4.2

STRUCTURE OF THE ATMOSPHERIC BOUNDARY LAYER IN THE CENTRAL SALT LAKE VALLEY DURING THE AFTERNOON-TO-EVENING TRANSITION

William J. Shaw* and John M. Hubbe
Pacific Northwest National Laboratory
Richland, Washington

1. INTRODUCTION

As part of a continuing effort to understand the process of turbulence decay in the atmospheric boundary layer, we have measured profiles of winds and turbulence variables in the central Salt Lake Valley. These data were collected in an October 2000 field program that is part of the U.S. Department of Energy's Vertical Mixing (VTMX) initiative. Sampling was done using three collocated instrument systems: a sonic anemometer mounted at 8.5 m, a single-axis minisodar, and a 915 MHz wind profiler/RASS. These systems operated continuously for nearly three weeks. In treating the wind profiler data, we have made extensive use of the NCAR Improved Moment Algorithm (NIMA) for extracting both winds and turbulence from the profiler. Through reprocessing the profiler spectral data, the NIMA allows credible profiles of winds and, in particular, dissipation rate, to be constructed for periods as short as 5 min.

In this paper we will discuss the process of turbulence decay as reflected in measurements of turbulence kinetic energy, dissipation rate, and heat flux from the sonic anemometer in the context of diurnal flows as well as the time-height structure of dissipation rate and mixed layer depth from the profiler.

2. THE OBSERVATIONS

The location within the Salt Lake Valley at which the observations for this study were made are shown in Figure 1. The site, which was called "Shay's Lounge" and had an elevation of 1330 m MSL, was near the Jordan River, which is in the middle of the valley. The terrain varies initially relatively gently in all directions. It rises gradually to the east for about 10 km toward the Wasatch Front and to the west for a similar distance before encountering the Oquirrh Mountains. The Wasatch Mountains and the Oquirrh range rise more than 1000 m above the valley floor. The valley rises to the south toward the Traverse Range, which is broken by the Jordan River. It descends slightly from Shay's Lounge northwest to Great Salt Lake, elevation 1280 m MSL. In the immediate vicinity of the measurement site, the vegetation was primarily grasses and forbs <1 m high and scattered trees roughly 3–4 m in height.

At Shay's Lounge, we operated three primary measurement systems: a sonic anemometer, a minisodar, and a 915 MHz wind profiling radar. The sonic was mounted 8.5 m AGL, and provided virtual temperature and the three components of wind at a sampling rate of 10 s^{-1}. The minisodar sampled using the vertical axis only, producing velocity spectra every 0.8 s at 5 m range gates between 5 m and 120 m. The minisodar data will not be discussed in this abstract. The wind profiler was operated in two modes: five beams with a range gate resolution of 60 m and five beams with a range gate resolution of 200 m. The profiler sampled in RASS mode for five minutes every half hour. We recorded spectral data from the profiler for the entire field program.

The sonic anemometer data were logged as ASCII data through the serial port of a laptop computer. The operating system for the laptop was Linux, and the acquisition code was a simple C program developed in-house. The data were processed for the entire field program to yield all first and second statistical moments as well as dissipation rate for each half hour. Second statistical moments were calculated after subtracting a linear trend from each half-hour's data, and this seems to have been an adequate high-pass filter. The dissipation rate was calculated from the inertial subrange of velocity spectra. All moments have been rotated into a geographical coordinate system.

Because of the coarser vertical resolution of the high-mode operation for the profiler and, equally important, because atmospheric conditions were such

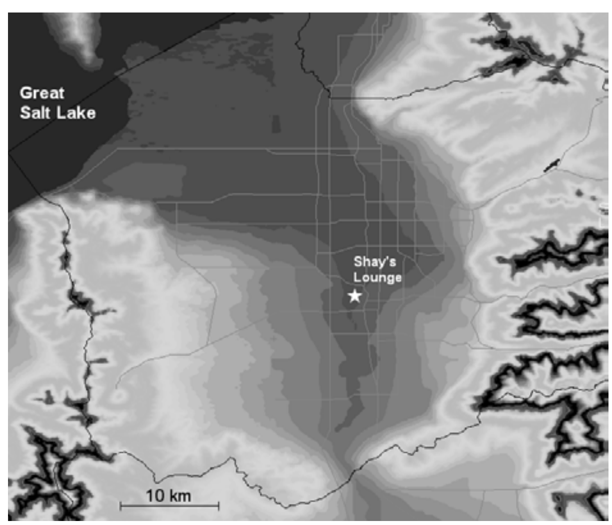

Figure 1. Salt Lake Valley, showing location at which data discussed in this paper were collected.

**Corresponding author address*: Will Shaw, Pacific Northwest National Laboratory, PO Box 999, MS K9-30, Richland, WA 99352; e-mail: will.shaw@pnl.gov.

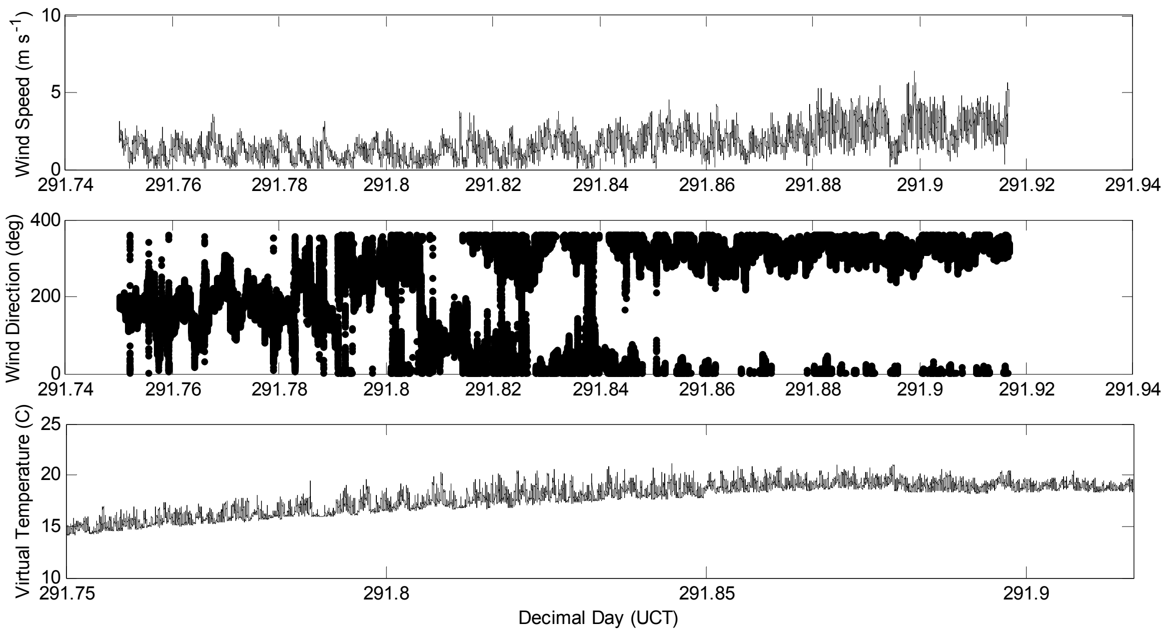

Figure 2. Time series of wind speed and direction and virtual temperature on Day 291 (17 October) 2000 showing the wind reversal that commonly occurred as part of the diurnal heating cycle during the VTMX field program.

that there was generally no significant gain in altitude coverage in that mode, we have restricted our analysis so far to the low-mode data. For a study of turbulence decay, it is important to obtain profiles of winds and turbulence as frequently as possible from the profiler. We have thus employed the NCAR Improved Moment Algorithm (Morse et al. 2002, Cornman et al. 1998), which uses a combination of fuzzy logic and pattern recognition to extract the necessary moments from wind profiler Doppler spectral peaks. The increased reliability of peak selection using this method also makes possible the computation of winds over periods as short as 5 min from the profiler. To obtain profiles of dissipation rate from the profiler, we have used spectral width data derived from NIMA processing and followed the methodology described by White et al. (1999) to relate spectral width to dissipation via the structure function. We have corrected for shear broadening effects following Gossard et al. (1998).

3. GENERAL BOUNDARY LAYER BEHAVIOR

Wind data from the profiler suggest that the circulation within the Salt Lake Valley during the VTMX field campaign can be viewed as having been of two broad types. In the first, local flow was dominated by strong large-scale pressure gradients, and winds were relatively strong and of a similar direction at all altitudes. In the second type, large-scale pressure gradients were weak, and the low-level winds exhibited a pronounced diurnal cycle: up-valley (to the south) in the daytime and down-valley at night. Doran et al. (2002) suggested a third circulation type in which upper-level winds were relatively strong and surface winds were light, but that does not appear to be practically different for our analysis from the second type above.

Figure 2 shows time series of wind speed, wind direction, and virtual temperature from the sonic anemometer for one afternoon. This day was typical of days with weak synoptic-scale pressure gradients. The wind speed was generally less than 2 m s^{-1} until early afternoon, when it strengthened to 3-4 m s^{-1}. However, the wind direction shifted from southerly, or down-valley, to northwesterly by midmorning. The virtual temperature trace shows numerous ramp structures, which are characteristic of the convective boundary layer, through most of the day. Although these were not as prominent after the wind reached its maximum value, there was no point, either around the wind direction shift or the wind speed increase, where there was a sudden drop in temperature that would be characteristic of a lake breeze front. Thus, a preliminary conclusion from these data is that a lake breeze, which is a form of a density current, is not as important a feature at this location as the general diurnal up- and down-valley flow. This is consistent with the observations of Doran et al (2002), who focused exclusively on the intensive observing periods of the field program.

Figure 3 shows the behavior of turbulence variables, as measured by the sonic anemometer, that were associated with the time series of Figure 2. This figure illustrates the typical pattern of turbulence decay as observed at the surface. The maximum buoyancy production of turbulence kinetic energy occurred about 4 hr before the heat flux dropped to zero in the afternoon. However, the shear production, as inferred from the wind speed, remained significant until the heat flux dropped to near-zero. As a result, the turbulence kinetic energy at the surface remained large well after the heat flux maximum, and the maximum values of

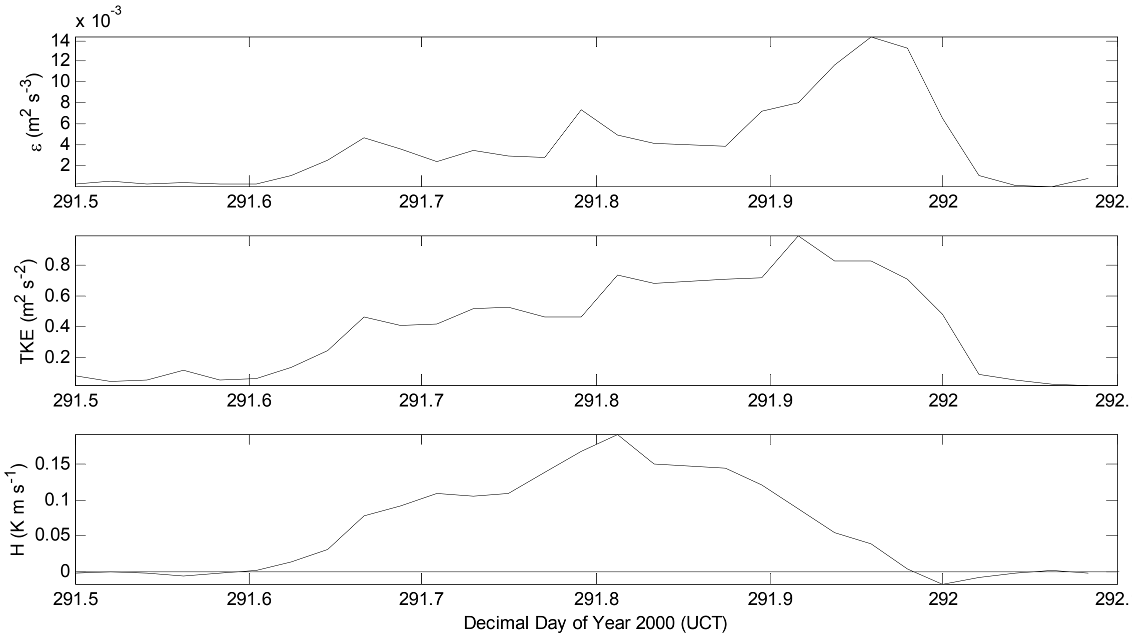

Figure 3. Turbulence decay as reflected at the surface in dissipation rate, turbulence kinetic energy, and surface sensible heat flux on 17 October 2000.

dissipation rate at the surface were observed after the heat flux became quite small.

Figure 4 shows the corresponding behavior of boundary layer depth during the daytime on Day 291. The range-corrected signal-to-noise ratio from the profiler shows a boundary layer that grew during the morning to a maximum depth of about 800 m. The boundary layer depth then decreased to about 300 m by 0000Z. This implies a subsidence velocity of at least 3–4 cm s^{-1} and a divergence that is an order of magnitude larger than that associated with synoptic-scale high pressure areas. It is most likely that this relatively large subsidence is a result of the return flow associated with near-surface winds moving up the Salt Lake Valley and its sidewalls. The evolution of boundary layer depth on Day 291 was typical of light-wind days during the field program.

Figure 5 shows a time-height cross-section of dissipation rate as inferred from the profiler. The data indicate larger dissipation rates near the surface, as would be expected. The evolution of the dissipation structure corresponds closely to the growth and decay of the mixed layer height.

4. IMPLICATIONS FOR SCALING

The investigation of scaling relationships for the boundary layer during the afternoon has been limited. Nieuwstadt and Brost (1986; hereafter NB) used a large eddy simulation (LES) to study the decay of turbulence in a boundary layer with zero wind in which surface heat flux was abruptly shut off. They found, among other things, that the integrated turbulence kinetic energy in the boundary layer, normalized by the convective velocity scale $w_* = \left(g\overline{w'\theta'_o}h/T\right)^{1/3}$, scaled with time normalized by $t_* = th/w_*$. Here $\overline{w'\theta'_o}$ is the heat flux prior to shut-off. NB also used a simple analytical model to suggest that turbulence decay under these conditions should approach a power-law after several decay time scales. Sorbjan (1997) extended the ideas of NB by using an LES with a more realistic quarter-sinusoid reduction of heat flux from its maximum value to zero during the afternoon. He found that a second time scale τ_f, the time between maximum and zero values of the heat flux, was also important. In addition, his results suggested that a velocity scale $V_* = (\varepsilon h)^{1/3}$ might be a better normalization for velocity variances than the convective scale w_*.

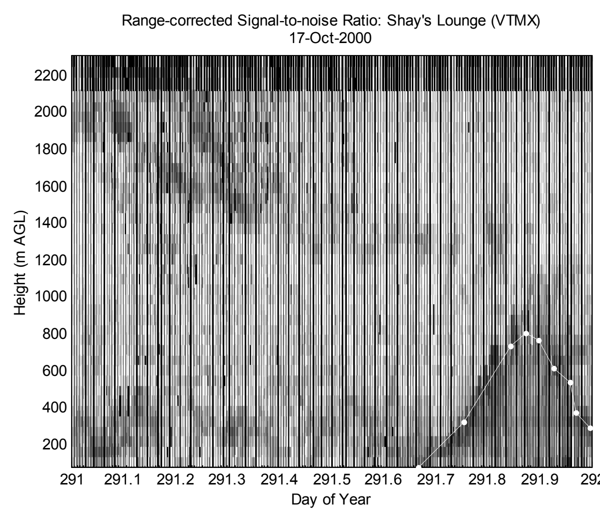

Figure 4. Time-height cross-section of range-corrected signal-to-noise ratio showing manually selected boundary layer depth.

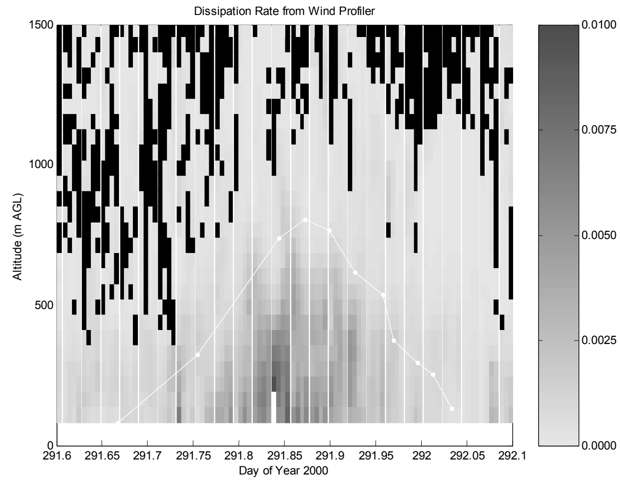

Figure 5. Time-height cross-section of dissipation rate as derived from the wind profiler. The white line is boundary layer depth as in Figure 4.

Both of the studies cited above are idealizations. In particular, the LESes did not include effects of wind or a time-varying boundary layer depth. The observations, however, show that these will be important features to consider in any scaling arguments for a realistic boundary layer.

5. CONCLUSIONS

We have completed an initial assessment of primary features of the structure of the atmospheric boundary layer in the Salt Lake Valley as measured from a central location during the October 2000 campaign of VTMX. In terms of understanding and scaling the transitional boundary layer in the afternoon, the following characteristics of the boundary layer in Salt Lake City are significant:

- For weak synoptic-scale gradients, there is a regular diurnal circulation of up-valley and down-valley winds that is primarily driven by sloping terrain. There was no clear signature of a lake breeze front in our surface fast-response data. Thus, it appears that a lake breeze is at most a second-order influence on the overall circulation of the central Salt Lake Valley.
- The decay of turbulence as reflected in the sonic anemometer data is delayed by shear generation of TKE as the heat flux drops toward zero. This characteristic is associated with the diurnal cycle of valley winds noted above.
- The sharp decrease of boundary layer depth in the afternoon is suggestive of subsidence an order of magnitude larger than conventional values under mid-latitude synoptic-scale weather systems. This is most likely related to valley circulations generated by diurnal heating. The strong variation in *h* can be expected to affect length scales for decaying turbulence and will have to be accounted for in any successful scaling arguments.

ACKNOWLEDGEMENTS

This work was supported by the U.S. Department of Energy (DOE), under the auspices of the Environmental Meteorology Program of the Office of Biological and Environmental Research. We are grateful to NCAR for providing NIMA to PNNL through a research license and for helpful discussions with Cory Morse of NCAR and Allen White of NOAA. This work was performed at Pacific Northwest National Laboratory, which is operated for DOE by the Battelle Memorial Institute under contract DE-AC0676RLO 1830.

REFERENCES

Cornman, L. B., R. K Goodrich, C. S. Morse, and W. L. Ecklund 1998: A fuzzy logic method for improved moment estimation from Doppler spectra. *J. Atmos. Ocean. Tech.*, **15**, 1287–1305.

Doran, J. C., J. D. Fast, and J. Horel 2002: The VTMX 2000 Campaign. *Mon. Wea. Rev.* (in press).

Gossard, E. E., D. E. Wolfe, K. P. Moran, R. A.. Paulus, K. D. Anderson, and L. T. Rogers 1998: Measurement of clear-air gradients and turbulence properties with radar wind profilers. *J. Atmos. Ocean. Tech.*, **15**, 321–342.

Morse, C. S., R. K. Goodrich, and L. B. Cornman 2002: The NIMA method for improved moment estimation from Doppler spectra. *J. Atmos. Ocean. Tech.*, **19**, 274–295.

Nieuwstadt, F. T. M., and R. A. Brost 1986: The decay of convective turbulence. *J. Atmos. Sci.*, **43**, 532–546.

Sorbjan, Z. 1997: Decay of convective turbulence revisitied. *Bound.-Layer Meteor.*, **82**, 501–515.

White, A. B., R. J. Lataitis, and R. S. Lawrence 1999: Space and time filtering of remotely sensed velocity turbulence. *J. Atmos. Ocean. Tech.*, **16**, 1967–1972.