Simultaneous monitoring of soil radon and moisture at different depths in a Fukushima forest site, Japan

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1. Introduction: Radon in soil

Radon Isotopes

<table>
<thead>
<tr>
<th></th>
<th>$^{219}\text{Rn}$</th>
<th>$^{220}\text{Rn}$</th>
<th>$^{222}\text{Rn}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series</td>
<td>$^{235}\text{U}$</td>
<td>$^{232}\text{Th}$</td>
<td>$^{238}\text{U}$</td>
</tr>
<tr>
<td>Half-life ($T_{1/2}$)</td>
<td>3.9 s</td>
<td>55 s</td>
<td>3.82 d</td>
</tr>
<tr>
<td>$\alpha$-decay energy (MeV)</td>
<td>6.946</td>
<td>6.404</td>
<td>5.490</td>
</tr>
</tbody>
</table>

In Geophysical exploration, Soil & atmospheric sciences

Radon
- Radioactive
- Water soluble
- Chemically inert

WHO handbook on indoor radon

In Geophysical exploration, Soil & atmospheric sciences

In Geophysical exploration, Soil & atmospheric sciences
2. Purposes

I. to elucidate possible relationships of soil radon and moisture with several parameters including soil properties and meteorological ones,

II. to evaluate dynamic properties of soil radon and also moisture quantitatively,

III. to apply radon as a tracer for soil gas and water transportation.

And further, to evaluate the fate of fallout nuclides in Fukushima forest site in our country by using soil radon as a tracer of moving soil gas and water in the future.
3. Location

Location: Fukushima University, Japan. (37.68N, 140.45E)
Stand: Temperate deciduous forest (Oaks, Pine, Chesnut etc.)

Mean Annual
Temperature: 13 °C
Precipitation: 1200 mm
Snow fall: 190 cm
(Japan Meteorological Agency)

Time series plots of Temperature, Precipitation and Snowfall in Fukushima. (May 2014 – Jun 2015)
4. Monitoring Procedures

Since August 2013~
- Radon Activity concentration
- Temperature
- Barometric pressure (VDG, Algade, France)

Since May 2014~
- Soil moisture
  (Soil moisture sensor, North One Co. Ltd., Japan)

Schematic diagram of setting probes
(Left: Rn, Right: Moisture)
5. Outline of the previous studies: Soil Properties

Depth profile of soil properties ($^{226}$Ra content, pH, Water content, and porosity: Aug. 21, 2013)

**Homogeneous soil**

Depth distribution profiles of $^{222}$Rn in soil in 2013; Upper (Jun.-Nov.), Lower (Dec.-Feb.)
5. Outline of the previous studies: Transport of $^{222}$Rn in soil

Effective Diffusion Coefficient of Rn ($D_e$)

$$D_e = \frac{1}{J} \cdot \frac{dC}{dz} \left[ \text{m}^2 \text{s}^{-1} \right]$$

C: Rn Activity concentration (Bq m$^{-3}$), z: Depth of the soil (m)

Rn flux ($J$)

$$J = 2 \sim 14 \times 10^{-2} \left[ \text{Bq} \text{ m}^{-2} \text{s}^{-1} \right]$$

$$\rightarrow D_e = 4.7 \sim 6.1 \times 10^{-6} \left[ \text{m}^2 \text{s}^{-1} \right]$$

The effect of Typhoon on $^{222}$Rn
6. Results:
Time series plots of Rn and moisture (May 28 ~ Nov. 1 in 2014)

Rn & water dynamics
5 events in soil

Rainfall intensity
0.9 (>mm h⁻¹)

Summer
1 (Jun 28 ~ Jul 3)
2 (Jul 9 ~ 14)
3 (Jul 17 ~ 24)

Fall
1 (Oct 5 ~ 13)
2 (Oct 13 ~ 21)
6. Results: Water Infiltration on soil radon

Water flow \( (q_z) \)

\[
q_z = 1.2 \times 10^{-5} \ (m \ s^{-1})
\]

from Gravitational drainage

Changing moisture (Upper) and \(^{222}\text{Rn} \) (Lower) in a rainfall event
6. Results: Dissolution rate of $^{222}$Rn in water

\[ A(t) = A_0 e^{-\left(\lambda + S\right)t} \]

- $A(t)$: Rn Concentration (Bq m$^{-3}$)
- $\lambda$: Decay constant (s$^{-1}$)
- $S$: Dissolution rate (s$^{-1}$)

Decreasing Rn level after saturation (Summer 1)
6. Results: Temporally rise and Dissolution rate of Soil $^{222}$Rn

### Rate of increase in soil radon

<table>
<thead>
<tr>
<th>Event</th>
<th>Rate of increase in soil radon (Bq m$^{-3}$ h$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td><img src="image-url" alt="Graph" /></td>
</tr>
<tr>
<td>Fall</td>
<td><img src="image-url" alt="Graph" /></td>
</tr>
</tbody>
</table>

### Dissolution rate of radon in water

<table>
<thead>
<tr>
<th>Event</th>
<th>Dissolution rate (h$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td><img src="image-url" alt="Graph" /></td>
</tr>
<tr>
<td>Fall</td>
<td><img src="image-url" alt="Graph" /></td>
</tr>
</tbody>
</table>

### Details of precipitation in each events

<table>
<thead>
<tr>
<th></th>
<th>Summer</th>
<th>Fall</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Event</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Precipitation (mm h$^{-1}$)</td>
<td>100</td>
<td>105</td>
<td>35</td>
</tr>
<tr>
<td>Duration (h)</td>
<td>25</td>
<td>27</td>
<td>40</td>
</tr>
<tr>
<td>Intensity (mean, mm h$^{-1}$)</td>
<td>4.0</td>
<td>3.9</td>
<td>0.9</td>
</tr>
</tbody>
</table>
6. Results:
Effect of decreasing moisture on soil radon after rain

Water flow $q_z$:
Diffusion - controlled (Evaporation & Capillary rise)

Changing moisture (Upper) and $^{222}$Rn (Lower) after a rainfall event
6. Results:
Comparing moisture diffusivity with soil Rn transport in soil

\[ q_z = -K_h(\theta) - D_h(\theta) \frac{d\theta}{dz} \]

- **q\_z**: Flow rate
- **K\_h**: Hydraulic conductivity
- **D\_h**: Moisture (Hydraulic) Diffusivity
- \( \frac{d\theta}{dz} \): Moisture gradient

\[ D_h(\theta) = 5.0 \times 10^{-7} \]
\[ \sim 7.0 \times 10^{-6} \text{ } \left[ m^2 s^{-1} \right] \]

**Effective Diffusion Coefficient of Rn**

\[ D_e = 4.7 \sim 6.1 \times 10^{-6} \text{ } \left[ m^2 s^{-1} \right] \]

Dynamics of Rn and Moisture in soil → Diffusion-controlled
“Time lag” between Rn and Moisture
I. Soil radon and moisture in soil show an opposite correlation at precipitation

II. There is some “time lag” between soil $^{222}\text{Rn}$ and moisture at the beginning and at the end of precipitation.

III. Same order of magnitude was obtained for the diffusivity of both radon and water in soil.
Acknowledgements:

We could appreciate Prof Akira Watanabe (Fukushima University Japan) for helping field works in our Fukushima forest site, and also Dr. Claude Bertrand (Algade, France) for giving valuable advices for Rn measurements.