Radon Dynamic in Soil and a Series of Earthquakes in Chiba Prefecture, Japan: Is There an Association? -

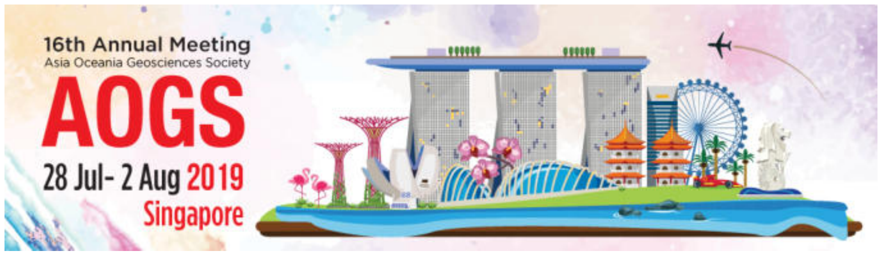
Peter BOSSEW[1], Miroslaw JANIK[2], Giorgia CINELLI[3]

1 German Federal Office for Radiation Protection (BfS), Berlin, Germany

2 Japanese institutes for Quantum and Radiological Science and Technology (QST), Chiba, Japan

3 European Commission, Joint Research Centre (JRC), Ispra, Italy

v.26.7.19



Content

- Motivation:
  Radon time series and seismic signals
- Background:
  Radon and tectonic activity
- Experimental:
  The study site and instrumentation
- Statistical methodology
- Results 😐

Motivation

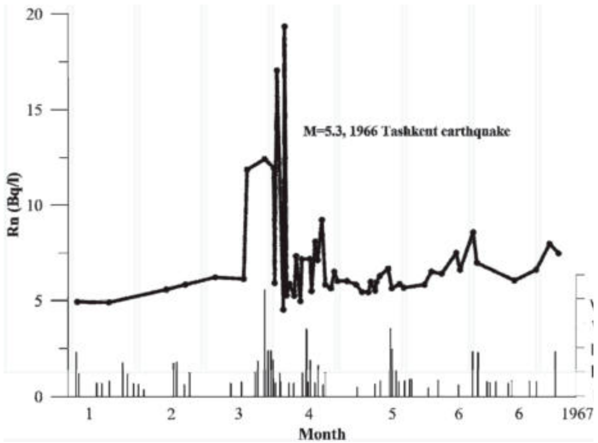
- The dynamic of radon concentration in different media (soil, ground and well water, outdoor and indoor air) is considered a candidate for assessing tectonic phenomena including seismic hazard.
- Seismic prediction is an eminently important task. Many studies have dealt with the subject with mixed success. Even if effects are proven, first and second kind prediction error probabilities are too high for practical application.
- Affected regions:
  In Europe: Italy, Turkey, Slovenia, Greece;
  In Asia / Oceania: Japan, Indonesia, PNG, NZ, Pacific islands,…
- For several years, we have been measuring Rn concentrations indoors, outdoors and in soil on a site at the QST Chiba (near Tokyo), together with environmental variables. We use the data for training our skills in Rn time series analysis; Since the region is subject to vivid seismic activity, we want to see whether seismic signals can be identified in Rn time series.

Physics background

- Tectonic activity – in particular build-up of stress/strain fields in rock – can increase Rn emanation and modify the gas permeability of the ground. This leads to higher Rn concentration in shallow soil and other media. Rn is mostly carried by CO_2, H_20 or CH_4.
- Problem: Rn dynamic has predominantly non-tectonic control which obscures possible tectonic signals $\rightarrow$ statistical challenge!
- The key is understanding Rn dynamic and being able to model and explain the non-tectonic controls. The main tool is therefore statistical analysis of Rn time series as functions of environmental controls / predictors.
- Geogenic predictors: Meteorology, tectonic activity;
  Anthropogenic predictors (for indoor Rn): human behaviour of residents and users of workplaces.

Research on Rn time series

famous example:

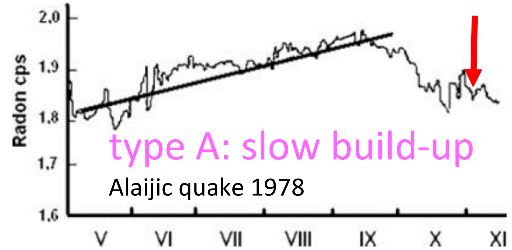


Rn in ground water before the 1966 Tashkent earthquake (M=5.3)(after Ulomov & Mavashev 1971)

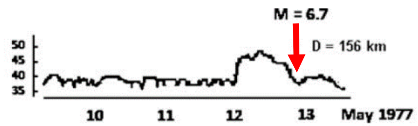
But has been measured in 1.9 km deep well, only 1.5 km from epicentre!

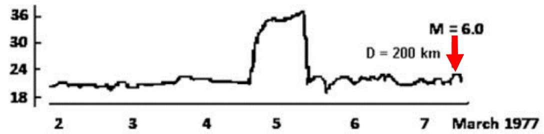
Much research for decades ...
Results little encouraging:
-The effect exists
-But no reliable prediction
(Reliable: low 1st and 2nd kind errors)

typology acc.Friedmann (2012):

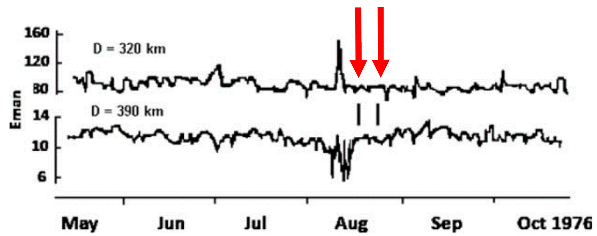


type A: slow build-up
Alaijic quake 1978





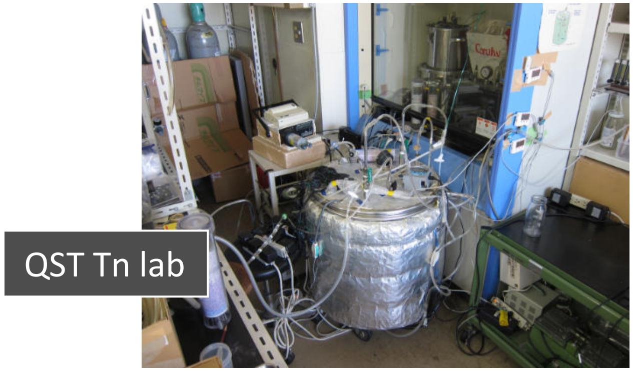
type B1: fast step, then stable
Ninghe, Chienan 1977

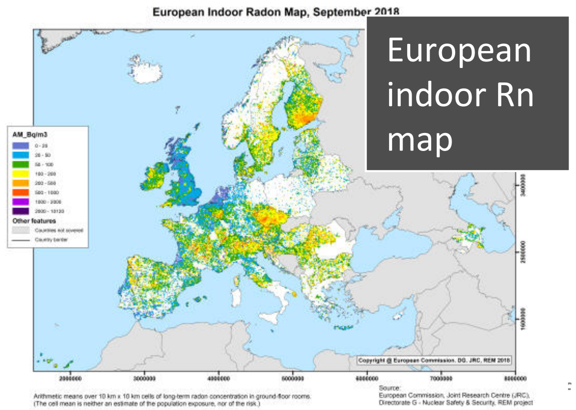


type B2: short peak
Sungpan 1976

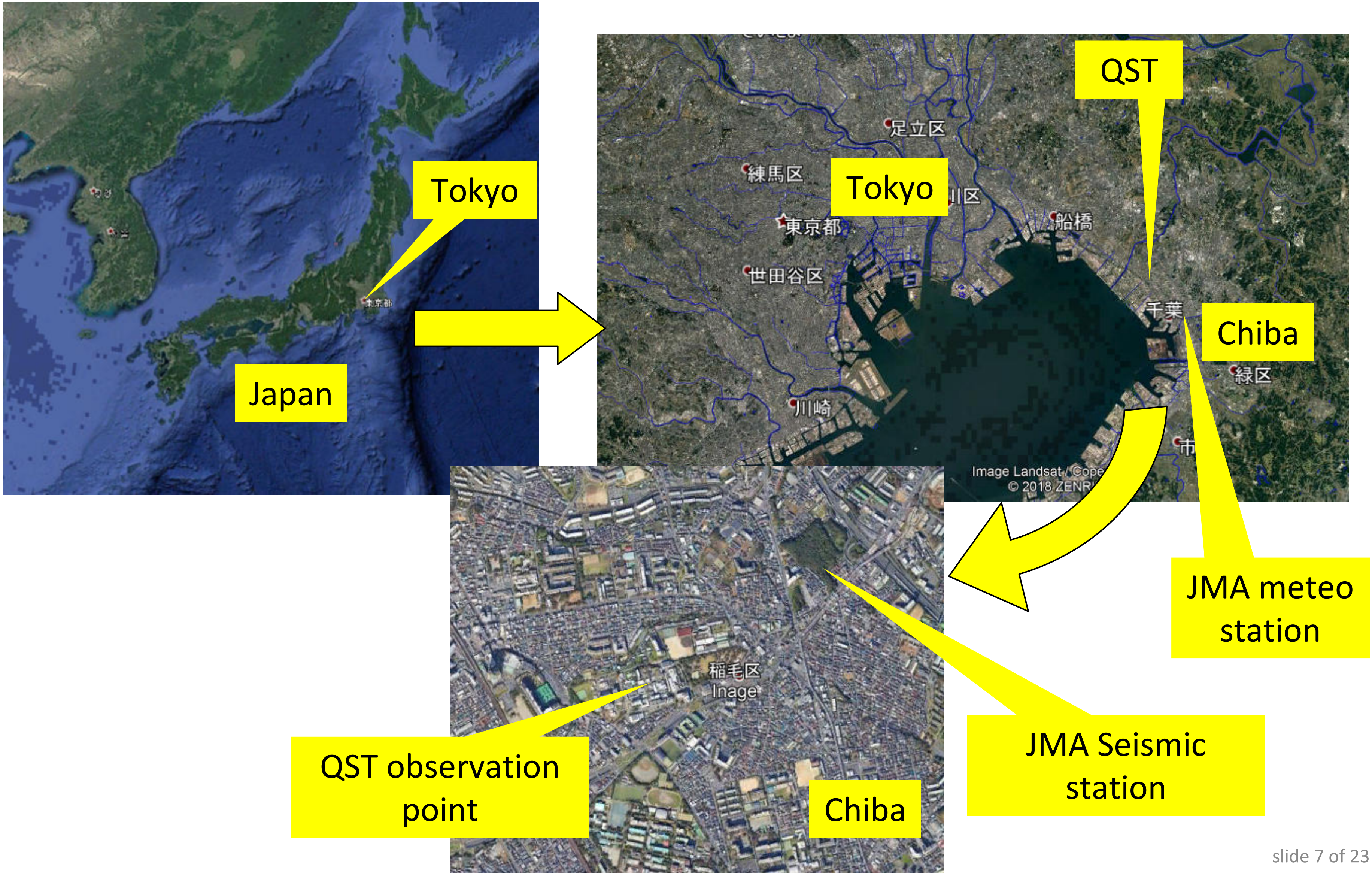
Radon research at QST, BfS & JRC

- **BfS** (German Federal Office for Radiation Protection) = the German radioprotection authority; among tasks: assure compliance with legislation $\Rightarrow$ Rn calibration, measurement QA, Rn mapping, design of surveys etc. This includes developing methodical and statistical skills.
- **QST** (Japanese institutes for Quantum and Radiological Science and Technology): Rn & Tn measurement methodology, time series analysis.
- **JRC** (Joint research centre of the European Commission): Rn metrology, contribution to European radioprotection legislation, radon data compilation and mapping in European scale.
- BfS + QST; BfS + JRC: cooperation for many years. Also cooperation with Italian colleagues.
- European level: EU-funded international research such as Metro Radon.



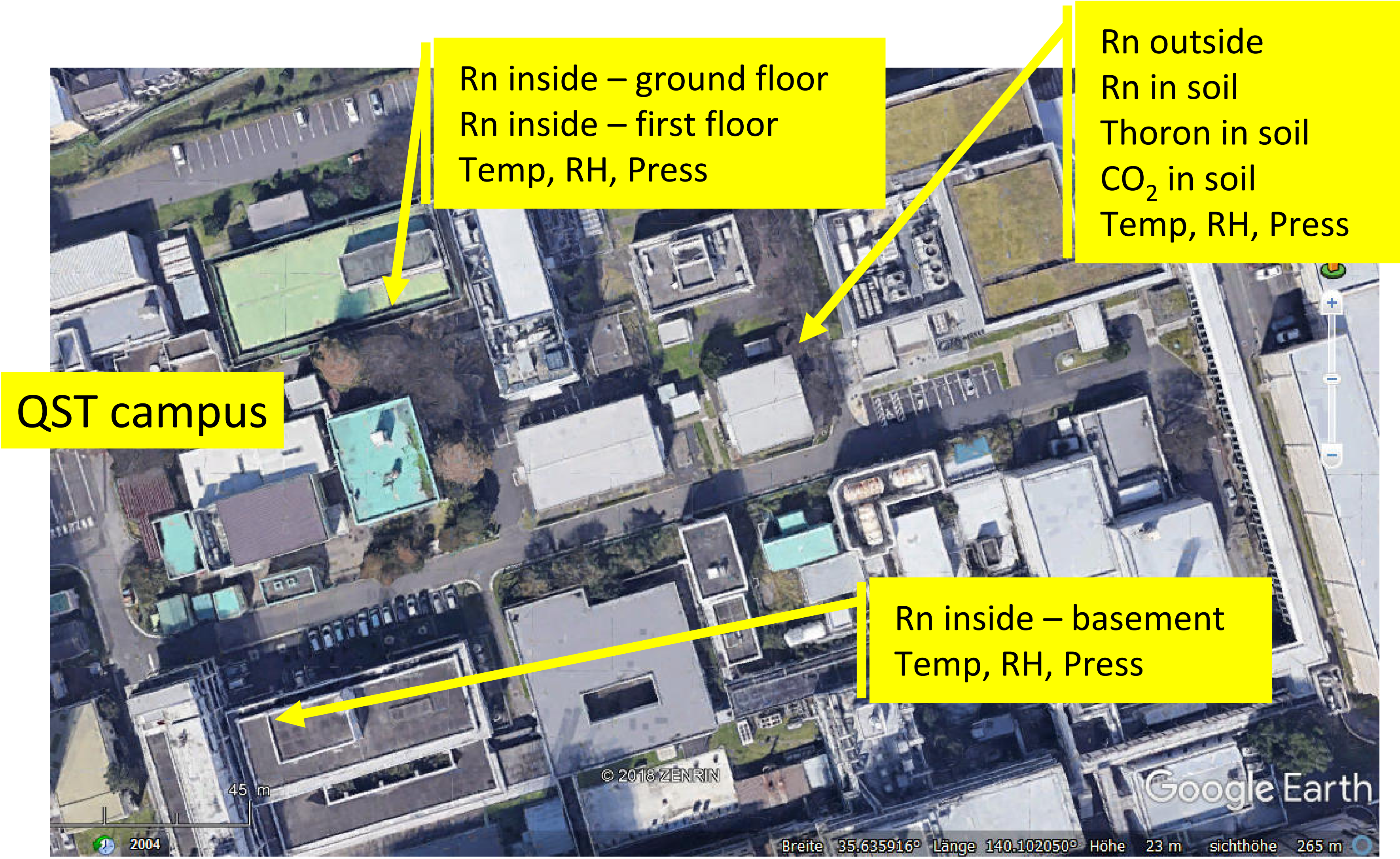


The site - 1



Tokyo
Japan
QST
Tokyo
Chiba
足立区
練馬区
東京都
世田谷区
川崎
船橋
千葉
緑区
JMA meteo station
稲毛区
Inage
QST observation point
Chiba
JMA Seismic station

The site - 2



Rn inside – ground floor
Rn inside – first floor
Temp, RH, Press
Rn outside
Rn in soil
Thoron in soil
CO_2 in soil
Temp, RH, Press
QST campus
Rn inside – basement
Temp, RH, Press
© 2018 ZENRIN
Google Earth
45 m
2004
Breite 35.635916° Länge 140.102050° Höhe 23 m sichthöhe 265 m

Measurement

- outdoor Rn (Alphaguard) + meteo (temp, press, hum)
- soil Rn + Tn (RTM-2220) + CO_2 + meteo

soil gas probe

exhalation measurement

this data will be analyzed in the following

2 x indoor Rn, ground + first floor (Alphaguard) + meteo

Available time series

- Rn indoor
  - basement of building 1: since 2011;
  - ground and first floor of building 2: since 2016
- Rn outdoor: since 2007
- Rn, Tn and CO_2 in soil: since 2015

  all together with temp., press, humidity

  on QST campus
- regional meteo data from Chiba meteorological station (JMA, Japan Meteorological Agency, station ca. 3.5 km SSE of QST)
- seismic data from JMA (Chiba station ca. 1 km NE of QST)

missing values (instrument maintenance, failure):
imputation by interpolation, ARMA or machine learning

Time series basics, 1

Time series X(t)

- t=1…n; i.e. temporal resolution scaled to 1 unit (here: 1 h).
- Decomposition 1: (phenomenological)
  $X(t) = X_0$ …………………… offset
  $+ x_1(t)$ ………………… long-term trend
  $+ g(t)$ ………………… periodic component
  $+ Z(t)$ ………………… aperiodic component

e.g. by Box-Jenkins, AR(F)IMA, EMD

- Decomposition 2: (functional)
  $X(t) = f[Y_1,\ldots,Y_m](t)$ …… explained by controls Y_i
  $+ u(t)$ ……………… unexplained

e.g. by multiple regression, machine learning, AR(F)IMAX ?

Example: linear dependence model:
$f[Y](t) = \int_{(-\infty \to t)} \varphi(t-t') \, g(Y(t')) \, dt' = \varphi * g(Y)$
$\varphi(u)$=transfer function, accounting for delayed effect
no delay: $\varphi(t-t') = \delta(t-t')$; shift: $\varphi(t-t') = \delta(t-t'-\Delta t)$

AR(F)IMA(X) – auto regressive (fractional) integrated moving average (with regression)
EMD – Empirical mode decomposition

Time series basics, 2

- Estimation of shift:
  shift = estimate of $E[\varphi]$
  Lagged or cross-correlation function, correlogram:
  $r_{12}(h) = \text{Pearson}(x_1(t), x_2(t+h))$
  variety: cross-covariance $c_{12}(h)=E[X_1(t)\, X_2(t+h)]$

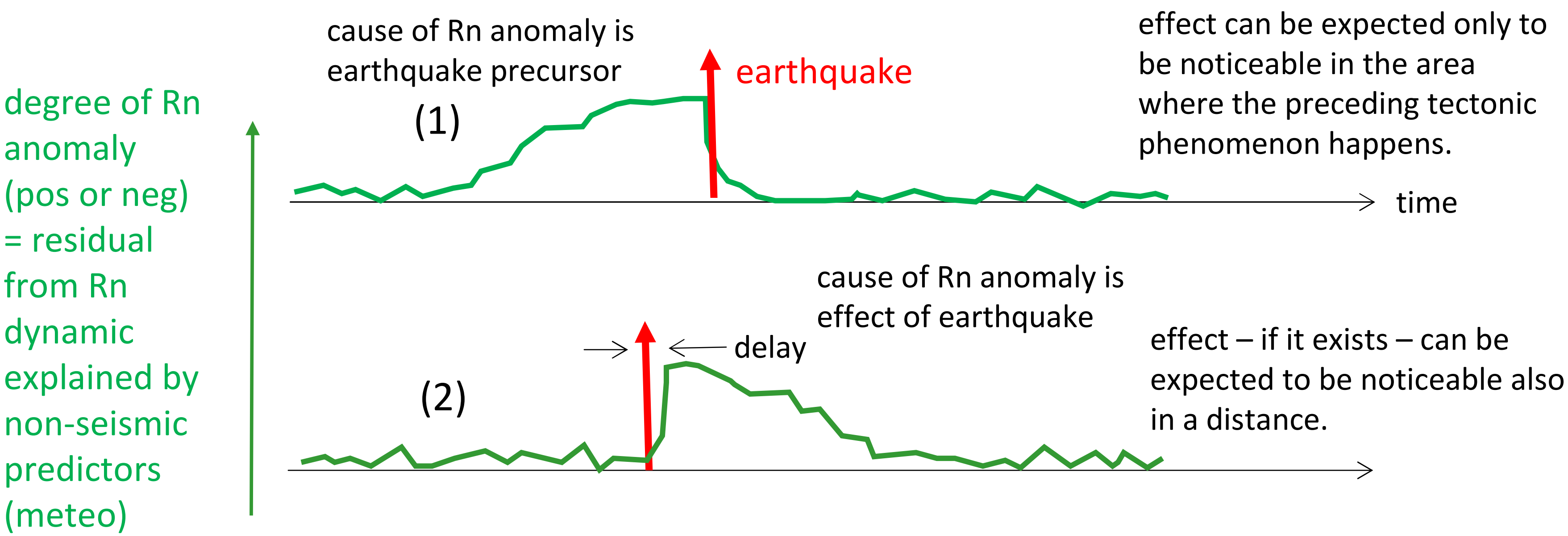
- Estimation of periodicity = periodic shift:
  Auto-correlation function ACF: $ACF(h)=\text{Pearson}(x(t),x(t+h))$
  Correlogram by Fourier transform,
  $x^*(\omega)= (2\pi)^{-1/2} \int_{(-\infty \ldots \infty)} \exp(-i\omega t)\, x(t)\, dt$,
  estimated by FFT algorithms (Fast Fourier Transform)
  Periods appear as peaks in the frequency spectrum $z^*(\omega)$

Rn response to tectonic dynamic

<u>Theoretical patterns:</u>

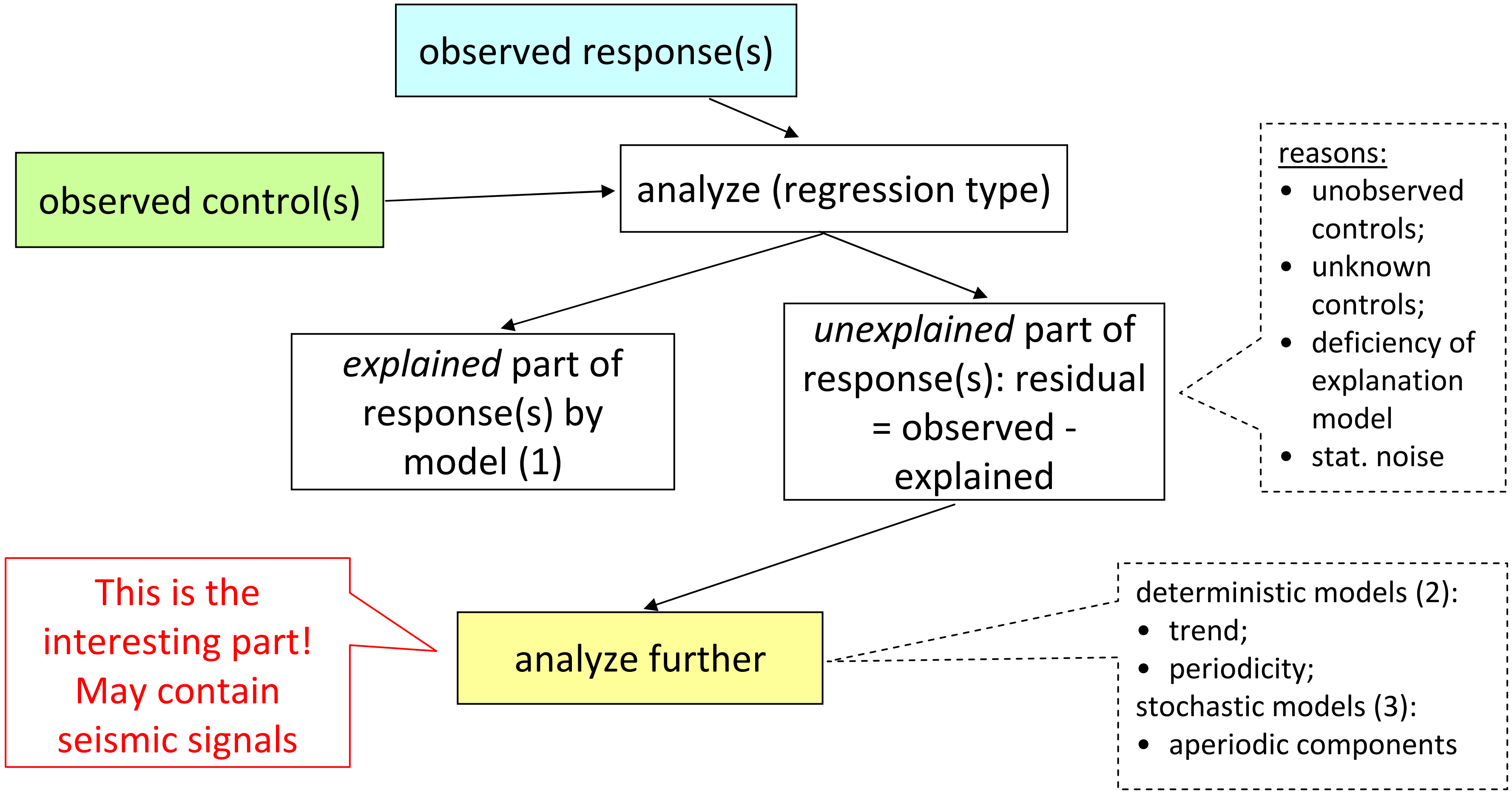
1. A Rn anomaly may indicate a tectonic process which may lead to a seismic event, such as build-up of stress;

2. Inversely, a seismic event may trigger changes in ground permeability or of hydrology, which leads to modified Rn transport.



Rn response not necessarily a point-type event! Association not easy to quantify!

Analysis flow



Forecast:

1) if available: generate series based on known controls, model (1)
2) generate series components based on deterministic model (2)
3) simulate stochastic component, model (3)

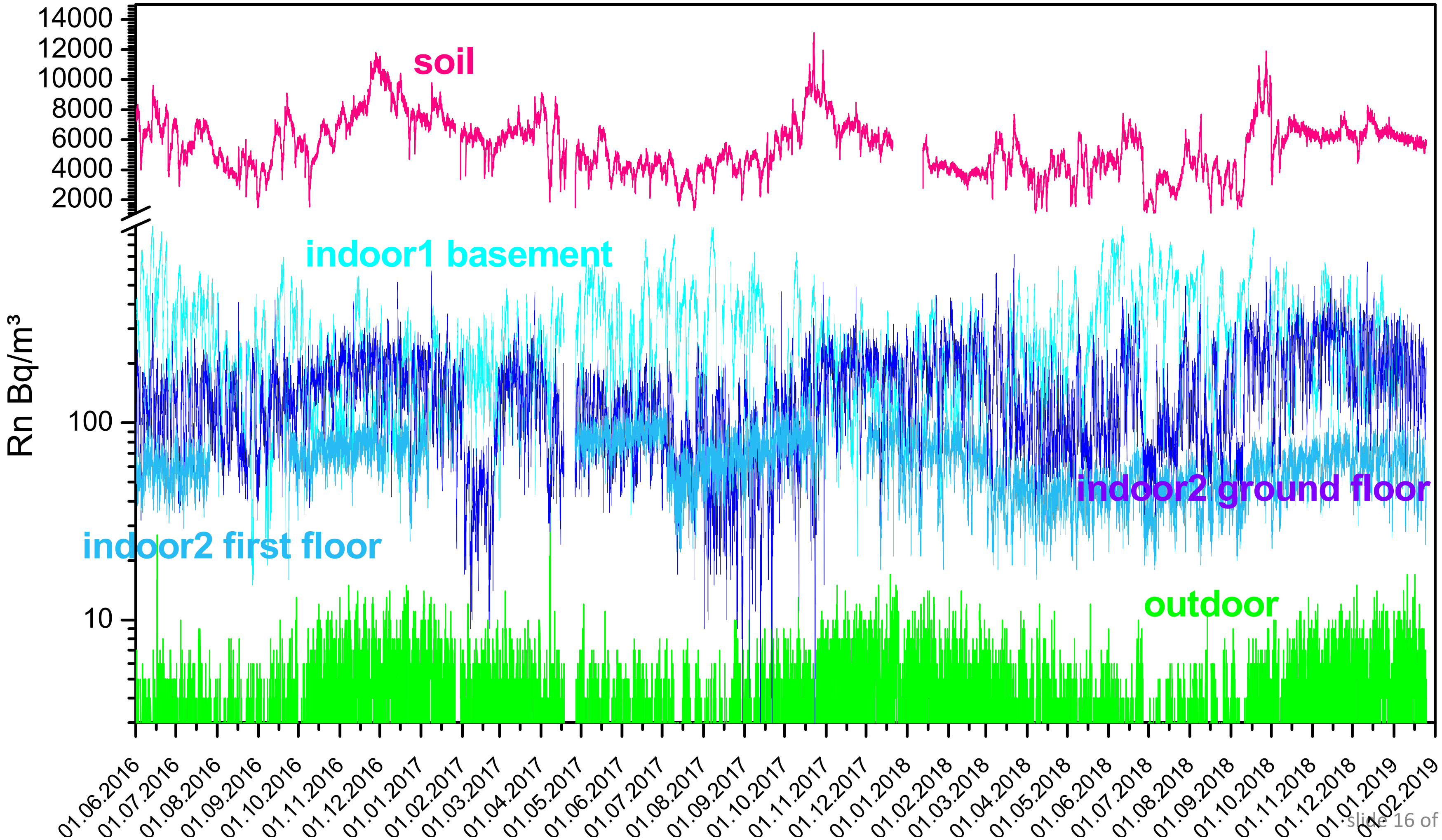
Statistical methods

- Exploratory analysis:
  - periodicity by correlogram
  - delayed response by cross-correlation
- Regression modelling:
  - multiple regression (MR - classical)
  - generalised additive model (GAM)
  - machine learning (ML), e.g.
    - -- gradient boosting machine (GBM)
    - -- multivariate adaptive regression spline (MARS)
    - -- random forest (RF)
    - -- support vector machine (SVM)
    - -- deep learning (DL, similar to ANN)
- Residual analysis:
  - (partial) autocorrelation analysis (classical)
  - Hurst analysis to find persistent memory structures
  - matching with point events (seismic events)

data 1: radon time series

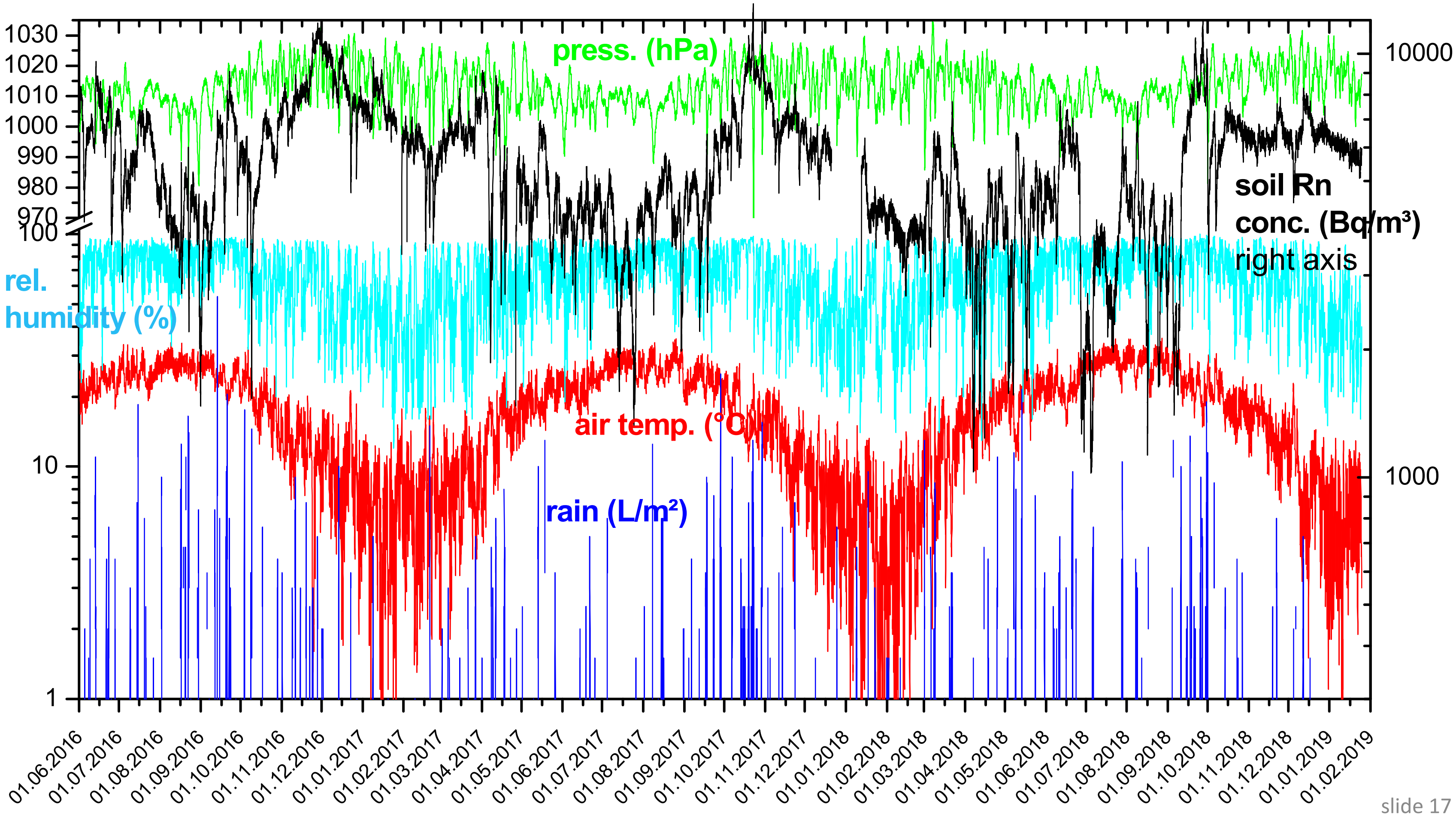
from 1 June 2016 – 20 Jan 2019

essentially similar pattern, but not concordant!



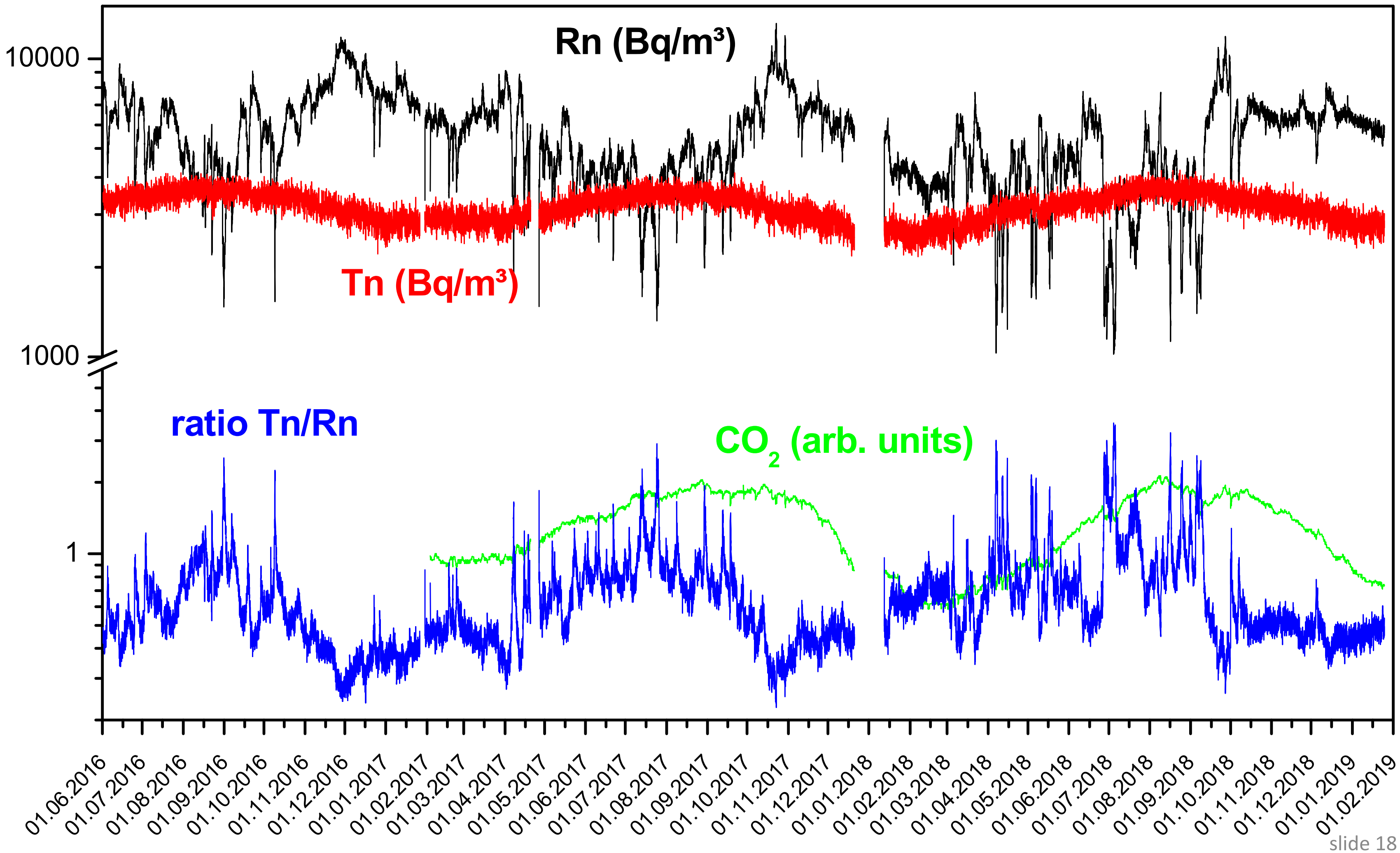
data 2: soil radon & meteo

evidently strong influence of meteo variables on soil Rn conc.



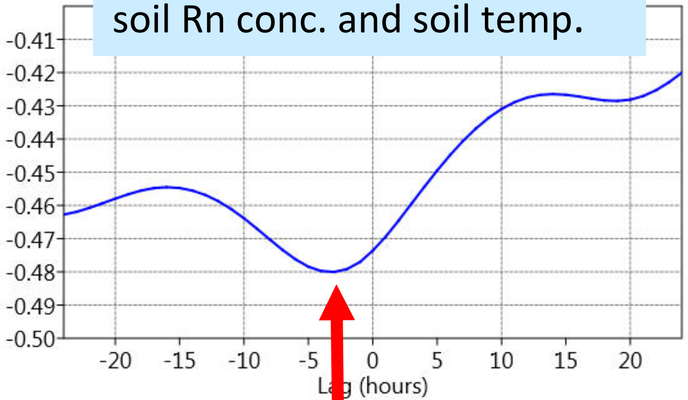
data 3: soil Rn, Tn, Tn/Rn ratio and CO_2

Rn and Tn not concordant!



relation soil Rn - meteo predictors

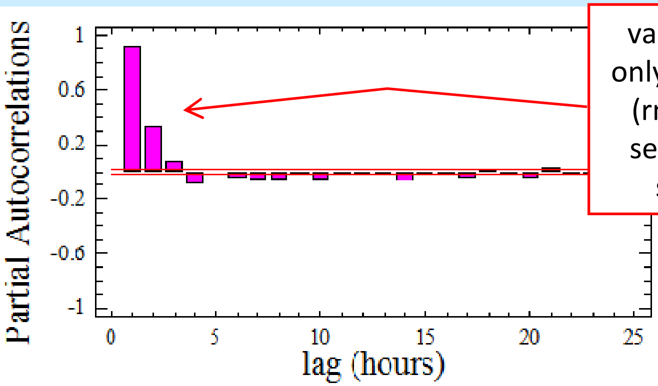
cross-correlation between soil Rn conc. and soil temp.



- soil temp. leads by 3 hours
- negative corr. between soil Rn and temp.

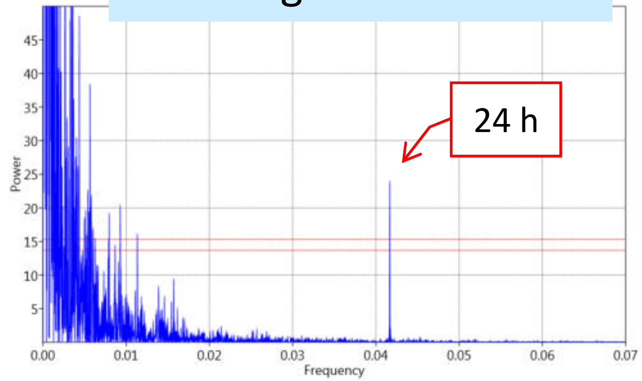
<u>First step</u>: explanatory data analysis, to detect structures in the data which may help improve models

Partial autocorrelation function (PACF) of soil Rn (24h cycle adj.)

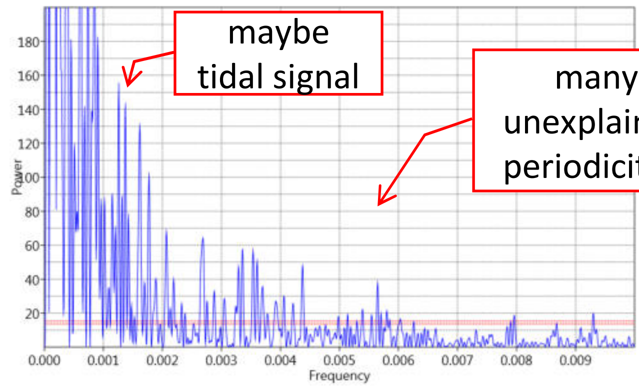


values depend not only on previous one (rnd walk), but on several previous... system inertia

Periodograms of soil Rn



24 h

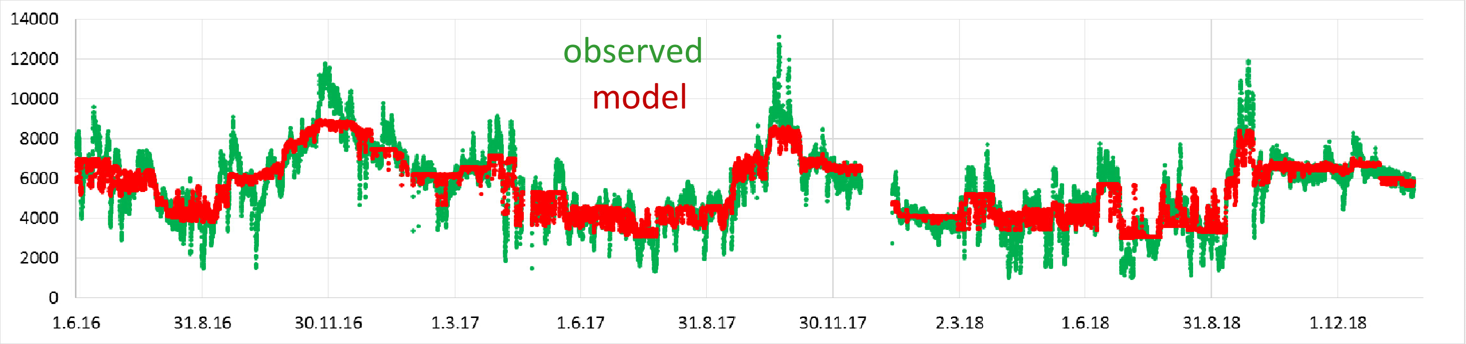


maybe tidal signal

many unexplained periodicities

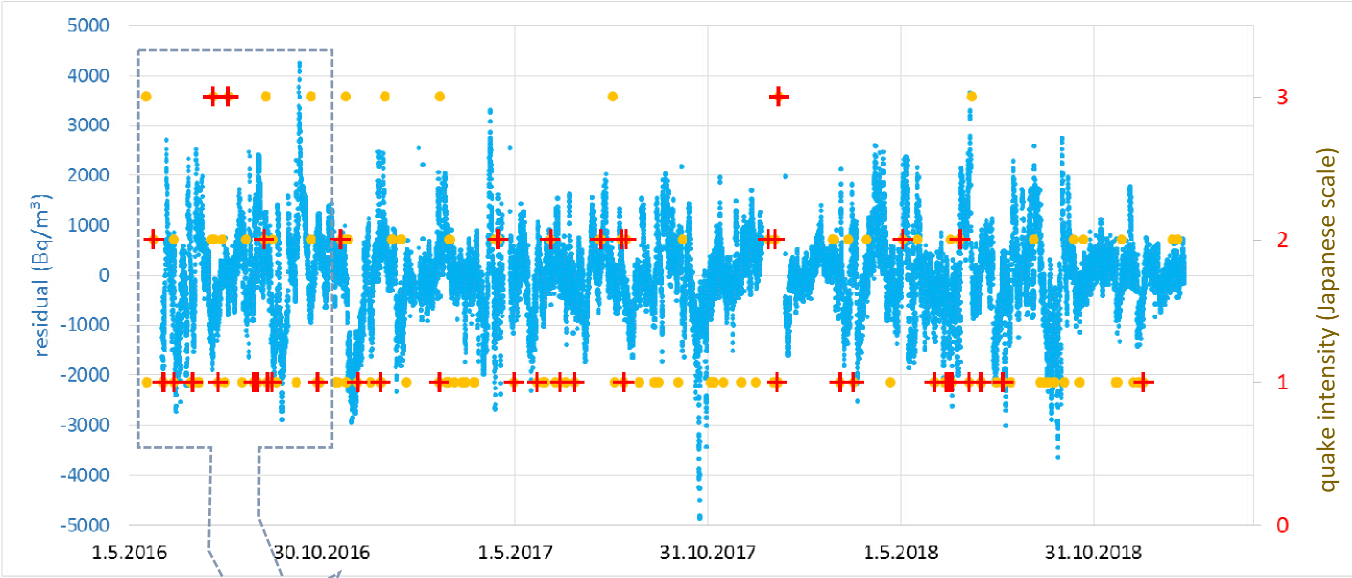
Regression methods applied

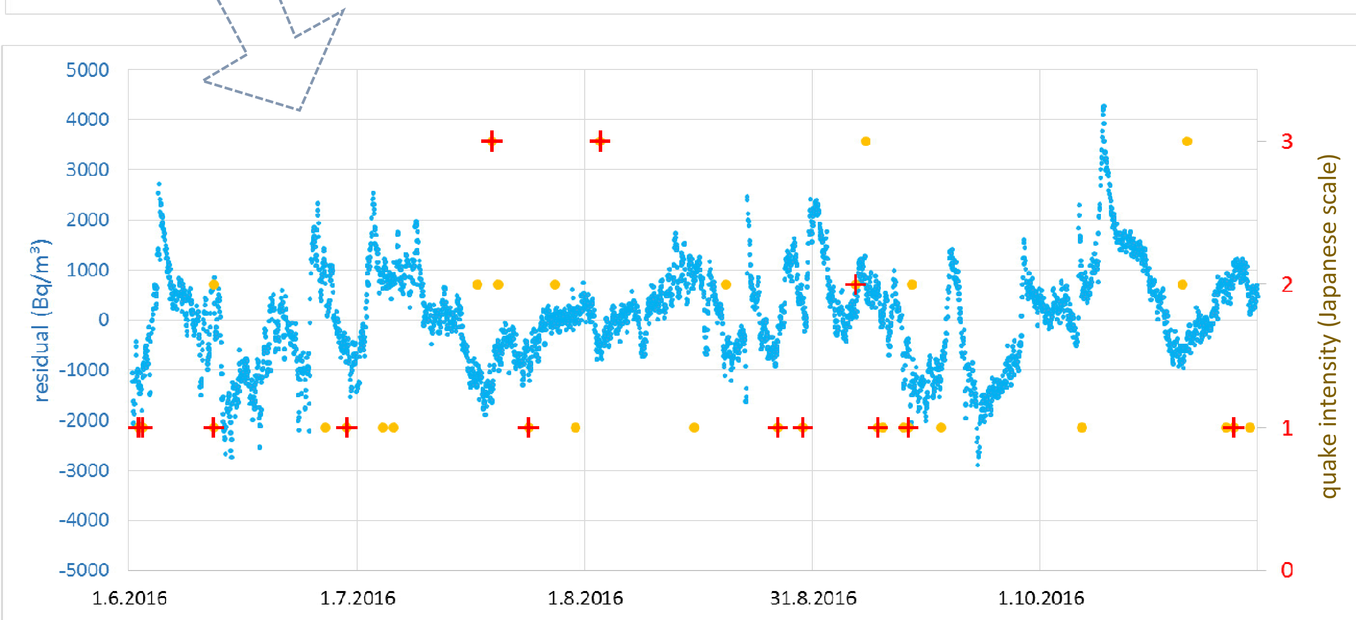
- MARS
- Random Forest
- Boosted Trees
- ANN
- SVM
- Software: Statistica 7; 25-30% random test data
- Predictors: rain, outdoor temp., soil temp., meteo station temp., x-component of wind speed, soil humidity, day of year (doy), running hour (t).
  (No time delay applied, because for some strange reason, lagged predictors perform worse.)
- Most important in all models: doy and t! These are not physical predictors, but statistical proxies for unknown predictors... a bit frustrating!
- Best model: Random Forest, r^2(obs. – test set)=0.81



extremes badly modelled!

seismic signals ???





- earthquakes

+ earthquakes < 40 km from Chiba (no Dobrovolsky formula applied)

- Residuals (pred-obs) of soil Rn conc. acc. RF model

- Residuals still contain a correlated, apparently aperiodic effect, which is unexplained
- No evident association with earthquakes can be recognized

Conclusions and to-do

- The soil Rn dynamic could not yet be explained satisfactorily. It seems that relevant predictors are missing, which are responsible for the Rn extremes (unknown or no data, like possibly fluctuating ground water level).
- Methodology seems to be essentially appropriate; further model selection and fine-tuning will still be necessary.
- In spite of seismic activity, no association between seismic and anomalous Rn signals is apparent.
- A metric for association between anomalies has still to be developed. (Seismic events are point-type phenomena, while the Rn response may be continuous.)
- Possible seismic induced anomalies are difficult to distinguish from ones of different cause (rain?, ground water level?)
- Perhaps the ground at the investigation site is not optimal for the purpose: late Pleistocene sedimentary terrace, sandy-clayey.
- The investigation will be continued. At least, we collect experience with statistical procedures necessary for Rn time series analysis.
- In any case, the association between seismic activity and Rn is a difficult matter, as also reflected by literature about the subject.

Thank you!

Bundesamt für Strahlenschutz

German Federal Office for
Radiation Protection

European
Commission

This work is supported by the European Metrology Programme for Innovation and Research (EMPIR), JRP-Contract 16ENV10 MetroRADON (www.euramet.com). The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States.

MetroRADON