Eddies, Mixing and all that:
Ocean Parameterization Developments
from 4m to 400km

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Balance, Boundaries, and Mixing in the Climate Problem
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Climate Forecasts (IPCC/CMIP Runs) have a very coarse ocean gridscale (>100km)

Resolution of Ocean Component of Coupled IPCC models

Ocean Model Resolution (km)

1980 2000 2020 2040 2060 2080 2100

Year

10^2

10^0

10^-2

10^-4

1st Rossby Range (Chelton et al. 98)
Approx. Baroclinic Instability Length

fit to median res.

fit to finest res.

400km

This Talk

4m

mesoscale

submesoscale

Langmuir turbulence
Parameterization

Questions:

- How will we use them?
- Will the largest features be resolved?
- What needs parameterization?
- What dynamics dominate the resolved and parameterized scales?
Different Uses, Different Needs

- **MORANS** (e.g., typical IPCC/CMIP; >50km)
  - *Mesoscale Ocean Reynolds-Averaged Navier-Stokes*
  - No instabilities resolved, all instabilities to be parameterized

- **MOLES = SMORANS** (e.g., grid 5-50km)
  - *Mesoscale Ocean Large Eddy Simulation*
  - *Submesoscale Ocean Reynolds-Averaged Navier-Stokes*
  - Same Resolution, Different Parameterizations!

- **SMOLES = BLORANS** (e.g., grid 100m-1km)
  - *Submesoscale Ocean Reynolds-Averaged Navier-Stokes*
  - *Boundary Layer Ocean Reynolds-Averaged Navier-Stokes*

- **BLOLES (e.g., grid 1-5m)**
  - *Boundary Layer Ocean Large Eddy Simulation*
Anyone who doesn't take truth seriously in small matters cannot be trusted in large ones either.

--Albert Einstein

The Character of the Submesoscale

(Capet et al., 2008)

- Fronts
- Eddies
- $Ro = O(1)$
- $Ri = O(1)$
- Near-surface
- 1-10 km, days

Eddy processes often involve baroclinic instability (Boccaletti et al. '07, Haine & Marshall '98). Parameterizations of baroclinic instability?
Mixed Layer Eddy Restratiﬁcation

Estimating eddy buoyancy/density ﬂuxes:

$$\mathbf{u}'b' \equiv \Psi \times \nabla \bar{b}$$

A submeso eddy-induced overturning:

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

in ML only:

$$\mu(z) = 0 \text{ if } z < -H$$

For a consistently restratiﬁed:

$$w'b' \propto \frac{H^2}{|f|} \left| \nabla_{H} \bar{b} \right|^2$$

and horizontally downgradient:

$$u'Hb' \propto -\frac{H^2 \partial b}{|f|} \nabla_{H} \bar{b}$$
Physical Sensitivity of Ocean Climate to Submesoscale Eddy Restratification:

MLE implemented in CCSM (NCAR), CM2M & CM2G (GFDL)

Deep ML Bias reduced
From Fox-Kemper et al., 2011

NO RETUNING NEEDED!!!

Improves CFCs Passive tracer

Bias w/o MLE Bias with MLE
Sensitivity of Climate to Submeso: AMOC & Cryosphere Impacts

May Stabilize AMOC

Affects sea ice

NO RETUNING NEEDED!!!

These are impacts: bias change unknown

Figure 10: Wintertime sea ice sensitivity to introduction of MLE parameterization (CCSM+ minus CCSM−): January to March Northern Hemisphere a) ice area and b) thickness and July to September Southern Hemisphere c) ice area and d) thickness.
Langmuir Turbulence Parameterizations

On a list of the 50 most important things to fix in the ocean model, Langmuir is number 51.

--Bill Large
The Character of the Langmuir Scale

- Near-surface
- \( Ro >> 1 \)
- \( Ri < 1: \) Nonhydro
- 10–100m
- mins, hours
- \( w, u = O(10\text{cm/s}) \)
- Stokes drift
- Eqtns: Craik-Leibovich
- unused params exist

Image: NPR.org, Deep Water Horizon Spill
An Immature Improvement to Air-Sea BL Mixing by Langmuir Turbulence

Forced by wind and waves

i.e., Stokes drift & Eulerian Shear

Scalings from LES, Observations disagree

We used a 2-part approximation

1) McWilliams & Sullivan (01) additional OBL mixing (within mixed layer)
2) Li & Garrett (98) Langmuir mixing depth (entrainment)

Roughly comparable to other schemes, but crude & incompletely validated

Needs only $u^*$, $u_s$ to work
Langmuir Mixing
Forced by Climatology

(Dong et al. Observations)

CCSM3.5 with Langmuir

CCSM3.5 Control without Langmuir

(Generalized Turbulent Langmuir)²
Projection of $u^*$, $u_s$ into Langmuir Direction

$$La^2_t = \frac{|u^*|}{|u_s|} \left[ \frac{|u^*| + |u_s| \cos \theta}{|u_s| + |u^*| \cos \theta} \right]$$

Webb et al. 2011 (in prep)
Tricky: Misaligned Wind & Waves

Van Roekel et al. 2011 (submitted)
Tricky: Misaligned Wind & Waves

Van Roekel et al. 2011 (submitted)
Tricky: Misaligned Wind & Waves

Van Roekel et al. 2011 (submitted)
Tricky: Misaligned Wind & Waves

Van Roekel et al. 2011 (submitted)
Van Roekel, Fox-Kemper, Sullivan, Haney & Hamlington (2011)

\[
\frac{\left\langle w'^2 \right\rangle}{u_*^2 ML} = 0.6 \cos^2 (\alpha_{LOW}) \left[ 1.0 + \left( 3.1 L_{ap_{proj}} \right)^{-2} \right] + \left( 5.4 L_{ap_{proj}} \right)^{-4},
\]

\[
L_{ap_{proj}}^2 = \frac{|u_*| \cos(\alpha_{LOW})}{|u_s| \cos(\theta_{ww} - \alpha_{LOW})},
\]

\[
\alpha_{LOW} \approx \tan^{-1} \left( \frac{\frac{u_*}{u_s(0)\kappa} \ln \left( \left| \frac{H_{ML}}{z_1} \right| \right)}{\sin(\theta_{ww})} + \cos(\theta_{ww}) \right)
\]
Coupling between Langmuir and Submeso?

- Together?
- Separate?
**Multiscale**

- Langmuir & Submeso resolving LES
- 20km x 20km x 0.3 km
- Grid 4096 x 4096 x 128
- 5 x 5 x <1m resolution
- Compromises--wind, front, wave, size, etc

Diagram:
- Mixed layer
- Ocean surface
- Mixed layer base
- Density jump
- OCEAN INTERIOR
- \( U(z) \)
- \( B \)
- \( H \)
- \( U_s, u_* \)
- 30°
Coupling Langmuir to Submesoscale?

From Scratch... No interpolation!

LES, Near-Surf. Temp. No Stokes Drift

The Scales, and the Sim

Day 6.5 of a Submeso Resolving run

Vert. Velocity = w
The Scales, and the Sim

\[ f^2 < \left| f \frac{\partial v}{\partial z} \right| = M^2 < (3f)^2 \]

\[ Ro \approx 0.1 \]

\[ Ri < 1 \]
Wind & Fronts Only

No Stokes Drift

Surf. Temp (K)

Temp (K)

x-Avg. Temp

-0.015

+0.015

x-Avg. Temp
Wind & Fronts Only

No Stokes Drift

Surf. Temp (K)

\[ w^2 \text{ (m}^2/\text{s}^2) \leq (400m/\text{d})^2 \]
Wind &
Fronts
Only

No Stokes
Drift

Surf.
Temp (K)

$w^2 \text{ (m}^2/\text{s}^2\text{)}$

Sub-Grid TKE
Wind & Fronts Only

No Stokes Drift

Surf. Temp (K)

\[ w^2 \text{ (m}^2/\text{s}^2) \leq (300 \text{m/d})^2 \]
Wind & Fronts Only

No Stokes Drift

Surf. Temp (K)

\[ w^2 (m^2/s^2) < (200m/d)^2 \]
Wind & Fronts Only
No Stokes Drift

Mid-ML Temp (K)

Low-Pass $w^2$ (Submeso) 

$w^2 (m^2/s^2) < (200m/d)^2$
Wind & Fronts Only

No Stokes Drift

Mid-ML Temp (K)

$v^2 \ (m^2/s^2) < (2cm/s)^2 < (2000m/d)^2$
Wind, Fronts, & Stokes Drift
Wind, Fronts, & Stokes Drift

$w^2$ (m$^2$/s$^2$) $< (600m/d)^2$

Total $w^2$
Wind, Fronts, & Stokes Drift

Surf. Temp (K)

$w^2 \text{ (m}^2/\text{s}^2) < (600 m/d)^2$
Wind, Fronts, & Stokes Drift

Low-Pass $w^2$ (Submeso)

$w^2 (m^2/s^2) < (400m/d)^2$
Mid-ML Temp (K)

Low-Pass $w^2$ (Submeso)

$w^2 (m^2/s^2)$

Wind, Fronts, & Stokes Drift
Wind, Fronts, & Stokes Drift

Mid-ML Temp (K)

Low-Pass $u^2$ (Submeso)

$u^2 (m^2/s^2) < (2000 m/d)^2$
Filaments are hard to see! even at mid-ML depth
Filaments are hard to see! even at mid-ML depth
Different Scales in filaments without Stokes
Power Spectral Density of $w^2$: No Stokes

Near Surface

Mid Mixed Layer
Power Spectral Density of $w^2$: With Stokes
Conclusions

- Mesoscale, Submesoscale, and Langmuir scale phenomena all have a nontrivial affect on the global climate, thus need accurate parameterizations.

- Parameterizations are developed by comparison to higher-resolution models, with careful diagnosis of interesting couplings.

- These high resolution models not only reveal loss of balance (if it’s there), but also random coupling/mixing of disparate...
Extrapolate for historical perspective: The Golden Era of Subgrid Modeling is Now!

<===SG Models===>
Mesoscale Parameterizations

Researchers have already cast much darkness on this subject and if they continue their investigations we shall soon know nothing at all about it.

--Mark Twain
The Character of the Mesoscale

(Capet et al., 2008)

- Boundary Currents
- Eddies
- Ro = O(0.1)
- Ri = O(1000)
- Full Depth

Eddies strain to produce Fronts
100km, months

Eddy processes mainly baroclinic & barotropic instability. Parameterizations of baroclinic instability (GM, Visbeck...).
MOLES Turbulence Like Potential Enstrophy cascade, but divergent

2008: F-K & Menemenlis Revise Leith Viscosity Scaling, So that diverging, vorticity-free, modes are also damped
Leith

F-K&M

Makes viscosity a bit bigger, especially near Eq.
But matters a lot for stability!

**Figure 4.** Maximum Courant number, $w\Delta t/\Delta z$, for vertical advection. Gray line is from the *LeithOnly* integration and black line is from the *LeithPlus* integration.
It works here!
Even with irregular grid!
Mesoscale Eddy Parameterizations all have the form:

\[ \mathbf{u'} \mathbf{T'} = - \mathbf{M} \mathbf{\nabla} \mathbf{T'} \]

\[
\begin{bmatrix}
\mathbf{u'} \mathbf{T'} \\
\mathbf{v'} \mathbf{T'} \\
\mathbf{w'} \mathbf{T'}
\end{bmatrix} = -
\begin{bmatrix}
M_{xx} & M_{xy} & M_{xz} \\
M_{yx} & M_{yy} & M_{yz} \\
M_{zx} & M_{zy} & M_{zz}
\end{bmatrix}
\begin{bmatrix}
\mathbf{\bar{T}}_x \\
\mathbf{\bar{T}}_y \\
\mathbf{\bar{T}}_z
\end{bmatrix}
\]

With John Dennis & Frank Bryan, we took a POP0.1° Normal-Year forced model (yrs 16-20)
Added 9 Passive tracers--restored x,y,z @ 3 rates
Kept all the eddy fluxes for passive & active
Coarse-grained to 2°, transient eddies, tracers to \[\mathbf{M}\]
\[
\mathbf{u'} \mathbf{\tau'} = - \mathbf{M} \mathbf{\nabla} \mathbf{\tau}
\]

**Sym Part** = Anisotropic* Redi

\[
\begin{bmatrix}
\mathbf{u'} & \mathbf{\tau'} \\
\mathbf{v'} & \mathbf{\tau'} \\
\mathbf{w'} & \mathbf{\tau'}
\end{bmatrix}
= -
\begin{bmatrix}
K_{xx} & K_{xy} & \hat{x} \cdot \mathbf{K} \cdot \mathbf{\nabla} \mathbf{z} \\
K_{yx} & K_{yy} & \hat{y} \cdot \mathbf{K} \cdot \mathbf{\nabla} \mathbf{z} \\
\hat{x} \cdot \mathbf{K} \cdot \mathbf{\nabla} \mathbf{z} & \hat{y} \cdot \mathbf{K} \cdot \mathbf{\nabla} \mathbf{z} & \mathbf{\nabla} \mathbf{z} \cdot \mathbf{K} \cdot \mathbf{\nabla} \mathbf{z}
\end{bmatrix}
\begin{bmatrix}
\mathbf{\tau}_x \\
\mathbf{\tau}_y \\
\mathbf{\tau}_z
\end{bmatrix}
\]

**AntiSym Part** = Anisotropic* GM

\[
\begin{bmatrix}
\mathbf{u'} & \mathbf{\tau'} \\
\mathbf{v'} & \mathbf{\tau'} \\
\mathbf{w'} & \mathbf{\tau'}
\end{bmatrix}
= -
\begin{bmatrix}
0 & 0 & -\hat{x} \cdot \mathbf{K} \cdot \mathbf{\nabla} \mathbf{z} \\
0 & 0 & -\hat{y} \cdot \mathbf{K} \cdot \mathbf{\nabla} \mathbf{z} \\
\hat{x} \cdot \mathbf{K} \cdot \mathbf{\nabla} \mathbf{z} & \hat{y} \cdot \mathbf{K} \cdot \mathbf{\nabla} \mathbf{z} & 0
\end{bmatrix}
\begin{bmatrix}
\mathbf{\tau}_x \\
\mathbf{\tau}_y \\
\mathbf{\tau}_z
\end{bmatrix}
\]

Yellow \(\mathbf{K}\) ‘are’ horizontal stirring & mixing
Could you have guessed it?
Result: Strong Anisotropy Along/Across Isopycnals

Mixing:

Stirring:
Result: Strong Anisotropy Along/Across PV Grads.

Mixing direction

Either along PV contours or across

1rst Eigenvector

2nd Eigenvector

Across PV contours