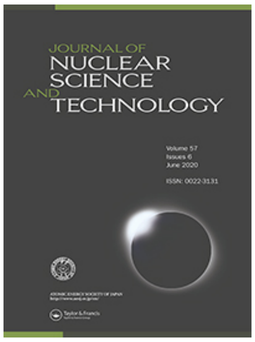

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Atmospheric-dispersion database system that can immediately provide calculation results for various source term and meteorological conditions

Hiroaki Terada[a], Haruyasu Nagai[a], Atsunori Tanaka[b], Katsunori Tsuduki[a] and Masanao Kadowaki[a]

[a]Nuclear Science and Engineering Center, Japan Atomic Energy Agency, Tokai-mura, Japan; [b]Monitoring Information Group, Shimane Prefectural Nuclear Power Environmental Center, Matsue, Japan

ABSTRACT

We have estimated source term and analyzed processes of atmospheric dispersion against atmospheric discharge of radioactive materials due to the Fukushima Daiichi Nuclear Power Station (FDNPS) accident by atmospheric-dispersion calculation using the Worldwide version of System for Environmental Emergency Dose Information (WSPEEDI). On the basis of this experience, we developed an atmospheric-dispersion calculation method that can respond to various needs for dispersion prediction in a nuclear emergency and provide useful information for emergency-response planning. By this method, if a release point, such as a nuclear facility, is known, it is possible to immediately obtain the prediction results by applying provided source term (released radionuclides, release rate, and release period) to the database of dispersion-calculation results prepared in advance without specifying source term. With this function, it is easy to compare results by applying many kinds of source term with monitoring data, and to find out the optimum source term. By preparing a database by this calculation with past long-term meteorological data, we can immediately get dispersion-calculation results for various source term and meteorological conditions. This database is useful for pre-accident planning, such as optimization of a monitoring plan and understanding of events to be supposed in considering emergency countermeasures.

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Atmospheric dispersion; numerical simulation; database system; nuclear emergency preparedness; WSPEEDI

1. Introduction

The Japan Atomic Energy Agency has been developing a numerical simulation system to predict the environmental transport of radioactive materials and radiological doses in the case of an atmospheric release of radioactive materials from nuclear facilities in Japan. At first, the System for Prediction of Environmental Emergency Dose Information (SPEEDI) was developed, and it was operated as a nuclear emergency-response system of Ministry of Education, Culture, Sports, Science and Technology (MEXT). By expanding the function of SPEEDI, a Worldwide version of SPEEDI (WSPEEDI) was constructed [1]. These prediction systems have been applied to cope with the discharge of radioactive materials into the atmosphere caused by actual nuclear accidents.

After the accident at the Fukushima Daiichi Nuclear Power Station (FDNPS) of the Tokyo Electric Power Company (TEPCO) due to the Great East Japan Earthquake on March 11, 2011, which caused a substantial discharge of radioactive materials into the atmosphere, SPEEDI and WSPEEDI have been providing atmospheric-dispersion predictions and detailed analysis results for consideration of emergency countermeasures and evaluation of environmental impacts by the accident. Because the source term of radioactive materials released into the atmosphere during the FDNPS accident is essential to evaluate the environmental impacts and resultant radiological doses to the public, we have estimated source terms by comparing measurements of air concentration of radioactive materials or dose rate in the environment with results calculated by atmospheric dispersion simulations using WSPEEDI [2–7]. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) used our source term [5] for estimating levels of radioactive material in the terrestrial environment and doses to the public where measurements did not exist [8]. The simulation of WSPEEDI using the estimated source term [7] successfully reproduced the local and regional deposition patterns of ^{131}I and ^{137}Cs derived from airborne monitoring [9,10] by considering topographical effects and meteorological conditions in detail.

We also applied WSPEEDI to predict atmospheric dispersion of radionuclides to cope with nuclear tests by North Korea in May 2009, February 2013, September 2016, and September 2017 [11,12]. The prediction results by WSPEEDI were provided to the Japanese Government to assist their responses to the nuclear tests, such as aerial monitoring. In this

CONTACT Hiroaki Terada terada.hiroaki@jaea.go.jp Nuclear Science and Engineering Center, Japan Atomic Energy Agency, 2-4 Shirakata, Tokai-mura, Naka-gun, Ibaraki 319-1195, Japan
Supplemental data for this article can be accessed here.

application, WSPEEDI calculations considering various release conditions were conducted daily on a regular basis after acquisition of online meteorological forecast data (provided by the Japan Meteorological Agency), and the prediction results for hypothetical release conditions decided based on an actual nuclear test, were provided to the Japanese Government immediately after the occurrence of the nuclear tests.

By reflecting on the above experiences and lessons learned, WSPEEDI has been improved. Because WSPEEDI uses sophisticated meteorological- and dispersion-simulation schemes, it needs much more computational time (for example, a few hours for the calculations for a 3-day period) than used by SPEEDI. This makes it difficult to respond immediately in case of an accident and to examine WSPEEDI predictions by comparing results with various calculation conditions.

Therefore, we developed a new calculation method [13] that can respond to various needs for dispersion prediction in a nuclear emergency and provide useful information for emergency-response planning. Atmospheric dispersion simulations by SPEEDI and WSPEEDI consist of detailed meteorological calculations for the target analysis area and dispersion and dose calculations using the outputs from meteorological calculations and release conditions of radioactive materials, i.e. source term. Once the target analysis area is determined, meteorological calculations can be conducted in advance by using meteorological forecast data up to several days in the future. In this situation, local-scale meteorological calculations have been conducted regularly in the operation of SPEEDI to prepare datasets for all the areas around nuclear facilities in Japan, and this has made it possible to start dispersion calculations immediately in case of a nuclear emergency. However, the source term (release point, released radionuclides, release start time and duration, release amount) is essential for the dispersion calculation, and it should be set up for each dispersion calculation before execution. Thus, it takes several minutes to obtain each SPEEDI prediction even though precomputation is used for meteorological calculations. The response time of WSPEEDI is much longer than SPEEDI because of its more sophisticated processes in dispersion calculation. To cope with this problem, we developed a new calculation method that enables precomputation of dispersion calculations.

By this new dispersion-calculation method [13], it is possible to immediately obtain prediction results by applying the source term to the database of dispersion-calculation results prepared in advance without specifying the source term except for the release point (nuclear facility). This function is very useful in the detailed post analysis of environmental impact from a nuclear accident, such as for source term estimation. It is easy to compare results obtained by applying many kinds of source term with monitoring data and to find out the optimum source term by which the difference between calculations and measurements can be minimized. This analysis method was applied for the refinement of the source term and improvement of atmospheric-dispersion simulation for the FDNPS accident in our recent study [14]. A dispersion database also was developed to be used for comprehensive dose assessment by coupling with the behavioral pattern of evacuees from the FDNPS accident.

On the other hand, by performing this calculation with past long-term meteorological analysis data and preparing the output as a database, it is possible to immediately get dispersion-calculation results for various source term and meteorological conditions. This database can be used for pre-accident planning, such as optimization of the monitoring plan, by analyzing dispersion-calculation results for various past weather conditions. To improve the usability of this database, we also developed user interface software to execute calculation codes, generate database of dispersion-calculation results, and obtain prediction results of interest. By integrating these calculation codes and software, we constructed the atmospheric-dispersion database system.

2. Atmospheric-dispersion database system

2.1. Structure of database system

The atmospheric dispersion database system consists of calculation functions, analysis functions, and user interface functions installed on a Linux-PC server (Figure 1). For the calculation functions, the meteorological- and dispersion-calculation codes of WSPEEDI are used (Section 2.2). These codes generate the database of calculation outputs by execution with line commands and shell scripts of the Linux operating system. After the database is generated on the Linux-PC server, dispersion-calculation results for various source term and meteorological conditions can be obtained and visualized by using analysis functions which are operated by a Web-based graphical user interface (GUI). By adopting a Web-based GUI, the database system can be operated easily by command menus shown on a Web browser from any network-connected PCs.

2.2. Calculation codes for atmospheric dispersion

The codes for the calculation function of the atmospheric-dispersion database system are based on the Weather Research and Forecasting model (WRF) [15] and the Lagrangian particle dispersion model GEARN [1], which are included in WSPEEDI.

WRF is a community meteorological model having many users all over the world. It is used for the official

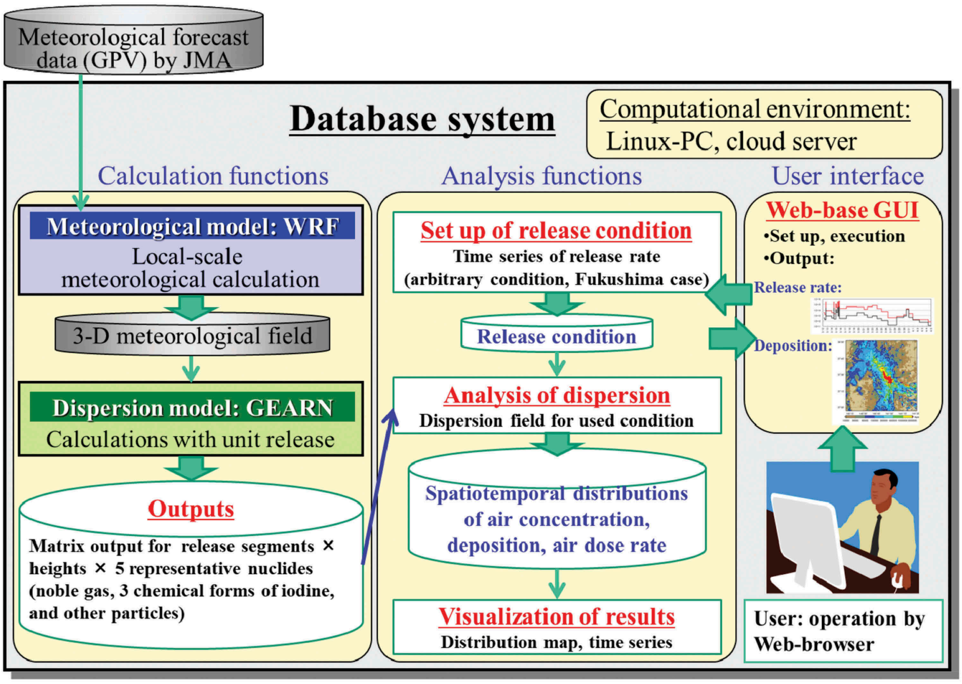

Figure 1. Structure of atmospheric-dispersion database system.

weather forecasting by some countries but also has many other useful functions such as nesting calculations, four-dimensional data assimilation, and many options of parameterizations for cloud microphysics, cumulus cloud, planetary boundary layer (PBL), radiation, and land surface processes. WRF outputs meteorological parameters such as wind velocity, diffusion coefficient, and precipitation amount necessary for dispersion calculation using GEARN.

GEARN calculates the atmospheric dispersion of radionuclides by tracing the trajectories of a large number (typically a million) of marker particles discharged from a release point. The horizontal model coordinates (x and y) are the map coordinates, and the vertical coordinate is the terrain-following coordinate (z*). By using the meteorological field predicted by WRF, the model calculates the movement of each particle affected by both advection due to mean wind and subgrid-scale turbulent eddy diffusion. GEARN also has a function of nesting calculation for two domains corresponding to WRF's nested domains. Two executables of GEARN for two nested domains are executed concurrently on parallel computers, and marker particles that flow out and in across the boundary of the inner domain are exchanged between domains. A part of the radioactivity in the air is deposited on the ground surface by turbulence (dry deposition) and precipitation (wet deposition). These processes are modeled considering dry and fog-water deposition, cloud condensation nuclei (CCN) activation, and subsequent wet scavenging due to mixed-phase cloud microphysics (in-cloud and below-cloud scavenging) for radioactive iodine gas (I_2 and CH_3I) and other particles (CsI, Cs, and Te) [6]. The air concentration in each Eulerian cell averaged over an output time interval and total surface deposition accumulated during the time interval are calculated by summing up the contribution of each particle to the cell. The radioactive decay is calculated at each time step and integrated in both air concentration and surface deposition calculations. The air absorbed gamma dose rate (Gy h^{-1}) is calculated by multiplying the air concentration and deposition of radionuclides by conversion factors [16]. Although decay chains are not treated explicitly as a process in GEARN, dose contribution of a radionuclide and its progeny nuclide with a short half-life can be taken into account simply in the calculation of radiological doses when radioactive equilibrium is assumed (e.g. ^{132}Te and ^{132}I in the Fukushima Daiichi nuclear power station accident [6]).

2.3. Calculation method for database

A database of spatiotemporal distribution of radioactive materials in the air and on the surface is constructed by a newly developed calculation method [13] as shown in Figure 2. The basic concept of this method is that dispersion calculation results for any source term can be obtained by a linear combination of calculation results with unit release condition for time segments of release period. And this procedure is carried out immediately after a particular source term is provided if calculation results for time segments are prepared comprehensively for conceivable release conditions (released radionuclides, release start time and duration,

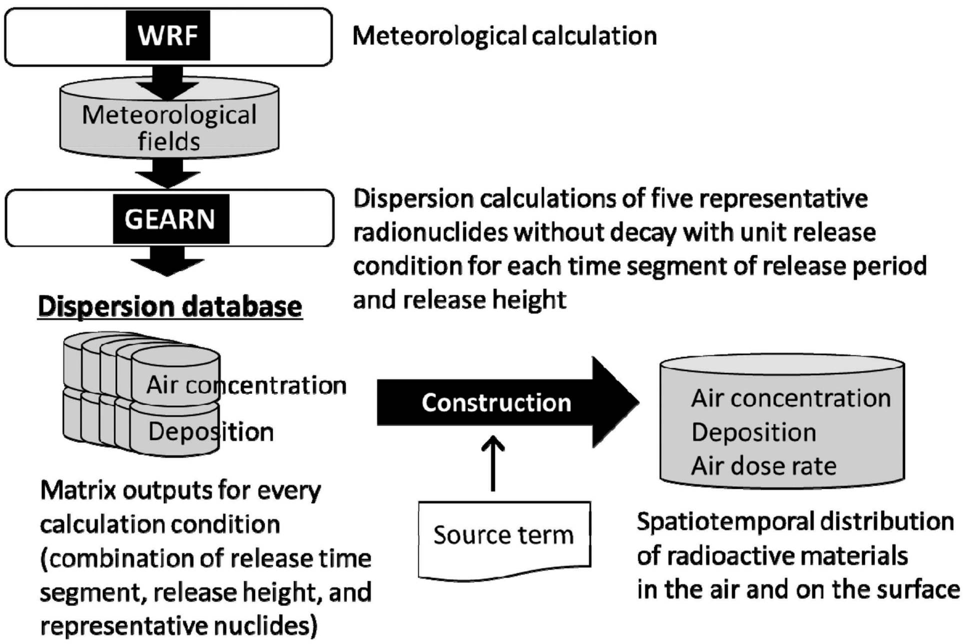

Figure 2. Calculation and analysis method for database.

temporal change of release amount). To achieve this, dataset of dispersion calculations for time segments are constructed as follows. The dispersion calculation by GEARN using meteorological fields by WRF calculations is conducted with a unit release condition for one hour release segment. This calculation is done for each combination of five representative radionuclides for deposition property (noble gas, particulate iodine, organic and inorganic iodine gases, and other particles) without decay, conceivable release heights (building, stack height, etc.), and release time segments (all 24 h of days in the analysis period). For this calculation, all radionuclides are separated into five groups with similar deposition property and only the datasets of dispersion calculation for the representative nuclides of the groups are constructed. The actual radioactivity concentration and deposition for a particular radionuclide are obtained afterward by applying the decay for the radionuclide to the dataset of the group including the radionuclide. From the above calculations, matrix outputs for every calculation case (hereafter, "dispersion database") are made. By the dispersion database, the spatiotemporal distribution of air concentration $C_{t,i,j,k,n}$ (Bq m^{-3}) and surface deposition $D_{t,i,j,n}$ (Bq m^{-2}) of radionuclides for a particular condition of source term are calculated by:

$$C_{t,i,j,k,n} = fd_{n,t} \sum_h \sum_r \left(Cdb_{r,h,t,i,j,k,m(n)} R_{r,h,n} \right), \quad (1)$$

$$D_{t,i,j,n} = fd_{n,t} \sum_h \sum_r \left(Ddb_{r,h,t,i,j,m(n)} R_{r,h,n} \right), \quad (2)$$

where $fd_{n,t}$ is decay rate for radionuclide (n) at output time (t) from shutdown time, $Cdb_{r,h,t,i,j,k,m(n)}$ and $Ddb_{r,h,t,i,j,m(n)}$ are matrix outputs for air concentration and surface deposition, respectively, for release segment (r), release height (h), output time (t), and representative radionuclide ($m(n)$) at grid point (horizontal: i, j, vertical: k), $R_{r,h,n}$ is release rate decay corrected at the shutdown time for release segment (r), release height (h), and radionuclide (n).

Table 1. Radionuclides available in the database system and the correspondence with the representative radionuclides classified by deposition property.

Radionuclide (source term)	Representative radionuclide (dispersion database)
^{83m}Kr, ^{85}Kr, ^{85m}Kr, ^{87}Kr, ^{88}Kr, ^{89}Kr, ^{90}Kr, ^{131m}Xe, ^{133}Xe, ^{133m}Xe, ^{135}Xe, ^{135m}Xe, ^{137}Xe, ^{138}Xe, ^{139}Xe, ^{41}Ar, STD*	Noble gas
^{129}I, ^{131}I, ^{132}I, ^{133}I, ^{134}I, ^{135}I, ^{136}I	Particulate iodine Organic iodine gas (CH_3I) Inorganic iodine gas (I_2)
^{3}H, ^{89}Sr, ^{90}Sr, ^{90}Y, ^{91}Y, ^{95}Zr, ^{95}Nb, ^{99}Mo, ^{103}Ru, ^{106}Ru, ^{115}Cd, ^{125}Sb, ^{127}Sb, ^{127m}Te, ^{127}Te, ^{129m}Te, ^{129}Te, ^{131m}Te, ^{132}Te, ^{134}Cs, ^{136}Cs, ^{137}Cs, ^{140}Ba, ^{140}La, ^{141}Ce, ^{144}Ce, ^{234}U, ^{235}U, ^{238}U, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{241}Am, ^{242}Cm, ^{244}Cm	Other particles

*Nonradioactive tracer gas.

60 radionuclides are applicable to the database system and the correspondence to the representative radionuclides for deposition property are summarized in Table 1. Note that STD in Table 1 is a hypothetical nuclide that neither decays nor gets deposited. The air absorbed gamma dose rate $DS_{t,i,j,n}$ (μGy h^{-1}) at the output time (t) and point (i, j) for radionuclide (n) is calculated assuming a submersion model by

$$DS_{t,i,j,n} = fcon_n C_{t,i,j,1,n} + fdep_n D_{t,i,j,n}, \quad (3)$$

where $fcon_n$ and $fdep_n$ are the conversion factors for air concentration and deposition, respectively, of radionuclide (n) [16] and $C_{t,i,j,1,n}$ demonstrates air concentration at the bottom layer with a typical width of 20 m. It should be noted that the air absorbed gamma dose rates calculated by the submersion model may be underestimated near a release point according to meteorological and release condition (e.g. release from high altitude in stable condition). The air absorbed gamma dose rates for each radionuclide and the total value of all target radionuclides are calculated. The air absorbed gamma dose rates from radionuclides in the air (cloud shine) and deposited on the ground (ground shine) and total value ($DS_{t,i,j,n}$) are outputted separately.

2.4. Analysis functions of database system

The main analysis functions in the atmospheric-dispersion database system are functions for setting of source term, calculation of spatiotemporal distribution of radionuclides by applying the source term to the dispersion database, and visualization of the calculation results (Figure 1). The system is also equipped with functions for downloading analysis results to user's PC terminals and file management (such as copying, deleting, and moving of files). To enable easy and efficient operation of the system, GUI of the analysis function were developed (Figure S1 of the supplemental material). Temporal variation of release rate and release height of radionuclides can be set arbitrarily in the GUI window for setting of source term (Figure S1(a)), where setting of release rate in both format of decay corrected values at the shutdown time and values at each release time are supported. The former and latter formats are convenient, for example, when we use data by reactor analysis and stack monitor, respectively. In the GUI window for application of source term to the dispersion database (Figure S1(b)), target dispersion-calculation results for a selected source term are quickly and easily obtained by selecting a source term. Horizontal-distribution maps of the calculation results are made easily in the visualization window (Figure S1(c)), where color shading, coastline resolution, and on/off of display for wind vectors can be selected. Time-series graphs of calculation results at locations listed in another GUI window are also produced by GUI (Figure S1(d)). The figures made by this system are displayed in the GUI window with a function of frame control (Figure S1(e)).

3. Performance test of database system

3.1. Calculation condition

The performance of the database system was examined by applying it to the area around the Shimane Nuclear Power Station (Shimane NPS) of the Chugoku Electric Power Co., Inc. Analysis domains are 372 × 372 km^2 in area with a 6-km horizontal grid resolution (Domain 1) and 98 × 98 km^2 in area with a 2-km horizontal grid resolution (Domain 2) (Figure 3). The calculation conditions for meteorological model WRF and dispersion model GEARN are summarized in Tables 2 and 3, respectively. The calculation period for the dispersion database was set as 4.5 days from 21:00 JST (Japan Standard Time UTC + 9 h) on June 14 to 9:00 JST on June 19, 2015, which was chosen because the meteorological condition during this period was expected to be the case with high computational cost. Release height cases for the dispersion database were set to 10 and 120 m (stack height). For air concentration data, only two-dimensional distributions at the surface layer were outputted to reduce the file size.

To verify the dispersion-calculation results by the database system, the following calculation conditions were applied to the dispersion database.

- Shutdown time: 0:00 JST on June 15, 2015
- Analysis period: 0:00 to 24:00 JST on June 15, 2015

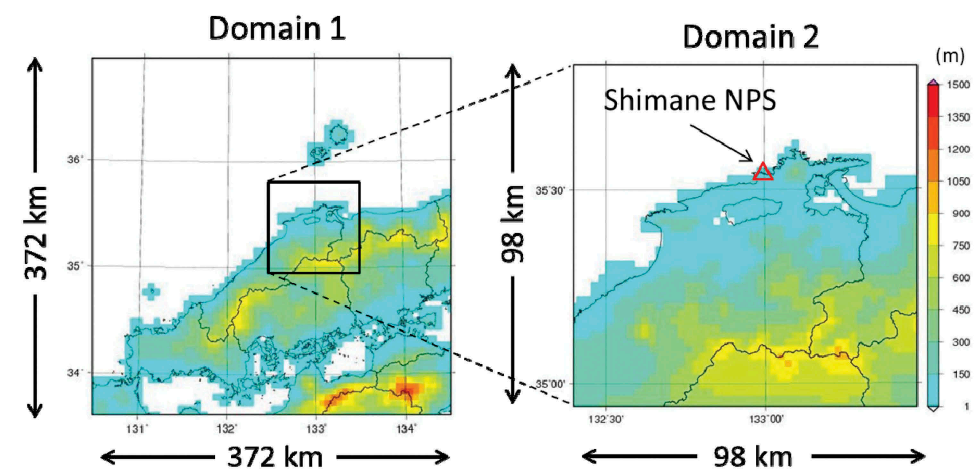

Figure 3. Calculation domains for performance test. Colored shades indicate ground height above sea level. Red triangle indicates the Shimane nuclear power station.

Table 2. Calculation conditions of meteorological model WRF for the performance test.

Calculation area	Domain 1 and Domain 2 (1-way nesting)
Horizontal grid number	64 × 64 (Domain 1); 51 × 51 (Domain 2)
Horizontal grid distance	6 km × 6 km (Domain 1); 2 km × 2 km (Domain 2)
Vertical layer	30 layers from surface to 100 hPa
Time step	30 s (Domain 1); 10 s (Domain 2)
Initial and boundary condition	Grid Point Value (GPV) of Meso-Scale Model (MSM) by Japan Meteorological Agency (JMA)
Output time interval	1 h
Analysis nudging	Applied only for Domain 1
Physical option	
Microphysics	Morrison microphysics [19]
Cumulus	Betts–Miller–Janjic (BMJ) Cumulus [20]
Land surface	Five-layer thermal diffusion [15]
Boundary layer	Mellor–Yamada–Nakanishi–Niino (MYNN) PBL (Level 2.5) [21]
Radiation	Shortwave: Dudhia [22], Long wave: Rapid Radiative Transfer Model (RRTM) [23]

Table 3. Calculation condition of dispersion model GEARN.

Calculation area	Domain 1 and Domain 2 (2-way nesting)
Horizontal grid number	62 × 62 (Domain 1); 49 × 49 (Domain 2)
Horizontal grid distance	6 km × 6 km (Domain 1); 2 km × 2 km (Domain 2)
Vertical layer	26 levels from 10 km to surface with 20-m-thick bottom layer
Time step	30 s (Domain 1); 10 s (Domain 2)
Input time interval of meteorological fields	1 h
Output time interval	1 h
Horizontal diffusion parameter	Pasquill–Gifford chart (stability: neutral)
Release point	Shimane nuclear power station (35.5385°N, 132.9995°E)
Release period	1 h
Release height case	10 and 20 m
Particle number	10,000 h^{-1}

- Release period: 0:00 to 24:00 JST on June 15, 2015
- Release radionuclide: ^{137}Cs
- Release rate: 1 Bq h^{-1}
- Release height: 10 m

In addition to this, the usual calculation by the original GEARN model was also conducted to compare calculation results and computation time. The specifications of the computer used for the dispersion calculations are as follows: Intel® Xeon® E5-2687W v4 CPU (3.0 GHz), 24 cores, 252-GB memory. Calculations to generate the dispersion database used 24 CPUs. The original GEARN calculation used 2 CPUs for the nesting calculation (Domains 1 and 2). The specifications of the computer used for the database system are as follows: Intel® Xeon® E5507 CPU (2.27 GHz), 4 cores, 24-GB memory. Analysis of source term application to the dispersion database by the database system was executed with a single CPU.

3.2. Results of performance test

The calculation results under the test condition (Section 3.1) by both methods almost agreed (Figures S2 and S3 of the supplemental material) and it demonstrates the diffusion calculation by the database method is proper. Although relatively large differences are seen at low values, they are due to statistical errors of random walk calculations using different series of random numbers in a particle dispersion model.

The results of computational costs for the performance test are as follows. The calculation of meteorological fields by WRF took 52.1 min. The WRF output file size was 2.5 GB in total for two domains and 4.5 days, with size of 15 MB for Domain 1 and 9 MB for Domain 2 for one output time. The GEARN calculations for making the dispersion database for two release height cases took 48.6 h. The file size of the dispersion database (total for the two domains) for two release heights of 10 and 120 m was 3.4 GB (1.9 GB for Domain 1 and 1.5 GB for Domain 2) and 3.2 GB (1.8 GB for Domain 1 and 1.4 GB Domain 2), respectively. The time to acquire the dispersion-calculation results took only 2.3 s to make results for Domain 2 by the database calculation method (i.e., application of a release condition to the database), while the atmospheric-dispersion calculation by the previous conventional method (i.e., execution of GEARN code with nesting calculation for Domains 1 and 2) took about 7 min. Thus, by the new database calculation method, the dispersion-calculation result for a particular source term was obtained in about 180 times less time than the previous conventional method. Although this improvement in analysis time varies depending on the analysis period, it was about 30 times better even for 4-day analysis conducted by expanding the analysis period of the test condition as 0:00 JST on June 15 to 0:00 JST on June 19, 2015.

4. Applications of database system

4.1. Source term estimation and reconstruction of atmospheric dispersion process

To assess the radiological dose to the public resulting from the FDNPS accident, the spatiotemporal distributions of radioactive materials in the environment were reconstructed by atmospheric dispersion simulations, for which the source term of radioactive materials discharged into the atmosphere is essential. Refinement of the source term estimated in our previous study [6] was carried out by effectively using the new calculation method based on the database system. Since the detailed description of this study is presented in another paper [14], only the outline of this study is described here.

In this analysis, the source term and atmospheric dispersion simulations were optimized by objective analysis based on Bayesian inference using various measurements (air concentration, surface deposition, and fallout), including newly released hourly air concentrations of ^{137}Cs derived by analyzing suspended particulate matter (SPM) collected at air pollution monitoring stations [17]. To apply this analysis to the local-scale atmospheric dispersion simulations, the new optimization method with a combination of ensemble meteorological calculations and the Bayesian inference method was developed. This optimization improved not only the source term but also the wind field in meteorological calculation by selecting the optimum case from ensemble members of meteorological calculations based on comparison results between the dispersion calculations and measurements of radionuclides.

As a result, the total amounts of ^{137}Cs and ^{131}I became 1.0×10^{16} and 1.2×10^{17} Bq, respectively, and decreased by 29 and 20%, respectively, in comparison with those by previous study [6]. The atmospheric dispersion simulation successfully reproduced both the air concentrations at monitoring points and surface depositions by airborne monitoring. The factor of 10 for total samples of air concentrations of ^{137}Cs at SPM monitoring points increased from 35.9% by the previous study to 47.3%. The scores became higher especially for the region of north of FDNPS. This area is important for dose estimation regarding the behavioral patterns of evacuees, and these improvements lead to the refinement of dose estimation. The deposition amount on the land decreased from 3.7×10^{15} Bq by the previous study to 2.1×10^{15} Bq, which was close to the measured amount of 2.4×10^{15} Bq. We also constructed the spatiotemporal distribution of some major radionuclides (total ^{131}I, ^{131}I chemical species (I_2, CH_3I, and particulate iodine), ^{134}Cs, ^{137}Cs, and ^{132}Te) in the air and on the surface (optimized dispersion database) by using the optimized release rates and atmospheric dispersion simulations. The optimized dispersion database was used for comprehensive dose assessment by coupling with behavioral patterns of evacuees from the FDNPS accident [18].

4.2. Utilization for nuclear emergency preparedness

The database system can provide results of atmospheric dispersion calculation for various source term and meteorological conditions (Figure S4 of the supplemental material). This function can be used for pre-accident planning by analyzing dispersion-calculation results for various past weather conditions. Atmospheric dispersion analysis for various hypothetical source terms makes it possible to understand events to be supposed in considering countermeasures in emergency. The database system is effective for the following practical applications:

- The atmospheric dispersion phenomenon conceivable in nuclear emergencies can be grasped by investigating the radioactive-plume movement affected by the meteorological and topographic conditions and consequent distribution patterns of surface deposition and air dose rate.
- The confirmation of a monitoring plan and the extraction of problems in the plan are possible by using simulated monitoring data generated by the database system using an assumed accident scenario, in emergency-response training.
- The effective monitoring method considering meteorological conditions and topographic characteristics can be examined by the analysis of calculation results at monitoring points and in surrounding areas.

Hereafter, a test analysis is demonstrated as an example of the third application as mentioned above. The effectiveness of monitoring points considering the meteorological conditions and topographic characteristics was examined by investigating the results of atmospheric dispersion calculation during a year produced by the database system. The aim of this analysis is to examine how much radiological hot-spots among monitoring points can be grasped from the measured values at the monitoring points.

For this analysis, the database was generated for the area around the Shimane NPS using meteorological analysis data for the year 2015. Calculation domains for the database were the same areas as shown in Figure 3, but higher horizontal grid resolutions (3 km for Domain 1 and 1 km for Domain 2) were used. The calculated results at the grid points on the main island of Japan within 30 km from the Shimane NPS (1,377 grids) obtained from the database of Domain 2 (9,409 grids in total) were used in the analysis. As the source term, a unit release of ^{137}Cs (1 Bq for 1 hour) from the stack height (120 m) was assumed, and dispersion calculations were carried out by setting the release start time at every hour from 00:00 JST on January 1 to 23:00 JST on December 24, 2015. As a result, atmospheric dispersion calculations of 8,592 (24 h × 358 days) release cases for different meteorological conditions were generated. Calculated values at 24 h after the release end time for each release case were used for the analysis to investigate the air dose rate from radionuclides deposited on the ground (ground shine). Calculated air dose rate values at 180 monitoring points around the Shimane NPS and those in surrounding areas were compared.

To analyze the dispersion-calculation results, we define 'grid-case number' as the numbers of release cases that satisfy a certain condition, summed up for all target grids. Total grid-case number is 11,831,184 (1,377 grids × 8,592 release cases), including the calculation results with value zero. We set a criterion for a valid value to be 1.0×10^{-18} μGy h^{-1} based on consideration of statistical errors in a particle dispersion model for this calculation condition. On the condition that calculated air dose rates were higher than the criterion of valid value, the grid-case number was 1,774,289 and 15.0% of the total grid-case number. This indicates the occurrence frequency of increase of air dose rate greater than the criterion for a valid value due to the ^{137}Cs plume from the Shimane NPS for different meteorological conditions during the year. The grid-case number for the condition that grid values exceeded twice the maximum value from the nearest four monitoring points was 140,213 (1.2% of the total grid-case number). Occurrence frequency with value exceeding twice the maximum value from the nearest four monitoring points (140,213) was 7.9% of the grid-case number with higher air dose rate than the criterion (1,774,289).

The number of release cases that satisfied both the condition that calculated air dose rates were higher than the criterion for a valid value (1.0×10^{-18} μGy h^{-1}) and grid point values exceeded twice the maximum value from the nearest four monitoring points was counted at each grid point on the main island of Japan within 30 km from the release point, and the ratio to the total release cases (8,592 cases) was plotted on a map (Figure 4). This ratio demonstrates occurrence frequency of the condition that grid point value exceeded twice the maximum value from the nearest four monitoring points at the grid where significant increase of air dose rate occurred. From

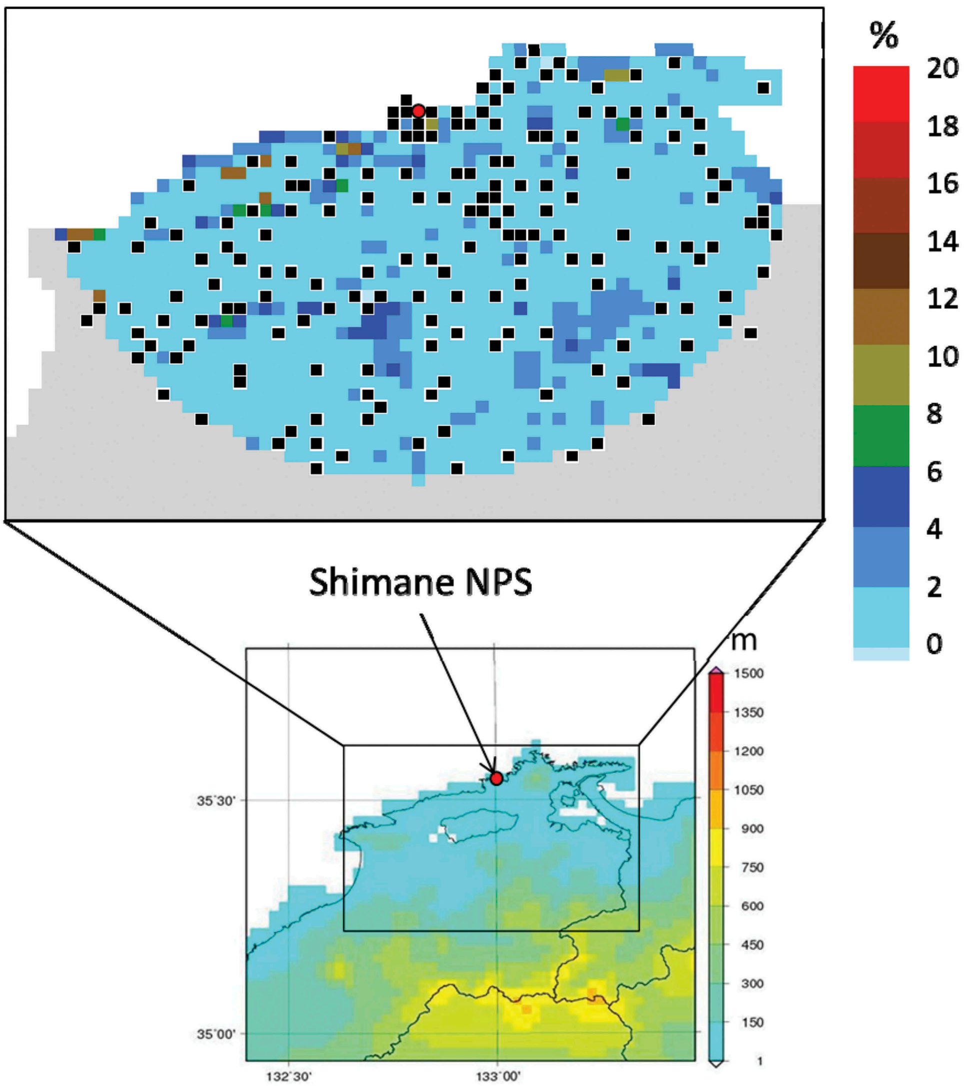

Figure 4. Distribution map of occurrence frequency of condition that grid point value exceeded twice the maximum value from nearest four monitoring points (colors in upper panel). Black-filled squares indicate monitoring posts and red-filled circles, the Shimane nuclear power station. Colors in lower panel indicate ground height above sea level.

Table 4. Grid-case numbers for condition that grid values exceeded twice the maximum value from nearest four monitoring points and the ratio of those with high contribution of wet deposition.

	Grid-case number for condition that grid values exceeded twice the maximum value from nearest four monitoring points	
Criteria values of air dose rates (μGy h^{-1})	Contribution of wet deposition > 90% (percentage of total)	Total
10^{-13}	350 (100)	350
10^{-14}	4,539 (88)	5,189
10^{-15}	13,563 (45)	30,350
10^{-16}	21,619 (32)	66,785
10^{-17}	28,783 (27)	105,347
10^{-18}	36,804 (26)	140,213

the map, low frequency (<2%) occurs at most of the grids within 30 km from the release point, where monitoring posts are located close together, although higher frequencies (2–12%) also occur at a few grids within 30 km from the release point.

Further analysis to understand the cause of high-frequency area was carried out by using calculated deposition amounts of ^{137}Cs which is directly related to the air dose rate (ground shine) used in the above analysis. Dry- and wet deposition amounts were analyzed separately. Table 4 demonstrates the grid-case numbers that satisfied the condition that grid values exceeded twice the maximum value from the nearest four monitoring points for different criteria values of air dose rate (10^{-18}–10^{-13} μGy h^{-1}) and the ratio of those with high contribution of wet deposition (>90%). From the results, the ratio of grid-case number for which the contribution of wet deposition exceeded 90% increased from 26 to 100% as the criteria values of air dose rate increased from 10^{-18} to 10^{-13} μGy h^{-1}. This result indicates that wet deposition is a major cause of the increase of air dose rate in areas with frequent occurrence of exceedingly high air dose rate. Thus, the layout of monitoring posts in this area can capture the distribution pattern of the deposition amount and consequent air dose rate (ground shine) during periods without rainfall. However, planning of additional measurements, such as mobile monitoring, in rainy-weather cases in the high-frequency areas is required.

5. Conclusion

By reflecting on the experiences and lessons learned from the applications of WSPEEDI to cope with the discharge of radioactive materials into the atmosphere caused by the actual nuclear accident, we developed the atmospheric-dispersion database system that can respond to various needs for dispersion prediction in a nuclear emergency and provide useful information for emergency-response planning. It is possible to immediately obtain the prediction results by applying the source term to the database of dispersion-calculation results that was prepared in advance without specifying source term (released radionuclides, release rate, and release period). The performance test showed the effectiveness of the database system, which can output prediction results at a speed several tens to hundreds of times faster than the conventional dispersion calculation by the original GEARN model.

The analysis method of the database system was applied to estimate source term of the FDNPS accident. In that analysis, the source term and atmospheric dispersion simulation were optimized by objective analysis based on Bayesian inference using various measurements. As a result, the atmospheric dispersion simulation successfully reproduced both air concentrations and surface depositions, and these data are used for comprehensive dose assessment by coupling with the behavioral patterns of evacuees from the FDNPS accident.

By performing this calculation with past long-term meteorological-analysis data and preparing the output as a database, it is possible to immediately get dispersion-calculation results for various source term and meteorological conditions. The database can be used for pre-accident planning in nuclear emergency preparedness by the following applications:

- Understanding events to be supposed in considering countermeasures in emergency by atmospheric dispersion analysis for various hypothetical source terms
- Extraction of problems in a monitoring plan by using simulated monitoring data generated by the database system with an assumed accident scenario, in emergency-response training
- Examination of the effective monitoring method considering meteorological conditions and topographic characteristics by analyzing dispersion-calculation results for various past weather conditions.

Disclosure statement

No potential conflict of interest was reported by the authors.

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