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Surface roughness analysis of a conifer forest canopy with airborne and terrestrial laser scanning techniques

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ABSTRACT

Two digital Canopy Height Models (CHMs) were generated using the novel Terrestrial Laser Scanning (TLS) technique combined with Airborne Laser Scanning (ALS) data, acquired over a conifer forest. The CHMs were used to extract cross-sections in order to derive surface geometric parameters. Different morphometric models were applied to estimate aerodynamic roughness parameters: the roughness length (z_0) and the displacement height (d_0). The CHMs were also used to derive the area–height relationship of the canopy surface. In order to estimate roughness parameters the observed canopy area–height relationship was modelled by uniform roughness elements of paraboloid or conical shape. The estimated average obstacle density varies between 0.14 and 0.24 for both CHMs. The canopy height distribution is approximately Gaussian, with average heights of about 26 m and 21 m for CHMs generated with data from TLS and ALS respectively. The estimated values of z_0 and d_0 depend very much on the selected model. It was observed that the Raupach models with parameters tuned to resemble the forest structure of the study area can be applied to a wide range of roughness densities. The cumulative area–height modelling approach also yielded results which are compatible with other models. The results confirm that, to model the upper canopy surface of the conifer forest, both the cone and the paraboloid shapes are fairly appropriate.

1. Introduction

Understanding the interaction between the Earth's surface and the lower part of the atmosphere is of paramount importance for many applications in meteorology, hydrology and related fields. It is known that this interaction is determined to an important extent by different exchange processes across the land atmosphere interface (Stull, 1988). One of the important exchange processes associated with the movement of air (wind speed) at the Earth's surface is the exchange of momentum (the product of mass and velocity of a volume of air). In the "free" atmosphere the movement of air is forced by the pressure gradient (difference in atmospheric pressure over a specified distance) resulting from differential solar heating of the surface and internal motion in the atmosphere. Once the moving air mass interacts with the surface of earth, the bottom layer is affected by the frictional forces (surface drag) acting against the motion. The surface drag acting on the bottom layer is transferred to the upper layers of the atmosphere by the internal stresses resulting in turbulence or irregular fluctuations in air motion. This entire process of momentum exchange at the surface of the earth is dominated by the surface roughness characteristic or the aerodynamic roughness.

Land surface models to estimate momentum exchange between the earth's surface and atmosphere often employ wind-profile relations above the surface using the flux-gradient approach or more specifically the relationship between momentum flux density (mass per unit area per unit time) and vertical gradient of wind speed above a surface (Garratt, 1992). However, the accuracy of model results depends much on the parameterization of aerodynamic roughness. Furthermore, the parameterization of aerodynamic roughness is important because it influences not only the momentum transfer, but also the exchange of heat, gases and aerosols across the earth. Parameterization of aerodynamic roughness has been done in hydro-meteorology by introducing two aerodynamic parameters: aerodynamic roughness length (z_0) and zero plane displacement height (d_0). The aerodynamic roughness length (also called momentum roughness length) is a surface length scale defined specifically by the logarithmic wind law for neutral conditions (Brutsaert, 1982). For homogeneous terrain under neutral conditions, the aerodynamic roughness length is the height at which the mean wind speed becomes zero, when extrapolating the logarithmic wind profile through the surface layer. When the wind

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Nomenclature

b	Width of the frontal part of a roughness element (5 m)
c	Empirical coefficient (0.37)
c_1	Constant (1.09)
c_2	Constant (0.29)
C_S	Drag coefficient of the substrate surface (0.003)
C_R	Drag coefficient for an isolated surface-mounted roughness element (0.3)
c_{d0}	Drag coefficient at $z = h/2$ (0.3)
c_d	Constant (0.6)
c_{d1}	Free parameter (15)
d_0	Zero plane displacement height (m)
h	Mean canopy height (m)
h^*	Height of cone/paraboloid (m)
k	von Karman's constant (0.41)
u_h	Wind speed at $z = h$ (ms^{-1})
u_*	Friction velocity (ms^{-1})
z	Height above ground level (m)
z_0	Aerodynamic roughness length (m)
α	Fractional surface area
β	C_R/C_S
γ	(u_h/u_*)
$\gamma_{\max}$	Constant value (0.3)
λ	Frontal area index
μ	Empirical stand specific constant (0.2–0.3)
ψ_h	Profile correction constant in the roughness sub layer (0.193)
τ_f	Form drag on the roughness elements per unit horizontal area
τ_s	Shear stress on the underlying substrate surface
τ_t	Total stress on the underlying substrate surface

blows over tall roughness elements like a vegetative canopy, there will be a vertical shift in the logarithmic form of the wind profile due to the surface roughness effects. The zero plane displacement height is the adjustment that has to be made in the measurement height due to this vertical shift from the ground surface. In physical terms, the displacement height is comparable to the level of action of the surface drag on the main roughness elements (Garratt, 1992). Using a semi-logarithmic plot of mean wind speed versus logarithm of height above the displacement height ($z - d_0$), z_0 may be graphically represented as the zero velocity intercept of the resulting straight line.

In general, roughness parameters are determined from micrometeorological or anemometric methods that use wind measurements by means of meteorological towers or balloon releases. Apart from anemometric methods, morphometric methods are also used. These methods use algorithms that relate roughness parameters to measurable dimensions of surface roughness elements. A review can be found in the literature (Hiyama et al., 1996; Grimmond and Oke, 1999; De Vries et al., 2003). Morphometric methods have distinct advantages over anemometric methods because they do not only avoid cumbersome measurements of meteorological variables but also allow estimation of roughness parameters for all wind directions. However, morphometric methods do have the disadvantage that they are mostly based on empirical relations and laboratory simulations and therefore require validation for natural environments.

Several studies were carried out recently to validate morphometric methods for different natural land surfaces. Hiyama et al. (1996) have evaluated algorithms to estimate regional roughness parameters of a complex landform with patches of various surface types. Grimmond and Oke (1999) have tested several morphometric methods to estimate aerodynamic parameters of urban landscapes. Menenti and Ritchie (1994) have computed the effective aerodynamic roughness in a complex landscape using airborne laser altimeter or LiDAR (Light Detection And Ranging) data to derive surface geometric features. Aerodynamic roughness of a natural forested area was determined with satellite imagery by Jasinski and Crago (1999) using Landsat images. Hasager et al. (2003) have used both Landsat and SPOT (Satellite Pour l'Observation de la Terre) images to estimate the aerodynamic roughness of a flat agricultural area with hedges. In a recent study, De Vries et al. (2003) have evaluated the use of laser altimeter data to extract surface geometric features of an area characterized by coppice dunes with interdunal areas partially covered with grass. More recently, Colin and Faivre (2010) estimated aerodynamic roughness length of landscapes ranging from dessert to grassland and irrigated farmland in the northwest of China from very high-resolution LiDAR data.

Although many surface types have been covered previously, few studies have used morphometric methods on surfaces dominated by forest canopies. However forests are complex ecosystems with unique characteristics and presently account for 30% of the global land area. Given the significant role of forests on the global energy and water balance, carrying out additional research to investigate aerodynamic roughness of such landscape is warranted. Particularly more attention should be paid to explore morphometric methods, those that employ state-of-the-art technology to determine aerodynamic roughness of forest surfaces. In order to develop operational methods to estimate forest aerodynamic roughness at regional scale, some improvements to existing methods are required. To be able to deal with large areas, the techniques should be computationally efficient and at the same time should produce results with a reasonable accuracy. In this regard progress can be made by adopting the recent advancement made in laser scanning techniques to map the upper canopy surface with a reasonable accuracy. When such detailed canopy surface maps are available, the method can be further refined by exploring new techniques to derive required surface morphometric parameters.

The aim of this study is to evaluate several morphometric methods to estimate the aerodynamic roughness of a region covered by forest. We adopted two different techniques to estimate surface morphometric variables of a densely vegetated terrain. We assumed that the upper canopy of a dense forest in principle acts as a spatially continuous impenetrable surface. Based on this assumption we digitally mapped the upper canopy surface which in turn was used to derive surface morphometric variables. One of the objectives of the study is to make use of a recently developed high resolution Terrestrial Laser Scanning (TLS) technique to digitally map the upper canopy surface through a multi-scanning approach including a range of different heights. Additionally, we used Airborne Laser Scanning (ALS) data to digitally map the canopy surface of the forest. Although the ALS technique is well established for large-scale canopy surface mapping (Hollaus et al., 2006), hardly any studies are known where this technique is applied to vegetative canopy surface roughness estimation (Menenti and Ritchie, 1994).

The structure of the paper is briefly outlined. Section 2 describes the study area and data used in the analysis, while Section 3 deals with existing models for estimating aerodynamic roughness and the methodology for generation of canopy height models. Sections 4 and 5 explain the two techniques adopted to derive surface morphometric parameters and subsequently discuss the results of different roughness models. Finally some concluding remarks are given in Section 6.