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Seasonal, Diurnal and Wind-Direction-Dependent Variations of the Aerodynamic Roughness Length in Two Typical Forest Ecosystems of China

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ABSTRACT

Aerodynamic roughness length (z_{om}) is an important parameter for reliably simulating surface fluxes. The parameter varies with wind speed, atmospheric stratification, terrain and other factors; however, variations of this parameter are not properly considered in most models, which may result in uncertainties in simulating surface latent heat and sensible heat flux. There have been few studies of the diurnal and wind-direction dependent variations in z_{om}. This study analyzes the seasonal, diurnal and wind-direction-dependent variations in z_{om} calculated from the profile of meteorological data for two forest systems of China, and explores the mechanism underlying these variations.

Annually averaged and monthly averaged diurnal variations in z_{om} are obvious and similar at a Changbai Mountain (CBS) site located in northeast China and a Qianyanzhou (QYZ) site located in southeast China. z_{om} is much higher at night than during the day. The diurnal variation in z_{om} is due to a change in atmospheric stratification. The seasonality of z_{om} differs at two sites. z_{om} has sizable seasonal variation and is lower in the leaf-off season than in the growing season at CBS. At QYZ, z_{om} does not have an obvious seasonal pattern. However, at QYZ, the short-term fluctuation is greater than that at CBS. The obvious seasonal variation in z_{om} at CBS is related to the great seasonal change in the leaf area index. The noticeable short-term wind-direction-dependent variations in z_{om} at QYZ are attributed to the heterogeneous terrain there.

Key words: Aerodynamic roughness, Seasonal variation, Diurnal variation, Wind-direction-dependent variation

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1. INTRODUCTION

Mass and energy exchanges at the land surface-atmosphere interface are the most critical components of the climate system (Hurtalová and Matejka 1999), surface latent heat flux (LE) and sensible heat flux (SH) play an especially key role in determining weather and climate at various scales. Therefore, an accurate simulation of LE and SH is of importance to numerical models with regard to weather, climate, hydrology and ecology. Different methodologies are currently employed for calculating LE and SH such as algorithms based on remote sensing and numerical simulation models built on the basis of principles governing energy exchange and transfer in the soil-vegetation-atmosphere continuum.

Aerodynamic roughness length z_{om} is an important parameter for calculating LE and SH. Theoretically, z_{om} is the height above the surface at which the mean logarithmic wind profile reaches zero (Monteith 1973). Previously, land surface was generally treated as completely homogeneous. Therefore, z_{om} was considered as a parameter related only to rough elements in the fetch and was calculated by fitting the wind speeds at several different levels above the ground. Monteith (1973) summarized the relationship between z_{om} and the height of rough elements and approximated the ratio of z_{om} to the averaged rough-element height (z_{om}/h) as 0.136. Many empirical relations for calculating z_{om} have been developed recently. For vegetation with incomplete canopies,

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z_{om} is smaller and the z_{om}/h relationship seems to vary more than for vegetation with closed canopies (Riou et al. 1987). Driese and Reiners (1997) reported averaged z_{om}/h values of 0.04, 0.04 and 0.13 for natural sagebrush, saltbush and greasewood, respectively. Van Dijk et al. (2004) found that z_{om}/h is 0.03 for a rain-fed cropping system with maize and cassava rotations. Some researchers have parameterized z_{om} as a function of h, frontal area index or leaf area index (LAI) (Schaudt and Dickinson 2000; Nakai et al. 2008a). However, empirical estimates of z_{om} are still used in many models. For example, z_{om} is considered as 0.136 h in the Surface Energy Balance System (SEBS) model (Su et al. 2001, 2002). Langensiepen et al. (2009) calculated transpiration using the Penman-Monteith equation with z_{om} set to 0.13 h. Sánchez et al. (2009) fixed z_{om} as 0.1 h to calculate energy fluxes.

In those models, z_{om} was assumed to change with the averaged rough-element height. Instead, ground surfaces are rarely homogeneous and uniform. In the case of regularly undulating topography, drag is a function of the surface terrain height and increases with terrain slope. In this case, z_{om} is related not only to the height of rough elements, but also to the distribution, density and geometry of rough elements. This parameter also depends on the surface-air temperature difference and atmospheric conditions. Therefore, z_{om} is affected by the integrated effects of aerodynamic and thermodynamic factors and rough elements, which means that z_{om} is actually a parameter varying with wind speed, wind direction, terrain, atmospheric stratification, and LAI (Zhang et al. 2004; Patil 2006; Zhou et al. 2006).

There have been studies on the seasonal variations of z_{om}, but few on the diurnal variations of z_{om}. Usually, z_{om} is taken as an invariant parameter and the inherent temporal variability is ignored in many models calculating LE and SH. These models neglect concomitant effects on momentum transfer, and thus there are definite uncertainties in the simulated LE and SH (Borak et al. 2005). Through a sensitivity analysis, Kustas et al. (1989) concluded that the error in a simulated SH would decrease by approximately an order of magnitude if z_{om} increased from 0.01 to 0.1 m. Additionally, Pitman (1994) pointed out that an error of 30% in z_{om} corresponds to a 15% uncertainty in the calculation of surface fluxes. Teixeira et al. (2008) analyzed energy fluxes and vegetation-atmosphere parameters in irrigated and natural ecosystems of semi-arid Brazil, and pointed out that the variability of aerodynamic resistance could be mainly explained by the friction velocity ($u*$), which in turn depends on z_{om}. Ignorance of variations in z_{om} will inevitably result in the failure of models to capture the seasonal or diurnal patterns of carbon, energy and water fluxes. Therefore, variations in z_{om} and corresponding effects on simulated fluxes need extra attention.

The primary objectives of this study are to (1) gain insight into the seasonal and diurnal variations of z_{om} in two typical forest ecosystems in China and (2) explore possible factors driving z_{om} variations in these two forest ecosystems.

2. DATA AND METHODS USED

2.1 Sites Description

Measurements taken from 1 January 2003 to 31 December 2004 at Qianyanzhou (QYZ) and Changbai Mountain (CBS) experimental stations were used in this study. The two stations belong to the ChinaFLUX network. QYZ (26°44'52"N, 115°03'47"E) is located on a hilly field of southwestern Jiangxi Province, China. The elevation at the flux tower site is 102 m above sea level. The flux tower is located in a sloping field with an elevation of 2.8 - 13.5°. The topography surrounding the tower is heterogeneous and the relative elevation range is 20 to 50 m (Fig. 1), so in the footprint region, the topography is relative flat. The vegetation is a planted forest composed mainly of *evergreen marsh pine*, *masson pine* and *fir*. There are 1773 stems per hectare in forest. The maximum LAI is 3.6, with small annual and sea-

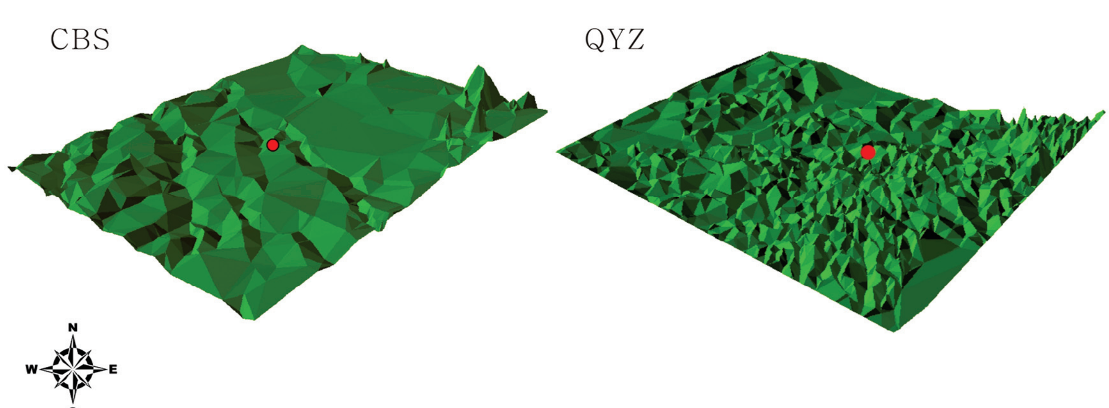

Fig. 1. The topographic maps of CBS (left, 125 - 130°E, 40 - 45°N) and QYZ (right, 114 - 118°E, 24 - 28°N). The pentagram represents the location of the observation tower. The two maps were made with ArcGIS software from DEM data provided by the Data-Sharing Network of Earth System Science of China. The spatial solution of the DEM data is 90 m by 90 m.

sonal variations (Liu et al. 2005, 2006). 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 tower is located in flat area, and the topography is predominately flat, with slopes of less than 4% (Fig. 1). 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 Mongolia*, *Fraxinus mandshurica* and *Acer Mono*. There are 560 stems per hectare with a canopy coverage of over 80% in a forest. And 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). Canopy height is important for calculating z_{om}. Recently Nakai et al. (2008b and 2010) proposed new methods to determine the aerodynamic canopy height or cumulative basal area inflection (CuBI) height, which are very useful for further micrometeorological studies. In this study, the canopy height was determined from the average measurements of an altimeter, which was commonly used by Chinaflux. The average canopy height in QYZ and CBS is 12 and 26 m, respectively.

Because of the influence of the eastern Asian monsoon, the climate in Asia differs from that in Europe and that in North America, with there being apparent latitudinal gradients of temperature and precipitation along the North-South Transect of Eastern China (NSTEC). Both CBS and QYZ are located in the NSTEC. They are typical ecosystems representing a temperate mixed forest and subtropical coniferous plantation, respectively. A deep understanding of the characteristics of z_{om} will be helpful for improving the simulations of carbon, water, and energy fluxes in forest ecosystems of China.

2.2 Data Used

At both QYZ and CBS, a seven-level routine meteorological profile system was mounted on the tower with an analyzer (Compbell Inc., USA). Within and above the forest air temperature and relative humidity (HMP45C, Vaisala Inc.), wind speed (A100R, Vector Inc.), wind direction (W200P, Vector Inc.), atmospheric pressure (CS105, Vaisala Inc.) and PAR (Li-Cor Inc., USA) were measured simultaneously. At QYZ, the measurements were taken at 1.6, 7.6, 11.6, 15.6, 23.6, 31.6, 39.6 m above the ground, respectively, while heights of measurements were taken at 2.0, 8.0, 22.0, 26.0, 32.0, 49.8, 61.8 m above the ground at CBS. 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 in further analysis. The LAI was derived from photosynthetically active radiation measured above and below the canopy (Baldocchi 1994; Soegaard and Thorgeirsson 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 affect 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 in 2003 and 2004 at both QYZ and CBS.

2.3 z_{om} Calculation Method

There are four typical methods for calculating z_{om} using meteorological data recorded at several heights above the ground and/or data recorded by a three-dimensional sonic anemometer at one height (Berkowicz et al. 1982; Dolman 1986; Zhang and Chen 1997; Martano 2000; Gao et al. 2002; Takagi et al. 2003). The traditional least-squares method was employed here to calculate z_{om} from wind speed and temperature profiles since a previous study demonstrated that this method is the best for calculating z_{om} under all atmospheric stratifications at the two sites (Zhou et al. 2007).

2.3.1 Least-Squares Method for Calculating z_{om} and $u*$

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

$$u = \frac{u*}{k}\left[\ln\left(\frac{z-d}{z_{om}}\right) - \psi_m\left(\frac{z-d}{L}\right)\right] \tag{1}$$

$$\theta = \frac{\theta*}{k}\left[\ln\left(\frac{z-d}{z_{oh}}\right) - \psi_h\left(\frac{z-d}{L}\right)\right] + \theta_0 \tag{2}$$

where u is the wind speed, $u*$ is the friction velocity, k is the von Karman constant and equals 0.4, z is the height at which the wind speed and temperature are measured, θ is the potential air temperature of each layer, $\theta*$ is friction temperature, z_{oh} is the thermal roughness length, and θ_0 is the potential temperature near the surface. L is the Obukhov length, which is calculated as

$$L = \frac{u*^2\theta}{\theta* kg} \tag{3}$$

where g is the acceleration due to gravity and equals 9.8. θ is calculated as

$$\theta = T\left(\frac{p_0}{p}\right)^{0.286} \tag{4}$$

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

In Eqs. (1) and (2), $\psi_m\left(\frac{z-d}{L}\right)$ and $\psi_h\left(\frac{z-d}{L}\right)$ 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

$$u = \frac{u*}{k}\left[\ln(z-d) - \psi_m\left(\frac{z-d}{L}\right)\right] - \frac{u*}{k}\ln z_{om} \tag{5}$$

$$\theta = \frac{\theta*}{k}\left[\ln(z-d) - \psi_h\left(\frac{z-d}{L}\right)\right] - \left(\frac{\theta*}{k}\ln z_{oh} - \theta_0\right) \tag{6}$$

Equations (5) and (6) can be expressed using a linear regression formula:

$$y = ax + b \tag{7}$$

For Eq. (5), $y = u$, $x = \ln(z-d) - \psi_m\left(\frac{z-d}{L}\right)$, $a = u*/k$, and $b = -a\ln z_{om}$. For Eq. (6), $y = \theta$, $x = \ln(z-d) - \psi_h\left(\frac{z-d}{L}\right)$, $a = \theta*/k$, and $b = -a\ln z_{oh} + \theta_0$.

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

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

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

$u*$ could be directly measured using the eddy covariance system. In this study, $u*$ was determined employing the above iteration method. The eddy covariance system is not widely available, while the meteorological data required to determine $u*$ using the iteration method is easily acquired.

2.3.2 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 shown that d changes with vegetation and atmospheric stratification (Thom 1975; Pieke 1987). In this study, d was determined through iteration. It was allowed to increase from 0.6 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}, $u*$, z_{oh}, and $\theta*$ 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.

3. RESULTS AND DISCUSSIONS

3.1 Seasonal Variations in z_{om}

Figure 2 shows 5-day mean values and standard deviations of derived half-hourly z_{om} in 2003 and 2004 at CBS and QYZ. At CBS, z_{om} has obvious seasonal patterns over two years and is lower in the leaf-off season than in the growing season. The averages of half-hourly z_{om} are 0.077 and 0.069 h in growing and leaf-off seasons in 2003 and 0.091 and 0.072 h in 2004, respectively (Table 1). There is no obvious seasonal pattern of z_{om} at QYZ. However, z_{om} has larger short-term fluctuations at QYZ than at CBS. The coefficients of variation (CV = standard deviation/mean value × 100%) are 33.5% and 24.2% in 2003 and 2004 at QYZ and 18.8% and 17.1% at CBS respectively. The annual means of half-hourly z_{om} are 0.083 and 0.097 h in 2003 and 2004 at QYZ and 0.072 and 0.079 h at CBS respectively. z_{om}/h is higher at QYZ than at CBS. It should be kept in mind that the canopy height at CBS is about twice that at QYZ. Whether and how z_{om}/h decreases with h requires further investigation.

At CBS, one of the major drivers of large seasonal variations in z_{om} is 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). The seasonal pattern of the 5-day mean of z_{om} closely follows that of the LAI. At the beginning of the growing season, the LAI is relatively low and new leaves are very soft. The resistance to flow on the canopy surface is small, which results in small z_{om}. With increases in the LAI and aging of the leaves, the geometric roughness length and resistance increase. Consequently, z_{om} increases to a maximum. With the decrease in the LAI, z_{om} starts to decrease in the middle of September. During the non-growing season, low canopy density results in low z_{om}. The relationship between z_{om} and the LAI identified in this study is consistent with the findings reported by Shaw and Pereira (1982) and Raupach (1994), and in good agreement with the study posted by McDonald et al. (1998) and Shao and Yang (2008). McDonald et al. (1998) proposed a relationship between z_{om} and the ratio of the frontal area (or the plan area) of the obstacles to the lot area. It was shown that with the increase of the ratio, the z_{om}/h increase firstly, and then decrease. Shao and Yang (2008) also studied the theory for drag partition over rough surfaces, in which it was shown the same phenomenon with McDonald's results. Nevertheless, the phenomenon disagrees with Lindroth's (1993) study. Therefore, the relationship between z_{om} and the LAI needs further study. For forests, z_{om}/h is a function not only of the LAI, but also of a density parameter, such as the frontal area index (Schaudt and Dickinson 2000) or stand density (Nakai et al. 2008a). However, data on the frontal area index and stand density were not easy to obtain thus far. Since the frontal area index and stand density are correlated with the LAI and the LAI

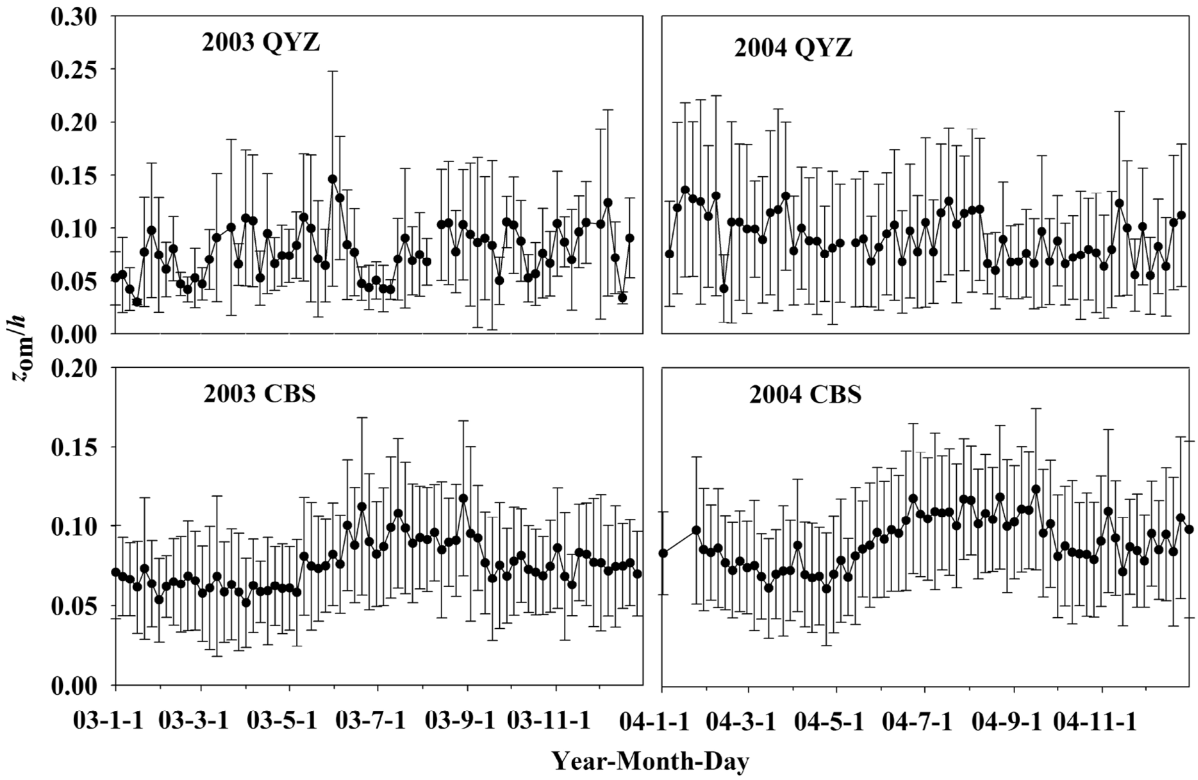

Fig. 2. Seasonal variations in z_{om} at QYZ and CBS in 2003 and 2004. Solid block points represent 5-day means of half-hourly z_{om}. Error bars are the standard deviations of half-hourly z_{om}.

Table 1. The annual averages and variation coefficients of half-hourly z_{om} at CBS and QYZ in 2003 and 2004 and those values in the growing and non-growing seasons at CBS.

Site	Year	Annual average z_{om}	Average z_{om} in the growing seasons	Average z_{om} in the non-growing seasons	Coefficient of variation (%)
QYZ	2003	0.083 *h*	-	-	33.5
	2004	0.097 *h*			24.2
CBS	2003	0.072 *h*	0.077 *h*	0.069 *h*	18.8
	2004	0.079 *h*	0.091 *h*	0.072 *h*	17.1

was easy to obtain by remote sensing, establishing relationships between the LAI and the frontal area index and stand density is helpful for z_{om} research; further study with data from more ecosystem stations is required.

3.2 Wind-Direction-Dependent Variation of z_{om} over Heterogeneous Terrain

It is well known that z_{om} calculated with wind speed profiles relates not only to the height of rough elements, but also to the distribution, density and geometry of rough elements (Taylor et al. 1989; Zhang et al. 2004; Zhou et al. 2005, 2009). z_{om} has more distinguishable short-term fluctuations at QYZ than at CBS, which is attributable to the different topographic characteristics of the two stations. The terrain is more heterogeneous at QYZ than at CBS. Additionally, the scopes of the regions were calculated with a flux source area model (FSAM) (Schmid et al. 1991; Schmid 1997, 2002) at QYZ and CBS. The FSAM footprint model is shown in Fig. 3, and the footprint results calculated with annually averaged z_{om} for the year 2003 are presented in Table 2. The scope length is about 1 - 2 km at both stations. At this scope, the 90 m × 90 m digital elevation model (DEM) map shows that the topography is more heterogeneous at QYZ than at CBS (Fig. 1 and Table 3). Table 3 presents the means, standard deviation (STDEV), and CV of elevations within 2 km × 2 km and 4 km × 4 km squares centered on the towers. The CVs of elevations are 14% and 22% for the 2 km × 2 km and

4 km × 4 km squares at QYZ, respectively, but only 3% and 4% at CBS (Table 3).

The heterogeneous topography causes z_{om} to change with wind direction at QYZ (Fig. 4). The average of z_{om} at QYZ decreases by more than 50% when the wind is from the north and northwest and south and southwest relative to the average of z_{om} for wind in other directions. With the wind direction change, z_{om} has distinguishable short-term fluctuations. The change in z_{om} with wind direction is less obvious at CBS than at QYZ. Consequently, the short-term fluctuation of z_{om} at CBS is relatively small.

Topographic characteristics are thus the main factors explaining the difference in short-term fluctuations of z_{om} at QYZ and CBS. In heterogeneous regions with undulant terrain, rough elements and their distribution change with wind directions. This leads to large wind-direction-dependent variations and short-term fluctuations of z_{om} in heterogeneous terrain.

3.3 Diurnal Variations of z_{om}

Annually and monthly averaged diurnal variations of half-hourly z_{om} in 2003 and 2004 were calculated. Figure 5 shows the annually averaged diurnal variations of half-hourly z_{om} in 2003 and 2004. The annual mean diurnal variations of z_{om} are almost identical for the two years. z_{om} is much

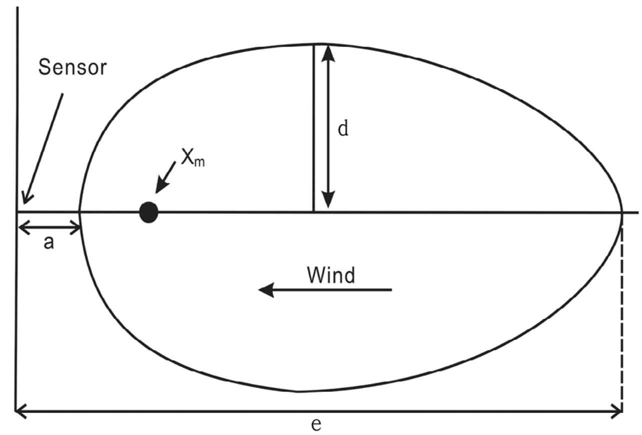

Fig. 3. Characteristic dimensions of the source area. x_m: location of maximum source; a: near end; e: far end; and d: maximum lateral half-width of the source area [source from Schmid et al. (1991)].

Table 2. Outputs of FSAM at QYZ and CBS.

Station	*a* (m)	*e* (m)	*d* (m)
QYZ	270.1	2620.2	712.8
CBS	147.4	1810.9	293.8

Note: The meanings of a, d, e are according to Fig. 3. a: near end; d: maximum lateral half-width of the source area; and e: far end.

Table 3. The mean value (MEAN), standard deviation (STDEV) and coefficient of variation (CV) of elevations within 2 km × 2 km and 4 km × 4 km squares surrounding the towers at QYZ and CBS.

SITE	QYZ (2 km × 2 km)	CBS (2 km × 2 km)	QYZ (4 km × 4 km)	CBS (4 km × 4 km)
MEAN (m)	118.94	750.43	107.48	750.97
STDEV (m)	16.76	20.51	23.97	27.72
CV (%)	14	3	22	4

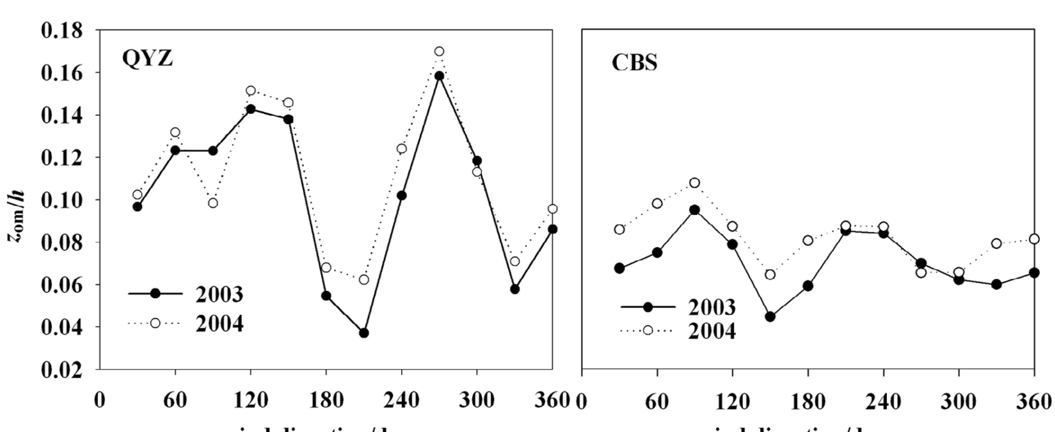

Fig. 4. Changes in averaged half-hourly z_{om} with wind direction at QYZ and CBS in 2003 and 2004. z_{om} values are binned in wind-direction intervals of 30°.

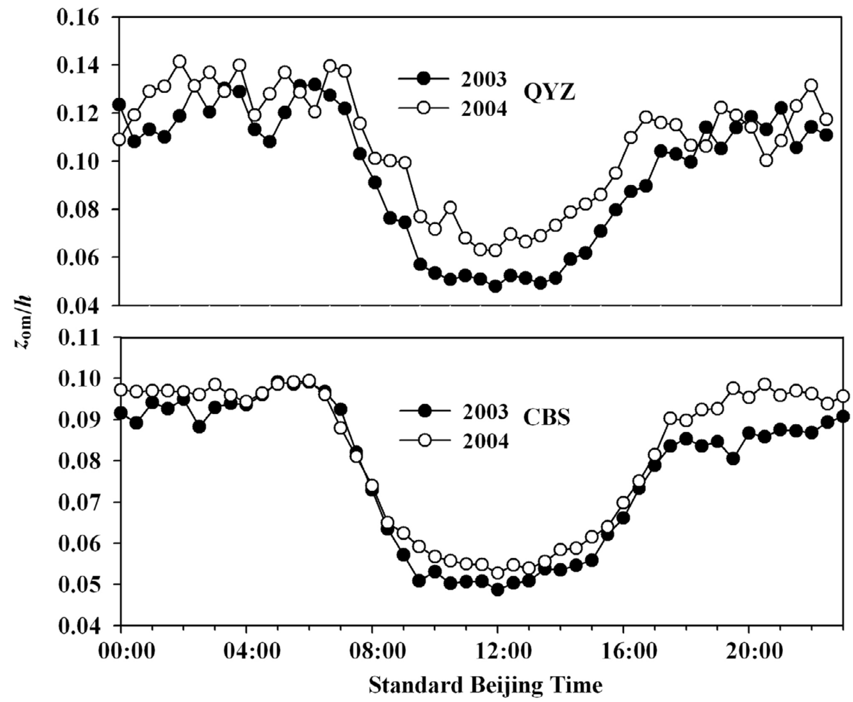

Fig. 5. Annually averaged diurnal variations of z_{om} at QYZ and CBS in 2003 and 2004.

larger at night (18:00 to 8:00) than during the day (8:00 to 18:00). It gradually decreases after sunrise and approaches a minimum at noon. It then increases until sunset. The slight increase in z_{om} continues during the period from sunset to midnight. The variation range of z_{om} is larger during the day than during the night. At QYZ, the annual means of daytime z_{om} are 0.065 and 0.084 h while those of nighttime z_{om} are 0.115 and 0.124 h in 2003 and 2004, respectively. At CBS, the daytime averages of z_{om} are 0.06 and 0.064 h and the nighttime averages of z_{om} are 0.091 and 0.094 h in 2003 and 2004, respectively (Table 4). The obvious diurnal variation in z_{om} is usually neglected in most models. This simplification would inevitably result in the failure of models to capture the diurnal patterns of fluxes.

The diurnal variations in z_{om} are related to diurnal changes in atmospheric stratifications (Liu et al. 1989; Chen et al. 1993; Lv and Dong 2004; Mao et al. 2006). During the day, atmospheric stratification is unstable and the Richardson number (R_i), which is an indicator of atmospheric stratification, is negative. The turbulence between vegetation canopy and the atmosphere is so intensive that it is easy for momentum to transfer between vegetation and the atmosphere. Consequently, z_{om} is lower. At night or in early morning, the atmospheric stratification is stable or neutral and R_i is no less than zero. The turbulence between vegetation and the atmosphere is so weak that it is difficult for the momentum to transfer between vegetation and the atmosphere. z_{om} is consequently high (Liu et al. 1989; Chen et al. 1993; Mao et al. 2006). In all wind directions, the average of z_{om} is highest under stable atmospheric stratification and lowest under unstable atmospheric stratification. The variation in z_{om} with atmospheric stratification over the Gobi and vegetation surfaces was previously reported by Lv and Dong (2004).

Monthly averaged diurnal variations of half-hourly z_{om} in 2003 and 2004 at QYZ and CBS are shown in Fig. 6. At both QYZ and CBS, z_{om} has diurnal variations and is much higher at night (18:00 to 8:00) than during the day (8:00 to 18:00) in all months from January to December, which is consistent with the nature of the annually averaged diurnal variations. z_{om} is much higher during times of full foliage than in barren periods at CBS, which is also consistent with the seasonal variations of z_{om}. Furthermore, at CBS in the leaf-off season, the difference between z_{om} during the day and at night is about 0.06 h, and during times of full foliage, the difference reaches 0.08 h. Meanwhile, at QYZ, monthly averaged diurnal variations in z_{om} have no seasonal variations, and z_{om} during the day and at night is about 0.09 h, which is higher than that at CBS. Additionally, the monthly averaged z_{om} at QYZ has obvious short-term fluctuations.

4. CONCLUSIONS

In this study, z_{om} was derived from the wind speed and temperatures measured at four heights in two typical forest ecosystems (CBS and QYZ) in China, and the temporal characteristics of z_{om} at the two sites were analyzed. From this study, the following conclusions can be drawn.

Table 4. Annual averages of half-hourly z_{om} during daytime and at night at CBS and QYZ in 2003 and 2004.

Station	Year	Annual mean of z_{om} during daytime (8:00 to 18:00)	Annual mean of z_{om} during night time (18:00 to 8:00)
QYZ	2003	0.065 h	0.115 h
	2004	0.084 h	0.124 h
CBS	2003	0.06 h	0.091 h
	2004	0.064 h	0.094 h

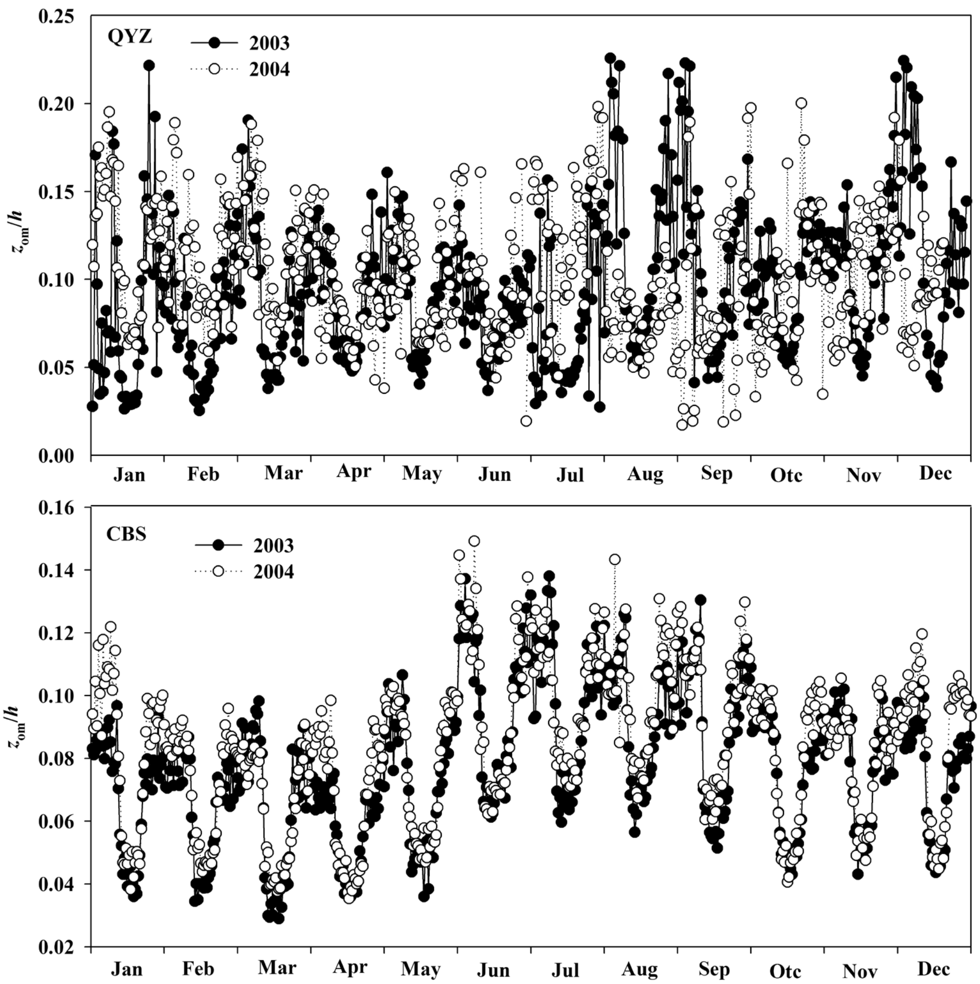

Fig. 6. Monthly averaged diurnal variations of z_{om} at QYZ and CBS in 2003 and 2004.

z_{om} has obvious seasonal variations at CBS, in that it is much higher in the growing season than in the leaf-off period. It does not have obvious seasonal variation at QYZ. The noticeable seasonal variation of z_{om} is mostly related to the large seasonal change in the LAI at CBS. The short-term fluctuation of z_{om} is more obvious at QYZ than at CBS since the terrain at QYZ is more heterogeneous.

At QYZ and CBS, z_{om} has similarly obvious diurnal variations. It is much lower during the day than at night owing to the difference in atmospheric stratification during these two periods. z_{om} is lower for unstable atmospheric stratification (mostly during the day) than for neutral or stable atmospheric stratification (mostly at night or in the early morning).

At QYZ, z_{om} having noticeable short-term fluctuation is attributable to the heterogeneous terrain in this region, which reflects the wind-direction-dependent variation in z_{om} where there is heterogeneous terrain.

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