JP1.4 SPECTRAL CHARACTERISTICS OF TURBULENCE FROM ROOFTOP METEOROLOGICAL STATIONS IN WASHINGTON, DC

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1. Introduction

The NOAA Air Resources Laboratory's Atmospheric Turbulence and Diffusion Division operates a network of 15 rooftop meteorological stations in the District of Columbia metropolitan area called DCNet (Pendergrass and Hicks, 2007; Vogel and Pendergrass, 2007; Vogel et al., 2009). Typical sites include a 10 meter aluminum tower with a sonic anemometer and mean meteorological instruments mounted near the top. The standard sampling rate for turbulence measurements is 10 Hz, however, an additional datalogging system is sometimes deployed at different sites to simultaneously investigate the flow at higher sampling rates (i.e., 32 Hz).

The following discusses spectral characteristics observed atop the Howard University Physics Building during the late Winter and Spring of 2008. Estimates of the urban canopy characteristics surrounding the site include building heights z_H = 15 m, sensor height z_s = 25 m, and a displacement height z_d = 10.5 m and roughness length z_0 = 1.5 m [0.7 z_H and 0.1 z_H respectively (Grimmond and Oke, 1999)]. This gives an effective sensor height of $z'_s = z_s - z_d$ = 7.5 m, and a sensor/canopy height ratio z_s/z_H = 1.7 (e.g, Roth, 2000).

The 32 Hz sonic signals of north-south, east-west, and vertical winds as well as temperature were logged continuously from 6 February to 19 May 2008. For the purposes of obtaining spectra and cospectra the data was binned into 3 hour blocks, and data was only analyzed when relative humidities were less than 85% (to ensure non-rain cases), and wind speeds greater than 2 m/s (to reduce the possibility of cases where the turbulence was not "fully developed"). A coordinate rotation was performed on all high frequency wind data so that the mean vertical wind $\bar{w}$ = 0, and the longitudinal direction was that of the mean wind vector. A centered subset (2^{18} points = 2.28 hours) of each of the 3 hour sets of data was then analyzed.

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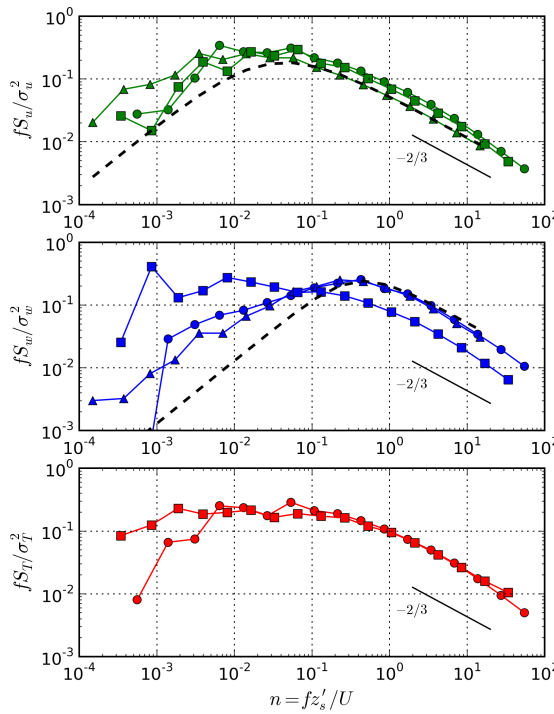

Figure 1: Sample spectra for 3 stability cases for u, w, and T. Stability z'_s/L values are -0.32 (○), -0.01 (△), and +0.10 (□). Curves resulting from the Kansas Experiment are shown as dashed lines.

2. Spectra

Sample spectra of u and w, the longitudinal and vertical winds, and temperature T are shown in Figure 1. The x-axis contains normalized frequency n where f is natural frequency, and U is the mean wind. The y-axes contain spectral density estimates multiplied by f and normalized by signal variance. The data were logarithmically block averaged to show the signal characteristics more clearly. The very near-neutral case in the temperature spectra plot was omitted since it is ill defined. In addition

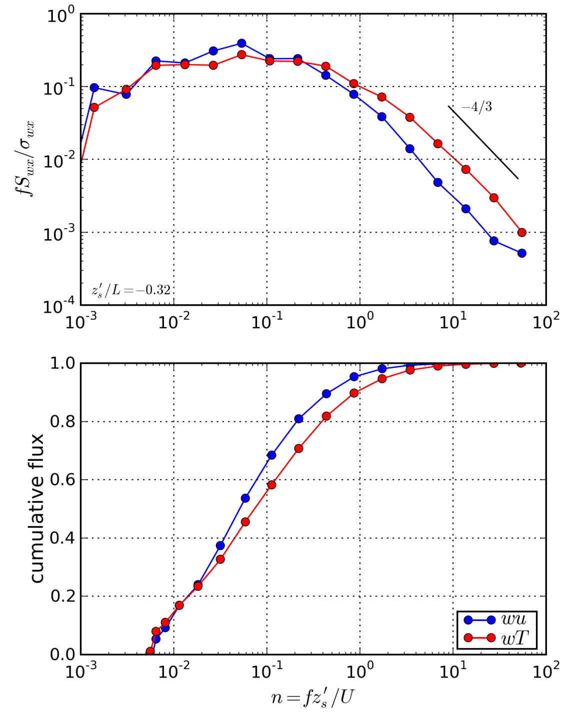

Figure 2: The upper plot shows sample cospectra plots of momentum wu and temperature wT covariance for an unstable case. The lower plot shows the associated cumulative flux as a function of normalized frequency.

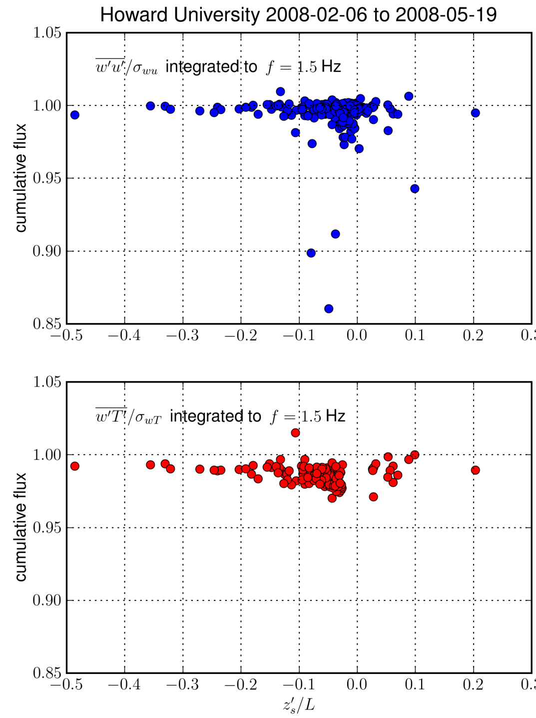

Figure 3: Cumulative flux values for momentum (upper plot) and heat (lower plot) f = 1.5 Hz. Very near-neutral values of cumulative heat flux were omitted.

to the three different stability cases, curves (dashed lines) representing empirical relations resulting from the Kansas Experiment (e.g, Roth, 2000; Kaimal et al., 1972; Højstrup, 1981; Panofsky and Dutton, 1984) are also shown. All three plots show the classic -2/3 power behavior according to the Kolmogorov relations in the inertial subrange for n values approximately greater than 1.

3. Cospectra

Of particular interest are cospectral characteristics of the data since they reflect the scales responsible for momentum and scalar fluxes. The upper plot of Figure 2 shows cospectral energy densities for momentum and heat, multiplied by f, and normalized by the respective mean covariance. Note the classic -4/3 behavior (Wyngaard and Coté, 1972). The lower plot gives the associated cumulative flux as a function of normalized frequency.

A frequently asked question is how fast does one need to sample to capture the great majority of the cospectral energy for particular canopy characteristics? As shown in Figure 3, for these particular measurements, at a natural frequency f = 1.5 Hz, in most cases over 98% of the energies responsible for the fluxes have been captured (in the Fig. 2 case U = 2.94 m/s so that f = 1.5 Hz corresponds to n = 3.8). Except for some isolated cases it is apparent that a slightly lesser amount of heat flux is resolved at 1.5 Hz than momentum. Values greater than one indicate a change of sign in the flux direction at some point in the lower frequencies.

Of additional interest are the primary scales responsible for momentum flux. Figure 4 shows peak normalized frequency n_{max} for all cases as a function of stability (e.g, Panofsky and Dutton, 1984). Block averaged values are shown as large circles. Although it is difficult to ascertain any trends as has been shown by others over a wider range of stability, peak frequency values are reasonably consistent with those found in other studies.

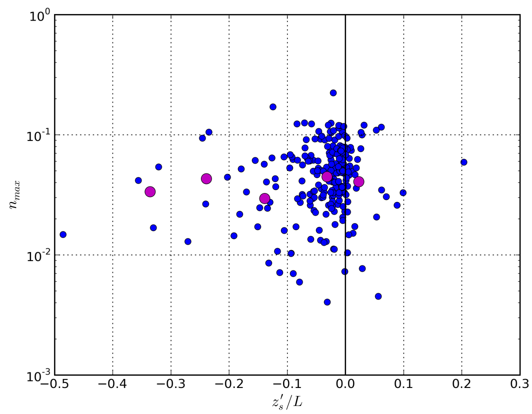

Figure 4: Normalized peak frequency n_{max} as a function of stability. Large circles indicate block averaged values.

4. Discussion

Some brief points can be made concerning this preliminary analysis. One is that the 237 3-hour data cases analyzed all fell into a relatively narrow near-neutral range. This is, of course, partially because of the small z_s' value characteristic of many rooftop measurements; however, it also indicates the primary influence of mechanical means to generate the turbulence over a relatively rough (i.e., urban) canopy. Further, although reliable demonstrations of turbulent behavior such as spectra and cospectra could possibly be expected from a single rooftop station (e.g, Raupach et al., 1991), there is evidence that quantities such as momentum flux may vary significantly horizontally and vertically within a roughness sublayer (Kastner-Klein and Rotach, 2004). This sort of analysis should be expanded to include many of the other DCNet sites for the assessment of horizontal variability, as well as to lead to more detailed studies of turbulent flow behavior at greater heights above the DC urban canopy.

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References

Grimmond, C. S. B. and T. R. Oke, 1999: Aerodynamic properties of urban areas derived from analysis of surface form. *J. Applied Meteorology*, **38**, 1262–1292.

Højstrup, J., 1981: A simple model for the adjustment of velocity spectra in unstable conditions downstream of an abrupt change in roughness and heat flux. *Boundary-Layer Meteorol.*, **21**, 341–356.

Kaimal, J. C., J. C. Wyngaard, Y. Izumi, and O. R. Coté, 1972: Spectral characteristics of surface layer turbulence. *Q. J. R. Meteorol. Soc.*, **98**, 563–589.

Kastner-Klein, P. and M. W. Rotach, 2004: Mean flow and turbulence characteristics in an urban roughness sublayer. *Boundary-Layer Meteorol.*, **111**, 55–84.

Panofsky, H. A. and J. A. Dutton, 1984: *Atmospheric Turbulence: Models and Methods for Engineering Applications*. John Wiley & Sons, New York, NY, USA.

Pendergrass, W. R. and B. B. Hicks, 2007: DC-Net: National Capital Region testbed. *Seventh Symposium on the Urban Environment*, American Meteorological Soc., 10–13 September, San Diego, CA.

Raupach, M. R., R. A. Antonia, and S. Rajagopalan, 1991: Rough-wall turbulent boundary layers. *Applied Mechanics. Rev.*, **44**, 1–25.

Roth, M., 2000: Review of atmospheric turbulence over cities. *Q. J. R. Meteorol. Soc.*, **126**, 941–990.

Vogel, C. A. and W. R. Pendergrass, 2007: Using autocorrelation to evaluate persistence forecasts for discrete wind vector fields in the national capital region. *Seventh Symposium on the Urban Environment*, American Meteorological Soc., 10–13 September, San Diego, CA.

Vogel, C. A., W. R. Pendergrass, J. R. White, and R. Meyer, 2009: The DCNet network. *NOAA Tech. Memo.*, to be submitted.

Wyngaard, J. C. and O. R. Coté, 1972: Cospectral similarity in the atmospheric surface layer. *Q. J. R. Meteorol. Soc.*, **98**, 590–603.