From Proceedings of the 24th International Laser Radar Conference (ILRC), Boulder, Colorado.
23-27 June 2008. Oral presentation & paper S03O-01.

OBSERVATIONS OF SEA-BREEZE FRONTS AND TURBULENCE NEAR THE SURFACE DURING STABLE CONDITIONS

Shane D. Mayor

National Center for Atmospheric Research, PO Box 3000, Boulder, CO 80307-3000, USA, E-mail: shane@ucar.edu

ABSTRACT

Fast-response in situ data and scanning elastic backscatter lidar imagery that were collected simultaneously during two very different atmospheric boundary layer states are presented. First, observations of a well-defined sea-breeze frontal passage moving through a turbulent daytime mixed layer are shown. Second, observations of turbulence 10—30 m above the surface during a stable and relatively quiescent evening period are presented. In situ data from a tower provides time-series and profiles of fluxes of fundamental quantities up to 30 m above the ground. The lidar provides time-lapse animations of horizontal and vertical atmospheric structure and motion as revealed by variations in the aerosol scattering to ranges of several kilometers.

1. EXPERIMENT

The observations presented in this paper were collected during the Canopy Horizontal Array Turbulence Study (CHATS). The goal of CHATS was to obtain microscale measurements of the velocity and scalar turbulence fields in a uniformly vegetated canopy, using arrays of sonic anemometer/thermometers augmented with fast response water vapor and carbon dioxide sensors. With this spatial information, the three-dimensional fields of velocity and scalar fluctuations on scales of less than 15 m will be studied to quantify turbulence transport processes and coherent structures throughout the canopy layer.

To accomplish this, a large commercial walnut tree orchard was identified to serve as an idealized forest canopy. The orchard was 1.6 km square and the trees were approximately 10 m tall. Arrays of up to 18 in situ sensors were installed on a horizontal bar that could be fixed at various heights within and above the canopy. In addition, an instrumented 30 m tall tower was installed 100 m from the horizontal array. The terrain was extremely flat and surrounded by other agricultural fields. The experiment took place from 15 March to 11 June 2007 to observe periods with and without leaves.

The Raman-shifted Eye-safe Aerosol Lidar (REAL) was installed 1.6 km north of the tower and about 1.4 km north of the northern edge of the orchard. This allowed the collection of near horizontal scans (as low as 0.2° elevation angle) over the orchard. At this elevation angle the lidar beam intersected the tower at approximately the 12 m height. The goal of the REAL deployment at CHATS was two-fold: First, to test the lidar's ability to detect the fine-scale coherent structures just above the canopy and, second, to provide two-dimensional imagery of the larger-scale flow and deeper atmospheric boundary layer that the in situ measurements were embedded within.

Wavelength	1.543 microns
Pulse energy	170 mJ
Pulse rate	10 Hz
Pulse duration	6 ns
Beam diameter at BSU	66 mm (1/e^2 points)
Beam divergence	0.12 mrad (half-angle)
Telescope dia.	40 cm
Receiver FOV	0.54 mrad
Digitizer speed	100 MHz
Digitizer range	14 bits
Detector type	200-μm InGaAs APD

Table 1: Parameters of the lidar system

2. LIDAR

REAL is described in detail in [1], [2], and [3]. The lidar operates at 1.5-microns wavelength in order to transmit high pulse energy safely. REAL is eye-safe at 0 meters range for a 10 second unaided stare according to ANSI standards. High-pulse energy operation at 1.5 microns enables use of an analog direct detection receiver and rapid scanning. Rapid scanning enables one to create time-lapse animations of flow as evidenced by variability in the aerosol backscatter. The system specifications, as configured for CHATS, are provided in Table 1.

The lidar operated nearly continuously and mostly unattended for almost three months. Visits by staff every few weeks were made to change laser flashlamps and hard disks. Only a few interruptions lasting more than an hour, and sometimes as long as a few days, occurred due to electrical power disruptions and, in one case, failure of a commercial digitizer card. The result of the deployment is very large data set—containing over 2.5 TB of raw data from over 1850 hours of operation.

A variety of scan strategies were conducted with the lidar during the experiment. Since the primary goal was to observe very fine-scale turbulent coherent structures over the orchard, the lidar was often programmed to make narrow RHI and PPI scans directly over the orchard. However, because ideal conditions for the in situ component of the experiment occurred only when the wind was from the south, interleaved wide angle RHI and PPI scans were collected at other times. By interleaving the horizontal and vertical scans, time-lapse animations of both horizontal and vertical atmospheric structure were obtained simultaneously.

From Proceedings of the 24th International Laser Radar Conference (ILRC), Boulder, Colorado.
23-27 June 2008. Oral presentation & paper S03O-01.

Just prior to the CHATS deployment, REAL benefited from several substantial improvements including: (1) the ability to run continuously and unattended for periods of several weeks, (2) the ability to interleave the collection RHI and PPI scans in order to provide horizontal and vertical animations during the same period, (3) backscatter polarization sensitivity [3], and (4) remote control and near-real-time perusal of "Quick-look" scan images via the internet. Analog to digital signal processing rates were increased to 100 mega-samples per s for CHATS in order to record backscatter at 1.5-meter intervals. Detection signal amplifier electronics were rebuilt in an effort to increase receiver bandwidth and sense finer scale variability along the beam.

3. SEA-BREEZES

Four well-defined sea-breeze fronts were observed during the approximately 3 month period of CHATS. In each case, marine airmasses with higher backscatter intensity advected over the site from the south in the presence of larger scale northerly flows. The Pacific Ocean is approximately 100 km from the lidar site and accessable through the San Francisco Bay. Note also that all of the sea-breeze frontal passage events identified in the data set occurred in the afternoon.

For brevity only one of the four cases is presented here. On 26 April the lidar was recording data to a maximum of 5.8-km range and collecting consecutively interleaved horizontal and vertical scans. A small selection of scans are shown in Fig. 2. The marine airmass, colored in red, exhibits approximately 3.5 dB higher aerosol backscatter signal than the environmental backscatter. The lidar shows that the front traveled 5.8 km in slightly less than 51 minutes, or an average speed of 1.9 m s^{-1}. RHI scans show that the airmass north of the front is turbulent with aerosol plumes reaching 1.5 km altitude. The RHI scans also show structures resembling Kelvin-Helmholtz billows shearing off the leading edge of the front and moving south. These billows reach altitudes over 1 km at distances of 1.5 to 2.0 km south of the leading edge of the front. The largest billows appear to have wavelengths on the order of 1 km. The lidar is uniquely capable of observing the speed of the leading edge of this density current and its vertical extent.

In situ time-series from sensors on the 30 m tall tower, shown in Fig. 1, indicate that the air temperature dropped by approximately 2°C and the relative humidity (not shown) increased by about 12% when this front passed over. The wind direction changed from northerly before the arrival of the front to southerly after the frontal passage. The wind speed during the hour surrounding the frontal passage did not exceed 5 m s^{-1} at the top of the tower. The z/L stability parameter at 12.5 m height ranged from -2.0 to -0.6 (strongly to moderately unstable) before the arrival of the front to -0.5 to -0.2 (moderately to weakly stable) after the passage of the front.

4. STABLE BOUNDARY LAYER

The images resulting from horizontal scans collected during the night at CHATS often reveal fine-scale wave activity. Applying numerical high-pass median filtering to the range-corrected backscatter signal better enables one to see the smaller scales (< 1 km) of coherent structures. Although many hundreds of hours of data are available for analysis, only one 2.5 hour period is presented here to highlight how the lidar data can be used to gain an improved understanding of boundary layer events.

Fig. 3 shows the time-series of vertical velocity, wind speed, temperature and wind direction from a height of 12.5 m on the tower. This 2.5 hour period occurred during the evening from sunset until 15 minutes before midnight. In contrast to the unstable boundary layer shown in the previous section, the z/L stability parameter at 12.5 m during this period was approximately + 0.035 indicating weakly stable stratification.

The top panel of Fig. 3 indicates very calm conditions from 4:45 to 5:27 UTC, followed by an abrupt episode of turbulence. The turbulence occurred when the wind speed reached approximately 2 m s^{-1}. The air temperature dropped by approximately 1°C. Figs. 4(a), 4(b), and 4(c) show the lidar horizontal scans just prior, at the onset of, and during this event. Before the episode, the aerosol backscatter in the vicinity of the tower is homogeneous. The onset of turbulence occurs as a large positive perturbation of aerosol backscatter intensity begins advecting across the site from the southwest to the northeast. During the turbulent period, the aerosol backscatter exhibits significant small-scale variability. Presumably, higher wind speeds and turbulence are lifting particulate matter from the surface and foliage where it then serves as a tracer of the turbulent motions. It is also plausible that the turbulent region brings higher backscattering air with it. In any case, this region of disturbed backscatter extends beyond the edges of the scan. The lidar data gives the impression that the feature causing the episode of turbulence is a soliton—possibly a shallow density current. Unfortunately, RHI scans during this period were only collected once per 12-minutes. This sample rate is insufficient to depict coherent motions of the aerosol features in a vertical plane.

5. CONCLUSION

Achieving eye-safety and high single-shot backscatter signal-to-noise ratio performance simultaneously has enabled the creation of a lidar system that can scan rapidly and operate almost continuously and unattended. These capabilities, in turn, enable improved lidar sampling of atmospheric boundary layer phenomena that are both challenging to observe and simulate. While the aerosol backscatter intensity data are not of a specific quantity, the high spatial resolution images are capable of depicting structure and movement of fine-scale features over scales that are impractical with networks or arrays of in situ sensors.

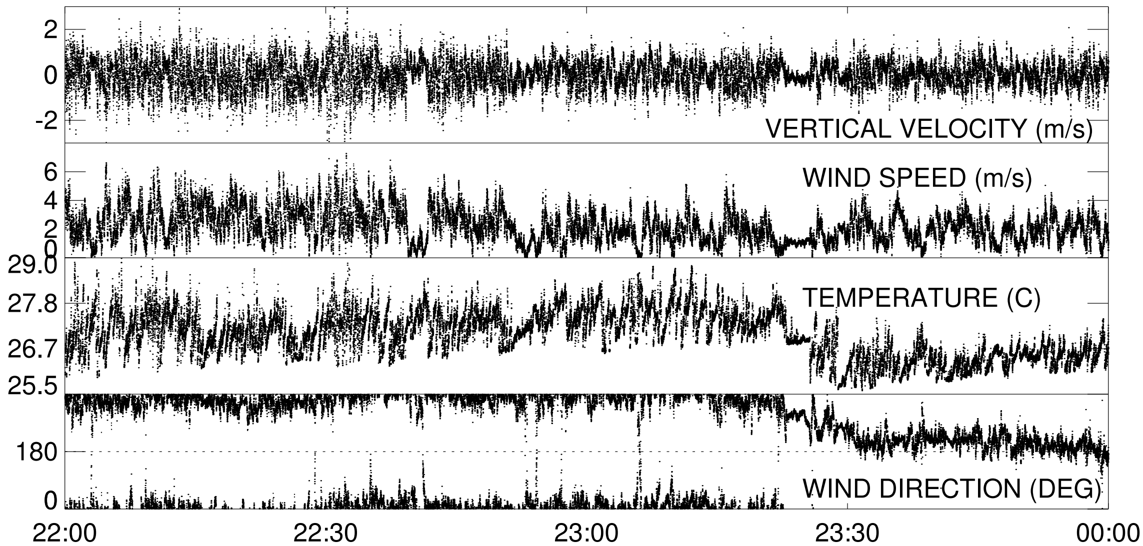
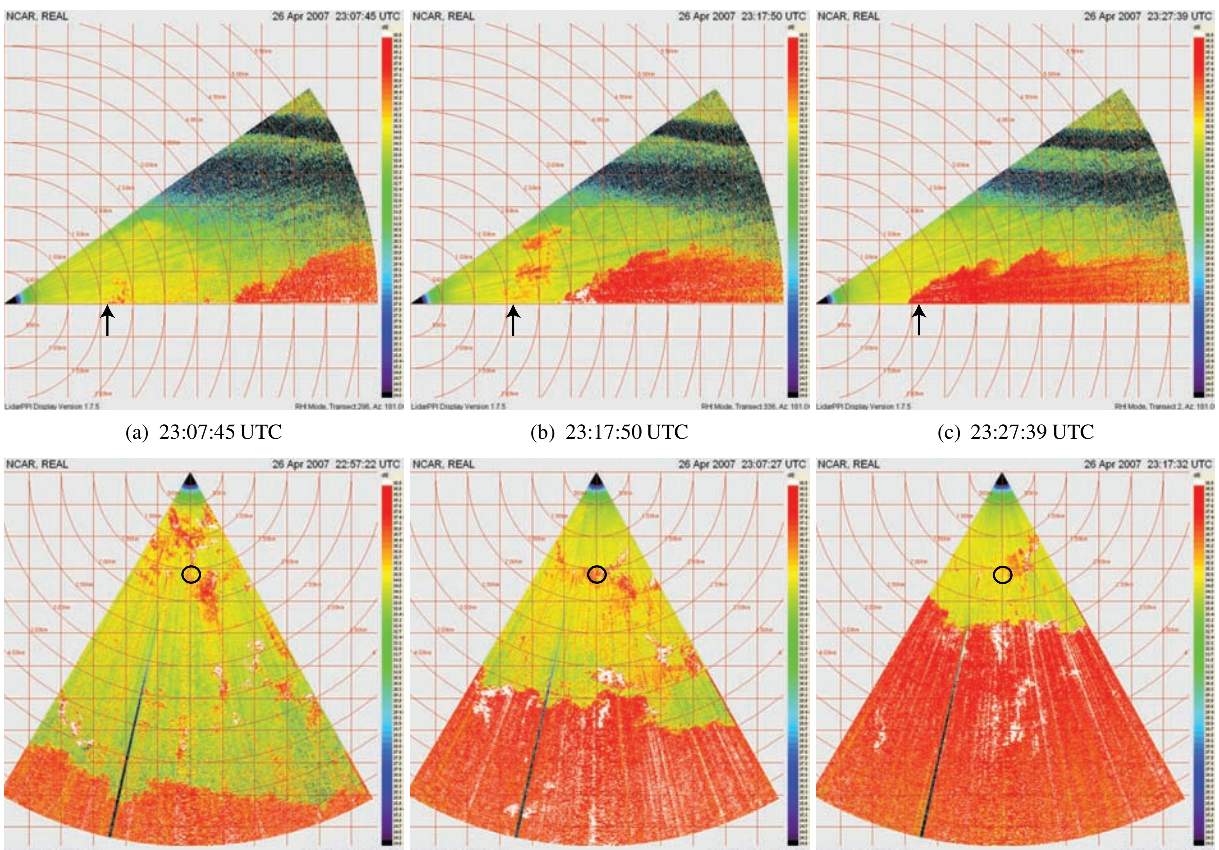


Figure 1: Time series of vertical velocity, horizontal wind speed, temperature, and wind direction collected from in situ sensors on a tower at 12.5 meters above the ground during the passage of the sea-breeze front and shown in Figure 2. These 6 Hz data shown were extracted from a 60 Hz time series. The sea-breeze front passed over the tower at approximately 23:27 UTC on 26 April.



(a) 23:07:45 UTC (b) 23:17:50 UTC (c) 23:27:39 UTC

(d) 22:57:22 UTC (e) 23:07:27 UTC (f) 23:17:32 UTC

Figure 2: Aerosol backscatter from selected vertical and near-horizontal scans 26 April 2007. The location of the instrumented 30 m tall tower is indicated by the black arrows on the RHI scans and the black circles on the PPI scans.

From Proceedings of the 24th International Laser Radar Conference (ILRC), Boulder, Colorado.
23-27 June 2008. Oral presentation & paper S03O-01.

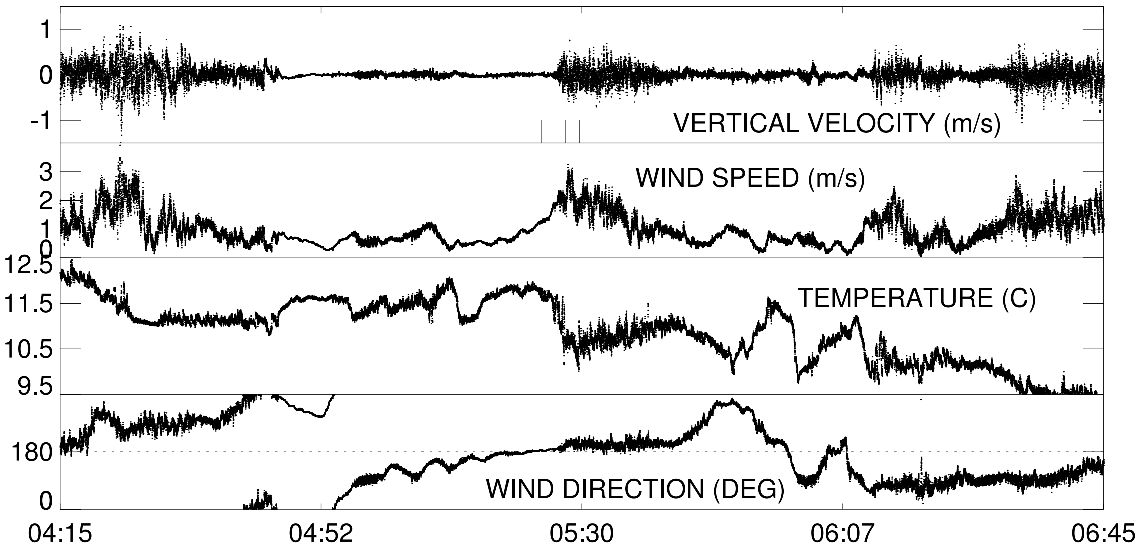
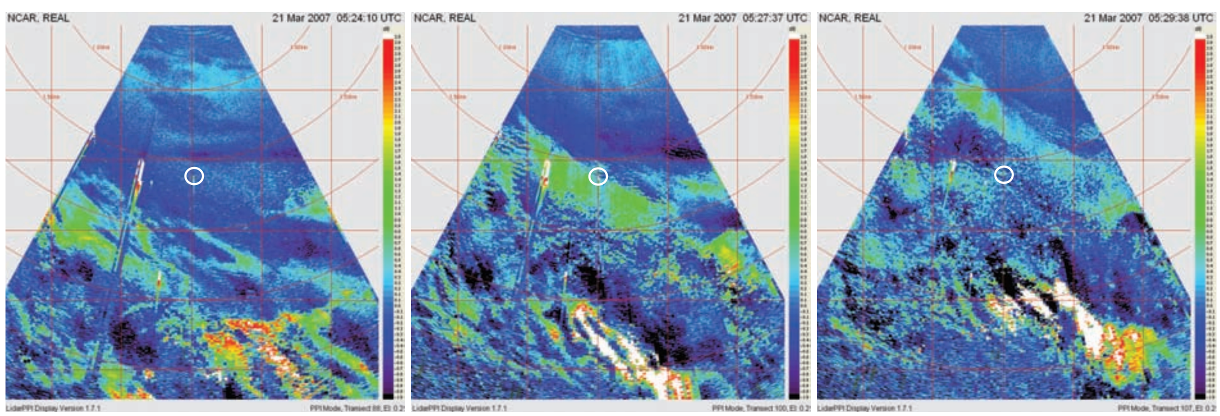


Figure 3: Time series of vertical velocity, horizontal wind speed, temperature, and wind direction collected from in situ sensors on a tower at 12.5 m above the ground during a stable evening boundary layer. These 6 Hz data were extracted from a 60 Hz time series. Times are in UTC. The three vertical lines near the middle of the top plot indicate the times of the frames shown in Fig.4.



(a) 05:24:10 UTC (b) 05:27:37 UTC (c) 05:29:38 UTC

Figure 4: High-pass median filtered aerosol backscatter from selected near-horizontal scans at 5:24:10, 5:27:37 and 5:29:38 UTC on 21 March 2007. The white circle near the middle indicates the location of the 30 m tall tower.

REFERENCES

1. Mayor, S. D. and Spuler, S. M. 2004: Raman-shifted Eye-safe Aerosol Lidar. *Appl. Optics,* **43**, pp. 3915-3924.

2. Spuler, S. M. and Mayor, S. D. 2005: Scanning Eye-safe Elastic Backscatter Lidar at 1.54 microns. *J. Atmos. Ocean. Technol.,* **22**, pp. 696-703.

3. Mayor, S. D. Spuler, S. M., Morley, and Loew, E. 2007: Polarization lidar at 1.54-microns and observations of plumes from aerosol generators. *Opt. Eng.,* **46**, doi:10.1117/1.2786406.

ACKNOWLEDGMENTS

Deployment of REAL at CHATS was funded by the NCAR Director's Opportunity Fund. NCAR is sponsored by the National Science Foundation. The author is indebted to Dr. Scott Spuler and Mr. Bruce Morley for their dedication to the development of REAL. Mr. Gordon McLean provided the ISFF data. Dr. Tom Horst calculated the stability parameters.