Measurements in a water channel for studying environmental problems
Part 2

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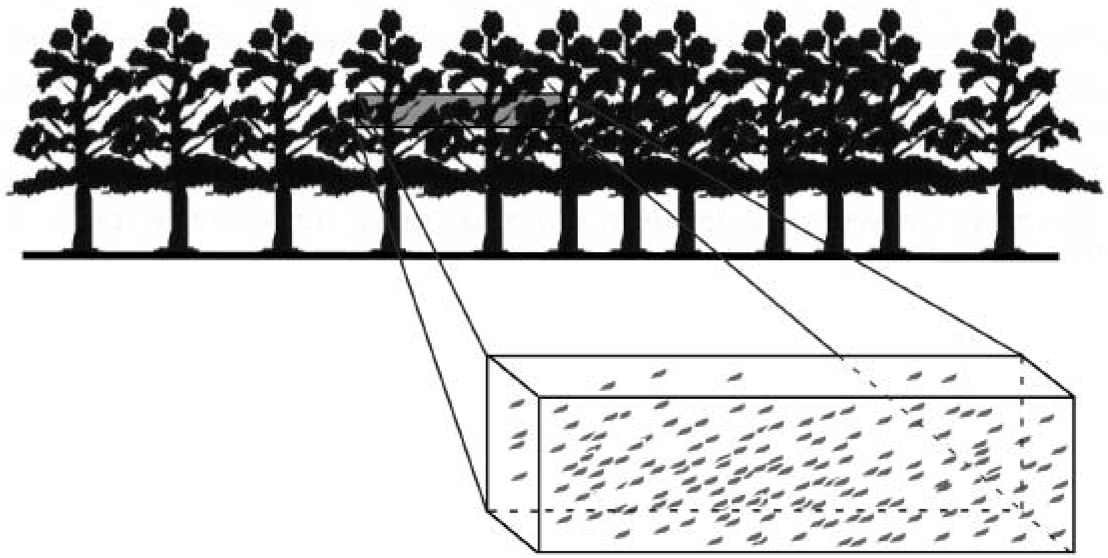
- Introduction
- Water channel characteristic properties
- Cohesive sediment properties
- Aerosol dry deposition on vegetative canopies

Introduction



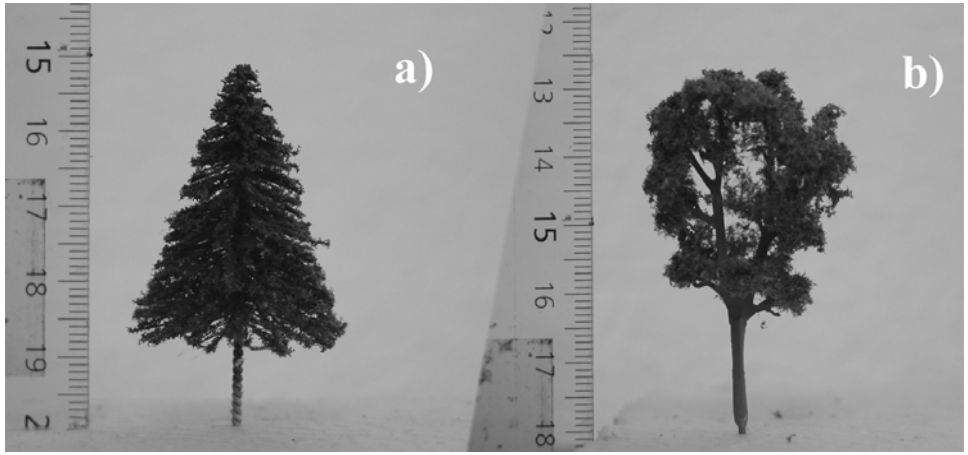
• Quantify the influence of different vegetative canopies on turbulent boundary layer properties

• Find limits for the validity of the mixing-layer analogy ?

Properties	**Boundary layer**	**Mixing layer**	**Canopy**
Inflexion point	No	Yes	Yes
σ_u / u^*	2.5-3.0	1.8	1.8-2.0
σ_w / u^*	1.2-1.3	1.4	1.0-1.2
$-<\overline{u'w'}>/(\sigma_u \sigma_w)$	~0.3	~0.4	~0.5
Pr_t	~1.0	~0.5	~0.5

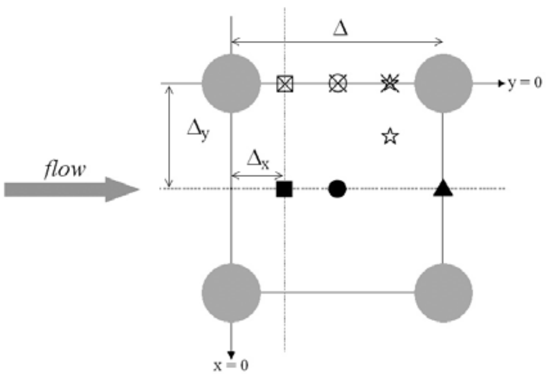
• Develop a « mechanistic » model for aerosol dry deposition through precise account of all the processes which are involved

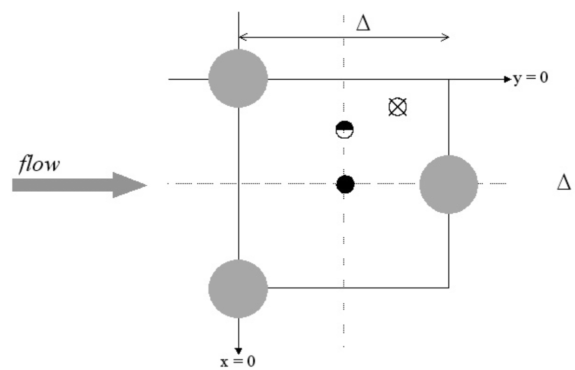
Experiments in IRPHE facilities



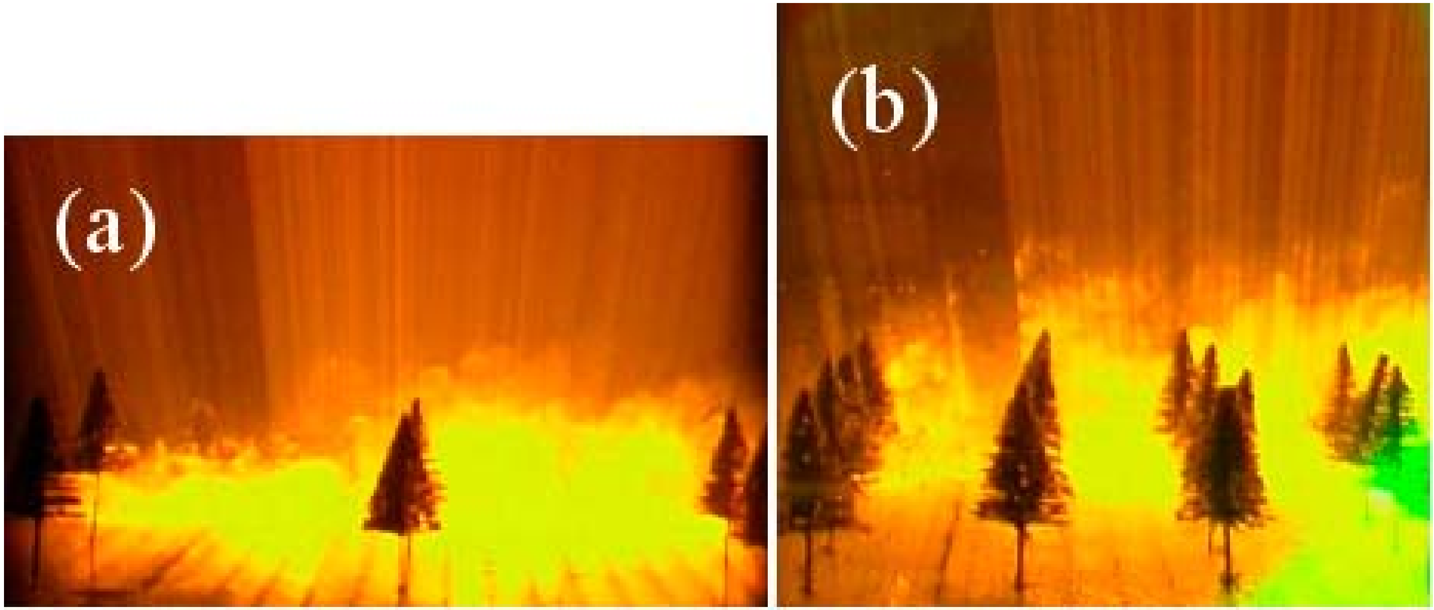
a) conifer-like, b) round tree

Typical elements of the artificial canopy (h = 5 cm $\approx$ 0.5-1 δ)





Aligned or staggered elements



Visualisations (and PIV measurements) first performed
in the water channel HERODE
to determine the most interesting situations (Δ/h = 2-a) and 1-b))

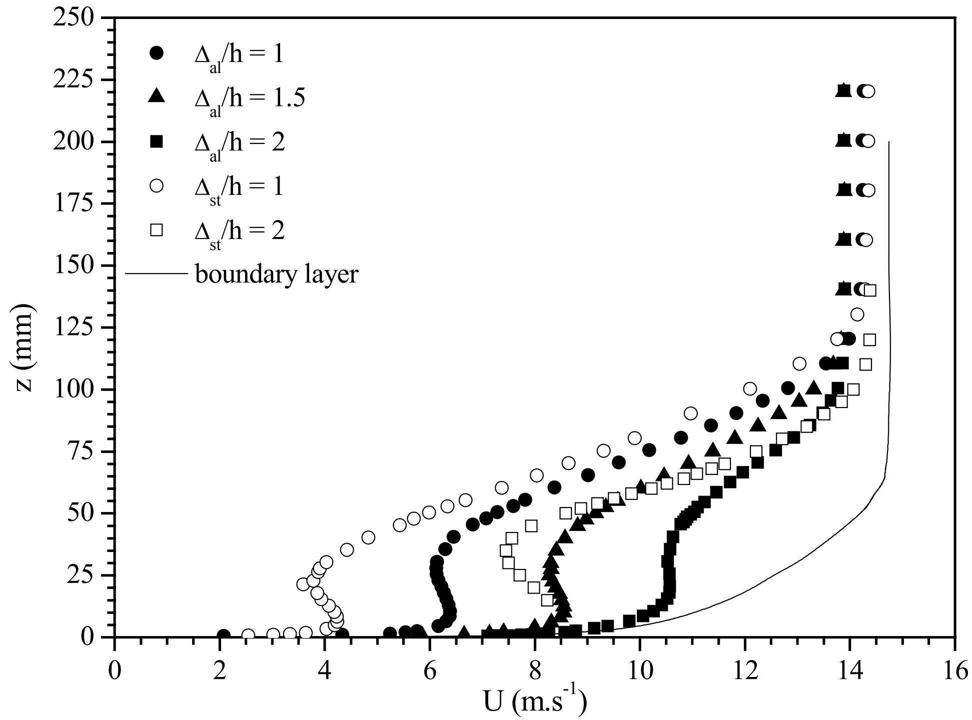
$$\lambda = LAI/2$$

(LAI : amount of leaf area per unit land area)

Authors	**Canopy**	**Δ/h**	**λ**	**u^* ($m.s^{-1}$)**	**u^*/U_h**
Green et al. (1995)	widely spaced spruces	0.5 – 1	0.4 – 1.6(*)	*unknown*	0.25 – 0.35
Poggi et al. (2004)	aligned steel cylinders	0.25 – 1	0.03 – 0.5	0.014 – 0.039	3.7 – 17
Zhu et al. (2006)	- corn field - staggered wooden sticks	0.1	3.7 1	0.47 0.913	0.31 0.29
Raupach et al. (2006)	random plastic pegs	1.75 – 5.7	0.0125 – 0.125	0.57 – 1	*unknown*
present data	- aligned trees - staggered trees	1 – 2	0.05 – 0.22	0.6 – 0.9 0.8 – 1.05	0.06 – 0.12 0.11 – 0.16

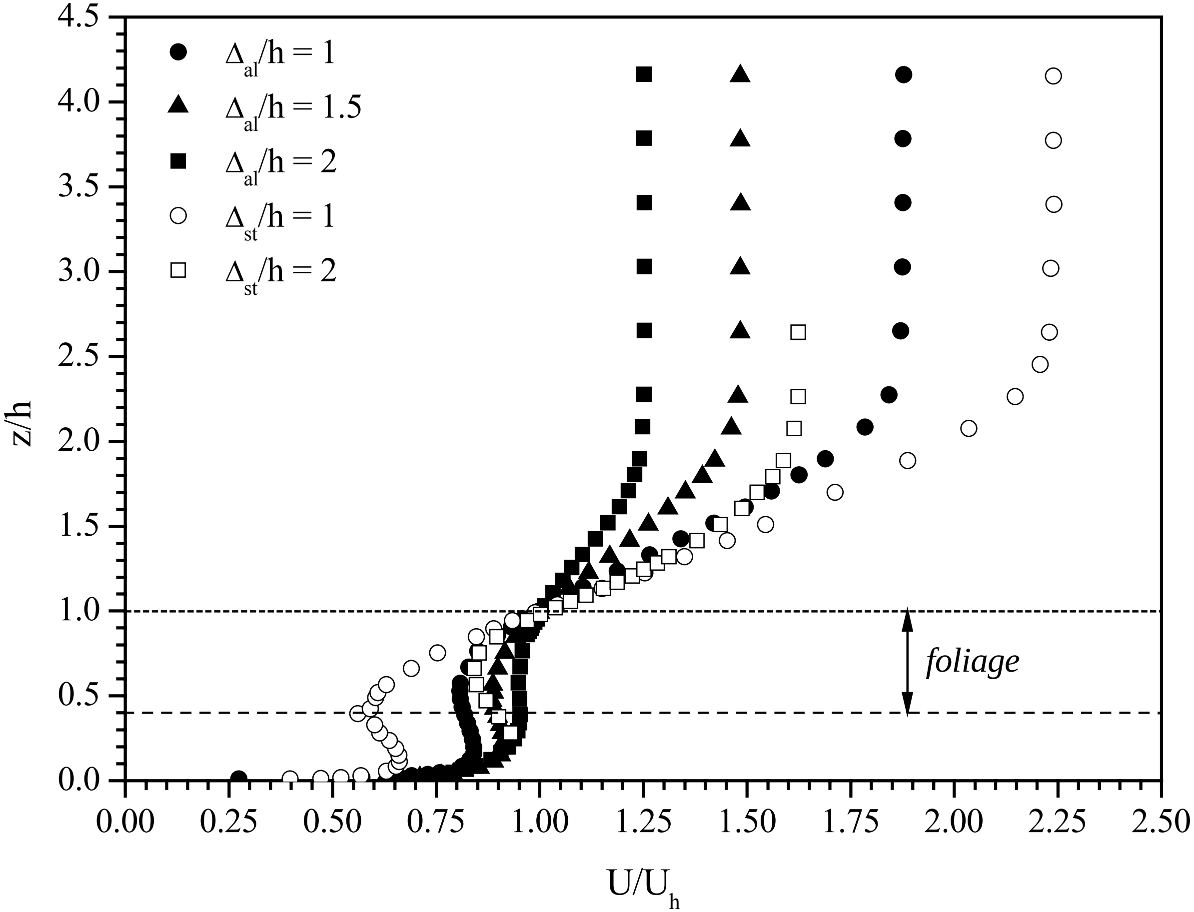
Sparse to dense

PIV + LDV measurements then performed in a wind tunnel



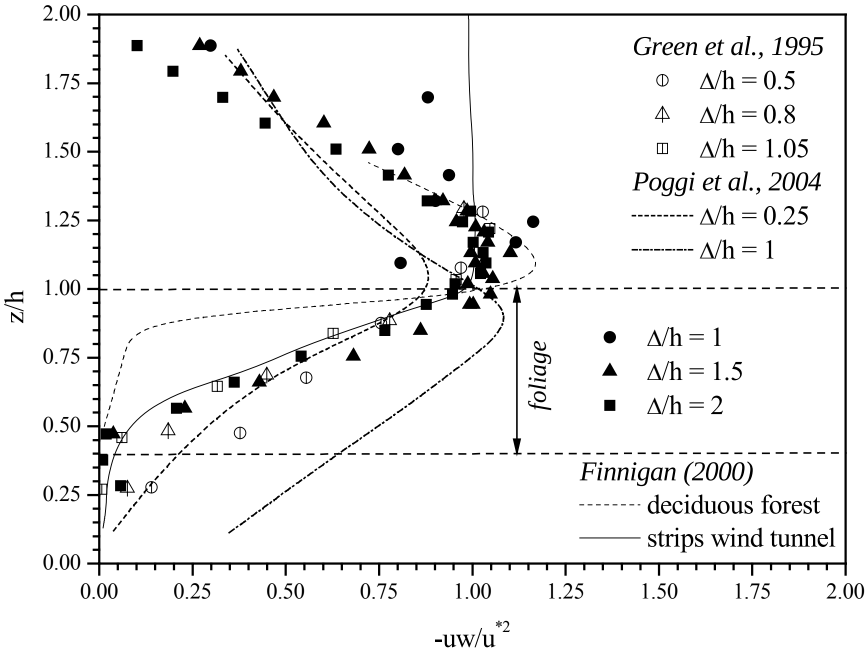
Raw effect of the canopy on mean velocity profiles

(closed symbols for aligned trees and open symbols for staggered trees)

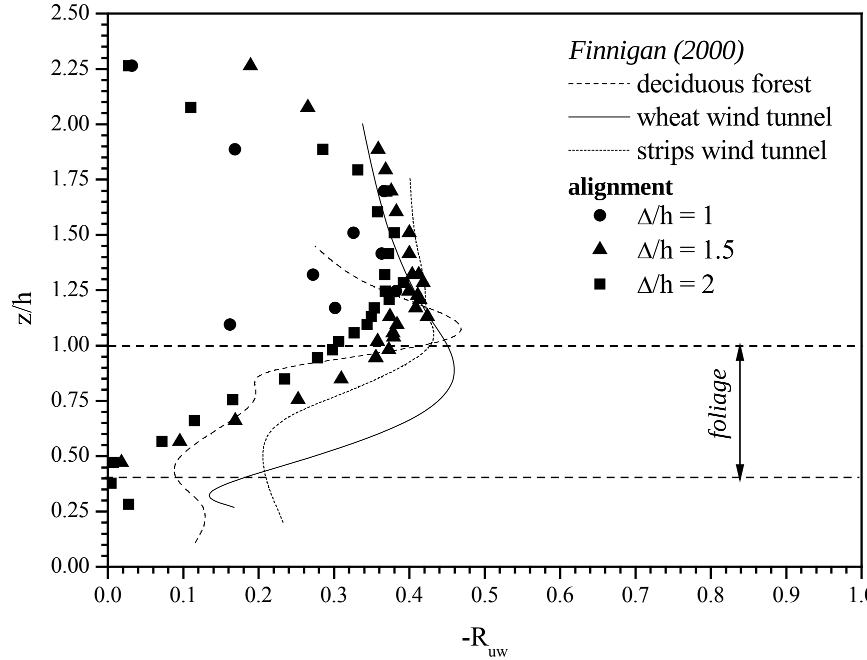


Normalized mean velocity profiles

(closed symbols for aligned trees and open symbols for staggered trees)



(a) Reynolds stress

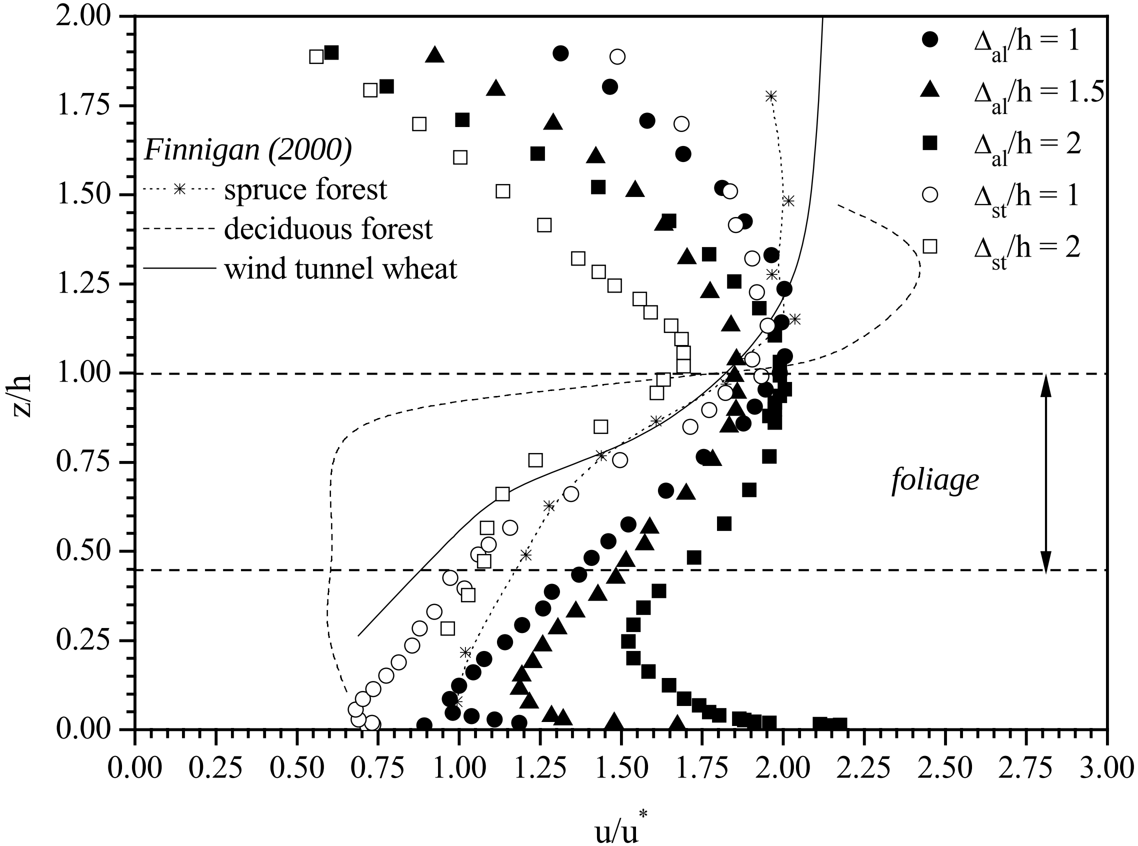


(b) Correlation coefficient

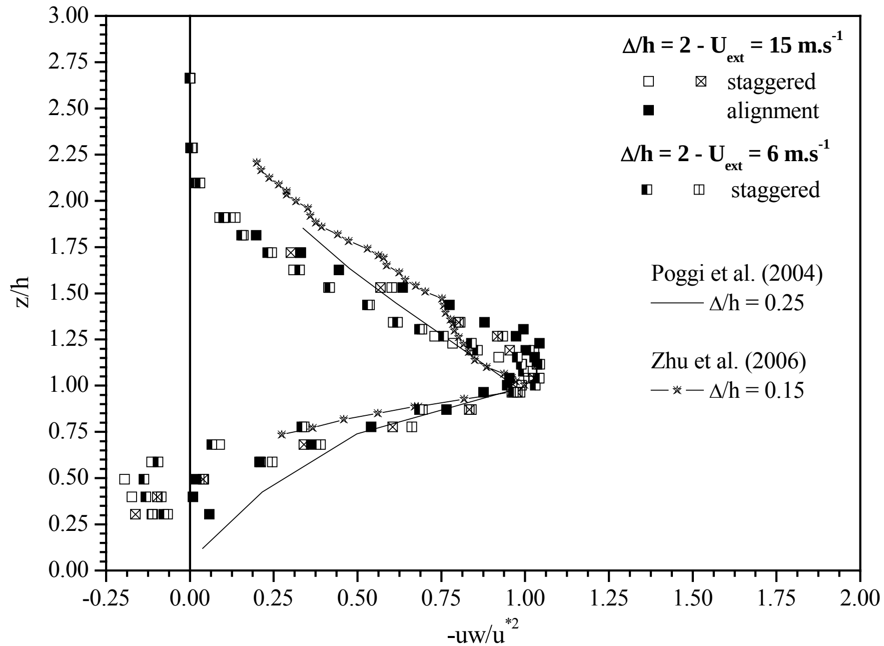
Vertical profiles in aligned canopies

Δ/h	u^{*2} ($m^2.s^{-2}$)
1	0.8 ± 0.36
1.5	0.68 ± 0.03
2	0.41 ± 0.02

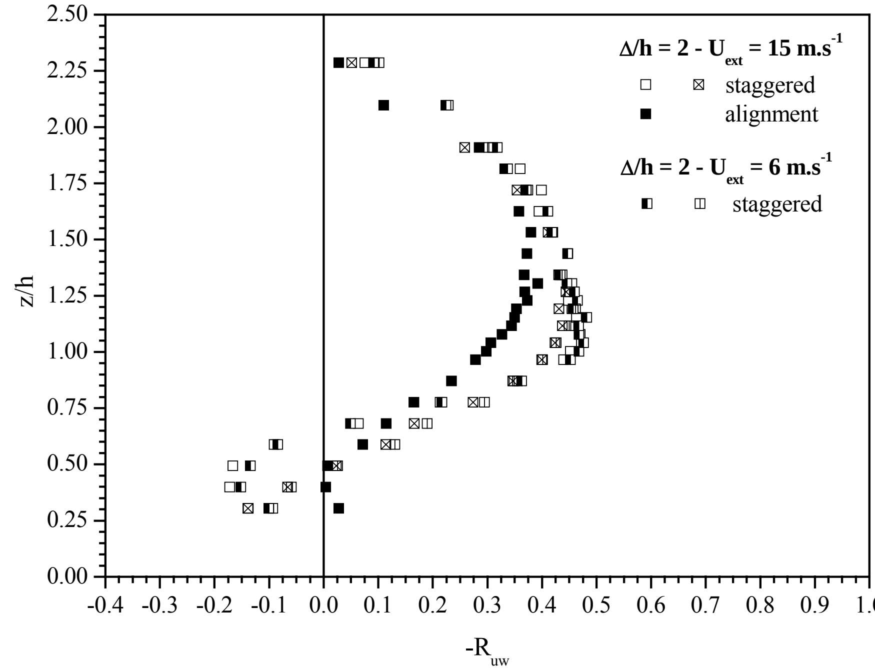
Estimation of the squared friction velocity for the three spacings in the aligned canopy



Root-mean square longitudinal velocity profiles
(same symbols as before)



(a) Normalized Reynolds stresses



(b) Correlation coefficient

For $\Delta/h = 2$ spacing, both spatial dispositions, two external velocities

Conclusion

• Results agree fairly well with litterature data for natural canopies as well as wind tunnel studies (except for the velocity skewness factor, not shown here, whose value is found to relax to the natural boundary layer value for z/h larger than only 1.5), in spite of the questionable small tree dimensions relatively to the boundary layer thickness.

• Departure from the mixing layer analogy is exhibited from the study of velocity statistical moments: disappearance of the inflectional point when density is reduced. Also (not shown here), the turbulent flow scales (mixing length) become more and more similar to those of a standard boundary layer when the canopy is sparse. However, the mean velocity profile for $\Delta/h = 2$ is still far from boundary layer typical profiles.

Aerosol dry deposition on vegetative canopies

(Alexandre PETROFF's thesis, 2005)

Introduction

• Dry deposition of particles such as sulphate, nitrate, or atmospheric aerosol transporting radio-active substances has been debated worldwide over the last 30 years, but there is still discrepancy between both measurement results and model predictions.

• Similar problems are encountered when considering biological hazards, for instance in connection with contamination by genetically modified organism spores or by bacteria (such as the legionnella bacteria).

⇨ **After a detailed review of the present knowledge, we found it necessary to reconsider the basic mechanical processes which control the aerosol deposition, in order to propose a new modelling approach.**

In a quasi-stationary regime, when the longitudinal pressure gradient and the advection flux are neglected, the aerosol transport within and above the canopy of height *h* is usually described by the following equations:

$$z \geq h \quad \frac{d}{dz}\left[-K_p \frac{d\gamma}{dz} - W_S \gamma\right] = 0$$

$$z < h \quad \frac{d}{dz}\left[-K_p \frac{d\gamma}{dz} - W_S \gamma\right] = -r_d \gamma,$$

where γ is the particle number or mass density of a given size class, W_S the settling velocity and K_p the particle eddy diffusivity (usually related to the eddy viscosity K_m by the turbulent Schmidt number $Sc_T = K_m / K_p$, =1 in general).

Thus, the aerosol flux F is constant above the canopy, and the deposition velocity V_d is defined through:

$$F = -V_d(z_R).\gamma(z_R)$$

It depends on the chosen reference height z_R.

The deposition velocities V_{d1} and V_{d2} at two different reference heights z_1 and z_2 above the canopy are related by

$$\frac{1}{V_{d2}} - \frac{1}{W_S} = \left(\frac{1}{V_{d1}} - \frac{1}{W_S} \right) e^{-W_S R_a(z_1, z_2)},$$

where Ra (z_1,z_2) is the aerodynamic resistance, which takes into account the influence of turbulence on the aerosol transport:

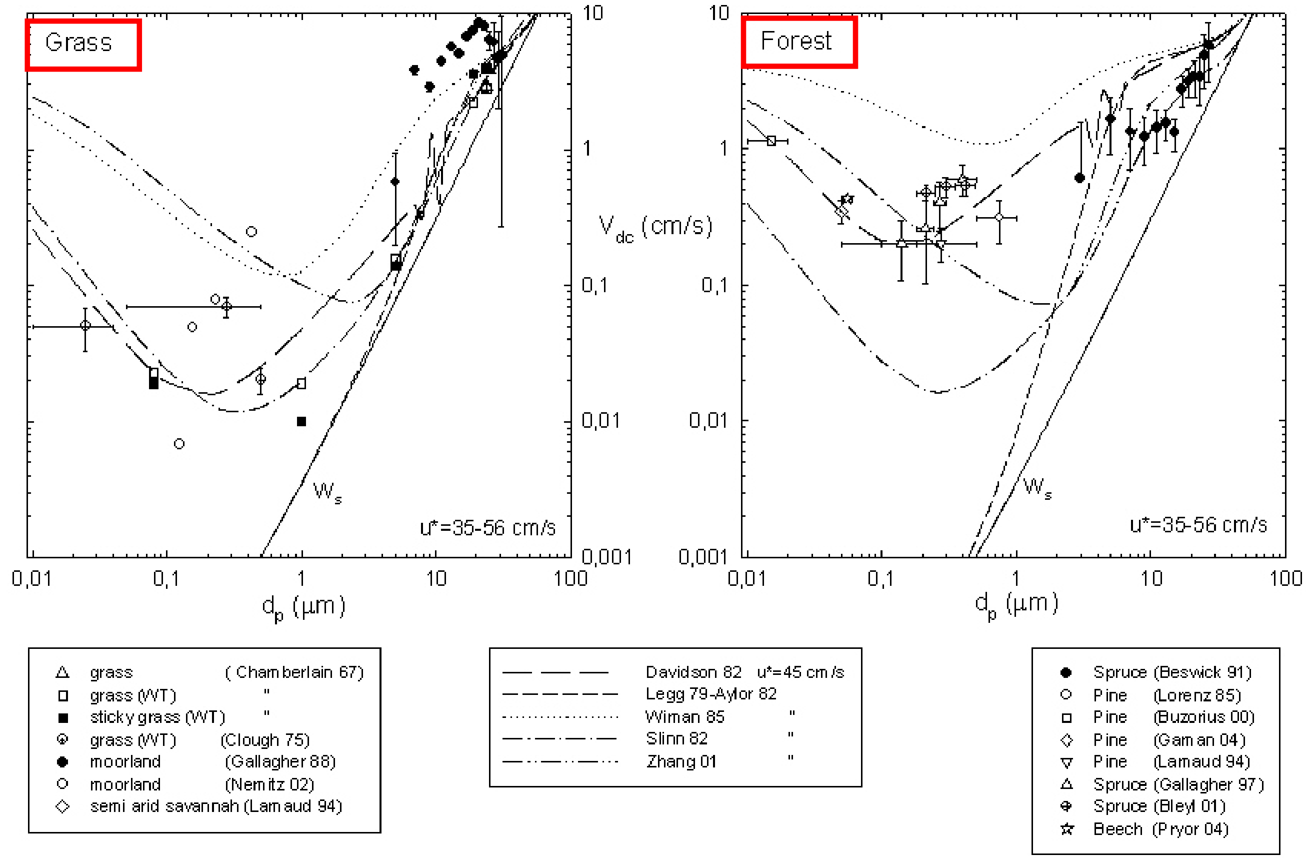
$$R_a\left(z_1, z_2\right) = \int_{z_1}^{z_2} \frac{dz}{K_p}.$$

The solution of the system of transport equations requires boundary conditions. At the top of the domain, the concentration is known. On the ground, one must provide a condition for the concentration or for the aerosol flux. Most of the models assume in a more or less explicit way a zero concentration on the ground. A flux condition can also be considered. This ground flux is described through a ground deposition velocity, noted V_g, which is often assimilated to the settling velocity, or given by $V_g = \varepsilon\, u^{*2}/U(h)$ (where ε is the the aerosol collection efficiency).

In usual « analytical » models, the deposition velocity is given by a formulation which is said to be "resistive". Deriving it requires, among other things, to be unaware of gravity in the particle transport and deposition, and, afterwards, to add a sedimentation velocity to the calculated deposition velocity. This last one is then expressed in terms of "resistances", one being the aerodynamic, and the other, named surface resistance and noted *Rs* , being related to the vegetable surface. Such models express the deposition velocity as:

$$V_d\left(z_R\right) = W_S + \frac{1}{R_a\left(h, z_R\right) + R_s} .$$

R_a and R_s have been modelled in global and more or less sophisticated ways (i.e. depending or not on u*, U(h), LAI, ……), providing good or rather poor agreement with measurements for different canopies.



Model predictions and measurements of the deposition velocity on grass and needle-leaf forest of an aerosol of density of $1000 kg.m^{-3}$ depositing in similar aerodynamic conditions.

Closed and open symbols correspond respectively to conditions of particle adherence (wet or sticky surfaces or liquid aerosol) and non adherence (dry surfaces with solid particles).

Our model considers, on the contray, in an explicit way, all the mechanisms which are involved in aerosol deposition :

- Brownian diffusion,
- Impaction,
- Interception,
- Sedimentation.

The magnitudes of these mechanisms depend on both the canopy properties (h, U(h), u*, LAI, …) and the particle size (sedimentation most influent for large particles (> 10 μm) and Brownian diffusion most influent for very small particles (< 0.1 μm)).

The balance equation for <γ> is derived in a proper way (after space + time averagings):

$$\frac{\partial}{\partial t}\langle\gamma\rangle+\nabla.\langle\mathbf{J}\rangle=\int_{-\infty}^{\infty}d\tau\iint_{\partial\Omega(\tau)}w\left[\mathbf{J}+\mathbf{J}_{IN}-\gamma\mathbf{v}_{\partial\Omega}\right].\mathbf{d\sigma}\,.$$

Thus, the aerosol phase undergoes the kinetic movement of gas molecules, which is expressed by a flux of Brownian diffusion, gravity and entrainment by the gas flow. Other influences, like phoretic effects (due to electric, thermal or gas fraction gradients) are neglected. These effects being assumed to act independently, the corresponding instant local particle resulting flux is:

$$\mathbf{J}=-D_B\nabla\gamma-W_S\gamma\mathbf{e}_z+\gamma\mathbf{u_a}\,,$$

where D_B , W_S , $\mathbf{e}_Z$, $\mathbf{u_a}$ are respectively the Brownian diffusion coefficient, the settling velocity of particles, the vertical upward unit vector and the aerosol Eulerian velocity.

After applying the space+time averaging operator, we then obtain that the aerosol behaviour within the canopy is described by:

$$\frac{\partial\langle\gamma\rangle}{\partial t}+\nabla.\left(\langle\gamma\rangle\langle\mathbf{u}\rangle+W_S\langle\gamma\rangle\mathbf{e}_z-\frac{K_m}{Sc_T}\nabla\langle\gamma\rangle\right)=dD\,,$$

where the deposition term is ($\overline{g}$ standing for the time average of g):

$$dD=\frac{1}{\omega}\iint_{\partial\Omega(M)}\left(\overline{\gamma}\,\overline{\mathbf{u}}_{\mathbf{e}}+\overline{\gamma'\,\mathbf{u}'_{\mathbf{e}}}-D_B\nabla\overline{\gamma}-W_S\overline{\gamma}\mathbf{e}_z+\overline{\mathbf{J}_{IN}}\right).\mathbf{d\sigma}\;.$$

Br. diff. Sedimentation Interception

Mean flow impaction Turbulent impaction

Thus, the deposition terms associated with the different mechanical processes have been formally derived.

They are not calculable in a deterministic way because of a lack of information concerning
- firstly the aerosol behaviour in the close neighbourhood of the vegetative surfaces (in terms of velocity and concentration),
-secondly the spatial repartition and orientation of all the vegetative surfaces of the canopy.

They have then to be modelled through a statistical approach, which accounts for all possible realizations in terms of leaf characteristics (size, orientation, …), velocity field, particle position within the canopy, and so on.

As a consequence of the statistical treatment, it can be shown that, finally, within the canopy, the aerosol budget equation is:

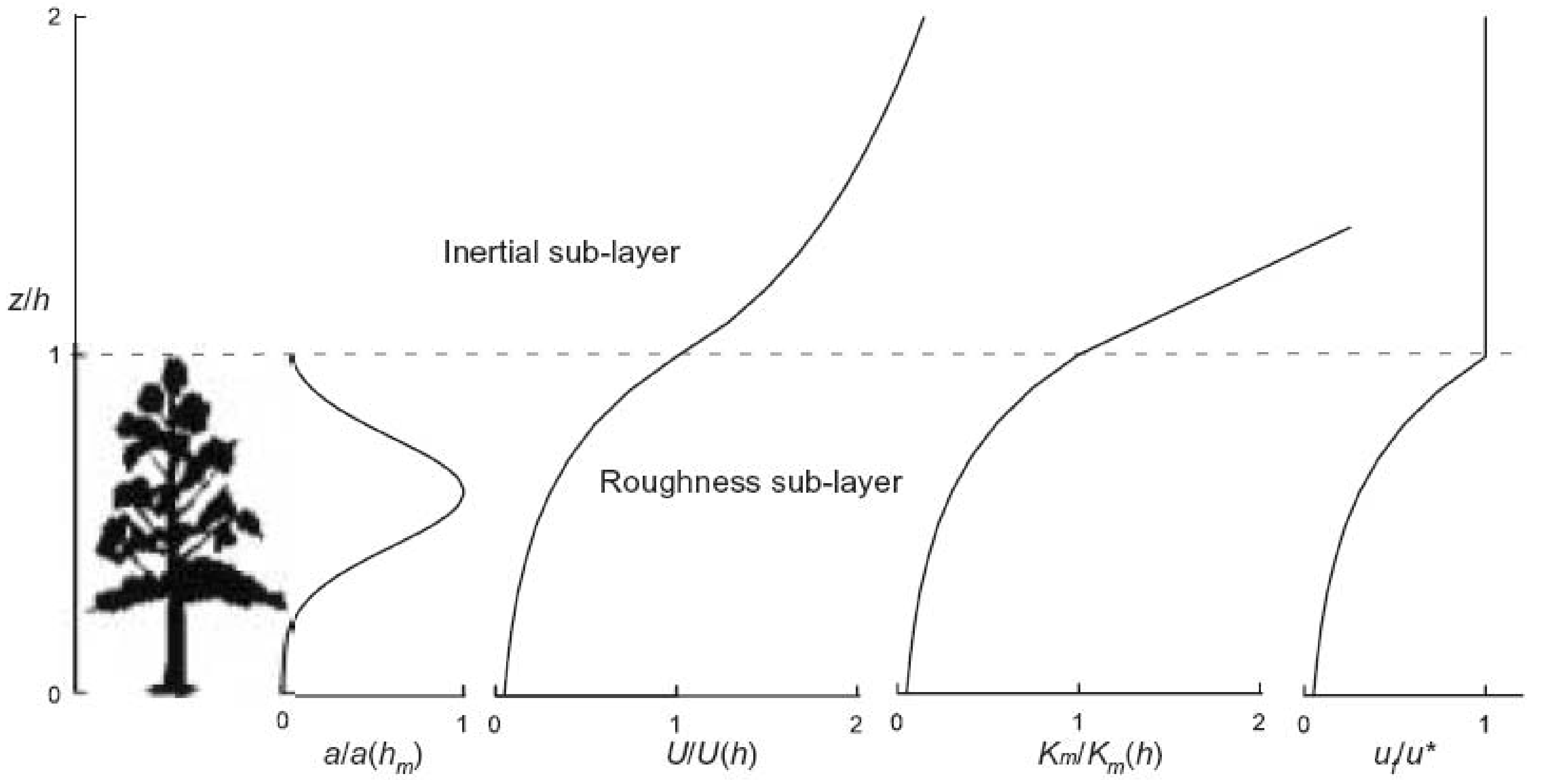
$$0 < z < h \qquad \frac{d}{dz}\left[\frac{K_m}{\mathrm{Sc}_T}\frac{d\langle\gamma\rangle}{dz} + W_S\langle\gamma\rangle\right] = a\langle\gamma\rangle\sum_{k=1}^{m} V_k .$$

For any particular process k, the deposition velocity is given by:

$$V_k = \int_{\mathrm{D}(\Psi_k)} \frac{s}{\overline{s}} v_k f \,\delta\Psi_k$$

(the associated multi-dimensional probability density function (pdf) $f(\mathbf{M},t,dp,\Psi_k)$ is specific of the deposition process under consideration; $v_k(\mathbf{M},t,dp,\Psi_k)$ is the elementary deposition velocity on a vegetable element).

The flow field and canopy characteristics are modelled as follows:



Constant turbulent mixing length within the canopy: this implies exponential profiles for the mean velocity and the eddy viscosity.

$u_f(z) = \sqrt{-\langle \overline{u'w'} \rangle}$ is the local friction velocity. Gaussian foliar density 'a'.

Expression of collection terms

Brownian diffusion

On any particular obstacle (needle or leaf), elemental collection velocity v_B, such that $d_B = -v_B\, s\, \gamma$, is usually modelled as $v_B = \mathrm{Sh}\, D_B/dn$, where Sh is the Sherwood number. According to published data, we will consider that $\mathrm{Sh} = C_B \mathrm{Sc}^{1/3} \mathrm{Re}^{n_B}$ (where C_B and n_B depend on the Reynolds Number based on the obstacle characteristic diameter dn).

Re	C_B	n_B
$1\text{-}4\ 10^3$	0.467	1/2
$4\ 10^3 - 4\ 10^4$	0.203	3/5
$4\ 10^4 - 4\ 10^5$	0.025	4/5

Then, $$V_B = \int_{D(d_n,h_n)} \frac{xy}{\overline{xy}} v_B(x) f_{d_n,h_n}(x,y)\,dxdy,$$

where $f_{dn,hn}$ is the joint statistical distribution of the obstacle diameter and height. Thus, if we assume they are independent parameters,

$$V_B = I_B v_B\left(\overline{d_n}\right) \quad \text{with} \quad I_B = \int_{D(d_n)} \left(\frac{x}{\overline{d_n}}\right)^{n_B} f_{d_n}(x)\,dx = \frac{\overline{d_n^{\,n_B}}}{\overline{d_n}^{\,n_B}}.$$

The proportionality coefficient I_B depends on the aerodynamic regime and the chosen distribution of the obstacle diameter.

	$n_B = 1/2$	$n_B = 3/5$	$n_B = 4/5$
Uniform over $\left[0; 2\overline{d_n}\right]$	0.94	0.95	0.97
Normal $(\overline{d_n}, \sigma)$	$0.98 \le I_B \le 1$	$0.98 \le I_B \le 1$	$0.99 \le I_B \le 1$
Lognormal $\left(d_{ng}, \sigma_{ng}\right)$	$0.78 \le I_B \le 1$	$0.79 \le I_B \le 1$	$0.86 \le I_B \le 1$

Interception

Interception strictly refers to particles which perfectly follow streamlines and which can collide with a surface (and get attached on) when they are less than one half diameter from the surface. The obstacle collection velocity is expressed with the help of an interception efficiency E_{IN}, defined as the ratio of the number of deposited particles to the number of particles that would travel through the obstacle space, if the streamlines would not be deviated by its presence.

The accessible surface for deposition by interception corresponds to the projected surface in the direction of the flow, that is s_x.
The elemental collection velocity is then expressed by:

$$v_{IN} = \frac{s_x}{s} E_{IN} U \, .$$

It is generally assumed (potential flow) that (in the absence of any better information) $E_{IN} \approx 2\frac{d_p}{d_n}$.

As a consequence, $\frac{V_{IN}}{U} = 2k_x \frac{d_p}{\overline{d}_n}$.

k_X is related to the leaf orientation distribution
(k_X and k_Z are estimated with the assumption of a uniform azimuth distribution).

Distribution	μ	ν	$\bar{\theta}$ (rad)	k_x	k_z
Horizontal	N.A.	N.A.	0	$2/\pi^2$	$1/\pi$
Planophile	2.770	1.172	0.47	0.24	0.27
Plagiophile	3.326	3.326	$\pi/4$	0.27	0.22
Erectophile	1.172	2.770	1.10	0.30	0.13
Vertical	N.A.	N.A.	$\pi/4$	$1/\pi$	0
Extremophile	0.433	0.433	$\pi/4$	0.26	0.19
Uniform	1	1	$\pi/4$	0.27	$2/\pi^2$

Inertial impaction

The inertial impaction of aerosol usually is described through an impaction efficiency, defined in a similar way as for the interception. The elemental deposition velocity is thus:

$$v_{IM} = \frac{s_x}{s} E_{IM} U \ .$$

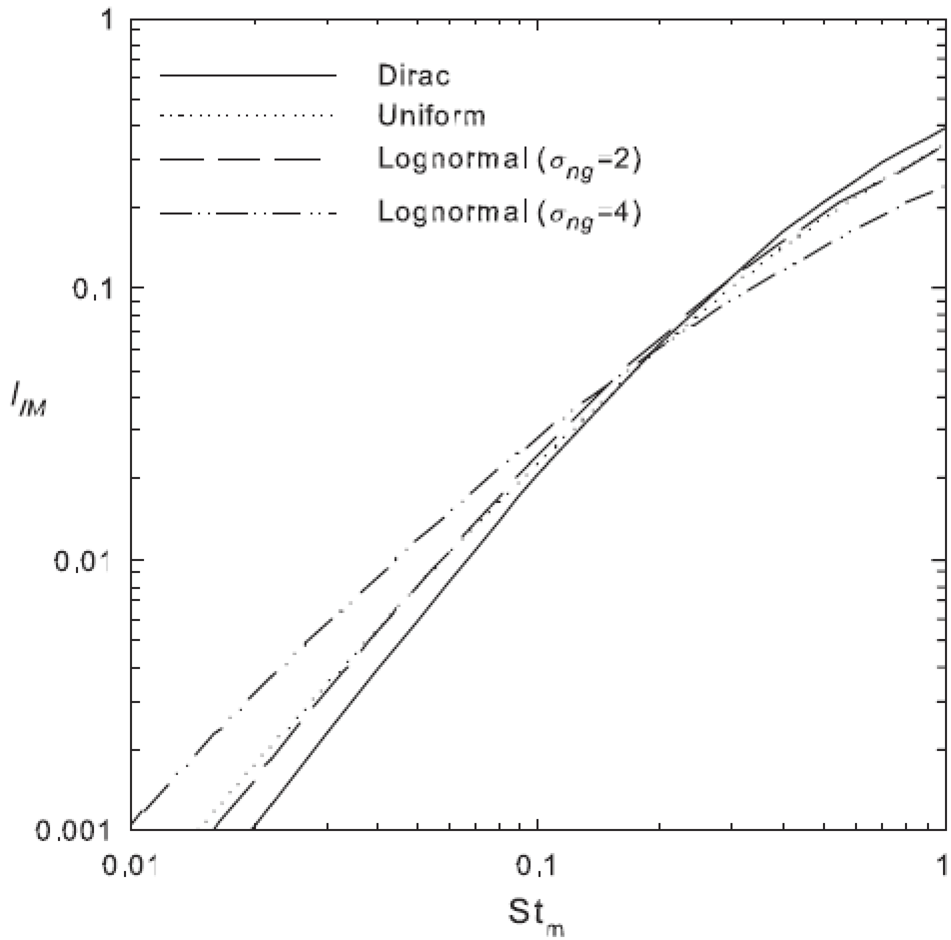
The impaction efficiency often is related to the Stokes number (β≈0.5),

$$E_{IM} = \left(\frac{\mathrm{St}}{\beta + \mathrm{St}} \right)^2 .$$

We then obtain:

$$\frac{V_{IM}}{U} = k_x I_{IM} \quad \text{with} \quad I_{IM} = \int_{\mathrm{D}(d_n)} \frac{x}{d_n} E_{IM}(x) f_{d_n}(x)\, dx \ .$$

The influence of the obstacle diameter distribution on I_{IM} is estimated by numerical methods. Its dependency on the mean Stokes number St_m (built on the mean diameter) is shown hereafter:



The uniform distribution presents the advantage (for implementing purpose) of leading to an analytical expression of the deposition velocity and thus will be used in the following applications:

$$\frac{V_{IM}}{U} = k_x \frac{\mathrm{St}_{\mathrm{m}}^2}{2\beta^2}\left[\frac{1}{1+2\beta/\mathrm{St}_{\mathrm{m}}} + \ln\left(1+2\beta/\mathrm{St}_{\mathrm{m}}\right) - 1\right].$$

Turbulent impaction

Aerodynamics in vegetated canopies is characterised by a large scale turbulence, which is produced at the top of the canopy and afterwards transported inside. Within the canopy, particles with sufficient inertia cannot follow the turbulent eddies and are ejected. When they are close enough from the surfaces, they cannot be caught by another eddy and deposit on vegetable surfaces after a phase of "free flight".

The phenomenon of turbulent impaction has been widely studied in case of fully turbulent pipe flow. Having defined the elemental collection velocity v_{IT}, a dimensional analysis states the following functional dependence, $v_{IT}/u_f = f(\tau^+_p)$, where τ^+_p is the dimensionless particle relaxation time, $\tau^+_p = \tau_p u_f^2 / \nu_a$.

We will here consider a simple empirical expression of the elemental collection velocity proposed in the litterature:

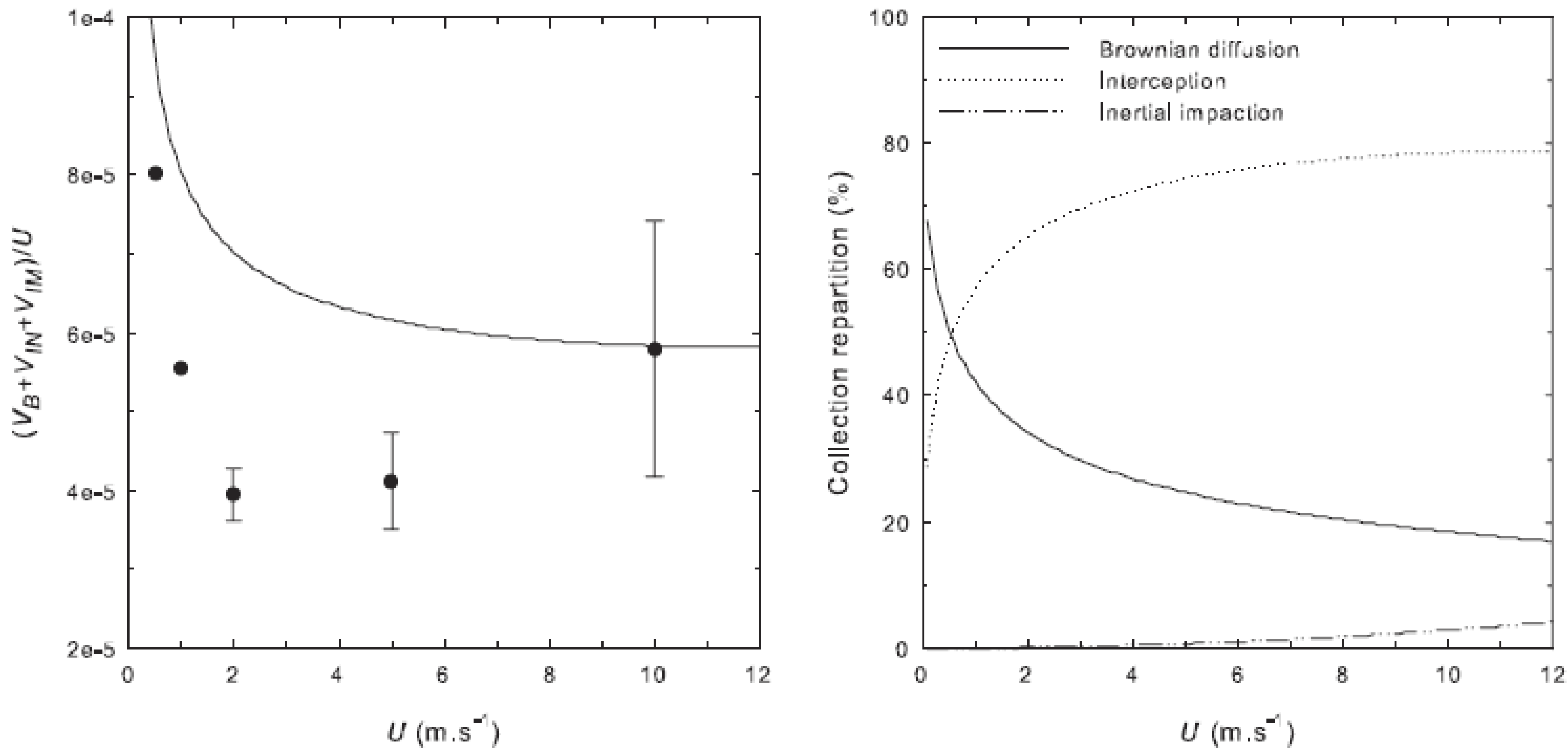
$$0.2 < \tau_p^+ < 20\ ,\ \ v_{IT} / u_f = K_{IT1}\ \tau_p^{+2}$$
$$20 \le \tau_p^+ \qquad\qquad ,\ \ v_{IT} / u_f = K_{IT2}\,,$$

with $K_{IT1} = 3.5\ 10^{-4}$ and $K_{IT2} = 0.18$. Since there is no influence any of the vegetation parameters, we then infer that V_{IT}=v_{IT}.

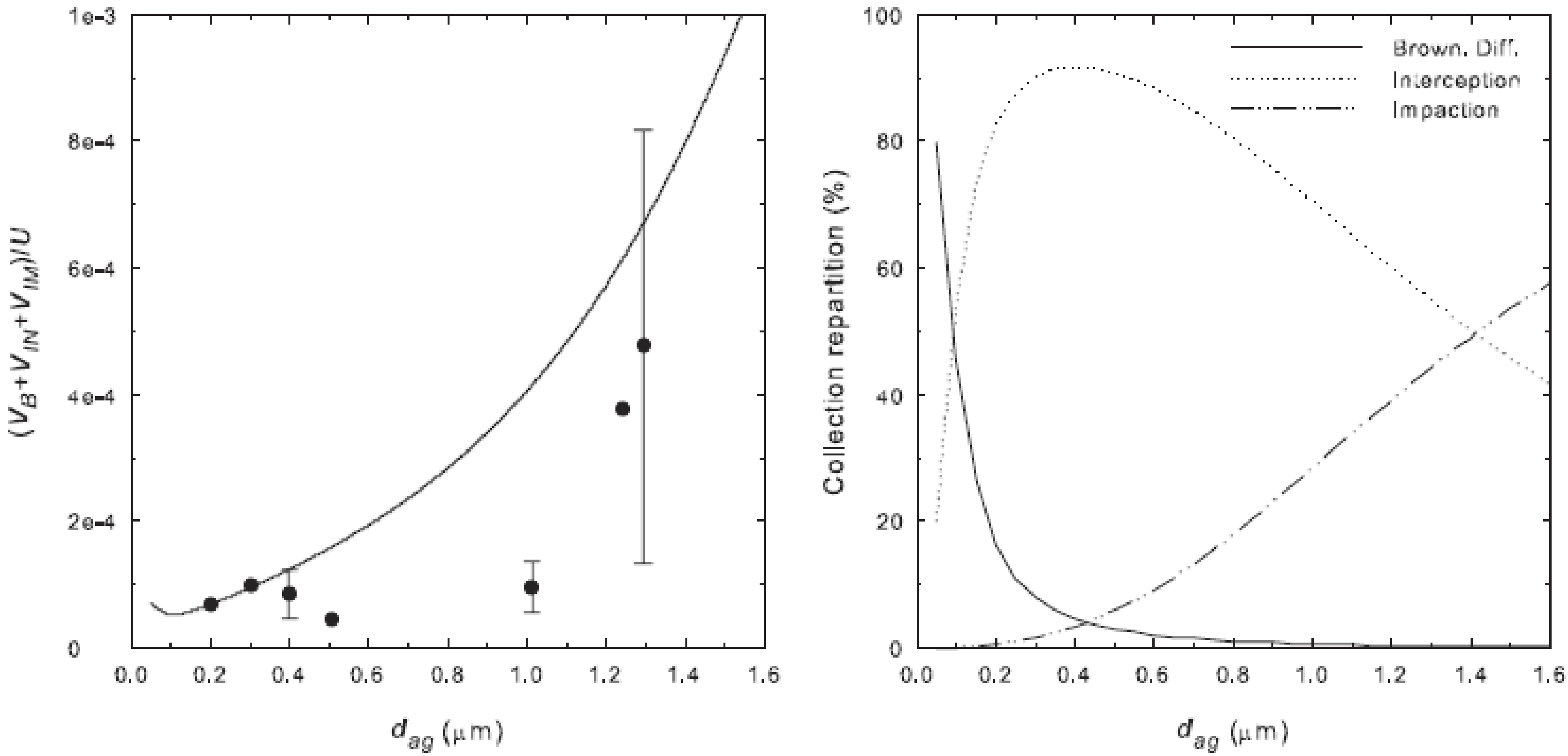
Sedimentation

The action of gravity upon particles is as usual described by the sedimentation velocity W_S , which is vertical.

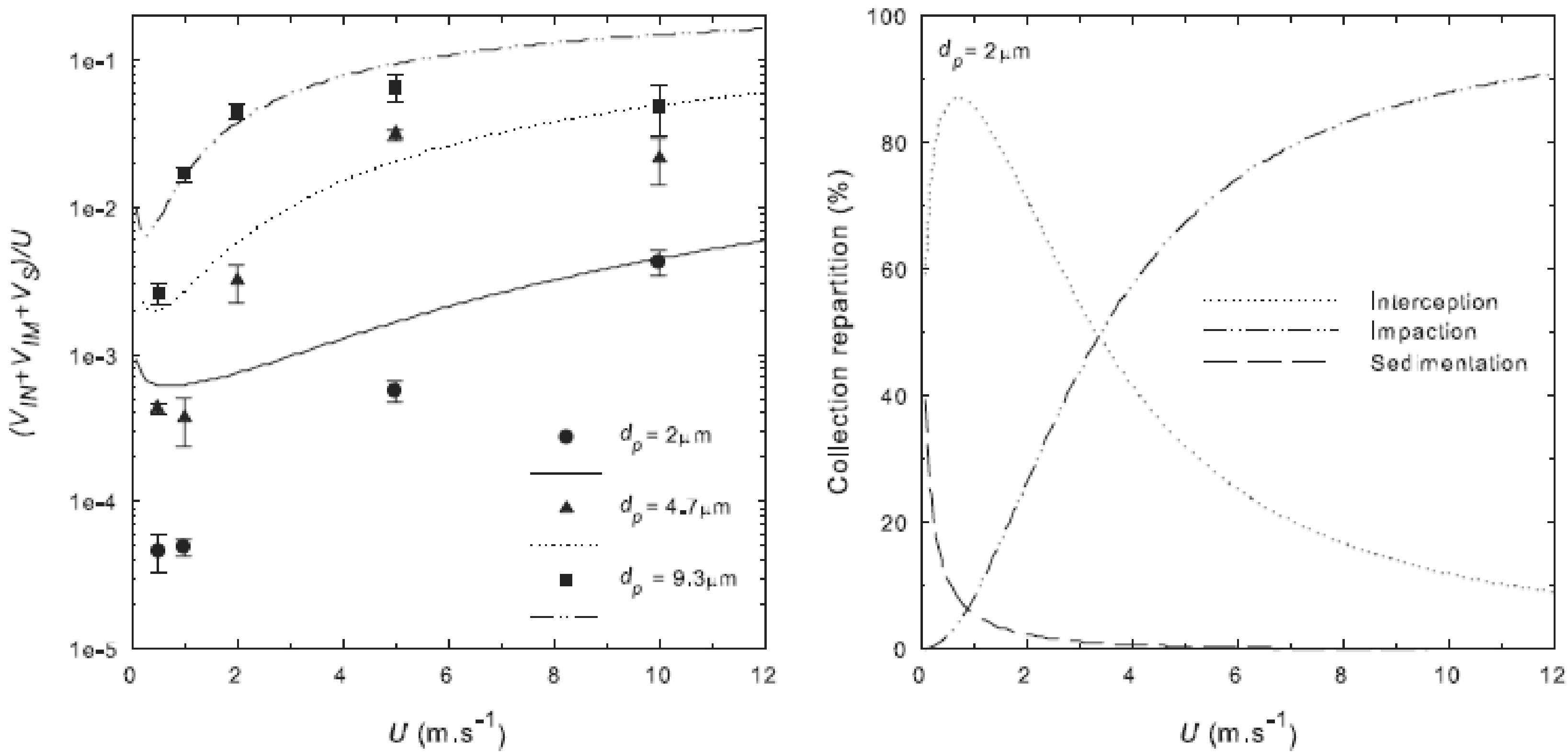
The accessible surface for this flux is the instantaneous projected surface in the horizontal plane s_z and the collection velocity is expressed by $v_S = W_S\, s_z/s$. Two random parameters control deposition, namely the obstacle area and the inclination angle. The averaged collection velocity is then expressed by $V_S = k_z W_S$, where k_z was given in the previously shown table for typical angular distributions.



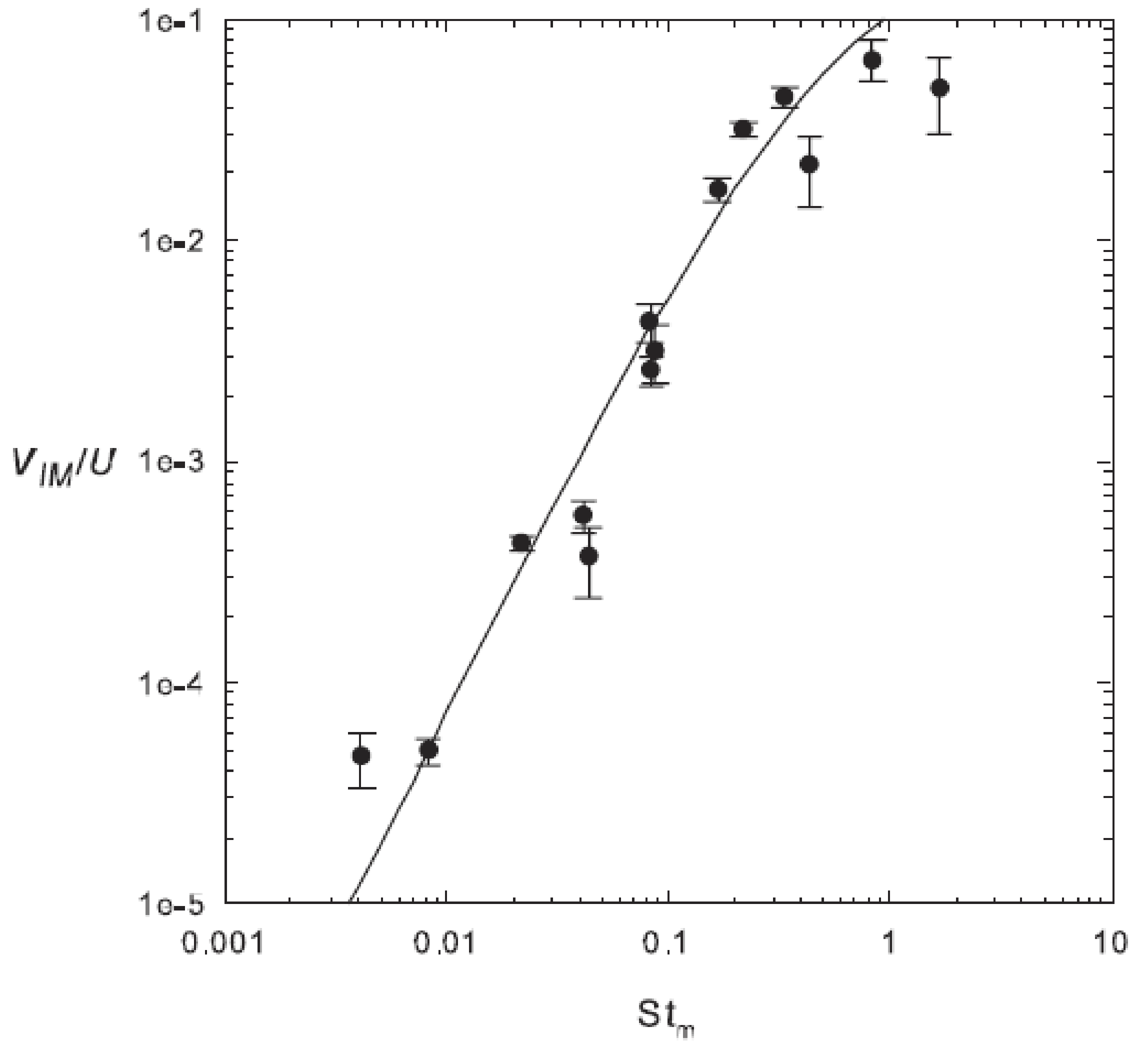
Validation of the model for the collection of 0.17µm mean diameter aerosol on Scots pine twigs.



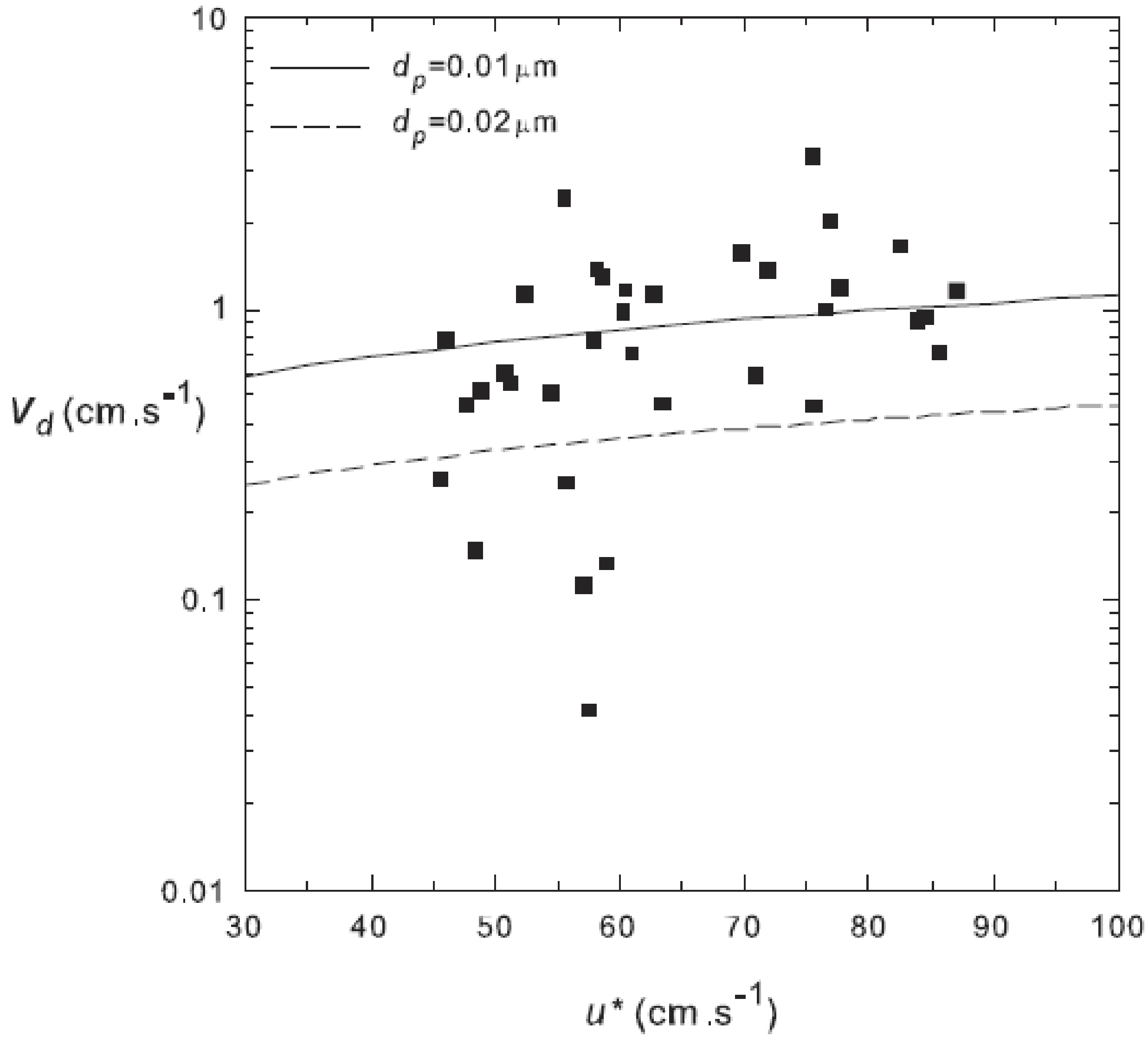
Validation of the model for the collection of accumulation mode aerosol on Scots pine twigs. The mean flow velocity is U=5m.s^{-1}.



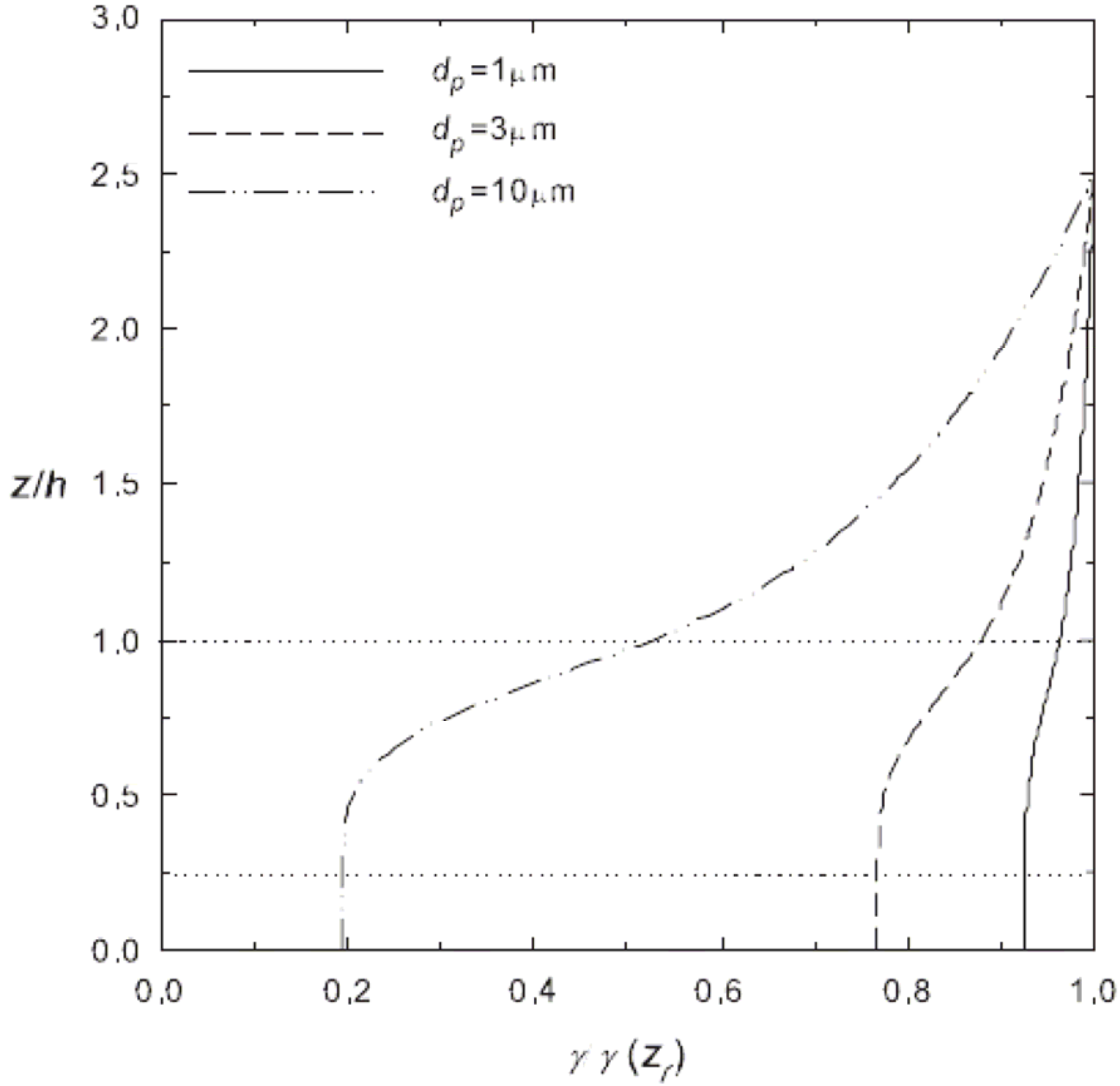
Validation of the model for the collection of micronic aerosol on Scots pine twigs.



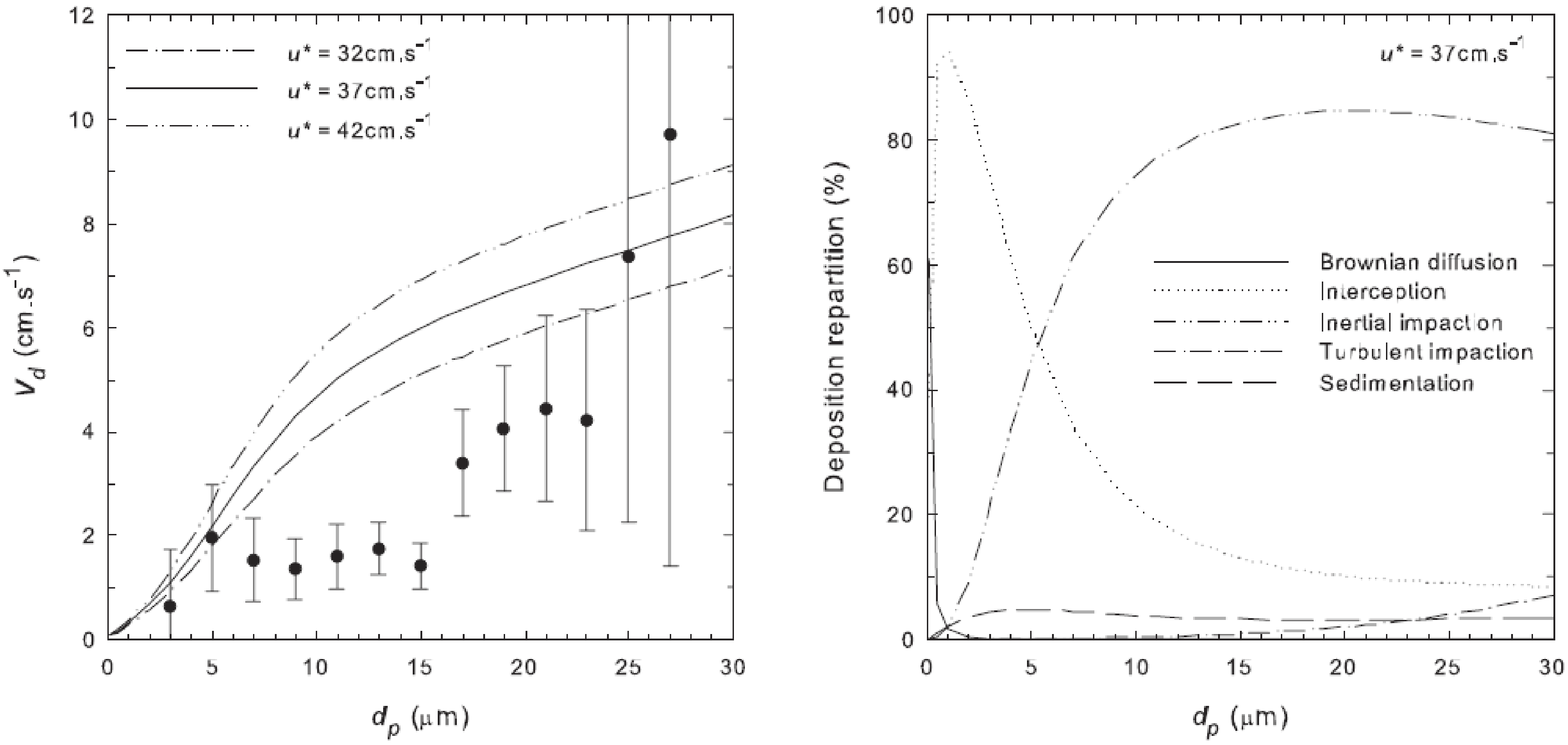
Comparison of micronic aerosol deposition experiments and impaction model.



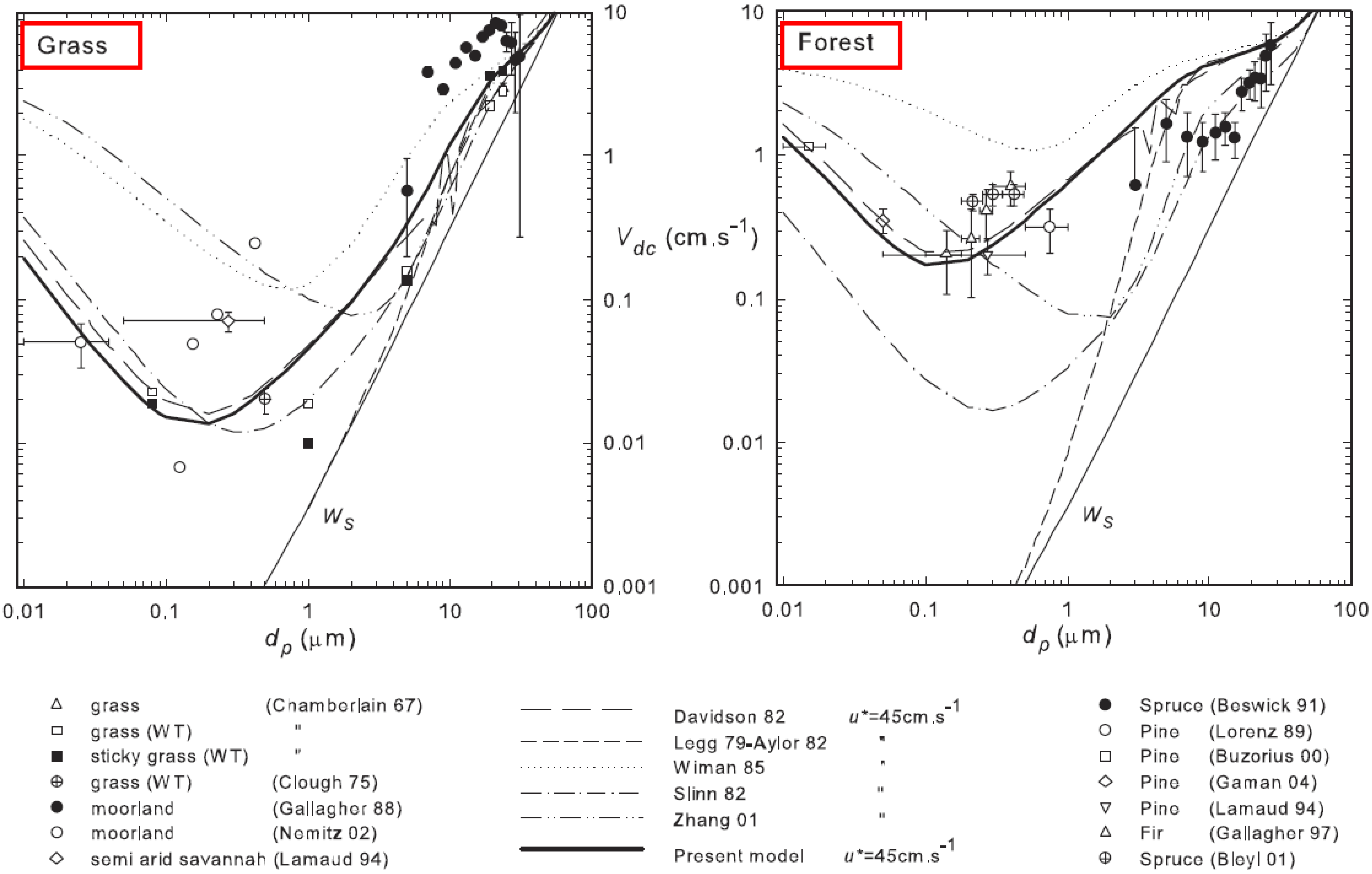
Deposition of nucleation mode particles on Scots pine.



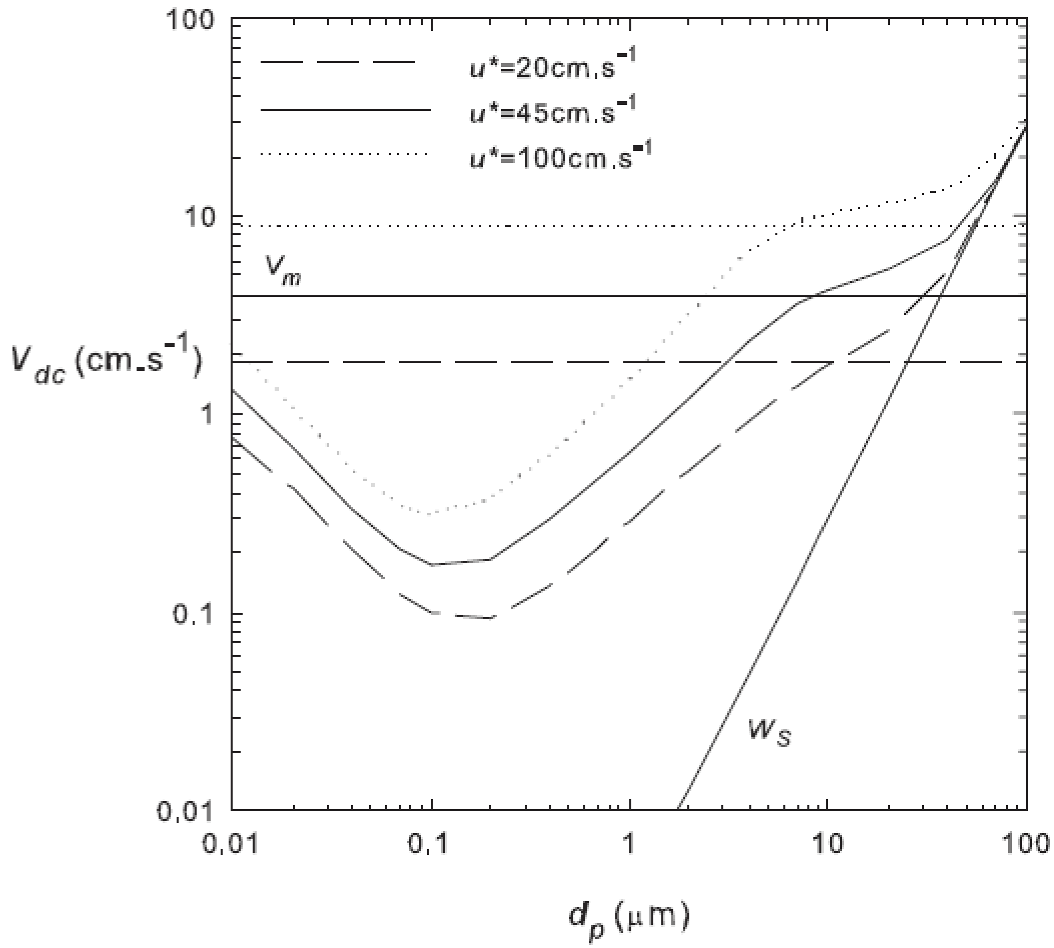
Droplet concentration within and above the canopy with u^*=37cm.s^{-1}.
The dotted lines represent foliar crown limits.



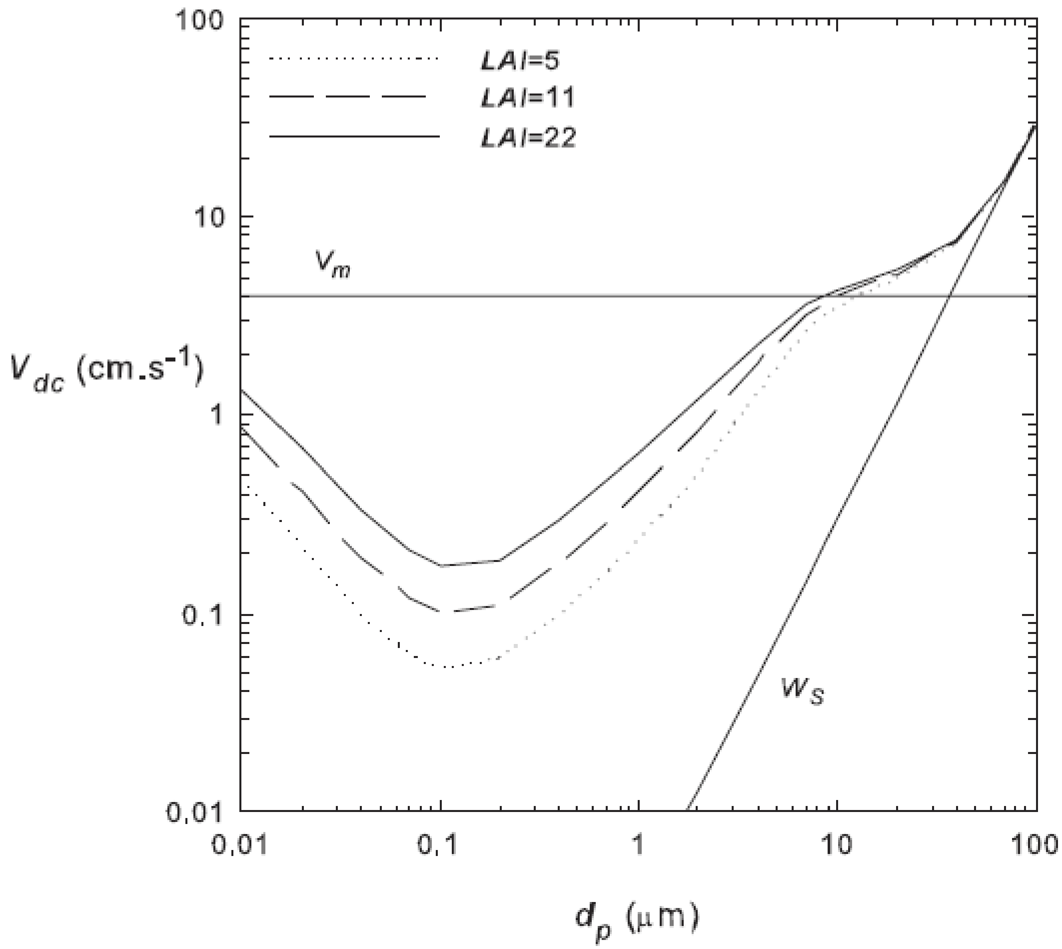
Size-dependence of fog deposition on a low spruce forest, with deposition velocity on l.h.s. and deposition repartition on r.h.s.



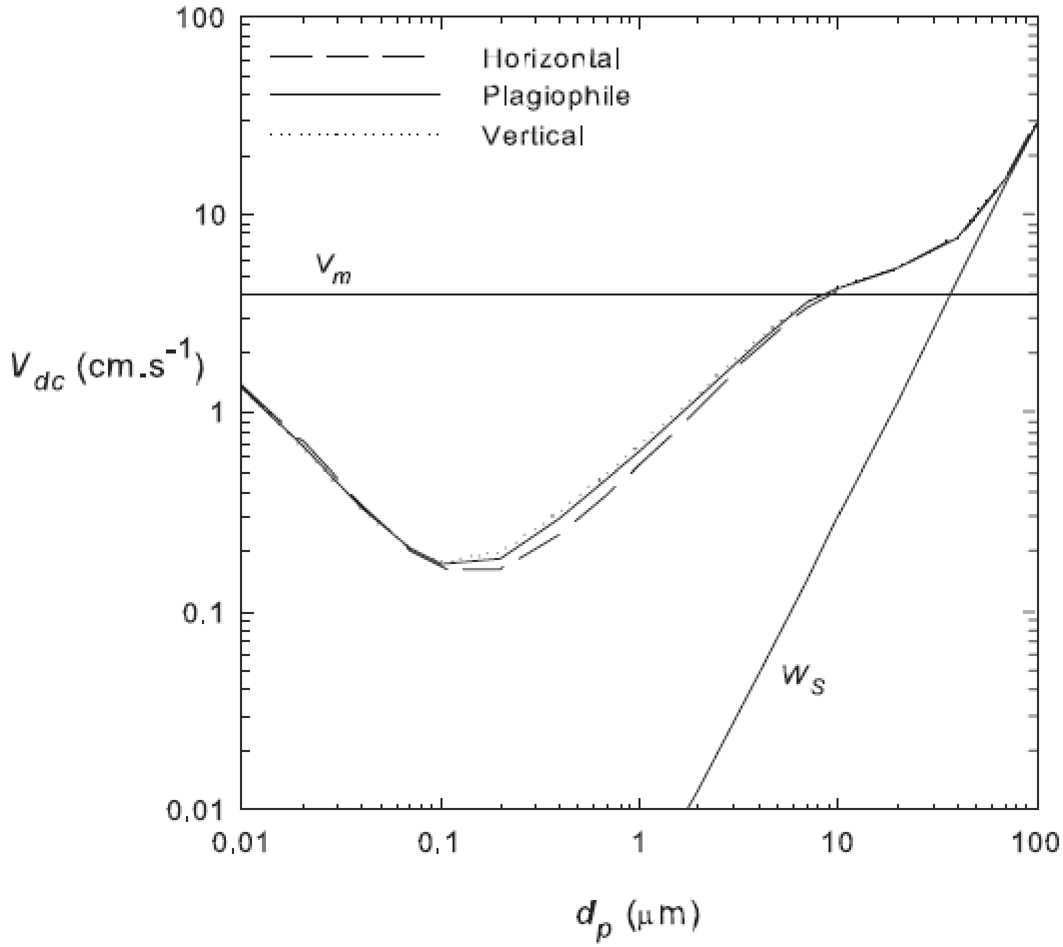
Comparison of deposition models and available experiments on grass and forest.



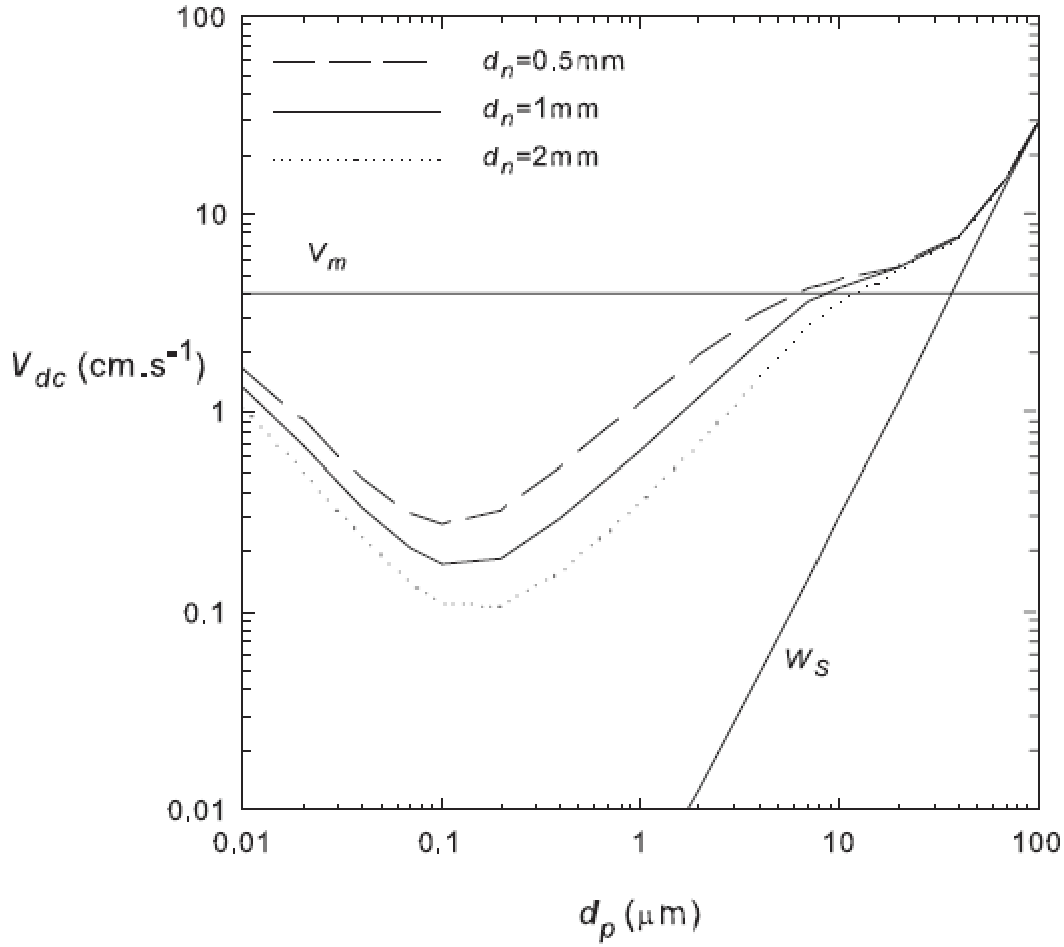
Model sensitivity to friction velocity.



Model sensitivity to leaf area index.



Model sensitivity to needle inclination distribution.



Model sensitivity to needle mean diameter.

Conclusion

- Detailed derivation of balance equation for the aerosol concentration (space-then-time averaging) allowed us to clearly identify the deposition terms

- Modelling these terms through a statistical treatment of all parameters (size, orientation, …, of the obstacles + global paramaters such as LAI or friction velocity) provides a new prediction tool which seems to provide rather good agreement with existing measurements

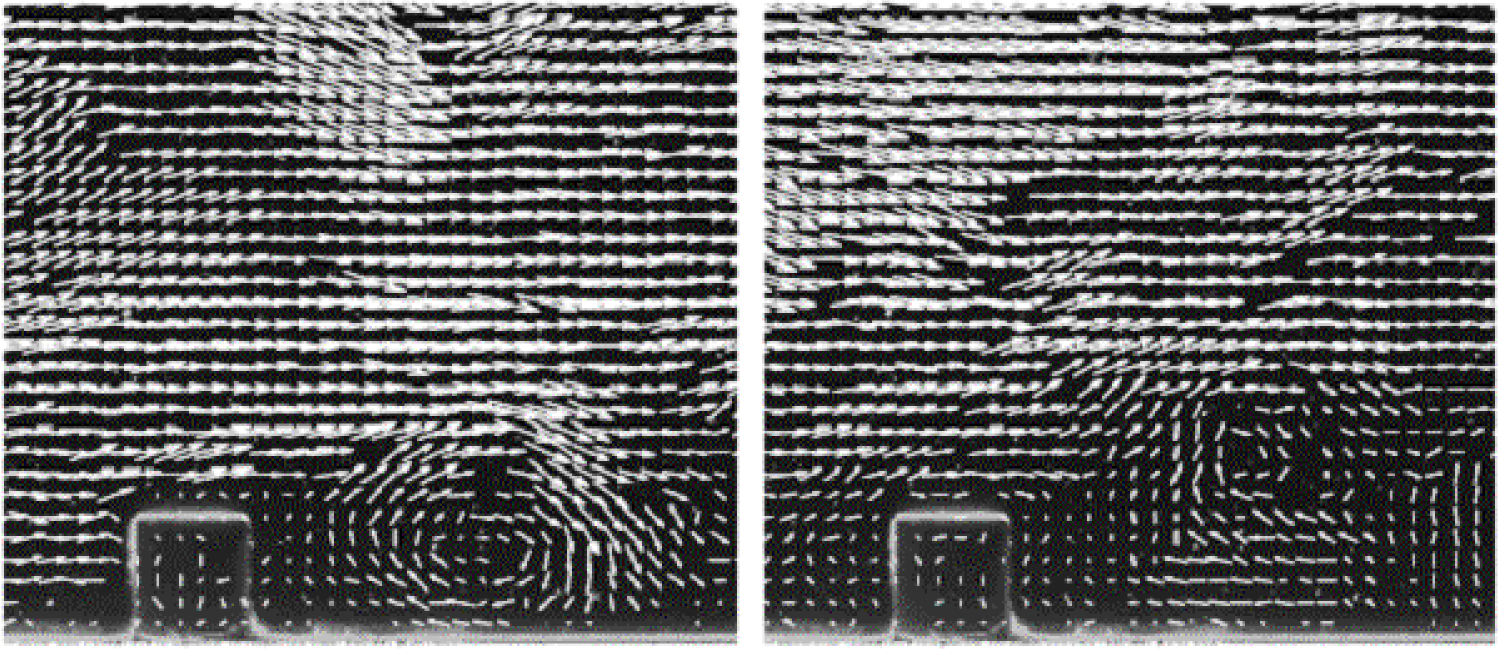
- Model efficiency for non-dense canopies ??
- Better account of rebound effects ??

Other studies in the water channel HERODE

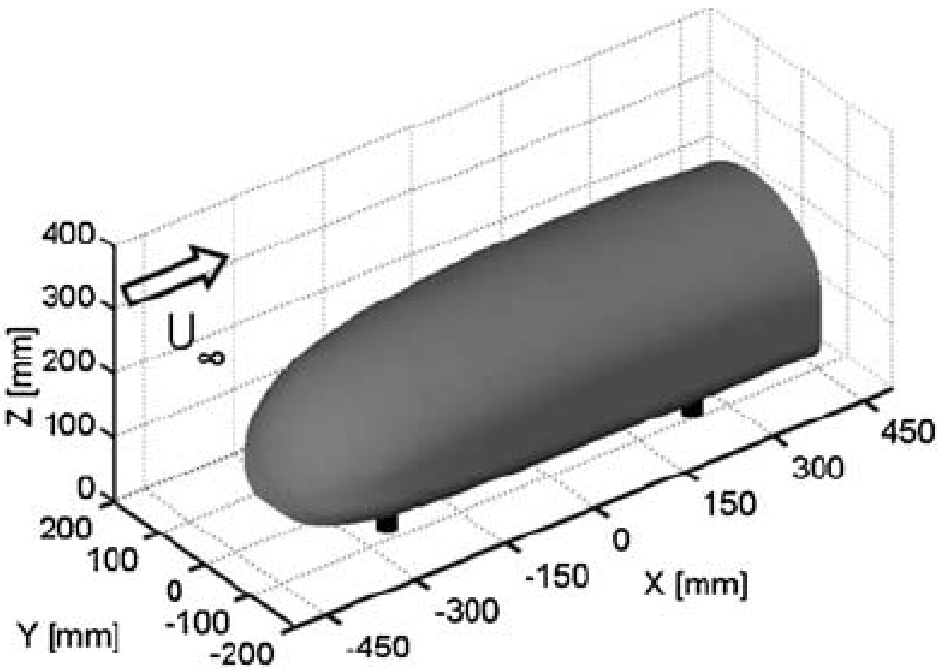
- Optimizing palm efficiency (swimming vs efforts) - O. Boiron

- Rough wall boundary layers, with R.A. Antonia and L. Djenidi

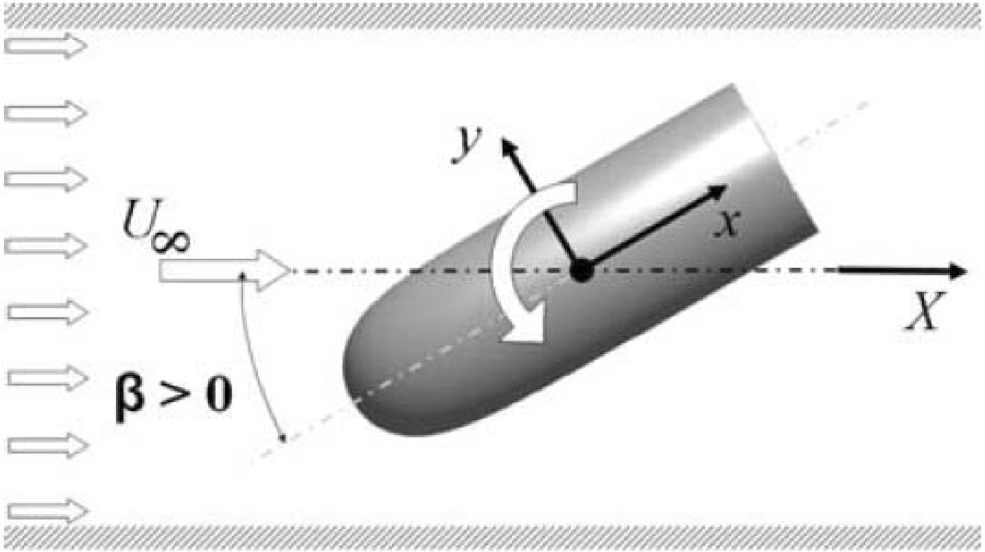
- Analysis of flow structures and forces on a 3D-bluff-body in constant cross-wind, with M. Gohlke and J.F. Beaudoin



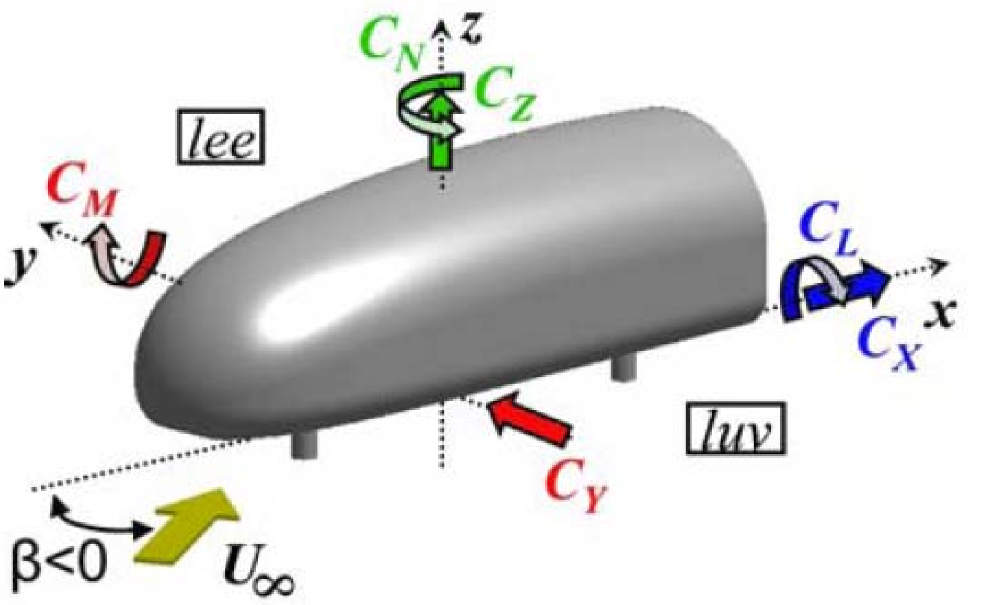
Contour of instantaneous velocity vectors displaying unstable shear layer vortices which are shed at the trailing edge of the roughness elements ($p = 10w$)



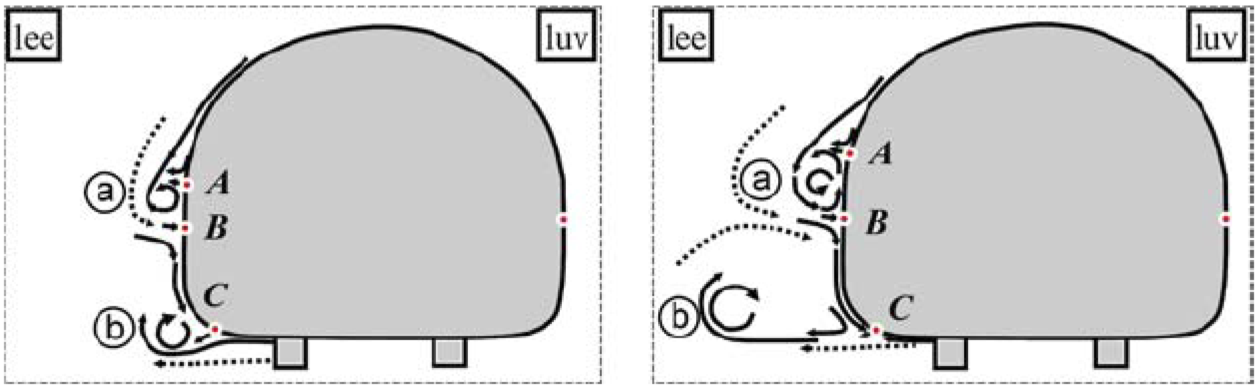
Car model « Willy » - water channel + wind tunnel
(flow visualisations, PIV+LDV, wall pressure, efforts)



(a) Orientation of the model in the wind-tunnel set up



(b) Image of the three dimensional force tensor in the model fixed coordinate system



Interpretation of lee-side flow field:
low angles β < 20 (sketch on the left hand side) and
high angles β > 20 (sketch on the right hand side)

Thank you …..