ESTIMATING METEOROLOGICAL INPUTS FOR URBAN DISPERSION MODELS

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Abstract: Meteorological variables such as surface friction velocity and heat flux are critical inputs to the current generation of dispersion models such as AERMOD. This paper examines methods to estimate these variables by applying Monin-Obukhov (M-O) similarity to measurements made on towers located in urban areas. The inputs to these methods are restricted to the wind speed and the standard deviation of temperature fluctuations data measured at a single level on a tower. The performance of these methods are evaluated with data collected at one urban and two suburban towers in Riverside, California during two months in 2007, The data consisted of mean winds and temperatures as well as heat and momentum fluxes using a sonic anemometer at one level on each tower. The major conclusions of this study are that during unstable conditions: 1) M-O theory provides adequate estimates of micrometeorological variables using urban measurements of mean winds and temperatures at one level when the standard deviation of temperature fluctuations is used to estimate heat flux, 2) the simple free convection estimate provides estimates of the heat flux that compare well with those from methods that account for stability effects through the M-O length, 3) all the methods overestimate heat flux close to neutral conditions, 4) the overestimation of heat flux does not appear to affect estimates of surface friction velocity, but results in overestimation of the vertical turbulent velocity. During stable conditions, 1) vertical and horizontal velocity fluctuations are related to friction velocity through similarity relationships derived in flat terrain, 2) estimates of the surface friction velocity based on temperature fluctuations do not improve upon those based on a constant value of θ_*, 3) the surface friction velocity is underestimated at low values of the surface friction velocity, and 4) assuming neutral conditions provides estimates of surface velocity that compare better with observations than those from methods that account for stability.

Key words: *Monin-Obukhov similarity, meteorological inputs, urban area, dispersion model.*

1. INTRODUCTION

This study is motivated by the need for meteorological inputs for dispersion models such as AERMOD (Cimorelli *et al.*, 2005), and it extends the work reported in Venkatram, A. and M. Princevac (2008). Its objective is to examine the performance of M-O similarity methods in estimating surface friction velocity (u_*), and vertical turbulent velocity (σ_w) using measurements of the mean wind speed and the standard deviation of temperature fluctuations at a single level on a tower located in an urban setting. The study was conducted with data collected at one urban and two suburban towers in Riverside, California during a field study conducted in March/April 2007. The next section describes the methods used to estimate these micrometeorological variables.

2. GOVERNING EQUATIONS

The heat flux under unstable conditions was estimated using the free convection relationship:

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

where σ_T is the standard deviation of temperature fluctuations, κ is the von Karman constant, and z_r is the height at which the temperature and mean wind are measured. The constant C_1=0.95 suggested by Tillman, J.E. (1972). The previous study (Venkatram and Princevac, 2008) indicated that Equation (1) provided adequate estimates of Q_0. However, the data analyzed in the current study that it was necessary to take C_1=1.3 to avoid overestimation of the heat flux.

We examined the possibility of improving upon the free convection estimate through a function of z_r/L, where L is the M-O length. The improved formulation is best introduced by writing the formal expression for the kinematic sensible heat flux as

$$\overline{w'T'} = r_{wT}\sigma_w\sigma_T \tag{2}$$

where σ_T is the standard deviation of temperature fluctuations, σ_w is the standard deviation of the vertical velocity fluctuations, and r_{wT} is the correlation coefficient between the velocity and temperature. We then express σ_w as a combination of a shear generated component, σ_{ws}, and a buoyancy generated component, σ_{wc}

$$\sigma_w = (\sigma_{ws}^3 + \sigma_{wc}^3)^{1/3}. \tag{3}$$

The shear component, σ_{ws}, is taken to be $\sigma_{ws} = 1.3u_*$, where u_* is the surface friction velocity. The convective component, σ_{wc}, is

$$\sigma_{wc} = 1.3\left(gQ_0 z_r / T_0\right)^{1/3}, \tag{4}$$

Equation (3) can be rearranged to obtain

$$\sigma_w = \sigma_{ws}\left[1+\left(\sigma_{wc}/\sigma_{ws}\right)^3\right]^{1/3}$$
$$= 1.3u_*\left(1-\frac{z_r}{kL}\right)^{1/3} \quad (5)$$

where L is the Monin-Obukhov (M-O) length. This expression for σ_w is very close to that presented by Panofsky et al. (1977) to fit a wide range of data. The difference is in the coefficient $1/k=2.5$ which differs from the value of 3 presented in Panofsky et al.(1977). Substituting Equation (5) into Equation (2) gives

$$Q_0 = r_{wT}\sigma_T 1.3u_*\left(1-\frac{z_r}{kL}\right)^{1/3}. \quad (6)$$

Equation (6) is useful only if we have value or an expression for r_{wT}. We found that $r_{wT}=0.3$ provided an adequate explanation of the data. In addition, we used an expression suggested by Tillman's (1972) formula for σ_T/θ_*,

$$r_{wT} = \frac{1}{1.3C_1}\left(C_2-\frac{z_r}{L}\right)^{1/3}\left(1-\frac{z_r}{kL}\right)^{-1/3}. \quad (7)$$

The right hand side of Equation (6) has an implicit dependence on Q_0 because both u_* and L are functions of Q_0; it has to be solved numerically. The surface friction velocity, u_*, is calculated using an approximation proposed by Wang and Chen (1980). The standard deviation of the vertical velocity fluctuations, σ_w, is computed from Equation (3).

During stable conditions, the relevant micrometeorological variables are computed using a method based on the empirical observation (Venkatram, 1980) that θ_* $(=-\overline{w'\theta'}/u_*)$ 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. This allows us to express the surface friction velocity as

$$u_* = C_D u\left(z_r\right)\left\{\frac{1}{2}+\frac{1}{2}\left[1-\left(\frac{2u_0}{C_D^{1/2}u}\right)^2\right]^{1/2}\right\} \quad (8)$$

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

$$u_* = \frac{1}{2}C_D u\left(z_r\right) \quad (9)$$

The values of σ_w and σ_v are computed from the similarity relationships, $\sigma_w = 1.3u_*$ and $\sigma_v = 1.9u_*$.

The second version of this method estimates θ_* 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 $\theta_* = 0.5\sigma_T$ (Stull, 1988). In principle, this should yield better results than assuming a constant θ_*.

3. RESULTS

The performance of the models is characterized using the geometric mean (m_g) and standard deviation (s_g). The deviation of m_g from unity tells whether the model is underpredicting or overpredicting. It is a measure of bias of the model estimate, and s_g is a measure of the uncertainty in the model prediction.

The roughness length, z_o, and displacement height, d_h, for each site are obtained using methods described in Princevac and Venkatram (2007). We found that z_o is 0.13, 0.27 and 0.31 for suburban Riverside, suburban Moreno Valley and urban Riverside sites respectively. The displacement height $d_h=5z_0$ based on Britter, R.E. and S.R. Hanna (2003).

Unstable conditions

Figure 1 compares estimates of heat flux from the three methods applied at the urban Riverside site during instable conditions. Note that C_1 was taken to be 1.3 in both Equation (1) and (7) to avoid overestimation of heat fluxes. However, all three methods still overestimate the fluxes at the urban Riverside site. The overestimation is smaller at the rural 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 2, 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 Riverside site. However, σ_w is overestimated by about 20% because the estimates depend explicitly on the surface heat flux, Q_0.

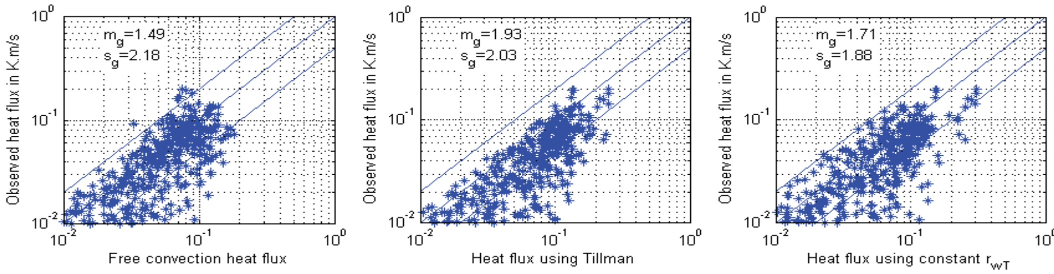

Figure 1. Comparison of heat fluxes computed by the three methods with observations made at the urban Riverside site during unstable conditions.

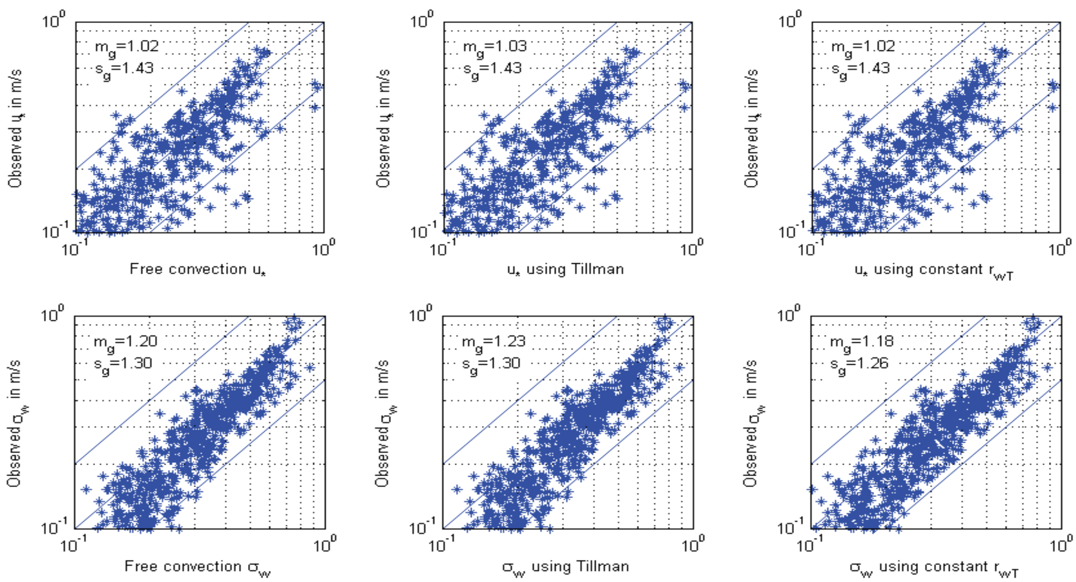

Figure 2. Plots of estimated u_*, σ_w using heat flux from free convection (left panel), from Tillman's method (middle panel) and from constant r_{wT} (right panel) with observations for urban Riverside site during unstable conditions

Stable conditions

Figure 3 indicates that the similarity relationships $\sigma_w=1.3u_*$ and $\sigma_v=1.9u_*$ provide adequate descriptions of the observed standard deviations of vertical and horizontal velocity fluctuations, although there is some scatter in estimates of σ_v. Thus, the surface friction velocity, u_*, is critical to modeling dispersion under stable conditions.

Figure 4 (left panel) compares u_* predicted from Equations (8) and (9) using constant θ_* (= 0.08°C) with observed u_* during stable conditions. We see that u_* is underestimated, especially for low values of observations. This leads to underestimation of σ_w and σ_v (not shown here).

The middle panel of Figure 4 indicates that using the additional information from $\theta_* = 0.5\sigma_T$ leads to a decrease in the scatter (s_g) for the urban Riverside site. But m_g decreases indicating that u_* is underestimated even more. Other formulations, such as those proposed by Beljaars, A. C. M. and A. A. M. Holtslag (1991), did not improve the underestimation. The right panel of Figure 4 indicates that neutral estimate, $u_* = kU(z_r)/\ln(z_r/z_o)$ provides the best description of the observations for the entire range of friction velocities.

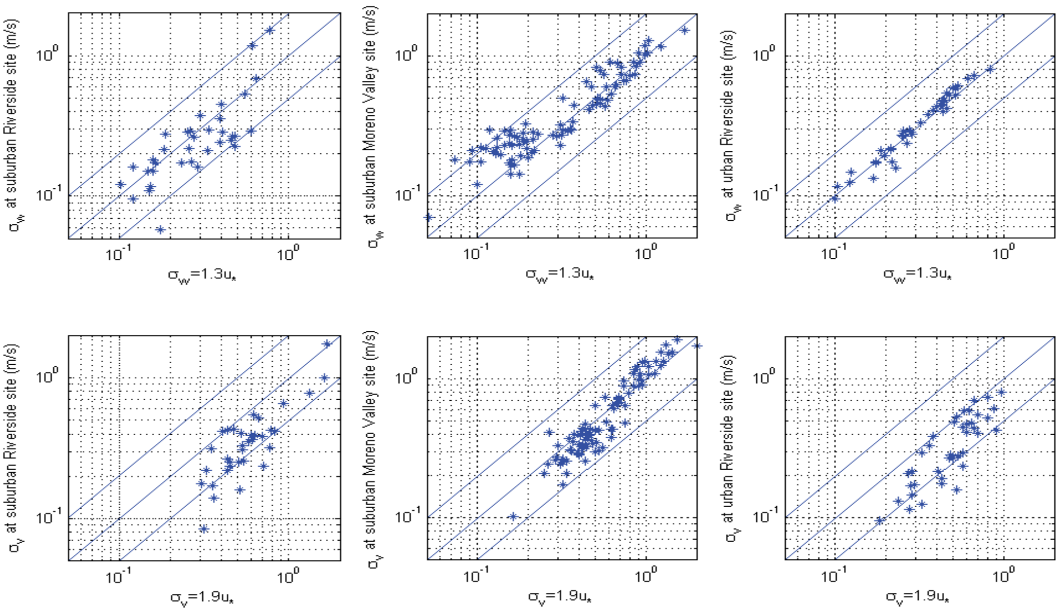

Figure 3. Relationship between measured u* and σ_w and σ_v at the suburban and urban sites.

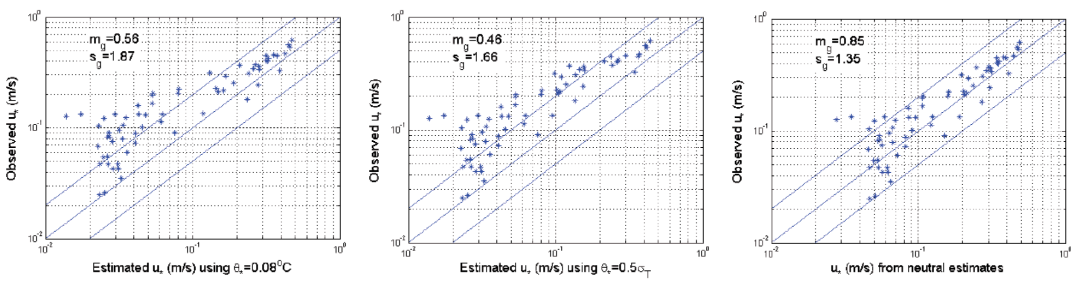

Figure 4. Comparison of u_* estimated using constant $\theta_* = 0.08$°C (left), $\theta_* = 0.5\sigma_T$ (middle), and neutral estimates (right) with observations for urban Riverside site during stable conditions.

4. 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 rural 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 was necessary to take C_1=1.3 instead of 0.95 in Equation (1) 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 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 standard deviations of vertical and horizontal velocity fluctuations are described well by similarity relationship even in suburban and urban areas. Estimates of surface friction velocity based on $\theta_*=0.5\sigma_T$ do not improve upon results based on a nominal value of $\theta_* = 0.08^{o}$C. It turns out that observed values of surface friction velocity are best estimated with the formula that assumes neutral conditions.

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