Reproducibility of Surface Wind and Tracer Transport Simulations over Complex Terrain Using 5-, 3-, and 1-km-Grid Models^①

TSUYOSHI THOMAS SEKIYAMA

Meteorological Research Institute, Tsukuba, Japan

MIZUO KAJINO

Meteorological Research Institute, and Faculty of Life and Environmental Sciences, University of Tsukuba, Tsukuba, Japan

(Manuscript received 1 October 2019, in final form 23 March 2020)

ABSTRACT

The reproducibility of surface wind and tracer transport simulations from high-resolution weather and transport models was studied over complex terrain in wintertime in Japan. The horizontal grid spacing was varied (5-, 3-, and 1-km grids), and radioactive cesium (Cs-137) from the Fukushima nuclear power plant was used as a tracer. Fukushima has complex terrain, such as mountains and valleys. The model results were validated by observations collected from the national networks of the automated meteorological data acquisition system and the hourly air pollution sampling system. The reproducibility depended on the model resolution, topographic complexity, and synoptic weather conditions. Higher model resolution led to higher reproducibility of surface winds, especially in mountainous areas when the Siberian winter monsoon was disturbed. In contrast, the model improvement was negligible or nonexistent over plain/coastal areas when the synoptic field was steady. The statistical scores of the tracer transport simulations often deteriorated as a result of small errors in the plume locations. However, the higher-resolution models advantageously performed better transport simulations in the mountainous areas because of the lower numerical diffusion and higher reproducibility of the mass flux. The reproducibility of the tracer distribution in the valley of the Fukushima mountainous region was dramatically improved with increasing model resolution. In the range of mesoscale model resolutions (commonly 1–10 km), it was concluded that a higher-resolution model is definitely recommended for tracer transport simulations over mountainous terrain.

1. Introduction

The time scale of atmospheric tracer transport simulations ranges from seconds to decades. The spatial scale also ranges from microscale to global. Global or synoptic-scale tracer simulations often assume that the tracer species are well mixed or continuously distributed in the atmosphere. The assumption is justified in treating carbon dioxide, ozone, or water vapor, which are universally present with widespread sources and sinks. However, the assumption often fails when the time scale is short (e.g., minutes or

hours), the spatial scale is limited (e.g., mesoscale or less), and the background concentration is extremely low (e.g., point source pollution). In that case, the tracer distributions are not continuous, and their plumes have sharply outlined edges with concentration jumps of more than several orders of magnitude.

Modeling these sharp-edged plumes in the troposphere is crucial for urban pollution predictions or environmental emergency responses (World Meteorological Organization 2006). However, model performance of sharp-edged plumes is lower than that of continuous distributions because small errors in the plume location lead to large uncertainties in the concentration variations. Generally, the plume location is strongly influenced by the accuracy of wind fields (Angevine et al. 2014; Sekiyama et al. 2017), in which the acceptable range of wind velocity errors is narrower than usually expected. Especially in the planetary boundary layer (PBL), the wind field becomes complicated over complex

^① Supplemental information related to this paper is available at the Journals Online website: <https://doi.org/10.1175/JAMC-D-19-0241.s1>.

Corresponding author: Tsuyoshi Thomas Sekiyama, tsekiyam@mri-jma.go.jp

terrain, which impairs the reproducibility of surface wind and plume transport simulations (Srinivas et al. 2016). Consequently, the topographic model resolution has a large impact on the accuracy of plume transport simulations over complex terrain (Sekiyama et al. 2015). Therefore, plume transport simulations are more challenging than continuous transport simulations.

Meanwhile, the model validation of PBL wind and plume simulations is not straightforward because it requires widespread and frequent observations over complex terrain, including rural or mountainous areas, for both wind velocity and tracer concentration. Therefore, the reproducibility of PBL wind and plume simulations over complex terrain has not been investigated in detail. Although some previous studies addressed the model resolution dependence of tracer transport simulations, such as inert gases, nitrogen oxides, sulfur dioxide, carbon dioxide, and ozone, using high-resolution models (e.g., Nachamkin et al. 2007; Tie et al. 2010; Pillai et al. 2011; Cécé et al. 2016; Dingwell et al. 2016; Feng et al. 2016; Tang et al. 2019), they validated the tracer distributions at only a few selected observatories over complex terrain. They did not conduct plume verifications that required many concentration/wind observations. Although Sugiyama et al. (2012), Katata et al. (2012a,b), and Sekiyama et al. (2015) performed high-resolution simulations for radionuclide plumes over complex terrain, they did not validate the plume concentrations and motions focusing on model resolution.

Sekiyama et al. (2015) conducted plume simulations of radioactive cesium (Cs-137) emitted by the Fukushima Daiichi Nuclear Power Plant (FDNPP) accident after the 2011 Tohoku great earthquake in Japan. The Japanese archipelago consists of steep mountains, narrow plains/basins, and small peninsulas/islands; that is, the terrain is highly complex (Fig. 1). In particular, Fukushima is one of the mountainous regions in Japan, and the FDNPP is located on the coastline of the Pacific Ocean and only a few kilometers from mountains as high as 1000 m. Fukushima also has 2000-m mountain peaks and a narrow basin between the 2000-m mountain peaks and the 1000-m mountains behind the FDNPP. In contrast, Tokyo, more than 200 km south-southwest of Fukushima, is located in the largest plain in Japan. Nevertheless, the largest Japanese plain, or the Kanto Plain, is only 100–150 km in diameter and is surrounded by 1000–2000-m mountains. The Cs-137 that originated from Fukushima is an ideal tracer over the complex terrain (cf. Bieringer et al. 2013); therefore, Sekiyama et al. (2015) proceeded with their tracer model experiments. However, Sekiyama et al. (2015) could not obtain enough Cs-137 concentration data to validate the plume simulations. Therefore, they validated only 1-month

FIG. 1. Observation stations used in this study for (a) surface Cs-137 concentrations provided by the SPM sampling network and (b) surface winds provided by the AMeDAS network. Capital letters P and T indicate the locations of the Fukushima Daiichi Nuclear Power Plant and Tokyo City, respectively. Brown shades indicate the elevations. Blue, gray, and red triangles represent coastal, interior, and mountainous stations, respectively.

accumulated deposition distributions without wind comparison.

Since then, the Cs-137 concentrations at more than 100 monitoring stations have been retrieved hourly by Tsuruta et al. (2014), Oura et al. (2015), and Tsuruta et al. (2018). These authors analyzed filter tapes for ambient suspended particulate matter (SPM) sampling in and near Fukushima and Tokyo. In addition, high-quality meteorological variables are universally measured in Japan by the Japanese government even immediately after the Tohoku great earthquake and during the FDNPP accident (cf. Sekiyama et al. 2017). These widespread and frequent observations for both surface winds and Cs-137 concentrations are used in this study to overcome the difficulty with plume transport model validation over complex terrain. This study must be the first attempt to investigate the reproducibility of both surface winds and plume concentrations over complex terrain and its dependence on the model resolution using high-resolution (5, 3, and 1 km) meteorological analyses and models. The details of the observational data are described in section 2a. Then, the meteorological analyses used for the tracer transport simulations are explained in section 2b. The transport model descriptions are also presented in section 2b. The results and discussion are presented in section 3, and the conclusions are given in section 4.

2. Data and models

a. Observational data

1) SURFACE CS-137 OBSERVATIONS

Tsuruta et al. (2014) developed a method to retrieve hourly averaged surface Cs-137 concentrations using SPM sampling filter tapes with a theoretical detection limit of 0.1 Bq m^{-3} . The SPM sampling network is nationwide and deployed by national and local governments. Some of the local governments provided the SPM sampling filter tapes for researchers to retrieve the Cs-137 concentrations during the FDNPP accident. Tsuruta et al. (2014) and Oura et al. (2015) released Cs-137 concentration data for 99 SPM sampling stations in eastern Japan. The air intakes are usually installed at a height of several meters at each sampling station. In addition, the Japan Atomic Energy Agency (JAEA) was operationally measuring hourly Cs-137 concentrations on the premises of their Tokai facilities (36.46°N , 140.60°E) located between Tokyo and Fukushima (Ohkura et al. 2012). These locations are illustrated in Fig. 1a for both the SPM sampling stations and Tokai facilities. As illustrated in Fig. 1a, the sampling stations are mainly distributed around the FDNPP (P in

the figure) and Tokyo (T in the figure). While the terrain surrounding the FDNPP is complex with mountains, valleys, and basins, the terrain surrounding Tokyo is relatively flat (the Kanto Plain). These Cs-137 observations are used for model validation when the value is larger than the practical detection limit (approximately 1.0 Bq m^{-3}).

2) SURFACE WIND OBSERVATIONS

To acquire widespread and frequent surface wind observations for model validation, we used a dataset from the automated meteorological data acquisition system (AMeDAS) managed by the Japan Meteorological Agency (JMA) of the Japanese government. The AMeDAS is a land surface observation network that comprises more than 1000 stations throughout Japan with an average interval of 10–20 km. Anemometers are usually installed at a height of 10 m at each AMeDAS station (hereinafter, we call the 10-m-height winds U_{10} or V_{10}). Although a few of the AMeDAS stations stopped working immediately after the earthquake, almost every station was operational even during the FDNPP accident. In this study, hourly AMeDAS data (5-min averages on the hour) were used. To restrict the wind field validation to the area with Cs-137 observations, the AMeDAS data in this study were limited within southern Tohoku (around the FDNPP), the Kanto Plain (around Tokyo), and the mountainous vicinity of these areas, as shown in Fig. 1b.

In general, AMeDAS stations are located in populated areas, that is, coasts, plains, and basins. However, fortunately, some of the stations are installed in mountainous locations. Thus, in this study, we categorized the AMeDAS stations into three location types, as shown in Fig. 1b: coastal, interior, and mountainous stations, which have approximately 40, 80, and 40 stations, respectively. The mountainous stations were selected only if they are surrounded on all four sides by steep terrain and located more than 350 m above sea level (MSL). Some stations were classified as interior locations since they are between steep slopes that shape valleys. We calculate the statistics classifying wind observation locations into these three categories (mountainous, interior, and coastal winds) and present them in the following sections.

b. Meteorological analyses and models

1) METEOROLOGICAL ANALYSES

Prior to the tracer transport simulation, we prepared meteorological analyses with three different horizontal resolutions (5-, 3-, and 1-km grids) to drive a tracer

FIG. 2. Domains for the 5-, 3-, and 1-km meteorological analyses. Grid lines are drawn every 100 grids for not only the 5-km analysis but also the 3- and 1-km analyses.

transport model. The 5-km-grid analysis was made from the operational mesoscale gridpoint value (hereinafter, meso GPV) dataset that is produced by the JMA and distributed to the public as a part of weather information. The 3-km-grid analysis was performed by Sekiyama et al. (2017). The 1-km-grid analysis was uniquely performed for this study. All of these analyses were calculated by the same weather forecast model using the unified observations.

The 5-km operational meso GPVs are calculated by the JMA nonhydrostatic-model four-dimensional variational data assimilation (JNoVA) system (Honda et al. 2005), whose domain covers East Asia (Fig. 2). The JNoVA system consists of the JMA nonhydrostatic regional weather forecast model (JMA-NHM; Saito et al. 2006, 2007) and a four-dimensional variational (4DVar) data assimilation module. The lateral boundary conditions are obtained from the JMA operational global analysis with an approximately 20-km horizontal resolution (World Meteorological Organization 2011). The JNoVA system assimilates meteorological observations quality controlled by the JMA; these data include land surface pressure, sea surface winds, and observations from radiosondes, pilot balloons, wind profilers, aircrafts, ships, buoys, radars, and satellites. Although the 5-km operational meso GPV dataset has been archived with a 3-h time interval, the tracer transport simulation requires meteorological analysis stored at higher time resolution. Therefore, we conducted a 5-km-grid JMA-NHM run every 3 h with the same model parameters as

the operational JNoVA settings using the 3-hourly 5-km operational meso GPVs as the initial and boundary conditions to obtain new hourly meteorological variables.

The 3-km-grid analysis was provided by another data assimilation system (Kunii 2014), which consists of the JMA-NHM and the four-dimensional local ensemble transform Kalman filter (4D-LETKF; cf. Miyoshi and Aranami 2006). Hereinafter, we call this system NHM-LETKF. This data assimilation system has been applied to Fukushima nuclear pollutant simulations (Sekiyama et al. 2015, 2017; Sekiyama and Iwasaki 2018; Iwasaki et al. 2019). Sekiyama et al. (2017) calculated the 3-km-grid analysis using the same JMA-NHM configurations as the 5-km-grid analysis or the operational meso GPVs except for the model resolution and the convective parameterization (not activated for the 3-km-grid JMA-NHM). The model domain covered only eastern Japan, of which lateral boundary conditions were obtained from the JMA operational global analysis same as the operational meso GPVs (Fig. 2). Sekiyama et al. (2017) assimilated the JNoVA observations except for radar precipitation and satellite radiance (but included satellite-observed wind velocities). Additionally, AMeDAS surface wind observations were assimilated for the 3-km-grid analysis.

The 1-km-grid analysis was calculated by the NHM-LETKF with the same observations and configurations as the 3-km-grid analysis (Sekiyama et al. 2017), except for the model domain and resolution. The lateral boundary conditions and perturbations were obtained from the outputs of the 3-km-grid analysis (Sekiyama et al. 2017), which implemented a one-way nested data assimilation scheme (Kunii 2014). In the same way as the 3-km-grid analysis (Sekiyama et al. 2017), the LETKF was driven by 20 ensemble members with a covariance localization of 50 km in the horizontal dimension, 0.1 natural-logarithm-pressure coordinate in the vertical dimension, and 3 h in the time dimension, employing an adaptive inflation scheme (Miyoshi 2011; Miyoshi and Kunii 2012). The model domain consisted of 461×509 horizontal grid points on the Lambert conformal projection and 60 vertical levels up to approximately 22 km in the terrain-following hybrid vertical coordinates, which included 11 levels below 1 km above ground level (the lowermost level is at 20 m above the ground), the same as the 5- and 3-km-grid analyses.

Terrain features in the model domains of the 5-, 3-, and 1-km-grid JMA-NHMs were generated from global elevation data with a horizontal grid spacing of 30 arc s (GTOPO30) from the U.S. Geological Survey (<https://doi.org/10.5066/F7DF6PQS>), which is approximately 700 m in the east–west direction and 900 m in the south–north direction. The terrains were numerically smoothed in the models of all resolutions to satisfy the

FIG. 3. Fukushima topography depicted by the 5-, 3-, and 1-km grid resolutions. The filled black circle is the location of the FDNPP. Arrows and green lines indicate the surface (10-m height) wind vectors of the analyses and their convergence zones, respectively, at 1500 Japanese standard time (JST) 12 Mar 2011. The arrows for the 1-km-grid wind field are shown at every third grid point (=3-km spacing). Thin black lines depict the coastline and a prefectural borderline.

maximum slope of 150‰ ($\approx 8.6^\circ$). This smoothing procedure was done to avoid numerical instability due to steep slopes. Fukushima's complex topography is depicted by the 5-, 3-, and 1-km-grid analyses in Fig. 3. Fine structures of small valleys and ridges are well reproduced by the 1-km-grid analysis, while the 5-km-grid analysis fails to detect them and barely reproduces the rough shapes of mountains and basins.

As described above, the 3-km-grid analysis (Sekiyama et al. 2017) and 1-km-grid analysis are perfectly consistent using completely the same model (JMA-NHM), data assimilation scheme (LETKF), observation dataset, and configurations except for the model resolution setup. Note that the 5-km-grid analysis is calculated by a different data assimilation scheme (4DVar) assimilating a slightly different observation dataset, although the same forecast model is used. However, previous studies have confirmed that the 4DVar and the LETKF generally provide comparable performances as meteorological data assimilation schemes (cf. Kalnay et al. 2007). Furthermore, all three of these analyses are confirmed to reproduce very close structures of synoptic-scale disturbances because they share the same global analysis as lateral boundary conditions. The lack of satellite radiance data assimilation does not have a large impact on the 3- and 1-km-grid wind fields, probably due to their small domain sizes. In addition, we find that the 3-km analysis often shows intermediate behavior between the 5- and 1-km analyses in the lower troposphere. For example, the location of the surface wind convergence zone undergoes a gradual transition from west to east with increasing resolution in the case of Fig. 3.

2) OFFLINE TRANSPORT MODEL

The tracer (Cs-137) transport simulations were performed by an offline Eulerian regional air quality model, which was driven by the 5-, 3-, and 1-km-grid

meteorological analyses mentioned above. The offline Eulerian regional air quality model was originally developed by Kajino et al. (2012, 2019a) for nonradioactive aerosol simulations and has subsequently been used for Fukushima nuclear pollutant simulations by Adachi et al. (2013), Sekiyama et al. (2015, 2017), Kajino et al. (2016, 2018, 2019b), Inomata et al. (2018), Kitayama et al. (2018), Mathieu et al. (2018), Sato et al. (2018), Sekiyama and Iwasaki (2018), and Iwasaki et al. (2019).

In this model, the radionuclide Cs-137 was assumed to be well mixed with sulfate aerosol particles when it was transported in the atmosphere. The aerosol particle size was assumed to be log-normally distributed with a number equivalent geometric mean dry diameter = $0.5\text{ }\mu\text{m}$, a geometric standard deviation = 1.6, a particle density = 1.83 g cm^{-3} , and a hygroscopicity = 0.4 assuming a sulfate-organic mixture. Compared with Kajino et al. (2012), simplified aerosol dynamics was implemented by assuming a constant particle size distribution, in which nucleation, condensation, and coagulation were not considered. However, the model still simulated the important nature of the aerosol dynamics, such as dry deposition and in-cloud/below-cloud scavenging (i.e., wet deposition) processes, based on the prescribed size distribution as described in Sekiyama et al. (2015).

The meteorological analysis was taken into the offline Eulerian model every 1 h and linearly interpolated to suitable time intervals (30, 24, and 8 s for the 5-, 3-, and 1-km-grid models, respectively). The vertical model coordinate was converted from 60 layers in the NHM-LETKF analyses (expanded from the surface to approximately 22 km) to 20 layers (expanded from the surface to approximately 10 km) to reduce the computational burden of calculations within the stratosphere.

FIG. 4. Taylor diagrams for a comparison of surface wind analyses with AMeDAS observations categorized as (a) outer-sea plume periods, (b) interior plume periods, and (c) coastal plume periods. Open triangles, squares, and circles indicate mountainous, interior, and coastal locations, respectively, for the surface wind observations. Blue, green, and red colors indicate 5-, 3-, and 1-km-grid analyses, respectively. Black filled circles indicate observations.

The vertical resolution in the PBL was mostly unchanged. The 5- and 3-km-grid simulations shared the same model domain equivalent to that of the 3-km-grid meteorological analysis. The 1-km-grid simulation covered a smaller domain equivalent to the 1-km-grid meteorological analysis, as shown in Fig. 2. The Cs-137 emission scenario was provided by Katata et al. (2015), which was based on a source term estimation method (cf. Bieringer et al. 2013, 2017). Aerosol particles with Cs-137 were injected into a grid cell above the FDNPP at heights of 20–150 m above ground level based on a time-varying emission scenario, which was the same for all simulations. Each tracer transport simulation was performed from 11 to 31 March 2011.

In addition, a test simulation was performed to separate the effects of atmospheric resolution and topographic resolution. The additional simulation was run by the 1-km-grid-spacing model in the same way as the 1-km-grid simulation but driven by the 5-km-grid meteorological analysis as used in the 5-km-grid simulation. The 5-km-grid meteorological analysis was interpolated at 1-km intervals in the additional simulation, in which the numerical resolution was finer, but the terrain elevation and land use remained coarse. The additional simulation result was used for discrimination between the benefits of a highly resolved atmosphere and a highly resolved terrain. Hereinafter, the additional simulation is called the “5-to-1-km-grid” run.

3. Results and discussion

a. Plume classification

Major leakage of radioactive substances by the Fukushima nuclear accident lasted for three weeks from the day after the great earthquake (Hatamura et al. 2012). Most of the radioactive plumes during the three weeks flowed offshore (eastward) to the Pacific Ocean with the Siberian winter monsoon. The time windows of onshore (westward) plumes were limited to less than 50 h in total during the three weeks (Nakajima et al. 2017). Tsuruta et al. (2014) classified the onshore Cs-137 propagations into nine plumes (P1–P9) based on the time, location, and direction detected by their SPM sampling filter-tape observations. Sekiyama and Iwasaki (2018) clearly illustrated these nine plumes, as shown in the online supplemental material, using time- and column-integrated mass flux analysis. The plume numbers (P1–P9) in this study are unchanged from Tsuruta et al. (2014).

We categorize these nine plumes into three groups: outer-sea plumes (P1, P5, and P6), interior plumes (P2, P3, and P8), and coastal plumes (P4, P7, and P9), as shown in the online supplemental material. The

outer-sea plumes were detected only at a few SPM sampling stations along the coastline very close to the FDNPP. Therefore, the prevailing wind direction during the periods of the outer-sea plumes was westerly, which appears to be the typical Siberian winter monsoon with the Siberian high and the Aleutian low, as indicated in weather charts. The areas of Fukushima and Tokyo were under the stable condition of high pressure systems during these periods. In contrast, cyclones were moving through the area of Fukushima and Tokyo during the periods of the interior and coastal plumes. During the interior plume periods, cyclones were centered on Fukushima or Tokyo and completely disturbed the Siberian winter monsoon over the area. This information means that the radioactive plumes never intruded inland unless low pressure disturbances passed over Japan in wintertime. The statistics of the surface wind and Cs-137 concentration are determined using these three categories (outer-sea, interior, and coastal plumes) in the following sections.

b. Surface winds

Figure 4 shows Taylor diagrams (Taylor 2001) for a comparison of the surface wind analyses to the AMeDAS 10-m wind observations. The analyses are snapshots on the hour, while the observations are 5-min averages on the hour. The zonal winds (U_{10}) and meridional winds (V_{10}) were collectively processed to calculate the Pearson correlation coefficients and standard deviations because the same tendencies were consistently maintained for the U_{10}/V_{10} combined and separate statistics. The wind analyses at 0000, 0300, 0600, 0900, 1200, 1500, 1800, and 2100 UTC are the initial fields, but those at other hours are the forecast fields because the analyses were calculated with a 3-h assimilation time window. Meanwhile, the AMeDAS 10-m wind observations were used for the assimilation of the 3- and 1-km-grid analyses. Although the influence of the AMeDAS wind data assimilation on the analyses is minute (Sekiya et al. 2017), the Taylor diagrams were drawn by a comparison of 1-h forecast fields, that is, the analyses at 0100, 0400, 0700, 1000, 1300, 1600, 1900, and 2200 UTC, to avoid a direct comparison of the initial fields with the assimilated observations.

Taylor diagrams indicate how observations and model results compare in terms of their correlation, root-mean-square error (RMSE), and standard deviations. Pattern similarities between the observed (y_i) and modeled (x_i) fields can be quantified by the Pearson correlation coefficient r . Amplitude similarities can be quantified by their standard deviations σ_x and σ_y . Now define the centered RMSE (CRMSE):

$$\text{CRMSE} = \left\{ \frac{1}{N} \sum_{i=1}^N [(x_i - X) - (y_i - Y)]^2 \right\}^{1/2},$$

where X (or Y) indicates the sample mean of x_i (or y_i) and N is the number of samples. The CRMSE indicates the model errors and tends to zero when the patterns and amplitudes of the two fields are very similar. Taylor (2001) indicated that these quantities (r , σ_x , σ_y , and CRMSE) are related by

$$(\text{CRMSE})^2 = \sigma_x^2 + \sigma_y^2 - 2\sigma_x\sigma_y r.$$

In Taylor diagrams, the standard deviations σ_x and σ_y are represented by the radial distances from the origin. The mark of observation data is always located on the x axis with the value of σ_y since the autocorrelation coefficient is 1 at all times. The Pearson correlation coefficient r between observations and model results is shown by the azimuthal position. Then, the distance between the observation mark and the model result mark shows the value of the CRMSE because of the law of cosines when the azimuth is represented by $\cos^{-1}r$. Taylor diagrams are often drawn with normalized standard deviations (NSD), in which σ_x , σ_y , and CRMSE are normalized to the standard deviation of observations σ_y (as shown in Fig. 4). This normalization allows multiple data plots with different locations and/or time periods. Nevertheless, the distance between the observation ($r = 1$; NSD = 1) and the model result indicates the relative model error.

Figure 4 illustrates that the model errors in surface winds, or the distances from the observation ($r = 1$; NSD = 1), are always in the order of “mountainous location > interior location > coastal location” for any model resolution (5-, 3-, and 1-km grids) or plume category (Figs. 4a–c). The spread of the CRMSEs is much smaller for the outer-sea plume periods (Fig. 4a) than for the interior/coastal plume periods (Figs. 4b,c). This result indicates that the topographic dependence of the model performance is small when the atmosphere is stable under high pressure systems with the prevailing Siberian winter monsoon. Interestingly, the accuracy of winds at coastal stations (indicated by open circles) is lower for Siberian winter monsoon conditions (Fig. 4a) than for cyclonic conditions (Fig. 4b), while the accuracy of winds at mountain stations (indicated by open triangles) demonstrates the opposite behavior.

In terms of the model-resolution dependence, the differences are completely negligible among the 5-, 3-, and 1-km-grid models even for mountainous locations when the Siberian winter monsoon prevails under high pressure systems (Fig. 4a). This finding is contrary to common expectations that a higher resolution leads to a

better performance. However, the 1-km grid resolution demonstrates the best performance among the three model resolutions during the interior plume periods (Fig. 4b), in which the Siberian winter monsoon over Japan is completely disturbed by cyclones. The model errors are consistently in the order of “5-km grid > 3-km grid > 1-km grid” for any location (mountainous, interior, and coastal areas) as expected. Although the 1-km grid resolution is constantly superior to the 5- and 3-km grid resolutions during the interior plume periods, the difference is particularly large for mountainous locations. This result is reasonable given that the complexity of the terrain features is remarkable in mountainous areas. The complexity results in a large discrepancy in modeled terrains between different resolutions. The different terrains yield different dynamics (=wind fields) in the models. On the other hand, the superiority of the 1-km grid resolution is not very noticeable during the coastal plume periods (Fig. 4c). Although the 1-km-grid model performs better than the others in the mountainous and interior locations (indicated by open triangles and squares, respectively), the 3-km-grid model is superior in the coastal location (indicated by open circles). Note that the improvement of the plume transport performance is significant even when the surface wind performance improves only slightly (Nachamkin et al. 2007; Sekiyama et al. 2017) because the transport error is accumulated along the route. Therefore, we expect the 1-km-grid model to produce superior transport simulations in the next section.

c. Cs-137 plumes

Figure 5 shows a Taylor diagram for a comparison of the modeled Cs-137 concentrations to the SPM sampling filter-tape observations. The outer-sea plumes are excluded from the statistics since only a few observations were obtained over land during the outer-sea plume periods. Station locations are not classified as in the comparison of the surface wind validation because 1) the number of Cs-137 observation stations is fewer than that of the AMEDAS, 2) only a few “mountainous” stations observed Cs-137, and 3) almost no concentration record is available in the interior areas during the coastal plume periods. The comparison is performed by using time-integrated concentrations at each station to avoid a deterioration of statistical scores caused by small differences in plume arrival times. The time integral intervals are 6 h since all interior plumes (plumes 2, 3, and 8) and coastal plumes (plumes 4, 7, and 9) lasted for 6 h by definition, as indicated by Tsuruta et al. (2014), Oura et al. (2015), Nakajima et al. (2017), and Sekiyama and Iwasaki (2018) (also see the online supplemental material).

FIG. 5. Taylor diagram for a comparison of Cs-137 transport model results with SPM sampling filter-tape observations. Colored filled squares and circles indicate statistics during interior and coastal plume periods, respectively. Blue, green, and red colors indicate 5-, 3-, and 1-km-grid model results, respectively. A black filled circle indicates observations.

Certainly, the 1-km grid resolution (indicated by red marks in Fig. 5) demonstrates a good performance among the three model resolutions during both the interior and coastal plume periods. However, the correlations are evidently weak for all resolutions and plume periods. In addition, the model performance is unexpectedly in the order of “3-km grid < 5-km grid < 1-km grid” for both categories. The normalized standard deviations range more widely (0.35–1.25) than those of the surface wind analyses (0.8–1.2). This contrast is partly caused by the wet deposition of aerosols, which leads to large discrepancies in the aerosol concentration when the precipitation location and timing are differently simulated. The precipitation and foggy areas are not exactly identical among the three resolution models, which leads to large discrepancies in the deposition location. The authors have previously performed some Fukushima simulations with and without deposition processes (Sato et al. 2018; Iwasaki et al. 2019). The impact of wet deposition on the simulations appeared large in the northern part of the Kanto Plain probably because of drizzle or fog on 15 March 2011 over the Kanto Plain. However, unfortunately, no observations for Cs-137 were obtained in the northern part of the Kanto Plain (Fig. 1a) because the local governments had disposed of the SPM sampling filter tapes. In addition, rainy areas (especially on 21 March 2011) were mainly

located in the ocean or coastal regions, where the model resolution effect is quite small. Therefore, the impact of wet deposition on the statistics cannot be evaluated adequately in this study. Perhaps, transport error accumulation is also the cause of the contrast because transport errors are accumulated along the route with wind errors (Nachamkin et al. 2007; Sekiyama et al. 2017). The 5-to-1-km-grid simulation statistics were nearly identical to those of the 5-km-grid simulation (not shown), which implies that the impact of topographic resolution on plume simulation is much larger than that of atmospheric resolution.

Scatter diagrams are exhibited in Fig. 6 for the comparison between Cs-137 observations and model results to clarify the situation of the interior plume statistics shown by the abovementioned Taylor diagram. The plot is partly magnified (from the right panels to the left panels in Fig. 6) since most of the samples range within 100 h Bq m^{-3} . The distributions for both the 3- and 1-km-grid models are clearly split into two clusters, while the 5-km-grid model evidently results in a widely scattered distribution, that is, a weak correlation. In Fig. 6b, cluster (p) indicates good performance by the 3-km-grid model with a high correlation and a moderate slope angle. This cluster extends to a higher-concentration area, as shown by (p'). However, cluster (q) is almost parallel to the x axis with a weak correlation, in which the modeled concentrations scarcely fluctuate even when high concentrations are detected at each station in actuality. The combination of clusters (p) and (q) results in the underestimation (i.e., $\text{NSD} < 1$) of the 3-km-grid model for the interior plumes shown in Fig. 5. Likewise, cluster (r) for the 1-km-grid model also shows a high correlation (Fig. 6c), although it overestimates the concentrations. This cluster smoothly extends to a higher-concentration area, as shown by (r'). Cluster (r') seems better than cluster (p') in terms of the correlation. Meanwhile, cluster (s) underestimates with a gradual slope. The combination of clusters (r) and (s) results in a plausibly good amplitude ($\text{NSD} \approx 1$), as shown in Fig. 5. The problem is that these split distributions for the 3- and 1-km-grid models make their overall correlations extremely lower even if each cluster is not widespread. Clusters (q) and (s) are formed by plumes that are slightly shifted from their real locations (as shown later), which is hardly avoidable in simulations of sharply edged plumes.

In contrast, in the case of the coastal plumes (Fig. 7), the differences are very small among the 5-, 3-, and 1-km-grid models, although the 1-km-grid model performs slightly better. The data points are almost evenly scattered, and no cluster is formed except for ones on the x axis. The reason for no plots on the y axis is that

the observations have a detection limit. The transport models have only small dependence on the model resolution for the coastal plumes since the coastal winds originally differ just slightly between the model resolutions at all times, as shown in Fig. 4 (indicated by open circles). Both the plume locations and Cs-137 observations are mostly located in the coastal areas for this plume category. Therefore, most of the plots are not sampled from complex terrain in Fig. 7. Although the coastal winds show a good performance ($r = 0.7 \sim 0.9$, $\text{NSD} \approx 1$), the transport simulations perform much worse due to small errors in the plume locations and precipitation areas. Small errors in the plume locations lead to deterioration of the correlation. Small errors in the precipitation lead to deterioration of the amplitude similarity.

Figures 8–10 illustrate the geographical distributions of the interior plumes over the Fukushima mountainous region, which is a typical example of a complex terrain, to detail the cluster formation described above in the scatter diagrams. At first glance, the plume shape of the 1-km-grid simulation appears sharper than those of the 5- and 3-km resolutions. The plume edges of the 5- and 3-km-grid simulations are blurred and broadened due to the strong numerical diffusion (or discretization error). The plume shape of the 5-to-1-km-grid simulation is very similar to that of the 5-km-grid simulation, but the plume edge diffusion is smaller in the 5-to-1-km-grid simulation. This indicates that the benefit of a highly resolved terrain is much larger than that of a highly resolved atmosphere. Moreover, the 5-km-grid plumes not only are numerically broadened but also are not blocked by the mountain range, or the Ou Mountains, and do not follow the shapes of valleys. Plume 8 (Fig. 8) of the 1-km-grid simulation coincides fairly well with observations, whereas that of the 5-km-grid simulation completely fails to move south along the central Fukushima Valley that is located between the mountain range (1000–2000 m MSL) and the Abukuma Highlands (500–1000 m MSL). These results indicate that the mountain range is not well reproduced in the 5-km-grid model. In the case of plume 8, the mass flux (shown by arrowheads) is evidently directed southward along the central Fukushima Valley in the 1-km-grid simulation, directed incorrectly northward in the 5-km and 5-to-1-km-grid simulations, and directed moderately southward in the 3-km-grid simulation. The mass flux along the valley strongly depends on the topographic resolution because the mountains/highlands seriously lower down using low-resolution terrains.

In contrast, in the case of plume 3 (Fig. 9), the high-concentration tail of the plume is successfully blocked by the mountains and does not intrude into the central

Plume Category: Interior

FIG. 6. Scatter diagrams for a comparison between Cs-137 observations and transport model results at each station for the interior plume category for the (a) 5-, (b) 3-, and (c) 1-km-grid models. The concentrations are 6-hourly time-integrated at each station. (left) Magnified views of a portion (range: 0–100 h Bq m⁻³) of the (right) full plots (range: 0–800 h Bq m⁻³). The symbols p, p', q, r, or s indicate each cluster of data points. The black lines with these symbols approximately indicate cluster locations and slopes, which are not regression lines.

Plume Category: Coastal

FIG. 7. As in Fig. 6, but for the coastal plume category.

FIG. 8. Geographical distributions of the 6-h time-integrated surface Cs-137 concentration over the Fukushima region for the time period of plume 8. Shaded colors indicate the (a) 5-, (b) 3-, (c) 1-, and (d) 5-to-1-km-grid model results. Color circles indicate SPM sampling filter-tape observations. Arrowheads indicate the

Fukushima Valley in the 1-km-grid simulation. However, the tails intrude broadly into the valley in the 5- and 3-km-grid simulations in contradiction to the observation results. This discrepancy is probably caused by the modeled height of the Abukuma Highlands that is properly reproduced by the 1-km-grid terrain but failed by the 5- and 3-km-grid terrains. The FDNPP is located at a narrow coastal area between the Abukuma Highlands and the Pacific Ocean. Therefore, the reproducibility of the Abukuma Highlands is crucial for the plume simulation. Meanwhile, the wide diffusion at the plume edges sometimes avoids large concentration errors. For example, in the case of plume 2 (Fig. 10), only the 1-km-grid simulation fails to reproduce the high-concentration observations in the central Fukushima Valley. This error results in cluster formation adjacent to the x axis, such as cluster (s). Numerical diffusion (or discretization error) improves the plume correlation in some situations. For example, plume 2 is broadened and extended to the central Fukushima Valley passing over the Abukuma Highlands in the 5- and 3-km-grid simulations. This is also caused by the lower altitude of the Abukuma Highlands in the lower-resolution simulations. Although the real plume distribution is unknown here, a large discrepancy is avoided because of this numerical diffusion, which probably results in good scores for the 5-km-grid simulation in Fig. 5. In both cases of plumes 2 and 3, the plume distributions of the 5-to-1-km-grid simulation are close to those of the 5-km-grid simulation because of the same terrain resolution. However, striped patterns often appear only in the 5-to-1-km-grid plumes, especially near the emission source. This is probably caused by spacing imbalance between wind fields and a transport resolution or by small diffusion of the 5-to-1-km-grid simulation relative to the 5-km-grid simulation.

In contrast with the Fukushima region, no large differences in the plume distribution among the three model resolutions (5-, 3-, and 1-km grids) are observed in the Kanto Plain or the Tokyo region (not shown). Unfortunately, these modeled plumes are slightly shifted from the actual distributions; therefore, the samples from the Kanto Plain compose cluster (q) or (s) close to the x axis in the scatter diagrams. Similar to the interior plumes arriving in the Kanto Plain, the coastal plumes do not show any noticeable differences among the three model resolutions since most of the coastal plumes are observed only in the Kanto Plain far from mountainous regions. We maintained the

←

direction of the 6-h time-integrated mass flux (Sekiya and Iwasaki 2018) at the ground surface in the models. The open triangle is the location of the FDNPP.

(a) Plume 3 (5-km grid) **(b) Plume 3 (3-km grid)** **(c) Plume 3 (1-km grid)** **(d) Plume 3 (5-to-1-km grid)**

FIG. 9. As in Fig. 8, but for plume 3.

(a) Plume 2 (5-km grid) **(b) Plume 2 (3-km grid)** **(c) Plume 2 (1-km grid)** **(d) Plume 2 (5-to-1-km grid)**

FIG. 10. As in Fig. 8, but for plume 2.

same vertical resolution and physics schemes for all the 5-, 3-, and 1-km-grid models in this study. The nuclear accident occurred in the cold winter season, when the PBL is relatively stable. In addition, vertical plume distribution strongly depends on modeled physics schemes for vertical diffusion, not the meteorological analysis (Iwasaki et al. 2019). Therefore, we could not find any noticeable differences in the boundary layer depth, static stability, and vertical plume distribution among the three model resolutions.

4. Conclusions

The surface wind and plume transport simulations in this study revealed that the model performance depends on the horizontal resolution, topographic complexity, and synoptic weather conditions. Higher model resolution surely led to higher reproducibility of surface winds in mountainous areas only when the synoptic weather conditions were disturbed. No resolution dependence was observed when the synoptic field was steady at least in the areas and periods we investigated in this study. Only a small dependence on the model resolution appeared in the coastal and plain areas. The concentration correlations tended to deteriorate due to small errors in the plume locations. However, the higher-resolution models could advantageously perform better transport simulations in the Fukushima mountainous region because of the lower numerical diffusion and higher accuracy of the mass flux. The model performance of the plume distribution in the valley of the Fukushima mountainous region was dramatically improved in the order of the model resolution (1, 3, and 5 km). The improvement was caused by the benefit of a highly resolved terrain, not a highly resolved atmosphere. The spatial representabilities of the observations for the surface winds and tracer concentrations are probably less than $1 \times 1 \text{ km}^2$ over complex terrain under disturbed synoptic conditions and more than $5 \times 5 \text{ km}^2$ otherwise. Mesoscale numerical weather prediction models are operated worldwide with horizontal resolutions of 1–10 km as of 2019 (World Meteorological Organization 2017). In this range of mesoscale model resolution, we conclude that a higher-resolution model is definitely recommended for tracer transport simulations over complex terrain.

Acknowledgments. This work was supported by the Environment Research and Technology Development Fund (1-1802) at the Environmental Restoration and Conservation Agency and by JSPS KAKENHI Grants JP17K00533, JP16H02946, and JP19H01155.

Data availability statement: The 3- and 1-km-grid data for both the meteorological and concentration analyses

are available upon request to the corresponding author (T. T. Sekiyama 2017, 2019, unpublished data). The 5-km-grid data for the concentration analysis are also available upon request to T. T. Sekiyama (2019, unpublished data). The 5-km-grid data for the meteorological analysis and the 20-km-grid data for the global analysis are provided operationally by the Japan Meteorological Agency via the Japan Meteorological Business Support Center (2019, updated daily, unpublished data), which are free for research purpose. The surface wind data can be obtained from the website of the Japan Meteorological Agency (2019, updated daily, unpublished data, <http://www.jma.go.jp/jma/indexe.html>, accessed 23 March 2020). The Cs-137 concentration data were obtained from Tsuruta et al. (2014, unpublished data) and Oura et al. (2015, unpublished data) in text-file format upon request. Only the Cs-137 concentration data at Tokai (Ohkura et al. 2012) are downloadable in PDF format (<https://jopss.jaea.go.jp/pdfdata/JAEA-Data-Code-2012-010.pdf>, accessed 23 March 2020).

REFERENCES

- Adachi, K., M. Kajino, Y. Zaizen, and Y. Igarashi, 2013: Emission of spherical cesium-bearing particles from an early stage of the Fukushima nuclear accident. *Sci. Rep.*, **3**, 2554, <https://doi.org/10.1038/srep02554>.
- Angevine, W. M., J. Brioude, S. McKeen, and J. S. Holloway, 2014: Uncertainty in Lagrangian pollutant transport simulations due to meteorological uncertainty from a mesoscale WRF ensemble. *Geosci. Model Dev.*, **7**, 2817–2829, <https://doi.org/10.5194/gmd-7-2817-2014>.
- Bieringer, P. E., S. Hanna, G. Young, B. Kosovic, J. Hannan, and R. Ohba, 2013: Methods for estimating the atmospheric radiation release from the Fukushima Dai-ichi nuclear power plant. *Bull. Amer. Meteor. Soc.*, **94**, ES1–ES4, <https://doi.org/10.1175/BAMS-D-12-00090.1>.
- , G. S. Young, L. M. Rodriguez, A. J. Annunzio, F. Vandenbergh, and S. E. Haupt, 2017: Paradigms and commonalities in atmospheric source term estimation methods. *Atmos. Environ.*, **156**, 102–112, <https://doi.org/10.1016/j.atmosenv.2017.02.011>.
- Cécé, R. D., D. Bernard, J. Brioude, and N. Zahibo, 2016: Microscale anthropogenic pollution modelling in a small tropical island during weak trade winds. Lagrangian particle dispersion simulations using real nested LES meteorological fields. *Atmos. Environ.*, **139**, 98–112, <https://doi.org/10.1016/j.atmosenv.2016.05.028>.
- Dingwell, A., A. Rutgersson, B. Claremar, S. Arellano, M. M. Yalire, and B. Galle, 2016: Seasonal and diurnal patterns in the dispersion of SO₂ from Mt. Nyiragongo. *Atmos. Environ.*, **132**, 19–29, <https://doi.org/10.1016/j.atmosenv.2016.02.030>.
- Feng, S., and Coauthors, 2016: Los Angeles megacity: A high-resolution land-atmosphere modelling system for urban CO₂ emissions. *Atmos. Chem. Phys.*, **16**, 9019–9045, <https://doi.org/10.5194/acp-16-9019-2016>.
- Hatamura, Y., and Coauthors, 2012: Final report. Investigation Committee on the Accident at the Fukushima Nuclear Power Stations of Tokyo Electric Power Company Rep., 454 pp., <https://www.cas.go.jp/jp/seisaku/icanps/eng/final-report.html>.

- Honda, Y., M. Nishijima, K. Koizumi, Y. Ohta, K. Tamiya, T. Kawabata, and T. Tsuyuki, 2005: A pre-operational variational data assimilation system for a non-hydrostatic model at the Japan Meteorological Agency: Formulation and preliminary results. *Quart. J. Roy. Meteor. Soc.*, **131**, 3465–3475, <https://doi.org/10.1256/qj.05.132>.
- Inomata, Y., and Coauthors, 2018: Estimate of Fukushima-derived radiocaesium in the North Pacific Ocean in summer 2012. *J. Radioanal. Nucl. Chem.*, **318**, 1587–1596, <https://doi.org/10.1007/s10967-018-6249-7>.
- Iwasaki, T., and Coauthors, 2019: Intercomparison of numerical atmospheric dispersion prediction models for emergency response to emissions of radionuclides with limited source information in the Fukushima Dai-ichi Nuclear Power Plant accident. *Atmos. Environ.*, **214**, 116830, <https://doi.org/10.1016/j.atmosenv.2019.116830>.
- Kajino, M., and Coauthors, 2012: Development of the RAQM2 aerosol chemical transport model and predictions of the northeast Asian aerosol mass, size, chemistry, and mixing type. *Atmos. Chem. Phys.*, **12**, 11 833–11 856, <https://doi.org/10.5194/acp-12-11833-2012>.
- , M. Ishizuka, Y. Igarashi, K. Kita, C. Yoshikawa, and M. Inatsu, 2016: Long-term assessment of airborne radio-cesium after the Fukushima nuclear accident: Re-suspension from bare soil and forest ecosystems. *Atmos. Chem. Phys.*, **16**, 13 149–13 172, <https://doi.org/10.5194/acp-16-13149-2016>.
- , and Coauthors, 2018: Lessons learned from atmospheric modeling studies after the Fukushima nuclear accident: Ensemble simulations, data assimilation, elemental process modeling, and inverse modeling. *Geochem. J.*, **52**, 85–101, <https://doi.org/10.2343/geochemj.2.0503>.
- , and Coauthors, 2019a: NHM-chem, the Japan Meteorological Agency's regional meteorology-chemistry model: Model evaluations toward the consistent predictions of the chemical, physical, and optical properties of aerosols. *J. Meteor. Soc. Japan*, **97**, 337–374, <https://doi.org/10.2151/jmsj.2019-020>.
- , and Coauthors, 2019b: Deposition and dispersion of radio-cesium released due to the Fukushima nuclear accident: Sensitivity to meteorological models and physical modules. *J. Geophys. Res. Atmos.*, **124**, 1823–1845, <https://doi.org/10.1029/2018JD028998>.
- Kalnay, E., H. Li, T. Miyoshi, S.-C. Yang, and J. Ballabrera-Poy, 2007: 4-D-Var over ensemble Kalman filter? *Tellus*, **59A**, 758–773, <https://doi.org/10.1111/j.1600-0870.2007.00261.x>.
- Katata, G., M. Ota, H. Terada, M. Chino, and H. Nagai, 2012a: 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. Radioact.*, **109**, 103–113, <https://doi.org/10.1016/j.jenvrad.2012.02.006>.
- , H. Terada, H. Nagai, and M. Chino, 2012b: Numerical reconstruction of high dose rate zones due to the Fukushima Dai-ichi Nuclear Power Plant accident. *J. Environ. Radioact.*, **111**, 2–12, <https://doi.org/10.1016/j.jenvrad.2011.09.011>.
- , and Coauthors, 2015: 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. *Atmos. Chem. Phys.*, **15**, 1029–1070, <https://doi.org/10.5194/acp-15-1029-2015>.
- Kitayama, K., and Coauthors, 2018: Atmospheric modeling of ^{137}Cs plumes from the Fukushima Daiichi Nuclear Power Plant—Evaluation of the model intercomparison data of the science council of Japan. *J. Geophys. Res. Atmos.*, **123**, 7754–7770, <https://doi.org/10.1029/2017JD028230>.
- Kunii, M., 2014: Mesoscale data assimilation for a local severe rainfall event with the NHM-LETKF system. *Wea. Forecasting*, **29**, 1093–1105, <https://doi.org/10.1175/WAF-D-13-00032.1>.
- Mathieu, A., and Coauthors, 2018: Fukushima Daiichi-derived radionuclides in the atmosphere, transport and deposition in Japan: A review. *Appl. Geochem.*, **91**, 122–139, <https://doi.org/10.1016/j.apgeochem.2018.01.002>.
- Miyoshi, T., 2011: The Gaussian approach to adaptive covariance inflation and its implementation with the local ensemble transform Kalman filter. *Mon. Wea. Rev.*, **139**, 1519–1535, <https://doi.org/10.1175/2010MWR3570.1>.
- , and K. Aranami, 2006: Applying a four-dimensional local ensemble transform Kalman filter (4D-LETKF) to the JMA nonhydrostatic model (NHM). *SOLA*, **2**, 128–131, <https://doi.org/10.2151/sola.2006-033>.
- , and M. Kunii, 2012: The local ensemble transform Kalman filter with the Weather Research and Forecasting model: Experiments with real observations. *Pure Appl. Geophys.*, **169**, 321–333, <https://doi.org/10.1007/s00024-011-0373-4>.
- Nachamkin, J. E., J. Cook, M. Frost, D. Martinez, and G. Sprung, 2007: Evaluation of dispersion forecasts driven by atmospheric model output at coarse and fine resolution. *J. Appl. Meteor. Climatol.*, **46**, 1967–1980, <https://doi.org/10.1175/2007JAMC1570.1>.
- Nakajima, T., and Coauthors, 2017: Model depiction of the atmospheric flows of radioactive cesium emitted from the Fukushima Daiichi Nuclear Power Station accident. *Prog. Earth Planet. Sci.*, **4**, 2, <https://doi.org/10.1186/s40645-017-0117-x>.
- Ohkura, T., and Coauthors, 2012: Emergency monitoring of environmental radiation and atmospheric radionuclides at Nuclear Science Research Institute, JAEA following the accident of Fukushima Daiichi Nuclear Power Plant. Japan Atomic Energy Agency Rep. JAEA-Data/Code 2012-010, 37 pp., <https://doi.org/10.11484/jaea-data-code-2012-010>.
- Oura, Y., and Coauthors, 2015: A database of hourly atmospheric concentrations of radiocesium (^{134}Cs and ^{137}Cs) in suspended particulate matter collected in March 2011 at 99 air pollution monitoring stations in eastern Japan. *J. Nucl. Radiochem. Sci.*, **15**, 2_1–2_12, https://doi.org/10.14494/jnrs.15.2_1.
- Pillai, D., and Coauthors, 2011: High-resolution simulations of atmospheric CO_2 over complex terrain—Representing the Ochsenkopf Mountain tall tower. *Atmos. Chem. Phys.*, **11**, 7445–7464, <https://doi.org/10.5194/acp-11-7445-2011>.
- Saito, K., and Coauthors, 2006: The operational JMA non-hydrostatic mesoscale model. *Mon. Wea. Rev.*, **134**, 1266–1298, <https://doi.org/10.1175/MWR3120.1>.
- , J. Ishida, K. Aranami, T. Hara, T. Segawa, M. Narita, and Y. Honda, 2007: Nonhydrostatic atmospheric models operational development at JMA. *J. Meteor. Soc. Japan*, **85B**, 271–304, <https://doi.org/10.2151/jmsj.85B.271>.
- Sato, Y., and Coauthors, 2018: Model intercomparison of atmospheric ^{137}Cs from the Fukushima Daiichi Nuclear Power Plant accident: Simulations based on identical input data. *J. Geophys. Res. Atmos.*, **123**, 11 748–11 765, <https://doi.org/10.1029/2018JD029144>.
- Sekiyama, T. T., and T. Iwasaki, 2018: Mass flux analysis of ^{137}Cs plumes emitted from the Fukushima Daiichi Nuclear Power Plant. *Tellus*, **70B**, 1–11, <https://doi.org/10.1080/16000889.2018.1507390>.
- , M. Kunii, M. Kajino, and T. Shimbori, 2015: Horizontal resolution dependence of atmospheric simulations of the Fukushima nuclear accident using 15-km, 3-km, and 500-m

- grid models. *J. Meteor. Soc. Japan*, **93**, 49–64, <https://doi.org/10.2151/jmsj.2015-002>.
- , M. Kajino, and M. Kunii, 2017: The impact of surface wind data assimilation on the predictability of near-surface plume advection in the case of the Fukushima nuclear accident. *J. Meteor. Soc. Japan*, **95**, 447–454, <https://doi.org/10.2151/jmsj.2017-025>.
- Srinivas, C. V., K. B. R. R. Hari Prasad, C. V. Naidu, R. Baskaran, and B. Venkatraman, 2016: Sensitivity analysis of atmospheric dispersion simulations by FLEXPART to the WRF-simulated meteorological predictions in a coastal environment. *Pure Appl. Geophys.*, **173**, 675–700, <https://doi.org/10.1007/s00024-015-1104-z>.
- Sugiyama, G., J. Nasstrom, B. Pobanz, K. Foster, M. Simpson, P. Vogt, F. Aluzzi, and S. Homann, 2012: Atmospheric dispersion modeling: Challenges of the Fukushima Daiichi response. *Health Phys.*, **102**, 493–508, <https://doi.org/10.1097/HP.0b013e31824c7bc9>.
- Tang, Z., J. Cai, Q. Li, and J. Zhao, 2019: The regional scale atmospheric dispersion of radionuclide ^{131}I : A simulation method based on WRF-Chem model. *Radiat. Phys. Chem.*, **156**, 81–93, <https://doi.org/10.1016/j.radphyschem.2018.10.029>.
- Taylor, K. E., 2001: Summarizing multiple aspects of model performance in a single diagram. *J. Geophys. Res.*, **106**, 7183–7192, <https://doi.org/10.1029/2000JD900719>.
- Tie, X., G. Brasseur, and Z. Ying, 2010: Impact of model resolution on chemical ozone formation in Mexico City: Application of the WRF-Chem model. *Atmos. Chem. Phys.*, **10**, 8983–8995, <https://doi.org/10.5194/acp-10-8983-2010>.
- Tsuruta, H., Y. Oura, M. Ebihara, T. Ohara, and T. Nakajima, 2014: First retrieval of hourly atmospheric radionuclides just after the Fukushima accident by analyzing filter-tapes of operational air pollution monitoring stations. *Sci. Rep.*, **4**, 6717, <https://doi.org/10.1038/srep06717>.
- , —, —, Y. Moriguchi, T. Ohara, and T. Nakajima, 2018: Time-series analysis of atmospheric radiocesium at two SPM monitoring sites near the Fukushima Daiichi Nuclear Power Plant just after the Fukushima accident on March 11, 2011. *Geochem. J.*, **52**, 103–121, <https://doi.org/10.2343/geochemj.2.0520>.
- World Meteorological Organization, 2006: Environmental emergency response: WMO activities. *WMO Bull.*, **55**, 37–41.
- , 2011: WMO Technical Progress Report on the Global Data Processing and Forecasting System and Numerical Weather Prediction Research 2011. Accessed 1 September 2019, https://www.wmo.int/pages/prog/www/DPFS/ProgressReports/2012/2011_GDPFS-NWP.html.
- , 2017: WMO Technical Progress Report on the Global Data Processing and Forecasting System and Numerical Weather Prediction Research 2017. Accessed 1 September 2019, <https://www.wmo.int/pages/prog/www/DPFS/GDPFS-Progress-Reports.html>.