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UPTAKE OF SMALL PARTICLES BY TREE CANOPIES

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Abstract

Most of the deposition data that are available to assess the radiological consequences of an accident have been acquired for low-growing vegetation and are inadapted to forest areas. Consequently, a programme was undertaken to study the deposition of particles on components of different trees and extrapolate the experimental data so obtained to large-scale canopies. The experiments were performed in a wind tunnel allowing canopy components to be exposed to a flow of suspended fluorescent particles of reasonably uniform size. Emphasis was put on particles in the 0.3-1.2 µm subrange, because most of the radioactive particles sampled at long distance from sources are comprised in this size interval. The uptake rates were determined for bare and leaf bearing twigs of several evergreen species (Picea abies, Pinus sylvestris and Quercus ilex), as a function of wind speed and particle size. The deposition rates obtained for the tree components were then used as input to a model that describes the uptake of particles by a large-scale canopy under specified conditions of weather and canopy structure. The model accounts for the diffusion of particles between different strata of the canopy, as well as deposition of particles on the canopy components. It calculates the rates of particle deposition to the horizontal surface of the canopy, and the repartition of the deposited particles within the canopy. Increases in wind speed cause increased deposition, but the effect is less important that it would have been for larger particles. The deposition is relatively insensitive to the size of particles within the subrange considered in this study.

Introduction

An understanding of particle deposition to vegetated surfaces of forest trees is important in predicting the input of detrimental compounds to forest ecosystems. Many studies have been carried out on the deposition of particles to low-growing herbaceous vegetation. In contrast, very few studies have been performed on the deposition of particles to forested areas, due to the difficulties encountered in sampling tree canopies. The rare data obtained suggest that the deposition of particles to forest canopies is particularly favoured by the large projected surface areas of the trees and the relatively high ventilation rate that characterize them.

The strategy used in the present work for studying the deposition of particles to stands of trees, was similar to the one already used by several investigators (Belot 1975, 1976; Thorne et al 1982, Lovett 1984)). It consists in measuring the deposition of well-characterized particles to isolated leaf-bearing twigs placed in a wind-tunnel under realistic conditions of particle size and wind velocity, and to extrapolate the data to a complete canopy of leaves in a forest by means of a model that simulates the uptake of particles and the cleansing of the atmosphere.

We put emphasis on particles in the submicrometer size range whose deposition is poorly known in spite of their importance in the long-range transport of products from accidental releases (Garland 1980, Nicholson 1988). The canopy elements chosen were taken from the evergreen species : Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*) and Holm oak trees (*Quercus ilex*) that can be found in extended areas and keep leaves during several consecutive years.

Experimental methods

A closed-circulation wind tunnel was used with an internal test section 130 cm long and 30 cm by 30 cm in cross section perpendicular to the flow. The tunnel produced wind speeds from 0.5 to 10 $m.s^{-1}$. The tunnel could be filled with humid air taken from the outside and freed from any particle by passage through a filter.

Particles of sodium fluorescein with a narrow dispersion of diameters were produced by an ultrasonic generator, such as used in inhalation therapy. The generator was fed with solutions of sodium fluorescein at different concentrations between 0.1 and 25 $g.l^{-1}$. After evaporation of water, particles of a fixed mass median diameter comprised between 0.2 and 1.4 µm were obtained. At the outlet of the generator inside the wind-tunnel, two radioactive sources of Thallium 204 were placed : they were designed to produce positive and negative small ions and neutralize the excess of electrical charge present on the generated particles.

In each determination, a leaf-bearing twig was placed in the center of the test section and exposed to the fluorescent aerosol at fixed windspeeds and particle sizes. During the exposure time (5-15 minutes) the particles present in the tunnel were sampled through a eight-stage Andersen cascade impactor and a total filter to determine the size characteristics and total concentration of particles. After exposure, the twig, impactor plates and filters were washed in 100 ml of a pH 9 buffer solution. The fluorescence of the rinse water was measured with a Perkin-Elmer fluorometer. The completeness of the particle washoff was provided by sequential rinsing of sample material, which showed no additional fluorescence removed after the first rinse.

The size characteristics of the aerosol used in each experiment was determined from the stage loadings of the Andersen impactor, by calculating the theoretical stage loadings associated with different log-normal functions, and by using a least square procedure to find the log-normal function that ensures the best fit between theoretical and measured stage loadings.

Results

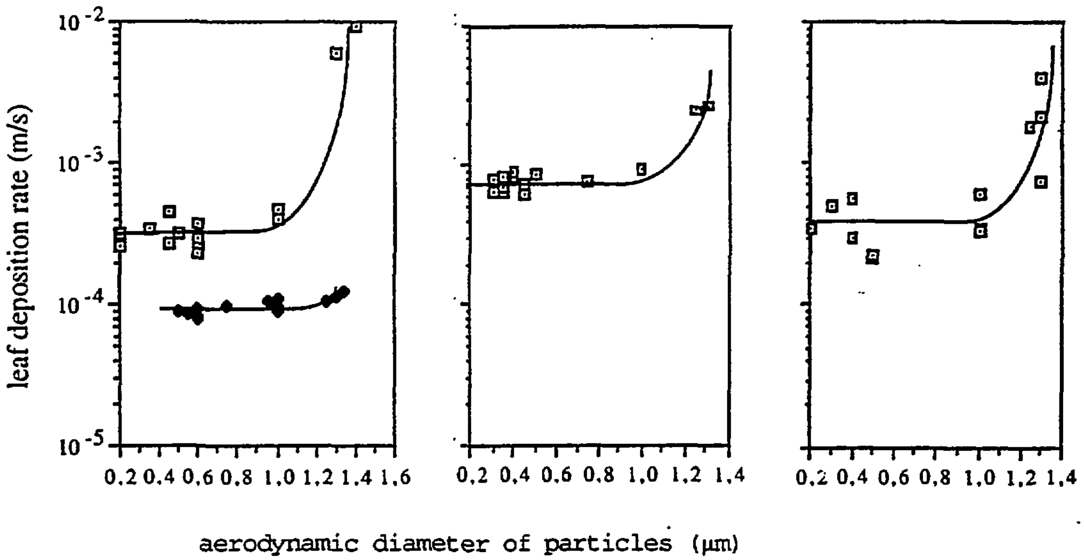

Figure 1 : Leaf deposition rate vs particle diameter for Norway spruce (left), Holm oak (middle) and Scots pine (right); wind speed u = 5 $m.s^{-1}$ (white dots) and u = 1 $m.s^{-1}$ (black dots).

A total of 60 separate determinations of particle uptake were made in the wind tunnel with a variety of target specimens, particle sizes and wind speeds. The total developed surface areas of the leaf-bearing twigs used in the experiments were of 200-300 cm^2. They were exposed to particles of a fixed aerodynamic mass median diameter (MMD) comprised between 0.2 and 1.4 µm with geometric standard deviations (GSD) between 1.3 and 1.5. The deposition of particles on the target was characterized by a leaf deposition rate defined as the flux of particles to the leaves (per unit area of leaf surface) divided by the air concentration of particles in the surrounding air. The leaf deposition rate was plotted against the size of particles for each of the three species.

It can be seen on the graphs of Fig.1 that the values of leaf deposition rate obtained for each species do not vary very much for MMD's in the subrange 0.3 - 1.0 µm. The average deposition rate is about 3.5×10^{-4}, 7×10^{-4} and 4×10^{-4} $m.s^{-1}$ at a wind speed of 5 $m.s^{-1}$ for Norway spruce, Holm oak and Scots pine respectively. It falls to 9×10^{-5} $m.s^{-1}$ at a wind speed of 1 $m.s^{-1}$ for Norway spruce, which shows that, at least in the explored range of windspeed, the deposition rate is proportional to the wind speed raised to the power 0.9 ± 0.1.

For particles larger than 1 µm the deposition rate increases rapidly with the size of particles and the wind speed.

Extrapolation to a canopy

The model used for extrapolation of wind-tunnel data to a real canopy is a model adapted from Waggoner (1968, 1971, 1975) and Lovett (1984). The model considers an uniform concentration of particles over a forest extending uniformly on all sides. The forest is arbitrarily divided into N strata of known surface area index (surface area of leaves per unit area of ground surface). The values of turbulent diffusivity and wind speed at the top of the canopy are calculated from the friction velocity and the geometrical characteristics of the canopy (Thom 1975). These parameters are considered to decrease exponentially within the canopy as a function of the cumulative surface area index, the extinction coefficients of the exponential term being -0.14 and -0.27 respectively (Lovett 1984).

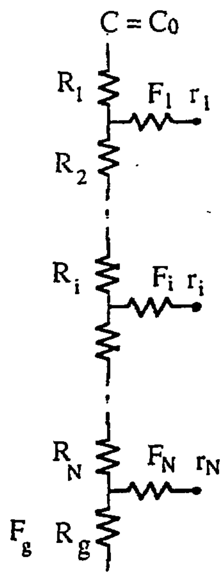

Figure 2 : The transfer of particles from a steady concentration C_0 at the top of a canopy through the resistances R of the air among foliage, through the resistances r of the boundary layers near the foliage. The bottom resistance is encountered by particles diffusing to the soil. The fluxes F are the amounts of particles deposited to each stratum per unit time and per unit of horizontal surface area.

The resistances R_i represent resistance to the turbulent diffusion of particles between layers in the canopy. The size of these resistances vary from stratum to stratum as

$$R_i = 0.5\ (\Delta z_i / K_i + \Delta z_{i-1} / K_{i-1}) \qquad (1)$$

where Δz is the layer thickness and K the turbulent diffusivity for the strata i and i-1. The resistance labelled r_i represent the boundary-layer resistance to transfer of particles from the air in a given stratum to the canopy surfaces. Each can be considered as the composite of the boundary-layer resistances of each of the canopy components acting in parallel. It is calculated as

$$r_i = [\ A_i\ .\ v_d(u_i)]^{-1} \qquad (2)$$

where A_i is the surface area index of the stratum i; $v_d(u_i)$ the leaf deposition rate of the particles, this deposition rate being a function of the wind speed (u_i) in each stratum. The values of the deposition rate are taken from the data obtained in the wind-tunnel experiments described above. The r_i will decrease with stronger ventilation and more abundant leaves.

Using electrical analogy, N algebraic equations can be written and then solved for the fluxes F_i of particles deposited in each stratum : the detail of equations is given in Waggoner (1971) and Lovett (1984). Finally, the fluxes F_i so obtained are multiplied by the resistances r_i to determine the average particle concentrations C_i in the air of each stratum.

Example of calculation

The model was applied to a typical stand of Norway spruces *(Picea abies)* aged 21 years and situated in the East of France. The average height of the trees is 11.4 m, their number per unit area of ground surface 4286 trees per ha. The canopy is segmented into 7 horizontal strata of known surface area index (see Table 1). These data are taken from a field study by Granier and Claustres (1989).

The calculation of particle transfer to the canopy is made for particles of diameter in the sub-range 0.2 - 1 µm using the experimental leaf deposition rates obtained for Norway spruce and assuming from these data that the deposition rate for particles of that size is proportional to the wind speed raised to the power 0.9. The data given as entry to the model are the height of each stratum midpoint, the leaf surface area index of each stratum, the average height of the trees, the displacement height and the roughness length of the canopy, and the wind friction velocity. The program calculates the turbulent diffusivity, wind speed, concentration of particles and deposition rate for each stratum of the canopy.

The data obtained in the case of a friction velocity of 0.5 $m.s^{-1}$ are given in Table 1. It appears that both wind speed and deposition rate decrease rapidly with the height of the stratum in the canopy. The depletion of the particle concentration in air within the canopy is rather small : only a few per mil of the concentration at the top of the canopy. Finally, by summing the deposition rates in the different strata, one obtains 8.05×10^{-4} $m.s^{-1}$ which represents the total deposition rate of particles on the canopy (canopy deposition rate). In the present case, the canopy deposition rate varies between 3.5×10^{-4} and 1.5×10^{-3} $m.s^{-1}$ for friction velocities between 0,2 and 1 $m.s^{-1}$.

Discussion

The leaf deposition rates obtained in the experimental part of this work, for particles in the subrange 0.2-1 µm, are situated between 10^{-5} and 10^{-3} $m.s^{-1}$. The values obtained are nearly independant of particle size, and depends particularly on leaf morphology and wind speed. The independance from particle size can be explained by the common observation that the deposition rate is generally minimal for particles in this size range and increases for particles outside that range. The dependance on morphology and wind speed is not surprising, since these two factors are recognized to have a pronounced influence on the thickness of the boundary layers and consequently on the deposition rate. The relationship found between the leaf deposition rate and the wind speed agrees with the theoretical relationship established for the diffusion of particles through a laminar or turbulent boundary layer (Levich 1962).

The model used for extrapolation of data to a canopy is useful for identifying the main factors that control the deposition of particles inside a canopy. In a dense homogeneous forest of extended area, the wind speed and hence the deposition rate of particles are strongly reduced, particularly in the low-level strata. As a consequence, in that type of forest, the canopy deposition rate of small particles is not very high in spite of the large surface area index of the trees : generally it amounts only to a few 10^{-4} m.s^{-1}. Nevertheless, it should be noticed that the model used in this work is a one-dimension model which assumes that the transfer of momentum and mass is primarily in the vertical direction, with net horizontal advection being negligible. This model does not apply when the forest in question has not sufficient upwind fetch to allow equilibrium to be reached between the airflow and the surface. In particular, the deposition rate is probably enhanced at the border of a forest or wooded strip where the trees are fully exposed to the wind.

Table 1 : Leaf area index, wind speed, particle air concentration and deposition rate in the different strata of a typical spruce canopy. Average height of trees : 11.4 m; displacement height : 9 m; roughness length : 0.3 m; friction velocity : 0.5 m.s^{-1}. The deposition rate per stratum is defined as the flux of particles to the stratum (per unit area of ground surface) divided by the air concentration of particles at the top of the canopy.

height of stratum midpoint (m)	leaf surface area index per stratum	wind speed in the stratum (m.s^{-1})	particle air concentration in each stratum*	deposit. rate per stratum (10^{-4} m.s^{-1})
10.64	2.56	1.94	0.998	3.82
9.23	2.44	0.99	0.997	1.98
8.42	3.42	0.45	0.996	1.36
7.58	3.33	0.18	0.995	0.58
6.82	3.38	0.07	0.995	0.26
6.04	0.77	0.04	0.995	0.04
3.02	0.00	0.04	0.995	0.00

* The air concentration of particles at the top of the canopy is equal to unity.

Conclusions

The results described in this paper demonstrate that the uptake of small particles (0.2-1µm) by leaf-bearing elements of a forest canopy is practically independant of particle size, but is mainly related to the morphology of the leaves and to the wind speed. For particles of that size the influence of wind speed on deposition is relatively moderate but nevertheless can be of importance in the deposition of particles to a complete canopy of leaves in a forest. This was particularly studied by using a model that describes the steady-state transfer of particles from the atmosphere to an extended forested area beneath. It appears that the deposition of particles is more important on the upper part of the trees than on their lower part which is much less exposed to the wind. The canopy deposition rate of small particles to extended forested areas is therefore lower than could be expected from the large surface area index of certain canopies. The deposition is certainly more important at the border of wooded areas.

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