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Surface roughness length dynamic over several different surfaces and its effects on modeling fluxes

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Abstract Roughness length and zero-plane displacement over three typical surfaces were calculated iteratively by least-square method, which are Yucheng Experimental Station for agriculture surfaces, Qianyanzhou Experimental Station for complex and undulant surfaces, and Changbai Mountains Experimental Station for forest surfaces. On the basis of roughness length dynamic, the effects of roughness length dynamic on fluxes were analyzed with SEBS model. The results indicate that, aerodynamic roughness length changes with vegetation conditions (such as vegetation height, LAI), wind speed, friction velocity and some other factors. In Yucheng and Changbai Mountains Experimental Station, aerodynamic roughness length over the fetch of flux tower changes with vegetation height and LAI obviously, that is, with the increase of LAI, roughness length increases to the peak value firstly, and then decreases. In Qianyanzhou Experimental Station, LAI changes slightly, so the relationship between roughness length and LAI is not obvious. The aerodynamic roughness length of Yucheng and Changbai Mountains Experimental Station changes slightly with wind direction, while aerodynamic roughness length of Qianyanzhou Experimental Station changes obviously with wind direction. The reason for that is the terrain in Yucheng and Changbai Mountains Experimental Station is relatively flat, while in Qianyanzhou Experimental Station the terrain is very undulant and heterogeneous. With the increase of wind speed, aerodynamic roughness length of Yucheng Experimental Station changes slightly, while it decreases obviously in Qianyanzhou Experimental Station and Changbai Mountains Experimental Station. Roughness length dynamic takes great effects on fluxes calculation, and the effects are analyzed by SEBS model. By comparing 1 day averaged roughness length in Yucheng Experimental Station and 5 day averaged roughness length of Qianyanzhou and Changbai Mountains Experimental Station with roughness length parameter chosen by the model, the effects of roughness length dynamic on flux calculation is analyzed. The maximum effect of roughness length dynamic on sensible heat flux is 2.726%, 33.802% and 18.105%, in Yucheng, Qianyanzhou, and Changbai Mountains experimental stations, respectively.

Keywords: ChinaFLUX, surface roughness length, dynamic, spatial heterogeneity, Yucheng Experimental

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Station, Qianyanzhou Experimental Station, Changbai Mountains Experimental Station.

Many model parameterizations of land-surface fluxes, including momentum, sensible heat and latent heat, require knowledge of aerodynamic roughness length. Roughness length is the height above the surface at which the mean logarithmic wind profile theoretically reaches zero. With the development research on regional surface fluxes, researcher's cognition for surface roughness length has been lasting three periods. In the first stage, roughness length was viewed as the reflection of surface rough degree and only related to surface condition. And it was considered as geometric roughness length till the 1970s[1]. Afterwards, in the second stage, further research indicated that, over surfaces with equivalent area in level and vertical scale, undulant terrain leads to the increase of drag coefficient, which means that roughness length over undulant surfaces is higher than that over flat surfaces. To explain the variation of surface roughness length with the terrain slope and the topography, equivalent surface roughness length was proposed[2,3]. Otherwise, researchers found that equivalent surface roughness length over flat and homogeneous is related to vegetation height, density and LAI. Therefore, roughness length can be obtained by look-up table according to vegetation height, density, and LAI in growing period. While actual surfaces are heterogeneous and complex, and the structure, type and distribution of the rough elements are obviously irregular, and roughness length is related to wind speed, wind direction, and friction velocity and atmospheric stability greatly, so the conception of equivalent roughness length can not meet the requirement. Therefore, aerodynamic roughness length was presented. Aerodynamic roughness length is the integration of geometric roughness length of rough elements and flow condition[4−8]. Correspondingly, this was the third period of roughness length development.

In flux reversion models, aerodynamic roughness length is obtained from look-up tables or by empirical method. Typically, modelers assume that the roughness length is identical for all locations that fall into a particular land cover class. They assumed values may be time-invariant, or may have simple seasonality for differentiating between leaf-off and leaf-on conditions. These look-up approaches ignore the inherent temporal and spatial variability of roughness length and its effects on fluxes calculation. Over homogeneous surfaces, aerodynamic roughness would changes obviously with LAI and other parameters. And as for heterogeneous surfaces, aerodynamic roughness length changes not only with vegetation conditions, but also with wind directions (terrain), wind speed, friction velocity and so on. So there would be errors for fluxes retrieval, especially for fluxes calculation on small temporal and spatial scale.

Yucheng, Qianyanzhou and Changbai Mountains experimental stations are three typical flux measurement stations. They stand for agriculture surfaces, complex and undulant surfaces and forest surfaces, respectively. However, the effect of roughness length dynamic on fluxes calculation and simulation in the three experimental stations is still unclear. It is quite important to analyze aerodynamic roughness length dynamic, and analyze its effects on simulation fluxes by models, which helps greatly to comparison, analysis and verification of the measured fluxes and simulated fluxes.

1 Locations, instruments and materials

In this paper, the data we used are all from the three flux measurement stations of ChinaFLUX with different surface conditions.

(1) Yucheng Integrated Experimental Station (36°50′N, 116°34′E, 28 m a.s.l.), which is in flat terrain and open surround, and it belongs to homogeneous surface basically. Wind speed was measured in four different levels (1, 2, 3 and 4 m) above the ground simultaneously, the height above surface is 1, 2, 3 and 4 m, respectively. The growing period of the winter wheat is from October to June of the next year. In this paper, 1 hour averaged roughness length from March to June in 1999 was calculated.

(2) The second is Qianyanzhou flux measurement station (26°44′52″N, 115°03′47″E, 102 m a.s.l.). The studied site is on undulating terrain with slopes among 2.8°−13.5°, and the relative elevation difference is

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20—50 m. The man-made forest mainly composed by marsh pine, masson pine and fir is closed community basically, and is lack of underbrush. And the vegetation height is 11—12 m. There is a conventional meteorological survey system in seven levels, and the height is 1.6, 7.6, 11.6, 15.6, 23.6, 31.6 and 39.6 m above the ground, respectively. There are wind speed, air temperature, humidity, atmospheric pressure and wind direction sensors in very level, and wind direction sensor in the uppermost level. In this paper, the data in 2003 of the uppermost four levels above canopy were used to calculate half hour averaged roughness length. Fig. 1 is the topographic map of Qianyanhzou Experimental Station, at which the dark point stands for the flux tower.

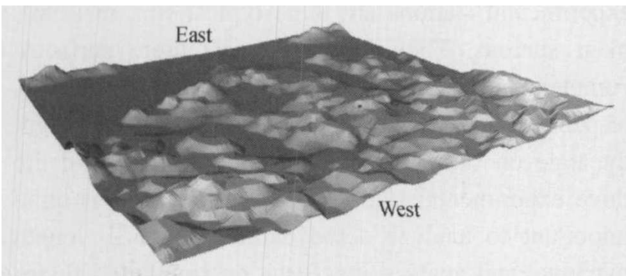

Fig. 1. Location of Qianyanzhou Experimental Station.

(3) The third is Changbai Mountains Experimental Station (41°24′09″N, 128°05′45″E, 761m a.s.l.), where there is mainly red broadleaf pine woods, and the land slope of forest is no more than 4%. The vegetation height is about 26 m. There is a conventional meteorological survey system in seven levels, and the height is 2.0, 8.0, 22.0, 26.0, 32.0, 49.8 and 61.8 m above the ground, respectively. In this paper, the data in 2003 from the uppermost four levels were used to calculate half hour averaged roughness length. The instrument and data of the three stations are the same, which is wind speed (A100R, Vector Ins., England) in various heights, wind speed (W200P, Vector Ins, England), and air temperature (HMP45C, VAISALA Co, Finland).

2 z_0 calculation method

2.1 *Wind and temperature profiles under various atmospheric stabilities*

d and z_0 were calculated iteratively by wind and temperature profiles. Wind and temperature profiles are as following[9]:

$$u = \frac{u_*}{k}\left[\ln\left(\frac{z-d}{z_0}\right) - \psi_m\left(\frac{z-d}{L}\right)\right], \quad (1)$$

$$\theta = \frac{\theta_*}{k}\left[\ln\left(\frac{z-d}{z_t}\right) - \psi_h\left(\frac{z-d}{L}\right)\right] + \theta_0, \quad (2)$$

when $z/L<0$, under unstable atmospheric stability

$$\psi_m = \ln\frac{1+x^2}{2} + 2\ln\frac{1+x}{2} - 2\mathrm{arctg}\, x + \frac{\pi}{2}, \quad (3)$$

$$\psi_h = 2\ln\frac{1+y}{2}, \quad (4)$$

$$x = (1-16\frac{z-d}{L})^{\frac{1}{4}}, y = (1-16\frac{z-d}{L})^{\frac{1}{2}}, \quad (5)$$

when $z/L>0$, under stable atmospheric stability

$$\psi_m = \psi_h = -5\frac{z-d}{L}, \quad (6)$$

when $z/L=0$, under neutral atmospheric stability

$$\psi_m = \psi_h = 0. \quad (7)$$

where θ is air temperature, u is wind speed, θ_* is friction temperature, u_* is friction velocity, z_0, d is aerodynamic roughness length and zero-plane displacement respectively. z_t is thermal roughness length.

2.2 *Least-square method for z_0 and u_**

As for a given initial u_* and θ_*, relation (1) was fitted as the following relation:

$$u = ax + b, \quad (8)$$

where

$$a = \frac{u_*}{k}, \quad (9)$$

$$x = \ln(z-d) - \psi_m, \quad (10)$$

$$b = -\ln z_0 \cdot a. \quad (11)$$

In the same way, z_0 and u_* were calculated by relation (2).

2.3 *The determination of d and z_0*

Many experiments indicate that, commonly d equals 0.67 h over surfaces covered by dense and homogeneous vegetations[10]. Yucheng Experimental Station is flat and covered by vegetations homogeneously, while average canopy height of Qianyanzhou and Changbai Mountains experimental stations is greater, more heterogeneous and sparser than that of Yucheng.

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Therefore, in Yucheng Experimental Station, the value of d is viewed as 0.67 h in this paper, and d of Qianyanzhou and Changbai Mountains Experimental Station should be calculated reasonably. Many researches indicate that d changes with atmospheric stability. In stable atmospheric stability, d equals 0.9 h, in neutral atmospheric stability, d equals (0.76±0.04) h, and in unstable atmospheric stability, d decreases to 0.7 h[11] .Therefore, in Qianyanzhou Experimental Station, d varies from 0.7 h to 0.9 h (h = 12 m). In this paper, d and z_0 are calculated iteratively by fitting the wind speed and temperature profiles. When d changes from 0.7 h to 0.9 h with 0.2 m as the step, as for any given d, there was a correlation coefficient for the fitting relation (8). And d is chosen as the correct value when the correlation coefficient reaches the maximum. Correspondingly, z_0 and u_* can be calculated. Similarly, d, z_0 and u_* of Mountains Experimental Station can be calculated by the same method.

3 Results and discussion

3.1 Aerodynamic roughness length dynamic

Growing season of the winter wheat in Yucheng Experimental Station is from October to June of the next year. During this period, LAI and canopy height of the wheat change greatly. In this paper, data from March to June was chosen to calculate 1 hour averaged roughness length. And daily averaged normalized roughness length (that is z_0/h) dynamic during March to June is shown in 2(a). The figure indicates that: (1) z_0/h is small, about 0.02 during 1th to 20th of the March; (2) z_0/h increases gradually from 20th March, to the beginning of April, and reaches the maximum, about 0.08; (3) from the beginning of March to the end of April, z_0/h always decreases, till 0.06; and from then on, z_0/h changes little. In the above three stages, z_0/h fluctuates slightly.

5-day averaged z_0/h dynamic of Qianyanzhou and Changbai Mountains experimental stations is shown in Fig. 2(b) and (c). Mean annual z_0/h of Qianyanzhou Experimental Station is about 0.083, variance is 0.026, and coefficient of variation is 0.313, and mean annual z_0/h of Changbai Mountains Experimental Station is about 0.072, variation is 0.014, and coefficient of variation is 0.194. Furthermore, in Changbai Mountains Experimental Station, z_0/h is higher and fluctuating greater in growing season than in leaf-off season. In growing season, mean value of z_0/h is 0.077 and variation is 0.053; while in leaf-off season, z_0/h is 0.069 and variation is 0.034. Obviously, in the three experimental stations, z_0/h dynamic in Qianyanzhou Experimental Station is the greatest.

z_0 is the integration of all rough elements, flow and turbulence. It means that z_0 depends on all rough elements (including geometric roughness length of roughness elements and its density and distribution) and the flow in the fetch. As for surfaces covered by vegetations, roughness conditions and drag of the surface are influenced by LAI and vegetation height. Commonly airflow fetch is a sector, therefore, rough conditions including rough elements and its distribution, types, and density are different in different wind directions, even in the same region. Furthermore, in the three experimental stations the surfaces are covered by elastic vegetations, so force that flow applies on vegetation changes with wind speed, which means that aerodynamic roughness length could be influenced by wind speed. In a word, roughness length is influenced by LAI, wind direction, and wind speed. The next following sections will analyze roughness length dynamic further.

3.2 Discussion

(1) z_0 Changes with wind direction. Aerodynamic roughness length changes with terrain and topography, which means that it changes with wind direction[12]. In a heterogeneous region with undulant terrain, rough elements and its distribution are diverse in different wind directions. Therefore, aerodynamic roughness length is different in different wind directions. Relation (12) indicates that undulate terrain leads to the increase of aerodynamic roughness length. In the relation, undulate terrain means the increase of ∇z_s, which leads to the increase of F_p. That is to say, as for a certain regin, z_0 would increases if terrain turns more undulant.

$$F_p = \int_A p_s \nabla z_s dxdy / A, \qquad (12)$$

where z_s is terrain height; ∇z_s is the degree of undulate; F_p, p_s and A are drag, pressure and area, respectively.

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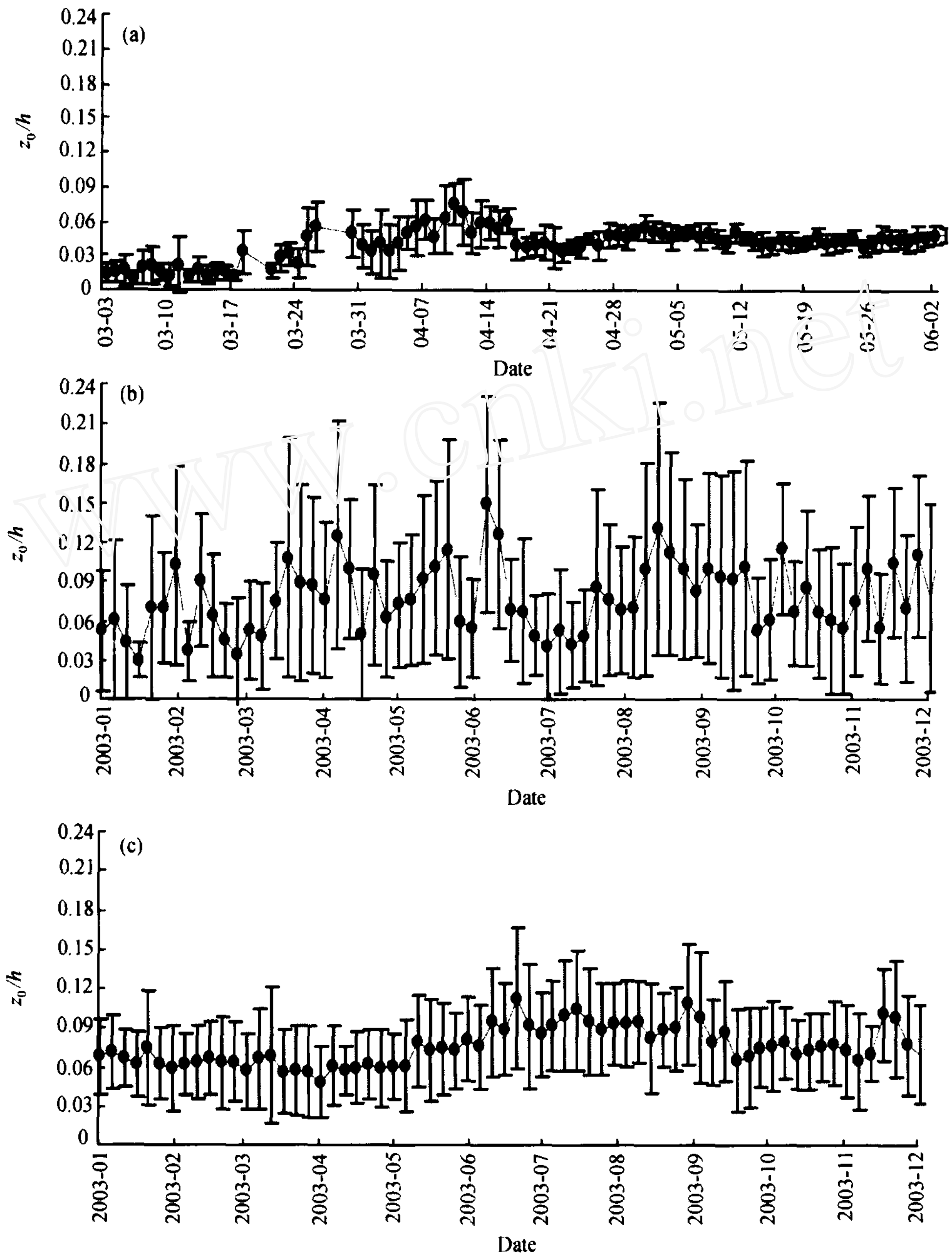

Fig. 2. 1-day averaged z_0/h dynamic of Yucheng Experimental Station (a), 5-day averaged z_0/h dynamic of Qianyanzhou Experimental Station (b) and Changbai Mountains Experimental Station (c).

The relation between wind direction (terrain) and z_0/h is shown in Fig. 3. Obviously, the main wind direction in Yucheng Experimental Station is 0−60°, 160−240° and 320−360°, in Qianyanzhou Experimental Station is 0−60°, 160−200° and 300−360°, and in Changbai Mountains Experimental Station is 0−120° and 200−360°. In Fig. 3 the straight-lines denote averaged z_0/h of the three stations respectively. Table 1 describes the mean values and variations of z_0/h in all kinds of atmospheric stability. Table 1 obviously indicates that z_0/h changes with wind direction in all experimental stations. There are two reasons for this phenomenon. The one is that because the surfaces are not homogenous and flat completely, rough conditions in different wind directions are diverse. The other reason is the influence of wind speed and atmospheric stability. Even in the same wind direction, z_0/h changes with atmospheric stability and wind speed. The characteristic of aerodynamic roughness length changes with wind direction in the three

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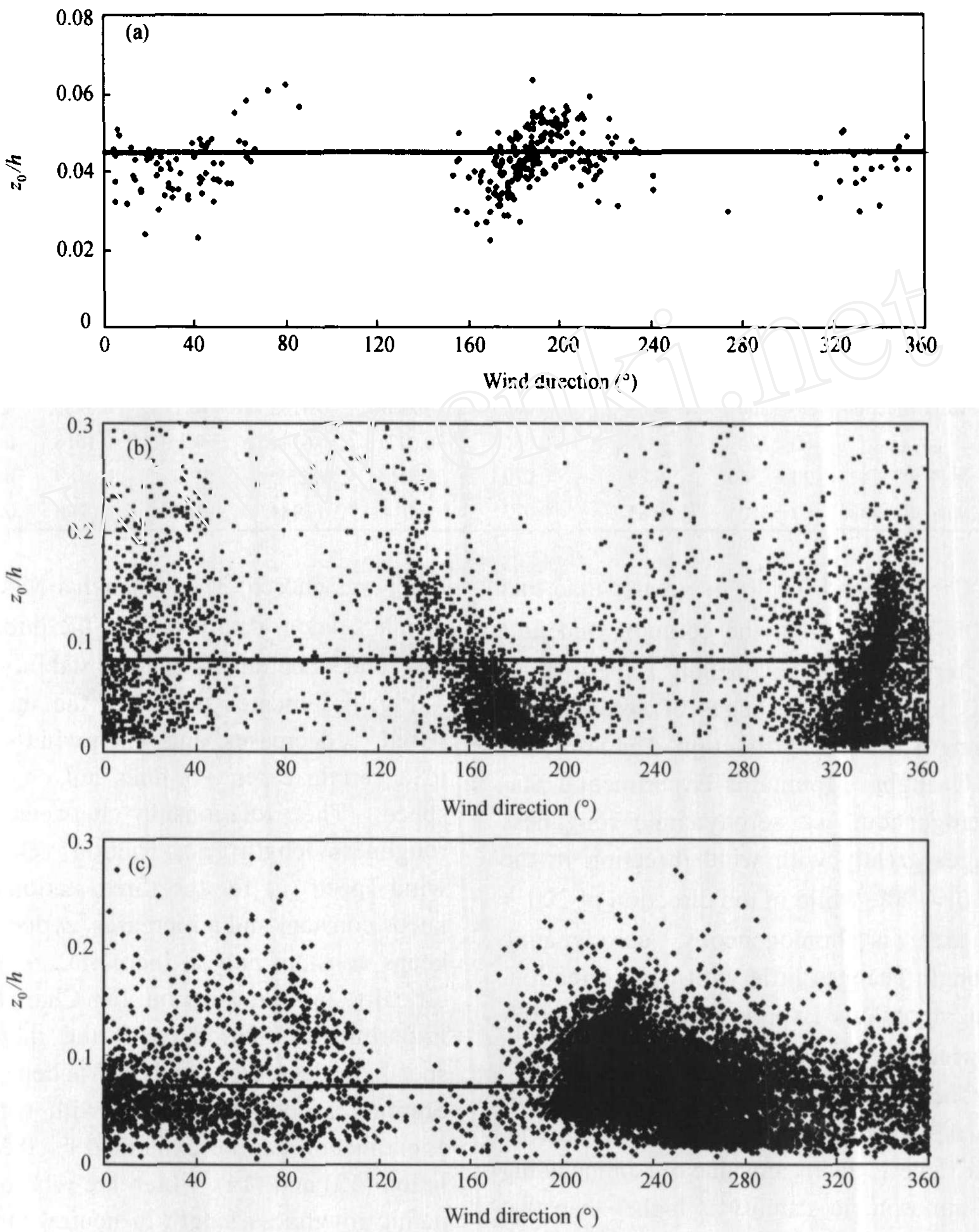

Fig. 3. Change of z_0/h with wind direction in Yucheng Experimental Station (a), Qianyanzhou Experimental Staion (b) and Changbai Mountains Experimental Staion (c).

stations is that, in Yucheng Experimental Station, z_0/h changes slightly with wind direction; in Qianyanzhou Experimental Station, z_0/h changes obviously and greatly with wind direction, except the direction of 160−200°; in Changbai Mountains Experimental Station, z_0/h changes greatly in 0−120°, while changes slightly in 200−360°. Compared with the other two experimental stations, in Yucheng Experimental Station, the surface is more homogenous and flat, and there are fewer obstacles influencing the airflow, Qianyanzhou Experimental Station lies in a hilly area, which leads to undulant and heterogeneous terrain. So, z_0/h changes more frequenly in Qianyanzhou Experimental Station than in Yucheng Experimental Station. Fig. 1 describes that terrain in the south area of Qianyanzhou Experimental Station is a hillslope with gentle and uniform slope, where the geographic roughness length of the rough elements is smaller than that in the north-western area with undulant terrain. So aerodynamic roughness

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Table 1 Average, variance and coefficient of variation of z_0/h in all kinds of wind directions in Yucheng, Qianyanhzhou and Changbai Mountains experimental stations

Location	Wind direction		Atmospheric stability: Percentage (%)	Mean value of z_0/h	Variance	Coefficient of variation	Neutral stability: Percentage (%)	Mean value of z_0/h	Variance	Coefficient of variation
Yucheng Experimental Station	prevailing wind direction	0−60°	25.1	0.042	0.0083	0.1969	8.7	0.0426	0.0061	0.1441
		160−240°	57.8	0.0465	0.0084	0.1801	21.6	0.0478	0.0064	0.1344
		320−360°	7.3	0.0458	0.0065	0.1429	1.5	0.0429	0.0077	0.1768
	wind direction	0−360°	90.2	0.0449	0.0085	0.1899	31.8	0.0464	0.0069	0.1507
Qianyanzhou Experimental Station	prevailing wind direction	0−60°	17.3	0.1051	0.0641	0.61	1.7	0.1131	0.0362	0.3199
		160−200°	21.9	0.044	0.014	0.3191	5.2	0.0478	0.0298	0.6246
		300−360°	44.2	0.0772	0.0357	0.4619	9.3	0.1052	0.0501	0.4762
	wind direction	0−360°	83.4	0.0833	0.026	0.3132	16.2	0.0985	0.0688	0.2265
Changbai Mountains Experimental Station	prevailing wind direction	0−120°	4.2	0.0767	0.0471	0.6144	0.2	0.1018	0.0319	0.3141
		200−360°	94.9	0.0703	0.0168	0.239	19.9	0.0789	0.0231	0.1989
	wind direction	0−360°	99.1	0.0721	0.014	0.1944	20.1	0.0790	0.0235	0.2972

length of 300−360° and 0−40° is greater than that of 160−200°. It means that the complex and heterogeneous terrain of Qianyanzhou Experimental Station leads to the great changes of aerodynamic roughness length with wind direction. The northeast area of the Changbai Mountains Experimental Station is heterogeneous, so aerodynamic roughness length changes greatly with wind direction in the direction of 0−120°, while in the direction of 200−360°, the area is homogeneous, aerodynamic roughness length changes little with wind direction. In Changbai Mountains Experimental Station, 70% of 0−120° wind direction distributes during May and September. Therefore, in leaf-on season, roughness length fluctuates greatly than that in leaf-off season. According to Table 1, the mean value of z_0/h including all kinds of atmospheric stability is higher than that under neutral stability only.

(2) z_0 changes with wind speed and friction velocity. z_0 changes with LAI, atmospheric stability and wind direction (terrain), therefore, in this paper data influenced less by atmospheric stability and wind direction was used to analyze the phenomenon that z_0 changes with wind speed and friction velocity: 1) in Yucheng Experimental Station, data under neutral stability and growing vegetation height and density changes slightly was used to analyze the roughness length changes with wind speed and friction velocity ; 2) in Qianyanzhou Experimental Station, data that is in the direction of 160−200° under neutral atmospheric stability was chosen; 3) in Changbai Mountains Experimental Station, data that is in the direction of 200−360° under neutral atmospheric stability was chosen.

Fig. 4 indicates that with the increase of wind speed, z_0 decreases, and when wind speed increases to a certain extent, z_0 does not change with wind speed. The relationship between aerodynamic roughness length (z_0), friction velocity (u_*), and wind speed (u) for the three stations is that, if u_* keeps constant and u increases, z_0 decreases, and if u keeps constant and u_* increases, z_0 increases. Specifically, in Qianyanzhou and Changbai Mountains Experimental Station, with the increase of wind speed, z_0 decreases, and in Yucheng Experimental Station, z_0 does not change with wind speed. The phenomenon can be explained by the following relation (13) and (14), which are relations for aerodynamic roughness length in neutral atmospheric stability based on Monin-Obukhov similarity theory:

$$z_0 = (z-d) \cdot e^{\frac{-ku}{u_*}}, \quad (13)$$

$$\frac{u}{u_*} = C_D^{-1/2}, \quad (14)$$

where C_D is the drag coefficient. Relation (14) and (15) indicate that with the increase of drag coefficient, z_0 increases. And the increase of u_* means the increase of friction, which indicates that the resistance increases and leads to the increase of z_0. The higher the wind speed is, the more strenuous the turbulence is, and the lower z_0 is[13]. Vogt *et al.*[14] found that the relationship

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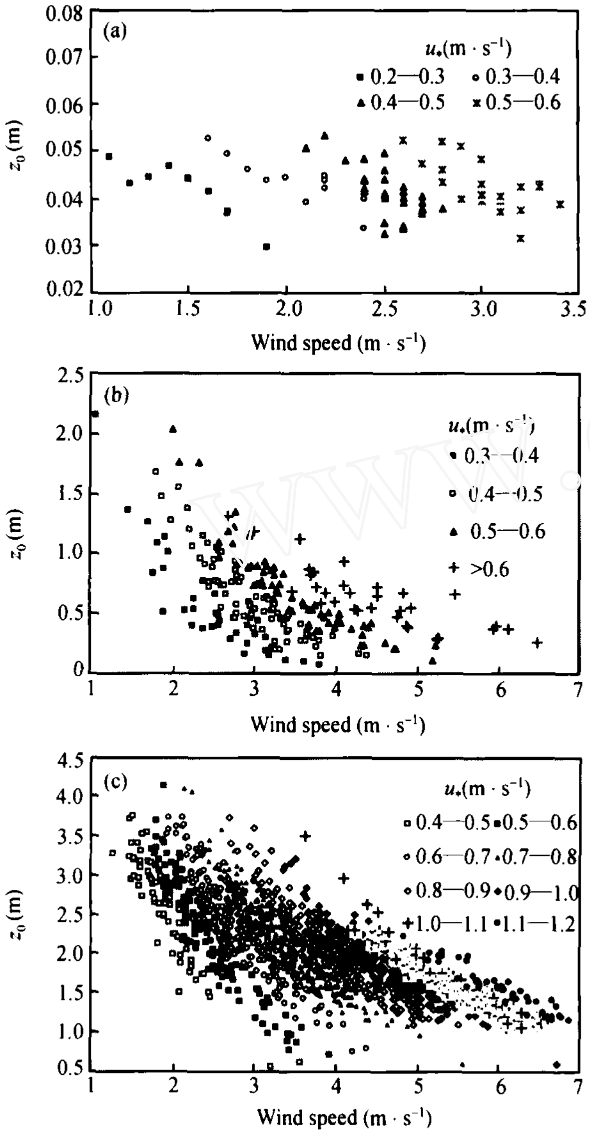

Fig. 4. Change of z_0 with wind speed in Yucheng Experimental Station (a), Qianyanzhou Experimental Station (b), and Changbai Mountains Experimental Station(c).

of z_0, d with wind speed is influenced by wind speed of the lowest level above vegetation, and the heights of wind profile. The relationship would change by changing the heights of wind profile, and the relationship needs further study.

(3) z_0 changes with LAI. In Yucheng Experimental Station, during March and June, vegetation height and LAI changes obviously and greatly. Vegetation height turned from 0 to 0.932 m, and LAI from 0 to 5. Fig. 5 (a) describes the relationship between z_0/h and LAI in Yucheng Experimental Station in 1999. With the increase of LAI, z_0/h increases, and when LAI increases to a certain value, z_0/h begins to decrease with the increase of LAI. It means that z_0/h related closely to LAI. At first, the vegetation is very sparse and low, leaves are very soft, and LAI is small, the resistance of flow on surface is small, which means z_0/h is small; gradually with vegetation growing, the LAI becomes large. It means the geometric roughness length increases, the resistance increases, which leads to the z_0/h increases; with LAI increases continuously and to a certain value, z_0/h begins to decreases. Fig. 5(b) shows the change of z_0/h with LAI in Changbai Mountains Experimental Station. Roughness length of Changbai Mountains Experimental Station has seasonality for differentiating between leaf-off and leaf-on conditions. During the leaf-off season from October to May of the next year, LAI is much smaller than that of leaf-on season from May to September. The data that in the direction of 200—360° was chosen to analyze the effect of LAI on roughness length. Fig. 5(b) indicates that with the increase of LAI, roughness length increases firstly, and then decreases. Shaw and Raupach found that z_0/h increase with the increase of LAI, and then decreases[15,16]. The relationship of the roughness length and LAI in this paper is the same as Shaw's result. As for Qianyanzhou Experimental Station, LAI changes slightly, and terrain is undulant and heterogeneous, the relationship between z_0/h and LAI is not obvious.

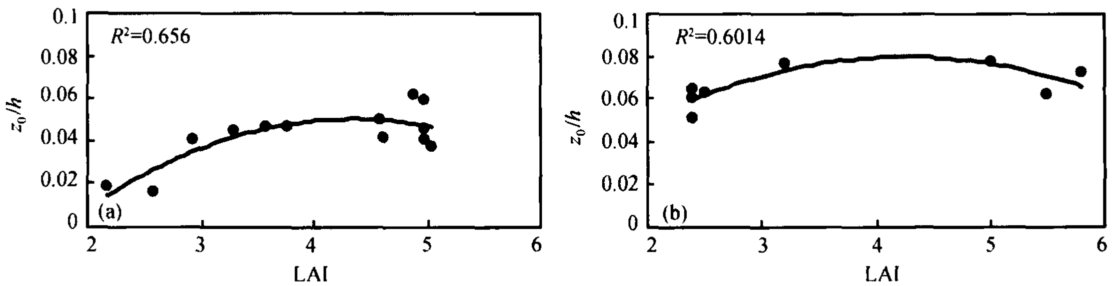

Fig. 5. Change of z_0/h with LAI in Yucheng Experiemntal Staion (a) and Changbai Mountains Experimental Staion (b).

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Shaw explained that if LAI varies from 1.9 to 6 and Z_{max}/h is larger than 0.6, d is about 0.6 to 0.86, and z_0/h is about 0.04−0.09. This result is applicable for forest surfaces with homogeneous terrain. In this paper, terrain of Qianyanzhou and Changbai Mountains Experimental Station are both incompletely homogeneous, especially Qianyanzhou Experimental Station, which leads to the increase of roughness length. So averaged z_0/h in Qianyanzhou is 0.083, but the maximum roughness length reaches 0.15. And in Changbai Mountains Experimental Station, z_0/h is mostly from 0.06 to 0.09, mean value is 0.072, and the maximum value reaches 0.12.

Zhao *et al.*[17] calculated roughness length of Changbai Mountains Experimental Station during August in 2002 to December in 2003 by Newton iterative method. One of he results is that z_0/h is higher in leaf-off season than that in leaf-on season, which is not matching with the result of this paper. The reason for this is that in this paper, roughness length was calculated in all kinds of atmospheric stability, including stable stability, unstable stability and neutral stability. Approximately 70% of 0−120° wind direction distributed in leaf-on season during May and September, while under neutral stability, only 0.2% of 0−120° wind direction distributed during leaf-on season. In 0−120° wind direction, the surface is heterogeneous and undulant, which is the factor that leads to the increase of roughness length. So in this paper, z_0/h is higher in leaf-on season and fluctuates more greatly than that of leaf-off season.

4 Effects of aerodynamic roughness length on flux calculation

Thermal and momentum roughness length, vapor resistance and some other parameters, which are the function of roughness length, are significant parameters in most fluxes reversion models. Actually, z_0 changes obviously with LAI, wind speed, wind direction and friction velocity, but in models, z_0 is always viewed as a constant. So there is deviation between actual roughness length and the roughness length used in models, and the deviation of roughness length will lead to modeled sensible heat inaccuracy. Kustas[18] once took a sensibility analysis about effects of z_0 on sensible heat flux calculation. The analysis indicated that there would be approximately 10% of error, if z_0 increases from 0.01 to 0.1. In this paper SEBS model[19] is chosen as an example to analyze the effects of z_0 on sensible heat flux calculation.

In SEBS model, sensible heat flux is calculated according to the following relations:

$$z_{om}/h=0.136, \tag{15}$$

$$z_{oh}=\frac{z_{om}}{\exp(kB^{-1})}, \tag{16}$$

$$u=\frac{u_*}{k}\left[\ln\left(\frac{z-d_0}{z_{om}}\right)-\Psi_m\left(\frac{z-d_0}{L}\right)+\Psi_m\left(\frac{z_{om}}{L}\right)\right], \tag{17}$$

$$H=ku_*\rho C_p(\theta_0-\theta_a)\left[\ln\left(\frac{z-d_0}{z_{0h}}\right)-\varphi_h\left(\frac{z-d_0}{L}\right)+\varphi_h\left(\frac{z_{0h}}{L}\right)\right]^{-1}, \tag{18}$$

where z is the reference height, d_0 is zero-plane displacement, u_* is friction velocity, ρ is air density, z_{oh} is thermal roughness length, z_{om} is momentum roughness length, θ_0 is surface potential temperature, θ_a is potential temperature at the parameter height, Ψ_m and Ψ_h are stability adjusted function for momentum and sensible heat transfer, L is Monlin-Obukhov constant.

In models, the roughness length is obtained by look-up tables. In this paper, the mean value of roughness length of Yucheng, Qianyanzhou, and Changbai Mountains Experimental Station were taken as the parameter of the model. However, as the fact that roughness length changes with wind speed, wind direction, LAI and some other factors, the deviation between actual roughness length and roughness length chosen by models will lead to calculated sensible heat flux error. In Yucheng Experimental Station, z_0 changes mainly with LAI and vegetation height. Therefore, data during 1th of May to 3th of June were chosen to calculate mean value of z_0. Correspondingly, time scale of Yucheng Experimental Station is 1 d, while in Qianyanzhou and Changbai Mountains Station is 5 d.

The effect of roughness length on sensible heat flux calculation γ is calculated by the following relation:

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$$\gamma = \frac{H_{\bar{z}_0} - H_{z_0}}{H_{z_0}} \times 100\%, \qquad (19)$$

where $H_{\bar{z}_0}$ is sensible heat flux calculated by mean roughness length, H_{z_0} is sensible heat flux calculated by actual roughness length. γ is sensible heat flux error between calculated sensible heat by mean roughness length and actual roughness length.

Fig. 6 (a) and (b) indicate the sensible heat flux error due to roughness length dynamics. In Yucheng Experimental Station, roughness length dynamic is minor, which leads to very small roughness length error. The maximal γ of Yucheng Experimental Station is 2.726%, while in Qianyanzhou and Changbai Mountains experimental stations, roughness length dynamic is greater, where the greatest error reaches to 33.802% and 18.105%, respectively. In the three stations, there are calculated flux errors because of roughness length dynamic, especially in Qianyanzhou Experimental Station. Therefore, roughness length dynamic should be taken accounted for fluxes calculating by models, and suitable roughness length should be taken according to different wind speed, wind direction, and LAI.

In conclusion, there are great error between calculated sensible heat by average roughness length and that by actual roughness length. Therefore, appropriate roughness length should be chosen to calculate fluxes by models.

5 Conclusions

In this paper, aerodynamic roughness length of Yucheng, Qianyanzhou, and Changbai Mountains experimental stations are calculated iteratively by least-square method with wind speed and temperature profiles in four horizontal levels. The result shows that, aerodynamic roughness length changes greatly with LAI, wind direction, wind speed and some other parameters.

(1) In Yucheng Experimental Station, aerodynamic roughness length changes mainly with LAI. With the increase of LAI, aerodynamic roughness length firstly increases to the peak, and then decreases. In Qianyanzhou Experimental Station, undulant and heterogeneous terrain is the main reason for great fluctuates of aerodynamic roughness length. In Changbai Mountains Experimental Station, the change of LAI in abscission and growing seasons and wind speed changes in the uppermost level lead to the aerodynamic roughness length fluctuate. In Changbai Mountains Experimental Station, with the increase of LAI, aerodynamic roughness length increases first to the peak, then decreases, which is the same as the aerodynamic roughness length change in Yucheng Experimental Station, and in Changbai Mountains Experimental Station, aerodynamic roughness length in growing season is higher than that in abscission season, and what is more, with the increase of wind speed in the uppermost level, aerodynamic roughness length decreases.

(2) By analyzing the effects of aerodynamic roughness length on sensible heat flux calculation with SEBS model, the result indicates that, in Yucheng Experimental Station, the error of sensible heat flux modeled by SEBS model can reach 2.726%, in Qianyanzhou Experimental Station, the maximum error is

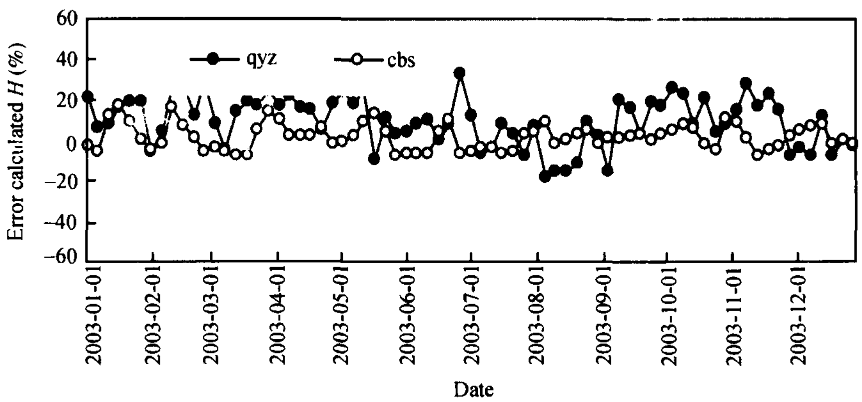

Fig. 6. Relative error of calculated H by SEBS model due to z_0 dynamic in Qianyanzhou and Changbai Mountains experimental stations.

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33.802%, and in Changbai Mountains Experimental Station, the maximum error is 18.105% respectively. So in order to calculate fluxes accurately, appropriate aerodynamic roughness length should be taken according to LAI, wind direction, and wind speed.

In this paper, aerodynamic roughness length was calculated iteratively by least-square method. This method has two uncertainties. The one is highly accurate wind speed data, the other is the undulant and heterogeneous terrain. The area of "source" is different in corresponding horizontal levels, and measured wind speed accuracy in various horizontal levels is uncertain. Nowadays, calculating roughness length in all atmospheric stabilities is still dependent on wind profiles, so the applicability of calculating method by wind profiles over heterogeneous surfaces needs to be studied further[20].

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