Directional radiometric temperature profiles within a grass canopy

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Abstract

The scalar roughness for sensible heat flux, \( z_{0h} \), which appears in Monin and Obukhov similarity theory has been shown to exhibit substantial variability. Brutsaert and Sugita (cf. W. Brutsaert and M. Sugita, J. Atmos. Sci. 53 (1996) 209–16) derived an expression for \( z_{0h} \) to account for variability in \( z_{0h} \) as a result anisothermal vegetation skin temperature, which assumes an exponential profile of canopy skin temperature. We examined this assumption through directional radiometric measurements of temperature profiles in a relatively uniform grass canopy. The temperature gradient steepened monotonely throughout the morning and was modeled successfully with an exponential profile. The root-mean-square error (RMSE) between measured and modeled profiles was small and ranged between 0.038°C and 0.530°C. One of the most significant findings of this research is that the decay coefficient, \( b \), of the exponential profile model was approximately constant with time for this canopy. This may provide a useful simplification in applying Brutsaert and Sugita’s (loc. cit.) parameterization for \( z_{0h} \).

Keywords: Radiometric surface temperature; Remote sensing; Scalar roughness; Vegetation; Sensible heat flux

1. Introduction

The exchange of mass and energy between land and atmosphere has significant effects on the hydrology and weather of a region. These fluxes can be modeled with varying degrees of complexity with sets of energy balance and continuity equations commonly referred to as land surface models (LSMs) or surface-vegetation–atmosphere transfer schemes (SVATs).

It is desirable to use directional radiometric surface temperatures, \( \theta_s \), in these models because of the spatial information that they contain. A directional radiometric temperature (DRT), is a radiometric surface temperature measurement made along a specific sensor zenith view angle (i.e., the angle measured with respect to a vertically downward view). It is derived from a radiative energy balance of the surface using a radiance measurement from a single direction with a narrow field of view, and provides the best approximation of the thermodynamic temperature based on a measurement of radiance [14]. However, vegetated surfaces impose difficulties on the modeling process. In general, \( \theta_s \) values for a vegetated surface are not unique due to the complicated structure and the vertical and horizontal distribution of the foliage skin temperatures. A marked vertical distribution of canopy surface temperature results under conditions of strong shortwave radiation and moderately sparse leaf area density.

Complex multilayer canopy models have been developed to accommodate this vertical complexity [13,20,26]. However, these complex models introduce a significant computational burden, and stringent requirements in terms of initialization and updating that are undesirable especially for operational weather models, which cover subcontinental to continental scales.

Other models take a lumped approach and treat the surface as a single “big leaf”. That is, they consider the canopy to be an isothermal entity [15,19]. Many of these models employ a bulk aerodynamic relationship for surface sensible (\( H \)) heat flux. An example is given by Chen et al. [3] as

\[
H = \rho c_p C_i u_a (\theta_{sfc} - \theta) = \rho c_p (\theta_{sfc} - \theta)/r_h, \tag{1}
\]

where \( \rho \) is the air density; \( c_p \) the coefficient of specific heat for air at constant pressure; \( C_i \) the bulk exchange coefficient for heat; \( u_a \) the wind speed; \( \theta_{sfc} \) the bulk surface temperature; \( \theta \) the temperature of the air; and \( r_h \)
is the aerodynamic resistance to heat transfer, \( r_h^1 = C_h u_a \).

\( C_h \) may be formulated directly from similarity theory in terms of atmospheric stability correction functions \( \psi_m \) and \( \psi_b \) for momentum and heat, respectively, and surface roughness lengths. When distinct roughness lengths \( z_{0m} \) and \( z_{0h} \) for momentum and heat are retained, \( C_h \) can be expressed as

\[
C_h = \left\{ \frac{k^2}{R} \right\} \left\{ \ln \left( \frac{z}{z_{0m}} \right) - \psi_m \left( \frac{z}{L} \right) + \psi_m \left( \frac{z_{0m}}{L} \right) \right\} \left\{ \ln \left( \frac{z}{z_{0h}} \right) - \psi_b \left( \frac{z}{L} \right) + \psi_b \left( \frac{z_{0h}}{L} \right) \right\},
\]

where \( z \) is the measurement height for wind speed and air temperature, \( k \) the von Kármán’s constant, \( L \) the Obukhov length, and \( R \), estimated at 1.0, is the ratio of the momentum and heat exchange coefficients in the neutral limit.

The scalar roughness \( z_{0h} \), which appears in (2) is an important quantity. Verhoef et al. [27] notes that all meteorological weather models currently include a parameterization for \( z_{0h} \), usually in the form of \( \ln \left( \frac{z_{0m}}{z_{0h}} \right) \). Furthermore, recent tests of the Pan and Mahrt [15] LSM by Chen et al. [3] show these bulk equations to be highly sensitive to the parameterization of \( z_{0h} \).

Numerous parameterizations of \( z_{0h} \) appear in the literature. Garratt and Francey [6] proposed a constant ratio \( z_{0m}/z_{0h} = e^2 \). Chen et al. [3] employed the formulation of Zilitinkevich [29], \( z_{0m}/z_{0h} = \exp \left\{ kc \sqrt{R_e} \right\} \), in the National Center for Environmental Prediction (NCEP/NOAA)Eta model, which is an operational mesoscale model. Here \( C \) is an empirical constant; and \( R_e \) the roughness Reynolds number which describes turbulence intensity. Using FIFE data, Qualls and Hopson [18] employed \( z_{0m}/z_{0h} = \exp \left\{ b_1 + b_2 (R_e / \text{LAI}) \right\} \), where LAI is leaf area index, the \( b_1 \) and \( b_2 \) were empirically determined constants and \( \Phi \) was a function of daily maximum solar zenith angle. Although the constants were determined empirically, this relationship is mathematically consistent with the expression for \( z_{0h} \) derived by Brutsaert and Sugita [2]. It does not account for diurnal variation of solar elevation nor does it account for sensor view angle effects. Stewart et al. [22] analyzed values of \( z_{0m}/z_{0h} \) obtained from eight different field experiments. Kustas et al. [10] tested a number of empirical expressions including \( z_{0m}/z_{0h} = \exp \left( b u_a (\theta_s - \theta) \right) \) where \( \theta_s \) was a DRT of the surface. Other examples exist (e.g., Qualls and Brutsaert [17]; \( z_{0h} \) is a function of LAI; Sun and Mahrt [25]; \( z_{0h} \) is a function of \( \theta_s - \theta \)/H; Sugita and Brutsaert [23] and Sugita and Kubota [24]; \( z_{0h} \) is a function of solar elevation; Matsushima and Kondo [13]; the aerodynamic conductance, which is related to the bulk transfer coefficient, \( C_h \) and \( z_{0h} \), is taken as a function of LAI, wind speed and atmospheric stability).

Many of these studies show that \( z_{0h} \) is neither constant nor proportional to the momentum roughness length \([3,10,13,17,18,25,27]\). In order to accommodate this variability of \( z_{0h} \), Chen et al. [3] modified the LSM of Pan and Mahrt [15] by parameterizing \( z_{0h} \) as a function of roughness Reynolds number. The revised LSM has been implemented into the NCEP operational mesoscale Eta model.

Although the revised LSM simulated spatially averaged directional radiometric temperatures (DRTs) from FIFE reasonably well, there are instances where the simulated and measured DRTs differed by as much as 2–6°C (see Fig. 5(d), panel C in Chen et al., [3]). When differences occur in the comparisons provided, the model tends to under-predict mid-day DRTs, and over-predict nighttime DRTs. Due to its sensitivity to \( z_{0h} \), when the model is used in a mode in which DRTs serve as input to calculate sensible heat fluxes, these temperature differences would produce significant errors in the modeled sensible heat fluxes. Studies by Qualls and Hopson [18] and Verhoef et al. [27] indicate that parameterization of \( \ln \left( \frac{z_{0m}}{z_{0h}} \right) \) by means of the roughness Reynolds number alone leaves some unexplained variability.

Some of this variability may be explained by vertical skin temperature gradients within the canopy and a distinct ground surface temperature. These cause the value of a DRT measured over a given surface to depend on the sensor view angle [8,12,28].

Fig. 1 illustrates the effect that a vertical foliage temperature gradient has on scalar roughness. Bulk formulations such as (3), shown later, operate under the assumption that the logarithmic air temperature profile \( \theta_s \) extends down into the canopy (see single-dashed line in Fig. 1), as if the atmospheric surface sublayer (SSL) extended all the way to the surface.

![Fig. 1. Air and canopy temperature profiles within the surface sublayer (SSL) and canopy sublayer (CSL).](image)
In reality, the canopy interferes with many of the processes so that we designate the region below the top of the vegetation as the canopy sublayer (CSL). Notably, both the actual temperature profile of the air within the canopy \( (\theta_s(z)) \) and the foliage skin temperature \( (\theta_f(z)) \) are disturbed from the \( \theta_s \) profile, where \( z \) is a non-dimensional depth into the canopy whose value is zero at \( z = h \), and one at \( z = 0 \). As a result, the fluxes at depth \( \zeta \) within the CSL are modulated by the \( (\theta_s(z) - \theta_f(z)) \) difference.

When a DRT of the canopy is used for the surface temperature in the bulk formulation, the assumed “height” \( z_{0h} \) corresponding to this temperature must be the height, where that value of \( \theta_s \) would occur on the extrapolated logarithmic \( \theta_s \) profile. This may be seen by the dash-double-dotted line extending down from \( \theta_s \) to \( \theta_f \) and then across to \( z_{0h} \) in Fig. 1. As noted above, \( \theta_s \) depends on both the skin temperature profile through the canopy and on the view angle of the sensor, hence \( z_{0h} \) must be variable.

Under sparse canopy conditions, the view angle effect may be dominated by a combination of two “sources”: a soil surface temperature and a single canopy temperature. “Dual-source” models have been developed to address these conditions [5,11]. However, with more dense canopies, including some grasslands, vertical skin temperature variations through the canopy itself may have a significant effect [13,20,21,26]. In order to address problems related to these vertical temperature gradients, canopy radiative transfer algorithms are often used. Based on the results of coupled canopy radiative transfer and climate models, Prevot et al. [16] found \( z_{0h} \) to depend on sensor view angle. They concluded that their model produced reasonable results but that field research was needed to verify the model. Furthermore, coupling a canopy radiative transfer algorithm to an LSM introduces a substantial computational burden.

Many experimental data sets include DRTs measured in situ, and from aircraft and satellite platforms. Some even have data for which DRTs were measured over the same point on the ground with sensors oriented at different view angles [28]. However, these data sets require one to infer the nature of the canopy temperature profiles or to generate the profiles by modeling [4]; the profiles cannot be validated by means of these data. This is not to say there have not been studies of the view angle effects on DRT [8,11–13,21,26], however, only a few studies exist, where canopy temperature profiles were measured [9].

Despite studies that have explicitly addressed the effects of view angle on DRT, there is no clear consensus on a method to overcome the problems associated with it. Some recent studies have shown that certain optimal view angles exist which minimize the view angle effects [2,13]. These typically range between 50° and 70° from nadir. However, these optimal angles are of little practical value since surface temperature data from satellite remote sensing images are measured across a range of angles, usually less than 50°.

In order to receive the benefit of spatial continuity which may be achieved through the use of spatially-distributed DRTs, while maintaining computational efficiency of a single canopy layer in an LSM, one must accommodate the anisothermal canopy profile and sensor view angle effects. Recent theoretical advancements in embedding the CSL effects within a bulk transfer equation by Brutsaert and Sugita [2], which have been furthered by Qualls and Hopson [18] and Crago [4], have created the opportunity to account for these effects more rigorously than was previously possible. To aid these developments, experimental studies regarding the representation of the canopy temperature profile are crucial.

The purpose of this paper is to present and model field observations of plant canopy DRT profiles and to show some realistic values of temperature gradients and their corresponding semi-diurnal variability that might be expected. In addition, we will conduct a sensitivity analysis of Brutsaert and Sugita’s [2] analytical expression for scalar roughness \( z_{0h} \), particularly with respect to realistic shapes and magnitudes of vertical skin temperature gradients within a plant canopy.

2. Methods

2.1. The anisothermal scalar roughness length

In practical applications, there are several possible ways to parameterize the heat transfer characteristics of a land surface covered with vegetation. One of the simpler methods is to use the bulk transfer approach given by Monin–Obukhov (M–O) similarity theory [1], which includes the scalar roughness length for sensible heat, \( z_{0h} \), given as

\[
\theta_s - \theta = \frac{H}{z_{0h} k u_* \rho c_p} \ln \left( \frac{z - d_0}{z_{0h}} \right) - \psi \left( \frac{z - d_0}{L} \right),
\]

where \( \theta \) is the potential temperature of the air at some reference height \( z \) within the surface sublayer (SSL); \( \theta_s \), an effective or bulk surface temperature intended here to be supplied by DRT; \( z_{0h}^{-1} \) the turbulent Prandtl number (which is a constant close to unity); \( k \) von Kármán’s constant; \( u_* \) the friction velocity; \( \rho \) the air density; \( c_p \) the coefficient of specific heat at constant pressure; \( d_0 \) the zero plane displacement height; \( L \) the Obukhov length; and \( \psi \) the stability correction function for the temperature profile in the SSL.

Unfortunately, \( z_{0h} \) is neither constant, nor proportional to the momentum roughness length, \( z_{0m} \), as noted earlier. In order to derive an expression for \( z_{0h} \) for anisothermal canopies, Brutsaert and Sugita [2] formulated...
and solved a differential equation for within-canopy scalar transport, and matched it to the M–O similarity flux profile equation for the SSL. The main results of their work were expressions for the isothermal and anisothermal roughness lengths, $z_{0h}$ and $z_{0m}$, respectively,

$$z_{0h} = z_{0hm} \exp \left\{ \frac{z_{0m} k u \rho C_p}{H} \left[ \frac{(r_2 + b C_2)}{r_2 (b^2 + ba - C_2)} + w \right] \right\},$$

(4)

$$z_{0m} = z_{0mm} \exp \left\{ \frac{h}{(h - d_0)} + \ln \left( \frac{h - d_0}{z_{0mm}} \right) \right\},$$

(5)

where $z_{0m}$ is the momentum roughness; $h$ the canopy height; $C_2 = (2 \text{LAI} \cdot C_t h)/(z_{0m}(h - d_0))$; LAI the leaf area index; $C_t$ the bulk transfer coefficient for foliage elements introduced in Brutsaert and Sugita [2]; $r_2 = [(a - (a^2 + 4C_2)^{1/2})]/a$; $a$ the extinction coefficient in the exponential shear stress profile and in the eddy diffusivity profile, which are assumed equal and have values between 2 and 4 for dense flexible elements (wheat, oats, immature corn); $b$ is the temperature profile decay coefficient described below; $H$ the sensible heat flux; and $w$ a temperature-weighting coefficient which relates the view angle dependent DRT to the foliage temperature at the top and bottom of the canopy, as discussed below. Note that $z_{0hi}$ only depends on the bulk canopy characteristics.

In their derivation, Brutsaert and Sugita [2] assume a vertically uniform canopy structure for which the foliage skin temperature in the canopy can be represented with an exponential decay model

$$\theta_i(\zeta) = \theta_{ig} + (\theta_{ih} - \theta_{ig}) e^{-k_\zeta},$$

(6)

where $\theta_i(\zeta)$ is the foliage skin temperature at depth $\zeta$ within the canopy defined as $\zeta = 1 - z/h$ where $z$ is the height above the ground surface, and $h$ is the canopy height. $\zeta$ varies from 0 at the top of the canopy to 1 at the ground. $\theta_{ih}$ is the foliage skin temperature at the top of the canopy and $\theta_{ig}$ is the asymptotic limit of the foliage temperature far below the bottom of the canopy as $\zeta$ becomes large.

2.2. Weighting coefficient, $w$

One of the long-term goals of this work is to develop a method to incorporate DRTs into LSM’s. Several studies have determined “optimal” view angles, which satisfy various criteria for sensible heat flux calculation [2, 4, 8, 13, 28]. One rarely has control over the view angle of the sensor. In fact, from scanning sensors a wide range of zenith view angles are presented in any given surface temperature image. Therefore, the ability to accommodate DRTs measured from arbitrary view angles is important. The relationship between a DRT and a given canopy temperature profile depends on the sensor view angle, and on the density and structure of the vegetation. These factors may be combined through the temperature-weighting coefficient, $w$, which appears in (4) and is discussed below.

Brutsaert and Sugita [2] employ the approximation that DRT can be represented as a linear combination of the foliage skin temperature at the top and bottom of the canopy

$$\theta_s = w \theta_{ih} + (1 - w) \theta_{ig},$$

(7)

where $\theta_s$ is the DRT measured at a known view angle. The weighting coefficient, $w$, depends on canopy density, architecture, and skin temperature profile shape (i.e. the decay coefficient, $b$), as well as on the view angle of the sensor.

Similarly in dual-source models [5, 11], the DRT is taken to be a combination of the soil surface temperature, $\theta_{soil}$, and of the canopy temperature, $\theta_{canopy}$, assumed to be isothermal, weighted by their respective fractions $f_{soil}$ and $1 - f_{soil}$ visible to the sensor,

$$\theta_s = f_{soil} \theta_{soil} + (1 - f_{soil}) \theta_{canopy}.$$

More correctly, the radiance corresponding to these temperatures should be added, but the linearization is a good approximation provided $\theta_{soil}$ and $\theta_{canopy}$ are not too different.

For anisothermal canopies, (8) may be modified by integrating through the canopy,

$$\theta_s = f_{soil} \theta_{soil} + \int_0^1 \left( - \frac{d}{d\zeta} \right) \theta_i(\zeta) d\zeta,$$

(9)

where $f$ is the fraction of the viewer field not yet obscured by foliage at the depth $\zeta$ into the canopy; $\theta_i(\zeta)$ the foliage skin temperature given by (6).

For a vertically uniform canopy, the fraction $f$ may be given by Beer’s law,

$$f(\zeta) = \exp \left\{ - g' \text{LAI} \zeta \cos \nu \right\},$$

(10)

where $g'$ is the leaf angle distribution parameter; LAI the leaf area index; $\nu$ the sensor zenith view angle. Friedl [5] estimated $g'$ using $g' = \cos(\phi_i)$, where $\phi_i$ is the mean leaf inclination angle measured from a horizontal plane. For grasslands and grass-like crops such as wheat, $\phi_i$ will be taken as 65°. Values of $\phi_i$ for these and other types of vegetation may be obtained from Gates [7]. The fraction $f_{soil}$, which appears in (9) may be obtained by setting $\zeta$ equal to 1 in (10).

For canopies whose foliage density is non-uniform in the vertical direction, LAI* $\zeta$ may be replaced by $\int_0^1 a(\zeta) d\zeta$, where $a(\zeta)$ is a function which describes the vertical distribution of canopy density as in Matsushima and Kondo [13].

Crago [4] obtained an expression for the weighting coefficient $w$ in (7). He did so by integrating (9) with
hand sides of (14), equal to zero, we can solve explicitly for $b$
\[
b = -\frac{\sum \zeta_i Y_i}{\sum \zeta_i^2}.
\]

Eq. (15) may be substituted into (13) to eliminate $b$. The resulting equation is an implicit equation for $\theta_{fg}$ since $b$ in (15) is a function of $\theta_{fg}$ through $Y_i$.
\[
\theta_{fg} = g(\theta_{fg}).
\]

Next, we defined a function $h(\theta_{fg}) = \theta_{fg} - g(\theta_{fg}) = 0$ and found the values of $\theta_{fg}$, which caused $h(\theta_{fg})$ to be zero. The exponent $b$ is then calculated with (15). These values of $\theta_{fg}$ and $b$ are those which minimize the sum of squared differences between measured and modeled temperatures for each profile.

In addition, we imposed the constraints: (1) $b > 0$; and (2) $\theta_{fg}(t_i) > \theta_{fg}(t_j)$ when $\theta_{fh}(t_i) > \theta_{fh}(t_j)$, where $t_i$ and $t_j$ are the times of two different profiles. The first of these constraints is required in order for $\theta(\zeta)$ to approach $\theta_{fg}$ as $\zeta$ becomes large. The second constraint was imposed on the basis of observations, which showed that profiles tended not to overlap and that successive profiles increase in curvature and steepness as temperature increases when averaged over a suitable time period on clear days.

In the following sections, we describe the data set used, and present results of field observations of directional radiometric canopy temperature profiles from which we obtain values for $\theta_{fg}$, $\theta_{fh}$, and $b$, and a sensitivity analysis.

3. Data set

The data used here came from an experiment carried out from June 19 to July 9, 1997 in a hay field north of Boulder, Colorado, located at latitude 40° 6′ 52.8″ N and longitude 105° 15′ 51.6″ W. During this experiment, DRT measurements of canopy temperature profiles were collected. The data used here were from the completely cloudless morning of July 1. The grass was characterized by a dense lower story 46 cm tall with sparse individual stocks extending up to 87 cm. The 15° field of view infrared thermometer was oriented horizontally, facing west, and moved manually up and down through the grass. Each profile consisted of measurements at 12 evenly spaced heights from 7 up to 84 cm. One measurement was collected each second, 5 at each height before moving the sensor to the next height, so that a complete profile was measured in 1 min. The measurements at each height during each minute were averaged together to represent the DRT at that height. Data were collected continuously from 6:18 to 11:30 a.m. mountain daylight savings time (MDST) with the exception of a 4-min and 20-min break in the data.
starting at 7:00 and 9:10 a.m., respectively. From these measurements, more than 18,500 values were consolidated into 30-min averages to which we refer in the text using the ending time of the 30-min (e.g., we refer to the average from 7 to 7:30 a.m. as “profile 7.5”). A few of the time periods were shorter than 30 min (6:18–6:30; 7:04–7:30; 9:00–9:10; and 11:30–11:50). We still refer to these by the ending time of the half-hour period. Table 1 contains the values of these 30-min profiles as a function of time and height above the ground.

4. Results and discussion

4.1. General observations

The 30-min averaged DRT profiles appear in Fig. 2. Several important features show up here. First, the profiles begin nearly isothermal at 6:30 a.m., and the mean profile temperature increases and the temperature gradient steepens as the morning progresses. Second, the sparse upper canopy remains nearly isothermal throughout the morning, and most of the gradient is concentrated in the dense lower canopy.

Since \( z_{th} \) given by (4) depends on the difference in temperatures between the bottom and top of the canopy, \( (\theta_{b} - \theta_{th}) \), we have plotted \( (\theta_{f}(7\text{ cm}) - \theta_{b}) \) from each 1-min profile as a function of time in Fig. 3, to get an idea of how \( (\theta_{f} - \theta_{b}) \) might behave. \( \theta_{th} \) is the average of all DRTs measured at and above \( z = 42 \text{ cm} \), and \( \theta_{f}(7\text{ cm}) \) is the temperature measured closest to the ground, at \( z = 7 \text{ cm} \). Hereafter, \( \theta_{f}(7\text{ cm}) \) will be denoted \( \theta_{f7} \). The vertically averaged temperature, \( \theta_{th} \), was used to represent the top of canopy temperature because the upper canopy was relatively sparse, approximately isothermal, and if the profiles exhibit an exponential shape, this occurs in the lower part of the canopy at and below 42 cm, as is clear in Fig. 2.

<table>
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<td>14</td>
<td>10.9</td>
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</table>

Fig. 2. A 30-min averaged DRT profiles. Numbers indicate range of times (HHMM) included in each profile.

Fig. 3. Evolution of bottom to top canopy temperature differences, \( \theta_{f7} - \theta_{th} \), for each one-minute profile, and for 30-min averages with time. Also shown is the evolution of solar zenith angle for comparison with temperature changes.
The solid line in Fig. 3 connects the values of \((\theta_l - \theta_h)\) taken from the 30-min averaged data. In addition, since we are interested in the diurnal progression of \((\theta_l - \theta_h)\) and its causes, we have plotted the solar zenith angle (dashed line) versus time in Fig. 3. This illustrates qualitatively, that as the sun rises higher in the sky (decreasing zenith angle), it penetrates more deeply into the canopy and causes significant warming of the lower canopy. The upper canopy remains cooler due to exposure to the wind.

The mean difference \((\theta_l - \theta_h)\) is zero at around 7:30 a.m. It then increases relatively steadily throughout the morning to a mean difference of about 10°C (±2°C) by 11:30 a.m. Solar noon occurs at this location at approximately 12:58 MDST. If \((\theta_l - \theta_h)\) continued to increase at the same rate shown in Fig. 3, one might expect \((\theta_l - \theta_h)\) to increase by another 3°C to a value of 13°C by solar noon at which time the solar zenith angle would be approximately 17°. This increase in \((\theta_l - \theta_h)\) would correspond to a decrease in \(z_h\) throughout the morning according to (4), other factors remaining the same.

4.2. Fitted profiles

The derivation of (4) in Brutsaert and Sugita [2] assumes an exponential temperature profile. To evaluate the realism of this assumption, we fitted exponential curves described by (6) to the 30-min average DRT profiles, using the least squares procedure described earlier. We used the average of the temperatures at and above 42 cm for \(\theta_h\) for the reasons explained above.

\(\theta_l\) and \(b\) converged to solutions which satisfied \(h(\theta_l) = 0\) and the imposed constraints for five of the profiles (#8, 10.5, 11, 11.5, and 12). The other cases failed for the following reasons:

1. Profiles 7.5, 8.5, and 9.5 violated constraint 2. Due to the small range in \(\theta_l\), curvature in the profile is obscured by the scatter in the data. The optimization procedure tends toward a straight line for \(\theta_l\) over the applicable range of \(\zeta\). This requires \(h = 0\) and \(\theta_l = \infty\), which caused a divide by zero error in (13).

2. Profiles 9 and 10 violated constraint 2. As in (1) above, the curvature is slight. The optimization procedure found a solution but \(\theta_l\) was larger than that for later profiles.

3. Profiles 6.5 and 7 reveal internal minima within their profiles so that the least squares solution becomes a vertical line through the average value of the lower five temperatures. This forces \(b\) to become excessively large in order for \(\theta(0)\) to equal \(\theta_h\).

In order to fit an exponential profile to those profiles which failed to converge and/or satisfy the constraints, we examined the temporal trend in \((\theta_l - \theta_h)\) for the five profiles for which the solution converged and satisfied the constraints, and compared the trend to that for \((\theta_l - \theta_h)\). We illustrate the comparison in Fig. 4. Considering the solid squares and their corresponding diamonds, it appears that \((\theta_l - \theta_h)\) is roughly proportional to \((\theta_l - \theta_h)\). This is physically realistic since (1) both \((\theta_l - \theta_h)\) and \((\theta_l - \theta_h)\) should become 0 simultaneously when the profile is isothermal, and (2) each successive profile appears to envelop the previous profiles and increase in steepness and curvature in Fig. 2.

The average value of the ratio of \((\theta_l - \theta_h)/(\theta_l - \theta_h)\) was \(\sim 1.46\). We determined \((\theta_l - \theta_h)\) for other profiles by multiplying their corresponding \((\theta_l - \theta_h)\) value by this ratio. The results are shown by the hollow square symbols in Fig. 4.

For each profile, we used these values of \((\theta_l - \theta_h)\) to determine \(\theta_l\), and then determined \(b\) by means of (15). Doing so gives the value of \(b\) that minimizes the sum of squared errors associated with the linearized temperature profile equation (14) for the specified value of \(\theta_l\). For each time period, Table 2 presents the values of \(\theta_l\), \(b\), \(\theta_l\), and the root-mean-square error (RMSE) between measured and modeled temperature profiles.

The measured (symbols) and modeled (lines) profiles determined from (6) using the data in Table 2 are shown in Fig. 5. The resulting values of \(b\) are all very similar and range between about 1.1 and 1.4 with an average value of 1.26, as shown in Fig. 6. The relatively constant nature of \(b\) is one of the important finding of this paper.

It is important to note that the RMSE did not increase substantially for those profiles for which \(\theta_l\) and \(b\) were estimated based on the ration method. In fact, the RMSE was relatively insensitive to \(\theta_l\). We illustrate this in Fig. 7. The solid line in panel (a) shows the RMSE as a function of \(\theta_l\) for profile 10. In decreasing the global optimum value of \(\theta_l = 66^\circ\)C by 26–40°C, RMSE only increases from about 0.11–14°C. Thereafter, the slope of RMSE increases, but in going to \(\theta_l = 30.0^\circ\)C (the value
obtained by the ratio method), RMSE only increases to 0.34°C. Although this is larger than the minimum value by a factor of 3, it still represents only 3.75% of the difference ($\theta_g - \theta_b$), which is certainly an acceptable error. The significance of this is that determination of $\theta_g$ by the ratio method did not substantially increase the error in modeling the measured profile.

In contrast, the profiles 8, 10.5, 11, 11.5, and 12, which satisfied the constraints in our original optimization run, exhibited much more significant changes in RMSE for small changes in $h_{fg}$. The solid line in panel b of Fig. 7 shows that an increase in RMSE for profile 12 from the global minimum to a value of 0.3°C only allows a range in $h_{fg}$ from about 35.5°C to 44°C. This is much smaller than the range 30°C to $+\infty$ allowed for profile 10 for the same change in RMSE, and indicates that the certainty in the value of $\theta_g$ for profiles 8, 10.5, 11, 11.5, and 12, which satisfied the constraints in the original optimization run is much higher than for the other profiles.

### 4.3. Sensitivity analysis

To demonstrate the behavior of $z_{th}$, we plotted, on a logarithmic scale in Figs. 8(a–d), the ratio $z_{th}/z_{0th}$ determined from (4) and (5) as a function of several variables. Values of the variables for the base scenario and their ranges are given in columns 2 and 3 of Table 3.

### Table 2

<table>
<thead>
<tr>
<th>Time (h)</th>
<th>$\theta_g$ (°C)</th>
<th>$b$</th>
<th>$\theta_g - \theta_b$ (°C)</th>
<th>RMSE (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.5</td>
<td>9.98</td>
<td>1.07</td>
<td>-1.61</td>
<td>0.530</td>
</tr>
<tr>
<td>7</td>
<td>11.9</td>
<td>1.18</td>
<td>-1.87</td>
<td>0.455</td>
</tr>
<tr>
<td>7.5</td>
<td>16.1</td>
<td>1.18</td>
<td>-1.04</td>
<td>0.163</td>
</tr>
<tr>
<td>8</td>
<td>19.7</td>
<td>1.44</td>
<td>1.63</td>
<td>0.137</td>
</tr>
<tr>
<td>8.5</td>
<td>22.5</td>
<td>1.19</td>
<td>3.74</td>
<td>0.255</td>
</tr>
<tr>
<td>9</td>
<td>24.2</td>
<td>1.29</td>
<td>4.48</td>
<td>0.208</td>
</tr>
<tr>
<td>9.5</td>
<td>25.6</td>
<td>1.24</td>
<td>5.39</td>
<td>0.322</td>
</tr>
<tr>
<td>10</td>
<td>30.0</td>
<td>1.29</td>
<td>8.03</td>
<td>0.339</td>
</tr>
<tr>
<td>10.5</td>
<td>32.9</td>
<td>1.16</td>
<td>10.7</td>
<td>0.050</td>
</tr>
<tr>
<td>11</td>
<td>34.3</td>
<td>1.31</td>
<td>11.4</td>
<td>0.099</td>
</tr>
<tr>
<td>11.5</td>
<td>36.3</td>
<td>1.39</td>
<td>13.2</td>
<td>0.038</td>
</tr>
<tr>
<td>12</td>
<td>38.3</td>
<td>1.46</td>
<td>14.4</td>
<td>0.099</td>
</tr>
</tbody>
</table>

Fig. 5. Measured (symbols) and modeled (lines) temperature profiles for lower half of the canopy, where the exponential profile appears to exist.

Fig. 6. Illustration of approximate constancy of the coefficient, $b$, in the exponential profile model (6).

Fig. 7. Value of root mean square error (RMSE) as a function of $\theta_g$. The dashed line represents the locally optimum value of $b$ corresponding to $\theta_g$. The RMSE for any pair of $\theta_g$, $b$ values is given by the value of the RMSE line directly above the pair. Panel (a) corresponds to profile 10; panel (b) corresponds to profile 12.
Panel (a) of Fig. 8 shows that \( z_{0h} \) decreases linearly on a logarithmic scale as a function of increasing temperature difference \( \theta_{tg} - \theta_{th} \). This is also clear based on simple inspection of (4). Panel (a) also shows the effects of increasing LAI, which are not as readily apparent from (4). An eightfold increase in LAI from 0.5 to 4 causes an increase in \( z_{0h} \) from about 0.024 to 0.31 for the base scenario. The incremental increase in \( z_{0h} \) decreases for each additional unit increase in LAI (e.g., there is a bigger change in going from LAI \( \hat{1} \) to 2, than from 2 to 3, etc.).

Although \( z_{0h} \) is non-linearly related to \( u_* \), due to the presence of \( u_* \) in the numerator and in \( C_z \), the direct influence of \( u_* \) in the numerator dominates, so that \( z_{0h} \) is essentially linearly related to \( u_* \) on a logarithmic scale. \( z_{0h} \) decreases from about 0.66 to about 0.02 for a change in \( u_* \) from 0.1 to 1 m/s for the base scenario (not shown).

The ratio \( z_{0h} \) is not very sensitive to \( b \). Panel (b) shows that a change in \( b \) from 0.5 to 1.5 produces a negligible change even for \( \theta_{tg} - \theta_{th} = 15^\circ C \). This is significant given the narrow range of \( b \) observed for this data set. Furthermore, even a large change in \( b \) from 1.5 to 7 only increases \( z_{0h} \) from around 0.26 to 0.4 for the base scenario. Crago [4] demonstrates that the weighting coefficient, \( w \), is very sensitive to \( b \), however, apparently this sensitivity does not propagate its way through to \( z_{0h} \). Panel (c) shows that \( z_{0h} \) becomes more sensitive to \( b \) as LAI decreases.

Finally, the effect of zenith view angle for a sensor located above the canopy is shown in panel (d). View angle affects \( z_{0h} \) by means of changes in the weighting coefficient, \( w \) given by (11), which relates DRT to \( \theta_{tg} \) and \( \theta_{th} \) through (6). Note here that, unlike LAI, a unit increase in view angle creates successively larger increases in \( z_{0h} \) as view angle increases. For the base scenario, a view angle of 71.39° causes \( z_{0h} \) to equal 1 for all values of \( \theta_{tg} - \theta_{th} \). Others have commented on the fact that various models and observations suggest that a large view angle causes \( z_{0h} \) to

### Table 3

Values of variables used for base scenario of sensitivity analysis and ranges of values allowed to vary in Figs. 8(a–d)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Base scenario</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \theta_{tg} - \theta_{th} )</td>
<td>5°C</td>
<td>0–15°C</td>
</tr>
<tr>
<td>( B )</td>
<td>1</td>
<td>0.5–7</td>
</tr>
<tr>
<td>LAI</td>
<td>3</td>
<td>0.5–4</td>
</tr>
<tr>
<td>( u_* )</td>
<td>0.4 m s(^{-1})</td>
<td>...</td>
</tr>
<tr>
<td>( v )</td>
<td>20°</td>
<td>0–70°</td>
</tr>
<tr>
<td>( H )</td>
<td>0.42 m</td>
<td>...</td>
</tr>
<tr>
<td>( A )</td>
<td>3</td>
<td>...</td>
</tr>
<tr>
<td>( z_{0h} )</td>
<td>h/8</td>
<td>...</td>
</tr>
<tr>
<td>( d_h )</td>
<td>2/3h</td>
<td>...</td>
</tr>
<tr>
<td>( C_t )</td>
<td>0.0715</td>
<td>...</td>
</tr>
<tr>
<td>( H )</td>
<td>150 W m(^{-2})</td>
<td>...</td>
</tr>
</tbody>
</table>

\[ C_z \left[ = f(C_t(Re_{\theta}(u_*))) \right] \]
behave as though the canopy were isothermal [2,4,8,13,28].

5. Summary and conclusions: significance to modeling $z_{0h}$

To summarize these results, it is useful to review some of the background on the scalar roughness, $z_{0h}$. First, a parameterization for $z_{0h}$ appears in all meteorological weather models [27], therefore improvements to it will have broad impacts. Secondly, many parameterizations for $z_{0h}$ have been proposed. Research indicates that $z_{0h}$ is neither constant nor is it proportional to the momentum roughness, $z_{0m}$. Furthermore, the roughness Reynolds number does not explain all of its diurnal variability.

Some of the diurnal variability may be due to vertical skin temperature gradients that form within vegetation as the sun rises higher in the sky and penetrates more deeply into the canopy. Brutsaert and Sugita [2] derived an expression to account for the influence of temperature gradients on $z_{0h}$. Their derivation assumed an exponential profile shape for the temperature gradients given by (6). This assumption limits the applicability of their method to canopies with a relatively uniform vertical structure. In this paper, we present data to evaluate this assumption and examine the semi-diurnal behavior of several variables, $b$, $\theta_{fg}$, and $\theta_{fh}$ which are important parameters in the exponential temperature profile (6). The specific conclusions from this work are listed below:

1. The exponential decay coefficient, $b$, may be approximately constant for a given canopy at a given growth stage, although it is likely to be a function of LAI (Fig. 6). This, together with the fact that $z_{0h}$ does not appear to be extremely sensitive to $b$ (Fig. 8(b)), suggests that for a given canopy, $b$ may not have a significant influence on $z_{0h}$. Furthermore, $b$ may be able to be estimated for a given canopy on the basis of a few profile measurements when solar zenith angle is small so that the curvature and range of $\theta(\zeta)$ in the profile is large.

2. $(\theta_{fg} - \theta_{fh})$ appears to increase in a consistent fashion on clear days as solar zenith angle decreases (Figs. 3 and 4). This behavior and the finding that $b$ is relatively constant may provide useful constraints for estimating $(\theta_{fg} - \theta_{fh})$ and $b$ from time series of DRTs measured from multiple view angles.

3. If we extrapolate the rate of increase in $(\theta_{fg} - \theta_{fh})$ to solar noon (∼1 p.m. MDST), it would attain a value of ∼20°C. Thus for this canopy/location/time of year, a rough estimate for the diurnal range of $(\theta_{fg} - \theta_{fh})$ is 0–20°C.

Although these conclusions do not provide enough information to apply Brutsaert and Sugita’s [2] parameterization for $z_{0h}$ operationally, they do provide some simplifications that will be helpful to evaluate the diurnal variability of $z_{0h}$.

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