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 $\mathcal{O}(100\text{s})$ of kilometers in horizontal directions while the smallest critical scales associated with spray and bubbles in the

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14. ABSTRACT
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.

15. SUBJECT TERMS

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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. 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

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. A total of six different LES cases were generated with wave effects neglected in these first cases.

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 K m^{-1} for $z < -33$ m. The LES domain $(X_L, Y_L, Z_L) = (750, 750, 150)$m is discretized using $(N_x, N_y, N_z) = (500, 500, 128)$ 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 $\sim$ 10 hours to generate turbulence. The LES is then restarted using these archived turbulent flow fields as initial conditions. 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 100,000 timesteps are needed to cover the entire 60 physical hours of interest. 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 is an example of the variable atmospheric forcing, *viz.,* the 10 meter winds and surface cooling, applied to the OBL at a point located $(55, 700)$ km east and north of the hurricane origin; the vortex is propagating northward (in the y direction) at a constant speed of 5.5 ms^{-1}. At this location, the time of maximum winds occurs at $t = y_{LES}/V_s \sim 35$ hours with $\sqrt{U_{10}^2 + V_{10}^2} \sim 43.5$ ms^{-1}. For specifying the OBL surface momentum fluxes a saturated wind speed dependent drag coefficient (Donelan *et al.* 2004 ; Powell *et al.* 2003 ; Zedler, 2007) is used while scalar fluxes are estimated adopting a relative humidity $q_{rel} = 0.8$ and a $\triangle T = 2.5$ degree K temperature difference between the water surface and the 10 meter reference height. Precise values of $(q_{rel}, \triangle T)$ are unknown but the values chosen here are typical (*e.g.,* Jacob & Shay, 2003; D'Asaro, 2003; Zedler, 2007).

We are just beginning to interrogate the parameter space of winds, scalar fluxes and wave fields and their impact on scalar mixing and SST with the LES solutions. One of the intriguing features of time varying forcing is the potential for regime changes in the OBL turbulence depending on the relative contributions of external cooling, shear, and wave forcings (*e.g.,* McWilliams *et al.* 1997; Li *et al.* 2005). Figure 3 compares the Monin-Obukhov length L for two different locations in the storm track, *viz.,* one near the radius of maximum winds and another located at 250 km to the east. Essentially L provides a measure of the relative contributions of shear and cooling in the surface layer of the OBL. By analogy with the atmospheric boundary layer (*e.g.,* Moeng & Sullivan, 1994), but in the absence of waves, we expect the OBL to be dominated by cooling when $-|h|/L > 20$ and by shear forcing when $-|h|/L \leq 1$. We notice that the hurricane OBL experiences a spectrum of forcing over the duration of the storm that also depends on the position relative to the storm track. In this example, shear is expected to dominate the OBL over the time period $20 < t < 50$ hours with both cooling and shear playing roles early and late in the simulation. The particular turbulent coherent structures that develop as a result of the forcing in each regime play important roles in the thermocline mixing, *e.g.,* convective rolls, shear vortices, and Langmuir turbulence. The introduction of surface waves into our LES using Craik-Leibovich vortex forces and wave breaking are expected to further modify the mixing process in the OBL (Sullivan *et al.* 2007).

In figures 4 and 5 we compare space averaged Huvmuller diagrams of potential temperature, *i.e.,* we show horizontally averaged vertical profiles of $\langle\theta(z, t)\rangle$ as function of time, from four LES computations over a period of nearly 60 hours. The LES domains are located left and right of the storm track and results are obtained with and without surface cooling. If we compare simulations on the same side of the storm track we notice surface cooling does alter the temperature state of the OBL. In other words, entrainment at the base of the thermocline is the dominate process for lowering SST in a hurricane but surface cooling also plays a role (*e.g.,* Zedler, 2007). The most striking impression from these simulations is the dramatic difference in mixing on the left and right hand side of the storm track. This is a consequence of vigorous entrainment at the OBL thermocline shown in figure 6. Note entrainment of cool water from below can be as much as 7 to 8 times the surface cooling flux depending on the location relative to the storm track.. As expected (*e.g.,* Price, 1981), deeper enhanced mixing is found on the resonant right-hand side of the storm with the mixed layer deepening to nearly 100 meters in this example compared to 60 meters on the left hand side. We note that the results in figures 4b and 5b are qualitatively similar to the observations presented by Sanford *et al.*(2007). A first inspection of the time dependent LES solutions at the time of maximum winds shows a complex system of gravity waves develops below the inversion that persist to late time in the simulations. Their role in the mixing process along with the introduction of surface waves will be pursued in the future.

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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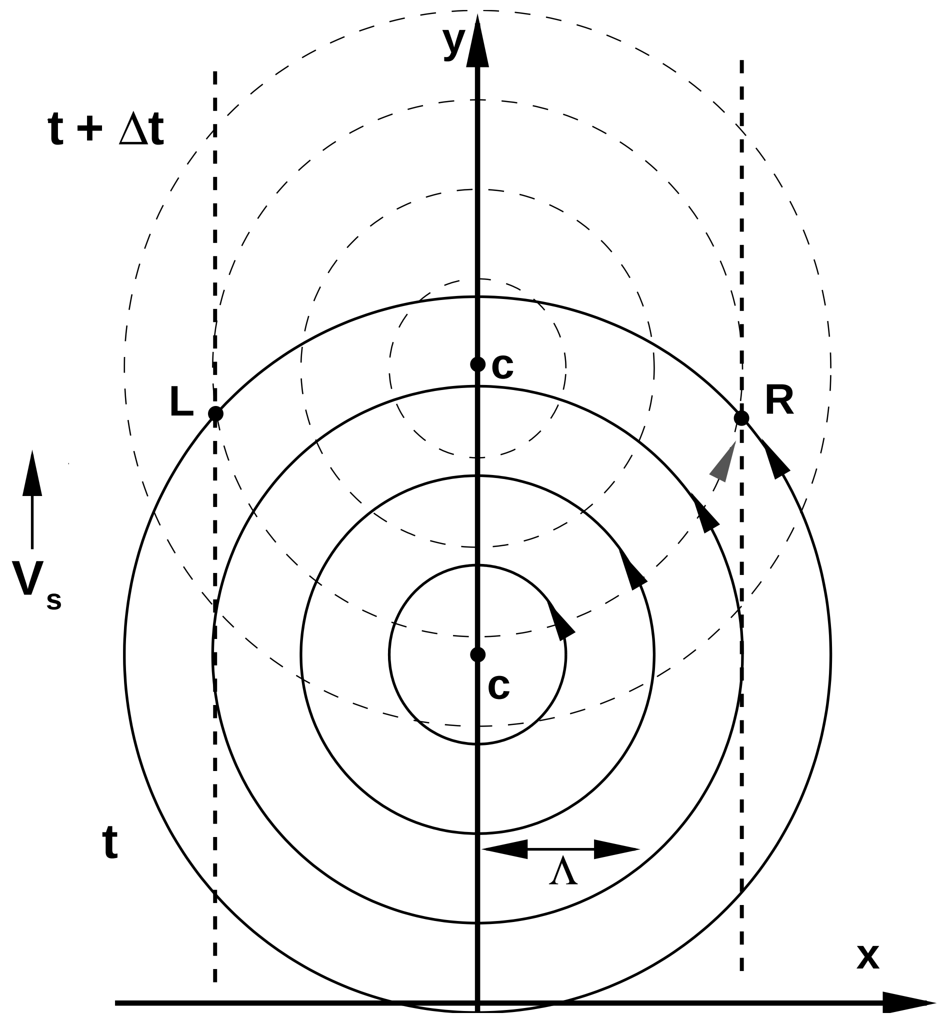

Figure 1: Sketch of an idealized hurricane vortex used for setting the surface conditions in LES. The vortex is propagating upward with speed V_s and has a characteristic length scale (radius of maximum winds) Λ. The families of solid and dotted circles indicate the position of the vortex at initial 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.

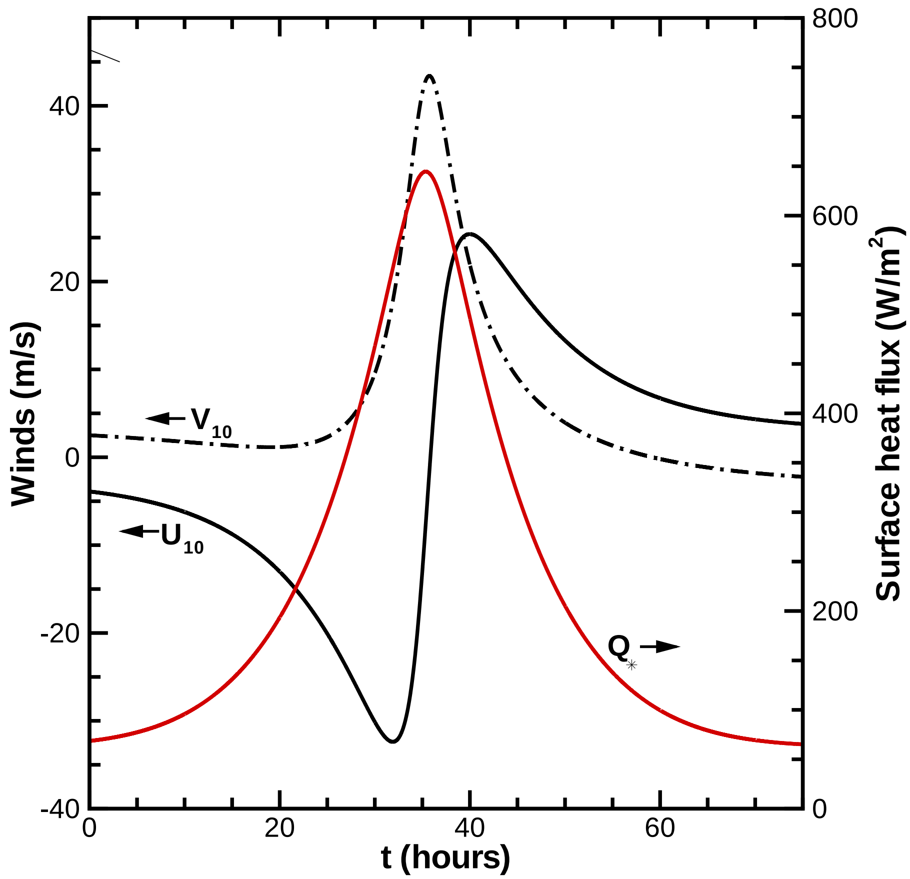

Figure 2: Time variation of the easterly and northerly wind components (U_{10}, V_{10}) and surface potential heat flux Q_* (at the 10 meter height) used to drive the ocean LES. In this example, the LES domain is located at $x = 55$ km to the right of the storm track, a location near the radius of maximum winds. Q_* is the sum of latent plus sensible heat fluxes and is based on a relative humidity of 0.8 and a 2.5 degree K temperature difference between the water surface and the 10 meter reference height. The wind field, typical of Hurricane Frances, is derived from the expressions given by Zedler (2007).

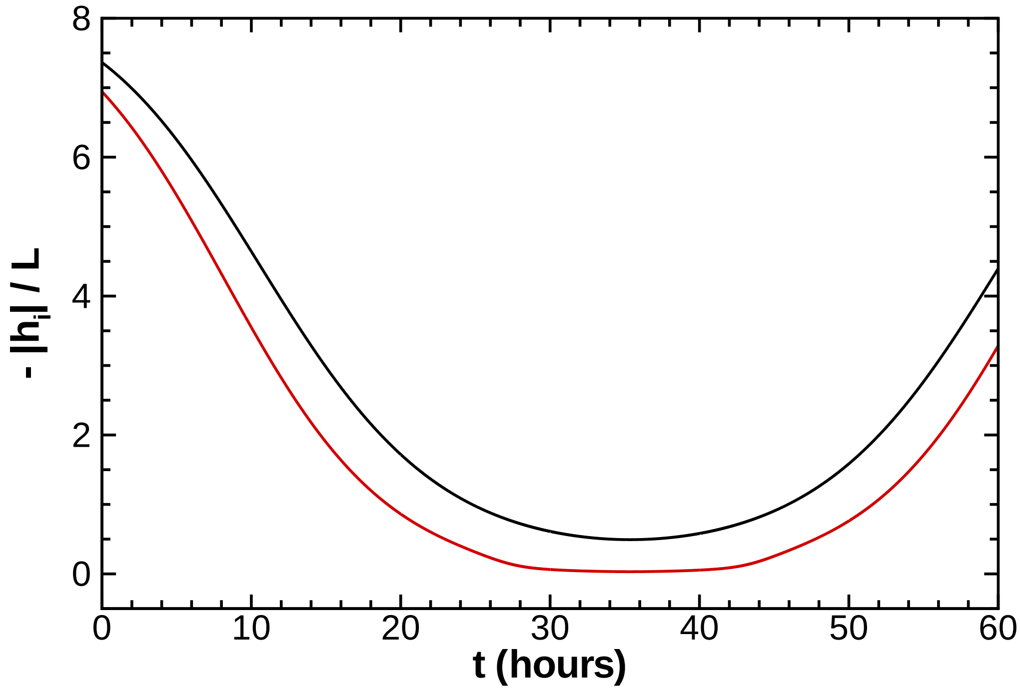

Figure 3: Time variation of the Monin-Obukhov lengthscale (in the water) for a hurricane distribution of winds and scalar fluxes. $L = -u_*^3/\beta\kappa Q_*$ where u_* is the friction velocity, β is the buoyancy parameter, κ is the von Kármán constant, and Q_* is the surface cooling flux. Here L is made dimensionless by the initial OBL depth $h_i = -33$ m. By analogy with the atmospheric boundary layer, we expect the OBL turbulence to be dominated by shear forcing when $-|h|/L < 1$ when wave effects are not considered. The red and black curve are results for points located $(55, 700)$km and $(250, 700)$ km east and north of the vortex origin respectively.

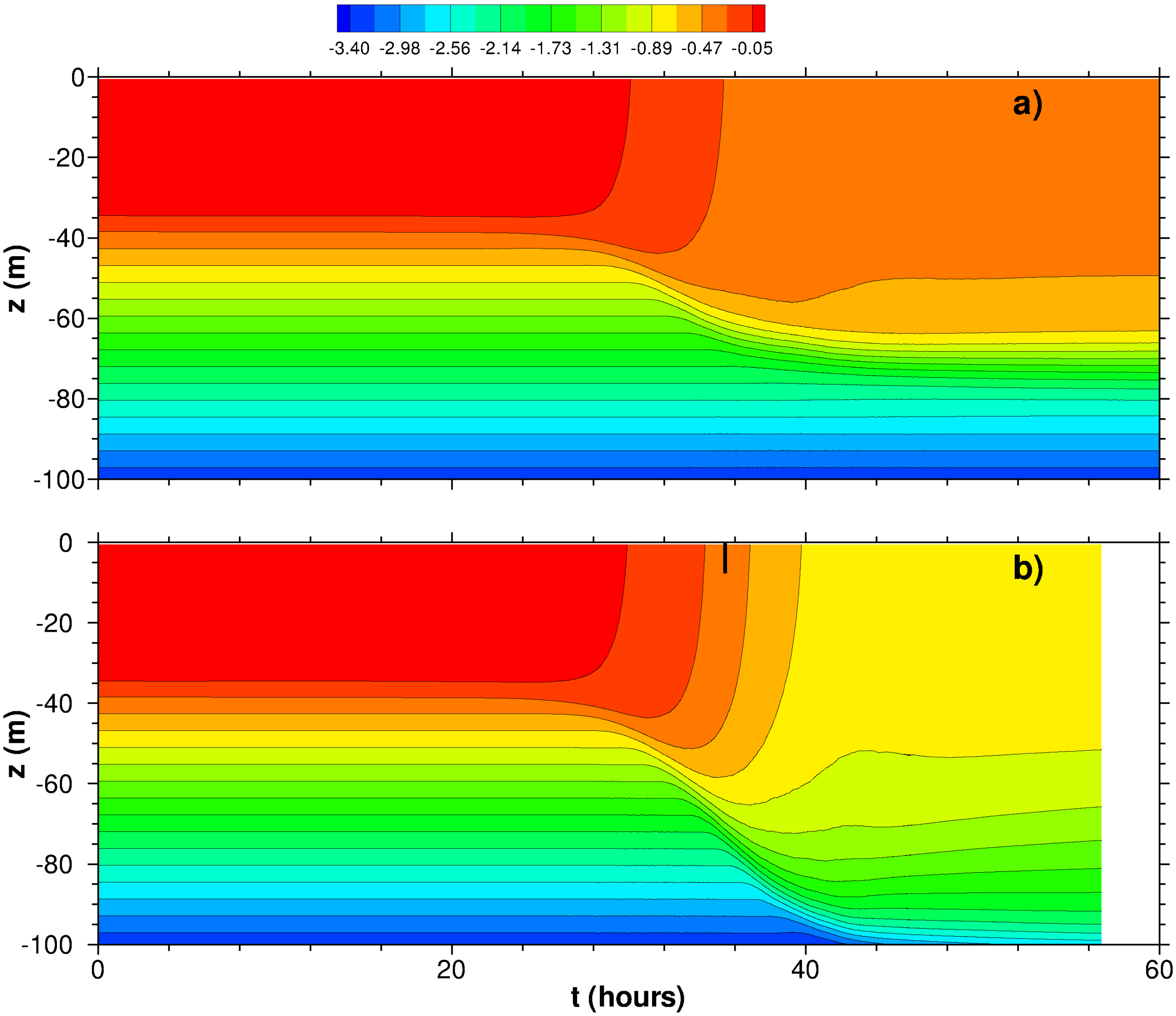

Figure 4: Variation of the vertical profile of potential temperature $\langle\theta(z)\rangle - \theta_{ref}$ for an OBL driven by a time varying wind field $\boldsymbol{U}(t)$ typical of Hurricane Frances (see figure 2) but with $Q_* \sim 0$. Here $\langle\ \rangle$ denotes a horizontal average (*i.e.,* an average over all $x - y$ in the LES domain) at each time step of the simulation. In panels a) and b) the LES domain is located on the left (right) hand side of the storm track, respectively, $x = \mp 55$ km. Note that the winds and currents are partially resonant on the right hand side (anti-resonant on the left hand side) of the storm track. Because of resonance the OBL mixes deeper and entrains more cool water in panel b). The vertical (northward) speed of propagation of the storm $V_s = 5.5$ ms^{-1}. The time of maximum winds, $t \sim 35.5$ hours, is indicated by a heavy vertical bar in panel b). The color bar is in units of degree K and is relative to the reference temperature $\theta_{ref} = 299.15$ K

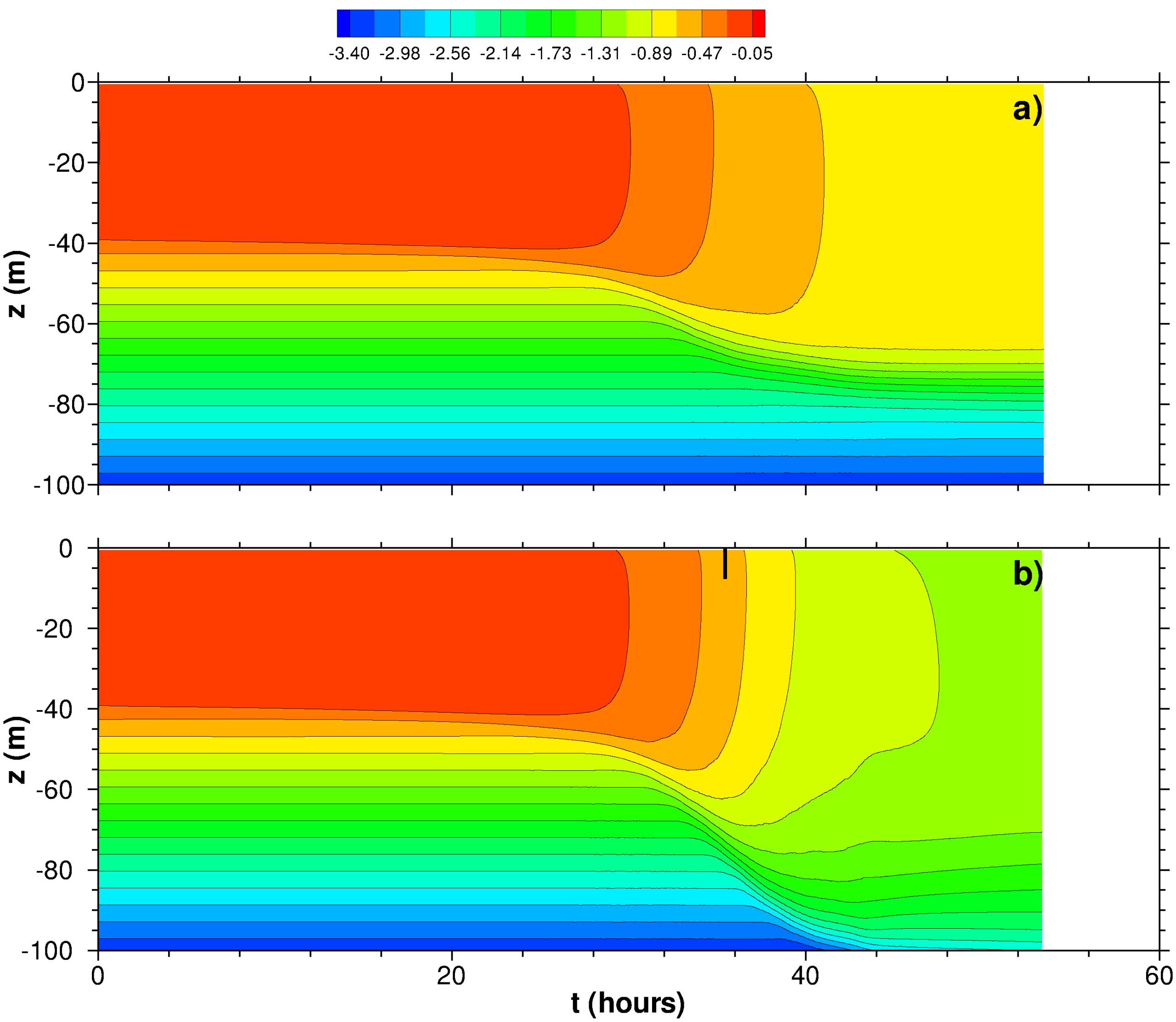

Figure 5: Variation of the vertical profile of potential temperature $\langle\theta(z)\rangle - \theta_{ref}$ with time as in figure 4, but now the OBL is driven by both winds and surface cooling which further decreases the SST in the OBL.

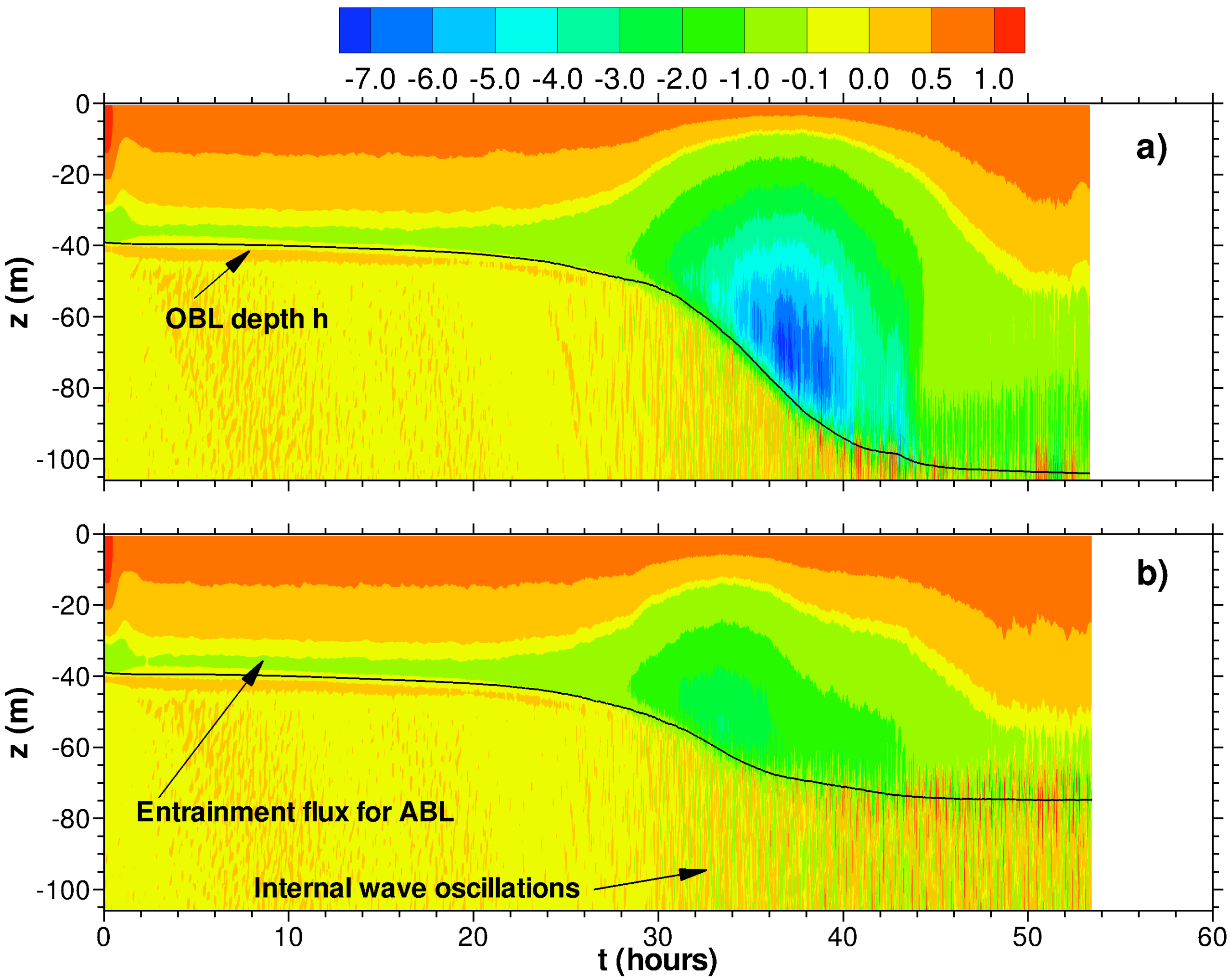

Figure 6: Variation of the vertical profile of turbulent scalar flux $\langle w'\theta' \rangle(z,t)$ as in figure 5, for points located on the resonance (panel a) and non-resonance (panel b) sides of the storm track. At each time, the scalar flux is normalized by its imposed surface value. In these figures the OBL depth h, determined as the location of the maximum vertical temperature gradient, is shown as a heavy black line. The light green contour shows the normalized entrainment flux (~ -0.2) for a classical daytime convective atmospheric boundary layer. The contours of scalar flux show that the bulk of the temperature decrease in the OBL is induced by entrainment cooling. The rapid oscillations in the scalar flux below the thermocline result from a complex system of internal waves excited by the strong wind forcing.