4.1 PROFILES OF TKE AND SENSIBLE HEAT AND MOMENTUM FLUXES IN THE ROUGHNESS SUB-LAYER OF A CITY

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ABSTRACT

Measurements with sonic anemometers on a number of towers in the suburban and urban domains of Oklahoma City during Joint Urban 2003 are examined to characterize the height dependence of turbulent properties within the roughness sub-layer (RSL). Values of the displacement height (d) for five tower locations have previously been shown to vary both with location and with wind direction. Values of d for the suburban locations obtained from measurements at 10 m varied from as little as 1.4m to as much as 6.1 m. Values for the urban locations varied from 4.2m to 7.5m. It is clear then that for the urban locations the sonic anemometer measurements at 10m (and below) were entirely within the RSL, while even those at suburban locations were often within this layer. In this paper we examine the profiles of turbulent kinetic energy, sensible heat flux, and momentum flux obtained at the various locations. We stratify the measurements by time of day and by wind direction in order to gain insight into the structure of this layer as it is affected by stability and surface roughness properties. We look, too, at profiles obtained from measurements on a taller tower (85m) to see whether a constant flux layer (CFL) might be identified at higher levels above the city.

1. INTRODUCTION

Roth (2000) divides the urban boundary layer into the following sub-layers or regions:

i. Urban canopy layer (UCL)
ii. Roughness sub-layer (RSL)
iii. Constant flux layer (CFL)
iv. Mixed layer (ML).

The UCL extends from the ground to about roof level (z_h) and is usually characterized by the zero plane displacement height (d), which may vary from about 0.5 to 0.8 z_h. The RSL, also called the transition or interfacial layer, includes the UCL and extends above it to a height (z_r), estimated by Raupach *et al* (1991) to vary from about 2 to 5 times z_h. The CFL, also called the inertial sub-layer, extends from the top of the RSL to about 0.1 times the height of the boundary layer and corresponds to the surface layer over homogeneous terrain. Oke *et al* (1989) have noted that it may happen that the depth of the RSL exceeds the potential depth of the CFL and that no such layer exists. Extending above the CFL to the height of the boundary layer is the ML. Using wind and turbulence data from sonic anemometers (R.M.Young, Mod. 81000) mounted on towers during Joint Urban 2003, we have examined profiles of turbulence properties within the RSL and attempted to determine its depth.

2. DATA COLLECTION AND ANALYSIS

In previous presentations (Chang *et al,* 2003; Garvey *et al,* 2004; Klipp *et al,* 2004; Yee *et al,* 2004) and in a companion paper at this conference (Huynh *et al,* 2005) we have described the experimental setup, quality control, and analysis procedures followed in examining wind and turbulence properties obtained from sonic anemometers mounted on five 10 m towers fielded by the Army Research Laboratory (ARL) in the Oklahoma City metropolitan area during the summer of 2003. Generally these analyses have focused on data obtained 10m above the ground at sites characterized as suburban or urban (industrial) and have emphasized the heterogeneity of the urban surface properties and the resulting wind and turbulent characteristics. For example, following a method proposed by Rotach (1994), values of the displacement height for the five tower locations have been shown to vary both with location and with wind direction. Values for the suburban locations obtained from measurements at 10m varied from as little as 1.4m to as much as 6.1m. Values for the urban locations varied from 4.2m to 7.5m. It is evident then that for the urban locations the sonic anemometer measurements at 10m (and below) were entirely within the RSL, while even those at suburban locations were often within this layer.

In this paper we focus on the profiles of turbulent properties, in particular, sensible heat and momentum flux and turbulent kinetic energy (TKE) and TKE flux. In addition to the 10m measurements we utilize data obtained at levels of 2.5 and 5m. Recognizing that for northerly wind directions these data may be affected by the towers themselves and noting that just a sixth of the wind measurements had a northerly component, we have only included data with wind directions having a southerly component in this analysis. In order to identify the top of the RSL and to see whether a constant flux layer (CFL) might exist at higher levels above the city, we also examine data obtained with similar sonic anemometers mounted on an 85m crane-supported cable fielded by co-investigators from Lawrence Livermore National Laboratory (LLNL) north of the central business district. (Lundquist *et al,* 2004).

3. RESULTS

3.1 *Vertical Variation of Turbulent Heat Flux*

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Figure 1 shows a typical diurnal variation of the turbulent kinematic heat flux ($H = \overline{w'T'}$) observed at 3 levels (10m, 5m, and 2.5m) from Tower #2 on July 29, 2003. Note that the local time (Central Daylight Saving Time, CDT) is 5 hours earlier than UTC. As expected,

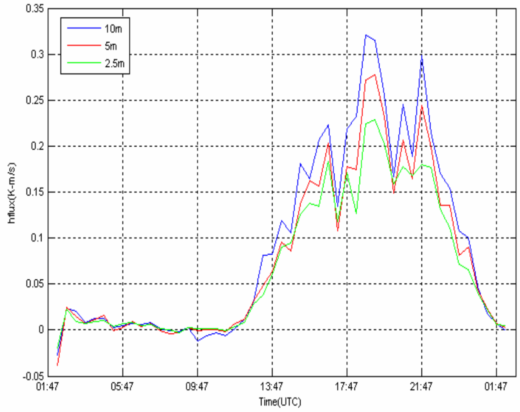

Figure 1. Heat flux at 10m, 5m, and 2.5m levels from Tower #2 on July 29, 2003.

H is usually small, though rarely negative, at night and in the early morning. In the day time, H increases with time at all three levels until it reaches a maximum in the early afternoon. Significantly, H increases with height from 2.5m to 5m, and from 5m to 10m during most of day time period. To further illustrate the vertical variation of H, scatter diagrams of H between 2 levels from both Tower #2 (industrial) and Tower #3 (suburban) are plotted in Fig. 2.

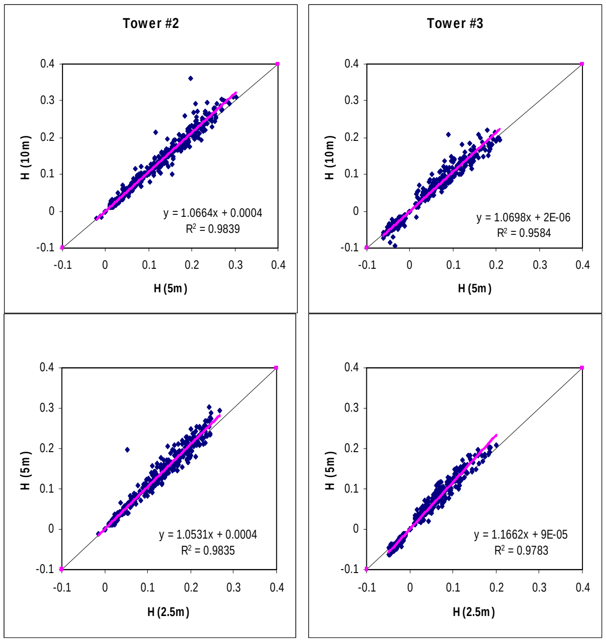

Figure 2. Scatter diagram of heat flux, H, for Tower #2 and Tower #3.

This figure shows that a general trend of slightly increasing H within the lowest 10m exists for both Tower #2 and Tower #3. Figure 3 presents the vertical variation of the averaged heat flux, $< H >$, for all five 10 m towers. The values of $< H >$ plotted are those for the 2.5, 5, and 10m levels for the two wind direction quadrants having a southerly component. In the first plot these averages are plotted against z, the level at which the measurements were made. In the second plot the reduced height ($z - d$) has been used in order to include the effect of the displacement height. The positive value of the slope of the linear regression indicates the general trend of slightly increasing H with height from 2.5 to 10m in the roughness sub-layer.

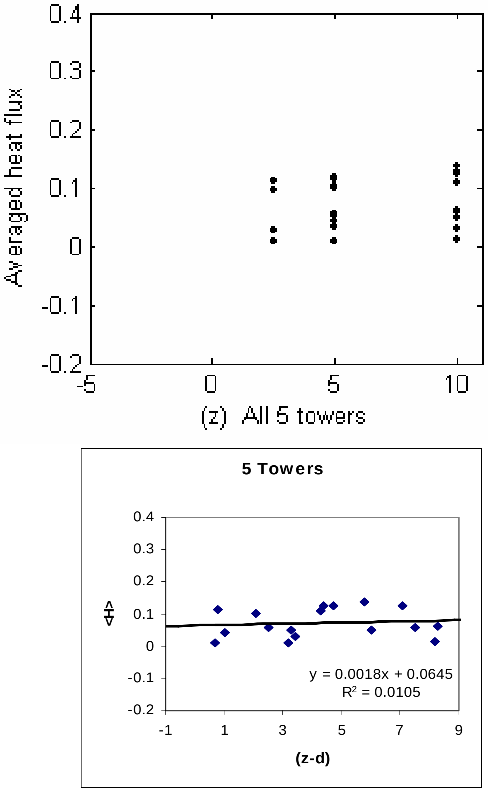

Figure 3. Vertical variation of averaged heat flux, <H>, for the 5 ARL towers.

3.2 *Vertical Variation of Momentum Flux (u_*)*

Similar to Fig. 2, Fig. 4 provides scatter diagrams of the friction velocity (u_*) between 5m and 10m as well as between 2.5m and 5 m from Tower #2 and Tower #3. This figure also indicates a general trend of the increase of u_* within the lowest 10m of the roughness sub-layer. This general trend of u_* is much stronger than the trend for the turbulent heat flux, the positive value of the slope of the linear regression being larger than that in Fig. 2.

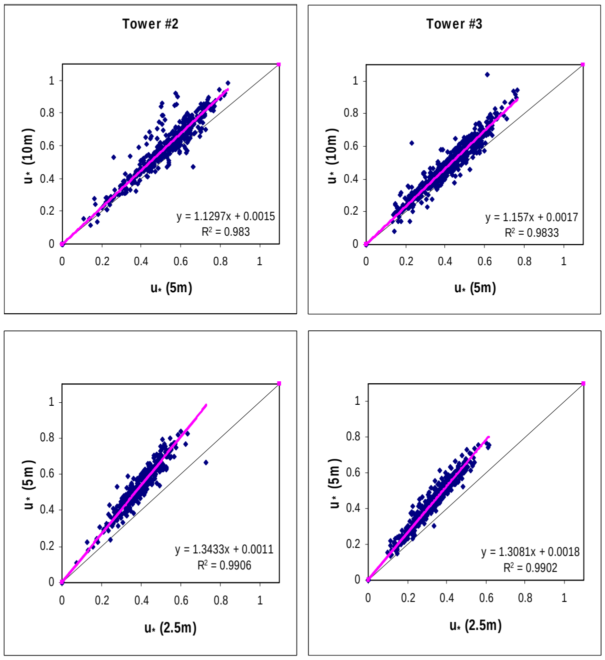

Figure 4. Scatter diagram of friction velocity, u_*, for Tower #2 and Tower #3.

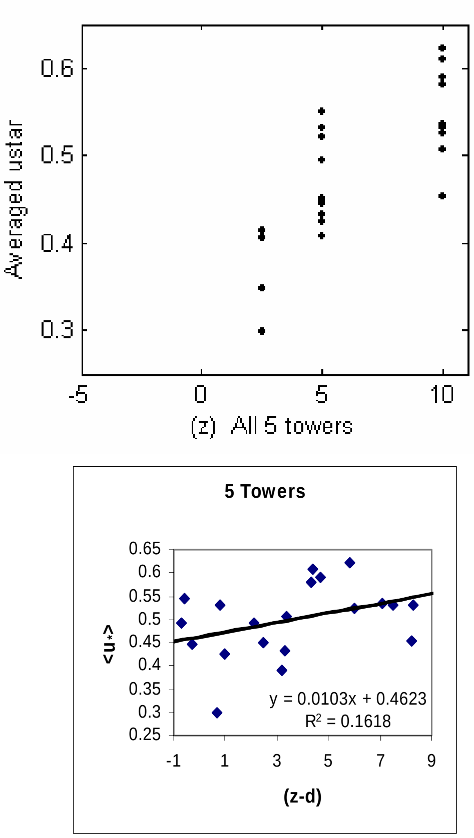

Figure 5. Vertical variation of averaged friction velocity, $<u_*>$, for the 5 ARL towers.

Similar to Fig. 3, Fig. 5 further shows the increase of the averaged friction velocity, $<u_*>$, with z and with the reduced height ($z-d$) for the 5 towers together.

The increase of $<u_*>$ with ($z-d$) is larger than the increase of $<H>$ with ($z-d$). Rotach (1993) has analyzed the vertical variation of Reynolds stress for the lowest few tens of meters of an urban roughness sub-layer. He also found that the Reynolds stress (u_*) increased with height in the roughness sub-layer. Our results from the 5 tower measurements as shown by Fig. 4 and Fig. 5 appear to agree with his results.

3.3 *Vertical Variation of Turbulent Kinetic Energy*

As shown in Fig. 6, the turbulent kinetic energy (TKE) also increases with height from 2.5 to 10m on the towers at both urban and suburban sites. The rate of increase is greater than that for the kinematic heat flux and comparable to that for the friction velocity.

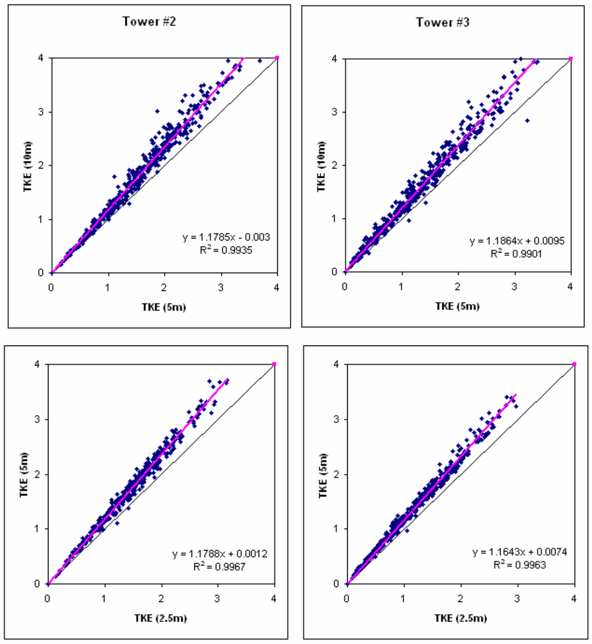

Figure 6. Scatter diagram of turbulent kinetic energy (TKE) for Tower #2 and Tower #3.

We also examined profiles of TKE above the 10m level. For four of the intensive observation periods (IOPs) during Joint Urban 2003, two daytime and two night time, we have analyzed hourly averages of profiles of wind and TKE as measured by sonic anemometers mounted on cables supported by a 90m crane instrumented by LLNL and located just north of the central business district (CBD). The results for IOPs 2, 3, 7, and 8 are shown in Fig. 7.

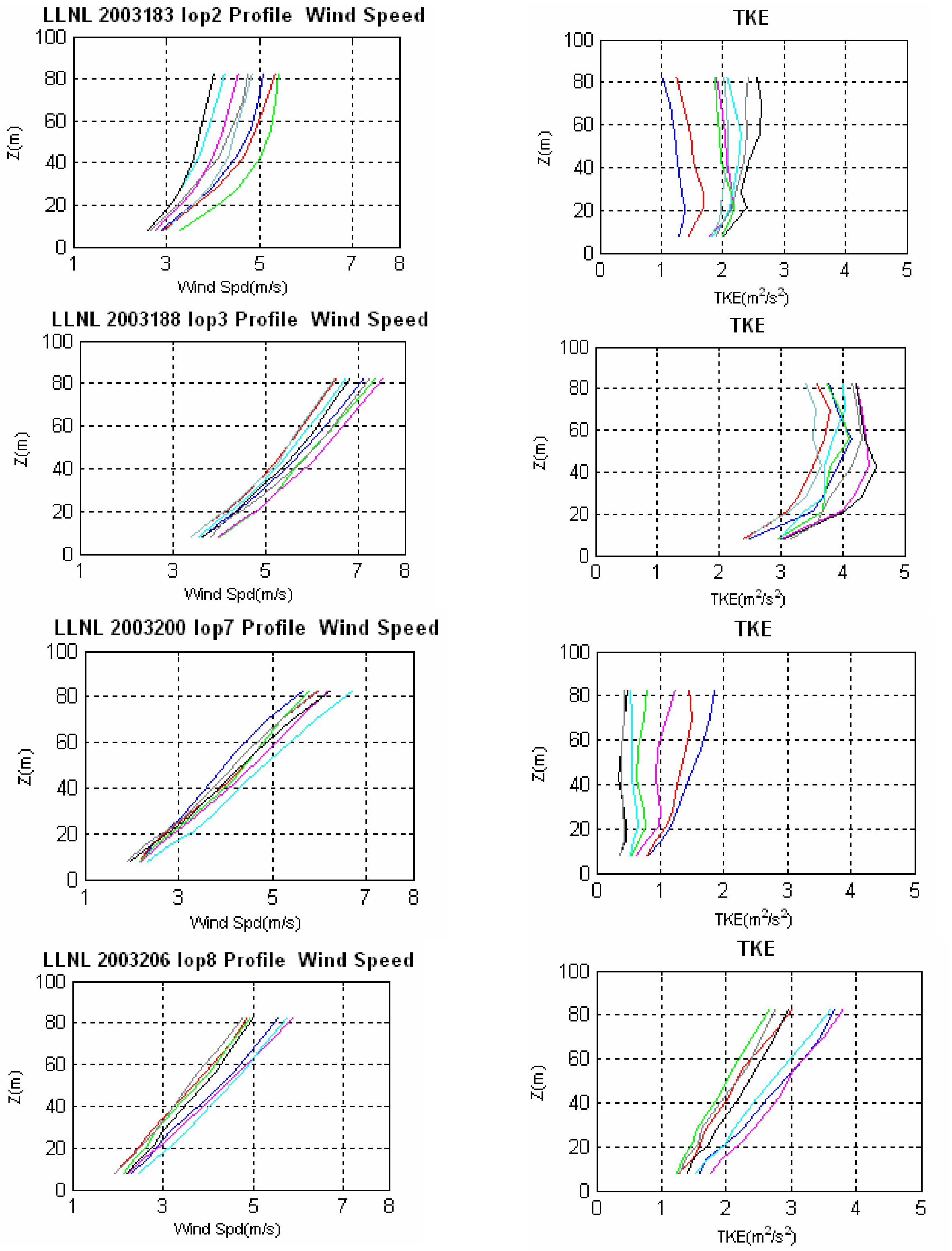

Figure 7. Hourly average profiles of wind speed and turbulent kinetic energy (TKE) for two daytime IOPs (2 and 3) and two night time IOPs (7 and 8) measured at the LLNL tower. The times for each of the colored curves are given in Figs. 8 and 9.

For IOPs 2 and 3 the magnitudes of the TKE increased with height from the lowest level (~8m) to 20m, only slightly for IOP2, more sharply for IOP3. During IOP2 the TKE above 20m was relatively constant up to 80m, at times showing a small decrease, at others a small increase; there was an increase in TKE with time at all levels during the first two hours. During IOP3 the TKE above 20m continued to increase with height, though more slowly than below, up to 40 or 70m, above which it decreased slightly. These profiles would suggest that there was a source of TKE at about 20m during IOP2 and a more elevated source varying from 40 to 70m during IOP3. The magnitudes of the TKE were larger during IOP3 than during IOP2, probably related to the higher wind speeds during IOP3. But the relative maximum in the TKE at 40 to 60m during IOP3 would indicate enhanced conversion of mean kinetic energy to TKE at levels below that of the maximum wind speed, perhaps due to wake effects induced downwind of the CBD.

3.4 *Vertical Profiles of Turbulent Fluxes up to 80 m*

In Figs. 8 and 9 we have plotted hourly averages of profiles of friction velocity (momentum flux), kinematic heat flux, and the vertical flux of TKE up to 80m for the two daytime IOPs (2 and 3) and the two night time IOPs (7 and 8). We looked for evidence of the top of the roughness sub-layer (RSL) and the existence of a constant flux layer (CFL) in these profiles.

The heat fluxes were relatively constant throughout the 80 m extent of the profiles, showing the expected more positive values during the day (Fig.8) as solar insolation increased. The nighttime heat fluxes (Fig.9, note the expanded scale) were close to zero but exhibited some interesting features. For IOP7 they were near-zero close to the surface but became negative at about 30 m and more negative above that level; for IOP8 they remained slightly positive and nearly constant throughout the 80m.

The friction velocity profiles all increase with height up to about 20m. Above that level for IOPs 2 and 7 they show no regular trend and are relatively constant; for IOPs 3 and 8, on the other hand, they continue to increase with height, up to 60m during IOP3 and all the way up to 80 m for IOP8.

During IOP2, the vertical fluxes of TKE were at times negative below 20m, but always positive above. During IOP3, the fluxes were negative from 20m to 60m, depending on the time, and positive above those levels. Both the magnitudes of the TKE and the TKE fluxes were larger during IOP3 than during IOP2. For IOPs 7 and 8 potential source levels of TKE were hard to identify. During IOP7 the TKE was nearly constant or slightly increasing with height; during IOP8 the TKE increased upwards at all levels at all times. During IOP7 the vertical fluxes were near zero or slightly negative at least up to 60m; for two of the hours during this IOP the flux was positive above 60m. During IOP8 the vertical flux was negative or near zero at all levels at all times, indicating a more elevated source level for TKE.

4. CONCLUSIONS

Kinematic heat fluxes and friction velocities calculated from measurements of eddy correlations on both the 10 m towers and the 85m tower just downwind of the CBD indicate that while the lowest layers (RSL and CFL) of the urban boundary layer may be considered a constant flux layer (varying by less than 10%) for sensible heat, the momentum fluxes in this region are far more complex.. Both night and day, the maximum gradient in the friction velocity with height occurs in the lowest 20m; above that level u_* can be relatively constant but often continues to increase, at times all the way up to the 80 m level. Therefore, the classical concept of a constant flux layer as in a homogeneous surface layer cannot be applied.

Both the profiles of TKE and their vertical fluxes indicate various source regions for turbulent kinetic energy. The data from the 10m towers indicates that there is generally a source of turbulence above 10m even in the suburban areas, probably resulting from the shear associated with the tops of buildings, trees, and other structures. At least downwind of the CBD there can exist more elevated source regions of TKE at levels below that of the maximum wind speed. In this domain the roughness sub-layer (RSL) can extend at least to 60m, and there is little evidence of a constant flux layer (CFL) for momentum above that level.

5. ACKNOWLEDGMENTS

We thank our ARL colleagues at White Sands Missile Range and our co-investigators at Lawrence Livermore National Laboratory for their efforts in providing the data examined in this analysis.

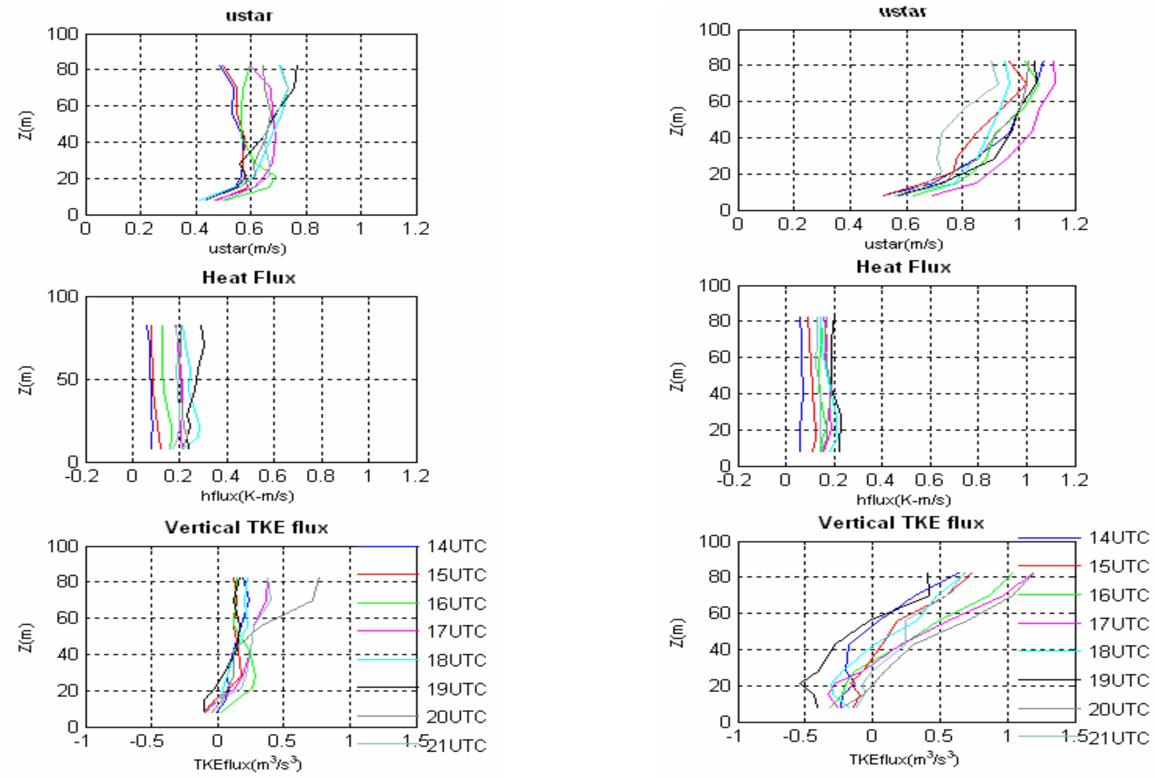

Figure 8. Hourly average profiles of u*, heat flux, and vertical turbulent kinetic energy (TKE) flux for two daytime IOPs (2 and 3) measured at the LLNL tower The times for each of the colored curves are given in the plots for TKE fluxes.

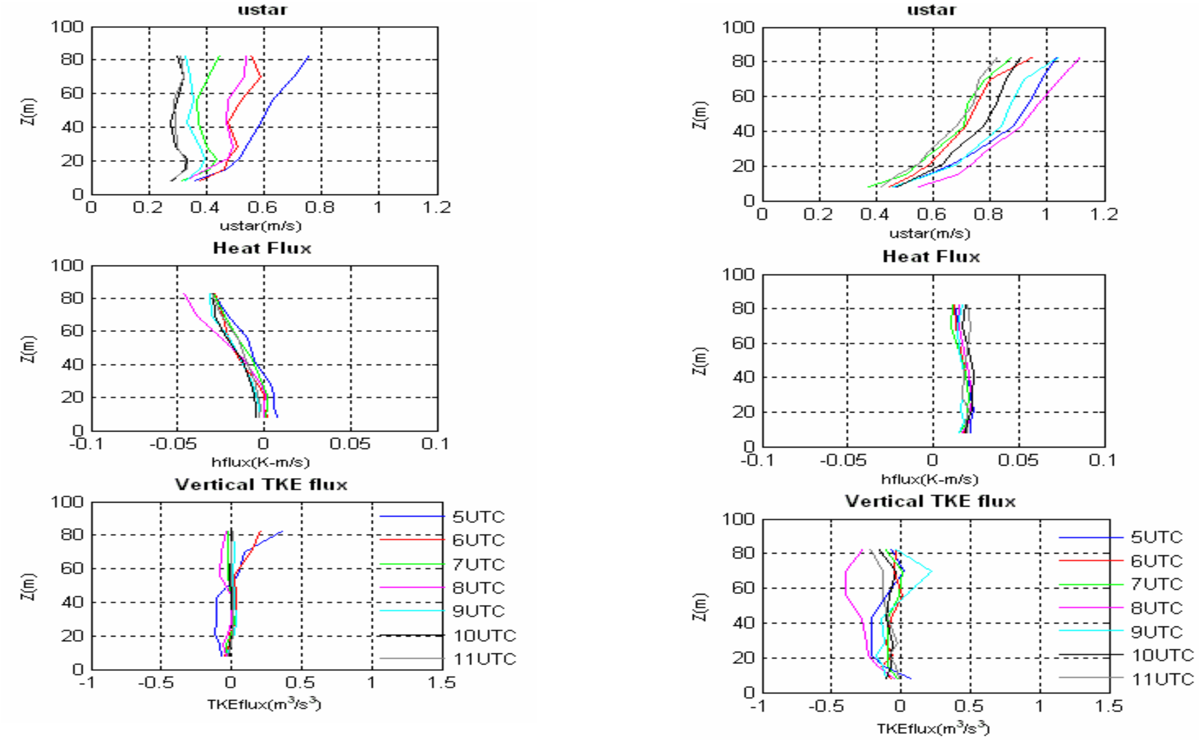

Figure 9. Hourly average profiles of u*, heat flux, and vertical turbulent kinetic energy (TKE) flux for two nighttime IOPs (7 and 8) measured at the LLNL tower. The times for each of the colored curves are given in the plots for TKE fluxes.

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