From Climate to Kolmogorov – Simulations Spanning Upper Ocean Scales

Baylor Fox-Kemper

with

Sean Haney (ATOC), Adrean Webb (APPM), Scott Bachman (ATOC), Katie McCaffrey (ATOC), Keith Julien (CU-Boulder), Peter Hamlington (CU-Boulder), Luke Van Roekel (Northland College), Peter Sullivan (NCAR), Ramsey Harcourt (UW), Eric D’Asaro (UW), Jim McWilliams (UCLA), Mark Hemer (CSIRO)

URI GSO Physical Oceanography Seminar
Sponsors: NSF 1245944, 0934737, 0825614, NASA NNX09AF38G
Now with Rhode Island Ingredients!

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The Earth's Climate System is driven by the Sun's light (minus outgoing infrared) on a global scale.

Dissipation concludes turbulence cascades to scales about a billion times smaller.
Climate model resolution has been an issue...
And will be an issue for centuries to come!

What are the processes capable of spanning scales?

What unresolved physics should we worry about?
And will be an issue for centuries to come!

What are the processes capable of spanning scales?

What unresolved physics should we worry about?
1963: Smagorinsky Devises Viscosity Scaling, Energy Flow is Preserved, but order-1 gridscale Reynolds #: $Re^* = UL/\nu_*$

$$\nu_{*h} = \left( \frac{\Upsilon_h \Delta x}{\pi} \right)^2 \sqrt{\left( \frac{\partial u_*}{\partial x} - \frac{\partial v_*}{\partial y} \right)^2 + \left( \frac{\partial u_*}{\partial y} + \frac{\partial v_*}{\partial x} \right)^2}.$$
The Ocean is Vast & Diverse: just one spectral cascade?
So, what to do?

Climate modelling requires that we truncate the model grid at coarse resolution (albeit improving slowly).

Whatever resolution we can afford will leave some physics unresolved or partially-resolved, so we need subgrid closures!

The vast & diverse scales of motion in the ocean suggest that we cannot use a one-size-fits-all approach, e.g., a turbulent cascade of 3d turbulence.

So, we have to invent new subgrid closures repeatedly, parameterizing processes important at each gridscale.
What is a subgrid model?

Express the coarse-grain averages of quantities (including the subgrid effects), e.g.:

\[
\frac{\partial \tau}{\partial t} \quad \frac{\partial u}{\partial x} \quad \frac{\partial u \tau}{\partial x}
\]

As a function of the resolved coarse-grain fields

\[
\frac{\partial \tau}{\partial t} = \frac{\partial \bar{\tau}}{\partial t} \quad \frac{\partial u}{\partial x} = \frac{\partial \bar{u}}{\partial x} \quad \frac{\partial u \tau}{\partial x} = \frac{\partial \bar{u} \bar{\tau}}{\partial x} + \frac{\partial u' \tau'}{\partial x}
\]

Note that nonlinear terms require special treatment

These couple different scales, small talks to large
Climate: What is important?

- To approximate absorption, reemission, and redistribution of the Sun’s energy across the globe
- Need atmospheric chemistry (greenhouse gases) & clouds for absorption & reemission
- Need ocean (surface) as it exchanges
  - sensible heat
  - latent heat (evaporation, freezing, precipitation)
  - gasses
  - momentum
- Plus, ocean transports heat itself!
Except... Ocean Turbulence isn’t 3d Turbulence at the mesoscale

- The ocean is wide (10,000km)
- But not deep (4km)
  - Motions in upper 1km
  - Motions are largely 2d
- The layer of blue paint on a globe has roughly the right aspect ratio!
2d Turbulence Differs

1996: Leith Devises Viscosity Scaling, So that the Enstrophy Flow is Preserved

\[ \nu_\ast = \left( \frac{\Lambda \Delta x}{\pi} \right)^3 \left| \nabla_h \left( \frac{\partial u_\ast}{\partial y} - \frac{\partial v_\ast}{\partial x} \right) \right| \]
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...).
F-K & Menemenlis Revise Leith Viscosity Scaling, So that diverging, vorticity-free, modes are also damped

\[ \nu_* = \left( \frac{\Delta x}{\pi} \right)^3 \sqrt{\Lambda^6 |\nabla_h q_2 d|^2 + \Lambda_d^6 |\nabla_h (\nabla_h \cdot \mathbf{u}_*)|^2} \]

ECCO2: Estimating the Current Climate of the Ocean

Phase II uses this viscosity scaling.

Note how no obvious artifacts occur at the grid joints, despite variations in grid scale, etc.
Big, Deep (meso) interact with Little, Shallow (submeso)

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 lead to baroclinic instability.

Parameterizations of submesoscale baroclinic instability?


Physical Sensitivity of Ocean Climate to MLE: Mixed Layer Eddy Restratification Improves Mixed Layers

Bias w/o MLE

Improves CFCs (water masses)

Bias with MLE

Physical Sensitivity of Ocean Climate to MLE: Mixed Layer Eddy Restratification Improves Mixed Layers

The Character of the Langmuir Scale

- Near-surface
- $Ro \gg 1$
- $Ri \ll 1$: Nonhydro
- 1-10m
- 10s to mins
- $w, u = O(10 \text{cm/s})$
- Stokes drift
- Eqtns: Craik-Leibovich
- Params: McWilliams & Sullivan, 2000, etc.

Image: NPR.org, Deep Water Horizon Spill
Combining Data w/ LES scalings:

Where does energy for Southern Ocean mixing come from?

Langmuir (wave-driven) and Convective

But, we don’t have wave-driven mixing in climate models!!!

Generalized Turbulent Langmuir No., Projection of $u^*$, $u_s$ into Langmuir Direction

$$\left\langle \frac{w^2}{u_s^2} \right\rangle_{ML} = \frac{0.6 \cos^2(\alpha_{LOW}) [1.0 + (3.1 L a_{proj})^{-2} + (5.4 L a_{proj})^{-4}]}{u_s^2},$$

$$L a_{proj}^2 = \frac{|u_s| \cos(\alpha_{LOW})}{|u_s| \cos(\theta_{ww} - \alpha_{LOW})},$$

$$\alpha_{LOW} \approx \tan^{-1}\left(\frac{\sin(\theta_{ww})}{\frac{u_s}{u_s(0)\kappa} \ln \left(\frac{H_{ML}}{z_1}\right) + \cos(\theta_{ww})}\right).$$

A scaling for LC strength & direction!

Estimated Mixing with Harcourt
Second Moment Closure Model:

- Expands on implementation of Langmuir mixing of Kantha & Clayson (and Mellor-Yamada, etc).
- Allows waves to affect diffusivity and vertical momentum flux as well as energy sources...
- Consistent treatment of wave-wind misalignment
- ARGO profiles near summer solstice initial condition.
- Pure 1D mixing vs. solar & fluxes only -- No ocean circulation or eddy restratification, etc.

Harcourt--Evolving Mixed Layer Depth Results
(Simulated by M. Hemer, CSIRO)

Potential for improvement! (not all look so good...)

NO WAVES  WAVES  Nearby ARGO PROFILES (dots)
Including Wave-driven Mixing Deepens the Wintertime and S. Ocean Mixed Layer!

Well that was fun...

Lots of small turbulence affects the upper ocean on seasonal timescales!

But, why stop now?

How do these small processes affect each other?
Perform large eddy simulations (LES) of Langmuir turbulence with a submesoscale temperature front.

Use NCAR LES model to solve Craik-Leibovich equations (Moeng, 1984, McWilliams et al, 1997).

\[
\frac{\partial \rho}{\partial t} + \mathbf{u}_L \cdot \nabla \rho = \text{SGS}\\
\nabla \cdot \mathbf{u} = 0
\]

\[
\frac{\partial \mathbf{u}}{\partial t} + (\omega + f\hat{z}) \times \mathbf{u}_L = -\nabla \pi - \frac{g \rho \hat{z}}{\rho_0} + \text{SGS}
\]

**Computational parameters:**

- Domain size: 20km x 20km x -160m
- Grid points: 4096 x 4096 x 128
- Resolution: 5m x 5m x -1.25m

What about Langmuir-Submeso Interactions?

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P. E. Hamlington, L. P. Van Roekel, B. Fox-Kemper, K. Julien, and G. P. Chini. Langmuir-submesoscale interactions:
Descriptive analysis of multiscale simulations. In preparation,
Diverse types of interaction

Slide & Movies by Peter Hamlington

But, why stop now?
How do these small processes affect each other?

Weakly, except near strong fronts... stay tuned...
OK, Langmuir Turbulence can interact with larger scales...

What about the surface waves themselves, do they interact?
Waves (Stokes Drift Vortex Force) $\rightarrow$ Submeso, Meso Balanced Flows Change!

Initial Submeso Front

Contours: 0.1

Perturbation on that scale due to waves (Stokes Force)

Contours: 0.014

Many more wave-climate effects to come... stay tuned!
Conclusions

- Climate modeling is challenging partly due to the vast and diverse scales of fluid motions.

- In the upper ocean, horizontal scales as big as basins, and as small as meters contribute non-negligibly to the air-sea exchange.

- Process models, especially those spanning a whole or multiple scales, are a powerful tool in studying these connections and improving subgrid models.

- Based on present rates of increase of computing power, we will need these subgrid models for at least another century!
Extrapolate for historical perspective: The Golden Era of Subgrid Modeling is Now!

All papers at: fox-kemper.com/research