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# Three-dimensional dose evaluation system using real-time wind field information for nuclear accidents in Taiwan

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**Abstract**

In Taiwan, the three operating nuclear power plants are all built along the coast over complex terrain. Dose estimates after a nuclear accident with releases of radioactive materials, therefore, cannot be accurately calculated using simple dispersion models. We developed a three-dimensional dose evaluation system, which incorporates real-time prognostic wind field information with three-dimensional numerical models to predict dose results. The proposed system consists of three models: a three-dimensional mesoscale atmospheric model (HOTMAC), a three-dimensional transport and diffusion model (RAPTAD), and a dose calculation model (DOSE). The whole-body dose and thyroid dose as well as dose rates can be rapidly estimated and displayed on the three-dimensional terrain model constructed by satellite images. The developed three-dimensional dose evaluation system could accurately forecast the dose results and has been used in the annual nuclear emergency response exercise to provide suggestions for protective measures.

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*Keywords:* Dose evaluation; Nuclear accident; HOTMAC/RAPTAD

## 1. Introduction

Emergency responses and protective actions taken for nuclear accidents differ from those for other accidents. According to the major nuclear disaster at Chernobyl in 1986 and other events related to accidental dispersion of radioactive sources, once accidents involving releases of radioactive materials have occurred, consequences for the general public and society are potentially catastrophic [1]. Therefore, the emergency response planning has to be prepared in advance to ensure that all necessary resources are available to protect the public from radiation exposure. In Taiwan, there are three operating nuclear power plants; they are Chinshan, Kuosheng, and Maanshan; the fourth one, Longmen, is under construction. According to the National Nuclear Emergency Response Plan published in 1980, the authority has to designate an Emergency Planning Zone (EPZ) for each plant in which the dose distribution must be evaluated in case of a nuclear accident.

Since 1996, the Institute of Nuclear Energy Research (INER) of Taiwan has developed two emergency radiological dose evaluation systems, which can estimate dose rates and projected doses with specific source terms. The Protective Action and Dose Evaluation System (PADES) [2] is a two-dimensional dose evaluation system, using a Gaussian plume model and straight-line trajectory model to calculate the dispersion of radioactive materials in the downwind direction. Gaussian plume models work well under idealized meteorological and boundary conditions but require too many assumptions to be useful

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for applications where meteorological variables change rapidly with time and space. Therefore, a more sophisticated wind field simulation and dispersion modeling should be employed to provide a more accurate dose prediction.

The Radiological Dose Prediction System (RPDOSE) [3] is another dose assessment program developed by the INER, which uses a three-dimensional Lagrangian random puff model and the digital terrain model of Taiwan to simulate the dispersion of radioactive materials over complex terrain. Typical wind fields for each season based on a long-term observation of meteorological conditions were embedded in this system for each plant. However, using a few typical wind fields as weather forecasts over the next 4 days is not enough to cover all kinds of meteorological phenomena for the subtropical climate in Taiwan.

In this study, we proposed a new version of RPDOSE, which combined real-time wind field information with the Lagrangian random puff model for accurately simulating the dispersion of radioactive materials and calculating projected doses and dose rates in case of a serious nuclear accident. The real-time wind field information provided by the Central Weather Bureau (CWB) of Taiwan is automatically transferred to the INER through the Internet. After calculating the concentration distributions of releases, the dose distributions can be obtained and displayed on a personal computer at the Nuclear Emergency Radiation Monitoring and Dose Assessment Center to provide suggestions of protective measures for the radiological emergency response.

## 2. Models

The three-dimensional dose evaluation system, RPDOSE, employs numerical models to predict the concentration distributions of radioactive materials within 4 days, and then calculates the dose distributions according to various exposure pathways. The system can be divided into three main parts in terms of their functions: mesoscale atmospheric modeling, radioisotope transport and diffusion, and dose calculation and demonstration, as described below.

### 2.1. HOTMAC

The Higher Order Turbulence Model for Atmospheric Circulation (HOTMAC) developed by Los Alamos National Laboratory is a mesoscale atmospheric model for forecasting three-dimensional distributions of wind speed, wind direction, temperature, water vapor, and turbulence over complex terrain [4–7]. The governing equations of HOTMAC are based on the conservation equations for mass, momentum, internal energy, mixing ratio of water vapor, and turbulence kinetic energy. It can take account of nocturnal drainage flows, convective upslope flows, and the shadow effect of solar shortwave, which are relatively important because the nuclear power plants in Taiwan are all located against the mountain facing the ocean.

A nested grid technique is used in the HOTMAC model, enabling us to address the specific area around the nuclear power plants in finer details with only a moderate increase in computational cost. The HOTMAC atmospheric modeling has been applied in some pollutant transport studies, and has been proven to successfully simulate the wind field under severe weather conditions [8].

### 2.2. RAPTAD

The RAndom Puff Transport and Diffusion (RAPTAD) model is a three-dimensional Lagrangian puff model, based

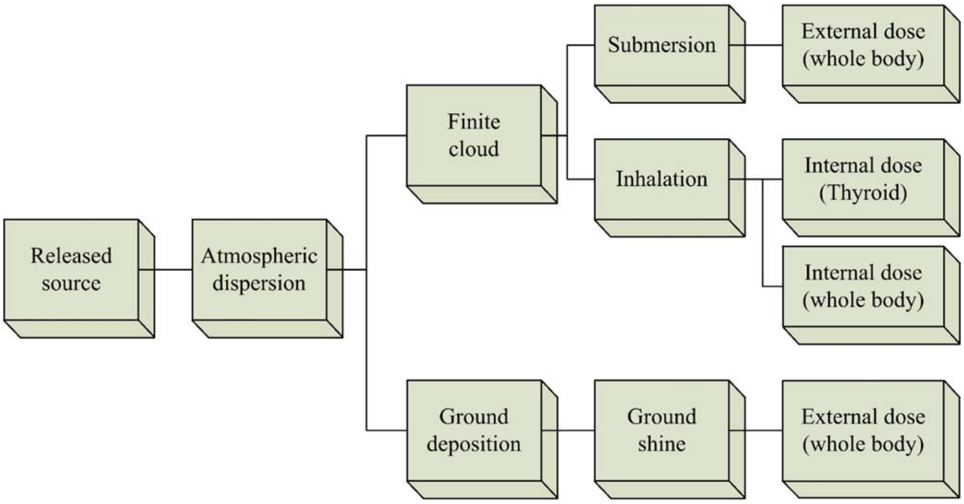


Fig. 1. The exposure pathways considered in the DOSE program.

on a random displacement method. It is used to calculate the transport and diffusion of airborne materials. The initial inputs required for simulating a puff are the wind conditions and turbulence parameters provided by the HOTMAC. When dealing with a continuous release, the original plume is divided into a number of individual puffs, which can be simulated separately. Subsequently, the concentration distribution at any given time is computed by summing all these individual puffs.

Table 1
Radionuclides calculated for accidental releases

| Nuclide | Half-life (days) | Nuclide | Half-life (days) |
|---|---|---|---|
| Kr-85 | 3950 | Co-58 | 71.0 |
| Kr-85m | 0.183 | Co-60 | 1920 |
| Kr-87 | 0.0528 | Mo-99 | 2.80 |
| Kr-88 | 0.117 | Tc-99m | 0.25 |
| Xe-133 | 5.28 | Ru-103 | 39.5 |
| Xe-135 | 0.384 | Ru-105 | 0.185 |
| I-131 | 8.05 | Ru-106 | 366 |
| I-132 | 0.0958 | Rh-105 | 1.5 |
| I-133 | 0.875 | Y-90 | 2.67 |
| I-134 | 0.0366 | Y-91 | 59.0 |
| I-135 | 0.280 | Zr-95 | 65.2 |
| Rb-86 | 18.7 | Zr-97 | 0.71 |
| Cs-134 | 750 | Nb-95 | 35.0 |
| Cs-136 | 13.0 | La-140 | 1.67 |
| Cs-137 | 11,000 | Ce-141 | 32.3 |
| Te-127 | 0.391 | Ce-143 | 1.38 |
| Te-127 m | 109 | Ce-144 | 284 |
| Te-129 | 0.048 | Pr-143 | 13.7 |
| Te-129m | 34.0 | Nd-147 | 11.1 |
| Te-131m | 1.25 | Np-239 | 2.35 |
| Te-132 | 3.25 | Pu-238 | 32,500 |
| Sb-127 | 3.88 | Pu-239 | $8.9 \times 10^6$ |
| Sb-129 | 0.179 | Pu-240 | $2.5 \times 10^6$ |
| Sr-89 | 52.1 | Pu-241 | $5.35 \times 10^3$ |
| Sr-90 | 10,300 | Am-241 | $1.6 \times 10^5$ |
| Sr-91 | 0.403 | Cm-242 | 163 |
| Ba-140 | 12.8 | Cm-244 | 6630 |

Table 2
Source terms and parameters used in the annual nuclear emergency response exercise conducted in 2005

| Case | Release date, time | Release duration (min) | Released radionuclides and activities (Bq) |
|---|---|---|---|
| 1 | 08/24/2005, 22:00 | 30 | I-131: $8.1 \times 10^6$<br>Kr-85: $9.3 \times 10^{13}$<br>Cs-137: $4.4 \times 10^5$ |
| 2 | 08/24/2005, 22:30 | 30 | I-131: $2.7 \times 10^7$<br>Kr-85: $2.4 \times 10^{14}$<br>Cs-137: $1.3 \times 10^6$ |
| 3 | 08/24/2005, 23:00 | 30 | I-131: $6.7 \times 10^7$<br>Kr-85: $2.8 \times 10^{14}$<br>Cs-137: $1.7 \times 10^6$ |
| 4 | 08/24/2005, 23:30 | 30 | I-131: $7.0 \times 10^7$<br>Kr-85: $4.8 \times 10^{14}$<br>Cs-137: $2.7 \times 10^6$ |
| 5 | 08/25/2005, 00:00 | 30 | I-131: $6.3 \times 10^7$<br>Kr-85: $4.1 \times 10^{14}$<br>Cs-137: $8.3 \times 10^5$ |
| 6 | 08/25/2005, 00:30 | 30 | I-131: $4.1 \times 10^5$<br>Kr-85: $9.3 \times 10^{11}$<br>Cs-137: $4.8 \times 10^4$ |

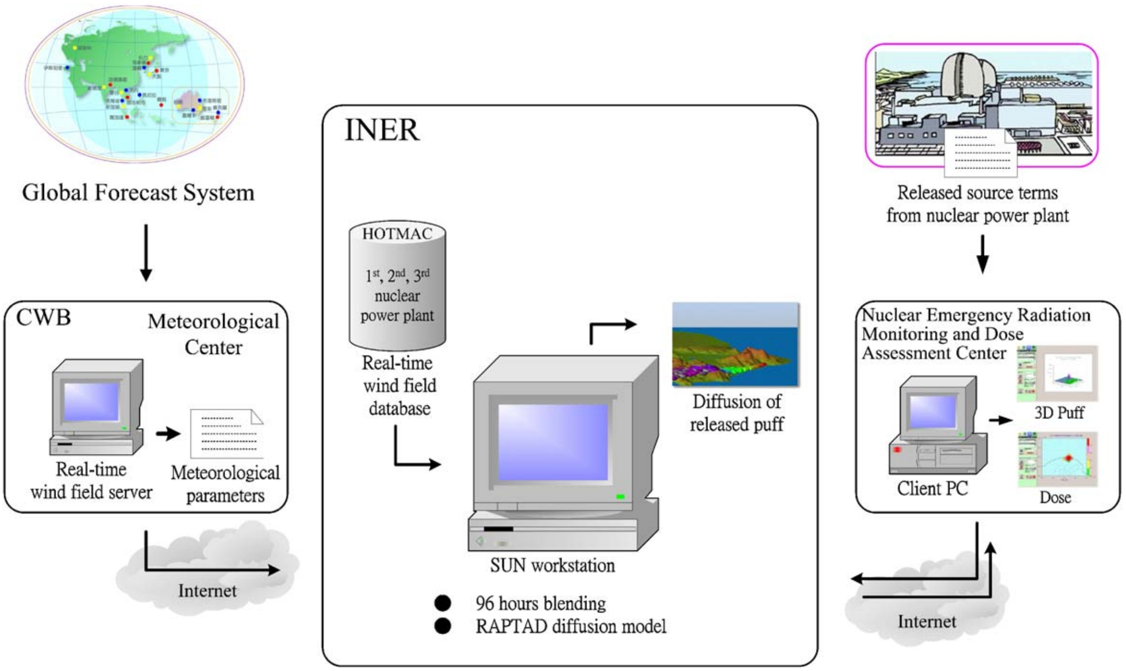


Fig. 2. The framework of the three-dimensional dose evaluation system.

The HOTMAC/RAPTAD modeling system is particularly useful for prediction of transport and diffusion processes over complex terrain where conventional methods fail. It has previously been tested against meteorological and tracer datasets with good results [6–8]. Yamada et al. [9] also compared the results predicted by the model with the data collected during the Mountain Iron diffusion experiment [10], and found that HOTMAC/RAPTAD predictions are potentially better than those obtained by diagnostic and empirical models. Therefore, this advanced forecasting capability gives us a promise of more accurate estimation of the dose distributions.

### 2.3. DOSE

After a release of radioactive plume, dose evaluation is performed by the DOSE program, which consists of two main functions, dose calculation and dose and puff demonstration. For dose calculation, DOSE can estimate cumulated doses over 4 days during the emergency phase. It can also provide suggestions for decision-making by comparing the dose results with the Protective Action Guide (PAG) levels. The exposure pathways considered in the algorithm include submersion and inhalation from a finite cloud as well as groundshine from ground-deposited materials (Fig. 1). The whole-body dose and thyroid dose contributed from these pathways are calculated using the atmospheric dispersion coefficients ($F_r$) provided by the RAPTAD, radionuclide release rates ($Q_0'$) provided by the Probabilistic Risk Assessment (PRA) information or by observation, and corresponding dose coefficients ($K$) adopted from various libraries. The doses contributed from a finite cloud can be expressed as

$$\begin{bmatrix} EC_0 \\ IC_0 \\ TC_0 \end{bmatrix} = Q_0' \times F_r \times \begin{bmatrix} K_{EC_0} & F_c \\ K_{IC_0} & B \\ K_{TC_0} & B \end{bmatrix} \times \frac{\exp[-\lambda(T_r + T_a)] \times [1 - \exp(-\lambda T_e)]}{\lambda} \tag{1}$$

where $EC_0$ is the whole-body dose from submersion, $IC_0$ the whole-body dose from inhalation, and $TC_0$ the thyroid dose from inhalation. $T_r$, $T_a$, and $T_e$ are the time between the occurrence of an accident and the release of a plume, the time when the plume reaches the target area, and the time when the plume passes the target area, respectively. $F_c$ is a correction factor from an infinite cloud to a finite cloud [11]. $B$ is the breathing rate ($3.4 \times 10^{-4}\,\mathrm{m^3/s}$) and $\lambda$ is the decay constant of a given radionuclide. Furthermore, the whole-body dose contributed from groundshine ($FD_0$) can

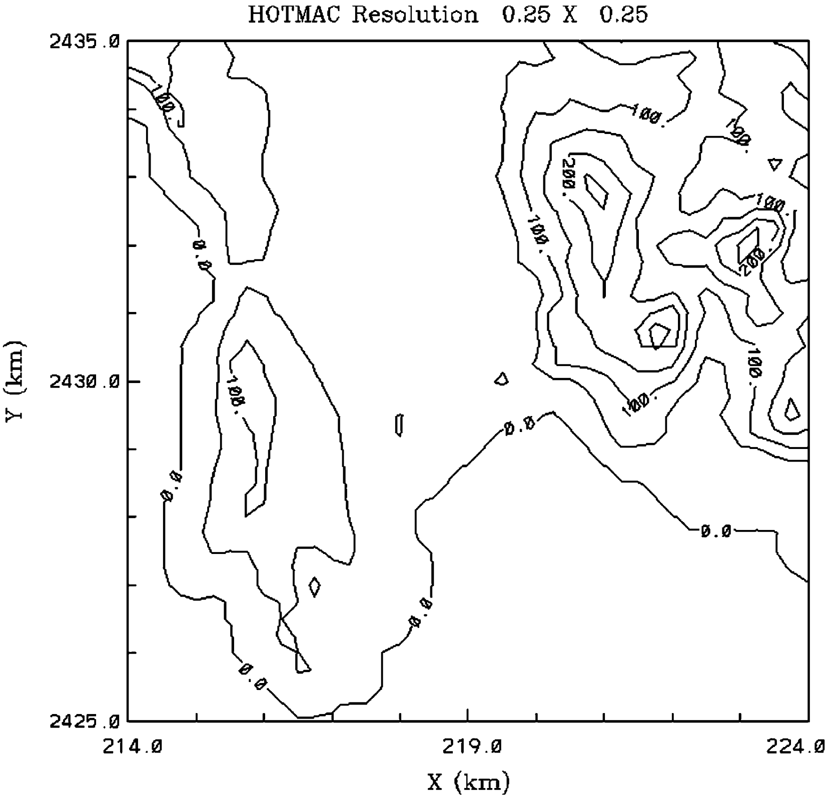


Fig. 3. The topography in the study area around the Maanshan nuclear power plant.

be expressed as

$$
\begin{aligned}
FD_0 &= K_{FD_0}\int_0^{T_e} F(t)\,dt \\
&= \frac{K_{FD_0}}{\lambda^2}\{\chi_0 \times V_d \times [1-(\lambda T_e+1)\exp(-\lambda T_e)] \\
&\quad +\lambda F_d[1-\exp(-\lambda T_e)]\} \qquad (2)
\end{aligned}
$$

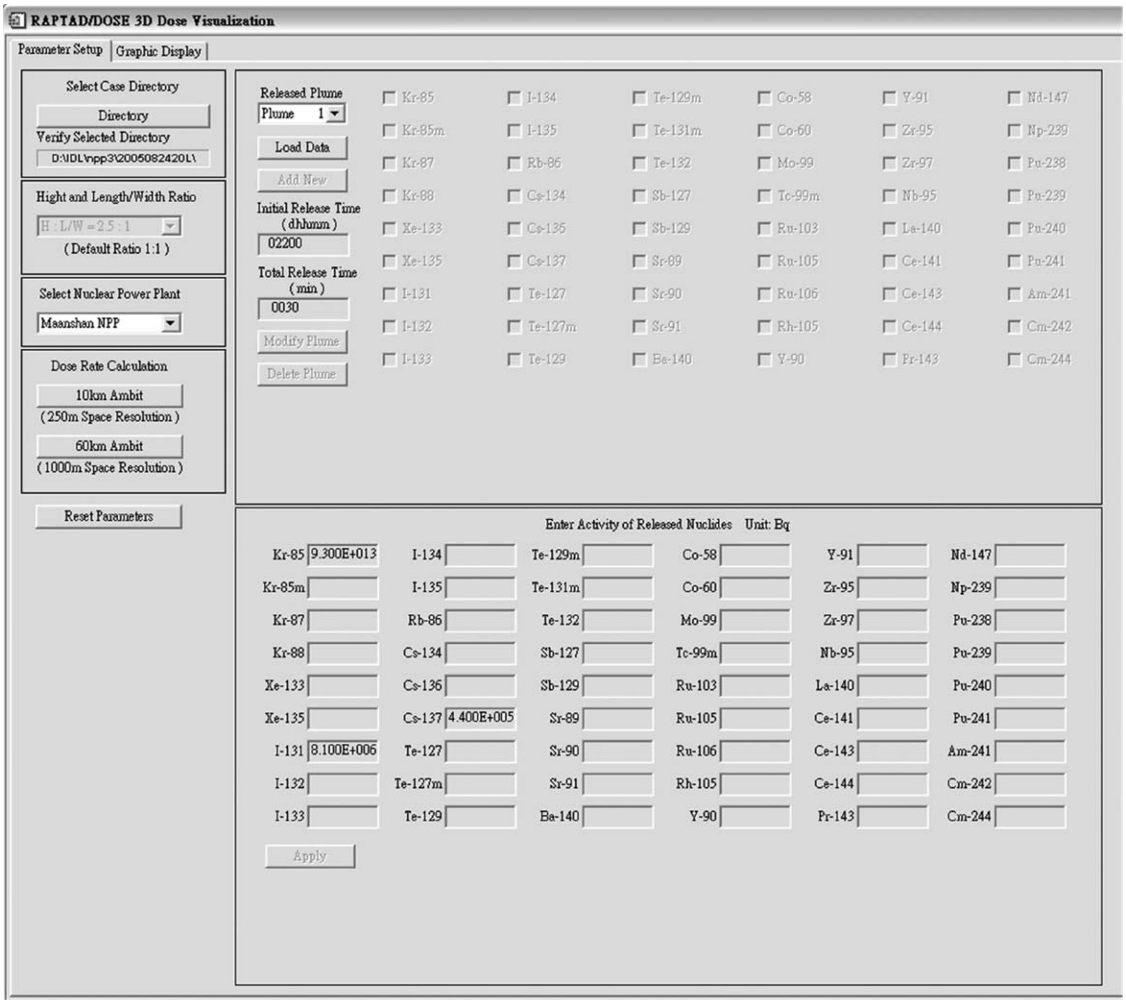
where $\chi_0 = Q_0' \times F_r \times \exp[-\lambda(T_r + T_a)]$, $V_d$ is the deposition velocity (0.3 cm/s) [12], and $F_d$ is the cumulated deposition from the previous plumes.

A total of 54 radionuclides that were considered important for accidental releases of nuclear facilities can be computed for their dose contributions (Table 1). For the exposure pathways of submersion and groundshine, the dose coefficients for these radionuclides were taken from the recommendations of the Radiation Protection Bureau of Health Canada, Atomic Energy Control Board [13] and the IAEA Safety Series No. 115 [14]; for the pathway of inhalation, the dose coefficients were obtained from the ICRP Database of Dose Coefficients: Workers and Members of the Public version 2.0.1 [15,16].

## 2.4. Functional structure

The framework of the three-dimensional dose evaluation system is shown in Fig. 2. The CWB analyzed monthly meteorological phenomena around each nuclear power plant using the observation data collected in the last 20 years. The HOTMAC simulations were performed using these statistical data to create approximately 900 sets of the 24-h wind field and turbulence field, which were then installed in the database server at the INER. Presently, the CWB provides a 4-day weather forecast every 12 h using its Global Forecast System, and sends a series of characteristic parameters to the INER automatically for selecting a proper set of atmospheric conditions.

When a nuclear disaster occurs, the Nuclear Emergency Radiation Monitoring and Dose Assessment Center will be



Verify Selected Directory: D:\IDL\npp3\2005082420L\

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Maanshan NPP

Released Plume: Plume 1

Initial Release Time (dhhmm): 02200

Total Release Time (min): 0030

Enter Activity of Released Nuclides Unit: Bq

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Kr-85 | 9.300E+013 | I-134 | | Te-129m | | Co-58 | | Y-91 | | Nd-147 | |
| Kr-85m | | I-135 | | Te-131m | | Co-60 | | Zr-95 | | Np-239 | |
| Kr-87 | | Rb-86 | | Te-132 | | Mo-99 | | Zr-97 | | Pu-238 | |
| Kr-88 | | Cs-134 | | Sb-127 | | Tc-99m | | Nb-95 | | Pu-239 | |
| Xe-133 | | Cs-136 | | Sb-129 | | Ru-103 | | La-140 | | Pu-240 | |
| Xe-135 | | Cs-137 | 4.400E+005 | Sr-89 | | Ru-105 | | Ce-141 | | Pu-241 | |
| I-131 | 8.100E+006 | Te-127 | | Sr-90 | | Ru-106 | | Ce-143 | | Am-241 | |
| I-132 | | Te-127m | | Sr-91 | | Rh-105 | | Ce-144 | | Cm-242 | |
| I-133 | | Te-129 | | Ba-140 | | Y-90 | | Pr-143 | | Cm-244 | |

Fig. 4. The user interface of DOSE. The plume information and activity of released radionuclides are required.

held immediately. Once there are radioactive materials released to the atmosphere, this center will execute the RPDOSE system and send corresponding parameters concerning source terms, time, and duration of the release to the INER. Subsequently, the RAPTAD is conducted with the real-time wind field and turbulence field prognosed by the CWB. The concentration distributions of a nested grid with a coarse grid of 1 km resolution within $60 \times 60\,\text{km}^2$ and a fine grid of 0.25 km resolution within $40 \times 40\,\text{km}^2$ centered at the release site are then calculated and transferred back to the center for further dose estimation and demonstration.

## 3. Case demonstration

We calculated the dose results for the Maanshan nuclear power plant according to the source terms used in the annual nuclear emergency response exercise conducted in 2005 in Taiwan. The wind field and turbulence field were selected according to the real-time meteorological forecast provided by the CWB at the time of evaluation. The associated source terms and parameters are listed in Table 2. We use this case as an example to demonstrate the functions of the three-dimensional dose evaluation system. Details about validation of the dose algorithm can be found in Ref. [17].

The topography of the Maanshan nuclear power plant provided for the calculation of wind fields for HOTMAC is shown in Fig. 3. Fig. 4 shows the input interface of source terms and plume information. After the required plume information is provided for transport and diffusion, the three-dimensional dynamic puff trajectory can be calculated and demonstrated as shown in Fig. 5, in which different plumes are represented by different colors. Users can zoom in/out, pan/tilt, and change view direction to obtain the optimal display conditions.

Fig. 6 displays the consecutive whole-body dose rate distributions of the first 4 h within $60 \times 60\,\text{km}^2$. The maximum dose rate level was $1.0 \times 10^{-1}$ mSv/h. Fig. 7 shows the cumulated whole-body dose and thyroid dose over 4 days within the EPZ. Dose range was automatically divided into 10 dose levels. The maximum levels for whole-body dose and thyroid dose were $1.0 \times 10^{-1}$ and $1.0 \times 10^{-3}$ mSv, respectively. We found that the isodose contours of the cumulated dose tended to distribute along the valley and coast. This demonstrates that the three-dimensional dose evaluation system has considered the terrain effect and wind field distribution. Thus, the dose

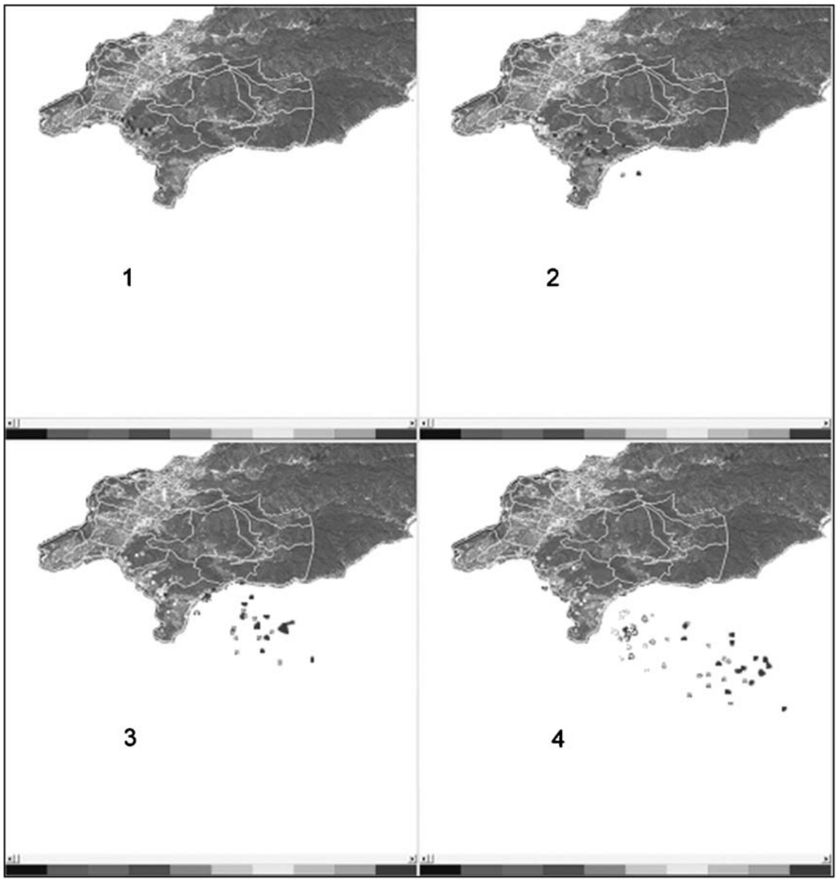


Fig. 5. The three-dimensional dynamic puff trajectory calculated by DOSE. Each plume is represented by different colors shown in the colorbar.

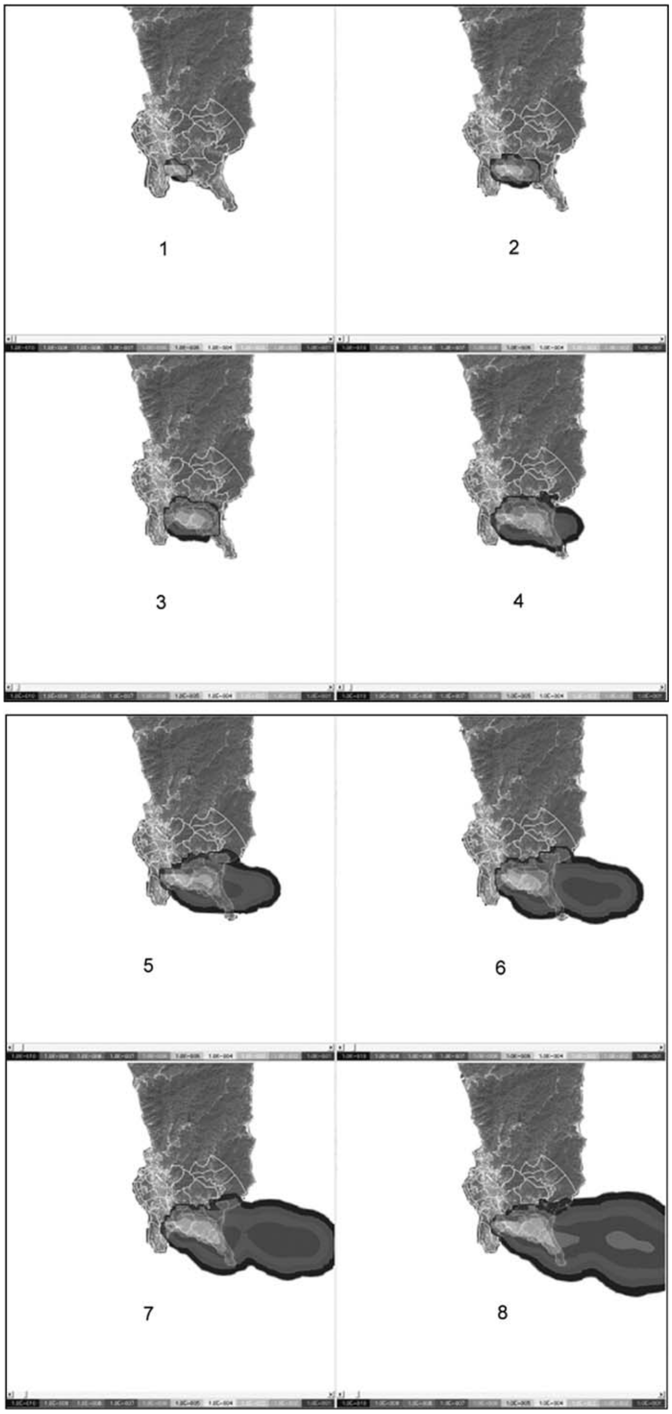


Fig. 6. Whole-body dose rate distributions (mSv/h) of the first 4 h within $60 \times 60\,\mathrm{km}^2$.

estimates calculated by RPDOSE are potentially more accurate than those predicted by the Gaussian model and other empirical models.

## 4. Discussion and conclusion

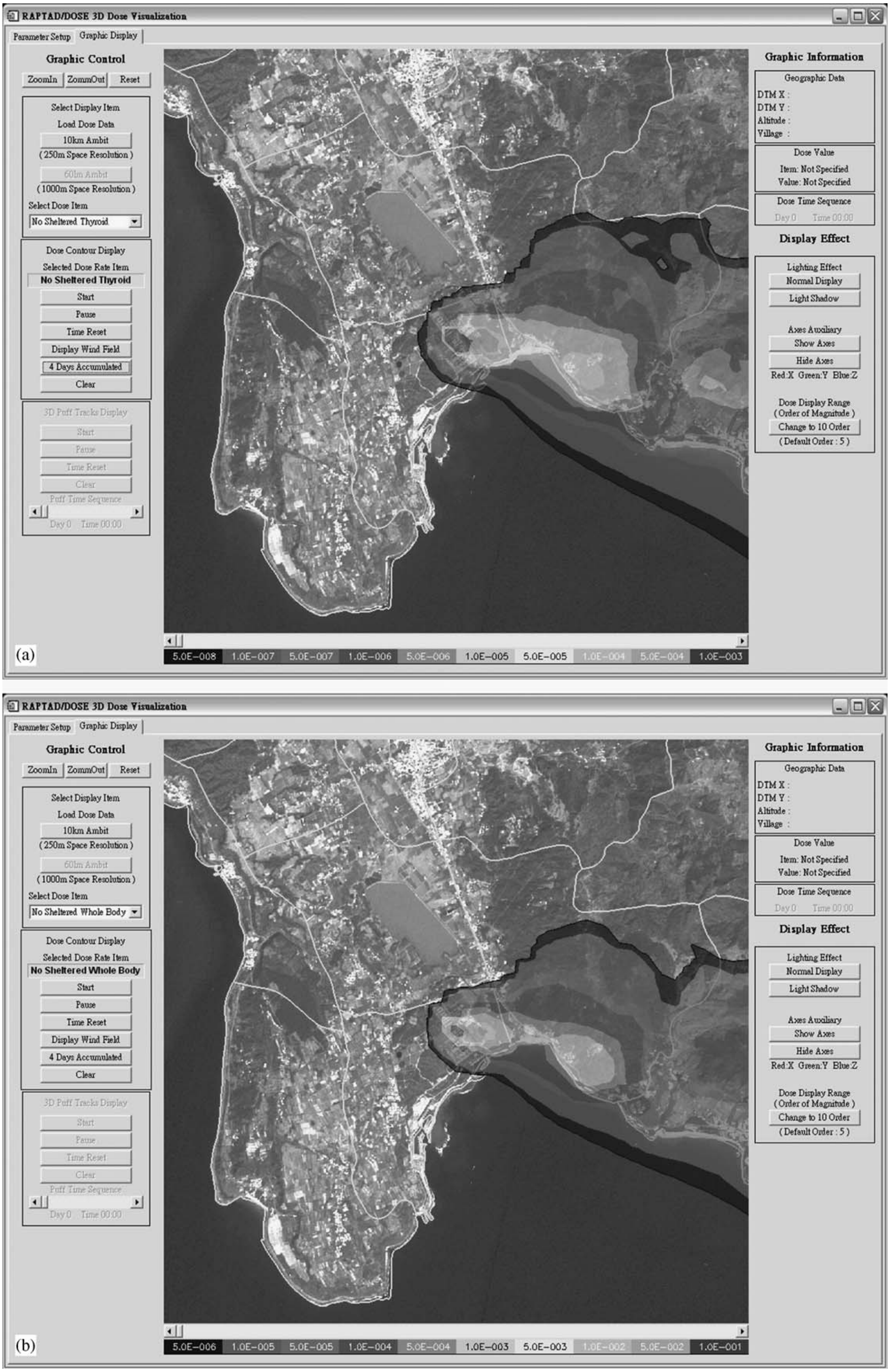
According to government regulations, once a serious nuclear accident or radiological emergency occurs, dose evaluation has to be conducted to provide appropriate suggestions for the protection of the public from radiation exposure during the emergency phase. Therefore, we have constructed a sophisticated and accurate three-dimensional dose evaluation system, RPDOSE, using real-time prognostic wind field information and random puff transport and diffusion model. The RPDOSE currently has been used in the annual nuclear emergency exercise, providing the decision-maker a reference for intervention actions.

In Japan, the Multiple Radiological Emergency Assistance System for Urgent RESponse (MEASURES) is used for utilities to identify the accident conditions and to evaluate the projected doses caused by radioactive releases [18]. The Environmental Dose Projection System (EDPS) is one of the four subsystems in MEASURES. It applies the Regional Atmospheric Modeling System (RAMS) developed by Colorado State University [19] to forecast the airflow status and diffusion status of radioactive materials. The RAMS is a meso-beta scale model ranging from 20 to 200 km [20] with a finest grid spacing of 100 m. Three different spatial grids are used in EDPS including a wide-area grid of $160 \times 160\,\mathrm{km}^2$, a medium-area grid of $40 \times 40\,\mathrm{km}^2$, and a narrow-area grid of $10 \times 10\,\mathrm{km}^2$. A 9-h forecast of this nested grid typically takes 10 min to simulate the grid point values by using a parallel processing system with 24 1.8 GHz XEON CPUs.

The EPZ of the nuclear power plant in Taiwan is presently set to a radius of 5 km, but actually the critical boundary is about 1.5 km [21]. Therefore, we need a storm-scale forecasting system, which can accurately predict the airflows and dispersion of pollutants in the hot zone. Based on this consideration, the HOTMAC/RAPTAD is a better choice than RAMS and other models because it is a meso- to microscale atmospheric model, which has a range less than 2 km with a finest resolution of 4 m. Moreover, it can be executed under the Windows system and has a friendly graphic user interface, which can accelerate the simulation process.

In our system, HOTMAC results have been calculated and stored in advance. No additional computation time is needed when an accident occurs. The execution time for a 4-h RAPTAD forecast is typically less than 3 min using a SPARC64 1.32 GHz workstation and, for the DOSE calculation, it takes about 1 min using a P4 2.0 GHz CPU. Therefore, the proposed three-dimensional dose evaluation system is suitable for a rapid emergency response.

Our future work will focus on the combination of the dose evaluation system and Geographic Information System (GIS). Other necessary databases, such as population distribution, evacuation routes, and decontamination equipments, will be augmented as additional data layers. Once radioactive sources are released to the atmosphere, the GIS can organize all necessary resources to provide suggestions of protective actions. The impact on the public and society in the emergency phase could be minimized, thus promoting greater public confidence in the responsible authority.



(a)

Select Dose Item: No Sheltered Thyroid

Selected Dose Rate Item: No Sheltered Thyroid

Item: Not Specified

Value: Not Specified

(b)

Select Dose Item: No Sheltered Whole Body

Selected Dose Rate Item: No Sheltered Whole Body

Item: Not Specified

Value: Not Specified

Fig. 7. Cumulated (a) whole-body dose and (b) thyroid dose over 4 days within the EPZ.

## Acknowledgments

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