New scheme for dry deposition of aerosols

Rostislav D. Kouznetsov and Mikhail A. Sofiev

The problem

Given concentration at some height above ground find the steady-state flux.

Deposition velocity:

$$v_d(z_1) = J/C(z_1)$$

Approaches:

- Fixed or size-dependant deposition velocity
- Resistance analogy (aerodynamic + quasi-laminar sub-layers etc. . .)
- Something more fancy. . .

On the resistance analogy

For gases – straightforward resistance analogy: steady-state flux over any layer is proportional to the difference of concentrations.
For particles:

$$J(z) = -K(z)\frac{\partial C}{\partial z} + v(z)C.$$

Resistance analogy does not apply for finite layers.

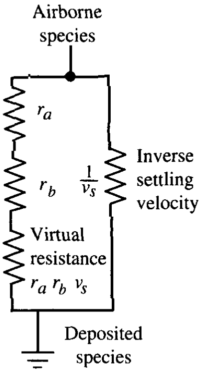
Evolution of Resistance approaches

Slinn 1980:

- Concepts of r_a, r_b and correction.

$$v_d = \frac{1}{r_a + r_b + v_s r_a r_b} + v_s$$

- Suggested for water surfaces.
- Rcommended by SP1998 for all surfaces.
- Very easy to implement, widely accepted.



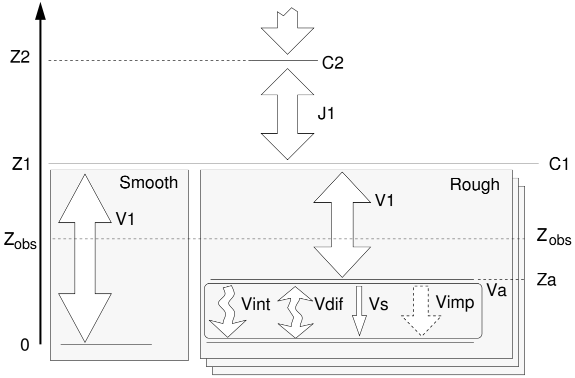
Zhang 2001:

- Surface dependent r_b
- 4 parameters, 15 LUC, 5 seasons
- Rcommended by SP2006

Petroff and Zhang 2010:

- "Exponential" form for aerodynamic layer
- 10 parameters, 15 LUC, 5 seasons
- Finally fits the data

The scheme



- "Exponential" scheme for finite layers
- Separate treatment of smooth and rough surfaces
- Rigorously derived scheme for smooth surfaces
- Small amount of parameters for rough surfaces

“Exponential” scheme

Steady-state particle flux equation below z_1:

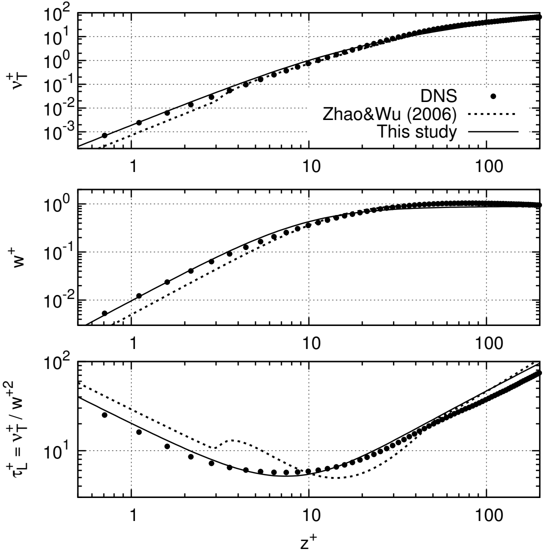
$$J(z) = -K(z)\frac{\partial C}{\partial z} + v(z)C = const$$

if $v(z) = v_s = const$ and $C(0) = 0$:

$$J(z_1) = \frac{C(z_1)}{1 - \exp(-v_s r)} v_s, \quad r = \int_0^{z_1} \frac{dz}{K(z)}$$

r is the resistance of the layer below z_1.
Can be also solved if $v(z) \neq const$ and for $C(0) \neq 0$.
The layer can be split at any point to evaluate corresponding concentration.

Smooth surfaces



- 1D problem
- Universal turbulence profiles (normalized by ν, u_*)
- Well studied
- Can be fit with rational functions
- Of interest: ν_t, w^2, τ_L

Smooth surfaces

Steady-flux equation above smooth surface

$$J = -(D + \nu_p(z))\frac{\partial C(z)}{\partial z} + (V_t(z) - v_s)C(z),$$

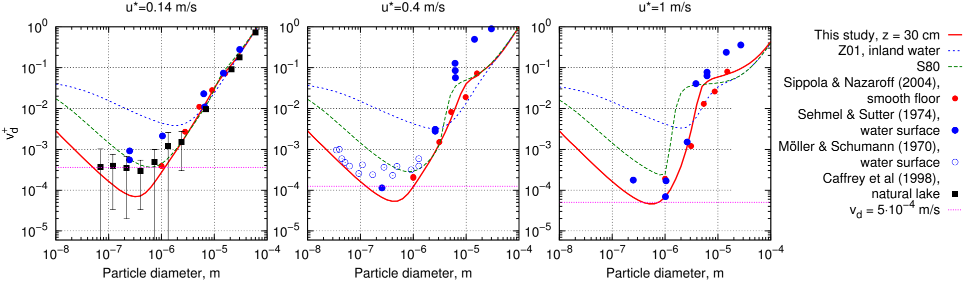
where D and ν_p are Brownian and (vertical) eddy diffusivity of particles, and V_t is turbophoretic velocity:

$$V_t = -\tau_p \frac{d w_p^2}{dz},$$

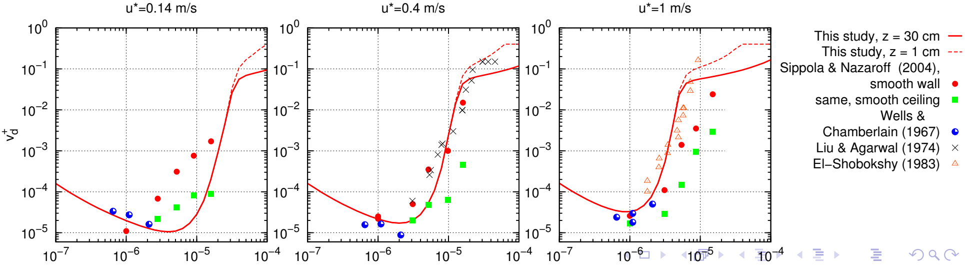
where w_p^2 is the mean square vertical velocity of a particle due to turbulence.
The profiles of turbulence over smooth surfaces are universal and can be approximated with rational functions.

Smooth surfaces: verification

Floor:



Wall:



Rough surfaces

Simple thoughts:

- Air moves in a canopy consisting of *collectors*
- Same collectors absorb momentum and matter
- Momentum flux is (more or less) well studied
- Ratio of corresponding cross-sections gives ratio of deposition velocities

Flow-collector interaction:

- $\mathrm{Re}_c = U d_c / \nu$

Particle-collector interaction:

- Diffusion $\mathrm{Sc} = \nu / D$
- Interception d_p / d_c
- Impaction $\mathrm{St} = \frac{2\tau_p U_{top}}{d_c}$

Rough surfaces (starting points)

- Correlations for deposition on rough surfaces (FdlM&F, 1982):

$$\Pi = \frac{d_p}{d_c}\mathrm{Re}_c^{1/2}\mathrm{Sc}^{1/3}$$

$$Y = \frac{d_p(V_d - v_s)}{D}$$

  Parameters: d_p/d_c, $\mathrm{Re}_c = Ud_c/\nu$, $\mathrm{Sc} = \nu/D$. $Y \sim \Pi$ in the diffusion range (small Π) and $Y \sim \Pi^3$ in the interception range (large Π).

- Single-element efficiency for spheres and cylinders (P&F, 1984):

$$\frac{d_p}{d_c}\mathrm{Re}_c\mathrm{Sc}\cdot\eta = \frac{d_p U}{D}\eta = A\Pi + B\Pi^3,$$

  $A \simeq 2$ and $B \simeq 1$ slightly depend on the collector shape.

- If u_* and z_0 are used as velocity and size, the correlation holds with different coefficients for each surface (Schack, 1985).

Rough surfaces (continued)

- Relevant velocity scale $U_{top} \simeq 3u_*$.
- Collection scale

$$a = \frac{u_*}{U_{top}} d_c$$

- Ratio u_*/U_top does not appear in

$$\Pi = \frac{d_p}{a} \mathrm{Re}_*^{1/2} \mathrm{Sc}^{1/3}$$

- Reynolds number

$$\mathrm{Re}_* = \frac{u_* a}{\nu}$$

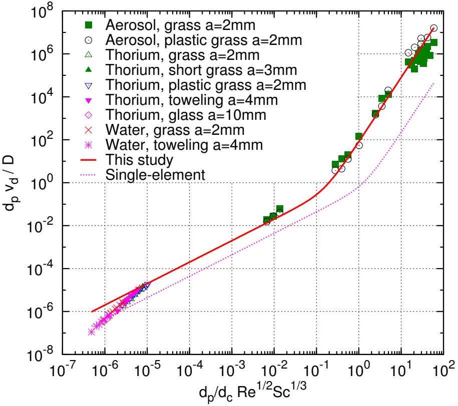
- Once fitted for the dataset of Chamberlain (grass in wind tunnel, $d_c = 5$ mm), the correlation

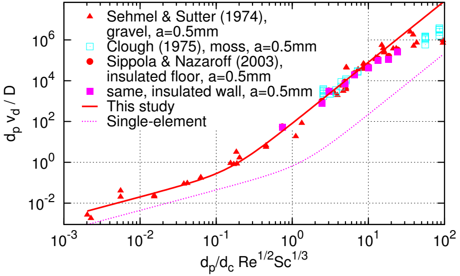
$$Y = 2\Pi + 80\Pi^3$$

fits other datasets with a single fitting parameter a.

Rough surfaces (continued)

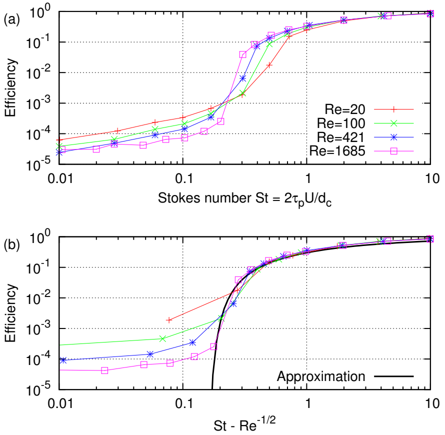
Π-Y correlation. "Learning" and "Control" datasets.





- "Learning" – given a, adjusted coefficients
- "Control" – fixed coefficients, adjusted a

Impaction



Stokes number can be expressed through the same scale:

$$\mathrm{St} = \frac{2\tau_p U_{top}}{d_c} = \frac{2\tau_p u_*}{a}$$

Effective stokes number (accounting for viscous layer):

$$\mathrm{St}_e = \mathrm{St} - \mathrm{Re}_c^{-\frac{1}{2}} = \mathrm{St} - \frac{u_*}{U_{top}}\mathrm{Re}_*^{-\frac{1}{2}},$$

The efficiency of impaction is approximated:

$$\eta_{imp}(\mathrm{St}_e) = \begin{cases} \exp\left\{\frac{-0.1}{\mathrm{St}_e - 0.15} - \frac{1}{\sqrt{\mathrm{St}_e - 0.15}}\right\} & \text{if } \mathrm{St}_e > 0.15, \\ 0 & \text{if } \mathrm{St}_e \le 0.15. \end{cases}$$

Rough surfaces summary

Deposition velocity within in-canopy layer:

$$V_d(z_0) = v_{dif} + v_{int} + v_{imp} + v_s,$$

$$v_{dif} = u_* \cdot 2\mathrm{Re}_*^{-1/2}\mathrm{Sc}^{-2/3},$$

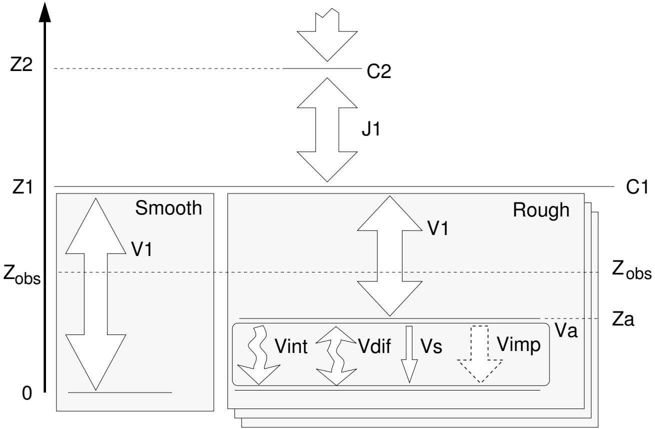
$$v_{int} = u_* \cdot 80 \left(\frac{d_p}{a}\right)^2 \mathrm{Re}_*^{1/2},$$

$$v_{imp} = u_* \frac{2u_*}{U_{top}} \cdot \eta_{imp}\left(\mathrm{St}_e\right).$$

Aerodynamic layer is accounted with exponential scheme:

$$\frac{1}{V_d(z_1)} = \frac{1}{V_d(z_0)} \exp(-v_s r_a) + \frac{1}{v_s}\left(1 - \exp(-v_s r_a)\right).$$

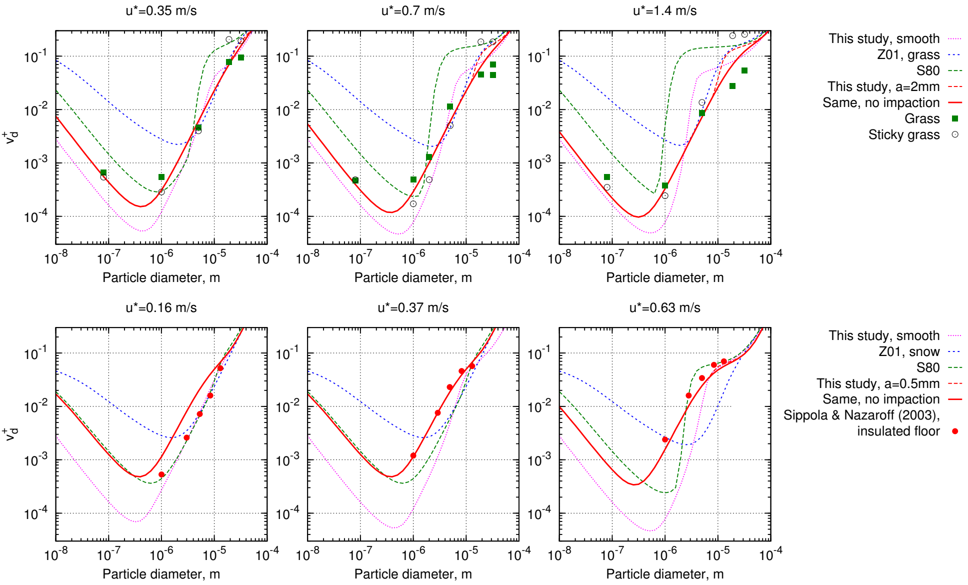
Overall scheme



Smooth or rough is decided from roughness Reynolds number.
Transition occurs:

$$2 < u_* z_0 / \nu < 4$$

Illustration: “grass” and “snow”



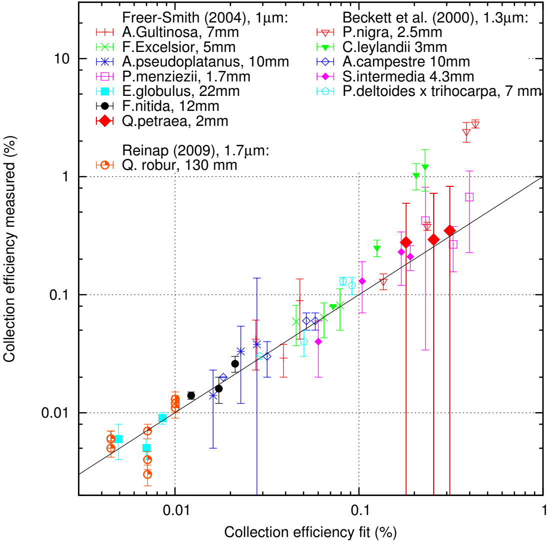
Account for the thermophoresis

- Thermophoresis: particles move to cooler regions

$$v_{TF} = \alpha(\mathrm{Kn}) \cdot \nu \frac{dT/dz}{T} = \alpha(\mathrm{Kn}) \cdot \mathrm{Pr} \frac{F_T}{T}$$

- The order of magnitude: 1 mm/s per kW/m2.
- Is important in the laminar layer for sub-micro range.
- Easy to estimate when TF enhances deposition (heat flux towards the surface) and/or when the surface is homogeneous
- Can block deposition to water surfaces for sub-micro particles

Collector size from WT: trees/branches



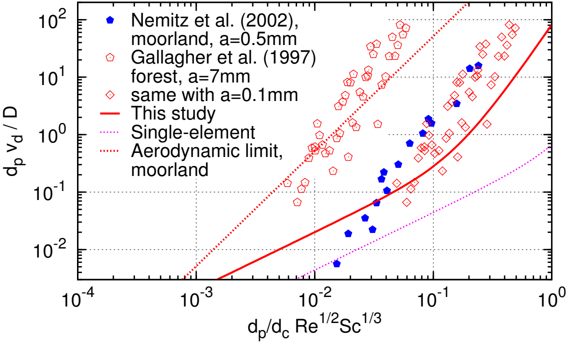
Courtesy of Walter Obermayer

Quercus Robur & Quercus petraea

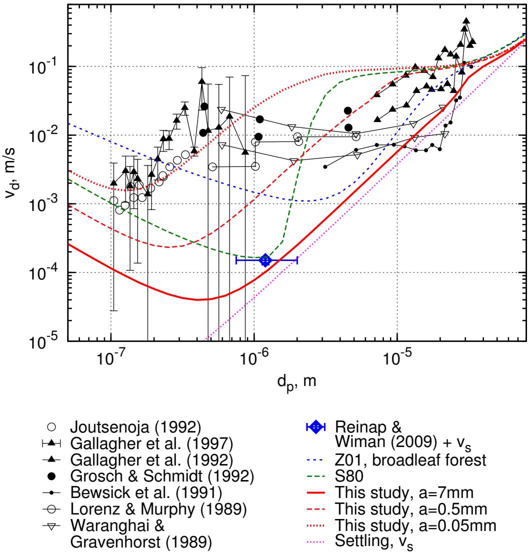
Problems:

- Few studies
- Wide and uncertain particle size spectra
- Experiments are done by botanists/ecologists. . .

Outdoor experiments



High vegetation



Probable causes of discrepancies:

- Electricity?
  - Boltzmann charging: no sharp size dependence
  - Dipole charging: 10 orders of magnitude weaker
- Wrong measured size?
- Complex particle shapes?
- Humidity?
- Something else?

Conclusions

- The new scheme is developed
- No fitting parameters for smooth-surfaces
- Universal empirical relationship and two scales for rough surfaces (z_0 and a)
- Does not fit outdoor experiments, esp. for high vegetation (as all other mechanistic models)
- The collection scales for natural surfaces are needed...
- Implemented into SILAM model

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