Effect of atmospheric electric field on the deposition of air pollutants and radioactive substances on plants

HANNES TAMMET

University of Tartu, Institute of Environmental Physics
Hannes.Tammet@ut.ee

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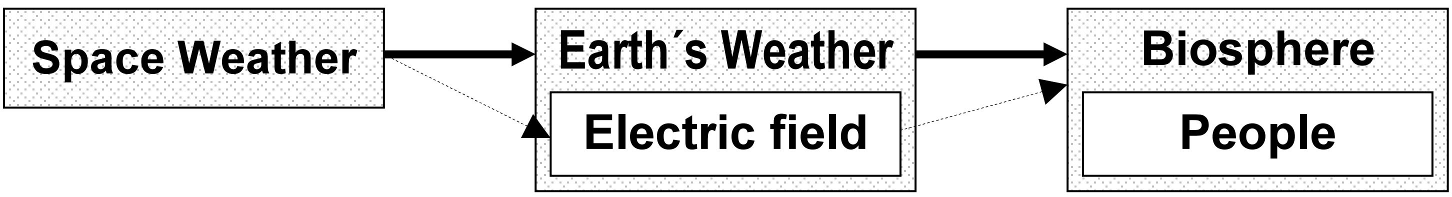


Direct biological effect of atmospheric electricity

- Story of Tchijevsky
- Immediate effect of air ions
- Immediate effect of electric field

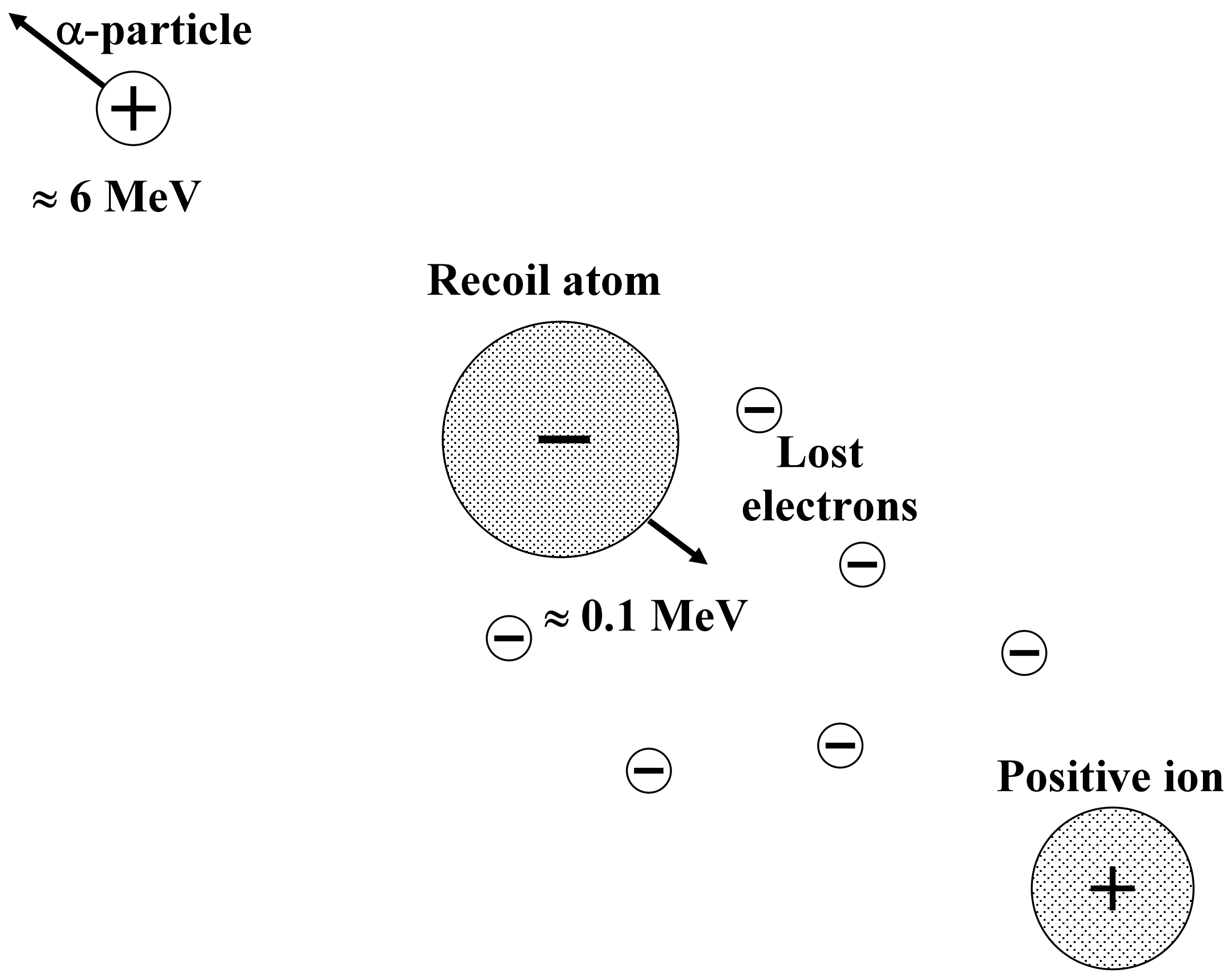
Deposition of radon daughters

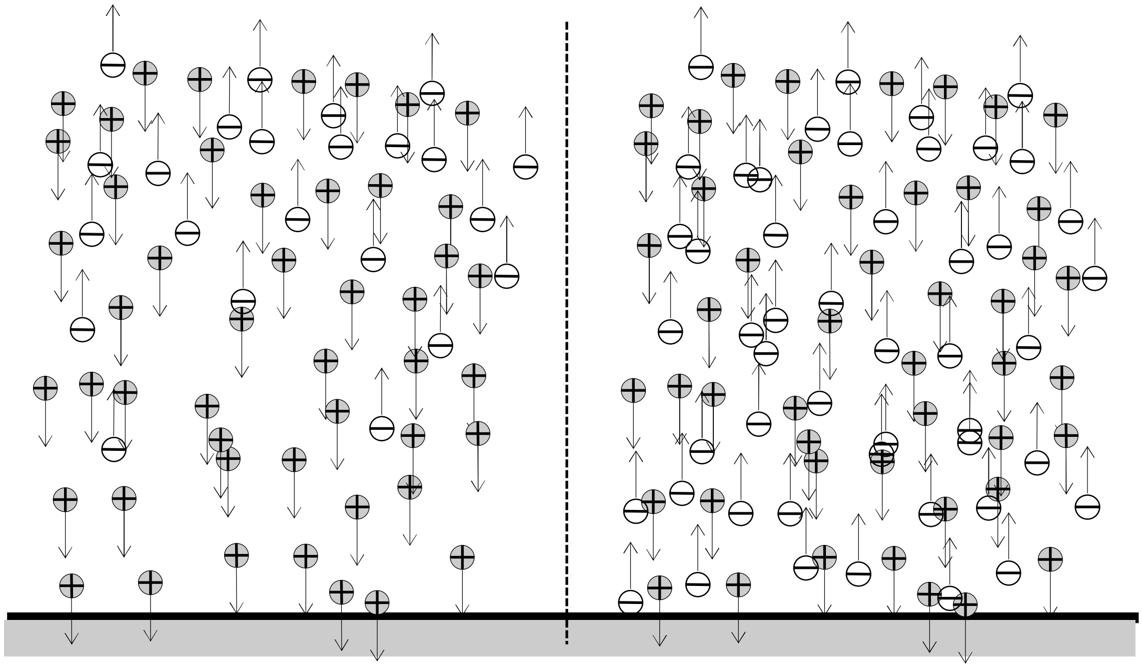
- The physical mechanism
- Wilkening effect
- Willett effect
- Henshaw effect
- Theoretical estimates
- Measurements in Estonia

Deposition of airborne particles

- The physical mechanism
- Theoretical estimates
- Examples

Conclusions


α-particle
≈ 6 MeV
Recoil atom
Lost electrons
≈ 0.1 MeV
Positive ion



Theoretical estimates of deposition of radon daughters

The deposition velocity is the ratio of the deposition flux to the surface area. Two mechanisms, the Brownian diffusion and electric field are responsible for deposition of radioactive ions on plant leaves and needles. A cylindrical wire is the simplest geometrical model to compare the deposition mechanisms on these natural structures.

Estimate of the diffusion deposition

Symbols:

R, $d = 2R$ – radius and diameter of the wire, m

v - air flow velocity, m/s

λ – heat conductivity, W/(m·K)

$D = kTB$ – coefficient of diffusion, m^2/s

μ – cinematic viscosity, m^2/s

a – temperature conductivity, $a = \lambda/c_p\rho$

h – coefficient of heat transfer, W/(m^2·K)

u_D – velocity of diffusion deposition, m/s

$\mathrm{Re} = \dfrac{2Rv}{\mu}$ – Reynolds number

***Model*:**

Nondimensional heat transfer equations are translated into the diffusion deposition equations replacing :

The Nusselt number with the Sherwood number:

$$\mathrm{Nu} = \frac{hd}{\lambda} \qquad \mathrm{Sh} = \frac{u_D d}{D},$$

The Prandtl number with the Schmidt number:

$$\mathrm{Pr} = \frac{\mu}{a} \qquad \mathrm{Sc} = \frac{\mu}{D}.$$

If the condition Re·Pr > 0.2 is satisfied (and it is well satisfied as a rule), the Churchill-Bernstein equation of heat transfer offers a good approximation:

$$\mathrm{Nu} = \left(0.3 + \frac{0.62\,\mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3}}{\left(1 + (0.4/\mathrm{Pr})^{2/3}\right)^{1/4}}\right)\left(1 + \left(\frac{\mathrm{Re}}{282000}\right)^{5/8}\right)^{4/5}.$$

When translated into the terms of diffusion it gives the Sherwood number and the velocity of diffusion deposition:

$$\boxed{u_D = \frac{D}{d}\mathrm{Sh} = \frac{kTB}{2R}\left(0.3 + \frac{0.62\,\mathrm{Re}^{1/2}\,\mathrm{Sc}^{1/3}}{\left(1+\left(0.4/\mathrm{Sc}\right)^{2/3}\right)^{1/4}}\right)\left(1+\left(\frac{\mathrm{Re}}{282000}\right)^{5/8}\right)^{4/5}}$$

Example:

Let: $d = 1$ mm, $u = 5$ m/s, $D = 0.03$ cm^2/s, and standard conditions.

Estimates: Re = 380, Sc = 4.4, Sh = 19.5, $\boxed{u_D \approx 6\ \text{cm/s}}$.

Experimental: 3 cm/s (grass) and 16 cm/s (wheat) (Porstendörfer, 1994).

Estimate of the electrostatic deposition of ions

Symbols:

u_E – velocity of electrostatic deposition, m/s
Z – electric mobility, m^2/(V·s)
E – electric field on wire surface, V/m
E_o – undisturbed atmospheric electric field
k – Boltzmann constant 1.38×10^{-23} J/K
T – temperature, K
e – ion charge 1.6×10^{-19} C
H – distance of the wire from grounded plain, m

Model:

$$u_E = ZE, \qquad Z = \frac{eD}{kT}, \quad E = \frac{2H}{d\ln(4H/d)}E_o,$$

(The field on the surface of a short needle is enhanced when compared with the estimate above)

$$u_E = \frac{eD}{kT}\frac{2H}{d\ln(4H/d)}E_o$$

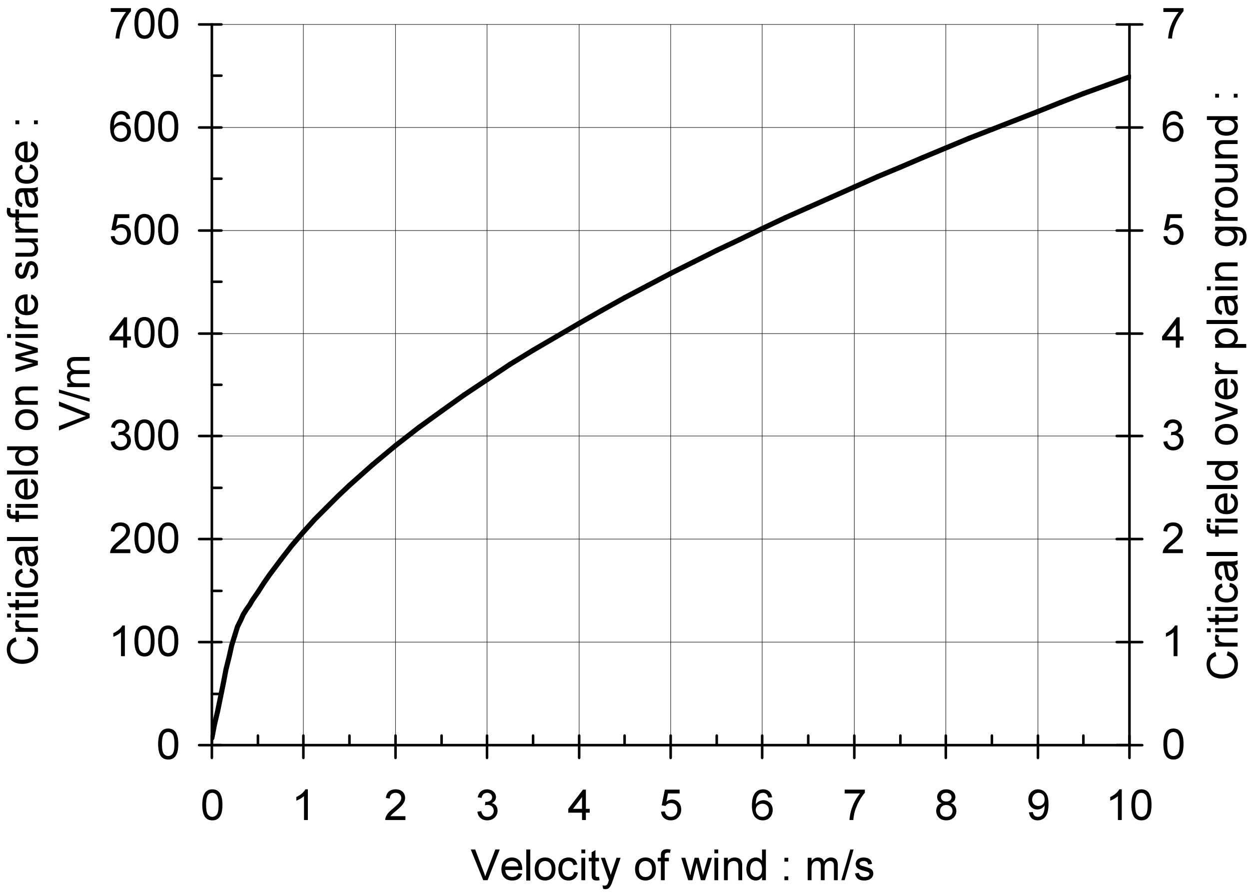
Example:

Let: $H = 1$ m, $d = 1$ mm, $D = 0.03$ cm^2/s, $E_o = 100$ V/m.

Estimates: $E = 24$ kV/m, $Z = 1.27$ cm^2/(V·s), $\boxed{u_E \approx 300\ \text{cm/s}}$.

Comparison of the diffusion and electrostatic deposition

$$\text{If} \quad E = E_{cr} = \frac{kT}{ed}\text{Sh} \quad \text{then} \quad u_E = u_D$$



Critical value of the electrostatic field. When the field exceeds the critical value, the electrostatic deposition exceeds the diffusion deposition.
Conditions assumed in the example:
$d = 1$ mm, $D = 0.03$ cm^2/s, $Z = 1.27$ cm^2 V^{-1}s^{-1}, $H = 36$ cm.

Selected measurements

Sample: needle fragments from …	**Bq/g**
… the top of a 6 m high spruce below of 330 kV AC line	5 – 20
… an internal branch of the same spruce	< 0.5

… the top of a 6 m high spruce away of 330 kV AC line	5
… the top of a 1.5 m high spruce in natural 120 V/m DC field	3
… the top of a 1 m high spruce connected to –1800 V	20 – 200
… the top of a 1 m high spruce connected to +1800 V	0.4

Theoretical estimates of deposition of particles

Electrostatic effect on deposition of neutral particles in natural electric field is negligible. Aerosol particles in atmosphere can be charged due to the thermal fluctuations. The natural distribution of particle charges is well known. When compared with ions, the gravitational and aerodynamic mechanism of deposition should be considered. The deposition velocities characterizing different deposition mechanisms are not exactly additive. A rough approximation is used to estimate the combined mechanical deposition velocity u_M:

$$u_M = \sqrt{u_G^2 + u_A^2 + u_D^2}\,.$$

The gravitational component u_G of deposition velocity over a horizontal plane is $u_G = mgB$, where g is the gravitational acceleration, m and B are respectively the mass and the mechanical mobility of the particle. The diffusion component u_D is estimated according to the same model as above. The aerodynamic component u_A is estimated according to the approximation of experimental data.

Estimate of the aerodynamic deposition

***Symbols*:**

r – radius of the particle, m
R – radius of the wire, m
v – air flow velocity, m/s
m – mass of the particle, kg
B – mechanical mobility of the particle, m/(N·s)
u_A – velocity of aerodynamic deposition, m/s
Stk – Stokes number of the particle $\mathrm{Stk} = \dfrac{vmB}{R}$

Model:

The data presented by *Fuchs* [1964] and *Wessel and Righi* [1988] are fitted with empirical equation:

$$u_A = \left[\left(\frac{\mathrm{Stk}}{0.6 + \mathrm{Stk}}\right)^2 + \frac{r}{R}\right]\frac{v}{\pi}.$$

Estimate of the electrostatic deposition of aerosol particles

Additional symbols:

ie – particle charge, e = 1.6×10^{-19} C

p_i – probability to carry the charge *ie*

Model:

The probabilities p_i are calculated according to the approximation [*Tammet*, 1991] improved considering the data by *Reischl et al.* [1996]

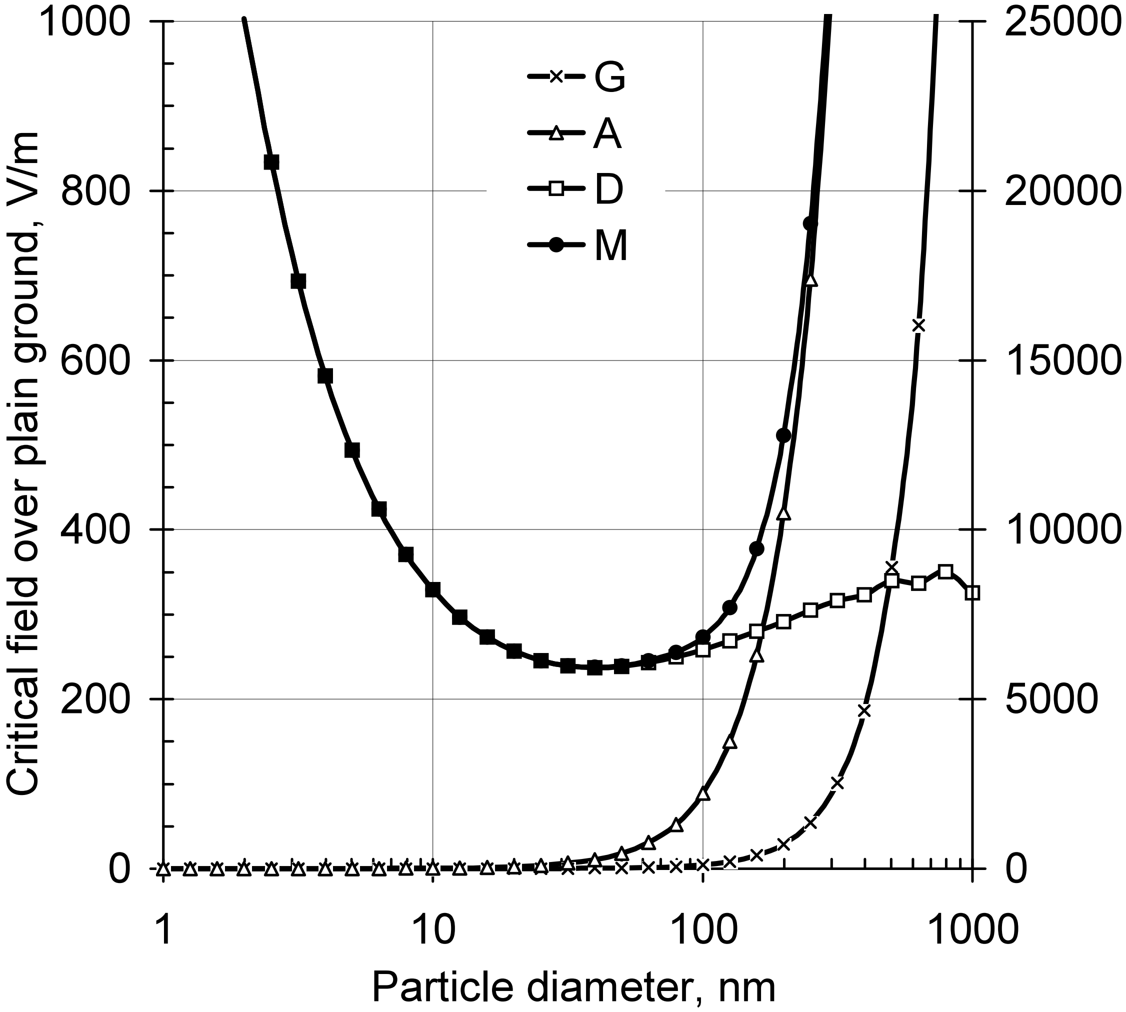
$$u_E = ZE, \qquad Z = \frac{ieD}{kT}, \qquad E = \frac{2H}{d\ln(4H/d)}E_o,$$

$$u_{Ei} = \frac{ieD}{kT}\frac{2H}{d\ln(4H/d)}E_o,$$

$$u_E = \sum_{i=1}^{\infty} p_i u_{Ei}$$

Examples

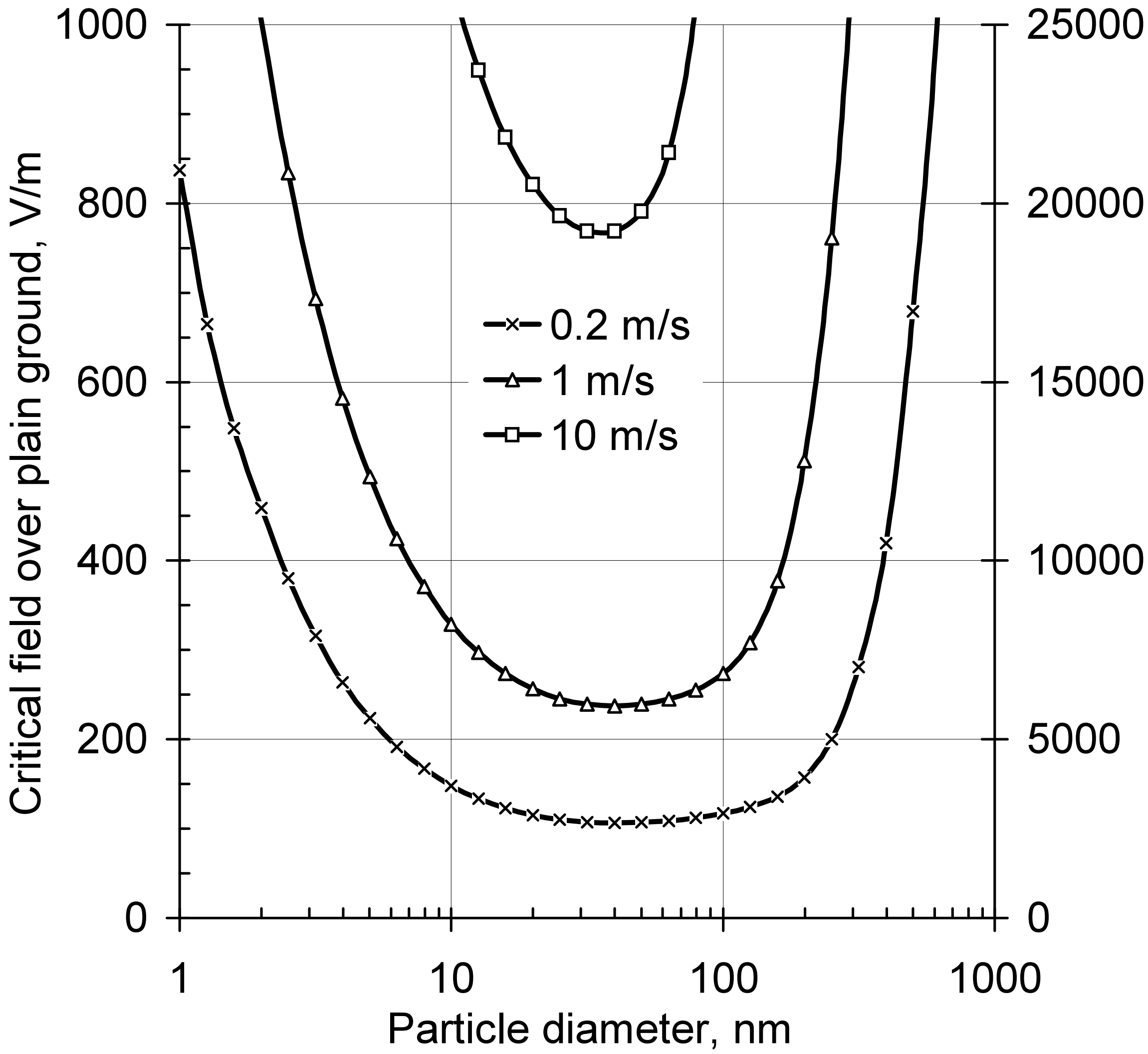
The critical field strength is defined as that which makes the velocity of electric deposition equal to the velocity of some other specific deposition. Different critical field strengths can be related to the gravitational, Brownian, aerodynamic, and joint mechanical deposition.



Critical electric field against different mechanisms of deposition:

G – gravitational,
A – aerodynamic,
D – diffusional,
M – joint mechanical.

Assumptions: Standard atmospheric conditions. Cylinder diameter 1 mm, height 7 cm, particle density 2 g/cm^3, $\lambda_+/\lambda_- = 2$. Wind velocity 1 m/s.



Critical electric field against joint mechanical deposition depending on the wind velocity.

Assumptions: Standard atmospheric conditions. Cylinder diameter 1 mm, height 7 cm, particle density 2 g/cm^3, $\lambda_+/\lambda_- = 2$. Wind velocity 1 m/s.

Conclusions

Atmospheric electric field is considered as a mediator of the effect of Space Weather on the Earth's ground level processes.

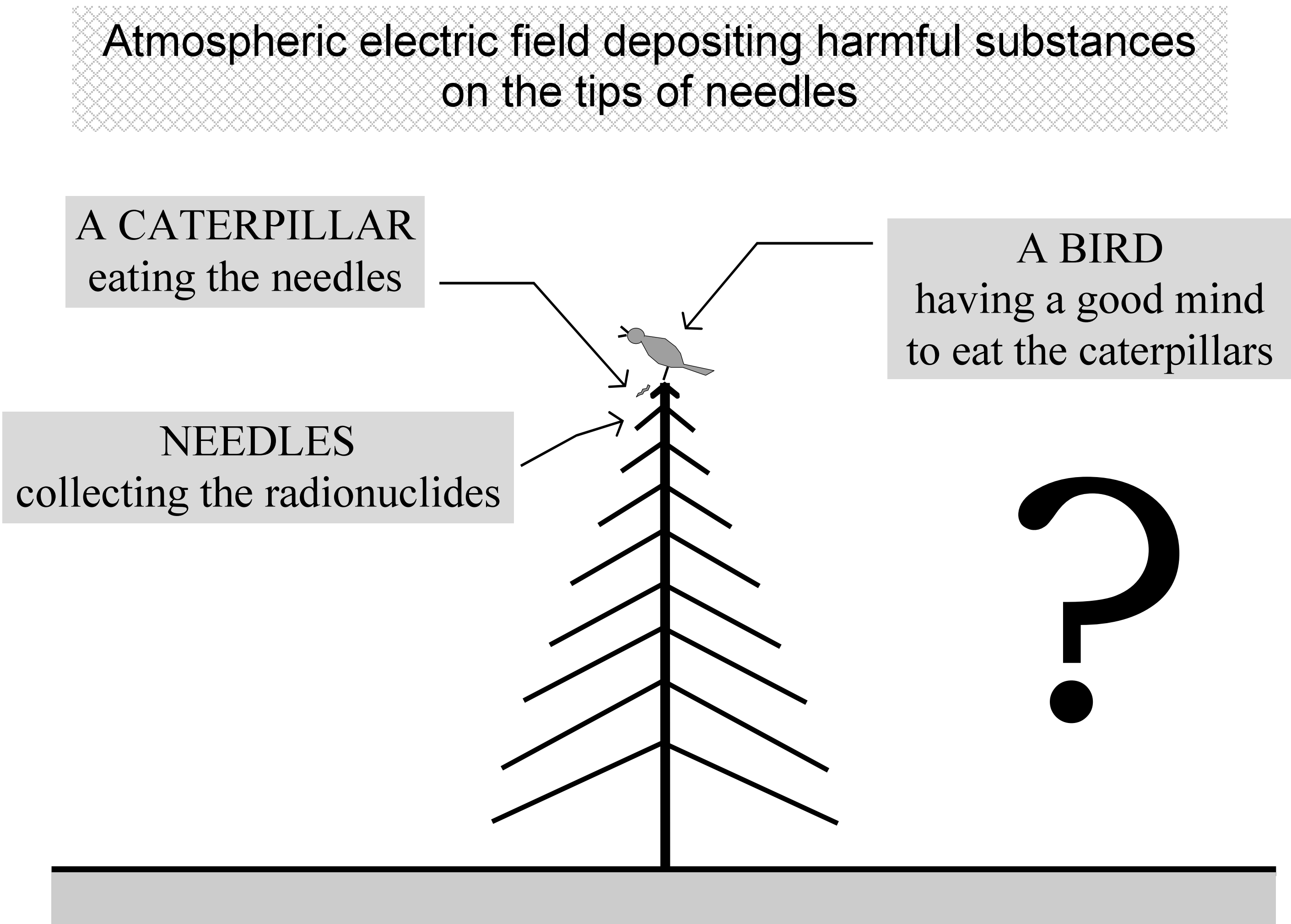
Atmospheric electric field is an important factor affecting the deposition of radon daughters.

Atmospheric electric field is a considerable factor affecting the deposition of particulate pollution on the tips of plants.

The effect of electric field of AC high voltage power lines does not essentially exceed the effect of natural fair weather electric field.

Electrostatic mechanism makes the deposition of pollutants on plants strongly non-uniform.

The biological consequences of the effect are ill known. Hypothetically, the effect of the atmospheric electric field could be considered when discussing enhanced pollution damages to the top branches of conifer trees.



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