Horizontal Resolution Dependence of Atmospheric Simulations of the Fukushima Nuclear Accident Using 15-km, 3-km, and 500-m Grid Models

Tsuyoshi T. SEKIYAMA, Masaru KUNII, Mizuo KAJINO, and Toshiki SHIMBORI
Meteorological Research Institute, Tsukuba, Japan

(Manuscript received 16 June 2014, in final form 1 October 2014)

Abstract

We investigated the horizontal resolution dependence of atmospheric radionuclide (Cs-137) simulations of the Fukushima nuclear accident on March 15, 2011. We used Eulerian and Lagrangian transport models with low- (15-km), medium- (3-km), and high- (500-m) resolutions; both models were driven by the same meteorological analysis that was prepared by our data assimilation system (NHM-LETKF) for each horizontal resolution. This preparation was necessary for the resolution-dependent investigation, excluding any interpolation or averaging of meteorological fields. In the results, the 15-km grid analysis could not reproduce Fukushima’s mountainous topography in detail, and consequently failed to depict a complex wind structure over mountains and valleys. In reality, the Cs-137 plume emitted from the Fukushima Daiichi Nuclear Power Plant (FDNPP) was mostly blocked by Mt. Azuma and other mountains along the Naka-dori valley after crossing over Abukuma Mountains on March 15, 2011. However, the 15-km grid simulations could not represent the blockage of the Cs-137 plume, which unnaturally spread through the Naka-dori valley. In contrast, the 3-km and 500-m grid simulations produced very similar Cs-137 concentrations and depositions, and successfully produced the plume blockage and deposition along the Naka-dori valley. In conclusion, low-resolution (15-km grid or greater) atmospheric models should be avoided for assessing the Fukushima nuclear accident when a regional analysis is needed. Meanwhile, it is reasonable to use 3-km grid models instead of 500-m grid models due to their similarities and the high computational burden of 500-m grid model simulations.

Keywords model simulation; resolution dependence; data assimilation; Fukushima nuclear accident; cesium-137

1. Introduction

1.1 Atmospheric simulations of the Fukushima nuclear accident

The 2011 Tohoku earthquake occurred off the Pacific coast of Japan on March 11, 2011 and triggered tsunami waves, which caused severe disaster at the Fukushima Daiichi Nuclear Power Plant (FDNPP). The accident became the largest nuclear disaster since Chernobyl, and resulted in the dispersion and deposition of a large amount of radionuclides in the environment of eastern Japan. Since then, many numerical simulations have been performed to predict or assess the effects of the nuclear accident using atmospheric chemistry transport models (e.g., Chino et al. 2011; Morino et al. 2011, 2013; Yasunari et al. 2011; Takemura et al. 2011; Schöppner et al. 2011; Sugiyama et al. 2012; Mathieu et al. 2012; Stohl et al. 2012; Katata et al. 2012a, b; Terada et al. 2012; Christoudias and Lelieveld 2013;
Adachi et al. 2013; Saito et al. 2015; Hu et al. 2014; Arnold et al. 2015). Some models were used to estimate the amount of radionuclides released from the FDNPP, coupled with a reverse analysis. Others were used to estimate the health damage to local residents or to investigate the meteorological causes of inhomogeneous radioactive contamination. Those models can be categorized into two types according to their domains: global and regional models. Global models have a large domain covering not only Japan but also America and Europe; however, their resolutions are not very fine compared with regional models. The horizontal resolutions of global models are approximately 50 km varying from 11 km to 110 km (Table 1). In contrast, regional models have a relatively finer resolution, but their domains often only cover eastern Japan. The horizontal resolutions of regional models are often 3 km, varying from 1 km to 9 km (Table 2). Incidentally, the atmospheric simulation models of the Chernobyl nuclear accident have often had lower resolutions, even when they were used with regional domains (Table 3). The lower model resolutions are most likely attributed to the topographical features of Chernobyl, which is located on very flat terrain. The nearest mountains are more than 500 km away from Chernobyl. It would be unnecessary to make the model resolution very high for continental-scale or very flat area simulations. However, it is unclear what resolution is good enough to regionally represent the advection and deposition of radionuclides in the case of Fukushima because Japan has a complex topography. More than 70% of the Japanese territory is mountainous. Small plains and basins are scattered throughout the remaining area where the population is concentrated. Fukushima is not an exception to the topographical complexity.

Table 1. Spatial resolution of Fukushima radionuclide atmospheric simulation models with a global domain.

<table>
<thead>
<tr>
<th>model</th>
<th>spatial resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schöppner et al. (2011)</td>
<td>$1^\circ \times 1^\circ$ ($\approx 90$ km $\times 110$ km)</td>
</tr>
<tr>
<td>Takemura et al. (2011)</td>
<td>$0.56^\circ \times 0.56^\circ$ ($\approx 50$ km $\times 60$ km)</td>
</tr>
<tr>
<td>Yasunari et al. (2011)</td>
<td>$1^\circ \times 1^\circ$ ($\approx 90$ km $\times 110$ km) [global domain]</td>
</tr>
<tr>
<td></td>
<td>$0.18^\circ \times 0.18^\circ$ ($\approx 16$ km $\times 20$ km) [regional domain]</td>
</tr>
<tr>
<td>Stohl et al. (2012)</td>
<td>$0.5^\circ \times 0.5^\circ$ ($\approx 45$ km $\times 55$ km)</td>
</tr>
<tr>
<td>Mathieu et al. (2012)</td>
<td>$0.5^\circ \times 0.5^\circ$ ($\approx 45$ km $\times 55$ km) [global domain]</td>
</tr>
<tr>
<td></td>
<td>$0.125^\circ \times 0.125^\circ$ ($\approx 11$ km $\times 14$ km) [regional domain]</td>
</tr>
<tr>
<td>Christoudias and Lelieveld (2013)</td>
<td>$0.5^\circ \times 0.5^\circ$ ($\approx 45$ km $\times 55$ km)</td>
</tr>
<tr>
<td>Arnold et al. (2015)</td>
<td>$0.2^\circ \times 0.2^\circ$ ($\approx 18$ km $\times 22$ km)</td>
</tr>
<tr>
<td></td>
<td>$0.5^\circ \times 0.5^\circ$ ($\approx 45$ km $\times 55$ km)</td>
</tr>
</tbody>
</table>

Table 2. Spatial resolution of Fukushima radionuclide atmospheric simulation models with a regional domain.

<table>
<thead>
<tr>
<th>model</th>
<th>spatial resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chino et al. (2011)</td>
<td>$2$ km $\times 2$ km</td>
</tr>
<tr>
<td></td>
<td>$3$ km $\times 3$ km</td>
</tr>
<tr>
<td>Morino et al. (2011)</td>
<td>$6$ km $\times 6$ km</td>
</tr>
<tr>
<td>Katata et al. (2012a, 2012b) and Terada et al. (2012)</td>
<td>$9$ km $\times 9$ km</td>
</tr>
<tr>
<td></td>
<td>$3$ km $\times 3$ km</td>
</tr>
<tr>
<td></td>
<td>$1$ km $\times 1$ km</td>
</tr>
<tr>
<td>Sugiyama et al. (2012)</td>
<td>$27$ km $\times 27$ km</td>
</tr>
<tr>
<td></td>
<td>$9$ km $\times 9$ km</td>
</tr>
<tr>
<td></td>
<td>$3$ km $\times 3$ km</td>
</tr>
<tr>
<td></td>
<td>$1$ km $\times 1$ km</td>
</tr>
<tr>
<td>Adachi et al. (2013)</td>
<td>$3$ km $\times 3$ km</td>
</tr>
<tr>
<td>Morino et al. (2013)</td>
<td>$3$ km $\times 3$ km</td>
</tr>
<tr>
<td>Hu et al. (2014)</td>
<td>$3$ km $\times 3$ km</td>
</tr>
<tr>
<td>Saito et al. (2015)</td>
<td>$5$ km $\times 5$ km</td>
</tr>
</tbody>
</table>
1.2 Fukushima’s topography

Fukushima is a mountainous region with few plains. FDNPP is located on the coastline of the Pacific Ocean, but the flat area around the power plant is very narrow (Fig. 1c). The Abukuma Mountains, which are as high as 1000 m, are located just behind the power plant; the distance between the FDNPP premises and Abukuma Mountain foothills is only a few kilometers. Fukushima City, the capital of Fukushima Prefecture, is situated beyond the mountain range; it is located in a long narrow basin that is approximately 70 m above sea level (asl). Mt. Azuma has several peaks of which the highest is 2035 m asl.

As mentioned above, the 3-km grid is the most popular horizontal resolution in the regional simulation models of the Fukushima nuclear accident (Table 2). However, it is not evident that the 3-km grid resolution can properly reproduce the advection and deposition of radionuclides associated with the FDNPP accident. On the other hand, the global simulation models of the FDNPP accident (Table 1) commonly use much lower resolutions than the 15-km grid scale that cannot depict Fukushima’s complex topography in detail (Fig. 1a). Nevertheless, some researchers validated their global simulation results with domestic observations in Japan (e.g., Stohl et al. 2012) and investigated the health damage to local residents (e.g.,

<table>
<thead>
<tr>
<th>model</th>
<th>spatial resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bradt et al. (2002)</td>
<td>25 km × 25 km [outer domain]</td>
</tr>
<tr>
<td></td>
<td>5 km × 5 km [inner domain]</td>
</tr>
<tr>
<td>Davoine et al. (2007)</td>
<td>1.125° × 1.125° (= 110 km × 140 km)</td>
</tr>
<tr>
<td>Evangelou et al. (2013)</td>
<td>2.5° × 1.27° (= 230 km × 140 km) [global domain]</td>
</tr>
<tr>
<td></td>
<td>0.66° × 0.51° (= 60 km × 55 km) [Europe domain]</td>
</tr>
</tbody>
</table>

Fig. 1. Fukushima’s topography depicted by the (a) 15-km, (b) 3-km, and (c) 500-m grid scales. The cross indicates the location of FDNPP. The Abukuma Mountains have peaks of approximately 1000 m. Fukushima City is located in a narrow basin 70 m above sea level (asl). Mt. Azuma has several peaks of which the highest is 2035 m asl.
Christoudias and Lelieveld 2013). If their simulations are accurate, then there is no need to use higher resolution models, because the computational burdens exponentially increase with finer model resolutions. However, the validity of using 15-km or lower resolutions for the regional assessment of the FDNPP accident has not been proven.

1.3 Objective

This study investigated whether the 3-km grid (representative of the regional model resolution) and 15-km grid (representative of the global model resolution) models adequately simulate the radioactive pollution of the FDNPP accident compared with a very high-resolution model (500-m grid). These simulations focused on Cs-137 radionuclides only because the available observations were spatially dispersed throughout Fukushima and its neighboring areas. To double-check the resolution dependence, we managed two types of chemistry transport models: the Eulerian and Lagrangian models. Both models were driven by the same meteorological analysis with 15-km, 3-km, and 500-m horizontal resolution grids. Eulerian models indirectly describe air motion by focusing on specific locations through which the air flows over time. Lagrangian models directly describe air motion by following an individual air parcel as it moves. Both models have advantages and disadvantages. For example, Eulerian models explicitly forecast radionuclide concentrations, and can implement chemical and physical processes in detail, but are not good at handling point source emissions. In contrast, Lagrangian models are good at handling point source emissions, but are susceptible to sampling noise when there are few Lagrangian particles.

In addition, we generally encounter difficulties in obtaining meteorological analyses with arbitrary horizontal resolutions. It is impossible for Lagrangian models to arbitrarily obtain a high- (low-) resolution analysis just by using simple interpolation (averaging) of the meteorological fields because the amount of information is not adequately increased (decreased enough) in the meteorological field by such simple calculation. Meanwhile, many Eulerian chemistry transport models are driven by the meteorological analysis calculated by their own dynamical module, wherein the meteorological field is nudged by another analysis with a different resolution. Consequently, the calculated meteorological analysis may be a mixture of the dynamical module simulation and another analysis with a different resolution. Therefore, we conducted the data assimilation to make the arbitrary-resolution analysis independent from other resolution models and analyses. The details of our data assimilation are described in Section 2.1. Then, the chemistry transport models are described in Sections 2.2 and 2.3. We present the results and discussion in Section 3, and the conclusion in Section 4.

2. Methodology

2.1 Preparation of meteorological analyses

Prior to calculating the radionuclide transport, we prepared meteorological analyses, which had three different horizontal resolutions, using a flow-dependent data assimilation system assembled and validated by Kunii (2013). This data assimilation system comprises the Japan Meteorological Agency’s non-hydrostatic model (JMA-NHM) and the local ensemble transform Kalman filter (LETKF), which are together called NHM-LETKF. The system calculated all the necessary meteorological variables, which were stored every 10 min, to subsequently drive the radionuclide transport models. In this study, the horizontal resolutions were set to 15 km, 3 km, and 500 m. Here, a one-way nested data assimilation scheme was implemented, wherein the first guess of a lower resolution model is used as a boundary condition for finer-resolution model integration (Kunii 2013). The nested inner model runs independently from the outer coarse model, except for the boundary condition. We defined the 15-km resolution as the typical grid scale of high-resolution global simulations (cf. Table 1). The 3-km resolution was defined as the typical grid scale of regional simulations implemented for the FDNPP accident (cf. Table 2). The 500-m resolution was considered higher than that of any other Fukushima simulation models and was expected to depict Fukushima’s complex topography.

The meteorological model JMA-NHM was developed by JMA (Saito et al. 2006, 2007) and has been used for government-operated weather forecasts. Operationally, JMA-NHM is initialized by the JMA non-hydrostatic-model four-dimensional variational data assimilation system (JNoVA, Honda et al. 2005). Most of the regional simulation models for the FDNPP accident use the JNoVA grid-point-value (GPV) data as the initial/boundary conditions or pseudo-observations (Chino et al. 2011; Morino et al. 2011, 2013; Katata et al. 2012a, b; Terada et al. 2012; Adachi et al. 2013; Draxler et al. 2015; Saito et al. 2015). In contrast, we calculated the meteorological analyses by running our own data assimilation system (NHM-LETKF) instead of using the JNoVA GPV. The data assimilation scheme LETKF
is an ensemble Kalman filter (EnKF) implementation developed by Hunt et al. (2007). The application of EnKFs enables an evaluation of uncertainties of the analysis fields and leads to a probabilistic prediction through ensemble forecasting. LETKF has been applied to various simulations, such as weather forecast modeling (e.g., Miyoshi and Aranami 2006; Miyoshi and Yamane 2007; Miyoshi and Kunii 2012; Kunii and Miyoshi 2012; Kunii et al. 2012; Kunii 2013) and chemistry transport modeling (e.g., Sekiyama et al. 2010, 2011a, b; Kang et al. 2011; Miyazaki et al. 2012; Nakamura et al. 2013).

In this study, the 15-km grid spacing analysis was calculated by the outer NHM-LETKF, whose domain covered East Asia (Fig. 2a), and was initiated at 6:00 UTC March 9, 2011 with 20 ensemble members. This domain comprises $241 \times 193$ horizontal grid points on the Lambert conformal projection and 50 vertical levels up to approximately 22 km in the terrain-following hybrid vertical coordinates, which include 11 levels below 1 km but above ground level (agl). The horizontal coverage of this configuration is similar to that of the JNoVA system routinely operated by JMA. The initial and boundary conditions of the NHM-LETKF cycle were obtained from the JMA operational global prediction system. We added initial and lateral boundary perturbations derived from the JMA operational one-week ensemble prediction system to each ensemble member in accordance with Saito et al. (2012). The 15-km grid spacing JMA-NHM implemented a modified Kain–Fritsch convective parameterization scheme (Kain and Fritsch 1993) along with the 3-ice-bulk cloud microphysics (Lin et al. 1983). For the turbulence scheme, the improved Mellor–Yamada level 3 closure model (Nakanishi and Niino 2004, 2006) was implemented. This LETKF analyzed all the prognostic variables of JMA-NHM, i.e., wind components ($u$, $v$, $w$), temperature ($T$), pressure ($p$), water vapor mixing ratio ($q_v$), and water/ice microphysics variables. Here, LETKF employed an adaptive inflation scheme, which adaptively estimates the multiplicative inflation factors at each grid point (Miyoshi 2011; Miyoshi and Kunii 2012). The covariance localization parameters were set to 150 km in the horizontal, $0.2 \ln p$ coordinate in the vertical, and 3 h in the time dimension. These localization parameters correspond to the length at which the Gaussian localization function becomes $e^{-0.5}$. The NHM-LETKF cycle was succeeded with a 6-h time interval, wherein the observation data were grouped into 1-h time slots and were four-dimensionally assimilated (Hunt et al. 2004). To assimilate the observation data, we used JMA’s operational dataset, which was integrated and quality-controlled for the JNoVA mesoscale weather prediction like Kunii (2013). The JNoVA dataset contains observations acquired by radiosondes, weather observatories, pilot balloons, wind profilers, aircrafts, ships, buoys, and satellites. However, satellite radiances and radar precipitation analyses were not assimilated in this study because observation operators for these observations have not yet been installed in the NHM-LETKF system. Instead, we additionally assimilated surface wind observations acquired by the automated meteorological data acquisition system (AMeDAS) and Tokyo Electric Power
Company (TEPCO) monitoring posts. AMeDAS is a surface observation network managed by JMA. The network currently comprises approximately 1,300 stations throughout the country, which are laid out at average intervals of 17 km. The TEPCO monitoring posts are placed at FDNPP, and the Fukushima Dai-ni Nuclear Power Plant that is located to 12 km south of FDNPP. The monitoring post datasets are freely available to the public at the TEPCO website (http://www.tepco.co.jp/nu/fukushima-np/index-j.html).

The 3-km grid spacing analysis was calculated by the nested NHM-LETKF, whose domain covered eastern Japan (Fig. 2b), and was initiated at 6:00 UTC March 10, 2011 with 20 ensemble members. This domain comprises 215 × 259 horizontal grid points in the Lambert conformal projection and 60 vertical levels up to approximately 22 km in the terrain-following hybrid vertical coordinate. The lateral boundary conditions were supplied from the outputs of the outer (15-km grid) NHM-LETKF cycle. Here, nearly the same configurations were implemented in both the 3-km grid spacing JMA-NHM and the 15-km simulation, but the convective parameterization scheme was not activated for the former. The covariance localization parameters were set to 50 km in the horizontal, 0.1 ln p coordinate in the vertical, and 3 h in the time dimension. The inner NHM-LETKF cycle was succeeded with a 3-h time interval, and its data assimilation was performed four-dimensionally. We used the same observation data (i.e., JNoVA, AMeDAS, and TEPCO datasets) that were used in the 15-km data assimilation. Furthermore, the 500-m grid spacing analysis was calculated by the second nested NHM-LETKF whose domain mostly covered Fukushima Prefecture (Fig. 2c) with 281 × 301 horizontal grid points in the Lambert conformal projection and 60 vertical levels up to approximately 22 km in the terrain-following hybrid vertical coordinate. In Fig. 2c, the location of the FDNPP is indicated with a cross along the coastline. The lateral boundary conditions were supplied from the outputs of the 3-km NHM-LETKF cycle. The covariance localization parameters were set to 25 km in the horizontal, 0.1 ln p coordinate in the vertical, and 3 h in the time dimension. Basically, the same configurations were implemented for the 500-m grid spacing JMA-NHM and the 3-km simulation. Moreover, the same observation data were assimilated during the second nested NHM-LETKF cycle. The triple-nested data assimilation experiments were conducted with horizontal resolutions of 15 km, 3 km, and 500 m.

To generate the terrain features in the computational domains of these 15-km, 3-km, and 500-m grid JMA-NHMs, we used the global digital elevation data with a horizontal grid spacing of 30 arc s (GTOPO30), which is approximately 900 m in the east–west direction and 700 m in the south–north direction, provided from the U.S. Geological Survey (https://lta.cr.usgs.gov/GTOPO30). For each domain, the GTOPO30 data was smoothed in the approximately 1.5 times coarser resolution of each model (i.e., 800 m for the 500-m grid model, 5 km for the 3-km grid model, and 25 km for the 15-km grid model). In general, this smoothing procedure is indispensable for meteorological model simulation to avoid the computational instability and error-amplification caused by precipitous terrains (= coordinate distortions). Figure 1 shows the terrains after the smoothing.

2.2 Eulerian transport model

We conducted Eulerian simulations using the Regional Air Quality Model 2 (RAQM2) that was originally developed to simulate Asian air quality and aerosol properties (Kajino et al. 2012). RAQM2 implements a Eulerian transport scheme and a triple-moment modal aerosol dynamics module. The aerosol dynamics, such as dry deposition, grid-scale rainout (cloud condensation nuclei and ice nuclei activations, and subsequent cloud microphysical processes), and washout (coagulation between aerosols and settling hydrometeors) processes, as well as advection, diffusion, sub-grid-scale convection/scavenging, and gravitational settling are calculated offline by coupling with meteorological models. In this study, RAQM2 was driven by the meteorological analyses with 15-km, 3-km, or 500-m resolutions prepared by NHM-LETKF. The analyses were taken into RAQM2 every 10 min and linearly interpolated within each 10-min interval. RAQM2 and NHM-LETKF shared the same model domain and horizontal grid resolution, but their vertical resolutions were converted from NHM-LETKF’s 50 or 60 layers (expanded from the surface to approximately 22 km asl) to RAQM2’s 20 layers (expanded from the surface to approximately 10 km asl). The radionuclide transport version of RAQM2 was developed for the Fukushima nuclear accident simulation (Adachi et al. 2013). This version of RAQM2 implements simplified aerosol dynamics compared with those of Kajino et al. (2012) by assuming aerosol hygroscopicity and perpetual particle size distribution; nucleation, condensation, and coagulation were not considered here. Still, we described the nature of the aerosol dynamics, such as
dry deposition and grid-scale rainout/washout (i.e., wet deposition) processes, based on the prescribed size distribution. Details of the dry and wet deposition processes are described in Sections 2.2.7 and 2.2.8 of Kajino et al. (2012), respectively. In this study, all the radioactive Cs-137 was contained in sulfate aerosol particles (mixed with organic compounds) when it was transported in the atmosphere. The particle size distribution of sulfate aerosols was assumed to be log-normal with a number equivalent geometric size distribution. Details of the dry and wet deposition processes, based on the prescribed gravitational settling, dry deposition, and wet scavenging was applied under the height of approximately 1500 m asl. The dry deposition was simply computed by the deposition rate of $10^{-5}$ s$^{-1}$ according to Sportisse (2007) and Draxler and Rolph (2012). For the gravitational settling, the particle size distribution of sulfate aerosols was assumed to be log-normal with a mean diameter of 1.0 µm, a standard deviation of 1.0, and a uniform particle density of 1.0 g cm$^{-3}$. The number of Lagrangian particles was set to a constant 100,000 per hour. The particles were uniformly emitted at the location of FDNPP from the ground surface to 100 m agl. After the model calculation, the hourly particle concentration and deposition outputs were multiplied by the hourly Cs-137 emission rate of JAEA (cf. Chino et al. 2011; Katata et al. 2012a; Terada et al. 2012) at the time of particles emission. Then, the multiplied values were summed at each grid point.

3. Results and discussion

3.1 Meteorology

In this study, we focused the simulation on March 15, 2011 (UTC) because we needed to investigate the radioactive plumes that outflowed landward. According to Morino et al. (2013), their standard experiment with the JAEA emission scenario indicates that most of the Cs-137 deposition over land (mainly in Fukushima Prefecture) occurred during the period from March 15 to 16 (Japanese Standard Time; JST) and accounts for 72% of the total deposition over land between March 10, 2011 and April 20, 2011.

The comparison of the meteorological analyses of NHM-LETKF is shown in Figs. 3 and 4. It was either raining or snowing over eastern Japan on March 15, 2011, as depicted by the JMA Radar/rain gauge-Analyzed Precipitation (RAP) data in Fig. 3a. JMA operationally produces the RAP data by calibrating radar echo observations with 1-h accumulated rain gauge precipitation data (AMeDAS) throughout Japan. Figure 3a shows a 24-h accumulation of RAP interpolated onto 1-km grids on March 15, 2011 UTC. In general, the quantitative simulation of precipitation is difficult for models, compared with dynamical variables, such as wind, pressure, and temperature because precipitation involves a chemical phase transition. Nonetheless, the NHM-LETKF analyses (Figs. 3b, c, d) demonstrated good agreement with RAP in regard to synoptic-scale precipitation. Note that the 24-h accumulated precipitation of the 15-km, 3-km, and 500-m grid spacing analyses were very
similar. The difference among them was smaller than that between RAP and the simulated precipitation. This similarity suggests that there would not be a large difference in the wet deposition due to the precipitation distribution of each model resolution.

In contrast, there was a large difference among the analyses of the horizontal winds in the planetary boundary layer (PBL), as shown in Fig. 4. The wind direction and speed (10-min mean) in the lowermost layer (from the surface to 40 m agl) at 15:00 UTC March 15, 2011 is depicted. The three scenes of Fig. 4 project the same area, including the northern part of the Abukuma Mountains, FDNPP, and Fukushima City. At the two AMeDAS points that were located in Souma City near the coastline and Fukushima City in the Naka-dori valley, we compared the wind direc-
tions and speeds with the corresponding AMeDAS observations (Table 4). The 15-km analysis (Fig. 4a) did not adequately simulate the northerly winds around Fukushima City along the Naka-dori valley because the model could not represent the Abukuma Mountains or the Naka-dori valley. As shown in Table 4, the wind direction of the 15-km grid analysis at Fukushima City was completely different from the corresponding observations that were consistent with the 3-km and 500-m grid analyses. For transport simulations, it was important that the wind direction was southerly or northerly in Fukushima City, because the Naka-dori valley is oriented in the north–south direction. Between the 3-km (Fig. 4b) and 500-m (Fig. 4c) grid analyses, the wind fields were roughly similar, although only the 500-m grid analysis depicted a fine wind structure over the mountains and valleys. When the wind blows in the east–west direction at the Naka-dori valley, the 15-km grid analysis performs reasonably in some situations. Indeed, the predominant wind direction was often westerly in the period between March 14 and 16, 2011 except the afternoon of March 15, in Fukushima City. During that period the 15-km grid analysis was sometimes consistent with the 3-km and 500-m grid analyses; however, the land contamination did not occur when the wind direction was westerly. Furthermore, while there was a large dependence of the PBL wind field on the spatial resolution, there was little difference in the free-tropospheric winds among the 15-km, 3-km, and 500-m grid analyses (not shown). These features are consistent with the previous study (Takemi 2013) that compared local-scale wind fields over Eastern Fukushima in March 2011 between 2-km and 400-m grid models. In the case of the FDNPP accident, the radionuclide release height was estimated to be low (20–150 m agl; Chino et al. 2011; Katata et al. 2012a; Terada et al. 2012); also winter is responsible for the

Fig. 4. Surface wind direction and speed (10-min mean) in the northern area of the Abukuma Mountains, Fukushima, at 15:00 UTC March 15, 2011 as simulated by the (a) 15-km grid model JMA-NHM, (b) 3-km grid model JMA-NHM, and (c) 500-m grid model JMA-NHM. The orange lines depict the contours of altitude. The cross indicates the location of FDNPP. The diamond symbol indicates the location of the AMeDAS Souma observatory, and the square symbol indicates the location of the AMeDAS Fukushima City observatory (cf. Table 4). Note that the wind vectors of the 500-m grid model are drawn for every other grid point.
relatively stable PBL. Considering these factors, the resolution dependence of the PBL wind field is likely to cause a large difference in the advection of the radioactive plumes between the 15-km simulation and the other simulations.

3.2 Surface concentration of Cs-137

According to the TEPCO monitoring post data, the northerly wind in the vicinity of FDNPP gradually shifted clockwise to a southeasterly wind between 6:00 JST (21:00 UTC the day before) and 12:00 JST (3:00 UTC) on March 15, 2011. Then, the southeasterly wind continued for more than 10 h and flowed from FDNPP on the coastline to an inland area. During that time, the radioactive plume is supposed to sweep across Fukushima and the neighboring prefectures. The simulation results of this dispersal is shown in Fig. 5, which illustrates the 24-h averaged Cs-137 concentrations in the lowermost layer (from the surface to 40 m agl) between 00:00 UTC on March 15 and 00:00 UTC on March 16.

Looking at the 3-km (Fig. 5b) and 500-m (Fig. 5c) grid Eulerian simulations, the Cs-137 distributions agreed well. The Cs-137 plume crossed over the Abukuma Mountains, and was mostly blocked by Mt. Azuma and other mountains along the Naka-dori valley. However, the 15-km grid Eulerian simulation (Fig. 5a) did not represent the blockage of the Cs-137 plume, which broadly spread out through the Naka-dori valley as far as Yamagata Prefecture. As expected by the PBL wind errors, the 15-km grid transport simulation behaved unnaturally. Similar characteristics were also observed in the Lagrangian simulation results. The 15-km grid Lagrangian simulation (Fig. 5d) behaved completely differently from the 3-km (Fig. 5e) and 500-m (Fig. 5f) grid Lagrangian simulations. Similar to the Eulerian simulations, the 3-km and 500-m grid Lagrangian simulations agreed well; the blockage of the Cs-137 plume was successfully reproduced along the Naka-dori valley. In addition, the 15-km grid Lagrangian simulation (Fig. 5d) had a very similar Cs-137 distribution to that of the Eulerian simulation with the same grid resolution (Fig. 5a); however, their concentrations were quantitatively different. This similarity was not expected because Eulerian models are generally not good at handling point-source-emissions compared with Lagrangian models.

An analogous diagnosis can be obtained by the calculation of the absolute spatial correlation coefficients among the 15-km, 3-km, and 500-m grid Cs-137 distributions (Table 5). All the correlations were calculated within the area of the 500-m grid model domain using the concentration values illustrated in Fig. 5. The values were used without logarithmic transformation. Both Eulerian and Lagrangian simulations presented high correlations between the 3-km and 500-m grid distributions (0.90–0.85). In contrast, there was a relatively low correlation between the 15-km and 500-m grid simulations (0.64–0.65), and between the 15-km and 3-km grid simulations (0.75–0.78).

3.3 Deposition of Cs-137

The Japanese government has conducted aerial surveys since the nuclear accident to measure cesium deposition amounts on the ground over the entire area of eastern Japan with JAEA (Torii et al. 2012), as shown in Fig. 6. Note that this deposition represents all of the cesium emissions from the FDNPP accident until the autumn of 2011. However, as mentioned above, most of the Cs-137 deposition over land (especially in Fukushima) occurred only on March 15, 2011. Therefore, it is possible to validate the simulation results of March 15, 2011, whether they are plausible or not, by comparing them with the aerial observations of the accumulated deposition. In fact, Fig. 6 clearly illustrates the northwestward-flowing Cs-137 pollution emitted from FDNPP and its blockage by the mountains along the Naka-dori valley. The model results of the one-day accumulated deposition of Cs-137 on March 15, 2011 UTC are shown in Fig. 7.

In both the 15-km grid Eulerian (Fig. 7a) and Lagrangian (Fig. 7d) model results, a highly polluted

<table>
<thead>
<tr>
<th>AMeDAS</th>
<th>15-km model</th>
<th>3-km model</th>
<th>500-m model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Souma</td>
<td>SW</td>
<td>ESE</td>
<td>SE</td>
</tr>
<tr>
<td></td>
<td>1.0 m s⁻¹</td>
<td>3.6 m s⁻¹</td>
<td>1.6 m s⁻¹</td>
</tr>
<tr>
<td>Fukushima City</td>
<td>NNE</td>
<td>ESE</td>
<td>NE</td>
</tr>
<tr>
<td></td>
<td>0.6 m s⁻¹</td>
<td>1.4 m s⁻¹</td>
<td>1.6 m s⁻¹</td>
</tr>
</tbody>
</table>
area broadly extended beyond Mt. Azuma and the other mountains through the Naka-dori valley as far as Yamagata and Niigata Prefectures. This distribution is similar to that of the surface concentrations shown in Figs. 5a and 5d. In addition, the most polluted area was not located near FDNPP but in the vicinity of the inland border between Fukushima and Yamagata Prefectures. This unrealistic pollution was caused by the wet deposition of the Cs-137 plume that passed over the mountains beyond the Naka-dori valley and intercepted a heavy precipitation area (cf., Fig. 3b). This pollution hotspot does not exist in the aerial observations (Fig. 6), but Arnold et al. (2015) also reported similar inland pollution with their simulation using a 0.2° (≈ 20 km) model resolution. This pollution might be a common characteristic of low-resolution models. In contrast, both the 3-km (Figs. 7b, e) and 500-m (Figs. 7c, f) grid models

![Fig. 5. Surface Cs-137 concentration averaged from 00:00 UTC March 15 to 00:00 UTC March 16, 2011 as simulated by the Eulerian model RAQM2 with the (a) 15-km grid spacing meteorological analysis, (b) 3-km grid spacing meteorological analysis, and (c) 500-m grid spacing analysis. The same as simulated by the RAQM2, but simulated by the Lagrangian model JMA-RATM with the (d) 15-km grid spacing meteorological analysis, (e) 3-km grid spacing meteorological analysis, and (f) 500-m grid spacing analysis.]

<table>
<thead>
<tr>
<th></th>
<th>15-km grid ↔ 3-km grid</th>
<th>3-km grid ↔ 500-m grid</th>
<th>500-m grid ↔ 15-km grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eulerian models</td>
<td>0.75</td>
<td>0.9</td>
<td>0.64</td>
</tr>
<tr>
<td>Lagrangian models</td>
<td>0.78</td>
<td>0.85</td>
<td>0.65</td>
</tr>
</tbody>
</table>
limited the heavily polluted area to mostly within eastern Fukushima near FDNPP and did not produce an unrealistic deposition in comparison with the aerial observations. However, there was a large discrepancy in the distribution and strength of Cs-137 deposition between the Eulerian and Lagrangian simulations. This discrepancy was caused by the difference of dynamical and physical processes in the aerosol models, such as the treatment of rainout and washout, which should be examined in a future study. The correlation coefficients among the simulated Cs-137 deposition distributions presented a good agreement between the 3-km and 500-m grid simulations, and a very poor agreement between the 15-km and 500-m grid simulations (Table 6). The correlations were calculated in the same way as in Table 5. The coefficient of the 3-km and 500-m Eulerian (Lagrangian) model simulations was 0.84 (0.63), while the coefficient was 0.42 (0.27) for the 15-km and 500-m simulations and 0.54 (0.54) for the 15-km and 3-km simulations. This result indicated that a 3-km grid model could be alternated with a 500-m grid model, but it was unacceptable to use a 15-km grid model instead of a 500-m grid model.

4. Conclusion

We investigated the horizontal resolution dependence of atmospheric radionuclide simulations of the Fukushima nuclear accident on March 15, 2011. We used Eulerian and Lagrangian transport models with low- (15-km), medium- (3-km), and high- (500-m) resolutions. Both Eulerian and Lagrangian models were driven by the same meteorological analysis that was independently prepared by an EnKF data assimilation system using the JMA operational weather forecast model. This independent preparation of each resolution analysis was definitely necessary for the resolution-dependence investigation, excluding any interpolation or averaging of meteorological fields.

Regarding the meteorological analyses, there was a large difference in the PBL wind field between the 15-km grid resolution and the other grid resolutions. The 15-km grid analysis could not reproduce Fukushima’s mountainous topography in detail. Consequently, it failed to depict a complex wind structure over mountains and valleys. This error in the wind field caused a large difference in the radionuclide transport and deposition simulations. In reality, the Cs-137 plume emitted from FDNPP was mostly blocked by Mt. Azuma and other mountains along the Naka-dori valley after crossing over the Abukuma Mountains. However, the 15-km grid simulations did not represent the blockage of the Cs-137 plume, which unnaturally spread through the Naka-dori valley. In contrast, the 3-km and 500-m grid simulations successfully replicated the Cs-137 plume blockage along the Naka-dori valley. The 3-km and 500-m grid simulations produced very similar Cs-137 surface concentrations and deposition distributions. Notably, the Eulerian and Lagrangian models qualitatively behaved in the same manner, but quantitatively yielded different results, although they were driven by the same meteorological analysis. This was most likely because these two models had completely different aerosol physics (cf. sensitivity studies conducted by Draxler et al. 2015; Morino et al. 2013; Hu et al. 2014) and vertical advection handling at the lowest model layer.

In conclusion, we suggest that it is illogical to use low-resolution (15-km or more grid) atmospheric models to assess the Fukushima nuclear accident when a regional analysis is needed due to the unrealistic performance of the 15-km grid simulations in the local Fukushima area. Meanwhile, it is reasonable to use 3-km grid models instead of 500-m grid models due to the similarities between the 3-km and 500-m grid simulations and the high computational
burden of 500-m grid simulations. In general, a 500-m grid simulation requires more than 200 times as many CPU resources as a 3-km grid simulation. Therefore, after ensuring the computational resources to perform a 3-km grid Fukushima simulation, other resources should be allotted for performing ensemble analysis or high-quality data assimilation. However, it is noted that the Fukushima nuclear accident occurred during winter, and a different resolution-dependence would have been found if the accident had occurred in another season.

Acknowledgments

We are grateful to Dr. K. Saito (MRI) and Prof. T. Iwasaki (Tohoku University) for their help and encouragement. We thank Dr. M. Chino (JAEA) for providing the emission inventory data and Dr. T. Torii (JAEA) for providing the aerial survey data.
This study was supported by JSPS KAKENHI Grant Number 24340115 and MEXT KAKENHI Grant Number 24110003.

References


Sportisse, B., 2007: A review of parameterizations for...


