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Estimations of the dissipation of turbulent kinetic energy using sonics, 3-d hot-films, and Doppler lidar during TREX

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1. INTRODUCTION

This paper concerns the estimation of the dissipation rate of turbulent kinetic energy in atmospheric flows. Dissipation is an important quantity for theoretical studies on the atmospheric boundary layer (Hunt 1984) and also is considered a fundamental quantity of interest in flows past bluff bodies (Hunt 1973). The dissipation rate is difficult to directly measure because of the required very high spatial resolution, and thus may be inferred using the measurement of large-scale quantities. The direct measurements are made using hot-film anemometers with utilization of the Taylor hypothesis, and the indirect evaluations are made either using inertial subrange of the spectra (by fitting Kolmogorov spectra) or via empirical correlations. In this paper, we report on progress towards comparing estimates of dissipation rates from sonics and lidar with measurements from hot-wire films. Estimates of the dissipation rate which do not require microscale measurements would be useful and convenient if their accuracy and range of applicability are understood.

During March and April of 2006, a field study was conducted in Owens Valley, California, the Terrain Induced Rotors EXperiment (TREX). A large number of both *in situ* and remote sensing instruments were deployed in the valley to investigate the powerful and turbulent rotational motions and downslope wind storms associated with periods of strong wave activity over the valley. Arizona State University's (ASU's) coherent Doppler lidar was placed in the valley (see Figure 1) within 1.5 km of a 30 m tower outfitted with high-speed sonic anemometers, and also within 1.5 km of a smaller tower fitted with 3-d hot-films. The ASU lidar is a *WindTracer* model manufactured by *Lockheed Martin*. The laser pulse is approximately 2 mJ with a wavelength of 2 μm. The ASU lidar was located at 36.79771° N, 118.175640° W in Owens Valley. The towers were operated by the National Center for Atmospheric Research (NCAR) and were predominantly well within the optimal range of the lidar, although ranges varied highly depending on ambient aerosol levels. ASU's lidar range varied from over 8 kilometers in dusty conditions to almost 0 kilometers during rainy conditions.

Figure 1. ASU lidar deployed in Owens Valley, California during TREX. Mountains in background are to the southwest.

2. METHODS

The retrieval methods required for lidar-based estimates of the dissipation rate are mathematically involved, due mainly to the inherent volumetric averaging over each range gate. Because the dissipation takes place primarily on scales of motion far below the lidar range-gate size, the method requires a deconvolution based on empirical turbulence relations. Classical turbulence theories of Kolmogorov and others provide a theoretical foundation for such estimates through a well-known relationship between the structure function and dissipation. Two versions to calculate the structure function exist, one utilizing a von Karman (1948) formulation, and the other using a formulation from Kaimal et al (1972). There are several steps to the retrieval: 1) the errors associated with radial wind velocity measurements from coherent Doppler lidar are estimated and the data are corrected, 2) the deconvolution to account for the spatial averaging effects is performed, and 3) estimates of turbulent kinetic energy dissipation rate are obtained (see Frehlich 1998).

In our implementation, the data is first filtered to remove the noisiest data. A two step process is used, following; filter based rejection of data with low Signal to Noise Ratio (SNR), followed by removal of data with an excessive relative jump of the velocity compared to the preceding and succeeding data points. If the jump is greater than a threshold value, the data point is replaced with the median value of the closest 20 data points (with respect to time) whose velocity is within the threshold value from the median velocity of the observed gate. The threshold value is generally set in order to separate the noise from the data and must be subjectively determined because of the individual variations associated with different datasets. By careful data examination and after trying several threshold values, the threshold of 5 m/s was adopted. The selection of this threshold reduced the noise of the spectra and gave a regime close to -5/3.

As part of the deconvolution, the values of the velocity variance and the integral scale (which can be related to the outer scale) are found through a curve fitting method. The rate of dissipation can then be estimated using:

$$\varepsilon = A\sigma_v^3 / L_0 \qquad (1)$$

where A is a turbulence parameter with a value of approximately 1.

One method of estimating the dissipation of turbulent kinetic energy with the high-speed sonics is through the inertial sub-range, which is well measured by sonic anemometers as explained in Lundquist et al. (2004). The dissipation rate is estimated from the frequency spectrum in the inertial frequency sub-range.

Dissipation rate for turbulent kinetic energy is given by:

$$\varepsilon = \frac{2\pi}{U}\left[\frac{f^{5/3}S_u(f)}{\alpha}\right]^{3/2}, \qquad (2)$$

where U is the mean streamwise speed, α (here 0.53) is the Kolmogorov constant for the velocity component, $f^{5/3}S_u(f)$ is the mean compensated spectral intensity in the inertial sub-range of the streamwise component of the winds, and f is the frequency.

3. PRELIMINARY RESULTS

At the time of writing, the initial results are from the first two steps of the lidar-based dissipation retrieval. Figure 2 shows a line plot of the radial velocity versus range for 16:05:00 UTC on the 28th of April, 2006. In the final days of the TREX campaign, more than twenty-four hours of data for a fixed "stare" of the lidar beam at the central tower were collected, and likewise for the smaller tower with the hot-films. Animations of line plots such as in Figure 2 show stability of the measurement out to approximately 2.7 km during this period.

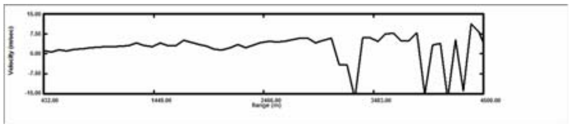

Figure 2. Example of radial velocity along lidar beam look-direction of 72.225 degrees azimuthally and -0.532 degrees in elevation (time: 16:05:00 UTC).

Figure 3 shows the power spectral density versus frequency. This will be compared with the equivalent sonic and hot-film data when available. It might be expected that the sonics and hot-films will not turn up as quickly for the larger frequencies, reflecting more complete resolution of the inertial subrange.

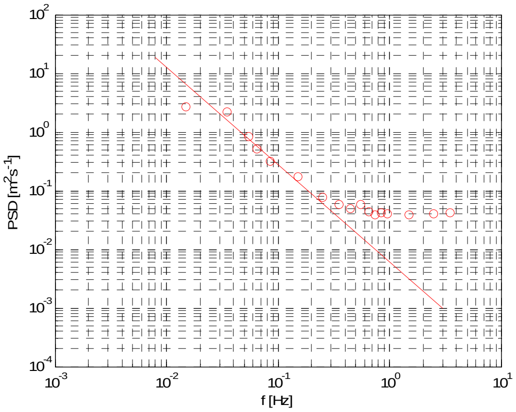

Figure 3. Power spectral density versus frequency of the lidar radial velocity.

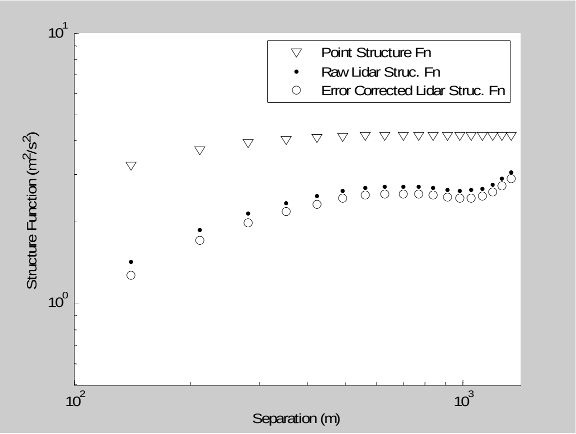

Figure 4. Structure function versus separation for 16:04:35 UTC to 17:04:35 of April 28, 2006 during TREX.

The value of various structure functions are compared in Figure 4. The lower two curves of data represent structure functions directly applied to the lidar data, and the corrected lidar data. A curve is fitted to the corrected lidar as a function of the integral scale and the velocity variance, which, once determined, can be used to calculate the dissipation rate. The integral scale and velocity variance obtained through the fitting process can also be used to estimate values for an “equivalent point-sensor” structure function, which is designated by the upper curve of data on the figure. Note the differences between estimated point-wise values and the range-gate averaged values of the structure function.

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References

Frehlich, R., S. Hannon, and S. Henderson, 1998: Coherent Doppler Lidar Measurements of Wind Field Statistics, *Boundary-Layer Meteorology*, 86, 233-256.

Hunt, J.C.R., 1973: A theory of turbulent flows around 2-dimensional bluff bodies, *J. Fluid Mech.*, 61, 625-706.

Hunt, J.C.R., 1984: Turbulence structure in thermal convection and shear-free boundary layers, *J. Fluid Mech*., **138**, 161-184.

Karman. T., 1948: Progress in the Statistical Theory of Turbulence, *Proc. Natl. Acad. Sci. U.S.*, 34, 530-539.

Lundquist, J.K., J. Shinn, and F. Gouveia, 2004: Observartions of the turbulent kinetic energy dissipation rate in the urban environment. *Symposium on Planning, Nowcasting, and Forecasting in the Urban Zone*, Seattle, WA, 10-15 January, 2004. Avail. at: atams.confex.com/ams/pdfpapers/71468.pdf

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