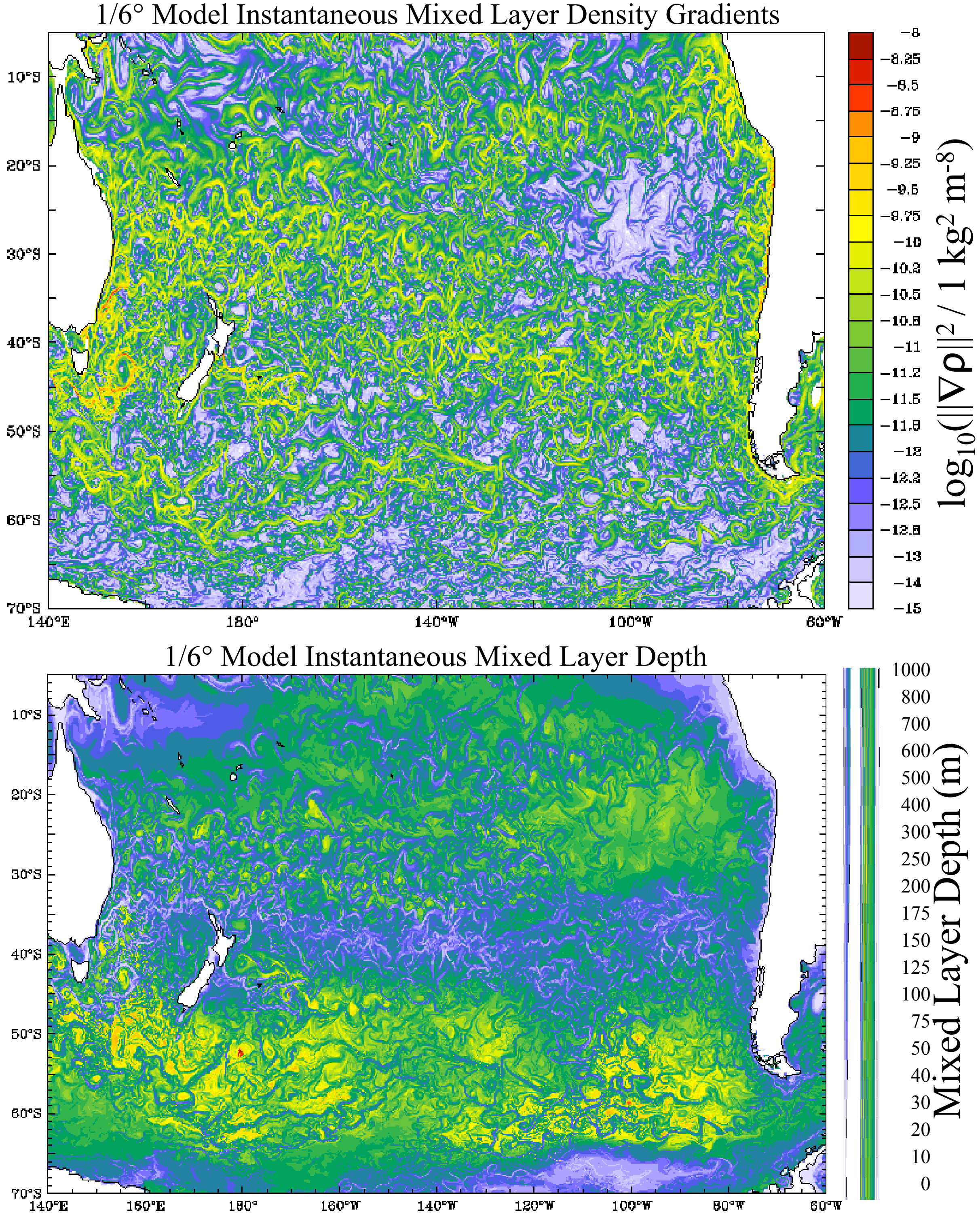


So, putting into a model:

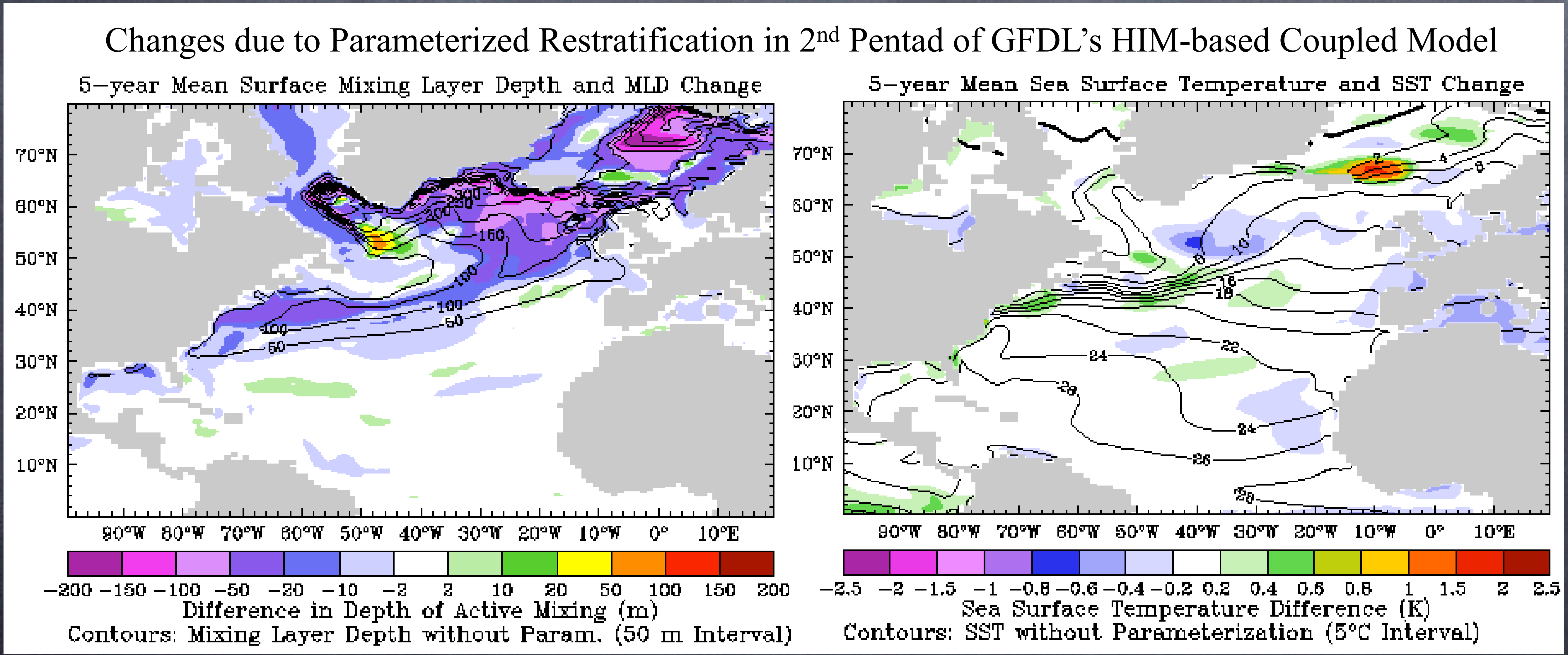
- Taper at equator, easy with Young (1994), but other tapering would not be terribly different
- Scale up resolved buoyancy gradient to buoyancy gradient appropriate for mixed layer eddies

SubMeso Restratification!

Mixed Layer Density Gradients and Mixing Layer Depth



Mixed Layer Depth and Temperature Effects

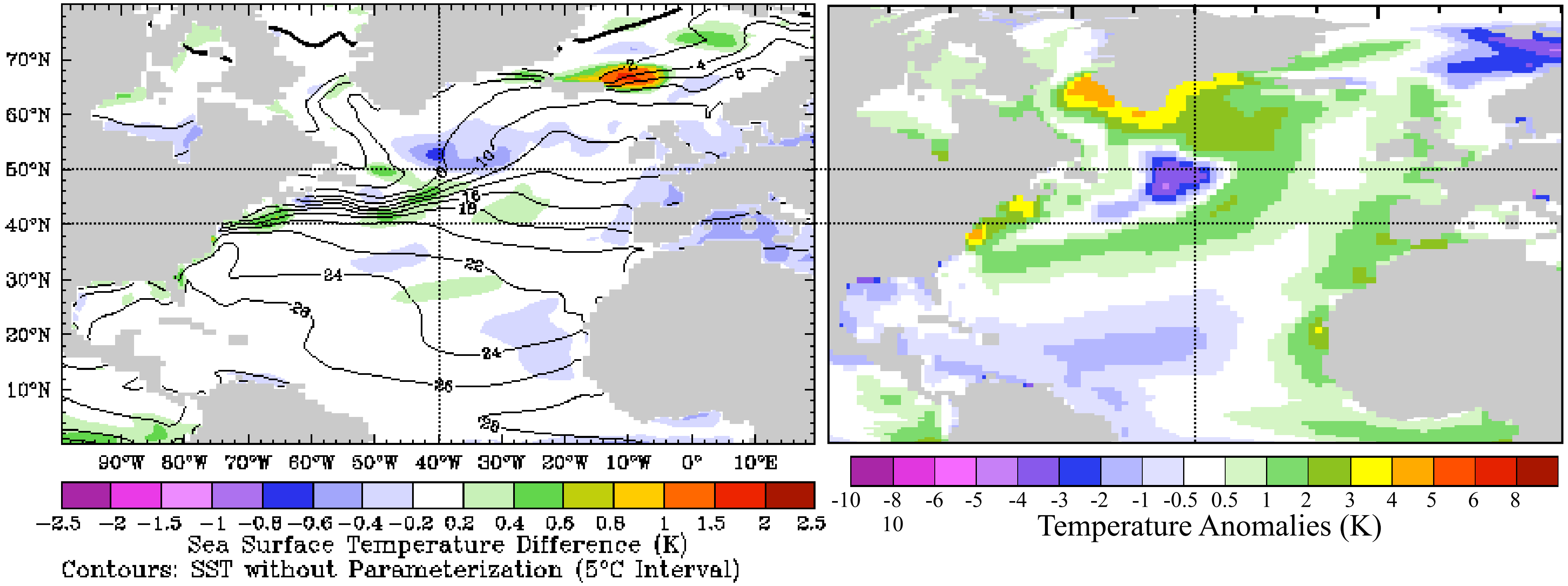


Tentative: Improvement?

SST Changes due to Parameterization Compared with Coupled Model SST Biases

SST Change Due to Parameterized Restratification
In Second Pentad of Coupled Model

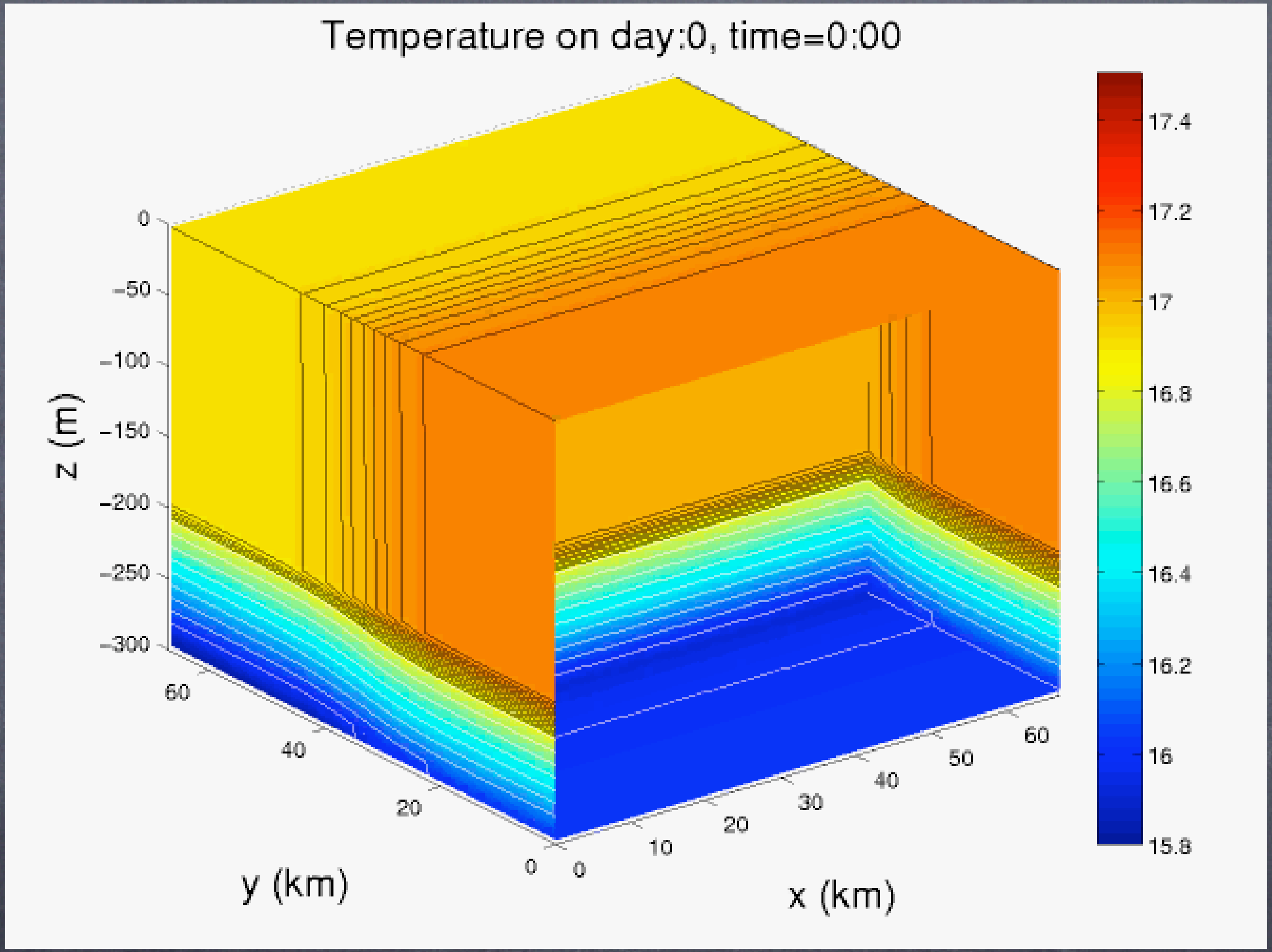
50-year Mean SST Bias
In Coupled Model without Parameterization

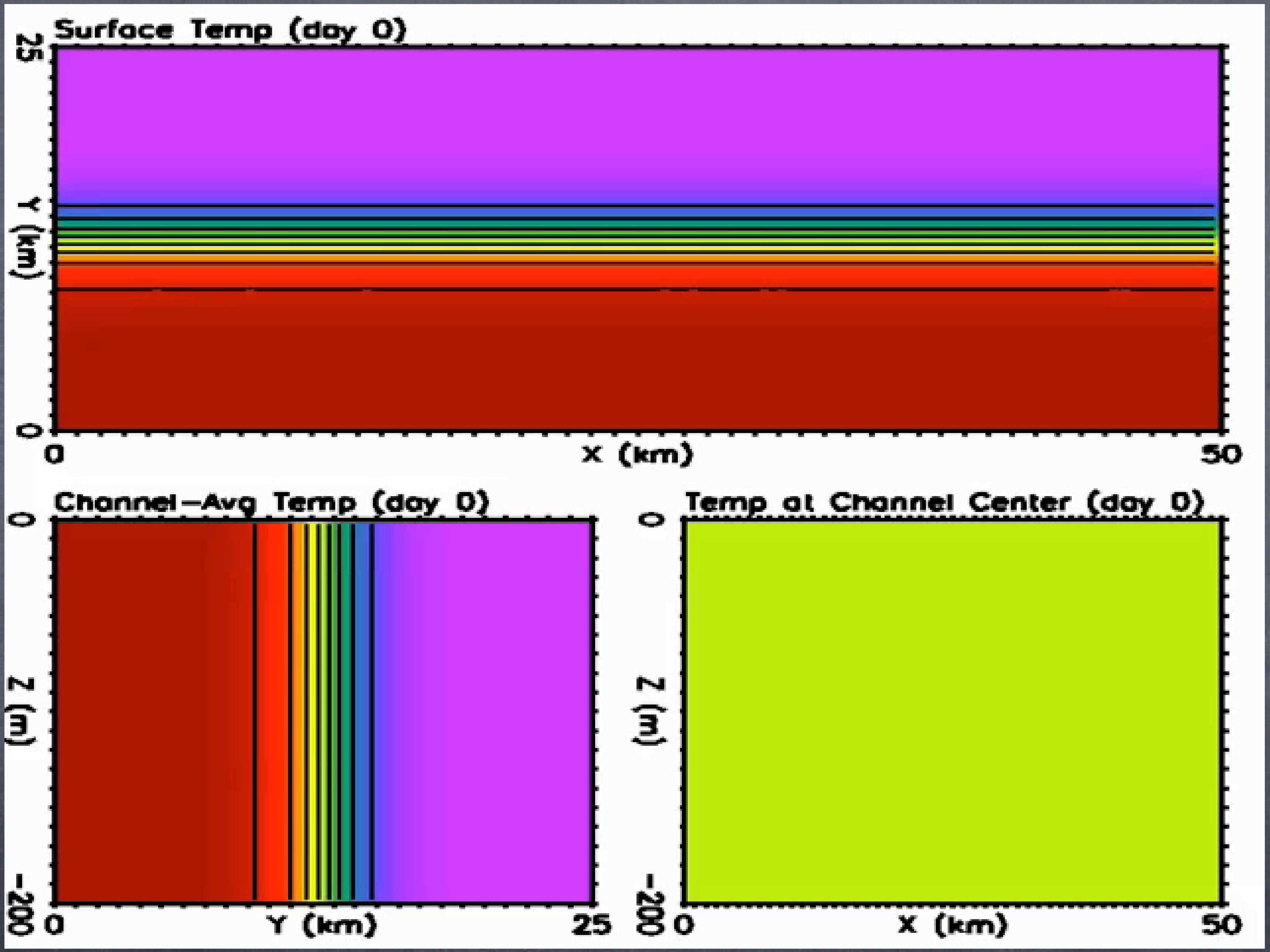


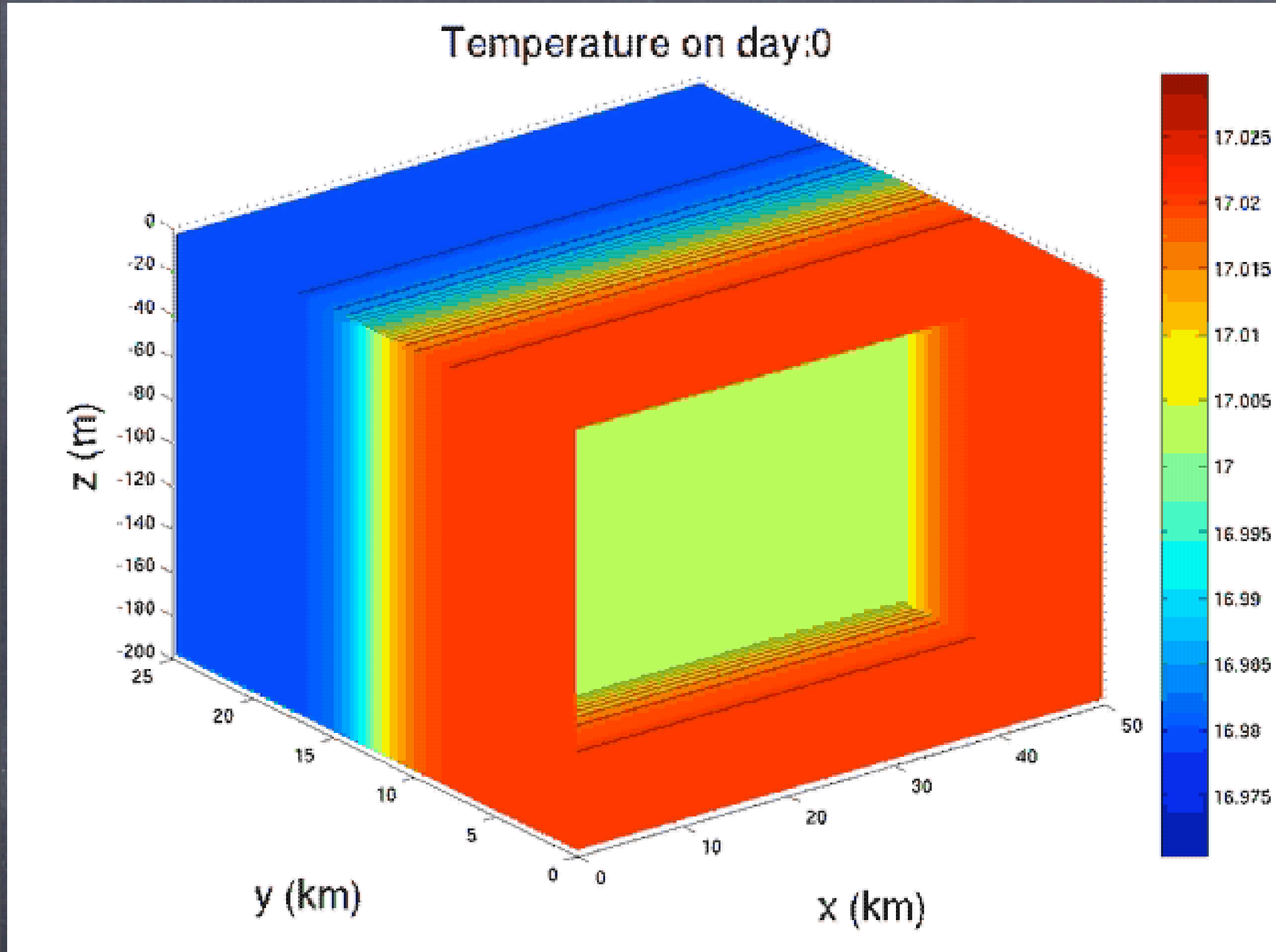
Note: 5 years is too short for robust estimates of the SST changes.

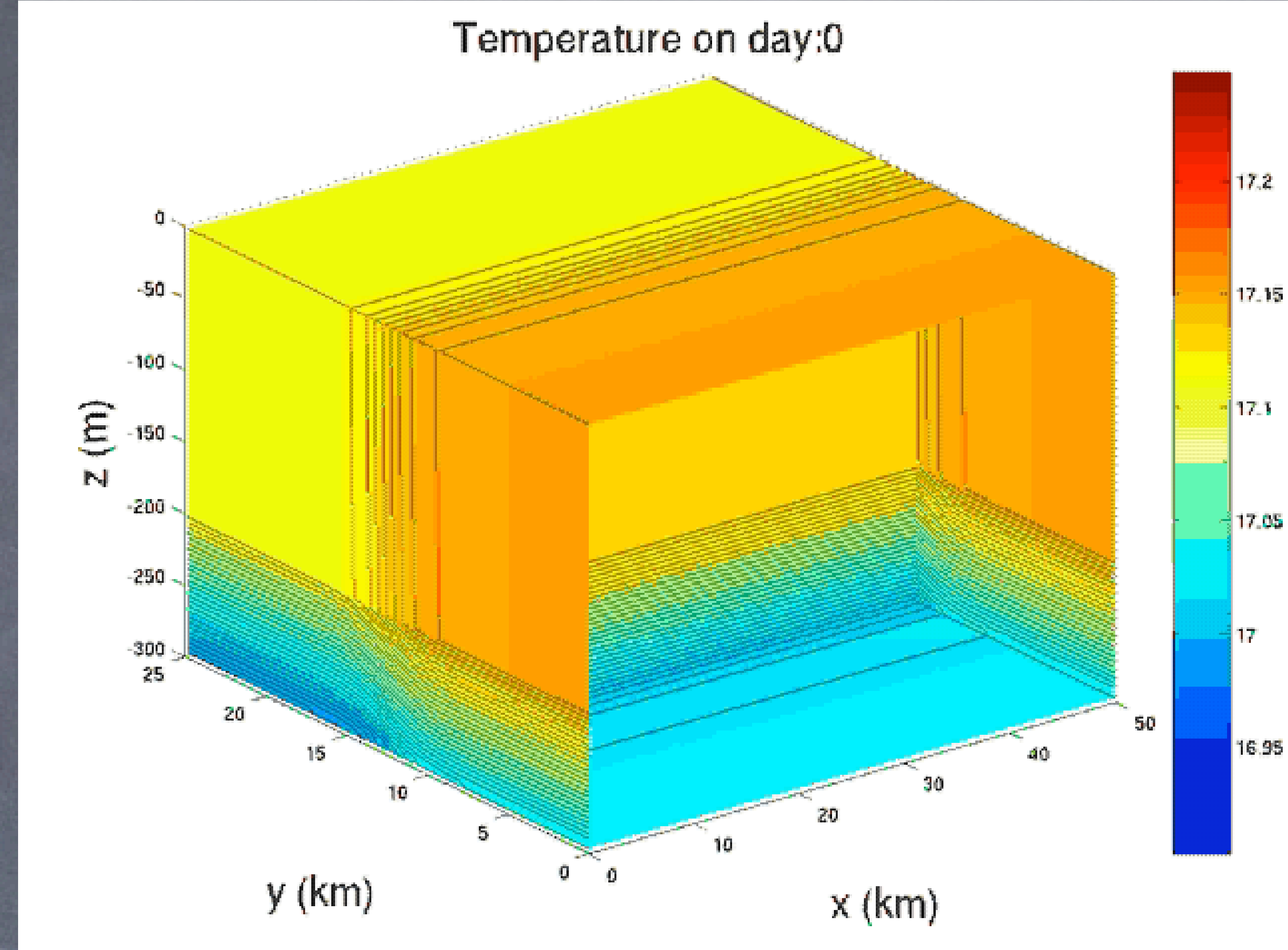
Conclusions

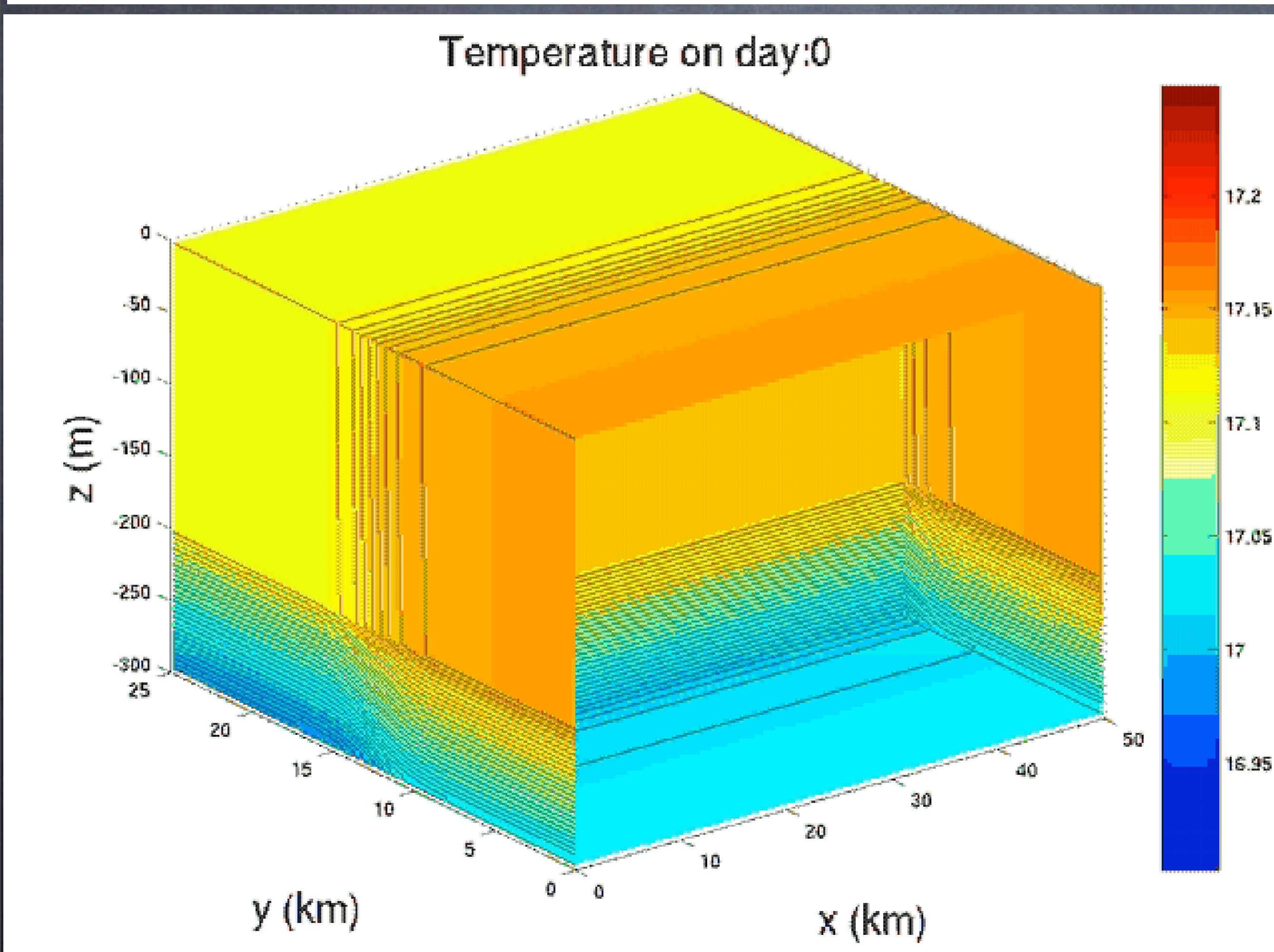
- Submesoscale Eddies naturally occur in typical ocean mixed layer stratification
- They have been observed
- They cannot be resolved, but their restratification can be parameterized
- Doing so seems to improve mixed layer properties

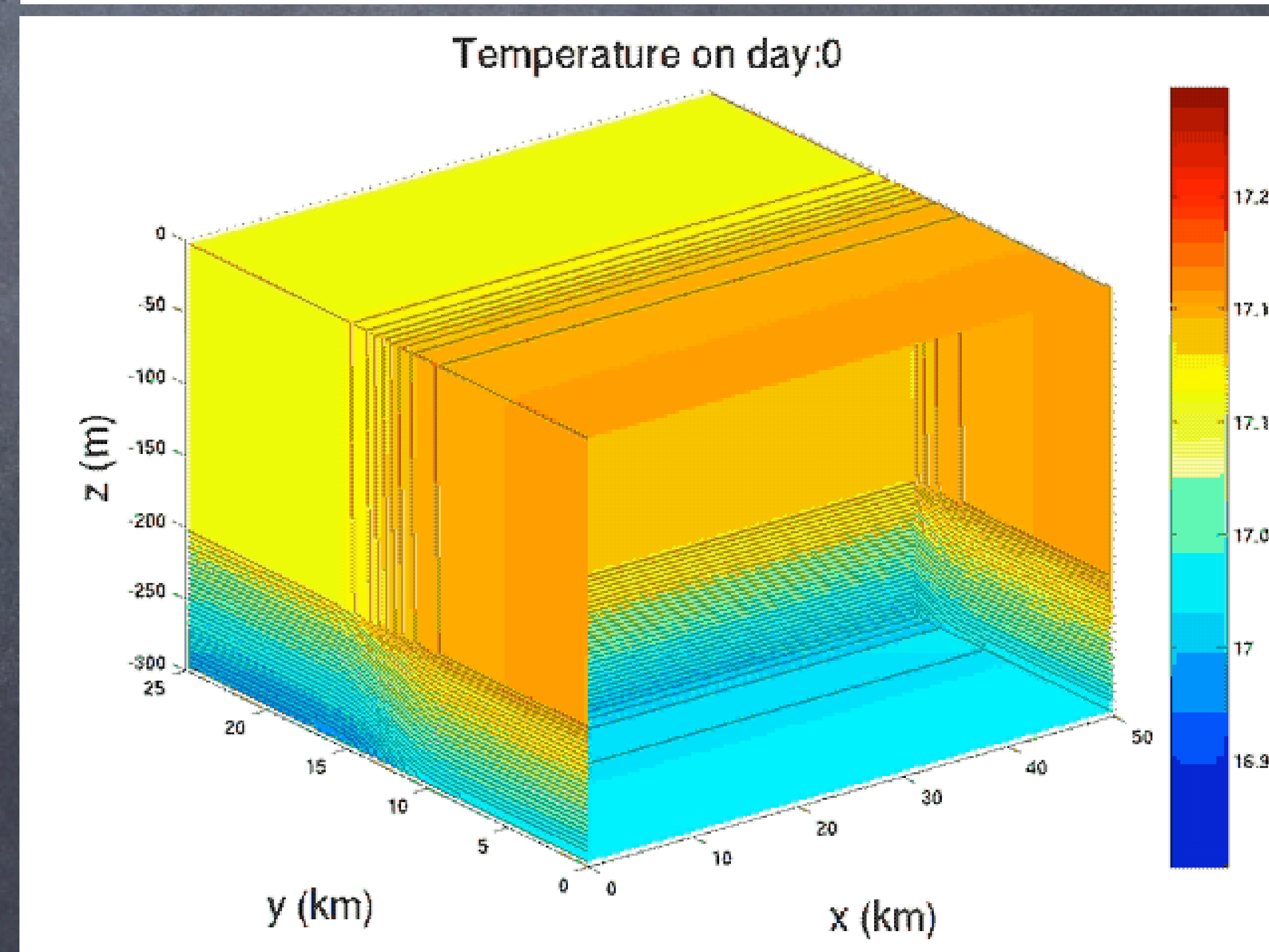

Temperature on day:0, time=0:00
z (m)
0
−50
−100
−150
−200
−250
−300
y (km)
60
40
20
0
x (km)
0
10
20
30
40
50
60
17.4
17.2
17
16.8
16.6
16.4
16.2
16
15.8

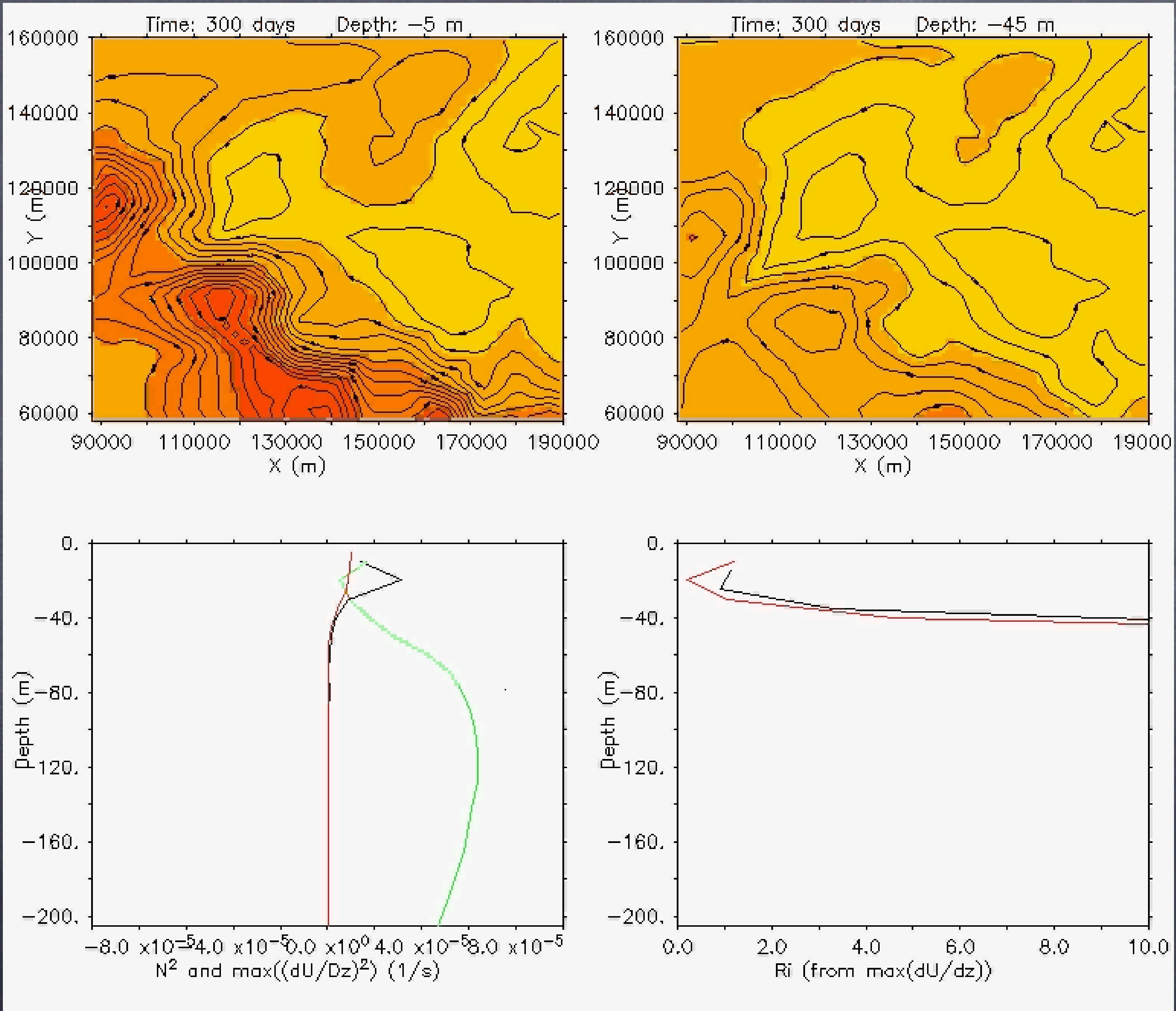

Surface Temp (day 0)
25
Y (km)
0
0
X (km)
50
Channel-Avg Temp (day 0)
0
Z (m)
-200
0
Y (km)
25
Temp at Channel Center (day 0)
0
Z (m)
-200
0
X (km)
50


Temperature on day:0
z (m)
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
y (km)
25
20
15
10
5
0
x (km)
0
10
20
30
40
50
17.025
17.02
17.015
17.01
17.005
17
16.995
16.99
16.985
16.98
16.975

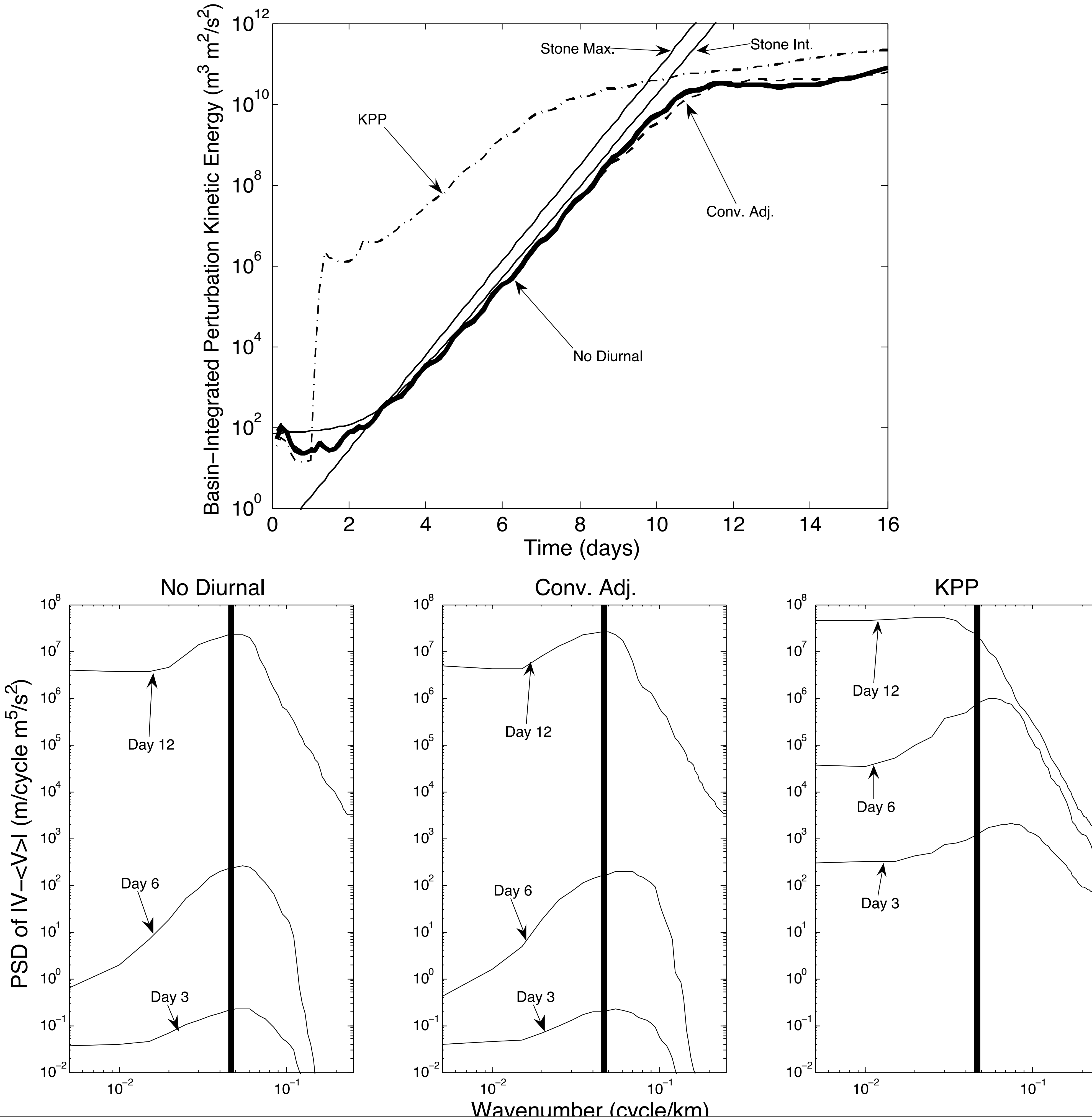

Temperature on day:0
z (m)
0
-50
-100
-150
-200
-250
-300
y (km)
25
20
15
10
5
0
x (km)
0
10
20
30
40
50
17.2
17.15
17.1
17.05
17
16.95

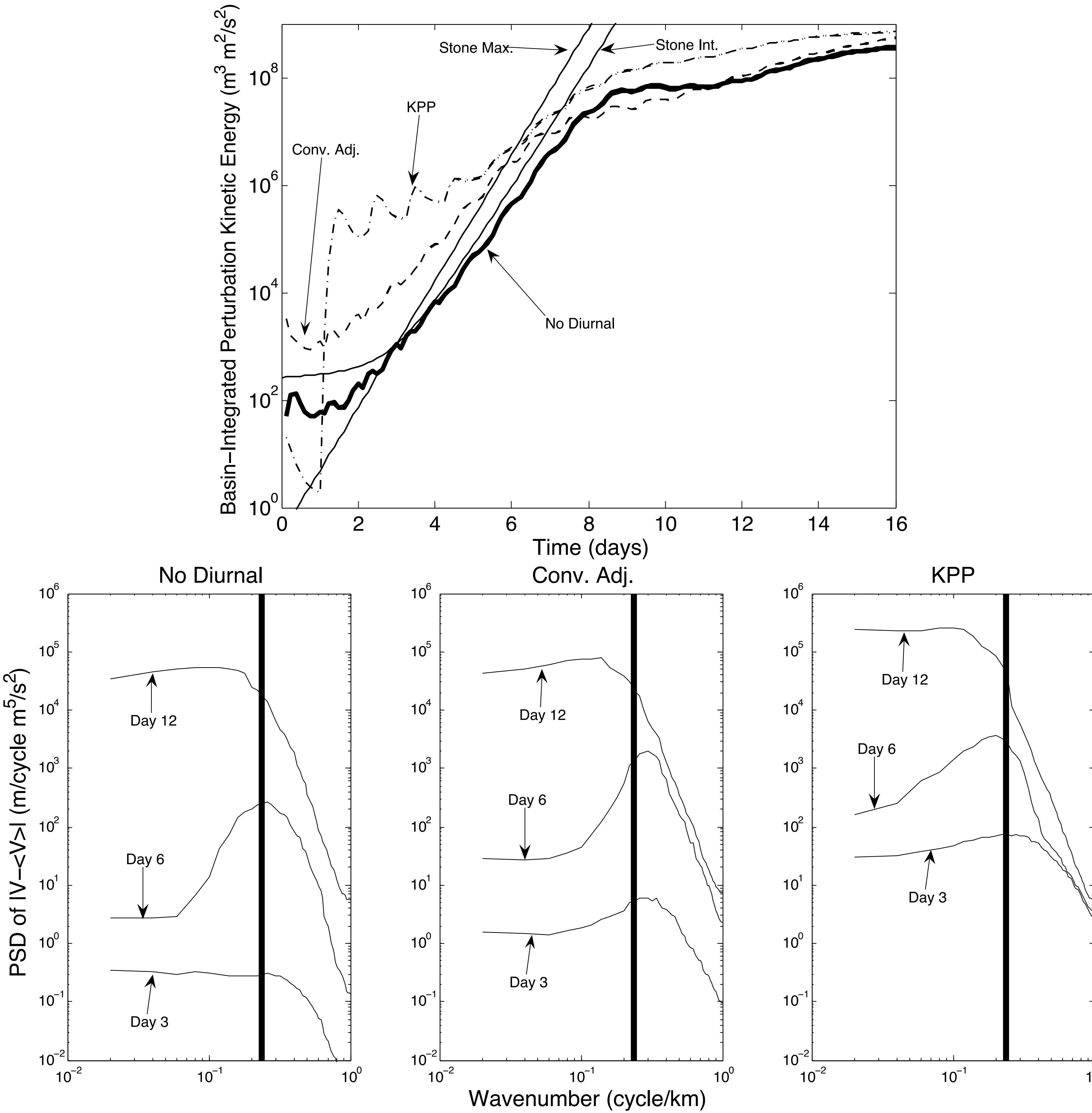

Temperature on day:0
z (m)
0
-50
-100
-150
-200
-250
-300
y (km)
25
20
15
10
5
0
x (km)
0
10
20
30
40
50
17.2
17.15
17.1
17.05
17
16.95


Temperature on day:0
z (m)
0
-50
-100
-150
-200
-250
-300
y (km)
25
20
15
10
5
0
x (km)
0
10
20
30
40
50
17.2
17.15
17.1
17.05
17
16.95

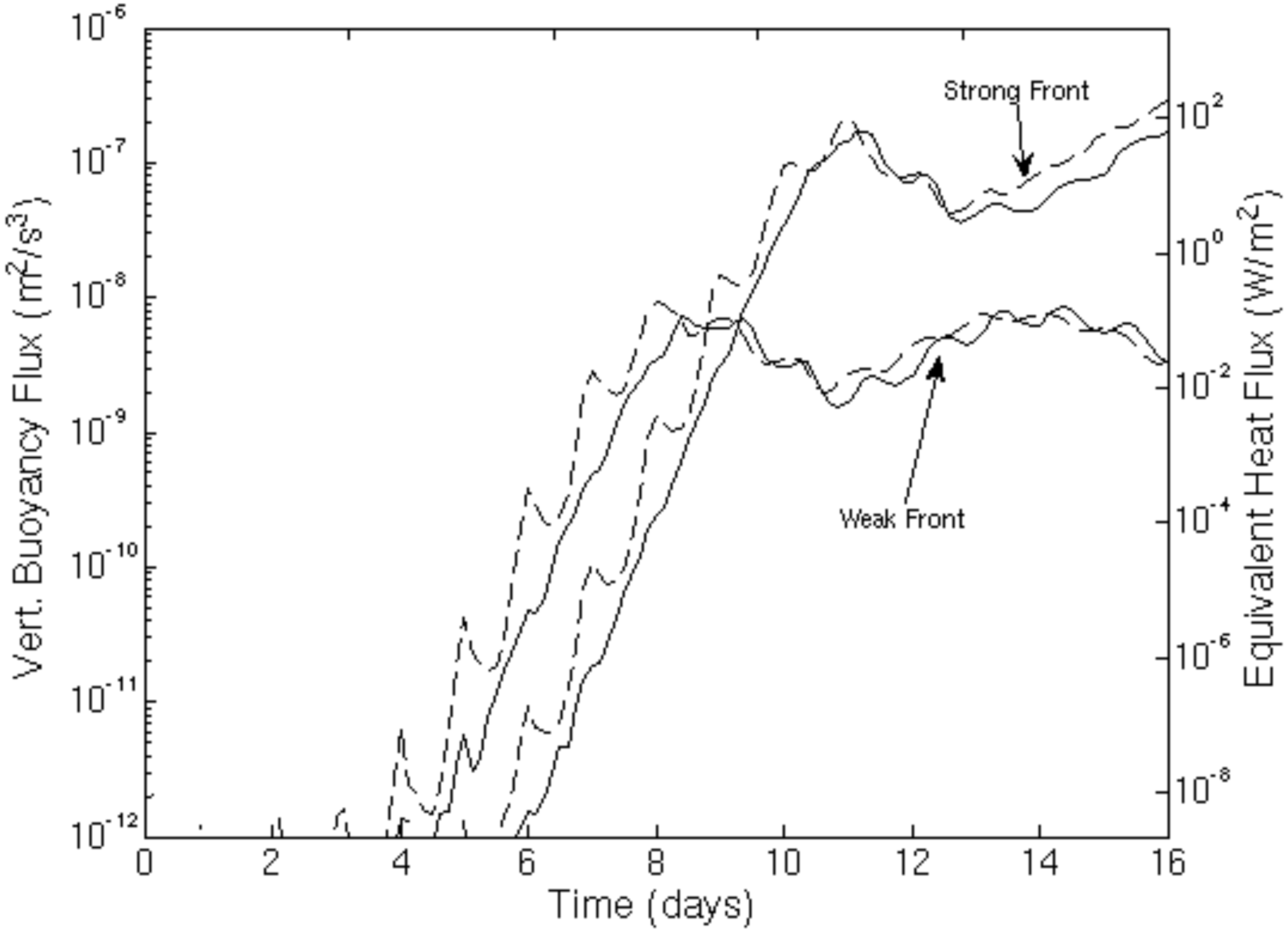


Time: 300 days Depth: −5 m
Time: 300 days Depth: −45 m
Y (m)
X (m)
Depth (m)
N² and max((dU/Dz)²) (1/s)
Ri (from max(dU/dz))


Basin-Integrated Perturbation Kinetic Energy (m^3 m^2/s^2)
Stone Max.
Stone Int.
KPP
Conv. Adj.
No Diurnal
Time (days)
No Diurnal
Conv. Adj.
KPP
Day 12
Day 6
Day 3
PSD of |V−<V>| (m/cycle m^5/s^2)
Wavenumber (cycle/km)



Basin-Integrated Perturbation Kinetic Energy (m^3 m^2/s^2)
Stone Max.
Stone Int.
KPP
Conv. Adj.
No Diurnal
Time (days)
No Diurnal
Conv. Adj.
KPP
PSD of |V−<V>| (m/cycle m^5/s^2)
Day 12
Day 6
Day 3
Wavenumber (cycle/km)



Strong Front
Weak Front
Vert. Buoyancy Flux (m2/s3)
Equivalent Heat Flux (W/m2)
Time (days)
10-6
10-7
10-8
10-9
10-10
10-11
10-12
102
100
10-2
10-4
10-6
10-8
0
2
4
6
8
10
12
14
16