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6.1 APPLICATION OF MONIN-OBUKHOV SIMILARITY OVER A MESQUITE DUNE SITE IN THE JORNADA EXPERIMENTAL RANGE

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1. INTRODUCTION

Monin-Obukhov similarity (MOS) theory has been a widely applied approach for estimating turbulent fluxes of heat and momentum in the surface layer and is used exclusively by Soil-Vegetation-Atmosphere-Transfer (SVAT) models for simulating surface-atmosphere processes. However, a number of studies have shown significant discrepancies between turbulent fluxes derived from MOS and measured directly by eddy covariance for rough and heterogeneous surfaces (e.g., Chen and Schwerdtfeger, 1989).

In this paper, we discuss the application of MOS using mean profiles of temperature, θ, and wind speed, u, for estimating sensible heat and momentum fluxes over a mesquite dune site in the USDA-ARS Jornada Experimental Range near Las Cruces, New Mexico. This site contains complex topography and heterogeneous cover where 0.5 m tall mesquite vegetation grow on dunes that are 1-2 m in height and ~10 m in width. Distances between dunes are on the order of 20 m. Very little if any vegetation exists in this interspace region.

2. THEORY

The method assumes that the vertical turbulent transport of a quantity F is proportional to the mean concentration gradient C

$$F(z) = K_C\, \partial C/\partial z \qquad (1),$$

where K_C is the height dependent eddy diffusivity and is assumed to be a function of the momentum transport and atmospheric stability. For momentum and heat, the gradients are related to the fluxes as

$$\partial u/\partial z = u_*/k(z-d_0)\ \phi_M[(z-d_0)/L] \qquad (2)$$
$$\partial \theta/\partial z = T_*/k(z-d_0)\ \phi_H[(z-d_0)/L] \qquad (3)$$

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where $u_*[=\tau/\rho]$ and $T_*[=H/(u_*\rho C_P)]$ are the velocity and temperature scales, and τ and H are the vertical fluxes of momentum and sensible heat with ρ and C_P the air density and heat capacity and k is von Karman's constant. The stability correction functions for momentum, ϕ_M, and heat, ϕ_H, are functions of the Monin-Obukhov stability parameter L, relating the strength of mechanical versus convectively driven turbulence made nondimensional by the height of the observation, z, above the displacement height, d_0. Their functional forms are derived from experimental data. Integrated forms of Eqs. (2) and (3) have been derived (Brutsaert, 1982). This allows computing the fluxes with two levels in the surface layer,

$$u_2 - u_1 = u_*/k\ \{\ln[(z_2-d_0)/(z_1-d_0)] - \Psi_M[(z_2-d_0)/L] + \Psi_M[(z_1-d_0)/L]\} \qquad (4)$$
$$\theta_1 - \theta_2 = T_*/k\ \{\ln[(z_2-d_0)/(z_1-d_0)] - \Psi_H[(z_2-d_0)/L] + \Psi_H[(z_1-d_0)/L]\} \qquad (5)$$

where Ψ_M and Ψ_H are integrated forms of ϕ_M and ϕ_H. With $u=0$ at the surface and observations of radiometric "surface" temperature, θ_S, only one level in the surface layer is needed (Brutsaert, 1982), but it also requires an estimate of the surface roughness for momentum, z_{OM}, and heat transfer, z_{OH},

$$u_z = u_*/k\ \{\ln[(z-d_0)/z_{OM}] - \Psi_M[(z-d_0)/L]\} \qquad (6)$$
$$\theta_z - \theta_S = T_*/k\ \{\ln[(z-d_0)/z_{OH}] - \Psi_H[(z-d_0)/L]\} \qquad (7)$$

In resistance notation, Eqs (6) and (7) can be combined yielding

$$H = \rho\, C_P\, [\theta_z - \theta_S]/R_{AR} \qquad (8)$$

where R_{AR} is the aerodynamic-radiometric resistance; this has been equated to the sum of aerodynamic resistance, R_A ($= u/u_*^2$) and an "excess" resistance term, R_{EX}, due to the fact that the radiometric surface temperature θ_S and not the aerodynamic temperature is a measurable quantity (Stewart et al., 1994). Therefore, $R_{AR}=R_A+R_{EX}$ is a function of MOS for R_A and an empirical resistance component, R_{EX}.

3. THE DATA

In May of 1996 a 10 meter tower was erected approximately 60 m south of the Radiation and Energy Balance Systems** (REBS) Bowen ratio (BR) station at the Mesquite dune site. The tower was instrumented with sensors to measure air temperature, vapor pressure, and wind speed at 3, 4, 5, 6, 8, and 10 m above the surface. Air temperature and vapor pressure were measured using Vaisala temperature and relative humidity probes (HMP 35C). The HMP 35C sensors were placed inside aspiration shields. Wind speeds were measured with R.M. Young 3-cup anemometers with 0.3 m s^{-1} threshold. Surface temperatures were estimated using 2 Everest Infrared Temperature Transducers (IRTs; Model 4000) located at the top of the 10 m tower. The IRTs had a field of view of 60^{O} and were oriented to the north and south and at angles of 45^{O}. Net radiation was estimated with a REBS Q7.1 located at 10 m.

In September 1996, H was estimated at a height of 3 m on the tower using eddy covariance, EC. A Campbell Scientific Inc. (CSI) 1-D sonic anemometer and fine wire thermocouple were used. Time series data of fluctuations of the three wind velocity components and virtual temperature were measured with a Gill Solent 3-D sonic (provided by Dr. D.I. Cooper) at 5m. The sampling frequency for the 1-D EC was 10 Hz and 20 Hz for the 3-D system. The sampling frequency for all other 10 m tower measurements was 10 s with a 30 minute average output.

5. PRELIMINARY RESULTS

The preliminary results will pertain to the analysis performed with the data collected in September, 1996 under unstable conditions. Neutral wind profiles were used for estimating d_0 and z_{OM} for the site yielding values of $d_0 \sim 1$ m and $z_{OM} \sim 0.07$ m.

To evaluate how well the u and θ profiles follow MOS, plots of normalized quantities $[u(z)-u(z_{10m})]/u_*$ and $[\theta(z_{10m})-\theta(z)]/T_*$ versus $\ln[(z-d_0)/(z_{10m}-d_0)]$ were made with u_* and T_* estimates from the EC systems (Chen and Schwerdtfeger, 1989). Actual versus MOS theoretical normalized profiles of u and θ are shown in Figure 1. These represent an average of all unstable profiles. There is significant departure from MOS for θ, but not for u.

The departure from MOS for the θ profile should cause significant discrepancies between observed H from the EC system, H_{EC}, and computed from Eqs.(4)-(5). The average H, $\langle H \rangle$, and resulting standard deviation, $\langle H \rangle_{SD}$ using Eqs. (4)-(5) and Eqs. (6) -(7) are listed in Table 1. Values of $\langle H \rangle$ computed by Eqs. (4)-(5), $\langle H_G \rangle$, are both significantly higher and lower than $\langle H_{EC} \rangle$ ($\approx$ 195 W m^{-2}) depending on what two levels are used in the calculation.

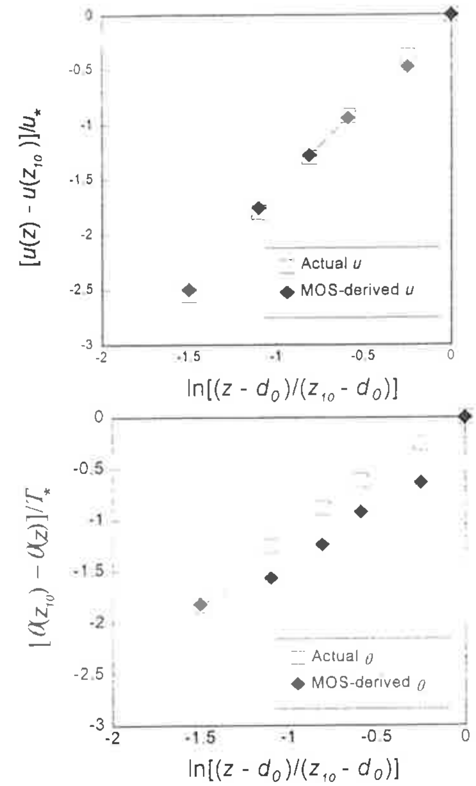

Figure 1 Actual versus MOS-derived u and θ normalized profiles.

In addition, these estimates have significantly more variability (i.e., an average coefficient of variation, CV ~0.8 versus CV~0.4 for $\langle H_{EC} \rangle$ where $\langle H_{EC} \rangle_{SD} \approx 85$ W m^{-2}). This result indicates not only are there surface roughness sublayer effects over most of the profile measurement height but also other limitations to the gradient diffusion approach related to eddy sizes and non-steady conditions of the mixed-layer (Chen and Schwerdtfeger, 1989).

On the other hand, using θ_S in Eqs. (6)-(7) or Eq. (8) the H estimates, H_{IRT}, are closer to H_{EC}. In Table 1, $\langle H_{IRT} \rangle$ estimates are only slightly less than $\langle H_{EC} \rangle$

Table 1. $\langle H \rangle$ and $\langle H \rangle_{SD}$ values (W m^{-2}) .

Model/Levels(m)	3-4/3	4-5/4	5-6/5	6-8/6	8-10/8	10
$\langle H_G \rangle$	78	172	243	125	288	-
$\langle H_G \rangle_{SD}$	69	134	162	82	384	
$\langle H_{IRT} \rangle$	192	188	188	187	185	187
$\langle H_{IRT} \rangle_{SD}$	102	103	102	102	101	101

**Company and trade names are given for the benefit of the reader and imply no endorsement by the USDA.

at all levels with only a slightly higher CV ~0.5.

Figure 2 is a comparison of H_{EC} with H_{IRT} from the 6 m level and H_G from 5-6 m levels. The results of this figure indicate that Eqs. (6)-(7) seem less affected by the roughness sublayer and other factors. This probably has to do with the significant influence of z_{OH} in Eq.(7). For sparse cover Stewart et al. (1994) recommends $z_{OH} \sim z_{OM}/10^3$, which in turn results in $R_{EX} \gg R_A$. The Root-Mean-Square-Difference (RMSD) is 60 and 230 W m^{-2} for H_{IRT} and H_G, respectively.

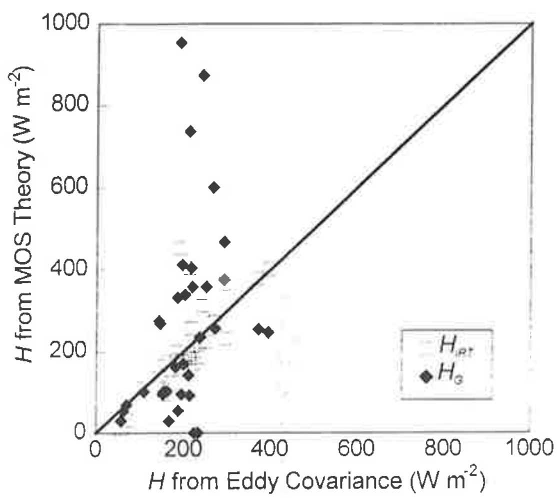

Figure 2. H_{EC} versus H_{IRT} and H_G

The impact of using θ_S as a boundary condition is more evident in the comparison of R_A versus R_{EX} values computed via Eq. (8). With EC measurements of H and u_*, R_A $(=u/u_*^2)$ and R_{AR} can be computed and R_{EX} solved as a residual, namely $R_{EX} = R_{AR} - R_A$. Values of $<R_{EX}>$ and $<R_A>$ for all 6 levels are listed in Table 2.

Table 2. $<R_{EX}>$ and $<R_A>$ values (s m^{-1}).

Level (m)	3	4	5	6	8	10
$<R_A>$	25	28	30	30	32	33
$<R_{EX}>$	44	42	42	42	41	40

From Table 2, more than ½ of the magnitude of R_{AR} is contributed by R_{EX}. As a result, the effects of the roughness sublayer, which mainly influences R_A, do not significantly affect surface flux calculations when using θ_S as the boundary condition for evaluating H.

A comparison between u_* from the 3-D sonic, u_{*3D}, and estimated using Eqs.(3)- (4), u_{*G}, and Eqs.(6)-(7), u_{*IRT}, is shown in Figure 3. The scatter is similar using either approach where RMSD values between u_{*G} and u_{*IRT} and u_{*3D} are both ≈ 0.10 m s^{-1}. This result indicates that the wind profile may not as strongly influenced as temperature by roughness sublayer effects and other boundary layer processes. This result is supported by other studies where it was observed that K_C for scalars is 2 to 4 times larger than K_C for momentum (Raupach et al., 1991).

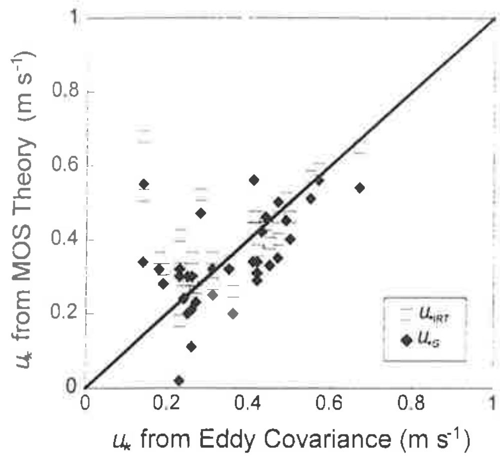

Figure 3. u_{*3D} versus u_{*IRT} and u_{*G}

Gradients of θ at $z \approx 2.5$ and 4.5 m were available from the REBS Bowen ratio system together with u observations at $z \approx 5$ m. Using the roughness parameters $d_0 \sim 1$ m and $z_{OM} \sim 0.07$ m, this allowed the computation of H with Eqs. (5) and (6). Estimates of H, H_{BR}, are compared to H_{EC} in Figure 4. Although the the scatter appears less than with H_G (see figure 2) the RMS is still > 100 W m^{-2}.

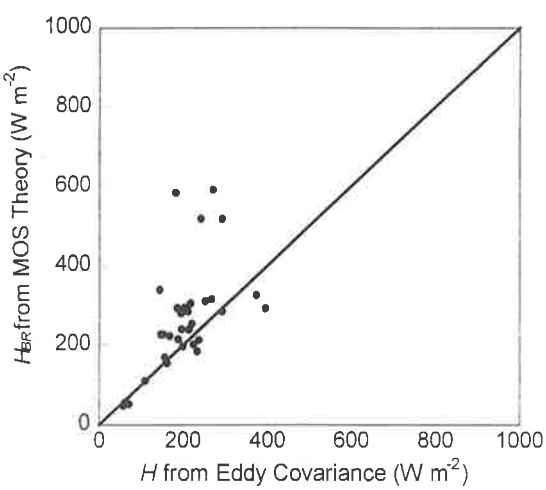

Figure 4. H_{EC} versus H_{BR}

6. DISCUSSION

Observations by Rotach (1993ab) over a rough urban surface indicate that by using a "local" scaling concept, MOS for variances and gradients is applicable within the roughness sublayer. This local scaling approach uses a variable u_* with height within the roughness sublayer since Rotach (1993a) found u_* increases with height over the depth of the roughness sublayer. However, Rotach (1993b) could only apply this local scaling concept to gradients in u and not θ. The reason the local scaling approach does not work for temperature may be related to the fact that the eddy diffusivity for heat, K_H, is not only dependent on the wind field but also the source distribution for heat (Coppin et al., 1986). Over this mesquite dune site, the source distribution heat is quite complicated with heat sources (interdune regions) and heat sinks (mesquite vegetation) randomly distributed over the surface.

The vertical extent of the roughness sublayer, Z_R, above mean obstacle height, h, appears to be proportional to obstacle spacing, D (Garratt, 1980). This depth is scaled by d_0 where experimental data suggest $Z_R - d_0 \sim 4D$ (Chen and Schwerdtfeger, 1989). With $D \sim 20$ m (i.e., spacing between dunes), $Z_R \sim 80$ m for this site, which encompasses the total depth of the surface layer (nominally 50 m)! Using a more conservative estimate of $Z_R - d_0 \sim 2h$ (Raupach et al., 1991), yields $Z_R \sim 5$ m. Clearly, using different rules of thumb for estimating Z_R yields very different values.

7. CONCLUSIONS

This preliminary analysis of wind and temperature profiles over a heterogenous and rough desert ecosystem indicates that application of MOS with mean gradients for predicting H is generally unreliable. For this surface it appears that the roughness sublayer, and other factors including the complicated source distribution for heat and other boundary layer processes more significantly affects the temperature profile compared to the wind (Figure 1). As a result, comparisons with measured H and u_* shows considerably more scatter for H than with u_* (cf. Figures 2 and 4 versus 3). This result is in qualitative agreement with other studies investigating the behavior of mean profiles u and θ within the roughness sublayer (e.g., Chen and Schwerdtfeger, 1989; Rotach, 1993b).

By using θ_S as the boundary condition for predicting H, the deviations of actual θ from MOS-predicted does not significantly affect computed H values (Figure 1). This appears to be mainly the result of a significant excess resistance component, R_{EX}, required for this surface. For more homogeneous surfaces where $D \ll h$ the magnitude of R_{EX} versus R_A may not be as significant, but $Z_R \sim h$ so that roughness sublayer effects are contained within a relatively small region of the surface layer depth.

Imposing surface boundary conditions for momentum (i.e., z_{OM}) and especially for heat transport via the use of θ_S and a resulting z_{OH} in MOS formulations may reduce the impact of surface roughness sublayer effects on the predicted H. It should be pointed out that using θ_S in a single source formulation such as Eq. (8) is generally prone to significant error, which is mainly related to determining an appropriate value of z_{OH} (Verhoef et al., 1997). This issue is beyond the scope of the present study.

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