Significant Decrease of Uncertainties in Sensible Heat Flux Simulation Using Temporally Variable Aerodynamic Roughness in Two Typical Forest Ecosystems of China

YANLIAN ZHOU
School of Geographic and Oceanographic Sciences, Nanjing University, Nanjing, China

WEIMIN JU
International Institute for Earth System Science, Nanjing University, Nanjing, China

XIAOMIN SUN AND XUEFA WEN
Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Science, Beijing, China

DEXIN GUAN
Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang, China

(Manuscript received 24 November 2011, in final form 21 January 2012)

ABSTRACT

Aerodynamic roughness length $z_{om}$ is an important parameter for reliably simulating surface fluxes. It varies with wind speed, atmospheric stratification, terrain, and other factors. However, it is usually considered a constant. It is known that uncertainties in $z_{om}$ result in latent heat flux (LE) simulation errors, since $z_{om}$ links LE with aerodynamic resistance. The effects of $z_{om}$ on sensible heat flux (SH) simulation are usually neglected because there is no direct link between the two. By comparing SH simulations with three types of $z_{om}$ inputs, it is found that allowing $z_{om}$ temporal variation in an SH simulation model significantly improves agreement between simulated and measured SH and also decreases the sensitivity of the SH model to the heat transfer coefficient $C_t$, which in turn determines the linkage between $z_{om}$ and thermal roughness length $z_{th}$.

1. Introduction

The estimation of atmospheric turbulent fluxes at the surface has long been recognized as most important to the determination of the exchanges of energy and mass among hydrosphere, atmosphere, and biosphere (Su 2002). The mass and energy exchanges at the surface–atmosphere interface are the most critical components in the climate system (Hurtalová and Matejka 1999). Sensible heat flux (SH) and latent heat flux (LE) are two key components. For models of surface–atmosphere exchange (including momentum, and sensible and latent heat fluxes), such as the soil–vegetation–atmosphere transfer (SVAT) model, and for moderate-scale numerical simulation and global climate change modeling, aerodynamic roughness $z_{om}$ is an important parameter (Borak et al. 2005). The parameter of roughness length has become a simple and useful tool that is widely used in such models.

The term $z_{om}$ is the height above the surface at which the mean logarithmic wind profile reaches zero (Monteith and Unsworth 1989). Many empirical relations for calculating $z_{om}$ have been developed recently for different vegetation types (Riou et al. 1987; Driese and Reiners 1997; Van Dijk et al. 2004). Some researchers have parameterized $z_{om}$ as a function of canopy height $h$, frontal area index, or leaf area index (LAI) (Schraud and Dickinson...

Corresponding author address: Weimin Ju, International Institute for Earth System Science, Nanjing University, 22 Hankou Road, Nanjing, Jiangsu Province, China.
E-mail: juweimin@nju.edu.cn

DOI: 10.1175/JAMC-D-11-0243.1

© 2012 American Meteorological Society
2000; Nakai et al. 2008). In fact, \( z_{\text{om}} \) has temporal variations (Zhang et al. 2004; Borak et al. 2005; Patil 2006; Zhou et al. 2006). However, the temporal variation and importance of \( z_{\text{om}} \) has always been neglected, and empirical estimates of \( z_{\text{om}} \) are still used in many models. For example, \( z_{\text{om}} \) is considered 0.136\( h \) in the Surface Energy Balance System (SEBS) model (Su et al. 2001; Su 2002). Langensiepen et al. (2009) calculated transpiration using the Penman–Monteith equation, with \( z_{\text{om}} \) set to 0.136. Sánchez et al. (2009) fixed \( z_{\text{om}} \) as 0.1\( h \) to calculate energy fluxes.

Much attention has been paid to the effects of \( z_{\text{om}} \) on LE, since \( z_{\text{om}} \) is related directly with aerodynamic resistance. However, the effects of \( z_{\text{om}} \) on SH are usually neglected. The assumption of a constant \( z_{\text{om}} \) within SH simulation ignores the inherent temporal and spatial variability of land cover and accompanying effects on momentum transfer (Borak et al. 2005), and will increase uncertainties in simulated SH. For example, Kustas et al. (1989) did a sensitivity analysis of the effect of \( z_{\text{om}} \) on sensible heat flux simulation, and he indicated an approximate 10% error for a \( z_{\text{om}} \) increase from 0.01 to 0.1 m. Pitman (1994) reported a 15% uncertainty resulting from an error of 30% in \( z_{\text{om}} \). Nevertheless, there is still little research on the determination of \( z_{\text{om}} \) in SH simulation. Therefore, reduction of the effects of \( z_{\text{om}} \) on SH simulation awaits further study.

In SH models, thermal roughness \( z_{\text{oh}} \) is an important parameter. However, it is difficult to measure accurately. Practically, \( z_{\text{oh}} \) is determined according to aerodynamic roughness length \( z_{\text{om}} \), because \( z_{\text{om}} \) may be derived from wind speed and temperature profiles, or from lookup tables. The parameter for determining \( z_{\text{oh}} \) is \( kB^{-1} \) \([kB^{-1} = \ln(z_{\text{om}}/z_{\text{oh}}); \text{Brutsaert 1982}] \), which links \( z_{\text{om}} \) with \( z_{\text{oh}} \) and affects the agreement between simulated and measured SH.

The term \( kB^{-1} \) can be calculated using theoretical or empirical models (Troutlleau et al. 1997; Verhoef et al. 1997; Massman 1999) and it varies over a wide range. Kustas et al. (1989) observed \( kB^{-1} \) values from 1.0 to 10.0 over several natural sparse vegetation types in California. Stewart et al. (1994) reported mean values of \( kB^{-1} \) from about 4.0 to 12.0, with some instantaneous values between 0 and 20.0, at eight different semiarid sites. For dense and homogeneous crops, \( kB^{-1} \) can be approximated as a constant around 2.0 (Thom et al. 1975; Garratt 1978; Kalma and Jupp 1990).

SEBS is a commonly used model for simulating SH and LE based on the principle of energy balance (Su et al. 2001; Su 2002; Jia et al. 2009; Van der Kwast et al. 2009). In the SEBS model, \( kB^{-1} \) is calculated by Eq. (13) discussed below. In the equation, there are several parameters that need to be determined, while the heat transfer coefficient \( C_t \) has large uncertainties and was difficult to be determined precisely. Therefore, proper determination of \( C_t \) is critical for reliable \( kB^{-1} \) and SH simulation. However, there is no practical or easy method to accurately measure or determine this parameter, and it varies over a very wide range. Therefore, the sensitivity of simulated SH to \( C_t \) has been used as a criterion for evaluating the influence of different \( z_{\text{om}} \) parameterization algorithms on SH simulation.

Both Changbai Mountain (CBS) and Qianyanzhou (QYZ) experimental stations are located in the north–south transect of eastern China (NSTEC). Along the NSTEC, there are apparent latitudinal gradients of temperature and precipitation, indicating the influence of the eastern Asian monsoon. Studies along the NSTEC contribute greatly to global change research. Furthermore, both CBS and QYZ are typical ecosystems representing temperate mixed forest and subtropical coniferous plantation, respectively. Therefore, CBS and QYZ were chosen for this study.

Since several works have shown the temporal variations in \( z_{\text{om}} \), its actual value should be input to flux models for accurate SH simulation. A deep understanding of sensible flux simulation will be helpful for improving the simulations of carbon, water, and energy fluxes in forest ecosystems of China. In this study, we find that, in comparison with commonly used \( z_{\text{om}} \) values, a calculated \( z_{\text{om}} \) with greater accuracy significantly reduces uncertainty in the SH simulation and also lessens the sensitivity of SH simulation to the \( C_t \) parameter.

2. Data and methods

a. Experimental area description

Both CBS and QYZ belong to the Chinese Terrestrial Ecosystem Flux Observational Research Network (ChinaFLUX) (Sun et al. 2006; Yu et al. 2006; Wen et al. 2010). CBS (41°24’09”N, 128°05’45”E) is located in the southeast of Jilin Province, China. The elevation at the tower site is 761 m. The topography is predominately flat, with slopes less than 4%. The vegetation is a mature, natural, temperate, broad-leaved Korean pine forest of the Changbai Mountains, with the dominant species being Pinus koraiensis, Tilia amurensis, Quercus mongolica, Fraxinus mandshurica, and Acer mono. The mean canopy height is about 26 m. The LAI varies from 2 in the winter to 6 in the summer (Guan et al. 2005; Zhang et al. 2006). QYZ (26°44’52”N, 115°03’47”E) is located in a hilly field of southwestern Jiangxi Province, China. The elevation at the flux tower site is 102 m above sea level. The topography surrounding the tower is heterogeneous and the relative elevation range is 20–50 m. The
vegetation is a planted forest composed mainly of Pinus massoniana, Pinus elliottii, and Cunninghamia lanceolata. Here \( h \) is about 12 m. The maximum LAI is 3.6, with small annual and seasonal variations (Liu et al. 2005, 2006).

b. Data used

Measurements taken from 1 January 2003 to 31 December 2003 at CBS and from 1 January 2004 to 31 December 2004 at QYZ experimental stations were used in this study. At both CBS and QYZ, a seven-level routine meteorological profile system and fluxes measurement system were mounted on the tower at 30-min intervals. Fluxes were measured with eddy covariance (EC), which is a micrometeorological technique that allows a noninvasive measurement of the exchange of CO\(_2\) between the atmosphere and a several hectare area of forest, shrubland, or grassland (Baldocchi et al. 1988; Sun et al. 2006; Wen et al. 2006). The SH was measured with the EC system (CSAT-3; Campbell Scientific, Inc.) and recorded by a datalogger (CR5000; Campbell Scientific) at 30-min intervals.

Routine meteorological quantities were also measured simultaneously and continuously along with the EC fluxes. Within and above the forest, air temperature, and relative humidity (HMP45C; Vaisala, Inc.), wind speed (A100R; Vector, Inc.), wind direction (W200P; Vector), atmospheric pressure (CS105; Vaisala), photosynthetically active radiation (Li-Cor, Inc.), and solar and longwave radiation (CM11; Kipp and Zonen, Inc.) were measured simultaneously. At CBS, the measurements were taken at 8.0, 22.0, 26.0, 32.0, 49.8, and 61.8 m above the ground, respectively, while at QYZ, the heights of measurements were 1.6, 7.6, 11.6, 15.6, 23.6, 31.6, and 39.6 m above the ground. Half-hourly measurements of meteorological variables at the uppermost four levels were used to calculate \( z_{om} \). If wind speed in the uppermost layer was lower than 1 m s\(^{-1}\), the data were excluded from further analysis.

The LAI was derived from photosynthetically active radiation measured above and below the canopy (Baldocchi 1994; Soegaarda and Thorgeirssonb 1998). There were some data gaps because instruments were out of operation, and the gaps were interpolated (Falge et al. 2001; Li et al. 2008). At both stations, all meteorological instruments were installed in appropriate directions to avoid the effect of the tower’s presence. The measurements of wind speed and direction show that there were no obvious diurnal and seasonal tendencies in wind directions at both QYZ and CBS. Measured half-hourly SH flux was used to validate model results. The measurements of SH were processed, gap filled, and quality controlled. More extensive description of the data process can also be found in Wen et al. (2006).

c. The \( z_{om} \) calculation method

There are four typical methods for calculating \( z_{om} \) from meteorological measurements at several levels above ground, and/or from a three-dimensional sonic anemometer at a single level (Berkowicz and Prahm 1982; Dolman 1986; Zhang and Chen 1997; Martano 2000; Takagi et al. 2003). They are 1) the iterative method by least squares fit (Takagi et al. 2003), 2) the Newton iterative method (Dolman 1986), 3) the temperature variance method (TVM) (Rotach 1994; Zhang and Chen 1997), and 4) a method proposed by Martano (Martano 2000; Gao et al. 2002). The traditional least squares method was used to calculate \( z_{om} \) using wind speed and temperature profiles, since a previous study proved the superiority of this method for calculating \( z_{om} \) under all atmospheric stratifications at these two sites (Takagi et al. 2003; Zhou et al. 2007).

1) LEAST SQUARES METHOD FOR CALCULATING \( z_{om} \) AND \( u_* \)

Wind speed and temperatures measured at four heights can be expressed as

\[
\begin{align*}
  u &= \frac{u_*}{k} \left[ \ln \left( \frac{z - d}{z_{om}} \right) - \frac{\psi_m}{C_20} \left( \frac{z - d}{L} \right) \right] \quad \text{and} \quad (1) \\
  \theta &= \frac{\theta_0}{k} \left[ \ln \left( \frac{z - d}{z_{om}} \right) - \frac{\psi_h}{C_19} \left( \frac{z - d}{L} \right) \right] + \theta_0, \quad (2)
\end{align*}
\]

where \( u \) is the wind speed, \( u_* \) is the friction velocity, \( k \) is the von Kármán constant (equal to 0.4), \( z \) is the height at which the wind speed and temperature are measured, \( \theta \) is the potential air temperature of each layer, \( \theta_* \) is friction temperature, \( z_{om} \) is the thermal roughness length, and \( \theta_0 \) is the potential temperature near the surface. The \( L \) is the Obukhov length, which is calculated as

\[
L = \frac{u_*^2 \theta}{\theta_* k g}, \quad (3)
\]

where \( g \) is the acceleration due to gravity and equals 9.8 m s\(^{-2}\). The \( \theta \) is calculated as

\[
\theta = \frac{T \left( \frac{p_0}{p} \right)^{0.286}}, \quad (4)
\]

where \( T \) is the mean air temperature, \( p \) is the ambient air pressure, and \( p_0 \) is 101 kPa.

In Eqs. (1) and (2), \( \psi_m \left[ (z - d)/L \right] \) and \( \psi_h \left[ (z - d)/L \right] \) are the stability correction factors for momentum and sensible heat transfers and they are determined according to atmospheric stratification (Panofsky 1963; Paulson 1970).
Equations (1) and (2) can be rearranged as
\[
 u = \frac{u_a}{k} \left[ \ln(z - d) - \frac{\psi_m(z - d)}{L} \right] - \frac{u_a}{k} \ln z_{om} \quad \text{and} \quad (5)
\]
\[
 \theta = \frac{\theta_a}{k} \left[ \ln(z - d) - \frac{\psi_h(z - d)}{L} \right] - \left( \frac{\theta_a}{k} \ln z_{oh} - \theta_0 \right). \quad (6)
\]
Equations (5) and (6) can be expressed using a linear regression formula:
\[
y = ax + b. \quad (7)
\]
For Eq. (5), \( y = u, \ x = \ln(z - d) - \psi_m[(z - d)/L], \ a = u_a/k, \) and \( b = -a \ln z_{om}. \) For Eq. (6), \( y = \theta, \ x = \ln(z - d) - \psi_h(z - d)/L, \ a = \theta_a/k, \) and \( b = -a \ln z_{oh} + \theta_0. \)

If \( d \) and \( L \) are known, \( z_{om}, u_a, z_{oh}, \) and \( \theta_a \) can be determined by fitting the temperature and wind speed measured at different levels into Eq. (7). However, \( u_a \) and \( \theta_a \) are required to calculate \( L. \) Therefore, \( z_{om}, u_a, z_{oh}, \) and \( \theta_a \) are iteratively determined for a given \( d \) value as follows:

(i) For given initial values of \( u_a \) and \( \theta_a, L \) is calculated using Eq. (3);
(ii) \( z_{om}, u_a, z_{oh}, \) and \( \theta_a \) are determined using Eq. (7);
(iii) \( L \) is calculated with Eq. (3) using the values of \( u_a \) and \( \theta_a \) determined in step ii.

Steps ii and iii are repeated until the difference in \( L \) in two adjacent loops is less than 0.01.

The \( u_a \) could be directly measured using the EC system. In this study, \( u_a \) was determined employing the above iteration method. The EC system is not widely available, while the meteorological data required to determine \( u_a \) using the iteration method are easily acquired.

2) FINAL DETERMINATION OF \( d \) AND \( z_{om} \)

The quantities \( d \) and \( z_{om} \) are interrelated. In this paper, \( d \) and \( z_{om} \) are concurrently optimized. Many experiments have showed that \( d \) changes with vegetation and atmospheric stratification (Thom et al. 1975). In this study, \( d \) was determined through iteration. It was allowed to increase from 0.6\( h \) to 0.9\( h \) (\( h \) is 12 and 26 m at QYZ and CBS, respectively) in intervals of 0.2 m. For each given \( d \), parameters \( z_{om}, u_a, z_{oh}, \) and \( \theta_a \) were determined using Eq. (7). The coefficients of correlation between measured and simulated wind speed and temperatures were simultaneously calculated. The optimum \( d \) and \( z_{om} \) were finally determined when the coefficient of correlation between measured and simulated temperature reached a maximum.

d. Model description

1) THE SEBS MODEL FOR SIMULATING \( SH \)

SEBS is a commonly used model for simulating \( SH \) and LE based on the principle of energy balance (Su et al. 2001; Su 2002; Jia et al. 2009; Van der Kwast et al. 2009). The SEBS algorithm is based on solving the basic surface energy balance equation:
\[
 R_n = G_0 + SH + LE, \quad (8)
\]
where \( R_n \) is net radiation (W m\(^{-2}\)), \( G_0 \) is soil heat flux (W m\(^{-2}\)), \( SH \) is sensible heat flux (W m\(^{-2}\)), and \( LE \) is latent heat flux (W m\(^{-2}\)).

This model consists of three modules: 1) a module calculating energy fluxes, 2) a module deriving \( z_{om}, \) and 3) a module deriving stability parameters. In the SEBS model, \( SH \) is calculated first. Then, \( LE \) is calculated from the energy balance equation. Here \( z_{oh} \) is needed for calculating \( SH \) and correlated with \( z_{om}. \) Therefore, the SEBS model is used to investigate the effects of \( z_{om} \)'s variations on simulated \( SH. \) In the following four equations, Eq. (9) describes the value of \( z_{om}. \) Eq. (10) describes the relationship between \( z_{om} \) and \( z_{oh}. \) Eq. (11) describes the wind speed profiles, and Eq. (12) is the function for \( SH \) simulation:
\[
z_{om}/h = 0.136, \quad (9)
\]
\[
z_{oh} = \frac{z_{om}}{\exp(kB^{-1})}. \quad (10)
\]
\[
u = \frac{u_a}{k} \left[ \ln \left( \frac{z - d}{z_{om}} \right) - \psi_m \left( \frac{z - d}{L} \right) + \Psi_m \left( \frac{z_{om}}{L} \right) \right]. \quad (11)
\]
and
\[
H = ku_a \rho C_p (\theta_0 - \theta_a) \left[ \ln \left( \frac{z - d}{z_{oh}} \right) - \psi_h \left( \frac{z - d}{L} \right) \right] + \psi_h \left( \frac{z_{oh}}{L} \right)]^{-1}, \quad (12)
\]
where \( z_{om} \) is the roughness height for momentum transfer, \( z_{oh} \) is the scalar roughness height for heat transfer, \( z \) is reference height, \( d \) is zero-plane displacement, \( u_a \) is friction velocity, \( \rho \) is the air density, and \( \theta_0 \) is the potential temperature near the surface. Here \( \theta_0 \) was calculated from observed longwave radiation by using Planck's function. The quantity \( \theta_a \) is the potential air temperature at height \( z; \psi_m \) and \( \psi_h \) are the stability correction functions for momentum and sensible heat transfer, respectively; and \( L \) is the Obukhov length. Here \( kB^{-1} \) is calculated following (Su et al. 2001):
where \( C_d \) is the drag coefficient of the foliage elements and is set to 0.2, \( f_c \) is the fractional canopy coverage and \( f_s \) is its complement, and \( C_t \) is the heat transfer coefficient of the leaf, bounded as 0.005N \( \leq C_t \leq 0.075N \) (\( N \) is the number of sides of a leaf participating in heat exchange). The quantity \( n_{ec} \) is the function of cumulative leaf drag area at the canopy top:

\[
kB_s^{-1} = 2.46(Re^*)^{1/4} - \ln 7.4. \tag{15}
\]

where \( LAI \) is the leaf area index and \( u(h) \) is the horizontal wind speed at the canopy top.

In Eq. (13), the heat transfer coefficient of the soil is given by \( C_t^s = P_r^{-2/3}Re^*^{-1/2} \), where \( P_r \) is the Prandtl number; the roughness Reynolds number \( Re^* = h/\nu_0 \), \( h \) being the roughness height of the soil. The kinematic viscosity of the air is \( \nu = 1.327 \times 10^{-5}(1013/p)(\theta/273.15)^{1.81} \). The \( kB_s^{-1} \) is calculated according to Eq. (15):

\[
kB_s^{-1} = \frac{kC_d}{4\nu_0/\nu(h)} \left[ \frac{u_0 h}{u(h)} \right] + 2f_s f_c \left[ \frac{u_0 z_{om}}{k u(h) h} \right] + kB_s^{-1} f_s^2, \tag{13}
\]

where \( CBs \) is the annual mean of derived \( z_{om} \), the annually averaged \( z_{om} \) is 0.072h and 0.097h, respectively. In simulation 3, \( z_{om} \) varies seasonally and diurnally (the solid line).

**Fig. 1.** The \( z_{om} \) values for three SH simulations at (top) CBS and (bottom) QYZ. In simulation 1, \( z_{om} \) is equal to a fixed annual value 0.136h (the thick dashed line). In simulation 2, \( z_{om} \) is the annual mean of derived \( z_{om} \) (the thin dashed line; at CBS and QYZ, the annually averaged \( z_{om} \) is 0.072h and 0.097h, respectively). In simulation 3, \( z_{om} \) varies seasonally and diurnally (the solid line).
2) Evaluation of the Effect of Temporal Variations on Simulated SH

Three numerical simulation experiments were conducted to investigate the effects of \( z_{om} \) variation on SH as simulated by the SEBS model, using data measured in 2003 at CBS and in 2004 at QYZ, using three different \( z_{om} \) parameterization schemes. In simulation 1, \( z_{om} \) was fixed at 0.136 \( h \) (as commonly used in the SEBS model) to analyze the effect of using an approximately constant \( z_{om} \) on simulated SH. In simulation 2, \( z_{om} \) was fixed at its annual mean to investigate the effect of ignoring temporal variations of \( z_{om} \) on simulated SH. Simulation 3 had the most accurate \( z_{om} \) in comparison to simulations 1 and 2, since it was assigned the monthly average of its derived values at each time step, thereby investigating any improvement of simulated SH through varying \( z_{om} \).

3) Evaluation of Agreement between Simulated and Measured SH

The agreement between simulated and measured SH was evaluated using Nash–Sutcliffe efficiency \( E \) (Nash and Sutcliffe 1970), and the root-mean-square error (RMSE):

\[
E = 1 - \frac{\sum_{i=1}^{n} (O_i - S_i)^2}{\sum_{i=1}^{n} (O_i - \bar{O})^2} \quad \text{and} \quad \text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (O_i - S_i)^2}{n - 1}},
\]

where \( O_i \) and \( S_i \) are the observed and simulated values, respectively; \( \bar{O} \) is the arithmetic mean of observed values; and \( n \) is the total number of samples.

3. Results and discussion

a. Comparison of \( z_{om} \) in three simulations

The \( z_{om} \) for the SH simulation is shown in Fig. 1. At CBS and QYZ over the entire year, \( z_{om} \) for simulation 1 was 0.136\( h \), the commonly used SH model value. In simulation 2, \( z_{om} \) was 0.072\( h \) and 0.097\( h \) at CBS and QYZ, which are annual average values. In simulation 3,
monthly averaged diurnal variations of half-hourly $z_{om}$, calculated from wind speed profiles, represent seasonal and diurnal variations over the entire year. At both QYZ and CBS, $z_{om}$ varied diurnally. It was much greater during the night (1800–0800 local time) than during the day (0800–1800) in all months of the year, which is consistent with the nature of annually averaged diurnal variations. The $z_{om}$ was much greater in the leaf-on season than in the leaf-off season at CBS, which is also consistent with $z_{om}$ seasonal variations. At CBS in the leaf-off season, the difference between $z_{om}$ during the day and at night was about 0.06$h$ and, in the leaf-on season, the difference reached 0.08$h$. Meanwhile, at QYZ, monthly averaged diurnal variations in $z_{om}$ showed no seasonal variability, and $z_{om}$ during both day and night was about 0.09$h$, greater than that at CBS.

Large seasonal variations in $z_{om}$ at CBS were due to the distinct seasonal pattern of the LAI, which increases from a minimum at the beginning of the growing season (early May) to a maximum in late June and starts to decrease in the middle of September (Zhou et al. 2006). With increases in the LAI and aging of the leaves, the $z_{om}$ increases to a maximum. With the decrease in the LAI, $z_{om}$ starts to decrease in the middle of September. The phenomenon is consistent with the findings reported by Shaw and Pereira (1982) and Raupach (1994). The diurnal variations in $z_{om}$ at both QYZ and CBS are probably related to diurnal variations in atmospheric stratification. The reason for the diurnal variation needs further study.

b. Reduction in sensitivity of simulated SH to $C_t$ with seasonal and diurnal variations of $z_{om}$

1) SENSITIVITY OF SIMULATED SH TO $C_t$ IN THREE SIMULATIONS

Figure 2 shows variations in RMSE and $E$ of simulated SH with $C_t$, in three simulations with different $z_{om}$ parameterization algorithms. When $C_t$ increased from 0.005 to 0.02, RMSE and $E$ changed slightly in all three simulations. For the $C_t$ range between 0.02 and 0.1, RMSE and $E$ changed greatly, and they were very different across the three simulations. RMSE increased and $E$ decreased most rapidly in simulation 1 (recall that $z_{om}$ was fixed annually at a constant 0.136$h$) at both two sites. The increase of RMSE and decrease of $E$ with $C_t$ were the least in simulation 3 (recall that $z_{om}$ was changed seasonally and diurnally). The higher RMSE...
and lower $E$ mean the higher sensitive of SH simulation to $C_t$ values. Therefore, the different rates of RMSE and $E$ changes with $C_t$ indicate that considering seasonal and diurnal variations of $z_{om}$ significantly reduces the sensitivity of simulated SH to $C_t$, which is an important parameter for the determination of $kB^{-1}$. It means that when simulating SH, considering the seasonal and diurnal variations of $z_{om}$ would lead to the stable simulated SH even if there were some uncertainties of $C_t$.

2) COMPARISONS OF SIMULATED SH UNCERTAINTIES CAUSED BY THREE $z_{om}$ PARAMETERIZATION ALGORITHMS

To obtain more details about the effects of $z_{om}$ parameterization algorithms on SH simulation, uncertainties of the three simulations were compared by choosing two representative values of $C_t$ that is 0.04 and 0.06. The effects of different $z_{om}$ parameterization algorithms on simulated SH was evaluated through comparing measured half-hourly SH with simulated SH, in three simulations at monthly scales. Both at CBS and QYZ, RMSE in simulation 1 was always the greatest and $E$ always the lowest for all months, indicating that the $z_{om}$ approximation of 0.136$h$ generates large uncertainties in simulated SH, especially during the growing season (Figs. 3 and 4).

In Fig. 3, the $C_t$ was considered 0.04. At CBS, RMSE was much higher and $E$ was much lower in growing seasons than that in leaf-off seasons, especially at the beginning and at the end of the growing seasons. In growing seasons, the RMSE of simulation 1 is almost three times than that of simulation 3, and RMSE of simulation 2 is much higher than that of simulation 3; in leaf-off seasons, the RMSE of simulation 1 is slightly higher than that of simulation 3, and RMSE of simulation 1 is nearly the same as that of simulation 3. At QYZ, the RMSE of simulation 1 is nearly twice than that of simulation 3, and the RMSE of simulation 2 were obvious higher than that of simulation 3 in the whole year.

In Fig. 4, the $C_t$ was considered 0.06. Both at CBS and QYZ, the RMSE and $E$ of three simulations appeared the same phenomenon with Fig. 3. And the differences of RMSE and $E$ between three simulations were even greater than that of Fig. 3.

3) COMPARISON OF SIMULATED SH IN THREE SIMULATIONS

Simulated SH by three experiments were compared by considering $C_t$ as 0.04 and 0.06. Compared with simulation 1, simulations 2 and 3 significantly improved the agreement between simulated and observed SH at
both CBS and QYZ (Figs. 5 and 6). The simulated and observed SH at CBS was shown in Fig. 5. In the daytime, simulation 1 produced the highest overestimation of SH, and it was much higher than that of simulations 2 and 3. Simulation 2 slightly overestimated the SH, and simulation 3 agreed well with observed SH. At night, the three simulations performed similarly, and they agreed well with observed SH. The improvement of simulation 3 was the most obvious in April and May. In these two months, SH accounts for the major fraction of the net energy balance. Also for these months, simulation 1 produced the highest daytime overestimation of SH, followed by simulation 2. Simulation 3 performed the best in SH simulation during these months.

The simulated and observed SH at QYZ was shown in Fig. 6. In the daytime, simulation 1 produced the highest overestimation of SH, which was much higher than that at CBS. Simulations 2 and 3 also overestimated the SH, while simulation 3 performed better than simulation 2. At night, three simulations performed similarly and they were all overestimated. With the increase of $C_r$, the discrepancy between measured and simulated SH in the three simulations increased. The overestimation at QZY might result from uncertainties of other parameters, which needs further investigation. Nevertheless, at QYZ, no matter how $C_r$ changes, compared to simulation 1 and 2, simulation 3 showed obvious better agreement between observed and simulated SH.

In this study, neither QYZ nor CBS is dominated by low rainfall, and $z_{om}$ has a great effect on SH simulation. And in dry regions, $z_{om}$ also has an effect on SH simulation. Kustas et al. (1989) studied the impact of $z_{om}$ on flux determination over dry and sparse canopy, and it was found that changing the $z_{om}$ affects the SH and LE greatly. Pitman (1994) used a land surface model to simulate LE and SH in a non-moisture-stressed tropical forest, coniferous forest, and grassland dominated by low rainfall. It was found that $z_{om}$ has one of largest impacts on flux simulation in non-moisture-stressed tropical forests, and in coniferous forest and grassland fluxes showed a relatively small sensitivity to $z_{om}$. In the moisture tropical forest simulation, increasing $z_{om}$ increased LE and SH, and in the grassland increasing $z_{om}$ increased SH rather than LE. It means that in non-moisture-stressed ecosystems, $z_{om}$ has a relatively greater effect on SH simulation than in moisture-stressed ecosystems, and in moisture-stressed ecosystems, $z_{om}$ has a greater effect on SH rather than LE. The reason is that...
the lack of available moisture prevented an increase in transpiration and the more efficient turbulent transfer led to an increase in SH. Therefore, in whatever ecosystem, $z_{om}$ would affect SH simulation, and the relative importance of $z_{om}$ depends on the moisture availability and the precipitation characteristics. The greater importance of $z_{om}$ means more attention should be paid to $z_{om}$’s temporal variations.

In summary, with available measurements of SH at QYZ, the $z_{om}$ approximation of $0.136h$ produced the greatest departure of simulated SH from the measurements in all months, as indicated by the largest RMSE and lowest $E$ of simulated SH in simulation 1. Simulation 3 performs better in the SH simulation than either simulation 1 or simulation 2 because of its consideration of $z_{om}$ seasonal and diurnal variation. Therefore, neglecting $z_{om}$ temporal variations would result in greater SH or LE simulation uncertainties, especially in ecosystems where $z_{om}$ has large seasonal or diurnal variations.

4. Conclusions

Proper parameterization of $z_{om}$ is very important in the simulation of SH. The use of an accurate $z_{om}$ improves agreement between simulated and modeled SH. It also effectively reduces the sensitivity of simulation SH to the heat transfer coefficient $C_t$, which is difficult to determine from the calculation of $kB^{-1}$. Therefore, developing an effective parameterization for the seasonal and diurnal changes in $z_{om}$ is necessary for reliable SH simulation.

Acknowledgments. This research was funded by National Natural Science Foundation of China (Grant 40901033) and the National Program on Key Basic Research Project of China (Grant 2010CB950702), the Ph.D. Programs Foundation of Ministry of Education of China (20090091120030 and 20090091110034) and a project funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions. We thank the researchers at Qianyanzhou and Changbai Mountain experimental stations for providing the measurement data. We gratefully acknowledge the reviewers for their constructive comments.

REFERENCES


Langensiepen, M., and Coauthors, 2009: Quantifying the uncertainties of transpiration calculations with the Penman–Monteith equation under different climate and optimum water supply conditions. Agric. For. Meteor., 149, 1063–1072.


