Aerodynamic roughness parameters in cities: Inclusion of vegetation

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1. Introduction

During neutral atmospheric stratification, the mean wind speed ($\overline{U}_z$) at a height $z$ above a surface can be estimated using the logarithmic wind law (Tennekes, 1973):

$$\overline{U}_z = \frac{U_*}{\kappa} \ln \left( \frac{z}{z_0} \right)$$

(1)

where $U_*$ is the friction velocity, $\kappa \approx 0.40$ (Högström, 1996) is von Karman’s constant, $z_0$ is the aerodynamic roughness length, and $z_0$ is the zero-plane displacement. The aerodynamic roughness parameters ($z_0$ and $z_0$) can be related to surface geometry using morphometric methods (e.g. Grimmond and Oke, 1999; Kent et al., 2017a).

Uncertainties in wind-speed estimations arise from using idealised wind-speed profile relations, as well as representing the surface using only two roughness parameters ($z_0$ and $z_0$), which are based upon a simplification of surface geometry. Both observations and physical experiments are therefore critical to assess the most appropriate methods to determine roughness parameters and for wind-speed estimation (e.g. Cheng et al., 2007; Tieleman 2008; Drew et al., 2013). Using the logarithmic wind law (Eq. (1)), Kent et al. (2017a) demonstrate that wind speeds estimated up to 200 m above the canopy in central London (UK) most resemble observations using morphometric methods which account for roughness-element height variability (specifically, the Millward-Hopkins et al., 2011 and Kanda et al., 2013 methods). However, an uncertainty of $>2.5$ m s$^{-1}$ exists ($>25\%$ of the mean wind speed) due to the flow variability throughout the profile (Kent et al., 2017a; their Fig. 7).

Bluff bodies (e.g. buildings) and porous roughness elements (e.g. vegetation) have different influences upon wind flow (Taylor, 1988; Finnigan, 2000; Guan et al., 2000, 2003) which need to be accounted for. Although morphometric methods have been developed for only buildings (examples in Mohammad et al., 2015) or vegetated canopies (e.g. Nakai et al., 2008), existing morphometric methods do not consider both solid and porous bodies (i.e. vegetation) in combination.

With the intention of collectively considering buildings and vegetation to determine $z_0$ and $z_0$, this work develops the widely-used Macdonald et al. (1998, hereafter Mac) morphometric method to include vegetation. The development applies to the more recently proposed Kanda et al. (2013, hereafter Kan) development of Mac which considers roughness-element height variability. The implications for estimating the logarithmic wind-speed profile (Eq. (1)) up to 100 m above different urban surfaces are discussed.

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2. Methodology

2.1. Macdonald et al. and Kanda et al. Morphometric methods

Morphometric methods traditionally characterise roughness elements by their average height ($H_m$), plan area index ($\lambda_p$) and frontal area index ($\lambda_f$). The $\lambda_p$ is the ratio of the horizontal area occupied by roughness elements ('roof' or vegetative canopy, $A_p$) to total area under consideration ($A_f$), whereas $\lambda_f$ is the area of windward vertical faces of the roughness elements ($A_f$) to $A_f$. By including the standard deviation ($\sigma_H$) and maximum ($H_{\text{max}}$) roughness-element heights, newer methods consider height variability (Millward-Hopkins et al., 2011; Kanda et al., 2013).

The $Mac$ method is derived from fundamental principles and without assumptions about wake effects and recirculation zones of solid roughness elements (Macdonald et al., 1998), which vary for porous elements (Wolfe and Nickling, 1993; Judd et al., 1996; Sutton and McKenna Neuman, 2008; Suter-Burri et al., 2013). The formulation of $z_d$ and $z_0$ is (Macdonald et al., 1998):

$$Mac_{zd} = \left[ 1 + a \times \exp \left( \frac{z_d}{H_m} \right) \right] H_m,$$

$$Mac_{z0} = \left( \left[ 1 - \frac{z_d}{H_m} \right] \exp \left[ \left\{ \frac{0.5 \beta \frac{C_D}{\sqrt{k}} \left( 1 - \frac{z_d}{H_m} \right) \lambda_f }{0.5} \right\} \right] \right) H_m,$$

where the constant, $a$, is used to control the increase in $z_d$ with $\lambda_f$, a drag correction coefficient, $\beta$, is used to determine $z_0$ and $C_D$ is the drag coefficient for buildings. Coefficients can be fitted to observations. For example, using Hall et al.'s (1996) wind tunnel data, Macdonald et al. (1998) recommend $C_D = 1.2$ and $a = 4.43$, $\beta = 1.0$ for staggered arrays; and $a = 3.59$, $\beta = 0.55$ for square arrays. The staggered array values and $C_D = 1.2$ are used here.

Using large eddy simulations for real urban districts of Japan, Kanda et al. (2013) argue that the upper limit of $z_d$ is $H_{\text{max}}$ and therefore:

$$Kan_{zd} = \left[ c_{zd} X^3 + \left( a_{zd} \lambda_{zd} - c_{zd} \right) X \right] H_{\text{max}},$$

$$X = \frac{\sigma_H + H_m}{H_{\text{max}}},$$

and

$$\beta$$ Dragg correction coefficient (Macdonald et al., 1998)

$\lambda_f$ Frontal area index of roughness elements

$\lambda_{f\text{-crit}}$ Frontal area index for peak $z_0$

$\lambda_p$ Plan area index of roughness elements

$\rho$ Density of air

$\sigma_H$ Standard deviation of roughness-element heights

$\sigma_v$ Standard deviation of lateral wind velocity (crosswind)

$\tau$ Surface shear stress

Abbreviations

CC$_{hv}$ City centre with high vegetation

CC$_{lv}$ City centre with low vegetation

Kan Kanda et al. (2013) morphometric method

Mac Macdonald et al. (1998) morphometric method

Pa Urban park

SB$_{hv}$ Suburban area with high vegetation

SB$_{lv}$ Suburban area with low vegetation

Additional subscripts

$ b $ Buildings

$ v $ Vegetation

l-on Leaf-on

l-off Leaf-off

$$Kan_{z0} = \left[ b_Y Y^2 + c_Y Y + a_Y \right] Mac_{z0},$$

$$Y = \frac{\lambda_p \sigma_H}{H_m},$$

where $0 \leq X \leq 1$, $0 \leq Y$ and $a_Y, b_Y, c_Y, a_1$ and $c_1$ are regressed constants with values: $1.29, 0.36, -0.17, 0.71, 20.21$ and $-0.77$, respectively.

2.2. Considering vegetation

Although, consideration has been given to treatment of vegetation within building-based morphometric methods (e.g. a reduction of height, Holland et al., 2008), the flexibility, structure and porosity of vegetation suggest the effects upon wind flow and aerodynamic roughness are more complex (Finnigan, 2000; Nakai et al., 2008). During the method development proposed here, vegetation porosity is used, as it is the most common descriptor of the internal structure (Heisler and Dewalle, 1988) and relatively easy to determine (Guan et al., 2002; Crow et al., 2007; Yang et al., 2017). Unlike other characteristics (e.g. structure or flexibility), porosity can be generalised across vegetation types or species with values between 0 (completely impermeable) and 1 (completely porous). Optical ($P_{2D}$) and volumetric/aerodynamic ($P_{3D}$) porosity can be related to each other: $P_{3D} = P_{2D}^\beta$ (Guan et al., 2003), $P_{3D} = P_{2D}^\beta$ (Grant and Nickling, 1998).

The drag of vegetation is also considered, which through absorbing momentum from the wind (Finnigan, 2000; Guan et al., 2003; Krayenhoff et al., 2015) can significantly reduce the surface shear stress ($\tau$) (Wolfe and Nickling, 1993), as well as reduce the exchange between in-canopy and above-canopy flow (Gronke and Rack, 2009; Vo et al., 2013).

The drag generated by vegetation (Wyatt and Nickling, 1997; Grant and Nickling, 1998; Gillies et al., 2000, 2002; Guan et al., 2003) and other porous structures (Seginer, 1975; Jacobs, 1985; Taylor, 1988) varies within building-based morphometric methods (e.g. a reduction of height, Macdonald et al., 1998), which vary for porous elements (Wolfe and Nickling, 1993; Judd et al., 1996; Sutton and McKenna Neuman, 2008; Suter-Burri et al., 2013).

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flexibility, leaf type) affect $C_D$ (Rudnicki et al., 2004). In addition, sheltering and the reconfiguration of shape and leaf orientation under varying flow characteristics means a single value for $C_D$ may be inappropriate (e.g. Guan et al., 2000, Guan et al., 2003; Vollinger et al., 2005; Pan et al., 2014). Although attempts have been made to separate the form and viscous components of vegetation drag (e.g. Shaw and Patton, 2003), the components tend to be considered in combination ($C_{DV}$), as is done here.

The $C_{DV}$ of foliage typically varies between 0.1 and 0.3 (Katul et al., 2004). From large eddy simulations, Shaw and Schumann (1992) and Su et al. (1998) propose $C_{DV} = 0.15$. Other numerical simulations suggest $C_{DV} = 0.25$ (da Costa et al., 2006) and $C_{DV} = 0.2$ (Zeng and Takahashi, 2000) for pine forests. Field studies in boreal canopies (pine, aspen and spruce) indicate $C_{DV}$ varies between 0.1 and 0.3 (Amiro, 1990). A $C_{DV}$ of 0.2 is commonly used in numerical studies of wind flow in vegetated canopies (Van Renterghem and Botteldooren, 2008). Whereas, rough- and smooth-surface cylinders have $C_D = 1.2$ (Simiu and Scanlan, 1996) or $C_D = 0.8$ (Guan et al., 2000), respectively.

There is evidence that $C_{DV}$ varies with wind speed, with higher $C_{DV}$ at lower wind speeds. Results from wind tunnel studies include: for seven 5.8–8.5 m British forest saplings $C_{DV}$ varied from 0.88 to 0.15 when wind speeds were between 9 and 26 m s$^{-1}$ (Mayhew, 1973); for 2.5–5.0 m tall conifer saplings with wind speeds between 4 and 20 m s$^{-1}$ $C_{DV}$ varied between 1.5 and 0.2 (Rudnicki et al., 2004); and, for five hardwood species $C_{DV}$ varied between 1.02 and 0.10 (Vollinger et al., 2005). Similarities are in the field, where Koizumi et al. (2010) report $C_{DV}$ for three poplar tree crowns varying from 1.1 to 0.1 with wind speeds between 15 and 1 m s$^{-1}$. These results indicate at high wind speeds the relative drag of an individual tree ($C_{DV}$ ~ 0.1–0.2) is small compared to that of buildings, but during some flow conditions $C_{DV}$ can approach that of a solid structure of similar shape (i.e. 1.2) and therefore exert similar drag to buildings.

The state of foliage on a tree (i.e. porosity) influences the amount of drag exerted on the flow. Koizumi et al.’s (2010) field observations at wind speeds of 10 m s$^{-1}$ found $C_{DV}$ to over half when tree crowns are defoliated (i.e. more porous). Current understanding of $C_{DV}$ variability with porosity is based upon artificial (i.e. two-dimensional) and natural (i.e. tree or tree model) wind break studies. Hagen and Skidmore (1971) found $C_{DV}$ to be similar to single tree values: $C_{DV}$ ~ 0.5 for one row deciduous windbreaks and $C_{DV}$ ~ 0.6–1.2 for coniferous windbreaks. Guan et al.’s (2003), their Table 5) synthesis of $C_{DV}$ for two-dimensional structures or naturally vegetated windbreaks of varying porosity provides a relation between $C_{DV}$ and porosity ($P_{3D}$):

$$C_{DV} = 1.08(1 - P_{3D}^{1.8})$$

(6)

Similarly, for an isolated model tree, Guan et al. (2000) show:

$$C_{DV} = -1.251P_{3D}^2 + 0.489P_{3D} + 0.803$$

(7)

Results of previous studies (summarised in Fig. 1) indicate that more impermeable roughness elements (i.e. $P_{3D} = 0$) tend to have the largest $C_{DV}$, approaching that of a solid structure (0.8–1.2). As aerodynamic porosity increases, $C_{DV}$ decreases approximately as a power function to zero for an open surface (i.e. $P_{3D} = 1$). Observations by Grant and Nickling (1998) for a single conifer tree (Fig. 1, GN) and wind tunnel studies by Guan et al. (2000) support evidence that the relation may peak at critical porosities (Grant and Nickling, 1998; Gillies et al., 2002).

2.3. Parameter determination and method development

In the methodology proposed here, the $H_{BV}$, $H_{max}$ and $\sigma_H$ of all roughness elements (i.e. buildings and vegetation) are determined.

Porosity is accounted for when determining $\lambda_p$ as vegetation has openings in the volume it occupies. The plan area of vegetation ($A_{Pv}$) is reduced by a porosity factor (i.e. $1 - P_{3D}$). The $\lambda_p$ of both buildings and porous vegetation becomes:

$$\lambda_p = \frac{\sum_{i=1}^{n} A_{Pv,ij} + \sum_{i=1}^{n} (1 - P_{3D}) A_{Pv,ij}}{A_T}$$

(8)

where $A_{Pv,ij}$ is the plan area of buildings and $i$ or $j$ refers to each individual built or vegetated roughness element, respectively.

The Mac method (Sect. 2.1) considers the drag balance at the top of a group of homogeneous roughness elements (of height $z$) approached by a logarithmic wind profile. If the roughness elements are of variable height, $z$ is replaced by their average height ($H_{av}$) (Macdonald et al., 1998). Numerical models demonstrate the relative impact of trees and buildings represented by the drag coefficient are not affected by each other and neither is the spatially-averaged flow (Krayerhoff et al., 2015). Therefore, the total surface drag ($F_{DV}$) can be determined as a combination of the drag from buildings ($F_{Db}$) and vegetation ($F_{Dv}$). Using the unsheltered frontal areas of buildings ($A_{fb}$), the drag at the building tops (height $H_{av}$) can be written (e.g. Millward-Hopkins et al., 2011):

$$F_{Db} = 0.5 \rho C_{Db}(U^2_A)_{fb}$$

(9)

and similarly, for still-air impermeable vegetation ($A^*_{fb}$) the drag on vegetation ($F_{Dv}$) is:

$$F_{Dv} = 0.5 \rho C_{Dv}(U^2_A)_{fb}$$

(10)

with $\rho$ the density of air. The total drag of both the buildings and vegetation per unit area is therefore:

$$\tau = \frac{F_{Db} + F_{Dv}}{A_T} = \rho u_A^2 = \frac{0.5 \rho C_{Db}(U^2_A)_{fb} + 0.5 \rho C_{Dv}(U^2_A)_{fb}}{A_T}$$

(11)

As the Mac method assumes the drag below the zero-plane displacement is negligible, the unsheltered frontal area exerting drag on the flow consists of only roughness-element frontal area above $z_d$. Therefore, $M_{mac}$ is calculated (Eq. (2)) with the influence of vegetation incorporated through $H_{av}$ and in the porosity parameterisation used in $\lambda_p$ (Eq. (8)). Since all roughness elements are assumed homogeneous in height, the relation between the unsheltered frontal areas of buildings and vegetation ($A^*_{fb}$) and their actual frontal areas ($A_{fb}$) is:

$$A_{fb} = \frac{z}{z - z_d} A^*_{fb}$$

(12)

The unsheltered frontal areas ($A^*_{fb}$ and $A^*_{fv}$) in Eq. (11) can be replaced
by actual frontal areas ($A_{b}$ and $A_{p}$):

$$0.5\rho U_c^2 \left(1 - \frac{z}{z_0}\right) A_b + 0.5\rho U_c^2 \left(1 - \frac{z}{z_0}\right) A_p = \rho u_*^2$$

(13)

Common factors are removed from the numerator on the left-hand side of Eq. (13). To state Eq. (13) in terms of $C_{Dv}$ only, the ratio of $C_{Dv}$ and $C_{Db}$ is used ($P_v$). Using the variation of $C_{Db}$ with porosity for a single tree, the Guan et al. (2000) relation (Eq. (7)) gives:

$$P_v = \frac{C_{Dv}}{C_{Db}} = \frac{-1.25P_0 \rho u_*^2 + 0.489P_0 \rho + 0.803}{C_{Db}}$$

(14)

Accounting for differential drag imposed by buildings and vegetation through $P_v$, Eq. (13) may then be written:

$$0.5\rho U_c^2 \left(1 - \frac{z}{z_0}\right) \frac{A_b + (P_v)A_p}{A_T} = \rho u_*^2$$

(15)

When substituted into the logarithmic wind law (Eq. (1)), cancellation and inclusion of the drag correction coefficient ($\beta$) proposed by Macdonald et al. (1998) provides $\pi_0$:

$$\frac{z_0}{z} = \left(1 - \frac{z}{z_0}\right) \exp \left[-\left(1 - \frac{z}{z_0}\right) \frac{A_b + (P_v)A_p}{A_T}\right]^{0.5}$$

(16)

Equation (16) is analogous to Macdonald et al.’s (1998) (Eq. (3)). However, the frontal area of buildings and vegetation are determined separately and $P_v$ is included within the $\beta$ term to describe the differential drag of buildings and vegetation of varying porosity.

It should be noted that the calculated frontal area of vegetation $A_{fv}$ is independent of porosity. $A_{fv}$ is determined assuming a solid structure with the same dimensions. Vegetation’s influence upon $z_0$ is a consequence of the change in the drag coefficient for vegetation with porosity ($P_v$, Eq. (14)). Additionally, $\beta$ is observed to be unity for staggered arrays of solid cubes. Without further experimentation upon arrays consisting of porous and solid roughness elements it is inappropriate to apply the drag correction to arrays including vegetation. Therefore, if any value other than unity is used for $\beta$, $P_v$ should be further reduced:

$$P_v = \frac{-1.25P_0 \rho u_*^2 + 0.489P_0 \rho + 0.803}{\rho C_{Dv}}$$

(17)

2.4. Demonstration of impact

Behaviour of the parameterisation is demonstrated for five study areas selected from a surface elevation database for Greater London (Lindberg and Grimmond, 2011). Study areas are selected to characterise different urban spaces in a European city (roughness elements with heights > 2 m): city centre with low vegetation (Fig. 2a, CC_lv), city centre with similar building and vegetation height (Fig. 2b, CC_hv), suburban area with low vegetation (Fig. 2c, Sb_lv), suburban area with tall vegetation (Fig. 2d, Sb_hv) and an urban park (Fig. 2e, Pa).

Geometric and aerodynamic parameters for each study area are calculated iteratively (Kent et al., 2017a methodology) using the Kormann and Meixner (2001) analytical source area footprint model. For each study area, the same meteorological conditions observed by a CSAT3 sonic anemometer (Campbell Scientific, USA) in central London (King's College London, Strand Campus, height 50.3 m above ground level, see Kotthaus and Grimmond, 2012, 2014a, b for methods) are used. The median meteorological conditions of the fastest 25% of winds in 2014 (30-min averages) are used. Inputs to the footprint model are: measurement height ($z$) = 50.3 m; standard deviation of the lateral wind velocity ($\sigma_v$) = 1.97 m s$^{-1}$, Obukhov length ($L$) = 1513 m;

![Fig. 2. Study areas representative of: (a) city centre with low vegetation (CC.lv), (b) city centre with similar building and vegetation heights (CC.hv), (c) suburban with low vegetation (SB.lv), (d) suburban with taller vegetation (SB.hv) and (e) an urban park (Pa). Source areas determined using the iterative methodology of Kent et al. (2017a), rotated into the wind direction (210°). Colour indicates roughness-element type and hue its height (see key). Axes labels are distances in metres.](image-url)
deviation of roughness-element heights (in metres), respectively, \( \lambda_p \) is plan area index and \( \lambda_f \) is frontal area index. Subscripts: \( v \) for vegetation, \( b \) for buildings, \( l-on \) for leaf-on and \( l-off \) for leaf-off.

\[ u_\ast = 0.94 \text{ m s}^{-1}; \text{ wind direction } 210^{\circ}; z_d \text{ and } z_p \]  
Source area calculations are initiated with open country values for the aerodynamic parameters (\( z_d = 0.2 \text{ m}, z_p = 0.03 \text{ m} \)), as the final values are insensitive to this initial assumption (Kent et al., 2017a). The source area analysed here is the cumulative total of 80% of the total source area.

Dynamic response of the source areas during the iterative procedure modifies the surface area considered. The initial source area is overlain upon the surface elevation databases (buildings and vegetation) for each study area and a weighted geometry is calculated, based upon the fractional contribution of each grid square in the source area. Source area specific aerodynamic parameters are determined, which are the input to the next iteration (the meteorological conditions and measurement height remain constant). Both buildings and vegetation are considered, assuming a leaf-on porosity of \( P_{D0} = 0.2 \) and leaf-off porosity of \( P_{D0} = 0.6 \) (more porous) (Heisler, 1984; Heisler and Dewalle, 1988; Grimmond and Oke, 1999).

Variations in meteorological conditions between sites probably occur, however the objective to obtain representative study areas (Fig. 2a) is reasonable. The resulting geometry and (more porous) (Heisler, 1984; Heisler and Dewalle, 1988; Grimmond and Oke, 1999).

Table 1

<table>
<thead>
<tr>
<th>Area</th>
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<th>Vegetation</th>
<th>Buildings</th>
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<tr>
<td></td>
<td>( h_{av} )</td>
<td>( H_{max} )</td>
<td>( v_t )</td>
</tr>
<tr>
<td>CC lv</td>
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<tr>
<td>Pa</td>
<td>11.30</td>
<td>29.00</td>
<td>4.67</td>
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</tbody>
</table>

\[ zd_{l-off} \text{ and } zd_{l-on} = \frac{\left[ h_{av} \left( 1 - \frac{v_t}{\lambda_v} \right) \right]}{\lambda_p}, \text{ assuming a leaf-on and leaf-off porosity, respectively.} \]

### 3. Results

#### 3.1. Geometric parameters

Obviously, the influence of vegetation and buildings upon geometric parameters depends upon the dominant roughness elements: when buildings dominate (CC lv and CC hv), height based geometric parameters for all roughness elements (both buildings and vegetation) are determined by buildings (Table 1); and, if vegetation is taller than buildings (SB hv and Pa), the \( H_{av}, H_{max} \) and \( v_t \) of all roughness elements become noticeably larger than \( H_{av,b}, H_{max,b} \) and \( v_{t,b} \) (Table 1, subscript \( b \) denotes buildings only). In all study areas, the effect of vegetation increases both plan and frontal areas, which is expectedly more obvious for leaf-on than leaf-off values. In CC lv the plan and frontal area indexes of vegetation \( \lambda_p, v \) and \( \lambda_f, v \) are effectively negligible. Elsewhere the taller and higher proportion of vegetation means \( \lambda_p, v \) and \( \lambda_f, v \) are greater than or similar to that of buildings \( \lambda_p, b \) and \( \lambda_f, b \). This means plan and frontal areas calculated for all roughness elements can be double or larger than that for buildings alone (Table 1, SB hv and CC hv).

Leaf state has a greater impact upon plan than frontal area, with mean differences of 0.12 \( (\lambda_p,l-on - \lambda_p,l-off) \) and 0.04 \( (\lambda_f,l-on \text{ and } \lambda_f,l-off) \), respectively, across the five study areas (subscripts \( l-on \) and \( l-off \) refer to leaf-on or off vegetation state, respectively). As this difference is proportional to the amount of vegetation present, it is maximum in Pa where leaf-on plan area index is approximately double leaf-off (0.6 and 0.3, respectively). Implications of ignoring vegetation (i.e. only considering buildings) are most obvious in Pa. Here the plan and frontal area of buildings approach 0, whilst \( \lambda_p, v \) is 0.41 and \( \lambda_f, v \) ranges between 0.3 and 0.59 for leaf-off and leaf-on porosity, respectively (Table 1). The average height of buildings is only 5.8 m with a maximum of 16.5 m. However, the average height of vegetation (\( H_{av,v} \)) is almost as large as the tallest building (11.4 m) and maximum tree height (\( H_{max,v} \)) is 29 m. Therefore, the geometry in Pa is primarily determined by the vegetation characteristics (Table 1).

### Table 2

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<td>18.33</td>
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3.2. Aerodynamic parameters

For aerodynamic parameter determination, the geometric parameters within the morphometric methods (e.g. Kan considers height variability) are important, in addition to the dominance of either buildings or vegetation. For a heterogeneous group of roughness elements, Kan$_a$ is

### Table 3

Percentage difference in aerodynamic parameters calculated using the (a) Macdonald et al. (1998) and (b) Kanda et al. (2013) morphometric methods from Table 2, between: buildings (x) and all roughness elements (y) assuming a leaf-on porosity (b, l-on); buildings (x) and all roughness elements (y) assuming a leaf-off porosity (b, l-off) and for all roughness elements assuming a leaf-on (x) or leaf-off porosity (y) (l-on, l-off). Percentage difference $= \frac{\Delta \text{parameter}}{\text{reference parameter}} \times 100$.

<table>
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<th>Area</th>
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<th>% difference</th>
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<td>$z_d$</td>
<td>l-on</td>
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<tr>
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<td>18.37</td>
<td>9.88</td>
<td>8.33</td>
</tr>
<tr>
<td>CC hv</td>
<td>62.48</td>
<td>13.53</td>
<td>50.00</td>
</tr>
<tr>
<td>SB lv</td>
<td>15.47</td>
<td>0.51</td>
<td>14.96</td>
</tr>
<tr>
<td>SB hv</td>
<td>57.25</td>
<td>10.01</td>
<td>66.31</td>
</tr>
<tr>
<td>Pa</td>
<td>-</td>
<td>-</td>
<td>137.35</td>
</tr>
</tbody>
</table>

### Table 4

Percentage difference in aerodynamic parameters calculated using the Macdonald et al. (1998, Mac) or Kanda et al. (2013, Kan) morphometric methods from Table 2, for buildings only and all roughness elements assuming a leaf-on porosity (l-on) and leaf-off porosity (l-off). Percentage difference $= \frac{\Delta \text{parameter}}{\text{reference parameter}} \times 100$.

<table>
<thead>
<tr>
<th>Area</th>
<th>Buildings</th>
<th>All</th>
<th>% difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$z_p$</td>
<td>$z_d$</td>
<td>l-on</td>
</tr>
<tr>
<td>CC lv</td>
<td>3.68</td>
<td>0.44</td>
<td>4.12</td>
</tr>
<tr>
<td>SB lv</td>
<td>12.57</td>
<td>18.10</td>
<td>5.56</td>
</tr>
<tr>
<td>SB hv</td>
<td>16.70</td>
<td>46.76</td>
<td>30.66</td>
</tr>
<tr>
<td>Pa</td>
<td>-</td>
<td>-</td>
<td>96.76</td>
</tr>
</tbody>
</table>

3.2. Aerodynamic parameters

For aerodynamic parameter determination, the geometric parameters within the morphometric methods (e.g. Kan considers height variability) are important, in addition to the dominance of either buildings or vegetation. For a heterogeneous group of roughness elements Kan$_a$ is
method variability of vegetation inclusion and its state (Table 3) tend to be over half the inter-
small increase in there is more vegetation, its inclusion and state (leaf-on or off), is as or
between the two morphometric methods (e.g. CC_hv and CC_lv). Where
is the only area where considering vegetation may reduce z₀ because a small increase in λ in is offset by a reduction in Hₚ (Table 2). Leaf-on z₀ is always greater than leaf-off, but the difference is less obvious for the Kan method as height variability (in addition to λₚ) is accounted for.

Kanₚ is consistently the order of Hₚv (or larger) and typically over double Mac₀ (Table 2). The range of percentage change for z₀ caused by vegetation inclusion and its state (Table 3) is to be over half the inter-method variability of Kan₀ and Mac₀ (Table 4). Thus, the priority of decisions for accurate determination of z₀ is firstly selection of the appropriate morphometric method, followed by the inclusion of vegetation and then its state (leaf-on or leaf-off). An exception is in Pa, where vegetation has the largest effect.

The effect of considering vegetation for z₀ depends upon: the height based geometric parameters, the increase in λ and λₚ and the associated change in z₀. The inter- and intra-method differences of Mac and Kan depend upon their response to changes in λ. Both methods indicate z₀ increases from zero to a maximum value at a critical λₚ (Table 3), after which z₀ decreases again. For Mac₀, λₚ is between ~0.15–0.25 and for Kan₀ this is 0.2–0.4 (Kent et al., 2017a; their Fig. 1). At larger λₚ there is a steeper decline in Mac₀ than Kan₀.

When an already large built front area is further increased due to the vegetation (CC_lv, CC_hv), leaf-on z₀ becomes smaller for both methods as there is a shift further away from λₚ. For both CC_lv and CC_hv the percentage changes are larger for Mac₀ than Kan₀, given the sensitivity of the former to changes of λ. The reduction is greater for leaf-on because of the larger λ (Table 1).

In locations with low built front areas (Table 1, SB lv, SB lv) the inclusion of vegetation should increase Mac₀ and Kan₀, given they move towards λₚ. (Table 3). This is true for Kanₚₚ, most obviously in SB lv (17% difference for leaf-on and 47% for leaf-off, Table 3) where vegetation is more dominant and Hₚ₀ₜₚ and λₚ become obviously larger. However, for Mac₀, the λₚ increase is offset by the concurrent increase in z₀ (Table 2). Therefore Mac₀ decreases for leaf-on conditions, but is similar for leaf-off. For Pa, inclusion of vegetation means Mac₀ₚₚ and Kan₀ₚₚ both increase from 0 m to 0.18 and 0.32 m, respectively during leaf-on, and to 0.99 and 0.92 m, respectively for leaf-off (Table 2). If only buildings are considered, the variability between Kan₀ₚₚₚ and Mac₀ₚₚₚₚ is less than 35% in all study areas apart from CC lv, where Kan₀ₚₚₚₚₚₚ is more than double Mac₀ₚₚₚₚₚₚ because of the large λₚ (~0.5).

Leaf-on z₀ is consistently smaller than leaf-off for both morphometric methods as a consequence of both λ and z₀ increasing. The greater sensitivity of Mac₀ₚₚ to λₚ results in a percent difference that is twice that of Kan₀, except in Pa where both experience large increases (Table 3). During leaf-off, areas with λₚ similar to λₚ (e.g. SB lv, SB lv) have mean inter-method variability of < ~10%. Whereas there are already high λₚ (SB lv, CC lv and CC lv), an increase in λₚ with leaf-on vegetation causes inter-method variability to increase, ranging between 48 and 95% (Table 4).

Therefore, if buildings dominate (e.g. CC lv) selection of the appropriate morphometric method is more critical for determining z₀ (causing a larger percentage difference in z₀) than if vegetation is included. The inclusion of vegetation increases inter-method variability between the two morphometric methods (e.g. CC lv and CC lv). Where there is more vegetation, its inclusion and state (leaf-on or off), is as or more important than the inter-method variability in z₀. This is especially true for Pa.

3.3. Influence of considering vegetation upon wind

Accurately modelling the spatially- and temporally-averaged wind-speed profile above urban surfaces is critical for numerous applications, including dispersion studies and wind load determination. Various methods to estimate the wind-speed profile exist, each developed from different conditions and with different inherent assumptions (e.g. Deaves and Harris, 1978; Emeis et al., 2007; Gryning et al., 2007). However, the aerodynamic roughness parameters (z₀ and Hₚ) are consistently used to represent the underlying surface. Although only two methods to determine the roughness parameters are used here (Mac and Kan), a range of methods exist which can influence wind-speed estimations (Kent et al., 2017a).

Using the logarithmic wind law (Eq. (1)), wind-speeds extrapolated using the Kan method tend to be less than those using Mac (Fig. 3a–e) because of the considerably larger Kan₀. Notably, where z₀ is largest in magnitude (e.g. CC lv, Table 2) wind speeds at 100 m calculated using the Kan or Mac aerodynamic parameters vary between 36 and 39% of each other (depending on vegetation state). Elsewhere, extrapolated wind speeds tend to be more similar, and the least variable aerodynamic parameters in SB lv and SB lv mean winds speeds at 100 m vary by less than 4% and 12%, respectively.

The difference in wind speed when both buildings and vegetation are accounted for (Fig. 3, dashed lines), in comparison to buildings alone (Fig. 3, solid lines) is least where buildings dominate. For example, in CC lv and SB lv vegetation has little effect and regardless of its state causes a maximum wind-speed variation of <5% for each respective morphometric method.

Consideration of vegetation in the morphometric methods has a greater influence upon predicted wind speeds where vegetation is taller and more abundant (e.g. CC lv, SB lv and Pa). In addition, vegetation state (i.e. leaf-on or leaf-off) is more influential upon wind speeds in these areas. Despite z₀ increasing with inclusion of vegetation, there is greater inter- and intra-method variability in z₀ (Sect. 3.2). Therefore, because estimated wind profiles are a function of both z₀ and z₀ no general comment can be made about wind-speed changes when including vegetation.

Vegetation’s effect is most noticeable in Pa. High wind speeds when only buildings are considered (because of low z₀ and z₀) are reduced by almost a factor of three upon consideration of vegetation (Fig. 3e). The reduction in wind speed is more obvious for leaf-off porosities, because of the larger associated z₀. In CC lv and SB lv the effect of vegetation is less obvious, however a decrease in z₀ means wind speeds extrapolated using the Mac parameters increase. In contrast, wind speeds extrapolated using the Kan parameters tend to decrease because of the larger z₀ and lesser sensitivity to changes in z₀ (Sect. 3.2).

In summary, when buildings dominate (CC lv) the morphometric method chosen to determine the wind profile (i.e. Mac or Kan) is more important than whether vegetation is considered. In contrast, where vegetation is taller and accounts for a greater surface area (CC lv, SB lv and especially Pa) vegetation’s consideration has larger implications for wind-speed estimation than the morphometric method used. In all cases, the differences between leaf-on and leaf-off wind speed are larger for the Mac than Kan method, because of the sensitivity of Mac to the porosity parameterisation.

4. Conclusions

Vegetation should be included in morphometric determination of aerodynamic parameters, but not in the same way as solid structures. A methodology is proposed to include vegetation in Macdonald et al.’s (1998) morphometric method to determine the zero-plane displacement (z₀) and aerodynamic roughness length (Hₚ). This also applies to Kanda’s (2013) extension, which considers roughness-element height variability.

The proposed methodology considers the average, maximum and
standard deviation of heights for all roughness elements (buildings and vegetation). The plan area index and frontal area index of buildings and vegetation are determined separately (and subsequently combined for use in the morphometric methods). Aerodynamic porosity is used to determine the plan area of vegetation. Whereas, the frontal area index of vegetation is determined assuming a solid structure with the same dimensions. During determination of \( z_0 \) a parameterisation of the drag coefficient for vegetation is used, accounting for varying porosity. This follows literature that demonstrates the drag exerted by trees can be like that of a solid structure and decreases as porosity increases (Grant and Nickling, 1998; Guan et al., 2000; Vollsinger et al., 2005; Koizumi et al., 2010). The relation between the drag coefficient and porosity of an individual tree (Guan et al., 2000) is used as the basis for the parameterisation, which other experimental data demonstrate is reasonable.

From analysis of five different urban areas within a European city, the effect of the inclusion of vegetation on geometric and aerodynamic parameters depends upon whether buildings or vegetation are the dominant roughness element. Where buildings are taller they control the height-based geometric parameters. The opposite is true when vegetation is taller. Inclusion of vegetation increases the plan area index \( (\lambda_p) \) and frontal area index \( (\lambda_f) \), most obviously during leaf-off periods.

The increases in \( \lambda_p \) and \( \lambda_f \) from inclusion of vegetation more obviously affect aerodynamic parameters than the change in height based geometric parameters. The higher \( \lambda_p \) produces a larger \( z_d \) for both morphometric methods in four study areas. In the fifth case, a reduction in average height offsets the increase in \( \lambda_p \). The increase in \( z_d \) is largest for leaf-off because of the higher \( \lambda_p \) as well as where vegetation is taller and more significant because of the greater increase in \( \lambda_p \) and average height \( (H_p) \). Given the large inter-method variability in \( z_0 \), selection of the appropriate morphometric method is most critical, followed by whether vegetation is considered, then by the vegetation state (leaf-on or leaf-off).

Inclusion of the effect of vegetation on \( z_0 \) depends upon: the geometric parameters determined without vegetation and the associated \( \lambda_f \) that the peak \( z_0 \) occurs for each morphometric method. Therefore, a broad statement about how \( z_0 \) responds to vegetation inclusion is difficult. However, the change in \( z_0 \) is more obvious where vegetation is taller and takes up a large proportion of area. In the same areas, whether vegetation is included and its state (i.e. porosity) is as, or more important, than the inter-method variability in \( z_0 \) determined by the morphometric methods. Leaf-off \( z_0 \) is consistently smaller than leaf-off, because of the combined increase in \( \lambda_f \) and \( z_d \) which create an effectively smoother surface.

Assuming a logarithmic wind profile, the influence on estimated wind speed up to 100 m is least when vegetation is lower and accounts for a smaller proportion of surface area, with wind speed varying by < 5% regardless of consideration of vegetation. In contrast, wind speeds above an urban park are demonstrated to be slowed by up to a factor of three (both methods). Therefore, if vegetation is taller and more abundant, vegetation’s inclusion is as, or more, critical for wind-speed estimation than the morphometric method used.

Of course, the ultimate assessment of the parameterisation for accurate aerodynamic parameter and wind-speed estimation is comparison to observations. An assessment of the parameterisation, demonstrates the seasonal change in aerodynamic parameters can be captured and wind-speed estimations improved (Kent et al. 2017b). Undoubtedly, further observations and wind tunnel experiments with various arrays of solid and porous roughness elements will be valuable to assess the parameterisation.

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