Mixed Layer Restratification

Baylor Fox-Kemper

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

Coupling?
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)
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)
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?

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 day25 (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 \( \frac{\zeta}{f} = 0 \) 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 $\overline{uv}$ (upper panel) and $|\overline{uv}|$ (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 *not* less than with cycle (ML).
Having a Mixed Layer Matters!

The vertical buoyancy flux in the ML ($<w'b'>$) without diurnal cycle is $4 \times$ 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.

![Diagram showing the evolution of the mixed layer depth and salinity over time with wind changes.](image-url)

**30 kt wind**

*Salinity* 32.7-33.8 psu

**After one day**

*Salinity* 24.5-25.5 psu

**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
As the relative dye injection was pre-injected into the shelfbreak jet (yd 226), the main patch located at yd 228 was separated from the shelf water (Fig. 1). Thus, the filament starts to restratify by overturning from the shelfbreak front. The relative stratification gradients on isopycnal surfaces across the front are the result of separation of parcels of shelf water due to the pre-injection section of CTD stations.
10 km along-isopycnal transport: submesoscale frontal instability?
Parameterization of Finite Amp. Eddies: Ingredients

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

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

Power Spectrum of KE

At Finite Amplitude
Horizontal Scale Unclear

Eddies at Finite Amplitude

Initially, Linear Prediction of Lengthscale good
Parameterization of Finite Amp. Eddies: Ingredients

**At Finite Amplitude**
Horizontal Scale Unclear

Initially, Linear Prediction of Lengthscale good

Eddies at Finite Amplitude

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

Finite Amplitude

\( N^2/f^2 \) vs. time (days)

- Unbalanced, \( R_i^0 = 0 \)
- Unbalanced, \( R_i^0 = 1 \)
- Balanced, \( R_i^0 = 1 \)
- Hi! res unbal, \( R_i^0 = 0 \)
- Bal, \( R_i^0 = 0 \)
Parameterization of Finite Amp. Eddies: Ingredients

Finite Amplitude

- 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

kinetic energy (m$^2$/s$^2$)
Parameterization of Finite Amp. Eddies: Ingredients

Finite Amplitude

Eddy Velocity Saturates
Parameterization of Finite Amp. Eddies: Ingredients

**Finite Amplitude**

<table>
<thead>
<tr>
<th>time (days)</th>
<th>kinetic energy ($m^2/s^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>15</td>
</tr>
<tr>
<td>8</td>
<td>20</td>
</tr>
<tr>
<td>10</td>
<td>25</td>
</tr>
<tr>
<td>12</td>
<td>30</td>
</tr>
<tr>
<td>14</td>
<td>35</td>
</tr>
<tr>
<td>16</td>
<td>40</td>
</tr>
</tbody>
</table>

**Eddy Velocity Saturates**

- Near Mean KE

<table>
<thead>
<tr>
<th>time (days)</th>
<th>kinetic energy ($m^2/s^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$10^{-8}$</td>
</tr>
<tr>
<td>5</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>10</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>15</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>20</td>
<td>$10^{0}$</td>
</tr>
<tr>
<td>25</td>
<td>$10^2$</td>
</tr>
<tr>
<td>30</td>
<td>$10^4$</td>
</tr>
</tbody>
</table>

**Initial Mean KE**

$2: \frac{1}{2}(M^2 H/f)^2$

**Unbalanced, $Ri_0=0$**

**Balanced, $Ri_0=1$**

**Hi res unbal, $Ri_0=0$**

**Bal, $Ri_0=0$**

$N^2/f^2$
Parameterization of Finite Amp. Eddies: Ingredients

Finite Amplitude

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

Eddy Velocity Saturates Near Mean KE

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

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

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

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

Unbalanced, \( R_i^0 = 0 \)
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

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 mean isopycnal slope
Magnitude Analysis: Vert. Fluxes

Extraction of potential energy by submesoscale eddies:

\[-\langle wb \rangle = \frac{\partial \langle PE \rangle}{\partial t}\]
Magnitude Analysis: Vert. Fluxes

Extraction of potential energy by submesoscale eddies:

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

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

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

$$\Psi \propto \frac{H^2 \nabla \bar{b} \times \hat{z}}{|f|} \quad \rightarrow \quad \mathbf{u}' \mathbf{b}' \equiv \Psi \times \nabla \bar{b}$$
Eddies effect a largely adiabatic transfer: thus representable by a streamfunction

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

For a consistently upward,

$$\mathbf{w}' \mathbf{b}' \propto \frac{H^2}{|f|} \left| \nabla_H \bar{b} \right|^2$$
Eddies effect a largely adiabatic transfer: thus representable by a streamfunction

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

For a consistently upward, horizontally downgradient flux:

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

horizontally downgradient flux.

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

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

For a consistently upward, horizontally downgradient flux.

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

And, extends/agrees with Deep Convection Studies: Jones & Marshall (93,97), Haine & Marshall (98)
It works for Prototype Sims:

Red: No Diurnal

Blue: With Diurnal

>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)

7d01h from 2d parameterization  7d01h from 3d MITgcm (smoothed)

\[ N^2 \]
Vertical Structure:
like $\langle w'b' \rangle$ 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

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

$$\log_{10}(||\nabla p||^2 / 1 \text{ kg}^2 \text{ m}^{-8})$$
Equator ($f \rightarrow 0$) and coarse resolution (up to 1 deg) are manageable

**Implements 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...

28 Aug - 6 Oct, 2004; GOES SST, Frances, Ivan and Jeanne
More to come...

NASA: Seawifs

Lots of Data! Satellites

Hurricane Wake Recovery...

28 Aug - 6 Oct, 2004; GOES SST, Frances, Ivan and Jeanne
Hurricane Wake Recovery...

NASA: Seawifs with Chlorophyll

Lots of Data! with Satellites

More to come...
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

And Profilers (Webb Research)
Preliminary Simulations

Temperature on: 0d0h

![3D Temperature Simulation Graph]

- Z (m)
- Y (km)
- X (km)
Compare with 2d (no eddies)
Coupling to 3d turbulence?

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

$S(k) \propto k^{-2}$
The Parameterization:

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

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

- The horizontal fluxes are downgradient:

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

- Vertical fluxes always upward to restratify:

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

- Adjustments for coarse resolution and \( f \rightarrow 0 \) are known.
Known Deep Bias in Models

MLD: MITgcm data assim

MLD from Obs.

1993-03
1997-03
2001-03

<2000m deep!

Hydrography of the Labrador Sea during Active Convection

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
Deep Bias Partly Convection, but also total absence of restratification, (GM can’t do it because of tapering)
What lengthscale dominates \( \langle w'b' \rangle \)?
What lengthscale dominates \(<w'b'>\)?

Vertical Structure from linear Soln OK!
Better than the competition:

\[ \Psi_d/\left(C_e H^2 M^2 |f|\right)^{1/2} \]
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)
Taper to SML at Equator

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

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

Converges to Young (1994)
Subinertial ML Approx.
at equator, which is gravity waves interrupted by mixing
Momentum is homogenized within the mixed layer with a timescale $-1.2000000179 - 0.4000000060 - 0.8000000100$. Rotation, the restratifying effect, vanishes.

Parameterizing SMI with Resolved Fronts

Results

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

$C_e \rightarrow C_e \frac{\Delta x}{L_d}$
Better than the Competition:

Red: No Diurnal

Blue: With Diurnal

Better than the Competition:

Red: No Diurnal

Blue: With Diurnal

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