COUPLING MARINE ATMOSPHERIC BOUNDARY LAYER WINDS TO THE OCEAN SURFACE

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Collaborators: Jim McWilliams, Edward Patton, Jeff Weil, Mike Banner, Tetsu Hara
Reviews:

Edson et al. (BAMS, 2004)
[CBLAST Low]

Wanninkhof et al. (ARMS, 2009)
[Air-sea gas exchange]

Sullivan & McWilliams (ARFM, 2010)
[Coupling winds, waves & currents]

D’Asaro (ARMS, 2011)
[Ocean turbulence]

Veron (ARFM, 2015)
[Ocean spray]

Wind Waves Workshop
(Procedia IUTAM, 2018)

Broadband spectrum of time and space scales

mm (bubbles, spray)  100’s m swell  10’s km surface heterogeneity
OCEAN SUBMESOSCALE TURBULENCE, $L_x \sim [0.1 \text{ – } 10] \text{ km}$

Plankton patterns, Arabian Sea

Submesoscale turbulent “soup” with fronts, instabilities, vortices, and SST anomalies in the upper ocean, ROMS (UCLA)

Coupled WRF+ROMS with 1D BL parameterizations exist!
LES EXAMPLES OF 1-WAY COUPLING WITH AN OCEAN SURFACE: GRID MESH $10^9$ POINTS

**Surface waves:**
- Surface fitted time varying grid
- Imposed time varying spectrum of waves

**Heterogeneous SST:**
- Imposed warm and cold fronts, and filaments
- “Fourier-fringe” technique to control inflow-outflow turbulence
- Run 2 LES concurrently!

*Sullivan et al. (JAS, 2014, 2020)*
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Large Eddy Simulations of Marine Atmospheric Boundary Layers

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Wave driven winds
U Contours in yz-plane, $U_g = 10$ m/s, $Q_* = 0.01$ K m/s

Wavy boundary: $H_s \sim 6$ m

Grid mesh: $dx \sim 3$ m, $dz \sim 1$ m
SPATIALLY EVOLVING BOUNDARY LAYER DOWNSTREAM OF A WARM SST FRONT

- Growing internal boundary layer
- Nonlinear in z vertical fluxes
- Intermediate maximum in w variance
- Impressive evolution distance
- Impact on entrainment
- Secondary circulations

Vertical velocity $w, z = 41$ m
SST jump location indicated by white line

Change in mean wind speed from upstream state

$\Delta u (\text{m s}^{-1})$

$\theta \quad \theta + 2K$
COMPUTATIONAL CHALLENGES FOR SIMULATING TURBULENT WINDS WITH LES

- Flat surface with measured drag?

- Surface layer mechanics & drag:
  - Waves, what scales support the wind stress as $U$ varies?
  - Flow separation, critical layers, non-separated layers, breaking?

- Non-linear wave models
- Statistical, measured, phase-resolved waves?
- Non-equilibrium conditions:
  - Remote-generated swell, wave age
  - Misaligned winds and waves
  - Unstable to stable stratification

- Algorithm complexity:
- Coupling:
  - Ocean boundary layer plus submesoscale turbulence
  - Finite depth water
  - Heterogeneous SST and currents

- Coupled models:
  - Flat surface with measured drag?
CHANGE IN WIND SPEED DOWNSTREAM OF AN SST JUMP: SPATIALLY EVOLVING BOUNDARY LAYERS

Sullivan et al (JAS, 2020)
Normalized $U/U_g$ contours in xz-plane, Wave age $C_p/U_a = 4.2$

LES of a wave driven wind
GLOBAL CLIMATOLOGY OF INVERSE WAVE AGE

\[ U_a \cos(\phi)/C_p \] AVERAGED OVER 1958 - 2001

Equilibrium \( \sim 0.83 \)

Non-equilibrium winds and waves

Hanley, Belcher, Sullivan, JPO, 2010
Fig. 5. Contours of the $u$ component of the horizontal wind field for cases with moving and stationary surface waves. The nondimensional field shown is $u/U_0$. (top) Wind following waves; (middle) wind opposing waves; and (bottom) stationary humps. For each case the geostrophic wind $(U_0, V_0) = (5, 0)$ m s$^{-1}$, and the wave slope $\alpha = 0.1$ where the wave amplitude $a = 1.6$ m. In the top and middle panels the wave phase speed $c = 12.5$ m s$^{-1}$. The color bar changes between the top and middle panels. Note the supergeostrophic winds near the surface in the top panel.
\[ U_g = 10 \text{ m/s} \quad C_p/U_a = 2.3 \quad Q_* = 0.01 \text{ K m/s} \]
VERTICAL VELOCITY MOMENTS OVER 3D WAVES WITH SURFACE HEATING

The diagram shows the vertical velocity moments for different wave conditions:

- **Swell waves**: Represented by the black line.
- **Flat surface**: Represented by the red line.

The variable $\langle w^2/u^2 \rangle$ is plotted on the x-axis, and $\zeta$ (in meters) is plotted on the y-axis. The diagram highlights the turbulent transport differences between the two wave conditions.
HIGH RESOLUTION AIR-SEA INTERACTION (HiRES)
SURFACE WINDS ~15 m/s

• Next generation LES model of the marine PBL with a phased resolved spectrum of surface waves $\lambda > O(5m)$

• Use empirical and measured 2D wave fields as surface boundary conditions in LES

• See 3D animation on my web page
  https://drive.google.com/file/d/0B44_2BA1czYIVUZ5YkU2d1h3VU0/view

Image courtesy Tihomir Hristov
(U,W) Vectors and Pressure over Active Breakers