Improvement of the computer-based decision support system “WSPEEDI” for nuclear emergency by introducing MM5 and its application to the Chernobyl accident

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1. Introduction

In 1986, the Chernobyl nuclear accident necessitated the evaluation of long-range transport of airborne radioactivity due to a severe nuclear accident in a foreign country. In response to this requirement, a computer-based decision support system, “WSPEEDI” (Worldwide version of System for Prediction of Environmental Emergency Dose Information) has been developed to predict the radiological impacts on the Japanese people due to a nuclear accident abroad by Japan Atomic Energy Research Institute (Chino et al., 1995).

WSPEEDI has been composed of two models, mass-consistent wind field model WSYNOP and particle dispersion model GEARN. The short points of these models are as follows:

1. Although the ranges of contamination are various, e.g., local, regional and global scale, WSPEEDI has no capability for simultaneous multi-scale predictions in such multiple regions.
2. The treatment of atmospheric boundary layer is simple, e.g., the time and space variation of the mixed layer is not considered.
3. The three-dimensional structure of precipitation is not considered for wet deposition.

To solve these problems, a meso-scale meteorological prediction model MM5 (Grell et al. 1994) is introduced to WSPEEDI in addition to WSYNOP. MM5 is a non-hydrostatic atmospheric dynamic model developed by the Pennsylvania State University and the National Center for Atmospheric Research (NCAR), which has many functions such as the choice of various physical options, the domain nesting calculation and the four-dimensional data assimilation. MM5 calculates meteorological fields with high resolution in time and space based on atmospheric dynamic equations. With the introduction of MM5, GEARN is modified to interface and utilize input data provided from MM5.

This new version of WSPEEDI is applied to the Chernobyl accident for model validation in this work.

2. Outline of model improvements

The model structure and calculation flow of new and old WSPEEDI are shown in Fig. 1.

Because the spatial and temporal resolutions of available meteorological input data are generally too coarse to use for atmospheric dispersion model, WSYNOP and MM5 reconstruct meteorological fields with finer meshes in the objective region. In WSYNOP only wind field and precipitation are calculated by interpolation and objective analysis of meteorological input data. On the other hand, MM5 can predict three-dimensional fields on wind, precipitation, diffusion coefficients, etc., with high resolution in time and space based on atmospheric dynamic equations. Therefore, GEARN combined with MM5 (GEARN-new) is expected to be improved in the simulation of three-dimensional dispersion and deposition of radionuclides by using sufficient input data from MM5.

GEARN-new is a Lagrangian particle dispersion model. The horizontal coordinate system is the map coordinates \((x_m, y_m)\) common to MM5, and the vertical one the terrain-following

Fig. 1 The structure and calculation flow of old and new version of WSPEEDI.
coordinate \((z^*-coordinate)\) described as the following equations,
\[
z^* = \frac{z - z_g}{h}, \quad h = (z_e - z_g)/z_e,
\]
where \(z\) is the vertical coordinate in Cartesian coordinates, \(z_g\) the terrain height, and \(z_e\) a specified constant top height of model domain.

Concerning the transport of radionuclides, GEARN-new solves the following advection and diffusion equation by the Lagrangian method in the \((x_m, y_m, z^*)\) coordinate system, when \((x_m, y_m, z^*)\) is expressed as \((x, y, z^*)\) for convenience,
\[
\frac{\partial C^*}{\partial t} + u_m \frac{\partial C^*}{\partial x} + v_m \frac{\partial C^*}{\partial y} + w^* \frac{\partial C^*}{\partial z} = K_{x,m} \frac{\partial^2 C^*}{\partial x^2} + K_{y,m} \frac{\partial^2 C^*}{\partial y^2} + K_{z,m} \frac{\partial^2 C^*}{\partial z^2},
\]
where \(C^*\) (Bq/m³) is the concentration, \(u_m, v_m\) (m/s) the horizontal wind components, \(w^*\) (m/s) the vertical wind, \(K_{x,m}\) and \(K_{y,m}\) (m²/s) the horizontal diffusion coefficients, and \(K_{z,m}\) (m²/s) the vertical diffusion coefficient. The horizontal wind components are provided from MM5. The vertical wind \(w^*\) is calculated by the interpolation of \(w\) on the \(\sigma^*\)-coordinate of MM5.

Horizontal diffusion coefficients, \(K_{x,m}\) and \(K_{y,m}\), are calculated from the following equation,
\[
K_{x,m} = \frac{\sigma_r}{h^2} \frac{1}{2h} \int_0^h \frac{dr}{dt} dr^2,
\]
where \(\sigma_r\) is the standard deviation of horizontal distribution from Gifford. The vertical diffusion coefficient is provided from MM5.

The wet deposition is modeled by the following equations,
\[
\frac{dq_n}{dt} = -\Lambda q_n,
\]
where \(q_n\) (Bq) is the radioactivity of \(n\)-th particle, \(\Lambda\) (1/s) the scavenging coefficient. In the GEARN combined with WSYNOP, it is assumed that the precipitation scavenging occurs in the whole vertical column where precipitation occurs at the surface. Then, scavenging coefficient is expressed as the following,
\[
\Lambda(x, y, z, t) = \alpha \gamma^\beta,
\]
where \(\alpha\) and \(\beta\) the parameters determined for each nuclide and \(\gamma\) (mm/h) the precipitation intensity.

GEARN-new calculates the precipitation scavenging by non-convective precipitation in the cell where the sum of mixing ratio of rainwater, snow and graupel is larger than 0 and the non-convective precipitation exists at the ground surface of vertical column including the cell. As for the precipitation scavenging by convective precipitation, the model assumes that precipitation occurs in the cell below the cloud top and the convective precipitation exists at the ground surface below the cell. The cloud top is defined as the top height of the cell where the accumulated cloud fractional cover is larger than 0. Then, new scavenging coefficient is expressed as the following equation,
\[
\Lambda(x, y, z, t) = \alpha \gamma_{con}^\beta \gamma_{non}^\beta ,
\]
where \(\gamma_{con}\) and \(\gamma_{non}\) are the convective and non-convective precipitation intensity, and \(q_{rain}\), \(q_{snow}\) and \(q_{graupel}\) the mixing ratios of rain, snow, and graupel accumulated during output time interval. Using this scavenging coefficient, wet deposition is calculated only when the particle exists in the cell where precipitation is occurring.

Because MM5 outputs vertical diffusion coefficient, precipitation, cloud fractional cover, and mixing ratios of rain water, snow, etc., GEARN can consider the temporal and spatial variations of three-dimensional diffusion coefficients for calculating dispersion and three-dimensional precipitation structure for wet deposition.
The Reynolds optimally interpolated weekly SST data set is used. About MM5 physical options, ‘Grell’ is used for cumulus parameterization, ‘Goddard’ for cloud microphysics, ‘MRF’ for planetary boundary layer (PBL) scheme.

It is assumed that Cs-137 was released from 00UTC 26 April to 00UTC 7 May in 1986 with time varying daily release rate. The release rates of Cs-137 are deduced from the ATMES project which evaluates the performance of long-range transport models using Chernobyl data. The release point is 51.138°N, 30.036°E (the circle painted in black in Fig. 2), and release height is roughly assumed as 1,500 m above the ground during the first 6 hours of the accident, 600 m throughout the following 42 hours to 00UTC by 28 April, and 300 m after that. The vertical depth of GEARN-new domain is 7,500 m and divided into 20 layers. The depth of bottom layer is set to 100 m. Time increments of MM5 and GEARN-new are 90 s and 120 s, respectively. Meteorological fields and air concentrations are calculated every three hours. Fujitsu vector-parallel computer VPP5000 is used to execute calculations.

**b. Results**

The general feature of the movement of the radioactive plume was similar to the consequences of former studies (e.g., Ishikawa...
The comparisons of calculated surface air concentrations of Cs-137 with the measurements are presented in Fig. 3 for 10 measurement points shown in Fig. 2. The measurement data used for the comparison are from Raes et al. (1989). The thin line represents the calculated results and the bold line the measured surface air concentrations. The background value of the surface air concentration of Cs-137 was 10^{-6} to 10^{-5} Bq/m^3 over Europe before the Chernobyl accident.

At Stockholm, Riso and Oslo, model simulated the occurrence of two major peaks of the surface air concentrations at the end of April and the early May. At Helsinki, Budapest, Saluggia, Cadarache, calculated results were generally in good agreement with measurement throughout the calculation period. The calculated concentration was slightly underestimated in 27 April at Riso, whereas rather overestimated during the early May at Helsinki, Stockholm, Riso, Oslo and Budapest. However, these differences in the values of air concentrations were within one order. At Mol and Harwell, the increase of air concentration was measured between 1 May and 3 May, and it was well simulated by calculation. At Saclay, the calculation agreed with measurement between 1 May and 2 May. At Helsinki, the detection of Cs-137 concentration between 2 and 7 May was not calculated by former studies, however, the new version of WSPEEDI could simulate it.

Figure 4 shows the scatter diagram of the measured and calculated surface air concentration of Cs-137. In producing this figure, the measured and calculated concentrations were reproduced to the daily averaged values. Totally, 150 points are plotted in Fig. 4 and several points on the vertical axis indicate that the calculated concentrations are less than 10^{-5} Bq/m^3. 107 points (71%) of calculated concentrations are within a factor of 10 of measured concentrations. This percentage is about 1.8 times as that of former studies (Ishikawa and Chino 1991).

These comparisons suggest that the present combination of models MM5/GEARN-new can simulate the transport of radioactivity over Europe quite well.

4. Conclusions

The combination of models, the atmospheric dynamic model, MM5 and the Lagrangian particle dispersion model, GEARN-new was introduced to WSPEEDI to improve the capability of prediction.

The results obtained by the calculations for the Chernobyl accident indicates that the combination of MM5/GEARN-new works well for the prediction of transport of radionuclides. The dispersion of Cs-137 due to the Chernobyl nuclear accident over the European region was calculated quite realistically in the quality such as the timing of arrival of the plume and the duration of high concentration appearance.

The verification studies for the combination of models MM5/GEARN-new will be continued by comparisons with local and regional deposition data around Chernobyl.

References


