Physics Problems for the Future of Global Ocean Modeling

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Many Collaborators, to be mentioned within...
Ancient Worries of Ocean Modeling

- **Accurate and Stable Numerics**—many known fixes

- **Flux Adjustments**—no longer needed (ca 1995)

- **Veronis Effect**—fixed with isoneutral schemes: Redi & Gent-McWilliams

- **Inertial runaway**—not really a problem with vorticity sinks (Fox-Kemper & Pedlosky, 04)

- **Visualization**—graphics, movies!
Recent Worries of Ocean Modeling

- Mesoscale eddies and boundary currents—resolving the deformation radius?

- Tropical biases—upwelling, double ITCZ, poor ENSO, etc.

- Boundary conditions for ocean-only runs—Flux or restoring?

- Depth, isopycnal, or sigma coordinates—the right vertical discretization?

- Sparse data for comparison—especially subsurface and repeat observations (also double-filtering problems)
Mesoscale eddies and boundary currents—resolving the deformation radius?

Figure 5. Taylor diagram showing the level of statistical agreement between the 1994–2001 average sea surface height anomaly from the 0.4° (red circles) and 0.1° (blue circles) global POP simulations and the AVISO (TOPEX/POSEIDON and ERS 1 and 2) altimetry. The arrows connect the results of both simulations evaluated over the following geographical regions: Global (70°S–70°N), North Atlantic Ocean (20°N–55°N, 100°W–20°W), Open Pacific Ocean (30°S–30°N, 150°E–110°W), and Southern Ocean (65°S–40°S). Lines of constant correlation coefficient (r) are solid; the long dashed curves denote lines of constant standard deviation ratio (σ); the short dashed curves denote lines of constant RMS difference, varying from 0.6 (small radius) to 0.9 by 0.1. The black semicircle represents the location of perfect agreement between the simulation and the comparison data set.

Credit: McClean et al. 06
Tropical biases—upwelling, double ITCZ, poor ENSO, etc.

Credit: P. Gent
Tropical biases—upwelling, double ITCZ, poor ENSO, etc.
Tropical biases--upwelling, double ITCZ, poor ENSO, etc.

East Pacific DJF ITCZ precipitation (mm/day colors) and 925-hPa convergence (contours) in 2° and 0.5° CCSM 3.5

Credit: P. Gent
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My Future Worries for Ocean Modeling

This talk

- Still missing physics: Multiscale interactions
- Focus on upper ocean: links to Climate and Biogeochemically active

Another day

- Energetic and Conservation consistency (enstrophy, too?)
- Internal waves and mixing
- Data assimilation and forecasting/hindcasting
Future Opportunities in Ocean Modeling

- Unfamiliar communities (at least to global modelers) of observationalists and theorists have knowledge and skills needed

- ‘Climate sensitivity’ of new physics--unknown

- Results will outlast a few generations of computer advances (mesoscale rich IPCC-class, perhaps 5yr away, submesoscale rich IPCC-class more than 50yr away)

- Will be fun!
Two Examples

- **Submesoscale Eddies** -- with Ferrari, Hallberg, Boccaletti, Flierl, CPT team.

- **Langmuir Mixing** -- with Adrean Webb, Large, Peacock, Chini, Julien, Knobloch
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

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The mixed layer is not TOTALLY mixed. Fronts are common.

This weakly-stratified, fairly rapidly mixed region is active at the submesoscale...

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**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)
Submesososcale Features

- \( \text{Ro}=\mathcal{O}(1), \text{Ri}=\mathcal{O}(1) \) (Post-geostrophic adjustment of fronts). *Multiscale-multiphysics.*

- **Frontogenesis:** McWilliams et al., Klein et al.


- **Eddies and Instabilities?** Fox-Kemper et al., Molemaker et al.

- **Wave Effects?** McWilliams, Sullivan, Fox-Kemper

- **Climate Significance:** The Ocean and Atmosphere ‘Talk’ through the Mixed Layer, and Phytoplankton live there
Typical Stratification Permits
Two Types of Baroclinic Instability:

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

Typical Stratification Permits
Two Types of Baroclinic Instability:

- **Mesoscale** Eddies: O(100km) 1 month
- **SubMesoscale** Mixed Layer Eddies: O(1km) 1 day
Mesoscale and SubMesoscale are Coupled Together:

ML Fronts are formed by Mesoscale Straining.

Submesoscale eddies remove PE from those fronts.

Friday, March 26, 2010
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 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 $\xi/f = 0$ 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.
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 $|\overline{u''h''}|$ (lower panel) take the largest magnitude.

Horizontal fluxes are Mesoscale and tend to stir
Remixing the Mixed Layer Counts!

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

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**Friday, March 26, 2010**
Remixing the Mixed Layer Counts!

The vertical buoyancy flux in the ML ($<w'b'>$) without diurnal cycle is $4 \times$ less than with cycle (ML)
Overturning Schematic
Prototype: Mixed Layer Front Adjustment

Simple Spindown  

Plus, Diurnal Cycle and KPP

Note: initial geostrophic adjustment overwhelmed by eddy restratification
Overturning Schematic

Mixed Layer

z (m)

ML Base

Pycnocline

\[ \Delta y \]

\[ \Delta z \]

Eddy Buoy. Flux

Overturning Streamfunction

y (km)
Parameterization of Finite Amp. Eddies: Ingredients

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

- unbalanced, \( R_i = 0 \)
- balanced, \( R_i = 1 \)

\( N \)
Parameterization of Finite Amp. Eddies: Ingredients

Finite Amplitude

\[ N^2/f^2 \] vs. time (days)
Parameterization of Finite Amp. Eddies: Ingredients

Finite Amplitude

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

\[ \text{avg. pert. } V^2 \text{ in front} \]

- basin-avg. pert. KE
- linear predict. pert. KE
- initial mean KE: \( \frac{1}{2} (M^2 H/f)^2 \)
- avg. pert. \( V^2 \) in front
Parameterization of Finite Amp. Eddies: Ingredients

Finite Amplitude

Eddy Velocity Saturates

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

\[ \text{avg. pert. } \sqrt{v} \text{ in front} \]

- basin-avg. pert. KE
- linear predict. pert. KE.

\[ N^2 f^2 \]

0 2 4 6 8 10 12 14 16

0 50 100 150 200

0 10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^0

0 5 10 15 20 25 30

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Parameterization of Finite Amp. Eddies: Ingredients

Eddy Velocity Saturates

Near Mean KE

Finite Amplitude

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Parameterization of Finite Amp. Eddies: Ingredients

Finite Amplitude

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

Eddy Velocity Saturates

Near Mean KE

\( \tilde{z} H \)

\( N^2 \bar{H}^2 \)

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

\( \text{basin-avg. pert. KE} \)
\( \text{linear predict. pert. KE.} \)
\( \text{initial mean KE: } \frac{1}{2} (\bar{M}^2 H/f)^2 \)
\( \text{avg. pert. } \sqrt{\tilde{v}} \text{ in front} \)
Parameterization of Finite Amp. Eddies: Ingredients

Finite Amplitude

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

Eddy Velocity Saturates near mean KE

Eddy Fluxes are at nearly \( 1/2 \) the mean isopycnal slope
Parameterization of Finite Amp. Eddies: Ingredients

**Finite Amplitude**

- **Eddy Velocity Saturates**
- Near Mean KE

**Linear Solution** $<w'b'>$ for vert. structure.
- As in Branscome '83...

**Eddy Fluxes**
- Are at nearly 1/2 the mean isopycnal slope

- $(b'_{\text{rms}}/N^2)$ scale with $H$
- Initial mean KE: $1/2(M^2 H/f)^2$
- Linear predict. pert. KE.
- Basin-avg. pert. KE.

**Notes**
- $f$ = Coriolis parameter
- $N^2 = \frac{g}{H}$

**Additional Information**
- $w'$ = Vertical velocity
- $b'$ = Bidimensional component
- $\bar{v}$ = Average velocity
- $\sigma$ = Standard deviation

**Graphs**
- Time Series of $N^2 H^2$
- Kinetic energy over time
- Eddy fluxes vs. time

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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:

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

- Vertical fluxes always upward to restratify with correct extraction rate of potential energy:

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

$N^2$
What does it look like?

Parameterization (2d, 10km grid)

Submesoscale-Resolving (3d, 500m grid)

$N^2$

Mixed Layer

Overturning Streamfunction

Eddy Buoy. Flux

ML Base

Pycnocline
What does it look like?

Parameterization (2d, 10km grid)
9d16h from 2d parameterization

Submesoscale-Resolving (3d, 500m grid)
9d16h from 3d MITgcm (smoothed)
What does it look like?

Parameterization (2d, 10km grid)

11d18h from 2d parameterization

Submesoscale-Resolving (3d, 500m grid)

11d18h from 3d MITgcm (smoothed)

Overturning Streamfunction
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N^2

Friday, March 26, 2010
What does it look like?

Parameterization (2d, 10km grid)

Submesoscale-Resolving (3d, 500m grid)

16d00h from 2d parameterization

16d00h from 3d MITgcm (smoothed)

N^2
The Global Parameterization:

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

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

Account for equator by going to subinertial ML approx (Young 94)

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

Account for coarse res.

\[ E_b(k) \sim k^{-2} \rightarrow \Psi = \left[ \frac{\Delta x}{L_f} \right] \frac{C_e H^2 \mu(z)}{\sqrt{f^2 + \tau^{-2}}} \nabla \bar{b} \times \hat{z} \]

Obs. reveal (Hosegood et al., 2006): \[ L_f \sim R_d \]
Improves Restratiﬁcation after Deep Convection

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

Change of Time-Mean Boundary Layer Depth in POP
Bias Reduction in POP/CCSM
Mixed Layer Depth

RMS error: 16m reduced to 8m

Skewness: 2.4 reduced to 0.6
Submeso Eddy Conclusion:

Submesoscale features, and mixed layer eddies in particular, exhibit large vertical fluxes of buoyancy and tracer that until recently were ignored in climate models.

A parameterization of mixed layer eddy fluxes as an overturning streamfunction is proposed. The magnitude comes from extraction rate of potential energy, and the vertical structure resembles the 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, CCSM, MITgcm, and MOM.

4 Papers so far... fox-kemper.com/research
Images of Langmuir circulation windrows: (a) a photograph of Rodeo Lagoon in CA (from Szeri, 1996), (b) an image of the surface of Tampa Bay (courtesy of G. Marmorino, NRL, D.C.), and (c) the evolution of vortexes in a LES of Langmuir turbulence (McWilliams et al., 1997). Reproduced from Chini et al. (2008).
Langmuir, do we care?

Ming Li, Konstantin Zahnov, Chris Garrett

Maybe:

Maybe Not:
Waves + Wind != Wind

- Langmuir is ‘in’ KPP, but only based on wind
- Really Langmuir depends on both $u^*$ and $u_s$
- Is there data? Altimeters do both simultaneously

Leading Slope $\rightarrow$ Swell
Inverse Area $\rightarrow$ Capillaries
Thus, Local wind
Waves + Wind ≠ Wind

With wave period assumed to produce a peak at fully-developed waves (uniform period for now...)

\[ u^* \equiv \sqrt{\frac{\tau}{\rho}} \quad \quad u_s \approx \frac{\pi^3 H^2_s}{gT^3_s} \quad \quad La \equiv \sqrt{\frac{u^*}{u_s}} \]

Figure 2: Aviso merged satellite dataset from 11/12/05 to 5/27/08 was used to calculate the (a) average Langmuir number and (b) compare \(10|u^*|\) to \(|u_s|\)
Wave Model -- agree with Obs, plus frequency and direction

Figure 3: Calculation of inverse turbulent Langmuir number squared, \((La^{-1})^2\), (top) using NOAA WaveWatch III model global output data (bottom)

Figure 4: Climatology of \((La^{-1})^2\) (blue) based on zonal and seasonal averages (black) with summer seasonal data (red)

Provides wave period & direction: for better Stokes Drift
Satellite versus WW3 Model

Aviso Merged Satellite Dataset, 11/12/05–05/27/08

WaveWatch III Data-Assimilating Wave Model (rescaled to find surface wind-stress)

Stokes’ Drift is *sensitive* to wave period.

\[ u_s \approx \frac{\pi^3 H_s^2}{g T_w^3} \]

---

Li v Garrett (1997)

\[ F_r = \frac{w}{u_s} \approx u_s^{4/3} \]

\[ H_s \approx 0.6 \]

---

McWilliams v Sullivan (2000)

\[ \kappa \rightarrow \kappa' = \kappa_{0.08} \]

\[ u_s^2 \approx \frac{\pi^3 H_s^2}{g T_w^3} \]

---

Stokes’ Drift is sensitive to wave period.
A Simple Scaling for Langmuir Depth/Entrainment:
(Li & Garrett, 1997)

\[ Fr = \frac{\omega}{NH} \approx 0.6 \quad \omega \approx \frac{V}{1.5} \approx \frac{\sqrt{u^*u_s}}{1.5} \]

The Algorithm
Use \( Fr \) to determine \( H \)
If \( H \) is deeper than KPP Boundary Layer depth, use \( H \)

Large came up with clever choices for \( N, H \) that lead to a robust implementation in KPP
With these choices, \( H \) and BLD converge over time.
Wave Model—agree with Obs, plus frequency and direction

Figure 4: Climatology of \((La^{-1})^2\) (blue) based on zonal and seasonal averages (black) with summer seasonal data (red)
Assuming for a moment that we already know how Langmuir Circulations scale, then...

Let's try it in a model!
CCSM3.5 Impact: MLD

- With reasonable parameters, can produce deeper mixed layers
- This often reduces bias in some regions, e.g., ACC

August mixed layer depths.
CCSM3.5 Impact: CFCs

- With reasonable parameters, can affect CFCs
- This reduces bias in some regions, e.g., ACC versus WOCE
- Potentially Large impact, change as large as bias

CFC in CCSM & P14S WOCE observations.
Nuance--CCSM3.5 and CCSM4.0

CCSM4.0 did not have the same initial improvement!

S & T particularly bad

Interactions with submeso?
Remaining Problems in Langmuir...

- Demonstrated potential sensitivity and impact, so accuracy needed. It will require:
  - Prognostic Wave Model coupled to CCSM
  - Better Parameterization of Langmuir Circulation mixing
  - Better understanding of regimes of Langmuir scalings
Other Effects of Wind+Waves != Wind

- Different Drag
- Same Wind
Conclusions

The focus of physics for ocean modeling is moving again to smaller scales, pushing ahead of resolution.

From submesoscale to finescale, new significant couplings are being found.

While these processes and couplings are poorly understood, their affect on air-sea exchanges is estimable.

Progress on parameterizations will be fun, and should involve interaction with new observationalists, so speak up folks!
Extensions: Forward Cascade?

Eady and MLI

- Extraction from mean
- Eddy flux
- Ekman friction

Eady without ML

- Extraction from mean
- Eddy flux
- Ekman friction

Energy fluxes

\[ \times 10^{11} \]
Changes To Mixing Layer Depth in Eddy-Resolving Southern Ocean Model
Changes To Mixing Layer Depth in Eddy-Resolving Southern Ocean Model
The Scaling of MLIs

Mixed Layer Eddies (MLEs) begin as ageostrophic baroclinic instability of a front in the Mixed Layer: the Mixed Layer Instability (MLI)

MLI=infinitesimal
MLE=finite amplitude

\[
L_s = \frac{2\pi U}{|f|} \sqrt{\frac{1 + Ri}{5/2}} \approx 5.6 \frac{NH}{|f|}
\]

\[
\tau_s = \sqrt{\frac{54}{5}} \frac{\sqrt{1 + Ri}}{|f|} \approx 4.6 \frac{NH}{|f|}
\]

(Fastest growing modes of Stone 66, 70, 72)

See Boccaletti et al 07, Fox-Kemper et al 08 & Hosegood et al 06
The Scaling of MLEs

MLEs form from MLIs, but scale differently due to an inverse cascade.

See Fox-Kemper et al 08

(i) the relevant time scale $\Delta t$ is *advective*: the time it takes for an eddy to traverse the decorrelation length with typical eddy velocities, $V$, is

$$\Delta t \propto \Delta y / V; \quad (7)$$

(ii) the horizontal eddy velocity $V$ scales as the mean thermal wind $U$ (see Fig. 5):

$$V \propto U = \frac{M^2 H}{f}; \quad (8)$$

(iii) the vertical decorrelation length scales with the ML depth (see Fig. 6):

$$\Delta z \propto H; \quad \text{and} \quad (9)$$

(iv) fluid exchange occurs along a shallower slope (i.e., PE extracting) and proportional to the mean isopycnal slope (see Fig. 7):

$$\frac{\Delta z}{\Delta y} = \frac{1}{C} \frac{M^2}{N^2}, \quad C > 1 \quad (10)$$
Extensions: e.g., Hurricane Wake Recovery
Param vs. unforced model

0d03h from 2d parameterization

0d03h from 3d MITgcm (smoothed)
Param. Applies to Other Scenarios:
e.g., Deep Convection (versus Jones & Marshall)

Param gives same scaling, but...

Jones & Marshall 97

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Param. Applies to Other Scenarios:
e.g., Deep Convection (versus Jones & Marshall)

Vertical structure is different...