The effect of terrain modeling on simulated dose rates

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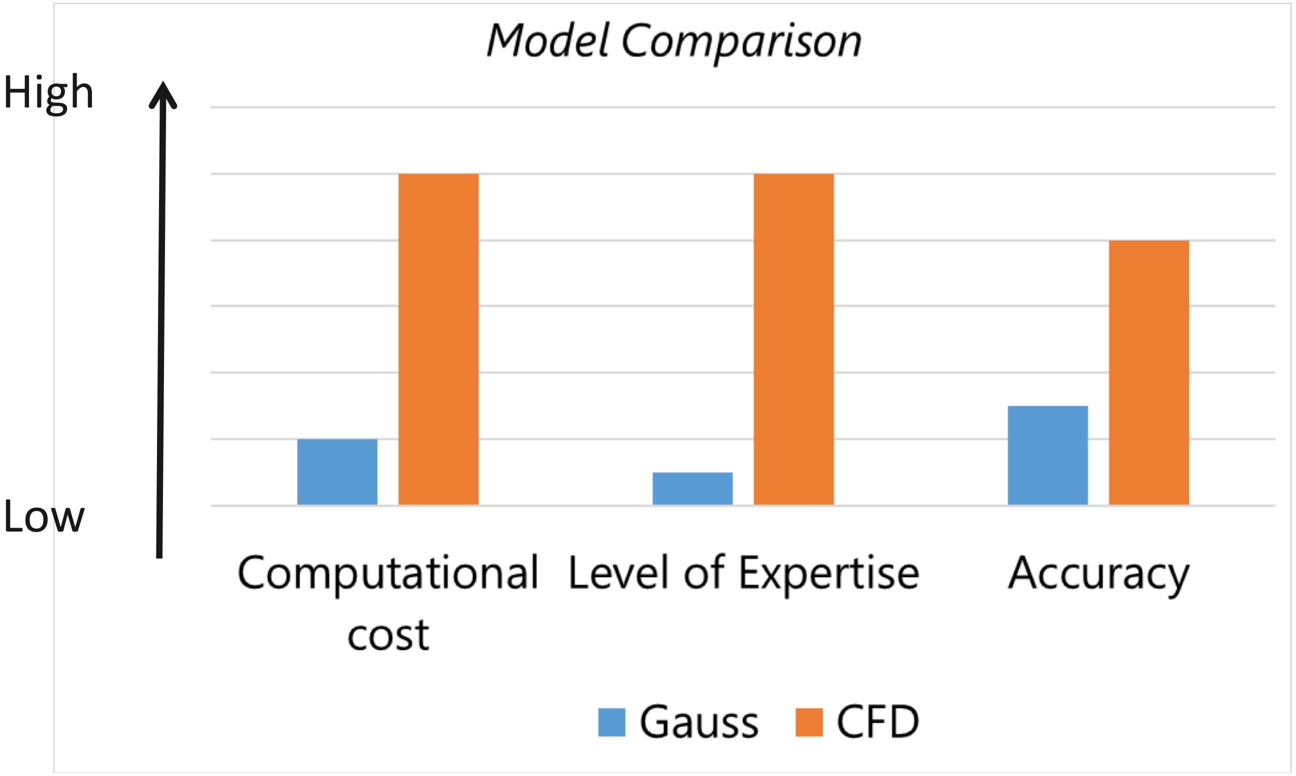
Problem statement

Near-range atmospheric dispersion can be modelled on various ways

- Different treatments of atmospheric conditions and terrain effects



Do dose rate simulations benefit from improved physical descriptions?

Content

Methodology

$$\frac{\partial c}{\partial t} + \boldsymbol{u} \cdot \nabla c = \nabla \cdot (\boldsymbol{K} \nabla c) + Q\delta(\boldsymbol{x} - \boldsymbol{x}_0), \qquad \forall \boldsymbol{x} \in D \subset \mathbb{R}^3 \tag{1}$$

with

c: the concentration field $[Bq/m^3]$

$\boldsymbol{u}$: the wind field $[m/s]$

$\boldsymbol{K}$: the eddy diffusivity $[m^2/s]$

Q: the source strength $[Bq/s]$

$\boldsymbol{x}_0$: the source location $[m]$

D: the simulation domain

Step 1: solve c from equation (1) for the near range around the source

- buildings are omitted
- terrain and atmospheric conditions are incorporated through the choice of $\boldsymbol{u}$ and $\boldsymbol{K}$

Methodology

Different choices of $\boldsymbol{u}$ and $\boldsymbol{K}$ lead to different models

- Assume a neutral atmosphere
- Wind field is assumed to be uniform in the horizontal plane

Model	$\boldsymbol{u}$	$\boldsymbol{K}$	**methodology**
Gaussian model	constant: $u(z) = u_0$	Pasquill-Gifford (PG) Bultynck-Malet (BM) (Tracer experiments)	Analytical solution from (1) (MATLAB)
Particle model	power law: $u(z) \propto z^{0.33}$	Taylor's statistical turbulence theory	Solve SDE with Euler-Maruyama scheme (MATLAB)
Vegetation canopy dispersion model	similarity scaling (>canopy) $\approx$ solve NS eqn[1] (in canopy)	Standard Gradient Hypothesis	Finite volume method (OpenFOAM)

[1] Yi C. 2008. Momentum transfer within canopies. J. Appl. Meteor. Climatol. 47: 262-275.

Methodology

Step 2: calculate the ambient gamma dose rates $\dot{d}_\gamma$ due to the gamma energy released per disintegration E_γ $[MeV]$ w.r.t. detector location $\boldsymbol{x}' \in \mathbb{R}^3$

$$\dot{d}_\gamma = \frac{K_c \mu_{\mathrm{en}} E_\gamma}{4\pi} \int\int\int_D \frac{B\big(\mu\, r(\boldsymbol{x})\big)}{r(\boldsymbol{x})^2} e^{-\mu r(\boldsymbol{x})} C(\boldsymbol{x}) \mathrm{d}\boldsymbol{x}\,, \qquad r(\boldsymbol{x}) = \|\boldsymbol{x} - \boldsymbol{x}'\|_2$$

with

$K_c = 1.6{\times}10^{-3} Gy \cdot kg \cdot MeV^{-1}$ a unit conversion factor
μ_{en}: the absorption coefficient for air $[m^2/kg]$
B: the buildup factor
μ: the linear attenuation coefficient in air $[m^{-1}]$
$\|\cdot\|_2$: the Euclidean norm

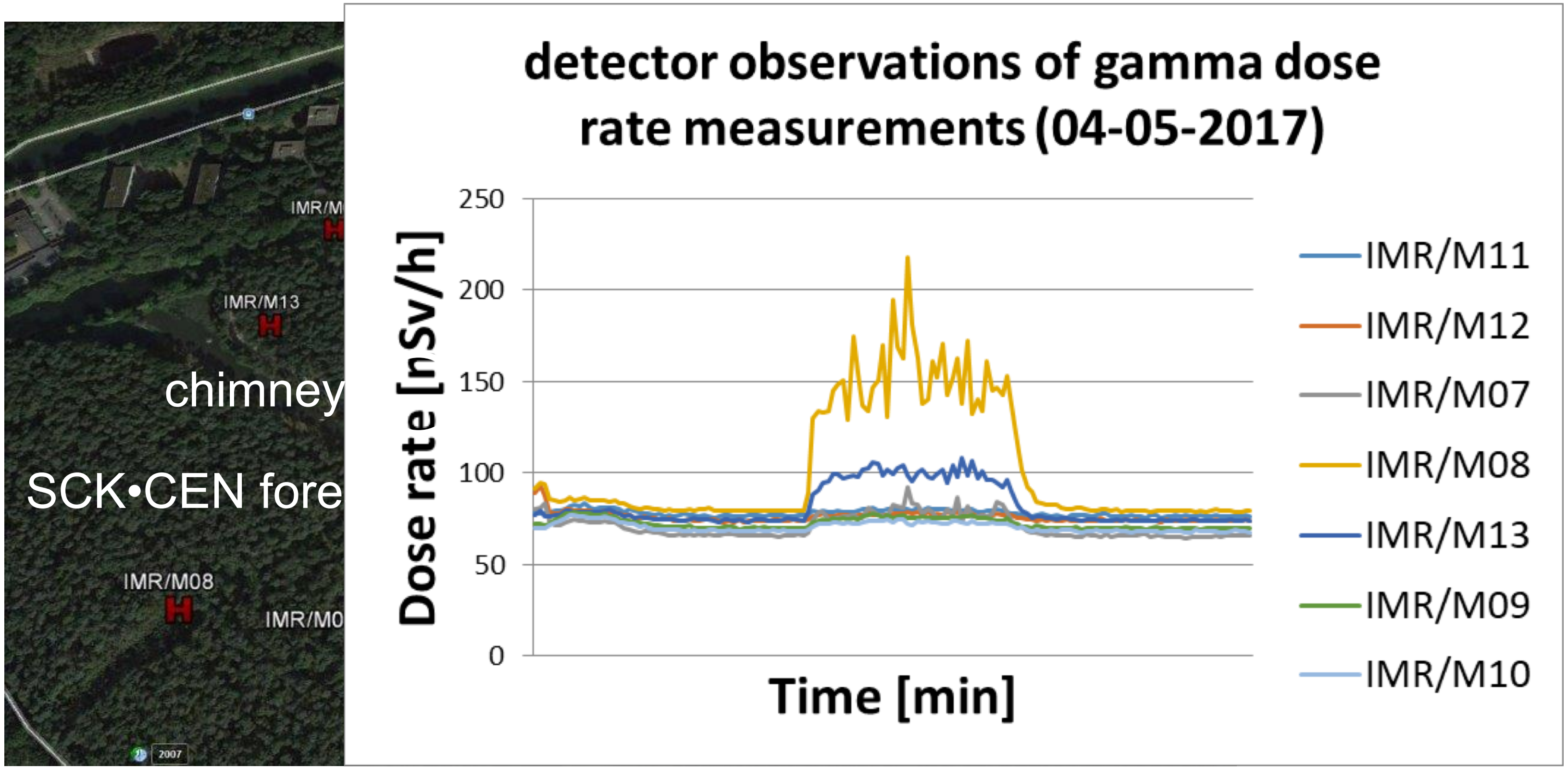
Kenis K, Vervecken L, Camps J. 2013. Gamma dose assessment in near-range atmospheric dispersion simulations. SCK•CEN Reports; No. ER-242. 1:26 p.

Content

- Methodology
- Results
  - Simulation of Ar-41 routine releases
  - Downstream calculations for a 2 km fetch
- Conclusions

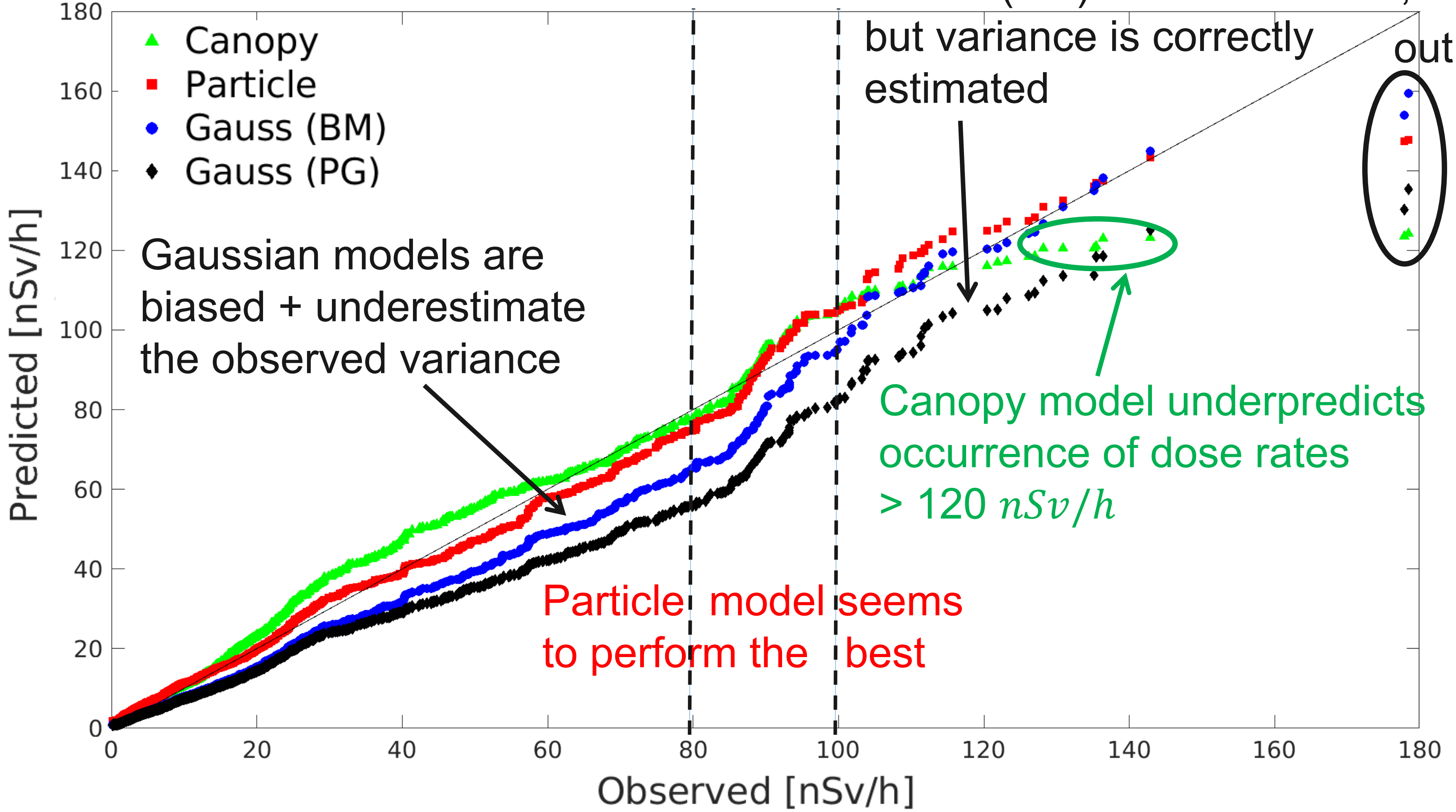
SCK•CEN site
case study

- Dose rate measurements for 7 locations on SCK•CEN site (Mol, Belgium)
  - Ar-41 releases from the BR1 through the chimney (60 m)
- Data was also distributed in context of the NERIS Atmospheric Dispersion Modelling (ADM) experiment (J. Camps, Dublin 2018 workshop)



Simulation of Ar-41 routine releases
Q-Q plot

Quantile = cut points that divide the range of a probability distribution into intervals with equal probabilities



Gauss (PG) model is biased, but variance is correctly estimated

outliers ?

Gaussian models are biased + underestimate the observed variance

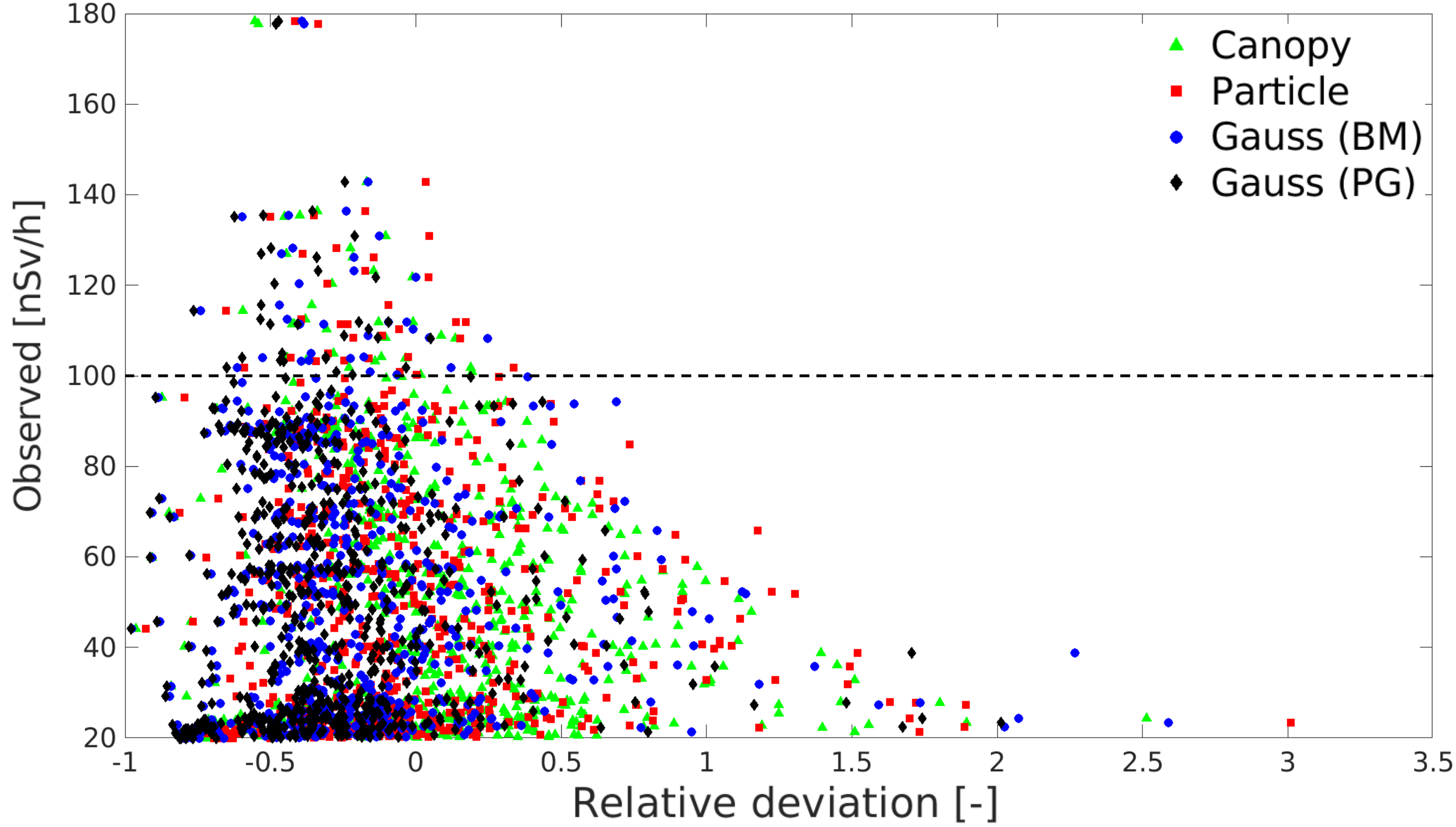
Canopy model underpredicts occurrence of dose rates > 120 nSv/h

Particle model seems to perform the best

Simulation of Ar-41 routine releases

Outliers?

Above 100 nSv/h: mainly underestimations



Simulation of Ar-41 routine releases

Statistical measures

Statistical measures [Chang & Hanna (2004)]: let the subscript o denote the observations and p the predictions, then

$$\mathrm{VG} = \exp\left\{\overline{\ln\left(\frac{\dot{d}_{\gamma,o}}{\dot{d}_{\gamma,p}}\right)^2}\right\}, \qquad \mathrm{FAC}n = \text{fraction of data that satisfy } \frac{1}{n} \leq \frac{\dot{d}_{\gamma,o}}{\dot{d}_{\gamma,p}} \leq n$$

Additionally, also a hypothetical ground release (10 m) was assumed for the same meteorological data as for the stack release.

Findings

- Stack release: $75\% < \mathrm{FAC2} < 90\ \%$, $\mathrm{FAC10} \approx 100\%$ (w.r.t. measurements)

Release height [m]	$\dot{d}_{\gamma,o}$	$\dot{d}_{\gamma,p}$	**VG [-]**	**FAC2 [-]**	**FAC10 [-]**
60	Gauss (PG)	Canopy	1.20	0.94	1.0
10	Gauss (PG)	Canopy	2.52	0.39	1.0

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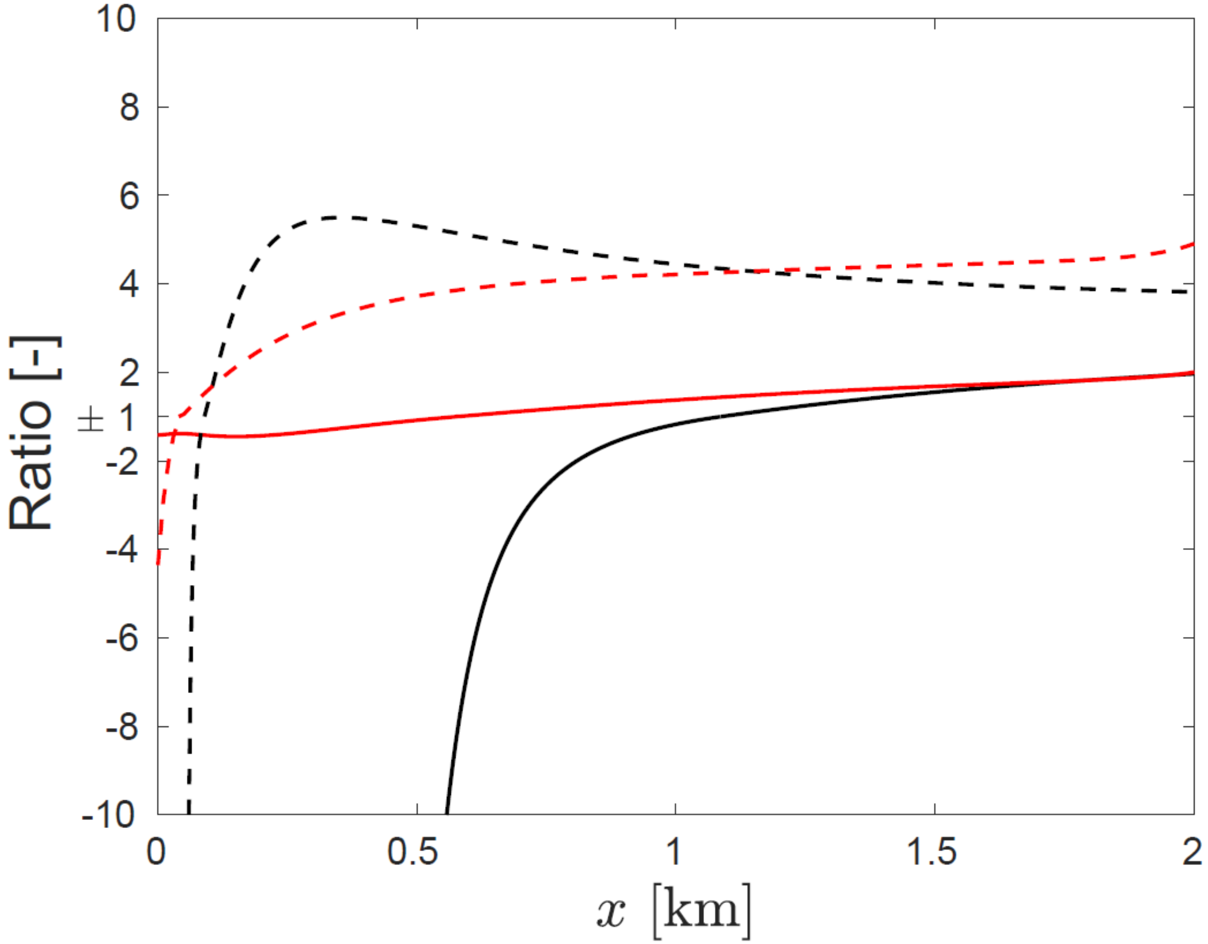
Downstream calculations for a 2 km fetch

Ratio's at ground level

Concentration discrepancy is much bigger close to the source than for dose rate

- concentration stronger influenced by terrain roughness modeling



Black = concentration ratio

Red = dose rate ratio

60 m release (-)

10 m release (--)

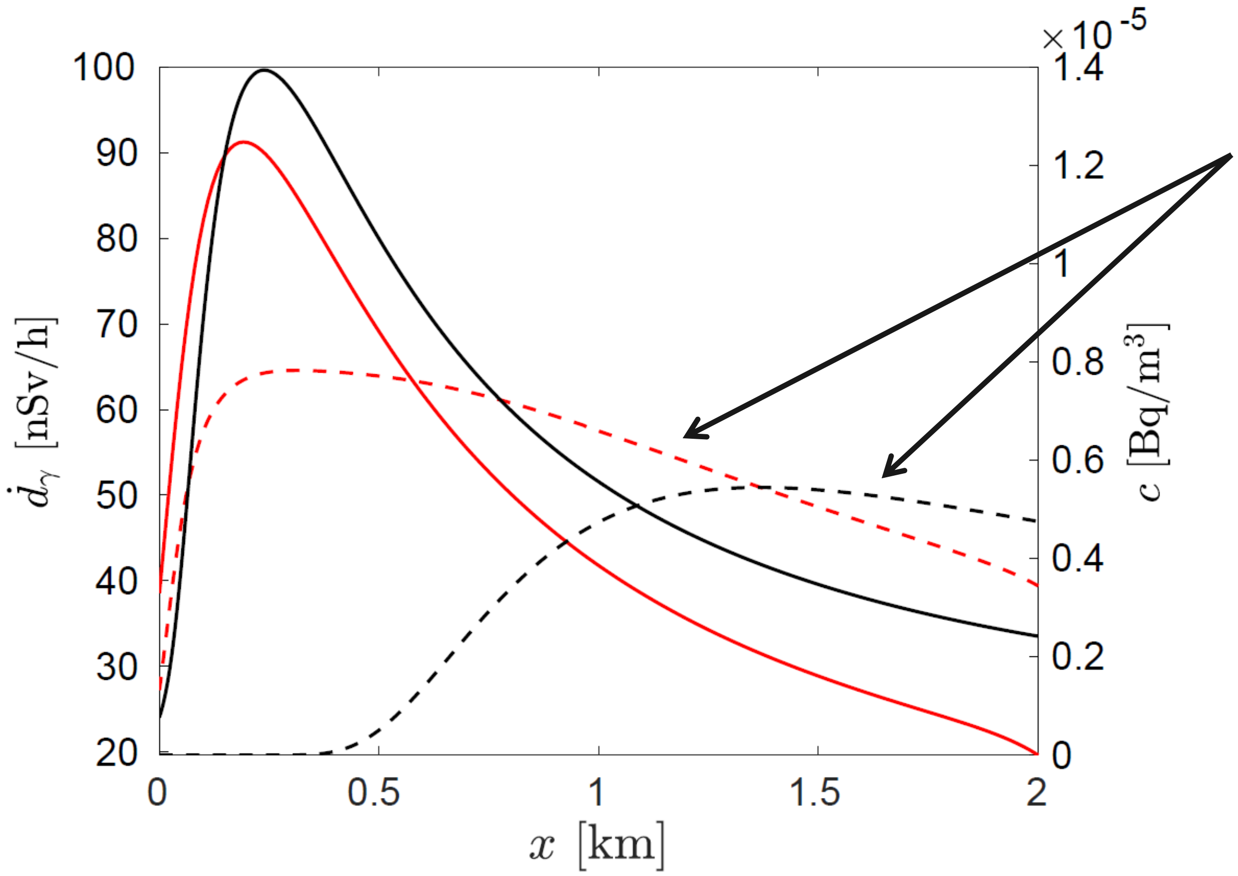
$$\text{Ratio} = \frac{\text{Gauss (PG)}}{\text{Canopy}} \text{ if } \geq 1$$

$$\text{Ratio} = -\frac{\text{Canopy}}{\text{Gauss (PG)}} \text{ if } < -1$$

Downstream calculations for a 2 km fetch

Ground profiles

- Higher roughness ⇒ concentration maximum closer to source
- Location of max. dose rate is stronger influenced by the source than by the max. concentration



Low roughness:
dose rate doesn’t scale with ground concentration

60 m release

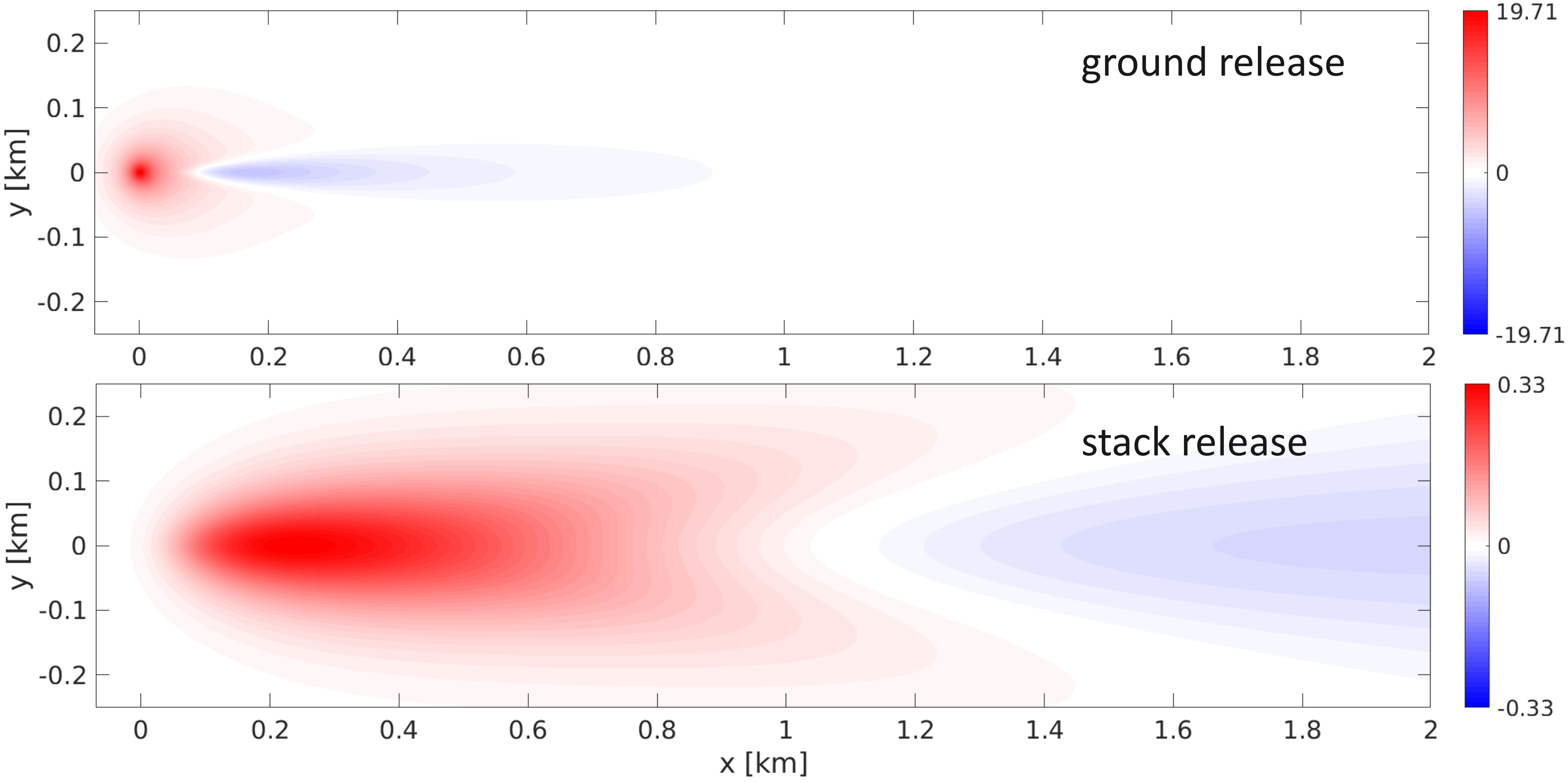
Black = concentration
Red = dose rate

Canopy (-)
Gauss PG (--)

Downstream calculations for a 2 km fetch

Non-dimensional ground concentration distributions

The canopy and the Gaussian model produce quite different concentration distributions for both release heights



Downstream calculations for a 2 km fetch

Discussion about the maximum values

Closer agreement between the models about the location and value of the max. dose rate than about the max. concentration!

Max. conc.	**Location [m]**		**Ratio [-]**
Release height [m]	**Canopy**	**Gauss (PG)**	$\frac{\text{Canopy}}{\text{Gauss}}$
60	238	1369	
10	1	155	

Max. dose	**Location [m]**		**Ratio [-]**
Release height [m]	**Canopy**	**Gauss (PG)**	$\frac{\text{Canopy}}{\text{Gauss}}$
60	191	310	
10	0.3	90	

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Conclusions (1)

Despite the different terrain parameterizations, all the three models were capable of

- Predicting more than 75% of the dose rates within a factor two
- Predicting the right order of magnitude of the dose rates

⇒ dose rates are robust quantities to estimate

⇒ interesting property for source inversion

Conclusions (2)

An improved physical terrain parametrization can still be beneficial

- It reduces the bias and improves the variance prediction of the dose rates
- More important further downstream (>1 km): dose rates were not found to be more robust there than concentrations
  - Factor 2 – 5 difference between canopy and open field
- Strong influence on the location and value of the max. concentration
  - Important for licensing of nuclear installations

Thank you!

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