A NOTE ON THE FLUX-VARIANCE SIMILARITY RELATIONSHIPS FOR HEAT AND WATER VAPOUR IN THE UNSTABLE ATMOSPHERIC SURFACE LAYER

Research Note

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Abstract. Atmospheric surface layer (ASL) experiments over the past 10 years demonstrate that the flux-variance similarity functions for water vapour are consistently larger in magnitude than their temperature counterpart. In addition, latent heat flux calculations using the flux-variance method do not compare as favorably to eddy-correlation measurements when compared to their sensible heat counterpart. These two findings, in concert with measured heat to water vapour transport efficiencies in excess of unity, are commonly used as evidence of dissimilarity between heat and water vapour transport in the unstable atmospheric surface layer. In this note, it is demonstrated that even if near equality in flux-profile similarity functions for heat and water vapour is satisfied, the flux-variance similarity functions for water vapour are larger in magnitude than temperature for a planar, homogeneous, unstably-stratified, turbulent boundary-layer flow.

Keywords: Atmospheric surface layer, Closure models, Flux variance method, Scalar transport, Scalar variance similarity functions.

1. Introduction

Estimating heat and water vapour fluxes using the so-called flux-variance method (FVM), first introduced by Tillman (1972), is gaining rapid popularity in surface hydrology and micrometeorology (Wesely, 1988; Weaver, 1990; Lloyd et al., 1991; De Bruin et al., 1991, 1993; De Bruin, 1994; Padro, 1993; Kustas et al., 1994; Albertson et al., 1995; Paw U et al., 1995; Katul et al., 1995, 1996; Hsieh et al., 1996; Bink, 1996; Bink and Meesters, 1997; Asanuma and Brutsaert, 1998; Andreas et al., 1998). The method is based on surface-layer similarity theory for scalar variances in the atmospheric surface layer (ASL) and is given by:

$$\frac{\sigma_c}{c_*} = \chi_c(\xi); \qquad \xi = \frac{-z}{L_{\mathrm{mo}}},$$

$$L_{\mathrm{mo}} = \frac{-\rho u_*^3}{kg\left(\dfrac{H}{\bar{T}c_p} + 0.61E\right)},$$

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where $\sigma_c (= (\overline{c'^2})^{1/2})$ is the standard deviation of the concentration fluctuation of a scalar entity (C), overbar is time averaging, primed quantities indicate departure from the mean state by turbulence, z is the height above the zero-plane displacement height, L_{mo} is the Obukhov length, E $(= \overline{w'q'})$ is the evaporation rate, u_* is the friction velocity, $\chi_c(\xi)$ is the flux-variance similarity for a given scalar C (χ_T and χ_q are the flux-variance similarity functions for heat and water vapour, respectively), c_* is a scalar concentration defined by

$$c_* = \frac{\overline{w'c'}}{u_*},$$

$k = 0.4$ is the von Karman constant, $H = \rho c_p \overline{w'T'}$ is the sensible heat flux, c_p is the specific heat capacity of dry air at constant pressure, ρ is the mean air density, w', T', and q' are the vertical velocity, temperature, and water vapour concentration fluctuations, respectively, $\bar{T}$ is the mean air temperature, and g is the gravitational acceleration.

Field experiments over the past 10 years demonstrated that:

(1) The flux-variance method reproduces eddy-correlation sensible heat flux well (Lloyd et al., 1991; Albertson et al., 1995; Katul et al., 1995; Hsieh et al., 1996).

(2) The latent heat flux comparisons between flux-variance predictions and eddy correlation measurements are inferior to those of sensible heat for the same site (Weaver, 1990; Padro, 1993; Katul et al., 1995; Roth and Oke, 1995; Asanuma and Brustsaert, 1998).

(3) For unstable atmospheric conditions, heat is transported more efficiently than water vapour (Katul et al., 1995; Roth and Oke, 1995; Bink, 1996; Asanuma and Brutsaert, 1998).

(4) When χ_c is expressed as $\chi_c = C_c(\xi)^{-1/3}$, the similarity constant C_c for heat (hereafter referred to as C_T) is smaller than that for water vapour (hereafter referred to as C_q). Many ASL field experiments (e.g., Wyngaard,1971; Sorbjan, 1989; Kader and Yaglom, 1990; Albertson et al., 1995; Katul et al., 1995; Roth and Oke, 1995; Asanuma and Brutsaert, 1998) determined a $C_T \approx 0.93$–0.98 while others (e.g., Hogstrom and Smedman-Hogstrom, 1974; Ohtaki, 1985; De Bruin et al., 1991; Katul et al., 1995; Roth and Oke, 1995; Asanuma and Brutsaert, 1998) determined a $C_q \approx 1.1$–1.5. We note that these ranges for C_T and C_q were determined using different sensor types (e.g., for humidity, these sensors include Lyman-α sensors, krypton hygrometers, and infrared gas analyzers; for temperature, these sensors are mainly fine wire thermocouples and triaxial sonic anemometer temperature). Hence, the fact that $C_T < C_q$ cannot be due to systematic instrument biases. In addition, the measurements

of σ_q/q_* while scaling well with $\xi^{-1/3}$ are more scattered when compared to σ_T/T_*, with a bias

$$\frac{\sigma_q}{q_*} > \frac{\sigma_T}{T_*}.$$

This inequality was used as a diagnostic for the lack of similarity between heat and water vapour (e.g., Roth and Oke, 1995; Andreas et al., 1998; Asanuma and Brutsaert, 1998). In fact, flux-profile similarity theory investigations reported in Brutsaert and Parlange (1992) conclude good agreement between eddy-correlation measured and predicted sensible and latent heat fluxes derived from measured profiles of $\bar{T}$ and $\bar{q}$. Asanuma and Brutsaert (1998) compared flux-variance calculations for heat and water vapour fluxes with eddy-correlation measurements and reported good agreement for heat but not water vapour. In addition, Asanuma and Brutsaert (1998) reported that C_q decreases with stronger correlation between temperature and water vapour fluctuations. In short, ASL field experiments over the past 10 years suggest that flux-profile similarity functions for heat (=$\phi_h(\xi)$) and water vapour (=$\phi_q(\xi)$) appear to be in closer agreement with each other when compared to their flux-variance similarity function counterparts (i.e., $\chi_q(\xi) \neq \chi_T(\xi)$) for planar homogeneous flow (e.g., Brutsaert, 1982; Ohtaki, 1985; Stull, 1988; Garratt, 1992; Kaimal and Finnigan, 1994). We note many other studies have demonstrated that $\phi_h(\xi) \neq \phi_q(\xi)$ even for a planar homogeneous flow (e.g., Warhaft, 1976; Bink, 1996).

The objective of this note is to demonstrate that even if $\phi_h(\xi) \approx \phi_q(\xi)$, $\chi_T(\xi)$ must be smaller than $\chi_q(\xi)$ for a planar-homogeneous unstable ASL in the absence of subsidence, advective transport, and flux-divergence. For advective conditions, it is known that $\phi_h(\xi) \neq \phi_q(\xi)$ as demonstrated by Lang et al. (1983) and McNaughton and Laubach (1998) and that $C_q \neq C_T$ as demonstrated by de Bruin et al. (1991), Katul et al. (1995), and Bink (1996). The proposed analytical approach is based on second-order closure principles applied to the flux-budget equations for heat and water vapour.

2. Theory

The steady-state one-dimensional equations for the budgets of $\overline{w'T'}$ and $\overline{w'q'}$, in the absence of flux-divergence terms but including the buoyancy production terms, are:

$$\begin{aligned}\frac{\partial\overline{w'T'}}{\partial t} &= 0 = -\overline{w'^2}\frac{\partial\bar{T}}{\partial z} - \overline{T'\frac{\partial p'}{\partial z}} + g\beta\overline{T'^2},\\ \frac{\partial\overline{w'q'}}{\partial t} &= 0 = -\overline{w'^2}\frac{\partial\bar{q}}{\partial z} - \overline{q'\frac{\partial p'}{\partial z}} + g\beta\overline{T'q'},\end{aligned} \tag{1}$$

where $\beta = 1/\bar{T}$, p is the static pressure, and $\overline{w'^2}$ (=σ_w^2) is the vertical velocity variance. In order to obtain expressions that are strictly dependent on surface-layer similarity flow variables, the classical Rotta type parameterization for the scalar-pressure covariances is used (Mellor, 1973; Mellor and Yamada, 1974; Launder et al., 1975; Lumley, 1978; Moeng and Wyngaard, 1986). These parameterizations are:

$$\overline{c'\frac{\partial p'}{\partial z}} = \frac{C_s}{\tau}\overline{w'c'}, \tag{2}$$

where c' is a scalar concentration fluctuation (e.g., T' or q'), C_s is a closure constant (Lumley, 1978), $\tau = T_{\mathrm{tke}}/\bar{\epsilon}$ is a relaxation time scale for dissipating the turbulent kinetic energy (T_{tke}), and $\bar{\epsilon}$ is the mean turbulent kinetic energy dissipation rate. Upon replacing this closure model in the flux-budget equations, we obtain:

$$\begin{aligned} \overline{T'^2} &= \frac{1}{g\beta}\left[\overline{w'^2}\frac{\partial \bar{T}}{\partial z} + C_s\frac{\overline{w'T'}}{\tau}\right], \\ \overline{T'q'} &= \frac{1}{g\beta}\left[\overline{w'^2}\frac{\partial \bar{q}}{\partial z} + C_s\frac{\overline{w'q'}}{\tau}\right]. \end{aligned} \tag{3}$$

The flux-profile similarity formulations for $\bar{T}$ and $\bar{q}$ is:

$$\begin{aligned} \frac{\partial \bar{T}}{\partial z} &= \frac{-\phi_h(\xi)T_*}{kz}, \\ \frac{\partial \bar{q}}{\partial z} &= \frac{-\phi_q(\xi)q_*}{kz}, \end{aligned} \tag{4}$$

where $T_* = \overline{w'T'}/u_*$, $q_* = \overline{w'q'}/u_*$, $\phi_h(\xi)$ and $\phi_q(\xi)$ are, as before, the stability correction functions for heat and water vapour flux-profile relations, respectively. Upon replacing these expressions in the flux-budget equations, we obtain:

$$\begin{aligned} \overline{T'^2} &= \frac{1}{g\beta}\left[-\overline{w'^2}\frac{\phi_h(\xi)T_*}{kz} + C_s\frac{T_*u_*}{\tau}\right], \\ \overline{T'q'} &= \frac{1}{g\beta}\left[-\overline{w'^2}\frac{\phi_q(\xi)q_*}{kz} + C_s\frac{q_*u_*}{\tau}\right]. \end{aligned} \tag{5}$$

By noting that $\overline{T'q'}$ is $R_{T,q}\sigma_T\sigma_q$, σ_q can be replaced by the identity

$$\sigma_q = \frac{1}{R_{T,q}}\frac{\sigma_T}{\overline{T'^2}}\overline{T'q'}. \tag{6}$$

Upon replacing the formulations in (5) for $\overline{T'q'}$ and $\overline{T'^2}$ in (6), we obtain:

$$\sigma_q = \frac{1}{R_{T,q}}\sigma_T \frac{\frac{1}{g\beta}\left[\overline{-w'^2}\frac{\phi_q(\xi)q_*}{kz} + C_s\frac{q_* u_*}{\tau}\right]}{\frac{1}{g\beta}\left[\overline{-w'^2}\frac{\phi_h(\xi)T_*}{kz} + C_s\frac{T_* u_*}{\tau}\right]}. \tag{7}$$

Upon dividing both sides by q_* and rearranging, (7) simplifies to:

$$\frac{\sigma_q}{q_*} = \frac{1}{R_{T,q}}\frac{\sigma_T}{T_*}\frac{\left[\overline{-w'^2}\frac{\phi_q(\xi)}{kz} + C_s\frac{u_*}{\tau}\right]}{\left[\overline{-w'^2}\frac{\phi_h(\xi)}{kz} + C_s\frac{u_*}{\tau}\right]}. \tag{8}$$

Equation (8) explicitly relates σ_q/q_* to σ_T/T_* for a planar homogeneous unstable ASL in the absence of scalar flux divergences. Simplifications to (8) in the context of the flux-variance similarity functions and heat/water vapour transport efficiencies are discussed next.

3. Results and Discussions

3.1. FLUX-VARIANCE SIMILARITY FUNCTIONS FOR HEAT AND WATER VAPOUR

If $\phi_h(\xi) = \phi_q(\xi)$, then (8) reduces to:

$$\frac{\sigma_q}{q_*} = \frac{1}{R_{T,q}}\frac{\sigma_T}{T_*}, \tag{9a}$$

and

$$\chi_q(\xi) = \frac{1}{R_{T,q}}\chi_T(\xi). \tag{9b}$$

Since the correlation coefficient $R_{T,q}$ is less than unity (as demonstrated by almost all ASL field experiments over homogeneous and heterogeneous surfaces), then

$$\chi_q(\xi) > \chi_T(\xi). \tag{10}$$

Note that (10) assumes similarity in mean temperature and water vapour profiles (i.e., $\phi_h(\xi) = \phi_q(\xi)$). That is, inequality in the flux-variance similarity relationships does not necessarily imply dissimilarity in the flux-profile relationships.

3.2. HEAT AND WATER VAPOUR TRANSPORT EFFICIENCIES

The result in (9) also explains why heat is more efficiently removed from a surface when compared to water vapour. A measure of the relative efficiency (λ) of heat to water vapour removal, as formulated by McBean and Miyake (1972) and Bink (1996), is

$$\lambda = \frac{R_{w,T}}{R_{w,q}}, \tag{11}$$

where $R_{w,T}$ and $R_{w,q}$ are the correlation coefficients between vertical velocity, and heat and water vapour, respectively. Starting with the Bowen ratio definition

$$\frac{\overline{w'T'}}{\overline{w'q'}} = \frac{R_{w,T}\sigma_t\sigma_w}{R_{w,q}\sigma_q\sigma_w} = \frac{R_{w,T}\sigma_T}{R_{w,q}\sigma_q}, \tag{12}$$

and upon rearranging, we obtain:

$$\frac{\sigma_q}{q_*} = \frac{R_{w,T}}{R_{w,q}}\frac{\sigma_T}{T_*}. \tag{13}$$

By comparing (9a) with (13), it is evident that

$$\frac{R_{w,T}}{R_{w,q}} = \frac{1}{R_{T,q}}, \tag{14}$$

demonstrating that λ exceeds unity for the unstable ASL despite equality between $\phi_h(\xi)$ and $\phi_q(\xi)$. Hence, heat can be more efficiently removed by turbulence when compared to water vapour (even if similarity in the flux-profile relationships is assumed). It must be emphasized here that the equality in (14) is not a strict equality given the closure approximation described by (2) and the assumption that C_s is the same for both scalars.

3.3. CONSISTENCY WITH WARHAFT'S (1976) THEORETICAL RESULT

Using second-order closure principles outlined by Donaldson (1973), Warhaft (1976) demonstrated that the ratio of heat (K_h) and water vapour (K_q) eddy diffusivities for the unstable ASL with moisture acting as a passive scalar is given by

$$\frac{K_h}{K_q} = 1 - \frac{1}{2}\frac{g}{\overline{w'^2}}\frac{\overline{T'^2}}{\bar{T}}\frac{1}{\partial\bar{T}/\partial z}\left(R_{T,q}\frac{R_{w,T}}{R_{w,q}} - 1\right). \tag{15}$$

In the unstable atmospheric surface layer, the eddy diffusivity for a scalar C is given by:

$$K_c = \frac{kzu_*}{\phi_c(\xi)}. \tag{16}$$

Upon replacing (16) in (15),

$$\frac{\phi_q(\xi)}{\phi_h(\xi)} = 1 - \frac{1}{2}\frac{g}{\overline{w'^2}}\frac{\overline{T'^2}}{\bar{T}}\left(\frac{1}{\partial\bar{T}/\partial z}\right)\left(R_{T,q}\frac{R_{w,T}}{R_{w,q}} - 1\right). \tag{17}$$

If $\phi_h(\xi) = \phi_q(\xi)$, then

$$\frac{R_{w,T}}{R_{w,q}} = \frac{1}{R_{T,q}}, \tag{18}$$

given that $\overline{w'^2}$, $\overline{T'^2}$, $\bar{T}$, $\partial\bar{T}/\partial z$ are not zero for the unstable ASL. A direct consequence of Warhaft's (1976) result is that even when $\phi_h(\xi) = \phi_q(\xi)$ (or when $K_h = K_q$), (14) must be satisfied and $\chi_q(\xi) > \chi_T(\xi)$ (except for the case when $R_{T,q} = 1$ as demonstrated by Hill, 1989).

3.4. VALIDATION

As validation for (10) and (14), measurements from three sites described in Katul et al. (1995) are used. These sites include a 19.5 m tall spruce and fir forest in eastern central Maine, a uniform bare soil site in Davis, California, and a 23 cm tall grass-covered forest clearing in Durham, North Carolina. The grass-covered forest clearing measurements are for optimal wind directions. The measurements selected for this validation are for dynamic-convective and near- convective conditions ($-z/L_{\mathrm{mo}} > 0.04$ as in Kader and Yaglom, 1990). In Figure 1, it is clear that $\sigma_q/q_* > \sigma_T/T_*$ and that the scatter in σ_q/q_* is larger than σ_T/T_*. In Figure 2, we note that the overall trend at all three sites satisfy (14). Measurements from the La Crau site reported by Bink and Meesters (1997) also satisfy (14) for unstable runs. In fact, Bink and Meesters (1997) derive (14) using a statistical approach that does not rely on closure models. The measurements from the Sevilleta site by Andreas et al. (1998) clearly demonstrate that $\chi_q(\xi) > \chi_T(\xi)$. In fact, Andreas et al. (1998) concluded that $\chi_q(\xi) \approx 1.28\chi_T(\xi)$. They also found that typical magnitude for $R_{T,q}$ is 0.76 (mainly a mid-day ensemble-averaged value). Based on (13) and (14), we find that for the Sevilleta site $\chi_q(\xi) \approx 1.32\chi_T(\xi)$ which is very close to their measured 1.28 value.

4. Conclusions

This study has demonstrated the following:

1. Dissimilarity in the flux-variance similarity functions for heat and water vapour does not imply dissimilarity in the mean profile relations. In fact, even if $\phi_h(\xi) = \phi_q(\xi)$, $\chi_T(\xi) \neq \chi_q(\xi)$.

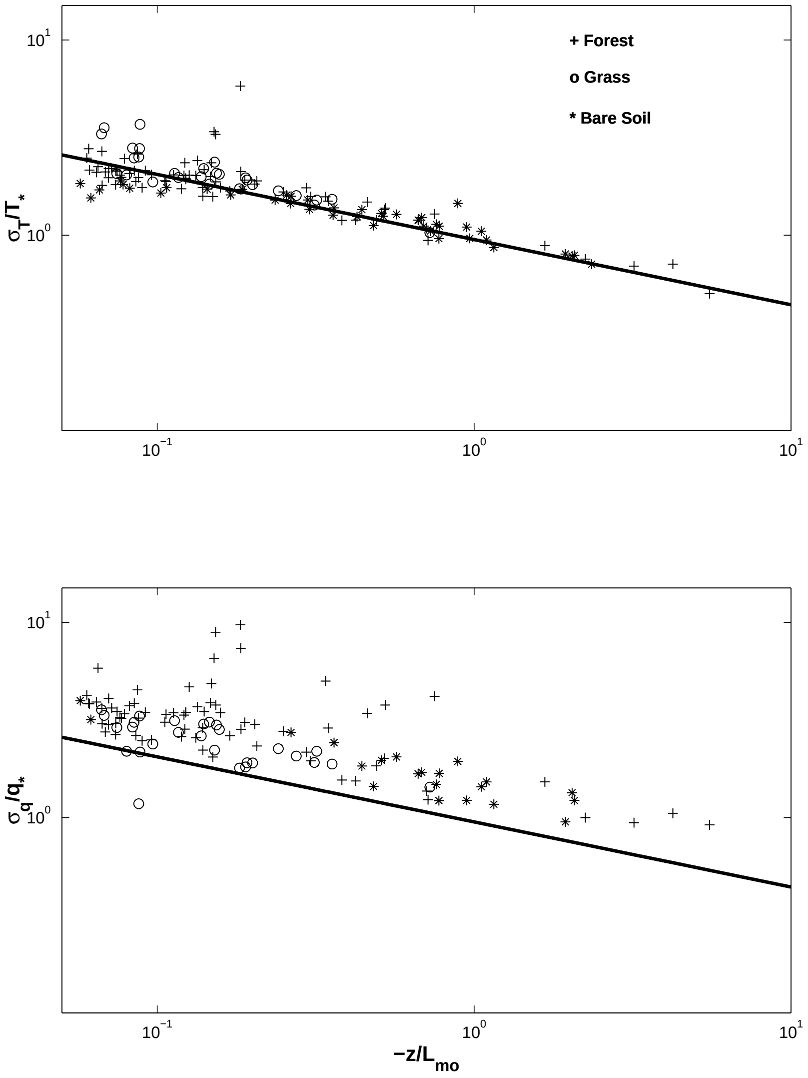

Figure 1. Measured σ_T/T_* (top) and σ_q/q_* (bottom) at the three sites as a function of $-z/L_{\mathrm{mo}}$ for dynamic-convective and near-convective conditions. The solid line is 0.95 $(z/L_{\mathrm{mo}})^{-1/3}$.

2. For the unstable surface layer, heat is transported more efficiently than water vapour from the ground surface due to the buoyant production terms. The transport efficiency $R_{w,T}/R_{w,q}$ was found to be identical to $1/R_{T,q}$ in agreement with previous finding and measurements from the La Crau site reported by Bink and Meesters (1997) and Andreas et al. (1998). The $R_{T,q}$, $R_{w,T}$, and $R_{w,q}$ measurements by Roth and Oke (1995) further confirm this result.
3. For the unstable ASL, $\sigma_q/q_* = (1/R_{T,q})\sigma_T/T_*$. In a planar-homogeneous turbulent flow, $R_{T,q}$ is partially influenced by dissimilarities in ground-heat

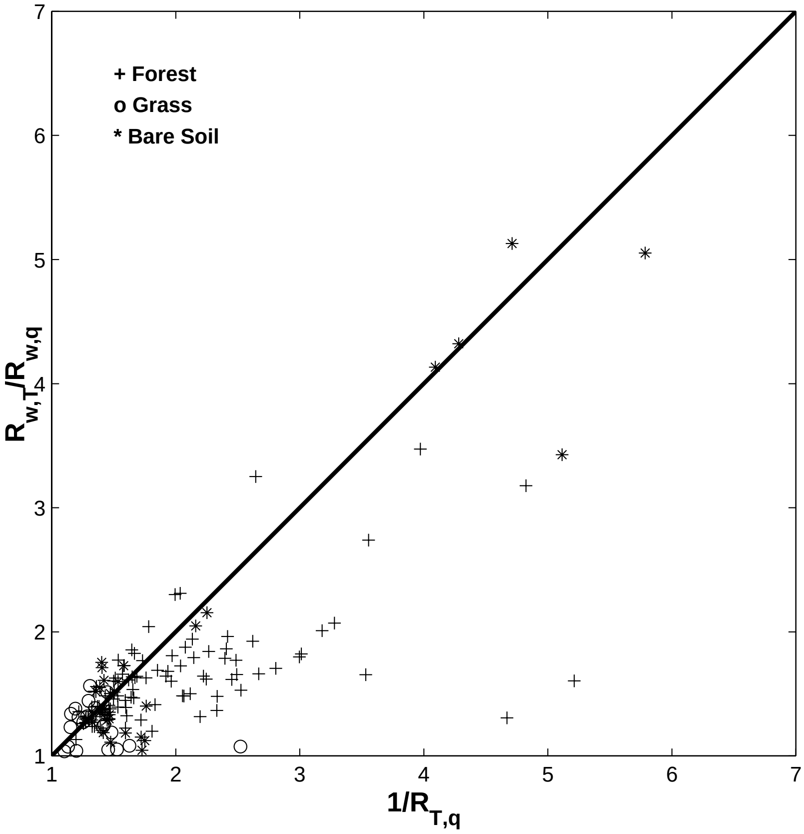

Figure 2. Comparison between $R_{w,T}/R_{w,q}$ and $1/R_{T,q}$ for all three sites. The 1 : 1 line is also shown.

and water vapour sources and sinks (Katul et al., 1995; Andreas et al., 1998) and, to a lesser extent, by entrainment from the capping inversion (though the role of this entrainment is likely to be small when z is much smaller than the atmospheric boundary layer depth as evidenced by recent large eddy simulations in Albertson and Parlange, 1998). Hence, in many ASL field experiments, $R_{T,q}$ varies in time and with atmospheric stability conditions, ground heating non-uniformity (Katul et al., 1995), and entrainment from the capping inversion (Roth and Oke, 1995). It is of no surprise that:

(3.1) When the flux-variance similarity function is expressed as $\chi_c = C_c(\xi)^{-1/3}$, $C_q > C_T$.

(3.2) The scatter in measured $\chi_q(\xi)$ is larger than $\chi_T(\xi)$ as in Katul et al. (1995), and Roth and Oke (1995),

(3.3) By assuming $R_{w,T} = R_{w,q}$, the flux-variance latent heat flux predictions do not compare as favorably with eddy correlation measurements when compared to sensible heat (see Katul and Hsieh, 1997, for details), and

(3.4) The similarity constant C_q decreases with increasing $R_{q,T}$ as demonstrated by the measurements in Asanuma and Brutsaert (1998).

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