J23.4 RELATIONSHIPS BETWEEN URBAN AND SUBURBAN MICROMETEOROLOGICAL VARIABLES

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1. INTRODUCTION

This study is motivated by the need for meteorological inputs for dispersion models such as AERMOD (Cimorelli et al., 2005). It extends earlier studies (Princevac and Venkatram, 2007; Venkatram and Princevac, 2008) on the performance of methods to estimate the surface friction velocity and turbulent velocities in both stable and unstable conditions. These estimates depend on the surface heat flux, which we showed could be estimated with measurements of temperature fluctuations using the free convection relationship proposed by Monin and Yaglom (1971). In the current study, we examine methods to improve these estimates for unstable conditions using formulations such as that proposed by Tillman (1972), who showed that the free convection estimate could be improved through a function of $\zeta = z_r/L$, which in turn was related to the skewness of temperature fluctuations. Here z_r is the distance from the ground and L is the Monin-Obukhov (M-O) length.

For the stable conditions, we examine modification of the earlier method to allow the use of σ_T , which in principle should provide information on the heat flux that is definitely not contained in the mean wind speed.

Besides, urban meteorology is not usually available; there is a need for methods that can estimate urban meteorological variables from more routinely available rural measurements.

In order to predict urban meteorology, a two-dimensional internal boundary layer (IBL) model coupled with Monin-Obukhov (M-O) surface similarity theory is examined with observations.

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As in the previous study, we evaluate the methods proposed here with data collected at urban sites, where air pollution models are most frequently used to estimate exposure caused by surface releases. This evaluation is based on comparison of the estimates of the micrometeorological variables with corresponding observations.

2. FIELD STUDY

The meteorological data used in this study were measured at three sites in Riverside County, California, in 2007. The three sites lie along an east-west transect designed to make measurements of the evolution of the nighttime boundary layer embedded in the easterly wind as it passed through a suburban site, an urban site, and then back to a downwind suburban site.

Figure 1 shows the location of the three sites on a Google Earth map. Site Suburban 1 is in a desert plain in Moreno Valley, site Suburban 2 is on top of a bluff located above the Santa Ana River in suburban Riverside, and the Urban site is located on the street corner of Arlington and Brockton in downtown Riverside.

Each site was equipped with a 3 meter tower instrumented with (1) a sonic anemometer, (2) two soil heat flux plates, (3) an infrared thermometer, (4) a krypton hygrometer, (5) two soil temperature probes, (6) a water content reflectometer, (7) two air temperature sensors, and (8) site Suburban 1 had a net radiometer.

3. GOVERNING EQUATIONS

The method to estimate heat flux from routine observations is based on the formal expression:

$$\overline{w'T'} = r_{wT}\sigma_w\sigma_T , \quad (1)$$

where σ_T is the standard deviation of temperature fluctuations (T'), σ_w is the standard deviation of the vertical velocity fluctuations (w'), and r_{wT} is the correlation coefficient between the velocity and temperature.

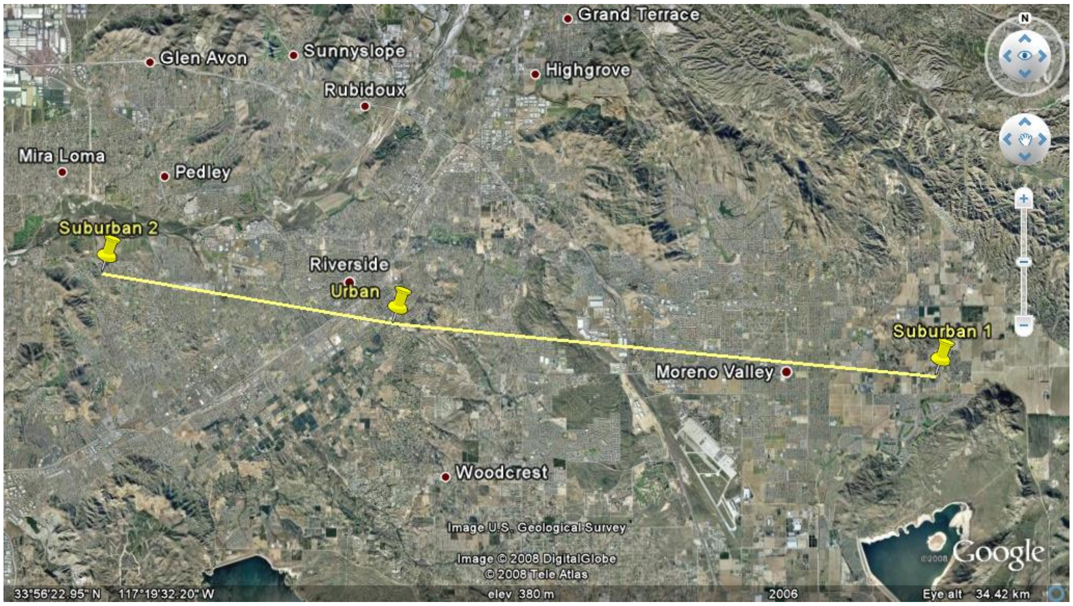

Figure 1. *Overview of the site locations*

3.1 *Convective Conditions*

During convective conditions, σ_w can be expressed as a combination of a shear generated component, σ_{ws}, and a buoyancy generated component, σ_{wc}. And it can be rearranged to obtain

$$\sigma_w = 1.3u_*\left(1-\frac{z_r}{\kappa L}\right)^{1/3} \tag{2}$$

where z_r is the height of measurement and L is the Monin-Obukhov (M-O) length. This expression for σ_w is that presented by Panofsky et al. (1977) to fit a wide range of data.

The proposed expression for the correlation coefficient, r_{wT}, is based on observations reported in the literature. Monin and Yaglom (1971) indicate that r_{wT} increases from about 0.35 for near-neutral conditions, to about 0.6 for Richardson number, R_i, in the range -0.3 to -0.8. Hicks (1981) also suggests that r_{wT} approaches a constant value, but this requires an unrealistic sign change across neutral conditions. As we will see, the expression presented by Tillman (1972) for σ_T/T_* implies an explicit formula for r_{wT} in terms of z_r/L.

The behavior of the correlation coefficient in the free convection regime can be derived by equating Monin and Yaglom's (1971) expression for the temperature fluctuations,

$$\frac{\sigma_T}{T_*} = -C_1\left(-\frac{z_r}{L}\right)^{-1/3}, \tag{3}$$

where C_1 is a constant. The explicit expression for the heat flux under free convection is

$$Q_0 = \left(\frac{\sigma_T}{C_1}\right)^{3/2}\left(\frac{g\kappa z_r}{T_0}\right)^{1/2}. \tag{4}$$

Tillman's (1972) semi-empirical correction to Equation (3)

$$\frac{\sigma_T}{T_*} = -C_1\left(C_2-\frac{z_r}{L}\right)^{-1/3}, \tag{5}$$

yields the following implicit expression for the sensible heat flux:

$$Q_0 = u_*\left(\frac{\sigma_T}{C_1}\right)\left(C_2-\frac{z_r}{L}\right)^{1/3}. \tag{6}$$

where C_1 = 0.95 and C_2 = 0.0549 are the suggested values. The value of Q_0 has to be obtained iteratively because both u_* and L are functions of Q_0.

We also examined the usefulness of a constant value of r_{wT} = 0.3 to explain the observed heat flux using the implicit expression,

$$Q_0 = r_{wT}\sigma_w\sigma_T = r_{wT}\sigma_T 1.3u_*\left(1-\frac{z_r}{\kappa L}\right)^{1/3}, \tag{7}$$

which also has to be solved iteratively.

The surface friction velocity, u_*, was estimated from the observed or estimated heat flux, Q_0, and the wind speed using the approximation suggested by

Wang and Chen (1980) to avoid iterative solution of similarity relations.

The vertical turbulent velocity, σ_w, is calculated using Equation (2). The horizontal turbulent velocity, σ_v, is computed from

$$\sigma_v = (\sigma_{vs}^3 + \sigma_{vc}^3)^{1/3}, \quad (8)$$

where the shear component $\sigma_{vs} = 1.9u_*$, and the convective component $\sigma_{vc} = 0.6w_*$.

The convective velocity scale w_* is defined as

$$w_* = \left(gQ_0 z_i / T_0\right)^{1/3}. \quad (9)$$

where the height of mixed layer, z_i, is calculated from a model of a mixed layer eroding a layer with a stable potential temperature gradient, γ (Carson, 1973)

$$\rho_a C_p \frac{1}{2}\gamma z_i^2 = \int_0^T H(t)dt, \quad (10)$$

where ρ_a is the air density, C_p is the heat capacity under constant pressure, *H* is the heat flux, *t* is time, and *T* is a time scale.

3.2 *Stable Conditions*

As in an earlier paper (Venkatram and Princevac (2008)), the surface friction velocity, u_* for stable conditions is estimated using the SU (stands for single U) method with the mean wind measured at a single height and estimates of the roughness and displacement heights. The method used the temperature scale, $T_* = -\overline{w'T'}/u_*$, as an input. The first version of the method, is based on the empirical observation (Venkatram, 1980), based on measurements made in Kansas (Izumi, 1971), Minnesota (Caughey et al., 1979) and Prairie Grass (Barad, 1958), that T_* varies little with u_*, so that $L \sim u_*^2$. Useful estimates of *L* and u_* can be obtained by taking T_* to be 0.08°C.

The second version of the SU method estimates T_* from measurements of the standard deviation of temperature fluctuations, σ_T, which in principle can be measured with inexpensive thermistors. The relationship between the two variables is taken to be (Stull, 1988):

$$T_* = 0.5\sigma_T \quad (11)$$

Venkatram and Princevac (2008) compared the performance of the two versions of the SU (single U) method in estimating u_* during stable conditions, and found that using σ_T to compute T_* does not make a noticeable improvement to the estimation of u_*.

In this paper, we first reexamine the two versions of the SU method for estimating u_* with the data from the Riverside field study. Then we compare the performance of the SU method in estimating u_* with that when assuming neutral conditions.

Heat flux is estimated using the definition, $\overline{w'T'} = -T_* u_*$, once u_* is obtained. Besides, based on the analysis of data collected at Davis, CA, Pahlow et al. (2001) suggested the following semi-empirical relationship:

$$\frac{\sigma_T}{T_*} = 0.05\left(z_r / L\right)^{-1} + 3. \quad (12)$$

From this expression, the heat flux can be calculated from

$$Q_0 = -T_* u_* = \frac{-\sigma_T u_*}{0.05\left(z_r / L\right)^{-1} + 3}, \quad (13)$$

We will compare the performance of the heat flux estimation from Equation (13), that from SU method and that from constant value of r_{wT}.

3.3 *Suburban Meteorology to Urban Meteorology*

Realizing that urban meteorology is not always available, we examined a simple scheme to estimate urban meteorological parameters in terms of suburban observations, and compare them with the Riverside data. This scheme is explained in detail by Luhar et al. (2006). We are interested in the internal boundary layer (IBL) formed over an urban area due to a change in surface roughness and heat flux. One of the formulas to estimate the growth of the IBL is based on Miyake's diffusion analogy and discussed by Savelyev and Taylor (2005) as

$$U(h)\frac{dh}{dx} = A\sigma_w, \quad (14)$$

where *h* is the height of the IBL, *x* is the downwind distance from the roughness change, *U*(*h*) is the wind speed at height *h*, and *A* is a constant (≈1). We consider the values of *U*(*h*) and σ_w to be those of the modified flow over the urban surface.

We assume that M-O surface similarity theory is valid within the IBL over an urban area. So we can substitute the mean wind profile from M-O similarity (e.g. van Ulden and Holtslag, 1985) and expressions of σ_w for unstable and stable conditions respectively into Equation (14).

The assumption about the M-O length over the urban area allows us to estimate the internal boundary layer height h as a function of x from Equation (14). Once h is known, the micrometeorological variables over the urban area can be calculated using two assumptions: 1) the micrometeorological variables above h are the same over the urban and the suburban areas, and 2) the urban profiles below h follow M-O similarity. Then the urban friction velocity can be obtained by equating the suburban and the urban wind speeds at $z_r = h$.

$$u_{*,U} = u_{*,R} \frac{\ln\left(\frac{h-d_R}{z_{0,R}}\right) - \psi_m\left(\frac{h-d_R}{L_R}\right) + \psi_m\left(\frac{z_{0,R}}{L_R}\right)}{\ln\left(\frac{h-d_U}{z_{0,U}}\right) - \psi_m\left(\frac{h-d_U}{L_U}\right) + \psi_m\left(\frac{z_{0,U}}{L_U}\right)} \quad (15)$$

4. EVALUATION WITH FIELD OBSERVATIONS

Next, we evaluate the model performance in estimating micrometeorology for unstable and stable conditions for both suburban and urban sites. Then we relate the suburban and urban micrometeorology using the IBL model.

The performance of the models in explaining observations is quantified using the geometric mean (m_g) and the standard deviation (s_g):

$$m_g = \exp(\langle \varepsilon_m \rangle),$$

and (16)

$$s_g = \exp(\text{standard deviation of } \varepsilon_\text{m}),$$

where ε_m is the residual between the logarithms of model estimate and observation,

$$\ln(C_o) = \ln(C_p) + \varepsilon_m, \quad (17)$$

where C_o and C_p are observed values and corresponding estimates respectively. The angle brackets refer to an average. The deviation of the geometric mean, m_g, from unity tells whether the model is underpredicting or overpredicting. It is a measure of bias of the model estimate. The geometric standard deviation, s_g, is a measure of the uncertainty in the model prediction with s_g^2 being approximately the 95% confidence interval for the ratio of C_o/C_p.

The calculation of the geometric mean, m_g, and the geometric standard deviation, s_g, using Equation (16) can pose problems when the observed concentration is close to zero and the corresponding model estimate is finite; the large logarithm of the ratio dominates the calculation. This can be avoided by equating m_g to the median of the ratio of the observed to predicted concentration ratio, and using the interquartile range of the ratios to estimate s_g.

First of all, the roughness length, z_o, and displacement height, d_h, for each site are obtained using methods described in Princevac and Venkatram (2007). We find that z_o is 0.13, 0.27 and 0.31 for the Suburban 1, Suburban 2 and Urban site respectively. The displacement height is taken to be $d_h = 5z_o$ based on Britter and Hanna (2003).

Figure 2 compares estimates of heat flux from the three methods applied at the Urban site during unstable conditions. Note that C_1 was taken to be 1.3 in both Equations (3) and (5) to avoid overestimation of heat fluxes. However, all three methods still overestimate the fluxes at the Urban site. The overestimation is smaller at the suburban sites, and the performance of the constant r_{wT} is similar to that of Tillman's method. It is important to note that the simple free convection estimate ($C_1=1.3$) provides estimates of the heat flux that compare well with those from methods that account for wind shear.

The overestimation of heat flux does not appear to affect estimates of u_*, as seen in Figure 3, which compares estimates from the free convection (left panel), from Tillman's method (middle panel) and from the constant r_{wT} (right panel) with corresponding observations for the Urban site. However σ_w and σ_v are overestimated because the estimates depend explicitly on the surface heat flux, Q_0.

For the stable conditions, we first reexamine the two versions of the SU method for estimating u_* with the data from the Riverside field study. We also estimate the heat flux using the definition, $\overline{w'T'} = -T_* u_*$.

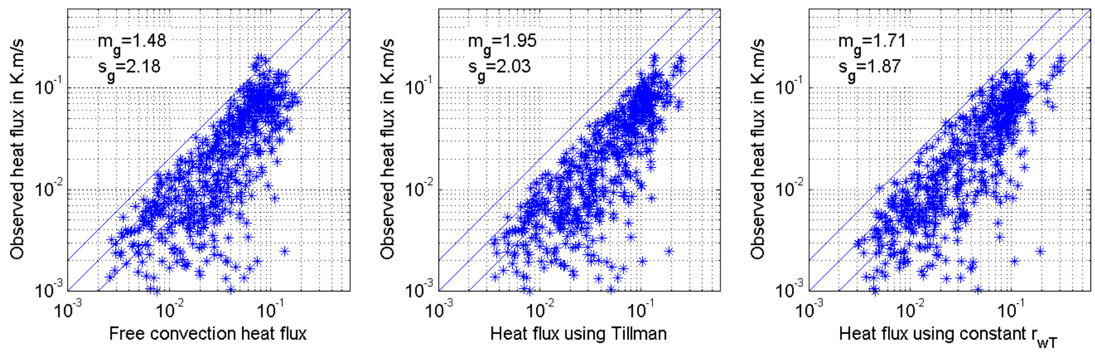

Figure 2. *Comparison of heat fluxes computed by the three methods in Equations (4), (6) and (7) with observations made at the Urban site during unstable conditions.*

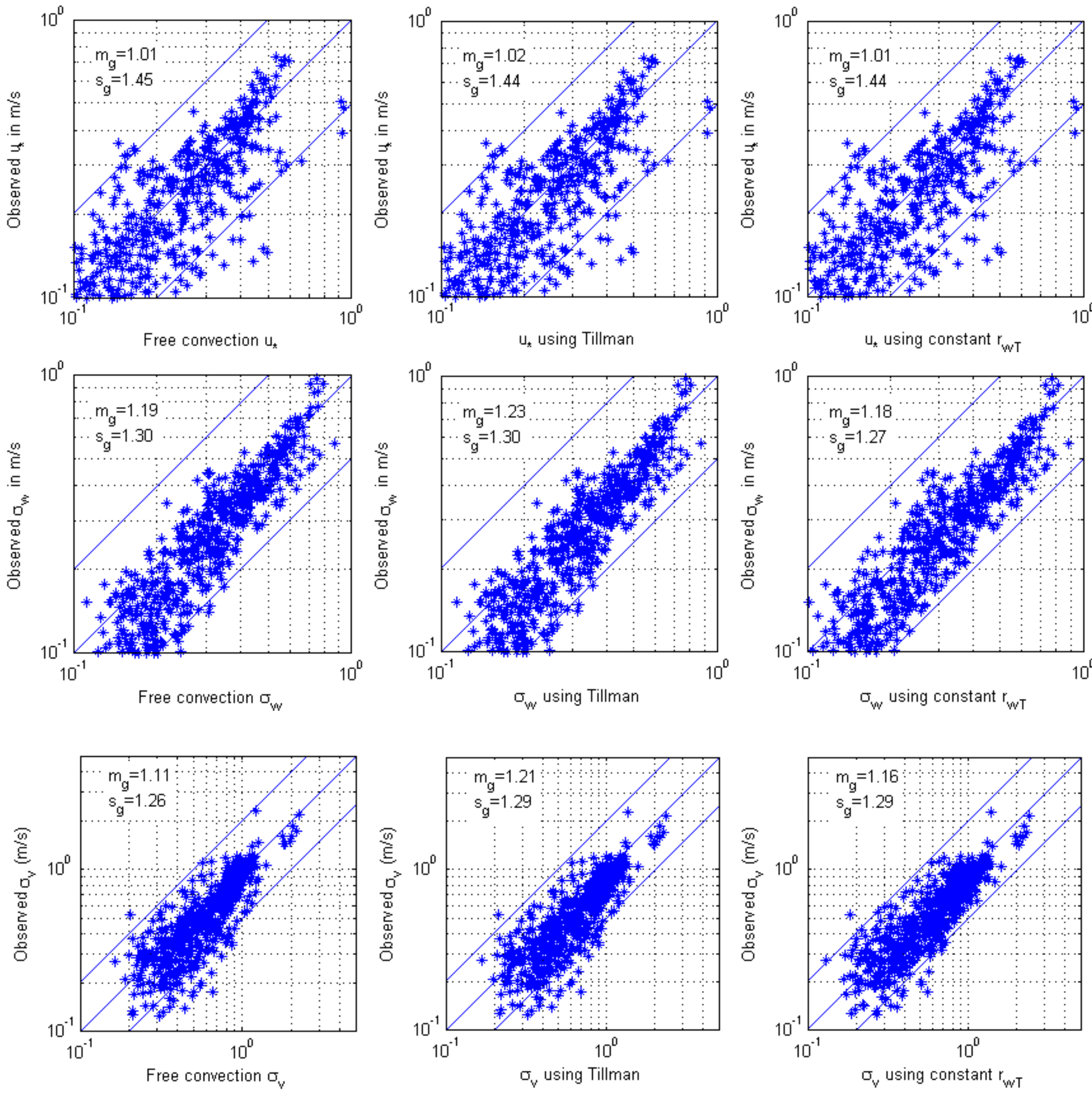

Figure 3. Plots of estimated u_*, σ_w and σ_v using heat flux from free convection (left panel), from Tillman's method (middle panel) and from constant r_{wT} (right panel) with observations for Urban site during unstable conditions

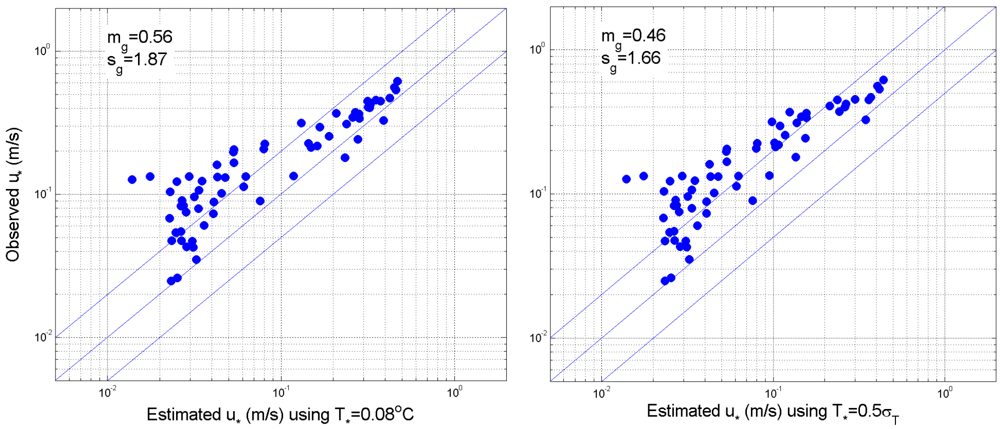

Figure 4: *Estimates of* u_* *using SU method with* $T_* = 0.08°C$ *(left) and* $T_* = 0.5\sigma_T$ *(right) with corresponding observations. Measurements were made at the Urban site.*

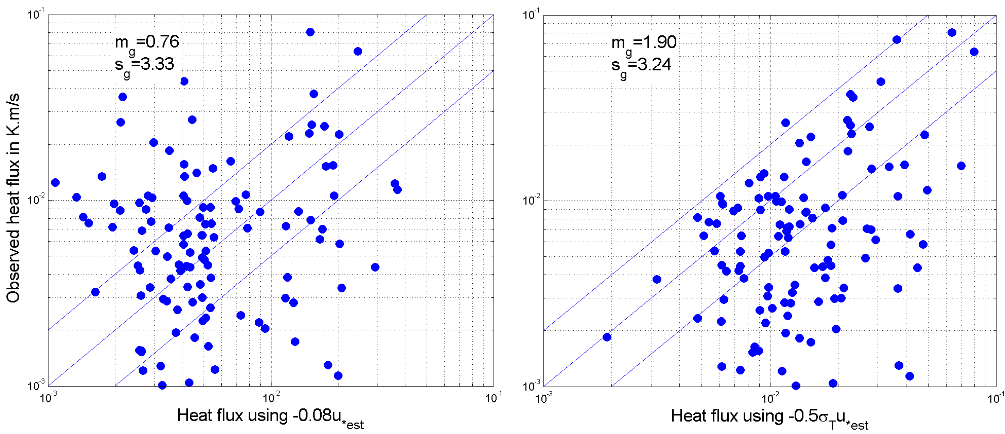

Figure 5. *Estimates of heat flux from estimated* u_* *using SU method with* $T_* = 0.08°C$ *(left) and* $T_* = 0.5\sigma_T$ *(right) with corresponding observations. Measurements were made at the Suburban 1 site.*

Figure 4 compares the performance of the two versions of SU method in estimating u_* for the Urban site in Riverside field study. We see that u_* is underestimated when $T_* = 0.08°C$ is used, especially for the low observations. Using σ_T to compute T_* leads to smaller scatter, but u_* is underestimated even more than when $T_* = 0.08°C$ is used.

Figure 5 compares observations of heat flux with estimates based on the definition, $\overline{w'T'} = -T_* u_*$, with $T_* = 0.08°C$ and $T_* = 0.5\sigma_T$. Here, u_* is estimated using the SU method with the two T_* calculation methods respectively. When constant $T_* = 0.08°C$ is used, the heat flux for the Suburban 1 site is underestimated by 24% and the scatter is large for all the three sites (not shown here). When $T_* = 0.5\sigma_T$ is used, the heat flux is overestimated, with m_g about 1.9, but the scatter of the prediction is smaller.

The incorporation of σ_T into the SU method does not improve the estimation of u_* but appears to reduce scatter in the estimates of heat flux. This suggests that σ_T might add value to a reformulated version of the SU method. This is examined in the following.

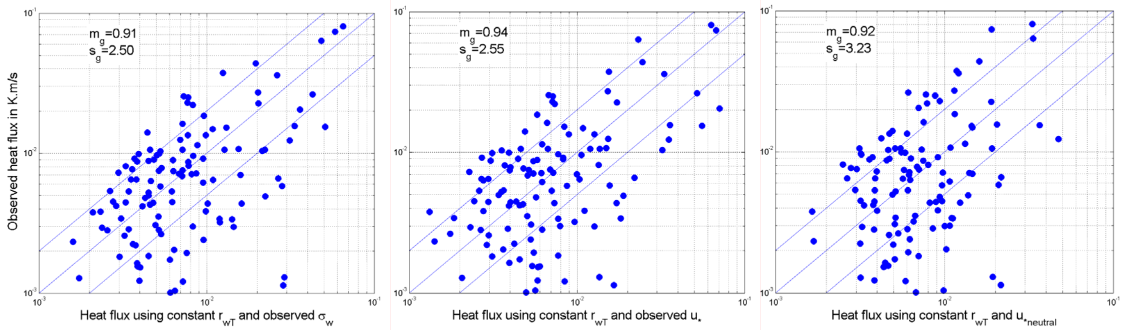

Figure 6: *Heat flux computed by Equation (1) using constant r_{wT} = -0.1 with observed σ_w (left panel), observed u_* (middle panel) and neutral estimates of u_* (right panel). Measurements were made at Suburban 1 site.*

Figure 6 used a constant value of r_{wT} = -0.1 to estimate heat flux from σ_w calculated from three methods. The estimates shown in the left panel correspond to observations of σ_w. In the middle panel, σ_w is calculated from $1.3u_*$ using the observed u_*. And in the right panel, σ_w is estimated from the neutral value $u_* = \kappa u(z_r)/\ln\left((z_r - h)/z_0\right)$.

The m_g value in the three plots in Figure 6 show that Equation (1) with constant r_{wT} = -0.1 yields similar estimates of heat flux for all three estimates of σ_w. But the uncertainty of this method is large, especially when u_* is calculated from neutral estimates.

Figure 7 shows that using the heat flux derived from Pahlow et al. (2001) with u_* from neutral conditions overestimates the heat flux.

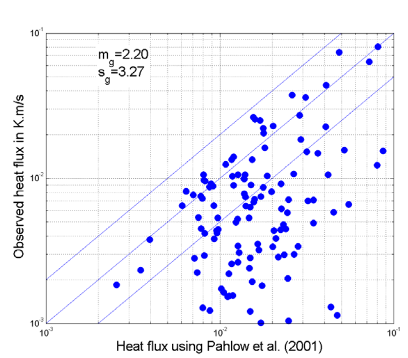

Figure 7: *Estimates of heat flux from Equation (13) with corresponding observations. Measurements were made at Suburban 1 site.*

(a) (b) (c)

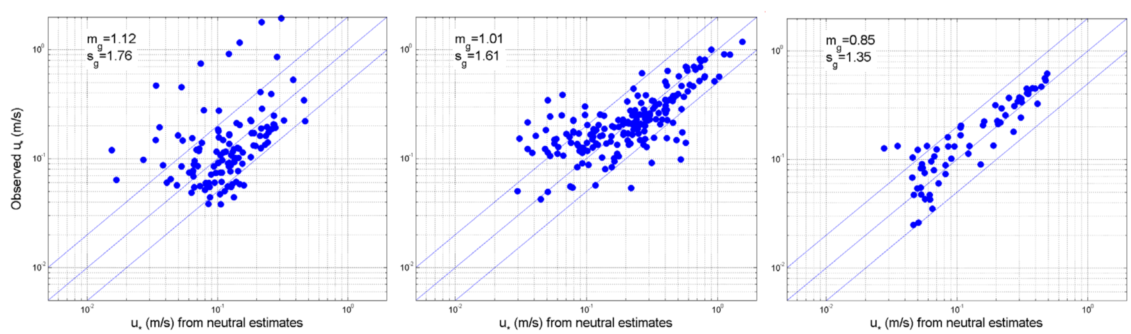

Figure 8: u_* from neutral estimates with corresponding observations for (a) Suburban 1 site, (b) Suburban 2 site, and (c) Urban site.

It turns out that the best estimate of u_* during stable conditions is the neutral estimate, $\kappa u(z_r)/\ln\left((z_r - h)/z_0\right)$, which does not account for stability effects. Figure 8 compares the neutral estimates of u_* with corresponding observations for all the three sites.

In the following, we are going to estimate urban meteorology from the suburban data. The Suburban 2 site was selected as the upwind suburban site in the model. And the meteorological estimates for the Urban site are compared with measurements. The suburban site is located 11 km west of urban site, and wind direction range 234°~324° is selected so that the urban area is downwind of the suburban measurement site.

At first, we assume $L_U = L_R$, when $L_R < 0$, and L_U is infinity when $L_R > 0$ (the subscripts R and U represent suburban and urban, respectively). This assumption was justified by Luhar, et al. (2006) for the data from the Basel Urban Boundary Layer Experiment (BUBBLE) conducted in the city of Basel, Switzerland (Rotach et al., 2005).

Figure 9 compares estimates of u_* at the Urban site from the IBL model to observed values. When the suburban conditions are stable (left), u_* is overestimated with m_g = 3.76. This implies that the assumption of L_U being infinity (neutral condition) when suburban conditions are stable might not be suitable for the Riverside data.

The right part of Figure 9 shows that, when the suburban conditions are unstable, u_* is also overestimated with m_g = 1.68, but the overall performance is better than that when suburban conditions are stable.

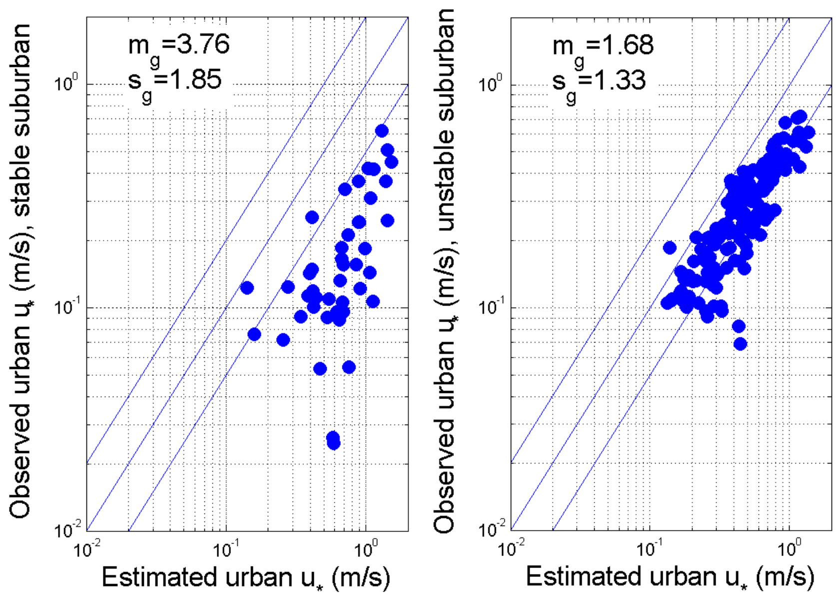

Figure 9. Scatter plot of u_* estimated from the IBL model when L_U is infinity for $L_R > 0$ (left), and $L_U = L_R$ for $L_R < 0$ (right) vs. the observed values over the urban area

We noticed that the measurement height in the Urban site is 3.06 m, which could be well within the roughness sublayer (RS). As suggested by Rotach (1993), $\overline{u'w'}$ (norm of Reynolds stress) appears to increase with height within the RS before reaching an approximately constant value in the inertial sublayer (IS). As a result, the friction velocity, u_*, will not be constant within the RS, which indicates that $u_{*,U}$ calculated from Equation (15) will provide good estimation for u_* above RS but not within the RS.

Rotach (2001) proposed the following profile for the friction velocity within the roughness sublayer.

$$\left(\frac{u_{*,l}(z)}{u_*^{IS}}\right)^b = \sin\left(\frac{\pi}{2}Z\right)^a \quad , \quad Z \le 1 \qquad (18)$$

where $u_{*,l}(z)$ is the local friction velocity, $Z = z'/z'_*$ is a non-dimensional height using $z' = z - d$ and $z'_* = z_* - d$. The parameters *a* and *b* are fitted to the experimental data Rotach (2001) collected to yield *a* = 1.28, and *b* = 3.0.

Estimates for z_* are often expressed as multiples of *h*, the average roughness element height. Raupach et al. (1991) conclude that z_* = 2*h* - 5*h* essentially covers the range of estimates from the literature they reviewed.

Now we use Equation (15) to estimate the friction velocity in the inertial sublayer, and then the local friction velocity at the measurement height is calculated from Equation (18). The average building height (h) is approximately 5 m, and z_* is set to be 2*h* for now.

Figure 10 shows the comparison of u_* estimated from Equation (15) combined with Equation (18) with the observed values. As we have expected, the overestimation of u_* is reduced when the u_* profile within the RS is taken into account. For the unstable suburban conditions (right), the estimation is improved so that m_g is 0.94. For the stable suburban conditions (left), u_* is still overestimated with m_g = 2.11.

After u_* is estimated from the IBL model with the use of the u_* profile in RS, wind speed and σ_w are then estimated by M-O similarity. Figure 11 compare the estimated similarity wind speed and σ_w with the observations. Although a portion of data is overestimated for both wind speed and σ_w, the overall performance is acceptable. The overestimation of wind speed and σ_w can be explained by the overestimation of u_* when suburban conditions are stable.

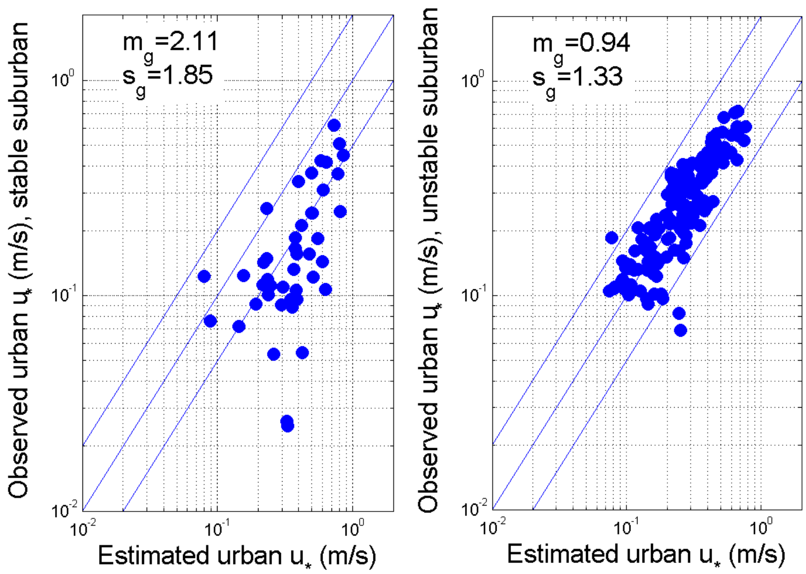

Figure 10. Scatter plot of u_* estimated from the IBL model and the u_* profile in RS when L_U is infinity for L_R > 0 (left), and L_U = L_R for L_R < 0 (right) vs. the observed values over the urban area

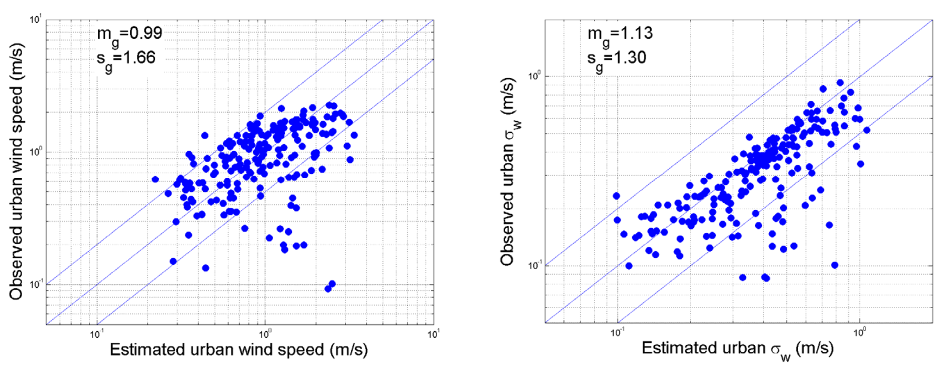

Figure 11. *Scatter plots of estimated wind speed (left) and σ_w (right) when u_* is estimated from the IBL model with the u_* profile in RS when L_U is infinity for L_R > 0 (left), and L_U = L_R for L_R < 0 (right), compared with the observed values over the urban area*

As we realized that when the suburban conditions are stable, u_* is still overestimated after using the u_* profile in the RS. This may due to the assumption of L_U to be infinity for $L_R > 0$. So we tried another simple assumption to make $L_U = L_R$ for $L_R > 0$ and then take into account the u_* profile in RS.

Comparing Figure 12 with left panel of Figure 10, we see that the overestimation of u_* has been reduced to an acceptable level when we assume $L_U = L_R$ and the scatter is also reduced.

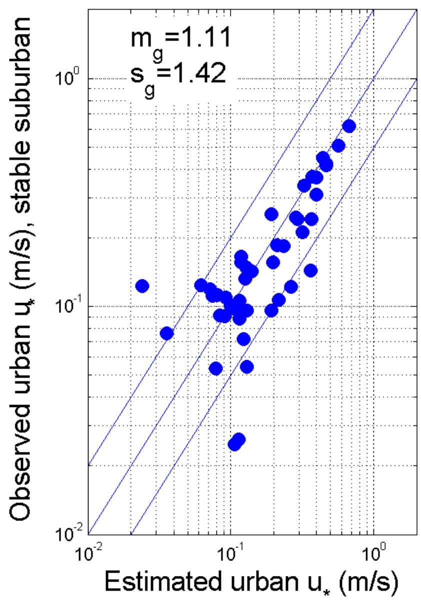

Figure 12. *Scatter plot of u_* estimated from the IBL model and the u_* profile in RS when assuming $L_U = L_R$ for $L_R > 0$ compared with the observed values over the urban area*

5. CONCLUSIONS

The results from this study show that measurements of wind speed and standard deviation of temperature fluctuations at one level yield useful estimates of parameters required to model dispersion in both suburban and urban areas.

Under unstable conditions, the estimates of heat flux based on measured σ_T and wind speed at one level provide adequate estimates of surface friction velocity and turbulent velocities. The surface heat flux is overestimated by the free convection approximation, especially for the urban site. The data analyzed in the current study shows that it is necessary to take C_1=1.3 instead of 0.95 in Equation (3) to avoid severe overestimation of heat flux. We also examined two methods that account for stability through the M-O length to estimate heat flux: one proposed by Tillman (1972) and the other based on a constant value of the correlation coefficient between temperature and vertical velocity fluctuations. The performance of these two methods is comparable, but they do not represent noticeable improvement over the simple free convection equation.

During stable conditions, the observed values of surface friction velocity are best estimated with the formula that assumes neutral conditions. The surface heat flux estimated using a measured value of σ_T, the neutral estimate for $\sigma_w = 1.3\, u_*$ based on the observed wind speed, and a constant correlation coefficient of -0.1 between the vertical velocity and temperature fluctuations does show improvement upon that from the previous version of the SU method.

We also examined a two-dimensional internal boundary-layer (IBL) model to estimate urban micrometeorology using measurements from suburban sites. This method uses Monin-Obukhov surface similarity theory and suburban variables as upwind inputs. The model assumes that the urban Obukhov length is the same as that in the suburban area under unstable conditions and is infinity (neutral) when suburban conditions are stable.

The IBL model itself overestimates the friction velocity, u_*, for the Urban site. Taking into account the u_* profile within the Roughness Sublayer (RS) proposed by Rotach (2001) can reduce the overestimation. Using the IBL model along with the u_* profile in RS provides adequate urban u_* estimation when the suburban conditions are unstable; but urban u_* is still overestimated during the stable suburban conditions. The assumption of M-O length over the urban area to be equal to that over the suburban area will reduce the overestimation, but such assumption is not justified.

6. ACKNOWLEDGEMENTS

The research described in this paper was sponsored by the National Science Foundation under grant ATMOS 0430776.

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