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Flow adjustment inside homogeneous canopies after a leading edge – An analytical approach backed by LES

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A R T I C L E I N F O

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A B S T R A C T

A two-dimensional analytical model for describing the mean flow behavior inside a vegetation canopy after a leading edge in neutral conditions was developed and tested by means of large eddy simulations (LES) employing the LES code PALM. The analytical model is developed for the region directly after the canopy edge, the adjustment region, where one-dimensional canopy models fail due to the sharp change in roughness. The derivation of this adjustment region model is based on an analytic solution of the two-dimensional Reynolds averaged Navier–Stokes equation in neutral conditions for a canopy with constant plant area density (PAD). The main assumptions for solving the governing equations are separability of the velocity components concerning the spatial variables and the neglection of the Reynolds stress gradients. These two assumptions are verified by means of LES. To determine the emerging model parameters, a simultaneous fitting scheme was applied to the velocity and pressure data of a reference LES simulation. Furthermore a sensitivity analysis of the adjustment region model, equipped with the previously calculated parameters, was performed varying the three relevant length, the canopy height (h), the canopy length and the adjustment length (L_c), in additional LES. Even if the model parameters are, in general, functions of h/L_c, it was found out that the model is capable of predicting the flow quantities in various cases, when using constant parameters. Subsequently the adjustment region model is combined with the one-dimensional model of Massman [*Bound. Layer Meteorol.*, 83(3):407–421, 1997], which is applicable for the interior of the canopy, to attain an analytical model capable of describing the mean flow for the full canopy domain. Finally the model is tested against an analytical model based on a linearization approach.

1. Introduction

In canopy turbulence, flow across edges and clearings is a field of particular interest, as the largest perturbations in the flow quantities can be encountered in the vicinity of such sharp transitions in surface roughness (Belcher et al., 2012). As pointed out by Dupont and Brunet (2008), these perturbations can influence the flow over distances of several tree heights downwind from canopy edges. Therefore, measurements inside and above canopies, e.g. of scalar fluxes like greenhouse gases, can also be influenced by edges over similar distances (Kanani-Sühring and Raasch, 2014). Due to the fact that these measurements mainly rely on the eddy covariance (EC) technique, heterogeneities in the measurement footprint play an even more important role, due to the requirements of the standard EC technique (Aubinet et al., 2012; Burba, 2013). While the effects of forest edges on flux measurements were already investigated in several studies (Chen et al., 1993; Cadenasso and Pickett, 2000; Dupont et al., 2011) stated that one key issue for interpreting flux measurement near to edges is the distance required by the flow to fully adjust with the canopy, which depends on the character of turbulent flow inside of the canopy.

To investigate turbulent flow inside canopies and close to canopy-edges, various approaches have been used in the past. While canopy-edge scenarios were mainly investigated by the comparison of numerical studies to wind tunnel measurements (Dupont and Brunet, 2008), field experiments (Dalpé and Masson, 2009; Schlegel et al., 2012; Kanani et al., 2014) or both (Yang et al., 2006; Banerjee et al., 2013), the number of analytical investigations is smaller. However, interpretation of EC measurements could benefit from the prediction of analytical models for the influence of edges at the measurement location. Apart from that, the determination of properties like the aerodynamic resistance of heterogeneous canopies can benefit from analytical models, as approaches for homogeneous canopies, like the one of

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Yang et al. (2001), might fail for canopies, which are mainly under the influence of edges.

Concerning analytical investigations of canopy flow, several studies, based on one-dimensional approaches were performed (Massman, 1987, 1997; Harman and Finnigan, 2007). These models, which are applicable for horizontally homogenous condition, resulted in the analytical solution of an exponentially decaying velocity profile inside the canopy. However these one-dimensional approaches are too limited to describe the effect of forest edge flow.

Improvements towards a two-dimensional analytical model were made by Belcher et al. (2003), where the governing flow equations were linearized on small perturbations, added to an incoming logarithmic velocity profile. The advantage of this approach was that the mean velocities could be calculated for all distinct regions of the canopy-edge-flow-scenario.

These regions are shown in Fig. D.1, where (i) labels the impact region before the edge, (ii) the adjustment region shortly past the edge, (iii) the canopy interior behind the adjustment region, (iv) the canopy shear layer located around the canopy top and (v) the roughness change region above the canopy. The adjustment region, where the unperturbed flow adapts to the canopy, and the canopy interior, where the flow has fully adapted to the canopy, are the two regions of major interest in the following work.

An essential ingredient of the linearization approach is the much smaller magnitude of the velocity perturbations in comparison to the incoming wind profile. As Belcher et al. (2003) stated, this translates to the requirement of a canopy that is either sparse or short enough that the flow is never able to fully adjust to it.

The aim of the presented work is to overcome this issue of a linearization approach. Therefore we derived an analytic solution to the governing flow equations in the adjustment region, where one-dimensional models fail. Studying the aforementioned adjustment zone is of interest, as a plethora of applications rely on the flow within this region. These applications include seed and pollen dispersal from adjacent areas into the canopy zone and conversely (Trakhtenbrot et al., 2014), determination of forest-floor fluxes of CO_2 or O_3 using micrometeorological methods (Launiainen et al., 2013), or separating aerosol-sized particle deposition onto foliage and forest floor in patchy forested environments (Grönholm et al., 2009; Huang et al., 2014; Katul et al., 2010), to name a few.

The analytical solution was developed for a neutral canopy-stripe-scenario in a predefined background wind, where the canopy stripe is homogeneous in crosswind direction (two-dimensional scenario) and is, therefore, defined by three length scales, the canopy length L, the canopy height h and the adjustment length scale L_c, which are also depicted in Fig. D.1. The adjustment length scale can be used to describe the width of the adjustment region, which can reach an extension of up to $15L_c$ (Dupont and Brunet, 2008).

Besides gaining a functional description of the velocity components and the pressure, another important outcome of the presented analytical investigation is the insight on the interplay of the three involved length scales L, h and L_c.

To determine the occurring model parameters (integration constants) a large eddy simulation (LES) of a reference canopy was performed employing the LES code PALM (Maronga et al., 2015). In Section 4, the analytical model for the adjustment region, equipped with these parameters, is subsequently tested on variations of the three defining length scales by performing further LES.

To gain an analytical model for the full range of the canopy and to deduce an expression for the length of the adjustment region, subsequently the adjustment region model was combined with the model of Massman (1997) for the canopy interior.

Finally the current model is compared with the model of Belcher et al. (2003) for increasing length L of the investigated canopy.

2. Derivation

2.1. Background

The basis of the subsequent analytical investigation of flow across a canopy edge are the Reynolds averaged continuity and momentum equation for an incompressible 2D flow when neglecting Coriolis and buoyancy effects (neutral case) within a canopy

$$\partial_i u_i = 0, \tag{1}$$

$$\partial_t u_i + \partial_j (u_i u_j) = -\frac{1}{\rho}\partial_i p + \partial_j \tau_{ij} - F_{di}, \tag{2}$$

where u_i is the mean velocity component in direction x_i, $\partial_j(u_i u_j)$ describes the advection of the flow field, ρ the mean fluid density, p the mean perturbation of the hydrostatic pressure, τ_{ij} the Reynolds stress tensor and F_{di} the drag force, the latter modeling the effect of the canopy on the flow. The drag force is defined according to Shaw and Schumann (1992) and Watanabe (2004) as

$$F_{di} = 1/L_c \|\vec{u}\| u_i \Theta(\mathrm{x}/h)\Theta(1 - \mathrm{z}/h), \tag{3}$$

where the adjustment length scale is defined following Belcher et al. (2003, 2012) through $L_c = 1/(C_d a)$ with the drag coefficient C_d and the PAD a, $\|\vec{u}\|$ is the wind speed, $\mathrm{x} = \mathrm{x}_1$, $\mathrm{z} = \mathrm{x}_3$ and Θ is the Heaviside step function ensuring the drag force to be zero outside of the canopy. The definition of the drag force, presented here, describes a canopy with constant canopy height h and with a canopy-edge located at $\mathrm{x} = 0$.

To simplify the analysis a constant a was considered throughout the canopy, defined by

$$a = \mathrm{PAI}/h \tag{4}$$

with the canopy height h and the plant area index PAI.

Focusing on a steady state scenario, the flow quantities were considered to be time independent ($\partial_t u_i = 0$). Therefore, Eqs. (1) and (2) in terms of the velocity components $u = u_1$ and $w = u_3$ inside the canopy are given by

$$\partial_\mathrm{x} u + \partial_\mathrm{z} w = 0 \tag{5}$$

$$\partial_\mathrm{x} u^2 + \partial_\mathrm{z}(uw) = -\frac{1}{\rho}\partial_\mathrm{x} p + \partial_j \tau_{1j} - \frac{1}{L_c}\left\|\vec{u}\right\| u \tag{6}$$

$$\partial_\mathrm{x}(uw) + \partial_\mathrm{z} w^2 = -\frac{1}{\rho}\partial_\mathrm{z} p + \partial_j \tau_{3j} - \frac{1}{L_c}\left\|\vec{u}\right\| w \tag{7}$$

Following the argument of Belcher et al. (2003), which relies on Townsend (1972) and Jackson and Hunt (1975), it becomes apparent that the Reynolds stress gradients have just a small impact in Eqs. (6) and (7) when compared to the remaining terms. In Appendix A this assumption is proven by comparing the magnitudes of the several terms for a LES of a canopy stripe with $h = 10$ m and $L_c = 16.7$ m, showing that the gradients of the Reynolds stress are mostly smaller than 5% of the residual terms. Therefore the Reynolds stress gradient terms will be neglected in Eqs. (6) and (7) in the subsequent investigations, which results in a turbulently inviscid scenario (Banerjee et al., 2013). Furthermore, following Banerjee et al. (2013), the pressure was eliminated from these two equations by computing their curl, which finally results in

$$\partial_\mathrm{x}\partial_\mathrm{z} u^2 + \partial_\mathrm{z}^2(uw) - \partial_\mathrm{x}^2(uw) - \partial_\mathrm{x}\partial_\mathrm{z} w^2 + 1/L_c[\partial_\mathrm{z}(\|\vec{u}\|\mathrm{u}) - \partial_\mathrm{x}(\|\vec{u}\|\mathrm{w})] = 0. \tag{8}$$

To non-dimensionalize the spatial variables x/z, they were re-scaled by h through the introduction of the new variables x and z by

$$x = \mathrm{x/h} \quad \text{and} \quad z = \mathrm{z/h} \tag{9}$$

Rewriting Eqs. (5) and (8), in these re-scaled quantities gives

$$\partial_x u + \partial_z w = 0, \tag{10}$$