Particle filtering capacity of urban vegetation: A microscale numerical approach

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Abstract

It is a generally accepted fact that urban vegetation has the potential to filter fine and ultra fine dust particles (PM10 and smaller) out of the air through deposition processes taking place at the leaf surfaces. It is therefore an obvious idea to investigate the potential of vegetation for improving the local air quality in urban areas, especially in those locations that are heavily polluted by local particle sources. Unfortunately, the prognosis of the impact of vegetation on local air quality is far from being trivial. Despite the fact that vegetation absorbs a certain amount of particles, it has also a large effect on the local wind flow which in return directly affects the dispersion of particles and therethrough the local air quality. This paper suggests a simple approach to quantify the net effect of vegetation on the local particle concentration. We will also discuss the open questions related to this area of research.

Keywords: PM10, particle deposition, microscale modelling, air quality, ENVI-met

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1 Introduction

In January 2005 the European guideline 1999/30/EG regulating the maximum allowed concentration of fine dust particles smaller or equal to 10μm (PM10) became legally binding. Against this background many cities all over Europe were forced to find solutions for those locations, where the new and more stringent threshold values are exceeded. This task soon turned out to be challenging, as the fine dust problem is both a multi-scale problem (regional background against local pollutants) and a multi-source problem (fine dust sources vary from car exhausts over tire rub offs up to natural sources such as sea spray).

From the collection of possible methods to improve local air quality, the application of vegetation seems to be an attractive tool to counteract air pollution. This is basically due to the undoubted fact, that vegetation structures can act as local sinks for dust particles through deposition processes at their leaf surfaces. In addition, vegetation influences the wind speed and direction and can therefore be used to modify the distribution of particles.

However, the question whether adding local vegetation is an appropriate tool to improve local air quality or not is above all a quantitative question. The local air quality in an urban environment is basically defined by two dominating aspects: The amount of released pollutants on the one hand and the ability to remove polluted air on the other. Especially inside narrow street canyons the second point is crucial. If the wind circulation is restricted and the polluted air cannot be replaced properly by fresh air, even average strong pollutant sources can lead to critical pollutant concentrations.

While vegetation is known to filter dust particles out of the air, it is also well known to act as an efficient wind shelter. This effect clearly works against the potential benefits of the filtering capacity. If located in the wrong place, vegetation can actually *increase* the local pollutant concentration as a consequence of the reduced wind circulation (Ries and Eichhorn, 2001; Watanabe et al., 2005).

In general, there are many different parameters that influence the overall effect of vegetation structures on local air quality and it is not possible to find an universal solution that will work in all situations. Hence, in order to analyse the impact of different design scenarios on local air quality and to optimize the design decision, computer simulations are an irreplaceable tool.

While the effects of vegetation elements on the wind flow and the local turbulence are well known and usable model approaches exist (see e.g. Wang and Takle, 1995), a black hole exists when it comes to quantify the deposition process of particles at the leaf surface. There are a number of empirical studies (see e.g. Freer-Smith et al., 2005; Sehmel, 1980) deducing the deposition velocity from measurements, but the range of observed velocities range from less than 0.01 cm s^{-1} up to more than 10 cm s^{-1}, which seems unrealistic even if taking into ac-

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count different types of vegetation and sizes of particles. Furthermore, empirically based deposition factors can not easily be transferred to complex urban situations where wind speed, turbulence and flow patterns show a large spatial variation.

Based on a very simple approach which neglects the exposure of the leafs to the emissions and the structure of the wind field, Litschke and Kuttler (2007) calculated for a 100 m long street segment with a daily traffic volume of 40,000 cars a potential removal of 8% of the car emissions if a deposition velocity of 0.1 cm s^{-1} could be reached and the maximum possible green cover is used. For a higher or lower deposition velocities, the amount increases and decreases accordingly.

Obviously, the correct estimation of the potential and actual particle absorption capacity of urban vegetation is not only of academic interest, but decisive when assessing the feasibility of air quality improvement through vegetation.

In this paper we will present a basic numerical approach to simulate the effects of vegetation on particle dispersion and removal. The approach is based on common laws from atmospheric physics and was adjusted partly to fit the special requirements of microscale urban environments.

2 The particle dispersion and deposition model: The prognostic equations

The particle dispersion and deposition model presented here is designed and implemented as a submodel of the microclimate model ENVI-met Version 3.0/3.1 (Bruse, 2004; Bruse and Fleer, 1998). Therefore the symbols used in this paper match with the notations used in the ENVI-met model descriptions.

2.1 Prognostic equations

The atmospheric dispersion of a particulate substance can be expressed using a standard advection-diffusion equation written in Eulerian notation as:

$$\begin{aligned}\frac{\partial\chi}{\partial t}+u_i\frac{\partial\chi}{\partial x_i} &= \frac{\partial}{\partial x_i}\left(K_\chi\frac{\partial\chi}{\partial x_i}\right) \\ &\quad +Q_\chi(x,y,z)+S_\chi(x,y,z)\end{aligned} \tag{1}$$

with the cartesian co-ordinates x_i =$\{x, y, z\}$ and the corresponding wind velocity vectors u_i = $\{u, v, w\}$.

χ is the local particulate matter concentration used in the pressure independent SI-unit [mg(χ)kg^{-1}(Air)]. Local processes that lead to a decrease or increase of χ like local pollutant sources or the sedimentation of particles are included explicitly into the prognostic equations using the source and sink terms Q_χ and S_χ respectively.

2.1.1 Formal definition of particle sources

Local particle sources can be separated into four different types with respect to their spatial structure (and consequently in the unit of their definition):

1. Point Sources: q_p, Unit [mgs^{-1}]
2. Line Sources: q_l, Unit [$mgs^{-1}m^{-1}$]
3. Area Sources: q_f, Unit [$mgs^{-1}m^{-2}$]
4. Volume Sources: q_v, Unit [$mgs^{-1}m^{-3}$]

Distinction between those four types is essential, when defining external sources (e.g. car exhausts) in the model area.

Before using sources in the prognostic model equations, their emission rate must be transformed into the non-dimensional unit [$mgkg^{-1}\,s^{-1}$] as required for Q_χ to fit with the prognostic equations.

First, all types of sources are transformed into q^* in [mgs^{-1}]:

$$\begin{aligned} q^* &= q_p \\ &= q_l\cdot\Delta x, y \\ &= q_f\cdot\Delta x\Delta y \\ &= q_v\cdot\Delta x\Delta y\Delta z\end{aligned}$$

Secondly, Q_χ is calculated with respect to the cell size in which the source is located:

$$Q_\chi = q^*\cdot(vol\cdot\rho)^{-1}$$

with cell volume $vol = \Delta x\Delta y\Delta z$. Note, that for the output of local concentrations, it is common to have the data related to the air volume in [$mg\,m^{-3}$] rather than related to the air mass in [$mg\,kg^{-1}$]. Therefore, for output the local concentration is converted by

$$\chi^* = \chi\cdot\rho$$

ENVI-met allows to simulate sources with time dependent emission rates. To implement this, each source is defined by 24 values representing the emission rates $q(h)$ for each hour h [0-23] of the day. The actual emission rate for a hour h and a minute m [0-59] is then linearly interpolated as:

$$q(h,m) = \frac{60-m}{60}\cdot q(h)+\frac{m}{60}\cdot q(h+1)$$

After hour h=23 the calculation restarts with h=0. The frequency of updating the emission rate can be selected by the user and should normally be around 10 min. Changes in emission rates only influence the local sources, no trend correction will be performed at the atmospheric grid points. In case of rapid changes in emissions, a smaller update interval is necessary to avoid unrealistic oscillations.

2.2 Implementation of particle sedimentation and deposition processes

The deposition of particles at different surfaces is complex process which is still not fully understood and lacks usable numerical parameterizations. The model approach used here is therefore based on classical approaches for particle dynamics in the atmosphere and at surfaces.

The local sink term S_χ in (1) is composed out of two individual components which, in their final balance, give the local sink rate of the component χ. These components are:

- concentration change due to gravitational settling including deposition at surfaces (composed of downward flux $\chi_\downarrow$ and flux received from grid boxes above $\chi^\downarrow$)
- deposition at leaf surfaces (χ_{plant})

(All fluxes in [$\text{mg}\,\text{kg}^{-1}\text{s}^{-1}$]). In the following sections, the estimation of these components will be presented in detail.

2.2.1 Formal description of sedimentation and deposition

The changes in local concentration due to sedimentation and deposition can be written analogous to an advective flux using the sedimentation / deposition velocity $v_{s/d}$ as the relevant transportation velocity:

$$\left.\frac{\partial\chi}{\partial t}\right|_{sed} = v_{s/d}\frac{\partial\chi}{\partial z} \tag{2}$$

The derivation of $v_{s/d}$ will be described in the next section.

As only downward fluxes can occur in the case of gravitational settling, a simple upstream scheme can be used to transform (2) into the finite-difference form:

$$\left.\frac{\Delta\chi}{\Delta t}\right|_{sed} = v_{s/d}\frac{\chi(z+1)-\chi(z)}{\Delta z} \tag{3}$$

where Δz is the vertical distance between the prognostic calculation points for level z and $z+1$. Please note, that the movement of particles due to vertical advection by the vertical wind vector component w is included in the base advection terms in (1). Hence, the vertical net flux of particle as calculated by (1) is the sum of the advective and the gravitational fluxes.

Splitting the equation above into a loss and a gain term we get

$$\left.\frac{\Delta\chi}{\Delta t}\right|_{sed} = v_{s/d}\frac{\chi(z+1)}{\Delta z} - v_{s/d}\frac{\chi(z)}{\Delta z} \tag{4}$$

where the reception of particles from the z-level above is counted positive and the loss of particles is counted negative.

The downward flux of particles per time unit ($\chi_\downarrow$) due to gravitational settling can be written as

$$\chi_\downarrow(z) = -v_{s/d}\frac{\chi(z)}{\Delta z} \tag{5}$$

and the gain of particles settling from the level above ($\chi^\downarrow$) is

$$\chi^\downarrow(z) = v_{s/d}\frac{\chi(z+1)}{\Delta z} \tag{6}$$

Obviously and in order to keep the model mass-conserving, eq. (6) for level z must be balanced with eq. (5) for level $z+1$.

If the concerned grid box is the lowest box above the ground surface or the box below is occupied by a building, the deposition velocity v_d (for calculation see Section 2.3.2) is used instead of the settlement speed v_s in (5).

Finally, we need to include the deposition of particles at vegetation elements into the mass balance. The flux of particles towards the leaf surface (χ_{plant}) can be written as:

$$\chi_{\text{plant}}(z) = LAD(x,y,z)\cdot f_{\text{cap}}\cdot v_d^p\cdot\chi(z) \tag{7}$$

where LAD is the local leaf area density (counted one-side) and f_{cap} is a leaf capacity dependent scale factor ranging from 1 for a fresh, clean leaf to 0 for a dirty leaf, whose filtering capacity is exhausted.

For the capacity factor f_{cap} there is lack of empirical data to formulate an appropriate capacity function. Therefore we set f_{cap} to a constant value of 1 and assume an infinite filtering leaf unless better data are available.

Finally, the total pollutant balance due to sedimentation and deposition can now be written as:

$$\frac{\partial\chi(z)}{\partial t} = \chi^\downarrow(z) + \chi_\downarrow(z) - \chi_{\text{plant}}(z) \tag{8}$$

or, as sink term for the prognostic equation:

$$S_\chi(x,y,z) = \chi^\downarrow(z) + \chi_\downarrow(z) + \chi_{\text{plant}}(z) \tag{9}$$

The total amount of deposed particle mass on a surface [mg m^{2}s^{-1}], is then calculated with

$$\frac{m_s}{\partial t} = \chi_{\downarrow} \cdot \rho \cdot \Delta z$$

with ρ being the density of the air (=1.29 kgm^{-3}). The total mass deposed in the grid box volume is projected onto the horizontal $\Delta x \Delta y$ surface area as the horizontal surface is the only place where deposed particles can accumulate.

For the leaf surfaces the equation

$$\frac{m_{\text{plant}}}{\partial t} = \chi_{\text{plant}}(z) \cdot \frac{1}{LAD(x,y,z)} \cdot \rho$$

is used in which the deposed mass inside the grid box is distributed evenly over the available leaf area inside the grid cell.

In the recent version of ENVI-met, no re-suspension of particles is taken into account. The calculation of the sedimentation and deposition processes is realized explicitly, which means that the concentration of the last time step is used to calculate the flux through the horizontal cell walls and to the leaf surface. This leads to an additional stability condition to ensure that no negative concentration values can occur in the case of high sedimentation rates (see Section 2.4 for details).

2.3 Calculation of sedimentation and deposition

2.3.1 Calculation of sedimentation speed v_s

The sedimentation speed (or settling velocity) of a particle depends on the particle diameter D, its density ρ_χ and the turbulence characteristics of the air flowing around the particle given by the Reynolds number Re.

For a given Re, the settling velocity v_s can be calculated following Seinfeld and Pandis (1999) with

$$v_s = \left(\frac{4\rho_\chi \cdot D \cdot g \cdot C_c}{3C_d \cdot \rho_\chi} \right)^{1/2} \tag{10}$$

where C_c is the so-called *Slip-Correction-Factor* given by (11) and C_d is the drag force on the particle calculated after (12).

$$C_c = \begin{cases} 1 + \frac{2\lambda}{D}\left(1.257 + 0.4\exp\left(-\frac{1.1D}{2\lambda}\right)\right) & ; D \leq 10\mu m \\ 1 & ; D > 10\mu m \end{cases} \tag{11}$$

The mean free path of air molecules (λ) used in the equation above is set to a constant value of 0.0651 μm which corresponds to an air temperature of 298 K, the small dependency of λ on the air temperature is hence neglected in the model. [1]

The drag force C_d on a particle is calculated with respect to the local Reynolds Number:

$$C_d = \begin{cases} s & Re < 0.1 \\ s\left(1 + \frac{3}{16}Re + \frac{9}{160}Re^2 \ln(2Re)\right) & 0.1 < Re < 1 \\ s\left(1 + 0.15Re^{0.678}\right) & 1 \leq Re < 900 \\ 0.44 & 900 < Re \end{cases} \tag{12}$$

with $s = 24/Re$. The transition values for switching between the equations have been changed from the original values given by Seinfeld and Pandis (1999) in order to allow a smoother transition between the definition intervals. For Reynolds numbers smaller then 0.1, the formulation of C_d is equivalent to the Stokes' law.

The Reynolds Number for a spherical particle is given by

$$Re = \frac{\rho_\chi \cdot v_s \cdot D}{\mu} \tag{13}$$

where μ is the viscosity of the air (=$1.8 \cdot 10^{-5}$ kgm^{-1}s^{-1} at 298K, kept constant).

Obviously, equation (10) for v_s cannot be solved directly as C_d depends on v_s over Re. The equation set can be solved quickly in a few iteration steps, starting with v_s calculated using the linear expression valid for $Re < 0.1$ as a first estimate:

$$v_s = \frac{\rho_\chi \cdot D^2 \cdot g \cdot C_c}{18\mu} \tag{14}$$

The iteration is canceled after the change of v_s per iteration step falls below 0.1 mm/s.

As a simplification we neglect the influence of the vertical flow component w on the Reynolds number which seems justifiable as the gravitational settling dominates only when the wind field is weak.

2.3.2 Calculation of deposition velocity $v_d^{(p)}$

The deposition velocity is distinguished into the deposition towards horizontal surface (v_d) and the deposition on leaf surfaces (v_d^p).

In general, the deposition velocity of a particle can be expressed as the inverse sum of two different transfer resistances r_a and r_b (Seinfeld and Pandis, 1999):

[1] For the calculation, all variables must be in SI units (D in [m], ρ_χ in [kgm^{-3}], ...)

$$v_{d,part}^{(p)} = \frac{1}{r_a^{(p)} + r_b + r_a r_b v_{s,0}} + v_{s,0} \qquad (15)$$

Here, r_a is the aerodynamic resistance of the ground or leaf surface and r_b is the sub-layer resistance of the surface, $v_{s,0}$ is the settlement speed close to the surface, set equal to v_s calculated after (10). The aerodynamic resistance is treated differently for a vertical ground surface (r_a) and for plant leafs (r_a^p) while r_b and $v_{s,0}$ are the same for both types of surfaces.

However, the formulation suggested above is only correct for a horizontal surface, where the gravitational settling is the main source of transport towards the leaf surface (see Fig. 1 a). If we assume the other extreme, a vertical orientated leaf, this component does not have any impact on the particle transport. In this case, the advective impact through the horizontal flow components is the dominating force (see Fig. 1 b) and we need to relate $v_{s,0}$ in (15) to $\mathbf{u}_{\mathrm{hor}}$ representing the horizontal flow field.

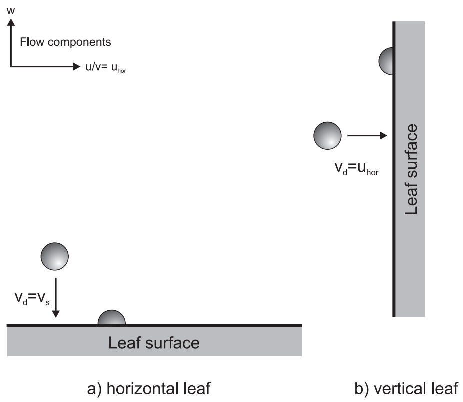

Figure 1: Interpretation of deposition velocity depending on leaf inclination.

Unfortunately, it is not clear to which fraction the horizontal flow components can be treated as a deposition velocity in case of a vertical leaf. As the air flows around the leaf and most of the particles follow the mean air flow, only some of them will be "shot" into the leaf surface. How large this number of impacted particles is related to the wind speed depends on the particle mass, the leaf surface structure and the morphological structure of the vegetation canopy. As this information is not available yet, we will use the vertical $v_{s,0}$ for all surfaces.

Aerodynamic Resistances r_a and r_a^p

The aerodynamic resistance of a surface to particles r_a is supposed to be the same as the resistance for heat transfer.

In the ENVI-met model, r_a can be derived directly from the turbulent exchange coefficient for heat at the ground surface or at the walls $K_{h,0}^{(w)}$ (more precisely here: roofs), in which the effect of thermal stratification is already included. Hence, the formulation for r_a at the ground surfaces, at roofs and at walls becomes:

$$r_a = \frac{\Delta_{(w)}}{K_{h,0}^{(w)}} \qquad (16)$$

in which $\Delta_{(w)}$ is the distance between the point where $K_{h,0}^{(w)}$ is defined and the ground or wall surface (Δz in the case of roofs and the ground surface).

At plant leafs, the aerodynamic resistance r_a^p is calculated following the expression given by Braden (1982):

$$r_a^p = A\sqrt{\frac{D^*}{\max(\mathbf{u}, 0.05)}} \qquad (17)$$

where $\mathbf{u}$ is the wind speed at the leaf surface which is set equal to the overall wind speed calculated for the corresponding grid box (all there components counted).

A and D^* are plant specific parameters which are set to A=87 $\mathrm{s}^{0.5}\mathrm{m}^{-1}$ for deciduous trees and grass and to A=200 $\mathrm{s}^{0.5}\mathrm{m}^{-1}$ for conifers. D^* represents the typical leaf diameter and is 0.02 m for conifers and grass and 0.15 m for deciduous trees (Schilling, 1990; Naot and Mahrer, 1989).

Within the framework of deposition modelling, the approaches introduced above which origin from heat transfer modelling are surly too simple for an accurate description of the processes taking place. There are many more factors that influence the aerodynamic resistance of a leaf surface, for example leaf hairs or the condition of the cuticula.

Sublayer Resistance r_b

The sublayer resistance r_b is an additional resistance caused by the quasi-laminar layer adjacent to the surface, across which the transfer velocity depends on the molecular properties of the transported substance as well as on the surface characteristics.

The sublayer resistance for particulate matters can be estimated as

$$r_b = \frac{1}{u_* \left(Sc^{-2/3} + 10^{-3/St}\right)} \qquad (18)$$

The Schmidt-Number Sc is defined as

$$Sc = \nu / D_\chi$$

with the kinematic viscosity of the air ν (set to $\nu = 1.5 \cdot 10^{-5}$ at 298 K). D_χ is the relevant diffusion velocity which is in case of particles equal to the Brownian diffusivity. The D_χ depends on the particle size as smaller particles experience faster Brownian motion and therefore less sublayer resistance than bigger ones.

The estimation of the Brownian diffusion coefficient is based on the Stokes-Einstein relationship :

$$D_\chi = \frac{k \cdot T \cdot C_c}{3\pi \cdot \mu \cdot D} \tag{19}$$

where k is the Boltzmann constant (=$1.38 \cdot 10^{-23}$ JK^{-1}), and C_c is the slip correction factor given by (11).

The Stokes Number is given by

$$St = \frac{v_s \cdot u_*^2}{g \cdot \nu} \tag{20}$$

For the ground surfaces (including water) and for roofs, the friction velocity is re-calculated from the corresponding exchange coefficient $K_{m,0}^{(w)}$ provided by the main model and the horizontal wind component with

$$u_* = \sqrt{K_{m,0}^{(w)} \frac{|\mathbf{u}_{hor}|}{\Delta^w}} \tag{21}$$

In case of vegetation elements, u_* is recalculated from the aerodynamic resistance r_a (see above) with

$$u_* = \sqrt{\frac{1}{r_a} |\mathbf{u}|} \tag{22}$$

where $\mathbf{u}$ is the three dimensional wind speed.

2.4 Numerical aspects

The explicit calculation of the sedimentation and deposition process adds a new stability criteria for the solution of the prognostic equation. The time step used must be small enough to ensure, that no negative concentrations can occur due to an overestimated downward sedimentation flux or deposition.

For each grid cell, a critical time t_{zero} is calculated, at which the concentration would be zero if all fluxes were kept constant:

$$t_{\text{zero}}(i,j,k) = \frac{\chi(i,j,k)}{-(\chi^{\downarrow}(i,j,k) - \chi_{\downarrow}(i,j,k) - \chi_{\text{plant}}(i,j,k)} \tag{23}$$

If t_{zero} is below 0, the concentration in the cell is increasing and no restriction for the time step apply. The maximum usable time step in the model can then be defined to be half of the time needed to reach the zero concentration condition:

$$\Delta t_{\max} = 0.5 t_{\text{zero}} \tag{24}$$

The determination of t_{zero} has to be performed after each solution of the prognostic equation. If $\Delta t_{\max}$ is below the main time step of the ADI system, the solution procedure is splitted into sub-loops using smaller time steps with $\Delta t = \Delta t_{\max}$ until the main time step is reached.

References

Braden, H. (1982). Simulationsmodell für den Wasser-, Energie- und Stoffhaushalt in Pflanzenbeständen. *Rep. Inst. Meteorol. Uni. Hannover*, (23).

Bruse, M. (2004). Updated overview over envi-met 3.0. Technical report, University of Bochum, see `www.envi-met.com`.

Bruse, M. and Fleer, H. (1998). Simulating Surface- Plant-Air Interactions Inside Urban Environments witha Three Dimensional Numerical Model. *Environmental Modelling and Software*, 13:373–384.

Freer-Smith, P. H., Beckett, K. P., and Taylor, G. (2005). Deposition velocities to *sorbus aria, acer campestre [...]* for coarse, fine and ultra-fine particles in the urban environment. *Environmental Pollution*, 133(1):157–167.

Litschke, T. and Kuttler, W. (2007). Die Filterung von Partikeln durch Vegetation– ein Literaturüberblick. In Emeis, S., editor, *METTOOLS VI – Fachtagung des Fachausschusses Umweltmeteorologie der Deutschen Meteorologischen Gesellschaft*, pages 5–7.

Naot, O. and Mahrer, Y. (1989). Modelling microclimate environments: A verification study. *Boundary Layer Meteorology*, 46:333–354.

Ries, K. and Eichhorn, J. (2001). Simulation of effects of vegetation on the dispersion of pollutants in street canyons. *Meteorologische Zeitschrift*, 10(4):229–233.

Schilling, V. K. (1990). A paramerization for modelling the meteorological effects of tall forests–A case study of a large clearing. *Boundary Layer Meteorology*, 55:283–304.

Sehmel, G. A. (1980). Particle and gas dry deposition: A review. *Atmospheric Environment- Part A*, 14(9):983–1011.

Seinfeld, J. H. and Pandis, S. N. (1999). *Atmospheric chemistry and physics*. Wiley-Interscience, New York.

Wang, H. and Takle, E. S. (1995). A numerical simulation of boundary-layer flows near shelterbelts. *Boundary Layer Meteorology*, 75:141–173.

Watanabe, H., Mochida, A., Sakaida, K., Yoshino, H., Jyunimura, Y., Iwata, T., and Hataya, N. (2005). Field measurements of thermal environment and pollutant diffusion in street canyon to investigate the effects of its form and roadside trees. In *Proceedings of International Symposium on Sustainable Development of Asia City Environment*, pages 509–515.