Time Trend of Air Dose Rate of Radiation in Eastern Japan after the Fukushima Daiichi Nuclear Power Plants Accident

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1. Introduction

A giant earthquake (East Japan major earthquake) of M9 struck East Japan at 14:46 on March 11, 2011. Subsequently, a tsunami of going up high 14m -15m attacked Fukushima Daiichi Nuclear Power Plant and all AC power supply fell into loss state. As a result, in all of 1-3 Nuclear reactors, meltdown befell [1], and a part of the molten fuel has begun to leak out to the nuclear reactor storage container. Hydrogen that was generated by the meltdown of the nuclear reactors caused explosions and fire, which led the nuclear reactors, turbine rooms and outskirts institution demolished. The process of the accident at Fukushima Daiichi Nuclear Power Plant is summarized in Table 1. Then, significant amounts of radioactive material have been released into environment. The atmospheres, soil, marine of the east Japan including the metropolitan area have been contaminated with radioactive materials such as I131, Cs134 and Cs137. The purpose of this study is to search environmental factors, other than decreasing of radioactive materials according to their half-lives, that effect on air dose rate of radiation in each spot of the East Japan. We are especially interested in 'effect of air dose rate of the day before', 'that of elapsed days from the accident', and 'that of weather condition of the day'.

Table 1. Process of the Accident at Fukushima Daiichi Nuclear Power Plant

		1st Unit	2nd Unit	3rd Unit	4th Unit
11 March	14:46	Shutdown	Shutdown	Shutdown	During Stop
	15:41	Power Supply Loss	Power Supply Loss	Power Supply Loss	
12 March	15:36	Hydrogen Explosion			
14 March	11:01			Hydrogen Explosion	
15 March	6:10		Abnormal noise outbreak		
	6:14			Smoke	Abnormal noise outbreak
	8:25		White smoke		
	9:38				Fire
16 March	8:37			White smoke	
21 March	15:55			Black smoke	
	18:20		White smoke		

2. Materials and Methods

The data we dealt with are "the spot-specific air dose rates of radiation (μSv/h) those were observed at 36 spots in eastern Japan", which were published in the morning edition of Asahi Shimbun[2] from 13 April 2011 to 13 August 2011. The weather conditions of days were obtained from the web site of Japan Meteorological agency [3].The time trends of air dose rate of radiation of each spot around Fukushima Daiichi Nuclear Power Plant are shown in Figure 1, in which the vertical axis represents the day-specific air dose rate of radiation in a log scale.

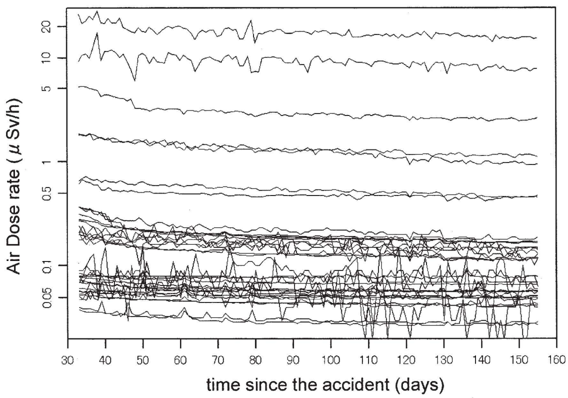

Figure 1. Spot-Specific air dose rates of radiation after the accident of Fukushima Daiichi Power Plant in eastern Japan

We assumed that the amount of emitted radiations was fixed at the day of accident and that the amounts of emitted radiations have been decreasing according to their half-lives, where the half lives of I131, Cs134 and Cs137 are 8.02 days, 2.065 years and 30.2 years [4],[5],[6], respectively. We also assumed that the initial attribution ratio of Cs134 and Cs137 to the air dose rate of radiation is 2.7 to 1, and that the mass ratio of Cs137 and Cs134 in the initial fallout is one to one[7]. Then the theoretical air dose rate of radiation at time t is expressed as

$$h(t \mid \beta_{1i}, \beta_{2i}) = C + \beta_{1i} \frac{2.7 \times 2^{-\frac{t}{753.7}} + 1.0}{3.7} + \beta_{2i} 2^{-\frac{t}{8.02}}, \qquad (1)$$

$$(t = 33, \cdots, 155;\ i = 1, \cdots, 36)$$

where C is the natural background of radiation dose rate having the value of 0.076μSv/h [8], and β_{1i} and β_{2i} are initial values of Cs and I131 at each spot, respectively. Let $y_i(t)$ be the air dose rate of radiation at t days after the explosion at spot i. The composite half-life model (1) is modified as follows

$$y_i(t) = h(t \mid \beta_{1i}, \beta_{2i}) \exp(\gamma_i ' z_{it} + \varepsilon_{it}), \qquad (2)$$

where z_{it} denotes the vector of explanatory variables that are considered to effect on an air dose rate, γ_i denotes the vector of coefficients to be estimated, and ε_{it} denotes error term that obeys $N(0, \sigma_i^2)$ independently. Logarithmic transformation of both side of the equation (2) provides the following formula,

$$\log\{y_i(t)\} = \log\{h(t \mid \beta_{1i}, \beta_{2i})\} + \gamma_i ' z_{it} + \varepsilon_{it}. \qquad (3)$$

Further, taking the effect of air dose rate of radiation at the previous day into consideration, we obtain from the equation (3) that

$$\begin{aligned} \log\{y_i(t)\} = \log\{h(t \mid \beta_{1i}, \beta_{2i})\} &+ \gamma_{1i} \times prey_{it} + \gamma_{2i} \times t \\ &+ \gamma_{3i} \times rain_{it} + \gamma_{4i} \times (rain_{it} \times t) + \gamma_{5i} \times (s\text{-}wind_{it}) + \varepsilon_{it}, \\ &(t = 34, \cdots, 155;\ i = 1, \cdots, 36) \end{aligned}$$

where '$prey_{it} \equiv \log\{y_i(t-1)\}$', '$rain_{it}$' is a dummy variable expressing the amount of precipitation on the day t at spot i, which takes 1 if the precipitation is more than 3 mm per day and 0 otherwise, '$s\text{-}wind_{it}$' is a dummy variable expressing the strength of south wind which takes 1 if the south wind is stronger than 1.5 m/sec and 0 otherwise. Using a nonlinear least square method (NLSE) [9], we estimated values of the parameters $(\hat{\beta}_{1i}, \hat{\beta}_{2i}, \hat{\gamma}_{1i}, \hat{\gamma}_{2i}, \hat{\gamma}_{3i}, \hat{\gamma}_{4i}, \hat{\gamma}_{5i}, \sigma_i)$ for each spot. The free software R-2.12.1 was used for the analysis.

3. Results

The results of our study were represented in Table 2 and Figure 2-9. Table 2 shows the spot-specific estimated vales of parameters. Figure 2 and Figure 3 show the estimated initial values of air dose rate of radiation due to Cs and I131, respectively. Relatively high values of air dose rate were estimated at the neighborhood of Fukushima Daiichi Nuclear Power Plant for both radio-nuclides. Figure 4 represents the geographical distribution of estimated coefficients of dose rates of the day before $(\hat{\gamma}_1)$, where strong auto-correlative trends can be found in almost entire region. The estimated coefficients of 't' were negative at almost all spots, which show that the air dose rates are decreasing day by day over the observed period after being adjusted for 'decreasing rate due to half-lives of radioactive materials', 'air dose rate at the previous day' and 'weather condition of a day'.

Table 2. Spot-specific estimated parameters with spot information

SID	name of spot	MCD	longitude	latitude	distance*	Cs	I131	prey	t	rain	rain*t	s-wind
1	Sendai	4100	140.87	38.27	95.4	0.195	0.000	0.4479	-0.0386	-0.0041	0.0348	0.0253
2	Shiraishi	4206	140.62	38.00	74.2	0.279	0.452	0.2992	-0.2723	0.0253	-0.0302	-0.0016
3	Yamagata	6201	140.35	34.25	111.1	0.028	0.271	0.2549	-0.0603	-0.0154	0.0207	-0.0006
4	Yonezawa	6202	140.12	37.92	98.1	0.020	0.139	0.0931	0.0402	-0.0178	0.0438	-0.0153
5	Fukushima	7201	140.45	37.75	62.2	1.393	3.554	0.2649	-0.1311	-0.0110	-0.0018	0.0032
6	Aizuwakamatsu	7202	139.92	37.50	97.8	0.162	0.459	0.1702	-0.0863	0.0407	-0.0445	-0.0197
7	Kooriyama	7203	140.37	37.40	59.6	1.398	2.646	0.3455	-0.2137	-0.0166	0.0104	-0.0026
8	Iwaki	7204	140.88	37.05	43.2	0.391	1.519	0.4154	-0.1010	0.0459	-0.0383	0.0008
9	Shirakawa	7205	140.22	37.13	79.8	0.663	1.302	0.2018	-0.1604	0.0016	0.0017	-0.0024
10	Minamisouma	7212	140.33	37.49	25.5	0.568	2.129	0.3657	0.0156	-0.0307	-0.0060	0.0058
11	Minamiaizu	7368	139.46	37.12	114.2	0.020	0.049	0.0693	-0.0693	0.0003	0.0341	0.0102
12	Akaugi(Namie)	7547	140.78	37.80	25.6	11.887	67.750	0.1603	-0.0358	-0.0550	0.0345	-0.0051
13	Shimotsushima(Namie)	7548	140.76	37.55	29.1	4.777	15.575	0.3302	-0.0605	-0.3109	0.2288	0.0238
14	Iitate	7564	140.73	37.68	38.9	1.668	9.664	0.5290	-0.0115	-0.0629	0.0350	-0.0005
15	Hitachi	8202	140.63	36.60	97.6	0.265	1.287	0.2762	-0.0947	0.0003	-0.0063	-0.0013
16	Hakahagi	8214	140.70	36.70	83.8	0.503	1.396	0.7294	0.0255	0.0265	-0.0222	0.0165
17	Kitaibaragi	8215	140.73	36.78	73.3	0.328	2.063	0.4376	-0.0187	0.0224	-0.0234	0.0113
18	Tsukuba	8220	140.08	36.03	171.6	0.087	0.351	-0.0011	-0.0594	-0.0609	0.0416	0.0111
19	Hitachinaka	8221	140.32	36.23	122.3	0.366	2.544	0.4700	-0.0289	-0.0194	0.0079	0.0103
20	Toukai	8341	140.58	36.47	113.4	0.121	1.205	0.1376	-0.1217	0.0076	-0.0050	0.0006
21	Hokota	8402	140.52	36.15	146.4	0.588	1.361	0.7232	-0.0056	0.0212	-0.0263	0.0090
22	Utsunomiya	9201	139.88	36.57	140.5	0.065	0.247	0.2935	-0.0258	0.0073	0.0205	0.0065
23	Koyama	9208	139.80	36.32	165.0	0.097	0.523	0.2534	-0.5193	-0.1879	0.2768	0.0035
24	Maoka	9209	140.02	36.43	141.9	0.053	0.366	0.1907	-0.1207	0.0057	-0.0242	0.0564
25	Nasu	9407	140.13	37.02	92.3	0.283	0.000	0.2997	-0.2364	-0.0160	0.0547	0.0078
26	Maebashi	10201	139.07	36.38	209.6	0.000	0.158	0.0097	-0.1938	0.1257	-0.1040	0.0131
27	Saitama	11100	139.38	35.51	213.3	0.048	0.152	0.2703	-0.0359	0.0203	-0.0153	-0.0082
28	Ichihara	12219	140.12	35.50	229.3	0.103	0.327	0.4405	0.0098	0.0020	0.0188	-0.0067
29	Shinjuku	13104	139.70	35.70	224.6	0.233	0.565	0.5674	0.0039	0.0090	-0.0058	-0.0026
30	Yokohama	14100	139.38	35.26	253.1	0.062	0.325	0.4251	-0.0428	0.0638	-0.0435	0.0021
31	Kawasaki	14130	139.42	35.31	241.7	0.161	0.384	0.4457	-0.0037	0.0061	-0.0034	0.0033
32	Yokosuka	14201	139.68	35.28	267.6	0.086	0.430	0.3466	-0.0662	0.0251	-0.0212	0.0022
33	Chigasaki	14207	139.40	35.33	274.3	0.079	0.137	0.3602	-0.0127	0.0413	-0.0284	-0.0001
34	Shibata	15206	139.33	37.95	161.4	0.000	0.000	0.0388	-0.0385	0.0591	-0.0181	0.0166
35	Aga	15385	139.27	37.40	141.8	0.024	0.019	0.1921	-0.0028	0.1412	-0.1038	0.0070
36	Minamiuonuma	15460	138.52	37.03	188.8	0.000	0.184	0.0233	-0.0606	0.0190	0.0455	0.0279

*'distance' denotes the distance (km) between the spot and Fukushima Daiich Power Plant.

Figure 5 shows that the estimated spot-specific air dose rate of radiation decreased at most spots after adjusting for the theoretical values due to the composite half-life model. About 8% excess reduction rates per 100 days in average were estimated. A characteristic spatial pattern of rain effect on the air dose rate was represented in the left panel of Figure 6, that is, when it was rainy day the air dose rates became lower at most 27% in a neighborhood of the nuclear power plants, on the other hand they became higher at most 15% in distant regions from the nuclear power plants. The spot-specific estimated interaction effects of rain and the elapsed time since the accident were shown in the right panel of Figure 6, where the geographical distribution suggests a negative correlation with the rain effect. As for wind effect, it is shown from Figure 7 that the air dose rate of radiation tend to low on a day with south-wind blowing in the shoreline of Tokyo bay area. In the other region we can give no clear explanation for the effect of south-wind. Figure 8 shows pair-wise correlations between residuals of two different spots, in which relatively high correlations (> 0.3) are observed among neighboring spots, and their correlations are diminishing in the distance more than 100km. Our model was fitted very well to the observed data. As an illustration, we show here the fitted values of air dose rates of radiation and observed ones at Fukushima City and Iitate Village in Figure 9, where the dashed curves represent the fitted values due to the composite half life model without any environmental explanatory variable. It is shown that the air dose rates of radiation at Iitate were almost completely explained through the composite half life model while those at Fukushima were more quickly decreasing than the expected trend through the composite half life model.

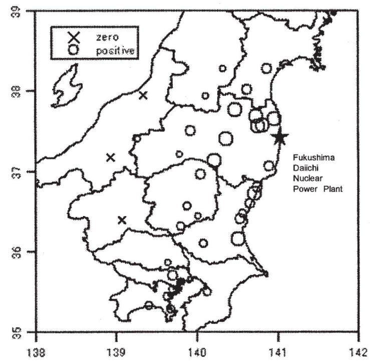

Figure 2. Estimated spot-specific initial air dose rate of radiation ($\hat{\beta}_1$) due to Cs. The symbol "★" represents the location of Fukushima Daiichi Power Plant.

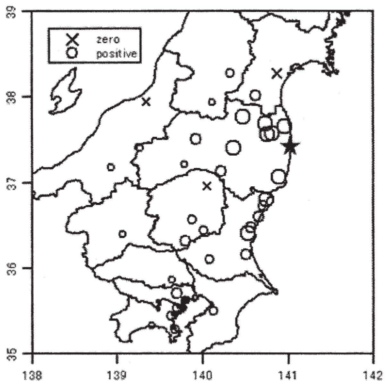

Figure 3. Estimated spot-specific initial air dose rate of radiation due to I131 ($\hat{\beta}_2$)

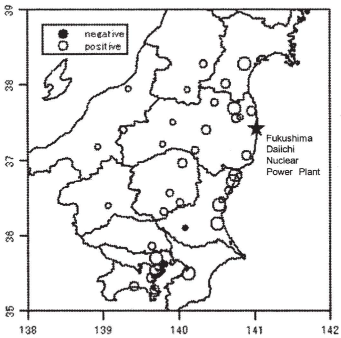

Figure 4. Spot-specific estimated effects $(\hat{\gamma}_1)$ of dose rates of the day before

Black and white circles indicate positive and negative values, respectively. The size of circle indicates the magnitude of the value. The dose rate of the day is positively correlated with that of the day before at most spots.

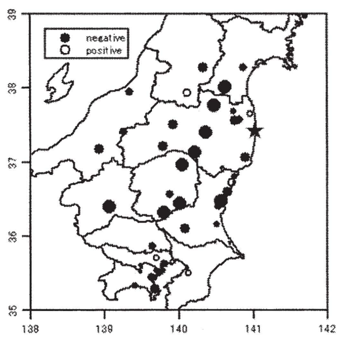

Figure 5. Spot-specific estimated effects $(\hat{\gamma}_2)$ of elapsed time from the accident.

The air dose rates of radiation were decreasing day by day over the observed period at most spots after adjustment for the composite half-life model of radio-isotopes.

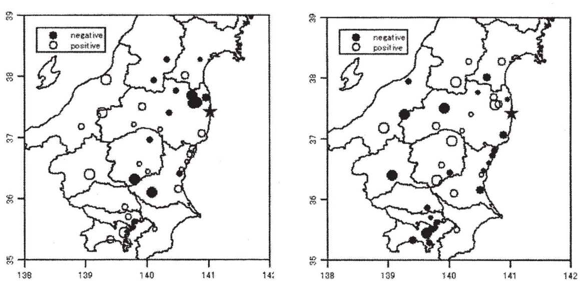

Figure 6. Spot-specific estimated coefficients of rain ($\hat{\gamma}_3$) and interactions of rain and time ($\hat{\gamma}_4$)

When it was rainy day, the dose rates decreased in around the nuclear power plants, they increased along shore lines on the other hand.

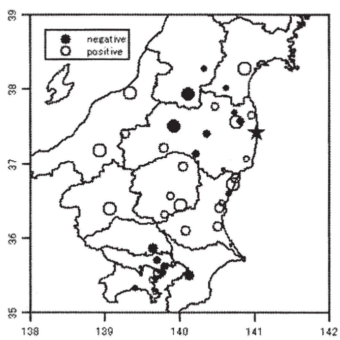

Figure 7. Spot-specific estimated effects ($\hat{\gamma}_5$) of south wind

It is shown that the air dose rates of radiation tend to low on a day with south wind blowing in the shoreline of Tokyo Bay.

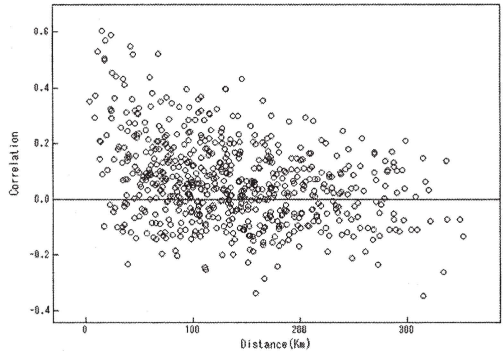

Figure 8. Correlation coefficients between residuals of two different spots by distance.

Relatively high correlation coefficients appear between residuals of two close spots, which implies that some common unknown factors are shared among them.

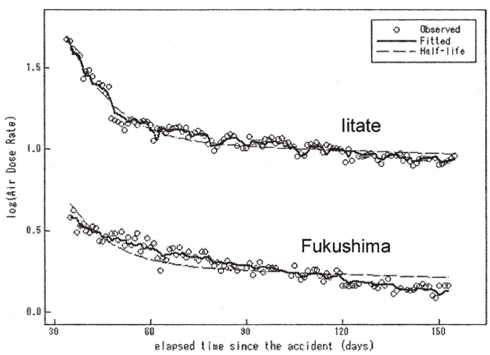

Figure 9. Observed dose rates of radiation and the fitted ones at Fukushima City and Iitate Village

The dashed curves represent the fitted values due to the composite half-life model without any environmental explanatory variable.

4. Discussion

The observed air dose rates of radiation had different fluctuations in each spots, which is thought to be due to various measurement errors such as a precision of instrument, a setting altitude of the instrument, etc. Our interest was not in a precise prediction of air dose rate but in estimations of degrees of involvement of factors that effect on air dose rates after being adjusted by decreasing due to half-lives of radioactive materials. So, we just analyzed the data of measurements for each spot separately. It is reported that intense rainfall in June and July can cause an additional air dose rate due to wet deposition of radio-nuclides [10]. Our result showed that the effects of 'rain' on air dose rates were different in each spots. Why rainfalls have the opposite effects between the neighboring region and the distant region of the nuclear power plants? So far we give no clear explanation to the question. The air dose rates of radiation in the shorelines of Kanto area tend to low on a day blowing south wind. We also cannot give the clear explanation about it. We consider that our model has a goodness of fit in a sense that every distant spots further than 150km have almost no common variation in their observed air dose rates of radiation which was implied by Figure 6. According to the results shown in Table 2, reduction of the air dose rates of radiation per one year were expected to be more than 19% in the median compared to the theoretical air dose rate obtained by the composite half-life model. It may be partly explained by migration of Cs137 in environment.

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Reference

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