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Identifying Existence Range of Diffusion Sources of Radioactive Small Particles

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Abstract- One of the serious fears for Japanese society is contamination of radioactive substances due to the huge earthquake and subsequent Fukushima No. 1 nuclear power plant disaster. This paper proposes a detection method to identify diffusion sources of radioactive small particles in the air based on publicly available data, which are composed of air dose rate, amount of rain, wind speed, and direction. Air dose rate is observed on each public monitoring point. The nearest weather observation station for each public monitoring point concerning air dose rate is also identified to analyze the relationship between air dose rate and weather conditions. This method focuses on all cases of continuous rainfall duration, because various sizes of spike concerning air dose rate on a public monitoring point are observed among the cases. Each spike starts when rainfall begins and the spike disappears when rainfall continues. This is because rainfall cleans up radioactive particles in the atmosphere. The method confirms a statistically significant difference of increase rate of air dose rate between each pair among rainfall cases. It also identifies an existence range of direction of diffusion sources based on significance tests of correlation coefficients.

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I. Introduction

After the huge earthquake in Japan on March 11, 2011, radioactive substance derived from the Fukushima No. 1 nuclear power plant could affect the world's environment and society. Japanese people were concerned about contaminated food, wood, resources, and goods due to air and water pollution in terms of radioactive substance. According to the nature blog news on December 21, 2012, one of the most interesting articles on social media is an academic article concerning the biological effect of the crippled Fukushima nuclear power plant [1]. Worldwide attention on this article means that the crippled nuclear power plant and diffusion of radioactive substance from the plant are a major concern and threat against our environment.

The Japanese government has a warning system, called SPEEDI (System for Prediction of Environmental Emergency Dose Information) [2], which is supposed to predict the radiation spread based on information concerning power plant, weather conditions, and geographic area in terms of dose rate. SPEEDI is intended to detect a serious accident at a nuclear power plant; however, it is not intended as a secondary diffusion from contaminated goods, water, and other items. In order to specify a radiation level, the Japanese government provides information collected from monitoring points in Japan [3]. This paper analyzes the relationship between radiation level and weather conditions toward development of a detection system to identify sources or origins of spreading radioactive substance.

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II. Diffusion of Radioactive Substance

Many researchers have been trying to clarify the environmental and social effects of radioactive substance. Yasunari et al. [4] estimated the amount of radioactive substance on and inside soil in Japan. Koyama drew a contamination map around Shizuoka prefecture due to the Fukushima No. 1 nuclear power plant [5]. Hayashi researched the contamination of wood in forests [6]. The Forestry Agency of Japan provides questions and answers concerning handling wood products because the products might be contaminated [7].

The Ministry of Agriculture of Forestry and Fisheries provides information concerning the limitation of export of Japanese products to other countries, and inspection of agricultural products and fisheries products with respect to cesium 137 contamination [8]. The Ministry of Land, Infrastructure, Transport, and Tourism of Japan provides a report on the result of inspection of drainage and sewage sludge with respect to radiation levels [9]. The Ministry of Health, Labor, and Welfare provides information concerning inspection results of water supply with respect to cesium 137 contamination [10].

According to these reports, agricultural and fisheries products and water supply contain a thousand times contamination of radioactive substance compared to that before the Fukushima nuclear power plant disaster. The clean association of Tokyo 23 waste reports that ashes contain radioactive substance continuously after the disaster. In addition, burning earthquake debris derived from the northeast regions in Japan is another significant concern of spreading radioactive particles because burning earthquake debris could make secondary spreading contamination worldwide, as much as the primary spreading contamination [11] [12].

III. Open Data Analysis

Diffusion factors of radioactive airborne particles are analyzed with open data concerning air dose rate, rainfall, wind speed, and wind direction. A set of three incineration plants in Kitakyushu city were employed as safe spreading origins of radioactive airborne particles because the Japanese Ministry of Environment approved the burning earthquake debris contaminated by radioactive substance derived from the Fukushima No. 1 power plant accident.

A monitoring post (MP) of the Yahata common building for government offices in Kitakyushu city was employed for analysis because it was the closest monitoring post from the incineration plants. Employing an original geo-coding database, which has the same function of Google geo-coding API, the nearest weather observation station for each MP is automatically identified in terms of the name of the stations, which contains prefecture and region names. The weather station information is publicly provided by Japan's meteorological agency.

a) Near Consistent Wind with Rainfall

In case A, consistent wind with rainfall flows from the plants to the near MP. When wind flows from an exact direction in terms of the set of incineration plants, many radioactive airborne particles are transferred from the diffusion origin. At the same time, rainfall starts, and the particles are starting to drop around MP.

Figure 1 illustrates trajectories of air dose rate, rainfall, wind speed and consistency. The former three values are rescaled between 0 and 1, based on the minimum and maximum values. The maximum and minimum air dose rates are 0.082 and 0.054 micro sievert per hour. The max and min amount of rainfall are 18 and 0 mm per hour. The max and min wind speeds are 5.7 and 1.7 meter per second. Wind consistency is defined by (cos(d) + 1)/2, where d is the difference between the origin's correct direction and wind direction. The range is between 0 and 1. The unit of x-axis is the time period where the unit is an hour. Table I summarizes the maximum and minimum values of dose rate and the three factors. The correlation coefficients between dose rate and the other factors, which are rainfall, wind speed and consistency, are -0.09178, -0.58939, and 0.865703, respectively.

According to correlation coefficients, wind consistency is the most important factor on increasing the dose rate because the coefficient is 0.986 and is close to 1.0. Start of rainfall is another factor for increasing dose rate; however, continuous rainfall leads to decrease of the rate because rainfall cleans all particles in the air. This is the reason for the low or correlation coefficient between dose rate and rainfall, which is -0.09178. Wind speed multiplies the effect of wind consistency on dose rate.

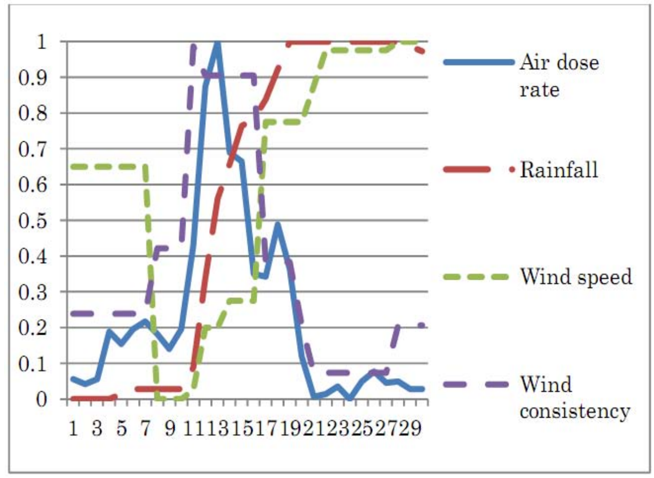

Figure 1: Near Consistent Wind with Rainfall

Table I : Min and Max in Case 1

	Min	Max
Air dose rate	0.058167	0.082
Rainfall	0	18
Wind speed	1.7	5.7
Wind consistency	0.07368	0.986

b) Near Inconsistent Wind with Rainfall

In case B, inconsistent wind with rainfall flows from the plants to the near MP. When wind flows different angles from the diffusion origin, the maximum air dose rate, which is 0.065, is not very high compared to the minimum rate 0.0585 (Fig. 2). In this case, the wind consistency is between 0.095492 and 0.383, which is quite low compared to case 1. Table II summarizes the maximum and minimum values of dose rate and the three factors. The correlation coefficients between dose rate and the other factors, which are rainfall, wind speed and consistency, are -0.42046, -0.2712, and 0.13966, respectively.

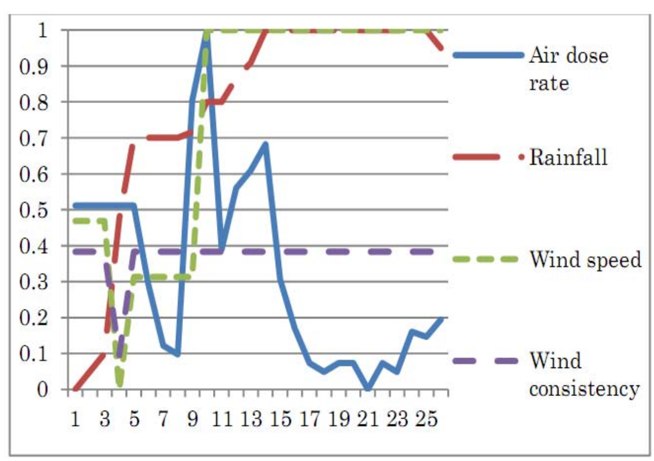

Figure 2 : Near Inconsistent Wind with Rainfall

Table II : Min and Max in Case 2a

	Min	Max
Air dose rate	0.0585	0.065
Rainfall	0	10
Wind speed	2.4	5.6
Wind consistency	0.095492	0.383

c) Near Long-Term Consistent Wind before Rainfall

In case C, long-term consistent wind before rainfall flows from the plants to the near MP. When consistent wind blows long term before rainfall, air dose rate reaches high value, which is 0.091333 in this case. A big spike on dose rate is observed at time period 9, when small rainfall starts (Fig. 3). The maximum dose rate is achieved when rainfall reaches the maximum level. Table III summarizes the maximum and minimum values of dose rate and the three factors. The correlation coefficients between dose rate and the other factors, which are rainfall, wind speed and consistency, are -0.12168, -0.17734, and 0.58694, respectively.

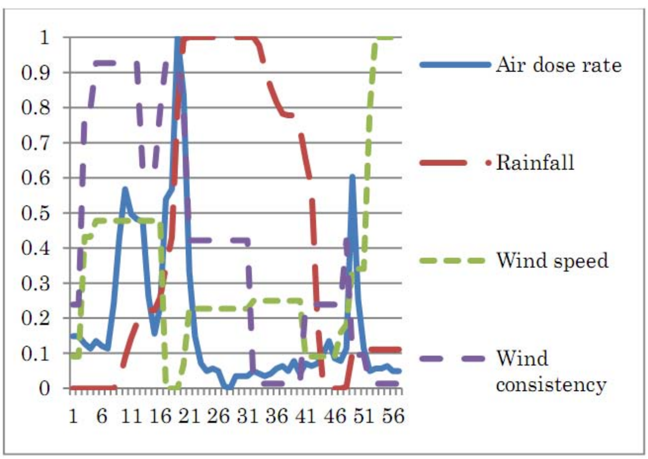

Figure 3 : Near Long-Term Consistent Wind before Rainfall

Table III : Min And Max In Case 3

	Min	Max
Air dose rate	0.067833	0.091333
Rainfall	0	18
Wind speed	2.6	7
Wind consistency	0.013815	0.92632

d) Effective Rainfall Duration, Wind Direction and Wind Speed

Based on the observations described in subsection A, B, and C, this paper proposes a method to identify diffusion sources of sparse radioactive small particles based on air dose rate, amount of rainfall, wind direction, and speed. It is difficult to measure radioactive small particles with monitoring points managed by the Ministry of Education and Culture, Sports, Science and Technology of Japan, because they are intended to measure high dose rate due to the serious effect of the severe nuclear power plant accident. However, they are able to detect the small particles when rainfall starts because it brings the particles to the ground from the air. Hence, based on the amount of increase, this method identifies diffusion sources with wind direction and speed.

Radioactive small particles contribute increase of air dose rate when rain falls. Hence, this method determines all durations of effective rainfall in terms of continuous rainfall. In the early stage of rainfall, radioactive small particles in the atmosphere have begun to drop on the ground, and they contribute an increase of air dose rates of monitoring points. When rainfall has continued long term, the dose rates are going to return to the normal rates because there are no more small particles in the air. Hence, the effective rainfall duration is defined as duration between the beginning of rainfall and the time period of returning to the normal air dose rate.

Eight cases of effective rainfall duration are extracted from one month dataset concerning a monitoring post of Yahata common building for government offices in Kitakyushu city and Yahata weather station. Figure 4 illustrates air dose rate, rainfall, and coefficient of wind direction and speed. In order to illustrate the values in a figure, air dose rate and rainfall are rescaled between 0 and 1 based on the minimum and maximum values, respectively. The minimum and maximum values of air dose rate are 0.0578 and 0.091333, respectively. The values of rainfall are 0 and 41, respectively. Coefficient of wind direction and speed ΘΘΘ(w) is defined as the following formula:

$$w = \frac{1}{2}\left(1 - \frac{1}{1+s}\right)\left(1 + \cos\left(\frac{\pi(\theta-\alpha)}{180}\right)\right) \quad 1$$

where s is wind speed, Θ is wind direction at a monitoring point, and α is direction to a diffusion source from the monitoring point.

North, east, south, and west winds are 0, 90, 180, and 270 on wind direction (Θ), respectively. On one hand, when wind is from a diffusion source ($\Theta=\alpha$), w 0approaches to 1 from 0.5. On the other hand, when wind flow is the opposite direction ($\Theta=\alpha+180$), w approaches to 0 from 0.5. When wind speed (s) is slow, w approaches to 0.5.

According to Fig. 4, when heavy rainfall is observed, high air dose rate per hour is observed, e.g., (c5) in Fig. 4. On the other hand, when light rainfall is observed, low air dose rate per hour is observed, e.g., (c6) in Fig. 4. In order to measure the amount of radioactive small particles in the air without the effect of different amounts of rainfall, the method evaluates increase of air dose rate per rainfall of one millimeter per

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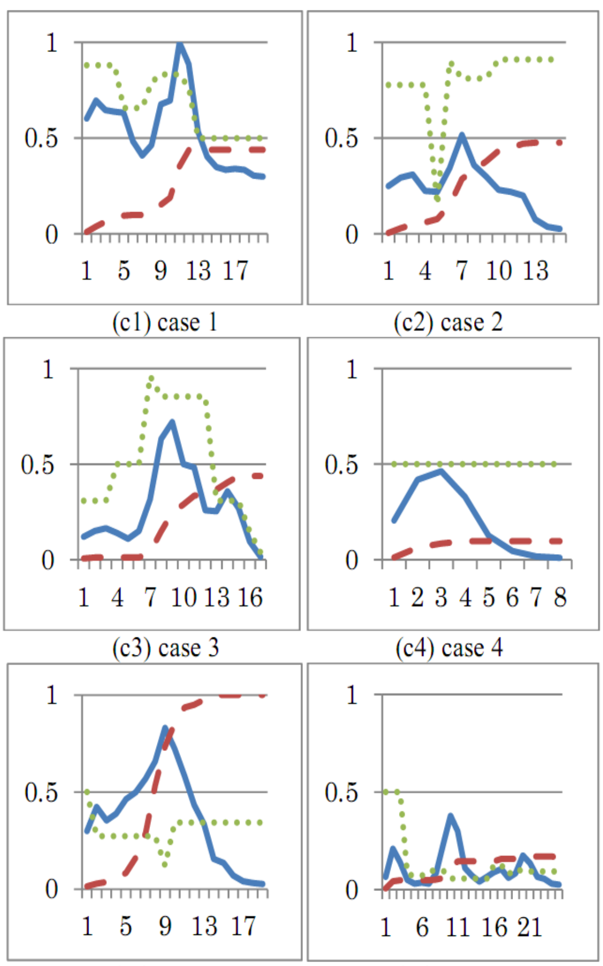
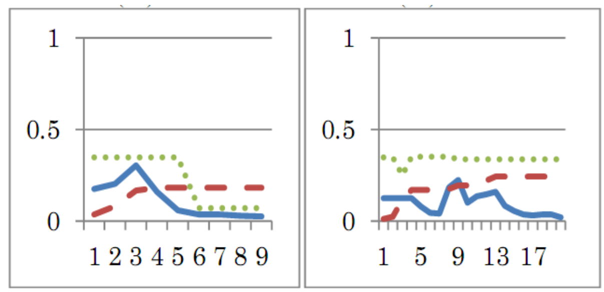
hour. Hence, the method can compare the amount of radioactive small particles among different cases of effective rainfall duration.

Figure 5 shows increase of air does rate per unit of rainfall. Table IV and Fig. 5 show effective rainfall duration, average, and standard deviation of increase of air dose rate. The increase of air dose rate is defined by the difference between a value of each time period and the minimum value among all eight cases. The cases are numbered in descendant order in terms of average of increase of air dose rate.

In order to discuss statistically significant differences of average of increase of air dose rate, three groups (group A of case 1 and 2, group B of case 3, 4, and 5, and group C of case 6, 7, and 8) are separated based on a statistical test of population variance with significance level of 5%. In each group, there is no significant difference on each pair of two cases based on a statistical test of difference of population mean with significance level of 5%. However, concerning three pair of cases among the different groups, there are significant differences between case 3 and three cases (case 6, 7, and 8), in terms of Welch's t-test with a significance level of 5%.

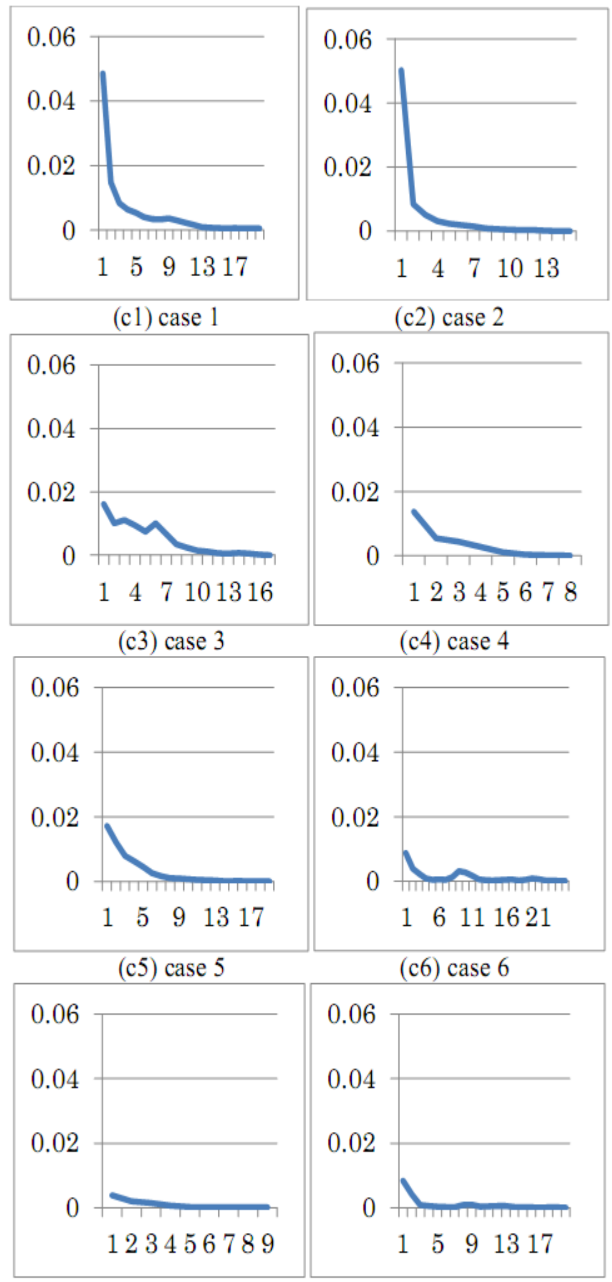


(c1) case 1 (c2) case 2 (c3) case 3 (c4) case 4 (c5) case 5 (c6) case 6



(c7) case 7 (c8) case 8

Figure 4 : Air dose rate, rainfall, wind direction, and speed



(c1) case 1 (c2) case 2 (c3) case 3 (c4) case 4 (c5) case 5 (c6) case 6 (c7) case 7 (c8) case 8

Figure 5 : Increase of air dose rate per rainfall

Table IV : Effective Rainfall Duration, Average, and Standard Deviation of Increase of air dose rate

	Hour	Average	SD
Case 1	20	0.00551	0.01070
Case 2	15	0.00504	0.01271
Case 3	17	0.00482	0.00501
Case 4	8	0.00350	0.00460
Case 5	19	0.00297	0.00478
Case 6	25	0.00129	0.00187
Case 7	9	0.00100	0.00129
Case 8	20	0.00099	0.00196

e) Identifying Range of Existence of Contamination Sources

In order to identify the existence range of diffusion source, correlation between unit increases of air does rate and coefficient of wind direction and speed is calculated for α from 0 to 359 with step one degree. Figure 6 illustrates the correlation and α, which is direction to a diffusion source from the monitoring point. According to a statistical test of popular correlation, the range between 76 and 113 is a significant range, where correlation is equal or greater than 0.8340, where F is greater than 13.7450, and it is the boundary of critical region of significance level of 1%. For significance level of 5%, the range between 64 and 137 is significant range, where correlation is equal or greater than 0.7068, where F is greater than 5.9874. The maximum direction is 92 degrees, where the maximum correlation is 0.8881. All coefficients of wind direction and speed are depicted in Fig. 6. The scatter diagram is illustrated in terms of coefficient of wind direction and speed and increase of air dose rate in Fig. 7.

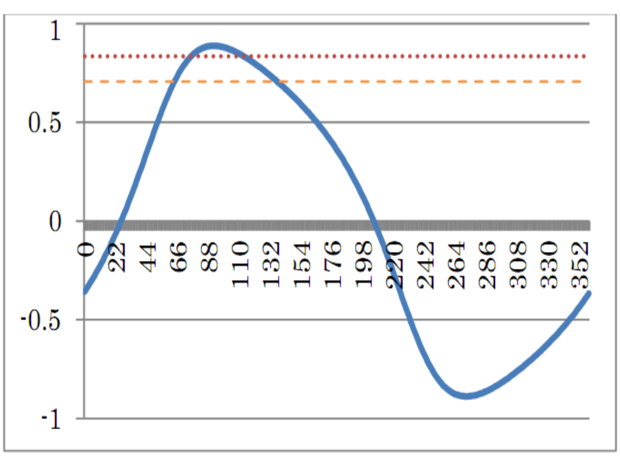


Figure 6 : Direction of diffusion source and correlation

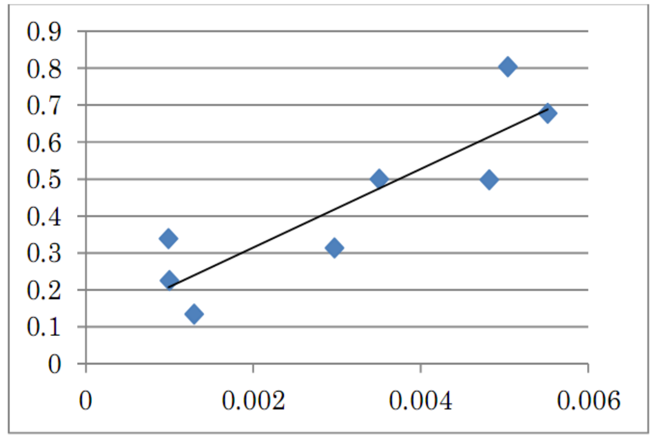


Figure 7 : Coefficient of wind direction and speed and increase of air dose rate

Figure 8 shows the monitoring point (MP) and three incineration plants with existence range of diffusion sources. Table V shows geographical location, distance, and direction concerning MP and three incineration plants. The third incineration plant in Shinmoji in Table V is located in the strict existence range between 76 and 113. The direction of the plant from MP is 90.0865, which is very close to the maximum degree 92. The second plant in Hiagari in Table V is located in the existence range between 64 and 137. The first plant in Kougasaki in Table V is outside of the range; however, the distance to MP is very close. Hence if the first plant in Kougasaki diffuses radioactive small particles, they have a continuous effect to MP in any wind direction. The range on the south part of the region is bigger than the north part in Fig 8. The south part is composed of downtown and forest, while the north part is coastline. The downtown and forest keep radioactive small particles from diffusion sources. Hence, the reason of the wide range in the south part is that the southeast wind brings the particles from the south part to MP.

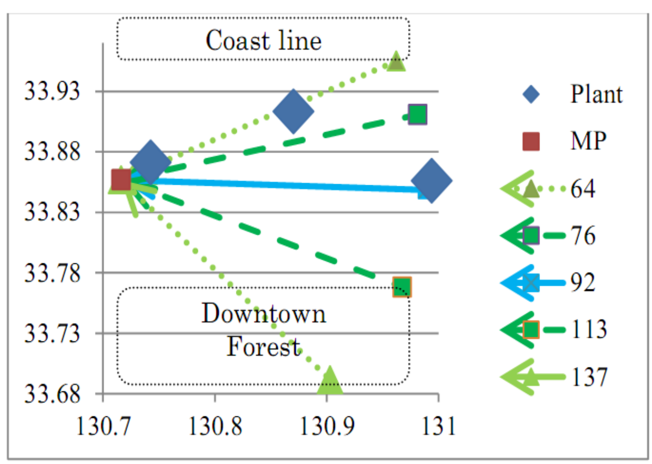


Figure 8 : Existence Range of Diffusion Source

Table V : Monitoring Point and Three Inceneration Plants

Name	Latitude	Longitude	Distance to MP	Direction from MP
Yahata common building for government offices in Kitakyushu city (MP)	33.8567	130.7163	0.0000	
Kougasaki	33.8711	130.7427	1.5741	56.8248
Hiagari	33.9135	130.8703	8.3925	66.0353
Shinmoji	33.8561	130.9939	13.8311	90.0865

IV. Conclusion

This paper proposed a statistical method to find diffusion sources of radioactive substances. Diffusion of radioactive substance could be a major concern worldwide. In section II, this paper summarized the contamination derived from the Fukushima No. 1 nuclear power plant in Japan. A set of three incineration plants in Kitakyushu city were employed as safe spreading origins of radioactive airborne particles because the Japanese Ministry of Environment approved the burning earthquake debris contaminated by radioactive substance derived from the Fukushima No. 1 power plant accident. Data concerning air dose rate and weather conditions were analyzed on the nearest MP of the spreading area. The detection method identifies contamination sources of radioactive substances in the air based on open data, which are composed of air dose rate, amount of rain, wind speed, and direction. This method focuses on all cases of continuous rainfall duration because of the various sizes of spike concerning air dose rate on a public monitoring point. Each spike starts when rainfall begins while the spike disappears when rainfall continues because rainfall cleans up radioactive particles in the atmosphere. The method confirms a statistically significant difference of increased rate of air dose rate between each pair among rainfall cases. It also identifies a range of direction from a monitoring point to diffusion sources based on significance tests of correlation coefficients.

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