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

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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$_2$O or CH$_4$.

• **Problem:** Rn dynamic has predominantly non-tectonic control which obscures possible tectonic signals → 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!

**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

Much research for decades ...

Results little encouraging:
- The effect exists
- But no reliable prediction
  (Reliable: low 1\textsuperscript{st} and 2\textsuperscript{nd} kind errors)
Radon research at QST, BfS & JRC

- **BfS** (German Federal Office for Radiation Protection) = the German radioprotection authority; among tasks: assure compliance with legislation ⇒ 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
- Chiba, Japan
- QST observation point
- JMA meteo station
- JMA Seismic station
The site - 2

- Rn inside – ground floor
- Rn inside – first floor
- Rn inside – basement
- Temp, RH, Press

- Rn outside
- Rn in soil
- Thoron in soil
- CO₂ in soil
- Temp, RH, Press

QST campus
Measurement

- outdoor Rn (Alphaguard) + meteo (temp, press, hum)
- soil Rn + Tn (RTM-2220) + CO₂ + meteo

this data will be analyzed in the following

soil gas probe

exhalation measurement

indoor Rn, basement (Alphaguard) + meteo

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 CO₂ in soil**: since 2015
  all together with temp., press, humidity

• **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)
  $$X(t) = X_0 \quad \text{offset}$$
  $$\quad + x_1(t) \quad \text{long-term trend}$$
  $$\quad + g(t) \quad \text{periodic component}$$
  $$\quad + Z(t) \quad \text{aperiodic component}$$

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

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: $\varphi(t-t') = \delta(t-t'-\Delta t)$
- e.g. by Box-Jenkins, AR(F)IMA, EMD
- e.g. by multiple regression, machine learning, AR(F)IMAX?
Time series basics, 2

- **Estimation of shift:**
  \[
  \text{shift} = \text{estimate of } E[\varphi]
  \]
  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:
  \[
  \text{ACF}(h) = \text{Pearson}(x(t), x(t+h))
  \]
  Correlogram by Fourier transform,
  \[
  x^*(\omega) = (2\pi)^{-1/2} \int_{-\infty}^{\infty} \exp(-i\omega t) x(t) \, dt,
  \]
  estimated by FFT algorithms (Fast Fourier Transform)
  Periods appear as peaks in the frequency spectrum \( z^*(\omega) \)
Rn response to tectonic dynamic

Theoretical patterns:

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!
observed response(s)

observed control(s)

analyze (regression type)

explained part of response(s) by model (1)

unexplained part of response(s): residual = observed - explained

analyze further

reasons:
- unobserved controls;
- unknown controls;
- deficiency of explanation model
- stat. noise

deterministic models (2):
- trend;
- periodicity;
stochastic models (3):
- aperiodic components

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)

This is the interesting part!
May contain seismic signals
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.

First step: 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

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
seismic signals

- 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.
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