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Estimating micrometeorological inputs for modeling dispersion in urban areas during stable conditions

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Abstract

We examine the performance of three methods to estimate the surface friction velocity and the Monin–Obukhov (MO) length in stable conditions. Estimates from these methods are compared with measurements made at two urban sites: the Wilmington site located in the middle of an urban area, and the VTMX site located on a sloping, smooth area in Salt Lake City. The first method uses the mean wind at a single height (Single U or SU), the second uses the wind speed at a single level and the temperature difference between two levels (U delta T or UDT), and the third method uses two levels of wind speed and temperature (delta U delta T or DUDT). The performance of the SU and UDT methods in estimating u_* are comparable. The SU method yields better estimates of the MO length than the UDT method does. The DUDT method performs poorly in estimating both u_* and L. The major conclusions of this study are that (1) measurements of mean winds and temperatures at one or two levels at an urban location can provide adequate estimates of micrometeorological variables required in modeling dispersion in the stable boundary layer, and (2) methods based on using differences in temperatures and velocities between two levels can provide unreliable estimates of these variables because these differences can be overwhelmed by inevitable uncertainties in the measurement of mean variables.

Keywords: Friction velocity; Monin–Obukhov length; Stable boundary layer; Wilmington; VTMX

1. Introduction

The surface friction velocity, u_*, and the Monin–Obukhov (MO) length, L, govern the mean and turbulence structure of the stable boundary layer, and hence are important inputs for models of dispersion in the stable boundary layer (Van Ulden and Holtslag, 1985). Because it is not practical to make routine measurements of the turbulent fluxes that determine these variables, several methods have been suggested to estimate them from simpler measurements of mean winds and temperatures. This paper evaluates the usefulness of three methods that have been suggested in the literature. These methods derive u_* and L parameters by fitting measurements of mean winds and temperatures at one or two levels to MO similarity profiles (Businger et al., 1971).

Venkatram (1980) and Irwin and Binkowski (1981) evaluated these methods to estimate u_* and L with data collected in flat rural sites with adequate homogeneous upwind fetches. In this study, however, the evaluation is conducted with measurements

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made in urban sites that are not ideal for the application of MO similarity. Although the sites are located in open areas, they are likely to be within the roughness sub-layer (RSL; Rotach, 1999) which extends to a height of 2–5 times the average height of buildings in the urban area. The RSL reflects the influence of urban buildings on flow and turbulence, and is thus horizontally and vertically inhomogeneous. Rotach (1993) suggests that when the wind speeds and temperatures are averaged over all wind directions, their gradients can be described using MO theory based on local values of u_* and L. Classical MO theory applies only in the "inertial" sub-layer, which lies between the top of the RSL and 1/10th of the boundary layer height.

While recognizing the limitations of applying MO theory to measurements made in urban sites, this study is motivated by the pragmatic need for meteorological inputs for dispersion models such as AERMOD (Cimorelli et al., 2005). Thus, the scope of this paper is limited to providing an empirical response to the question: do MO similarity methods that apply to flat terrain provide useful estimates of u_* and L when the inputs are mean wind speeds and temperatures measured with a 10 m tower located in an urban area?

2. Governing equations

All three methods examined in this paper are based on fitting measurements of mean wind and temperature to profiles given by MO similarity theory (Businger, 1973):

$$u(z_r) = \frac{u_*}{k}\left(\ln\left(\frac{z_r}{z_0}\right) + \beta\frac{(z_r - z_0)}{L}\right), \tag{1}$$

where u_* is the friction velocity, k is the von Karman constant, z_r is the height at which the mean wind, u, is measured, z_0 is the surface roughness length, $\beta = 4.7$ is a constant and L is the MO length defined by

$$L = -\frac{T_0}{g}\frac{u_*^3}{k\,\overline{w'\theta'}} = \frac{T_0}{g}\frac{u_*^2}{k\theta_*}. \tag{2}$$

Here g presents the acceleration due to gravity and T_0 is a reference temperature. The height, z_r, in the equation is measured relative to a displacement height, d.

Venkatram (1980) proposed a simple method to solve for u_* and L using a single measurement of mean wind speed. The method is based on the empirical observation, derived from measurements made in Kansas (Izumi, 1971), Minnesota (Caughey et al., 1979) and Prairie Grass (Barad, 1958), that $\theta_* = -\langle w'\theta'\rangle/u_*$ varies little with u_*, so that $L \sim u_*^2$. Useful estimates of L and u_* can be obtained by taking θ_* to be 0.08 °C. Van Ulden and Holtslag (1985) provided theoretical support for this empirical result, and proposed a modification that accounts for the effect of clouds during stable conditions. We realize that there is no a priori justification for using a value of θ_* determined in experiments conducted in rural areas to urban surfaces.

If we take θ_* to be a constant in Eq. (2), and substitute for L in Eq. (1), we obtain a quadratic equation for u_*, which yields

$$u_* = C_D u(z_r)\left\{\frac{1}{2} + \frac{1}{2}\left[1 - \left(\frac{2u_0}{C_D^{1/2}u}\right)^2\right]^{1/2}\right\}, \tag{3}$$

where $C_D = k/\ln(z_r/z_0)$, $u_0^2 = \beta(z_r - z_0)/kA_L$, and $A_L = T_0/(gk\theta_*)$. When the term $2u_0/C_D^{1/2}u$ within the square root sign exceeds unity, the surface friction velocity is computed from

$$u_* = \tfrac{1}{2}C_D u(z_r), \tag{4}$$

which means that the friction velocity for these cases is approximated as half of the value of the friction velocity under neutral conditions. The MO length is computed from $L = A_L u_*^2$. This is the simplest of all three methods and requires estimates of the surface roughness z_0 and displacement height d. We will refer to this method as SU to stand for single U.

Irwin and Binkowski (1981) proposed the Bulk Richardson method based on using additional information on the difference in potential temperatures between two levels, z_1 and z_2, which is given by

$$\Delta\theta = \frac{\theta_*}{k}\left[\ln\left(\frac{z_2}{z_1}\right) + \frac{\beta(z_2 - z_1)}{L}\right]. \tag{5}$$

The Bulk Richardson method, which we refer to as the UDT (Single U and delta T) method, obtains an explicit expression for u_* using the following definitions:

$$\alpha = \frac{\theta_*}{u_*},$$
$$A = \frac{\beta g k}{T_0},$$

$$B = \frac{\ln(z_2/z_1)}{\ln(z_r/z_0)},$$
$$a = (\Delta z - B\,\Delta z_r)A, \qquad b = Bku(z_r), \tag{6}$$

where $\Delta z = z_2 - z_1$, $\Delta z_r = z_r - z_0$.

Eqs. (1), (2) and (5) can be combined to obtain a quadratic equation for α, whose real root is

$$\alpha = \frac{b}{2a}\left[\left(1 + \frac{4ak\Delta\theta}{b^2}\right)^{1/2} - 1\right]. \tag{7}$$

Then, u_* and θ_* can be expressed as

$$u_* = \frac{ku(z_r) - \alpha A\,\Delta z_r}{\ln(z_r/z_0)},$$
$$\theta_* = \alpha u_* \tag{8}$$

Irwin and Binkowski (1981) did not use Eq. (8) but derived an implicit equation for L, which was solved using a numerical iterative technique. The UDT method, like the SU method, requires an estimate of the surface roughness z_0 and displacement height, d.

The DUDT method uses velocity measurements at two heights, z_1 and z_2, to eliminate surface roughness from the equations. If the velocities and temperatures are measured at the same heights, z_1 and z_2, it follows from Eqs. (7) and (8),

$$u_* = \frac{1}{\ln(z_2/z_1)}\left[k\,\Delta u - A\,\Delta z\frac{\Delta\theta}{\Delta u}\right],$$
$$\theta_* = \frac{\Delta\theta}{\Delta u}u_*, \tag{9}$$

where $\Delta u = u(z_2) - u(z_1)$. If the velocities and temperatures are measured at different pairs of heights, we can replace z_0 in Eqs. (6)–(8) by the first height at which the wind speed is measured, z_r by the second height, and $u(z_r)$ by Δu.

Estimates of θ_* from the UDT and DUDT methods are used to compute L from Eq. (2). Eqs. (8) and (9) can result in negative values of u_* under very stable conditions when the bulk or gradient Richardson numbers exceed about $1/\beta = 0.2$, although the actual value depends on the heights of velocity and temperature measurements. Under these circumstances, we set $u_* = 0.0$.

Table 1 summarizes these methods. The temperature scale is defined by $\theta_* = -\overline{w'\theta'}/u_*$, where $\overline{w'\theta'}$ is the kinematic heat flux. The UDT method has been recommended for generating inputs for AERMOD (Cimorelli et al., 2005). As mentioned earlier, Irwin and Binkowski (1981) refer to the UDT method as the bulk Richardson method and the DUDT method as the gradient Richardson method.

The next section compares estimates of u_* and L from the three methods from measurements made at two different urban sites.

3. Field observations

Data from two field studies were used to evaluate the three methods for u_* and L described earlier.

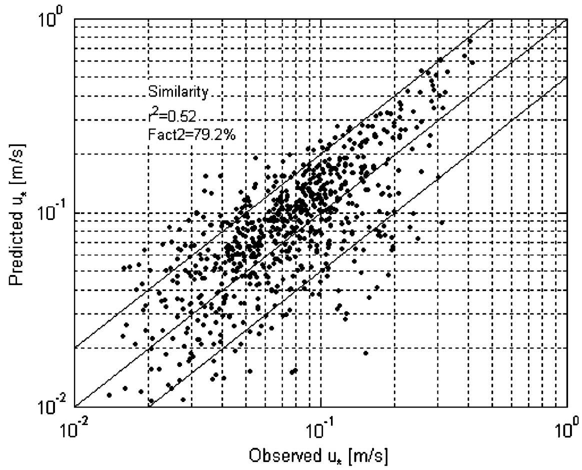

Fig. 1. Determination of z_0 by fitting Eq. (1) with measurements of u_* and L made during Wilmington study. Taking $d/z_0 = 5$, r^2 and the number of data points within a factor of two of the observations were maximized to obtain $z_0 = 0.4$ m.

Table 1
Description of methods to estimate surface friction velocity

Name used in paper	No. of wind levels	No. of temperature levels	Estimate of z_0 and d	Estimate of θ_*	Reference
Single U (SU)	1	None	Required	Assumed constant: $\theta_* = 0.08\,°C$	Venkatram (1980)
U Delta T (UDT)	1	2	Required	Calculated	Irwin and Binkowski (1981)
Delta U Delta T (DUDT)	2	2	z_0 not required	Calculated	Irwin and Binkowski (1981)

The studies are Wilmington 2005 (Yuan et al., 2006) and VTMX 2000 (Monti et al., 2002).

3.1. Wilmington study

The Wilmington field study, sponsored by the California Air Resources Board and California Energy Commission, took place in the city of Wilmington, California, during the summer months of 2004 and 2005. Wilmington is a small community located next to the Port of Los Angeles. It is surrounded by numerous small industries, transportation corridors, and port businesses, which are located to the south of residential areas. The instruments used in this analysis were deployed at the Harbor Generating Station of the City of Los Angeles's Department of Water and Power (LADWP). The residential areas, consisting mostly of one storey buildings about 4 m high, are located upwind of the LADWP site during the dominant nighttime, stable, northwesterly flows.

The meteorological instrumentation deployed at LADWP consisted of mini-Sodar, net-radiometer, krypton hygrometer, IR surface temperature measurements, thermistors, RH probe and two sonic anemometers mounted at 3.1 and 6 m above ground level (agl). The sonic anemometers were used to measure three velocity components (resolution and

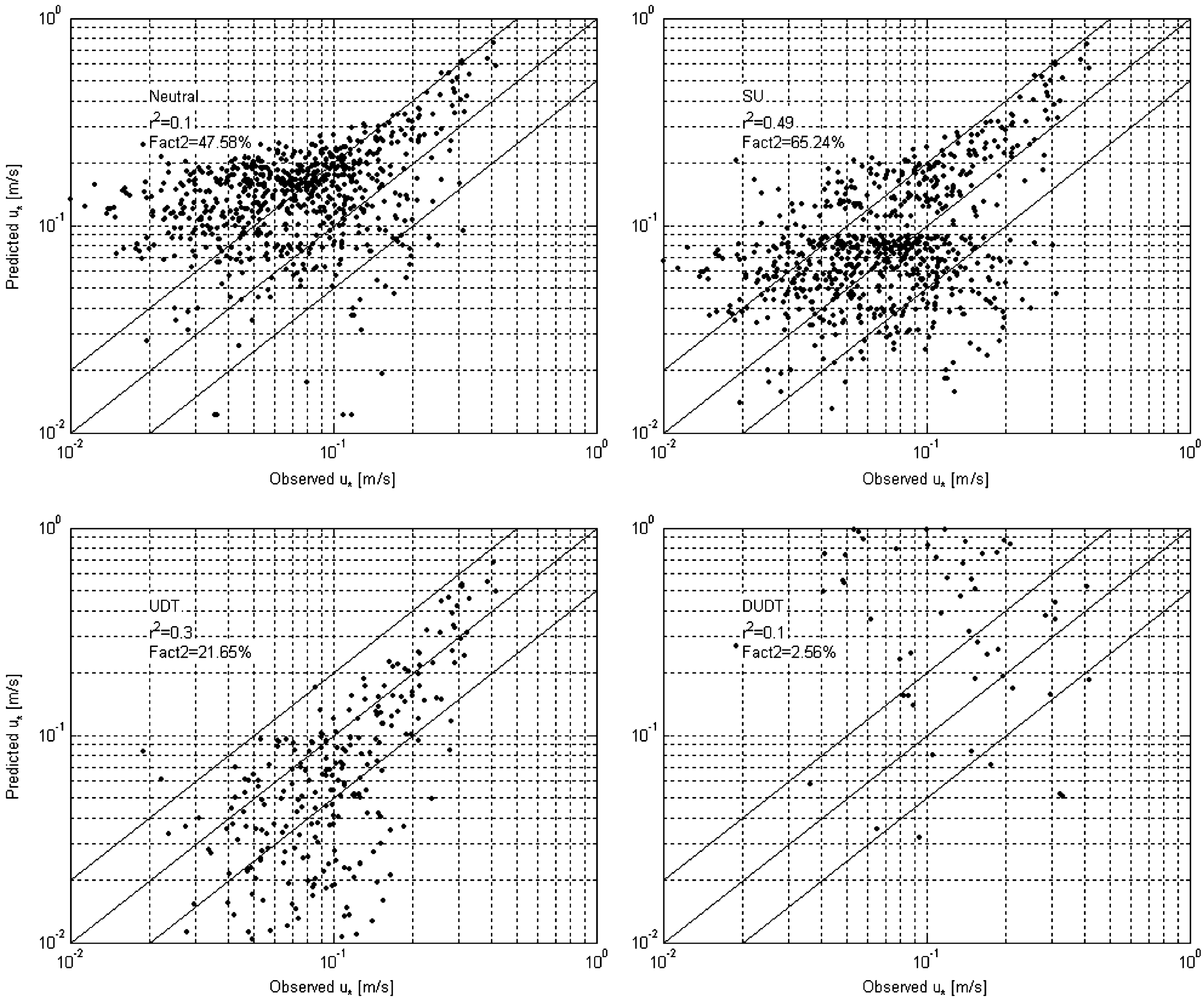

Fig. 2. Comparison of observed u_* from the Wilmington study with estimates from four methods: Top left corresponds to Eq. (10) for neutral conditions, top right corresponds to the SU method, bottom left to the UDT method, and bottom right to the DUDT method. The estimates use $z_0 = 0.4$ m and $d/z_0 = 5$.

accuracy: 0.01 and $\pm 0.05\,\mathrm{m\,s^{-1}}$) and virtual air temperature T (resolution and accuracy: 0.01 and $\pm 0.05\,^{\circ}\mathrm{C}$) at 10 Hz.

The analysis that follows is based on 5 min averaged data from the sonic anemometer. In the SU method, wind speed data from a height of 6 m were used to minimize local building effects. In the UDT method temperatures at heights of 3.1 and 6 m were used. The DUDT method used both temperatures and winds at these two heights.

We first determined the roughness length, z_0, empirically by fitting the similarity wind profile, Eq. (1), to the observed wind data using values of u_* and L calculated from surface shear stress and heat flux measurements. To account for the effects of the buildings upwind of the site, we incorporated a displacement height, d, in the similarity profiles using a constant ratio of $d/z_0 = 5$ based on a recommendation in Britter and Hanna (2003). Fig. 1 compares the estimates of u_* obtained with a z_0 of 0.4 m with corresponding observations. This value of z_0 is consistent with the urban location of the site, which is an open area surrounded by buildings with an average height of 4 m. The figure indicates that $r^2 = 0.52$ and about 79% of the observations are within a factor of two of the model estimates. These performance measures represent the best possible description of the wind profile using similarity theory.

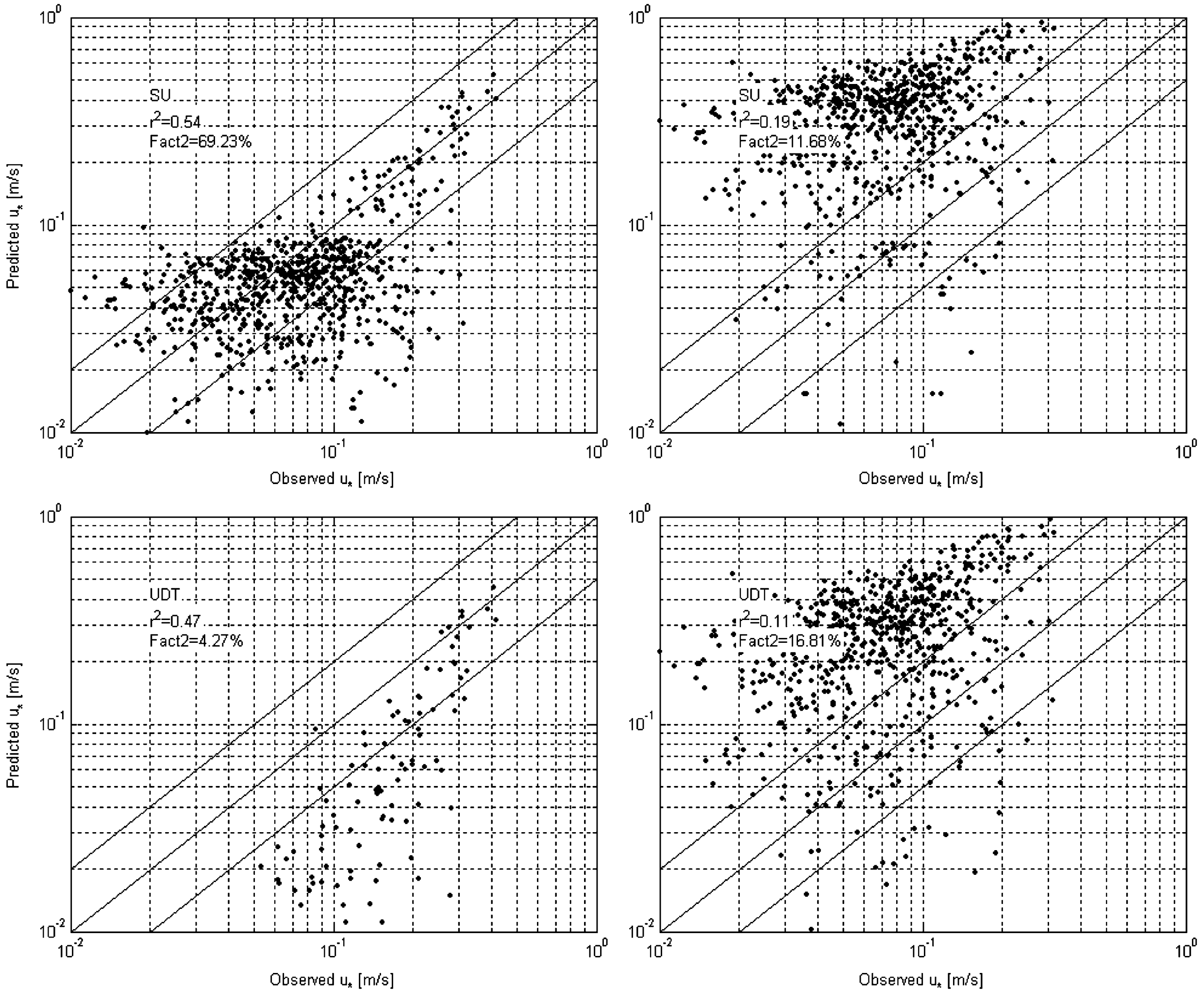

Fig. 3. Influence of z_0 on estimates of u_* for Wilmington study: Top left corresponds to the SU method with $z_0 = \frac{1}{2}z_{0\mathrm{optimal}}$, top right to the SU method with $z_0 = 2z_{0\mathrm{optimal}}$, bottom left to the UDT method with $z_0 = \frac{1}{2}z_{0\mathrm{optimal}}$, and bottom right to the UDT method with $z_0 = 2z_{0\mathrm{optimal}}$. The ratio $d/z_0 = 5$ was kept constant.

Fig. 2 compares the relative performance of the three methods in estimating the surface friction velocity. The top left panel indicates the performance of the neutral estimate,

$$u_* = \frac{ku(z_r)}{\ln(z_r/z_0)}, \tag{10}$$

which represents the simplest possible estimate in the absence of knowledge about stability. As expected, Eq. (10) does not perform as well as that based on the similarity profile (see Fig. 1).

The top right panel in Fig. 2 indicates that Eq. (4), the SU method, based on a constant θ_*, yields an $r^2 = 0.49$ and 65% of the observations are within a factor of two of the model estimates. The simple correction for stability appears to be an improvement over the neutral estimate from Eq. (10).

The UDT method or the bulk Richardson method does not perform as well as the SU method: $r^2 = 0.3$ and only 22% of the observations are within a factor of two of the model estimates. Using two levels of velocity leads to further deterioration in estimating u_*. These results suggest, as pointed out by Irwin and Binkowski (1981), that using several levels of velocity and/or temperature can lead to poor estimates of the surface friction velocity if the uncertainties in the observed velocity/temperature differences are comparable to the velocity/temperature differences predicted by the similarity profiles.

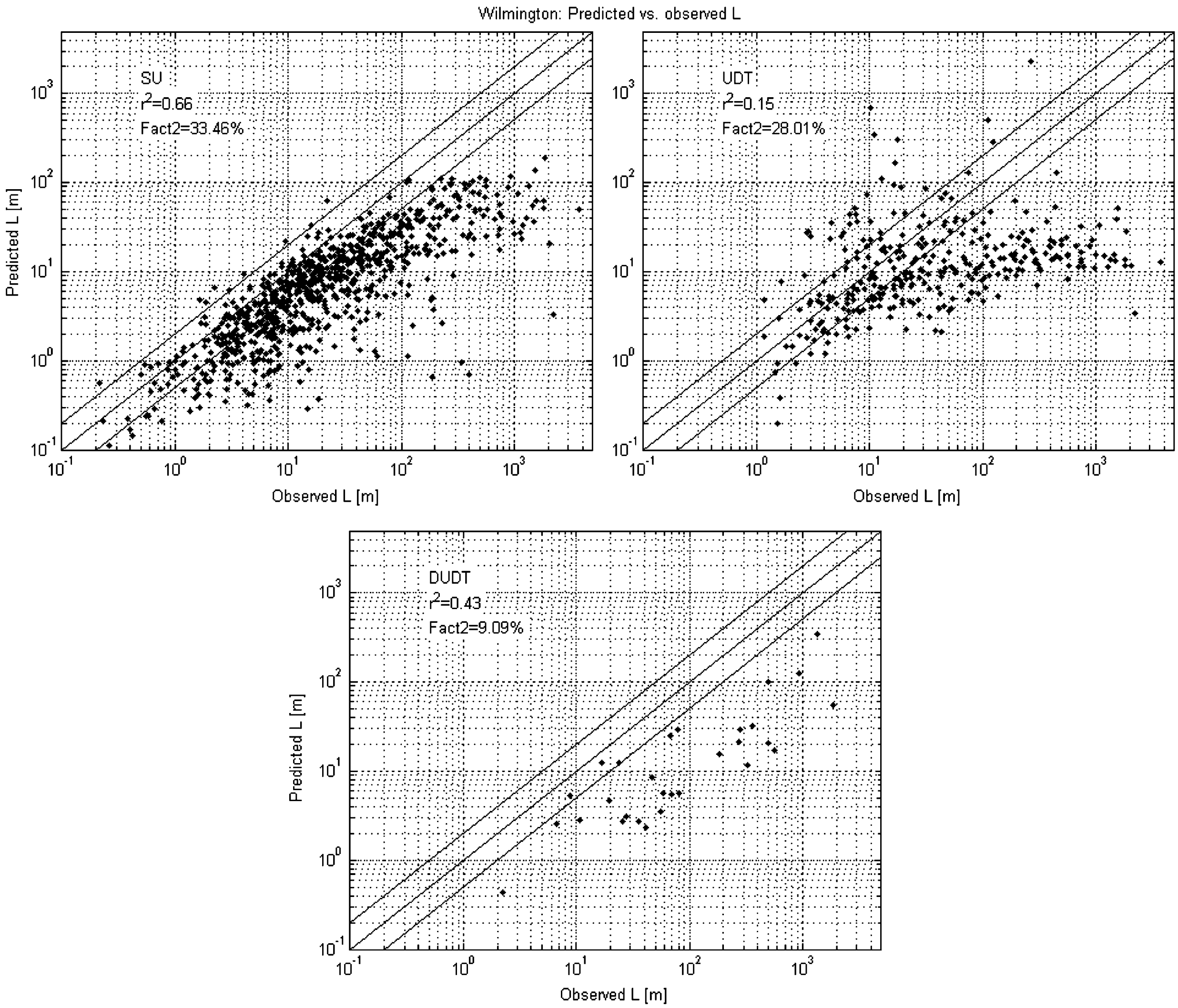

Fig. 4. Comparison of estimates of the Monin–Obukov length from the SU, UDT, and DUDT methods with observations made at the Wilmington site. Here $z_0 = 0.4$ m and $d/z_0 = 5$.

Estimates of z_0 and d used here are based on knowledge of momentum and heat fluxes, which are unavailable for routine dispersion applications. The estimates are usually based on the physical dimensions of roughness elements surrounding the measurement site (Britter and Hanna, 2003). Because such an estimate can be uncertain, we have examined the sensitivity of the methods that require z_0 to variations of z_0 by a factor of two.

Fig. 3 shows that for the SU method, decreasing z_0 by a factor of two leads to slight improvements in both r^2 and the factor of two percentage compared to the optimum z_0 results. Increasing z_0 by a factor of two leads to deterioration in r^2 and overestimation of u_*: the factor of two measure decreases from 65% to 12%. This happens because z_0, which is 0.8 m in this case, is comparable to the effective measurements height, which is $z_r - d = 2$ m. The UDT method is more sensitive to factor of two variations in z_0; the factor of two measure decreases from its optimum value of 22% for both $2z_0$ and $0.5z_0$.

Fig. 4 shows that estimates of L from the simplest SU method compare best with observations although the method has a tendency to underestimate at values of $L > 100$ m. About 28% of the observations are within a factor of two estimates from the UDT method, but there is little correlation between model estimates and observations. The DUDT method performs poorly presumably because of the reasons discussed earlier. We next consider the performance of these methods for the VTMX site.

4. VTMX site

The Vertical Transport and Mixing Experiment (VTMX), sponsored by the US Department of Energy, took place in the Salt Lake City metropolitan area in October 2000. The Salt Lake City (SLC) metropolitan area is located in a wide valley ~1400 m above the mean sea level (msl). The valley is about 30 km wide (along the East–West direction) and 50 km long (North–South direction) and is surrounded by elevated mountains (up to 3000 m above the msl). The southern shoreline of the Great Salt Lake is the northwestern border of the valley. Data used in this analysis was collected by the Arizona State University's Environmental Fluid Dynamics Program at the Arizona Cemetery Site (ACS). The ACS was located in the northeastern side of the valley, in a grassy open area (aerodynamic roughness length <0.1 m), having a gentle slope (~0.07, i.e. 4°). Because the measurements were made away from buildings and trees, the data can be considered free from the immediate effects of obstacle wakes. The fetch was fairly uniform for 100 m uphill and 80 m downhill distances. The closest uphill feature was the Utah National Guards' Building (10 m high), but it was not in the direct downslope path of the nighttime stable katabatic flow through the measurement station. The closest downstream feature was a mild drop in slope to accommodate a football stadium and a school with building height approximately 15 m which is not expected to have any upstream influence. On a much larger (~km) scale, the major topographic perturbation was provided by Wasatch Mountain range abutting the gentle slope. More details on VTMX campaign can be found in Monti et al. (2002) and Doran et al. (2002).

The meteorological instruments deployed at the ACS consisted of a 14 m mast equipped with cup anemometers, thermistors, an upward facing spectral pyranometer, a downward facing pyrgeometer, and two sonic anemometers–thermometers placed at 4.5 and 13.86 m above ground level. Also, two tethered systems were deployed at the site to analyze the vertical structure of the lower atmosphere. For this study only the data from the sonic anemometers were utilized. The SU and UDT methods used the wind speeds at the 4.5 m level.

Fig. 5 shows the results of fitting the similarity wind profile to observations to determine z_0. The

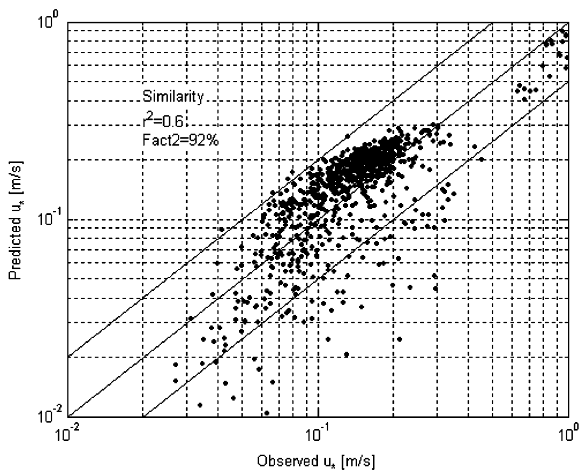

Fig. 5. Determination of z_0 by fitting Eq. (1) with measurements of u_* and L from the VTMX study. r^2 and the number of data points within a factor of two of the similarity based estimates were maximized to obtain $z_0 = 0.02$ m.

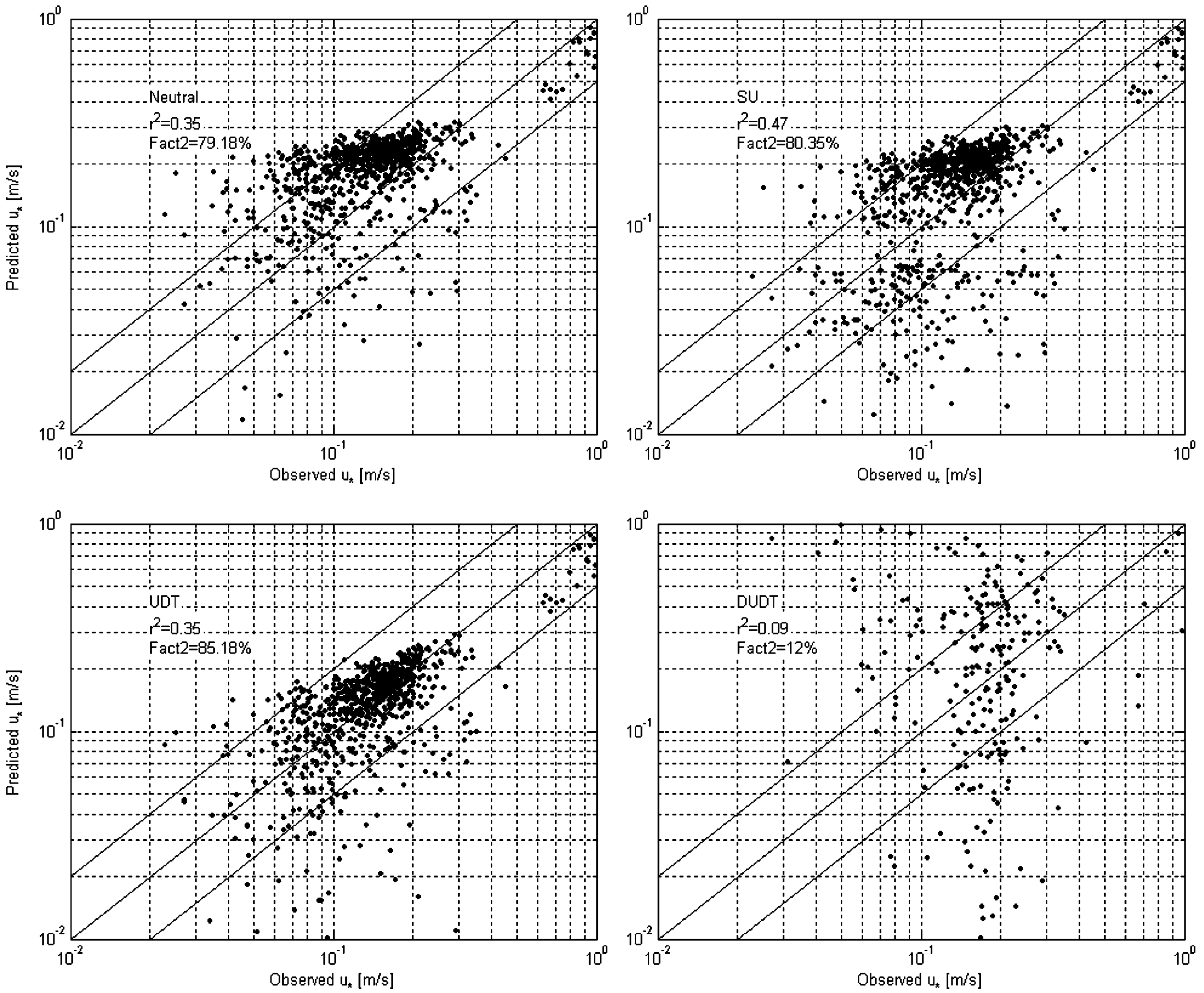

Fig. 6. Comparison of observed u_* from the VTMX study with estimates from four methods: Top left corresponds to Eq. (10) to neutral conditions, top right to the SU method, bottom left to UDT method, and bottom right to the DUDT method. Here $z_0 = 0.02$ m and $d = 0$ were used.

optimum value of 0.02 m is consistent with that associated with the grassy area surrounding the measurement site.

Fig. 6 indicates that the relative performance of the four methods to estimate u_* is similar to that observed from the Wilmington site, although the overall level of performance is higher. This could be related to the fact that the VTMX site is more rural and has a larger uniform upwind fetch.

The SU and UDT methods yield similar results in explaining the observed variation of friction velocity. The r^2 is higher for the SU method but the factor of two measure is lower than that of the UDT method. The DUDT method yields poor results as in the Wilmington study. Fig. 7 indicates that changing the roughness length by a factor of two does not lead to significant changes in model performance.

Fig. 8 compares estimates of L from the three methods with values observed at the VTMX site. The methods perform better at the VTMX site than at the Wilmington site presumably because of the smooth upwind fetch at the VTMX site. Estimates of L from the simple SU method indicate little bias in estimating the MO length; the r^2 is 0.74 and the factor of two measure is 79%. Both the UDT and DUDT methods underestimate L; the performance measures of the UDT method are slightly better than those of the DUDT method.

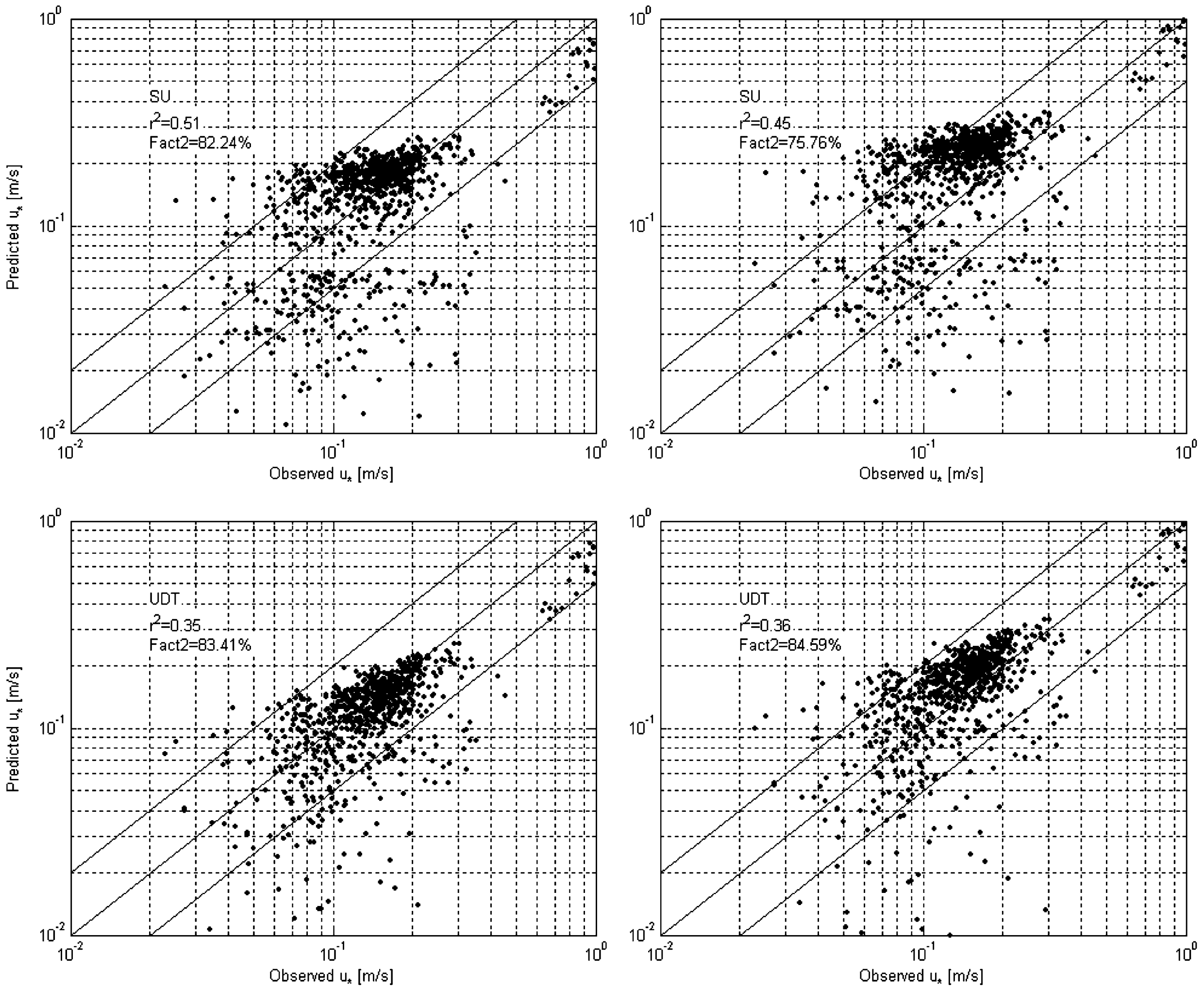

Fig. 7. Influence of z_0 on estimates of u_* at the VTMX study. Top left corresponds to the SU method with $z_0 = \frac{1}{2}z_{0\text{optimal}}$, top right to the SU method with $z_0 = 2z_{0\text{optimal}}$, bottom left to the UDT method with $z_0 = \frac{1}{2}z_{0\text{optimal}}$, and bottom right to the UDT method with $z_0 = 2z_{0\text{optimal}}$.

5. Conclusions and discussion

The results from this study indicate

1. MO similarity provides an adequate description of velocity and temperature profiles in the near surface stable layer even when the measurements are made in an open area in the vicinity of buildings. However, as expected, MO similarity provides a better description of the profiles at the more "ideal" VTMX site than at the urban Wilmington site.
2. Methods based on measurements of mean winds and temperatures measured at one or two levels at a non-ideal urban site can provide adequate estimates of the surface friction velocity and MO length during stable conditions. The methods perform better at the VTMX site than at the Wilmington site.
3. The performance of the SU method based on a wind speed measurement at a single level (Venkatram, 1980) in estimating u_* and L is better or comparable to that of the UDT method (Bulk Richardson number method, Irwin and Binkowski, 1981) based on a single level wind speed and two levels of temperature. The DUDT method based on measurements of both wind speeds and temperatures at two levels (Gradient Richardson number method, Irwin and Binkowski, 1981) does not perform as well.

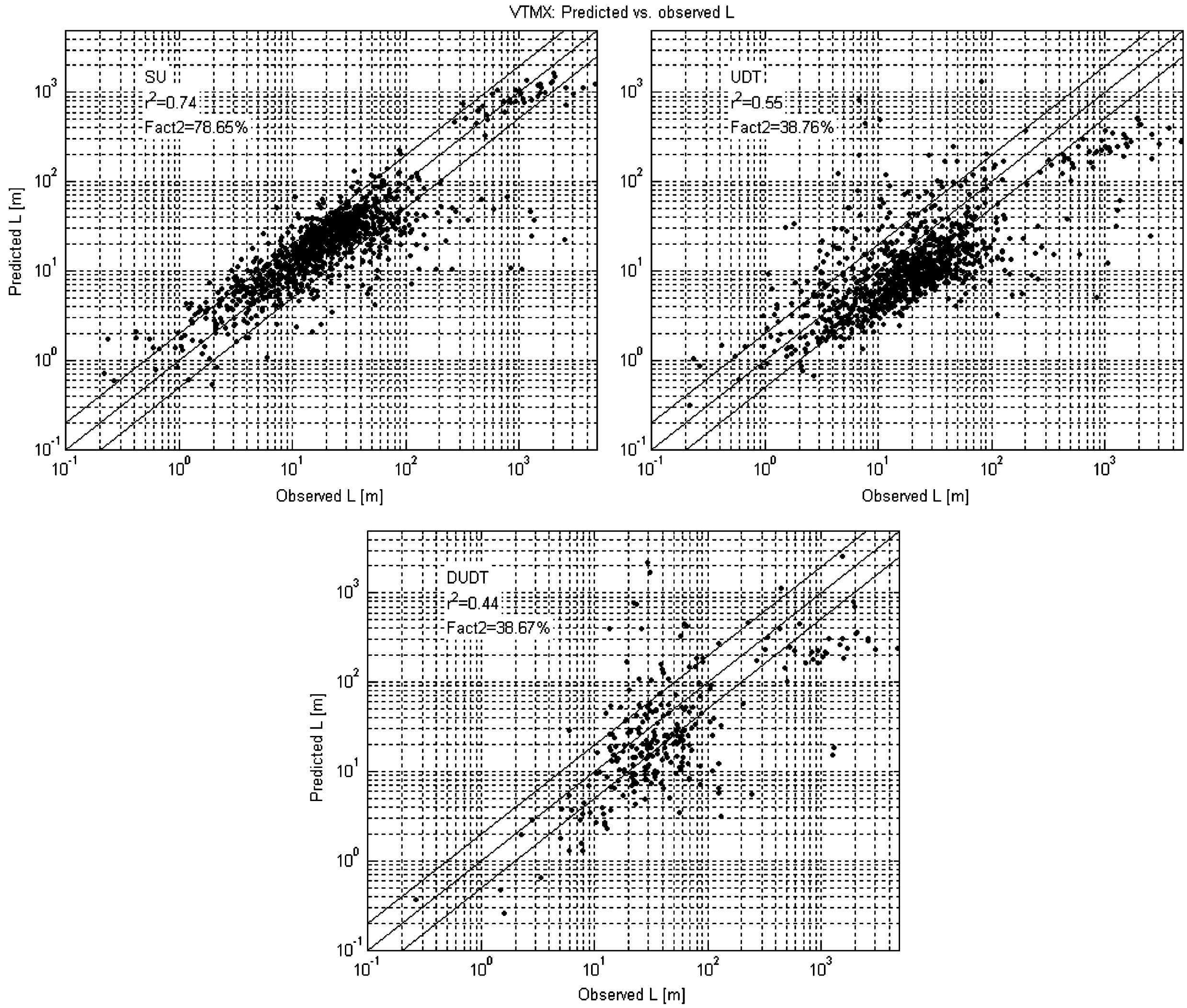

Fig. 8. Comparison of estimates of the Monin–Obukov length from the SU, UDT, and DUDT methods with observations made at the VTMX site.

4. The methods that worked, the SU and UDT methods, require estimates of the surface roughness length, z_0 and d. Factor of two reductions in z_0 from their optimum values did not affect model performance significantly. However, model performance deteriorated when z_0 was doubled and became comparable to the effective measurement height.
5. Using two levels of wind speed led to poor results presumably because unavoidable uncertainties in measuring the differences in velocities were comparable to differences predicted by similarity. In principle, the statistical uncertainty can be reduced by increasing the averaging time as long as the time scale governing turbulence is much less than the time scale of interest, say 1 h, and mesoscale motions occur over much longer time scales. This spectral gap between turbulence and mesoscale motions is not likely to be found in the complex flows at the Wilmington and VTMX sites; sea and land breezes were superimposed on the dominant northwesterly flow in Wilmington, while an oscillatory downslope flow with a time period of 30 min governed the flow at the VTMX site (Fernando and Princevac, 2004). The uncertainty associated with velocity and temperature gradient measurements can also be reduced by increasing the distance between the measurement levels to increase the observed differences.

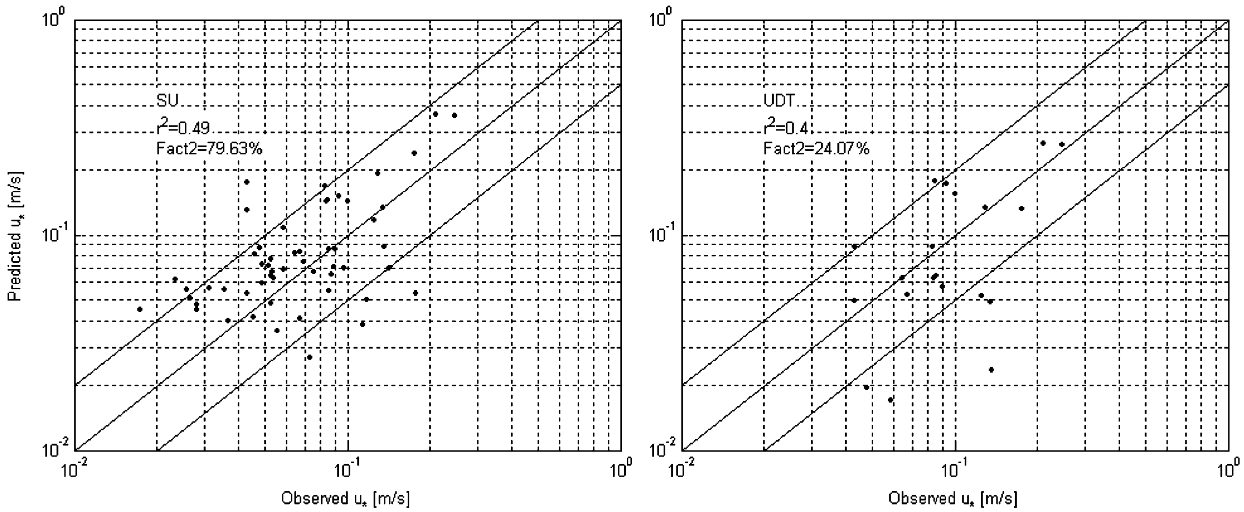

Fig. 9. Comparison of observations of 1-h averaged u_* from Wilmington study with estimates from the SU (left) and the UDT (right) methods.

We re-calculated u_* and L using 1-h averaged data with the three methods described earlier, and the major conclusions did not change. Fig. 9 shows that the SU method provides better estimates of u_* than the UDT method does at Wilmington. The DUDT method produced very poor results, which are not shown. The performance of the methods deteriorated at VTMX because of the effects of the oscillatory slope flow mentioned earlier.

This indicates that surface fluxes at non-ideal sites are best estimated using mean variables averaged over intervals that are small compared to the nominal time scale of 1 h; the averaging period has to be still several times the eddy time scale of z_r/U where U is the mean wind at the measurement height, z_r. Surface variables, such as u_*, calculated for small time intervals within any given hour can then be used to estimate corresponding dispersion inputs such as standard deviations of vertical velocity fluctuations, σ_w, which in turn can be combined to construct 1-h averages.

This study shows that a wind speed measured at one level can provides useful estimates of u_* and L during stable conditions. Supplementing the wind speed with a single temperature difference between two heights does not always improve results; adding information on the difference in wind speeds between two levels can lead to deterioration of the estimates. These problems associated with uncertainties in velocity/temperature differences can be avoided by using multiple measurement levels. Then, estimates of micrometeorological surface variables can be obtained by fitting similarity profiles to the values of temperature and velocity (Nieuwstadt, 1978) measured at these levels; this approach does not rely on and is thus insensitive to observed differences between levels. It is also plausible that better estimates of u_* and L can be made with towers that extend beyond the RSL height. Note that increasing the measurement height will increase the uncertainty in measurements of differences between temperature and velocities at different levels because (1) the turbulent time scale, which is proportional to the measurement height, will increase, and (2) the gradients generally decrease with height.

Acknowledgments

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