The Transport of Oil in Water Bodies Subjected to Waves

Jim Weaver, PhD
National Exposure Research Lab, Athens GA
Weaver.jim@epa.gov

Michel C. Boufadel, PhD, PE
Temple University, Philadelphia Pennsylvania
boufadel@temple.edu

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- Traditional oil spill models focus on large-scale transport

-The physics of waves and their effects on oil droplets are not directly addressed

The situation where dispersal of oil has just occurred: How are droplets transported in non-breaking waves?

Oil Droplet Transport Concept

Wave Theory: water velocity ↔ Buoyancy and Dispersion

↓

Movement of Oil Droplets

- Boufadel, Bechtel, and Weaver , Marine Pollution Bulletin, 2006
- Boufadel, Du, Kaku, and Weaver, Environmental Modeling & Software, 2006

Convection-Diffusion Equation with Buoyancy

$$\frac{\partial c}{\partial t^*} = -U^* \frac{\partial c}{\partial x^*} - V^* \frac{\partial c}{\partial y^*} - \left(W^* + w_B^*\right)\frac{\partial c}{\partial z^*} + \frac{\partial}{\partial x^*}\left(D_x^* \frac{\partial c}{\partial x^*}\right) + \frac{\partial}{\partial y^*}\left(D_y^* \frac{\partial c}{\partial y^*}\right) + \frac{\partial}{\partial z^*}\left(D_z^* \frac{\partial c}{\partial z^*}\right)$$

•Numerical solution suffers from numerical dispersion
•Use Langrangian (particle tracking) approach
•Neglibible transverse velocity (v* = 0)

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Bouyant Velocity, w_B

$$w_B \propto \Delta\rho,\ d,\ \frac{1}{C_d}$$

- $\Delta\rho$ = density difference = $\rho_w - \rho_o$
- d = particle diameter
- C_d = drag coefficient

$$w_B \uparrow \propto \Delta\rho\uparrow,\ d\uparrow,\ C_d\downarrow$$

$$w_B \uparrow \propto \rho_o\downarrow,\ d\uparrow,\ C_d\downarrow$$

$$0 \le w_B \le 0.15$$

Smaller or more dense vs. Larger or less dense

Non-dimensional Particle Tracking

$$x_{n+1} = x_n + u\,\Delta t + \varepsilon\, R\sqrt{2D\,\Delta t}$$

$$z_{n+1} = z_n + \varepsilon\left(w + w_B\right)\Delta t + \varepsilon\, R\sqrt{2D\,\Delta t}$$

- Updated particle positions due to
  - Time (Δt)
  - Velocity (u, w)
  - Turbulent Diffusion ($(2D\Delta t)^{0.5}$)
  - Randomness (R)
  - Wave Steepness (ε)
  - (in z) buoyancy (w_B)

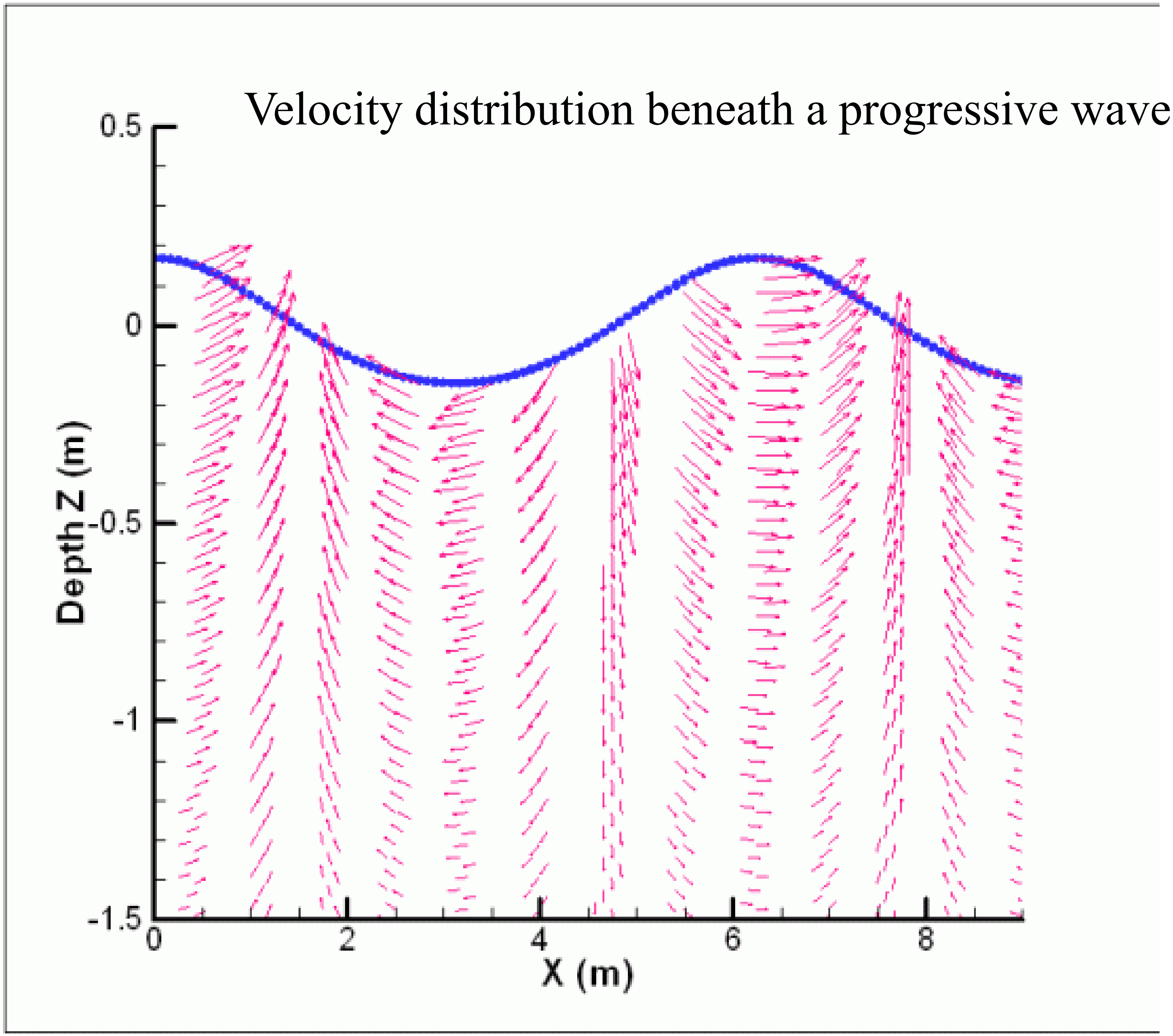
Velocities from Stokes Second Order Wave theory

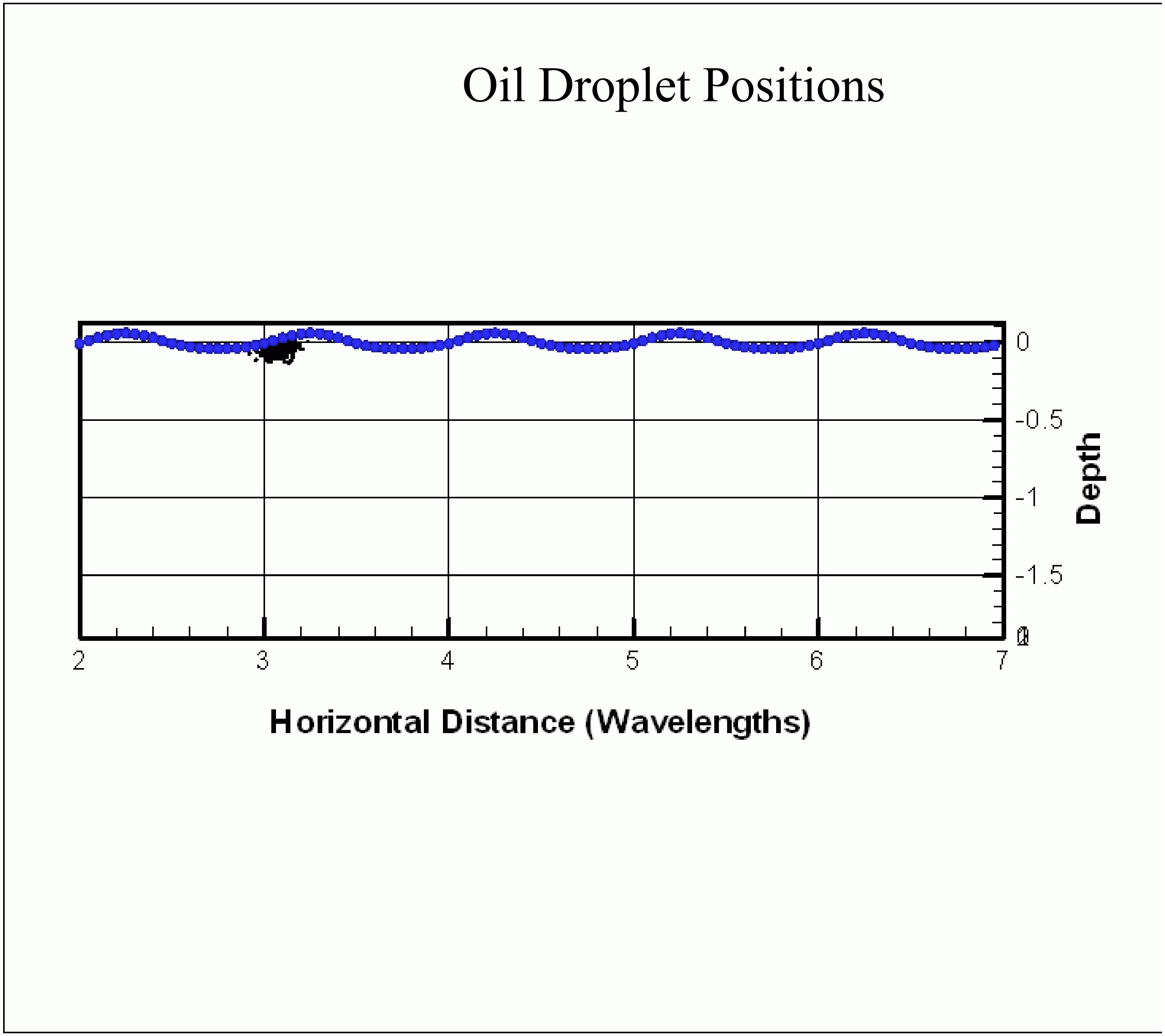
$$u^* = \frac{Hgk}{2\sigma} e^{kz^*} \cos\left(kx^* - \sigma t^*\right) + \frac{3H^2\sigma k}{16} e^{2kz^*} \cos 2\left(kx^* - \sigma t^*\right)$$

$$w^* = \frac{Hgk}{2\sigma} e^{kz^*} \sin\left(kx^* - \sigma t^*\right) + \frac{3H^2\sigma k}{16} e^{2kz^*} \sin 2\left(kx^* - \sigma t^*\right)$$

$$u = \frac{u^*}{\frac{L}{T}}; \; w = \frac{w^*}{\frac{H}{T}} \qquad k = \frac{2\pi}{L}; \; \sigma = \frac{2\pi}{T}$$

- H = wave height
- L = wave length
- T = wave period
- $\sigma = 2\pi/T$


Velocity distribution beneath a progressive wave
0.5
0
-0.5
-1
-1.5
Depth Z (m)
0
2
4
6
8
X (m)



Oil Droplet Positions
0
-0.5
-1
-1.5
Depth
2
3
4
5
6
7
Horizontal Distance (Wavelengths)

Monte Carlo Simulation

Wave steepness: $$\varepsilon = \frac{H}{L} = 0.05 \ and \ 0.1$$

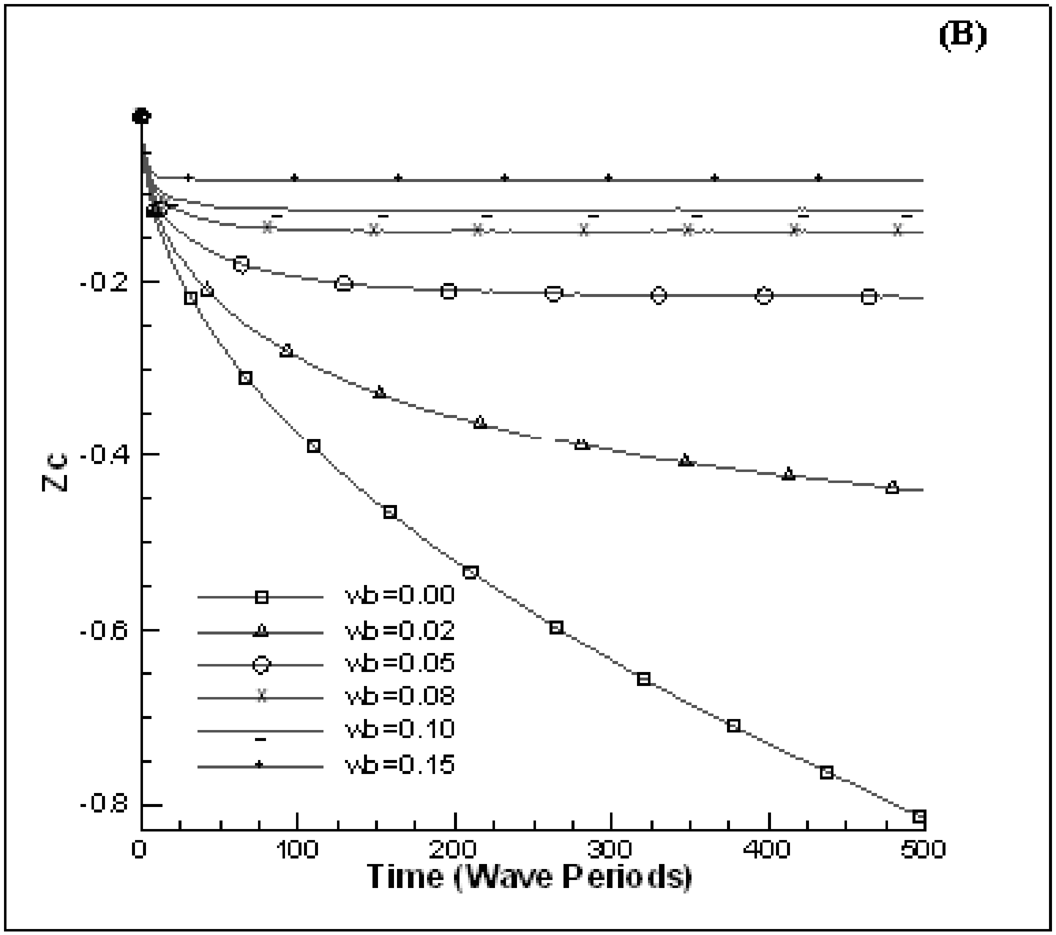
Buoyancy Velocity:

$$w_B = \frac{w_B^*}{\frac{H}{T}} = 0.0 \ to \ 0.15$$

Dimensionless turbulent diffusion coefficient: $$D = \frac{D^*}{\frac{H^2}{T}} = 0.1$$

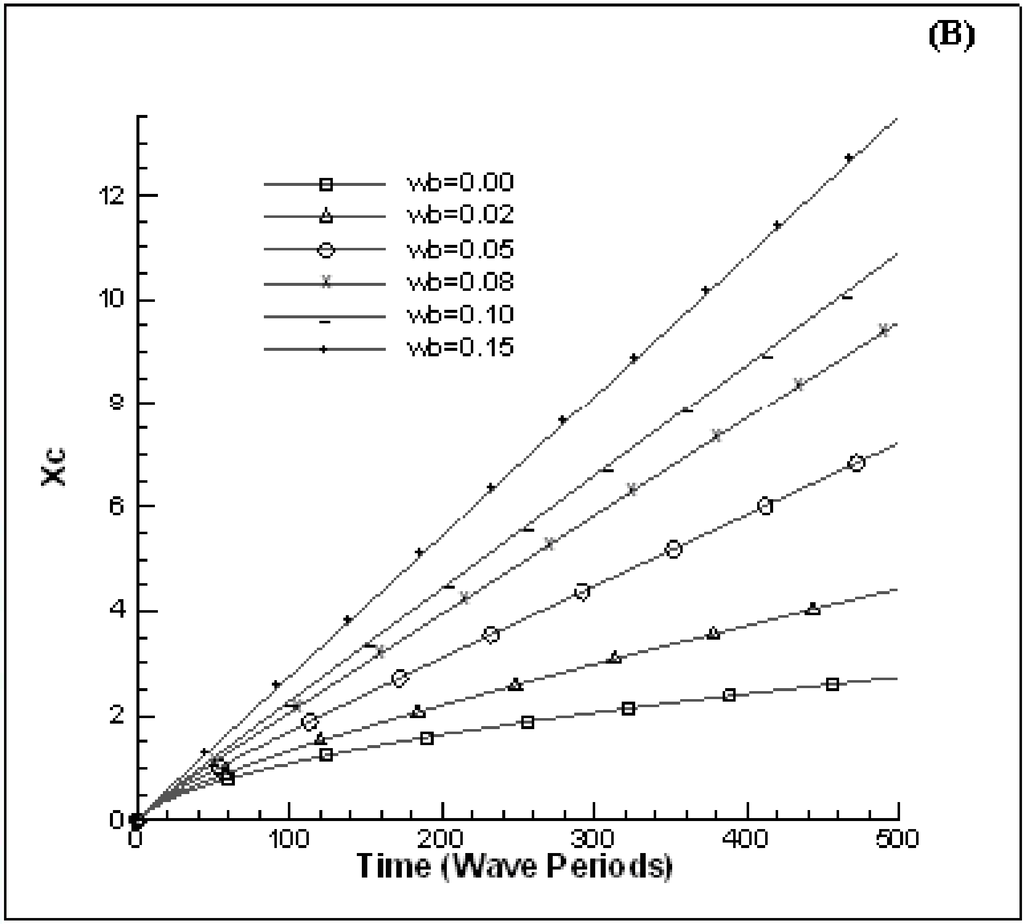
600 particles and 500 simulations

Effect of buoyancy on the vertical location of the centroid, Zc for H/L=ε=0.1. Depth unit is wavelength



- Lighter, larger droplets near surface
- Neutrally bouyant or smaller drop

Effect of buoyancy on the horizontal location of the centroid, Xc for H/L= ε =0.1.



Stoke's drift velocity:

$$\left(\frac{\pi H}{L}\right)^2 \frac{C}{2} \exp\left(\frac{4\pi z}{L}\right)$$

- Z = 0 at water surface
- Lighter, larger experience higher velocity

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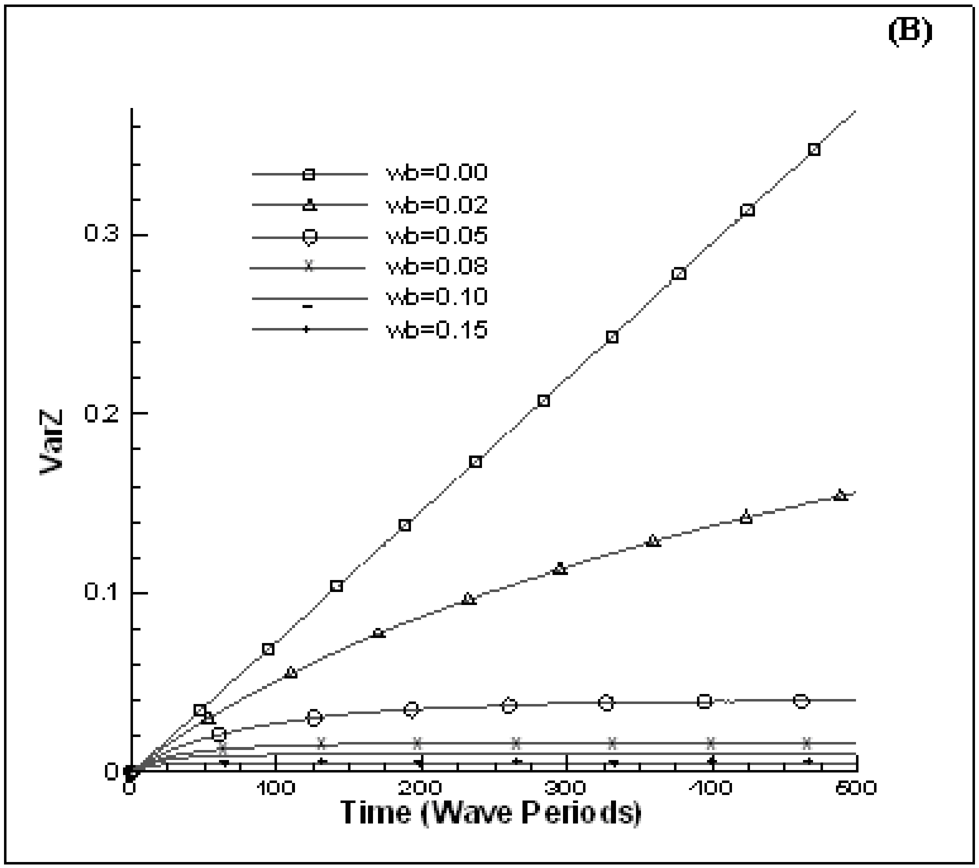
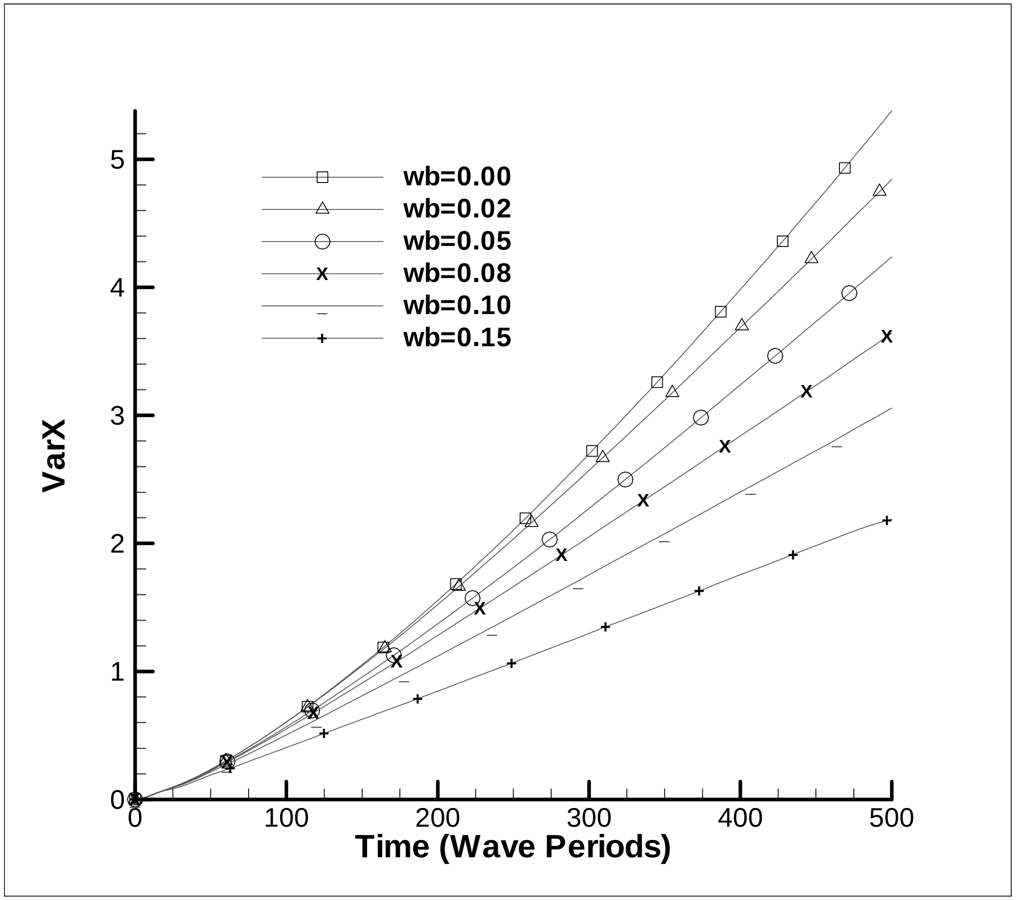
Effect of buoyancy on the dimensionless vertical variance, σ_z^2 for H/L= ε=0.1.



- Lighter, larger droplets remain in smaller zone with lower variance

Effect of buoyancy on the dimensionless horizontal variance, σ_x^2 for ε=0.1.



- Lighter, larger droplets spread less—less variation in Stoke's velocity

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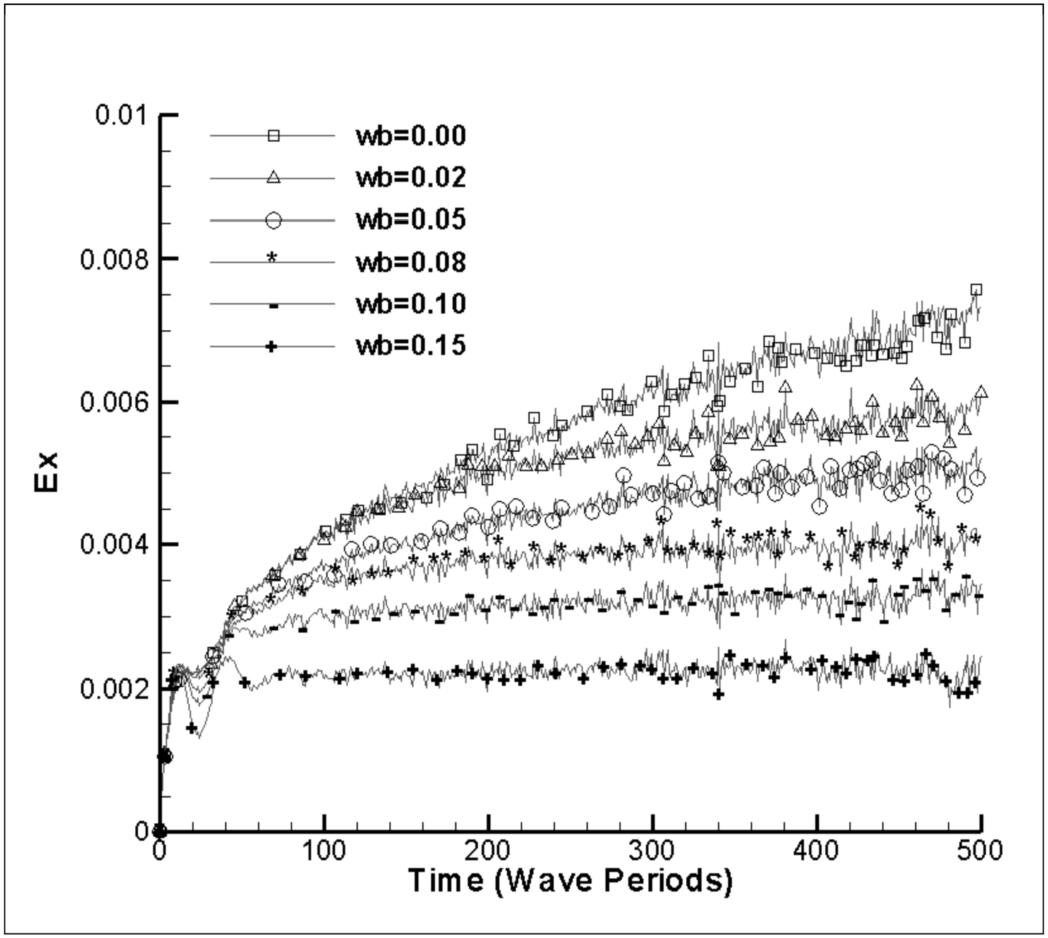
Dimensionless spreading coefficients E_x as function of time for H/L 0.10.



$$E = \frac{1}{2}\frac{d}{dt}\sigma^2$$

- Horizontal spreading coefficients tend toward constant value: D + drift

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- For the same size distribution, light oils moves faster but spread less than heavy oils.
- In fairly general conditions, the oil droplets become well mixed in the top 5 meters of the water column within 15 to 20 minutes.
- A novel dimensionless formulation to generalize the results to any oil was introduced.

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