The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Development of a process-based high-resolution radon flux map for Europe: not a straight-forward exercise

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This project 19ENV01 traceRadon has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme. ***19ENV01 traceRadon*** *denotes the EMPIR project reference.*

Radon: a tracer for transport in atmosphere and soil

- Radon has relatively well-defined source and sink characteristics:
  - As a decay product of uranium, it is exhaled from all natural soils
  - As a nobel gas, its only sink is radioactive decay with a half-life of 3.82 days

- Radon is often applied as atmospheric mixing tracer …

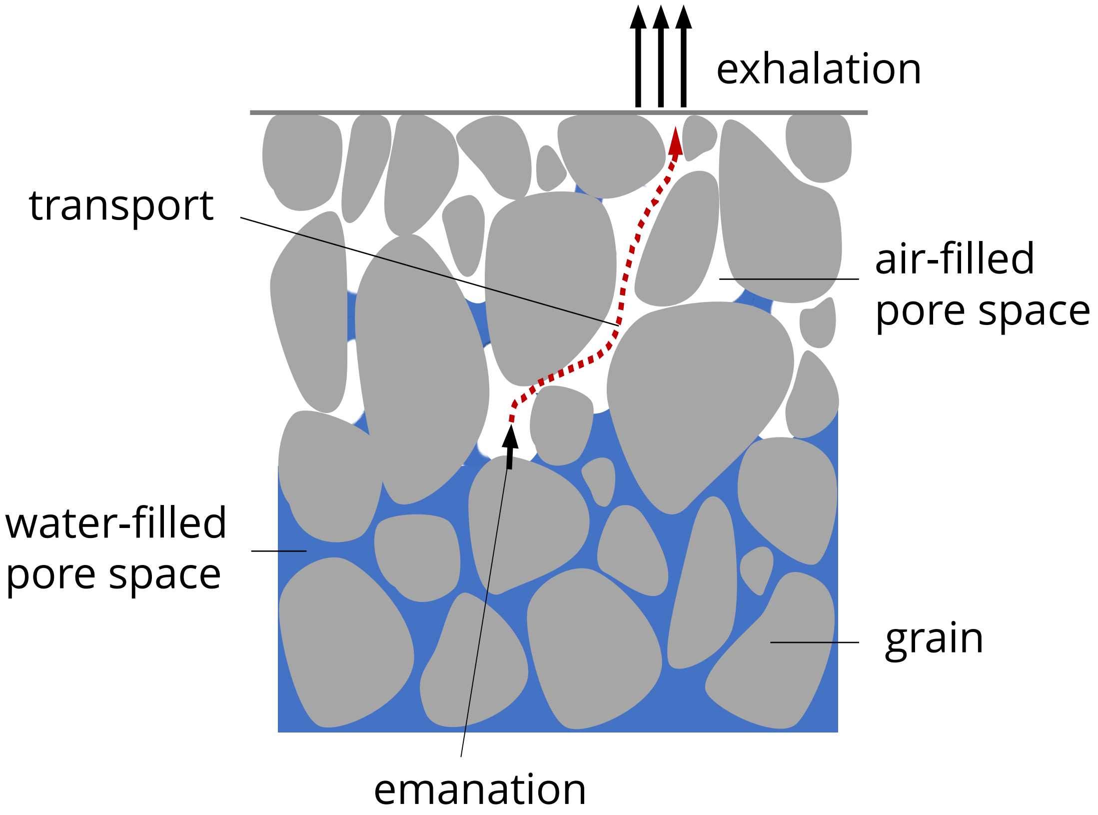
… but this requires knowledge of the continental radon flux

Contents

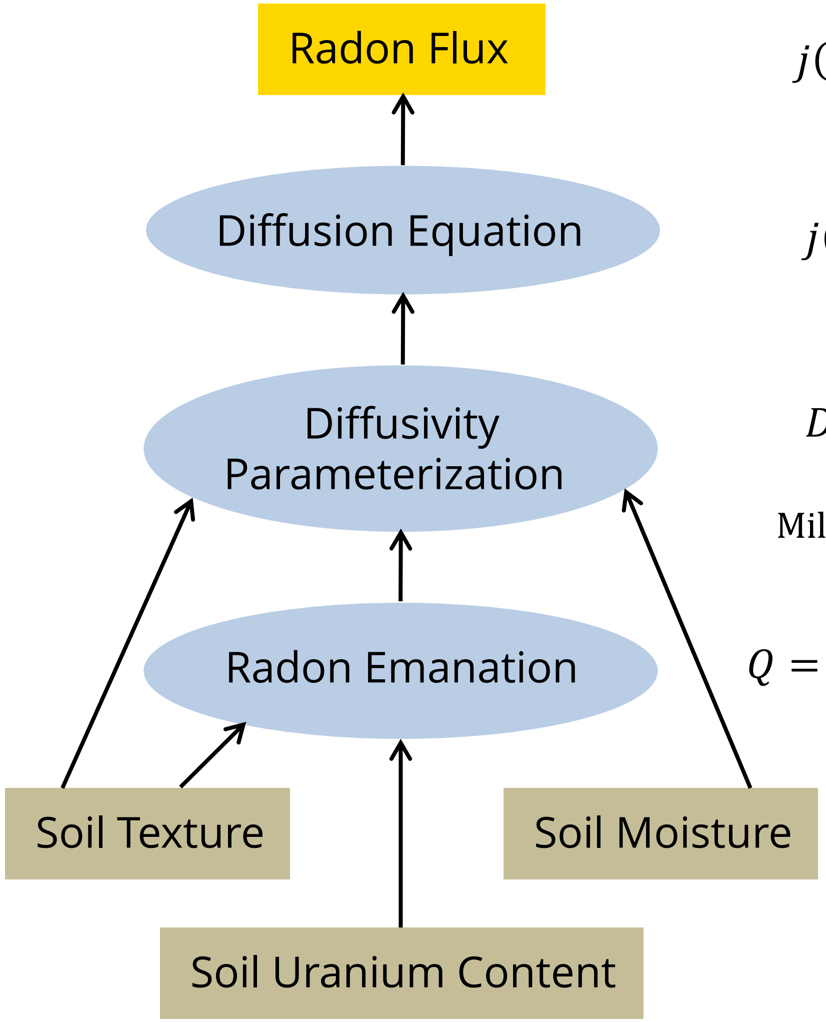
- Radon production and transport in the unsaturated soil zone
- Current implementation of these processes in a process-based radon flux map for Europe
- Input parameters to model radon exhalation rates from European soils
- New high-resolution traceRadon observational radon flux data and their relation to meteorological parameters
- Future needs to improve our understanding of the radon flux variability in Europe

Modelling radon flux from soils (Karstens et al., 2015)

Processes



Parameterisation



$$j(z=0) = -Q\sqrt{\frac{D_e}{\lambda}}$$

$$j(z) = -D_e\frac{\partial c(z)}{\partial z}$$

$$D_e = D_a\frac{(\theta_p-\theta_w)^2}{\theta_p^{\frac{2}{3}}}\left(\frac{T}{273K}\right)^{\frac{3}{2}}$$

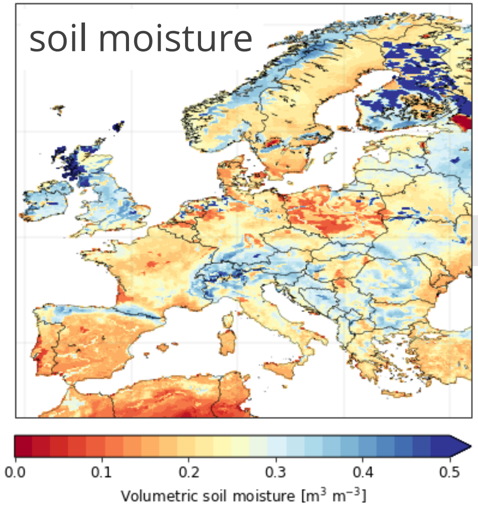
Millington and Quirk (1960)

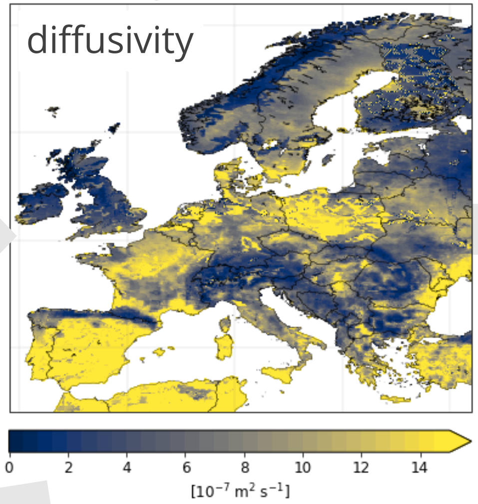
$$Q = \lambda\,\rho_b(z)\,c_{Ra}(z)\,\varepsilon(z,T,\theta_w)$$

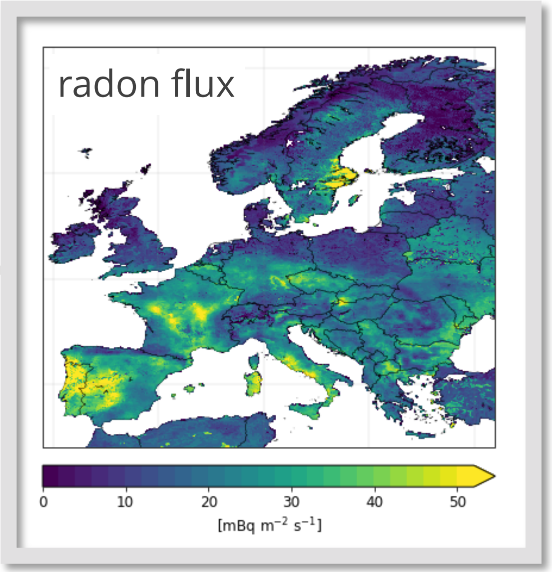
Radon flux model: components and workflow

variable

ERA5-Land reanalysis

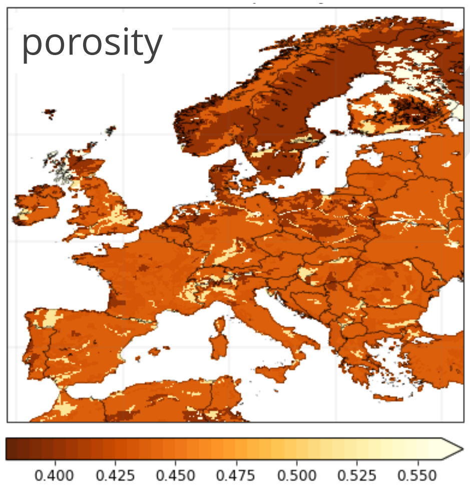


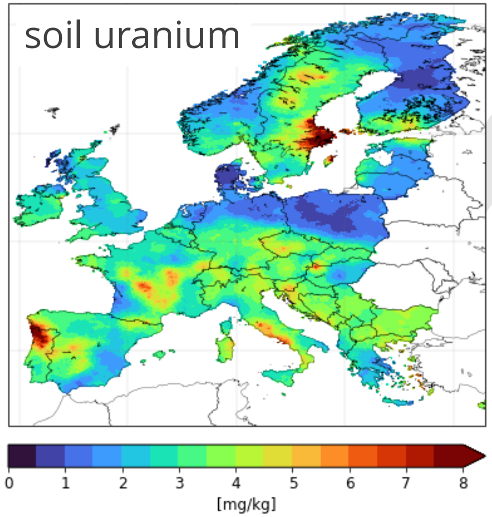




static

soil properties





Digital Atlas of Natural Radiation
(EC JRC, 2019)

+

European Soil Database

soil texture
- % clay
- % sand
- % silt

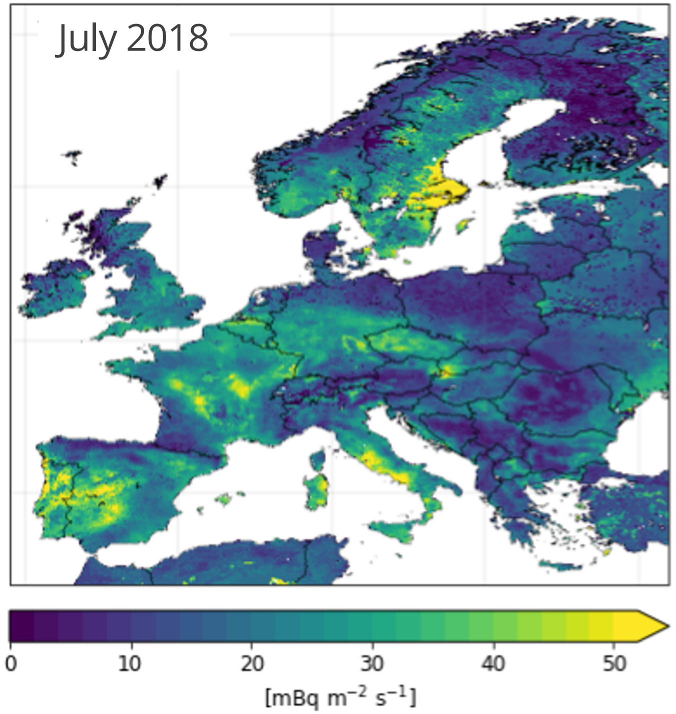
bulk density

(Hiederer, 2013)

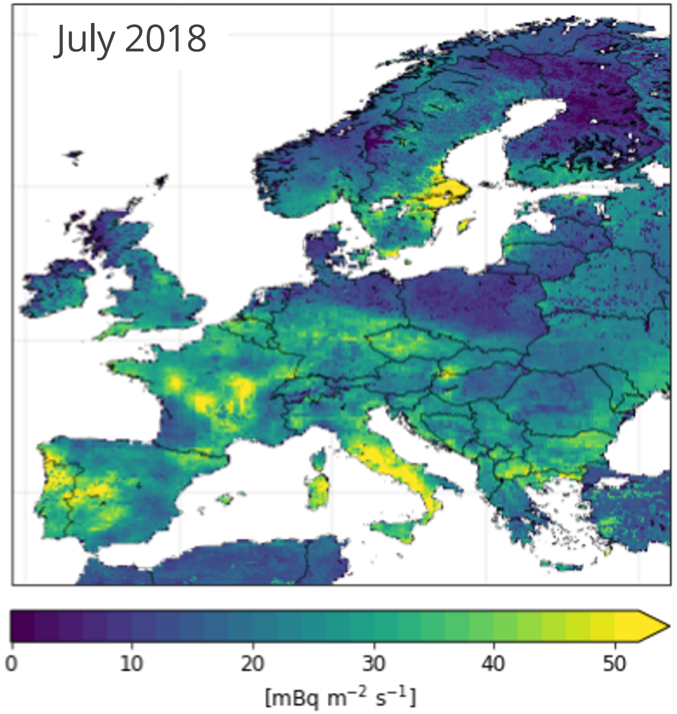
EURAMET

Radon flux based on different soil moisture re-analyses

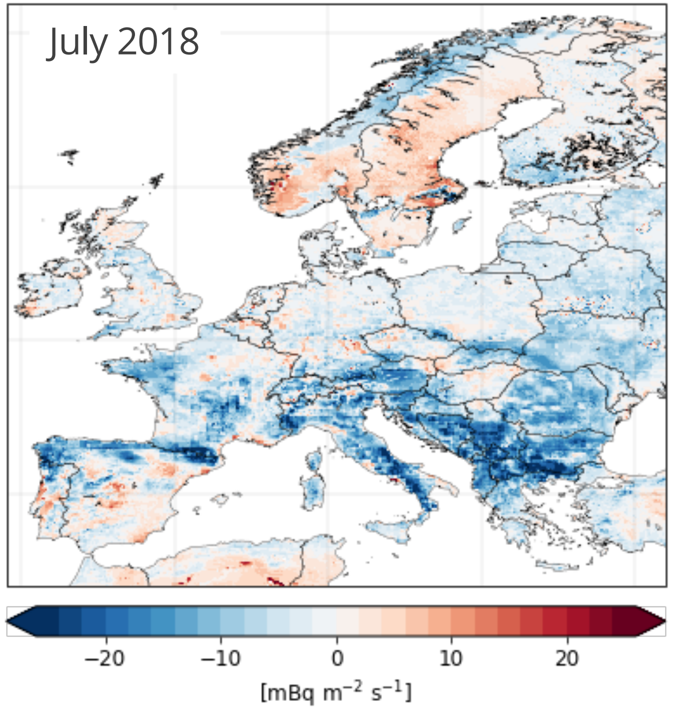
ERA5-Land soil moisture



GLDAS-Noah v2.1 soil moisture



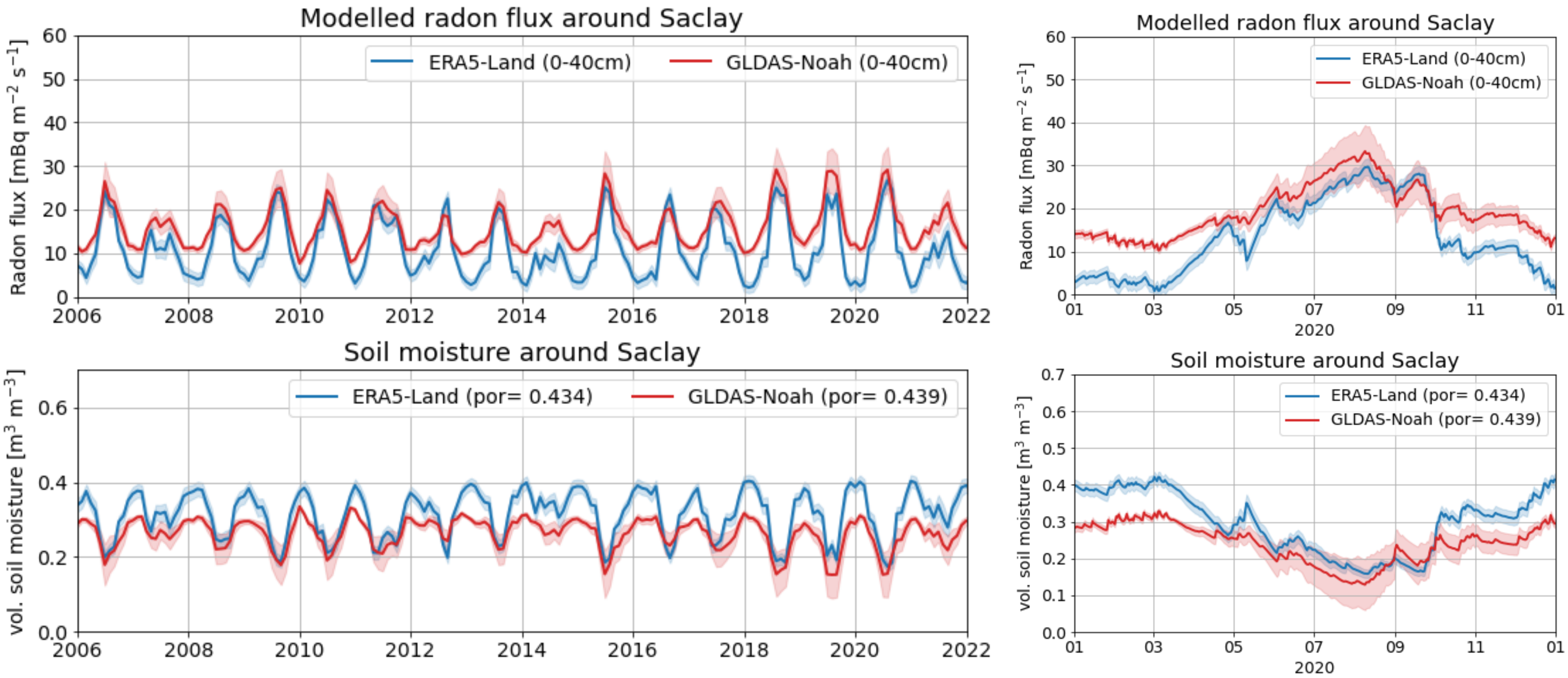
ERA5-Land – GLDAS-Noah



differences can be as large as absolute radon flux

traceRadon EURAMET

Radon flux model results and soil moisture re-analyses



0.5° x 0.5° spatial average and heterogeneity

Current radon flux model

- Radon flux model is based on steady-state assumption and purely diffusive transport ➔ soil moisture dominates temporal variability
- Validation of soil moisture on large scale is limited due to a lack of representative high-quality soil moisture observations
- Validation of radon fluxes was hampered by only episodic observations

Measurement campaigns

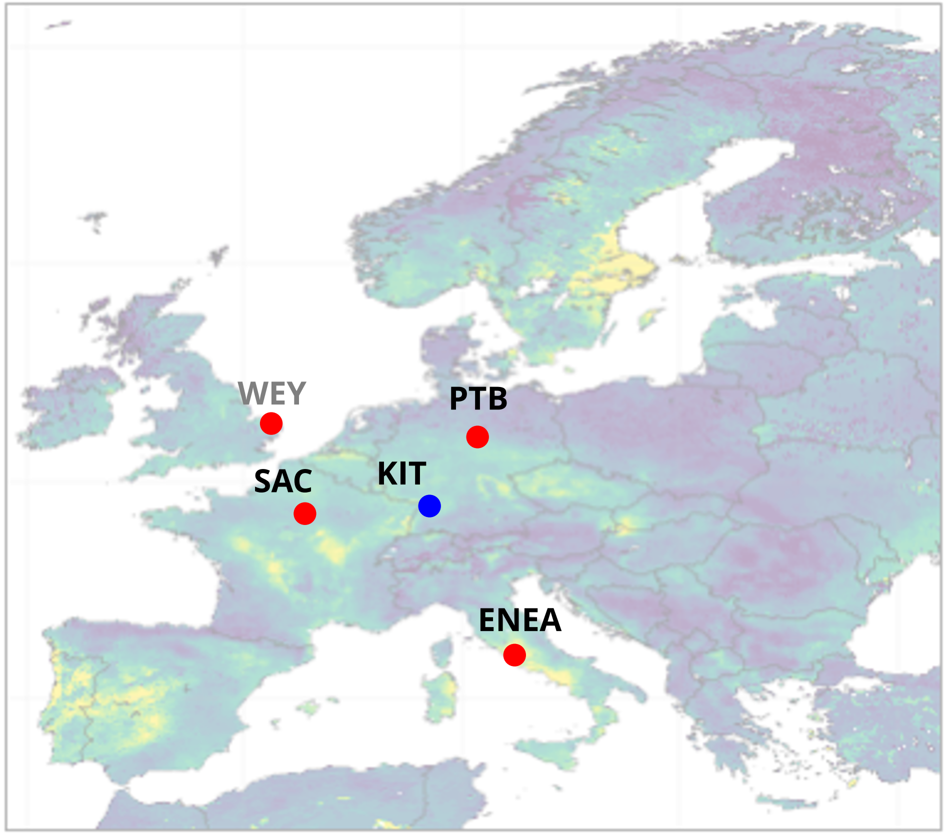
traceRadon measurement campaigns

- at PTB, ENEA, SAC, WEY (starting soon)
- 2-3 months of measurements at each site
- 3-hourly radon flux (ANSTO AutoFlux)
- soil moisture and temperature profiles
- soil parameters (radium, porosity, type)

➔ for more information see poster 34 by Grossi et al.

Uni Heidelberg measurements

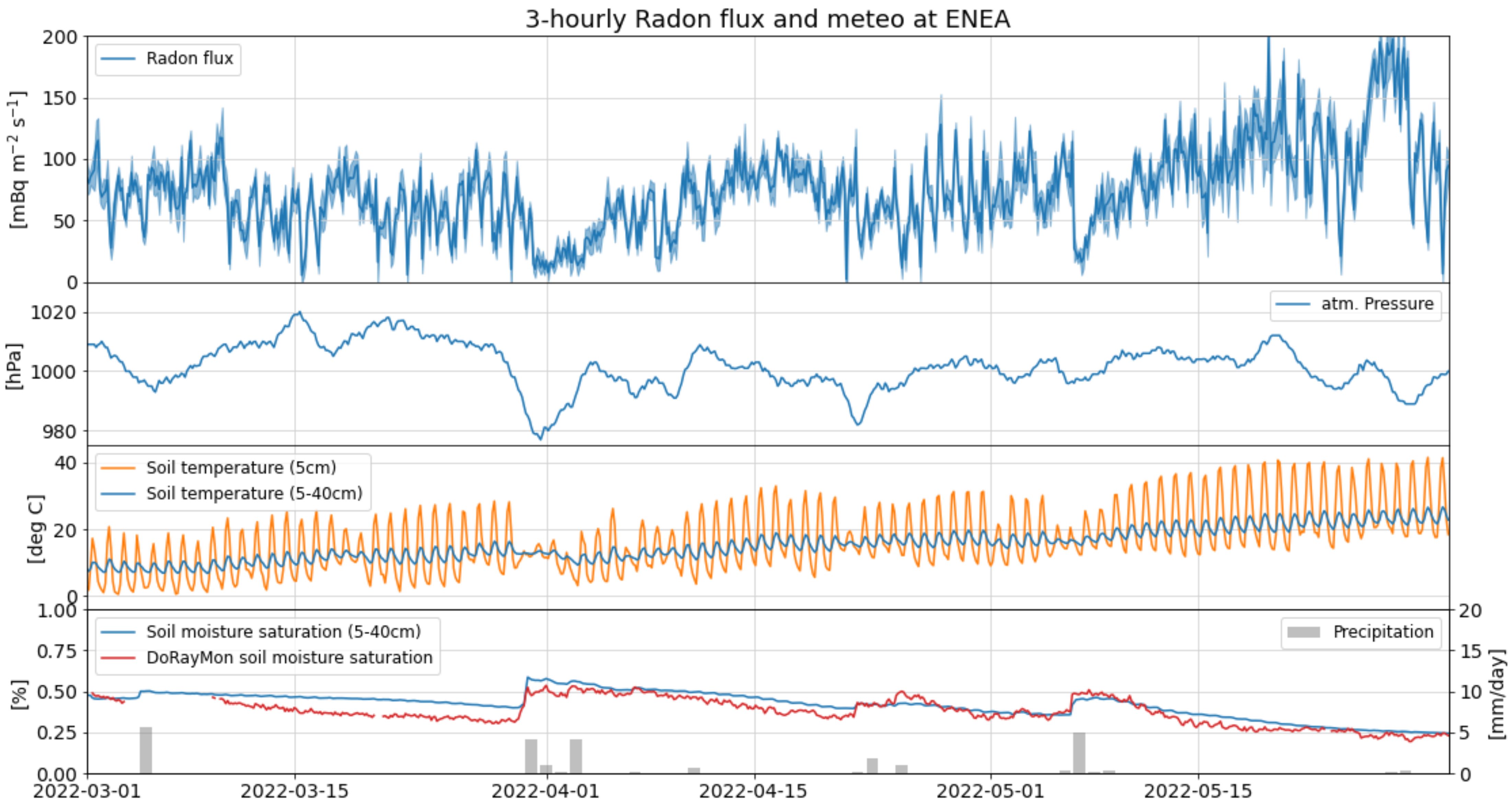
- at KIT (Nov 2021 – May 2022)
- 3-hourly radon flux (ANSTO AutoFlux)
- soil moisture and temperature in 5 cm depth
- soil parameters (radium, porosity)



Which parameters potentially influence the day to day radon flux variability ?

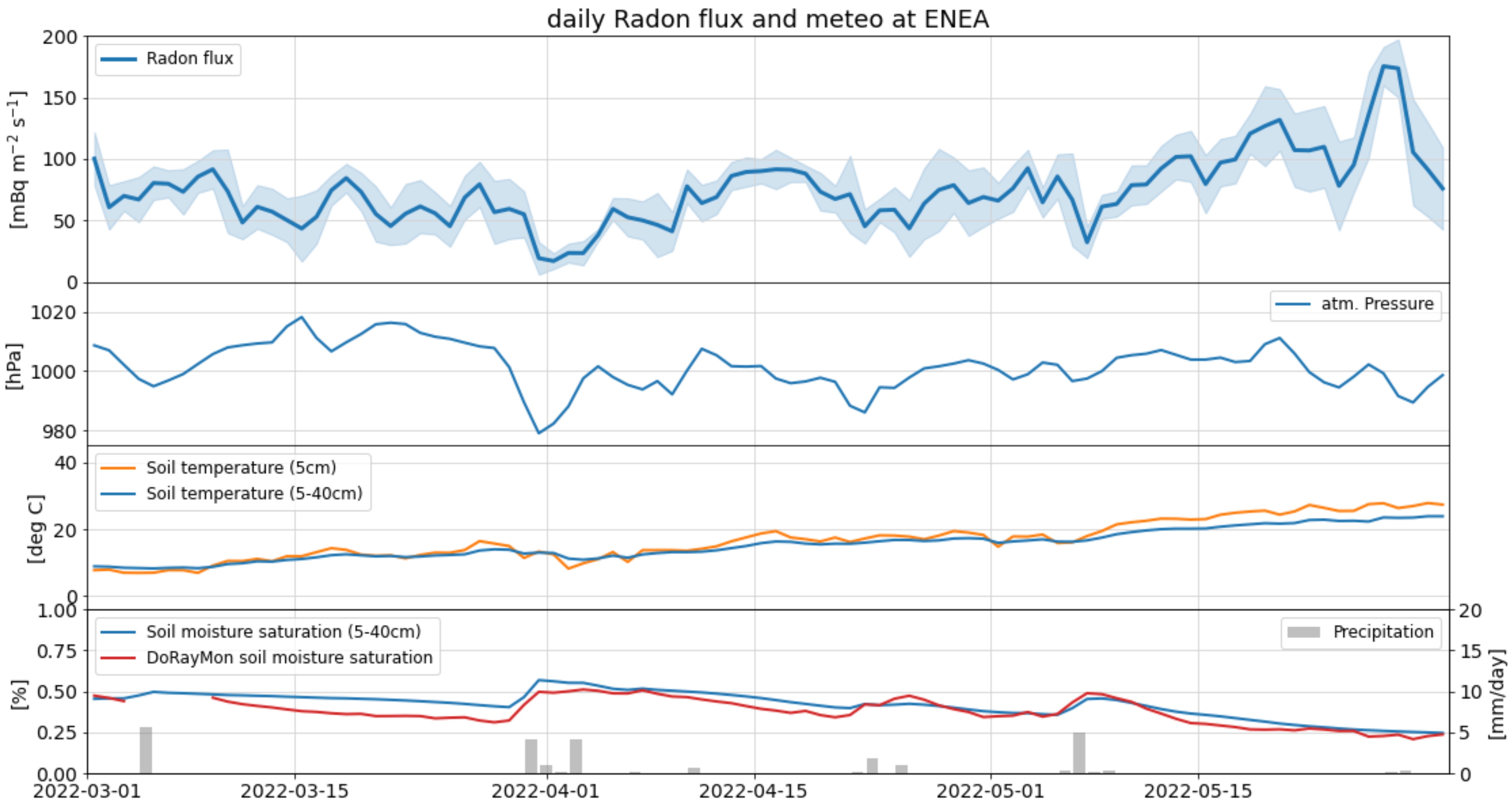
	ENEA	SAC	PTB	KIT	
	spring	summer	winter	winter	spring
soil moisture					
pressure change					
soil temperature					
precipitation					

Radon flux measurements at ENEA   March – June 2022

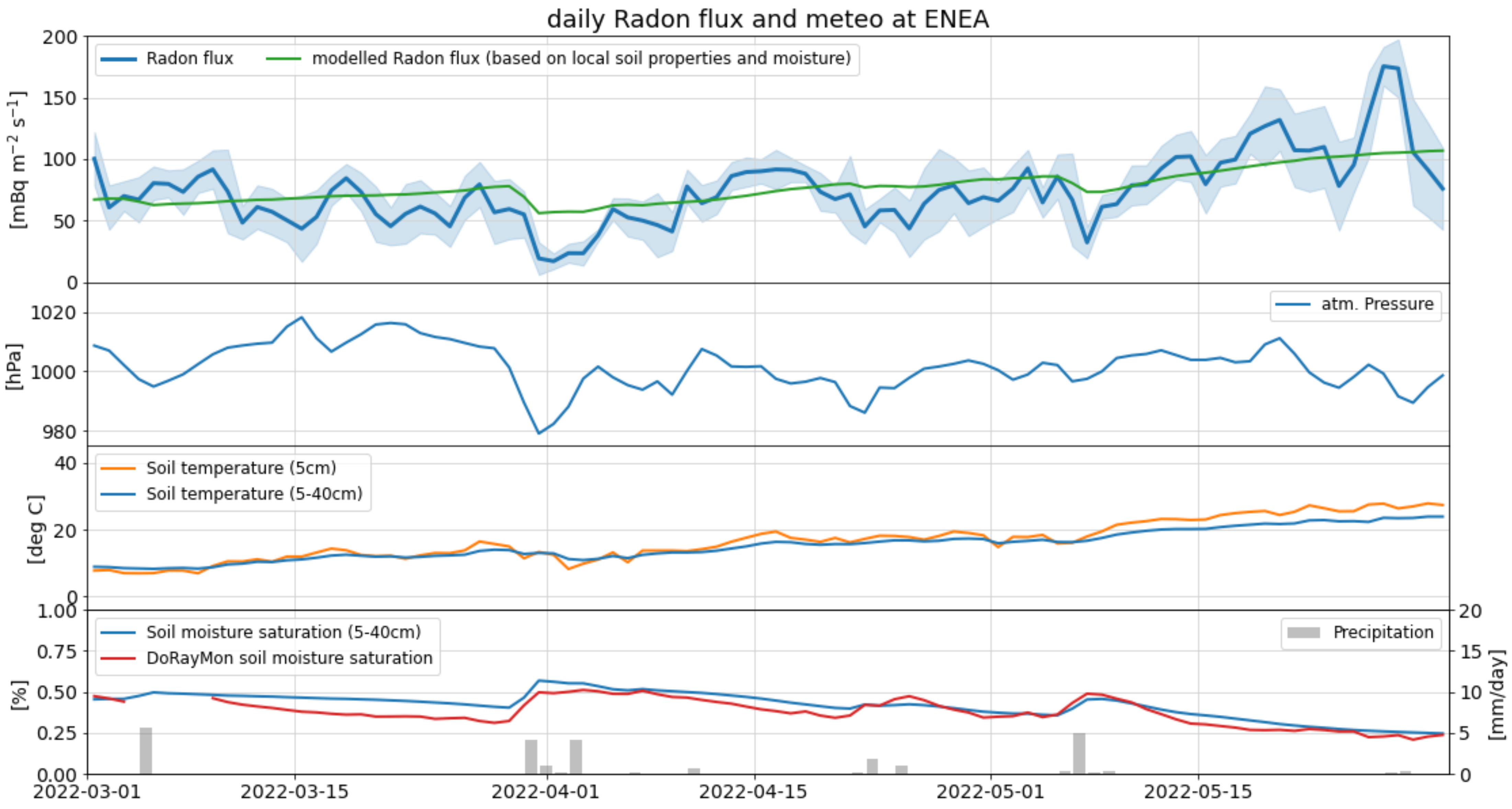


for information on DoRayMon measurements and soil moisture estimation see poster 28 by Vargas et al.

Radon flux measurements at ENEA   March – June 2022



Radon flux measurements at ENEA March – June 2022

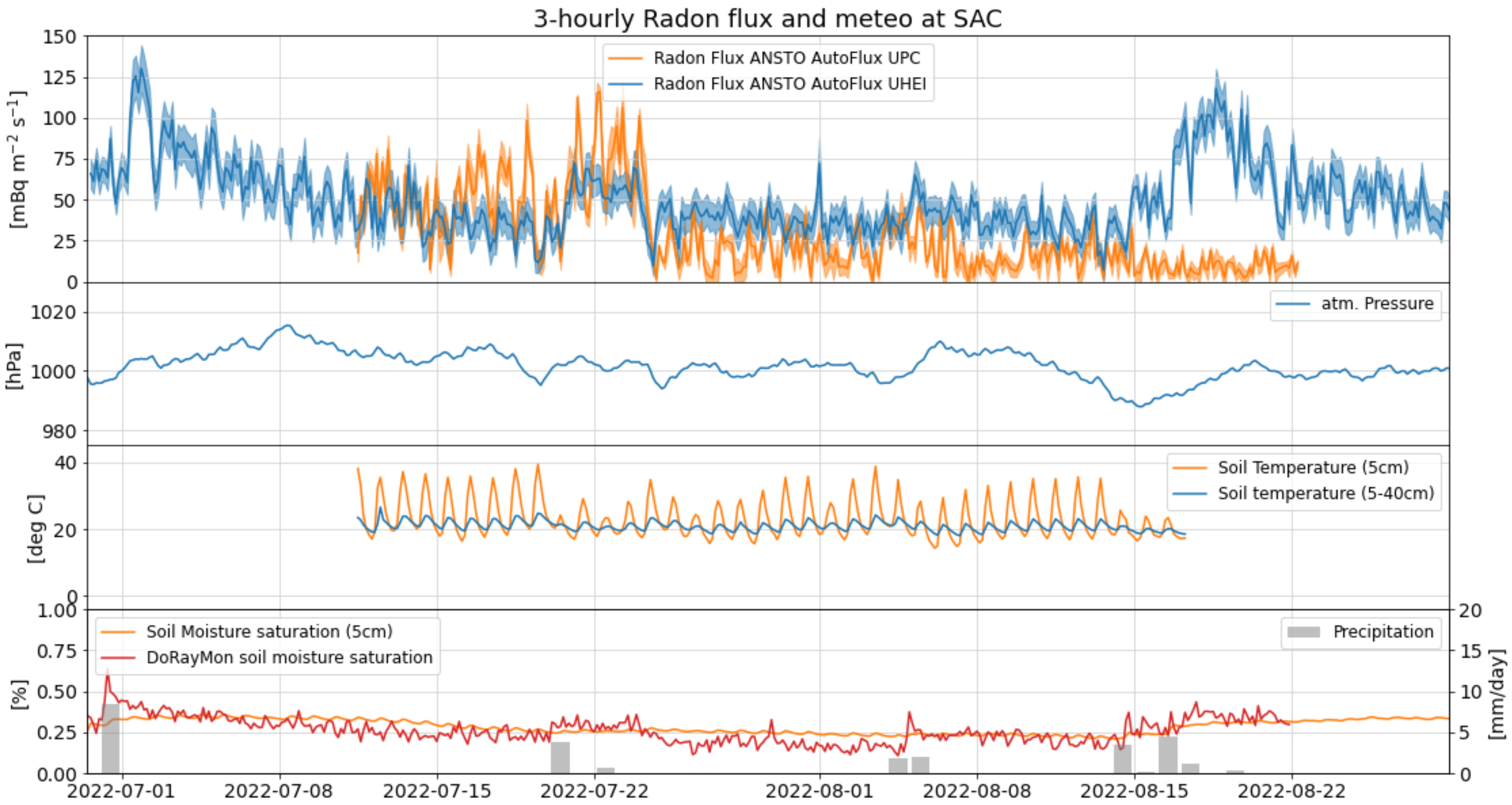


Which parameters potentially influence the day to day radon flux variability ?

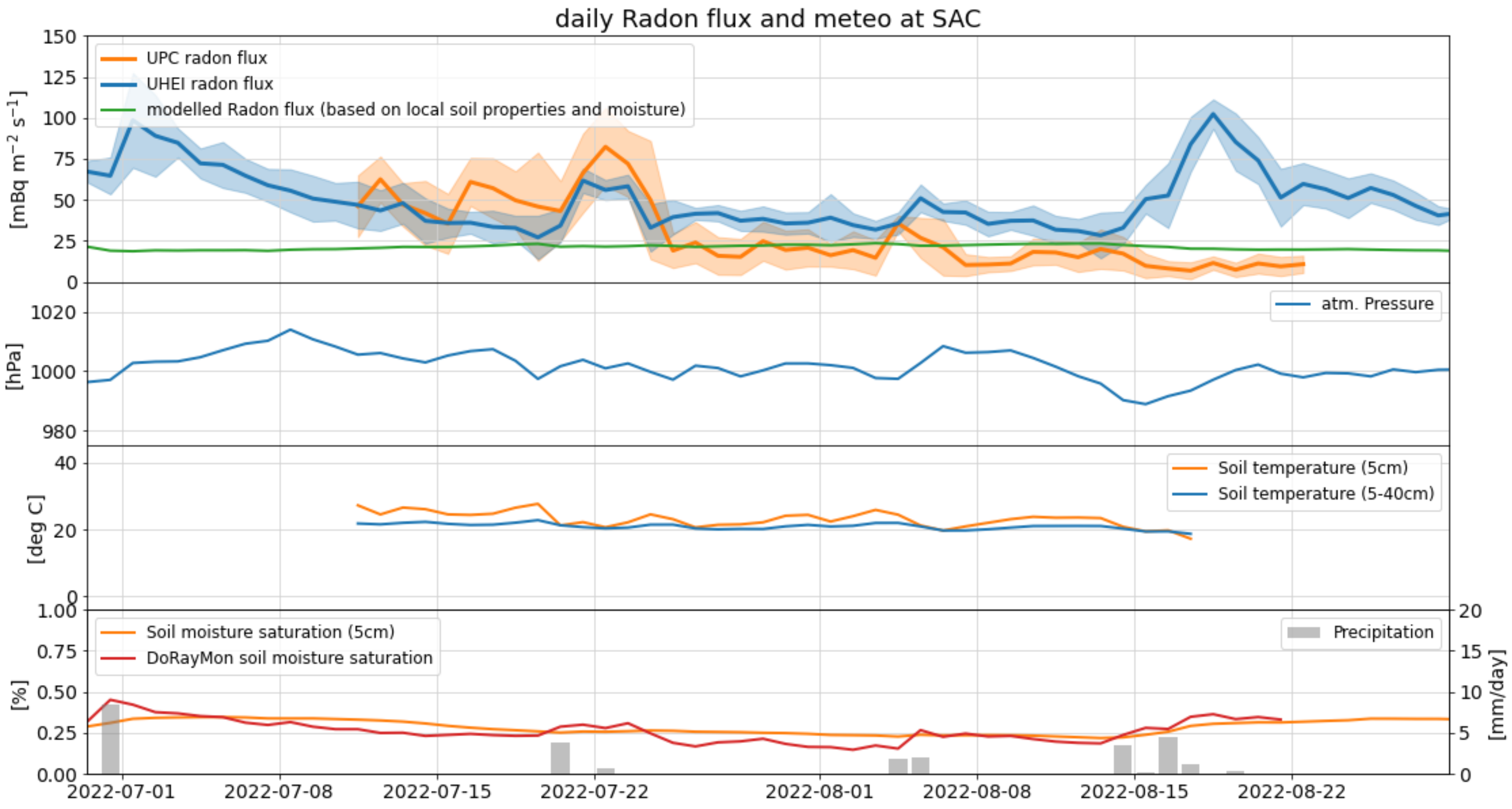
	ENEA	SAC	PTB	KIT	
	spring	summer	winter	winter	spring
soil moisture	↓				
pressure change	—				
soil temperature	↑				
precipitation	↓				

— no correlation   ↓ negative correlation   ↑ positive correlation

Radon flux measurements at SAC   July – Aug 2022



Radon flux measurements at SAC   July – Aug 2022

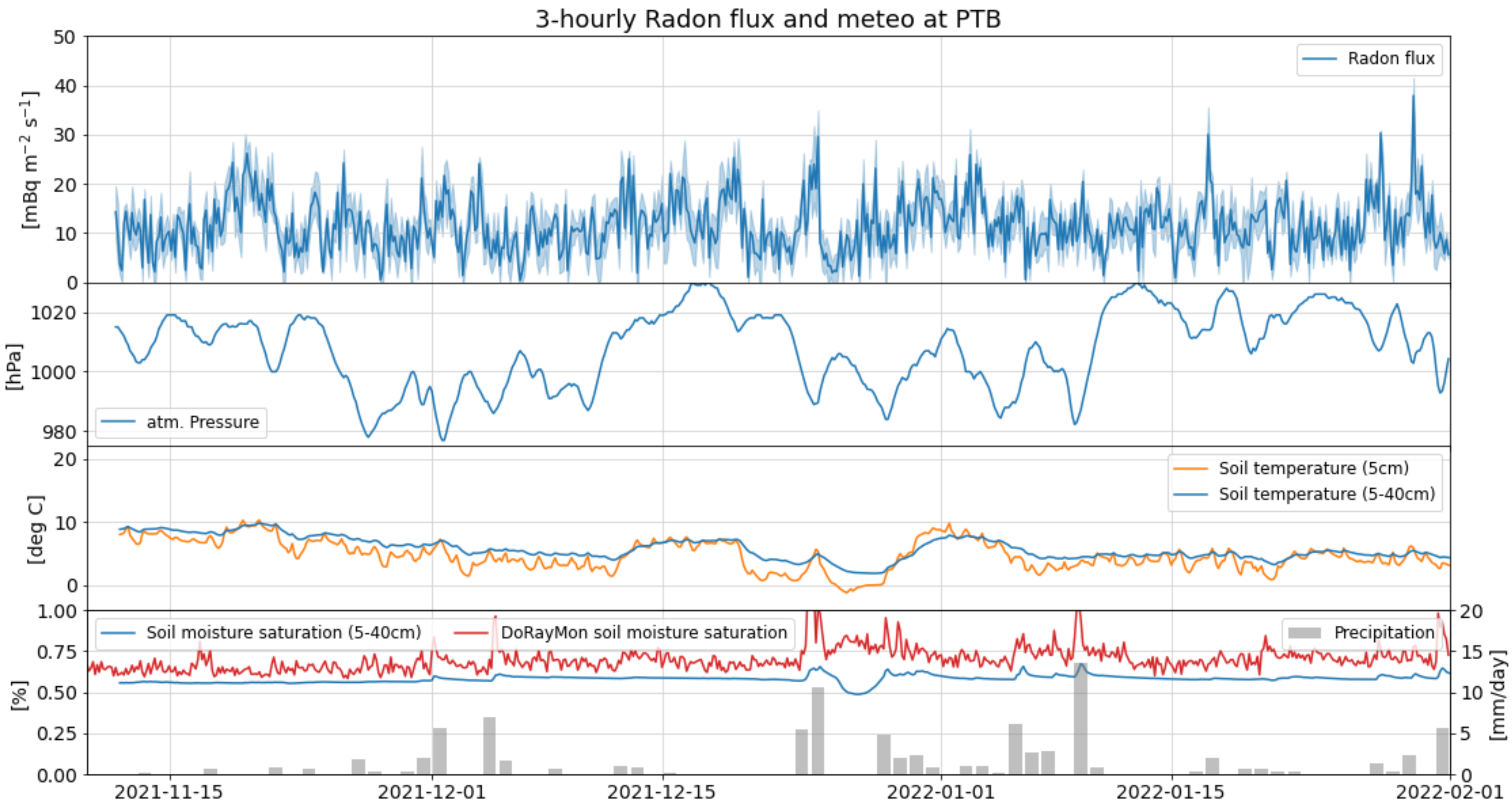


Which parameters potentially influence the day to day radon flux variability ?

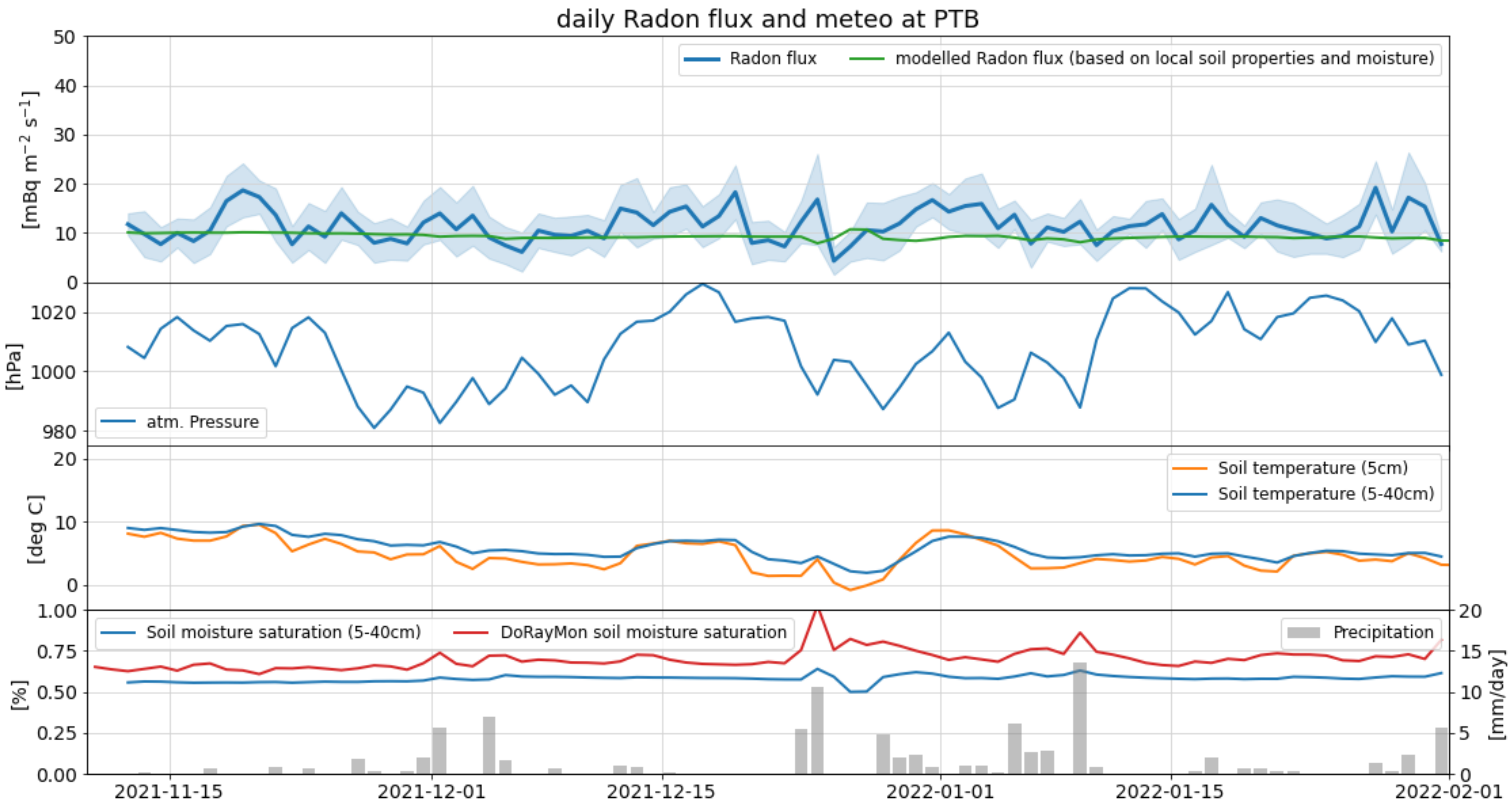
	ENEA	SAC	PTB	KIT	
	spring	summer	winter	winter	spring
soil moisture	↓	↑			
pressure change	—	—			
soil temperature	↑	↓			
precipitation	↓	↑			

— no correlation　　↓ negative correlation　　↑ positive correlation

Radon flux measurements at PTB   Nov 2021 – Jan 2022



Radon flux measurements at PTB   Nov 2021 – Jan 2022



Which parameters potentially influence the day to day radon flux variability ?

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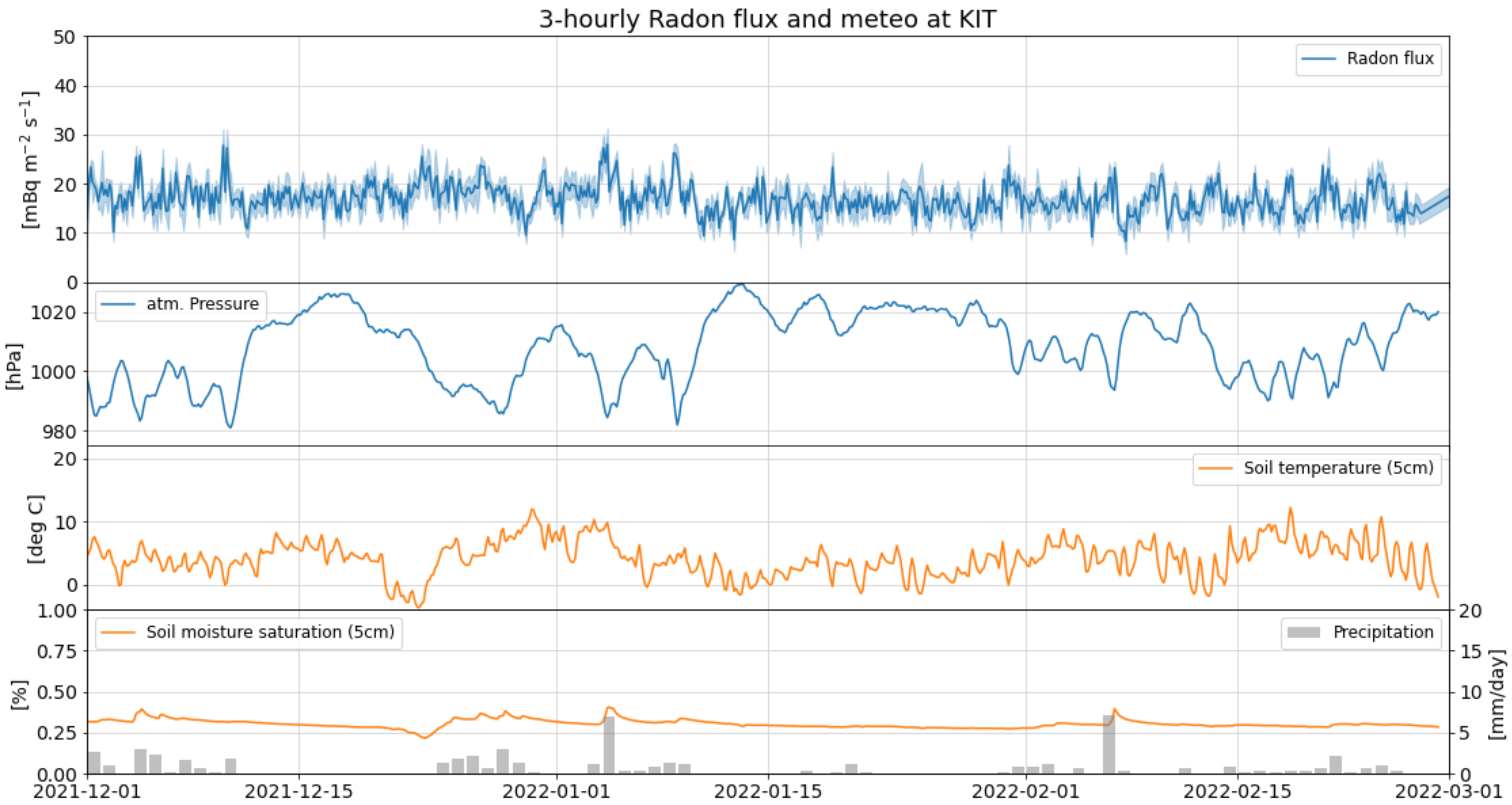
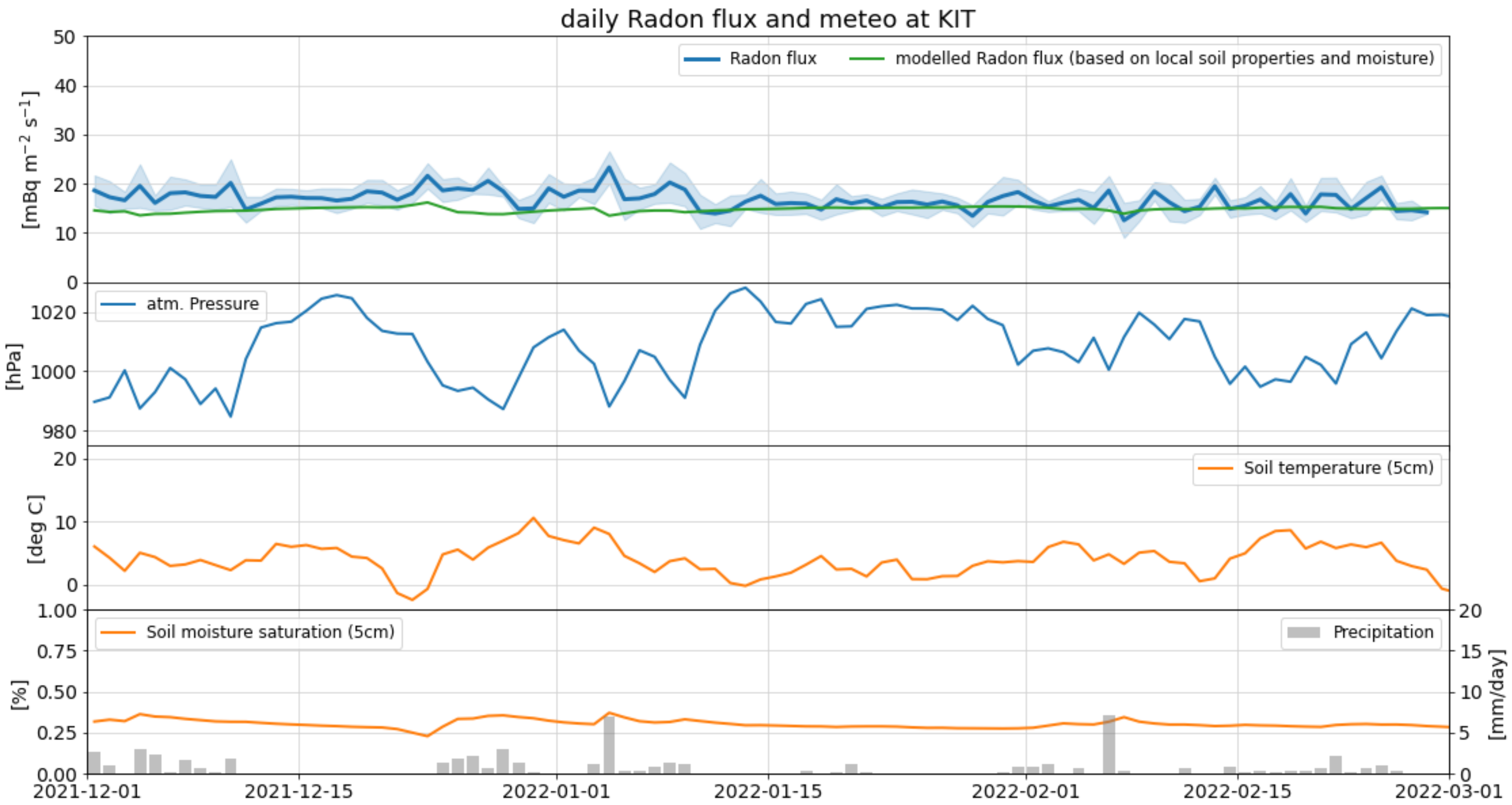
	spring	summer	winter	winter	spring
soil moisture	↓	↑	—		
pressure change	—	—	—		
soil temperature	↑	↓	↑		
precipitation	↓	↑	—		

— no correlation ↓ negative correlation ↑ positive correlation

Radon flux measurements at KIT   Dec 2021 – Feb 2022



Radon flux measurements at KIT   Dec 2021 – Feb 2022



Which parameters potentially influence the day to day radon flux variability ?

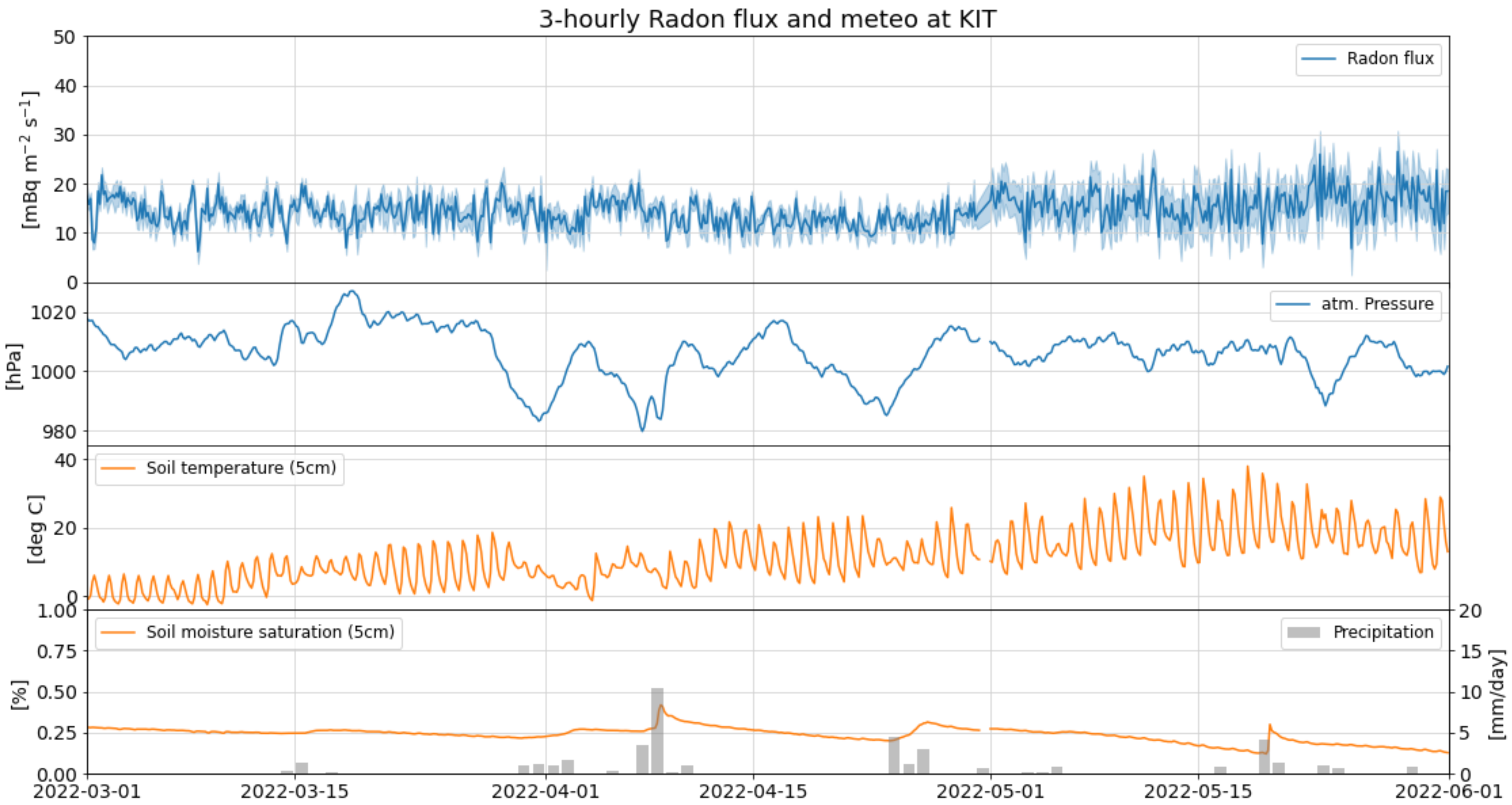
	ENEA	SAC	PTB	KIT	
	spring	summer	winter	winter	spring
soil moisture	↓	↑	—	↓	
pressure change	—	—	—	↓	
soil temperature	↑	↓	↑	—	
precipitation	↓	↑	—	↓	

— no correlation

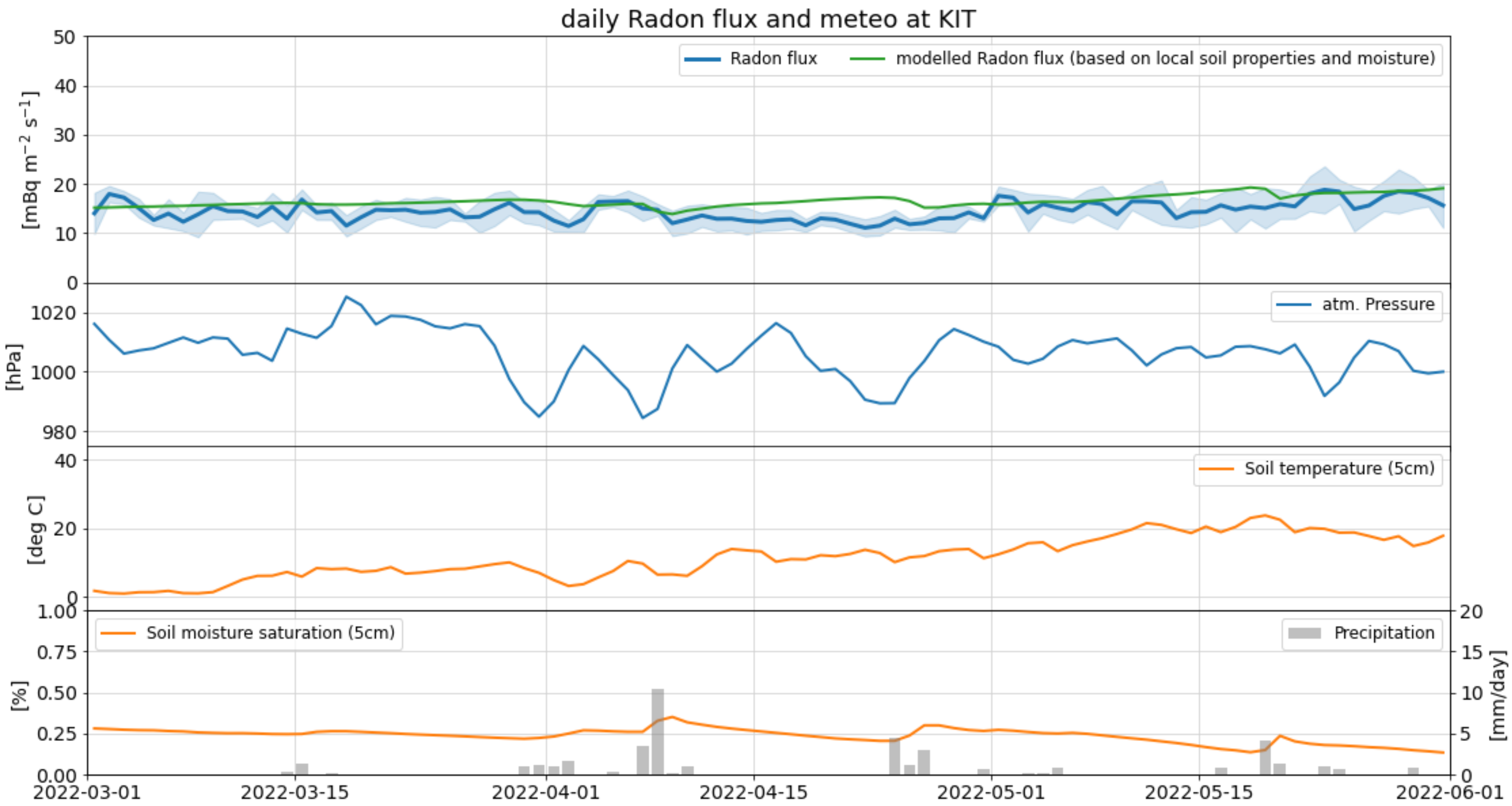
↓ negative correlation

↑ positive correlation

Radon flux measurements at KIT   March – May 2022



Radon flux measurements at KIT   March – May 2022

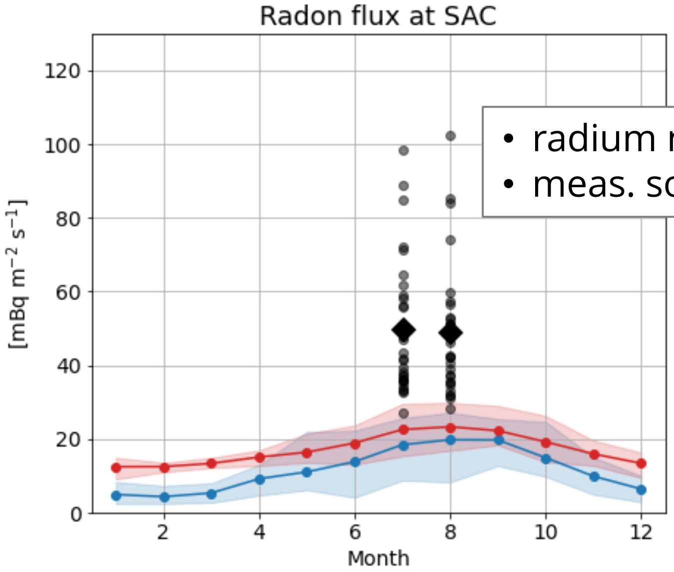


Which parameters potentially influence the day to day radon flux variability ?

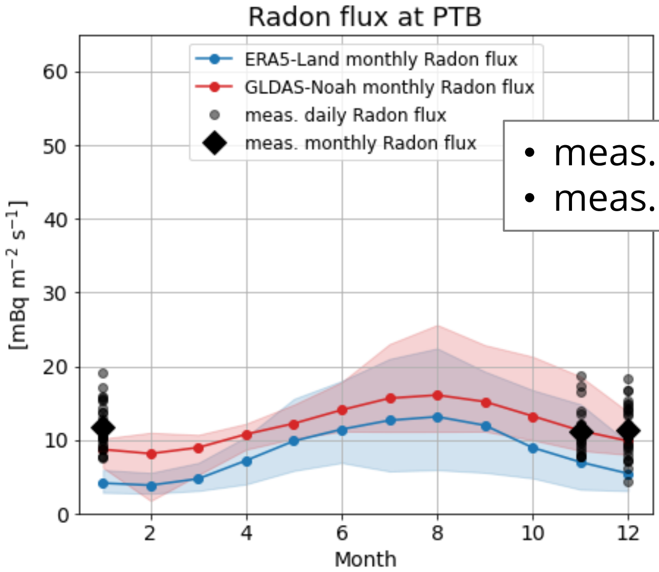
	ENEA	SAC	PTB	KIT	
	spring	summer	winter	winter	spring
soil moisture	↓	↑	—	↓	↓
pressure change	—	—	—	↓	↓
soil temperature	↑	↓	↑	—	↑
precipitation	↓	↑	—	↓	—

— no correlation ↓ negative correlation ↑ positive correlation

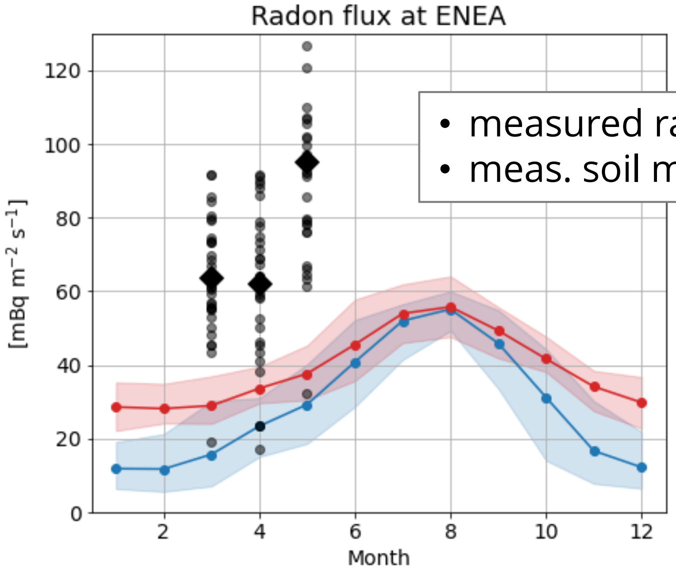
Comparison flux map climatology (2006-2021) – measurement data



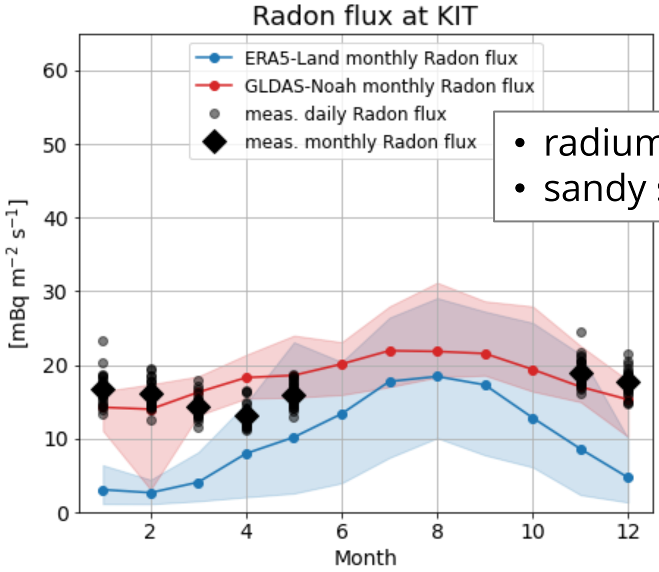
- radium not yet measured
- meas. soil moisture < reanalyses



- meas. radium ≲ map
- meas. soil moisture ≈ GLDAS-Noah



- measured radium ≫ map
- meas. soil moisture ≈ GLDAS-Noah



- radium not yet measured
- sandy soil → soil moisture dynamics

Conclusions

- New high-resolution continuous radon flux measurements show an unexpectedly huge variability ➔ model parameterizations need to be refined
- On shorter timescales of hours or days, the steady state assumption is no longer valid, as e.g. pressure changes could induce non-steady state advection fluxes
- Correlations of radon flux and environmental parameters are inconclusive and even contradictory ➔ need to understand causalities for modelling
  - Radon emanation increases with soil moisture and radon flux decreases with soil moisture
  - Interdependence between soil temperature and other environmental parameters
- More dedicated and extended measurements of radon flux and environmental parameters in other soil types and climatic conditions are needed to better understand (and model) the interplay of the various processes

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Thank you for your attention !

For general applications of radon flux maps see these presentations:

Kikaj et al. (Thursday plenary)
Yver Kwok et al. (Poster 68)
Barbosa et al. (Poster 67)
Chung et al. (this session)
Cinelli et al. (this session)

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Radon flux model: basic assumptions

- **Production rate** of radon in the soil

$$Q = \lambda\ \rho_b(z)\ c_{Ra}(z)\ \varepsilon(z, T, \theta_w/\theta_p)$$

λ radon decay constant
ρ_b soil bulk density
c_{Ra} radium activity concentration
ε emanation coefficient (soil type)

Uranium
Soil texture
Soil moisture
Soil temperature

- **Transport of radon** in the soil air (molecular diffusion)

$$j(z) = -D_e \frac{\partial c(z)}{\partial z}$$

j flux
c concentration
D_e effective diffusivity

- **Diffusivity** of radon in the soil

Parameterisation based on air-filled pore space (soil porosity, soil moisture, ...)

Millington and Quirk (1960) selected based on radon profile measurements

$$D_e = D_a \frac{(\theta_p - \theta_w)^2}{\theta_p^{\frac{2}{3}}} \left(\frac{T}{273K}\right)^{\frac{3}{2}}$$

D_a diffusion coefficient of radon in air
θ_p soil porosity
θ_w soil water content
T soil temperature
z depth

Soil texture
Soil moisture
Soil temperature

- **Radon flux** at the soil surface

$$j(z = 0) = -Q \sqrt{\frac{D_e}{\lambda}}$$

Radon flux