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

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

Friday, 9/14/18
10:30—11:30

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)

URI GSO
Physical Oceanography Seminar Series
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A photo of same in Narragansett Bay (courtesy P. Cornillon)
The Ocean Mixed Layer

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)
3 Effects Dominate open ocean
“Wave-Averaged Equations”:
(Craik, Leibovich, McWilliams et al. 1997)
All rely only on Stokes drift of waves

1: Stokes Advection: parcels, tracers, momentum move with Lagrangian, not Eulerian flow

2: Stokes Coriolis: water parcels experience Coriolis force during this motion

3: Stokes Shear Force

3 Wave Effects, 3: Stokes Shear Force and the CL2 mechanism for Langmuir circulations
Flow directed along Stokes shear=downward force

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

$\epsilon = \frac{V^S H}{f \, L \, H^s}$

<: Stokes-shear force    ●: water parcel
<: Lagrangian flow velocity

“wavy hydrostatic” if $\epsilon \gg 1$

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
What's plotted are surfaces of large vert. velocity, colored by temperature.
Thorpe, 04

**Typical effect:** Downward Force for down-Flow Stokes

\[
\frac{\alpha^2}{Ri} \left[ \frac{\partial w}{\partial t} + \nu_j \frac{\partial w}{\partial x} + \frac{M_{\text{Ro}0}}{Ri} w \frac{\partial w}{\partial z} \right] = -\pi, z + b - \varepsilon v_j^L v_j^s, z + \frac{\alpha^2}{Re Ri} w, jj
\]

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

1) Observations obey a particular scaling for $<w^2>$!

### Table 3: Root mean square errors (RMSE, 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).

<table>
<thead>
<tr>
<th>Case</th>
<th>Summer</th>
<th>Winter</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Global</td>
<td>South of 30°S</td>
<td>30°S-30°N</td>
<td>Global</td>
<td>South of 30°S</td>
<td>30°S-30°N</td>
</tr>
<tr>
<td>CTRL</td>
<td>10.62±0.27a</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>
</tr>
<tr>
<td></td>
<td>(13.40±0.19)b</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>
</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±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>

\[a\] Numbers with ± sign give the 90% confidence interval, estimated from the RMSEs of 1000 bootstrap estimates of the 48-year (for Wave-Ocean only experiments) and 20-year (for fully coupled experiments) mean mixed layer depth.

\[b\] Numbers shown in the parentheses are for the fully coupled experiments.

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Stommel Demon, Subsurface Temperature (also CFCs, S, etc.): Improved vs. Observations with Langmuir

How accurate do we need the waves to be?

Langmuir Turbulence Parameterizations are robust to large approximations in wave modeling, e.g., replacing wave models with climatology, theoretical scalings using a full-Physics Prognostic Wave Model (WaveWatch-III).

How accurate do we need the waves to be?

Langmuir Turbulence Parameterizations are robust to large approximations in wave modeling, e.g., replacing wave models with climatology, theoretical scalings.

Using a Climatology of Langmuir Enhancement instead of a wave model (Data Waves)

How accurate do we need the waves to be?

Langmuir Turbulence Parameterizations are robust to large approximations in wave modeling, e.g., replacing wave models with climatology, theoretical scalings using an empirical/theoretical Stokes drift profile, with rules of thumb and one tunable parameter (Theory Waves).

Do Details of Turbulence Matter Much?

- Our parameterization of Langmuir Turbulence comes in 2 parts:
  - Enhanced mixing within the boundary layer (based on Stokes parameters)
  - Enhanced entrainment (recasting the predicted boundary layer depth in terms of Stokes-dependent unresolved shear)


Q. Li, B. Fox-Kemper, 2017: Assessing the effects of Langmuir turbulence on the entrainment buoyancy flux in the ocean surface boundary layer. JPO. In Preparation.
Something that happens often with waves:
Tricky: Misaligned Wind & Waves


Tricky: Misaligned Wind & Waves

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Tricky: Misaligned Wind & Waves

Generalized Turbulent Parameter (Langmuir Number)

Projection of $u^*$, $u_s$ into Langmuir Direction

$$La_{proj}^2 = \frac{|u_*| \cos(\alpha_{LOW})}{|u_s| \cos(\theta_{ww} - \alpha_{LOW})}.$$

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

Also, benefit from Harcourt & D’Asaro (2008) to use a Surface Layer Average, rather than surface $La$ to be robust to wind waves vs. monochromatic

Do Details of Turbulence Matter Much?

Dissipation Rate Regimes of S. Ocean

Do Details of Turbulence Matter Much?

Dissipation Rate Evaluation using LES

Do Details of Turbulence Matter Much?

Entrainment Rate Evaluation using LES

Obs.

No Lang.

Early Entrain Guess.

Mixing w/o Entrain Eval.

Mixing & Refined Entrain.

Lang.
Langmuir Mixing in Climate: Boundary layer Depth Improved

<table>
<thead>
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<th>Case</th>
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<td>11.65 ± 0.29</td>
<td>11.91 ± 0.83</td>
</tr>
<tr>
<td>LF17</td>
<td>8.48 ± 0.24</td>
<td>8.92 ± 0.39</td>
</tr>
</tbody>
</table>

No Lang. Mixing w/o Entrain Eval.

Mixing & Refined Entrainment


Conclusions: Waves on Turbulence & Climate

- The inclusion of Langmuir (wave-driven) mixing is justified by obs., LES, and reduction of climate model bias.

- Generally, these schemes make mixed layer deeper—affecting air-sea, CFCs, carbon exchange, etc.

- The Data Waves and Theory Waves versions of our scheme are available through CVmix—no wave model required!

- Improvement of scalings vs. LES has worked very well to date, but as nearly all present schemes agree well with LES—returns are diminishing.
Do Stokes forces affect (sub)meso-scales?

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: Stronger Langmuir (small) Turbulence

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

What's plotted are surfaces of large vert. velocity, colored by temperature.
Do Stokes force directly affect larger scales?

\[ \varepsilon / Ro \]

"Wavy hydrostatic" if \( \varepsilon \gg 1 \)

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

\[ Ro = \frac{U}{fL} \]

Wavy Submesoscale Instability Different: Symmetric Instability

Ri < 1 \quad \Rightarrow \quad SI

Ri = 0.5
Stokes Forces Stabilize SI

Cross front velocity for the fastest growing mode

Ri = 2
Stokes Forces Destabilize SI

S. Haney, BFK, K. Julien, and A. Webb.
Symmetric and geostrophic instabilities in the wave-forced ocean mixed layer. JPO 45:3033-3056, 2015.
Diverse types of interaction


Typical effect: Downward Force for down-flow Stokes

\[ \alpha^2 \left[ w_{,t} + u_j^L w_{,j} + \frac{M}{RoRi} w w_{,z} \right] = -\pi_{,z} + b - \varepsilon v_j^L v_j^s + \frac{\alpha^2}{ReRi} w_{,jj} \]

“Wavy hydrostatic” if \( \varepsilon \gg 1 \)

Figure 1: windrows practice to amalgamate within the

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

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

Wind, Waves

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

Initially every surface node has 1 drifter, so there are 851796 drifters in the picture.

After 80 Min

Surface Drifters
Do (wavy hydrostatic) Stokes Forces Matter?
Yes! At Leading Order (in LES)

Table 3. Integrated Budget for Overturning Vorticity

<table>
<thead>
<tr>
<th>Responsible Force</th>
<th>Relative Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Relative Tendency of Overturning Circulation along the Cell Boundary</strong></td>
<td></td>
</tr>
<tr>
<td>Net tendency</td>
<td>11 ± 8%</td>
</tr>
<tr>
<td><strong>Sources</strong></td>
<td></td>
</tr>
<tr>
<td>Buoyancy anomaly</td>
<td>100%</td>
</tr>
<tr>
<td>Stokes shear force anomaly</td>
<td>44 ± 4%</td>
</tr>
<tr>
<td>Interaction with $\nu^H$</td>
<td>44 ± 8%</td>
</tr>
<tr>
<td>Frontal anomaly in pressure gradient</td>
<td>6 ± 9%</td>
</tr>
<tr>
<td>Nonlinear interaction with $\nu^B$:</td>
<td>2 ± 1%</td>
</tr>
<tr>
<td><strong>Sinks</strong></td>
<td></td>
</tr>
<tr>
<td>Frontal turbulence anomaly</td>
<td>−82 ± 11%</td>
</tr>
<tr>
<td>(mostly, imbalance in wavy Ekman relation)</td>
<td></td>
</tr>
<tr>
<td>Coriolis on along-front jet</td>
<td>−66 ± 2%</td>
</tr>
<tr>
<td>Lagrangian advection of $(\nu^\psi, w^\psi)$</td>
<td>−36 ± 7%</td>
</tr>
</tbody>
</table>

Conclusions

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

- Stokes forces, as treated here, can be included in hydrostatic models like GCMs (wavy hydrostatic).

- Stokes forces affect Langmuir turbulence, but also (sub)mesoscale fronts (more energy, anisotropy) and submesoscale instabilities. Need to assess climate & environmental impact!

- All papers at: fox-kemper.com/pubs
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, $\text{Ri} = 0.5$. Lines of constant buoyancy and absolute momentum are only parallel when $\text{Ri} = 1$. 

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 \( z = 0 \).

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

\[
U + U^S = -\Psi_y^L, \text{ such that } U = -\Psi_y, \text{ and } V + V^S = \Psi_x^L = 0.
\]
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.

\[ fQ = f^2N^2 - M^4 - fM^2U_z^S < 0. \]

Vert. Density Gradient  Horiz. Density Gradient  Anti-Stokes Shear

Do Stokes forces affect 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.)

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

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.
For typical conditions, the Stokes effect amounts to a small change in geostrophic instability (mixed layer eddy) growth rates.

Do (wavy hydrostatic) Stokes Forces Matter? Yes! At Leading Order (in LES)

<table>
<thead>
<tr>
<th>Name</th>
<th>Term</th>
<th>Relative Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rate of Change of Overturning Circulation KE</strong></td>
<td>$(\partial_t + u^j_i \partial_j) v^v v^v + \frac{w^5 w^5}{2}$</td>
<td>45 $\pm$ 6%</td>
</tr>
<tr>
<td><strong>Sources</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buoyancy production</td>
<td>$w^\psi b'$</td>
<td>100%</td>
</tr>
<tr>
<td>Energy increase due to interaction with $v^H$</td>
<td>$v^\psi (-F^h)$</td>
<td>49 $\pm$ 5%</td>
</tr>
<tr>
<td>Stokes shear force work</td>
<td>$w^\psi (-u^i_j \partial_j u^i_j)$</td>
<td>24 $\pm$ 1%</td>
</tr>
<tr>
<td>Energy increase due to nonlinear interaction with $v^B$</td>
<td>$v^\psi (-F^v)$</td>
<td>7 $\pm$ 1%</td>
</tr>
<tr>
<td><strong>Sinks</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Generation of along-front jet by Coriolis turning of $v^\psi$</td>
<td>$-fv^\psi u^H$</td>
<td>$-69 \pm 3%$</td>
</tr>
<tr>
<td>Work done against Coriolis of background flows</td>
<td>$v^\psi (\partial_y p^B + \partial_z L^B)$</td>
<td>$-45 \pm 3%$</td>
</tr>
<tr>
<td>Generation of shear turbulence</td>
<td>$L^B_j \partial_j u^i_k$</td>
<td>$-16 \pm 1%$</td>
</tr>
<tr>
<td>Turbulent transport through the cell boundary</td>
<td>$-\partial_j (u^i_k L^B_j)$</td>
<td>$-2 \pm 0.4%$</td>
</tr>
</tbody>
</table>

$$\frac{\alpha^2}{Ri} \left[ w, t + v^L_j w, j + \frac{M_{Ro}}{RoRi} w w, z \right] = -\pi, z + b - \varepsilon v^L_j v^s_j, z + \frac{\alpha^2}{ReRi} w, jj$$
