Parameterisation of aerodynamic roughness
over boreal, cool- and warm-temperate forests

Taro Nakai\textsuperscript{a,b,*}, Akihiro Sumida\textsuperscript{b}, Ken’ichi Daikoku\textsuperscript{c},
Kazuho Matsumoto\textsuperscript{c}, Michiel K. van der Molen\textsuperscript{d},
Yuji Kodama\textsuperscript{b}, Alexander V. Kononov\textsuperscript{e}, Trofim C. Maximov\textsuperscript{e},
Albertus J. Dolman\textsuperscript{d}, Hironori Yabuki\textsuperscript{f}, Toshihiko Hara\textsuperscript{b},
Takeshi Ohta\textsuperscript{c,a}

\textsuperscript{a}CREST, Japan Science and Technology Agency, Kawaguchi, Saitama 332-0012, Japan

\textsuperscript{b}Institute of Low Temperature Science, Hokkaido University, N19 W8, Kita-Ku, Sapporo 060-0819, Japan

\textsuperscript{c}Graduate School of Bioagricultural Sciences, Nagoya University, Nagoya 464-8601, Japan

\textsuperscript{d}Department of Hydrology and Geo-Environmental Sciences, Faculty of Earth and Life Sciences, Vrije Universiteit, de Boelelaan 1085, 1081 HV, Amsterdam, The Netherlands

\textsuperscript{e}Institute for Biological Problems of Cryolithozone, Siberian Division of Russian Academy of Sciences, 41 Lenin ave., Yakutsk 677891, Russia

\textsuperscript{f}Institute of Observational Research Center for Global Change, Yokosuka 237-0061, Japan
Abstract

Roughness length and zero-plane displacement over boreal, cool- and warm-temperate forests were observed and parameterised using forest structure data. Previous models for roughness length and zero-plane displacement using leaf area index and frontal area index did not describe intersite differences, and the model for zero-plane displacement did not express seasonal variations with the change of leaf area that was smaller in dense forest than in sparse forest. The observed results show that intersite differences of normalised zero-plane displacement were related to stand density, and seasonal variations were related to leaf area index at each forest, with the degree depending on stand density. From these observations, a new concept is proposed for normalised zero-plane displacement: the basal part is primarily determined by the density of stems and branches (stand density), while the seasonal variation depends on the density of leaves (leaf area index), which is limited to the residual of the basal part. Based on this concept, a new model was developed and verified to express both intersite differences and seasonal variations in observed roughness length and zero-plane displacement.

Key words: roughness length, zero-plane displacement, stand density, leaf area index

* Corresponding author. Tel.: +81-11-706-7437; fax: +81-11-706-7142. Email address: taro@pop.lowtem.hokudai.ac.jp (Taro Nakai).
1 Introduction

Zero-plane displacement $d$ (m) and roughness length $z_0$ (m) are essential for micrometeorological studies over tall vegetation canopies. $d$ is regarded as the level of action of the drag on the roughness elements (Thom, 1971), and is required for many variables, such as the stability parameter $\zeta = (z - d)/L$ (where $z$ [m] is the measurement height above the actual ground surface, and $L$ [m] is the Obukhov length), since most theories of the atmospheric boundary layer are built for the scale height $z - d$ (e.g. Garratt, 1994). On the other hand, $z_0$ is the length scale that characterises the loss of wind momentum attributable to the roughness elements (Minvielle et al., 2003). $d$ and $z_0$ are calculated from the vertical profile of wind speed measured at several heights. However, it is recognised that determination of $d$ and $z_0$ is practically difficult since they can vary with uncertainty in the measurements (e.g. Schaudt, 1998). When $d$ and $z_0$ are used for length scale, as mentioned above, representative values of these terms are required.

$d$ and $z_0$ are also important factors in global climate models. The land surface models for general circulation models require $d$ and $z_0$ to be representative for the scale of each grid cell of the models (e.g. Verhoef et al., 1997; Schaudt and Dickinson, 2000). Since the site-specific data of $d$ and $z_0$ represent small local scales, $d$ and $z_0$ for such models are expected to be parameterised as a function of forest structure factors that can be obtained from satellite data.

From the above circumstances, many efforts have been made to develop parameterisations for $d$ and $z_0$ with canopy structures (Yang and Friedl, 2003). The simple relations of $d$ and $z_0$ to canopy height $h$ (m), such as $d/h = 0.64$
(Cowan, 1968) and $z_0/h = 0.13$ (Tanner and Pelton, 1960), are frequently used. However, $d/h$ and $z_0/h$ are not constants and vary with the density of roughness elements (see Garratt, 1994). To represent the density of the canopy, two parameters have been used. Choudhury and Monteith (1988) used leaf area index (LAI) to parameterise $d/h$ and $z_0/h$ based on the second-order closure model results of Shaw and Pereira (1982). Raupach (1994) provided the method to derive $d/h$ and $z_0/h$ using frontal area index (FAI), which is the total frontal area (width $\times$ height of elements) per unit ground area. Recently, FAI and the model of Raupach (1994) were adopted to estimate $d/h$ and $z_0/h$ from satellite data (e.g. Jasinski and Crago, 1999; Schaudt and Dickinson, 2000). However, few studies have checked the applicability of these models to $d/h$ and $z_0/h$ obtained from field experiments over forests (e.g. Yang and Friedl, 2003).

The objectives of this study were to assess the validity of previous models of $d/h$ and $z_0/h$ against observed data from five different forests in boreal, cool-temperate and warm-temperate areas, and to provide alternative parameterisation to describe the observed $d/h$ and $z_0/h$ using forest structure factors.

2 Previous models for $d/h$ and $z_0/h$

Choudhury and Monteith (1988) proposed the following parameterisations of $d/h$ and $z_0/h$ with LAI, $A$ ($m^2 m^{-2}$), by fitting them to curves derived from the second-order closure model given by Shaw and Pereira (1982).

$$
\frac{d}{h} = 1.1 \ln \left[ 1.0 + (c_d A)^{1/4} \right]
$$

(1)
where $c_d (= 0.2)$ is the mean drag coefficient for individual leaves and $z_0'$ is the roughness length of the soil surface. Following Schaudt and Dickinson (2000), the value of $z_0'/h = 0.000860$ was used as the asymptotic value for bare soil.

However, Raupach (1994) related $d/h$ and $z_0/h$ to FAI, $\lambda$ (m$^2$ m$^{-2}$), and derived the following expressions.

$$
\frac{d}{h} = 1.0 - \frac{1.0 - \exp(-\sqrt{a_1} \lambda)}{\sqrt{a_1} \lambda} \quad (4)
$$

$$
\frac{z_0}{h} = a_2 \exp(-b_2 \lambda^{c_2}) \lambda^{d_2} + \frac{z_0'}{h} \quad (\lambda \leq 0.152) \quad (5)
$$

$$
\frac{z_0}{h} = \frac{a_3}{\lambda^{d_3}} [1.0 - \exp(-b_3 \lambda^{c_3})] + f_2 \quad (\lambda > 0.152) \quad (6)
$$

where $a_1 = 15.0$, $a_2 = 5.86$, $b_2 = 10.9$, $c_2 = 1.12$, $d_2 = 1.33$, $a_3 = 0.0537$, $b_3 = 10.9$, $c_3 = 0.874$, $d_3 = 0.510$ and $f_2 = 0.00368$ (Schaudt and Dickinson, 2000).

After Raupach (1994), Schaudt and Dickinson (2000) considered effects of both LAI and FAI on $d/h$ and $z_0/h$. Their method is based on Raupach (1994), and included the effect of LAI using the dependence of $d/h$ and $z_0/h$ on LAI from Lindroth (1993). They proposed the functions $f_d$ for $d$ as

$$
f_d = 1.0 - 0.3991 \exp(-0.1779A), \quad (7)
$$

and $f_z$ for $z_0/h$ as

$$
f_z = 0.3299A^{1.5} + 2.1713 \quad (A < 0.8775), \quad (8)
$$
\[ f_z = 1.6771 \exp(-0.1717A) + 1.0 \quad (A \geq 0.8775), \quad (9) \]

and parameterised \( d/h \) and \( z_0/h \) by multiplying Eq. (4) by \( f_d \) and Eq. (5) or Eq. (6) by \( f_z \).

Hereafter, the models of Choudhury and Monteith (1988), Raupach (1994) and Schaudt and Dickinson (2000) are referred to as CM88, R94 and SD00, respectively.

3 Observations

Meteorological observations and forest surveys were conducted in five forest sites: a larch (deciduous conifer) forest (YL) and a pine (evergreen conifer) forest (YP) in Spasskaya Pad, near Yakutsk, Russia (boreal forests); a birch (deciduous broadleaf) forest (MB) and a mixed forest of evergreen conifer and deciduous broadleaf (MM) in Moshiri, Japan (cool-temperate forests); and a mixed forest of evergreen and deciduous broadleaf species (SM) in Seto, Japan (warm-temperate forest). Figure 1 shows the locations of these regions. Locations and altitudes (m) of the sites are listed in Table 1.

Figure 1

Table 1

To calculate \( d \) and \( z_0 \), we observed two wind speeds \( U_1, U_2 \) (m s\(^{-1}\)) at heights \( z_1 \) and \( z_2 \) (m) with cup anemometers, and friction velocity \( u_* \) (m s\(^{-1}\)) at \( z_e \) (m) with an ultrasonic anemometer. These observation heights are also listed in Table 1. The cup anemometers used at these sites were AC-750 (Makino,
Japan) at sites YL and YP, and 010C (MetOne, USA) at sites MB, MM and SM; the ultrasonic anemometers were R3-50 Solent ultrasonic anemometers (Gill Instruments, UK) at sites YL, YP, MB and MM, and DAT-540 (Kaijo, Japan) at site SM. $U_1$ and $U_2$ were sampled at 10-s intervals and averaged over 30 min, and $u_*$ was calculated every 30 min from wind speed data sampled at a rate of 10 Hz. For R3-50, angle-of-attack-dependent errors were corrected in calculating $u_*$ (Nakai et al., 2006). $d$ and $z_0$ under neutral conditions were then calculated as follows (e.g. Rooney, 2001):

$$d = \frac{z_2 \exp(k U_1 / u_*)}{ \exp(k U_1 / u_*)} \frac{\exp(k U_2 / u_*) - 1}{\exp(k U_2 / u_*) - 1}$$

$$z_0 = \frac{z_1 - d}{\exp(k U_1 / u_*)},$$

where $k = 0.4$ (dimensionless) is the von Kármán constant. In calculating daily and monthly $d$ and $z_0$, daily- and monthly-averaged $U_1$, $U_2$ and $u_*$ were calculated using data under neutral conditions ($|z_e/L| < 0.05$, where $L$ [m] is the Obukhov length) and within a limited range of wind directions (see Table 1) to avoid the shadow effect of the tower. Data from 2006 were used for sites YL and YP, from 2004, 2005, and 2006 for sites MB and MM, and from 2004 and 2006 for site SM.

Forest surveys were conducted in 2003 (YL, YP, MB), 2004 (YL, YP, MM), 2005 (SM) and 2006 (YP) to obtain stand density $\rho_s$ (trees ha$^{-1}$), tree height $h_t$ (m), height to the lowest live branch $h_b$ (m), and stem diameter at breast height (1.3 m in height) $D$ (m). The number of sampled trees taller than 1.3 m for each forest was 202 (YL), 643 (YP), 471 (MB), 1029 (MM) and 475 (SM). LAI of these sites was measured using a plant canopy analyser (LAI-2000, LI-COR, Inc., USA) and is thus considered ‘effective LAI’ (Chen et al., 1991);
i.e., the ratio of the total one-sided area of vegetation elements over the unit ground area (Nackaerts et al., 2000). FAI $\lambda$ was calculated using the method of Schaudt and Dickinson (2000). The frontal area of each tree sample $A_f$ was calculated for broadleaf trees as

$$A_f = h_b \times D + \frac{\pi}{4} \times r \times (h_t - h_b)^2$$

(12)

and for coniferous trees as

$$A_f = h_b \times D + \frac{1}{2} \times r \times (h_t - h_b)^2$$

(13)

where $r$ is the crown aspect (height-to-width) ratio given in Table 1 of Schaudt and Dickinson (2000). $A_f$ was calculated for all samples, and $\lambda$ was then calculated as total $A_f$ divided by plot area. Stand density $\rho_s$, LAI $A$ and FAI $\lambda$ are listed in Table 1.

In comparing $d$ and $z_0$ between different forest sites, canopy height $h$ is a key parameter to normalise $d$ and $z_0$ as $d/h$ and $z_0/h$, respectively. This $h$ should be determined by the same objective means without arbitrariness. Mean tree height was the most commonly used parameter. However, for site MM, although the maximum tree height was 33.6 m, the mean tree height was 5.3 m because of the presence of a large number of shorter trees. Thus, a mean tree height does not always represent the canopy structure of a forest.

The representative height of a forest canopy would be better expressed by taking into account the basal areas (cross-sectional area of the trunk at 1.3 m in height) of trees, since taller trees composing the crown surface or the upper canopy would have large basal areas. If several such taller trees occur within a similar height class, the basal areas of trees belonging to this height
class would be largest. Therefore, we could reasonably consider the height of
the distribution peak of the basal areas of trees belonging to each tree height
class as the representative canopy height of a forest. To evaluate this canopy
height analytically, we adopted the following procedure.

1. Sort tree height of samples in increasing order.
2. Plot cumulative basal area against the tree height of samples.
3. Fit this plot by the Gompertz function (e.g. Gompertz, 1825; Franses,
4. Differentiate the fit function of (3) and find the peak of this derivative.

Figure 2 shows the plots of the observed cumulative basal area against tree
height, the fitting curve (Gompertz function) to the observed data, and the
derivative of this fit function for each forest site. The canopy height $h$ was
determined as the height at which the peak of this derivative appeared. Table
1 lists the value of $h$ of each forest. Note that although the maximum tree
height of site MM was taller than the measurement height, this highest tree was
located downslope and distant from the tower (Nakai et al., 2006). Similarly,
the meteorological tower of site SM was located on a mountain ridge, and
relatively tall trees were located downslope. In both sites, the tree heights
near the tower were almost the same as the canopy heights obtained here.
4 Results and discussion

4.1 Validity of previous models

The validity of previous models was checked against observed $d/h$ and $z_0/h$ in the five forest sites. For these analyses, the summertime (JJA) averaged data of daily $d/h$ and $z_0/h$ were used.

Plots in Fig. 3 are scatter diagrams of $d/h$ and $z_0/h$ against LAI, $A$ (Fig. 3a) and FAI, $\lambda$ (Fig. 3b) together with the model outputs of CM88 (Fig. 3a) and R94 (Fig. 3b), respectively. Observed $d/h$ and $z_0/h$ deviated from both CM88 and R94 outputs, especially in site YL, indicating that both models were insufficient to describe actual roughness parameters of forests.

Figure 3

The LAI-based model, CM88, is based on the numerical simulation results of Shaw and Pereira (1982). The model of Shaw and Pereira (1982) dealt with agricultural crops, such as a corn canopy, and thus CM88 would be appropriate for herbaceous plants. However, no attempt was made to represent forest-like stands with a relatively open trunk space in the model of Shaw and Pereira (1982). In the case of agricultural crops, LAI may represent the canopy density, and thus $d/h$ may monotonically increase with LAI. However, for forest stands, stems and branches may affect $d/h$. For example, Dolman (1986) reported that $d/h$ of non-foliated oak forest was 0.57 (stand density 3000 trees ha$^{-1}$). This effect cannot be described by models with only LAI data. In addition, natural self-pruning of branches occurs in forests and may be influenced by stand density (e.g. Mäkinen, 1999). Actually, the relationship between stand density
and LAI in our sites was not clear, and in the case of sites MB, MM and SM, LAI decreased with stand density (Fig. 4). Furthermore, LAI of the forest may reflect effects of stand density and seasonal variation that would be hard to distinguish. Therefore, LAI may not be a good parameter to represent the density of a forest.

However, FAI may also present problems. FAI in this study was calculated using the stand inventory data and crown aspect ratio given by Schaudt and Dickinson (2000). However, this is only an approximate estimate, and the exact (or actual) FAI would be hard to estimate since the shapes of trees are complex. Raupach (1994) indicated that FAI can be estimated as half of LAI, $\lambda = 0.5A$. In this case, the same problem as encountered with CM88 is again raised. So far, arbitrariness or uncertainty in determining FAI cannot be eliminated. In addition, a further question is raised: since FAI is the total frontal area (width $\times$ height of elements) per unit ground area, does the same FAI indicate a high stand density in a short canopy or a low density in a tall canopy (see Fig. 5)? If so, $d/h$ would be large in a short canopy and small in a tall canopy even if both canopies had the same FAI. Hence, FAI also may not represent the density of the forest. The relationship between stand density and FAI in our sites was similarly scattered (Fig. 4).

Figure 4

Figure 5

Figure 6 shows calculated results of $d/h$ and $z_0/h$ with R94 and SM00 against observed values. Considering the effect of LAI, $d/h$ with SD00 became smaller than R94, whereas $z_0/h$ with SD00 was larger than R94. As a result, SM00 provided better estimates in all sites than R94, although the $z_0/h$ results in
YP were less accurate than the R94 results. Nevertheless, the outputs of SM00 still seemed to deviate from the observed d/h and z₀/h.

Figure 6

4.2 Parameterisation using observed data

Since previous models did not properly represent our observed results for d/h and z₀/h, alternative parameterisation is required. From a previous observational study, d/h and z₀/h varied in two ways: intersite differences and seasonal variations (Nakai et al., 2005). In analysing the relationships between roughness parameters and forest structure factors, JJA averaged d/h and z₀/h were used for intersite differences, and monthly data of d/h and z₀/h were used for seasonal variations.

Intersite differences of d/h and z₀/h were well described by stand density ρ_s, although the results of site YP deviated somewhat (Fig. 7a). This result indicates that ρ_s well represented the density of the forest.

However, monthly-averaged d/h in sites MB, MM and SM increased with LAI A, indicating that seasonal variations in d/h can be parameterised by A (Fig. 7b). When these variations were fitted by linear regressions, the slopes of the regression lines decreased with ρ_s, whereas the intercepts increased with ρ_s (Fig. 7c), indicating that seasonal variation in d/h with LAI was large in sparse forests and small in dense forests. This phenomenon might be construed as follows. In the case of dense forest, many branches remain in the crown space after defoliation, and these act as the resistance for momentum transfer into the forest, and hence the decrease in d due to defoliation is small. On the
other hand, in a sparse forest, the momentum can be easily transferred into the forest after defoliation, and hence the seasonal variation in $d$ becomes large. To parameterise these phenomena, it is necessary to consider the effect of stems/branches and leaves separately. Therefore, we introduce a new concept below.

- The basal part of $d/h$ is primarily determined by the density of stems and branches (stand density).
- The seasonal variation depends on the density of leaves (LAI), and the degree of this variation is dependent on stand density.
- Final $d/h$ is the sum of these variable components.

This concept is similar to that of Schaudt and Dickinson (2000), but different in that they assumed the effect of plant spacing and shapes (R94 model: Eqs. (4), (5), (6)) correspond to either fully-vegetated plants or solid objects, and considered the effect of LAI by multiplying $f_d$ and $f_z$ by Eqs. (4) and (5) or (6), respectively. As a result, SD00 provides that seasonal variation in $d/h$ with LAI is large in a dense canopy and small in a sparse canopy, which is inconsistent with our observations.

In the case of $z_0/h$, this was sufficiently parameterised using the linear relationship between $d/h$ and $z_0/h$ from Fig. 7(d), which is almost the same as Eq. (3) which was originally proposed by Thom (1971). It should be noted that this relation is valid for relatively dense canopies where $z_0/h$ decreases with the density of the canopy, since $z_0/h$ would have a peak at a moderate canopy density and increases with canopy density in sparse canopies, as described by the CM88 and R94 models or the often reported (e.g. Seginer, 1974; Shaw and Pereira, 1982). In our study sites, where the stand density was no less than
808 trees ha$^{-1}$, this phenomenon for lower density was not observed, and thus it could not be parameterised from our observed results.

Figure 7

4.3 New models

Based on the concept introduced in section 4.2 and the observed results, new models for $d/h$ and $z_0/h$ over forests were developed. The basal part of $d/h$ is parameterised with $\rho_s$ as follows.

$$\frac{d}{h} = 1.0 - \frac{1.0 - \exp(-\alpha \rho_s)}{\alpha \rho_s} = 1.0 - f_D, \quad (14)$$

where $\alpha$ is a constant, and $f_D$ represents the residual of basal $d/h$. The behaviour of Eq. (14) is shown in Fig. 8(a).

Seasonal variations in $d/h$ were represented by regression lines in section 4.2, but the relationship between $d/h$ and $A$ would also be a curve close to unity for infinite $A$. Thus the similar curve function to Eq. (14) was applied for the function of $A$ as follows, neglecting the effect of $\rho_s$.

$$\frac{d}{h} = 1.0 - \frac{1.0 - \exp(-\beta A)}{\beta A} = 1.0 - f_A, \quad (15)$$

where $\beta$ is a constant and $f_A$ represents the residual of the effect of leaves on $d/h$. From section 4.2, the slope of the linear regression between $A$ and $d/h$ decreased with $\rho_s$, whereas intercepts increased with $\rho_s$ (Fig. 7c). This observation can be interpreted as the effect of seasonal variation being limited to the residual of the basal part of $d/h$, $f_D$. Therefore, the actual effect of leaves on $d/h$ in a forest can be represented by $f_D (1.0 - f_A)$, which provides
the behaviour as shown in Fig. 8(b), depending on $\rho_s$.

Finally, the total effect of stems/branches and leaves on $d/h$ is given by the sum of Eq. (14) and $f_D (1.0 - f_A)$ and written as follows.

$$\frac{d}{h} = (1.0 - f_D) + f_D (1.0 - f_A) = 1.0 - f_D f_A$$

$$= 1.0 - \frac{1.0 - \exp(-\alpha \rho_s) \cdot 1.0 - \exp(-\beta A)}{\alpha \rho_s \cdot \beta A}$$

(16)

The behaviour of this total effect (Eq. (16)) is shown in Fig. 8(c). The values of the coefficients $\alpha$ and $\beta$ were determined by fitting Eq. (16) to monthly-averaged $d/h$ of five forest sites as $\alpha = 0.000724$ and $\beta = 0.273$, respectively.

$z_0/h$ was parameterised by linear regression between $d/h$ and $z_0/h$ (Fig. 7d) as follows.

$$\frac{z_0}{h} = 0.264 \left(1.0 - \frac{d}{h}\right)$$

(17)

Figure 8

Figure 9 shows the comparison of observed and calculated results of $d/h$ (Fig. 9a) and $z_0/h$ (Fig. 9b) for JJA averaged values. The new models in this study provided almost valid results against observed $d/h$ and $z_0/h$. Compared to the results of previous models, CM88, R94 and SD00, validity of the new models in this study was improved in accuracy and applicability to all sites, although the accuracy of $d/h$ in site YP was somewhat worse. Since $d/h$ in site YP varied largely and the standard deviation was larger (0.24) than for other sites (0.11 in YL, 0.07 in MB, 0.05 in MM and 0.09 in SM) for JJA, the result of the new model might represent the observation for site YP adequately. On the other hand, the estimation errors of the previous one-parameter models, CM88 and
R94, were significant in site YL (section 4.1, Fig. 3). Therefore, the concept of a two-parameter model proposed in this study is adequate to describe $d/h$ and $z_0/h$ of forests, including the boreal forests, YL and YP.

Figure 9

Figure 10 shows the seasonal variation in $d/h$ and $z_0/h$ of monthly and daily values and calculated results from the new models. In calculating model outputs, seasonal variations in LAI of the five forest sites were approximated by the Gompertz curve (e.g. Sánchez-Guerrero et al., 2005). LAI in site YP was constant ($A = 1.0$) since it is an evergreen conifer forest and no significant seasonal variation was observed. Although observed values were somewhat scattered, seasonal variations in observed $d/h$ and $z_0/h$ of different types of forests in different climatic zones were almost represented by the same, simple two-parameter models. Since LAI can be obtained from satellite data (e.g. Pisek and Chen, 2007) and some efforts have recently been made to estimate stand density using satellite data (e.g. Sivanpillai et al., 2006), the new two-parameter model proposed in this study would provide an alternative method for land surface models and climate models to represent $d/h$ and $z_0/h$, considering both intersite differences and seasonal variations.

Figure 10

5 Conclusion

In this study, we proposed a new model to represent $d/h$ and $z_0/h$ observed in five different forests located in three climatic zones. Previous models using LAI and FAI were not valid for our observed results. Observed $d/h$ and $z_0/h$ had
two variable components: intersite differences and seasonal variations. Intersite differences in $d/h$ were related to stand density, and seasonal variations in $d/h$ were related to LAI at each forest with the degree depending on stand density. To explain these observations, a new concept was proposed for $d/h$.

1. The basal part is primarily determined by the density of stems and branches (stand density).
2. The seasonal variation depends on the density of leaves (LAI).
3. The degree of seasonal variation with LAI is dependent on stand density.

From the concepts (2) and (3), the seasonal variation part in $d/h$ was regarded as limited to the residual of the basal part. In the case of $z_0/h$, the linear relationship between $d/h$ and $z_0/h$ (Thom, 1971) was adopted by fitting it to our observed results, though it should be valid for relatively dense canopies. The parameterisation of $z_0/h$ for sparse canopy conditions cannot be provided in this study, since the studied forests were not appropriate for such a condition.

Based on this concept, a new two-parameter model was developed using stand density and LAI. With this model, both intersite differences and seasonal variations in observed roughness length and zero-plane displacement were relatively well represented. Since both LAI and stand density are recorded in most micrometeorological observation sites, and both parameters have recently become available from satellite data, the new two-parameter model proposed in this study provides an alternative method to estimate $d/h$ and $z_0/h$ in actual experiment sites and in land surface models.

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Captions of figures

**Fig. 1.** Locations of Yakutsk, Moshiri and Seto, where our observations were conducted.

**Fig. 2.** Plots of the observed cumulative basal area against tree height, fitting curve (Gompertz function) to the observed data and the derivative of this fit function for each forest site.

**Fig. 3.** Scatter diagrams of observed $d/h$ and $z_0/h$ against leaf area index $A$ (a) and frontal area index $\lambda$ (b) together with the model outputs of CM88 (a) and R94 (b), respectively. Summertime (JJA) data were used for observations.

**Fig. 4.** Scatter diagram of leaf area index $A$ and frontal area index $\lambda$ against stand density $\rho_s$.

**Fig. 5.** Schematic diagram of a fundamental question of frontal area index (FAI), i.e., since FAI is the total frontal area (width $\times$ height of elements) per unit ground area, does the same FAI indicate a high stand density in a short canopy or a low density in a tall canopy? If so, $d/h$ would be large in a short canopy and small in a tall canopy even if both canopies had the same FAI.

**Fig. 6.** Scatter diagrams of calculated results of $d/h$ (a) and $z_0/h$ (b) with the models R94 and SD00 against observations (JJA).

**Fig. 7.** Scatter diagrams of observed results in this study: (a) $d/h$ and $z_0/h$ (JJA) against stand density $\rho_s$, (b) $d/h$ (monthly) against leaf area index $A$, (c) slope and intercept of the regression line in Fig. 6(b) against stand density $\rho_s$, (d) $z_0/h$ against $d/h$ (monthly).

**Fig. 8.** Behaviour of the new model for $d/h$ developed in this study. (a) Effect of stems and branches on $d/h$, (b) effect of leaves on seasonal variation part
of \( d/h, \ f_D(1 - f_A) \), (c) total effect of stems/branches and leaves on \( d/h \).

**Fig. 9.** Scatter diagrams of calculated results of \( d/h \) (a) and \( z_0/h \) (b) with the new model developed in this study and previous models against observations (JJA).

**Fig. 10.** Seasonal variations in \( d/h \) and \( z_0/h \) in five forest sites. Open circles and triangles indicate the monthly data of \( d/h \) and \( z_0/h \), and closed circles and triangles indicate daily data of \( d/h \) and \( z_0/h \), respectively. Solid and dashed lines are the model output of \( d/h \) and \( z_0/h \), respectively, calculated with the new two-parameter model proposed in this study.

**Certificate of English revision**

The English in this document has been checked by at least two professional editors, both native speakers of English. For a certificate, see:

http://www.textcheck.com/cgi-bin/certificate.cgi?id=Dw9Yh7
Table 1: Location, measurement conditions and stand characteristics of the five observation sites.

<table>
<thead>
<tr>
<th>Site</th>
<th>YL</th>
<th>YP</th>
<th>MB</th>
<th>MM</th>
<th>SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude</td>
<td>62° 15' 18'' N</td>
<td>62° 14' 29'' N</td>
<td>44° 23' 03'' N</td>
<td>44° 19' 19'' N</td>
<td>35° 15' 29'' N</td>
</tr>
<tr>
<td>Longitude</td>
<td>129° 37' 08'' E</td>
<td>129° 39' 02'' E</td>
<td>142° 19' 07'' E</td>
<td>142° 15' 41'' E</td>
<td>137° 04' 54'' E</td>
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<tr>
<td>Altitude (m ASL)</td>
<td>220</td>
<td>220</td>
<td>585</td>
<td>340</td>
<td>205</td>
</tr>
<tr>
<td>Height of ultrasonic anemometer $z_e$ (m)</td>
<td>32.0</td>
<td>18.2</td>
<td>21.1</td>
<td>31.6</td>
<td>19.5</td>
</tr>
<tr>
<td>Height of cup anemometer $z_1$ (m)</td>
<td>32.0</td>
<td>18.2</td>
<td>21.1</td>
<td>31.6</td>
<td>14.0</td>
</tr>
<tr>
<td>Height of cup anemometer $z_2$ (m)</td>
<td>27.0</td>
<td>13.8</td>
<td>16.0</td>
<td>28.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Wind direction (clockwise from north)</td>
<td>-30° to 30°</td>
<td>30° to 90°</td>
<td>255° to 270°</td>
<td>255° to 285°</td>
<td>290° to 320°</td>
</tr>
<tr>
<td>Stand density $p_s$ (trees ha$^{-1}$)</td>
<td>808</td>
<td>2572</td>
<td>3925</td>
<td>2573</td>
<td>1900</td>
</tr>
<tr>
<td>Leaf area index $A$ (m$^2$ m$^{-2}$)</td>
<td>0.8 - 1.3</td>
<td>1.0</td>
<td>0.6 - 3.2</td>
<td>1.2 - 3.4</td>
<td>1.7 - 4.2</td>
</tr>
<tr>
<td>JJA averaged $A$ (m$^2$ m$^{-2}$)</td>
<td>1.2</td>
<td>1.0</td>
<td>2.5</td>
<td>3.0</td>
<td>3.5</td>
</tr>
<tr>
<td>Frontal area index $\lambda$ (m$^2$ m$^{-2}$)</td>
<td>0.86</td>
<td>0.47</td>
<td>6.24</td>
<td>3.26</td>
<td>3.63</td>
</tr>
<tr>
<td>Canopy height $h$ (m)</td>
<td>20.5</td>
<td>10.4</td>
<td>11.9</td>
<td>25.0</td>
<td>8.9</td>
</tr>
</tbody>
</table>
Figure 01
Figure 02

- **YL**: Derivative of fit function
  - Tree height (m): 20.5 m
  - Cumulative basal area (m²): 2.5
  - Derivative of fit function: 11.9 m

- **YP**: Derivative of fit function
  - Tree height (m): 10.4 m
  - Cumulative basal area (m²): 2.0
  - Derivative of fit function: 25.0 m

- **MB**: Derivative of fit function
  - Tree height (m): 8.9 m
  - Cumulative basal area (m²): 1.0
  - Derivative of fit function: 11.9 m

- **MM**: Derivative of fit function
  - Tree height (m): 25.0 m
  - Cumulative basal area (m²): 2.5

- **SM**: Derivative of fit function
  - Tree height (m): 10.4 m
  - Cumulative basal area (m²): 2.0
  - Derivative of fit function: 8.9 m

Legend:
- ○ Cumulative basal area
- Fit function
- Derivative of fit function
Figure 03

(a) CM88

Leaf area index $A$ ($m^2 m^{-2}$)

Frontal area index $\lambda$ ($m^2 m^{-2}$)

(b) R94

$d/h, z_0/h$ vs. Leaf area index $A$ ($m^2 m^{-2}$)

$d/h, z_0/h$ vs. Frontal area index $\lambda$ ($m^2 m^{-2}$)
Figure 04

![Graph showing LAI, A, FAI, λ vs. Stand density ρ_s (trees ha$^{-1}$)](image_url)

- LAI, A
- FAI, λ

Stand density ρ_s (trees ha$^{-1}$)

- YL
- YP
- MM
- SM
- MB
- Same frontal area index
- $h_1 < h_2$

Short trees  

Tall trees

High ← Stand density → Low
Large? ← d/h → Small?
Figure 07

(a) Graph showing the relationship between stand density ($\rho_s$, trees ha$^{-1}$) and $d/h$. The data points are labeled YL, SM, and MB. The graph also includes a linear regression line ($z/h = 0.264 (1 - d/h)$).

(b) Scatterplot showing the relationship between leaf area index ($A$, m$^2$ m$^{-2}$) and $d/h$. The data points are labeled MB, MM, and SM. The regression lines are indicated as $0.0137A + 0.705$ (MB), $0.0246A + 0.651$ (MM), and $0.0354A + 0.511$ (SM).

(c) Graph showing the slope of the regression line (Slope) and the intercept of the regression line (Intercept) against stand density ($\rho_s$, trees ha$^{-1}$). The data points are labeled YL, SM, and MB.

(d) Graph showing the relationship between $z/h$ and $d/h$. The data points are labeled YL, SM, and MB. The equation $z/h = 0.264 (1 - d/h)$ is indicated.
(a) Effect of stems and branches

\[ \frac{d}{h} \]

Stand density $\rho_s$ (trees ha$^{-1}$)

(b) Effect of leaves

\[ f_D (1 - A) \]

Leaf area index $A$ (m$^2$ m$^{-2}$)

\[ \rho_s = 1000 \quad \rho_s = 2000 \quad \rho_s = 3000 \quad \rho_s = 4000 \]

(c) Total effect

\[ \frac{d}{h} \]

Leaf area index $A$ (m$^2$ m$^{-2}$)

\[ \rho_s = 4000 \quad \rho_s = 3000 \quad \rho_s = 2000 \quad \rho_s = 1000 \]
Figure 09

(a) d/h

Calculated d/h vs. Observed d/h

(b) z₀/h

Calculated z₀/h vs. Observed z₀/h

Legend:
- ● This study
- □ CM88
- △ R94
- ○ SD00

Sites:
- YP
- YL
- MB
- SM
- MM