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The effects of the canopy medium on dry deposition velocities of aerosol particles in the canopy sub-layer above forested ecosystems

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ABSTRACT

Understanding how the leaf area density ($a(z)$) and its depth integrated value, the leaf area index (LAI), modify dry deposition velocities (V_d) of aerosol particles within the canopy sub-layer is needed for progressing on a plethora of aerosol related problems in climate change, air quality, and ecosystem service evaluation. Here, the interplay between $a(z)$ (and LAI) of tall and densely forested canopies, the flow dynamics, and V_d are explored via model calculations. A multi-layer size-resolving deposition model (hereafter referred to as MLM) is coupled to a second-order closure model (WS77), which are then used to explore a subset of the manifold of $a(z)$ and LAI variations and their concomitant effects on the relationship between V_d and particle diameter (d_p). The combined MLM-WS77 calculations are evaluated against V_d measurements collected above a Scots pine stand in Hyytiälä (southern Finland) in which $a(z)$ was experimentally manipulated via forest thinning. Three key findings are derived from these model calculations: (1) at a given LAI, a near-constant $a(z)$ yields the lowest V_d for a given d_p class, (2) when the foliage is concentrated in the upper layers of the canopy, increasing LAI predictably increases V_d at a given d_p, though some saturation occurs thereafter, but (3) suppressing turbo-phoresis leads to an opposite conclusion, decrease of V_d with LAI increase, for a d_p class between 0.5 and 5 μm. Comparison between the combined MLM-WS77 calculations and a recently proposed pipe-flow analogy formulation that includes turbo-phoresis are also presented.

1. Introduction

The role of forests in removing particulate matter, especially aerosols, is now drawing increased attention in a number of scientific disciplines and regulatory agencies (Holmes and Morawska, 2004; Pryor et al., 2008; Petroff et al., 2008a). Despite some 50 years of theoretical work, field and wind-tunnel experiments, progress in quantifying the dry deposition rates of these particles onto forests has been relatively slow due to a large number of inter-related factors, too numerous to list here. Any enumeration attempts however cannot ignore (1) problems associated with field measurements of particle size resolved fluxes and mean concentrations, (2) lack of detailed measurements of the canopy medium (e.g. leaf area density), and (3) challenges in describing all the main features of the transporting agent (turbulence) within and immediately above the canopy (hereafter this layer is referred to as the canopy sub-layer or CSL), known to lack the 'niceties' of its atmospheric surface layer (ASL) counterpart (Raupach et al., 1996; Finnigan, 2000; Poggi et al., 2004a,b,c).

Progress on factors (1) and (2) is now rapid with eddy-covariance and eddy-accumulation estimates providing continuous size-resolved fluxes and mean concentrations at few forested sites (Wesely et al., 1977; Fairall, 1984; Rannik et al., 2003, 2009; Pryor, 2006; Pryor et al., 2007; Gaman et al., 2004; Grönholm et al., 2007, 2009), and advances in remote sensing and high-resolution imagery are now providing an unprecedented view of the canopy morphology (including leaf area density and index) along with ground topography (Lefsky et al., 2002). Field experiments have also produced an expansive 'portrait' of bulk flow statistics within the CSL collected in a wide range of canopy structures (Finnigan, 2000). Despite these efforts, basic questions concerning how the canopy medium impacts dry deposition of aerosol particles above forests remain a formidable research challenge (Petroff et al., 2008a,b; Pryor, 2006; Pryor et al., 2007, 2008). In the CSL, the underlying canopy has direct impact on the turbulent flow field and both direct and indirect impacts on the particle deposition processes. Any

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attempt to explore how the canopy medium alters dry deposition velocities must be explicit in its accounting of leaf area density ($a(z)$) or leaf area index (LAI).

To progress on these issues, a multi-layer and size-resolving model (hereafter referred to as MLM) for dry deposition of particulate matter (Katul et al., 2010) is coupled to a second-order closure model (WS77) that computes the first and second moments of the velocity field (Wilson and Shaw, 1977). The MLM-WS77 calculations are carried out and reported in three phases: The first phase sets LAI to a typical value for dense forested canopies but varies the shape of the leaf area density profile from a near-constant case to positively, quasi-symmetric, and negatively skewed distributions. The second phase assumes a canonical shape for the leaf area density profile, and varies LAI sequentially from relatively dense to very dense values. In addition, the sensitivity of a pipe-flow analogy model (PFAM) described by Feng (2008) to $a(z)$ and LAI variations is compared to MLM. The third phase considers the changes in LAI using a forest thinning experiment conducted at the Hyytiälä forest station (in southern Finland) as a case study. This forest thinning resulted in a reduction in the all-sided LAI due to selective logging of smaller- to mid-sized trees (Vesala et al., 2005). The size-resolved turbulent fluxes and their concomitant mean concentration measurements from a meteorological tower were then analyzed by wind direction sectors, where the wind originating from the thinned sector was assumed to represent (or in equilibrium with) the deposition velocity of the thinned stand. Hence, the data set from this forest thinning experiment also serves in evaluating the model skills.

The majority of dry deposition velocity measurements above tall forests are carried out in the CSL, often at $z_\mathrm{R}/h = 1.1 - 1.6$ (z_R is the reference measurement height and h is the canopy height). Hence, the model results are summarized as deposition velocity variations with particle diameter (d_p) for $z_\mathrm{R}/h = 1.5$, which is commensurate with the reference height at which size-resolved long-term particle deposition velocity measurements are collected in the Hyytiälä forest in Southern Finland (Vesala et al., 2005; Grönholm et al., 2007, 2009).

2. Theory

Throughout, the following notation is used: t is time, x_i ($x_1 = x$, $x_2 = y$, $x_3 = z$) are the longitudinal, lateral, and vertical directions respectively with $z = 0$ being the forest floor, u_i ($u_1 = u, u_2 = v, u_3 = w$) are the instantaneous velocity components along x_i, over-bar represents planar and temporal averaging, and primed quantities represent turbulent excursions from the averaged quantities. For a stationary ($\partial u_i/\partial t = 0$) and planar homogeneous ($\partial u_i/\partial x = \partial u_i/\partial y = 0$) flow in the absence of subsidence ($\overline{w} = 0$), when combining the mean continuity equation for aerosol particles of diameter d_p with a gradient-diffusion representation for the particle turbulent flux (F_c) results in:

$$\frac{\partial}{\partial z}\left[- \left(D_{\mathrm{p,m}} + D_{\mathrm{p,t}}(z)\right) \frac{\partial \overline{C}(z)}{\partial z}_{F_\mathrm{c}} + V_\mathrm{s}\overline{C}(z)\right] + \frac{a(z)}{\pi} \underbrace{\left[\sqrt{-\overline{u'w'}(z)}\left(\theta Sc^{-2/3} + 10^{-3/St(z)}\right) + V_t\right]}_{\text{Vegetation Collection Terms}} \overline{C}\,(z) = 0, \quad (1)$$

where, $\overline{C}(z)$ is the mean aerosol particle concentration for d_p, $D_\mathrm{p,t}$ and $D_\mathrm{p,m}$ are the particle turbulent and molecular diffusivities, respectively, V_s is the settling velocity, $a(z)$ is the all-sided leaf area density ($\mathrm{m^2\,m^{-3}}$), $\overline{u'w'}$ is the turbulent flux of momentum, $Sc = \nu/D_\mathrm{m,p}$ is the particle Schmidt number where ν is the air molecular viscosity, $St = V_\mathrm{s}(-\overline{u'w'}(z))/(g\nu)$ is the turbulent Stokes number, g is the gravitational acceleration, and $\theta \approx \pi c_\nu/c_\mathrm{d} \approx 1$ is a constant that depends on a number of factors including the ratio of the leaf viscous-to-form drag (c_ν/c_d), and V_t is the turbo-phoretic velocity that can be approximated by (Caporaloni et al., 1975; Reeks, 1983; Guha, 1997; Young and Leeming, 1997; Zhao and Wu, 2006a,b; Feng, 2008)

$$V_\mathrm{t} = -\tau_\mathrm{p}\frac{d\sigma^2_\mathrm{w,p}}{dz}, \quad (2)$$

where τ_p is the particle relaxation time scale and $\sigma_\mathrm{w,p}$ is the particle vertical velocity standard deviation, and $\mathrm{d}\sigma^2_\mathrm{w,p}/\mathrm{d}z$ must be determined within the viscous sub-layer just above the depositing surface. This particle velocity statistic can be related to the flow statistics via (Wilson, 2000)

$$\frac{\sigma^2_\mathrm{w,p}}{\sigma^2_\mathrm{w}} = \frac{D_\mathrm{p,t}}{K_\mathrm{t}} = \left(1 + \frac{\tau_\mathrm{p}}{\tau}\right)^{-1}, \quad (3)$$

where $\sigma_\mathrm{w} = \overline{w'^2}^{1/2}$ is the turbulent vertical velocity standard deviation, $K_\mathrm{t} = -\overline{u'w'}/|\partial\overline{U}/\partial z|$ is the eddy viscosity, $\overline{U}$ is the mean longitudinal velocity, and τ is the Lagrangian turbulent time scale given as $\tau = K_\mathrm{t}/\sigma^2_\mathrm{w}$ (Taylor, 1921). For particles in the micrometer diameter range, $\tau_\mathrm{p}/\tau << 1$ so that $D_\mathrm{p,t} \approx K_\mathrm{t}$ (and hence the turbulent particle Schmidt number is unity though we did not adopt this simplification here).

When the viscous sub-layer above the leaf is much thicker than the micro-roughness elements of the isolated leaf surface, a first-order estimate of the vertical gradient of vertical velocity variance is given as

$$\frac{\mathrm{d}\sigma^2_\mathrm{w}}{\mathrm{d}z} \approx \frac{\sigma^2_\mathrm{w}\sqrt{-\overline{u'w'}}}{b_o\nu}, \quad (4)$$

where $b_o \approx 25$. The basis for $b_o \approx 25$ are the experiment by Poggi et al. (2002) who reported the kurtosis of the w' above a smooth boundary layer. These experiments indicated a rapid transition from near Gaussian statistics (presumably within the turbulent region) to non-Gaussian statistics around $b_o \approx 25$ (presumably higher intermittency due to viscous effects) thereby supporting this two-regime (viscous/fully turbulent) delineation. However, other multi-regime treatment in the vicinity of a leaf can also be used if the leaf micro-roughness is known. For example, the proposed approach by Zhao and Wu (2006b) that decomposes the boundary layer above the depositing surface into three regimes (rather than 2 as done here) allows for more realistic treatment of the driving gradients of V_t.

With the two-regime formulation for V_t, the particle mean continuity equation (Eq. (1)) becomes:

$$\frac{\partial}{\partial z}\left[- \underbrace{\left(D_{\mathrm{p,m}} + D_{\mathrm{p,t}}(z)\right) \frac{\partial \overline{C}(z)}{\partial z}}_{F_\mathrm{c}} + V_\mathrm{s}\overline{C}(z)\right] + \frac{a(z)}{\pi} \underbrace{\left[\sqrt{-\overline{u'w'}(z)}\left(\theta Sc^{-2/3} + 10^{-3/St(z)} + \frac{\tau_\mathrm{p}}{(1+\tau_\mathrm{p}/\tau(z))}\frac{\sigma^2_\mathrm{w}(z)}{b_o\nu}\right)\right]}_{\text{Vegetation Collection Terms}} \overline{C}(z) = 0. \quad (5)$$

The deposition velocity $V_\mathrm{d}(z) = -F_\mathrm{c}(z)/\overline{C}(z) + V_\mathrm{s}$ can hence be computed from $\overline{C}(z)$ providing the boundary conditions. An upper boundary condition is $C(z_\mathrm{r}) = C_{o,\mathrm{r}}$, where $C_{o,\mathrm{r}}$ is known. Because fluxes to the forest floor can be large (Grönholm et al., 2009; Donat and Ruck, 1999), the lower boundary condition ($z = 0$) assumes that the particle deposition process to the forest floor closely resembles deposition on rough-wall boundary layers and can include turbophoresis. A pipe-flow analogy model (PFAM) described by Feng (2008) is used to compute this lower boundary condition. The canonical form of PFAM applied at the forest floor is given as: