Mixed Layer Restratification

Baylor Fox-Kemper

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

WHOI PO Seminar
Tuesday 2/27/07, 15:00-16:00
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
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
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?

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 Stratification Permits
Two Types of Baroclinic Instability:

**Mesoscale** and **SubMesoscale** (Boccaletti et al., 2006)

![Graph showing depth vs. N and Uz](image)
The Stratification Permits
Two Types of Baroclinic Instability:

Mesoscale and SubMesoscale (Boccaletti et al., 2006)
The Stratification Permits Two Types of Baroclinic Instability:

**Mesoscale** and **SubMesoscale** (Boccaletti et al., 2006)
The Stratification Permits
Two Types of Baroclinic Instability:

Mesoscale and SubMesoscale (Boccaletti et al., 2006)
The Stratification Permits
Two Types of Baroclinic Instability:

**Mesoscale** and **SubMesoscale** (Boccaletti et al., 2006)

![Graph showing growth rate vs. wavenumber for Mesoscale and SubMesoscale eddies](image)
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?

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. ($\zeta > 100$ 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 and tend to restratify**

**Horizontally fluxes are Mesoscale and tend to stir**

*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 $\text{Re} = N^2 |\bar{\tau}| - 2 = N^2 f^2 M^2$. Typically, $N^2$ changes more than $M^2$, as the initial front is wide compared to the...*
Having a Mixed Layer Counts!

The vertical buoyancy flux in the ML ($\langle w'b' \rangle$) without diurnal cycle is **not less** than with cycle (ML).

![Plan View Temp. at Surface](Day: 900)

![Plan View Temp. at 205m Depth](Day: 900)

![Temperature Section along Channel Center](Day: 900)
Having a Mixed Layer Counts!

The vertical buoyancy flux in the ML ($<w'b'>$) without diurnal cycle is \textbf{4x less} than with cycle (ML).
AESOP Observations of Rapid Restratin of
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, 30 m mixed layer depth

10 kt wind, stratified to surface

After one day

30 kt wind

10 kt wind

Courtesy E. D’Asaro
Prototype: Mixed Layer Front Adjustment

Simple Spindown

Plus, Diurnal Cycle and KPP

Note: initial geostrophic adjustment overwhelmed by eddy restratification
Schematic of the overturning
Schematic of the exchange process (Fig. 1) can be visualized using the vertical density profiles from CTD stations. The density structure indicates the presence of a pre-injection section of CTD stations located seaward of the shelfbreak, which provides evidence of the transport of shelf water into the oceanic gyre. This injection is characterized by an increase in the density gradient on isopycnal surfaces across the front. The pre-injection section of CTD stations is marked by a significant density stratification, indicating the presence of a shelf water patch. The density profiles also show a decrease in the density gradient at the shelfbreak, suggesting the mixing of shelf water with the oceanic water. The density profiles were obtained from the tows from the shelfbreak and provide evidence of the transport of shelf water into the oceanic gyre.
10 km along-isopycnal transport: submesoscale frontal instability?
Parameterization of Finite Amp. Eddies: Ingredients
Parameterization of Finite Amp. Eddies: Ingredients

Eddies at Finite Amplitude
Parameterization of Finite Amp. Eddies: Ingredients

Resolution

Eddies at Finite Amplitude

Convergence
Parameterization of Finite Amp. Eddies: Ingredients

Power Spectrum of KE

Eddies at Finite Amplitude
Parameterization of Finite Amp. Eddies: Ingredients

At Finite Amplitude
Horizontal Scale Unclear

Initially, Linear Prediction of Lengthscale good

Power Spectrum of KE
Parameterization of Finite Amp. Eddies: Ingredients

Power Spectrum of KE

Eddies at Finite Amplitude

At Finite Amplitude
Horizontal Scale Unclear

Initially, Linear Prediction of Lengthscale good

Inverse Cascade => No Results from Linear Instability
Parameterization of Finite Amp. Eddies: Ingredients

![Graph showing time (days) vs. $N^2/f^2$ for different cases of unbalanced and balanced conditions with $Ri_0=0$ and $Ri_0=1$.]
Parameterization of Finite Amp. Eddies: Ingredients

Finite Amplitude

\[ \frac{N^2}{f^2} \]

time (days)

unbalanced, \( R_i^0 = 0 \)

unbalanced, \( R_i^0 = 1 \)

balanced, \( R_i^0 = 1 \)

high resolution unbalanced, \( R_i^0 = 0 \)

balanced, \( R_i^0 = 0 \)
Parameterization of Finite Amp. Eddies: Ingredients

Finite Amplitude

N^2/f^2

time (days)

kinetic energy (m^2/s^2)

basin avg. pert. KE

linear predict. pert. KE

initial mean KE^2: 1/2(M^2 H/f)^2

avg. pert. v^2 in front

unbalanced, Ri_0=0

unbalanced, Ri_0=1

balanced, Ri_0=1

unbal, Ri_0=0

bal, Ri_0=0
Parameterization of Finite Amp. Eddies: Ingredients

Eddy Velocity Saturates

Finite Amplitude

\[
\frac{N^2}{f^2}
\]

\[
\text{kinetic energy (m}^2/\text{s}^2)\]

\[
\text{time (days)}
\]

\[
\text{basin avg. pert. KE}
\]

\[
\text{linear predict. pert. KE.}
\]

\[
\text{initial mean KE}^2: \frac{1}{2}(M^2 H/f)^2
\]

\[
\text{avg. pert. } v^2 \text{ in front}
\]
Parameterization of Finite Amp. Eddies: Ingredients

Finite Amplitude

Eddy Velocity Saturates Near Mean KE

Finite Amplitude

kinetic energy (m$^2$/s$^2$)

basin avg. pert. KE

linear predict. pert. KE.

initial mean KE

$2: 1/2(M^2 H/f)^2$

avg. pert. v$^2$ in front

unbalanced, $Ri_0=0$

unbalanced, $Ri_0=1$

balanced, $Ri_0=1$

hi res unbal, $Ri_0=0$

bal, $Ri_0=0$
Parameterization of Finite Amp. Eddies: Ingredients

Finite Amplitude

Vert. Excursions \((b'_{rms}/N^2)\) scale with \(H\)

Eddy Velocity Saturates Near Mean KE

- basin–avg. pert. KE
- linear predict. pert. KE.
- initial mean KE\(^2\), \(1/2(M^2 H/f)^2\)
- avg. pert. \(v^2\) in front

**Notes:**
- Time (days)
- Kinetic energy (m\(^2\)/s\(^2\))
- Unbalanced, Ri\(_0\) = 0
- Balanced, Ri\(_0\) = 1
- Hi
- Res unbalanced, Ri\(_0\) = 0
- Balanced, Ri\(_0\) = 0
Parameterization of Finite Amp. Eddies: Ingredients

Finite Amplitude

Vert. Excursions
\( \frac{b'_{\text{rms}}}{N^2} \)
scale with \( H \)

Eddy Velocity Saturates
Near Mean KE

Eddy Fluxes are at nearly \( 1/2 \) the slope
Magnitude Analysis: Vert. Fluxes

Extraction of potential energy by submesoscale eddies:

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

\[\langle wb \rangle \propto -\frac{\Delta z \Delta b}{\Delta t}\]
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.

\[\langle wb \rangle \propto -\frac{\Delta z \Delta b}{\Delta t}\]
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.

\[\langle wb \rangle \propto -\Delta z \left( \Delta y \frac{\partial \bar{b}}{\partial y} + \Delta z \frac{\partial \bar{b}}{\partial z} \right) \]

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

\[\Delta z \Delta b \]
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:

\[\frac{\Delta y}{\Delta z} \propto -\frac{\partial b}{\partial z}\frac{\partial \langle PE \rangle}{\partial t}\]

\[\langle wb \rangle \propto -\Delta z \left( \Delta y \frac{\partial b}{\partial y} + \Delta z \frac{\partial b}{\partial z} \right) \frac{\partial \langle PE \rangle}{\partial t}\]
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:

\[\frac{\Delta y}{\Delta z} \propto \frac{-\partial \bar{b}}{\partial y}\]

\[\langle wb \rangle \propto \frac{\Delta z \Delta y \partial \bar{b}}{\Delta t}\]
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:

$$\frac{\Delta y}{\Delta z} \propto -\frac{\partial b}{\partial z} \frac{\partial b}{\partial y}$$

Time scale is turnover time

$$\langle wb \rangle \propto \frac{\Delta z \Delta y \partial b}{\Delta t} \frac{\partial b}{\partial y}$$
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:

\[\frac{\Delta y}{\Delta z} \propto -\frac{\partial \bar{b}}{\partial y}\]

Time scale is turnover time

\[\langle wb \rangle \propto \frac{\Delta z \Delta y \frac{\partial \bar{b}}{\partial y}}{\Delta y/V}\]
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:

\[\frac{\Delta y}{\Delta z} \propto -\frac{\partial b}{\partial z} \frac{\partial b}{\partial y}\]

Time scale is turnover time from mean thermal wind:

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

\[\frac{\Delta y}{\Delta z} \propto -\frac{\partial \bar{b}}{\partial z} \frac{\partial \bar{b}}{\partial y}\]

Time scale is turnover time from mean thermal wind:

Vertical scale known: \(\Delta z \propto H\)

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

\[ \frac{\Delta y}{\Delta z} \propto -\frac{\partial \bar{b}}{\partial z} \]

Time scale is turnover time from mean thermal wind:

Vertical scale known: \( \Delta z \propto H \)

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

Fox-Kemper et al., 2007
Eddies effect a largely adiabatic transfer: thus representable by a streamfunction

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

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

$$
\overline{u'_{H b'}} \propto -\frac{H^2}{|f|} \frac{\partial \bar{b}}{\partial z} \nabla_H \bar{b}
$$
Eddies effect a largely adiabatic transfer: thus representable by a streamfunction

$$\Psi \propto \left( H^2 \nabla \bar{b} \times \hat{z} \right) \frac{1}{|f|} \rightarrow u'b' \equiv \Psi \times \nabla \bar{b}$$

For a consistently upward,

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

$$u'H \bar{b}' \propto \frac{-H^2 \frac{\partial \bar{b}}{\partial z}}{|f|} \nabla_H \bar{b}$$
Eddies effect a largely adiabatic transfer: thus representable by a streamfunction

\[ \Psi \propto \frac{H^2 \nabla \bar{b} \times \mathbf{\hat{z}}}{|f|} \]

For a consistently upward,

\[ \overline{w'b'} \propto \frac{H^2}{|f|} |\nabla_H \bar{b}|^2 \]

And horizontally downgradient flux.

\[ \overline{u'Hb'} \propto \frac{-H^2 \frac{\partial \bar{b}}{\partial z}}{|f|} \nabla_H \bar{b} \]
It works for Prototype Sims:

Red: No Diurnal

Blue: With Diurnal

>2 orders of magnitude!

Circles: Balanced Initial Cond.
Squares: Unbalanced Initial Cond.
Better than the competition:

\[ \frac{\Psi_d}{C_e H^2 M^2 f \lambda^{-1}} \]
Better than the competition:

Vs. Green (1970)
Better than the competition:

Vs. Green (1970)

Vs. Stone (1972)
Better than the competition:

Vs. Green (1970)

Vs. Stone (1972)

And, extends/agrees with Deep Convection Studies:

Jones & Marshall (93,97), Haine & Marshall (98)
What lengthscale dominates \( <w'b'> \)?
What lengthscale dominates $\langle w' b' \rangle$?

Stone fastest-mode Soln OK!

$$
\mu(z) = \left[1 - \left(\frac{2z}{H} + 1\right)^2\right] \left[1 + \frac{5}{21} \left(\frac{2z}{H} + 1\right)^2\right]
$$
What does it look like?

7d01h from 2d parameterization

7d01h from 3d MITgcm (smoothed)

$N^2$
Vertical Structure: like \langle w'b' \rangle from Eady solution.

Stone Solution to $O(Ro^2)$

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

Vert. velocity of typical submesoscale eddies: $> 20$ m/day
Underprediction of Biology/Chlorophyll near deep convection

Seawifs

PlanktOM5

[Chl] mg/m³

Courtesy M. Manizza
Underprediction of Biology/Chlorophyll near deep convection

When Light-Limited: More Stratification $\rightarrow$ More Biomass!
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

$\log_{10}(||\nabla p||^2 / 1 \text{ kg}^2 \text{ m}^{-8})$
Known Deep Bias in Models

MLD: MITgcm data assim

MLD from Obs.

Hydrography of the Labrador Sea during Active Convection

Courtesy I. G. Fenty

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)

Fenty/MITgcm

Pickart et al 02.
Deep Bias Partly Convection, but also total absence of restratification, (GM can’t do it because of tapering)

Pickart et al 02.
Equator ($f \to 0$) 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.

How to add effects of frontogenesis and friction??
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.

How to add effects of frontogenesis and friction?? *Ask Leif and Mike!*
The Parameterization:

\[ \Psi = \frac{C e H^2 \mu(z)}{|f|} \tilde{\nabla} b \times \hat{z} \]

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

- The horizontal fluxes are downgradient:

\[ \mathbf{u}' \mathbf{b}' = -\frac{C e H^2 \mu(z)}{|f|} \frac{\partial \tilde{b}}{\partial z} \nabla_H \tilde{b} \]

- Vertical fluxes always upward to restratify:

\[ \mathbf{w}' \mathbf{b}' = \frac{C e H^2 \mu(z)}{|f|} |\nabla \tilde{b}|^2 \]

- Adjustments for coarse resolution and \( f \to 0 \) are known
More to come on this...
Coupling to turbulence?

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

Plan View of T
A Blumen multi-SQG model allows an approximate coupled run to equilibrate.
Taper to SML at Equator

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

Converges to Young (1994) Subinertial ML Approx.
at equator, which is gravity waves interrupted by mixing
This is well-behaved, even when momentum is homogenized within the mixed layer with a timescale 

Fox-Kemper et al., (previous session) find that in the limit of strong rotation, the restratifying 

Parameterizing SMI with Resolved Fronts 

Results
Better than the Competition:

Red: No Diurnal

Blue: With Diurnal

But, Agrees with Deep Convection Studies:
Jones & Marshall (93,97), Haine & Marshall (98)
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

Depth (m)

$N^2$ and $\max((dU/dz)^2)$ (1/s)

$Ri$ (from $\max(dU/dz)$)

Depth (m)
How I got into ML Stuff

Layer 9, $T=750.08$ yrs., $\rho=1026.6\text{kg m}^{-3}$
How I got into ML Stuff