Parameterization of Heat Transfer between the Land Surface and the Atmosphere in Mongolian Steppe

KOTANI Ayumi[1] and SUGITA Michiaki[2]

1 Japan Science and Technology Agency, 322-0012, Japan
2 Graduate School of Life and Environmental Sciences, University of Tsukuba, 305-8572, Japan

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Introduction

Roughness length, which is needed for the estimation of surface flux of momentum and scalar variables, is one of the most important parameters for surface parameterization of the atmospheric circulation model (e.g., Noilhan and Planton, 1989; Dolman, 1993) or the application of the remotely sensed temperature data to flux estimation (e.g., Brutsaert and Sugita, 1992). Furthermore, investigation of its characteristics helps understanding mechanisms of the interaction between land surface and overlying atmosphere. Over the past few decades, several studies have been made on these surface parameters such as transfer coefficients, conductance or resistance in addition to roughness length and their correspondence with various vegetation types.

The object of this paper is to investigate relation between plant parameters and roughness length for heat transfer at the extremely sparse vegetation field of Mongolian Steppe area.

Data

The dataset used in this study was collected in the framework of the Rangelands Atmosphere-Hydrosphere-Biosphere Interaction Study Experiment in Northeastern Asia (RAISE, Sugita et al., 2006). The RAISE study area covers the Kherlen river basin in the north-eastern part of Mongolia, where arid to semi-arid climate is dominant with a boreal forest in the northern and upper reaches of the watershed and steppe area towards the southern and downstream parts. The target area was located at and around a village called Kherlenbayan-Ulaan (47° 13´ N, 108° 44´ E, 1235 m ASL, to be referred to as KBU hereafter); its surface vegetation is comprised mainly of the cool-season C_3 species and a few C_4 species (Li et al., 2006) with their height around 0.2 m and leaf area index 0.5 even at the peak growing season mainly because of the extensive grazing activities in this area (Sugita et al., 2006). In addition to the KBU station, data from the four other measurement stations were used. Those stations locate on the pasture field around the RAISE study area and the distance from the KBU site is 140 km at most.

At KBU, the details of the observation station have been presented in Li et al. (2006) and Sugita et al. (2006), but for the purpose of the present study, use was made of the air temperature and wind velocity components measured at 10 Hz by the combination of an ultrasonic anemometer-thermometer (SAT-550, Kaijo Sonic Co.) and an open path infrared gas-analyser (LI7500, LI-COR Inc.), and the surface flux of the sensible heat H and the latent heat LE calculated by the eddy covariance method for 30 minutes after a process of coordinate rotation (McMillen, 1988; Kaimal and Finnigan, 1994). Also a test of turbulent conditions (Foken and Wichura, 1996) was carried out to eliminate invalid data. The other items used in this study are radiation components (CNR-1, Kipp and Zonen B.V.), air temperature and humidity (HMD45D, Vaisala Oyj.) measured at 2.5m above the ground, which are also averaged over 30 minutes. A correction based on atmospheric effect was carried out with LOWTRAN7 (Kneizys et al., 1988) for thermal radiation from the ground, from which surface radiant temperature was calculated.

At four other observation stations (AWS: Automatic Weather Station), continuous measurement of the meteorological and hydrological data such as radiation components (MR-40, EKO Instruments Co. Ltd.), wind speed and direction (03002, M. R. Young Co.), air temperature and humidity (HMP-45D, Vaisala Oyj.) were made. At these sites, occasional observations of H and LE with similar performance instruments (R3, Gill Instruments, Ltd. and KH20, Campbel Science, Inc.) was carried out four times during the plant growing season of 2003 (one or two days in June, July, August and October for each site). Those data were processed and selected as the same way as the KBU station.

The leaf area index (LAI) A_L, mean plant height h, plant coverage C, and aboveground biomass B was measured at the KBU station (Li et al., 2005; Urano, 2004), and at the AWSs (Kojima, 2004) during the same period of flux observation. Figure1 shows seasonal variations of measured A_L, h, C and B at these stations. For the data of KBU station, the temporal gaps of these measurements were filled by the cubic fitting curve derived by least square and the data set of dairy value was produced. The period during which plant was active was from April 23 to October 21 as reported by the Bio-stations operated by Institute of Meteorology and Hydrology of Mongolia.

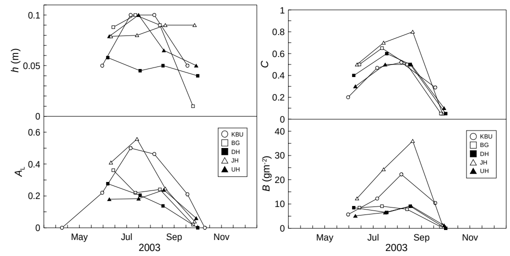

Figure 1. Seasonal variation of plant height (h), leaf area index (A_L), plant coverage (C), and above-ground biomass (B). BG, DH, JH and UH is name of the AWS station.

The roughness length was calculated with Monin-Obukhov similarity (MOS), in which surface fluxes of momentum and sensible heat are related to vertical profiles of wind speed and temperature, respectively (i.e., Brutsaert, 1982);

$$u = \frac{u_*}{k}\left[\ln\left(\frac{z-d}{z_{0m}}\right) - \Psi_m\right] \qquad (1)$$

$$\theta_s - \theta = \frac{H}{ku_*\rho c_p}\left[\ln\left(\frac{z-d}{z_{0h}}\right) - \Psi_h\right] \qquad (2)$$

where z_{0m} and z_{0h} are the roughness length for momentum and heat transfer, respectively, z is the reference height, U is the wind speed, θ is the air temperature, u_* is the friction velocity, $k = 0.4$ is the von Kármán constant, c_p is the specific heat for constant pressure, ρ is the air density. The surface temperature θ_s was evaluated by the infrared radiation from the ground surface as described above. The displacement height d was estimated from a general relationship to the height of roughness elements that is representative plant height h in this study (e.g., Brutsaert, 1982): $d = (2/3)h$. The symbols Ψ_m and Ψ_h present the stability correction function for momentum and heat transfer, respectively. From these equations, the roughness length for momentum and heat can be calculated.

For the evaluation of the surface roughness length, the data, checked from the viewpoint of turbulent measurement as described above, were further filtered by some criteria; i) no precipitation was observed, ii) mean wind velocity and friction velocity were larger than 1.0 and 2.5 m s^{-1}, respectively, iii) wind flow was not from direction of the instruments, and iv) atmospheric stability was near neutral ($-0.1 < (z - d)L^{-1} < 0.1$ with Obukhov length L). In addition, for the case of calculation of temperature roughness length, v) value of measured H was larger than 50 W m^{-2}, and vi) difference between the air temperature and the surface radiant temperature was more than 3 K, and thus the number of dataset is smaller for temperature roughness.

The KBU data set from July to September 2003 as active vegetation period, and April 2006 as dormant vegetation period was used for the analysis, and after the all data screenings, 11 data for July to August 2003, 9 for September 2003, and 20 for April 2006 were selected. The AWS data was also selected with the same criteria and 44 dataset of four sites for all the observation period were used for the analysis.

Results and Discussion

The values of roughness length show dependence on the surface characteristics and the atmospheric conditions in various time scales and both of them related in complex manner. To see the seasonal variation due to the surface characteristics, a plot of z_{0m} and z_{0h} for 30 minutes average against the leaf area index (LAI) is shown in Figure 2 and 3, respectively. When the LAI value was close to zero, which corresponds to the period before plants growth starts (for KBU) and the plant senescence period (for AWSs), the value of z_{0m} was smaller and z_{0h} was larger than those of active vegetation period. Consequently, the ratio of z_{0m} to z_{0h} was smaller when LAI was small, which is common for smooth surface (Brutsaert, 1982). The momentum roughness was almost constant through the active vegetation period, which indicates that effect of increasing plant was smaller than that of surface geometry.

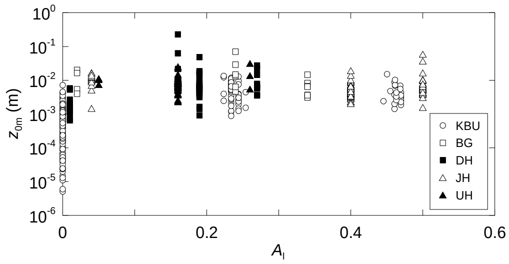

Figure 2. Relation between roughness length for momentum (z_{0m}) and leaf area index (A_L).

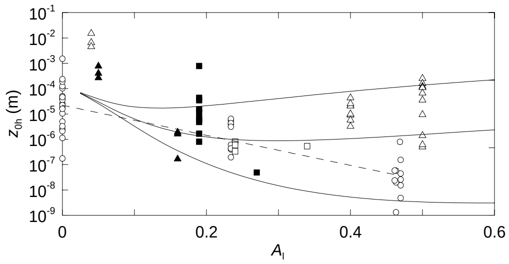

Figure 3. Relation between roughness length for heat (z_{0h}) and leaf area index (A_L). Solid and broken lines present the model results based on Watanabe (1994) and fitting curve for the KBU value.

On the other hand, the temperature roughness decreased with increasing LAI until around 0.3 - 0.4 and beyond there the tendency was not clear. One explanation for this tendency is that difference in canopy structure of the sites affects the transfer process. Quantitatively vegetative characteristics at KBU and JH are similar in terms of plant height and LAI through the active vegetation period but rather different in aboveground biomass as shown in Figure 1. Biomass of JH was larger than the other sites especially at the peak of plant growing. This difference is due to the definition of LAI. It contains only live leaves while stems and dead leaves are excluded from LAI. The plant canopy of JH contained some forbs having more stems (Li, personal communication), which might increase surface area and become source of sensible heat. The change of z_{0h} with increasing LAI is also presented in some model studies, in which contribution of the soil surface was considered and LAI was used for determining vertical structure of momentum or scalar source and transfer parameters inside vegetation canopy (i.e., Massman, 1999; Lhomme et al., 2000). Application of the multi-layer canopy model of Kondo and Watanabe (1992) and its parameterized expression derived by Watanabe (1994) indicates that the tendency of z_{0h} at this LAI range depends on ratio of leaf transfer coefficient for momentum and heat, and these lines are also drawn in Figure 3. This ratio partly depends on direction of leaves, and the different characteristics of canopy structure mentioned above could contribute to that parameter. From the observation results, the dependency of z_{0h} on LAI is also parameterized by several authors such as Qualls and Brutsaert (1996), who showed a negative relation between LAI and $\ln(z_{0m} / z_{0h})$, that can be translated to a positive relation between them with almost constant z_{0m}. However, their data of LAI cover mainly more than 0.5 and the decrease of z_{0h} at small LAI was not presented.

Here, a simple parameterization of z_{0h} based on Figure 3, in which relation of z_{0h} and LAI is shown exponentially, is proposed as

$$z_{0h} = z_{00} \exp\left(bA_L\right) \qquad (3)$$

where z_{00} indicates temperature roughness length of bare soil surface, and z_{00} and constant b could be determined to minimize the rms difference between the observed and the predicted H. With our dataset of the KBU site, they were optimized as $z_{00} = 1.0 \times 10^{-5}$ and $b = -12.8$. This functional curve is also drawn in Figure 3. Furthermore, considering the effect of wind speed and temperature difference as treated by Kustas et al. (1989), these terms are added to (3) as follows;

$$z_{0h} = z_{00} \exp\left(bA_L + U^{c_1} \left(\theta_s - \theta\right)^{-c_2}\right) \qquad (4)$$

The constants c_1 = 8.8, and c_2 = 5.4 were also determined by the same manner as the other optimized constants, and estimation of H with these constants and Eq.(4) results in 18 W m^{-2} of rms difference from the observation as shown in right panel of Figure 4. This formulation intends to represent the seasonal variation following plant growth and daily variation due to the atmospheric conditions. However, the inter-seasonal variability of z_{0h} due to the effects of wind speed and temperature difference is not clear since data tested in this study is limited in near neutral condition (Figure 4, left). For comparison, some of z_{0h} parameterizations proposed in the literature were also tested to evaluate sensible heat flux. First, for rough surface without permeable feature such as vegetative canopy, the theoretical model of Brutsaert (1975) is applicable, in which the ratio of z_{0m} to z_{0h} is expressed with roughness Reynolds number. Second is Su et al. (2001)'s parameterization based on Massman (1999)'s dual source model, which consists of vegetative and soil surface and these sources are weighted with the cover fraction. Meanwhile, Yang et al. (2003) proposed the empirical formulation at very sparse and short grassland. These expressions reproduced 30-40 W m^{-2} of rms difference from the observation (Table 1).

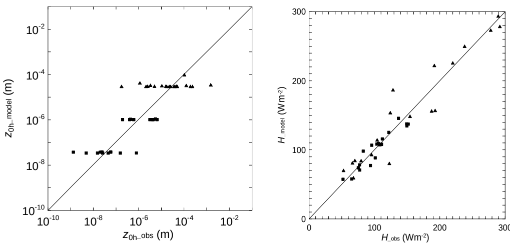

Figure 4 (left) Comparison of the estimated z_{0h} with (4) and the observed. (right) same for sensible heat flux H.

Table 1 Results of sensible heat estimation

Model	RMSD(Wm^{-2})
Brutsaert (1975)	30
Su et al. (2001)	27
Yang et al. (2003)	43(34*)
This study : Eq. (4)	18

* in the case of empirical constants optimized for the current dataset

Finally, the expression (4) was applied to the AWS data to evaluate temperature roughness and sensible heat flux. The rms error of the calculated H from observed H with eddy covariance methods falls around 50 W m^{-2}. This rather large deviation might have been caused by insufficient accuracy of temperature measurement by a thermometer with only natural ventilation at the AWS, and the different tendency of z_{0h} due to the characteristics of vegetation canopy which is not presented by LAI alone.

Conclusion

Roughness length for momentum and heat

transfer, based on Monin-Obukhov similarity expressions, obtained at Mongolian steppe field was investigated. In the study area, active vegetation season began at the end of April and lasted to the middle of October and maximum LAI 0.5 and mean canopy height 0.2 m were observed at the middle of July. The analysis was carried out with the dataset of ground-based observation from July through September of 2003 and April of 2006.

The development of vegetation was followed by temperature roughness length while the momentum roughness was almost constant. The roughness length for heat transfer is explained mainly by LAI, and parameterization with LAI, wind speed and difference of air-surface temperature reproduced the sensible heat flux of 18 W m^{-2} of rms difference from the observation. This parameterization produced better result than previous formulations.

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