

Increasing complexity in Aerodynamic Gradient flux calculations inside the roughness sublayer applied on a two-year dataset

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ABSTRACT

Over tall canopies such as forests the atmospheric surface layer is subdivided into an inertial sublayer (ISL) and a roughness sublayer (RSL). Inside the RSL the classic aerodynamic gradient method using Monin-Obukhov similarity theory (MOST) by itself does not represent the gradient well and is insufficient to calculate fluxes. Over the past decades multiple studies have proposed methods to extend MOST to account for the different turbulent conditions within the RSL, containing a wide range of approaches and complexity. In this study we investigate how much complexity is necessary to calculate the flux more accurately and what we can learn from the respective complexity. A large dataset is required to assess the statistical robustness of the respective complexity during different environmental conditions. To this end, we study and apply the effect of forest roughness and directional heterogeneity in our flux calculations on a two-year dataset (2009-2010) of the sensible heat flux measured over a Douglas fir forest in the Netherlands. We apply standard MOST, an observational based method (the α -factor) and a physically based method (Harman and Finnigan, 2007, 2008) (hereafter HF07/08) together with a range of methods for the displacement height (d). Our results show that both a simple method (the α -factor) and a complex method (HF07/08) are able to more accurately represent the flux but that, as expected, standard MOST (regardless of the method estimating d) alone is insufficient. Both the α -factor and (HF07/08) allow to analyze large scale patterns in canopy turbulence. Differences between the methods lie in the level of detail and practical usability.

1. Introduction

Fluxes of (trace) gases between surface and atmosphere have been a topic of interest for a long time (e.g. Baldocchi (2014)). Historically, most fluxes were inferred from gradient measurements using the Aerodynamic Gradient Method (AGM). Nowadays the Eddy Covariance (EC) method, which is a direct method to measure the flux, has become common practice for e.g. momentum, heat, CO₂ and H₂O. However, the AGM is still relevant for understanding historical datasets and for species for which there are currently no fast analyzers available or that are still in development (such as for NH₃ e.g. Swart et al. (2023)). Moreover, the AGM is essential to provide the coupling between the surface and the atmosphere in weather and climate models (Bonan et al., 2021), making it an important method to quantify.

The AGM relies on simultaneous concentration measurements at multiple heights combined with gradient measurements of wind velocity, potential temperature and moisture in the atmospheric surface layer (ASL). These quantities are translated to a flux using the Monin-Obukhov similarity theory (MOST, e.g. Moene and Van Dam (2014)). Under the presence of tall roughness elements, profiles of wind, temperature and scalars are displaced with displacement height d . Canopies in general (but especially tall canopies such as forests), however, also strongly affect the turbulence close to the surface, making MOST only valid well above the canopy (Högström, 1996). This poses a problem for flux gradient measurements at forest sites, as the tall canopy and logistical issues often prevent from measuring high enough.

The layer that is under direct influence of the canopy is referred to as the roughness sublayer (RSL) and typical estimates of the RSL thickness

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range between 1.5 and 2.5 times the canopy height (h_c) (e.g. Arya, 2001), thereby separating itself from the inertial sublayer (ISL) which is not affected by the tall canopy. It was found by several studies that inside the RSL the exchange of heat (buoyancy) and momentum, although not at the same rate, is increased compared to what would be expected from MOST (Thom et al., 1975; Raupach, 1979; Garratt, 1980; Denmead and Bradley, 1985; Höglström et al., 1989; Höglström, 1996; Raupach et al., 1996). Next to buoyancy and momentum, the tall canopy also influences the exchange of reactive gases by altering their exchange fluxes and that of their reactive counterparts (Brown et al., 2020). In search for a physical understanding of exchange processes inside the RSL Raupach et al. (1996) introduced the mixing-layer analogy, which was later extended by Finnigan et al. (2009) and corroborated with Large-Eddy Simulations (LES). The mixing-layer analogy states that there is an inflection point in the mean windspeed ($\bar{u}$) at h_c due to a concurrent low-velocity flow through the canopy and high-velocity flow above the canopy. The inflection point causes a hydrodynamic instability which generates organized turbulent structures, causing increased mixing near h_c (or inside the RSL). More information on canopy turbulence is reviewed in Brunet (2020) and focused on scalar transport in Katul et al. (2013).

Over the past decades multiple studies have been devoted to account for the altered turbulent conditions inside the RSL. It has been proposed to scale the ‘universal’ functions of MOST with the RSL-thickness (z_*) (Garratt, 1980; Mölder et al., 1999; De Ridder, 2010; Mo et al., 2022), use empirical scaling of MOST with observations (the α -factor) (Bosveld, 1991; Duyzer et al., 1992), use an enhancement factor of MOST based on diffusivity constants (Cellier and Brunet, 1992) and finally more physical based models have been developed (Harman and Finnigan, 2007, 2008; Siqueira and Katul, 2010). These physical based models incorporate the coupling between in- and above-canopy flow and have been corroborated with LES studies (Finnigan et al., 2009). Most of these methods have been verified with observations, ranging from a couple of days to a couple of months. From these models we know that the leaf area index (LAI) and stability (ζ) are relevant variables in the different methods, which can vary over a long dataset. Shapkalijevski et al. (2016) found that the turbulent diffusivity of momentum, heat and moisture is affected by seasonal changes in canopy phenology, getting twice as large during leafless state compared to full-leaf state. Furthermore, Harman (2012) shows that diabatic stability influences roughness characteristics such as the displacement height. In order to systematically assess to what extent the different methods take the dependence on phenology (LAI) and stability (ζ) into account, a single multiyear dataset is required. Moreover, a multiyear dataset allows to assess the impact of directional heterogeneity (i.e. through wind direction) and seasonal variability (through phenology and meteorology) on the RSL behavior.

The previously proposed methods vary widely in complexity and as such may vary in their performance or practical usability. Therefore, we are interested in how much complexity is needed to describe the flux more accurately compared to standard MOST and what can be learned from the respective methods. We aim to answer the following questions:

- i. Can both a simple observational based method and complex physical based method reproduce the EC measured flux and how much input parameters are required to do so?
- ii. Can both methods be used to investigate directional and seasonal patterns in the RSL behavior over a heterogeneous forest and does the inclusion of these patterns lead to a better representation of the flux?

To investigate this, we apply standard MOST (as a baseline), the α -factor (Bosveld, 1991) and (Harman and Finnigan, 2007, 2008) (hereafter HF07 and HF08 respectively) on a two-year dataset (2009-2010) of the sensible heat flux (H) over a Douglas fir forest. We measure both temperature and wind speed profiles from which we derive gradients needed for the H (H_{AGM}), which we can compare to EC

measurements of H (H_{EC}). In this comparison, H_{EC} serves as a reference flux. Here we use temperature gradients and the sensible heat flux to study the various methods, with the aim to apply these insights to other scalars as well in future studies. The two chosen methods are both extensions of MOST, but are fundamentally different in their approach to deal with the canopy turbulence and such form a useful selection of all methods introduced earlier. The method of Bosveld (1991) (hereafter the α -factor) has a phenomenological basis, but does not involve a description of the physical processes related to the canopy. It fits observations and is easy to use. In turn, the study of HF07/08 gives an elaborate description of the physical processes and is presented to be uniformly applicable. This method is currently applied in meteorological (e.g. Shapkalijevski et al. (2022)) and climate models (e.g. Bonan et al. (2018)). Each method will be described in more detail in Section 3. As the displacement height d is an essential parameter in AGM and is treated differently in the different RSL methods, we also incorporate 3 different methods with different complexity for d . These will be introduced and discussed in Section 3.

2. Materials & methods

2.1. Observation site

Observations are collected at the Speulderbos measurement site (52.25°N, 5.69°E) (see e.g. Duyzer et al. (1992) and Schilperoort et al. (2020)). Speulderbos is located in the middle of the Netherlands in the northwest of Natura 2000 area ‘Veluwe’. The site is located in a dense Douglas fir stand and is surrounded by mixed forest. See insert left panel in Fig. 1 for its location. The left panel of Fig. 1 displays a height map of the area for 2007-2014, which shows that the surroundings consists of patches with different tree species and roughness characteristics (i.e. element spacing and canopy height). This image is suitable to give an impression of the surroundings, but not for determining exact heights at the time of the measurement period. The location of the tower is marked with a red triangle and the surrounding homogeneous patch (hereafter referred to as DFP) is marked with a red line. This patch consists of Douglas fir trees and has been rapidly growing between 1992 and 2020. (Duyzer et al., 1992; Su et al., 2009; Weligepolage et al., 2012a; Schilperoort et al., 2020). It is characterized by a closed forest canopy with mean canopy height $h_c = 32$ m in 2006 and has no understory. Since 2006, multiple studies have estimated the LAI, ranging from 3.4 to 6.1 (see also Supplementary material S1). In this study we adopt the most advanced method, which was also obtained during our measurement period, of Mustafa et al. (2013) who found $LAI = 6.1 \text{ m}^2\text{m}^{-2}$. See also e.g. Schilperoort et al. (2020) for a map indicating the land use type of the surrounding patches.

From the tower, the Douglas fir patch (DFP) extends 45m to the north, 80 m to the east, 50 m to the south and 160 m to the west. A flux footprint climate analysis (Kljun et al., 2015) showed that at least 70 % of the flux originates from the Douglas fir patch. More information on the influence of the limited fetch can be found in Supplementary material S2. Based on the inhomogeneity of the surroundings we subdivided the dataset in four sections: Section S (green) - transitioning from open and low to closed and high canopy, Section W (yellow) - homogeneous canopy, Section N (blue) - transitioning from open to closed canopy and finally Section Excluded (red) is removed from analysis as it is disturbed by the tower itself. These sections will be used later on to analyze directional variability in RSL behavior.

2.2. Data collection & Treatment

Temperature, wind, turbulent variables and other standard meteorological observations were collected from a 46 m tall tower as part of the NitroEurope (NEU) and ECLAIRE projects between 2007 and 2014 (Skiba et al., 2009; Owen et al., 2011; Flechard et al., 2020). For this study we use the data collected between 01-01-2009 and 31-12-2010

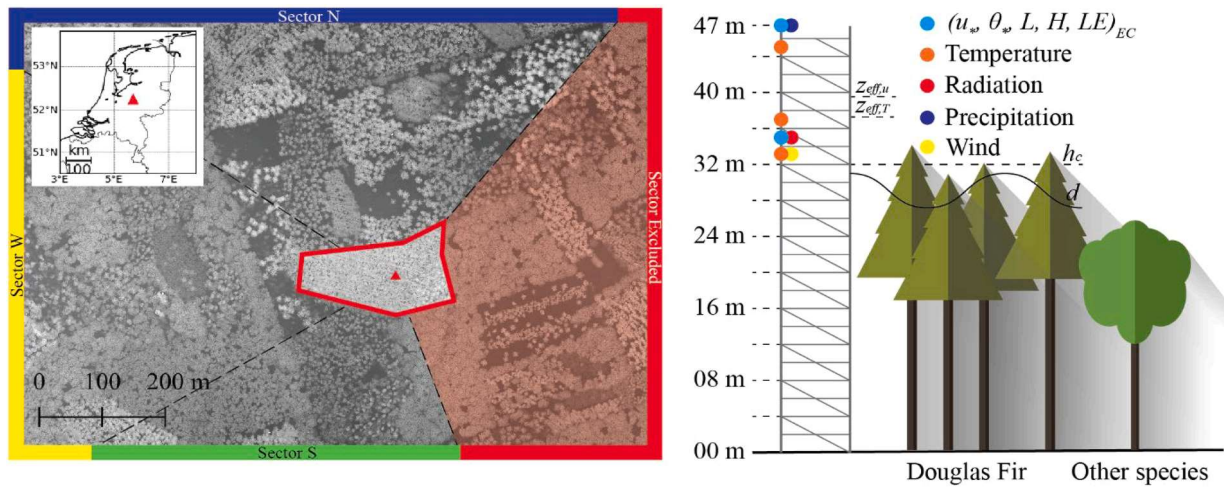


Fig. 1. (left insert) Location of observation tower. (left) Height map of surroundings of the observation tower, where dark pixels indicate low heights and bright pixels indicates high heights. The observation tower is denoted with a red triangle and the surrounding Douglas fir patch (DFP) is enclosed by a red line. Note that this image is collected from AHN3 (AHN.nl), which was acquired in 2007–2014. This is an impression of what the forest looks like but cannot be used to obtain absolute values. Therefore, we left out the legend on purpose. Height differences between minimum and maximum values in this plot are in the order of h_c . The different sectors are marked with dashed lines and colors. Source: AHN.nl. (right) Overview of the observation tower with location of the instruments. The mean canopy height (h_c) is marked with a dashed line and a dynamic form of the displacement height d is shown with the continuous line.

only. Turbulent variables (including momentum flux ($\overline{w'u}$), sensible heat flux ($\overline{w'\theta}$), latent heat flux ($\overline{w'q}$), friction velocity (u_*), Obukhov length (L), wind velocity and wind direction) were measured with two 3D 20 Hz sonic anemometers (CSAT3, Campbell Sci. Inc., USA) and $\text{CO}_2/\text{H}_2\text{O}$ open path analyzers (LI-COR 7500) installed at 35 and 47 m. The horizontal wind speed was measured at an additional level at 33 m with a Mierij MMW05 sensor (MMW05, Mierij Meteo, NL) until mid-June 2009 and afterwards with a Gill 2D sensor (Gill sonic 2D, Gill instruments Ltd, UK). Temperature was measured at 33.3, 37.3 and 45.3 m (thermocouples type E, TC inc., USA). The thermocouples were capped with a radiation shield in order to protect them from direct incoming radiation without hampering natural ventilation. Under neutral-unstable conditions ($-0.1 \leq \zeta < 0$, $|\overline{w'\theta}| < 0.01 \text{ K m s}^{-1}$ and $\bar{u} > 1 \text{ m s}^{-1}$) we found an offset of -0.005 K m^{-1} . In turn, under neutral-stable conditions ($0 \leq \zeta \leq 0.1$, $|\overline{w'\theta}| < 0.01 \text{ K m s}^{-1}$ and $\bar{u} > 1 \text{ m s}^{-1}$) we found an offset of -0.002 K m^{-1} between the 33 and 45 m sensors. To avoid artificial gradients, we removed this offset at the lower two levels accordingly with respect to their height and stability class. Furthermore, precipitation was measured at 47 m (WXT510, Vaisala, FIN) and radiation data was collected at 35 m (CNR1, Kipp & Zonen BV, NL). An overview of the locations of the instruments is given in the right panel of Fig. 1.

The sonic and LI-COR output was processed using Alteddy software (version 3.5 and 3.6) (Elbers, 1998) on a daily and annual basis. As part of the CarboEurope project the Alteddy software has been compared with other softwares like Eddysoft. Results of this comparison are reported in Mauder et al. (2008) with the applied corrections as summarized in Table 2 from Mauder et al. (2008). The Alteddy software, however, allows several choices for processing. For this study we applied the double rotation method (instead of planar fit) and the WPL correction (Webb et al., 1980) on 30 minute periods. Quality flags are determined based on Foken et al. (2005) and for our study we use data with flag 3 or lower only.

We filtered the data as described in the Table 1 to guarantee a useful comparison between AGM and EC. Filters 2, 4, 5, 6 and 10 are applied on the lower sonic (35 m). Filter 2 excludes sections which are disturbed by the tower itself. Filter 5 was introduced to avoid decoupling between canopy air and atmosphere (e.g. Jocher et al. (2020)) and the value of 0.4 m s^{-1} is adopted from Schilperoort et al. (2020). After filtering, 12.0 % (4183 datapoints) of the two-year dataset (35040 datapoints) remain

Table 1

Filters used for analysis of gradient and EC sensible heat fluxes (H). Data was collected between 01-01-2009 and 31-12-2010. Acceptance rate shown applies to filter criteria applied in sequence.

Filter #	Condition	Acceptance
0	2009–2010 dataset Unfiltered	100 % 81.3 %
1	No rain	80.5 %
2	Exclude disturbed region	$WD \leq 40^\circ$ or $WD \geq 160^\circ$ 55.9 %
3	Stationarity*	$QF H_{EC} \leq 3$ 50.1 %
4	Temp gradient sufficient, outside level of detection	$\left[\frac{\partial \theta(z)}{\partial z} \right]_{z=33}^{z=45} > 0.05$ 46.4 %
5	Mixing of temperature sensors	$\bar{u} > 1$ 39.6 %
6	Canopy air and atmosphere coupled	$u_* > 0.4$ 22.9 %
7	Developed turbulence	$ \theta_* > 0.05$ 15.0 %
8	Temperature profile consistent	$\left[\frac{\partial \theta(z)}{\partial z} \right]_{z=33}^{z=37} \cdot \left[\frac{\partial \theta(z)}{\partial z} \right]_{z=37}^{z=45} > 0$ 13.7 %
9	Wind velocity profile consistent	$\bar{u}_{47} > \bar{u}_{35}$ 13.7 %
10	Gradient flux and sonic H in same direction	$\left[\frac{\partial \theta(z)}{\partial z} \right]_{z=33}^{z=45} \cdot \overline{w'T} < 0$ 13.3 %
11	Upper limit flux not larger than radiation balance	$H < (Q_{Sin} + Q_{Lin} + Q_{Sout} + Q_{Lout})$ 12.0 %

* Based on Foken, T., Göckede, M., Mauder, M., Mahrt, L., Amiro, B., & Munger, W. (2005). Post-Field Data Quality Control. In X. Lee, W. Massman, & B. Law (Eds.), *Handbook of Micrometeorology: A Guide for Surface Flux Measurement and Analysis* (pp. 181–208). Springer Netherlands. https://doi.org/10.1007/1-4020-2265-4_9

for further analysis. Supplementary Fig. 2 in the supplementary materials shows how these points are distributed in space and time.

As a rough indication of the accuracy of the flux measurements, the energy balance closure (Foken, 2008) was examined. Averaged over the campaign, the closure was 92 %. This is slightly better than the average closure of 83 % reported for forests in the comprehensive analysis done by Stoy et al. (2013). Possible causes for non-closure were not studied, and to avoid additional data loss and extra uncertainty fluxes were not corrected for the lack of energy balance closure.

3. Theory/Calculations

3.1. AGM Flux calculation

3.1.1. Standard MOST

In standard MOST the flux for momentum (M), heat (H) or scalars (χ) can be approximated using flux-profile relations $\phi_i(\zeta)$. These flux-profile relations are different for momentum, active (buoyantly), passive and reactive scalars, denoted with subscript i (Vilà-Guerau de Arellano et al., 1995; Maronga and Reuder, 2017). ζ denotes the stability of the atmosphere ($\zeta = (z - d)/L$), where L denotes the Obukhov length and is calculated with:

$$L = \bar{\theta} \cdot u_*^2 / \kappa g \theta_* \quad (1)$$

For more information on MOST see e.g. Moene and Van Dam (2014). In this study we use the integrated form ($\Psi_i(\zeta)$) to calculate the fluxes.

$$F_M = \overline{w'u} = -u_* u_* = -\kappa u_* \frac{u(z_2) - u(z_1)}{\ln\left(\frac{z_2 - d}{z_1 - d}\right) - \Psi_M(\zeta_2) + \Psi_M(\zeta_1)} \quad (2a)$$

$$F_H = \overline{w'\theta} = -u_* \theta_* = -\kappa u_* \frac{\theta(z_2) - \theta(z_1)}{\ln\left(\frac{z_2 - d}{z_1 - d}\right) - \Psi_H(\zeta_2) + \Psi_H(\zeta_1)} \quad (2b)$$

Where κ is the von Kármán constant (0.4), u_* the friction velocity, θ_* the characteristic scale of temperature, z the measurement height and $\Psi_i(\zeta)$ the integrated form of $\phi_i(\zeta)$. In this study we use for unstable situations (i.e. $\zeta < 0$) the functions by Paulson (1970) and Dyer (1974) and for stable situations (i.e. $\zeta \geq 0$) the functions by Beljaars and Holt-slag (1991) (see also Supplementary Material S4). The methods for d are discussed in Section 3.2. We applied Equations 1 and 2 on 30 minute averages of temperature and wind profiles, such that we get 30 minute average fluxes. By definition, u_* , θ_* and ζ share variables. Therefore, we iterated our calculations until the results were stable, which was typically after 3 iterations. As we have three observational levels for temperature, the stability corrected gradient is calculated with a linear regression through the temperatures and the natural logarithm of the stability corrected heights, following (Wichink Kruit et al., 2009). For the wind-velocity gradient we use measurements of the two sonics only. For consistency we use the same method to calculate the gradients for temperature and for wind-velocity and Equation 2a and 2b are solved simultaneously. As there were no humidity sensors available at the same height as the temperature sensors, we omit the effect of humidity on buoyancy and assume that the gradient in virtual potential temperature and potential temperature are approximately equal (i.e. $\Delta\theta_v \approx \Delta\theta$). The flux calculation scheme described above will from now on be referred to as standard MOST.

3.1.2. The α factor

The α -factor was first proposed by Bosveld (1991) and later further discussed in Bosveld (1997). Furthermore, Duyzer et al. (1992) applied it to NH_3 gradient flux data at the same site as in this study. Physically the α -factor can be seen as an enhancement factor of MOST. It is defined as the neutral ($-0.05 < \zeta < 0.05$) crossing point of ϕ_i . During neutral conditions there is no need for stability corrections and thus ϕ_i should be equal to one. Due to the presence of the RSL, however, this is not the case and is accordingly corrected for with α_i . The flux profile relations are then scaled as follows:

$$\zeta < 0; \phi_i|_{\text{RSL}} = \alpha_i \cdot \phi_i|_{\text{ISL}} \quad (3a)$$

$$\zeta > 0; \phi_i|_{\text{RSL}} = \alpha_i + (\phi_i|_{\text{ISL}} - 1), \quad (3b)$$

where $|_{\text{RSL}}$ and $|_{\text{ISL}}$ indicate the domain in which the function is valid. The studies mentioned above found α_i to be different for momentum and heat/scalars. In this study we will determine α_i at the effective mea-

surement height z_{eff} for both momentum and heat. z_{eff} is defined as the geometric mean of the flux measurement level above the displacement height (see also Fig. 1). The α -factor is determined as follows: (i) First standard MOST (see previous section) is applied to calculate the left-hand-side of Equation 4.

$$\frac{\partial \bar{u}}{\partial z} \frac{\kappa z}{u_*} = \phi_M|_{\text{RSL}}(\zeta) \quad (4a)$$

$$\frac{\partial \bar{\theta}}{\partial z} \frac{\kappa z}{\theta_*} = \phi_H|_{\text{RSL}}(\zeta) \quad (4b)$$

(ii) Second the observations are filtered as described in Table 1 with an additional filter for neutral conditions ($-0.05 < \zeta < 0.05$). (iii) As ζ and ϕ are both non-linear functions of stochastic variables θ and u , using time averages (30 min) of these variables will result in biased estimates of ζ and ϕ . To overcome this issue, we use the Decreased Bias Estimate through Classification method (DBEC, Bosveld (1991)). DBEC calculates bin averages of similar conditions by sorting the data. Here, we sort the observed ϕ_i with increasing ζ and we subsequently average every 10 successive values to one bin. This method will also be applied to the comparison of H_{AGM} and H_{EC} , as it substantially decreases the RMSE and increases the correlation coefficient. Furthermore, it allows for easier graphical presentation and interpretation as there are a factor 10 fewer observation points. (iv) Finally, α_i is retrieved by taking the median of these averaged values. The flux was subsequently calculated with a modified form of Eq. (2a):

$$\zeta < 0$$

$$\left\{ \begin{array}{l} F_M = -\kappa u_* \frac{u(z_2) - u(z_1)}{\alpha_M \left(\ln\left(\frac{z_2 - d}{z_1 - d}\right) - \Psi_M(\zeta_2) + \Psi_M(\zeta_1) \right)} \end{array} \right. \quad (5a)$$

$$\left\{ \begin{array}{l} F_H = -\kappa u_* \frac{\theta(z_2) - \theta(z_1)}{\alpha_H \left(\ln\left(\frac{z_2 - d}{z_1 - d}\right) - \Psi_H(\zeta_2) + \Psi_H(\zeta_1) \right)} \end{array} \right. \quad (5b)$$

$$\zeta \geq 0$$

$$\left\{ \begin{array}{l} F_M = -\kappa u_* \frac{u(z_2) - u(z_1)}{\alpha_M \ln\left(\frac{z_2 - d}{z_1 - d}\right) - \Psi_M(\zeta_2) + \Psi_M(\zeta_1)} \end{array} \right. \quad (5c)$$

$$\left\{ \begin{array}{l} F_H = -\kappa u_* \frac{\theta(z_2) - \theta(z_1)}{\alpha_H \ln\left(\frac{z_2 - d}{z_1 - d}\right) - \Psi_H(\zeta_2) + \Psi_H(\zeta_1)} \end{array} \right. \quad (5d)$$

3.1.3. Harman and Finnigan 2007/2008 (HF07/HF08)

The Harman and Finnigan scheme was presented in two papers, one for momentum (HF07) and one for scalars (HF08) and attempts to reproduce the physics of the interaction between canopy and atmosphere. Their proposed method uses the mixing layer analogy which provides an extra length scale, the vorticity thickness (δ_w). δ_w represents a typical length scale of the turbulent eddies formed at h_c . It is defined as $\delta_w = \bar{u}/[d\bar{u}/dz] = [l_i/\beta]_{h_c}$, where l_i gives the mixing length for the vertical momentum or scalar flux and β is a stability dependent parameter proportional to the surface drag (c_d). When sonic observations of u_* are available it is calculated as:

$$\beta_{\text{obs}} = u_* / \bar{u}(h_c) \quad (6)$$

The RSL modified form ϕ_i is given by $\phi_i|_{\text{RSL}} = \hat{\phi}_i(\zeta, \delta_w) \cdot \phi_i|_{\text{ISL}}$. The form of $\hat{\phi}_i$ is exponential and converges asymptotically to 1 with increasing z . $\hat{\phi}_i$ is given by:

$$\hat{\phi}_i(\zeta, \delta_w) = 1 - c_{1,i} \exp\left[-\frac{\beta c_{2,i}(z - d)}{l_i}\right] \quad (7)$$

Where $c_{1,i}$ scales the amplitude of the RSL scheme, given by:

$$c_{1,i} = \left(1 - \frac{\kappa S_c}{2\beta}\right) \exp\left(\frac{c_{2,i}}{2}\right) \quad (8)$$

And $c_{2,i}$ represents a scaled depth over which the RSL function works, for which we adopt the value of 0.5 from HF07 and S_c denotes the Schmidt number at h_c . The RSL-modified form of Equation 2 is then given by:

$$F_M = -\kappa u_* \frac{u(z_2) - u(z_1)}{\ln\left(\frac{z_2-d}{z_1-d}\right) - \Psi_M(\zeta_2) + \Psi_M(\zeta_1) + \hat{\Psi}_M(\zeta_2, \delta_\omega) - \hat{\Psi}_M(\zeta_1, \delta_\omega)} \quad (9a)$$

$$F_H = -\kappa u_* \frac{\theta(z_2) - \theta(z_1)}{\ln\left(\frac{z_2-d}{z_1-d}\right) - \Psi_H(\zeta_2) + \Psi_H(\zeta_1) + \hat{\Psi}_H(\zeta_2, \delta_\omega) - \hat{\Psi}_H(\zeta_1, \delta_\omega)} \quad (9b)$$

Where $\hat{\Psi}_i$ is the integrated form of $\hat{\phi}_i$ and is solved numerically because of its strong non-linear character. HF07 introduces also a method for d , following the theory of Jackson (1981), with the following set of equations:

$$d = h_c - d_t \quad (10)$$

$$d_t = \frac{\int_{-\infty}^{\infty} z u(z)^2 / L_c dz}{\int_{-\infty}^{\infty} u(z)^2 / L_c dz} = \beta^2 L_c \quad (11)$$

$$L_c = 1/(c_d \cdot a) = 4h_c/LAI \quad (12)$$

Where L_c is a length scale for the absorption of momentum and following HF07/08 it is assumed to be constant. c_d is assumed constant and we adopted the value of 0.25 of HF07. a denotes the leaf area per unit volume. When using solely gradient observations, β is parameterized as β_{HF07} :

$$\beta_{HF07} \cdot \phi_M\left(\frac{L_c}{L}\right) = \beta_N \quad (13)$$

Where β_N gives the value of β under neutral conditions ($-0.05 < \zeta < 0.05$). We found $\beta_N = 0.3$, which corresponds well with values found by (Harman and Finnigan, 2007, 2008; Harman, 2012; Shapkalijevski et al., 2016). Equation 13 was found to work well if $L_c/|L| < 2$, but becomes questionable under strong unstable conditions. To overcome this issue the parameterization was later extended by Harman (2012) to:

$$\beta_{H12}(L_c/L) = \begin{cases} \beta_{HF07} & \text{if } L_c/L > -a_2 \\ \beta_{norsl}(L_c/L) + \frac{\beta_{HF07}(L_c/L) - \beta_{norsl}(L_c/L)}{1 + a_1|L_c/L - a_2|^{a_3}} & \text{else} \end{cases} \quad (14)$$

Where β_{norsl} is the value of β when not accounted for the RSL. The parameters a_1 , a_2 and a_3 are site specific and determine the location of maximum difference from β_{norsl} . After optimization with β_{obs} by minimizing the RMSE, we adopt the values of 0.7, -0.15 and 1.6 respectively. Note that HF07/08 states that when flux and profile data are available, β should be determined from observations (β_{obs}). Hence we include both and make a distinction in d when using β_{obs} or β_{HF} , giving d_{obs} and d_{HF} respectively. For completeness:

$$d_{obs} = h_c - \beta_{obs}^2 L_c \quad (15)$$

$$d_{HF} = h_c - \beta_{H12}^2 L_c \quad (16)$$

Previous studies (e.g. Shapkalijevski et al. (2017)) found β_{obs} to show little variability with stability and adopted the constant value of β_N . We are, however, especially interested in the dynamic form of HF07/HF08 which is largely controlled by β and thus continue with its dynamic form. By this method, a separate value for d is calculated for each half hourly observation. Important assumptions of HF07/08 to consider are: (i) a homogenous canopy and (ii) a constant L_c . For more information we

refer to the papers of HF07 and HF08 and Harman (2012).

3.2. Displacement height

From the previous section it becomes clear that the displacement height d is an essential parameter in flux calculations. d is defined as the height at which drag acts on the canopy elements (Thom, 1971; Jackson, 1981). Following Raupach (1979), we assume the displacement height for momentum and heat to be equal (i.e. $d = d_M = d_H$). Over the past decades multiple methods have been proposed to determine the displacement height, e.g. (Jackson, 1981), Weligepolage et al. (2012b) and (Graf et al., 2014). In this study we will use three different methods with increasing complexity; i.e. the basic (rule of thumb) estimate, the methods of Weligepolage et al. (2012b) (hereafter W12), and Equation 15 and 16 (HF07). In the previous section we already introduced the method of HF07, which is the most complex form used in this study and variable for each half hour.

The least complex form follows the basic estimate where d is estimated as a fraction of the canopy height (h_c):

$$d_{2/3h_c} = 2/3 \cdot h_c \quad (17)$$

Which gives $d_{2/3h_c} = 21.3$ m for our site. This method, however, gives only a rough estimate as the plant area index, the height of maximum foliage (Massman, 1997) and canopy element spacing (e.g. Raupach, 1992; Foken, 2017) all affect the surface drag, making it a more complicated, time dependent, parameter.

W12 used a modified form of Equation 7 to retrieve d (following Nakai et al. (2008)). Besides the incorporation of HF07 in this equation, they applied two other AGM methods involving the RSL (Mölder et al., 1999; De Ridder, 2010). Subsequent application of these relations on forests with different canopy heights (amongst which Speulderbos) they fitted the following relation for d :

$$d_{W12} = 0.0087h_c^2 + 0.566h_c \quad (18)$$

For more information on this relation we refer to W12. Equation 14 gives $d_{W12} = 27$ m for our site.

4. Results

To validate, analyze and assess the added value of increased complexity in flux calculation schemes and their sensitivity, we increase the complexity step-by-step according to the schematic overview below (Fig. 2). Subsequently we compare H_{AGM} to H_{EC} . For this, we use the sonic at 35 m level as it is the closest to the geometric mean of the gradient flux (38 m) and we assume a constant flux layer. The validity of such a comparison is discussed in Section 5.1.

Fig. 3 shows an overview of the results of the eight different flux calculation schemes with different combinations of AGM methods and methods for d . The resulting H_{AGM} is compared to H_{EC} and the statistics of the regressions are summarized in Table 2. For all flux calculation schemes the correlation coefficient (r) was 0.95 or higher. The various

M1 MOST $d_{2/3h_c}$	M2 MOST d_{W12}	M3 Constant α d_{W12}	M4 Directional α d_{W12}
M5 Seasonal α d_{W12}	M6 HF07/08 d_{HF}	M7 HF07/08 d_{obs}	M8 HF07/08 d_{opt}

Fig. 2. Schematic overview of flux calculation schemes with increasing complex forms of the displacement height and of AGM method.

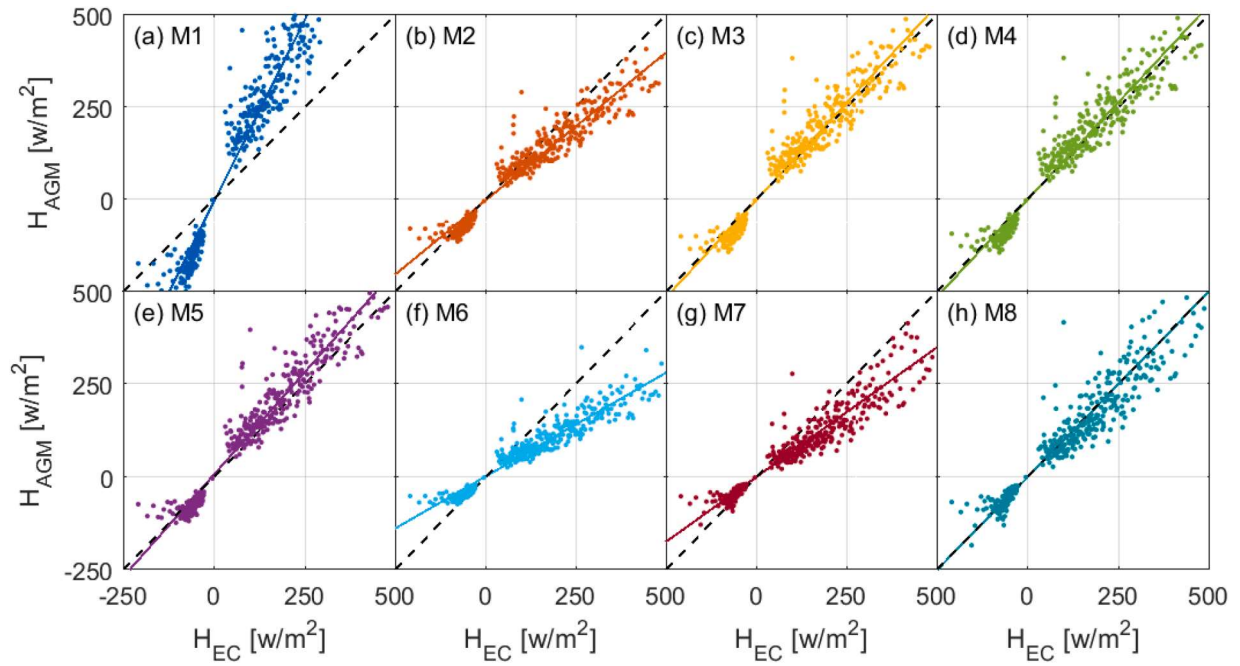


Fig. 3. Comparison between H_{AGM} and H_{EC} (35 m) for the different calculation schemes after application of DBEC

Table 2

Summary of the statistics of the different RSL schemes compared to H_{EC} . Slope gives the slope between H_{AGM} and H_{EC} , RMSE the root mean squared error between H_{AGM} and H_{EC} and STD the standard deviation of H_{AGM} . The slope has been retrieved with a linear orthogonal regression. Bolt printed values denote the three slopes closest to 1.

Fig. 3	Flux calculation method			Slope	Intercept	RMSE	STD
		EC (35 m)					
(a)	M1	MOST	$d_{2/3h_c}$	1.97	− 6.74	163.74	162.87
(b)	M2	MOST	d_{w12}	0.80	− 2.83	53.42	310.76
(c)	M3	Constant α	d_{w12}	1.06	− 2.08	50.19	131.51
(d)	M4	directional α	d_{w12}	1.05	− 1.30	50.37	170.97
(e)	M5	Seasonal α	d_{w12}	1.10	6.11	51.89	170.71
(f)	M6	HF07/08	d_{HF}	0.56	1.16	79.06	178.52
(g)	M7	HF07/08	d_{obs}	0.70	− 0.33	64.72	93.43
(h)	M8	HF07/08	d_{opt}	1.00	− 1.40	56.21	115.71
							162.72

schemes produce a wide range of outcomes, which we will discuss in more detail in Section 4.4. First, we will discuss the behavior of the different flux calculation methods (sect 4.1-4.3). Note that when using M6, which uses d_{HF} , very small values were found for the displacement height in 19 of the 4202 cases, sometimes even resulting in negative values, leading to erroneously large fluxes. This is a result of very small gradient in u , causing strongly unstable conditions which do not converge when iterating. To prevent these data from dominating the comparative statistics, we discard the half hours with $d_{HF} < 25$ m for all methods. This has a negligible impact on the statistical results of the other methods.

4.1. MOST

Fig. 3a shows the results when applying MOST with the standard estimate for the displacement height ($d_{2/3h_c}$). Contrary to the expectations when applying MOST in the RSL, the flux is in this case overestimated by a factor 2. When applying d_{w12} (Fig. 3b) the flux is underestimated with approximately 20 %. First, this shows that flux calculations are very sensitive to a choice for d . A difference of 5.7 m (note that this is a large difference) leads to a decrease in the flux of 120 %. Second, it shows that using the basic estimate of $d = 2/3h_c$ can be considered as too simple. Finally, it shows that using a more complex method for d involving canopy turbulence does by itself not lead to a

better representation of the flux. The flux-profile relations itself must also be adjusted to account for the enhanced turbulence inside the RSL.

4.2. The α -factor

The α -factor is a simple extension of MOST to account for the enhanced turbulence within the RSL. Here, we apply it as a constant (Section 4.2.1) and investigate its directional (Section 4.2.2) and seasonal (Section 4.2.3) behavior. A directional pattern in α might reveal effects of different canopy structures upwind from the tower, as the surroundings of the tower are heterogeneous (see Fig. 1). A seasonal pattern in α might indicate an effect of different meteorological conditions on the behavior of the RSL. Furthermore, it might also show an effect of phenological changes (expressed in different LAI values) in the surrounding forest patches. The constant α -factor (Fig. 4a) was determined by using the entire dataset. The directionally varying α -factor (Fig. 4b) was determined by taking 20-degree bins of wind direction. The seasonally varying α -factor (Fig. 4c) was calculated for every 3-month period (quarter). Unfortunately, the data coverage is not sufficient to let the α -factor vary in space and time simultaneously.

4.2.1. Constant α -factor (M3)

Fig. 4a shows the constant α -factor (as median) to be 0.92 for momentum and 0.83 for heat, together with its spread. This shows that

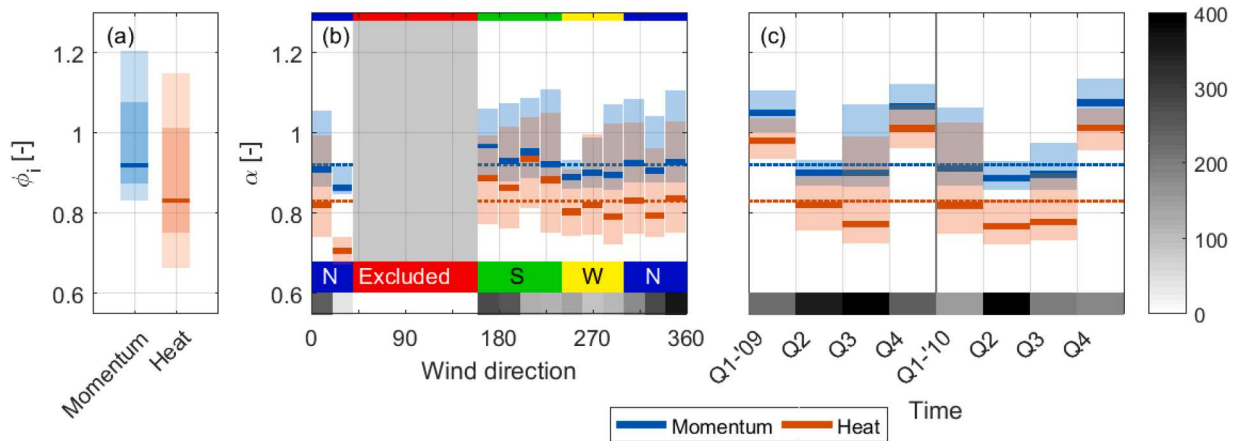


Fig. 4. For both momentum and heat (a) the distribution of neutral crossing points, where the median indicates the constant α -factor. (b) Directional variability of the α -factor. The colors above and below represent different sectors, see Fig. 1. (c) seasonal variability of the α -factor. The gray bar denotes the number of measurements that pass the conditions specified in Section 3.1.2 and that are used for the respective sections. The dotted lines denote the constant α -factor and the shaded bar shows the 25 % and 75 % percentiles of the α -factor.

momentum and heat are not affected by the RSL in the same way, as was also found by numerous other studies (e.g., Garratt, 1980; Raupach et al., 1986; Högström et al., 1989; Shapkalijevski et al., 2016). This difference is due to the larger turbulent length scale over forests, as eddies are able to penetrate the canopy. This allows eddies to collect air further down of the gradient and as sources/sinks of heat and momentum are not collocated, this results in increased mixing of heat compared to momentum (Shapkalijevski et al., 2016). It must be noted, however, that $z_{eff,u}$ is slightly higher than $z_{eff,T}$ (see also Fig. 1) which also leads to a larger α -factor for momentum (Bosveld, 1997).

4.2.2. Directional α -factor (M4)

The directionally dependent α -factor varies between 0.87 and 0.97 for momentum and between 0.71 and 0.94 for heat and have a similar pattern (see Fig. 4b). Between 160° and 240° (Sector S, green) the α -factor reaches relatively high values and between 240° and 360° (Sector N, blue) it is lower and approximately constant. From Fig. 1 we can see that in Sector S the upwind extent of the DFP is limited and transitions to a lower and more open canopy. Upwind in Sector W the DFP is relatively large. In contrast, upwind in Sector N its size is limited and transitioning to a more open canopy. To investigate the effect of forest transitions we compare the different sectors to Sector W, which has the longest uniform fetch and serves as a baseline. We find that: (i) a transition from open to closed canopy (N to DFP) leads to a similar α -factor. A study to the effect of inhomogeneous forest to downwind turbulence by Boudreault et al. (2017) shows that the main difference between an open canopy and a closed canopy is located near the edge of transitioning, leading to a larger distortion of the flow over a closed canopy due to reduced flow penetration. (ii) A transition from open and low to closed and tall canopy (S to DFP) leads to a larger α -factor (hence less disturbance or RSL impact). Wuyts et al. (2008) found that the effect of forest edges (in this case expressed as a transition from low to high canopy) on turbulence lead to a strong increase in turbulence at the canopy top, but that a gradual increase limits the effect. Combining Boudreault et al. (2017) and Wuyts et al. (2008), it is expected that a transition from an open and low canopy to a closed and high canopy leads to an even larger disturbance. Taking (i) and (ii) together suggests that history of canopy height in the flow is a more important factor in determining the α -factor than the history in the openness of the canopy. The directional heterogeneity will be further discussed in Section 4.3.1.

4.2.3. Seasonal α -factor (M5)

The seasonally varying α -factor varies between 0.89 and 1.08 for momentum and between 0.77 and 1.01 for heat (see Fig. 4c). A clear

seasonal cycle is visible, with maximum values in winter and minimum values in summer. The moment of peaking is however not directly clear from Fig. 4c, as in 2009 it peaks in Q1 and Q4, and in 2010 it peaks in Q4. In the case of momentum an α -factor larger than one (1.07 in Q4-2010) was observed, which is not expected inside the RSL. Moreover, there are no clear physical processes that could explain such a value. Although Douglas fir trees are not subject to seasonal leaf degradation, there are, especially Southwards, broadleaf species in the vicinity with a seasonal cycle in LAI. An extensive analysis of the spatial and temporal variability in the vicinity of the tower can be found in Mustafa et al. (2013). Shapkalijevski et al. (2016) showed that during leafless periods (Q1 and Q4) the turbulence is stronger than during leafy periods (Q2 and Q3), as a dense (leafy) canopy is more homogeneous and thus has less roughness. This would translate to a smaller value for α during winter and a larger value during summer, which is the opposite of our observations and thus not likely to explain the pattern found here. A second, and more likely, explanation could lie in the different meteorological conditions during summer (which is dominated by local and mesoscale systems) and winter (which is dominated by synoptic scale systems), presenting itself as an artifact in the calculated α -factor. During Q1 and especially during Q4 the stability range of points determining α tends more towards the positive values for ζ , leading to a larger α -factor. This suggests that during these stable conditions mixing inside the RSL is less enhanced.

4.3. HF07/HF08 (M6, M7 and M8)

The largest improvement of HF07/HF08 with respect to the previous AGM-RSL method is that they made both the RSL modification $\hat{\phi}$ and the displacement height d a function of the flow rather than having a fixed value. The dynamic variability of d is driven by β (see Eqs. (15) and (16)), but d is a more intuitive parameter than β and therefore we will focus on d in the following sections. This also allows us to compare the effect of the parameterizations of both L_c and β on d simultaneously. For completeness, the different methods for β are plotted against stability in Supplementary Fig. 3. The dynamic variability of $\hat{\phi}$ is driven by both β and S_c , but for practical purposes we do not show S_c in this study.

4.3.1. Dynamic variability of d_{HF} and d_{obs}

In Fig. 5a d_{HF} and d_{obs} are plotted against atmospheric stability. It can be seen that especially d_{obs} shows a lot of scatter. A pattern becomes visible after application of DBEC (with $n = 100$) and for d_{obs} two functions were fitted for unstable and stable conditions. The transition from neutral conditions to stable conditions is characterized by a strong jump

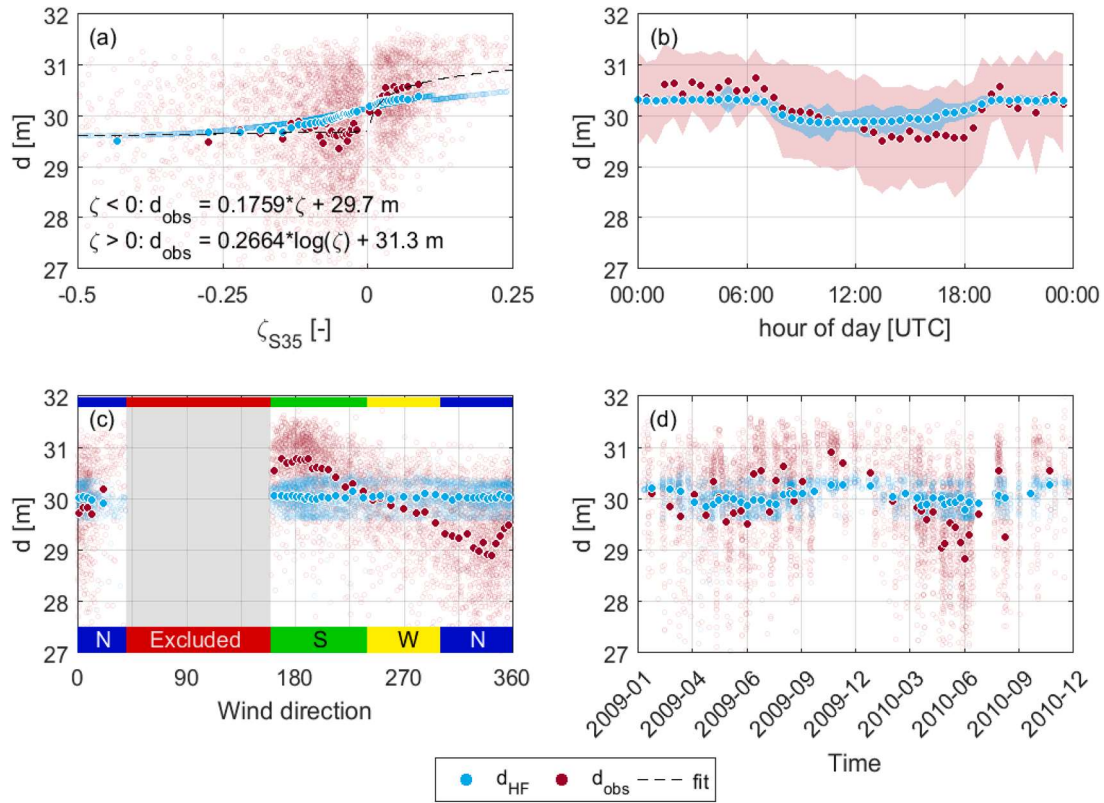


Fig. 5. Variability of d_{HF} and d_{obs} against various parameters. In each panel we applied DBEC with the respective x-axis, where the small dots indicate half-hourly values and large dots after application of DBEC with averaging sample size $N = 100$. (a) Relation between d and atmospheric stability using turbulent fluxes measured with the sonic at 35 m. (b) Average diurnal variability with 1σ uncertainty band. (c) Directional variability of d . The colors above and below represent different sectors, with: Sector N (blue), Sector Excluded (red), Sector S (green) and Sector W (yellow). (d) Variation of d throughout measurement period.

after which it stabilizes. Such behavior in the stable regime is in agreement with earlier observations (Shaw et al., 1988; Simpson et al., 1998; Lee, 2003; Rannik et al., 2003; Harman and Finnigan, 2007) (See also Supplementary Fig. 3 to see the behavior of β with stability directly). HF07 studied this behavior extensively. They hypothesized that β decreases (and d increases) with increasing stability, as it is directly coupled to the mixing length which decreases by a factor $1/\phi_m$ (given that L_e is constant). Following the same hypothesis, the opposite should occur under an unstable regime. However, under an increasingly unstable atmosphere buoyancy mixing increasingly dominates over shear at the canopy top. This is quantified by the subsequent decrease of the momentum flux. From Fig. 5a, it seems that the decrease in mechanical mixing and increase in buoyancy mixing are approximately equally important with decreasing ζ , compensating their opposite effects. The net effect on d is that it remains approximately constant in the unstable regime. The hypothesis above is the underlying theory for the parameterization of β_{HF12} . Fig. 5a shows that the general patterns of d_{obs} and d_{HF} are in agreement, although there are some distinct differences: (i) The jump from neutral to stable is much less distinct in d_{HF} , (ii) during stable conditions d_{HF} is smaller than d_{obs} and (iii) d_{obs} shows much more scatter than d_{HF} , which is not surprising due to the fact that d_{HF} is a parameterized variable. These differences translate into a dampened pattern in Fig. 5b-d compared to d_{obs} .

In Fig. 5b the average diurnal pattern of d_{obs} can be seen. It is at its maximum (30.5 m) during the night, while it is at its minimum (29.6 m) in the afternoon. This corresponds well to Fig. 5a, where it is expected that above the canopy the atmosphere is mostly stable during the night and more unstable during the day. A similar but smoother pattern is visible in d_{HF} .

The dynamic form of d also allows us to investigate its directional and seasonal variability. In Fig. 5c d_{obs} is plotted against the wind

direction. As we compare observations from the entire measurement period here, we expect no dominant preference for stability with wind direction. Hence, the effect of the stability on the emerging pattern should not be dominant. Instead, it allows us to investigate the effect of directional differences on the RSL induced mixing. The DBEC averaging reveals a directional pattern of d_{obs} that varies between 28.7 m and 31.0 m, with maximum values in the South and minimum values in the Northwest. The pattern is in general similar to the directional pattern of the α -factor (Section 4.2.2 and Fig. 4) with higher values in the South (Sector S) and lower values in the West (Sector W). The pattern of d_{obs} , however, shows more details with a minimum in northwest and a maximum in the northeast. Fig. 1 shows that upwind in the northern direction the canopy is more open. This would indicate that a more open canopy leads to a higher RSL impact. The maximum in the northeast is opposite from the α -factor, which has a minimum here. Both behaviors are not directly evident from Fig. 1. Note that there are only limited number of observations in this sector. The parameterized form d_{HF} shows almost no directional variability. It is characterized by two modes, at ~ 30.3 m and at ~ 29.7 m, which are related to the sharp contrast in d_{HF} between a stable and a neutral atmosphere (Fig. 5a). Consequently, the DBEC mean lies in between the two modes. The hypothesis that stability is not a dominant factor in directional variation is confirmed by the facts that (i) the variability of d_{HF} is solely controlled by stability and (ii) there is no directional variability in d_{HF} , while there is in d_{obs} and in the α -factor. Instead, the directional patterns in α and d_{obs} are determined by wind direction specific conditions, showing that observed parameters adapt to site specific conditions.

In Fig. 5d the variation of d_{obs} throughout the measurement period is plotted. There is a pattern on the seasonal scale, although the amplitude is not the same for 2009 and 2010, with a maximum value (30.9 m) during winter (2009) and a minimum value (28.6 m) during summer

(2010). Again, the pattern is similar to the seasonal variation in the α -factor. In the same line of thought as in Section 4.2.3, we do not expect that changes in leaf coverage play a role here. Instead, there seems to be a stability dominated effect, with more stable situations (hence less mixing) during winter and more neutral/unstable situations (hence more mixing) during summer. A similar but dampened pattern is visible in d_{HF} .

4.3.2. Sensitivity of d to L_c

In HF07/08 the site-specific information is captured in the canopy penetration depth L_c , through h_c , c_d and LAI (which are all assumed to be constant in space and time), eventually expressed in d (which is flow dependent, see also Equations 10–12). When following HF07, c_d is given and LAI is used as an input parameter. However, in reality c_d is also site dependent and hence we investigate the sensitivity of d (and thus the flux) to both LAI and c_d through L_c . In the left panel of Fig. 6 the sensitivity of d to L_c is given and their optimal value when using β_{HF} and β_{obs} is indicated with a dashed line. In the right panel of Fig. 6 the sensitivity of L_c to LAI and c_d is given. The optimal for value L_c (i.e. when H_{AGM}/H_{EC} is closest to 1) when using β_{HF} ($L_c = 35$ m) and β_{obs} ($L_c = 30$ m) is indicated with colored contours. The best estimate from literature for L_c (calculated with $c_d = 0.25$ and $LAI = 6.1$) is indicated with a black contour ($L_c = 21$ m). A larger L_c than the optimal value will lead to an overestimation of the flux, while a smaller value will lead to an underestimation. When assuming $c_d = 0.25$ (i.e. following HF07), this corresponds to an optimal LAI of 3.5 for d_{HF} and 4.25 for d_{obs} . Both are within the range of estimates for LAI as given in Supplementary Material S1 but are significantly lower than the value of 6.1 found by Mustafa et al. (2013) which we adopted in Section 2.1. We include the optimized d_{obs} as d_{opt} in further analysis (see also M8, Fig. 3h).

The large values for L_c indicate that the eddies (almost) have length scales similar to the canopy height, and hence can reach the surface. An L_c larger than the canopy height (h_c), as we found when using β_{HF} , is obviously unphysical. However, since we are dealing with a (partly) heterogeneous surface, the homogenous theory may not be valid anymore. Our plausible explanation is that the flow is still adjusting to the changed roughness of the surface. This process is not accounted for in the representations and might lead to unphysical estimations of L_c . In this case it may be useful to consider that L_c is related to the adjustment length, being the horizontal distance that the boundary layer requires to adjust to the roughness elements (Finnigan and Brunet, 1995; Belcher et al., 2003).

4.4. Validation of H_{AGM}

Now we can examine to what extent the increased complexity in the flux calculation schemes allow for a better representation of the flux compared to standard MOST. Our first observation was that MOST, even when a more complex estimate for d was used, was not able to capture the enhanced mixing due to the tall canopy. Table 2 (and Fig. 3) shows

the statistics of a comparison between H_{EC} and H_{AGM} . It makes only sense to compare the RMSE and STD when the slopes are comparable and close to one. Of the three different applications of α , the constant (M3) and directionally dependent (M4) α -factors give similar results with slopes 1.06 and 1.05 respectively. A seasonal dependent α -factor (M5) gives less precise and less accurate (although acceptable) results. This could be an artifact of the fact that the data coverage during winter months is lower, resulting in a less representative α -factor during these months. We were able to identify large scale directional and seasonal patterns in turbulence which we partly confirmed with HF07/08.

Using the more complex method of HF07/08 with d_{HF} (M6) and d_{obs} (M7) underestimates the flux strongly with slopes of 0.56 and 0.69 respectively and without any modifications produces worse results than standard MOST (M2). We were able to close the discrepancy with H_{EC} ($H_{AGM} = 1.00 \cdot H_{EC}$) by adopting a different L_c value. Assuming $c_d = 0.25$, this gave a LAI of 4.25 (M8) that is within the range of estimates of LAI for our site (3.4 – 6.1), although we have no indication that the LAI value we adopted in Section 2.1 is biased. This suggests that care has to be taken when parameterizing L_c (with c_d and LAI), but given a certain value HF07/08 is able to reproduce H_{EC} . Another factor that could play a role in the failure of HF07/HF08 using d_{obs} is the fact that at our site there were no observations of $\bar{u}$ available at h_c (32 m), but at 1 meter above h_c (33 m). However, the mean canopy height h_c is a difficult concept to define and we do not expect that measuring $\bar{u}$ one meter lower would significantly have improved the results.

In Fig. 7 the mean diurnal cycles of H_{AGM} for MOST (M2), constant α (M3), directional dependent α (M4), and HF07/08 with d_{opt} (M8) are given, together with H_{EC} (35 m) and a 1STD uncertainty band. For completeness we also added HF07/08 with optimized d_{HF} (Fig. 7d). The mean diurnal cycles are calculated with all data that passed the quality control (see Table 1).

Fig. 7 shows that both methods for α and HF07/08 are able to reproduce H_{EC} , but there are also some differences. The constant and directional dependent α -factor tend to underestimate the flux during stable conditions (nighttime), but generally capture the daytime pattern well. The fact that the α -factors underestimate the flux during nighttime may indicate a sampling bias of ϕ_M (by filtering according to Table 1) towards more turbulent conditions during the nighttime. Finally, the 1STD band of the α -factors is very similar to the 1STD band of H_{EC} , indicating that the variation throughout the measurement period is similar. HF07/08 performs well during both nighttime and daytime, but has a larger 1STD band than H_{EC} when using β_{H12} as well as β_{obs} , indicating that it is less precise than the constant α -factor. For β_{obs} this is due to the introduction of an extra, highly variable, parameter. For β_{H12} this is due to the slope in d_{HF} in unstable and neutral conditions (which we did not found with d_{obs}), which leads to a relatively large error in d for an uncertainty in ζ .

Fig. 7 shows a stronger deviation in the morning for M3, M4 and M6 optimized. In M2 this feature is absent, but it could be masked by the fact that it underestimates the flux during daytime. Supplementary Fig. 4

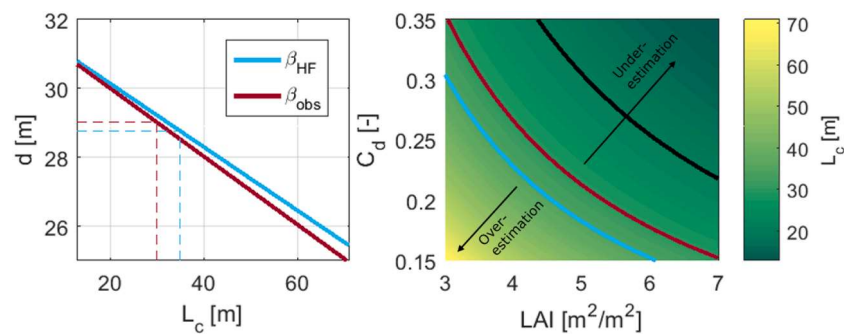


Fig. 6. (left) Sensitivity of d to L_c . The dashed lines indicate the optimal value for L_c as found with optimization. (right) Sensitivity of L_c to both LAI and c_d . The colored contours indicate the optimal values for β_{HF} and β_{obs} . The black contour indicates the best estimate from literature.

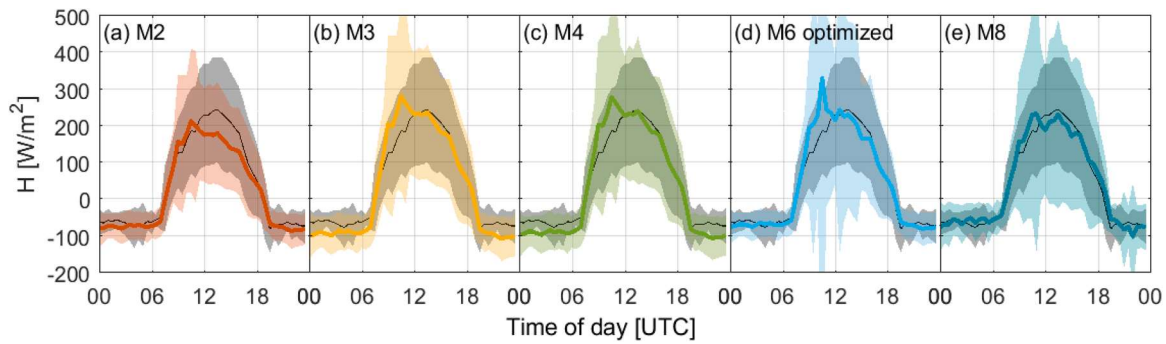


Fig. 7. Mean diurnal cycle in H_{AGM} using (a) MOST, (b) constant α -factor, (c) directional dependent α -factor, (d) HF07/08 with optimized d_{HF} and (e) HF07/08 with d_{opt} , together with (black line) H_{EC} (35 m). The shaded bands show the 1σ uncertainty of the AGM and EC method.

shows the mean diurnal cycle of u_* and θ_* . The morning peak also arises in θ_* , but not in u_* . Speculations on the origin of this peak are that it may be due to (i) an instrumental bias due to exposure to sunlight, (ii) different weights of the input variables in the different methods which can lead to dominance of some terms, or (iii) a physical explanation, i.e. the peak in H is caused by the complex dynamics of the morning transition including flushing of the canopy (see also Dupont et al. (2024)). The fact that this deviation is not (or less) apparent in M8 is due to the fact that at the same time it underestimates u_* , counter effecting the overestimation of θ_* . To fully explain this feature would require additional analyses beyond the scope of this study.

We found three methods that were able to reproduce the H_{EC} flux. The constant α -factor (M3), which has a very low complexity, the directional dependent α -factor (M4), which has an intermediate complexity level, and the HF07/08 method with a modified L_c , which has a very high complexity and is physical based. The α -factor is easy to implement, allows for analysis of large-scale patterns and produces acceptable results. The HF07/08 method is more difficult to use and more sensitive to input parameters such as the LAI , but if adopted the right value is able to represent the flow more accurately during a large diabatic stability range. The parameterized form of HF07/08 (M6, d_{HF}) is able to reproduce the variability as a function of stability (although in a diminished way) and shows seasonal patterns in canopy turbulence. However, it misses (by design, as it assumes a homogeneous canopy) other processes that capture the directional variation and as such leads to a loss of information on the flow. These processes are still retrievable by parameterizing beta with stability, wind sector or season and subsequent optimization of L_c , but requires more effort compare to when using d_{obs} .

5. Discussion

5.1. On the comparison between different flux methodologies

In this study we have compared different flux calculation schemes involving canopy turbulence and validated our results against the measured flux H_{EC} . Such a validation can only be made under the assumption that the outcome of the two methods should be the same. There are two remarks on this assumption. First, the energy balance closure problem. In Section 2.2 we briefly mentioned that at our site we have a 92 % closure of the energy balance, meaning that 8 % of the incoming radiation is unaccounted for. A common approach is to assume that the measured Bowen ratio ($B = H/LE$) is correct and divide the remaining energy over the sensible heat flux (H) and latent heat flux (LE) accordingly (Foken, 2008). At our site we found a median Bowen ratio of 1.18. This means that when this correction would have been applied H would have been approximately 5 % larger than as shown in this study.

Second, in general comparing different flux methodologies comes with uncertainties. Both methods have different underlying assumptions and errors which should be considered when comparing. An overview of

differences and similarities between underlying assumptions, required corrections and errors can be found in Loubet et al. (2013) and Trebs et al. (2021). A comparative study between EC and AGM was done by Loubet et al. (2013) for H , LE (latent heat flux), CO_2 and O_3 over a maize field. It was found that both methods agree well on the sensible heat flux, but the AGM underestimates u_* with 15 % compared to the u_* found by EC. However, a similar comparative study, also over a maize field, by Zhu et al. (2020) found a 99 % agreement for u_* between AGM and EC methods. Based on the above, and given the fact that the modified flux-profile relations and the displacement are correctly accounted for, we expect a strong agreement between H_{AGM} and H_{EC} .

Finally, in Section 2.2 we applied quality criteria after which only a small fraction of the entire dataset remained. Moreover, with this selection (especially with filter #5, $u_* > 0.4$) neutral conditions are favored over (strongly) unstable or (strongly) stable conditions. This also leads to an uneven distribution of sampling throughout the day and year (See also Supplementary Fig. 2). We introduced the quality criteria as would be appropriate when studying scalar fluxes. If one is solely interested in the momentum or sensible heat flux, less strict criteria could be applied. When filtering for $u_* > 0.1$ the α -factors deviate slightly more from H_{EC} , the HF07/08 method is unaffected.

5.2. On the displacement height

In Section 3.2 we introduced three methods for d with increasing complexity and from the sections above we saw that the AGM is very sensitive to its value. The methods of $d_{2/3h_c}$ and d_{W12} give values of 21.3 m and 27.0 m respectively and are constant in space and time. The sub-methods for d of HF07 d_{HF07} and d_{obs} give on average 30.0 ± 0.3 m (1σ) and 29.9 ± 1.1 m (1σ) respectively. Although W12 uses the equations of HF07, it is significantly lower than d_{obs} and d_{HF} . The approach of W12 to estimate d is, however, very different from HF07/08 and not necessarily site specific. From the analysis above it seems that both d_{obs} , d_{HF} and d_{W12} can be used when calculating the flux. However, as d_{obs} , and d_{HF} are a property of the flow they behave different under different stability regimes, leading to a better representation of nocturnal fluxes. Furthermore, using d_{obs} allows for extensive directional and seasonal analysis of canopy turbulence.

5.3. Additional remarks and recommendations

Throughout this analysis we made a comparison between the α -factor and HF07/08. Both methods are fundamentally different in their approach to deal with the canopy turbulence and hence a comparison must be made in that context. The α -factor has a large degree of freedom as it involves effects of LAI , h_c and meteorology. In the HF07/08 method, however, these are all used as input parameters to feed the physical processes. Therefore, it can be expected that it shows a strong sensitivity towards these parameters. This also illustrates differences in practical usage of the different methods. Whereas the α -factor is a generic

method, it needs to be derived (and validated) for each site separately. In contrast, the HF07/08 method is developed for use in models and is easy to apply over multiple sites simultaneously, given a few input parameters such as the *LAI*.

In Table 2 and Fig. 7 we found that when using β_{obs} and β_{HF} to calculate d_{opt} , there is more scatter in the flux compared to using a fixed d (d_{W12}). As stated earlier, this originates from the highly variable character of β_{obs} and the linear relation between β_{HF} and ζ . A possible improvement can be made by aggregating (or fitting) observed data to create a site specific parameterized β , as we have done in Fig. 5a.

In the previous section we stated that the dynamic form of HF07/08 is determined by both β and S_c (or in this case the Prandtl number (Pr)). Out of practical considerations we decided to focus on β , but we recommend a future study to also investigate the temporal and directional behavior of S_c in the RSL.

In this study we decided to focus on two methods for the RSL with different approaches, but as we mention in the Introduction, many more have been developed over the past decades. Other schemes can be useful as well, e.g. for modelling purposes. This study contains a methodological gap for RSL methods using z/z_* . We've chosen to omit these methods because z_* is a poorly defined concept. However, if one is solely interested in which method involving canopy turbulence gives the best representation of the flux, the method of De Ridder (2010) (or another scheme using z/z_*) should also be evaluated.

6. Conclusion

In this study we analyzed two different flux calculation methods using gradient measurements (AGM) over a tall canopy inside the roughness sublayer, surrounded by directional heterogeneous land use. We applied standard Monin-Obukhov Similarity Theory (MOST) and two methods involving modification to account for the canopy turbulence, the α -factor and (Harman and Finnigan, 2007, 2008) (HF07/08) which have different physical assumptions. The α -factor uses observations to empirically fit new flux-profile functions valid inside the roughness sublayer (RSL) and should be derived for each site separately. In turn, the HF07/08 method includes the main features of the impact of canopy on turbulence and is presented to be uniformly applicable. Moreover, it requires few input parameters (such as canopy height (h_c) and leaf area index (*LAI*)) and is therefore also suitable for use in models. We used the different methods to investigate both seasonal patterns and directional patterns related to the heterogeneity of the surroundings (through wind direction) in canopy turbulence, revealing that local site information is wind direction dependent. Particular emphasis is placed in understanding the impact of the displacement height on the AGM-RSL methods and its sensitivity to forest canopy characteristics because of its physical relevance and their close connections to each other. The results are compared to a multiyear dataset of the EC sensible heat flux (H_{EC}). Our main findings are:

- Applying standard MOST misrepresents the physical processes over tall canopies and underestimates the flux. The estimation of the displacement height d has a strong impact on the inferred flux. Solely adopting a more complex form for d does not lead to a better description of the flow but, as expected, the flux-profile should be modified as well.
- We applied three different forms of α , as a constant, wind direction dependent and seasonally dependent. All forms were able to represent H more accurately than standard MOST, of which the constant and directionally dependent α -factor performed slightly better. The directional and seasonal dependent α -factor allowed to identify patterns in canopy turbulence related to canopy characteristics and meteorological circumstances.
- The method of HF07/08 is physically based but requires more information of the site as it is sensitive towards its input parameters and hence requires more effort to implement than the α -factor. We

applied two dynamic forms of d : observed (d_{obs}) and parameterized (d_{HF}). The observed form allows to investigate patterns in space and time which largely confirmed the patterns we found with the α -factor, but shows more detail. The parameterized form was largely able to reproduce temporal patterns (although strongly reduced) but misses, by design, processes that capture directional patterns. Adopting d_{obs} leads to a better representation of the flow, but also introduces more noise compared to a constant d . Our results show the parameterization of L_c to be very sensitive to the c_d and the *LAI*. Using a site specific, best estimate *LAI* value obtained from literature and the c_d prescribed in HF07 led to a large underestimation of the flux. We were, however, able to improve the flux estimate by applying a *LAI* value within a range of estimates found in literature for our site.

- We found that both the observational based (simple) method (α -factor) and the physically based (complex) method (HF07/08 with modified *LAI*) allowed for a more accurate representation of a two-year dataset of the sensible heat flux (as measured by *EC*) compared to standard MOST. Using a physically based method (HF07/08) gives a better representation of the flux during all atmospheric stability regimes.
- We found that the α -factor allows for investigation of directional and seasonal patterns in RSL behavior, but including these patterns does not lead to improved results compared to the constant α -factor. Moreover, care has to be taken when data coverage is low when deriving the (seasonal dependent) α -factor. The HF07/08 method calculates the RSL behavior for each averaging period, and as such can easily be used to extensively investigate directional and seasonal patterns. With d_{obs} we were able to confirm the patterns found with the α -factor. When using d_{HF} , the seasonal pattern was strongly diminished and we did not find a directional pattern.

CRedit authorship contribution statement

E.A. Melman: Writing – original draft, Visualization, Software, Investigation, Formal analysis, Conceptualization. **S. Rutledge-Jonker:** Writing – review & editing, Supervision, Conceptualization. **M. Braam:** Writing – review & editing, Software. **K.F.A. Frumau:** Writing – review & editing, Methodology, Investigation. **A.F. Moene:** Writing – review & editing, Conceptualization. **M. Shapkalijevski:** Writing – review & editing, Software. **J. Vilà-Guerau de Arellano:** Writing – review & editing, Conceptualization. **M.C. van Zanten:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Supplementary materials

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