Report

A review of the model comparison of transportation and deposition of radioactive materials released to the environment as a result of the Tokyo Electric Power Company's Fukushima Daiichi Nuclear Power Plant accident



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Sectional Committee on Nuclear Accident

Committee on Comprehensive Synthetic Engineering, Science Council of Japan

This report is the results of deliberations of the Sectional Committee on Nuclear Accident, Committee on Comprehensive Synthetic Engineering, Science Council of Japan, reflecting the results of deliberations of the Subcommittee to Review the Investigation on Environmental Contamination Caused by the Nuclear Accident and the results of the Working Group for Model Intercomparison in the Subcommittee.

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Preface

This report evaluates and compares the models used to analyze the transportation and deposition of radioactive materials that were released into the environment after the Tokyo Electric Power Compan's Fukushima Daiichi Nuclear Power Plant (FDNPP) accident on March 11, 2011. A Working Group for Model Intercomparison was formed in July 2012 under the Subcommittee of Investigation on the Environmental Contamination Caused by the Nuclear Accident in the Sectional Committee on Nuclear Accident, the Committee Comprehensive Synthetic Engineering, Science Council of Japan (SCJ). The purpose of this working group (SCJ WG) is to compare existing model results and to assess the uncertainties in the simulation results. The emerging knowledge will be invaluable for various applications designed to mitigate environmental contamination in wide areas. The working group solicited international colleagues and groups to provide their model simulation results for the intercomparison.

This report evaluates the simulation results of nine regional atmospheric models, six global models and eleven oceanic models for the transportation of radioactive materials; the results were provided by the contributing groups that responded to the solicitation. We greatly appreciate the national and international support and assistance in this initiative. We hope that this reports will provide assistance in societal efforts to recover from disasters by providing scientific knowledge of the modeling capability of existing models.

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1. Introduction

The Tohoku Region Pacific Coast Earthquake occurred at 14:46 JST on March 11, 2011; 13-m high tsunami waves arrived at the Tokyo Electric Power Company's Fukushima Daiichi Nuclear Power Plant (FDNPP) at 15:27, and the diesel engine of the plant stopped at 15:41 (TEPCO, 2011). A large amount of radioactive materials were released by the explosion of the 1st reactor housing at 15:36 on March 12 and of the 3rd reactor housing at 11:01 on March 14. Monitoring data suggested that there were other emission sources to the atmosphere from depressurized ventilation of the reactors and to the ocean from leakages of contaminated cooling water.

The atmospheric pressure regime in the spring of 2011 was of a prevailing winter pattern with strong northwesterly winds; therefore, a large amount of the released materials, at least more than 60% of the amount released to the atmosphere, were transported to the Pacific Ocean (Takemura et al., 2011; JAEA workshop, 2012). Field and airborne measurements showed that a complex distribution of deposited radioactive materials was formed by various migrating pressure systems and precipitation prevailing at the time. The data showed hot spots exceeding 1,000 kBq m⁻² ¹³⁷Cs occurring beyond the 30-km area around the power plant (Morino et al., 2011). The 3rd (May-July 2011) and 4th (October-November, 2011) MEXT (Ministry of Education, Culture, Sports, Science and Technology, Japan) airborne monitoring of the air dose rate indicated that the air dose rate decreased in the Abukuma Mountains and increased in the coastal region, which suggested a significant transportation of the radioactive materials via rivers. A portion of the radioactive materials were discharged directly to the ocean. Ship observation after April 2011 detected a wide areal distribution of radioactive cesium across the North Pacific Ocean. There were hot spots of a high ¹³⁷Cs concentration of 196 Bq m⁻³, which were two orders higher than what was found in the surrounding region (Aoyama et al., 2012; JAEA workshop, 2012). The total deposition of ¹³⁷Cs on the land surface of Japan is estimated as about 2.7 PBq from the airborne monitoring.

As previously stated, a wide area was contaminated by the radioactive materials emitted from the power plant accident, and the characteristic distributions of the radioactive materials were simulated by various models, including the SPEEDI (System for Predictions of Environmental Emergency Dose Information) operational model. The amount of radioactive ¹³⁷Cs released to the atmosphere was estimated to be in a range from 9 to 37 PBq (Aoyama et al., 2012; Stohl et al., 2012; Terada et al., 2012; Kobayashi et al., 2013; Winiarek et al., 2014). The amount of direct discharge to the ocean was estimated to be in a range from 2.3 to 26.9 PBq (Kawamura et al., 2011; Tsumune et al., 2012; Estournel et al., 2012; Miyazawa et al., 2012; Bailly du Bois et al., 2012; JAEA workshop,2012). Large uncertainties were caused by insufficient monitoring data and meteorological data that resulted from a loss of monitoring posts after the tsunami, electricity outages, and errors in the model and inversion scheme. The distribution of radioactive xenon gas and iodine, which have short decay times, are important for estimating the early phase exposure; however, these distributions are difficult to retrieve other than by model simulation.

Based on this situation, a thorough review of the existing modeling capability in the simulation of radioactive materials dispersal is important for improving models and observation systems, which are required to evaluate the contamination effects and mitigation actions to reduce the amount of radioactive material in the environment.

In this report we compared the simulation results from nine regional atmospheric models, six global atmospheric models and eleven oceanic models that were provided by global groups and based on the events of the Fukushima Daiichi Nuclear Power Plant accident.

2. Notes for comparison

The contributing groups were asked to provide their best simulation results for the 2013 spring accident at the FDNPP. Unified conditions were not imposed for the comparison; therefore, there were large differences in the model setup (grid resolution, integration time interval, etc.) and data (meteorological data, emission scenario, etc.) used to constrain the simulation, which simplified the evaluation of the accuracy of the compared models. However, it was difficult to investigate the causes of differences in the simulation results, so we produced sensitivity tests using several models to study how the model parameters controlled the key processes in the models.

The following three chapters present the intercomparison results from the regional atmospheric models, global atmospheric models, and oceanic models. Each chapter begins with a description of the model specifications and setup procedure for the simulation, which is followed by the results of the model comparisons. Chapter 6 illustrates an emission source estimation using the JMA inverse model to discuss the emission scenario uncertainties.

3. Regional atmospheric model intercomparison

3.1. Introduction

Several researchers have reported that the transport and deposition of radionuclides released from the accident at the FDNPP were strongly affected by the regional-scale meteorological field and geography (e.g., Chino et al., 2011; Morino et al., 2011). The SCJ WG for radionuclide dispersion modeling, therefore, organized a subgroup to assess the regional-scale dispersion and deposition of radionuclides caused by the accident. The 9 members of the SCJ WG for regional models have provided a total of 9 simulations. Table 3.1 summarizes the resolution, target area, and treatment of radionuclides in each model. Certain members have conducted additional simulations with different release rates or different wet deposition schemes to evaluate such impacts on the dispersion and deposition of radionuclides.

3.2. Regional models participating in the SCJ WG

Table 3.1 summarizes the horizontal resolution, horizontal gird sizes, and vertical layers of the attending models. Almost all of the models cover the east side of Japan, including the Fukushima and Kanto area, with cloud-resolving (3-5 km) grids. The objective of most of the model simulations is to understand the processes of local transport and deposition that occurred in March and April 2011. Figure 3.1 shows the computation domain for each model. In contrast, the model domain from the Seoul National University (SNU) model covers East Asia, and the objective of the SNU model simulation is to assess the continental transport of radionuclides in Asia. The horizontal resolution of the SNU model is relatively larger than the resolution of the other models that target the local transport over east Japan; however, it is still higher than most of the global models, and the result of the SNU model simulation is included in the intercomparison of regional models. The details for each model are found in Appendix A.

For an intercomparison of the total amount of deposited radionuclides over the land and sea, an overlapped domain between 138.0E and 142.5E longitude and 34.5N and 40.5N latitude was selected. The outputs from all of the participating models were interpolated into 0.1 degree \times 0.1 degree grids within the domain. The calculation period was also different in each model, and we selected the common calculation period from 00Z March 12, 2011 to 00Z April 1, 2011. The total amount of deposited radionuclides over the land and sea was

estimated using these grid cells, and the accumulated deposition was calculated during this period. The Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT) conducted observations from aircraft after the accident (cf. http://radb.jaea.go.jp/mapdb/download.html), and the observational data were also interpolated into the common domain for the intercomparison. The observational flights in the spring of 2012 were used for the intercomparison, but the observed values might be affected by deposition after April 2011, resuspension from the land surface, and transition into the deep soil or river water.

3.3. Meteorological overview

A summary of the meteorological conditions during the critical phases of the atmospheric emissions was included in the first report of the WMO (WMO, 2011) and in reports by several other researchers (Morino et al., 2011; Kinoshita et al., 2011; Korsakissok et al., 2011; Stohl et al., 2012; Sugiyama et al., 2012).

The key results are summarized as follows:

March 9 – 11: A weak low pressure trough over eastern Japan from March 9 to 11 caused light rain from the 9th until the morning of the 12th.

March 12 - 13: A high pressure system moved eastward along the south coast of the main island of Japan from the 12th through the 13th. The wind direction was from the south below 1 km and from the west above 1 km on the afternoon of March 12, the time of the hydrogen explosion at reactor number one.

March 14 – 17: Another weak low pressure trough moved eastward off of the southern coast of the main island from the 14th until the 15th and then moved towards the northeast and developed rapidly after the 15th. Light rain was observed from the 15th until the morning of the 17th because of a weak low pressure system, which moved northeastward off of the east coast of Japan. In particular, rain was observed in the Fukushima Prefecture from 1700 JST March 15 until 0400 JST March 16 (Kinoshita et al., 2011), which corresponded with significant emissions. The low-level winds were from the southwest during the morning of the 14th, which corresponded with the hydrogen explosion at reactor number three. The 950 hPa winds were from the west until the morning of the 15th; however, they changed to a north-northeast direction during the day of the 15th, which corresponded with the container burst of reactor number two. Chino et al. (2011) estimated that the maximum 131 I emissions occurred between 0900 and 1500 JST (0000-0600 UTC). After 1500 JST, the winds turned to a direction from the east-southeast and then changed to north after 0000 JST on the 16th

(1500 UTC 15th).

March 18 - 19: High pressure dominated during this period, and the winds were generally from the west.

March 20 – 22: A low pressure system passed over the main island from March 20 to 22 and caused moderate rain in the Kanto area (Ibaraki, Chiba, Tochigi, Saitama Prefectures and Tokyo) from the 20th until the 23rd.

3.4. Accumulated deposition of ¹³⁷Cs

Figure 3.2 shows the horizontal distributions of the accumulated deposition of 137 Cs until 00Z 1 April 2011. A high-deposit area from the FDNPP is clearly observed to the north up to Fukushima city, and the maximum value exceeds 8×10^5 Bq m⁻² in this area. Several related papers mentioned that this high-deposit area was related to the passage of low pressure from March 14 to 15 (cf. Chino et al., 2011; Katata et al., 2012; Morino et al., 2011; Takemura et al., 2011). Therefore, this structure can be reproduced by most of the models except SNU, which applied a lower horizontal resolution (27 km) than the others (3-5 km).

There is also a high-deposit area in the central area of the Fukushima Prefecture (Naka-dori region) and Tochigi Prefecture. It is estimated the deposition in this area corresponded to the weak precipitation occurring in these areas on the afternoon of March 15. Some models (e.g., MRI, NIES, and JMA) succeeded in reproducing the accumulated deposition over this area. The JAMSTEC model showed a weak deposition despite being driven by the same meteorological data (JMA MSM) as used by the NIES and JMA groups. However, the meteorological field was recalculated by the meteorological models (MM5, WRF, etc.) to drive the chemical transport model; so although they are based on the same meteorological data (JMA-MSM), there might be a small difference in the meteorological fields in the models caused by differences of the meteorological models, model domains, and model configurations.

There are additional high-deposit areas to the south of the FDNPP in Ibaraki Prefecture and north in Iwate Prefecture. The transport to southward areas might have occurred on the 14, 16, 20, and 21 of March. Certain models (e.g., CRIEPI, CEREA, IRSN, and JAEA) show a high deposition over the southern areas. Deposits over the northern Tohoku areas, such as the Iwate Prefecture, are clearly observed in some models (e.g., JAEA and JAMSTEC). In contrast, the CRIEPI, CEREA, and SNU models do not show a large amount of accumulated deposits over the northern Tohoku area.

Figure 3.3 illustrates the scatter plot of the accumulated deposits of 137 Cs until 00Z 1

April 2011. Each dot shows the model and observed values in the same cells over the interpolated domain, which is mentioned in section 1.1. Most of the models were able to estimate the accumulated deposition of ¹³⁷Cs in March 2011 in the range of a factor of 10 and 0.1. The ensemble mean of the models (black squares) reproduced the observed values, although certain models (IRSN and MRI) tended to overestimate the observed values, whereas other models (JAMSTEC, etc.) tended to underestimate the observed values.

The total amount of the accumulated deposits of ¹³⁷Cs over the land and sea in the models and from the MEXT aircraft observations are shown in Table 3.2. The simulated and observed values were interpolated into the same domain and grid cells, which was mentioned in section 1.1 and shown in Fig. 3.3. The difference in the estimated values was caused by the difference of meteorological fields, source terms, and deposition processes. In the observation, there were no data over the ocean, and the estimated amount was 2.65 PBq. Most of the models showed 1.3-3.8 PBq over the land, and these values were close enough to the observed values. However, the contributions of the wet and dry deposits are dissimilar. The MRI and NIES models estimated that the wet deposition process caused most of the deposits, and the IRSN and SNU models estimated that dry deposition played an important role. An estimated deposit of approximately 0.9-5.5 PBq of ¹³⁷Cs occurred in March 2011 over the coastal ocean; this estimate is common to all of the model domains.

3.5. Ratio of accumulated deposition of radionuclides (137Cs to 131I)

Figure 3.4 shows the horizontal distributions of the ratio of accumulated deposition of ¹³⁷Cs to that of ¹³¹I until 00Z 1 April 2011. The difference in the area ratio is caused by the different levels of emissions at the FDNPP and different removal processes among the radionuclides. The models in Fig. 3.4 commonly used the source term estimated by the JAEA and driven by the output of the JMA MSM meteorological model; therefore, the main cause of the difference of ratios among the models might have been differences in the removal process from the atmosphere and differences in the interpolated or re-calculated meteorological fields for each time step of the chemical transport models. Some models (CRIEPI, JAEA, JAMSTEC, and JMA) show values between 0.05 and 0.5 over land. The JAEA, JAMSTEC, and JMA) show values between 0.05 and 0.5 over land. The sale of the MRI model shows a relatively large value, indicating that ¹³¹I is relatively smaller relative to the other models, especially over land. In contrast, the NIES model shows a relatively smaller value (0.01 to 0.1). All of the models show relatively smaller values over the Sea of Japan, with the two Lagrangian models (JAEA and JMA) showing clear land-sea

contrasts around the Sea of Japan.

3.6. The impact of different release rates on the concentration and deposition of radionuclides

A modeling group from the NIES conducted simulations with three sets of emission data, which were from JAEA (Terada et al., 2012), the Norwegian Institute for Air Research (NILU) (Stohl et al., 2012), and Tokyo Electric Power Company (TEPCO) (TEPCO, 2012). All three emission estimates are based on inversion methods using simulation models and observational data. The JAEA analysis combined local- and regional-scale models, the NILU used a global-scale model, and TEPCO used a local-scale model. The model from the JAEA uses a grid size of 1 km for the regional scale and 3 km for the eastern area of Japan, and the model from TEPCO uses a grid size of 1 km.

The model performance is evaluated by a comparison between the CTM results and the airborne monitoring data. The simulation results with the JAEA emissions (standard simulation) are the most consistent with observations. In high-deposition areas (≥ 10 kBq m⁻²), the standard simulation reproduces the observations within one order of magnitude in most cases (96%), the simulation with the NILU emissions overestimates the observations by more than one order of magnitude for 12% of the observational area, and the simulation with the TEPCO emissions underestimates the observations by more than one order of magnitude for 11% of the observational area (Figure 2 and Table 2 of Morino et al., 2013). Overall, the simulations using the JAEA emission estimates best reproduce the observed deposition patterns over eastern Japan. This result suggests that to simulate the deposition patterns of fine particles on a regional scale, emission estimates should also be conducted with a regional-scale model rather than a local- or global-scale model.

3.7. Sensitivity tests of parameters on the deposition

A modeling group from the NIES compared three wet deposition settings. In the CMAQ model, wet deposition rates of accumulation-mode aerosols are calculated by considering the washout time, which is calculated from the ratio of the water content of precipitation to that of clouds (Byun and Schere, 2006). The wet deposition module is process based, and the wet deposition amounts of aerosols calculated with the CMAQ have been validated in several previous studies (Appel et al., 2011). The NIES group also conducted a simulation with the wet deposition module of the JAEA model (WD2 case) (Terada et al., 2012). In the model,

the wet deposition rates are calculated using a scavenging coefficient (Λ), which is a function of the precipitation rate (cf. Appendix A4). This wet deposition module is an empirical module with fitting parameters included.

In the WD2 simulation, the high-deposition areas extended farther from the FDNPP compared to the observations and the standard simulation. Simply multiplying the scavenging coefficient of the JAEA model by a factor of 10 improved the model's reproduction of the observed deposition pattern. The wet deposition modules of Terada et al. (2012) appear to underestimate Λ , and a simulation with Λ multiplied by a factor of 10 produced more accurate observations. As Λ varies greatly among studies (Morino et al., 2013), the choice of Λ is a source of much uncertainty. In an atmospheric simulation of radionuclides after the Chernobyl accident, a wet deposition scheme based on relative humidity was able to more accurately reproduce the observed radiocesium deposition than a parameterization based on the precipitation rates (Brandt et al., 2002). These results indicate that wet deposition modules based only on precipitation rates include large uncertainties; therefore, the process-based wet deposition module is recommended.

3.8. Statistical analysis on accumulated deposition of ¹³⁷Cs

A series of statistical analyses were conducted until 0Z 1 April 2011 for the modeled and observed accumulated deposition of ¹³⁷Cs. As in section 1.4, the modeled and observed values were interpolated into the same domain and grid cells. Observational data over the ocean was not available from the MEXT aircraft observation; therefore, the comparison between modeled and observed values was only conducted for cells with observed values that exceeded 10,000 Bq m⁻². The statistical results of the attended models are summarized in Table 3.3. Each column denotes a correlation (r), fractional bias (FB), figure of merit in space (FMS), factor of exceedance (FOEX), percentage of cells within a factor of 2 (%FA2), Kolmogorov-Smirnov parameter (KSP), which was defined as the maximum absolute difference among the cumulative distributions of observed and calculated deposition, and overall metrics, which were defined as the function of the particular metrics, respectively. A detailed explanation of the overall metrics can be found in Appendix A of the WMO report (WMO, 2013). Most of the models showed good correlations with the observed distribution, and the IRSN showed a relatively lower (r < 0.5) correlation because of the overestimation of deposition in Niigata Prefecture. FB is a metric for overestimation or underestimation; the CEREA, IRSN, JAEA, and JMA estimates had an FB>20%, and the CRIEPI, JAMSTEC, and SNU estimates had an FB<20%. The FMS is a metric for the similarity of the distributed pattern, and the CEREA, IRSN, CRIEPI, JAEA, and NIES estimates had an FMS>60. The JAMSTEC estimate did not show a deposition in Naka-dori of Fukushima Prefecture and Kanto area, and it had an FMS that was relatively lower than other models. The FOEX and %FA2 are metrics for the area fraction of reproducibility in each cell, and the JAEA and CEREA estimates showed a good performance. The %FA2 of the NIES estimate was 57%, which indicated that the NIES model can estimate the observed values within a factor of 2 for 57% of the cells. For more complex evaluations, metrics 1 to 4 were calculated using four different functions using other metrics (r, FB, FMS, FOEX, %FA2, and KSP). The CEREA, CRIEPI, JAEA, MRI, and NIES estimates showed good performances with these metrics.

These statistical analyses were applied to the ensemble mean of all of the attended models. The ensemble mean showed a better performance than did the best single model, such as the NIES, in some metrics.

3.9. Summary

This review summarized the current activity of the regional atmospheric model groups. The 9 members of the SCJ WG for regional models provided 9 simulations. The model domain, horizontal and vertical resolution, meteorological fields, and source terms were different in each model, and a portion of the differences in the models might have been caused by differences in the model configurations. For more detailed analyses, a series of sensitivity tests with the same configuration (source term, meteorological fields, etc.) should be performed.

The results are summarized as follows:

1) meteorological fields play an important role in radionuclide deposition, and the differences in the model treatments of deposition and in the configuration of meteorological models, such as in their microphysics and convection parameters, might cause a large difference in the horizontal distribution of accumulated deposition;

2) the wet deposition process has a strong impact on the reproducibility of deposition, especially on March 15;

3) ensemble means might be useful for the estimation of accumulated deposition.

| Organizations | Model | Horizontal Resolution | Number of grids | Layers | Tracer models |
|---------------|----------------|--------------------------|--------------------|--------|------------------|
| CEREA | Polyphemus | Approximately 4 km | 270×260 | 15 | Eulerian |
| CRIEPI | CAMx | 5 km | 190×180 | 30 | Eulerian |
| IRSN | ldX | Approximately 10 km | 301×201 | 11 | Eulerian |
| JAEA | GEARN | 3 km | 227×317 | 28 | Lagrangian |
| JAMSTEC | WRF-Chem | 3 km | 249×249 | 34 | Eulerian |
| JMA-MRI | NHM-LETKF-Chem | 3 km | 213×257 | 19 | Eulerian |
| JMA | JMA-RATM | 5 km | 601×401 | 50 | Lagrangian |
| NIES | CMAQ | 3 km | 237×237 | 34 | Eulerian |
| SNU | ETM | 27 km | 164×119 | 25 | Eulerian |

Table 3.1. List of attending models.

Table 3.2. Total amount of accumulated deposition of ¹³⁷Cs over the land and sea until 0Z 1 April, 2011. Units are PBq. The MEXT aircraft observation was based on the value on 31 May, 2012. Percentages of each removal process to the total emissions are also shown for the model calculations.

| | over the land | | over t | he sea | Total depo. | Total | |
|--------------------|---------------|---------------------------|------------|------------------------|------------------|----------|--|
| | total dep. | percentage of wet dep. | total dep. | percentage of wet dep. | target region | emission | |
| MEXT aircraft | 2. | 2.65 | | - | - | - | |
| CEREA | 3.35(17%) | 68% | 2.62(14%) | 85% | 5.97 (31%) | 19.3 | |
| CRIEPI | 2.37 (27%) | 79% | 0.90 (10%) | 54% | 3.27 (37%) | 8.8 | |
| IRSN | 3.14 (15%) | 46% | 5.52 (27%) | 71% | 8.66 (42%) | 20.6 | |
| JAEA | 3.79 (43%) | 67% | 1.22(14%) | 65% | 5.01 (57%) | 8.8 | |
| JAMSTEC | 1.95 (22%) | 67% | 1.45 (16%) | 67% | 3.40 (39%) | 8.8 | |
| JMA | 2.65(30%) | 50% | 1.18 (13%) | 36% | 3.83(44%) | 8.8 | |
| MRI | 3.31 (38%) | 92% | 1.72 (20%) | 97% | 5.03 (57%) | 8.8 | |
| NIES | 2.90(33%) | 98% | 1.06(12%) | 96% | 3.96 (45%) | 8.8 | |
| SNU | 1.29 (15%) | 32% | 1.76 (20%) | 36% | 3.05(35%) | 8.8 | |
| ensemble mean | 2.75(27%) | 67% | 1.94(16%) | 67% | 4.69(43%) | 11.3 | |
| standard deviation | 0.73(10%) | 20% | 1.36(5%) | 22% | 1.68(9%) | 4.6 | |

Table 3.3. Statistical analysis of the accumulated deposition of ¹³⁷Cs. *r*, FB, FMS, FOEX, %FA2, and KSP denote the correlation, fractional bias, figure of merit in space, factor of exceedance, percentage of a factor of two, and Kolmogorov-Smirnov parameter, respectively. Metrics 1-4 are functions of these statistical values for the evaluation of forecast precision, with higher values showing a better performance.

| | r | FB | FMS | FOEX | %FA2 | KSP | Metric1 | Metric2 | Metric3 | Metric4 |
|-------------|------|-------|-------|--------|-------|-------|---------|---------|---------|---------|
| CEREA | 0.79 | 0.09 | 74.32 | -8.74 | 49.45 | 12.84 | 3.28 | 3.03 | 4.10 | 4.60 |
| CRIEPI | 0.60 | -0.25 | 63.39 | -19.95 | 40.44 | 22.40 | 2.85 | 2.62 | 3.45 | 3.85 |
| IRSN | 0.39 | 0.30 | 63.39 | -17.49 | 38.52 | 28.69 | 2.28 | 2.05 | 2.99 | 3.32 |
| JAEA | 0.76 | 0.22 | 68.85 | -8.74 | 40.16 | 22.68 | 3.10 | 2.81 | 3.92 | 4.33 |
| JAMSTE C | 0.62 | -0.38 | 26.50 | -37.43 | 13.93 | 54.37 | 2.44 | 2.32 | 2.70 | 2.84 |
| MRI | 0.49 | 0.17 | 45.90 | -18.58 | 18.03 | 36.34 | 2.53 | 2.25 | 3.16 | 3.34 |
| JMA | 0.68 | 0.44 | 49.45 | -17.76 | 27.87 | 35.79 | 2.64 | 2.43 | 3.29 | 3.57 |
| NIES | 0.85 | 0.03 | 68.31 | -18.58 | 57.10 | 19.13 | 3.37 | 3.25 | 3.99 | 4.57 |
| SNU | 0.27 | -0.81 | 42.08 | -26.50 | 19.40 | 39.34 | 2.05 | 1.83 | 2.52 | 2.72 |
| ensemble | 0.77 | 0.04 | 70.41 | -13.56 | 49.86 | 22.19 | 3.22 | 3.04 | 3.98 | 4.49 |



Figure 3.1. Model domains of the regional models evaluated by the SCJ WG. The domain for SNU is excluded because it covers the East Asia region.



Figure 3.2. Latitude-longitude distributions of the accumulated deposition of ¹³⁷Cs until 00Z 1 April 2011. Units are Bq m⁻². The shaded region denotes the fraction of ocean in the WRF model that exceeds 50% of each of the grids.



Figure 3.3. Scatter plot of the accumulated deposition of ¹³⁷Cs over the land within the common domains of the evaluated models. The X-axis shows the MEXT aircraft observations, and the Y-axis shows the regional models in the same cell. Black circles denote the ensemble of all of the attended models, and red lines denote factors of 10, 1, and 0.1.



Figure 3.4. Latitude-longitude distributions of the ratio of the accumulated deposition of ¹³⁷Cs to the accumulated deposition of ¹³¹I until 00Z 1 April 2011. Only models that evaluate ¹³¹I and ¹³⁷Cs are shown. The color scale is same as in Fig. 4 of Torii et al. (2013).

4. Global atmospheric model intercomparison

4.1. Models

The intercomparison of long-range transport models used to estimate the radionuclides released from the FDNPP included five global transport models, one regional transport model, and 12 simulated results. Four of the five global models, SPRINTARS, EMAC, MASINGAR-1, and MASINGAR mk-2, are global aerosol models that are on-line coupled with general circulation models. The remaining models include the global transport model TM5 and the regional transport model MRI-PM/r, which are off-line models that use the assimilated meteorological fields or previously calculated meteorological fields by another model. The details of the participating models are described in Appendix A, and the specifications of the models are listed in Table 4.1.

In this intercomparison experiment, all of the participating models are grid point Eulerian or semi-Lagrangian advection models; no Lagrangian particle dispersion models are included. However, the global transport studies with numerical simulations include Lagrangian atmospheric dispersion models, such as those be Stohl et al. (2012).

4.2. Estimated time series of the radionuclides emission

In this intercomparison experiment, the source terms of the radionuclides are not specified; therefore, the participating research organizations selected or assumed the source terms. The simulations include source terms that were determined from inversion analyses by the Japan Atomic Energy Agency (JAEA) (Chino et al., 2011; Terada et al., 2012) and Stohl et al. (2012) (Fig. 4.1).

The JAEA estimated the time series of the radionuclides (131 I and 137 Cs) released from the FDNPP accident by inverse analysis. The total release of 137 Cs until the end of April 2011 was 12.6 PBq, which was estimated by Chino et al. (2011) and updated to 8.8 PBq by Terada et al. (2012). In the inverse analysis from the JAEA, only the observations within Japan were used. Stohl et al. (2012) estimated the time series of the releases of 133 Xe and 137 Cs using an inversion analysis method and included global observations using the atmospheric dispersion model FLEXPART. The estimated total release of 137 Cs until 20 April was 36.6 PBq (range of uncertainty of 20.1 – 53.1 PBq), which was approximately 4-fold greater than the estimate

by the JAEA. Stohl et al. (2012) estimated the total release of 133 Xe as 15.3 EBq (range of uncertainty of 12.2 - 18.3 EBq).

4.3. Global mass budget

Table 4.2 shows the simulated global total, dry and wet depositions of ¹³⁷Cs on March 31, 2011. In all of the simulations, most of the released ¹³⁷Cs was removed by the wet deposition processes of precipitation. The ratio of dry deposition varied by models, and the percentage of the dry deposition to total deposition ranged from 0 to 12%. The range of the variation of dry/wet deposition ratio was small compared with the intercomparison of the regional model simulations.

4.4 Temporal variation of the total atmospheric loading of ¹³⁷Cs

Figure 4.2 shows the temporal variation of the daily averaged global total atmospheric loading of 137 Cs. The simulations using the JAEA release rate show complex temporal variations. All of the simulated total atmospheric loadings show a maxima from March 15 to 20 and reach 0.7 – 2.7 PBq. The maximum atmospheric loadings of 137 Cs differ by a factor of 3 – 4. The plausible cause of the difference can be attributed to the differences in the deposition processes among the models. The simulations with the JAEA release rate show a maxima of atmospheric loading at the end of March, and the loading reaches 1 – 3 PBq.

However, simulations using the Stohl et al. (2012) release rate show a much larger atmospheric loading than the simulations using the JAEA emissions, which was expected. The maximum total loadings appear on March 15, 2011, and the total atmospheric loading reaches 10 - 16 PBq. Five days after the peak, the atmospheric loadings of ¹³⁷Cs increase again and reach 6 - 10 PBq from March 19 to 20. After the second peak, the total atmospheric loading of ¹³⁷Cs at the end of March shows a distinct difference between the JAEA and Stohl et al. (2012) release rate of ¹³⁷Cs.

4.5 Temporal variation of daily deposition of ¹³⁷Cs

The time series of the global total daily deposition of ¹³⁷Cs are depicted in Fig. 4.3a and Fig. 4.3b. Most of the simulations with the release rate by JAEA show a maxima of the daily global total deposition of ¹³⁷Cs on March 15, 20 and 30, 2011 (Fig. 4.3a). However, some

differences exist in the temporal variation of the daily total deposition, and there are simulations that show a maxima of daily total deposition on March 25 and April 2. Most of the simulations show the maximum total deposition of approximately 1 - 3 PBq day⁻¹ on March 15.

The simulations with the estimated release rate by Stohl et al. (2012) show a maximum total deposition on March 15, 2011, and the daily total deposition reaches 8 - 11 PBq day⁻¹ (Fig. 4.3b). A second maximum of the daily deposition appears from March 20 - 21.

4.6. Horizontal distribution of the total ¹³⁷Cs deposition

Figure 4.4 illustrates the horizontal distribution of the total deposition of ¹³⁷Cs at the end of March 2011. All of the simulated results show that the ¹³⁷Cs deposited in a wide area of the Northern Hemisphere, concentrated in the Pacific Northwest region. Common characteristics of the deposition are found from the FDNPP to the Aleutian Islands and the eastern region of the Kamchatka Peninsula, which stretches to the northwestern region of North America. However, differences in the simulations are found among the models and the employed source term of ¹³⁷Cs. The simulated ¹³⁷Cs distributions indicate greater differences with longer distances toward the eastern side of the FDNPP, namely in Europe and Russia, which suggests that the differences are caused by the different lifetimes of ¹³⁷Cs in the atmosphere caused by the wet deposition process.

The simulated distributions suggest that a portion of the ¹³⁷Cs that leaked into the North Pacific Ocean reached the Pacific Southwest region by a northeasterly wind from the Asian winter monsoon. The observatories in Taiwan (Huh et al., 2011) and Vietnam (Long et al., 2012) and the CTBTO observatory in the Philippines detected radionuclides that were possibly from the FDNPP. However, the magnitude of the deposition of simulated ¹³⁷Cs over Southeast Asia showed large differences between the models.

4.7. Comparison with observed atmospheric concentrations

The simulated results were compared with the atmospheric concentrations measured by the observatories of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) and by the European network of radionuclide measurements (Masson et al., 2011). Appendix B includes a brief description of the observed data. Figure 4.5 shows the scatterplots of the observed and simulated daily average atmospheric concentrations of ¹³⁷Cs. In the range of relatively high ¹³⁷Cs concentrations (> 0.01 μ Bq m⁻³), the simulated concentrations are

broadly within the range of a factor of 10 from the observed concentration. However, some of the simulated results, especially those using the JAEA source terms, show underestimations in the low concentration range (< ~0.01 μ Bq m⁻³), which is likely resulted from the JAEA source term being derived from an inversion analysis that only includes observations from within Japan and tends to underestimate the release rate of ¹³⁷Cs that flows to the Pacific side. From the comparison of scatterplots, the models with higher horizontal resolution do not necessarily produce better results.

The models that use both the JAEA and Stohl et al. (2012) source terms, the MASINGAR 1/mk-2 and EMAC T106/T255 show different tendencies. The MASINGAR 1 and mk-2 tend to overestimate the ¹³⁷Cs with the Stohl et al. (2012) source term, whereas it tends to underestimate the ¹³⁷Cs concentration with the JAEA source term. However, the EMAC T106 and T255 are reasonably consistent with the Stohl et al. (2012) source term and tend to underestimate the ¹³⁷Cs concentration with the JAEA source term. From these results, we cannot conclude which of these source terms more realistically represents the release rate of ¹³⁷Cs.

4.8. Ensemble average

To derive the statistical average and magnitude of variance of the global simulations evaluated in the intercomparison, an ensemble analysis was performed. Because the horizontal resolutions of the simulated results were different between the models, the data were resampled into a $1^{\circ} \times 1^{\circ}$ grid. The simulated results that did not use the JAEA source terms from Terada et al. (2012) were scaled to the magnitude of Terada et al. (2012) so that the relative importance of the spatial variations were equally evaluated among the simulations. Figure 4.6 shows the ensemble average and the coefficient of variation (the ratio of the standard deviation to the average) of the total ¹³⁷Cs deposition until the end of March 2011. Relatively small coefficients of variation can be found in the highly contaminated area of the Pacific Northwest region, which indicates that the uncertainties of the ¹³⁷Cs deposition amount were relatively small. Areas that were further apart from the FDNPP showed larger coefficients of variation, which means that considerable variation existed among the simulations and that the simulated results were highly uncertain.

4.9. Summary

For the intercomparison of the global transport of radionuclides from the FDNPP

accident, five global transport models and one regional transport model contributed to the long-range transport comparison, and 12 simulated results were submitted. The simulated results included source terms that were inversely analyzed by the Japan Atomic Energy Agency (Chino et al., 2011; Terada et al., 2012) or Stohl et al. (2012). The simulated results were compared with each other and with available observations. Most of the models removed ¹³⁷Cs from the atmosphere mainly by wet deposition, which accounted for 88 to 100% of the total deposition. The results showed a large dependence on the differences in the treatment and magnitude of wet depositions and, therefore, the lifetime of the ¹³⁷Cs.

Generally, the contributed results were relatively consistent in the pattern of ¹³⁷Cs deposition over the Northwestern Pacific, which stretched to the Aleutian Islands and reached the western side of North America. Differences were found in the long-range transportation to areas of Europe and Russia. The models also exhibited differences in the transport to Southeast Asia by the Asian winter monsoon.

The comparison of the simulated results with the observed data of the atmospheric concentration of ¹³⁷Cs were relatively consistent, although the simulated results tended to underestimate the low concentration range (< ~0.01 μ Bq m⁻³). From the intercomparison, we cannot conclude which of these source terms of ¹³⁷Cs (JAEA or Stohl et al. (2012)) was more realistically representative of the release rate of ¹³⁷Cs.

| Model name | SPRINTARS | MASINGAR mk-2 | MASINGA R-1 | MPIC/ EMAC v1.92 | TM5 | MRI-PM/r |
|----------------------------------|---|--|---|---|---------------------------------|--|
| Institute | Kyushu University | MRI, JMA | MRI, JMA | Cyprus Institute | KNMI | MRI, JMA |
| Region | Global | Global | Global | Global | Global | Regional |
| Source term | JAEA (Terada et al. 2012) | JAEA (Terada et al. 2012), Stohl et al.(2012) | JAEA (Terada et al. 2012), Stohl et al.(2012) | JAEA (Chino et al. 2011), Stohl et al.(2012) | JAEA (Terada et al. 2012) | JAEA (Terada et al. 2012) |
| Resolutio n (grids) | T213 (640×320) | TL319 (640×320) | T106 (320×160) | T106 (320×160), T255 (768×384) | 3° × 2° (120×90) | 60 km (234×120) |
| Layers | 20 (~8 hPa) | 40 (~0.4 hPa) | 30 (~0.4 hPa) | 31 (~10 hPa) | 60 | 20 (~10 km) |
| Eulerian or Lagrangia n | Euler | Euler | Euler | Euler | Euler | Euler |
| Dynamics | Online (MIROC) | Online (MRI-AGCM 3) | Online (MRI/JMA 98) | Online (ECHAM5) | Offline (ECMWF) | Offline (WRFv3) |
| Meteorolo gical Analysis | NCEP reanalysis, nudging technique | JCDAS (extended, near real time JRA-25), Newtonian nudging technique | JCDAS (extended, near real time JRA-25), Newtonian nudging technique | ECMWF ERA-Interi m (for nudging dynamics only, precipitatio n is model generated) | ECMWF Operation al Data | NCEP FNL analysis, grid nudging technique |

Table 4.1. Specifications of the participating numerical models.

| | Total Deposition [PBq] | Total wet Deposition [PBq] | Total dry Deposition [PBq] | Wet/Total ratio[%] |
|--------------------------|------------------------------|----------------------------------|----------------------------------|-----------------------|
| SPRINTARS | 8.33 | 7.30 | 1.03 | 87.6 |
| SPRINTARS1 | 8.42 | 7.43 | 0.99 | 88.2 [†] |
| MASINGAR mk-2 (JAEA) | 7.05 | 6.93 | 0.13 | 98.2 |
| MASINGAR mk-2 (Stohl) | 34.61 | 34.08 | 0.53 | 98.5 [†] |
| MASINGAR-1 (JAEA) | 6.63 | 6.45 | 0.18 | 97.3 |
| MASINGAR-1 (Stohl) | 32.86 | 31.97 | 0.9 | 97.3 [†] |
| EMAC T255 (JAEA) | 5.46 | 5.10 | 0.36 | 93.4 |
| EMAC T255 (Stohl) | 34.59 | 33.13 | 1.45 | 95.8 [†] |
| EMAC T106 (JAEA) | 5.50 | 5.24 | 0.25 | 95.4 |
| EMAC T106 (Stohl) | 34.27 | 32.74 | 1.53 | 95.5 [†] |
| KNMI TM5 (JAEA) | 8.28 | 8.28 | 0.0 | 100.0 [†] |
| MRI-PM/r | 4.45 | 3.85 | 0.6 | 86.5 |
| ensemble mean | 15.87 | 15.21 | 0.72 | 93.4 |
| standard deviation | 13.51 | 13.19 | 0.49 | 4.6 |

Table 4.2. Simulated total, wet and dry deposition of ¹³⁷Cs until March 31, 2011.

 \dagger : excluded from the ensemble calculation



Figure 4.1. Comparison of the time series of the estimated source terms of ¹³⁷Cs used in the intercomparison of the global transport simulations.



Figure 4.2a. Comparison of the time series of the simulated global total atmospheric loading of ¹³⁷Cs.



Figure 4.2b. Same as Fig. 4.2a but with a different ordinate scale.



Figure 4.3a. Comparison of the time series of the simulated global total daily deposition of ¹³⁷Cs with estimated source terms by the JAEA (Chino et al., 2011; Terada et al., 2012).



Figure 4.3b. Same as Fig. 4.3a but with estimated source terms by Stohl et al. (2012).



Figure 4.4. Horizontal distributions of the accumulated ¹³⁷Cs deposition from March 11 to 31, 2011. Units are Bq m⁻³.



Figure 4.5. Scatter plots of the observed and simulated atmospheric ¹³⁷Cs concentrations. The thick solid line in the middle is the one-to-one line, and the upper and lower dashed lines are overestimates and underestimates by a factor of 10.



(a) Ensemble averaged ¹³⁷Cs total deposition (11 Mar. - 31 Mar.)

Figure 4.6. (a) Ensemble average and (b) coefficient of variation of the accumulated deposition of ¹³⁷Cs until March 31, 2011 with the evaluated simulations.

180

1.2

150E

1

0.8

120E

0.6

150W

1.6

1.4

120W

1.8

90W

2

60W

2.2

30W

0

30N

0

60E

0.2

SOF

90E

0.4

5. Oceanic dispersion model intercomparison

5.1. Models

The oceanic dispersion model intercomparison is based on eleven models from ten groups. The numerical models for the dispersion of radionuclides in the ocean generally consist of two parts. The first part is an oceanic circulation model that calculates evolving circulation patterns in which the observed physical parameters can be directly assimilated or the assimilated fields can be used as the boundary conditions. The second part is a dispersion model that calculates the movement and spread of radionuclides in the ocean based on the circulation patterns produced by the oceanic circulation models. The specification of basic model settings and characteristics for the participating models are listed in Table 5.1, and the model domains are summarized in Fig. 5.1. Detailed descriptions for each model can be found in Appendix A.

The domain, grid system, and grid spacing differ significantly among the models and reflect the different main foci of their studies. In addition, there are two conceptually different formulations of the radionuclide dispersion calculation. Seven models use the Eulerian framework, and the remaining four models utilize Lagrangian particle tracking methods.

All of the models have a source term of the radionuclide directly discharged from the FDNPP. For the temporal evolution of the direct discharge, some models adopt a scenario similar to the one proposed by the JAEA (JAEA type; see Kawamura et al., 2011), which incorporates shorter time-scale variations, whereas the other models utilize a simplified scenario proposed by the CRIEPI (CRIEPI type; see Tsumune et al., 2012). The total amount of directly discharged ¹³⁷Cs differs significantly among the models, and the values range from 3.5 PBq to 26.9 PBq (Fig. 5.2).

The seven models also include ¹³⁷Cs deposited to the ocean surface from the atmosphere, and the deposition is calculated by the atmospheric dispersion models. Figure 5.3 shows the horizontal distribution of accumulated ¹³⁷Cs depositions until April 1st, 2011 from the seven models, and significant differences in the spatial distribution and the amount of deposition are found among the models. The uncertainty in the source terms and models themselves is inevitably mirrored in the subsequent results of oceanic dispersion.

5.2. Dispersion of surface ¹³⁷Cs activity

The ten-day averaged ¹³⁷Cs concentrations and circulation fields at the upper-most level of each model in a region off of the Tohoku area are compared in Fig. 5.4 to Fig. 5.7. The monitoring observation results are also shown in Fig. 5.4 and Fig. 5.6 as a reference for the model results. Here, we only show the results for the March 22-31 and April 21-30 periods. Appendix B summarizes all of the ten-day averaged data until the end of June 2011.

March 22-31

The monitoring data indicate high concentrations of 137 Cs larger than 20,000 Bq m⁻³ along the coast near the FDNPP (Fig. 5.4(1)). The data from the observation stations 30 km offshore from the coast also show 137 Cs contamination with a magnitude of approximately 10,000 to 15,000 Bq m⁻³. The lack of observations, unfortunately, makes it difficult to assess the details of the simulated 137 Cs distributions at the end of March.

Most of the models capture the high ¹³⁷Cs concentration along the coast of Fukushima that tends to expand southward at the end of March (Fig. 5.4). The surface current fields in these models demonstrate a weak southward flow at a magnitude of 10 cm s⁻¹ or less along the coast in front of the FDNPP (Fig. 5.5). The local flow patterns along the coast are susceptible to wind forcing over this region, show a higher temporal variability associated with synoptic weather disturbances, and subsequently generate coastal trapped waves in the ocean.

A large difference among the model results in terms of the ¹³⁷Cs distribution pattern is generated from the assumptions of atmospheric deposition. The ¹³⁷Cs distributions in the KIOST/IMMSP, Kobe U, MSSG, and WHOI-3D models with no atmospheric deposition are confined along the Fukushima coast, whereas those in the CRIEPI, JAEA, JCOPE, NIES, and WHOI-2D models with atmospheric deposition indicate relatively large ¹³⁷Cs concentrations in a wide region, even in the offshore area. Relatively large concentrations in a region near the Sendai Bay in the latter five models are a distinct example of the difference. Note that the IRSN model includes an atmospheric deposition at the sea surface; however, the deposited area is limited to the coastal region near the FDNPP (see Fig. 5.3).

Another important factor that determines the distribution of 137 Cs in offshore regions is a broad southward flow off of the Tohoku area in a region east of 141.5°E and north of approximately 36.5°N with the magnitude of 20 to 50 cm s⁻¹ (e.g., Fig. 5.5(a), (i), (k), and others). The 137 Cs contamination in the offshore region tends to spread southward between the coast and the region of the southward flow. Concurrently, the southward flow brings

water with a low-contamination from the north and creates complex spatial distributions of ¹³⁷Cs concentrations. The contaminated water is then captured by the northern flank of the eastward flowing Kuroshio Current (see Fig. 5.4(i) and Fig. 5.4(j) for clear examples).

Although the general tendencies of the current fields and ¹³⁷Cs distributions are similar, the small-scale distributions are different among many models. Such an example can be observed in the eddy-like structures of the surface current and associated ¹³⁷Cs distributions off of the coast of Ibaraki in the region between 36.7°N and the Kuroshio Current. Clear examples of the anticyclonic eddy can are centered at 36.4°N, 141°E in the KIOST/IMMSP (Fig. 5.5(f)) and MSSG (Fig. 5.5(h)) cases. A similar eddy structure with weaker magnitude can also be observed in other model results (see the figures for April 1-10 in Appendix B); however, the structure appears as part of a strong dipole eddy structure in the JAEA (Fig. 5.5(d)) and WHOI-3D (Fig. 5.5(k)) results. The horizontal distribution of the sea-surface temperature and chlorophyll-a concentrations from satellite observations indicate a warm-core eddy-like feature off the coast of Ibaraki from the end of March to May (see Appendix C), which indicates anti-cyclonic circulation. The ¹³⁷Cs concentrations of the CRIEPI, JAEA, JCOPET, and NIES results are affected by the eddy structure, whereas those in the other models did not reach the region of these eddies by the end of March.

April 21-30

In the observations for April 21-30, the high 137 Cs concentration spreads toward the offshore area by the end of April, whereas the radioactivity along the line 30 km offshore reduces slightly to an approximate value of 10,000 Bq m⁻³ or less, except for three locations where a value of more than 20,000 Bq m⁻³ are observed (Fig. 5.6(1)). New observation stations are set in the region off of Ibaraki; however, the observed values are all under the detection level, which is set to 10,000 Bq m⁻³ for this time period.

Most of the models show a northeasterly dispersion of the ¹³⁷Cs at the end of April (Fig. 5.6); this dispersion appears to be associated with the northeastward surface flow distributed near the FDNPP that is linked to the anticyclonic circulation off of the Ibaraki coast (Fig. 5.7). This northeastward dispersion is broadly consistent with the radioactivity distribution near the coast of the FDNPP that was observed by aerial measurements on April 18, 2011 (Appendix D), although the observation shows only a limited area near the FDNPP. The anticyclonic circulation off the Ibaraki coast tends to prevent the high ¹³⁷Cs from coming down to the south along the coast. The IRSN and WHOI-2D cases, however, show high ¹³⁷Cs concentration off of the Ibaraki coast, most likely as a result of weak or no anticyclonic eddy

in the circulation fields.

However, the southern or southeasterly movements of the ¹³⁷Cs in the offshore region can also be observed in many of the model results except for the IRSN and MSSG cases. This relatively high ¹³⁷Cs transported to the south or southeast is captured by the northern flank of the Kuroshio Current, which spreads the ¹³⁷Cs quickly to the east into the interior of the Pacific Ocean. The above suggests that the surface circulations in the region between 37°N and the Kuroshio Current are sensitive to the small-scale current fields that are mainly associated with the meso-scale eddies and variability of the Kuroshio Current, which in turn are strongly affected by the data assimilation processes in the larger domain models.

Note that the observed monitoring stations can cover only a small portion of the region with relatively high concentrations, which suggests the necessity of a wider monitoring network to estimate the radionuclide distribution and to evaluate the model results.

5.3. Comparison with observed time series

To verify the model performance in reproducing a time series of the surface ¹³⁷Cs concentration near the FDNPP, we have compared the time series of the simulated ¹³⁷Cs concentrations at the Fukushima Dai-ni (2F) NPP, Iwasawa coast (Fig. 5.8), and 30 km offshore monitoring stations (Fig. 5.9) with the observed values. The 2F NPP and Iwasawa coast are located approximately 10 km and 16 km south of the FDNPP, respectively. Until mid-April, many of the models produced relatively accurate reproductions of the time variations at the 2F NPP, including the short period of variability from late March and early April, which is associated with the local wind variations. Although a gradual decrease of the ¹³⁷Cs concentrations is well-simulated by all of the models, half of the models underestimate the ¹³⁷Cs concentrations after mid-April. One reason for this underestimation could have resulted from influences of the atmospheric deposition in March and early April still existing over a large area near the coast as well as the offshore regions. As will be discussed later, however, the atmospheric deposition into the ocean appears small in all of the models and causes an underestimation of the ¹³⁷Cs concentrations near the 2F NPP. Another possible reason for the underestimation is the northward flow along the Fukushima coast during late April that is mentioned in section 2; in this flow, water with low ¹³⁷Cs concentrations is transported from the south to the Fukushima coast. However, as a result of a lack of any observed current data for this time period off the coast of Fukushima, it is difficult to evaluate the simulated current field, especially near the coastal region.

The discrepancy between the observed and simulated time series becomes larger in

general for the 30-km offshore stations. Because the direct discharge of ¹³⁷Cs from the FDNPP starts in late March and because the four models (GEOMAR, KIOST/IMMSP, Kobe U, and MSSG) without atmospheric deposition significantly underestimate the ¹³⁷Cs concentration during March, it is reasonable to assume that this offshore contamination during March and early April is a result of atmospheric deposition. This is consistent with the conclusion of Tsumune et al. (2012), who analyzed the ratio of the ¹³¹L/¹³⁷Cs activities. Even the models that include atmospheric deposition underestimate the ¹³⁷Cs concentrations before mid-April. This suggests that all of the atmospheric deposition data may be too small to provide adequate boundary conditions for the oceanic dispersion simulations.

Again, most of the models produced a significant underestimation of the ¹³⁷Cs concentrations in late April and May. Therefore, more thorough analyses and comparisons of the current fields and associated dispersion of ¹³⁷Cs are necessary to determine the possible reasons for the discrepancy, which may be different from those for the coastal region.

5.4. Comparison with R/V Ka'imikai-o-Kanaloa observations

Additional important observed reference data for the evaluation of the model performance in reproducing the ¹³⁷Cs dispersion was collected during the R/V Ka'imikai-o-Kanaloa (KOK) cruise in June 2011 in the Kuroshio extension region and a region off of the Fukushima and Ibaraki coasts (Buesseler et al., 2012). Fig. 5.10 and Fig. 5.11 compare the horizontal distribution of ¹³⁷Cs at the sea surface and at a depth of 100 m, respectively, between each model result and the observed values. Most of the model results indicate that the ¹³⁷Cs spreads across a much wider area, particularly to the north and northeast of the observation array, compared to the observed region. All of the models capture the region of high ¹³⁷Cs concentrations off the coast of Fukushima and Ibaraki at the surface, whereas several models do not show the high concentration off the coast at a 100 m depth. The R/V KOK observations demonstrate that the maximum concentration of ¹³⁷Cs at the surface does not appear at the observation station closest to the FDNPP but at the stations at approximately 36.3°N, 141.7°E. As suggested by Buesseler et al. (2012), the meso-scale eddies and associated streamer-like structures can be observed in several model results, which supports the rapid spread of ¹³⁷Cs as a result of relatively strong ocean currents. However because the simulated current fields in each model differ significantly as a result of the different model settings and nonlinear nature of the current variations, each model shows a different horizontal distribution of ¹³⁷Cs concentrations in the study area.

The total inventory of ¹³⁷Cs within the observed area is reported as 1.9 to 2.1 PBq

(Buesseler et al., 2012). Fig. 5.11 also indicates the inventory values within the observed area in the middle of June for each model result, in which the value spans from 1.33 PBq to 4.52 PBq. These wide-spread inventories in the simulated results reflect different vertical profiles of ¹³⁷Cs averaged within the observed area (Fig. 5.12). Three models (IRSN, JCOPET, and NIES) that produce high inventory values tend to overestimate the subsurface ¹³⁷Cs concentrations in the off-shore region (35.0°N-38.0°N, 143.5°E-147.0°E), whereas the other models appear to underestimate the concentrations in the layer below a depth of 25 m. However, in the near-shore region (36.0°N-38.0°N, 141.4°E-143.5°E), all of the models tend to underestimate the concentrations compared to the observed values. Such differences in vertical profiles among the model results could have been caused by the different vertical mixing parameterizations and mixing coefficients used in each model. In addition, the surface momentum, heat and freshwater fluxes may also affect the vertical mixing process near the sea surface. Another factor controlling the vertical profiles, particularly near the bottom, might be a scavenging process and the transport of radionuclides between the sea-water and bottom sediments. Observations at this stage do not show the importance of the latter processes on the ¹³⁷Cs concentrations in the whole water column. However, they may be important in the near-shore region when water that is highly contaminated by ¹³⁷Cs is discharged directly from the FDNPP and generates "hot spots" of highly contaminated areas on the sea floor. Most of the models except for the JAEA, KIOST/IMMSP, and MSSG do not incorporate the scavenging and transport processes near the bottom in their model formulations.

5.5. Concluding remarks

Although there are notable similarities among the model results, significant discrepancies are identified in both the spatial distributions and temporal variations of the ¹³⁷Cs concentration as shown in Sections 5.2 and 5.3. Considering the quantitative differences among the models due to mixing and scavenging/transport effects, a simple comparison is not straightforward. Detailed systematic comparison studies, such as ones that use the same radionuclide forcing with different models and/or the same model with different forcing scenarios, are required. Considering the significant uncertainty in the surface flux forcing, ocean circulation fields, and mixing and scavenging/transport parameterizations, we cannot conclude at this stage which model produces the most accurate simulations of the ¹³⁷Cs distribution discharged by the FDNPP accident. Further efforts under international coordination are required.

| Table 5.1. | Model s | pecifications |
|------------|---------|---------------|
|------------|---------|---------------|

| Model | Resolution (degrees) | Grids | Dispersion model type | Atmosphe ric Fallout | Direct discharge | Note |
|---------|----------------------|-----------|-----------------------------|-------------------------|---------------------------------|--|
| CRIEPI | 1/120 ×1/120 | 855 × 615 | Euler | CRIEPI | CRIEPI type (3.5 PBq) | |
| GEOMAR | 1/8 × 1/10 | 480 × 284 | Euler | N/A | Instant release (2.3 PBq) | Using 1993 ECMWF forcing, which yields similar oceanic conditions as 2011 (Dietze and Kriest, 2012) |
| IRSN | $1/48 \times 1/60$ | 623 × 743 | Euler | IRSN pX | IRSN (26.9 PBq) | Wind-tuned Case |
| JAEA | 1/54 × 1/72 | 191 × 218 | Lagrangian | JAEA | JAEA type (3.5 PBq) | |
| JCOPET | 1/36 × 1/36 | 830 × 578 | Euler | JAMSTEC | CRIEPI type (6.0 PBq) | |
| KIOST | $1/60 \times 1/60$ | 601 × 661 | Euler | N/A | JAEA type (3.8 PBq) | Original grid is an unstructured system |
| Kobe U | 1km × 1km | 512 × 512 | Euler | N/A | CRIEPI type (6.9 PBq) | Model domain is rotated horizontally to align with the Fukushima coastline |
| MSSG | 1/55.6×1/55.6 | 168 × 239 | Lagrangian | N/A | CRIEPI type (5.7 PBq) | |
| NIES | $1/20 \times 1/20$ | 91 × 97 | Euler | NIES | CRIEPI type (3.6 PBq) | |
| WHOI-2D | 1/10 × 1/10 | 351 × 111 | Lagrangian | Stohl et al. (2012) | JAEA type (16.2 PBq) | Geostrophic flow with satellite sea-surface height data |
| WHOI-3D | 1/10 × 1/10 | 170×101 | Lagrangian | N/A | JAEA type (16.2 PBq) | NCOM output |



Figure 5.1. Domain of each model evaluated in the model intercomparison. A red square indicates the location of the FDNPP. The region surrounded by dotted lines shows the area of observations conducted by the KOK cruise (Buesseler et al., 2012), and the gray square is the region in the models compared with the KOK observations.



Figure 5.2. Time series from March 21 to June 30, 2011 of the ¹³⁷Cs direct discharge from the FDNPP into the ocean in each model. Numbers in parentheses in the legend indicate the total discharged amount of ¹³⁷Cs for each model.



Figure 5.3. Cumulated atmospheric deposition of ¹³⁷Cs from March 11 to April 1, 2011 for the (a) CRIEPI, (b) IRSN, (c) JAEA, (d) JCOPET, (e) NIES, and (f) WHOI models. Only the deposition over the ocean is shown. Note that the period of accumulation is from March 11 to 25 for the IRSN case. The WHOI-2D and WHOI-3D models use the same atmospheric deposition as shown in (f).



Figure 5.4. (a)-(k) Horizontal distributions of the ¹³⁷Cs concentrations averaged over a 10-day period from March 22 to 31, 2011, with the name of the models indicated above each panel. Red squares indicate the location of the FDNPP. Black thin lines superimposed onto the ¹³⁷Cs concentration indicate contours of 0.5 m/s of surface current magnitude and show the general locations of the Kuroshio Current and other dominant features in this region. Panels with green (yellow) labels show results from models with (without) atmospheric deposition. Panel (I) shows the distribution of the observed ¹³⁷Cs concentrations during the same 10-day period.