J11.3 Urban Canyon Data Analysis using a Surface Stress which Incorporates the Effects of Canyon Walls

Cheryl Klipp, PhD *
US Army Research Lab, Adelphi, MD

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1. Abstract

In many urban turbulence studies, sonic anemometers are deliberately placed in the inertial sublayer (ISL), usually located several roughness heights above a canopy, in part to avoid the problems of interpreting data from within the urban roughness sublayer (RSL). The need to accurately predict dispersion within urban areas for air quality modeling and emergency response requires detailed knowledge of turbulent statistics and improved scaling schemes for data taken within urban roughness sublayers. The data from urban canyon studies have been difficult to interpret, and conflicting results can be found in the literature.

One problem is that the vertical surfaces which define the urban canyons also produce drag. The standard method of calculating u_* from $\overline{u'w'}$ and $\overline{v'w'}$ does not capture the full amount of momentum lost to surfaces within urban canyons because, in streamwise coordinates, the momentum flux for flow along a vertical surface is expressed as $\overline{u'v'}$. Inclusion of $\overline{u'v'}$ is made with a Reynolds stress tensor derived analog to u_*. The performance of this u_* analog is compared to u_* for use in urban flow within and immediately above an urban canyon in Oklahoma City during JU2003 as well as in neighboring street intersections. This u_* analog is shown to be a useful tool for better understanding urban roughness sublayer flows.

Some of the problems of using data from within the roughness sublayer include the fact that the data are representative of only a local area, flows are typically not fully adjusted to the heterogeneous surface properties, and the presence of obstacles makes tilt correction extremely problematic. However, knowledge of flow and fluxes within the RSL will improve our understanding of urban and forest transport.

* *Corresponding author address*: Cheryl Klipp, US Army Research Lab, attn AMSRD-ARL-CI-ED, 2800 Powder Mill Rd., Adelphi, MD 20783. cheryl.l.klipp@us.army.mil

2. Introduction

This work was initially motivated by the problem of how to correct for sonic anemometer tilt in the RSL (Klipp 2004). Some aspects of the problem are the presence of multiple wall normal directions and the fact that most RSL flows are not fully adjusted to the surface conditions at the instrument location. For flow past an obstacle, $\hat{y}$ becomes the wall normal instead of $\hat{z}$, making $\overline{u'v'}$ the primary surface stress term instead of $\overline{u'w'}$ (Fig 1). More difficult to define is a total surface stress or an effective surface stress for a location equidistant from two differently oriented walls. Also undefined is the surface stress a short distance downstream from such a situation.

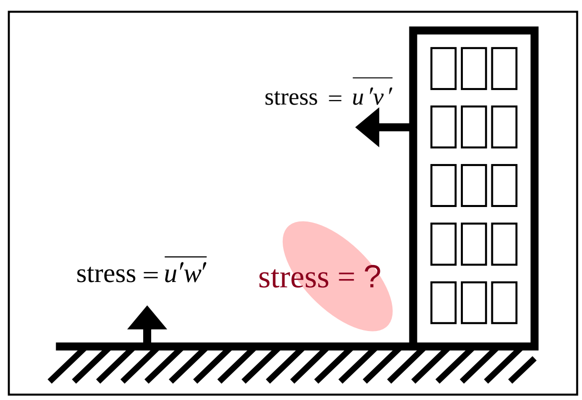


Figure 1 Wall normal is no longer parallel to the gravity vector near buildings, making stress difficult to define

Since $\overline{u'v'}$ becomes important in the urban RSL, one could add a third term to redefine u_* as $u_*^2 = \left(\overline{u'w'}^2 + \overline{v'w'}^2 + \overline{u'v'}^2\right)^{1/2}$, but this is not mathematically consistent with the tensor qualities of the terms. Tensor invariants are a mathematically sound choice. In addition, the invariants are independent of the sonic anemometer orientation, thereby eliminating the need for tilt correction (Wilczak *et al*. 2001).

A substitute for u_* is proposed as a tool for use in scaling schemes within the RSL. This proposed u_* substitute utilizes invariants of the Reynolds stress tensor which are independent of the choice of coordinate system, making it more reliable for use in the roughness sublayer. It has the added advantage of approximating standard u_* values when applied to data from the ISL. The empirical formula is based on data from lab flows as well as atmospheric field data from JU2003.

3. Reynolds stress tensor

There are an infinite number of sets of three mathematically independent invariants for a second rank tensor in three dimensions such as the Reynolds stress tensor (Arfken 1985). For this application it makes sense to use the eigenvalues and corresponding eigenvectors. The eigenvectors form an orthogonal coordinate system which defines the fundamental directions for the wind fluctuations as expressed in the Reynolds stress tensor, and the eigenvalues are the corresponding fundamental variance values. In other words, the usual boundary layer coordinate system of along wind, cross wind and vertical directions is not the primary coordinate system for the turbulent fluctuations.

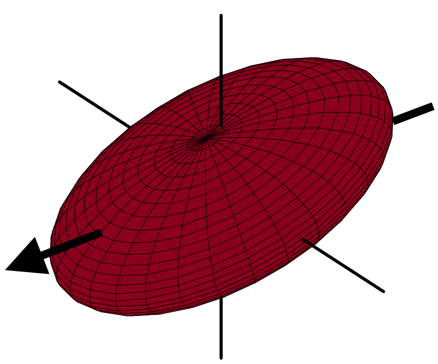


Figure 2 Idealized TKE ellipsoid based on lab flows

In laboratory flows (Liberzon *et al*. 2005, Hanjalic and Launder 1972) and in the boundary layer over flat terrain in near-neutral and shear dominated cases (Klipp 2007), this primary coordinate system is nearly aligned with the usual boundary layer coordinate system, but is rotated approximately 17° around the cross stream axis in the direction of the mean wind (Fig 2), resulting in an approximately 73° angle between the mean wind direction and the eigenvector associated with the smallest eigenvalue.

4. Scaling term using tensor invariants

For flow inside the RSL, this simple relationship between the two coordinate systems no longer holds, however, the Reynolds stress tensor can still be diagonalized. The resulting diagonal matrix can be rotated 17° in the opposite sense to create a value in the upper right and lower left locations, where $\overline{u'w'}$ would be (Eq 1).

$$\begin{pmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{pmatrix}\begin{pmatrix} \lambda_B & 0 & 0 \\ 0 & \lambda_M & 0 \\ 0 & 0 & \lambda_S \end{pmatrix}\begin{pmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{pmatrix}$$

$$= \begin{pmatrix} \lambda_B\cos^2\theta + \lambda_S\sin^2\theta & 0 & (\lambda_S - \lambda_B)\cos\theta\sin\theta \\ 0 & \lambda_M & 0 \\ (\lambda_S - \lambda_B)\cos\theta\sin\theta & 0 & \lambda_S\cos^2\theta + \lambda_B\sin^2\theta \end{pmatrix}$$

Equation 1

Using $u_{*R}^2 = -(\lambda_S - \lambda_B)\cos\theta\sin\theta$ is analogous to $u_*^2 = -\overline{u'w'}$. Using 17° for the rotation angle yields $u_{*R}^2 = 0.280(\lambda_B - \lambda_S)$. For open terrain this substitute for u_*^2 has approximately the same value as $u_*^2 = \left(\overline{u'w'}^2 + \overline{v'w'}^2\right)^{1/2}$ (Fig 3).

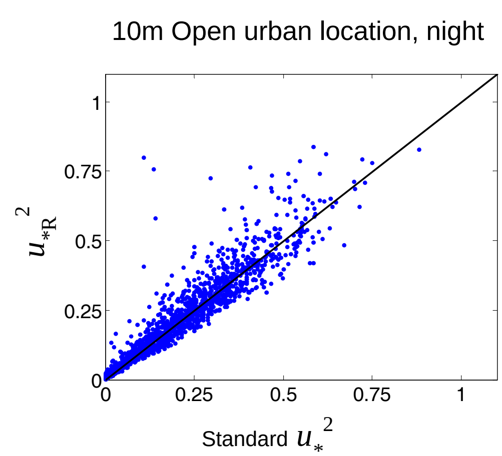
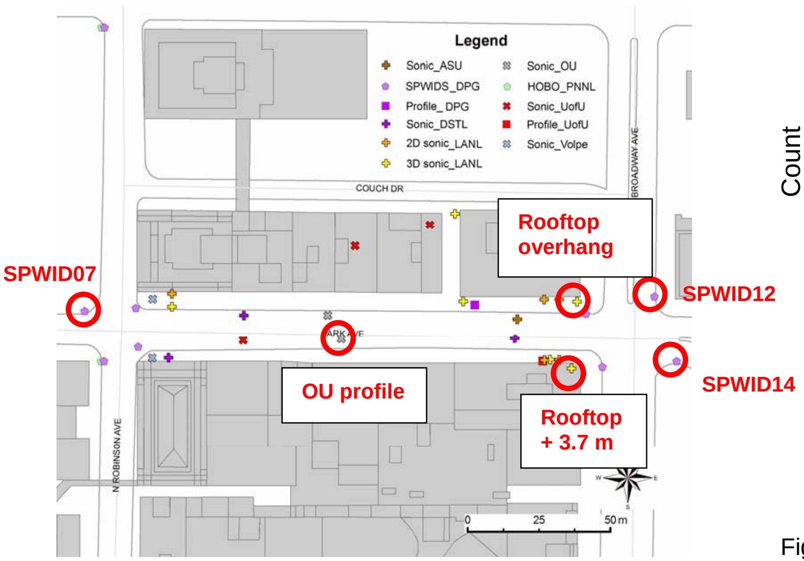


Figure 3 Standard definition u_*^2 compared to idealized u_{*R}^2, open location, night

5. Data

For this analysis, data from the Joint Urban 2003 field campaign Park Avenue street canyon of Oklahoma City, OK are used.



Map from Allwine and Flaherty 2006: PNNL-15967

6. u_{*R} as more consistent than u_*

Due to the presence of vertical surfaces, u_* fails to capture the full surface stress within urban roughness sublayers. This could lead to inconsistently measured values of u_* from one location to a nearby location. Although it is expected that the surface stress will vary throughout the urban canyon and intersections, some consistency with small changes in location is desirable.

Using the ratio of simultaneous values taken at nearby locations (SPWID 12 and 14) as a measure of consistency, u_* and u_{*R} are compared for locations across the street from each other at the intersection of Park Avenue and Broadway (Fig 4). The ratio for u_* (blue line) shows a consistent bias with the value measured at one corner (SPWID 14) consistently smaller than the value across the street (SPWID12). The ratio for u_{*R} (red line) is fairly close to 1.0, and the distribution is narrower than for u_*, but u_{*R} can still vary by a factor of 2 at any given time.

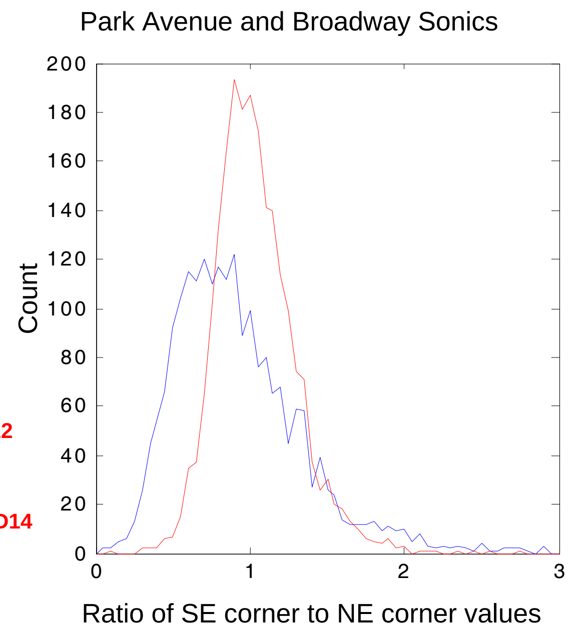


Figure 4 The ratio between the u_* value at the NW corner to the u_* value at the SW corner at the same time (blue line), and the ratio between the u_{*R} value at the NW corner to the u_{*R} value at the SW corner at the same time (red line). The u_{*R} ratio is closer to 1.0 than the u_* ratio, indicating that u_{*R} is more consistent from one corner to the next.

7. Measurments within RSL

Values of the standard u_* within the RSL can become small as the importance of $\overline{u'v'}$ increases. The Reynolds stress tensor derived u_{*R} values are almost always larger (Figs 5 and 6) than the standard u_* values. In addition, the intersection values are larger than the mid-canyon values. The profiles of u_* and u_{*R} not only reflect this, but also indicate a different curvature to the profiles near the street. Of interest is the effect at the building rooftop level. For u_* there is a maximum at the rooftop, while for u_{*R} the maximium is above the rooftop for both day and night. This location in the urban canyon requires more research

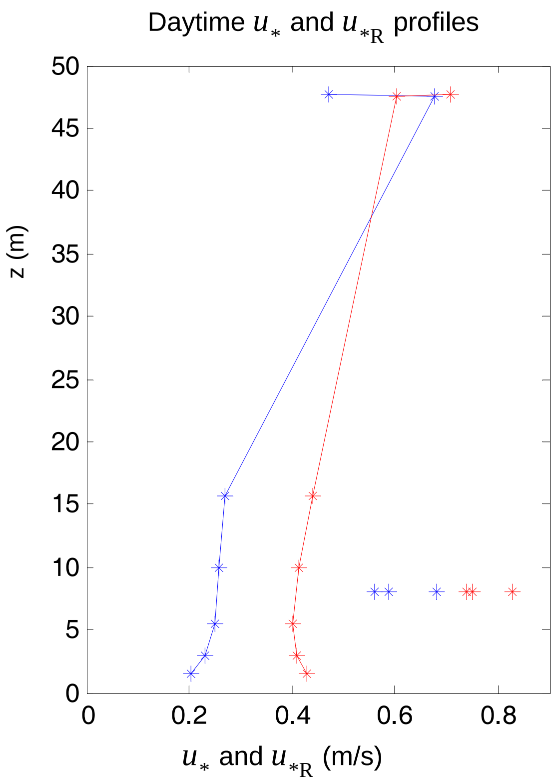


Figure 5 Comparison of u_* and u_{*R} profiles in downtown urban canyon of Park Ave in Oklahoma City. Values at intersection are larger than mid-canyon values. u_{*R} values are almost always larger magnitude than u_*. u_* shows largest value at rooftop, while u_{*R} shows largest value above rooftop. Profiles also show different curvature near surface.

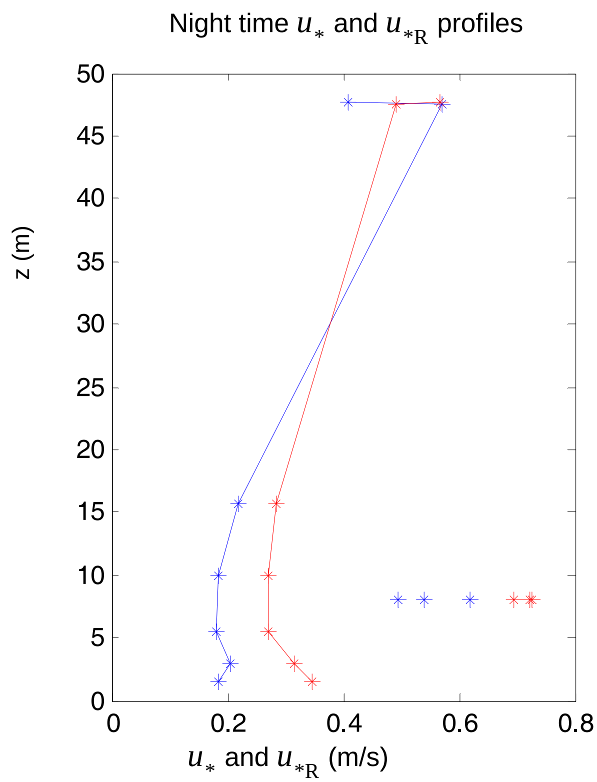


Figure 6 Comparison of u_* and u_{*R} profiles in downtown urban canyon of Park Ave in Oklahoma City. Values at intersection are larger than mid-canyon values. u_{*R} values are almost always larger magnitude than u_*. u_* shows largest value at rooftop, while u_{*R} shows largest value above rooftop. Profiles also show different curvature near surface.

8. Conclusions

Capturing the full surface stress within a roughness sublayer results in different assessments of profiles as well as absolute values of the stress. This is most notable in the qualitative results at rooftop level.

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