ESTIMATION OF RADIOACTIVE POLLUTANTS ADVECT FOR FUKUSHIMA NUCLEAR POWER PLANT BY A PARTICLE MODEL

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ABSTRACT: On March 11, 2011, the Great East Japan Earthquake brought strong shakes and tsunami in East Japan, and Fukushima Daiichi Nuclear Power Plant became out of control. Finally worldwide radioisotope pollution occurred. Especially hydrogen explosions and vent operations emitted radioisotopes and impacted neighbouring areas significantly. In this study, an atmospheric diffusion simulation was carried out for each pollution using a simple particle model. Without complex and vast calculation, instantaneous diffusion damage predictions for the accident or trial atmospheric diffusion simulation before the accident are expected with much effect. Calculations with the particle model were carried out from Mar 12 to 30, 2011. The wind velocity and direction data were from atmospheric analytical data in 5 km-grid every hour with 8-class heights from surface to 3000 m. The precipitation data were used from the composite data of RADAR and AMeDAS. Radar-Amedas is precipitation data in 1 km-grid every 30 minutes. Particles were 10 sizes of 0.01 to 0.1 mm in diameter with specific weight of 2.65 and vertical speeds given by the Stokes equation. In rainy time, the particles fell down at a moment as wet deposit in calculation. The altitudes on the ground were given by DEM with 1 km-grid. The spatial dose by emitted radioisotopes was referred to the observation data at monitoring posts of Tokyo Electric Power Company. The falling points of radioisotopes were expressed on the map using the particle model. As a result, almost the same distributions were obtained as the surface spatial dose of radioisotopes in aero-monitoring by Ministry of Education, Culture, Sports, Science and Technology. By the particle model, the falling positions on the ground were estimated each particle size and height. Particles with more than 0.05 mm of size were affected by the topography and blocked by the mountains with the altitudes of more than 700 m.

1. INTRODUCTION

On March 11, 2011, the Great East Japan Earthquake brought the earthquake and tsunami in East Japan, and Fukushima Daiichi Nuclear Power Plant became out of control, finally worldwide radioisotope pollution occurred. Atmospheric diffusion of radioisotopes was simulated by SPEEDI and various methods so far as validations and reproduction (Japan Atomic Energy Agency, 2011). Although in 2012 Tokyo Electric Power Company presented analytical results on radioisotope emission estimation (Tokyo Electric Power Company, 2012), still the estimate at the accident and the examination for simulation methods are modified continuously. However, the atmospheric diffusion model could not accurately evaluate the accident pollution. In this study, an atmospheric diffusion simulation was carried out using a simple particle model. Without complex and vast calculation, instantaneous diffusion damage predictions in the accident or trial atmospheric diffusion simulation before the accident are expected with much effect.

2. Methods

2.1 Outlines

In advection diffusion of radioisotopes in the air, mostly an atmospheric diffusion model and a particle model are available. The atmospheric diffusion model is often used for process of migration for gaseous contamination, but various parameters are required: atmospheric stability, the source height, a mixing layer height, and a deposition rate. On the other hand, in a particle model, since only particle sizes are a parameter for calculation, the total calculation is very simple as characteristics. In this study, most radioisotopes were emitted from Fukushima Daiichi Nuclear Power Plant by hydrogen explosions, vent operations, and leak with pressure increase in the containment vessels, and they are assumed to move with concrete debris in hydrogen explosions or aerosols in the air using a particle model.

2.2 Calculation methods

Radioisotopes were particles or gaseous at leaked parts in the nuclear power plant, but actually most radioisotopes adhered on the concrete debris in hydrogen explosions and aerosols in the air and crystallized, finally travelled in the air and fell down on the ground. In this study, this state was assumed as a particle with a diameter of 0.01 to 0.1 mm in the calculation.

Horizontal velocities are the same as wind data, while vertical velocities are the Stokes equation as next.

$$v_s = \frac{D^2(\rho_p - \rho_a)}{18\mu} \qquad (1)$$

where v_s: a falling velocity (m),

ρ_p: particle density (2650kg/m^3)

ρ_a: air density (1.225kg/m^3)

μ: viscosity coefficient (1.8Pas)

Polluted particles were two types: in a gaseous state in a constant elevation speed and flying state in hydrogen explosions. Here, all particles started at the initial speed 0 km/h from each elevation layer in GPV, hourly atmospheric analytical data and travelled with winds and constant falling velocities. The judgement for deposit used elevation values. From this, over Abukuma Hills the advective flow state of radioisotopes was examined topographically. Each calculation was ended when each particle fell down and flied out of the calculating area. The relationship between wind data and topography data is as shown in Figure 1.

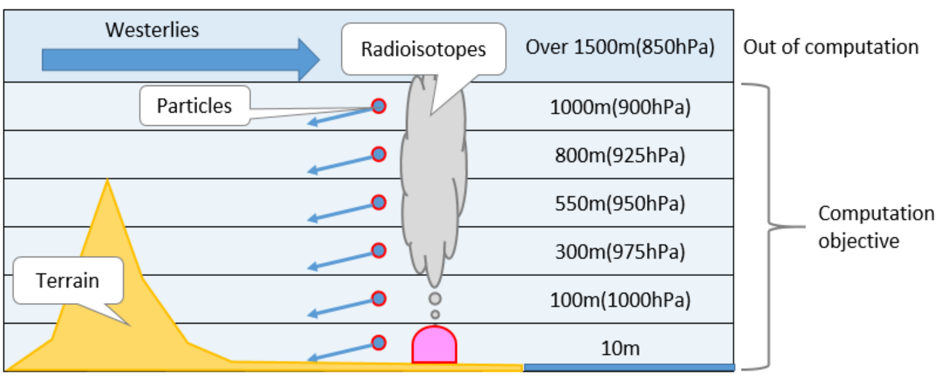

Figure 1. Relationship between wind and topography data

Distinction between dry and wet deposits was judged by observed precipitation occurred each mesh when particles migrated. Namely, if it did not rain it was dry deposit, otherwise, even a little (precipitation R>0), it was wet deposit, in the route of the particle advection to landing on the ground surface. The calculation time was from 15:00(JST) on March 11 to 31, 2011, including 15:30 on March 11, 2011 when the tsunami caught on Fukushima Daiichi Nuclear Power Plants. The time resolution was taken as 10 minutes with consideration the calculated mesh size (about 1 km).

2.3 Objective area

Figure 2 shows location of Fukushima nuclear power plant, located 280 km away from Tokyo. On the east side it faces the Pacific Ocean, where tsunami flowed in. On the other hand, on the west side it faces Abukuma highlands, where the flat land near the plant continues to steep slopes on the surroundings. Objective area is shown in Figure 3, which is the most polluted from Aerial monitoring by Ministry of Education, Culture, Sports, Science and Technology (2011). In the square of 100 km east to west and 200 km north to south from Fukushima Daiichi Nuclear Power Plant,1 km by 1 km grids were calculated as shown in Figure 3. Radioisotopes released to the Pacific Ocean were excluded from this study.

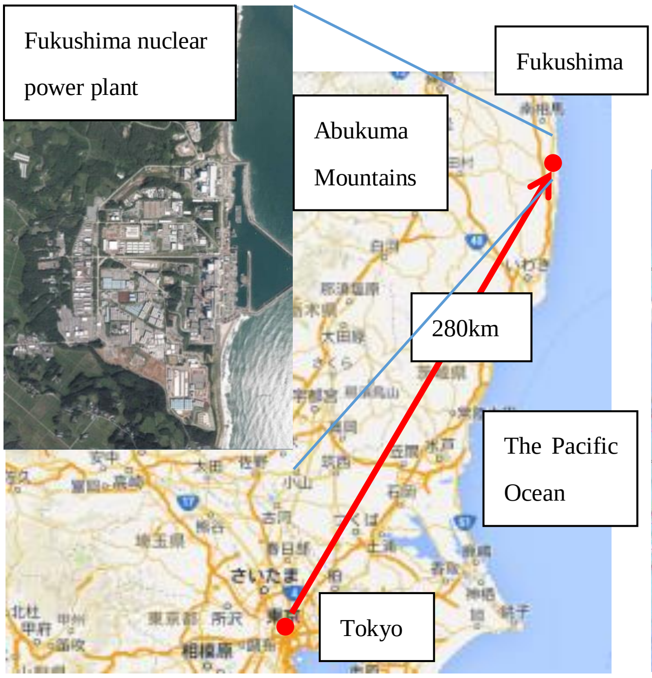

Figure 2. Location of Fukushima nuclear power plant

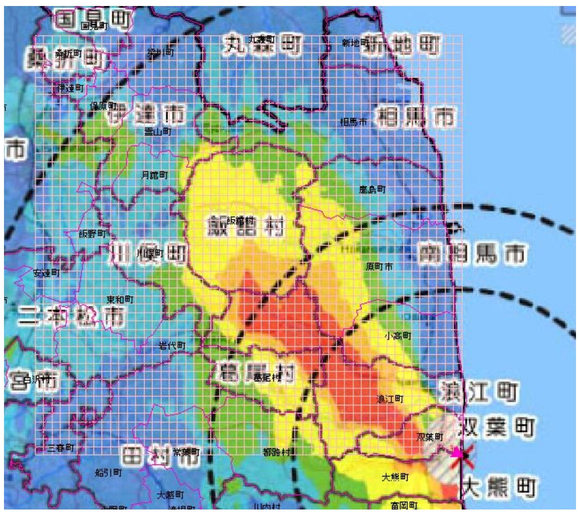

Figure 3. Aerial monitoring results and the objective area in this study

2.4 Used data

2.2.1 Wind directions and velocities

In this study, wind velocity and direction data were from hourly atmospheric analytical data, GPV (Grid Point Value) in the mesoscale model, MSM. Hourly atmospheric analytical data, GPV are modified by the wind profiler observation from wind predicted data in MSM as the initial data. These data are analytical ones of surface winds and winds aloft (Meteorological Bureau, 2006). If the wind profiler observation such as AMeDAS is available, this value and its distance correct the values in MSM and accurate wind direction and velocity data are offered. Since the format is constant without wind profiler observation, the uniform continuous calculation is always possible. The spatial resolution is 0.05 deg. by 0.0625 deg. and 16 layers in elevation for surface winds and winds-aloft. In this study, because of the objective radioisotopes deposited inland, high-rise wind of 850 hPa (1,500 m above the ground) which is greatly influenced by the westerly wind is excluded from the calculation.

2.2.2 Precipitation

In this study, precipitation data were used from the composite data of RADAR and AMeDAS in Meteorological Bureau. The composite data of RADAR and AMeDAS in Meteorological Bureau are obtained from radars and AMeDAS, areal rain gages in the surface in Japan with 1-km grids. The data are shown in hourly precipitation every 30 minutes (Meteorological Bureau). Since the format is constant without areal data, the uniform continuous calculation is always possible even if the nearest areal observation data is not available by the accident in this study. In this study these data were used for the judgement dry deposit and wet deposit.

2.2.3 Topography data

In this study, the third grid data, elevations and slopes in the digital national land information were used. These data spatial resolution is 1 km by 1 km. The elevation maps open in Japan have fine grid data, but 1 km by 1 km grids were used in this study corresponding to wind direction and velocity data and precipitation data with 1 km by 1 km grids and the temporal resolution with 10 minutes. These data include the mean, maximum, minimum and elevations, but the mean data were used.

Used data for the analysis were as Table 1.

Table 1. Used data for calculation

Data	Data name	Spatial resolution	Time resolution
Wind data	Hourly atmospheric analysis data, GPV*	0.05deg. × 0.0625deg. (5km × 5km)	60min
Precipitation	Radar -AMEDAS**	0.008333deg. × 0.0125deg. (1km × 1km)	30min
DEM	Digital national land information, altitude and slopes, 3D grid data***	0.008333deg. × 0.0125deg. (1km × 1km)	-

* Meteorological Bureau (2006),

** Meteorological Bureau,

*** Ministry of Land

2.2.4 Monitoring data

Monitoring data published by TEPCO was used as reference information on the time-series concentration of radiation emitted from Fukushima Daiichi Electric Power Plant. In the calculation using the particle model, it is possible to confirm how much dose the particles arrived at the ground surface when they were released from Fukushima Daiichi Power Plant. However, the absolute amount of released radioactive material was not evaluated since these data are largely affected by the position of the monitoring posts, the wind direction wind speed and the surrounding circumstances.

3. RESULTS

Figure 4 shows the results of particle advection from March 11 to 31 since the earthquake occurred and the result of aircraft monitoring. Many particles diffused and dropped around Fukushima Daiichi Nuclear Power Plant, and they were transported to northwest, which is similar to the aerial monitoring results. In this figure, red dots represent dry deposition and purple dots represent wet deposition. Pollution in the northwest part of Fukushima Daiichi Electric Power plant was affected by mainly wet deposition.

3.1 Difference from atmospheric diffusion model

The calculation result of the atmospheric diffusion model is a continuous shape like a normal distribution. On the other hand, the particle model could express contaminated states such as hot spots, because the locations of radioactive materials deposited are specified for each particle independently. An example is shown in Figure 5, which indicates the particles did not drop to the places where the dose was small.

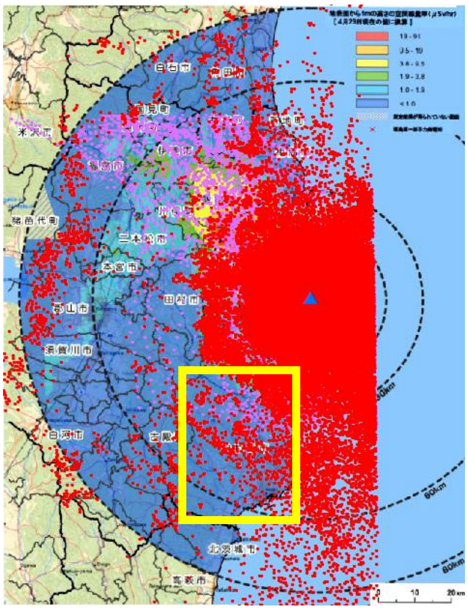

Figure 4. Results of particle advection

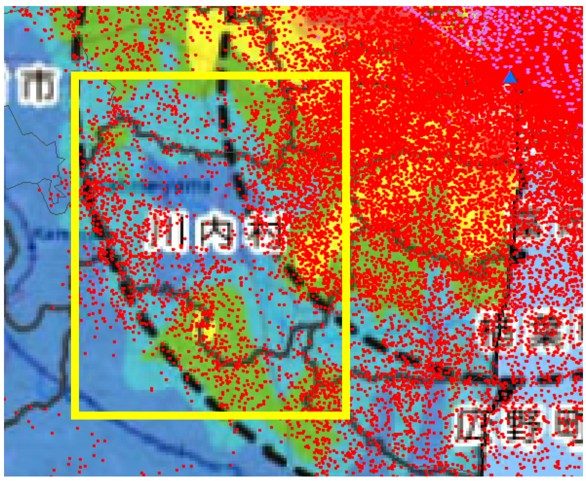

Figure 5. Characteristics of particle model

3.2 Consistency with monitoring data

For confirming consistency with monitoring data, focus on calculation results of the period when high concentration of radioisotopes was released into the atmosphere and the period when significant increase in radiation dose was observed. Table2 shows the periods when high concentrations of radioactive substances were released into the atmosphere.

Table 2. High concentrations of radioactive substances were released into the atmosphere

Time (JST)	Reactor	Events	Dose* [μSv/h]	Wind direction	Precipitation
3/12 10:17	1	vent operations	4.3	N	
14:30	1	vent operations	10	S	
15:36	1	Hydrogen explosion	270.5	SE	
3/13 8:41	3	vent operations	307.8	SW	
11:00	2	vent operations	54.3	NW	
3/14 5:20	3	vent operations	420	NE	
11:00	3	Hydrogen explosion	259.4	W	
20:00	2	Nuclear fuel damage	5.4	N	
3/15 0:02	2	vent operations	188.9	NW	
6:00	4	Hydrogen explosion	73.2	N	
6:10	2	Hydrogen explosion	73.2	N	
8:00	2	Nuclear fuel damage	873.1	NE	
12:00	2	Radioisotopes release	2431	SE	Precipitation
3/16 4:00	2	Pressure vessel breakage	1047	N	Precipitation

From Table 2, the pollution of the northwestern part of the Fukushima Daiichi Electric Power Plant could be largely contributed by the explosion of Unit 1 on March 12 and the release of radioisotopes from Unit 2 on March 15. Therefore, focus on the calculation results of March 12 and March 15. From the observation of radioisotopes at monitoring posts of Tokyo Electric Power Company (Tokyo Electric Power Company), a time series of March 12 to 21 with intense spatial dose are shown in Figure 6, showing pollution time on northwest of Fukushima Daiichi Nuclear Power Plant by east to south winds

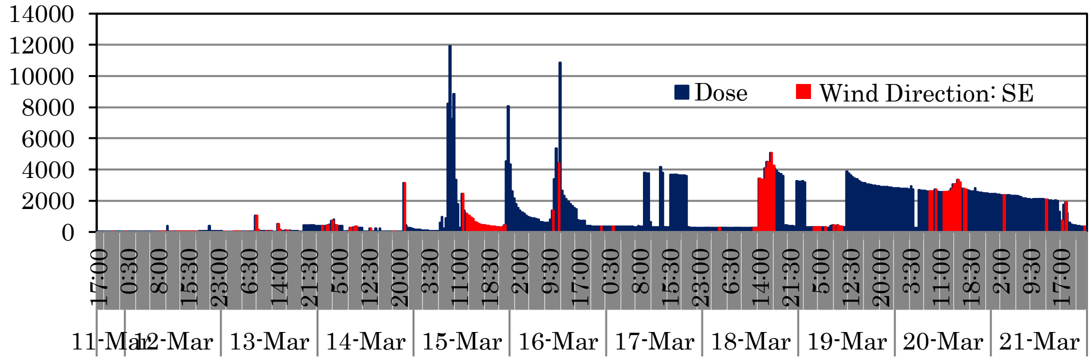

Figure 6. A time series of spatial dose (unit: μSv/h) and the ratio of pollution for Objective area.

The bar graph shows the spatial dose each time and red bars indicate the time when east to south winds blew. Then, the spatial dose was very high on March 18 and 20 by east to south winds. Therefore, focus on it to calculation result of March 12 and March 15.

On March 12: By a particle model, pollution state on March 12 was estimated as Figure 7. Circles expressed particle sizes. At this time wind directions were different very much each altitude: small particles trended to flow to the Pacific Ocean, while large particles fell down to the northwest from Fukushima Daiichi Nuclear Power Plant. From this result, particles emitted by an explosion on March 12 did not seem to approach west of Abukuma Hills by the effects of winds and geography.

On March 15: The result on March 18 is shown in Figure 8. **A**t 16:00 on March 15 it was rainy northwest of Fukushima Daiichi Nuclear Power Plant. Rain clouds passed over Fukushima city from west, and at 21:00 they caught pollution particles east of Fukushima Prefecture. Wet deposit continued on the ground through the trajectory of particles. As a result, radioisotopes flied over Abukuma Hills and approached the west slopes of mountains. Till 24:00 most particles deposited wetly.

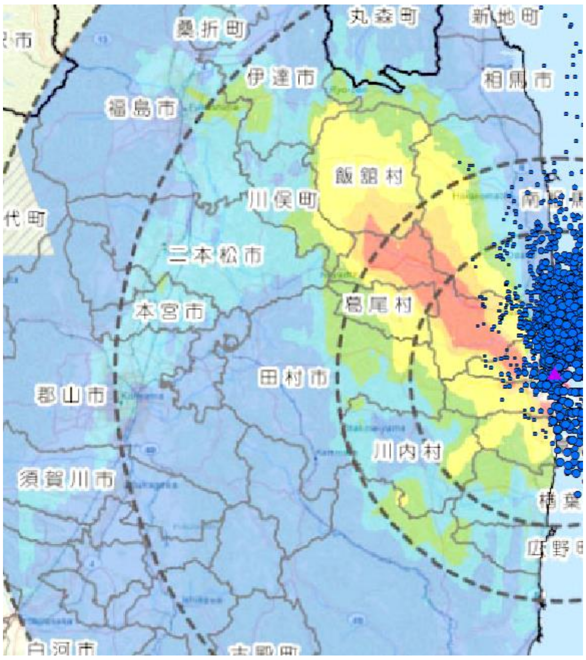

Figure 7. Particle trajectory estimated from wind directions and velocities on March 12

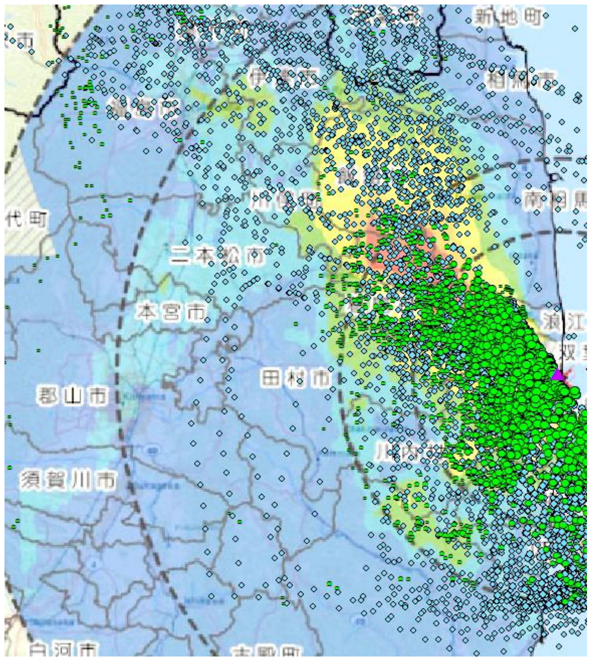

Figure 8. Particle trajectory estimated from wind directions and velocities on March 15
Green point: dry deposit, Blue point: wet deposit

On March 18: The result on March 18 is shown in Figure 9. On this day, most of particles flied to northwest, but did not fly over the Abukuma Hills and concentrated within 15 km from the nuclear power plant. Less than 0.02 mm particles trended to fly to north. It shows high consistency with the contamination map.

On March 20: The result on March 20 is shown in Figure 10. Most of particles on this day trended to fly to north northwest uniformly in height and particle sizes. The horizontal distribution of polluted particles was more widely than other three days.

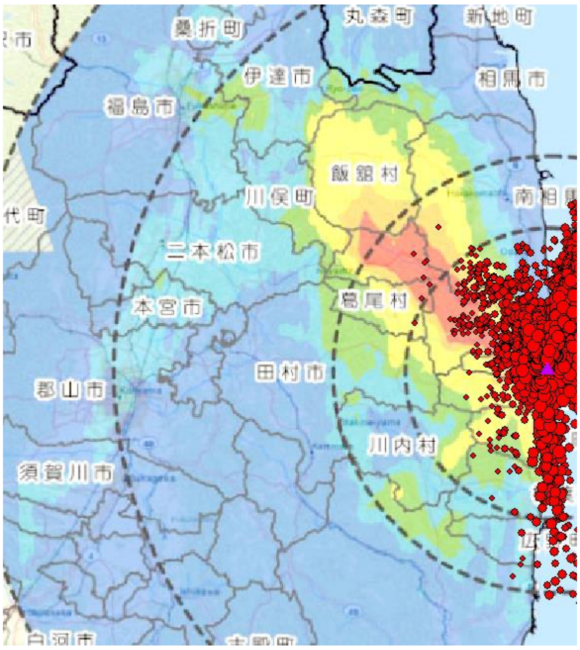

Figure 9. Particle trajectory estimated from wind directions and velocities on March 18

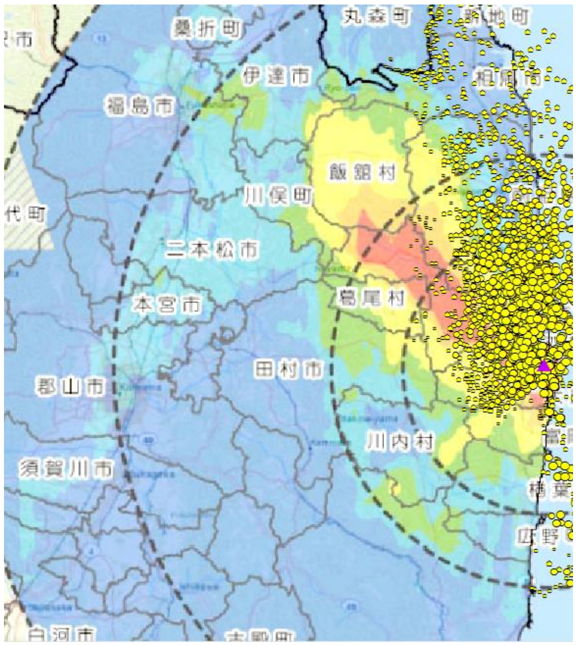

Figure 10. Particle trajectory estimated from wind directions and velocities on March 20

On March 22: In the advection calculation using the particle method, the time of discharge and the dropping points are obtained for each particle. Figure 11 shows the release time of particles from Fukushima Daiichi Nuclear Power Plant. Therefore, in addition to tracking particles in the period when the radiation dose was high by monitoring, it is possible to confirm the dose at the time of release of particles falling to high contamination ground points. The left figure shows focusing on the red frame part in the right figure.

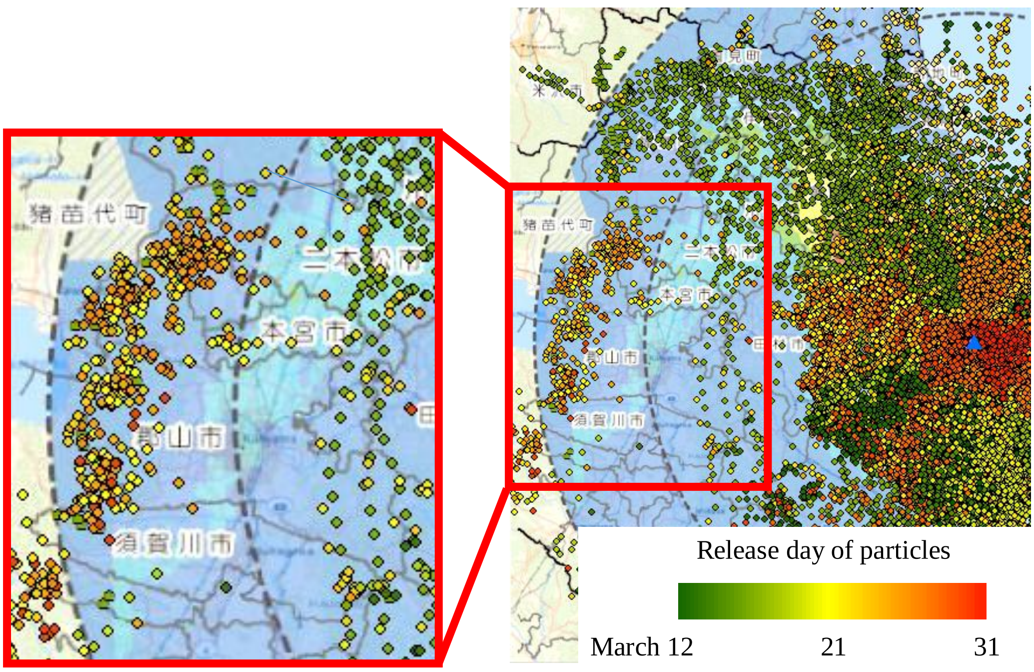

Figure 11. Particle diffusion deposit map with monitoring data

In this figure, high pollution particles did not drop along the national road, but they fell on the east slope of the western mountains. The release time of these particles was around 18 o'clock on March 20. According to the monitoring data of TEPCO, the release of radioactive substances was at a high level until March 21, and the release amount during this period cannot be ignored.

4. DISCUSSION

In this study, contamination advection was calculated with the particle model for contamination of the northwest part of Fukushima Daiichi Nuclear Power Plant. The particle model could calculate discontinuous contamination shapes which could not be clarified by the atmospheric diffusion model. Pollution on northwest of Fukushima Daiichi Nuclear Power Plant started from hydrogen explosion on March 12, but the most of contribution for pollution was twice pollutions, on March 15 and 18. Pollution on March 12 was affected only by radioisotopes near 100 m height, but the result did not fit with aircraft monitoring results, and then this contribution was estimated to be small. On March 15, 18 and 20, radioisotopes under 200 m, 500 m, and 500 m height flew into inland, respectively. Among them, on March 15 particles flied over the Abukuma Hills and it rained after flowing, thus, the result became intense pollution. The particle model distinguished the different states of dry and wet deposit. On March 18 it was not rainy and wind was weak, and then pollution was limited for nearer areas on the northwest of the nuclear power plant. Therefore, the total pollution was contributed mostly by the radioisotope diffusion of hydrogen explosions and the leak of the containment vessel. Moreover, the pollution distribution was determined mainly by geography. On any days radioisotopes were blocked out by the Abukuma Hills, especially, against mountains with altitude 500 to 1192 m radioisotopes fell down on the slopes of and adsorbed in contaminant. The calculation result of March 22 was inconsistent with the Aerial monitoring results. Compared with the aerial monitoring results, the calculated dose at horizontal distance indicated about 15 km longer than observed dose. Considering the influence of horizontal air resistance should be considered.

5. CONCLUSIONS

From above results, the next items were concluded.

(1) Advection calculation for radioisotopes using a particle model does not request any parameters, which an atmospheric diffusion model uses, atmospheric stability, the source height, a mixing layer height, and a deposition rate. Although a particle model is a simple method, the overall migration process for radioisotopes was estimated.

(2) The particle model could express discrete contaminated state such as hot spots.

(3) Pollution of Fukushima Daiichi Nuclear Power Plant was limited because diffusion of radioisotopes was controlled by mountains with altitude 500 m to 1192 m.

(4) It is necessary to consider air resistance horizontally, because some polluted parts are not consistent with the Aerial monitoring results.

6. FUTURE ASSIGNMENTS

To improve fitness with monitoring results, horizontal air resistance should be considered as future assignment. Moreover, for radioisotope migration after its deposit, next geographic elements should be evaluated.

(1) Consideration of horizontal air resistance for deposition locations.

(2) Discharge from rivers or groundwater, and absorption for land uses or land covers.

(3) Effect by transportation: vehicles and railroads

By using approximation of these items in simple ways, emission by explosions and leaks, advection diffusion in the air, and migration on the earth surface should be estimated near future. Finally, instantaneous diffusion damage prediction in the accident and trial simulation for atmospheric diffusion before the accident should be solved with such simple ways.

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