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An exploration of dry deposition research by FOI - with emphases on winter conditions

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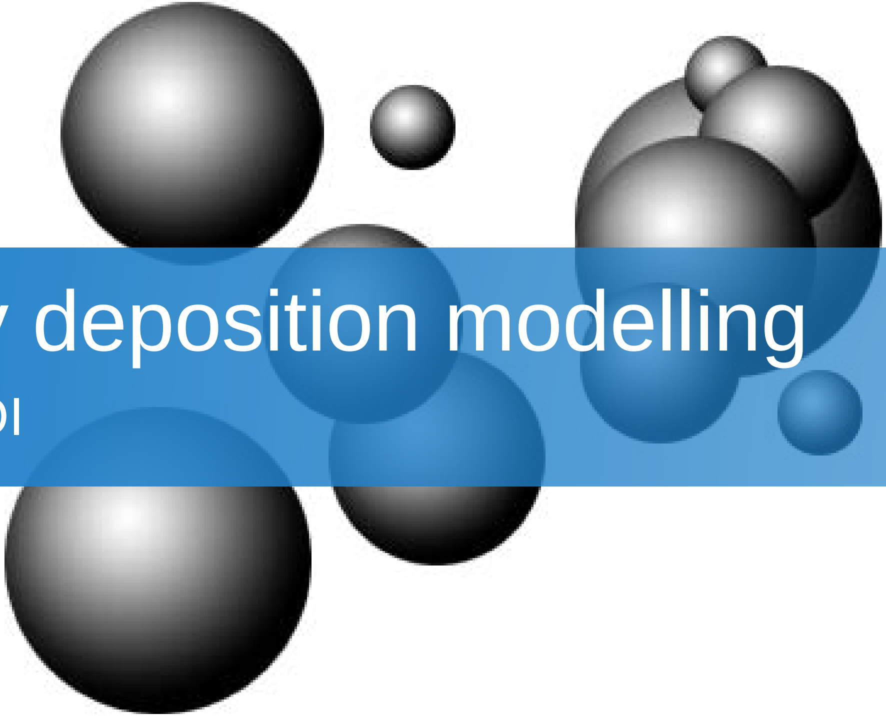


Dry deposition modelling

at FOI

Dry deposition modelling

General model used by FOI

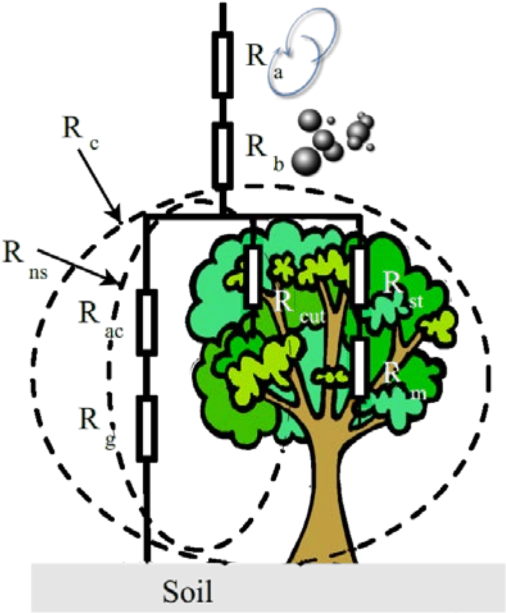
Traditional resistance model

- Aerodynamic, R_a
- Sub-layer resistance, R_b
- Surface/canopy resistance, R_c
- Large set of partial resistances and parameters

Gas and particles treated differently

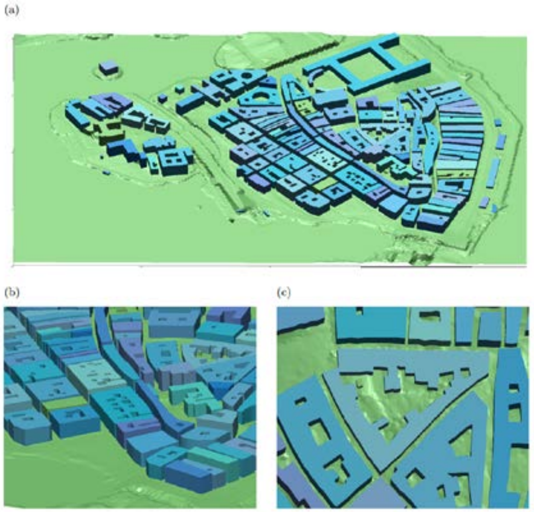
Particles have

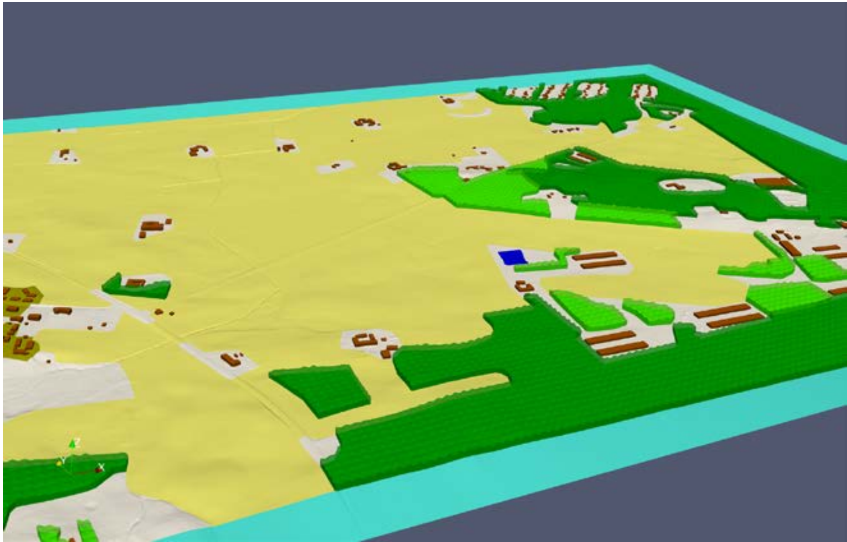
- Settling velocity
- R_c=0
- No influence of leaf bioactivity



Current model development
Terrain

- Topography
- Roughness
- Vegetation/ground types
  - Deposition





Ground types

- Land Use Classes (LUC)
  - FOI uses 26 classes
  - IGBP uses 17 classes
  - Zhang uses 15 classes
  - Transformation required between sets of LUC

  LUC provides estimates of
  - LAI
  - Roughness
  - Resistances
- Leaf Area Index (LAI)
  - Area leafs (one-sided) relative to ground area
  - Seasonal dependent

IGBP LUC

Evergreen Needleleaf Forest	Grasslands
Evergreen Broadleaf Forest	Permanent Wetlands
Deciduous Needleleaf Forest	Croplands
Deciduous Broadleaf Forest	Urban and Built-Up
Mixed Forest	Cropland/Natural Vegetation Mosaic
Closed Shrublands	Snow and Ice
Open Shrublands	Barren or Sparsely Vegetated
Woody Savannas	Water Bodies
Savannas	

Surface resistance, R_c

Substances

SO_2 and O_3 used as scaling factors [1]

- α– parameter : Aqueous solubility (SO_2)
- β– parameter : Aqueous oxidizing capacity (O_3)
- They operate in parallel

1. Zhang, L., et al., *Modelling gaseous dry deposition in AURAMS: a unified regional air-quality modelling system.* Atmospheric Environment, 2002. **36**(3): p. 537-560.

Implementation

The method provides continuous flow, i.e. peeling of model particles.

Concentration is unknown for independent model particles. Wilson´s method provides a solution for this by introducing a stochastic process [1].

$$\frac{1-R}{1+R} = \sqrt{\frac{\pi}{2}}\frac{v_d}{\sigma_w}$$

std for vertical vel.

reflection prob.

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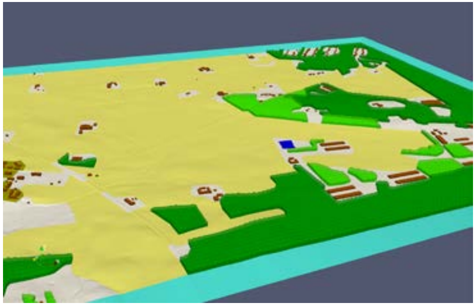
1. Wilson, J., F. Ferrandino, and G. Thurtell, *A relationship between deposition velocity and trajectory reflection probability for use in stochastic Lagrangian dispersion models.* Agricultural and forest meteorology, 1989. **47**(2-4): p. 139-154.

UPELLO

FOI's new particle model



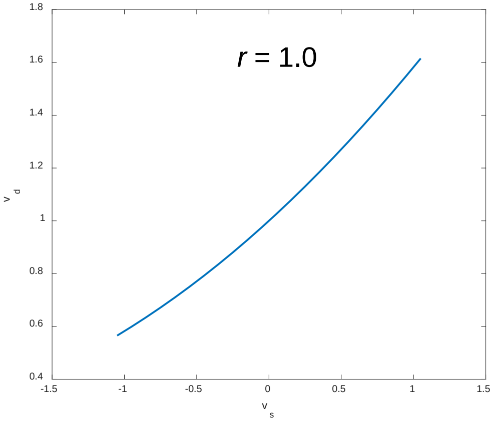
- Uses Venkatram [1] for deposition
  - Mass consistent
  - Allows for deposition in all directions

$$v_d = \frac{v_s}{1-e^{-r v_s}}$$

r is the total resistance

$$v_s << \frac{1}{r}, \quad v_d = \frac{1}{r}$$

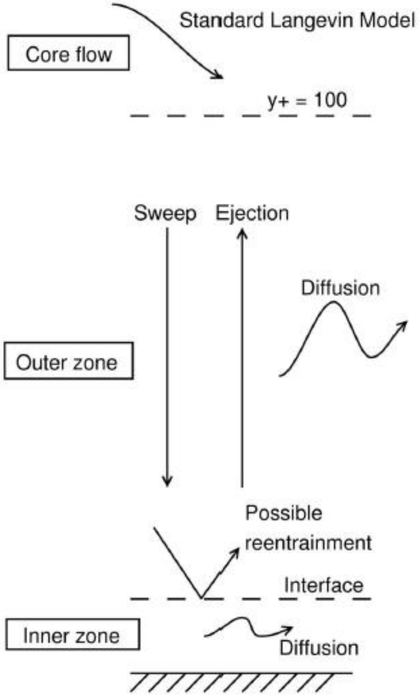
$$v_s >> \frac{1}{r}, \quad v_d = v_s$$



1. Venkatram, A. and J. Pleim, *The electrical analogy does not apply to modeling dry deposition of particles.* Atmospheric Environment, 1999. **33**(18): p. 3075-3076.

Refined model

- Resolving the domain close to the surface
- Idea is to make use of CFD-information better
- Numerical demanding



Henry, C., J. P. Minier and G. Lefevre, 2012: Towards a description of particulate fouling: From single particle deposition to clogging. Adv Colloid Interfac **185**, 34-76.
Weil, J. C., P. P. Sullivan and C. H. Moeng, 2004: The use of large-eddy simulations in Lagrangian particle dispersion models. J Atmos Sci **61**, 2877-2887.

Some considerations

- In principal, the resistance model, LUC and substance parameters α & β provide information and methods to calculate v_d.
- Problem with different sets of LUC
  - Incorporate NWS and satellite imagery?
- How accurate are the α– & β– parameters?
- How to use deposition modelling within a forest?
- Does the model handle the atmospheric stability accurately?
- There is little published data on CWA
- Stochastic or peeling deposition?
- How to incorporate saturation effects?

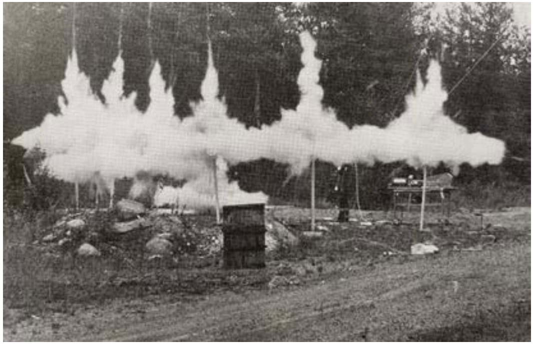
Deposition work

at FOI

FOI trials

- Flow exchange and adsorption in buildings of sarin, NH_3 and Cl_2 and simulants for VX experimentally [1]
  - Effects of different wall covers and carpets
  - Unpainted concrete showed high adsorption for nerve agents

- Primary Contamination – A Field trial [2]
  - Low contamination of person compared to ground



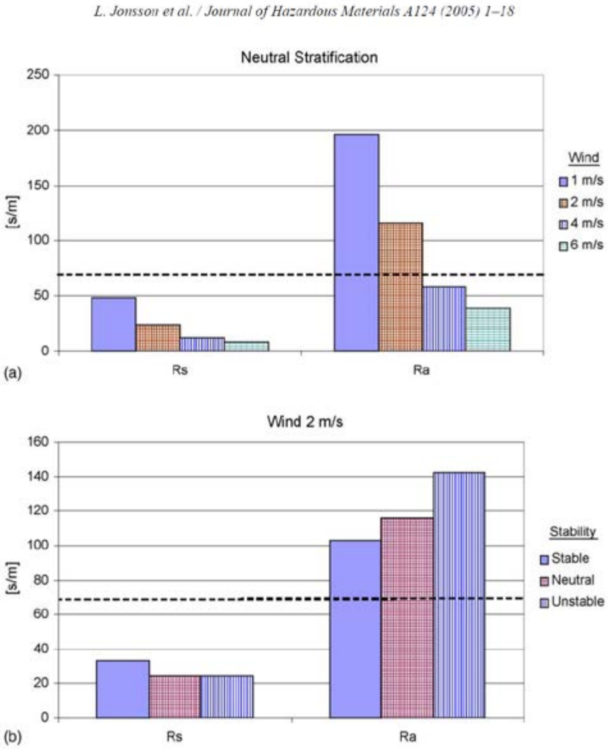
1. Karlsson, E. and T. Berglund, *Inläckning, adsorption och återgivning av giftig gas i vanliga byggnader och skyddsrum*. 1994, Swedish Defence Research Agency.
2. Koch, B., et al., *Primär Kontaminering - Ett Fältförsök*. 1988: Swedish Defence Research Agency.

Meteorological impact on dry deposition of gases

Investigation by models

- Evaluation of the influence of the weather on the dry deposition [1]

- Particulate dry deposition in urban settings [2]
  - u* strongly influence v_d



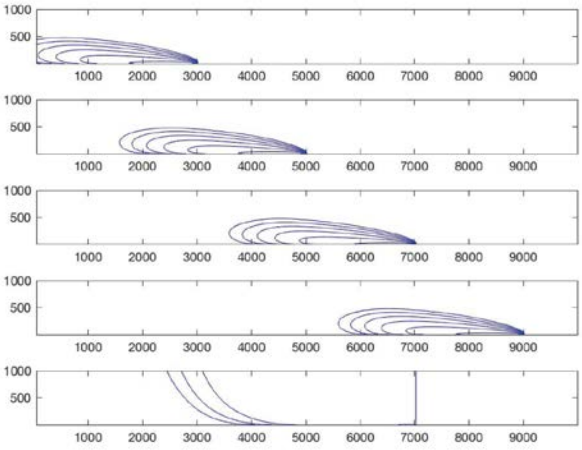
1. Jonsson, L., E. Karlsson, and L. Thaning, *Toxic gas clouds: Effects and implications of dry deposition on concentration.* Journal of hazardous materials, 2005. **124**(1-3): p. 1-18.
2. Jonsson, L., E. Karlsson, and P. Jönsson, *Aspects of particulate dry deposition in the urban environment.* Journal of Hazardous Materials, 2008. **153**(1–2): p. 229-243.

Inverse modelling

Including deposition

Deposition poses a hard problem

Methodology development [1]



1. Persson, L. and J. Burman, *Torr- och våtdeposition i ajdungerade linjära konvektions-diffusionsmodeller*. 2017, Swedish Defence Research Agency.

Winter conditions

Words for snow of different type

In Swedish…

- Blötsnö
- Djupsnö
- Drivsnö
- Fimmeln
- Firnsnö
- Fjöcksnö
- Flister
- Fnyk
- Fåk
- Hårdsnö
- Julkortssnö
- Klabbsnö
- Klibbsnö
- Knarrsnö
- Konstsnö
- Kornsnö
- Kramsnö
- Modd
- Natursnö
- Nysnö
- Pudersnö

- Pulversnö
- Rensartäcke
- Skare
- Skarsnö
- Sockersnö
- Snörök
- Spårsnö
- Sursnö
- Trindsnö
- Tösnö
- Upplega
- Yrsnö
- Snöblask
- Snödrev
- Snöflinga
- Snöglopp
- Snölega
- Snömodd
- Snöras
- Snöregn
- Snöyra

Snow and ice

Snow is a type of ice, they differ due to different creation processes

pH of 5 - 6

Density 10 - 400 kg/m^3

Snow water equivalent (SWE) or snow to liquid ratio (SLR) is important

Snow content

- Solid ice crystals
- Liquid water
- Air
- Particles
- Pollutants
- Insects
- Deposited substances
- …

Seasons

Winter with snow

- Snow/ice surfaces
- Low LAI
- Low biological activity
- Meteorology
  - Atmospheric stability
- High anthropogenic emissions
- Low natural emissions

Measurements in the literature

Deposition in winter conditions

Substances

- Ozone
- Sulfur dioxide
- NO_x
- Not much on CW

Main findings

Low deposition velocities, v_d
v_d 5-10 times higher to vegetation than snow
v_d for veg. much lower in winter than in summer

Temperature dependency
v_d for snow increases strongly with temperature
There is a 10 nm water layer on snow close to 0°C
Wet snow acts as water
Water content dependency

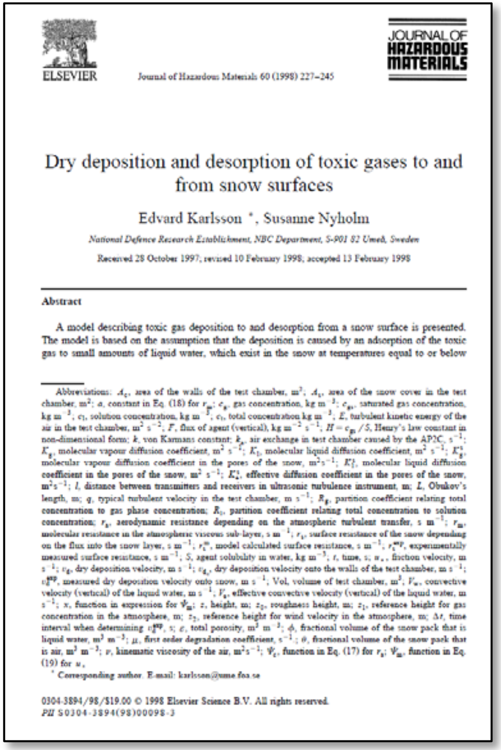
Snow “age” dependency
Saturation effects may be present
SO_2 has a v_d to snow of ~ 0.04-0.6 cm/s

Understudied subject, mainly quite old experiments
All reported data is not consistent, i.e. there are uncertainties

A model for gas-snow interaction

M.P. Valdez, R.C. Bales, D.A. Stanley, G.A. Dawson
Gaseous deposition to snow: 1. Experimental study of SO_2 and NO_2 deposition, J. Geophys. Res. 92 (1987) 9779

R.C. Bales, M.P. Valdez, G.A. Dawson
Gaseous deposition to snow: 2. Physical-chemical model for SO_2 deposition, J. Geophys. Res. 92 (1987) 9789



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Journal of Hazardous Materials 60 (1998) 227–245

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Dry deposition and desorption of toxic gases to and from snow surfaces

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Abstract

A model describing toxic gas deposition to and desorption from a snow surface is presented. The model is based on the assumption that the deposition is caused by an adsorption of the toxic gas to small amounts of liquid water, which exist in the snow at temperatures equal to or below

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Abbreviations: A_c, area of the walls of the test chamber, m^2; A_s, area of the snow cover in the test chamber, m^2; a, constant in Eq. (18) for r_m; c_g, gas concentration, kg m^{-3}; c_{gs}, saturated gas concentration, kg m^{-3}; c_l, solution concentration, kg m^{-3}; c_t, total concentration kg m^{-3}; E, turbulent kinetic energy of the air in the test chamber, m^2 s^{-2}; F, flux of agent (vertical), kg m^{-2} s^{-1}; $H = c_{gs}/S$, Henry's law constant in non-dimensional form; k, von Karmans constant; k_e, air exchange in test chamber caused by the AP2C, s^{-1}; K_g, molecular vapour diffusion coefficient, m^2 s^{-1}; K_l, molecular liquid diffusion coefficient, m^2 s^{-1}; K_g^s, molecular vapour diffusion coefficient in the pores of the snow, $m^2 s^{-1}$; K_l^s, molecular liquid diffusion coefficient in the pores of the snow, m^2 s^{-1}; K_e^s, effective diffusion coefficient in the pores of the snow, $m^2 s^{-1}$; l, distance between transmitters and receivers in ultrasonic turbulence instrument, m; L, Obukov's length, m; q, typical turbulent velocity in the test chamber, m s^{-1}; R_g, partition coefficient relating total concentration to gas phase concentration; R_l, partition coefficient relating total concentration to solution concentration; r_a, aerodynamic resistance depending on the atmospheric turbulent transfer, s m^{-1}; r_m, molecular resistance in the atmospheric viscous sub-layer, s m^{-1}; r_s, surface resistance of the snow depending on the flux into the snow layer, s m^{-1}; r_s^m, model calculated surface resistance, s m^{-1}; r_s^{exp}, experimentally measured surface resistance, s m^{-1}; S, agent solubility in water, kg m^{-3}; t, time, s; u_*, friction velocity, m s^{-1}; v_g, dry deposition velocity, m s^{-1}; v_{g_c}, dry deposition velocity onto the walls of the test chamber, m s^{-1}; v_g^{exp}, measured dry deposition velocity onto snow, m s^{-1}; Vol, volume of test chamber, m^3; V_w, convective velocity (vertical) of the liquid water, m s^{-1}; V_e, effective convective velocity (vertical) of the liquid water, m s^{-1}; x, function in expression for Ψ_m; z, height, m; z_0, roughness height, m; z_1, reference height for gas concentration in the atmosphere, m; z_2, reference height for wind velocity in the atmosphere, m; Δt, time interval when determining v_g^{exp}, s; ε, total porosity, m^3 m^{-3}; ϕ, fractional volume of the snow pack that is liquid water, m^3 m^{-3}; μ, first order degradation coefficient, s^{-1}; θ, fractional volume of the snow pack that is air, m^3 m^{-3}; ν, kinematic viscosity of the air, $m^2 s^{-1}$; Ψ_s, function in Eq. (17) for r_a; Ψ_m, function in Eq. (19) for u_*.

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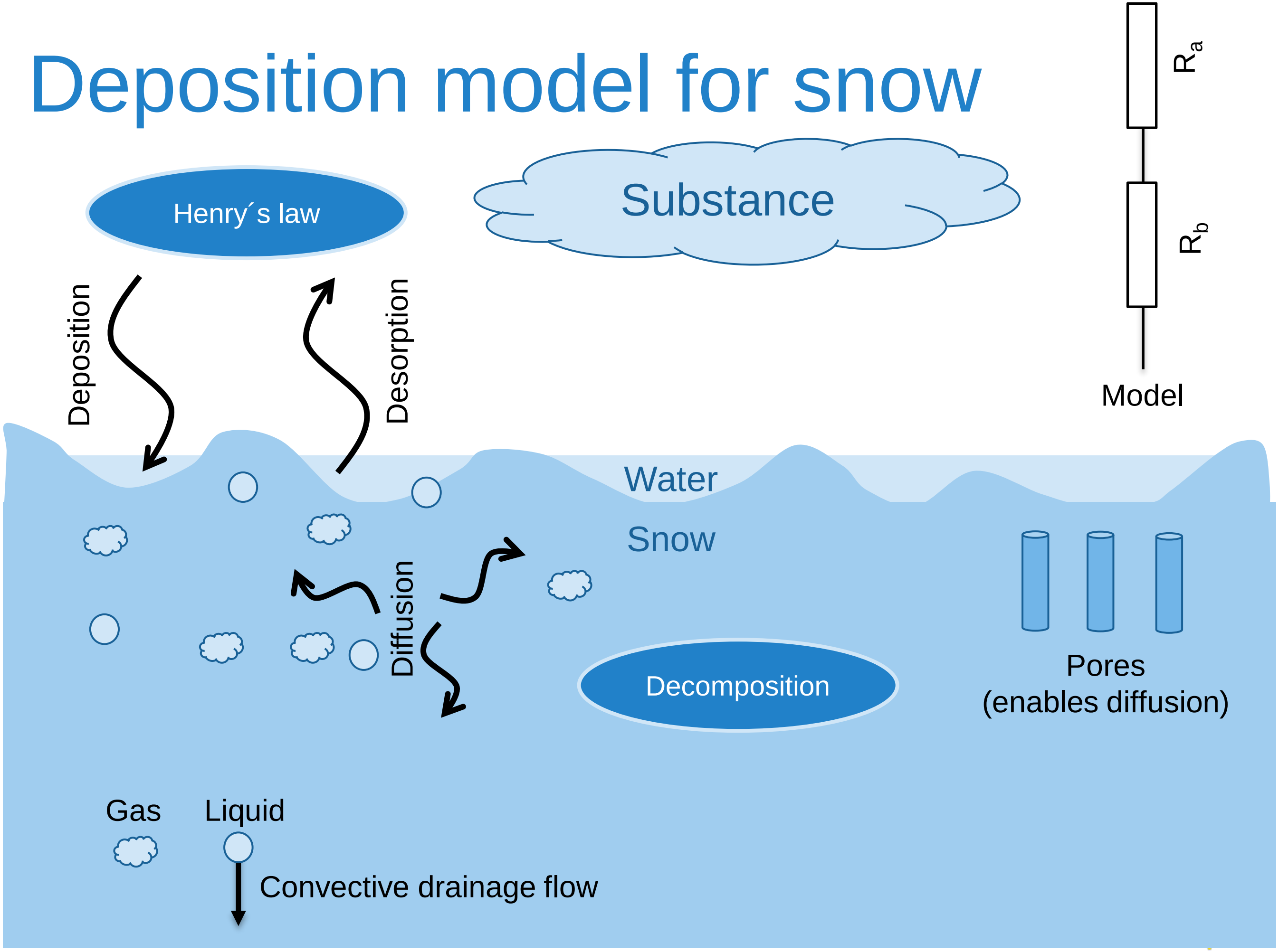
Deposition model for snow



Henry´s law

Substance

R_a

R_b

Model

Deposition

Desorption

Water

Snow

Diffusion

Decomposition

Pores
(enables diffusion)

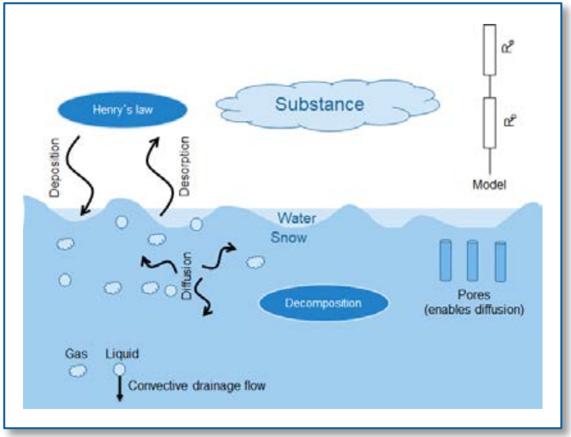
Gas

Liquid

Convective drainage flow

Comparison with experiments on GB

- Saturation is captured by Henry´s law
- Temperature dependence is captured by the amount of water on top of the snow
- Decreased deposition with time
- Decreased deposition with decreasing temperature
- Deposition increase with snow age (density)
- Desorption might overtake deposition
- Desorption decrease with time
- Model overpredicts the surface resistance



Thank You