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Momentum roughness and view-angle dependent heat roughness at a Southern Great Plains test-site

Jennifer M. Jacobs[a,]*, Wilfried Brutsaert[b]

[a]Department of Civil Engineering, University of Florida, Gainesville, FL 32611, USA
[b]School of Civil and Environmental Engineering, Cornell University, Ithaca, NY 14853, USA

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Abstract

Surface roughness parameters were determined for harvested wheat fields over level terrain at the US Department of Energy's Cloud and Radiation Testbed (CART) site in north-central Oklahoma. Measurements of wind speed and temperature were made by radiosondes and instruments mounted on 2 and 10 m towers during neutral and unstable atmospheric conditions in the atmospheric surface layer. Surface temperatures were measured radiatively over 750 m trajectories. Roughness heights were calculated for the region using the Monin–Obukhov similarity theory. The scalar roughness and the local momentum roughness were determined using wind speed measurements at 10 m and temperature measurements at 2 m combined with eddy correlation measurements for u_*. The scalar roughness z_{oh} was determined to be 0.0021 and 0.0038 m for the nadir and the off-nadir viewing angle, respectively. It was estimated that the displacement height d is negligible. A regional momentum surface roughness of $z_o = 0.15$ m was determined by means of the radiosonde profiles. Good agreement ($r = 0.92$) between measured and calculated sensible heat flux values was found using an independent data set of radiosonde profiles. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

A standard, if not the only way, to determine fluxes from mean profile measurements in the atmospheric surface layer (ASL) is by the Monin–Obukhov similarity relationships. These can be written in integral form as

$$V = \frac{u_*}{\kappa}\left[\ln\left(\frac{z-d}{z_o}\right) - \Psi_m\left(\frac{z-d}{L}\right)\right] \quad (1)$$

$$\theta_s - \theta = \frac{H}{\kappa u_* \rho c_p}\left[\ln\left(\frac{z-d}{z_{oh}}\right) - \Psi_h\left(\frac{z-d}{L}\right)\right] \quad (2)$$

where V is the wind speed, $u_* = (\tau_o/\rho)^{1/2}$ the friction velocity, τ_o the surface shear stress, ρ the density of air, $\kappa = 0.4$ von Karman's constant, z the height above the surface, d the displacement height, z_o the momentum roughness length, θ the potential temperature, θ_s the potential temperature at the surface, H the sensible heat flux, z_{oh} the scalar roughness for sensible heat, $\Psi_m[(z-d)/L]$ and $\Psi_h[(z-d)/L]$ the stability correction functions for momentum and sensible heat, respectively, and L the Obukhov length. L is defined by

$$L = \frac{-u_*^3 \rho}{\kappa \boldsymbol{g}(H/T_a c_p + 0.61E)} \quad (3)$$

* Corresponding author. Fax: +1-352-392-3394.

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where $\boldsymbol{g}$ is the acceleration of gravity, E the surface flux of water vapor, c_p the specific heat at constant pressure, and T_a the air temperature near the ground.

Recently proposed (Brutsaert, 1992) expressions for Ψ_m and Ψ_h, which are consistent with the theory of Kader and Yaglom (1990), and with recent experimental data, are

$$\Psi_m(y) = \begin{cases} 0, & \text{for } y > -0.0059 \\ 1.47\ln\left[\dfrac{(0.28+(-y)^{0.75})}{(0.28+(0.0059-y_o)^{0.75})}\right] & \\ -1.29[(-y)^{1/3}-(0.0059-y_o)^{1/3}], & \text{for } -0.0059 \geq y \geq -15.025 \\ \Psi_m(-15.0025), & \text{for } y < -15.025 \end{cases} \quad (4)$$

and

$$\Psi_h(y) = 1.20\ln[(0.33+(-y)^{0.78})/0.33] \quad (5)$$

where $y = z/L$ and $y_o = z_o/L$.

These similarity equations require knowledge of local surface conditions prior to their application. These local conditions are accounted for by the zero plane displacement height d and by the two integration constants, momentum roughness z_o and scalar roughness z_{oh}. While general estimates exist for z_o, most are either for generic types of surfaces or are based on data from a limited number of experiments (Wieringa, 1993; Sellers et al., 1996a,b). In practical applications, these general estimates still need to be calibrated for specific cases. Moreover, to date very limited information has been published on z_{oh}. In any event, there is still no substitute for direct measurements.

The goal of the present study was to determine the momentum and sensible heat roughnesses for the harvested wheat fields (stubble) over level terrain surrounding the Department of Energy's Cloud and Radiation Testbed (CART) site in north-central Oklahoma. In this paper, the surface parameters are presented on the basis of Monin–Obukhov similarity with local surface layer measurements. An independent test of the resulting surface parameters is also presented.

2. Experimental data

The data for this research were acquired in June–July of 1995 at the Central Facility (CF) of the US Southern Great Plains CART field research site which is operated by the US Department of Energy within its Atmospheric Radiation Measurement (ARM) Program. A detailed description of the ARM Program and the CART sites is provided by Stokes and Schwartz (1994). The CF is a 0.65 km^2 complex located in north-central Oklahoma between Lamont and Billings, Oklahoma (7°30′W, 36°37′N). The topography of the area is flat with only small changes in relief; small tree stands dot the landscape. During the experiment, stubble fields covered 80% of the region and pasture and range land covered the remainder.

2.1. Atmospheric surface layer profiles

At the CF, half-hourly average measurements were made of wind speed using a wind propeller-vane mounted atop a tower at 10 m. This tower was located on the western edge of a small pasture (~150 m wide) that was surrounded by wheat fields. The pasture's vegetation was mainly grass (~0.3 m high), interspersed with bushes ~0.5 m high on average. The anemometer had open exposure on all sides for several hundred meters. Half-hourly average air temperature measurements were made using a sonic anemometer–thermometer (Applied Technologies, Inc.) mounted on a separate tower at 2 m. This 2 m tower was located immediately adjacent to a harvested wheat field; it was surrounded by wheat stubble to the south and west and pasture to the north and east. The two towers were separated by approximately 50 m.

Radiosondes attached to helium filled balloons were released at the CF's northern edge (07°29′24″W and 36°36′36″N) four times per day during daylight hours (0630, 0930, 1230, and 1530 CDT). The balloon-borne sounding system (Vaisala RS-80L-H, Vaisala, Inc.) consisted of an instrument package with sensors for measuring pressure, air temperature, and relative humidity. During a flight, the radiosonde was tracked using the LORAN C network to determine its position in order to derive 10 s average wind speeds and directions. Wind speeds averaged over 10 s correspond to a vertical resolution of approximately 50 m. Temperature and humidity were sampled every 2 s. The response time of the temperature and humidity sensors was <2.5 s and 1 s, respectively. For this analysis, the temperature measurements were adjusted by shifting all data back in time by 2 s (e.g. temperature reported at 2 s is output at 0 s). Similarly, humidity measurements were adjusted by averaging two consecutive measurements and assigning the average humidity value to the earlier time.

The radiosonde wind speed measurements were considered somewhat unreliable indictators of mean wind speed in the ASL on account of their coarse vertical resolution and of their typically noisy appearance. Therefore, the tower wind speeds were used to establish the surface roughness parameters. Subsequently, however, as will be shown later, the radiosonde measurements could still be used to validate these parameters.

2.2. Surface flux measurements

An energy balance Bowen ratio (EBBR) system (Radiation and Energy Balance Systems, Inc.) was collocated with the 10 m tower in the pasture. The EBBR system measured air temperature T and vapor pressure e at 0.96 and 1.96 m above the vegetation, in addition to net radiation R_n and soil heat flux G. Using these measurements, the EBBR calculated half-hour average values of sensible heat H and latent heat LE.

Eddy correlation fluxes were calculated from the sonic anemometer–thermometer measurements on the 2 m tower. The system produced half-hour averages of the turbulent fluxes of sensible heat, latent heat, and momentum.

2.3. Surface temperature measurements

Two infrared thermometers (IRTs) were used to make surface temperature measurements over a 750 m transect at the CF. These IRTs were mounted on a portable yoke and carried by a porter as described by Slater et al. (1987). Both IRTs viewed about the same 10 cm diameter sampling area, one from a nadir viewing angle and the other from 50° off-nadir. The IRTs (Model 4000.2L, Everest Interscience, Inc.) had a 4° field of view and a 5 Hz sampling frequency.

Surface temperature was measured between 0800 CDT and 1600 CDT by hourly transect walks. Additional measurements were made on the half-hour as necessary to match radiosonde releases. The transect consisted of a 600 m harvested wheat portion followed by a 150 m pasture portion. The regional surface temperature was estimated by averaging a transect's measurements.

3. Analysis

3.1. Momentum roughness

The surface roughness z_0 was calculated with wind speed measurements from the 10 m tower and surface flux measurements from the eddy correlation system. Profiles (132) having near neutral to unstable atmospheric conditions were identified on the basis of the stability criterion $L \leq -20$ m.

An initial estimate of the displacement height was obtained from regional features. Around the CF, sparse tree clusters of 10–20 trees and occasional hedgerows were observed at typical separation distances of 1.5 km. These obstacles had heights and widths of the order of 10 and 3 m, respectively. With this information, one can obtain a rough idea of the magnitude of d, on the basis of expressions from the literature. For instance, following the procedure of Raupach (1992), the placement density λ is

$$\lambda = \frac{nbh}{S} \tag{6}$$

where n is the number of roughness obstacles, b the obstacle width, h the obstacle height, and S the ground area. In the present case, Eq. (6) yields $\lambda = 0.0012$, which suggests (see Figure 5, Raupach, 1992) that $d/h \leq 0.1$ or that d, as a result of the tree clusters, is likely to be smaller than 1 m.

For each profile, z_0 was calculated by Eq. (1) using a three-step process: (1) calculate an initial value of z_0

under the assumption of neutral conditions ($\Psi_m = 0$); (2) adjust z_o for atmospheric instability by repeating the previous calculation, but this time including Ψ_m where y_o in Eq. (4) was set to the previous z_o/L; and (3) repeat step (2) until the z_o value converges. The analysis of surface roughness was conducted with d set to several trial values that ranged between 0.0 and 1.0 m.

Previous studies applied different averaging methods to experimentally determined roughness values. The individual z_o values were averaged by means of the following three methods,

$$z_{o,a} = \frac{1}{N}\sum_{i=1}^{N} z_{o,i} \tag{7a}$$

$$z_{o,b} = \exp\left[\frac{1}{N}\sum_{i=1}^{N} \ln(z_{o,i})\right] \tag{7b}$$

$$z_{o,c} = \exp\left[\frac{1}{N}\sum_{i=1}^{N} \frac{1}{\ln(z_{o,i})}\right]^{-1} \tag{7c}$$

where N is the total number of profiles and $z_{o,i}$ the surface roughness of profile i. Eq. (7a) simply gives the linear average of calculated z_o values. Eq. (7b) and Eq. (7c) were proposed by Sugita and Brutsaert (1992) and Qualls and Brutsaert (1996), respectively, in earlier attempts to yield a roughness that would provide less biased estimates of surface fluxes on average.

For each of the three methods, z_o changed less than 1 cm for trial values of d over the range $0 \text{ m} \leq d \leq 1.0$ m. This means that d can be assumed to be negligible and only the results where $d = 0$ m are presented. The z_o values were 0.080, 0.041 and 0.076 m for Eq. (7a), Eq. (7b) and Eq. (7c), respectively. These values agree with the surface roughness values of 0.04–0.09 m obtained in previous studies for low mature agricultural crops (e.g. Table VIII in Wieringa, 1993).

Because the z_o values are based on point measurements of u_* at 2 m and on V at 10 m, they must be considered 'local', that is representative of horizontal scales of at most 1 km. This means that these roughness values do not quite incorporate the effect of the scattered tree clusters, with as mentioned earlier, typical separation distances of the order of 1.5 km. It also means that the momentum roughness at larger scales, that is, for use with wind speed measured at higher elevations, on the order of 10^2 m, should be taken larger than the values of around 0.07 m calculated here.

This is confirmed by other studies in the Southern Great Plains, where markedly larger values of z_o were obtained. For example, Asanuma et al. (1998), determined that z_o is around 0.48 m in the Little Washita River watershed in Oklahoma, a gently rolling land-surface which is, however, more wooded than the area surrounding the CF. Beljaars (1994), concluded that $z_o = 0.34$ m for the BLX83 experiment in Oklahoma on the basis of aircraft data from Stull (1994).

While the surface roughness value for the region surrounding the Central Facility is undoubtedy larger than the local value of 0.07 m, the topography and tree drag effects do not appear to be as large as those effects found in these two previous studies. Therefore, in applications at the mesogamma scale (2–20 km) and up, and with measurements aloft in the atmospheric boundary layer, it is probably appropriate to adopt the intermediate value, $z_o = 0.15$ m, as the regional roughness. This roughness is also the mid-range roughness value of the next roughest surface category in Table VIII of Wieringa (1993), namely mature crops such as grain. Interestingly, a value of $z_o = 0.13$ m is listed as the roughness for the region surrounding the CF in a data set with $1° \times 1°$ resolution, compiled as part of an effort by the International Satellite Land Surface Climatology Project (ISLSCP) by Sellers et al. (1996a,b,c).

3.2. Scalar roughness

The scalar roughness can be estimated by solving Eq. (2) for z_{oh} with the available data. The eddy correlation system provided 30 min averages of θ, u_*, H, and LE. The average nadir and off-nadir surface temperature values were available from the IRTs. Surface temperature values were interpolated to the midpoint of the eddy correlation measurements.

A total of 54 profiles and 56 profiles were identified for the nadir and the off-nadir surface temperature measurements, respectively, for the conditions $H \geq 20$ Wm^2 and $\theta_s - \theta \geq 2$°C. Of the nadir and the off-nadir profiles, 53 were coincident. For each profile z_{oh} was calculated by Eqs. (2) and (5).

Table 1
Comparison between the average H values from the eddy correlation system and the average calculated H values determined from regional estimates of z_{oh}, using-four different averaging techniques with nadir and off-nadir surface temperature measurements

Averaging method	Nadir			Off-nadir		
	z_{oh} (m)	$\langle H \rangle$ (W m^{-2})	$\langle H_{ec} \rangle$ (W m^{-2})	z_{oh} (m)	$\langle H \rangle$ (W m^{-2})	$\langle H_{ec} \rangle$ (W m^{-2})
Eq. (8a)	0.01403	244.44	171.02	0.01406	217.50	167.73
Eq. (8b)	0.00153	162.34	171.02	0.00245	155.85	167.73
Eq. (8c)	0.00526	199.00	171.02	0.00643	184.57	167.73
Best fit	0.0021	170.49	171.02	0.0038	167.71	167.73

Previous studies showed that z_{oh} may be a function of hour angle t (as a substitute for solar elevation) or u_* (Qualls and Brutsaert, 1996; Sugita and Brutsaert, 1996; Sugita et al., 1997). The relationships between z_{oh} and t as well as between z_{oh} and u_* were analyzed by ordinary least squares linear regressions. The present results indicated that there was no statistically significant relationship (α = 0.05) between z_{oh} and t, or between z_{oh} and u_*. This result is reasonable as the stubble cover is more sparse and more rigid than the dense vegetation of the previously cited studies. As the stubble allows the soil surface to be exposed to solar radiation and wind, the surface's scalar roughness would be expected to behave somewhat differently from that of a densely vegetated surface.

The individual z_{oh} values were averaged by the following three methods,

$$z_{oh,a} = \frac{1}{N}\sum_{i=1}^{N} z_{oh,i} \tag{8a}$$

$$z_{oh,b} = \exp\left[\frac{1}{N}\sum_{i=1}^{N}\ln(z_{oh,i})\right] \tag{8b}$$

$$z_{oh,c} = \exp\left[\left[\frac{1}{N}\sum_{i=1}^{N}\frac{1}{\ln(z_{oh,i})}\right]^{-1}\right] \tag{8c}$$

where $z_{oh,i}$ the scalar roughness of profile i. Table 1 gives the average values of z_{oh} obtained this way along with the mean values of the calculated sensible heat flux $\langle H \rangle$ and the mean values of measured sensible heat flux $\langle H_{ec} \rangle$. Averaging techniques Eq. (8b) and Eq. (8c) gave better estimates of the average surface sensible heat flux than Eq. (8a).

In a different approach, an 'optimal' estimate of z_{oh} was then determined such that on average the calculated sensible heat fluxes equal the measured H values. In other words, the magnitude of z_{oh} was adjusted by trial and error until $\langle H \rangle / \langle H_{ec} \rangle$ = 1.00. The results of this analysis are given in Table 1 as the 'best fit' averaging method. For the nadir surface temperature measurements, this optimal value is z_{oh} = 0.0021 m. An ordinary least squares regression for this value of z_{oh} yielded H_{ec} = 89.8 + 0.48H with r = 0.63. For the off-nadir surface temperature measurements, the optimal value is z_{oh} = 0.0038 m that results in an ordinary least squares regression of H_{ec} = 70.5 + 0.58H and r = 0.65. It can be seen that these optimal values lie between the values determined by Eq. (8b) and Eq. (8c).

As a sensitivity test, $\langle H \rangle$ was recalculated for profiles with the nadir surface temperature measurements with the optimal off-nadir scalar roughness z_{oh} = 0.0038 m. On average, the calculated sensible heat flux (188.10 W m^{-2}) overestimated surface measurement by approximately 10%. A similar series of calculations was made with the off-nadir surface temperature measurements and with the optimal nadir scalar roughness z_{oh} = 0.0021 m. In this case, the average calculated sensible heat flux (152.11 Wm^{-2}) underestimated the sensible heat flux by slightly less than 10%.

3.3. Estimation of surface fluxes with ASL radiosonde measurements

The values of d = 0, z_o = 0.15 m, the nadir z_{oh} = 0.0021 m, and the off-nadir z_{oh} = 0.0038 m were subsequently used to estimate u_* and H with an independent data set of radiosonde atmospheric profile measurements. The profiles selected for analysis had measurements of temperature and wind speed in the ASL and coincident surface flux measurements

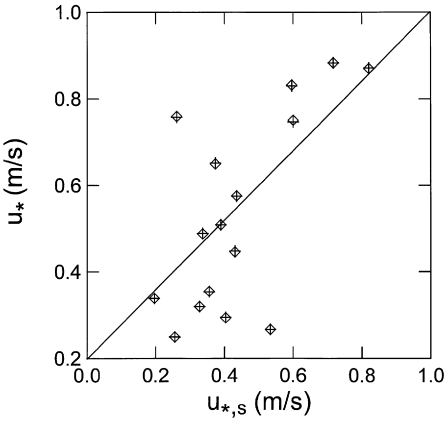

Fig. 1. Comparison between the $u_{*,s}$ values and the u_* values calculated from the radiosonde surface layer profiles with Monin–Obukhov similarity and the u_* values calculated by iterative solution between Eqs. (1)–(3). For the nadir surface temperature measurements, the individual u_* values are diamonds. For the off-nadir surface temperature measurements, the individual u_* values are crosses. The correlation coefficient is r = 0.66 for both nadir and off-nadir surface temperature measurements.

from the eddy correlation system. The ASL height range was determined for each profile. The bottom of the ASL was taken just above the Earth's surface. The top of the ASL was taken as $0.10h_i$ where h_i is inversion height. h_i was initially determined for each radiosonde profile as the height at which $d\theta/dp > 4°C/100$ mb where θ is the potential temperature and p the pressure. The results were confirmed by inspection. Most ASL profiles had 2–4 simultaneous measurements of wind speed and temperature at heights ranging between roughly 30 and 150 m above the ground level.

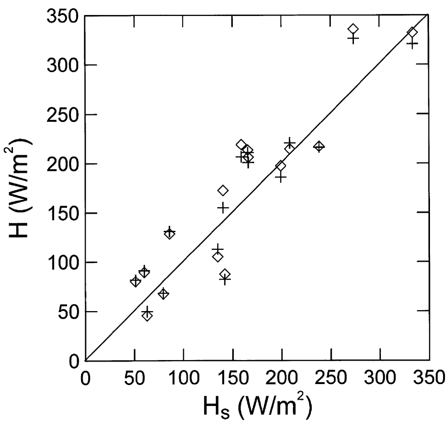

Fig. 2. Comparison between the H_s values and H values calculated from the radiosonde surface layer profiles and analyzed with Monin–Obukhov similarity with H calculated by iterative solution between Eqs. (1)–(3). For the nadir surface temperature measurements, the individual H values are diamonds. For the off-nadir surface temperature measurements, the individual H values are crosses. The correlation coefficient is r = 0.92 for both the nadir and off-nadir surface temperature measurements.

Sixteen profiles with unstable conditions ($\theta_s - \theta > 2°C$) were selected. Separate analyses were performed with the nadir and the off-nadir surface temperature measurements. H and u_* were calculated for each profile by iteratively solving Eqs. (1)–(3) until the solution converged. In order to derive representative values for the entire region for these analyses, the measured sensible heat flux was taken as the average of the measurements from the energy balance Bowen ratio station (representing the grass covered areas) and the eddy correlation station (representing the stubble covered areas) weighted according to the regional vegetation distribution ($H_s = 0.8H_{ec} + 0.2H_{ebbr}$).

Fig. 1 compares the ASL similarity estimates of the surface momentum fluxes with the measured values. The surface temperature viewing angle had little effect on the calculated values of u_*. The mean values of the reference momentum fluxes was $\langle u_{*,s} \rangle$ = 0.439 m s^{-1}. For both the nadir and the off-nadir surface temperature measurements, $\langle u_* \rangle$ = 0.537 m s^{-1} and the ordinary least squares regression line was $u_* = 0.87u_{*,s} + 0.155$ with r = 0.661. These results indicate that the calculated surface fluxes tended to overestimate the measured fluxes by about 22% on average. Although the sample is small, this is not surprising as momentum fluxes calculated with radiosonde data are more representative for regional roughness conditions, while the measured surface momentum fluxes reflect u_* with a horizontal scale that is smaller by an order or two of magnitude. Given this difference in scale, it is difficult to draw conclusions about the ability of Monin–Obukhov similarity to calculate regional u_* values.

The comparison of the calculated H vs the measured H_s values appears in Fig. 2 for the nadir and the off-nadir surface temperature measurements. The mean value of the reference flux was $\langle H_s \rangle$ = 156.24 W m^{-2}. For the nadir surface temperature measurements, $\langle H \rangle$ = 169.59 W m^{-2} and the ordinary least squares regression line was $H = 1.011H_s + 11.656$ with r = 0.92. For the off-nadir surface

Table 2
Sensitivity analysis of the dependence of the sensible heat flux on the value of z_o with the nadir surface temperature measurements.

z_o (m)	$\langle H_s \rangle$ (W m^{-2})	$\langle H \rangle$ (W m^{-2})	a	b (W m^{-2})	r
0.05	156.2	179.9	1.100 (±0.131)	7.99 (±22.90)	0.913
0.10	156.2	173.3	1.043 (±0.120)	10.35 (±21.03)	0.918
0.15	156.2	169.6	1.011 (±0.114)	11.65 (±20.00)	0.921
0.20	156.2	167.0	0.989 (±0.111)	12.54 (±19.31)	0.923
0.25	156.2	165.1	0.972 (±0.108)	13.19 (±18.80)	0.924

The results give the mean value of the reference flux $\langle H_s \rangle$, the mean value of the estimated flux $\langle H \rangle$, and the regression relationship of the form $H = aH_s + b$ with r the correlation coefficient. Numbers inside round brackets are standard deviation values.

temperature measurements, the calculated H values had better agreement with the measured values on average. The mean sensible heat flux was $\langle H \rangle$ = 166.32 W m^{-2} and the ordinary least squares regression line was $H = 0.968H_s + 15.126$ with $r = 0.92$.

As a sensitivity test, the H values were recalculated for a range of surface roughness values from 0.05 to 0.25 m and then compared with the measured values. The results are shown in Table 2. Ideally, both the ratio $\langle H \rangle / \langle H_s \rangle$ and a should be unity and b should be close to zero. The results in Table 2 show two opposite tendencies; as z_o increases, the ratio $\langle H \rangle / \langle H_s \rangle$ gradually improves (i.e. approaches unity), whereas a and b appear to worsen. On the other hand, from the considerations in section 3.1, it is clear the z_o should definitely not be smaller than 0.10 m. Thus the results of this test confirm that z_o = 0.15 m is an appropriate choice for this area. More importantly perhaps, these results also indicate that the sensible heat flux estimates are not very sensitive to the choice of z_o.

4. Summary

Measurements of wind speed and of temperature in the atmospheric surface layer under neutral or unstable atmospheric conditions were analyzed to determine surface roughness parameters for harvested wheat fields over level terrain at the US Department of Energy's Cloud and Radiation Testbed (CART) site in north-central Oklahoma. The surface roughness values determined using Eq. (1) were consistent with the results of previous experimental studies such as those listed by Wieringa (1993); because they were obtained with measurements at 10 m, they are roughness values representative for horizontal scales of 100 m up to 1 km at most. Regional surface flux calculations with profile measurements at larger heights require a larger roughness; therefore, a surface roughness value z_o = 0.15 m was found to be reasonable and appropriate. The scalar roughness analysis resulted in a larger value, z_{oh} = 0.0038 m, for the off-nadir surface temperature measurements, than that for the nadir surface temperature measurements, z_{oh} = 0.0021 m. The scalar roughness did not show any dependence on the surface shear stress or on the solar elevation.

An independent analysis with radiosonde data at higher elevations in the ASL, tested the surface parameters over a larger horizontal scale than that of the initial analysis. This analysis showed that momentum fluxes calculated with radiosonde data which in principle are representative of regional (i.e. mesogamma scale) roughness conditions, can differ considerably from the measured surface momentum fluxes which are representative of horizontal scales that are smaller by an order or two in magnitude. In contrast, the regional estimates of sensible heat flux were in excellent agreement with the ground based measurements (r = 0.92). This indicates that the scalar roughness length is more scale independent than the momentum roughness. Overall, the results support the adopted values of the parameters.

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