Surface Waves Drive a Turbulent Ocean

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Waves Provide Stokes Drift

& Stokes Drift drives Langmuir Turbulence

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

Monochromatic:

\[ u^s = e^{w} \frac{8\pi^3 a^2 f_p^3 \frac{8\pi^2 f_p^2}{g}}{g} \]

Wave Spectrum:

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


Wave-Averaged Equations

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

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

\[ v_j^L = v_j + v_j^s \]

Lagrangian advection!

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

Lagrangian geostrophic!

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

\[ b_{t} + v_j^{L} b_{,j} + \frac{M_{Ro}}{RoRi} w b_{z} + w = 0 \]

\[ v_{j,j} + \frac{M_{Ro}}{RoRi} w_{z} = 0 \]

nonhydrostatic Stokes Shear Force!

LAGRANGIAN (Eulerian+Stokes) advection & Coriolis

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


Stokes Shear Force:
Craik-Leibovich mechanism for Langmuir circulations
Flow along Stokes shear $\Rightarrow$ nonhydrostatic downforce

$\left( \frac{\alpha^2}{Ri} \right) \left[ w_{,t} + v_j^L w_{,j} + \frac{M_{Ro}}{RoRi} w w_{,z} \right] = -\pi_{,z} + b - \varepsilon v_j^L v_j^{s,z} + \frac{\alpha^2}{ReRi} w_{,jj}$

Traditional Stokes effect: Langmuir Turbulence

- Near-surface
- Convection, Wind & Langmuir Turbulence
- Ro >> 1
- Ri < 1: Nonhydro
- 1-100m (H=L)
- 10s to 1hr
- w, u = 0 (10 cm/s)
- Stokes Drift
- Equations: Wave-averaged, Nonhydrostatic

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

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

Improved vs. Observations with Langmuir Mixing

Subsurface Temperature errors reduced (monthly means vs. Observations)

<table>
<thead>
<tr>
<th>Case (depth)</th>
<th>Global</th>
<th>90°S - 30°S</th>
<th>30°S - 30°N</th>
<th>30°N - 90°N</th>
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</thead>
<tbody>
<tr>
<td>CTRL (0 m)</td>
<td>1.53</td>
<td>0.90</td>
<td>1.10</td>
<td>3.01</td>
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<td>VR12-MA (0 m)</td>
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<td>1.04</td>
<td>1.14</td>
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<td>1.39</td>
<td>1.92</td>
<td>2.88</td>
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<tr>
<td>VR12-MA (100 m)</td>
<td>1.75</td>
<td>1.29</td>
<td>1.60</td>
<td>2.76</td>
</tr>
</tbody>
</table>

- Global
- Southern Hem.
- Equatorial
- Northern Hem.
Not Traditional: Stokes forces affect Submesoscale Fronts & Instabilities

(Capet et al., 2008)

- Fronts
- Eddies
- $\text{Ro}=O(1)$
- $\text{Ri}=O(1)$
- near-surface ($H=100\text{m}$)
- 1–10km, days

Eddy processes often baroclinic instability


Routinely resolved in 2100


Obs. Indicate Stokes force directly affects the 1km-100km (sub)mesoscale!!

\[ \varepsilon / Ro \]

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

\[ \varepsilon = \frac{V_s H}{fL H_s} \]

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

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
1000x more gridpoints than CESM

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

Diverse types of interaction

Stokes Shear Force Affects Fronts and Filaments


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

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

Waves May Give 30% of Power Produced at Front
In multiscale problems—difficult to use AMR or other regional techniques since small-scales are ubiquitous!

Here we see evidence of this in vertical velocity.
Stokes Shear force affects 0(100m) Symmetric Instabilities (criterion & effects)

Ri = 0.5

Ri = 2

Cross front velocity pattern shows growing mode—black lines indicate density surfaces

So, if \( f < 0 \) indicates likely regions of symmetric instability—Surface Waves STRONGLY affect SI!

Conclusions

- Upper Ocean Turbulence, Fronts, & Instabilities are important, and are beautiful to contemplate.
- Interesting transition in physics, as nonhydro. & ageostrophic effects begin to dominate.
- Nonhydrostatic effects of the Stokes forces on 1m to 10km dynamics are under-appreciated.
- Applications & parameterizations just beginning!
- All papers at: fox-kemper.com/pubs