MEMOIRS OF THE COLLEGE OF SCIENCE, UNIVERSITY OF KYOTO, SERIES B,
Vol. XX, No. 4, Article 6, 1953.

Radon Content and its Change in Soil Air near the Ground Surface.

By

Zin'itirô HATUDA

Geological and Mineralogical Institute, University of Kyoto

(Received Aug. 10, 1953)

Abstract

Radon gas escaping from the ground takes part in the ionization of the atmosphere, which, in turn, influences atmospheric electricity and meteorology. Radon content of soil air was measured from three different depths once a day for more than two years. Besides seasonal change, the results show temporary variations due to changes of atmospheric pressure and precipitation. Some discussions are given for the results observed.

It seems that the felt earthquakes in most cases were followed by an increase in the concentration of radon: In one case, the increase of radon preceded the earthquake, and what is more interesting, the deeper the sampling site was, the greater proportionately was the increase in concentration, an instance opposite to the case where meteorological influences are at work.

Introduction

It is well known that the soil air which fills the pores of the soil or rock has a tolerable quantity of radon, and that the radon content shows considerable changes near the ground surface, though it gradually increases with increasing depth approaching asymptotically a finite value. It depends not only on radium content and the emanating power of soil or rock, but on the changes in aeration caused by sunshine, changes of atmospheric pressure and precipitation. In general, the radon content of soil air is several thousands times as much as that of the atmosphere and yet is by far less than the equilibrium quantity with radium in the soil. According to J. Satterly[1], for example, it is only from one fifth to one twentieth of the equilibrium quantity. The radon escaping from the soil takes part in the ionization of the atmosphere. Though radon is heavier than other gases usually found in the surface atmosphere and, furthermore, rapidly disintegrates with a half-life period of 3.8 days, its effect in ionizing the air may be considerable even far up in the sky*. Thus the radon exhaled from the ground plays an important rôle in atmospheric electricity and meteorology.

---

* According to V. F. Hess (1912), the ionization in a closed ionization chamber decreases with height above the ground up to about 400 m and then shows gradual increase owing to the predominating cosmic-ray intensity.

So far as the author is aware of, studies of radon in the atmosphere have been made by several authors, but those of radon in ground soil air have been few, among which those by H. Bender[2] and H. Israel-Köhler[3] are of importance. Taking meteorological factors into consideration, the author made two series of observations by measuring the concentration of radon in soil air once a day over more than a year respectively (Oct., 1944—Oct., 1945 and Aug., 1946—Sept., 1947). This was for the purpose of obtaining some reference data mainly for radioactive exploration. The result was that the radon in soil air seems to show not only seasonal variation, but also temporary variations due to changes of atmosperic pressure, precipitation and the like. These variations imply the escape of radon from the earth as well as aeration near the ground surface, and in this sense will be important for meteorology, the science of atmospheric electricity and agriculture.

Observations

The first term observation (from Oct.1, 1944 to Oct. 31, 1945) :

Sampling was made by replacing the water filling the sampling flask with soil air sucked up through a collecting tube from the ground. We used three collecting tubes made of iron pipe of 22 mm diameter and whose lengths were different so as to be fit for sampling soil air from three different depths (0.6, 1 and 2 m). These three tubes were driven at 3 m spacings into the ground in back of our laboratory, where the soil was of granite sand.

The tubes had many holes between five and twenty-five centimeters from the lower end, through which soil air was to be sucked in. At the top of each tube there was a rubber plug penetrated by glass tube with a stop-cock. Just before sampling, the air in the collecting tube was drawn out with the device mentioned above and ejected. The sampling flask filled with soil air was then brought to the laboratory where the radon content was determined by the Schmidt type fontactoscope as is usually done in the radioactive measurement of spring water. Three sets of fontactoscopes were used; the same one for the samples from the same depth. The constants of the fontactoscopes were as follows :

Instruments	Constants*
No. 401	3.61×10^{-10} curies
No. 403	2.62 〃 〃
No. 404	2.82 〃 〃

The second term observation (from Sept. 1, 1946 to Sept. 30, 1947) :

---

* The quantity of radon in the ionization chamber required to produce a shifting velocity of one division per minute of the indicator on the scale just when radon first is received (initial activity).

The second term observation was principally the same as in the first term, but different from the latter in method, number of samplings and the instrument by which the radon content was measured. The soil air was sampled from the depth of 1 m only. In this case, the soil air was directly drawn up into the ionization chamber through a drying tube, which had been evacuated in advance. The ionization chamber was 2950 c.c. in volume and combined with an electroscope. The constant of this radon-meter was determined as 5.37×10^{-10} curies by calibration with the standard solution of radium from the former Institute of Physical and Chemical Research in Tokyo.

Results

The observed results are shown in Tables 1–2 and Figs. 1–2. Generally speaking, the change in radon content is rather gradual, especially when meteorological changes are not conspicuous. The averages of the contents of radon in the first term observation were 5.41, 11.7 and 19.2 Eman (1 Eman $= 10^{-10}$ curies per 1 litre) for soil air at 0.6, 1 and 2 m respectively. These figures are a little higher than the results of other observers, which may be explained by the peculiar nature of the soil concerned, which is mainly decomposed sand derived from Kitasirakawa granite whose radium content had been measured by the author[4], and had proved to be more radioactive than average common rocks. Since sampling was made at about eleven a.m. daily, there would be no objection in the comparison of daily values though there might possibly be a diurnal variation of radon concentration in the soil air.

Table 1.

The radon content of soil air taken from 0.6, 1 and 2 m in depths during Sept. 11, 1944 – Oct. 1, 1945.

Date	Radon content		
	0.6m	1m	2m
1944			Eman
IX–11		9.3	
12		9.9	
13		9.9	
14		9.6	
15		9.5	
16		11.1	
17		11.3	
18		12.4	
19	5.00	13.3	
20	4.37	11.1	
21	4.09	12.2	
22	3.93	11.1	
IX–23	3.69	11.5	
24	4.66	11.1	
25	4.00	11.4	
26	4.88	11.7	
27	4.88	11.3	
28	3.84	11.8	22.0
29	4.70	10.5	20.9
30	3.92	11.4	21.3
X– 1	5.87	11.2	21.7
2	5.21	12.2	21.4
3	5.93	11.1	21.4
4	5.81	11.8	21.5
X– 5	6.50	13.5	21.5
6	6.24	12.5	21.1
7	5.94	13.6	22.3
8	10.55	15.5	25.4
9	8.14	15.0	26.0
10	7.32	15.9	25.5
11	6.51	15.4	25.5
12	5.47	14.6	24.7
13	5.15	13.5	23.1
14	4.30	12.7	23.6
15	3.60	11.2	22.0
16	4.08	10.8	21.6

Table 1. (Continued)

Date	Radon content		
	0.6m	1m	2m
1944			Eman
X–17	4.65	10.9	22.2
18	6.03	11.9	22.3
19	5.64	10.9	21.5
20	6.80	11.9	21.4
21	6.93	13.2	21.5
22	5.00	12.0	20.8
23	5.00	11.0	20.1
24	4.16	12.0	21.6
25	4.64	11.6	20.5
26	4.54	11.5	21.7
27	4.73	11.3	21.4
28	6.12	12.9	21.2
29	6.31	12.1	21.0
30	5.70	12.0	21.0
31	5.70	12.5	20.8
XI– 1	5.24	12.2	20.9
2	5.10	11.9	21.5
3	5.80	12.2	19.6
4	6.08	12.2	17.5
5	5.03	11.8	18.8
6	4.50	12.1	18.1
7	4.41	12.0	18.7
8	4.42	11.1	18.5
9	5.13	12.0	18.5
10	5.56	12.6	17.8
11	5.58	10.7	20.5
12	5.68	13.2	20.9
13	5.19	12.4	21.5
14	4.58	12.9	21.5
15	4.98	12.4	21.8
16	5.14	12.1	19.6
17	5.12	12.2	19.7
18	5.12	12.1	20.1
19	5.27	12.0	19.5
20	5.30	12.3	20.3
21	5.40	12.6	20.7
22	5.36	12.3	20.5
23	5.11	12.1	19.0
24	5.07	11.7	20.4
25	5.53	11.9	20.4
26	6.50	12.9	19.1
27	6.50	12.3	20.5

Date	Radon content		
	0.6m	1m	2m
1944			Eman
XI–28	7.69	13.2	19.4
29	6.45	13.5	19.3
30	6.31	12.9	17.7
XII–1	6.40	11.9	18.0
2	6.63	12.9	18.0
3	7.04	12.3	18.2
4	6.14	10.2	18.7
5	5.07	12.4	17.8
6	5.02	11.2	16.3
7	5.68	11.4	21.9
8	6.85	13.8	22.5
9	6.35	12.2	22.0
10	6.00	12.2	21.4
11	5.52	12.0	21.4
12	6.00	12.4	21.7
13	9.38	12.6	22.1
14	5.67	11.6	17.4
15	5.80	9.8	19.9
16	5.27	10.3	19.7
17	5.01	9.2	18.3
18	3.96	7.3	16.7
19	4.30	9.1	16.0
20	4.23	8.8	15.4
21	3.61	10.9	17.7
22	4.51	10.9	16.4
23	4.74	11.0	18.0
24	5.21	11.5	18.5
25	5.15	10.9	18.9
26	4.54	11.3	18.2
27	5.24	10.7	18.9
28	4.96	10.8	18.6
29	4.87	11.3	17.2
30	5.18	11.4	18.5
1945 31	5.61	10.6	18.5
I– 1	3.72	9.5	15.3
2	4.59	10.1	18.7
3	4.25	9.2	16.3
4	4.60	8.8	17.3
5	3.79	9.8	16.6
6	4.53	10.5	19.1
7	4.40	9.8	18.0
8	4.94	9.6	17.0

Date	Racon content		
	0.6m	1m	2m
1945			Eman
I– 9	4.80	10.8	19.4
10	4.30	10.3	17.6
11	4.17	9.3	15.8
12	4.57	9.7	16.6
13	4.62	8.9	17.5
14	4.27	8.7	15.7
15	2.98	6.4	16.1
16	3.27	6.6	14.7
17	4.01	8.5	15.8
18	3.78	7.8	16.2
19	3.64	9.0	15.9
20	3.74	8.3	16.7
21	4.82	9.2	17.6
22	4.25	8.9	17.7
23	4.71	10.6	18.1
24	3.76	7.9	15.3
25	3.62	10.4	16.4
26	3.76	7.6	16.8
27	3.31	7.4	16.5
28	3.33	9.1	16.8
29	2.83	8.4	16.3
30	3.39	8.5	14.8
31	3.71	8.8	16.3
II– 1	3.53	8.7	14.4
2	4.77	8.2	13.4
3	4.42	8.0	11.8
4	4.23	9.1	13.1
5	4.00	10.2	15.3
6	3.96	7.7	13.8
7	4.15	9.2	16.6
8	4.31	9.3	14.2
9	3.77	9.3	14.4
10	3.16	9.3	12.4
11	4.33	8.4	13.9
12	4.02	7.7	13.4
13	3.72	8.5	14.8
14	4.87	9.4	14.4
15	4.61	8.7	12.9
16	4.50	11.1	16.5
17	5.30	10.0	15.6
18	4.54	10.1	16.3
19	5.21	11.1	17.8

Table 1. (Continued)

Date	Radon content		
	0.6m	1m	2m
1945			Eman
II–20	4.65	10.8	17.9
21	3.98	10.0	16.8
22	4.55	10.8	14.8
23	3.53	8.2	14.1
24	3.91	9.7	15.3
25	3.93	9.4	11.1
26	4.40	7.6	14.2
27	4.77	9.6	17.0
28	5.73	10.3	16.0
III–1	5.52	11.8	12.1
2	5.81	9.3	16.4
3	5.96	12.0	15.0
4	5.98	11.5	14.3
5	4.45	14.6	17.5
6	10.00	16.5	20.2
7	9.86	17.6	21.0
8	9.23	18.2	22.1
9	8.83	17.6	22.4
10	8.68	17.5	23.8
11	7.68	16.9	22.5
12	7.37	16.6	21.2
13	6.59	16.4	—
14	6.63	15.2	19.8
15	9.04	15.9	21.2
16	8.86	14.6	20.8
17	8.59	16.3	19.9
18	7.94	16.6	21.8
19	7.31	16.7	21.2
20	6.64	14.6	21.7
21	6.70	14.9	20.7
22	7.77	14.9	21.8
23	9.12	13.6	21.1
24	7.29	16.1	19.9
25	6.65	13.7	17.4
26	6.09	13.1	19.7
27	5.50	12.8	19.7
28	5.66	14.1	19.5
29	5.57	12.4	20.2
30	5.59	12.8	20.0
31	5.73	14.3	19.3
IV–1	5.20	13.3	20.7
2	4.89	13.2	20.5
IV–3	4.56	12.2	19.8
4	4.54	13.1	20.6
5	4.21	12.7	19.7
6	4.32	12.1	19.7
7	3.68	11.4	18.6
8	3.81	11.4	19.3
9	4.68	11.2	19.1
10	6.17	11.3	19.5
11	7.08	12.2	19.5
12	7.40	12.7	20.3
13	6.42	8.2	19.3
14	4.98	12.0	19.6
15	5.08	12.3	19.9
16	4.76	11.8	20.3
17	4.27	11.6	19.7
18	3.97	11.4	19.7
19	4.23	11.9	20.1
20	6.05	12.5	20.8
21	6.45	13.8	20.2
22	5.79	12.9	20.6
23	5.24	11.6	20.9
24	4.97	12.2	20.0
25	4.78	12.1	16.0
26	4.95	12.1	18.3
27	4.71	12.6	21.2
28	4.95	12.2	21.4
29	3.96	11.5	19.0
30	3.48	10.5	19.8
V–1	3.62	10.5	19.5
2	4.86	10.4	19.5
3	5.88	11.1	19.1
4	5.33	11.6	18.8
5	5.51	11.6	19.0
6	6.15	11.1	19.3
7	5.16	11.0	19.6
8	4.57	12.0	19.9
9	4.92	11.2	19.0
10	5.73	12.0	19.5
11	5.76	10.6	19.4
12	6.48	15.4	19.6
13	9.00	16.2	22.0
14	8.16	16.2	21.8
V–15	7.53	15.1	21.5
16	8.09	15.1	21.7
17	7.60	15.2	21.4
18	7.42	15.8	19.7
19	6.22	15.1	20.1
20	7.66	16.5	20.8
21	8.25	17.0	22.4
22	8.88	16.6	22.8
23	8.58	16.0	20.9
24	7.94	16.1	20.0
25	6.38	15.0	16.0
26	5.80	14.7	18.0
27	4.45	13.4	21.2
28	3.51	11.6	21.4
29	3.89	12.2	19.0
30	3.92	11.5	19.4
31	3.65	11.0	18.7
VI–1	3.79	11.6	18.9
2	5.14	12.2	20.6
3	6.07	14.1	20.5
4	5.37	9.9	19.4
5	4.71	10.1	18.6
6	4.74	12.3	18.7
7	5.13	11.8	18.9
8	6.47	14.5	19.6
9	6.85	15.1	20.6
10	5.99	13.9	20.9
11	4.85	13.0	20.1
12	5.51	14.7	20.4
13	9.99	14.8	22.7
14	8.66	17.1	22.6
15	6.87	17.5	22.0
16	7.38	16.1	22.9
17	6.58	15.7	22.5
18	5.45	14.2	21.9
19	5.23	13.5	20.7
20	3.32	10.5	16.8
21	3.79	12.9	16.7
22	3.41	11.6	17.8
23	3.36	10.9	18.3
24	4.67	10.8	17.7
25	6.17	9.1	20.2

Table 1. (Continued)

Date	Radon content			Date	Radon content			Date	Rodon content		
	0.6m	1m	2m		0.6m	1m	2m		0.6m	1m	2m
1945			Eman	1945			Eman	1945			Eman
VI-26	5.51	13.0	20.0	VIII-8	2.12	7.9	17.4	IX-20	4.70	11.2	18.8
27	5.62	13.6	19.1	9	2.11	6.4	17.6	21	4.31	11.2	19.6
28	5.74	11.4	20.4	10	2.57	8.0	17.9	22	4.71	11.2	19.4
29	4.77	13.1	19.5	11	2.41	7.1	16.5	23	7.90	10.7	21.0
30	7.62	14.2	19.0	12	2.34	7.4	16.0	24	7.45	13.0	20.5
VII-1	7.82	13.4	18.9	13	2.76	9.1	17.9	25	5.87	13.8	22.1
2	8.17	10.2	16.2	14	2.78	8.9	17.6	26	4.47	13.6	21.0
3	6.59	9.5	17.5	15	2.46	8.6	15.1	27	4.64	12.2	18.7
4	8.62	14.7	21.1	16	—	—	—	28	5.99	12.8	18.8
5	6.50	13.8	21.7	17	—	—	—	29	6.23	13.0	17.6
6	6.07	12.5	20.7	18	—	—	—	30	4.77	12.7	22.1
7	7.93	14.7	21.8	19	—	—	—	X- 1	5.16	13.3	18.0
8	5.27	13.6	21.3	20	—	7.4	14.2	2	4.62	12.6	21.4
9	5.05	12.8	21.1	21	—	8.6	16.1	3	4.21	9.8	19.0
10	3.55	9.5	17.7	22	3.61	8.1	15.2	4	5.09	10.6	19.8
11	3.08	9.6	18.3	23	3.41	7.9	14.5	5	8.29	12.2	20.0
12	4.29	9.0	18.1	24	3.20	6.4	14.4	6	9.73	11.9	20.8
13	5.82	9.8	18.0	25	4.10	8.9	14.9	7	7.26	9.0	23.5
14	4.86	12.3	19.1	26	2.46	4.9	11.6	8	5.80	14.6	19.2
15	4.48	11.8	19.6	27	4.40	9.4	17.6	9	10.76	12.8	24.3
16	3.86	9.5	17.4	28	3.98	10.2	17.9	10	13.74	18.3	25.7
17	3.83	9.8	18.2	29	4.05	8.9	17.2	11	10.54	17.0	22.9
18	8.08	12.2	23.1	30	3.97	8.8	14.5	12	8.39	14.1	27.3
19	6.36	11.1	21.5	31	3.63	8.1	17.7	13	6.17	15.4	25.0
20	4.45	12.3	21.1	IX- 1	6.25	9.5	17.1	14	4.81	13.1	24.0
21	4.66	11.0	21.0	2	6.80	12.3	18.7	15	4.13	12.8	22.8
22	7.08	13.8	23.1	3	7.52	13.6	18.6	16	3.81	11.2	23.1
23	6.04	15.1	21.8	4	7.80	13.6	19.5	17	3.30	10.9	20.5
24	—	—	—	5	9.29	11.2	21.8	18	4.12	11.0	18.3
25	3.61	8.0	17.7	6	4.34	13.1	19.0	19	4.71	11.3	18.1
26	—	8.4	18.7	7	10.19	16.5	21.5	20	5.60	7.8	17.1
27	—	8.3	18.9	8	—	—	—	21	—	—	—
28	2.37	8.8	17.9	9	7.10	11.9	21.5	22	5.91	10.8	16.5
29	2.41	8.6	18.3	10	7.28	15.2	23.8	23	5.82	12.2	17.0
30	2.50	8.7	17.0	11	7.62	16.2	21.8	24	5.85	13.6	20.0
31	2.34	8.7	16.6	12	5.54	13.5	20.5	25	5.34	14.2	20.1
VIII-1	2.25	7.9	17.6	13	6.32	12.2	20.2	26	4.46	13.1	18.3
2	2.40	10.0	21.1	14	6.28	13.2	22.8	27	3.67	10.9	16.2
3	2.10	7.7	17.6	15	6.90	12.3	18.8	28	3.82	12.9	19.3
4	2.16	7.2	17.8	16	6.03	10.6	17.0	29	4.11	11.0	19.0
5	—	6.2	16.5	17	5.97	10.2	16.4	30	4.10	10.5	19.2
6		8.3	17.3	18	6.46	11.4	20.4	31	3.45	11.5	17.0
7	1.99	8.1	16.9	19	4.63	10.0	17.1				

Table 2.

The radon content of soil air taken from 1 m in depth during Aug. 19, 1946 – Oct. 1, 1947.

Date	Radon cont. 1m	Date	Radon cont. 1m	Date	Radon cont. 1m	Date	Radon cont. 1m	Date	Radon cont. 1m
1946	Eman	1946	Eman	1946	Eman	1946	Eman	1947	Eman
VIII-19	8.2	IX-29	—	XI- 9	14.0	XII-20	10.2	I-30	13.8
20	8.6	30	12.2	10	—	21	10.5	31	12.6
21	8.5	X- 1	—	11	13.6	22	10.6	II- 1	12.0
22	8.3	2	11.4	12	—	23	10.6	2	12.3
23	8.0	3	—	13	9.5	24	11.1	3	12.8
24	8.3	4	11.6	14	11.8	25	—	4	12.7
25	—	5	—	15	—	26	10.3	5	12.5
26	8.3	6	12.8	16	11.2	27	—	6	12.2
27	—	7	—	17	—	28	12.1	7	11.5
28	7.8	8	13.8	18	10.5	29	—	8	11.4
29	—	9	—	19	—	30	12.7	9	11.4
30	8.4	10	12.8	20	10.5	1947 31	—	10	11.3
31	—	11	—	21	—	I- 1	12.6	11	11.6
IX- 1	7.7	12	12.6	22	11.2	2	—	12	11.2
2	—	13	—	23	—	3	12.1	13	10.7
3	7.9	14	12.8	24	10.7	4	—	14	10.9
4	—	15	12.4	25	—	5	12.4	15	11.2
5	8.4	16	—	26	10.1	6	—	16	11.7
6	—	17	10.9	27	—	7	13.0	17	12.1
7	8.3	18	—	28	—	8	—	18	12.1
8	—	19	9.6	29	12.7	9	13.1	19	12.1
9	7.8	20	—	30	—	10	13.0	20	11.9
10	—	21	8.5	XII-1	11.8	11	12.1	21	11.8
11	7.9	22	—	2	—	12	13.3	22	12.0
12	—	23	9.6	3	12.5	13	13.5	23	12.1
13	7.3	24	—	4	—	14	14.0	24	11.7
14	—	25	8.9	5	12.6	15	13.4	25	—
15	7.8	26	—	6	—	16	13.1	26	11.2
16	—	27	9.6	7	11.2	17	12.7	27	11.0
17	7.9	28	8.8	8	—	18	13.2	28	11.1
18	—	29	—	9	—	19	14.5	III- 1	10.4
19	8.2	30	8.5	10	13.5	20	14.9	2	10.6
20	—	31	—	11	—	21	14.8	3	11.4
21	7.7	XI- 1	10.4	12	12.6	22	14.4	4	11.8
22	—	2	—	13	—	23	14.6	5	12.0
23	7.8	3	10.3	14	12.6	24	14.4	6	11.3
24	—	4	—	15	—	25	14.1	7	12.1
25	8.8	5	11.9	16	12.3	26	13.7	8	12.2
26	—	6	—	17	—	27	14.1	9	12.8
27	11.3	7	13.2	18	10.8	28	14.1	10	12.7
28	12.5	8	—	19	—	29	13.4	11	12.6

Table 2. (Continued)

Date	Radon cont. 1m	Date	Radon cont. 1m	Date	Radon cont. 1m	Date	Radon cont. 1m	Date	Radon cont. 1m
1947	Eman	1947	Eman	1947	Eman	1947	Eman	1947	Eman
III–12	12.1	IV–22	12.4	VI– 2	12.2	VII–13	12.7	VIII-23	8.0
13	11.9	23	12.4	3	11.9	14	12.4	24	—
14	12.1	24	11.9	4	11.2	15	11.5	25	8.1
15	12.5	25	10.6	5	10.4	16	11.0	26	7.6
16	12.4	26	10.3	6	10.1	17	10.1	27	7.7
17	12.2	27	—	7	10.2	18	9.8	28	7.7
18	11.6	28	8.7	8	10.1	19	11.8	29	—
19	10.9	29	9.9	9	10.7	20	—	30	8.5
20	11.1	30	11.0	10	10.6	21	12.8	31	8.5
21	11.0	V– 1	12.0	11	9.9	22	13.5	IX– 1	8.2
22	12.2	2	10.4	12	10.8	23	12.5	2	8.3
23	—	3	10.1	13	10.9	24	11.4	3	8.1
24	12.2	4	10.9	14	11.1	25	10.7	4	—
25	12.1	5	11.7	15	11.1	26	10.9	5	7.8
26	13.2	6	12.1	16	11.3	27	—	6	8.1
27	13.5	7	12.7	17	12.3	28	9.5	7	7.8
28	13.5	8	13.0	18	11.5	29	10.2	8	7.7
29	13.1	9	14.5	19	11.8	30	11.1	9	7.5
30	14.0	10	14.2	20	11.9	31	10.3	10	7.4
31	13.7	11	14.0	21	11.5	VIII– 1	9.4	11	7.4
IV– 1	13.2	12	15.3	22	11.5	2	9.2	12	7.6
2	13.4	13	15.1	23	12.7	3	9.2	13	7.9
3	13.5	14	15.7	24	13.6	4	8.6	14	—
4	13.3	15	14.9	25	14.1	5	8.0	15	9.9
5	13.6	16	14.2	26	14.2	6	8.2	16	11.8
6	12.6	17	13.9	27	14.3	7	—	17	12.5
7	12.2	18	13.6	28	13.7	8	—	18	11.9
8	12.0	19	14.6	29	15.0	9	—	19	11.2
9	12.1	20	14.6	30	15.6	10	8.1	20	10.7
10	12.6	21	14.5	VII– 1	15.5	11	7.3	21	—
11	11.8	22	14.5	2	15.3	12	8.9	22	13.1
12	11.7	23	14.7	3	15.6	13	7.3	23	12.4
13	11.0	24	14.4	4	15.2	14	7.6	24	—
14	11.1	25	14.2	5	14.0	15	7.6	25	10.1
15	10.4	26	13.3	6	—	16	8.3	26	11.4
16	10.5	27	13.2	7	12.5	17	8.0	27	11.1
17	10.5	28	12.4	8	11.9	18	8.1	28	—
18	10.7	29	12.0	6	11.3	19	8.1	29	11.1
19	10.4	30	11.8	10	12.7	20	8.4	30	10.9
20	10.4	31	11.8	11	13.6	21	8.4	X– 1	10.0
21	11.4	VI– 1	—	12	13.7	22	7.8		

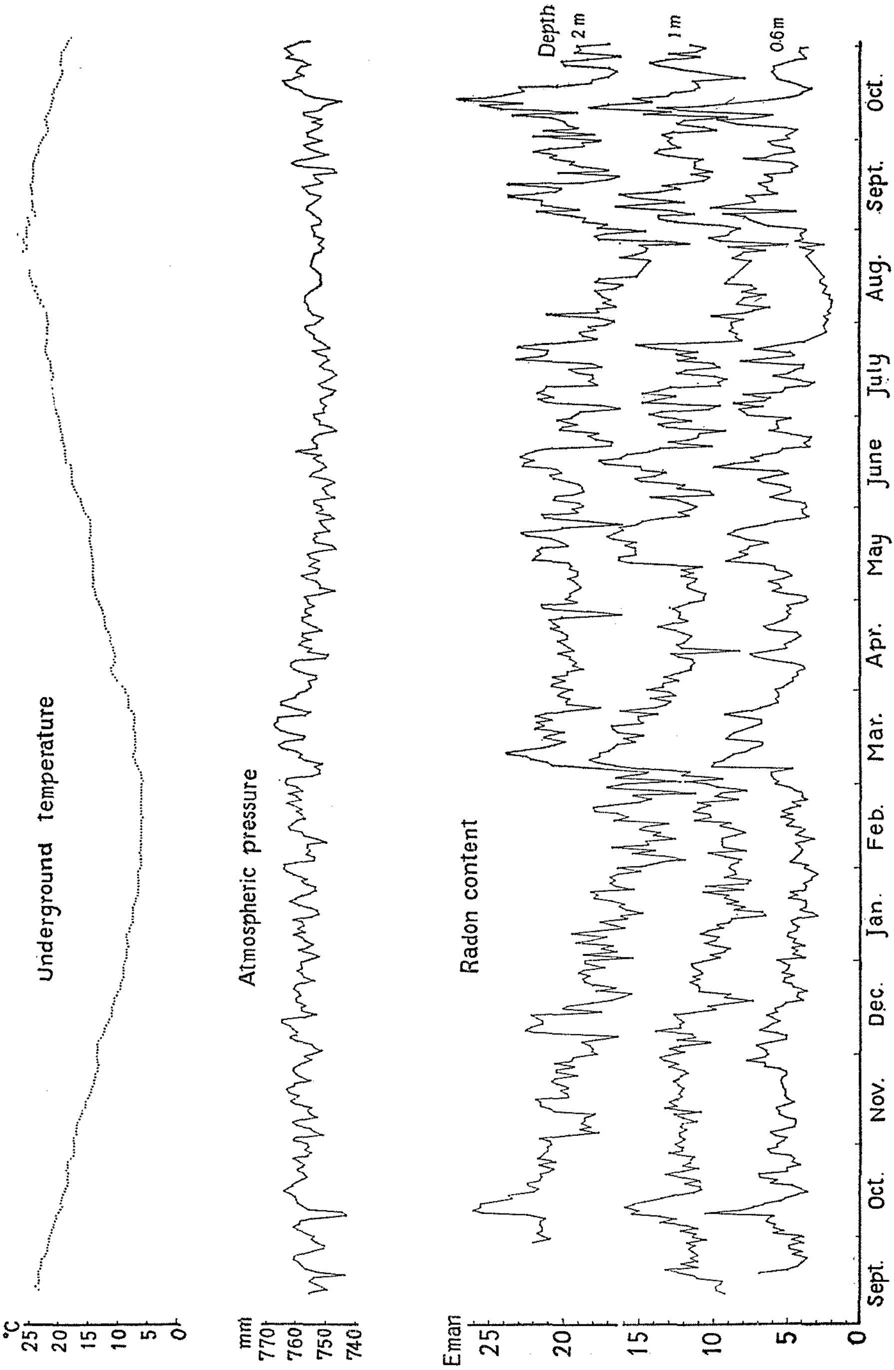

Fig. 1. The radon content of soil air taken from 0.6, 1 and 2 m in depths during Sept., 1944–Oct., 1945.

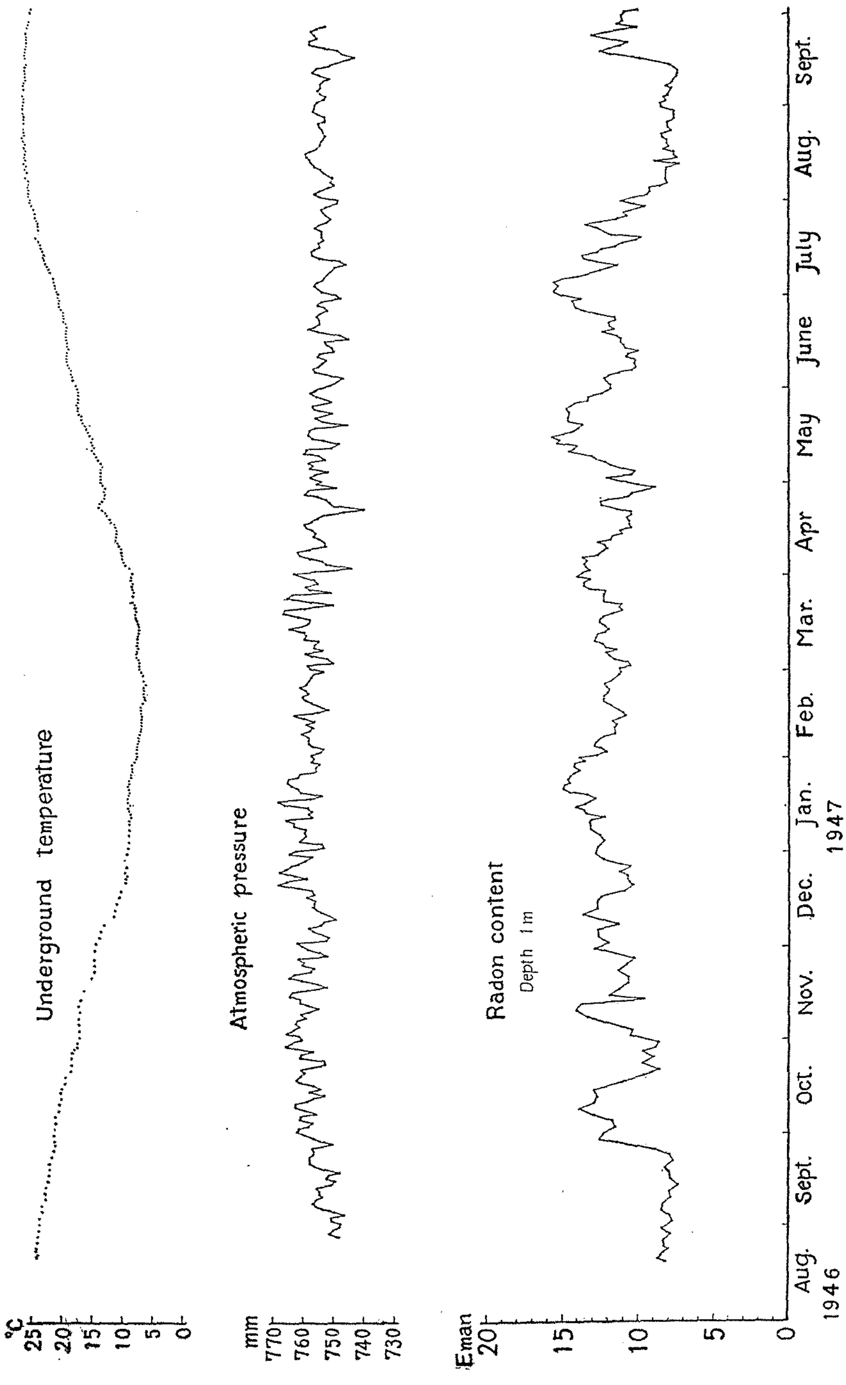

Fig. 2. The radon content of soil air taken from 1 m in depth during Aug., 1946—Oct., 1947.

(A) The Influence of Change in Atmospheric Pressure.

The effect of precipitaion and that of change in atmospheric pressure cannot easily be separable. It seems, however, that change of pressure by itself influences the radon concentration in soil air, for we can find cases in which radon concentration increased with the lowering of pressure attended by little or no rain. (Cf. Oct. 15, 27, Dec. 9, 1946; Feb. 28, May 26 and April 21, 1947). The cases of increase in radon concentration accompanied by the lowering of pressure are, ten to one, followed by precipitation, notable examples of which are to be found in the record of: Sept. 17, Oct. 7–8, Nov. 21, 1944 and Feb. 26, March 15, April 10, June 2, 24–25, July 21–22, Sept. 18, Oct. 5, 1945; Sept. 27, Oct. 7–8, 23, Dec. 3, 1946 and Jan. 18, March 2, 21–22, April 28, May 3,

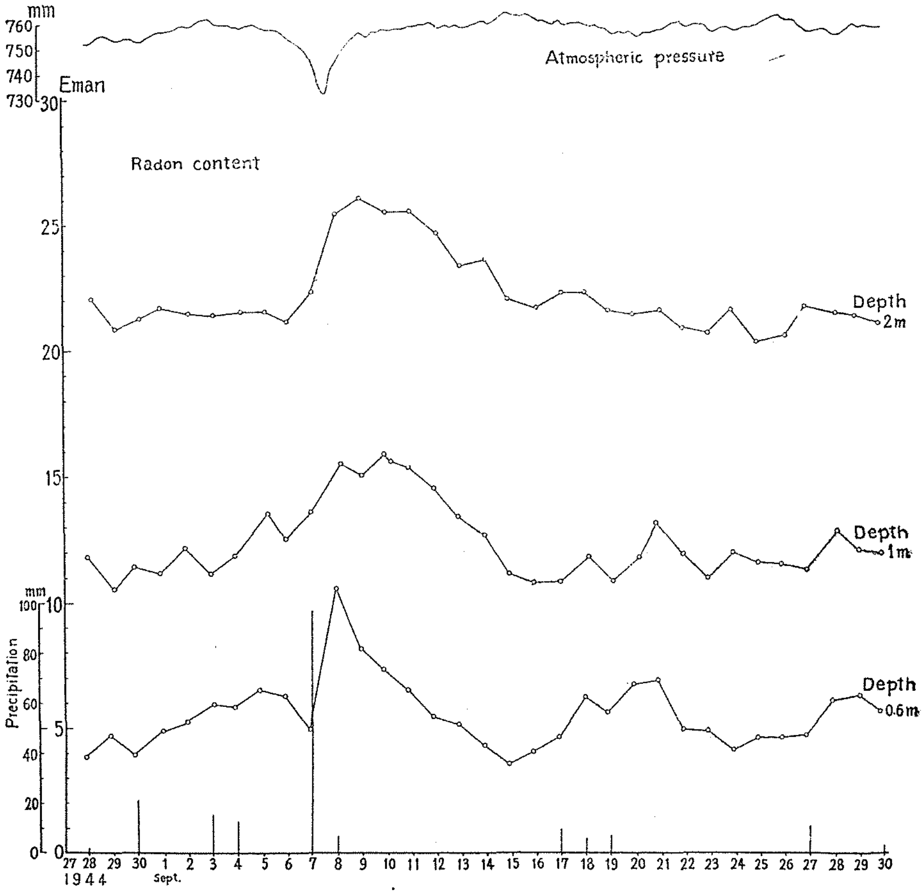

Fig. 3 The change of radon content during the passage of the typhoon of Sept. 7–8. 1944.

19, 1947. Among them, the most typical are to be seen in the records of Sept. 17 and Oct. 7–8, 1944 when mighty typhoon passed by this district, at which time the definite V-shaped pressure curves were recorded by our barograph (Fig. 3). Exceptional cases were also observed though not frequently. Such examples may be seen in the records of the periods of depression: Feb. 8–9, May 16–17, Oct. 12, Nov. 16–17, 1946; Jan. 1, Aprl 2, 1947. These cases might be explained by assuming that the approach of the depressions occurred while the radon content was undergoing change due to other causes.

On the contrary, the effect of increasing pressure is a decrease of radon concentration, but usually a rather obscure one. The explanation for this may be found in the fact that peaks of high pressure are usually not sharp and moreover not intensive; besides high pressure lasts for a time with only minor fluctuations. In addition to this, low pressure in most cases, is followed by precipitation which causes the increase of radon concentration as shown in the next paragraph, while high pressure is not attended with favourable conditions for decreasing radon concentration.

The reason why the concentration of radon in soil air at a depth varies with the rising or lowering of atmospheric pressure will be explained by the change of level of the equi-concentration surface. As illustrated in Fig. 4, the equi-concentration surface near the ground surface will be raised as the depression approaches, a phenomenon which would naturally give rise to the escaping of soil air into the atmosphere and the reverse would be the case with the approach of a high atmospheric pressure.

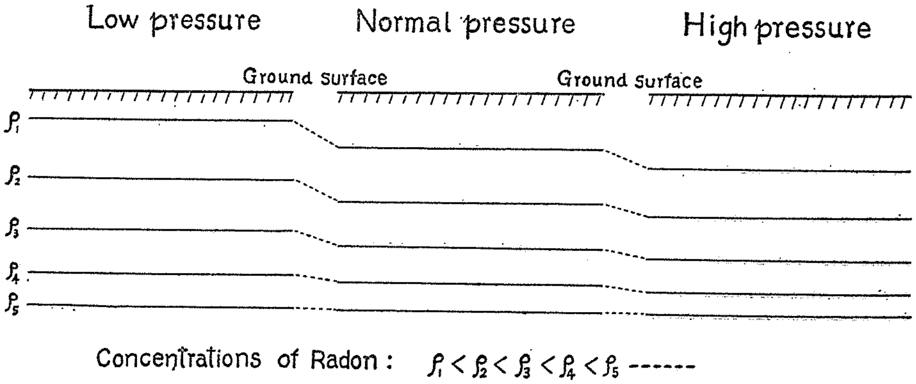

Fig. 4. The effect of atmospheric pressure on the concentration of radon at a depth near the ground surface.

J. A. Priebsch *et al*⁵⁾, and other authors⁶⁾ reported that the concentration of radon in the atmosphere near the ground level increased with decreasing atmospheric pressure. The fact will be elucidated by the above mentioned vertical movement of equi-concentration surface caused by the change of atmospheric pressure.

As naturally anticipated, there exists a time-lag between the change of pressure and that of radon concentration in soil air. Because of the measurement once a day, the amount of time-lag was not decidedly determined, but we can find one typical example of the low pressure of the typhoon of Oct. 7–8, 1944 (Cf. Fig. 3), in which the time-lag can roughly be estimated to be 10 hr. for 0.6 m, 12–14 hr. for 1 m, 30 hr. for 2 m depth from the surface of the ground.

In the same example, the relation between radon concentration and atmospheric pressure was observed as follows:

Date: Oct. 7–8, 1944

Drop in pressure	(a)	75.8-73.2=2.6 cmHg.		
Depths from which samples were taken	(b)	0.6	1	2 m
Increase in radon concentration	(c)	3*	3.3	4.5 Eman
Pressure coefficient of radon concentration**(c)/(a)	(d)	1.15	1.27	1.73Eman/cm Hg.
Normal value of radon concentration	(e)	6.5	12.7	21.5 Eman
Ratio of pressure coefficient to the normal value (d)/(e)	(f)	0.18	0.10	0.08

In this example, it may be concluded that the less the depth, the greater the effect of pressure depression.

H. Bender (loc. cit.) mentioned that rising barometric pressure increases the emanation content of the air in the soil, while decreasing pressure causes the opposite effect. At first sight, this is contradictory to our result. Taking the time-lag described above into consideration, however, a conclusion similar to our own will be reached. For he used the difference of pressure at two and twelve hours before sampling of soil air, while the time-lag for 1 m was found to be 12–14 hours as just above described. At a very shallow depth, however, where the time-lag becomes negligible and the changes in soil air pressure keep pace with those of the atmosphere, his statement will be held.

(B) The Effect of Precipitation

In order to know the effect of precipitation upon the concentration of soil air, we compared the radon concentration of the days before and after the day on which the amount of precipitation exceeded 10 mm, from Oct. 1, 1944 to Oct. 31, 1945 (Table 3–A). The precipitation data were supplied by the Kyoto Sectional Meteorological Observatory. The results are shown in the following:

---

* Inaccurate owing to precipitation.

** Including inseparable influence of precipitation, though less with increasing depth.

Table 3.

(A)

Date	Precipitation (mm)	Radon Concentration					
		Depths					
		0.6m		1.0m		2.0m	
		(+)	(-)	(+)	(-)	(+)	(-)
1944 X 3	15	0.8			0.3		
4	13	0.6		2.4		0.1	
7	97	4.2		3.1		4.3	
17	11	2.2		1.0			0.7
27	11	1.5		1.4			0.4
XI 3	25	1.0		0.2			2.6
8	11	0.8		—			0.3
16	15	0.1			0.2		2.1
27	32	1.2		0.4		0.3	
30	15		0.1		1.6		1.3
XII 1	19	0.3		—		0.3	
1945 I	—	—		—		—	
II 2	14	0.9			0.8		2.6
III 2	19	0.4		0.2		3.0	
6	29	5.4		3.0		3.4	
14	13	2.4			0.4	—	
15	18	2.2			0.6	1.0	
23	21		0.4	1.1			1.8
IV10	21	2.4		1.0		0.3	
19	31	2.0		1.0		1.0	
V 2	18	2.2		0.6			0.4
8	12		0.2	0.3			0.5
11	36	0.7			1.6	0.2	
15	14		0.1	4.0			0.2
VI 2	37	2.3		2.4		1.6	
7	47	1.7		2.2		0.8	
12	84	5.1		0.8		2.6	
13	11	3.1		3.4		2.0	
1945 VI23	11	1.3			0.8	—	
24	21	2.8			1.8	1.9	
30	33	2.1		0.2			0.7
VII 1	12	0.5			4.0		2.9
2	18		1.3		3.8		1.3
12	35	0.7		0.2			0.3
13	16	0.5		3.3		1.1	
17	50	4.2		2.7		5.7	
20	14		1.7		0.1		0.5
VIII23	13		0.4		1.7		0.8
31	70	2.3		0.8		2.6	
IX 2	23	1.3		4.0		1.5	
3	84	1.0		1.4		0.8	
4	21	1.8			2.3	3.2	
9	86		2.9		1.3	2.3	
14	24	0.6		0.2			1.6
17	10	0.5		0.8		3.5	
22	21	3.5			0.5	1.3	
23	35	2.8		1.8		1.3	
27	26	1.5			0.9		2.1
X 3	15	0.5			2.0		1.6
4	38	4.0		2.5		1.0	
5	53	4.8		1.2		1.0	
8	32	3.0		3.7		0.8	
9	108		0.3	4.0			1.3
10	15		5.1		4.2	1.6	
11	22	1.5			3.3		1.2
19	21	0.3		3.1			0.6

(B)

Date	Precipitation (mm)	Radon Concentration	
		Depth	
		1.0m	
		(+)	(-)
1946 IX 4	12	0.5	
13	12		0.1
18	17	0.3	
27	23	2.5	
1946 X 4	54	0.7	
6	14	1.1	
7	38	1.1	
11	13		0.2

Table 3. (Continued)

Date	Precipitation (mm)	Radon Concentration Depth 1.0m (+)	(−)
1946 X 12	21	0.0	
22	18	1.0	
31	24	1.9	
XI 4	12	1.7	
6	39	1.3	
XII 2	28	0.7	
27	30	1.7	
1947 I 8	10	0.2	
11	19	0.4	
17	18	0.1	
18	16	1.8	
II 14	23	0.5	
III 2	16	1.0	
21	12	1.2	
28	11		0.4
IV 2	32	0.3	
28	27	0.5	
V 3	18	0.5	
7	73	1.0	
11	30	1.0	
17	13	0.6	
1947 V 18	23	0.7	
22	12	0.3	
VI 8	18	0.6	
15	14	0.3	
25	11	0.6	
27	27		0.5
28	24	0.6	
VII 1	28	0.2	
9	11	0.8	
10	42	1.5	
18	29	1.7	
19	16	2.4	
20	10	1.0	
24	25	1.9	
VIII 7	19	—	
19	15	0.3	
IX 14	77	2.0	
15	36	2.9	
20	48	0.8	
25	32	0.3	

	Depths in m 0.6	1	2
Number of cases of increase of radon........(a)	45	30	29
Number of cases of decrease of radon........(b)	10	20	23
(a/b) ....(c)	4.5	1.5	1.3
Mean amount of increase of radon ....(d)	1.89	1.77	1.74 Eman
Mean amount of decrease of radon..........(e)	1.25	1.61	1.21 Eman
Mean radon concentration through this observation term...........................(f)	5.41	11.74	19.16 Eman
Percentage of the average increment to the mean value (d/f)×100 ....(g)	34.9	15.1	9.1 %
Percentage of the average decrement to the mean value (e/f)×100 ....(h)	23.1	13.7	6.3 %
Mean change (ad−be)/(a+b) ....(i)	+1.32	+0.49	+0.44

The numbers of increase and decrease cited here may involve those due to effects other than those of precipitation and observational error. However, the ratios of increase to diminution (a/b) are evidently larger at the shallower depth. Therefore, statistically speaking, precipitation usually has the effect of increasing radon, and the amount of increase and as well that of change decreases nearly hyperbolically with the increase in depth. (Cf. Fig. 5).

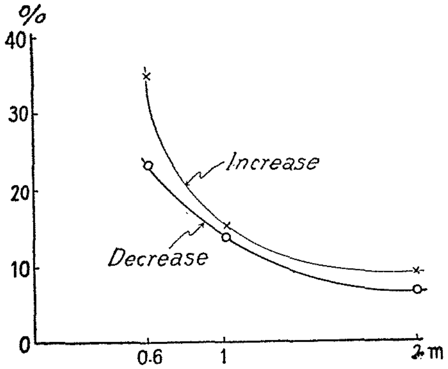

Fig. 5. Changes of radon at different depths by precipitation in percentages to mean value.

The relation between the amount of precipitation and changes in radon content was also plotted in Fig. 6. According to this figure precipitation of more than 30 mm per day seems to have something to do with increase of radon in soil air.

A similar tendency was found in the observation at 1 m depth during the second term (Sept. 1, 1946—Sept. 30, 1947). In this case we found: a=43, b=4, c=11, d=0.99 Eman, e=0.30 Eman, f=11.46 Eman, g=8.6%, h=2.6% and i= +0.88. The diminution was less than that found in the observation terms and chiefly to the differences in methods of measurement.

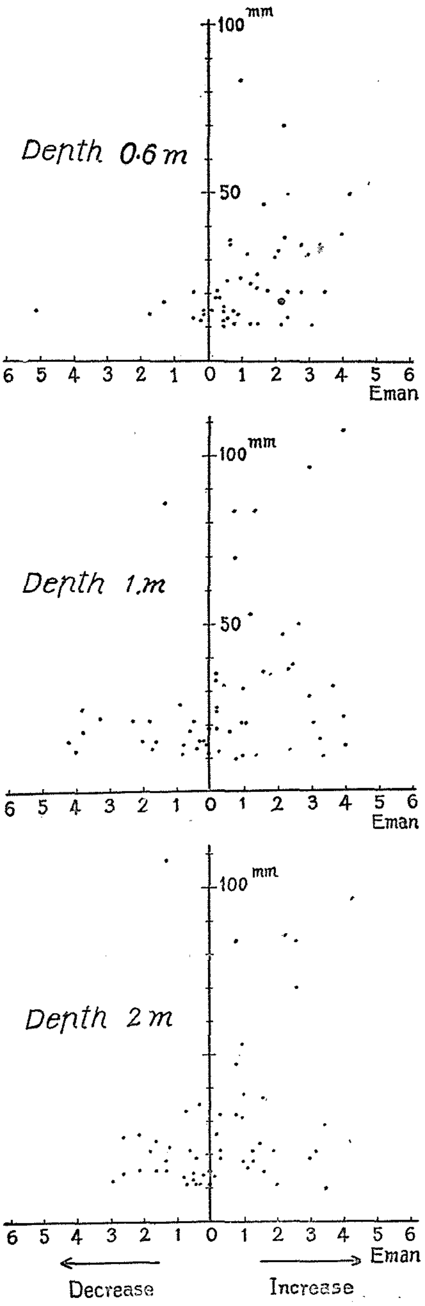

Fig. 6. The relation between the amount of precipitation and changes in radon content.

In the first period of observation, we used the circulation method in which the soil gas was introduced into the ionization chamber (ca. 1000 c.c.) by means of hand bellow (ca. 350 c.c.) from the sampling bottle (ca. 900 c.c.), while in the second, soil air was directly introduced through a drying tube into the ionization chamber (ca. 3000 c.c.) evacuated beforehand. Under these conditions, the method of the measurement employed during in the second period would be superior in accuracy to that of the first.

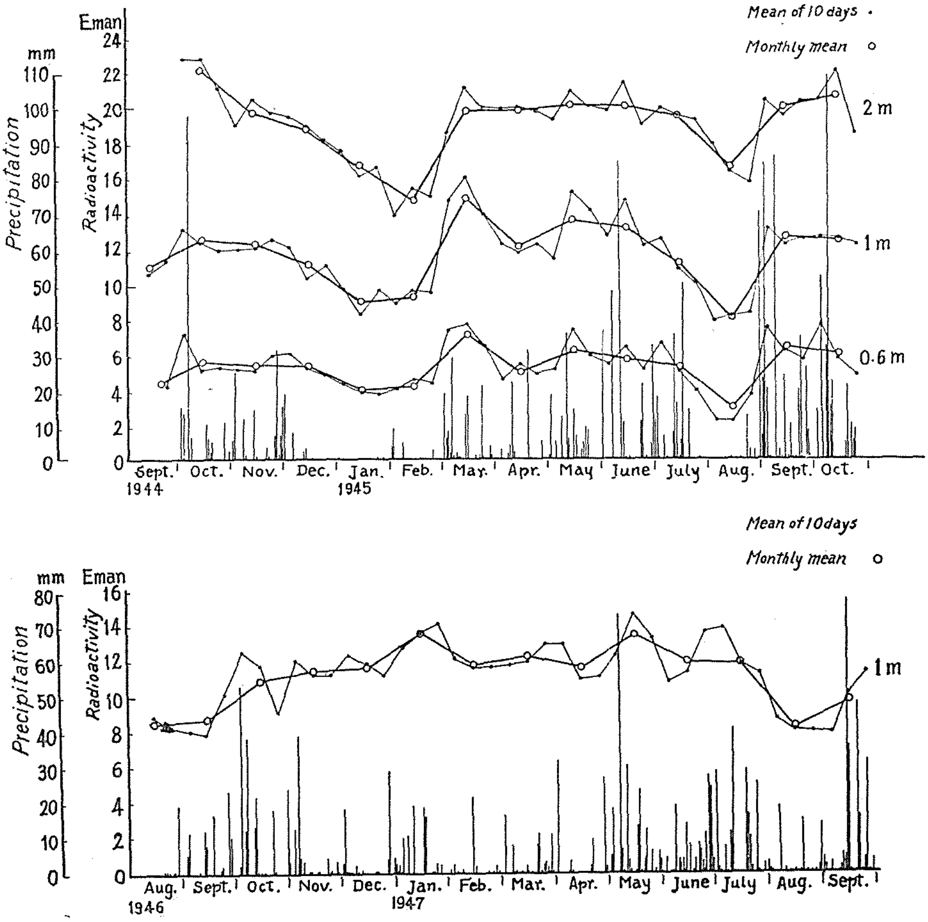

Fig. 7. Seasonal variation of radon contents with the data of precipitation.

The seasonal variation of radon content in soil air was also observed (Fig. 7). In general, radon content increased during the rainy seasons and decreased during the dry. For example, the concentration of radon had a minimum during the period from the middle of Dec. 1944 to Feb. of the following year, when we had little rain, while it began to rise with the frequent rainfalls which started from the beginning of March, 1945, and attained a maximum in the middle of the month, and then a minimum by the middle of April. In the rainy season from May to the beginning of July, it showed considerable fluctuations while keeping rather high values. In the dry season from the middle of June to the beginning of September, there appeared a conspicuous low of radon concentration which gradually increased with the approach of the rainy season in Autumn. These seasonal variations were also observed in the later year observation, but differed in time. A minimum appeared about August, 1946. However, we had no minimum during the period from Jannuary to February. This might probably due to rainy weather.

Now the explanation of the question why rain exerts an influence on the contents of radon in soil air will be found in the following: (1) Rainfall and melted snow prevent the escape of soil air into the atmosphere by filling up the pores of surface soil with water. That the freezing of the ground surface and blanketing with snow would have a like effect has been reported by other observers[2-3]. (2) Rain water affects the emanating power (ability of releasing radon) of the soil. This would take place when the rain water permeates into the depth concerned. This effect is, however, rather complex as will be shown below. When cold rain water in autumn lowers the temperature of the ground, the emanating power will be reduced, and increased when warm rain water in spring raises the temperature of the ground. In either case it is necessary that the rain should be heavy and last for a long time. It seems that rain water promotes the reduction of free radon in soil air, as water dissolves radon gas. But, on the other hand, the emanating power of radium salts grows larger in the presence of water*. Therefore our task would be to clarify the conditions under which the balance of the various effects of rain water would or would not be in favour of the increase of the radon content of soil air. In any case, however, diffusion would be the predominating factor controlling the radon content of soil air.

(C) The Effect of Temperature

While the radon content was being measured, the temperature at 1 m depth was observed as shown in Figs. 1–2. The annual variation of ground temperature at this depth nearly follows a sine curve, having a minimum (ca. 6°C) in February and a maximum (ca. 25°C) at the end of August. In this connection, the annual mean temperature of Kyoto is ca. 14°C and extremes of the monthly means are 2.8°C in Jannuary and 26.8°C in August. The mean rate of change found from the most steep part of the curve was at most 0.2°C/day. The solubility of radon for water changes by one part in a hundred per 1°C

---

* Especially oxides, hydroxides, chlorides and bromides of radium are more conspicuous in this property than carbonates and sulphides.

between 10–15°C, and therefore the effect of temperature upon the radon content in soil air would be practically negligible. The emanating power of the solid part of the soil is also a function of temperature, but no obvious change was observed in the concentration of radon even with actual difference in temperature of about 20°C.

(D) The Effect of Earthquakes

Changes of radon content in soil air were examined before and after all the felt earthquakes which were recorded at the Kyoto Sectional Meteorological Observatory during the periods from Dec. 1, 1944 to Oct. 31, 1945 and from Dec. 20, 1946 to Sept. 30, 1947. The results are as follows:

Table 4. The Effect of Earthquakes.

Depths	Number of cases			Periods
	Increase	No change	Decrease	
2 m	10	0	9	Dec.1, 1944 —Oct. 31, 1945
1 m	11	1	7	
0.6 m	10	1	9	
1 m	9	2	6	Dec.20, 1946 —Sept. 30, 1947

It seems that, at first sight, earthquakes have little influence on radon content, and that the changes are mostly due to other causes including uncertainty in measurement. Considering that, however, the majority of the earthquakes cited were after-shocks of the great Tônankai Earthquake which occurred on Dec. 7, 1944 at a point (136.2° E and 33.7° N) 20 km off southeast coast of Kii Peninsula, the number of cases of increase may be considered as less than those in which the same shocks occurred after sufficiently large intervals of time, because the radon content once raised by an earthquake shock would become rather insensible

Table 5. Effect of Earthquakes near Kyoto.

Depths	Number of cases			Periods
	Increase	No change	Decrease	
2 m	3	0	1	Dec. 1, 1944 —Oct. 31, 1945
1 m	3	0	1	
0.6 m	3	0	1	
1 m	4	1	2	Dec. 20, 1946 —Sept. 30. 1947

to later successive shocks and would moreover show a gradual decrease to the normal value owing to the decay of radon with a half-period of 3.8 days. In the case of the local earthquakes near Kyoto, the tendency of radon increase was more clearly observed. (Table 5).

It may be concluded, therefore, that in most cases felt earthquakes increase the radon content in soil air, provided there are no disturbing cases.

During the Tônankai Earthquake mentioned above, a striking change in radon content was observed, which was comparable with that occurring when the typhoon described above (Cf. p. 297) passed by this district. On the day of this

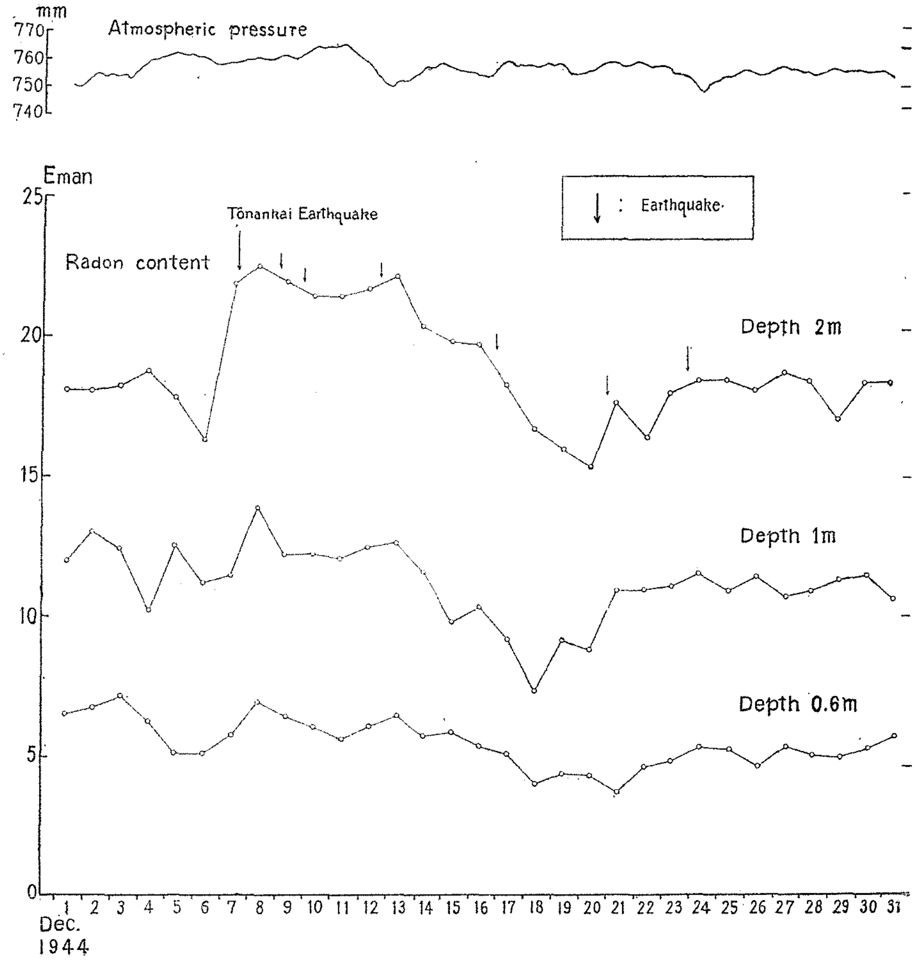

Fig. 8. The change of radon contents during the Tônankai Earthquake.

earthquake, samples of soil air were taken at $10^h 33^m$, $10^h 51^m$ and $12^h 35^m$ from 0.6 m, 1 m and 2 m depths respectively. The arrival of the earthquake wave recorded at the Kyoto Sectional Meteorological Observatory was at $13^h 36^m$. As seen in Fig. 8, the abnormal increase of radon concentration was intimately related to the occurrence of this earthquake. It is worth especially noticing that the increase of radon commenced prior to the arrival of the earthquake wave. As can be seen in the figure, the increase was remarkable for the soil air taken from 2 m depth and the time of its sampling was closest to the earthquake shock. In these days the meteorological conditions were calm except for a rainfall of about 8 mm on the previous day, and moreover, as can be observed in the figure, the greater the depth, the more obvious the change. This would suggest that the cause is in the underground but not in the atmosphere.

Though it is dangerous to conclude the possibility of earthquake-prediction from the change of radon content in soil air from a single example, it may possibly give a clue towards research in earthquake prediction, for the present measurement was made under favourable meteorological conditions, as stated above. A contrary example was the next great earthquake which occurred on Dec. 21, 1946 (the Nankai Earthquake; of which epicentre is 135.7°E, 33.0°N, 50 km off Kii Peninsula in the open sea, southeast of Shiono-misaki); the variation of radon content at 1 m depth was very slight before and after the earthquake. According to E. Nisimura(7) of the Geophysical Institute, Kyoto University, the tiltmeter at Kamigamo in Kyoto recorded no remarkable variation before this earthquake. But the same tiltmeter showed a singular variation before the Tônankai Earthquake, which accompanied, as described above, a remarkable increase of radon content in soil air. The correspondence between the radioactivity of soil air and of ground-tilt is very interesting and suggests that some common geological factor may underlie both. It is highly probable that the point where our sampling of the soil air was made lies just or nearly above a fault covered with alluvial deposits, and this would be an important thing for the further study of the problem from the geological and geophysical points of view.

In conclusion, the author wishes to express his thanks to Emeritus Professor M. Matuyama and Professor N. Kumagai for the cordial guidance and encouragement, and also to Lecturer N. Kawai, Messrs. K. Yao, T. Hanaoka, the late T. Kin, and K. Matsumoto who helped the author in his daily observations over so long a period.

References

1. Satterly, J.: Proc. Cambr. Soc., **16**, 336, 356, 514 (1911/12).
2. Bender, H.: Gerl. Beitr. Geophys. **41**, 401 (1934).
3. Israel-Köhler, H. and F. Becker: Gerl. Beitr. Geophys. **48**, 13–58 (1936).
4. Hatuda, Z.: Mem. Coll. Sci., Kyoto Univ., B. **X**, 63 (1934).
5. Priebsch, J. A., G. Radinger und P. I. Dymek: Gerl. Beitr. Geophys. **50**, 55–57 (1937).
6. Hess, V. F.: Wien. Sitz-Ber. **IIa**, 119, 145 (1910).
   Kohlrausch, K. F. W.: Wien. Sitz-Ber. **IIa**, 119, 1577 (1910).
   Kosmath, W.: Gerl. Beitr. Geophys. **25**, 95 (1930).
   Macek, O. und W. Illing: Gerl. Beitr. Geophys. **43**, 388 (1935).
7. Nisimura, E.: Private communication. And also
   Sassa, K. and E. Nisimura: Trans. Amer. Geophys. Union, **32**, no. 1, 1–6 (1951).