8.6 VARIATIONS OF BOUNDARY LAYER MEAN AND TURBULENCE STRUCTURE USING SYNTHESIZED OBSERVATIONS

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1. INTRODUCTION

The coastal atmospheric boundary layers are characterized by strong spatial and temporal variations due to the complicated land/sea surface forcing and the large and mesoscale flow field related to terrain and surface thermal effects. This variability is even larger over an island, where the near-surface boundary layer is very sensitive to the direction of the mean wind and gust. Hence, when analyzing the measurements conducted on the coast of an island, one needs to be cautious in determining the accurate upwind environment. On the other hand, these measurements may provide the best opportunity to study the boundary layer response to the changing environment, which is the main focus of this paper.

As part of the Coupled Boundary Layer Air-Sea Transfer, Low Wind Project (CBLAST-low), we made extensive ground-based measurements on Nantucket Island, MA between July 22 and August 27, 2003. The main objectives of the measurements were to characterize boundary layers in a variety of meteorological conditions and to provide in situ data for the evaluation of mesoscale models, such as the Navy's operational forecast model, COAMPS™. Figure 1 shows the location of Nantucket Island relative to Martha Vineyard, upwind of which major activities of CBLAST-low projects occurred. Our measurement site was situated within the complex of the Nantucket Waste Water Treatment Factory on the south coast of Nantucket. The shortest distance (N-S direction) from the 20-m mast to the waterfront is 94 m. The land surface was relatively flat, except to the east and south east where sand dunes towards the water gradually increased to about 30 m at about 150-200 m distance to our site. Since the wind was predominantly south or south westerly, the site was chosen so that we had better chance to measure the marine air.

Figure 1. Location of CBLAST-low Nantucket site, denoted by the red star. Predominant wind in the area is south and south-westerly.

2. THE INSTRUMENTATION

The CBLAST-low Nantucket site deployed a suite of in situ and remote sensing instruments designed to fully characterize the changing boundary layer properties on the coast of an island. On a 20-m mast, there are two levels (10 and 20 m) of high-rate sampling sonic anemometers for 3-D wind components and a LICOR fast hygrometer at 20 m for water vapor and CO_2 concentration. These high-rate measurements yields momentum, sensible heat flux, latent heat and CO_2 fluxes (at 20 m only) through the eddy correlation method. The mean wind, temperature, and relative humidity (RH) were also measured at 5, 10, and 20 m respectively at 10-minute sampling interval. Meanwhile, soil temperatures at 10 and 30 cm below the surface and soil volumetric water contents between 10 and 20 cm below surface were also measured at the bottom of the 20-m mast. About 10 m north to the 20-m mast, a small mast was instrumented to measure air temperature, RH, wind speed and direction, air pressure, precipitation, and downward solar and IR radiation at 1 minute interval. The sensors were set at about 2 m.

The Nantucket instrument suite also includes a Remtech (PA2) SODAR system for measuring the vertical profiles of mean wind, turbulence variances, and momentum fluxes at a vertical resolution of 40 m. Helmis *et al.* (2004) focuses on the findings from the SODAR measurements. A laser ceilometer was used to detect the cloud base height continuously. In addition, rawinsondes were launched two to six times daily in coordination with other CBLAST activities. We also experimented with tethered rawinsondes at the

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lower 200 m of the atmosphere (no wind) for August 14 and August 25 and tethered balloon soundings for August 15. These tethered sondes at short time intervals were designed to study the rapid evolution of boundary layer thermodynamic structure, particularly the development of the internal boundary layers.

Figure 2a shows the vertical profiles of potential temperature from the rawinsonde measurements. One can see that the lower atmosphere was in general in

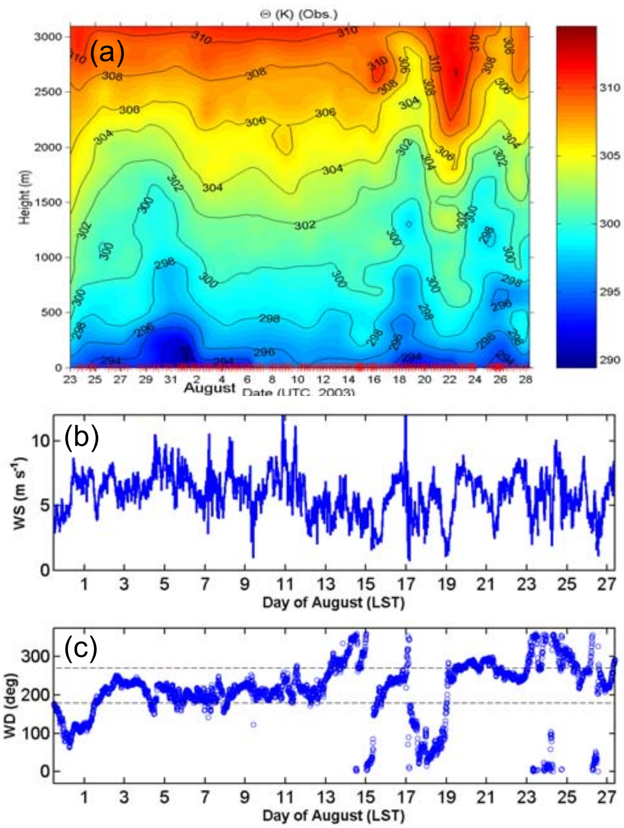

Figure 2. (a) Contour plot of vertical profiles of potential temperature from the rawinsonde measurements, where red * at the bottom of the figure denotes the time when soundings were made; (b) wind speed and (c) wind direction from 20 m for the entire intensive observation period.

stable stratification except during a few days in the cold air mass. For the entire intensive observation period (IOP), wind speed was usually less than 8 ms^{-1}. South and south-westerly wind dominated mostly in early August and varied for the rest of the IOP.

3. TURBULENT FLUXES

The measurements from the high-rate sensors were quality controlled and processed to result in turbulent fluxes of momentum, sensible heat, and latent heat at 30 minutes interval. These fluxes were grouped into two categories; one represents results from the marine atmospheric boundary layer (MABL), the other from the land surface boundary layer (LBL). Figures 3

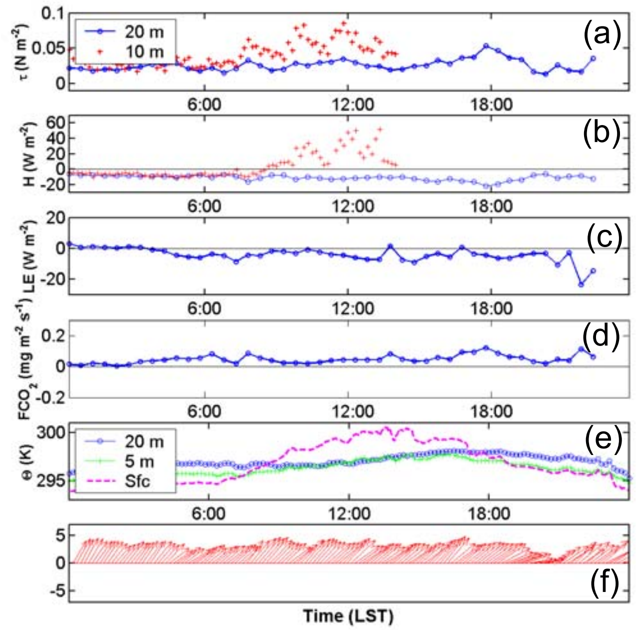

Figure 3. Variations of (a) momentum flux, (b) sensible heat flux, (c) latent heat flux, (d) CO_2 flux, (e) potential temperature and surface IR temperature, and (f) wind vector at 20 m on August 16, 2003.

illustrates the difference in surface fluxes of the two types of boundary layers. In this case, although the site was downwind of the ocean, the 10 m fluxes clearly show the diurnal variation in momentum flux (Figure 3a) and sensible heat flux (Figure 3b) in response to surface heating (Figure 3e). The 20 m fluxes, on the other hand, show no signs of local surface forcing. Hence, Figure 3 suggests that the internal boundary layer (IBL) top was between 10 and 20 m. The 20 m measurements thus represent the MABL. Similar analysis was made for all other days with south to south westerly wind to determine the effects of IBL on 20 m

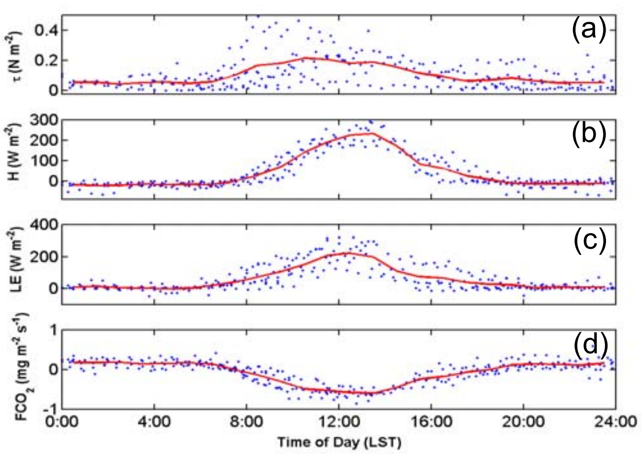

Figure 4. Composite diurnal variation of (a) momentum flux, (b) sensible heat flux, (c) latent heat flux, and (d) CO_2 flux in LBL. The solid line is the composite mean.

measurements. In general, 20 m is above the IBL except on very weak wind (less than 3 ms^{-1}) conditions.

Figure 4 shows the composite diurnal variation of turbulent fluxes from all the LBL measurement at 20 m on the Nantucket mast. The results here are consistent with strong surface heating during the daytime and the resultant large positive sensible and latent heat fluxes. The CO_2 flux is negative during daytime and slightly positive at night, an indication of the aspiration of plants. At night, negative heat flux prevails with mean sensible and latent heat fluxes being –13 and 10 Wm^{-2}, respectively (averaged between 6PM and 6AM). In contrast, the MABL fluxes shows small variations and no sign of diurnal variation. The mean sensible and latent heat fluxes are –11 Wm^{-2} and -2 Wm^{-2}, respectively (averaged from all MABL data). The observed stress in MABL averaged to 0.04 Nm^{-2}, compared to 0.08 Nm^{-2} in LBL at night.

Using Monin-Obukhov similarity functions and the observed mean wind, temperature, and fluxes, we calculated the surface roughness height for the MABL. The similarity functions used here is the same as those in the current COARE surface flux scheme (Fairall et al. 2003). In Figure 5, the roughness length, z_0, is plotted against the mean wind at 20 m. While, the largest variations of z_0 is seen between 4 and 5 ms^{-1}, z_0 appears to increase rapidly with increasing wind when wind speed is higher than 6 ms^{-1}. For wind speed smaller than 4 ms^{-1}, z_0 trends to increase with decreasing wind. This is not conclusive, however, due to the scarcity of the data points, since 20 m is likely in the IBL in very low wind conditions and we have filtered out data points in such condition. The measurements from the main CBLAST tower in the water (Edson et al. 2004) should provide the most comprehensive dataset for such analysis.

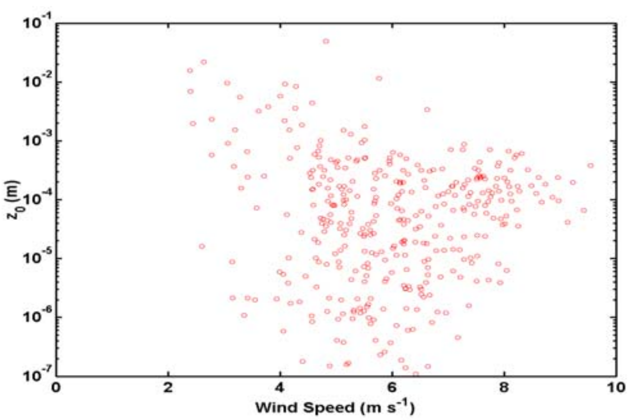

Figure 5. Marine boundary layer surface roughness length, z_0, plotted against the mean wind speed at 20 m on the mast.

4. BOUNDARY LAYER EVOLUTION IN RESPONSE TO CHANGING ENVIRONMENT

We tested on the use of the Loran-C rawinsonde tethered on a wrench to probe the vertical profiles of temperature and humidity only in the lower several hundred meters of the atmosphere. The lightweight sonde package allowed us to use a small balloon so the measurement was feasible on a relatively wide range of wind conditions. We were also able to probe the boundary layer in a very short time period owing to the relatively fast response

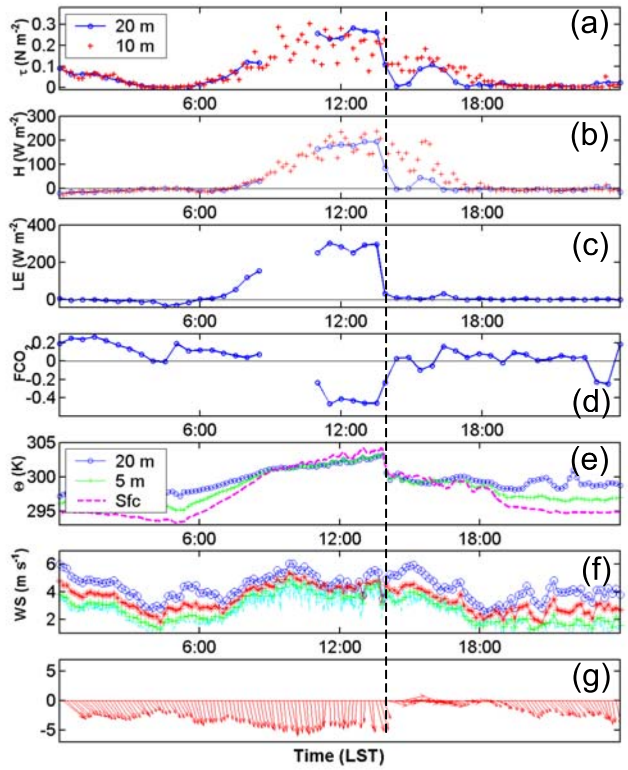

Figure 6. Variations of (a) momentum flux, (b) sensible heat flux, (c) latent heat flux, (d) CO_2 flux, (e) potential temperature and surface IR temperature, (f) relative humidity, and (g) wind vector at 20 m on August 14, 2003

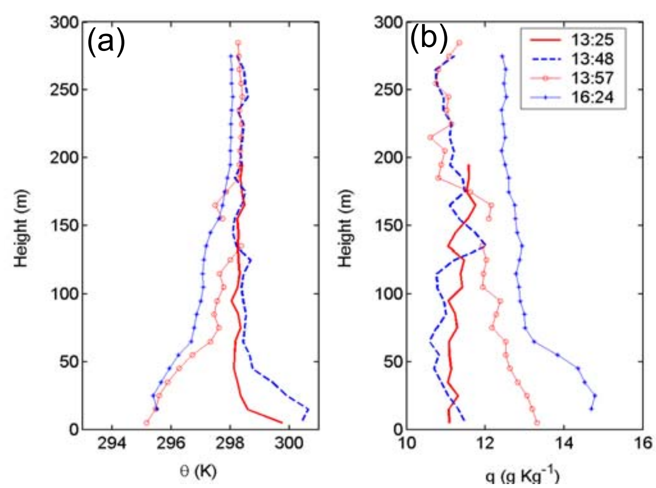

Figure 7. Evolution of boundary layer vertical profiles of (a) potential temperature and (b) specific humidity at the time of rapid wind direction change (13:50) on August 15, 2003.

of the rawinsondes. This practice was made on August 14, and 25 2003, where an abrupt change in wind direction occurred at 13:50PM (Figure 6g, dash line denotes the time of this change). The cause of the westerly wind is unclear, but it is not isolated to the island since the nearby buoys also showed westerly wind at the time. The westerly wind brought cooler and moister air and also immediately cooled the surface temperature (Figures 6e and 6f). Figure 6 shows the decrease of all fluxes at 20 m following the change in wind direction; the 10 m fluxes are not modified significantly.

Figure 7 shows a comparison of the vertical profiles of potential temperature and specific humidity before and after the wind change. These soundings were obtained by the tethered rawinsonde. We clearly see two groups of soundings, unstable and dry surface layer in the northerly wind and stable and moist boundary layer in the westerly wind. The decrease in surface fluxes is thus caused by the sudden increase in thermal stability. We also notice, that the wind shear between 2, 5, and 10 m (Figure7f) did not change significantly before and after the event, but the shear between 10 and 20 m significantly increased, another indication of increased stability between these two levels. Given that the 10 m fluxes did not change drastically, we may guess that the 10 m height is now within the IBL of the local surface, while the 20 m level is above the IBL.

5. DEVELOPMENT OF NOCTURNAL BOUNDARY LAYER

During 2003 IOP, we observed many cases of nocturnal boundary layer development. An example is shown in Figure 8 where the vertical profiles were again made by tethered rawinsondes on August 25.

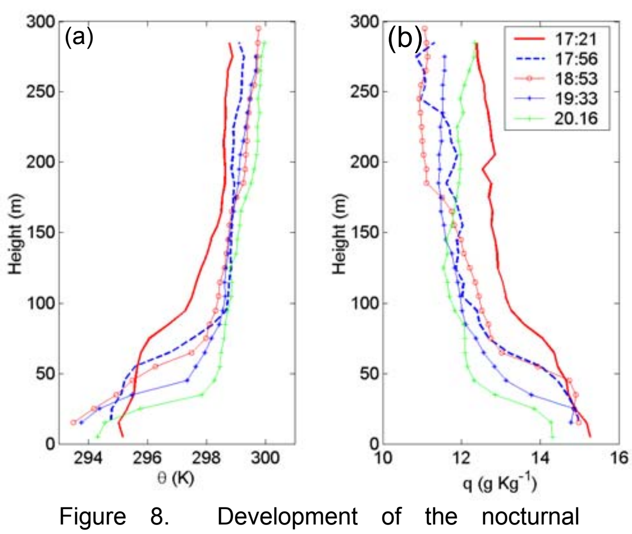

Figure 8. Development of the nocturnal boundary layer, vertical profiles of (a) potential temperature and (b) specific humidity. Day of the measurement was August 15, 2003.

Figure 8 shows the rapid development of the nocturnal boundary layer in the late afternoon. At the 17:21, the boundary layer is weakly stable with the top at about 70 m. The boundary layer quickly lowers to about 60 m and cooled in the next half hour and became increasingly stable as time goes. At 20:16, the inversion is the strongest with a thin weakly stable layer at the lowest 10 to 20 m. The temperature at 5 m was about 1.7 K higher than the surface temperature, and the 20 m level is about 2.1 K warmer than the 5 m level. The specific humidity profiles are consistent with the temperature profiles.

6. SUMMARY AND CONCLUSIONS

We have investigated the measurements from a suite of instruments from the CBLAST-low Nantucket site to characterize the mean and turbulence properties in marine and land surface boundary layers. The MABL typically has negative sensible heat flux, consistent with its stable stratification; while strong diurnal variations were typical in the LBL. Efforts were made to study the development of the internal boundary layer in order to determine the accurate upwind environment. We found that the IBL was in general less than 10 m at night and can reach 20 m at noon, particularly in low-wind conditions. In situations of abrupt change of mean wind direction, the boundary layer mean and turbulence structure response on the order of 10 minutes or less.

7. ACKNOWLEDGEMENTS

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