Modeling the Influences of Surface Gravity Waves in the Oceanic Boundary Layer:

Stokes-Drift Vortex Forces and Material Advection

and

Impulses and Stirring by Breaking Waves

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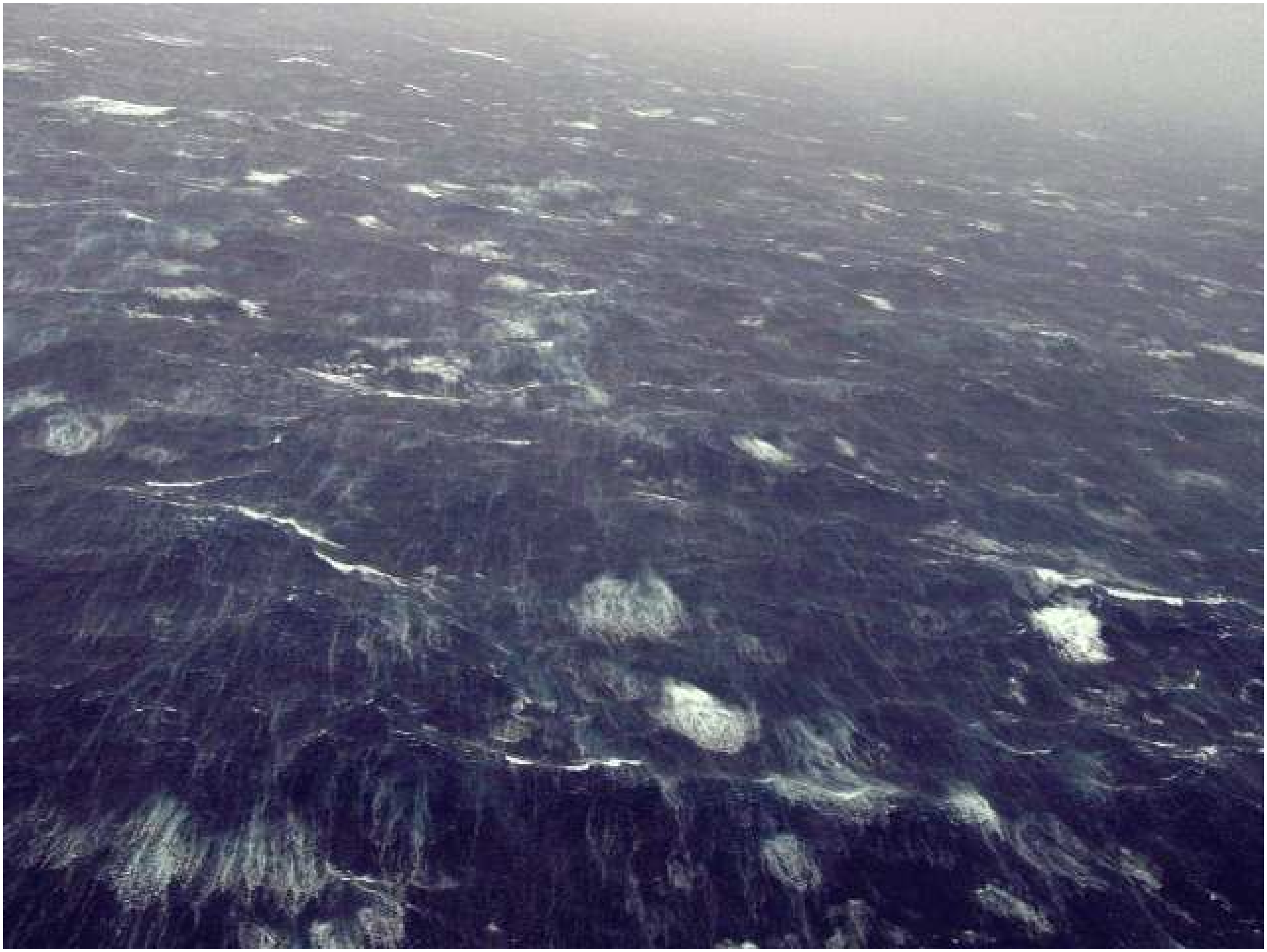
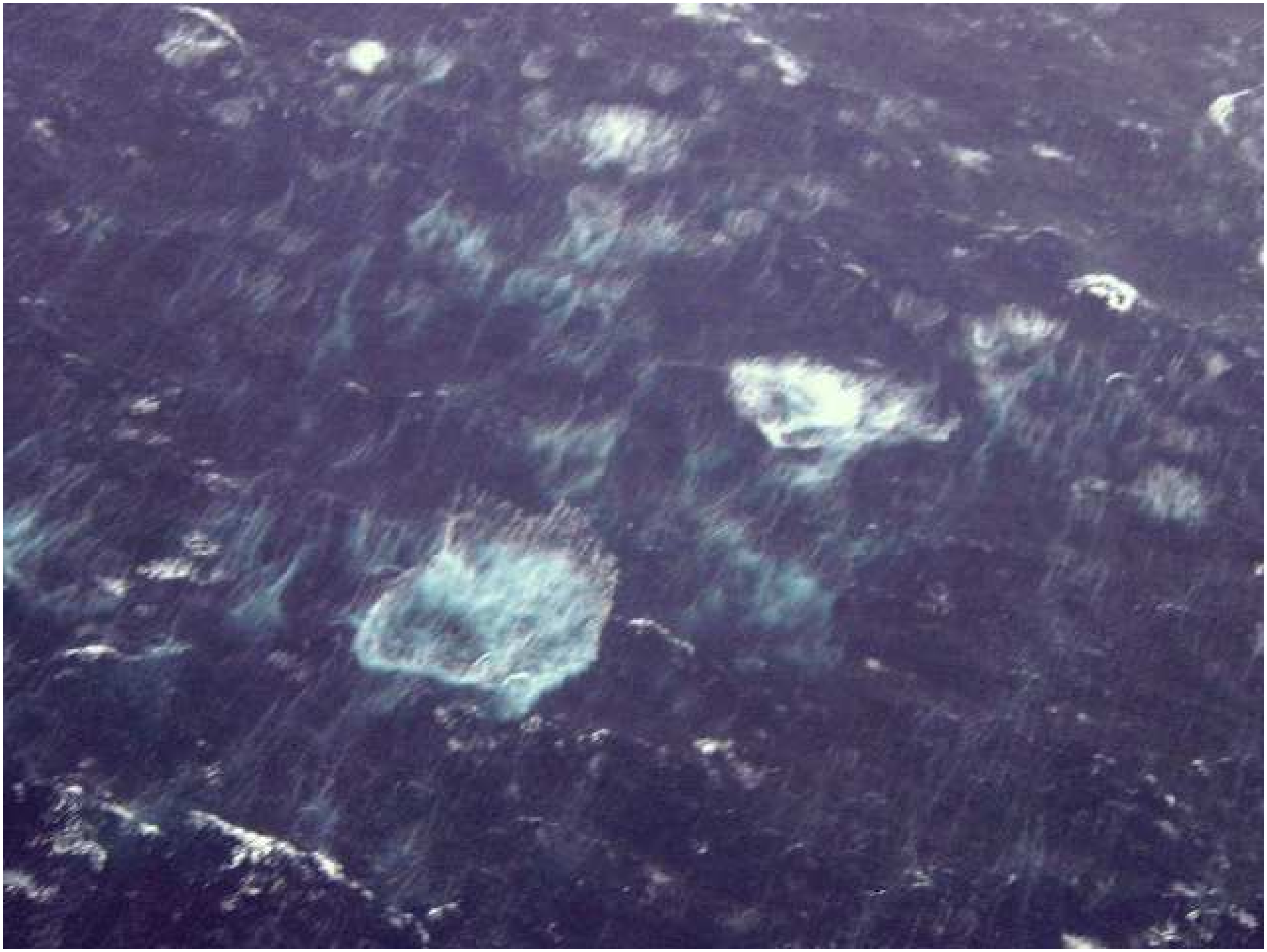


Sea surface under Hurricane Isabel photographed from a height of 150 m. Wave heights are ~ 10 m. (M. Montgomery, CSU).



Sea surface under Hurricane Isabel photographed from a height of 200 m Wave heights are ~ 10 m. (M. Montgomery, CSU).

Effects of surface waves on winds and currents:

- wave drag: wind momentum $\longrightarrow$ wave momentum (& sometimes *vice versa*).
- wave pumping: turbulent momentum flux by wave-correlated eddies.
- wave breaking: wave momentum $\longrightarrow$ current momentum; wave-enhanced dissipation and mixing; bubbles and droplets.
- wave-induced vortex force and Lagrangian transport $\Rightarrow$ *e.g.*, Langmuir circulations (*cf.*, radiation stress divergence).

... $\Rightarrow$ wind-wave-current co-evolution.

Why has it been so difficult to make progress on wind-wave-current interactions?

- The pattern complexity is high.
- The instrumental environment is fierce.
- The problem, in its entirety, is uncomputable.

Our approach is to isolate particular aspects by a combination of asymptotic theory and artful (i.e., non-fundamental) computations.

An Asymptotic Theory for Wave Effects on Currents

Elements:

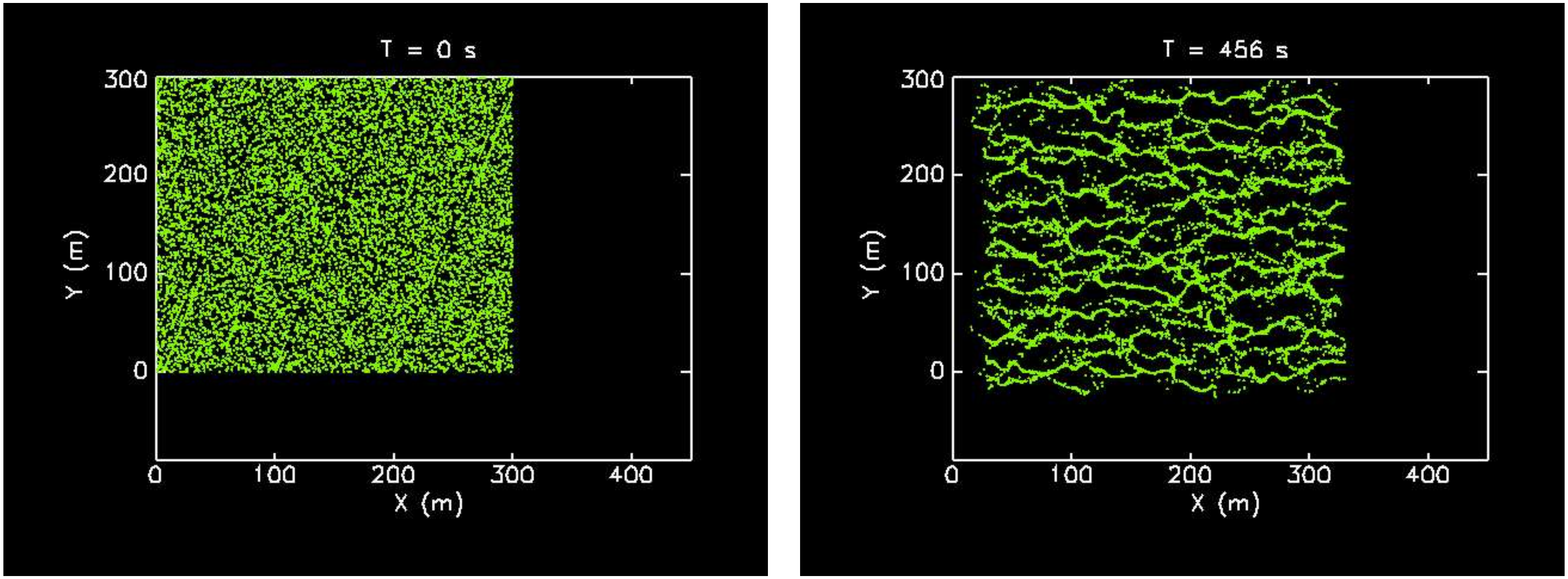
- primary waves: $\eta \sim a_o$, $L \sim 1/k_o$, $u \sim \epsilon c_o$ $\quad (\epsilon \equiv a_o k_o \ll 1)$.
- wave-forced long waves and sea-level set-up: $\eta \sim \epsilon a_o$, $L \gtrsim 1/\epsilon k_o$, $u \sim \epsilon^2 c_o$.
- currents in a rotating, stratified fluid: $\eta \sim \epsilon a_o$, $L \gtrsim 1/k_o$, $u \sim \epsilon^2 c_o$.

Wave-Averaged Large-Eddy Simulation (LES) Equations for Currents:

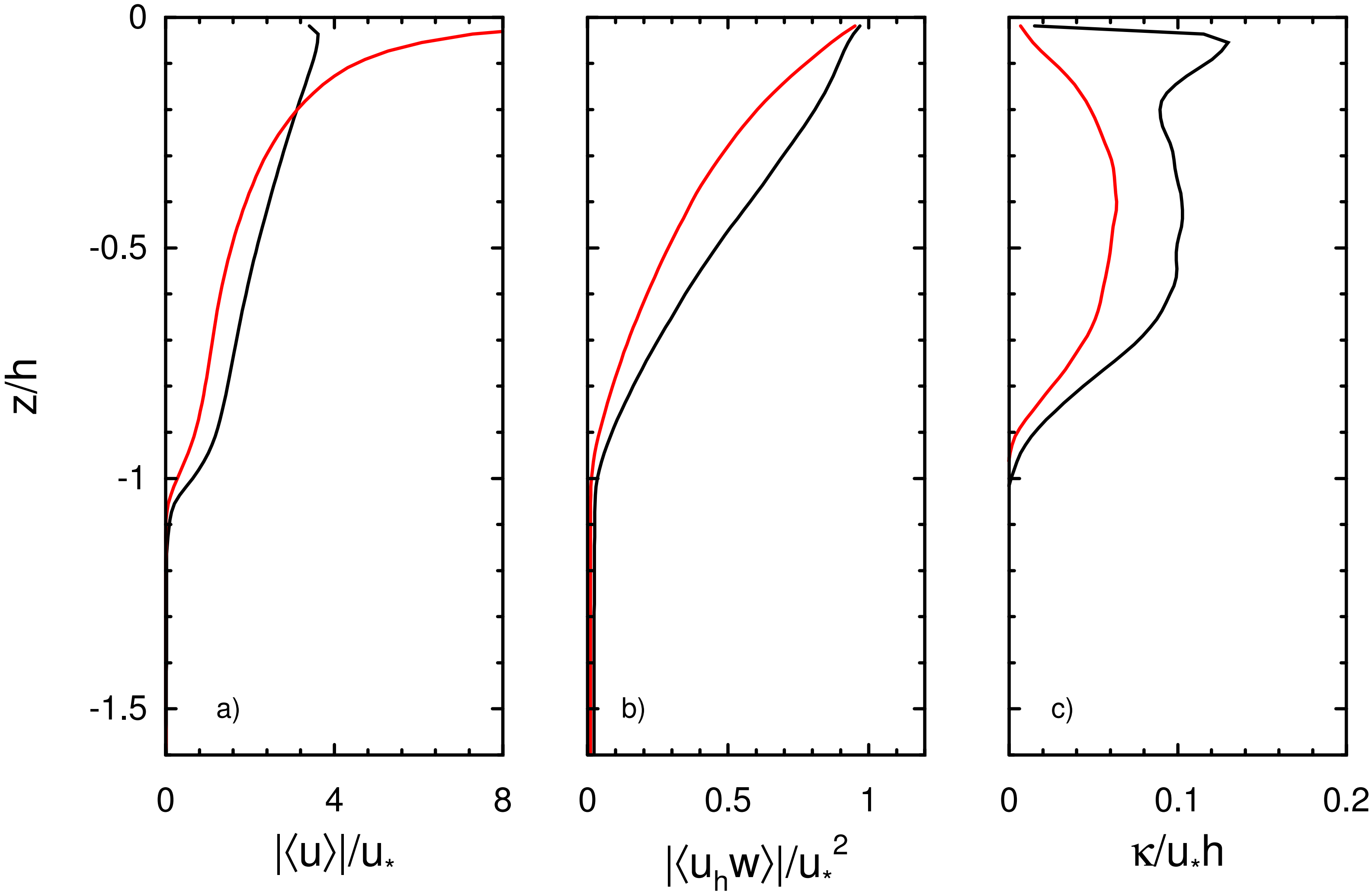
$$
\begin{aligned}
\frac{D\mathbf{u}}{Dt} + 2\boldsymbol{\Omega} \times \mathbf{u} + \frac{1}{\rho_o}\boldsymbol{\nabla} p + \frac{g\rho}{\rho_o}\hat{\mathbf{z}} &= -\boldsymbol{\nabla}\mathcal{B} + \boldsymbol{\mathcal{V}} + \mathcal{SGS} \\
\boldsymbol{\nabla} \cdot \mathbf{u} &= 0 \\
\frac{D}{Dt}(\rho, C) &= -\mathbf{u}^{St} \cdot \boldsymbol{\nabla}(\rho, C) + \mathcal{SGS} \ ,
\end{aligned}
$$

with wave-averaged forcing terms

- Bernoulli head: $\mathcal{B} = \frac{1}{2}\overline{\mathbf{u}^{wave} \cdot \mathbf{u}^{wave}}$.
- Vortex force: $\boldsymbol{\mathcal{V}} = \mathbf{u}^{St} \times (2\boldsymbol{\Omega} + \boldsymbol{\nabla} \times \mathbf{u})$.
- horizontal Stokes drift: $\mathbf{u}^{St} \perp \hat{\mathbf{z}} = \overline{[\,(\int^t \mathbf{u}^{wave}\, dt') \cdot \boldsymbol{\nabla}]\, \mathbf{u}^{wave}}$.
- Stokes vertical pseudo-velocity: $\mathbf{u}^{St} \cdot \hat{\mathbf{z}} = -\boldsymbol{\nabla} \cdot \, (\int^z \mathbf{v}^{St}\, dz')$.



Location of 10^4 buoyant surface particles initially and ten minutes after being randomly released in a LES of equilibrium rotating, stress-driven flow with the wave-averaged vortex force.



Down-wave, down-wind $\overline{u}(z)$ (left), $|\overline{\mathbf{u}'_\perp w'}|(z)$ (center), and diagnosed eddy viscosity, $\kappa(z)$ (right), in a LES of equilibrium rotating, stratified, stress-driven flow with (black) or without (red) the wave-averaged vortex force. h is boundary layer depth, and u_* is friction velocity.

Forcing DNS & LES Models by a Stochastic Representation of Wave Breaking

We assume that a breaking wave locally provides a forward momentum impulse $\mathbf{A}$ and sub-grid-scale energy generation W in a volume spreading downward and forward from the point of breaking.

This is modeled by adding terms to resolved momentum and SGS energy equations:

$$\frac{\partial \mathbf{u}}{\partial t} = \ldots + \mathbf{A}, \quad \frac{\partial e}{\partial t} = \ldots + W \ .$$

$\mathbf{A}$ & W depict the effect of a breaking event after the completion of the initial plunging and/or spilling motions.

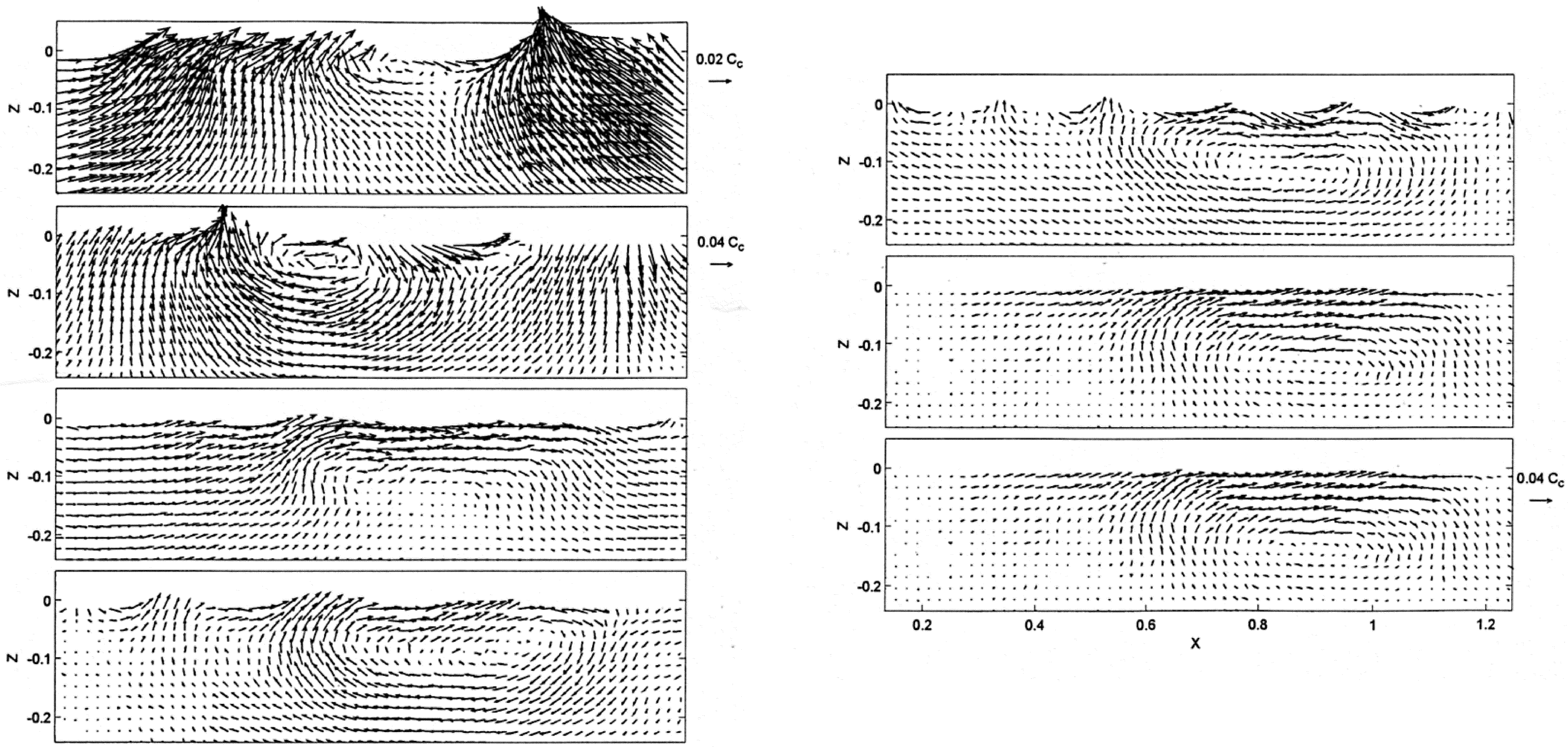
The net impulse from $\mathbf{A}$ compares to surface stress $\boldsymbol{\tau}$ by

$$\int_{-H}^{0} \mathbf{A}_{hor}\, dz' \quad \Longleftrightarrow \quad \frac{1}{\rho_o}\boldsymbol{\tau} \ .$$

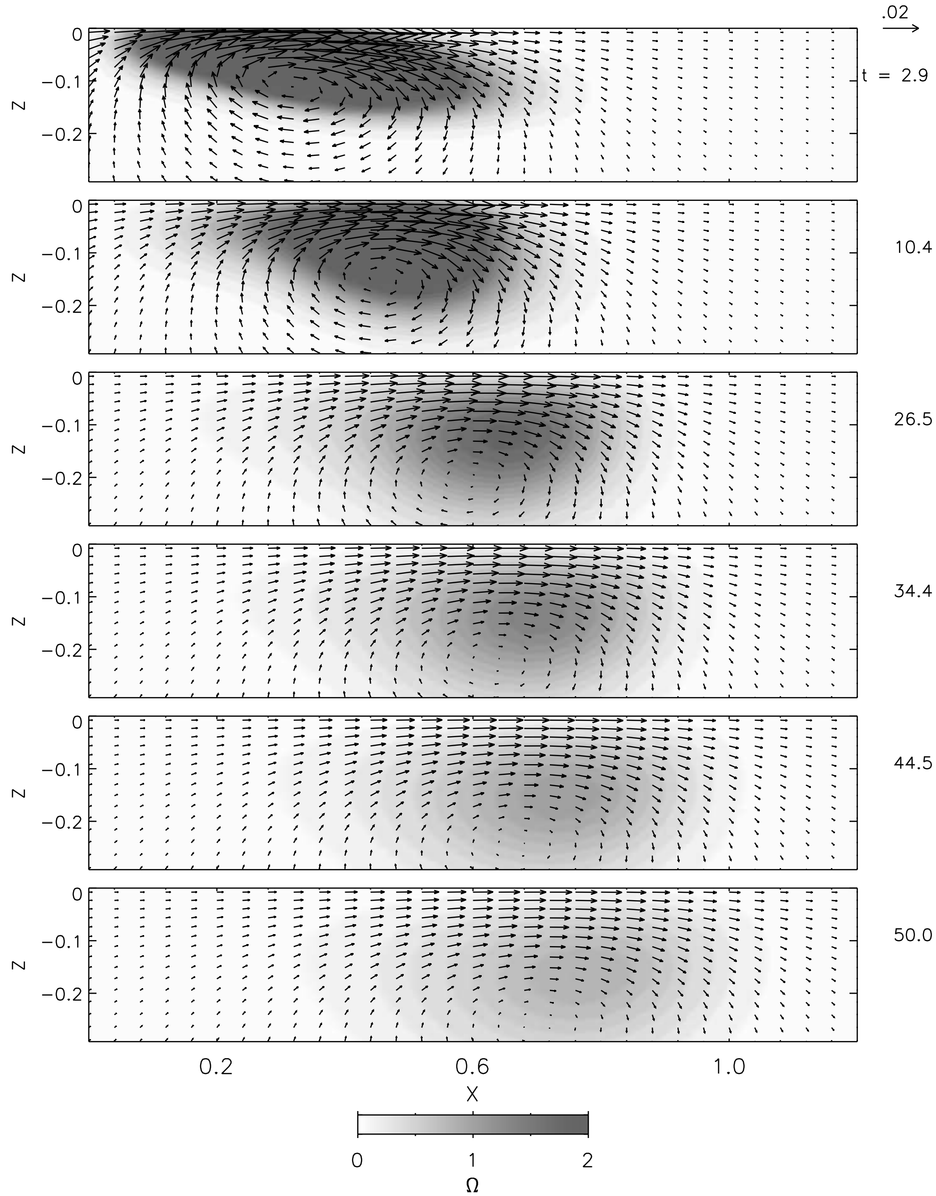
$\mathbf{A}$ & W are the sum of discrete breaking events randomly located in $(\mathbf{x}, t)$ and randomly distributed in $\mathbf{k}$ (or $\mathbf{c}$), each with a specified $(\mathbf{x}, t)$ shape locally.

DNS: Turbulence develops from the instability of the coherent impulses from $\mathbf{A}$, and $W = 0$.

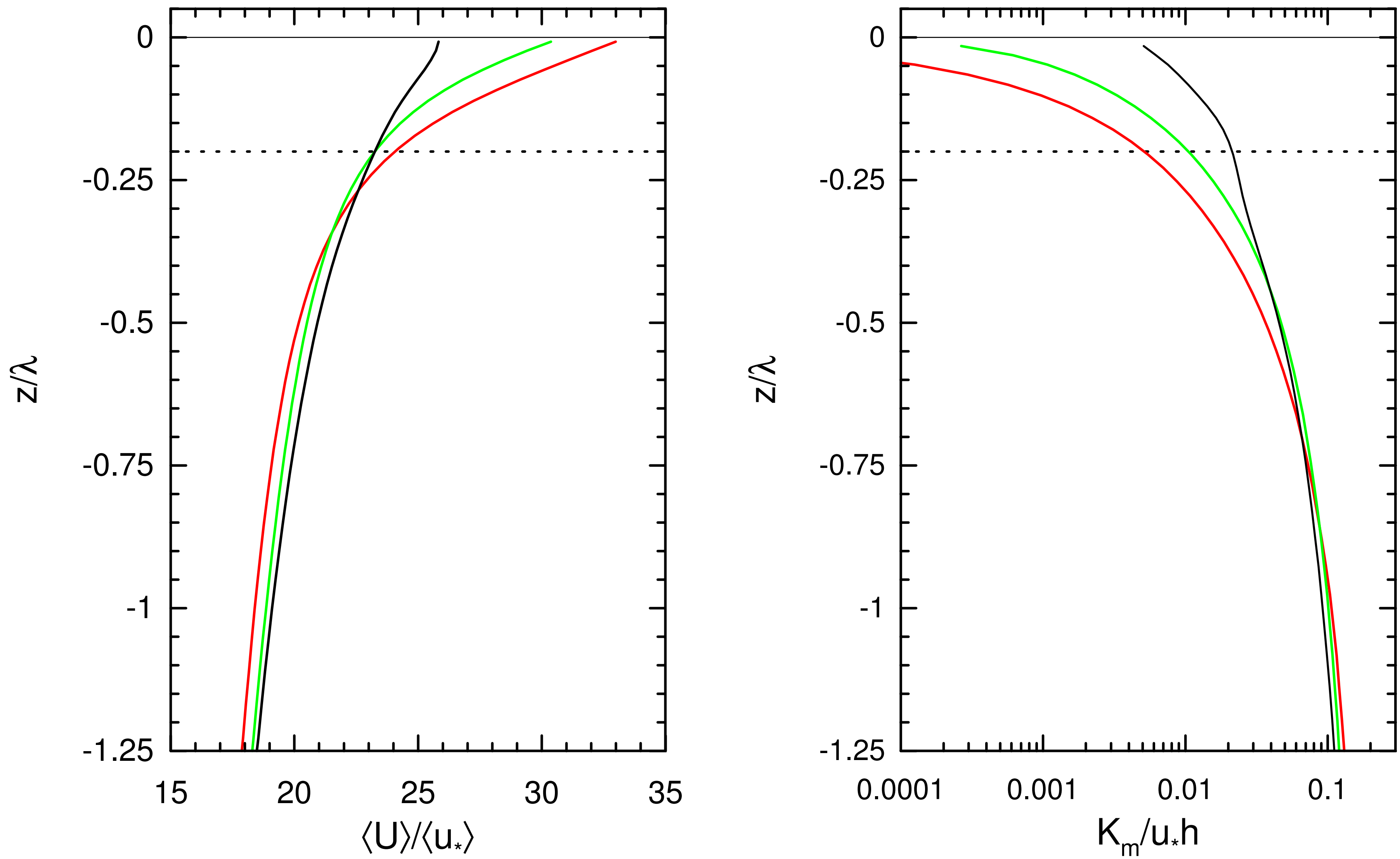
LES: $\mathbf{A}$ and $W \neq 0$ must be filtered to the resolved scales in $(\mathbf{x}, t)$, while preserving the total momentum and energy injection rates.



Composited velocity fields in a laboratory tank at a sequence of times after a breaking wave event: Δt = 3, 10, 26, & 35 s (left) and 43, 50, & 58 s (right). After Melville *et al.* (2002).



DNS of the (x, z)-velocity and y-vorticity for a single breaking wave modeled with impulse, $A^x > 0$, active over $\delta x/\lambda \approx 0.2$, $\delta t\, c/\lambda \approx 0.3$, and above $z/\lambda \approx -0.05$.



Down-stress, down-wave $\overline{u}(z)$ (left) and diagnosed $\kappa(z)$ (right) in a DNS for non-rotating, unstratified flow with equal surface stress alternatively as Couette b.c. (red), uniform stress (green), and stochastic breaking-wave impulses (black). λ is surface wavelength $\ll$ domain height.

Summary

1. We are examining pieces of the wind-wave-current interaction problem, focusing on wave-averaged effects

- drag, pumping, breaking, vortex force, Lagrangian advection

and moving towards putting them all together in boundary-layer and larger-scale LEddyS models (and LWaveS models someday).

2. In the oceanic boundary layer, the primary effects of waves are

- wave-averaged vortex force and 3D Stokes advection.
- breaking-wave impulses and mixing/dissipation.

3. The wave-averaged influences cause coherent Langmuir circulations that enhance the turbulent variance and dissipation rate, transport efficiency, and boundary-layer entrainment rate.

4. The breaking-wave influences modify the near-surface profiles of $\mathbf{u}(z)$ and $(\rho, C)(z)$, Langmuir circulations, and turbulence due to enhanced intermittency, mixing, and dissipation (in comparison with Monin-Obukhov structure near a solid boundary).

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