Wind waves in the coupled climate system

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Expanding on past work with:
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Many more wave-climate effects to come... stay tuned!

Air-Sea Flux Errors vs. Data (Large & Yeager 09)
LES of Langmuir-Submeso Interactions?

Perform large eddy simulations (LES) of Langmuir turbulence with a submesoscale temperature front using wave-averaged equations.

2 Expts: 1 with Stokes forcing 1 without

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

Surface Waves are...

fast, small, irrotational solutions of the Boussinesq Equations
Stokes driftin’ away

Take wave solns, compare the velocity of trajectories vs. Eulerian velocity, Taylor Expand, calculate:

\[ u^L(x_p(t_0), t) - u^E(x_p(t_0), t) \approx [x_p(t) - x_p(t_0)] \cdot \nabla u^E(x_p(t_0), t) \]
\[ \approx \left[ \int_{t_0}^{t} u^E(x_p(t_0), s')ds' \right] \cdot \nabla u^E(x_p(t_0), t). \]

Monochromatic:

\[ u^S = e^w \frac{8 \pi^2 a^2 f^3}{g} e^{\frac{8 \pi^2 f^2}{g_{pZ}}} = e^w a^2 \sqrt{gk^3 e^{2kz}}. \]

Spectrum:

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

Depth-Integrated:

\[ u^{S-int} = \int_{-\infty}^{0} u^S(z)dz = 2\pi \int_{0}^{\infty} H_*(f)fS_f(f) df \]


Stokes forcing on the Langmuir Scale

- Langmuir turbulence
  - $Ro >> 1$
  - $Ri < 1$: Nonhydro
  - 1-100m ($H=L$)
  - 10s to 1hr
  - Eqtns: Craik–Leibovich
  - Resolved routinely in year 2170

"Wave-forcing and hence Langmuir turbulence could be important over wide areas of the ocean and in all seasons in the Southern Ocean."


Image: NPR.org, Deep Water Horizon Spill

Data + LES, Southern Ocean mixing energy: Langmuir (Stokes-drift-driven) and Convective

\[
\frac{B_s}{u_s^2 u_s / h} = \frac{w_s^3 / h}{w_s^3 / h} = \frac{h}{L_s}.
\]

\[
\frac{u_s^2 u_s / h}{w_s^3 / h} = \frac{u_s^3 / h}{w_s^3 / h} = L_s^2.
\]

\[
e_{h/u_s^3}
\] from LES Scaling
Including Stokes-driven Mixing (Harcourt 2013) Deepens the Mixed Layer!

See Also: Fan & Griffies (2013)

CLB as equations for Large Eddy Simulations: Tricky: Misaligned Wind & Waves

Tricky: Misaligned Wind & Waves

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Tricky: Misaligned Wind & Waves

Stokes Depth vs. OSBL Depth


Langmuir Mixing in KPP

- WaveWatch-III (Stokes drift) <-> POP2 (U, T, HBL)
- CORE2 interannual forcing (Large and Yeager, 2009)
- 4 IAF cycles; average over last 50 years for climatology

\[
W = \frac{k U_* \mathcal{E}}{\phi}
\]

\[
\kappa_v = WH_k G(-z/H_k)
\]

Enhancement factor to vertical velocity scale \( W \)

Alignment of wind and waves

McWilliams and Sullivan, 2000; Van Roekel et al., 2012
Summer Mixed Layer Depth (JAS for NH & JFM for SH)

RMSE (m)

<table>
<thead>
<tr>
<th></th>
<th>Global</th>
<th>20S-20N</th>
<th>South of 30S</th>
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<tbody>
<tr>
<td>OBS</td>
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<td>CTRL</td>
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<tr>
<td>No Langmuir Mixing</td>
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<tr>
<td>Aligned $u^*$ and $u_s$</td>
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<tr>
<td>Misaligned $u^*$ and $u_s$</td>
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<td>With Stokes shear</td>
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</tr>
<tr>
<td>VR12a</td>
<td>15.63</td>
<td>17.89</td>
<td>19.50</td>
</tr>
<tr>
<td>VR12g</td>
<td>16.92</td>
<td>22.74</td>
<td>15.81</td>
</tr>
<tr>
<td>VR12h</td>
<td>18.11</td>
<td>24.97</td>
<td>14.59</td>
</tr>
</tbody>
</table>

OBS: de Boyer Montégut et al. 2004
Winter Mixed Layer Depth (JFM for NH & JAS for SH)

<table>
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<tr>
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<th>20S-20N</th>
<th>South of 30S</th>
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<tbody>
<tr>
<td>RMSE (m)</td>
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<td>OBS: de Boyer Montégut et al. 2004</td>
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<td>Slide Courtesy of Qing Li</td>
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</table>

RMSE (m):
- Global: 49.70
- 20S-20N: 19.24
- South of 30S: 62.59

OBS: de Boyer Montégut et al. 2004
Including Stokes-driven Mixing in CESM, too!

(with another param.: Harcourt & D’Asaro, 2008; Van Roekel et al, 2012)

Remains to be co-tuned with mixed layer eddy, mesoscale, and near-inertial mixing parameterizations

**pCFC11 Bias**

**Southern Hemisphere**

**RMSEs are reduced by 6% ~ 18%**

**GLODAP: Key et al. 2004**
RMSEs are reduced by 6% ~ 19%
Conclusions

Stokes forces affect OSBL turbulence, enhancing W by up to a factor of 2.

A number of similar parameterizations are now in testing for next generation of CMIP models.

OSBL is deepened *consistently in all cases* in the S. Ocean especially, in both summer and winter.

Bias vs. observations is reduced, with RMSE decreasing by roughly 20% south of 30S, and staying constant overall.

CFC-11 bias is substantially reduced in both S. Hemisphere and equatorial region.

Overall: Stokes-driven turbulence is important!!
Diverse types of interaction

Dimensionless Boussinesq Spanning Mesoscale to Stratified Turbulence following McWilliams (85)

\[
\begin{align*}
\frac{\text{Ro}}{\text{Re}} \left[ v_{i,t} + v_j v_{i,j} \right] + \frac{M_{\text{Ro}}}{\text{Ri}} w v_{i,z} + \epsilon_{i j k} v_j &= -M_{\text{Ro}} \pi_{,i} + \frac{\text{Ro}}{\text{Re}} v_{i,j j} \\
\frac{\alpha^2}{\text{Ri}} \left[ w_{,t} + v_j w_{,j} + \frac{M_{\text{Ro}}}{\text{RiRi}} w w_{,z} \right] &= -\pi_{,z} + \frac{\alpha^2}{\text{ReRi}} w_{,jj} \\
b_{,t} + v_j b_{,j} + \frac{M_{\text{Ro}}}{\text{RiRi}} w b_{,z} + w &= 0 \\
v_{,j,j} + \frac{M_{\text{Ro}}}{\text{RiRi}} w_{,z} &= 0
\end{align*}
\]

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

following Lane et al. (07), McWilliams & F-K (13) and Suzuki & F-K (14)
(for horizontally uniform Stokes drift)

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

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

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

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

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

LAGRANGIAN (Eulerian+Stokes) advection & Coriolis

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

Plus boundary conditions
Stokes Shear Force
and the CL2 mechanism for Langmuir circulations
Flow directed along Stokes shear=downward force

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

Stokes forcing of the (Sub)mesoscale

(Capet et al., 2008)

- Fronts (mesoscale & submesoscale)
- Eddies
- Ro = O(1)
- Ri = O(1)
- near-surface
- 1-10 km, days
- Resolved: yr 2050 to 2100


When is $\varepsilon = \frac{V_s H}{f L H_s}$ big?

- Isopycnal slope is $O(0.1-0.01)$ for submesoscale
- Isopycnal slope is $O(0.0001)$ for mesoscale
Consider perturbing from geostrophic, hydrostatic soln:

\[ \phi = \phi_{00000} + \varepsilon \phi_{10000} + Ro \phi_{01000} + \frac{1}{\sqrt{Ri}} \phi_{00100} + \frac{\alpha^2}{\sqrt{Ri}} \phi_{00010} + \frac{1}{Re} \phi_{00001} \]

\[ + \varepsilon^2 \phi_{20000} + \varepsilon Ro \phi_{11000} + Ro^2 \phi_{02000} + \frac{Ro}{\sqrt{Ri}} \phi_{01100} + \ldots \]

\[ + O(Ro^3) \]

\( \frac{\varepsilon}{Ro} = \frac{V_s}{fL} \frac{H}{H_s} \frac{fL}{V_s} = \frac{V_s}{V} \frac{H}{H_s} \)

**Figure 1.** (Colour online) Estimated ratio \( \varepsilon/Ro \approx (|u_s \cdot u| h) /(|u|^2 h_s) \) governing the relative importance of Stokes effects versus nonlinearity. Eulerian velocity \( (u) \) is taken as the
Enhances Fronts for Down-Front Stokes
Opposes Fronts for Up-Front Stokes
Are Fronts and Filaments different with Stokes shear force?

\[ \frac{\alpha^2}{Ri} \left[ w_t + v_j^L v_{,j} + \frac{M_{Ro}}{RoRei} w_{,z} \right] = -\pi_{,z} + b + \epsilon v_j^L v_{j,z} + \frac{\alpha^2}{ReRei} w_{,zz} \]

\[ \frac{\alpha^2}{Ri} \left[ w_t + v_j^L v_{,j} + \frac{M_{Ro}}{RoRei} w_{,z} \right] = -\pi_{,z} + b + \epsilon v_j^L v_{j,z} + \frac{\alpha^2}{ReRei} w_{,zz} \]


Let’s examine a particular front with \( \varepsilon = \frac{V^s H}{f LH_s} \approx 20 \)

Along-Front and 10min Average

$$\varepsilon = \frac{V^s H}{f L H_s} \approx 20$$
Along-Front and 10min Average

\[ \varepsilon = \frac{V^s H}{f LH_s} \approx 20 \]
Along-Front and 10min Average

\[ \varepsilon = \frac{V s H}{f L H_s} \approx 20 \]

Stokes Shear force Enhances Frontogenesis for Down-Front Stokes:
Adds 30–40% to frontal kinetic energy production, pressure does no net work.
Stokes also influences Submesoscale & Langmuir-scale Instabilities through Lagrangian shear (Holm ’96) & Lagrangian Thermal Wind

\[ \mathbf{q} = (f + \nabla \times \mathbf{u}) \cdot \nabla b \approx [f + \nabla \times (u^L - u^s)] \cdot \nabla b \]

So, \( q < 0 \)

Is not the same as \( Ri < \frac{f}{\zeta} \)

Reinterpret Hoskins, Stone, & Charney-Stern-Pedlosky with care!


Conclusion:

SI win if
\[ Ri_L < \frac{1}{4} \]

SI win if
\[ \frac{1}{4} < Ri_L < 1 \]

BCI win if
\[ \frac{1}{4} < Ri_L < 1 \]
and
\[ f_q > 0 \]

KH win if
\[ Ri_E > 1 \]

and
\[ f_q < 0 \]

\[ f_q < 0 \]

\[ Ri_E < 1 \]
and
\[ f_q > 0 \]

\[ f_q > 0 \]

\[ Ri_E < 1 \]
\[ \frac{1}{4} < Ri_L < 1 \]

B.C. win

Conclusions

Stokes shear force affects frontogenesis. Add/subtract 30-40% of frontal KE production for downfront/upfront Stokes drift.

The controlling parameter, $\mathcal{E}$, measures nonhydrostatic frontal effects. It can dominate other nonlinear effects, such as $O(1)$ Rossby, and is $O(20)$ in these simulated submesoscale fronts.

Down-Stokes fronts are sharper than those directed across or esp. against Stokes and have horizontal velocity and pressures that are not antisymmetric about the max $w$.

Future/Present: Cross-frontal transport pathways, wave-mean 2-way interaction, and Stokes effects on frontal instabilities.

Overall: Stokes force can affect submesoscale dynamics as well as Langmuir turbulence.

All papers at: fox-kemper.com/
Along-Front and 10min Average

\[ \epsilon = \frac{V^s H}{f LH_s} \approx 20 \]

Along-Front and 10min Average

\[ \epsilon = \frac{V^s H}{fLH_s} \approx 20 \]