Modeling the Bubbly Ocean

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Sea surface under Hurricane Isabel (2003) from a low-level flight ($U_{10}>40\text{m/s}$). Photo taken by M. Black.
Sea surface under Hurricane Isabel (2003) from a low-level flight ($U_{10}>40\text{m/s}$). Photo taken by M. Black.
The acoustic backscatter intensity near ocean station P
(Subarctic Pacific, $U_{10} \sim 12\text{m/s}$)

Measuring bubbles $r = 30$ to $40\mu\text{m}$
($1\mu\text{m} = 10^{-6}\text{m}$)

Emerson and Hedges 2008 (Data from S. Vagle)
Bubble Genesis

Bubble number density

Deane and Stokes [2002]
Bubble Evolution

• Buoyant rising
• Turbulent transport
• Gas exchange with ambient water
• Size change (caused by change of ambient water pressure or the amount of gases inside)
• Complete dissolution / Bursting at the ocean surface

Langmuir circulations (dominant OBL turbulence in most global ocean [Belcher et al., 2012])
Roles of Bubbles

• Gas bubbles modify the acoustic and optical properties of the ocean.
  • Identification of upper ocean dynamic processes and marine vehicles [e.g. Farmer and Li, 1995, Trevorrow et al., 1994].
  • Remote sensing of ocean color [Zhang et al., 1998].
  • Geoengineering [Seitz, 2011].

• Gas bubbles modify upper ocean dynamic.
  • Increase in upper ocean stratification and weakening of downward currents [e.g., Smith, 1998].

• Marine aerosol production.
  • Bubble-bursting contributes to marine aerosol production [Blanchard, 1963].
Roles of Bubbles

- Bubble-mediated gas transfer [Woolf, 1997]
  - Enhancement of air-sea gas transfer rate.
  - Bubble-induced supersaturation.

\[
\begin{align*}
\text{Net gas flux} & \quad F_n = F_s + \mathcal{F} \\
\text{Gas flux thru surface} & \quad F_s \\
\text{Gas flux thru bubbles} & \quad \mathcal{F} \\
\text{Supersaturation level} & \quad \Delta = \left( \frac{C}{C_{eq}} - 1 \right) \times 100\% 
\end{align*}
\]
The ocean is supersaturated in equilibrium with the atmosphere when there are bubbles.

\[ F_n = F_s + \mathcal{F} = 0 \]

\[ F_s < 0 \]

\[ \mathcal{F} > 0 \]

\[ \Delta = \Delta_{eq} > 0 \]
Objectives

- Develop a model for bubble evolution in the oceanic boundary layer
- Study subsurface bubble evolution
- Evaluate the importance of bubbles on boundary layer dynamics
A coupled - LES - bubble - dissolved gas model

- Breaking of Surface Gravity Wave
  - Momentum/Energy Flux
  - Bubble Entrainment
  - Bubble Loss

- Wind
  - Non-breaking surface gravity waves
  - Turbulence, Temperature
  - Change of Density
  - Gas exchange

- Large Eddy Simulation Model
  - Surface Gas Flux

- Bubble Model
  - Dissolved Gas Model

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NCAR LES for oceanic boundary layer with the effects of surface gravity waves [e.g., McWilliams et al., 1997; Sullivan and McWilliams, 2010].

- It has been configured to study oceanic boundary layer turbulence under different surface [e.g., Van Roekle et al., 2012; Sullivan et al., 2012] and lateral [e.g., Kukulka et al., 2011] forcing.

- Injected bubbles induce a density anomaly:

\[ \bar{\rho} = (1 - \alpha_b) \rho_w + \alpha_b \rho_a \]

\(\alpha_b\) is the bubble volume fraction.
Bubbles of different sizes are modeled.

[O₂]₀, [N₂]₀, and [CO₂]₀ are the concentration of O₂, N₂, and CO₂ in bubbles of radius r at time t, and at location x.

Formulas for bubble physics: Thorpe [1982], Woolf and Thorpe [1991].

Bubble coalescence and fragmentation are not included.

Near the surface, bubble injection is parameterized based on laboratory and in-situ measurements [Lamarre and Melville, 1991; Terray et al., 1996; Melville et al., 2002; Deane and Stokes, 2002; Sullivan et al., 2004 and 2007].
Model configuration

- Wind: [5 : 2.5 : 20] m/s.
- Wave: (1) in equilibrium with wind; (2) observed wave ages at ocean station P.
- Model grid: 300 x 300 x 96 (Lx, Ly = 150 to 300 m; Lz = 110 m).
- Bubble sizes: 17 sizes ($r_{\text{min}} = 35 \mu\text{m}, r_{\text{max}} \sim 1.2 \text{ cm}$).
- Bubble components: $\text{N}_2$ and $\text{O}_2$. 
Wind=15 m/s
wave

Simulated instantaneous total bubble number density (m$^{-3}$)

Consistent with observations (e.g., Farmer and Li, 1995; Vagle et al., 2010)

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Bubble distribution sharpens at both ends with a peak at around 100 μm

$U_{10} = 10 \text{ m/s}$
Bubble Content Profile

\[ U_{10} = 20 \text{ m/s} \]
Mean Bubble Number Density

\[ \langle C_b(z) \rangle = C_0 \exp \left( \frac{z}{z_0} \right) \]

Observations: Crawford and Farmer [1987]
Mean Bubble Number Density

\[
\langle C_b(z) \rangle = C_0 \exp \left( \frac{z}{z_0} \right)
\]

What is the wind speed dependence of bubble e-folding depth \((z_0)\)?
Bubble e-folding depth $z_0$ is proportional to turbulence strength in the boundary layer:

$$w_t \frac{\partial \langle c_b \rangle}{\partial z} = \frac{1}{r} \frac{dr}{dt} \langle c_b \rangle \Rightarrow \langle c_b \rangle = \langle c_0 \rangle \exp\left(\frac{z}{z_0}\right) \text{ with } z_0 \propto w_t \Rightarrow z_0 \propto u_* = \sqrt{c_d U_1}$$

**Bubble Budget**

Overview | Bubble Modelling | Parameterization | Summary
--- | --- | --- | ---
Dependence of $Z_0$

Blue circles are solutions forced by a spectrum of waves locally in equilibrium with a wind speed.

$z_0 = 75.35 u_* - 0.13$ (m); $u_* = (c_d)^{0.5} U_{10}$ (m/s)

($c_d$ calculated following Large and Pond [1981])

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Impact of wave forcing

Error bar: A conservative estimate of the variability caused by variable wave conditions.

Other meteorological conditions such as wave forcing and heat flux [Vagle et al., 2012] play a role in subsurface bubble distribution.
Velocity Variances

$U_{10} = 20 \text{ m/s}$
Resolved TKE Budget

$U_{10} = 20 \text{ m/s}$
Objectives

- Determine $\Delta_{eq}$ from bubbly flow solutions
- Evaluate the importance of $\Delta_{eq}$ in a global model

Parameterization including bubble-induced supersaturation (e.g., Woolf 1997)

- $F_n = K_T C_{sat} (\Delta_{eq} - \Delta)$

Parameterization in current climate simulations

- $F_n = K_T C_{sat} (- \Delta)$
\[ F_n = F_s + \mathcal{F} = -K_T C_{sat}(\Delta_{eq} - \Delta) \]

\[ F_n = F_s + \mathcal{F}_C + \mathcal{F}_P = -K_s C_{sat} \Delta + \mathcal{F}_C + K_b C_{eq}(\Delta_P - \Delta) \]

\[ K_s \propto u_* \quad (\text{COAREG: Fairall et al., [2011]}) \]
$K_T = K_b + K_s$

$\Delta_{eq} = \frac{K_b}{K_T} \Delta_P + \frac{F_C}{K_T C_{sat}}$

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\( \Delta_{eq} = \frac{K_b}{K_T} \Delta_P + \frac{\mathcal{F}_C}{K_T C_{sat}} \)

\( \Delta_{eq} \) is inversely related to temperature.
Global transport model (Khatiwala et al., 2005)

- Simulates the equilibrium concentrations of a tracer in the ocean

Model configuration

- Global circulation, temperatures and ice coverage: Mean fields from the ocean carbon model intercomparison project (OCMIP) (2.8° horizontal resolution; 15 vertical levels).
  - Wind: QuikSCAT long-term mean.
  - SLP: NCEP Reanalysis long-term mean.
- Two runs
  - Control run: with $\Delta_{eq}$
  - No $\Delta_{eq}$ run
[Control Run]

Mixing

Cooling

Ito et al., 2007

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Overview  |  Bubble Modelling  |  Parameterization  |  Summary

[Control Run]  |  [Control Run] - [No $\Delta_{eq}$ run]

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Surface bubble-induced supersaturated water is brought into the abyssal ocean by deep water masses.
Bubble Modeling

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Parameterization

\[ F_n = -K_S C_{sat} \Delta + F_C + K_b C_{eq}(\Delta_P - \Delta) \]

\[ K_S \propto u_\ast \text{ (COAREG: Fairall et al., 2011)} \]