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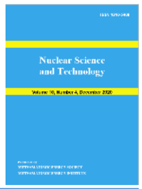

Simulation of atmospheric radiocesium (^{137}Cs) from Fukushima nuclear accident using FLEXPART-WRF driven by ERA5 reanalysis data

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Abstract: This study investigates short-range atmospheric transport of radiocesium (^{137}Cs) after Fukushima nuclear accident using the Weather Research and Forecasting (WRF) model and the Lagrangian particle dispersion FLEXPART-WRF model. The most up-to-date ERA5 reanalysis dataset is used as initial and boundary condition for the WRF model for every hour. Four experiments were carried out to examine the sensitivity of simulation results to micro-physics parameterizations in the WRF model with two configured domains of 5 km and 1 km horizontal resolution. Compared with observation at Futaba and Naraha station, all experiments reproduce reasonably the variation of ^{137}Cs concentration from 11/03 to 26/03/2011. Statistical verification as shown in Taylor diagrams highlights noticeable sensitivity of simulation results to different micro-physics choices. Three configurations of the WRF model are also recommended for further study based on their better performance among all.

Keywords: *^{137}Cs dispersion, Fukushima Daiichi nuclear power plant, FLEXPART–WRF model, ERA5 reanalysis data, Futaba, Naraha.*

I. INTRODUCITON

The massive earthquake in Japan occurred at 14:46 JST on 11/03/2011, with a magnitude of 9.0 [1] that caused heavy damage to infrastructure along the east coast. It was followed by the inundations of tsunami that caused power outages and flooding in a large residential and industrial area. This event had a major impact on five nuclear power plants along Japan's northeast coast, Higashidori, Onagawa, Fukushima Daiichi, Fukushima Daini and Tokai Daini. Fig. 1 shows the epicenter of the earthquake was far from Fukushima Daiichi nuclear power plant (FDNPP) 180 km in the northeast and Onagawa NPP 130km in the east [2,3].

The FDNPP consists of six units that were strongly impacted by the earthquake and tsunami, leading to a serious nuclear accident, radioactive substances were released from the plant area and released into soil, water and air environments (Fig. 2). The most serious is that radioactive materials are released into the air, they will be spreaded under different weather conditions and can be fell in continent and sea areas that is very far from the accident site.

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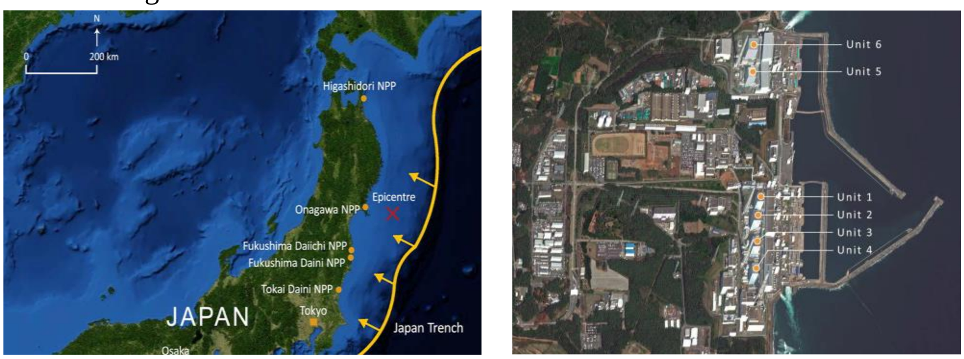
A number of computational models have been used to study radioactive contamination in the vicinity of the FDNPP from the 15/03/2011 [4], the regional simulation [5-8], and global scale simulation [9-11]. The results of these models are quite consistent in reproducing high radioactive deposition at the center of Fukushima prefecture. However, these models have not yet accurately assessed the radioactive matter deposition in the vicinity of the factory, especially at radioactive monitoring stations within a radius of 10 km.

Currently, the rapid development of numerical dynamical weather model as well as of particle dispersion models allows high-resolution simulation of atmospheric radionuclides [12]. An important factor for these simulation is global meteorological datasets driven the regional models. Implementing Global Environmental Multiscale model, the Canadian Meteorological Center (CMC) provides analysis data with horizontal resolution of approximate 33 km and at 80 pressure levels [13]. The National Center for Environmental Prediction (NCEP) runs the global data assimilation system (GDAS) four times per day (i.e. 00, 06, 12, and 18 UTC) to provide prediction issues [14]. The UK Met Office gives a forecast data 6 hourly at horizontal resolution of 25km with 70 pressure levels [15].

Especially, the European Regional Weather Forecast Center (ECMWF) provides high resolution global forecasts with a frequency of twice a day at 00 UTC and 12 UTC, used innovative 4D-Var data assimilation system with 91 different pressure levels [16]. Recently, the ECMWF created a new ERA5 reanalysis data with horizontal resolution of 31 km and 137 different pressure levels. In addition, the land surface and ocean surface data are provided, including precipitation, temperature at 2 m and atmospheric radiation [16].

In this study, the most up-to-date ERA5 reanalysis dataset will be used as initial and boundary condition for a numerical weather prediction model. Then, simulation output of this weather model will force a particle dispersion model, in order to simulate the transport of radiocesium (^{137}Cs) after the Fukushima nuclear accident. In addition, different experiments are carried out to evaluate the sensitivity of simulation results to physics choices of the atmospheric model. The sensitivity can be evaluated by discrepancies among outputs of experiments, as analyzed in the following sections.



(a) (b)

Fig. 1. (a) The epicenter of the massive earthquake in Japan on 11/03/2011 [2] and **(b)** the satellite image of the FDNPP site [3]

II. EXPERIMENT DESIGN

In this study, the WRF model and a Lagrangian particle dispersion model (LPDM) are used to simulate short-range atmospheric transport of radionuclides (i.e. ^{137}Cs). Figure 2 depicts the process to carry out experiments, in form of a flow-chart. The WRF model is a numerical dynamical atmospheric simulation model, governed by compressible and non-hydrostatic Euler equations [17]. The Advanced Research WRF (ARW) dynamics solver which implements flux-form equations with variables that have conservation properties and a terrain-following mass vertical coordinate, is used in this study (Fig. 2). The LPDM applied in this study is FLEXPART-WRF model which is modified version of the FLEXPART model to works with the WRF model [12, 18]. The FLEXPART-WRF model differs from its preceding versions in that it has novel turbulence scheme for the convective boundary layer [12].

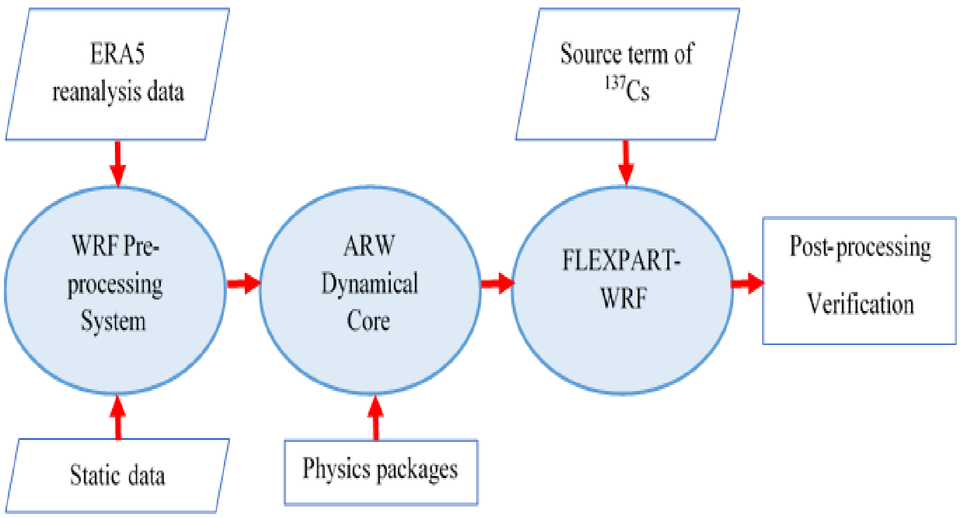
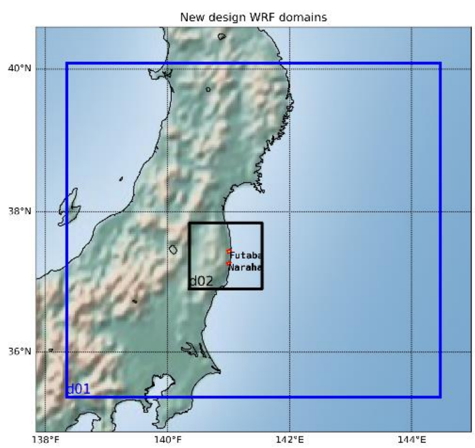
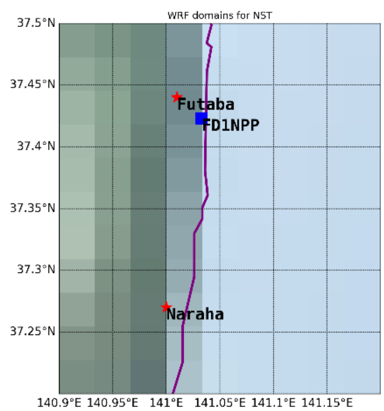


Fig. 2. Flow-chart of simulation processes in this study, implemented the WRF-ARW atmospheric model and the FLEXPART-WRF dispersion model



(a)



(b)

Fig. 3. Simulation domains of the WRF model **(a)** with horizontal resolutions of 5 km (d01 – blue rectangle) and 1 km (d02 – black rectangle) and **(b)** location of Futaba, Naraha station as well as Fukushima Daiichi Nuclear Power Plant (FD1NPP)

The WRF model provides spatial and temporal meteorological variables as forcing for the FLEXPART-WRF to simulate the spread of radionuclides. Two domains of the WRF model are configured in this study with horizontal resolutions of 05 km and 01 km (Fig. 3). Topography of the vicinity of the FNPP is very complicated, with coastal lines on the East and surrounded by mountains on the West. The computational domain with a high-resolution of 01 km inside the 100 km vicinity of the plant (domain d02) and 05 km for the outside of 100km region (domain d01) is expected to reasonably capture the spead of radiocesium plumes. The WRF model runs with 51 vertical levels of the atmosphere and 04 soil layers of 10, 30, 60, 100 cm thick. The ERA5 reanalysis data is used as initial and boundary conditions for the WRF model with hourly update timestep. Simulation time is from 21:00 UTC on March 11, 2011 to 01:00 UTC on March 26, 2011.

Physical processes are parameterized in the WRF model include (1) micro-physics, (2) cumulus parameterization, (3) planetary boundary layer, (4) land surface model, and (5) radiation processes. The cumulus parameterization is only valid for coarse grid resolution (i.e. greater than 10 km) as convective assumptions will be violated for finer resolution. Therefore, in this study, the convection parameterization schemes are not activated. The Noah surface scheme was used to calculate the soil temperature and moisture content in soil layers, taking into account snow cover and freezing processes in the soil [19]. Yonsei University (YSU) planetary boundary layer scheme [20], Dudhia short-wave radiation scheme [21] and Rapid Radiative Transfer Model (RRTM) long-wave radiation scheme [22] are used in this research. Radiation schemes are updated with time steps of 5 minutes and 1 minute for 05 km and 01 km-resolution domains, respectively.

The sensitivity of the atmospheric radionuclide simulation to different micro-physics options will be investigated with four experiments (Table I). Different microphysical options will yield different moisture variables, depending on the phase transitions and interactions of water and ice particles. The Kessler scheme is suitable for a warm cloud consisting of water vapor, water droplets and raindrops, and the other processes including the generation, fall and evaporation of raindrops [23]. The WSM 6-class scheme includes snowfall and other related processes and the phase transition of ice [24]. This scheme is suitable for dealing with grids that contain clouds while other processes are similar to WSM 3-class scheme [25]. Thompson's scheme assumed snow size distribution depends on both temperature and ice water content and is represented as a sum of exponential and gamma distributions [26].

Table I. List of experiments in this study

No.	Experiment name	Microphysics	Description	Reference
1	Exp 1	Kessler scheme	Warm rain (i.e. no ice or idealized case)	Kessler (1969)
2	Exp 2	WRF Single-Moment (WSM) 3-class	Simple ice (3 arrays)	Hong et al., (2004)
3	Exp 3	WSM 6-class graupel scheme	Cloud scale, single moment (6 arrays, graupel)	Hong and Lim (2006)
4	Exp 4	Thompson graupel scheme	Double moment (8-13 arrays)	Thompson et al., (2004)

In order to run a dispersion model, a specific emission source is required to indentify. The source term of ^{137}Cs radioactive nuclide released from the reactor area by time and position is determined based on the analysis report of Katata et al., (2015) [27]. To evaluate simulation results, the time-series analysis of atmospheric radiocesium at two monitoring sites (i.e. Futuba and Naraha) after the Fukushima accident are used [28]. In addition to comparison on time-series plot and map of concentrations, the Taylor diagram are used to compare simulation results [29]. This diagram provides a concise statistical verification of how well simulation match observation, in terms of Pearson's correlation coefficient, root-mean-square difference, and the ratio of standard deviations [29].

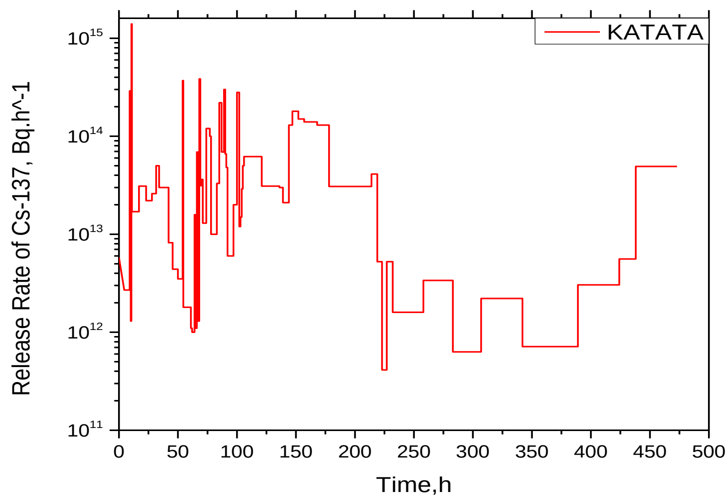


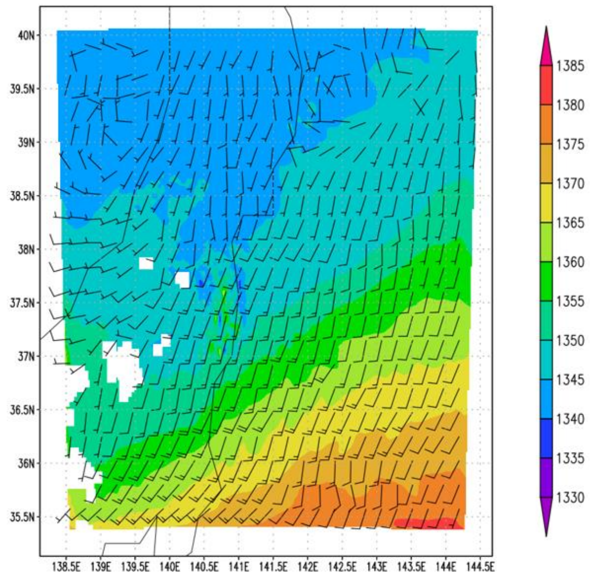
Fig. 4. The source term of ^{137}Cs over the time after the accident, retrieved from [27]

III. RESULTS AND DISCUSSIONS

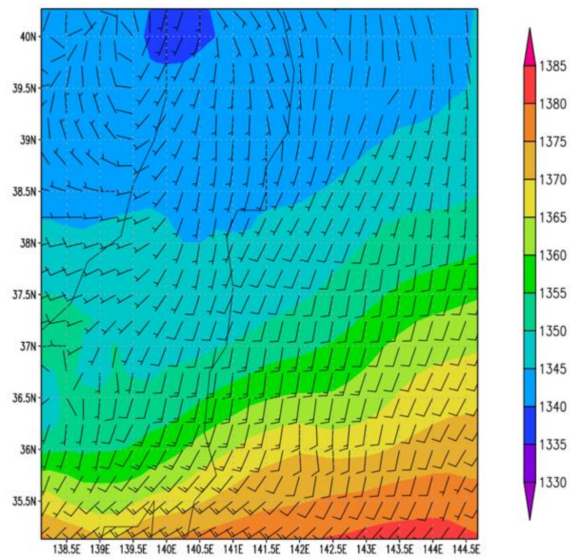
A. Simulation of meteorological conditions

With coarse resolution of approximately 31 km, the ERA5 reanalysis data can not reproduce meteorological variables over complex terrain of Japanese region. The WRF model can downscale dynamically to finner mesh resolutions (i.e. 05 km and 01 km in this study). Fig. 5 shows that the WRF model can maintain well the spatial pattern of geo-potential height over Japanese region from the forcing ERA5 data. The high pressure system located at the North of Japan as well as the pressure gradient followed Northwest-Southeast axis are reproduced well in the WRF model (Fig. 5). It's worthy to note that, for facilitating "eyeball" verification, the number of wind barbs in Fig. 5(a) is thinned with factor of 10. It means that the WRF model can provide much more details of atmospheric circulation over study area.

Because precipitation is an important factor for the wet deposition of radioactive material in plumes, simulated precipitation should be compared with observed data and other previous published data. Fig. 6 presents accumulated simulated precipitation from the WRF model in Exp 1, from 09:00 to 15:00 on March 15, 2011. Rainfall amount and intensity in this case is highly similar to simulation results from Katata et al., (2015) [27]. Heavy rain, from 5 mm to 10 mm per 6 hours, occurred over broad area around Fukushima region. Due to the impacts of earthquake and tsunami, almost all the meteorological observation equipments were inoperable after the nuclear accident. Therefore, it's difficult to obtain good quality meteorological observation in this case. Large-scale meteorological information during the occurrence of radioactive material emissions into the air was presented in the 2013 World Meteorological Organization (WMO) report by previous research groups such as Kinoshita et al., (2011) [30], Stohl et al., (2012) [10] and Sugiyama et al., (2012) [31]. In fact, rain occured over the north area of Fukushima prefecture from 17:00 JST March 15 to 04:00 JST on the March 16 [30]. On the 20 to 22 March, sustainable low pressure caused moderate rainfall in the vicinity of Tokyo.



(a)



(b)

Fig. 5. Simulation of geo-potential height (shaded color) and wind field (barbs) on level of 850 mb, at 12h00 UTC 15/03/2011 from the WRF model in **Exp 1 (a)**, in comparison with the ERA5 reanalysis data **(b)**. Notice: Factor of 10 is applied to thin the number of wind barbs in **(a)**

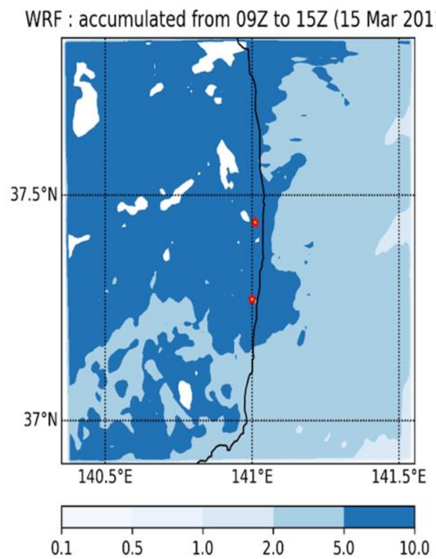


Fig. 6. Accumulated simulated precipitation from the WRF model in experiment **Exp 1**, from 09:00 to 15:00 on March 15, 2011

B. Evaluation of atmospheric radiocesium

The Futaba station, an observatory station in the town of Futaba, is very close to the Fukushima NPP. The distance between Futaba town and the plant is only about 3.2 km, where was severely affected by both earthquakes, tsunamis and the effects of radiation [28]. For the other researches of global radioactive dispersions, the vicinity areas of the plant are often not taken into account, because of the limitation of the grid resolution. In this paper, high resolution of 01 km is very suitable for considering the geographical location of Futaba station, as well as other neighboring stations (e.g. Naraha station). Calculation results of the concentration of atmospheric radiocesium ^{137}Cs for every hour at Futaba and Naraha station are displayed in Fig. 7 and Fig. 8, respectively. The observation data displayed in these figures are retrieved from Tsuruta et al., (2011) [28].

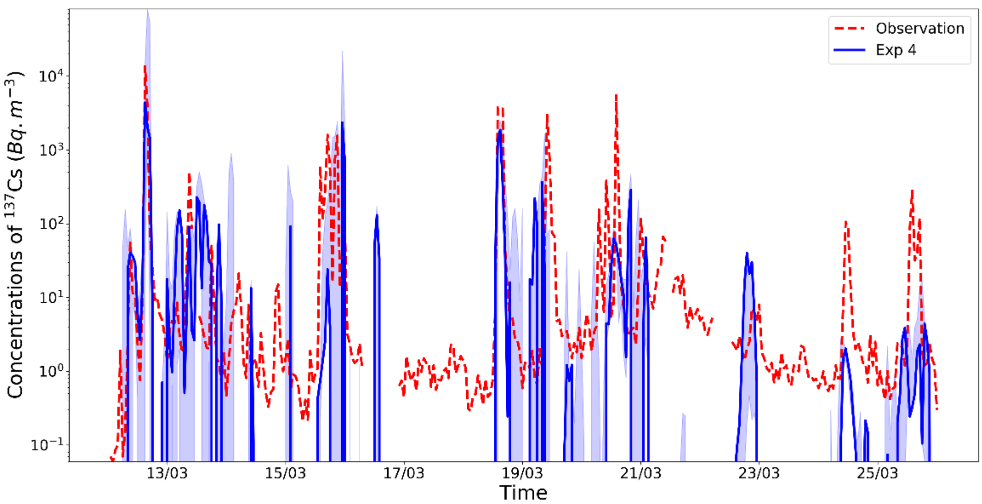


Fig. 7. Hourly accumulated concentration of ^{137}Cs at Futaba station from observation (red dashed line) and Exp 4 (blue solid line) with range of simulation results from all experiment (shaded light blue)

From Fig. 7 and Fig. 8, it can be seen that simulation results have a good agreement with the observed data, especially from 12 to 14/03/2011 at Futaba station and from 15 to 16/03/2011 at Naraha station. Peak values of ^{137}Cs concentration on 12 and 19/03/2011 at Futaba station are reproduced well in all experiments. Peak values on 15, 16 and 19/03/2011 at Naraha station are also captured well by the FLEXPART-WRF model. The range of simulated values from four experiment (i.e. shaded light blue area in Fig.7 and Fig. 8) can be recorgnized, especially for concentrations of less than 10^2 $Bq.m^{-3}$ per hour. The uncertainty in simulation or the sensitivity of calculation results to different micro-physics option is more clear in the case of Futaba station than in Naraha station. This can be seen on simulated range of 13-14/03/2011 and 19-21/03/2011 in Fig. 7. The Exp 4 was displayed due its better performance, in comparison with others experiments, which is confirmed by statistical verification shown in Fig. 9.

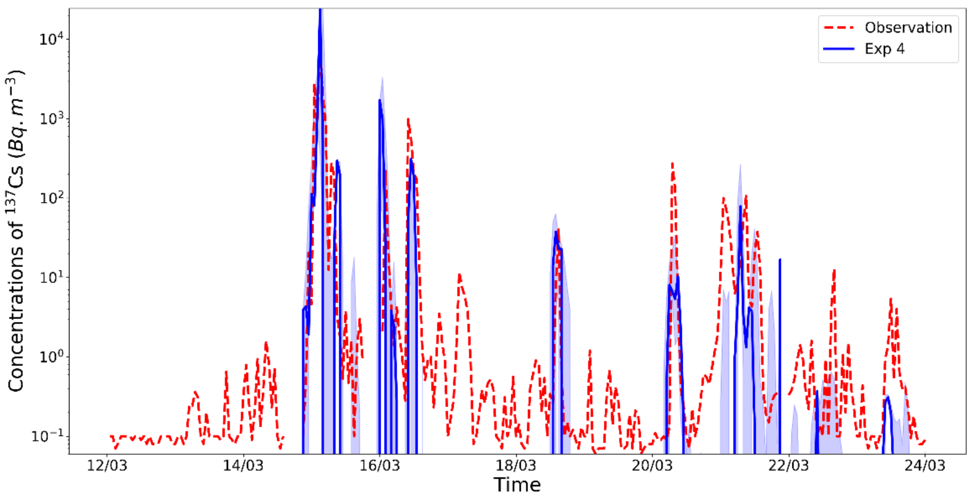
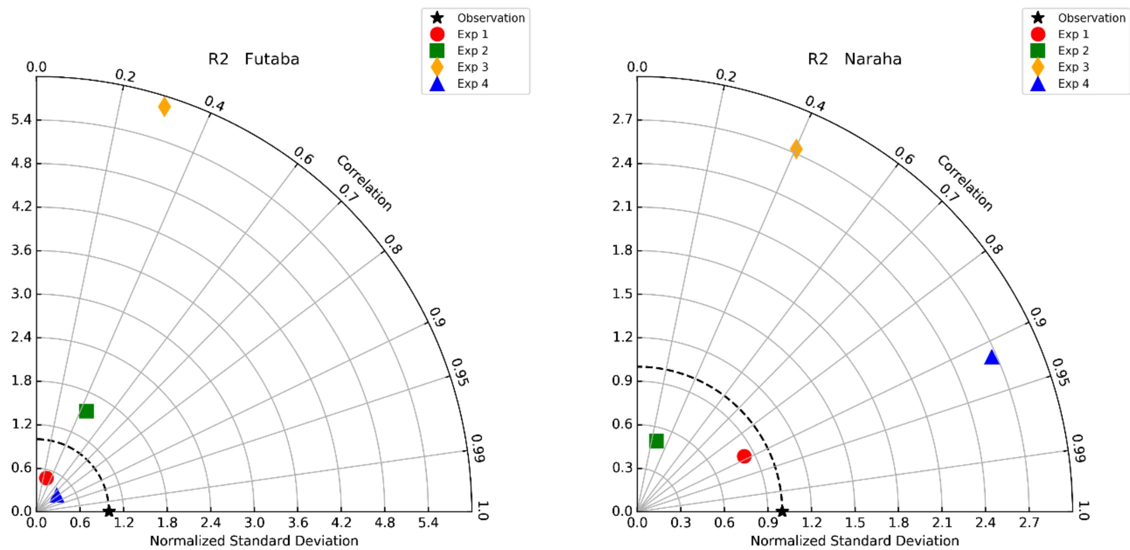


Fig. 8. Hourly accumulated concentration of ^{137}Cs at Naraha station from observation (red dashed line) and Exp 4 (blue solid line) with range of simulation results from all experiment (shaded light blue)



(a) (b)

Fig. 9. Taylor diagram compares simulation results from 04 experiments using Pearson correlation coefficient and Normalized Standard Deviation for **(a)** Futaba and **(b)** Naraha station. Observation value is depicted by black star

Fig. 9 demonstrates high sensitivity of simulation results to different micro-physics options of the WRF model. Scatter of experiment's points on the Taylor diagram highlights the significant variations of not only correlation coefficients (CC) but also standard deviations (σ) of simulated atmospheric radiocesium retrieved from four experiments. For example, at Futaba station, simulation result from experiment Exp 1 has CC value of 0.28 and normalized σ of 0.48. While respective verification metrics for Exp 4 are 0.77 and 0.36 which means better capture of hourly observed release of ^{137}Cs air concentration. At Naraha station, the higher CC values can be seen, in comparison with simulation results at station Futaba (i.e. 0.92 for Exp 4 or 0.89 for Exp 1). Based on this Taylor diagram, the experiment Exp 3 show worse simulation results than Exp 1, Exp 2 and Exp 4. Therefore, the configuration of Exp 1, Exp 2 or Exp 4 can be recommended for further study in the future.

From Fig. 10, dispersion plume of 137Cs concentration at 100 m can be seen for three different days. These distrubition maps explain the peak of concentration shown in Fig. 7 and Fig. 8. At level of 100 m, atmospheric radionuclide propagated to the North on 12/03/2011 which plumes spreaded widely to Southwest on 15/03/2011. Smaller plumes in both area and intensity blowed along coastal line to the South are simulated on 19/03/2011. These results show a similarity to the results of Tsuyoshi et al., (2015) [1] in which different horizontal grid resolutions are used to calculate radioactivity concentration on 15/03/2011.

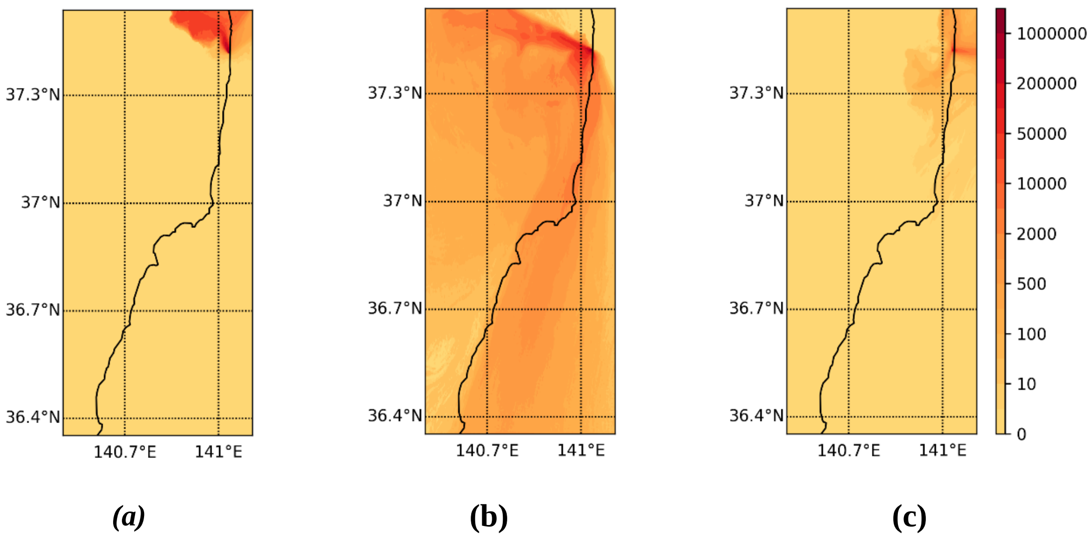


Fig. 10. Local-scale spatial distributions of accumulated concentrations of 137Cs at 100 meter from Exp 4 retrieved **(a)** from 00 UTC 12 to 00 UTC 13/03/2011, **(b)** from 00 UTC 15 to 00 UTC 16/03/2011 and **(c)** from 00 UTC 19 to 00 UTC 20/03/2011. Unit: Bq.m-3

IV. CONCLUSIONS

This study investigates short-range atmospheric transport of radionuclides after Fukushima nuclear accident using a numerical weather model and a Lagrangian particle dispersion model. Four different experiments were carried out using the FLEXPART-WRF model coupled with the WRF model. The ERA5 reanalysis data is used as initial and boundary conditions for the WRF model with hourly update time step. The WRF model is configured with two domains of 05 km and 01 km. Both meteorological conditions and dispersion of atmospheric radiocesium (^{137}Cs) are evaluated. In comparison with observation at Futaba and Naraha station, all experiments captured reasonably the variation of ^{137}Cs concentration from 11/03 to 26/03/2011. Analysis on Taylor diagram confirm the noticeable sensitivity of simulation results to four selected micro-physics parameterizations. The configurations of Exp 1, Exp 2 and Exp 4 are recommended for further study due to their better performance among all.

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