12.4 ON THE BEHAVIOR OF THE NONDIMENSIONAL WIND SHEAR IN AN URBAN ROUGHNESS SUBLAYER

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1. Introduction

The well known logarithmic wind profile relation for the atmospheric surface layer has been studied extensively in the field, and numerous parameterizations for its nondimensional form have been presented (e.g., Frenzen and Vogel, 2001; Foken, 2006). The vast majority of these studies involved measurements taken above the roughness sublayer (RSL), a layer in the lowest portion of the atmospheric surface layer (ASL) where the wind field is directly affected by the presence of individual roughness elements rather than from a horizontally averaged footprint. Most work has been done above the RSL because theory assumes horizontal homogeneity, and most of the terrain used in the studies involved RSL layers that were shallow extending centimeters or meters above the canopies. However, over much rougher terrain such as found in suburban and urban areas this layer can potentially extend hundreds of meters above the ground (i.e., 2 to 5 canopy heights; Raupach et al. (1991)), and because people live and work within these canopies, it is of concern in many applications, including air quality, climate, and atmospheric dispersion.

The nondimensional wind shear in the RSL can be expressed as:

$$\frac{kz}{u_*}\frac{\partial U}{\partial z} = \phi_m(z/L)\;\phi_*(z/z_*) \qquad (1)$$

where U is the mean wind, u_* is the friction velocity, k is the von Karman constant (assumed to be 0.4 for this analysis), L is the Monin-Obukhov length, and z_* is the height of the RSL. The height $z = z_s - d$ where z_s is the measurement height above ground and d is the displacement height. The function ϕ_m is a function of stability, and is by definition equal to one at neutral. The function ϕ_*, so far largely presented as a function of height relative to the height of the RSL, is not well understood, but should equal one at the top of the RSL, and approach zero as we approach the displacement height d plus roughness length z_0. Garratt (1992), for example proposed $\phi_* = \exp[-0.7(1 - z/z_*)]$.

As part of the NOAA DCNet Program (Pendergrass and Hicks, 2007; Vogel and Pendergrass, 2009), from Spring 2008 to Spring 2009, a mini doppler sodar (Remtech PA1 model) was deployed on the roof of the DOE Forrestal Building in Washington, DC (38.88656 N, 77.02513 W) adjacent to an existing DCNet flux tower station. The tower site provides continuous 15 minute averages of standard meteorological variables, as well as turbulence statistical quantities including the fluxes of heat and momentum. Having both instrument suites collocated allowed for an initial assessment of the behavior of the nondimensional wind shear within the RSL.

2. Analysis

a. Data Processing

The mini sodar output included wind speeds and directions at 10 meter intervals from 20 to 500 m above measurement height. However, due to the ambient noise levels accurate winds could only consistently be resolved up to 200 meters above the instrument. Further, for every 30 minute profile measured not all measurement heights were sometimes resolved. Consequently, a linear interpolation for the time series at each height level was used to fill in any missing data. Data were not used where there was greater than a 30 minute gap between successive profiles. In addition, the profiles were found to be noisy at 30 minute intervals (perhaps indicating too short an averaging time), and a 2.5 hour running mean was employed at each level to smooth the data. The 2.5 hour running mean window falls within the range of assessed persistence times from a previous analysis of winds from the DCNet network (Vogel and Pendergrass, 2007).

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b. Canopy Characteristics

The downtown Washington, DC canopy is relatively uniform in height compared to many other urban areas. The building height z_H of the Forrestal facility was approximately 30 meters, whereas the heights of the sodar and turbulent flux tower measurements were 1 and 7 meters respectively above the top of the building. Plan area density λ_p — the horizontal surface area of structures per total horizontal area, obtained through the National Building Statistics Database Version 2 (Burian et al., 2004, 2008) — in the vicinity of the tower was approximately 0.2 to 0.4. These values would arguably place the measurements within a "skimming flow" flow regime (Grimmond and Oke, 1999).

c. Wind Profiles

To reduce uncertainties only daytime, very near neutral profiles $(-0.05 < z/L < 0)$, assumed to be so based on surface [canopy top] heat and momentum flux values, were analyzed so that ϕ_m could be assumed to equal 1. Thus, the nondimensional wind shear on the left in equation 1 is considered to be solely explained by the function ϕ_*. Further, a number of other criteria were employed on the data, namely, to only use cases 1) where the relative humidity was less than 85% (to reduce any chance of high humidities or rain affecting the instruments), 2) where $\sigma_u/U < 0.5$ (to reduce significant deviations from Taylor's Hypothesis and the steady state assumption), and 3) where U at the surface was greater than 4 m/s (to ensure "fully developed" turbulence). This ultimately reduced the number of 30 minute profiles from over 7500 to 85.

In order to determine the height of the RSL, and assess wind shear behavior within the layer, a fifth order polynomial was fitted to all profiles. An objective method chosen for determining RSL heights was to determine the height at which the curves exhibited maximum positive curvature (i.e., utilize the second derivative). Figure 1 shows the results through a histogram of RSL height values in units of canopy multiples. An RSL height of 3.2 z_H was determined. No obvious dependence on wind direction was noted in analyzing the profiles for RSL heights.

In addition to determining a mean RSL height, profile fits were used to calculate nondimensional shear values according to Eq. 1. Figure 2 shows the resulting shear values as a function of height relative to the RSL height z_*. A simple Gaussian function (here $\phi_* = a_0 \exp[-(z/z_* - a_1)/(2a_2^2)]$ where $a_0,\ a_1,\ a_2$ = 3.78, .769, .141) was fitted to the data to compare with other forms such as the Garratt (1992) parameterization above.

It should be noted that absolute values of the nondimensional shears are significantly affected by the choice of u_* with which to normalize. In this case we had available only values measured near the canopy top. However, there is evidence that momentum flux may not be constant within the RSL (see Roth, 2000; Kastner-Klein and Rotach, 2004), and that the u_*s used may be too small. Thus, the results presented should be observed in a more qualitative rather than absolute sense. Nevertheless, the amount of vertical momentum flux divergence would not negate the fundamental observed behavior of the nondimensional shears, and their departure from traditional parameterizations.

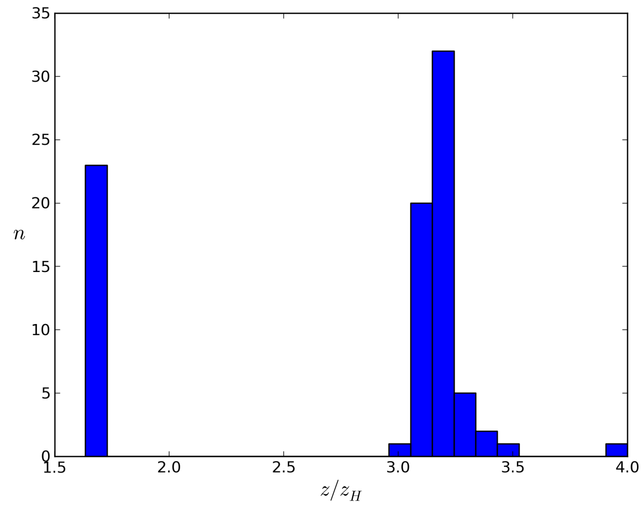

Figure 1: A histogram showing computed RSL heights in canopy multiples through analysis of profile fit curvature. Note the outliers near 1.6 and 4.0 canopy heights due to inadequacies in accurately fitting profiles.

3. Summary

The wind profiles observed above the urban canopy of downtown Washington, DC, as might have been expected, showed marked differences from those predicted by the classical log profile relation. A mean RSL height of approximately 3.2 z_H was observed, and within the RSL nondimensional wind shear showed marked departures from a parameterization previously suggested. It would appear that there is a region within the RSL close to the canopy top where shear is significantly reduced, but then also a region where the shear increases markedly, peaking near 0.8 z_*, to work to bring the wind profiles back close to those predicted by the log profile relation applicable to the main portion of the ASL. Both the parameterization presented here and Garratts form are displeasing since no scales relating to the canopy architecture and other physical quantities are employed.

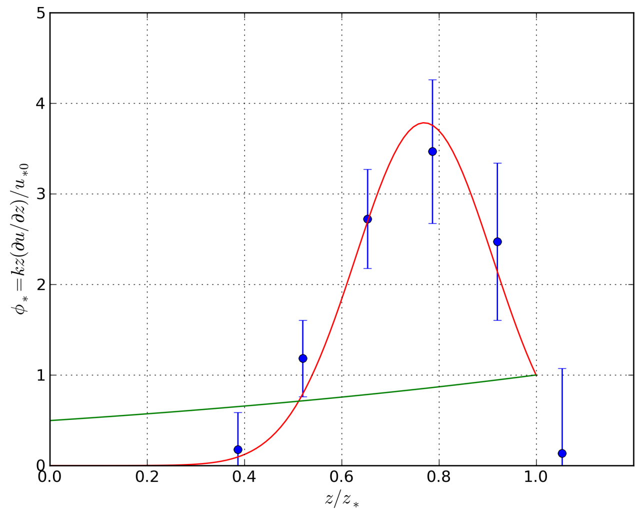

Figure 2: The behavior of the nondimensional shears as measured at the DOE Forrestal Building with a simple Gaussian function fitted to the data. Note the marked departure from the parameterization proposed by Garratt (1992), shown as the green line.

More work needs to be performed relating the canopy architecture to RSL heights and the behavior of flow variables within the layer.

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