Effects of Ocean Surface Waves:
On Turbulence, Climate, and Frontogenesis

Expanding on past work with:
Jim McWilliams (UCLA), Peter Hamlington (CU-Boulder), Eric D’Asaro & Ramsey Harcourt (UW), Luke Van Roekel (LANL), Adrean Webb (TUMST), Keith Julien (CU-APPM), Greg Chini (UNH), Peter Sullivan (NCAR), Mark Hemer (CSIRO)

Friday, 13/01/16
16:00-17:00

Baylor Fox-Kemper
with Nobuhiro Suzuki
(Brown University), Qing Li (Brown), Sean Haney (UCSD)

Reading University NCAS Seminar, 11/3/16
Sponsors: NSF 1258907

Weather, Atmosphere
Fast
Ocean, Climate
Slow
3.4m of ocean water has same heat capacity as the WHOLE atmosphere

ECCO Movie: Chris Henze, NASA Ames
Weather, Atmosphere
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The Ocean Mixed Layer

Mixed Layer Depth (Δ density=0.001) in month 1

Stommel's Demon: ocean properties at depth set by deepest wintertime mixed layer & its properties
From Argo float data courtesy C. de Boyer-Montegut
We Will Examine the Effects of Surface Waves on:

- Boundary Layer Turbulence (wave-driven or Langmuir Turbulence)
- Climate through Langmuir Turbulence (via MLD changes)
- Submesoscale Fronts & Instabilities within the Mixed Layer (Stokes forces and Langmuir coupling)
Surface Waves are...

Fast, small, irrotational solutions of the Boussinesq Equations

Have a Stokes drift depending on sea state (wave age, winds)


Wave-Averaged Equations following Holm (96), Lane et al. (07), McWilliams & F-K (13), and Suzuki & F-K (16)

Coupling Depends on Stokes drift—WAVE effects in YELLOW

**Boundary conditions, plus:**

\[
\begin{align*}
\alpha^2 \left[ w_{,t} + v^L_j w_{,j} + \frac{M_{Ro}}{RoRe} w w_{,z} \right] &= -\pi_{,z} + b - \varepsilon v^L_j v^S_j,_{z} + \frac{\alpha^2}{ReRi} w_{,jj} \\
\frac{\alpha^2}{RoRe} w_{,t} + v^L_j w_{,j} + \frac{M_{Ro}}{RoRe} w b_z &= \frac{1}{Pe} b_{,jj} \\
v_{j,j} + \frac{M_{Ro}}{RoRe} w_{,z} &= 0 \\
\end{align*}
\]

**Lagrangian** geostrophic

\[
\varepsilon v^L_j = -M_{Ro} \pi_{,i} + \frac{Ro}{Re} v_{i,jj}
\]

**Re** = \( \frac{UL}{\nu} \)  \quad **Ro** = \( \frac{U}{fL} \)  \quad **Ri** = \( \frac{N^2}{(U_z)^2} \)  \quad \alpha = \frac{H}{L}  \quad M_{Ro} \equiv \max(1, Ro)

---


3 Wave Effects, 1: Lagrangian Advection:
Particles, tracers, momentum flow with Lagrangian, not Eulerian flow

\[ Ro \left[ v_{i,t} + v_{j}^{L} v_{i,j} \right] + \frac{M_{Ro}}{Ri} w v_{i,z} + \epsilon_{izj} v_{j}^{L} = -M_{Ro} \pi_{i} + \frac{Ro}{Re} v_{i,jj} \]

\[ \frac{\alpha^{2}}{Ri} \left[ w_{,t} + v_{j}^{L} w_{,j} + \frac{M_{Ro}}{RoRi} w w_{,z} \right] = -\pi_{,z} + b - \epsilon v_{j}^{L} v_{j,z} + \frac{\alpha^{2}}{ReRi} w_{,jj} \]

\[ b_{t} + \frac{M_{Ro}}{RoRi} w b_{z} = \frac{1}{Pe} b_{,jj} \]

Adding a Stokes advection term converts total to Lagrangian advection

\[ v_{j}^{L} = v_{j} + v_{j}^{S} \]

Lagrangian  Eulerian  Stokes

3 Wave Effects, 2: Lagrangian Coriolis:

Particles, tracers, momentum flow with Lagrangian, not Eulerian flow—Experience Coriolis force during this motion

\[
Ro \left[ v_{i,t} + v^L_j v_{i,j} \right] + \frac{M_{Ro}}{Ri} wv_{i,z} + \epsilon_{izj} v^L_j = -M_{Ro} \pi_{,i} + \frac{Ro}{Re} v_{i,\dddot{j}}
\]

\[
\frac{\alpha^2}{Ri} \left[ w_{,t} + v^L_j w_{,j} + \frac{M_{Ro}}{RoRi} ww_{,z} \right] = -\pi_{,z} + b - \varepsilon v^L_j v^S_j,_{z} + \frac{\alpha^2}{ReRi} w_{,\dddot{j}}
\]

\[
b_{,t} + v^L_j b_{,j} + \frac{M_{Ro}}{RoRi} wb_{z} = \frac{1}{Pe} b_{,\dddot{j}}
\]

Adding a Stokes Coriolis term converts total to Lagrangian

\[ v^L_j = v_j + v^S_j \]

Lagrangian Eulerian Stokes

3 Wave Effects, 3: Stokes Shear Force and the CL2 mechanism for Langmuir circulations

Flow directed along Stokes shear=downward force

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

\( \varepsilon \gg 1 \) is "wavy hydrostatic"

\[
\frac{\alpha^2}{Ri} \left[ w_{,t} + \nu_j^L w_{,j} + \frac{M_{Ro}}{RoRi} ww_{,z} \right] = -\pi_{,z} + b - \varepsilon \nu_j^L \nu_{j,z} + \frac{\alpha^2}{ReRi} w_{,ij}
\]

The Character of Langmuir Turbulence

- Near-surface
  - Ro >> 1
  - Ri < 1: Nonhydro
  - 1-100m (H=L)
  - 10s to 1hr
  - w, u = O(10cm/s)
  - Stokes drift
- Eqtns: Wave-Averaged
- Params: McWilliams & Sullivan, 2000, Van Roekel et al. 2011
- Resolved routinely in 2170
Typical effect: Downward Force for down-Flow Stokes Drift

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

To quantify Langmuir Turb. effects on climate: 3 WAYS

1) From OBSERVATIONS, estimate wave effects on key parameters ($<\omega^2>$, 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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No Retuning! All coefficients from LES
Data + Large Eddy Simulation for scaling laws, Southern Ocean data to determine available mixing energy

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

Turbulent Langmuir number = sqrt(wind/waves)

Including Stokes-driven Mixing should deepen the Mixed Layer!


As estimated with: Argo-observed stratification, modeled waves, an LES-validated mixing parameterization, and observed winds, solar, latent, etc.
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Technical Note

User manual and system documentation of WAVEWATCH III™ version 3.14 †

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Something that happens often with waves:  
**Tricky: Misaligned Wind & Waves**


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Langmuir Mixing in KPP for use in CESM1.2


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

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

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

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

Revise Enhancement factor to vertical velocity scale \( W \)

Aligned wind and waves

Langmuir Mixing in Climate: Boundary Layer Depth Improved

<table>
<thead>
<tr>
<th>Case</th>
<th>Summer Global</th>
<th>Summer South of 30°S</th>
<th>Summer 30°S-30°N</th>
<th>Winter Global</th>
<th>Winter South of 30°S</th>
<th>Winter 30°S-30°N</th>
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</thead>
<tbody>
<tr>
<td>CTRL</td>
<td>10.62±0.27</td>
<td>17.24±0.48</td>
<td>5.38±0.14</td>
<td>43.85±0.38</td>
<td>57.19±0.76</td>
<td>12.57±0.28</td>
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<tr>
<td></td>
<td>(13.40±0.19)</td>
<td>(21.73±0.32)</td>
<td>(6.71±0.09)</td>
<td>(45.50±0.40)</td>
<td>(56.53±0.59)</td>
<td>(16.16±0.29)</td>
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<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±0.30</td>
<td>12.65±0.47</td>
<td>6.61±0.22</td>
<td>40.99±0.37</td>
<td>51.78±0.65</td>
<td>14.23±0.30</td>
</tr>
<tr>
<td></td>
<td>(11.83±0.29)</td>
<td>(18.13±0.62)</td>
<td>(7.52±0.16)</td>
<td>(42.02±0.39)</td>
<td>(50.78±0.67)</td>
<td>(15.67±0.35)</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) % Summer Change

b) % Winter Change


Subsurface Temperature: Improved vs. Observations with Langmuir

Equatorial (improves despite worse mean BLD)

Global

Southern Hem.

Northern Hem.

DASHED = LANGMUIR
SOLID = NO LANGMUIR

Root-Mean-Squared Error = RMSE (°C)

Ocean Uptake: Chlorofluorocarbons (manmade pollutant, detectable & known source)

Improved vs. Observations with Langmuir Mixing

So, we’ll quantify Langmuir effects on climate

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No Retuning! All coefficients from LES
Mid-way Conclusions

- Stokes forces may accelerate upper ocean mixing, leading to a wind-wave-convective turbulence driven partly by Stokes forces: Langmuir turbulence.

- Three effects of Stokes drift are important: Stokes Advection, Stokes Coriolis, and Stokes Shear Force.

- The Stokes Shear Force enhances downward and upward velocities in boundary layer turbulence.

- Including Langmuir mixing in climate models improves the climate model MLD, T, and uptake of CFCs.

- All papers at: fox-kemper.com/pubs
The Character of the Submesoscale

(Capet et al., 2008)

- Fronts
- Eddies
- Ro=O(1)
- Ri=O(1)
- near-surface (H=100m)
- 1-10km, days

Eddy processes often baroclinic instability

Parameterizations = BFK et al (08-11).


LES of Langmuir-Front Interactions?

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

Diverse types of interaction

What's plotted are surfaces of large vert. velocity, colored by temperature.
Stokes force makes small-scale Turbulence stronger

With Stokes Forcing

More Downward Momentum Mixing
with Stokes Drift Forcing/Langmuir Turbulence

Without Stokes Forcing

More Downward Momentum Mixing
with Stokes Drift Forcing/Langmuir Turbulence
As we’ve seen, waves can drive turbulence that affect larger scales indirectly. This is expected.

What about direct effects of waves on larger scales?

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

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 not the Eulerian!

The Eulerian response to Stokes is often to cancel it out! (Anti-Stokes flow, Lab: Monismith et al., Obs: Lentz et al.)

Like Eady, but with Lagrangian Thermal Wind Background State

\[ U + U^S = -\Psi_y^L , \text{ such that } U = -\Psi_y , \text{ and } \]

\[ V + V^S = \Psi_x^L = 0 . \]

Fig. 2. The background flow with arbitrary \( \theta \) (the angle between the Stokes drift and the geostrophic flow) and a prescribed exponential Stokes drift \( U^S, V^S \) profile. The geostrophic flow \( U^G \), corresponding to the imposed buoyancy gradient, is shown with blue arrows.
Analytic & Numerical Wavy Submesoscale Stability: Geostrophic Instabilities

Charney, Stern, Pedlosky criteria (appropriately generalized) apply:

- Instability allowed if:

1) $Q_Y^L$ changes sign in the interior of the domain;
2) $Q_Y^L$ is the opposite sign as $U_z^L$ at $z = 0$;
3) $Q_Y^L$ is the same sign as $U_z^L$ at $z = -H$;
4) $U_z^L$ has the same sign at $z = -H$ and $z = 0$.

\[
Q^L = \nabla_H^2 \Psi + \beta Y + \partial_z \left( \frac{f_0^2}{N^2} \frac{\Psi_z^L}{B_z} \right)
\]

Streamfunctions with and w/o Stokes

$U + U^S = -\Psi_y^L$, such that $U = -\Psi_y$, and $V + V^S = \Psi_x^L = 0$.

For typical conditions, the Stokes effect amounts to a small change in geostrophic instability (mixed layer eddy) growth rates.
Hoskins (1974) showed that if a front in thermal wind balance is symmetrically unstable, the PV must be anticyclonic.

Haney et al extend Hoskins’ analysis to flows in Lagrangian thermal wind balance in the special case that the Stokes shear is constant.

In the absence of Stokes drift, this is equivalent to the familiar criteria on Richardson Number, with Stokes drift is distinct.

\[ fQ = f^2N^2 - M^4 - \left( fM^2U_z \right) < 0. \]

Fig. 1. A schematic of the (a) downfront and (b) upfront Stokes drift scenarios. The blue lines show isopycnals, with darker blue indicating denser water. The red lines show surfaces of constant downfront absolute Eulerian momentum, with darker red indicating greater momentum. The perturbation equations are written from the perspective of the lower of the two parcels. A change of all signs would be from the perspective of the upper parcel and have the same stability. For example, in (b) the lower parcel moves to the right ($v' > 0$) along an isopycnal and brings with it lower downfront momentum than its surroundings ($u' < 0$). This exerts an acceleration in the cross-front $v'$ direction due to the Coriolis force that further enhances the initial perturbation ($v' > 0$). In both cases, $Ri = 0.5$. Lines of constant buoyancy and absolute momentum are only parallel when $Ri = 1$. 

**Ri < 1 ⇒ SI**

**Numerical Wavy Stability Criterion:**

**Symmetric Instability**

\[ \text{PV} = 0 \]

---

\[ \text{Isopycnals} \]

---

\[ \text{PV}=0 \]

---

Cross front velocity for the fastest growing mode

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**fQ<0 ⇒ SI**
So, if $fQ < 0$ indicates likely regions of symmetric instability—Surface Waves STRONGLY affect SI!

Stokes force directly affects larger scales?

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

\[
\varepsilon = \frac{V^s H}{f L H_s}
\]

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

Are Fronts and Filaments different with Stokes shear force?

\[
\frac{\alpha^2}{R_i} \left[ w_t + v^L_j w, j + \frac{M_{Ro}}{RoR_i} w, w, z \right] = -\pi, z + b - \varepsilon v^L_j v^{s^j, z} + \frac{\alpha^2}{ReR_i} w, j
\]

Run Including Stokes Forces

Run Without Stokes Forces


velocity in the x-direction - the horizontal mean (ms$^{-1}$) at $z = -11.25$m

buoyancy - the horizontal mean (m s$^{-2}$) at $z= -11.25m$

vertical velocity (ms$^{-1}$) at z = -11.25m

Wind, Waves

Stokes Shear Force in Budgets for Overturning

- 2nd Largest Source in Ang. Momentum (26% of buoyancy)
- 3rd Largest Source in Overturning KE (24% of buoyancy)
- 2nd Largest Source of Overturning Vorticity (44% of buoyancy)

\[
\frac{\alpha^2}{\text{Ri}} \left[ w_t + v_j^L w_j + \frac{M_{Ro}}{\text{RoRi}} \right] w w_z = -\pi_z + b - \varepsilon v_j^L v_j^s z + \frac{\alpha^2}{\text{ReRi}} w_{jj}
\]

Stokes Shear Force Affects Fronts and Filaments


Enhances Fronts for Down-Front Stokes
Opposes Fronts for Up-Front Stokes

\[
\frac{\alpha^2}{Ri} \left[ w_{,t} + v^L_j w_{,j} + R_i \frac{M R_o}{R_o R_i} w w_{,z} \right] = -\pi z + b - \varepsilon v^L_j v^s_j, z + \frac{\alpha^2}{Re R_i} w_{,j,j}
\]
Can it be observed?

CARTHE LASER (next week)

Aerostat
CAR THE LASER (Feb.)
About 45 Min Later.
Conclusions

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.

Interesting transition occurs on the Submeso to Langmuir scale boundary, as nonhydro. & ageostrophic effects begin to dominate.

Langmuir mixing scalings consistent with LES & obs., reduce climate model biases in MLD, T, CFCs vs. observations by 5-25%.

The 25-45% forcing effects of the Stokes Shear force on submesoscale dynamics are under-appreciated.

All papers at: fox-kemper.com/pubs
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 $\mathbf{u}_L = \mathbf{v} + \mathbf{v}_s$

Misalignment enhances degree of wave-driven LT

**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).
The State of the Art: Observations vs. Mixed Layers in CESM1.2

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.


May partly account for large annual cycle errors.

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Generalized Turbulent Parameter (Langmuir Number) projection of $u^*$, $u_s$ into Langmuir Direction

\[ La^2_{proj} = \frac{|u^*| \cos(\alpha_{LOW})}{|u_s| \cos(\theta_{ww} - \alpha_{LOW})}, \]

A scaling for LC strength & direction!
Enough for climate model application

Fig. 5. Profiles of energy production terms ($BP = \overline{w'\overline{b'}}$, $ESP = \overline{u'w'} \cdot \overline{U_z}$, and $SSP = \overline{u'w'} \cdot \overline{U_z^S}$) for the flow shown in Fig. 4. (a) Partially downfront and (b) partially upfront Stokes drift. Both cases have positive cross-front Stokes drift $V^S$. Recall that the averaging operator ($\overline{\cdot}$) is an average over the small horizontal scales $x$ and $y$. The velocities and length scales in the energy production terms have been nondimensionalized according to Table 1.
More wave effects to come!
All papers at fox-kemper.com

Wind-wave dependent processes in the coupled climate system
Towards coupled wind-wave-AOGCM models