High Wind Upper Ocean Mixing with Explicit Surface Wave Processes

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LONG-TERM GOALS

The work described here supports the Office of Naval Research Departmental Research Initiative (DRI) for research on the "Impact of Typhoons on the Western Pacific Ocean" (ITOP). The theme of the DRI is to better characterize and predict the ocean boundary layer (OBL) and its impact on typhoon (hurricane) evolution. This is one component of developing improved prediction models for the coupled atmosphere-ocean-wave system. Cooling of the sea surface temperature (SST) is a critical coupling variable influencing atmosphere-ocean hurricane dynamics; SST is largely determined by OBL turbulence, surface wave processes, and mixed layer entrainment. Our research goal is to model the strongly forced wind and wave driven upper OBL using turbulence resolving large-eddy simulation (LES) with explicit wave effects, *viz.,* wave-current interactions and breaking waves and examine their impact on ocean mixing during hurricane events.

OBJECTIVES

The specific research objectives for ITOP are: (1) conduct process studies using LES of the OBL with different combinations of time varying large scale forcings and surface wave effects and examining their impact on ocean mixing; (2) evaluate and compare these LES results with predictions obtained using a 1-D column model of the OBL based on the K-Profile Parameterization (KPP); and (3) compare our simulation results with available observations. Inertial resonance, storm residence time, and the larger scale environment are some of the processes to be examined in our simulations.

APPROACH

Present computer power is insufficient to simultaneously resolve all the dynamical scales in a hurricane driven ocean basin where the largest scales of motion are $\mathcal{O}(100s)$ of kilometers in horizontal directions while the smallest critical scales associated with spray and bubbles in the

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air-sea interface are $\mathcal{O}(1)$ mm. Our interest is the strongly forced wind and wave driven upper ocean mixed layer where the turbulent motions are $\mathcal{O}(1-500)$ m. In order to examine this range of scales we developed an LES model of the OBL that accounts for surface wave effects through non-conservative breaking waves and phase-averaged, conservative wave-current interactions which lead to Langmuir circulations (Sullivan *et al.* 2007). The equations for the resolved flow components are the Craik-Leibovich (CL) theory with crucial wave-current coupling through the vortex force. The larger scale forcing (momentum and scalar fluxes) and wave fields are externally imposed in the LES.

WORK COMPLETED

Meetings: We attended a PI meeting in Honolulu HI that focused on refining elements of the ITOP field campaign. The discussion concentrated on the deployment of the numerous drifters, buoys, and floats and the coordination with the aircraft. A summary of the discussion is available from E. D'Asaro (U. Washington). We also presented a summary of our modeling results from the HRES and ITOP (Impacts of Typhoons on the Western Pacific Ocean) departmental research initiatives at the ONR program review (June, 2009) in Chicago.

Publication: Last year we wrote an article for *Annual Review of Fluid Mechanics* (see Sullivan & McWilliams, 2010). Our contribution discusses the coupling processes between surface gravity waves and adjacent winds and currents in the marine boundary layers. Wind-wave and wave-current interactions are important as these processes modulate the exchanges of momentum, heat, and gases between the atmosphere and ocean. Atmospheric processes we discuss are wind-driven waves, wave-driven winds, steep waves and drag laws. In the ocean boundary layer, we summarize the currently accepted views of wave-current interactions, the modeling of Langmuir circulations, impacts of breaking waves, and the implications of wave-current interactions for mixing at high winds.

Modeling Work: During this first phase of ITOP we concentrated on adapting our large-eddy simulation code for the OBL to a high wind regime with time varying winds, surface scalar fluxes, and wave fields. For our LES process studies, Hurricane Frances is selected as a canonical storm. Frances was a large category 4 hurricane that developed in the Atlantic basin in 2004 and was one of the most heavily studied storms in the ONR-sponsored Coupled Boundary Layer Air-Sea Transfer (CBLAST) program (Black *et al.* 2007). Novel profiling floats (Sanford *et al.* 2007) document the upper ocean mixing induced by this storm. The impact of the storm on currents and scalars is also extensively examined by Zedler (2007) using the MIT ocean modeling system. Zedler (2007) estimates Hurricane Frances had a radius of maximum winds $R = 40$ km with a surface rotational wind speed $V_r \sim 50 \text{ms}^{-1}$.

The general design of the LES experiments is to pass a hurricane vortex over small LES domains as sketched in figure 1. Then the surface fluxes and wave fields imposed at the water surface vary with time depending on the storm propagation speed V_s and the location of the LES domain (x_{LES}, y_{LES}) within the storm track (see discussion in RESULTS). Our process studies examine the impact of resonant and anti-resonant wind and inertial-current forcing (*e.g.,* Price, 1981) by locating LES domains to the right and left of the storm track. Also, the solution sensitivity to surface cooling is considered, *i.e.,* simulations with and without a surface cooling flux are performed.

The initial temperature state of the OBL for all the LES experiments is neutrally stratified over the region -33 m $< z <$ 0 m bounded by a stable inversion of 0.05 C m^{-1} for $z < -33$ m. The LES domain $(X_L, Y_L, Z_L) = (750, 750, -195)$m is discretized using $(N_x, N_y, N_z) = (500, 500, 160)$

gridpoints; the vertical spacing varies smoothly from $\triangle z = 1.0$ m near the water surface to about $\triangle z = 1.4$ m near the lower boundary. Each simulation is first run from a cold start for a period of ~ 10 hours to generate turbulence. The LES is then restarted using these archived turbulent flow fields as initial conditions. For LES experiments with wave effects, we set the turbulent Langmuir number $La_t = 0.3$ and wave age $= 0.6$ which fixes the parameters in an exponential Stokes drift profile (Sullivan & McWilliams, 2010). As shown in figure 2, the winds vary considerably with t and as a result the computational timestep $\triangle t$ decreases from about 7.1 seconds at the beginning of the simulation to about 0.65 seconds at the time of maximum winds. More than 190,000 timesteps are needed to cover the entire 60 physical hours of interest for cases located along the path of maximum wind speed. We note that the OBL LES code used here is a variant of the new highly parallel atmospheric code that is being developed for the high resolution air-sea interaction (HRES) DRI. The algorithm is based on an incompressible Boussinesq flow model and solves the governing equations utilizing a mixed finite-difference pseudospectral scheme. The parallelization is accomplished utilizing the Message Passing Interface and a 2-D domain decomposition, see Sullivan & Patton (2008) for further details.

RESULTS

Figure 2 shows the variable time forcing applied to the water surface on the right-hand-side of the storm track and the resulting profiles of vertical scalar flux and vertical velocity variance. At each time, the profiles of $\langle w'\theta \rangle$ and $\langle w'^2 \rangle$ are obtained by averaging over a time window of about 30 minutes. The scalar flux and vertical velocity variance are normalized by the surface heat flux Q_* (shown in the upper panel of figure 2) and the surface friction velocity u_{*o}^2 found from a saturated bulk aerodynamic drag rule (Zedler, 2007), respectively. The temporal variation of the maximum entrainment flux is interesting. Over the period $t = [0, 20]$ hrs the maximum entrainment flux ratio $-\langle w'_e \theta \rangle / Q_* \sim [0.2, 0.5]$, *i.e.,* the entrainment flux is only slightly larger than is observed in the daytime convective boundary layer over land (*e.g.,* Sullivan *et al.* 1998). We attribute this increase to the presence of Langmuir cells shown in figure 4 as discussed in McWilliams *et al.* (1997). For $t > 20$ hrs the rapid increase in surface winds drives the OBL into a shear dominated regime and then the OBL temperature evolution is dominated by entrainment dynamics. The maximum entrainment flux $-\langle w'_e \theta \rangle / Q_* \sim 12$ occurs near $t \sim 35$ hrs, *i.e.,* at the time of maximum winds. Beyond $t > 40$ hrs the evolution of the temperature field is complex as the surface wind and wave forcing relaxes and the OBL turbulence decays on a background of strong stable stratification. Also the hurricane wake becomes strongly three dimensional (Sanford *et al.*2007) which is an effect not captured in our small scale LES domains. The vertical velocity variance shows a layer between $0 \leq -z \leq 30$ m of enhanced vertical velocity variance. The maximum $\langle w'^2 \rangle / u_{*o}^2$ is about 3.5 and persists over the majority of the simulation period $16 < t < 54$ hrs. This elevated vertical velocity variance is observed in all LES with vortex force under steady wind forcing with the amplitude of the vertical velocity maximum dependent on the wave field.

The impact of track location on the sea surface temperature is given in figure 3. In these idealized LES the cooling is greatest on the resonant right-hand-side due to inertial shear instabilities, as expected. The inclusion of vortex force, based on a simple model for Stokes drift, lowers the sea surface temperature by about $-(0.11, 0.41, 0.22)$ degrees C or $(43, 37, 15)\%$ at $t = (30, 40, 50)$ hours. This is primarily a consequence of the vigorous Langmuir circulations that develop in the mixed layer (see figure 4). Comparing the vertical velocity at similar depths we notice that organized streaky structures elongated in the $y-$direction form in the presence of vortex force. At this depth, the Langmuir cells have length-to-width aspect ratios of about 8:1 with the instantaneous downwelling speeds in these structures exceeding -0.25 m s^{-1}.

IMPACT/APPLICATIONS

The LES results obtained here for hurricane driven OBLs can be used to guide the interpretation of observations collected during the ITOP program. In addition, the results can be used to test simpler 1-D parameterizations of the ocean mixed layer that are used in large scale models. Our particular interest is in evaluating and improving the so-called K-profile parameterization (KPP) that is routinely used in the Regional Ocean Modeling System (ROMS).

TRANSITIONS & RELATED PROJECTS

The present work has links to the ONR DRI on High Resolution Air-Sea Interaction (HRES) that focuses on the interaction of waves and turbulence in the atmospheric surface layer. The LES model being developed for HRES is also being used in the present work.

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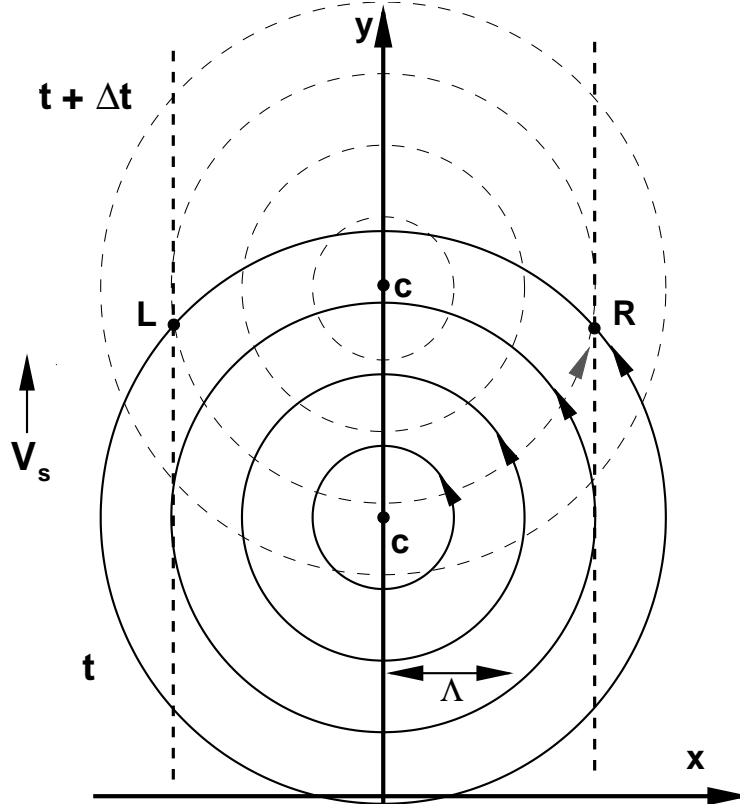
Figure 1: Sketch of an idealized hurricane vortex used for setting the surface conditions in LES. The vortex is propagating upward with speed V_s and has a characteristic length scale (radius of maximum winds) Λ. The families of solid and dotted circles indicate the position of the vortex at initial time t and at a later time $t + \triangle t$, respectively. The fixed LES domains to the right (R) and left (L) of the vortex center (c) feel the time history of wind speed and direction along the dotted vertical lines.
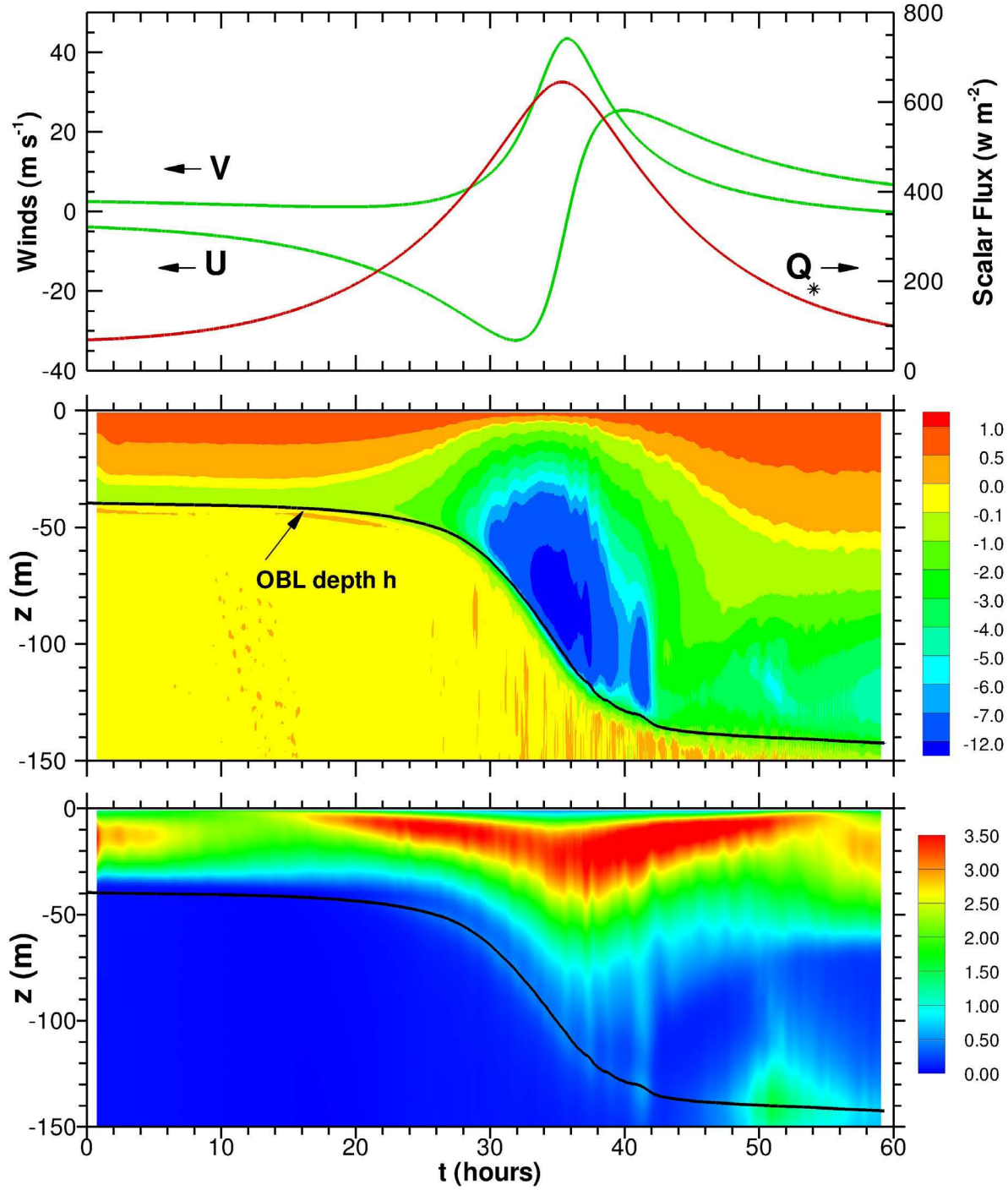
Figure 2: Vertical profiles of turbulent scalar flux and vertical velocity variance from an LES of an OBL driven by Hurricane Frances winds and buoyancy with vortex force. The time variation of the wind (U, V) and buoyancy forcing Q_* is given in the upper panel. The LES domain is located on the right hand (resonance) side of the storm, initially $(55, 700)$ km east and north of the storm center. The storm propagates northward at 5.5 m s^{-1}. The total scalar flux $\langle w'\theta' \rangle / Q_*$ and vertical velocity variance $\langle w'^2 \rangle / u_{*o}^2$, are shown in the middle and lower panels, respectively. The black line is the depth of the maximum vertical temperature gradient, which can be interpreted as the OBL depth. The mesh is $500 \times 500 \times 160$ gridpoints and the timestep $\triangle t$ varies from 15 s to 0.4 s over the length of the simulation. The total number of timesteps $\sim 200,000$.
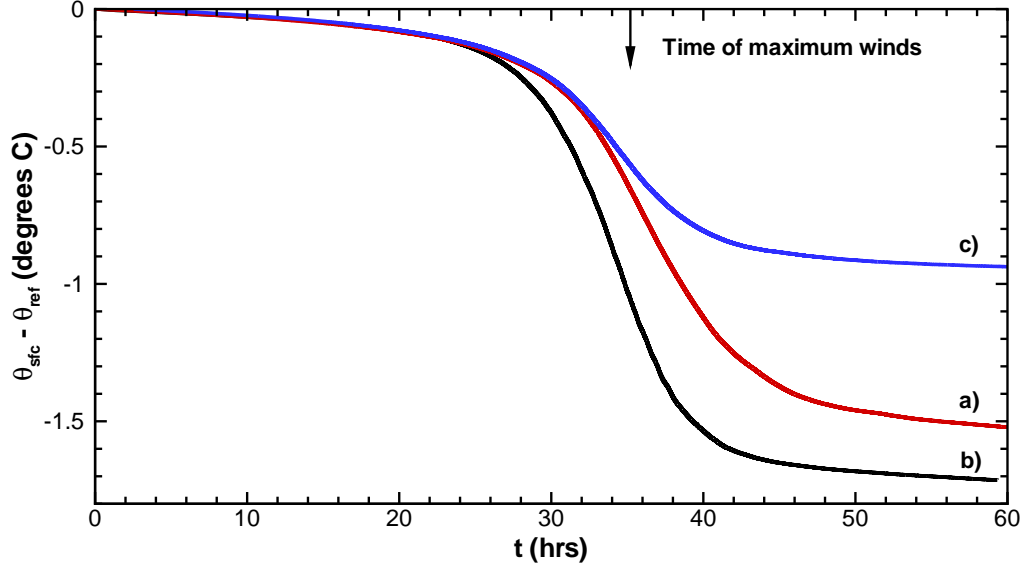
Figure 3: Variation of SST for three different LES driven by time varying winds and cooling. a) resonant side of storm track and no wave effects; b) resonant side of storm track with simple model of Stokes drift; and c) non-resonant side of storm track and no wave effects.
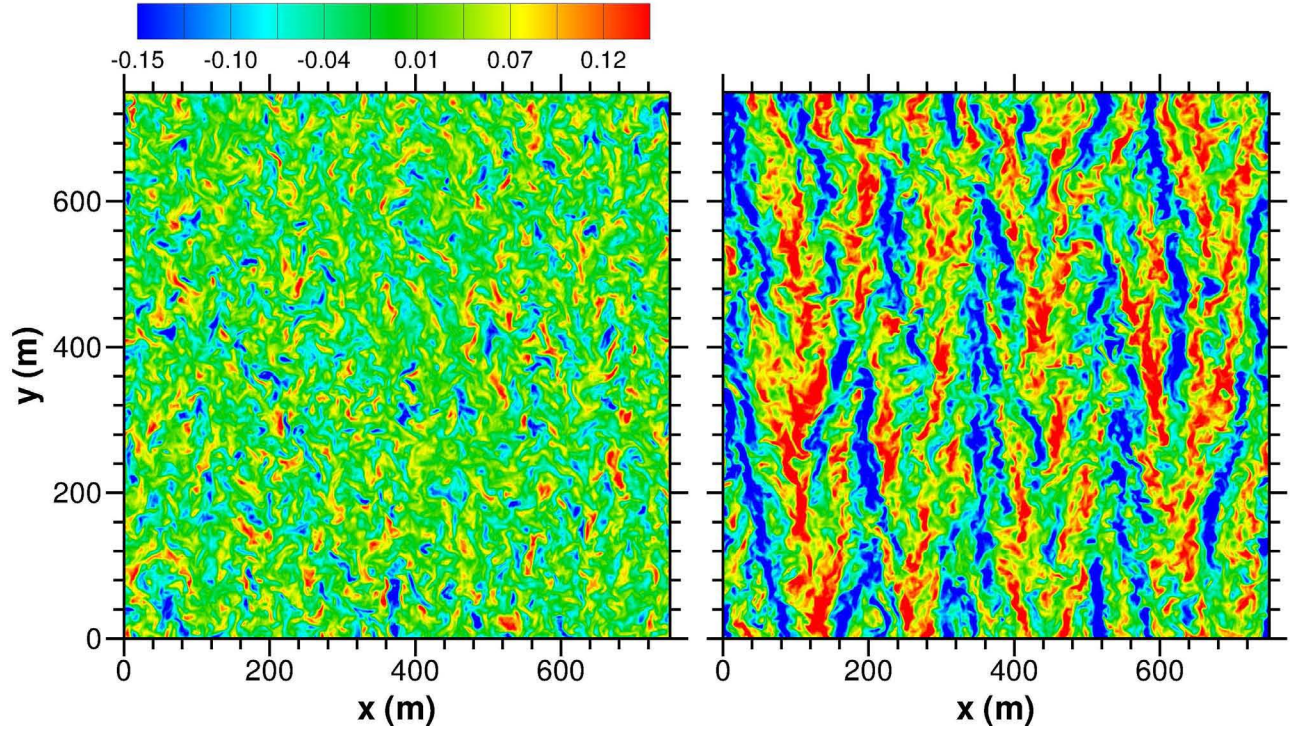
Figure 4: Visualization of the vertical velocity field in an $x - y$ plane at $z = -30.0$ m at the time of maximum winds shown in figure 2, $t \sim 35.3$ hrs. The left panel shows results from an LES with no vortex force while the right panel is a simulation with $La_t = 0.3$ and wave age $= 0.6$. At this simulation time, the wind and wave-propagation directions are south to north. In the right panel, the elongated regions with $w << 0$ (the blue contours) are the downwelling signatures of Langmuir circulations. The color bar is in units of $\mathrm{m\,s^{-1}}$.

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