The role of the ocean surface—and its dynamics—in climate

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The Earth’s Climate System is forced by the Sun on a global scale (20,000-40,000km).

Next-gen. ocean climate models simulate globe to 10km: Mesoscale Ocean Large Eddy Simulations (MOLES)

Turbulence cascades to scales about 10 billion times smaller $O(1\text{mm})$.
Resolution will be an issue for centuries to come!

Here are the collection of IPCC models...

If we can’t resolve a process, we need to develop a parameterization or subgrid model of its effect.
Air-Sea Flux Errors vs. Data

Heat capacity & mode of transport is different in A vs. O
>90% of GW is oceanic, 10m 0=whole A

The Ocean Mixed Layer

Stommel’s Demon: ocean properties at depth set by deepest wintertime mixed layer & its properties: Subsurface T, S, CFCs, etc., affected. Use to check! 

From Argo float data courtesy C. de Boyer-Montegut
Figure 3: Impact of Langmuir mixing on the summer mean mixed layer depth (MLD; m) for both hemispheres. (a) shows the observation from de Boyer Montégut et al. (2004), updated to include the ARGO data to 2012. (c) shows the control run without Langmuir mixing. (d) - (h) are results with Langmuir mixing implemented in different parameterization schemes (See Table 2 for description). MLDs are averaged over Jul., Aug. and Sep. (JAS) for the Northern Hemisphere (NH) and Jan., Feb. and Mar. (JFM) for the Southern Hemisphere (SH). (b) shows the latitudinal distribution of root mean square errors.

Figure 4: As Fig. 3, but for the winter mixed layer depth. Averaged over JFM for the NH and JAS for the SH.

So, climate models aren’t perfect. Now what?

- Resolve more! (marginally possible)
- Make existing parameterizations better! (not today)
- Look for important neglected physics!
  - Submesoscale Eddies (100m resolution req’d)
  - Langmuir (Wave-Driven) Mixing (4m resolution req’d)
- Combinations?
The Character of the Submesoscale (NASA GSFC Gallery) (Capet et al., 2008)

Eddy processes often baroclinic instability Parameterizations = F-K, Ferrari et al (08-11).


http://oceancolor.gsfc.nasa.gov/
Submesoscale (1-10km) fronts & the eddies that form on them help restratify the boundary layer.

Mixing balances restratification.

Physical Sensitivity of Ocean Climate to Submesoscale Mixed Layer Eddy Restratification:

MLE implemented in NCAR, GFDL, Hadley, NEMO,...

Implements CFC uptake (Atlantic water masses)

With MLE Parameterization

Bias w/o MLE

A problem with **Mixed Layer Eddy Restratification**—Southern Ocean already too shallow!

Sallee et al. (2013) show a shallow S. Ocean MLD bias is in most* climate models even those with MLE parameterization!

*CMIP5 ensemble

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The Character of Langmuir (Wave-driven) Turbulence

- Near-surface
  - \( R \gg 1 \)
  - \( R < 1 \): Nonhydro
- 1-100m (H=L)
- 10s to 1hr
- \( \omega, u = O(10 \text{cm/s}) \)
- Stokes drift
- Eqtns: Craik-Leibovich, Wave-Averaged Equations
- Resolved routinely in 2170

Figure 1 Sketch showing the pattern of mean flow in idealized Langmuir circulation. The windrows may be 2m to 300m apart, and the cell form is roughly square (as shown). In practice the flow is turbulent, especially near the water surface, and the windrows (Figure 2) amalgamate and meander in space and time. Bands of bubbles or buoyant algae may form within the downward-going (or downwelling) flow (see Figure 3).
Wave-Averaged Eqtns:
Stokes Drift Affects Slower Phenomena

- Formally a multiscale asymptotic equation set:
  - 3 classes: Small, Fast; Large, Fast; Large, Slow
  - Solve first 2 types of motion in the case of limited wave steepness, irrotational $\rightarrow$ Deep Water Waves!
  - Average over deep water waves in space & time,
  - Arrive at Large, Slow equation set with wave effects

In these equations all Wave Effects involve the Stokes Drift

$$La_t^2 = \frac{u^*}{u_s}$$

Friction Velocity

$$u^* = \sqrt{\tau / \rho}$$

Craik & Leibovich 1976; Gjaja & Holm 1996; McWilliams et al. 2004
Waves Provide Stokes Drift

& Stokes Drift drives Langmuir Turbulence

Stokes: Compare the velocity of wave trajectories vs. Eulerian velocity; leading difference = Stokes:

Monochromatic:

Wave Spectrum:

\[ u^S = \frac{8\pi^3 a^2 f^3}{g} e^{\frac{8\pi^2 f^2}{g^2} z} \]

\[ u^S = \frac{16\pi^3}{g} \int_0^\infty \int_{-\pi}^{\pi} (\cos \theta, \sin \theta, 0) f^3 S_{\theta}(f, \theta) e^{\frac{8\pi^2 f^2}{g^2} z} d\theta df. \]

Turbulent Langmuir #

\[ L \alpha_t^2 = \frac{u^*}{u_S} \]


To quantify Langmuir Turb. effects on climate: 3 WAYS

1) From OBSERVATIONS, estimate wave effects on key parameters ($\langle \omega^2 \rangle$, sources of energy) using scalings from Large Eddy Simulations. MODEL INDEPENDENT

2) OFFLINE 1d mixing with waves parameterized, mixing into observed Argo profiles, reanalysis winds, waves, cooling. ROBUST TO MODEL ERRORS

3) In a climate model, *add in a wave forecast model as a new component in addition to atmosphere, ocean, ice, etc.*, use this to drive parameterizations of wave mixing in ocean component. FEEDBACKS PRESENT

No Retuning! All coefficients from LES
1) Observations obey a particular scaling for \( \langle w^2 \rangle \! \\

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Including Stokes-driven Mixing (Harcourt 2013) Deepens the Winter Mixed Layer about 30%!


Waves can be dominant source of energy for OSBL mixing!

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Climate Model Parameterization based on Large Eddy Simulations of Langmuir Turbulence. Tricky: Misaligned Wind & Waves

Vertical Velocity (m/s)

Tricky: Misaligned Wind & Waves

The form and orientation of Langmuir cells for misaligned winds and waves.
Tricky: Misaligned Wind & Waves

Langmuir Mixing in KPP for use in CESM1.2


- WaveWatch-III (Stokes drift) <-> POP2 (U, T, H_{BL})
- CORE2 interannual forcing (Large and Yeager, 2009), or fully coupled climate
- 4 IAF cycles; average over last 50 years for climatology (over 200 years total)

Enhancement factor to vertical velocity scale \( W \)

1) Assume aligned wind and waves

\[ \mathcal{E} = \sqrt{1 + 0.08La_t^{-4}} \]

\[ \mathcal{E} = \sqrt{1 + (3.1La_t)^{-2} + (5.4La_t)^{-4}} \]

\[ La_t^2 = \frac{|u_*|}{|u_s(0)|} \]

\[ R_i b = \frac{d [b_r - b(d)]}{\langle u_r \rangle - \langle u(d) \rangle^2 + U_t^2 + |u_s(0)|^2} \]

Revise

Wave Mixing in CESM: Reduces MLD Errors

Table 3: Root mean square difference (m) of summer and winter mean mixed layer depth in comparison with observation (de Boyer Montégut et al. (2004), updated to include the ARGO data to 2012).\(^a\)

<table>
<thead>
<tr>
<th>Case</th>
<th>Global</th>
<th>Summer</th>
<th>30°S-30°N</th>
<th>Global</th>
<th>Winter</th>
<th>30°S-30°N</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTRL</td>
<td>10.62 (13.40)</td>
<td>17.24 (21.73)</td>
<td>5.38 (6.71)</td>
<td>43.85 (45.50)</td>
<td>57.19 (56.53)</td>
<td>12.57 (16.16)</td>
</tr>
<tr>
<td>MS2K</td>
<td>15.37</td>
<td>15.47</td>
<td>17.03</td>
<td>119.91</td>
<td>171.92</td>
<td>40.31</td>
</tr>
<tr>
<td>SS02</td>
<td>36.79</td>
<td>63.83</td>
<td>7.54</td>
<td>99.32</td>
<td>164.34</td>
<td>17.39</td>
</tr>
<tr>
<td>VR12-AL</td>
<td>9.06</td>
<td>13.47</td>
<td>6.49</td>
<td>40.45</td>
<td>50.33</td>
<td>14.52</td>
</tr>
<tr>
<td>VR12-MA</td>
<td>8.73 (11.83)</td>
<td>12.65 (18.13)</td>
<td>6.61 (7.52)</td>
<td>40.99 (42.02)</td>
<td>51.78 (50.78)</td>
<td>14.23 (15.67)</td>
</tr>
<tr>
<td>VR12-EN</td>
<td>8.95</td>
<td>10.52</td>
<td>8.91</td>
<td>41.94</td>
<td>52.98</td>
<td>19.58</td>
</tr>
</tbody>
</table>

\(^a\) Numbers shown in the parentheses are for the fully coupled experiments.


Despite MLD bias increase in near Equator—better ventilation and subsurface effects when Langmuir is included, even near Equator!

Wave Mixing in CESM Improves Subsurface Properties & Stommel’s Demon!

So, we’ll quantify Langmuir effects on climate

1) From OBSERVATIONS, estimate wave effects on key parameters (<w^2>, sources of energy) using scalings from Large Eddy Simulations. MODEL INDEPENDENT

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3) In a climate model, *add in a wave forecast model as a new component in addition to atmosphere, ocean, ice, etc.*, use this to drive parameterizations of wave mixing in ocean component. FEEDBACKS PRESENT

No Retuning! All coefficients from LES
Something Else?

- Including submesoscale restratification in climate models improves the boundary layer.
- Including wave-driven (Langmuir) mixing in climate models improves the boundary layer.

- But, fundamental physics remains!
- What if these are combined? What interactions?
- How do Stokes effects change submesoscale?
- Fronts? Geostrophic Instabilities? Symmetric Instabilities?
Dimensionless Boussinesq Eqtns.
Spanning Global to Stratified Turbulence
following McWilliams (85)

\[
\begin{align*}
\text{Ro} \left[ v_{i,t} + v_j v_{i,j} \right] + \frac{M_{\text{Ro}}}{Ri} w v_{i,z} + \epsilon_{ij} v_j &= -M_{\text{Ro}} \pi_i, \\
\alpha^2 \left[ w_{,t} + v_j w_{,j} + \frac{M_{\text{Ro}}}{RoRi} w w_{,z} \right] &= -\pi, + b + \frac{\alpha^2}{ReRi} w_{,jj} \\
b_{t} + v_j b_{,j} + \frac{M_{\text{Ro}}}{RoRi} w b_{,z} + w &= 0 \\
v_{j,j} + \frac{M_{\text{Ro}}}{RoRi} w_z &= 0 \\
\end{align*}
\]

\[
\begin{align*}
\text{Re} &= \frac{UL}{\nu} \quad \text{Ro} = \frac{U}{fL} \quad \text{Ri} = \frac{N^2}{(U,z)^2} \quad \alpha = \frac{H}{L} \\
M_{\text{Ro}} &= \max(1, \text{Ro}) \quad \nu = \text{horiz. vel.} \quad w = \text{vert. vel.}
\end{align*}
\]
Wave-Averaged Equations

following Lane et al. (07), McWilliams & F-K (13) and Suzuki & F-K (15)
(for horizontally uniform Stokes drift)

\[ \varepsilon = \frac{V^s H}{fLH_s} \]
\[ v_j^L = v_j + v_j^s \]

Lagrangian geostrophic!

\[ \text{nonhydrostatic!} \]

Plus boundary conditions

LAGRANGIAN (Eulerian+Stokes) advection & Coriolis

Stokes shear force is NEW *nonhydrostatic* term in Vert. Mom.


Perform large eddy simulations (LES) of Langmuir turbulence with a submesoscale temperature front. Use NCAR LES model to solve Wave-Averaged Eqtns.  

2 Versions:
1 With Waves & Winds
1 With only Winds

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

What’s plotted are surfaces of large vert. velocity, colored by temperature.

Diverse types of interaction

What are some direct effects of waves on larger scales?

**Thermal Wind Balance**

\[ f \times \frac{\partial v}{\partial z} = -\nabla b \]

Becomes **Lagrangian Thermal Wind Balance**

\[ f \times \frac{\partial}{\partial z} (v + v_s) = f \times \frac{\partial v_L}{\partial z} = -\nabla b \]

Now the temperature gradients govern the Lagrangian flow, not the Eulerian!

Stokes Shear Force:
Mechanism for Langmuir circulations & Stokes effects on fronts!
Flow directed along Stokes shear = downward force

\[
\frac{\alpha^2}{Re Ri} \left[ w,_{t} + v_{j}^{L} w,_{j} + \frac{M_{Ro}}{Ro Ri} w w,_{z} \right] = -\pi,_{z} + b - \varepsilon v_{j}^{L} v_{j},_{z} + \frac{\alpha^2}{Re Ri} w,_{jj}
\]

Wave-Averaged Equations following Lane et al. (07), McWilliams & F-K (13) and Suzuki & F-K (15) (for horizontally uniform Stokes drift)

\[ Ro \left[ v_{i,t} + \frac{\nu_j^L v_{i,j}}{R_i} \right] + \frac{M_{Ro}}{R_i} \nu v_{i,z} + \varepsilon_{izj} \frac{\nu_j^L}{\nu_j^s} = -M_{Ro} \pi_i + \frac{Ro}{Re} \nu_{i,jj} \]

\[ \frac{\alpha^2}{R_i} \left[ \nu_{,t} + \frac{\nu_j^L \nu_{,j}}{ReRi} \nu \nu_{,z} \right] = -\pi_{,z} + b - \varepsilon \nu_{ij}^L \nu_{ij}^s + \frac{\alpha^2}{ReRi} \nu_{jj} \]

\[ b_{t} + \frac{\nu_j^L b_{,j}}{ReRi} - \nu b_{z} + \nu = 0 \]

\[ \nu_{j,j} + \frac{M_{Ro}}{ReRi} \nu_{z} = 0 \]

LAGRANGIAN (Eulerian+Stokes) advection & Coriolis

Stokes shear force is NEW *nonhydrostatic* term in Vert. Mom.


Stokes shear force directly affects the (sub)mesoscale!!

\[ \frac{\varepsilon}{Ro} \]

\[ \varepsilon = \frac{V_s H}{f L H_s} \]

\[ Ro = \frac{U}{f L} \]

Example: Stokes Shear Force on Submesoscale Cold Filament

\[
\frac{\alpha^2}{Ri} \left[ \frac{w_t + v_j^L w_{,j}}{Ro} + \frac{M_{Ro}}{RoRi} w w_{,z} \right] = -\pi z + b - \varepsilon v_j^L v_j^s + \frac{\alpha^2}{ReRi} w_{,ij}
\]

Waves Give 30–40% of Power Produced at Front
Are Fronts and Filaments different with Stokes shear force?

\[
\frac{\alpha^2}{R_i} \left[ w, + v_j^L w, + \frac{M_{Ro}}{RoR_i} w, z \right] = -\pi, + b - \varepsilon v_j^L v_j, z + \frac{\alpha^2}{ReR_i} w, jj
\]

N. Suzuki and BFK. Surface Wave Stokes Forces Influence Frontogenesis, JPO, in prep, 2015.


Analytic Stability Criterion: Stokes Affects Submesoscale Instability?

- Charney-Stern-Pedlosky found criteria for quasigeostrophic baroclinic instability (i.e. Mixed Layer Eddies)

- Hoskins (1974) criterion: symmetrically unstable fronts must have $\nabla \times \mathbf{v} > 0$

- Haney et al extend both results to flows in Lagrangian (i.e. with Stokes drift) thermal wind balance.
  
  - Minor Stokes effects on Mixed Layer Eddies
  
  - Major Stokes effects on Symmetric Instabilities

\[ fQ < 0 \Rightarrow SI \]

**Realistic amounts of Stokes Drift strongly affect Symmetric Instability!**

- **PV in Lagrangian TW affected by Stokes**
  - \( Ri = 0.5 \)
  - Unstable to SI all depths Without Stokes

- **PV in Lagrangian TW affected by Stokes**
  - \( Ri = 2 \)
  - Stable to SI all depths Without Stokes

**Stokes Stabilized**

- Isopycnals
- \(- - \) PV=0

Cross front velocity for the fastest growing mode

So, if negative PV indicates likely regions of symmetric instability—
Surface Waves STRONGLY affect SI!
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 and climate.

- The Submeso & Langmuir scales are dynamically interesting, as non-hydro. & ageostrophic effects begin to dominate.

- The effects of the Stokes forces on boundary layer and submesoscale dynamics are under-appreciated.

- Stokes forces affect fronts, filaments, and instabilities at the submesoscale as well as driving Langmuir turbulence on smaller scales.

- All papers at: fox-kemper.com/pubs
Wind-wave dependent processes in the coupled climate system
Towards coupled wind-wave-AOGCM models


More to come!
All papers at fox-kemper.com
How well do we know Stokes Drift? <50% discrepancy

RMS error in measures of surface Stokes drift, 2 wave models (left), model vs. altimeter (right)

Year 2000 data & models

Why? Vortex Tilting Mechanism

In CLB: Tilting occurs in direction of $u_L = V + V_s$

Misalignment enhances degree of wave-driven LT

Figure 17. Temporal and zonal median and interquartile range of $La_i$ and $La_{proj}$ for a realistic simulation of 1994–2002 using Wave Watch III.

Figure 1 Sketch showing the pattern of mean flow in idealized Langmuir circulation. The windrows may be 2 m to 300 m apart, and the cell form is roughly square (as shown). In practice the flow is turbulent, especially near the water surface, and the windrows (Figure 2) amalgamate and meander in space and time. Bands of bubbles or buoyant algae may form within the downward-going (or downwelling) flow (see Figure 3).
Data + scaling laws consistent with preceding Southern Ocean data to determine available mixing energy

So, waves are likely to drive mixing via Stokes drift (combines with cooling & winds)

A scaling for LC strength & direction!

Enough to use in a climate model

When the Stokes drift and geostrophic flow are aligned, the anti-Stokes flow yields reduced Eulerian shear.

Less Eulerian shear near the surface results in lower growth rates and wavenumbers for GI.