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Improvement of atmospheric dispersion simulation using an advanced meteorological data assimilation method to reconstruct the spatiotemporal distribution of radioactive materials released during the Fukushima Daiichi Nuclear Power Station accident

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Abstract

To improve the atmospheric dispersion simulations of radioactive materials released due to the Fukushima Daiichi Nuclear Power Station (FNPS1) accident, we adopted four-dimensional variational data assimilation (4D-Var) of the data assimilation system (WRFDA) and confirmed the effectiveness of the existing 4D-Var technique for the reproducibility of dispersion simulation during the FNPS1 accident. The simulation was performed by the community meteorological model (WRF) and our atmospheric dispersion model (GEARN). The accuracy of simulated ^{137}Cs deposition patterns in the area closed to FNPS1 and the Ibaraki, Tochigi, and Fukushima Prefectures was increased due to improvements in wind and rain fields in 4D-Var calculations. The results demonstrated that 4D-Var was effective for improving local- and regional-scale atmospheric dispersion simulations.

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Keywords: Atmospheric dispersion; meteorological data assimilation; emergency response; radiological dose assessment; Fukushima Daiichi Nuclear Power Station accident

1. Introduction

A significant amount of radioactive material was accidentally emitted into the atmosphere from the Fukushima Daiichi Nuclear Power Station (hereafter referred to as FNPS1) due to the earthquake and resulting tsunami that occurred on March 11, 2011. As a result, radiological contamination has occurred over eastern Japan [1]. Atmospheric dispersion models, which can simulate spatiotemporal distributions of radioactive material, have been utilized to estimate source term and to reveal the atmospheric dispersion processes during the FNPS1 accident. The simulation result strongly depends on input meteorological field to drive an atmospheric dispersion model. Thus, the problem needed to reduce uncertainty of input meteorological field has already been frequently pointed out. In the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) for evaluating radiation risk and for establishing protective measures based on scientific knowledge, atmospheric dispersion simulations have been used to assess radiological doses to the public; demonstrating that the accuracy of simulated meteorological fields has room to be improved for better atmospheric dispersion estimates [2]. To increase the accuracy of the meteorological data, four-dimensional variational data assimilation (4D-Var) is one of widely accepted method in communities of weather research and forecasting [3-5].

In our previous study, the detailed source term was estimated by using WSPEEDI (Worldwide version of System for Prediction of Environmental Emergency Dose Information) [6] including new deposition scheme [7]. By using the estimated source term and WSPEEDI with new deposition scheme, the local and regional deposition patterns of ^{131}I and ^{137}Cs were successfully reproduced. For further improvement of WSPEEDI simulation, we attempted to update the meteorological field by adopting the up-to-date meteorological calculation model, the Weather Research and Forecasting Model (WRF [8]), instead of the former atmospheric model MM5 [9] in the original WSPEEDI. Furthermore, we introduced the 4D-Var technique to calculate more reliable meteorological field by effectively assimilating meteorological observation data. As the result, the reproducibility of local and regional deposition patterns of ^{137}Cs derived from airborne monitoring was improved.

The present study aims to demonstrate the effectiveness of the existing 4D-Var technique for the reproducibility of dispersion simulation during the FNPS1 accident in comparison of results from WRF simulations with and without 4D-Var. Then, its impact on modelled plume movements and deposition patterns of ^{137}Cs during the FNPS1 accident is evaluated by comparing simulation results with airborne monitoring surveys.

2. Models and experimental designs

In this study, we used our Lagrangian particle dispersion model GEARN and the community meteorological model WRF. To improve the meteorological fields calculated by WRF, an advanced meteorological data assimilation system (WRFDA) was utilized to assimilate available meteorological input data obtained in eastern Japan (section 2.4) based on the 4D-Var technique.

2.1. WRF

To obtain the meteorological variables to drive GEARN, we used the WRF model version 3.6.1, which is a non-hydrostatic, fully compressible model developed by the National Center for Atmospheric Research [8]. The model predicts three-dimensional meteorological fields by solving several governing equations of the atmospheric dynamics. This model has various physics options applied to the processes of microphysics, cumulus clouds, land surface, boundary layer and radiation.

2.2. WRFDA

In order to increase accuracy of meteorological fields, 4D-Var was conducted using WRF data assimilation system (WRFDA) [10]. WRFDA deals with the process to combine observational datasets with meteorological model output. Assimilated observational datasets are shown in section 2.4.

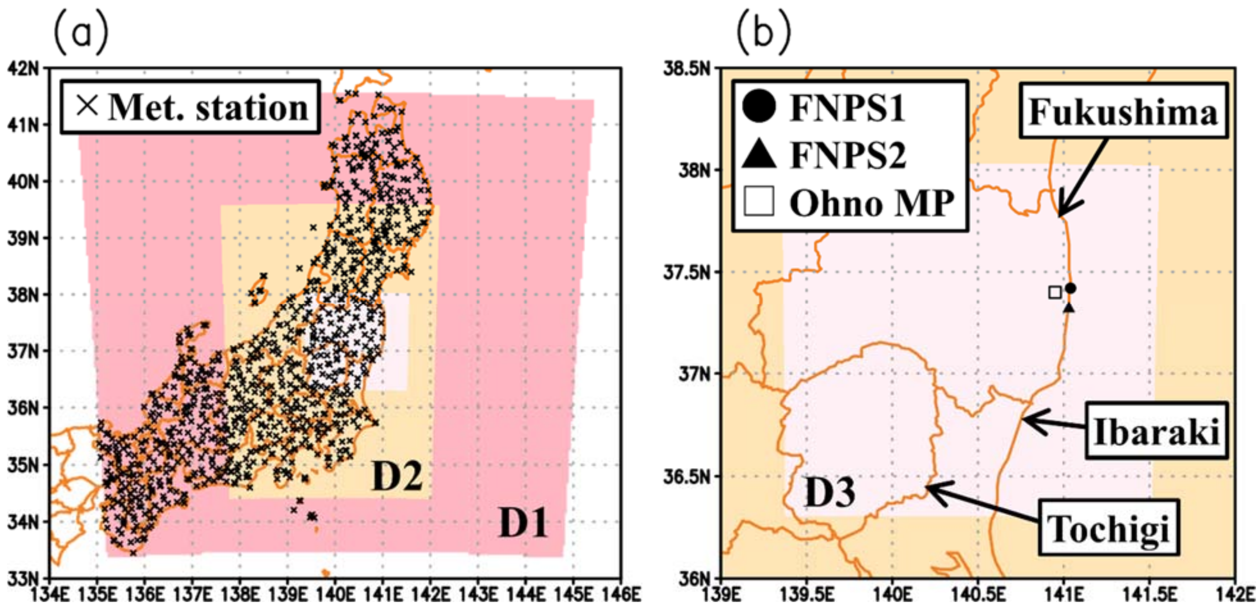

Fig. 1. (a) Simulation domains for GEARN and WRF. Domains 1, 2, and 3 are shown as pink (D1), yellow (D2), and light pink (D3), respectively. The symbols in (a) and (b) represent the locations of observed data for 4DVAR case.

Table 1. Simulation settings of WRF, WRFDA and GEARN.

		Domain1	Domain2	Domain3
Applied WRFDA calculations		Yes	No	No
Applied GEARN calculations		No	Yes	Yes
Simulation period		3:00 JST on March 12 to 6:00 JST on March 31, 2011		
Horizontal grid number		100 × 100	190 × 130	190 × 190
Horizontal resolution (km)		9	3	1
Vertical levels of WRF		31 eta levels[a] from surface to 100 hPa		
Vertical levels of GEARN			29 levels from surface to 10 km	
Time step of WRF (second)		60	20	6
Time step of GEARN (second)		-	6	3
Boundary and initial conditions of WRF		JMA-GPV(MSM, 0.1° × 0.125° for atmosphere, 0.05° × 0.0625° for the surface layer)		
Time window for 4D-Var (hour)		6	-	-
Interval time of data insert for 4D-Var (hour)		1	-	-
Physics options for WRF	Microphysics	WSM6 [18]		
	Cumulus	Betts-Miller-Janjic [19]		-
	Land Surface	5-layer thermal diffusion		
	Boundary layer	MYNN Level 2.5 [20]		
	Long-wave radiation	RRTM [21]		
	Short-wave radiation	Dudhia [22]		

[a]Terrain-following half-sigma levels as 1.000, 0.997, 0.994, 0.992, 0.986, 0.973, 0.959, 0.946, 0.933, 0.900, 0.869, 0.838, 0.808, 0.750, 0.696, 0.619, 0.548, 0.482, 0.421, 0.366, 0.315, 0.268, 0.226, 0.187, 0.151, 0.119, 0.090, 0.064, 0.040, 0.019, 0.000.

2.3. GEARN

GEARN simulates the atmospheric dispersion process of discharged radionuclides using the three-dimensional movement of marker particles of the meteorological variables [7,11]. The processes of advection and diffusion of radioactive plumes, radioactive decay, dry, wet, and fog water deposition onto the ground surface are modelled. GEARN has been validated using several datasets, including those from the European Tracer Experiment [12], the Chernobyl accident [6,13], the release from the nuclear fuel reprocessing plant in Rokkasho, Japan [14], and the FNPS1 accident [7,15-17].

2.4. Simulation settings, observational data and experimental scenarios

The simulation settings of WRF, WRFDA, and GEARN are summarized in Table 1. Meteorological input data, Grid Point Value (GPV) of the Meso-Scale Model (MSM) provided by the Japan Meteorological Agency (JMA), are used for initial and boundary conditions of WRF. The largest simulation domain covers the whole eastern Japan around FNPS1 with two nested computational domains used for WRF calculations as shown in Figure 1.

In WRF calculations, WRFDA was performed only in domain 1. The WRFDA assimilates the following meteorological datasets: wind speed and direction at the ground surface (FNPS1 and Ohno in Fukushima Prefecture) and those at 120 m above Fukushima Daini Nuclear Power Station (hereafter referred to as FNPS2), and wind speed and direction, air temperature, pressure, and relative humidity at the ground surface (452 points of meteorological stations managed by JMA in eastern Japan). The locations of the above stations are shown in Figure 1.

To confirm the impact of 4D-Var on atmospheric dispersion simulation results, the following two simulations were performed: WRF with WRFDA (4DVAR) and without data assimilation method (ORIGINAL). GEARN is applied to Domains 2 and 3 with two-way nesting, i.e., by considering in- and out-flow between the domains. Our latest source term of ^{137}Cs from the FNPS1 accident until the end of March 2011 [7] was applied to the atmospheric dispersion simulations.

To validate the surface deposition patterns of ^{137}Cs calculated by GEARN in both runs, airborne monitoring results that cover Domains 2 and 3 shown in Figure 1a are required. The airborne monitoring intended for Japan started on Jun 23, 2011 and finished on May 31, 2012. Therefore, the surface deposition patterns of ^{137}Cs of airborne survey on May 31, 2012 [23], which are compiled all airborne monitoring surveys covering our target domains completely, were utilized for the validation.

3. Results and discussion

Simulated and observed cumulative surface depositions of ^{137}Cs are shown in Figure 2. In comparison with ORIGINAL case, 4DVAR case showed the improvements of deposition patterns at the area of Tochigi and Fukushima (1 in Fig. 2a), Ibaraki Prefectures (2 in Fig. 2a), and to northwest and south direction from FNPS1 (3 in Fig. 2a). The improvements in 4DVAR case at each area are summarized below.

In Tochigi and Fukushima Prefectures, the over- and underestimation of observed ^{137}Cs deposition (Fig. 2c) appeared in ORIGINAL case (Fig. 2b) were improved in 4DVAR case (1 in Fig. 2a). These are because, when the plume passed over the area between 16:00–17:00 JST on March 15, cumulative precipitation in Tochigi Prefecture calculated in 4DVAR case (Fig. 3a) was lower than that in ORIGINAL case (Fig. 3b). In the period, the plume of high concentration in 4DVAR case did not reach the precipitation band over Tochigi Prefecture, in which the vertical accumulated concentration of the plume in 4DVAR case (Fig. 3c) were significantly lower than that in the ORIGINAL case (Fig. 3d) because the plume in 4DVAR case was strongly diluted till 14:00 JST on March 15 (blue contours in Fig. 3c) in compared with that in ORIGINAL case. Although the wind direction in ORIGINAL case was easterly then, that in 4DVAR case around the prefecture-border between Fukushima and Ibaraki Prefectures changed from easterly to southerly (not shown in figures); therefore, the plume in 4DVAR case was transported to Fukushima Prefecture (black contours in Fig. 3c) due to southerly wind. The different distributions of the plume between 4DVAR and ORIGINAL cases mainly resulted from wind fields. As a result, larger amount of wet deposition in southern central area of Fukushima Prefecture was calculated in 4DVAR case than ORIGINAL case occurred (Fig. 3c). The results suggest that the accuracy of surface deposition in Tochigi and Fukushima Prefectures was increased by 4D-Var technique (1 in Fig. 2a) that changed precipitation and wind fields of WRF.

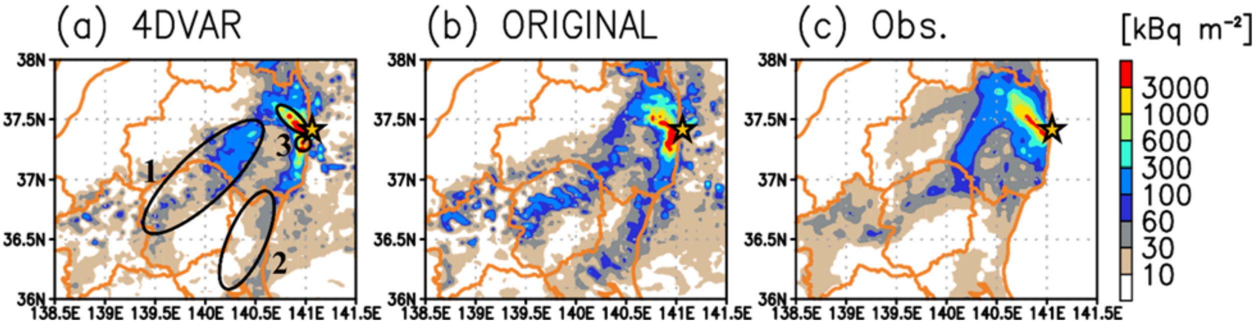

Fig. 2. ^{137}Cs deposition after the FNPS1 accident based on the GEARN calculations on April 1, 2011, in (a) 4DVAR and (b) ORIGINAL cases and (c) airborne observations on May 31 2012. Symbols of star indicate the location of FNPS1. Improved areas are shown as numbered circles in (a).

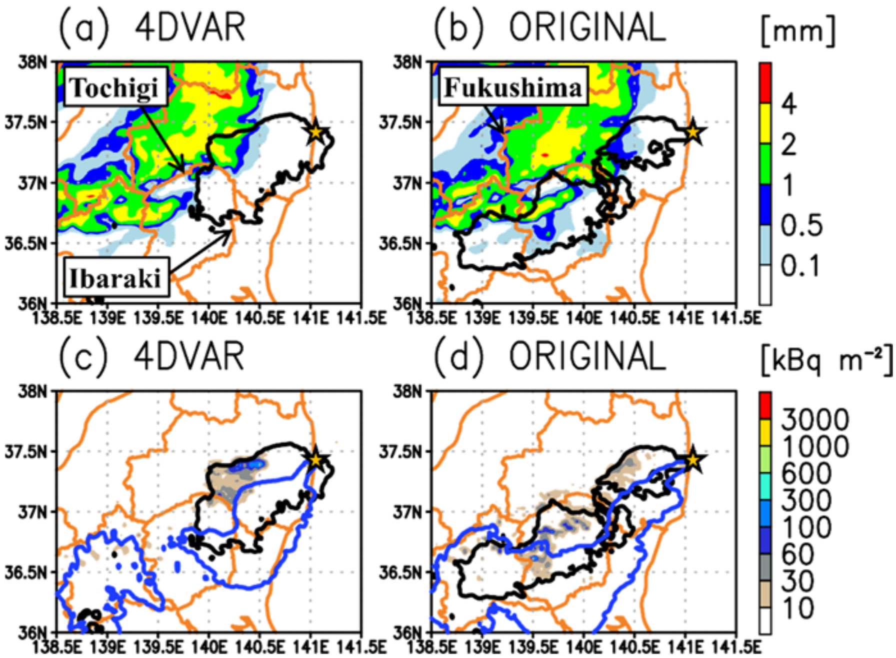

Fig. 3. Cumulative precipitation simulated in [(a) and (c)] 4DVAR case and [(b) and (d)] ORIGINAL case between 16:00–17:00 JST on March 15. Blue and black contours represent vertically accumulated air concentration of ^{137}Cs (100 Bq m^{-3}) for all atmospheric layers at 14:00 and 17:00 JST on March 15, respectively. Symbols of star indicate the location of FNPS1.

The deposition pattern in 4DVAR case in Ibaraki Prefecture was also consistent to observed ones (2 in Fig. 2). This was caused by wet deposition event occurred between 7:00–12:00 JST on March 21 [15]. Although the spatial distribution of the plume in 4DVAR case (Fig. 4c) was similar to that in ORIGINAL case (Fig. 4d), cumulative precipitation calculated in the former case was clearly lower at the area of the south of Ibaraki Prefecture. Therefore, the change in precipitation patterns due to 4D-Var technique caused the better agreement in surface deposition between calculations in 4DVAR case and observations (2 in Fig. 2a).

In the northwestern area close to FNPS1, 4DVAR case also agreed better with the observations of surface deposition than the ORIGINAL case (3 in Fig. 2). The contamination area was created by wet deposition during the major release of ^{137}Cs from FNPS1 between 19:00–23:00 JST on March 15 [7]. In this period, although precipitation

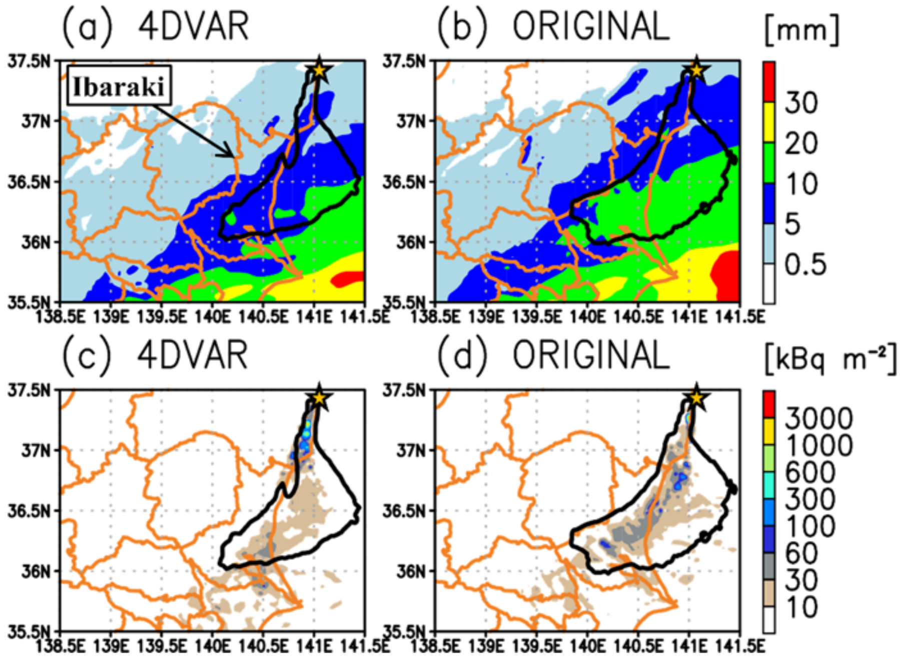

Fig. 4. Cumulative precipitation simulated in [(a) and (c)] 4DVAR case and [(b) and (d)] ORIGINAL case between 7:00–12:00 JST on March 15. Black contours represent vertically accumulated air concentration of ^{137}Cs (100 Bq m^{-3}) for all atmospheric layers at 7:00 JST on March 15. Symbols of star indicates the location of FNPS1.

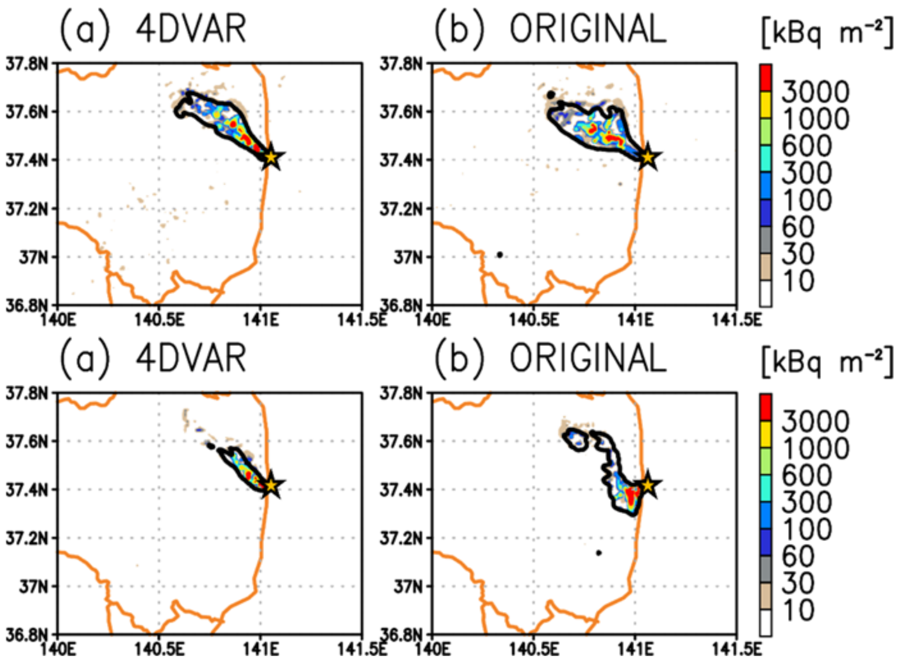

Fig. 5. Cumulative deposition of ^{137}Cs simulated in [(a) and (c)] 4DVAR and [(b) and (d)] ORIGINAL cases [(a) and (b)] between 20:00–21:00 JST on March 15 and [(c) and (d)] between 23:00 JST on March 15 and 0:00 JST on March 16. Black contours represent vertically accumulated air concentration of ^{137}Cs (100 Bq m^{-3}) for all atmospheric layers at [(a) and (b)] 21:00 JST on March 15 and [(c) and (d)] 0:00 JST on March 16, respectively. Symbols of star indicates the location of FNPS1.

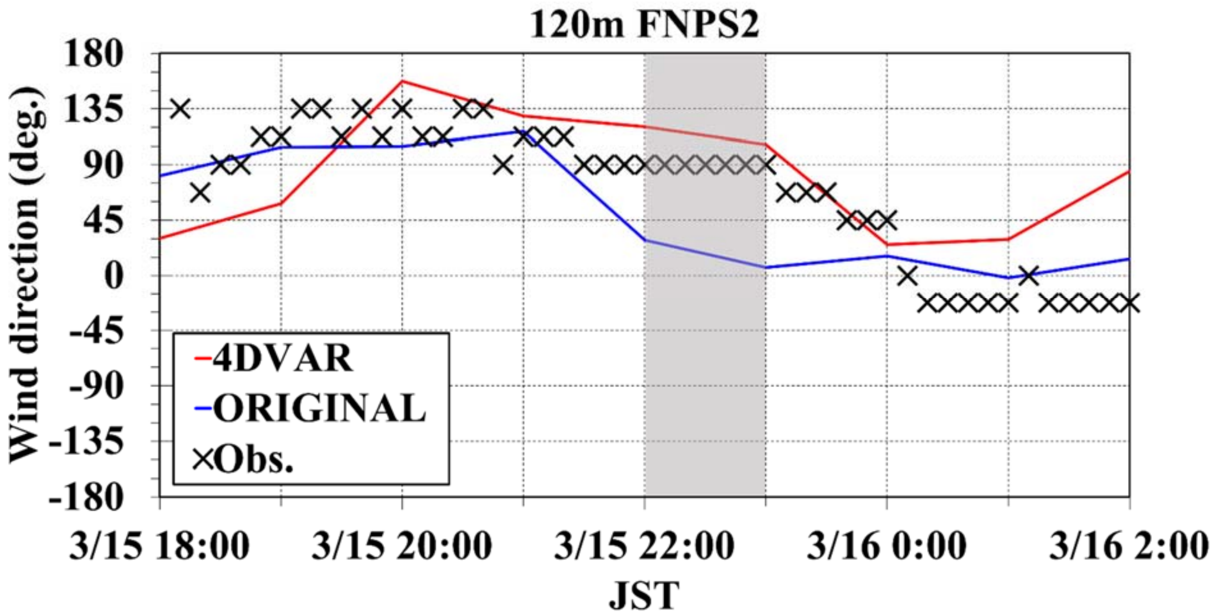

Fig. 6. Simulated and observed wind directions 120 m above FNPS2. 0° and 90° indicate northerly and easterly winds, respectively. The shaded area represents the period of the maximum release of ^{137}Cs on March 15.

patterns in 4DVAR case were almost similar to those in ORIGINAL case (not shown in figures), temporal change of wind direction nearby FNPS1 was clearly different between 4DVAR and ORIGINAL cases. Figure 6 shows simulated and observed wind direction at 120 m above FNPS2 from 18:00 JST on March 15 to 2:00 JST on March 16. As shown in the figure, the significant release on FNPS1 occurred from 22:00–23:00 JST on March 15, in which observed easterly wind was reproduced better in 4DVAR case than ORIGINAL case. Since wind direction in ORIGINAL case changed from south-easterly to northerly wind at 22:00 JST on March 15 (blue line in Fig. 6), the plume flowed toward the south (Fig. 5d) and caused the overestimation of wet deposition compared with airborne survey (Figs. 2b and 2c). Therefore, in local-scale atmospheric dispersion simulation during the FNPS1 accident, the 4D-Var technique with wind data is effective for reproducing surface deposition patterns around the FNPS1. Further studies are required to clarify what kind of meteorological data at any locations used in WRFDA highly contributed to improve the atmospheric dispersion simulation.

4. Conclusion

The impact of the 4D-Var technique on atmospheric dispersion simulation of radionuclides discharged into the atmosphere due to the FNPS1 accident were investigated. By taking into account of 4D-Var into the meteorological model WRF, the accuracy of surface deposition of ^{137}Cs by our atmospheric dispersion model GEARN was improved. The most apparent improvements were noted in Tochigi, Fukushima, and Ibaraki Prefectures, and in northwest and south directions from FNPS1. These results were predominantly attributed to the changes in wind and precipitation fields. In the case of the Ibaraki Prefecture, the reproducibility of ^{137}Cs deposition pattern increased because of the simulated precipitation. For local-scale atmospheric deposition simulation during the FNPS1 accidents, 4D-Var has a significant role in improving horizontal wind fields calculated by meteorological model.

Acknowledgements

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References

[1] NRA: Airborne Monitoring Results in each prefecture, available at: http://radioactivity.nsr.go.jp/en/list/203/list-1.html(last access: 29 September, 2016); 2012a.

[2] UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation), UNSCEAR 2013 Report: Sources, Effects and Risks of Ionizing Radiation, Vol. I, United Nations, New York, USA; 2014.

[3] Honda Y, Nishijima M, Koizumi K, Ohta Y, Tamiya K, Kawabata T, and Tsuyuki T, A pre-operational variational data assimilation system for a non-hydrostatic model at the Japan Meteorological Agency: Formulation and preliminary results. J. Roy. Meteor. Soc. 2005;131: p. 3465–3475.

[4] Rawlins F, Ballard S.P, Bovis K.J, Clayton A.M, Li D, Inverarity G.W, Lorenc A.C, and Payne T.J, The Met Office global 4-Dimensional data assimilation system. J. Roy. Meteor. Soc. 2007;133: p. 347–362.

[5] Gauthier P, Tanguay M, Laroche S, and Pellerin S, Extension of 3DVAR to 4DVAR: Implementation of 4DVAR at the Meteorological Service of Canada. *Mon. Wea. Rev.* 2007:135: p. 2339–2364.

[6] Terada H, Chino M. Improvement of Worldwide Version of System for Prediction of Environmental Emergency Dose Information (WSPEEDI), (II) Evaluation of numerical models by ^{137}Cs deposition due to the Chernobyl nuclear accident. J. Nucl. Sci. Technol. 2005;42: p. 651–660.

[7] Katata G, Chino M, Kobayashi T, Terada H, Ota M, Nagai H, Kajino M, Draxler R, Hort M.C, Malo A, Torii T, Sanada Y. Detailed source term estimation of the atmospheric release for the Fukushima Daiichi Nuclear Power Station accident by coupling simulations of an atmospheric dispersion model with an improved deposition scheme and oceanic dispersion model. Atoms. Chem. Phys. 2015;15: p. 1029–1070.

[8] Skamarock W.C, Klemp J.B, Dudhia J, et al. A description of the Advanced Research WRF Version 3, NCAR Tech. Note NCAR/TN-475STR, National Center for Atmospheric Research, Boulder, Colorado, USA. 2008.

[9] Grell, G. A., Dudhia, J., and Stauffer, D. R.: A Description of the Fifth-generation Penn State/NCAR Mesoscale Model (MM5), NCAR Tech. Note NCAR/TN-3921STR, Boulder, CO, 122 pp.,1994.

[10] Barker D, Huang X-Y, Liu Z, Bulletin of American Meteorological Society. 2012;93:831.

[11] Terada H, Furuno A, Chino M. Improvement of Worldwide Version of System for Prediction of Environmental Emergency Dose Information (WSPEEDI), (I) New combination of models, atmospheric dynamic model MM5 and particle random walk model GEARN-new. J. Nucl. Sci. Technol. 2004;41: p. 632–640.

[12] Furuno A, Terada H, Chino M and Yamazawa H. Experimental verification for real-time environmental emergency response system: WSPEEDI by European tracer experiment. Atmos. Environ. 2004;38: p. 6989–6998

[13] Terada H, Chino M. Development of an atmospheric dispersion model for accidental discharge of radionuclides with the function of simultaneous prediction for multiple domains and its evaluation by application to the Chernobyl nuclear accident. J. Nucl. Sci. Technol. 2008;45: p. 920–931.

[14] Terada H, Nagai H, Yamazawa H. Validation of a Lagrangian atmospheric dispersion model against middle-range scale measurements of ^{85}Kr concentration in Japan. J. Nucl. Sci. Technol. 2013;50: p. 1198–1212.

[15] Terada H, Katata G, Chino M, Nagai H. Atmospheric discharge and dispersion of radionuclides during the Fukushima Dai-ichi Nuclear Power Plant accident, Part II: Verification of the source term and analysis of regional-scale atmospheric dispersion, J. Environ. Radioactiv. 2012;112: p. 141–154.

[16] Katata G, Terada H, Nagai H and Chino M. Numerical reconstruction of high dose rate zones due to the Fukushima Daiichi Nuclear Power Plant accident. J. Environ. Radioact. 2012a;111: p. 2–12.

[17] Katata G, Ota M, Terada H, Chino M and Nagai H. Atmospheric discharge and dispersion of radionuclides during the Fukushima Dai-ichi Nuclear Power Plant accident, Part I: Source term estimation and local-scale atmospheric dispersion in early phase of the accident, J. Environ. Radioactiv. 2012b;109: p. 103–113.

[18] Hong S-Y, Lim J-O.J. The WRF single-moment 6-class microphysics scheme (WSM6). J. Korean Meteolo. Soc. 2006;42: p. 129–151.

[19] Janjic Z.I, Comments on “Development and evaluation of a convection scheme for use in climate models”. J. Atoms. Sci. 2000;57: p. 3686–3686.

[20] Nakanishi M, Niino H. An improved Mellor–Yamada level-3 model with condensation physics: Its design and verification. Boundary-Layer Meteorol. 2004;112: p. 1–31.

[21] Mlawer E.J, Taubman S.J, Brown P.D, Iacono M.J, Clough S.A. Radiative transfer for inhomogeneous atmosphere, RRTM, a validated correlated-k model for the long wave. J. Geophys. Res. 2001;102: p. 16663–16682.

[22] Dudhia, J. Numerical study of convection observed during the winter monsoon experiment using amesoscale two-dimensional model. J. Atmos. Sci. 1989;46: p. 3077–3107.

[23] NRA: Hokkaido Prefecture and the Eastern Part of Japan (Revision), available at: http://radioactivity.nsr.go.jp/en/list/203/list-1.html (last access: 28 October, 2016); 2012b.