A Real-Time Accident Consequence Assessment System for Tianwan NPP

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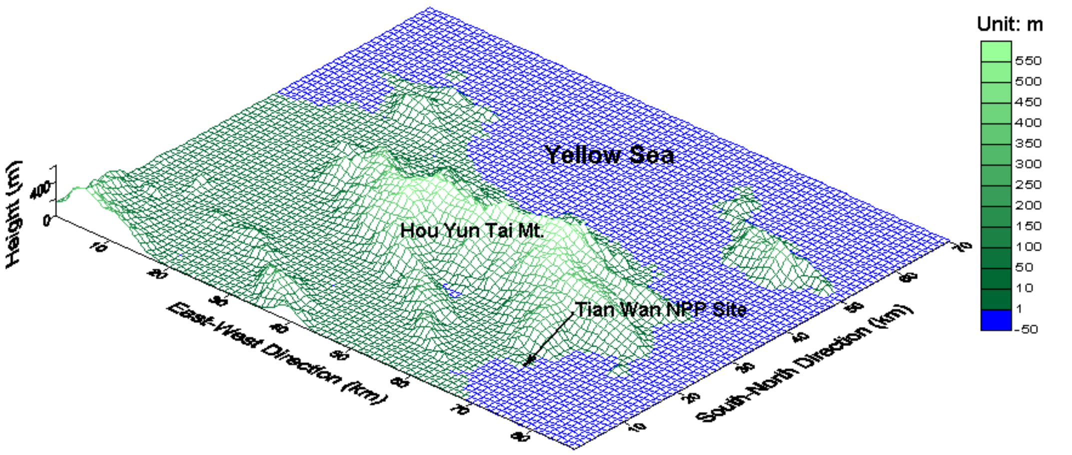
Abstract. A comprehensive real-time nuclear accident consequence assessment system, TW-NAOCAS, designed for real-time assessment of nuclear accidental releases from Tianwan Nuclear Power Plant (NPP) to off-site local scale, has been established by integrating a number of existing preprocessors, wind field forecasting, atmospheric dispersion, dose estimating and intervention countermeasure models together with on-line available meteorology. The system provides a mean for quickly determining the concentration distributions of radioactive materials, various dose levels and areas by dose intervention levels during the early phase of the release after accident. The preliminary results of model-evaluation and system-system intercomparison demonstrate that the numerical methods used in the TW-NAOCAS system are accurate, and that transport and dispersion of tracers was generally well simulated in the microscale and mesoscale cases studied.

KEYWORDS: Nuclear Accidental; Off-site Consequence; Assessment System; Tianwan NPP.

1. Introduction

Tianwan Nuclear Power Plant (NPP) located in Lianyungang on the eastern coast of China and located at 119.5°E vs. 34.7°N is composed of 2×1000 MW WWER-1000/428 PWR units introduced from Russia. The reactor is double contained (inner and outer shells) ensuring the maximum protection against accidental radioactive release into the environment. Unit 1 went into commercial operation on May 17, 2007 and Unit 2 on August 16, 2005. The design lifetime of the NPP main equipment is 40 years. Tianwan NPP site is located in the eastern part of Lianyungang City area on the east shore of Yellow Sea and is surrounded by mountains. The most prominent topographical feature is a 500 to 600m range of mountains named by Hou Yun Tai (HYT). **Figure 1** shows the topographic map of the site.

Figure 1: Location of Tianwan NPP and topography map.



This paper describes a comprehensive nuclear accident consequence assessment system, named TW-NAOCAS, and its on-going evaluation. This system was designed for real-time assessment of

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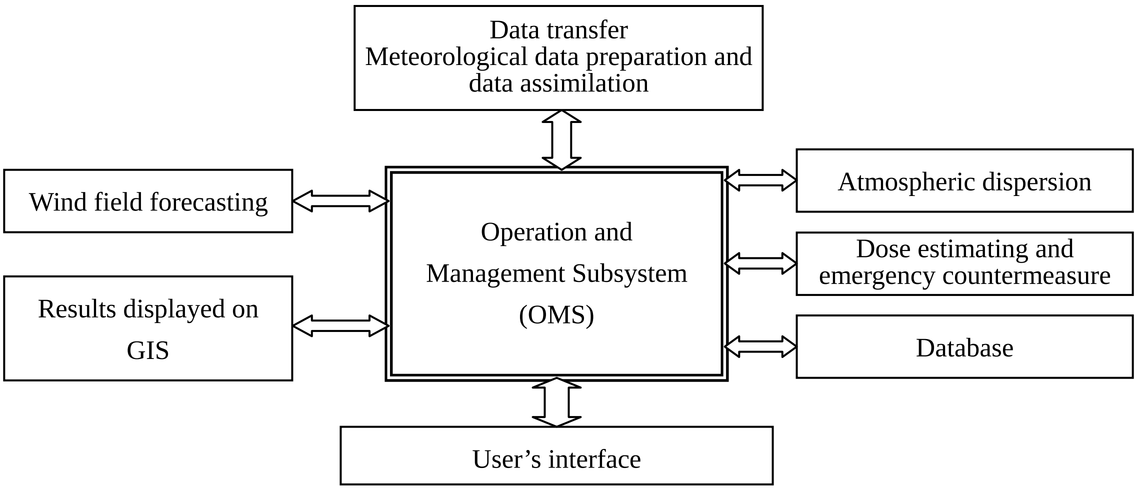
nuclear accidental releases from the Tianwan NPP to off-site local scale. The development of TW-NAOCAS has been achieved through the successful integration of state-of-the-art knowledge across a wide range of disciplines. Its flexible coding enables it to cope with different sites of NPP through changing site and plant characteristics, GIS data, statistical data on grids, emergency management data, etc. This system contains preprocessors together with on-line available meteorology, wind field forecasting, dispersion, and dose estimating and emergency countermeasure models.

2. Overview of Software Systems

Figure 2 shows the construction of TW-NAOCAS system. The general design idea is that the Operation and Management Subsystem (OMS) written in the VB language is the core of the whole system which controls the input and output data and run manners of all other subsystems and physical modules. The system allows to define runs for the early phase modules without the selection of the model itself and also runs different model chains in the interactive manner for the routine calculations and analysis, training, etc.

Figure 2: Construction of TW-NAOCAS system.



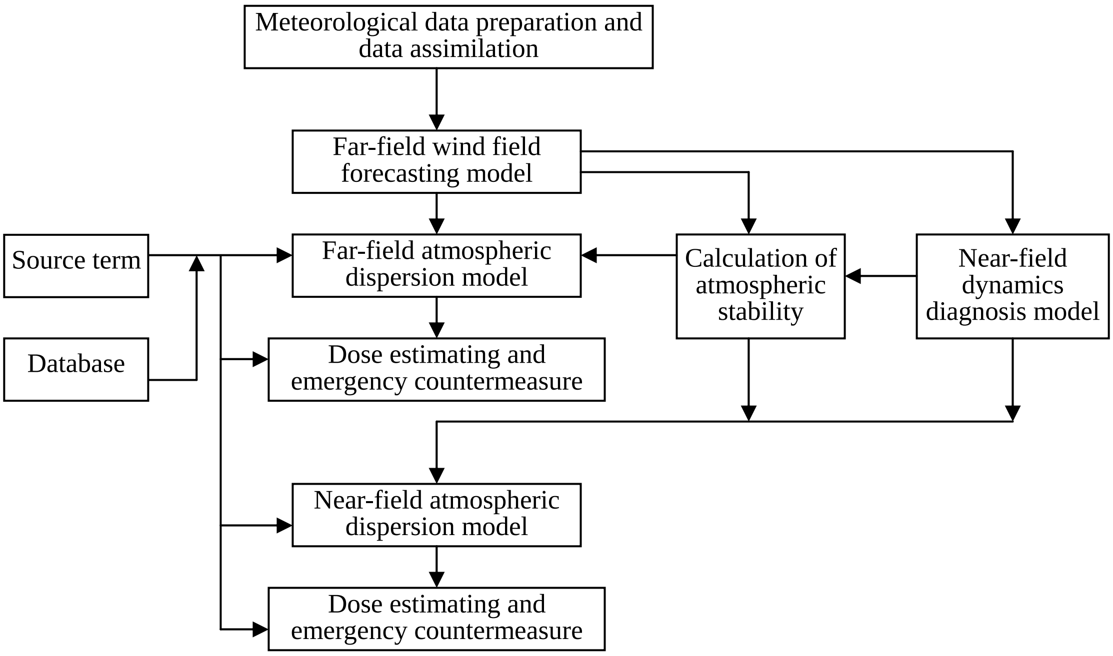
Data transfer and pre-processor module is in charge of interface between the system and outside, such as acquiring meteorological data from SQL server database in local area network, carrying out preparation of all model-input parameters and releasing the results to the server of local area network.

Data management module manages environment information, source-term data, meteorological data, dose transfer coefficients, model parameters, etc. The user can append, modify, moved, delete, inquire about, and cite all data. In addition, all information of model chains and model parameters for each run is saved in the database in order to reproduce the history records.

Figure 3 shows the model chains and data stream of the system in the automatic manner. The evaluating area is divided with two different sizes, i.e. the far field of 80 km × 80 km with a resolution of 4 km × 4 km and near field of 20 km × 20 km with 500 m × 500 m grids. The wind field forecasting and diagnostic models provide the future 24 hours meteorological data.

All results can be displayed as a layer in graphics window which has all GIS functions because OMS uses the COM modules of ArcView8.1. The information for graphics display includes wind field, concentration and dose contours, distribution of area for each intervention countermeasure. In general, the time to create results can be less than 10 to 15 min depending on the complexity of the source term, the availability of meteorological data, weather conditions, and the preparation of the model-input parameters. But then, all wind fields and concentration fields could be displayed automatically during running of the system.

Figure 3: Model chains and data stream of TW-NAOCAS system in the automatic manner.



3. Models

3.1 Meteorological Data Preparation

There are a 100 m meteorological tower and several surface stations, some of which belong to the local government. The atmospheric stability can be determined by using wind and temperature data from the meteorological tower. A mass consistent diagnostic wind field model constructs the initial mean wind fields based on a variety of interpolation methods and using an adjustment procedure based on the variational principle.

3.2 Wind Field Models

A quasi-hydrostatic numerical prognostic model [1] is used to simulate airflow over complex underlay. The wind field model is divided into a model for far field and a model for near field. The former covers a square area of 80 km × 80 km with the grid interval of 2000 m to simulate land and sea breezes caused by the temperature difference between land and sea and to provide the wind fields during the future 24 hours with 1 hour duration. The latter covers a square area of 20 km × 20 km with the grid interval of 500 m to simulate airflow around hills, airflow over ridge, blocking flow, leeward side flow and so on caused by dynamic action of topography.

3.3 Dispersion Model

The Lagrangian mesoscale puff dispersion model can cope well with the instationary and inhomogeneous meteorological situations, which are often of interest in connection with calculations used to estimate the consequences of the short term (accidental) release of airborne materials into atmosphere. On the other hand, diffusion in complex terrain at Tianwan site has show evidence of plume splitting and layer decoupling due to channeling and slope flows. Consequently a puff-splitting scheme is applied to model this such that a cluster of new puffs overlay and by that simulate the concentration distribution of the original single puff.

3.4 Dose Estimating and Intervention Countermeasure

A scenario of emergency actions in case of a radioactive release generally is a combination of single actions varying spatially and temporally, carried out before or during a developing radiological situation. The atmospheric dispersion model considers this variability by modeling and storing all processes defining the radiological situation on a spatial and temporal grid. The spatial grid is described above. The temporal grid is the scale of maximum 48 time steps each with 30 minutes duration, the whole time scale covering maximum 24 hours.

The temporal development of activity concentrations, gamma radiation, potential doses, normal living doses and expected doses after 2 days from accident release is calculated by the dose estimating module during all time steps of the scenario. Especially during the time interval the nuclide specific fields of activity concentrations and gamma radiation are combined with organ- and exposure pathway specific dose factors. This yields histories of potential individual doses for each grid location, each pathway, and each organ. The intervention countermeasure module is mainly to calculate avertable doses of each intervention countermeasure (such as 2 days-sheltering, 7 days-evacuation and administration of iodine tablets) corresponding the Design-Base Accident (DBA) and Beyond Design-Base Accident (BDBA) in which the additional dose has been considered for evacuation pathway.

4. Model Verification and Evaluation

4.1 Atmospheric Dispersion Models

4.1.1 Field Experiments

The experimental and theoretic studies on atmospheric dispersion for Tianwan site were performed by China Institute for Radiation Protection during 1997 to 1998 [2, 3]. The field observations included: (a) 2 years observation using a 100m high meteorological tower, (b) observation at three low-level sounding stations, (c) the short-term measurements of turbulent characteristics, (d) SF_6 tracer experiment, 12 times, and (e) wind tunnel simulations.

4.1.2 Verification of Wind Field Forecasting

Figure 4 and Figure 5 show an example for the simulation of generating and disappearing of typical land and sea breezes occurring on August 23, 1997. These figures only gave the wind fields predicted by far-field model and near-field model at 1600 Beijing Time (BJ) and 2400 BT with in-flow of SW wind direction. It can be seen from the simulation results that the onshore flow and offshore flow were converged along the shoreline and the onshore flow gradually disappeared at 1600 BJ. In addition, it is consistent for the results from two models and ones from near-field model were finer.

Figure 4: The wind fields predicted by far-field model at 1600 BT (left figure) and 2400 BT (right).

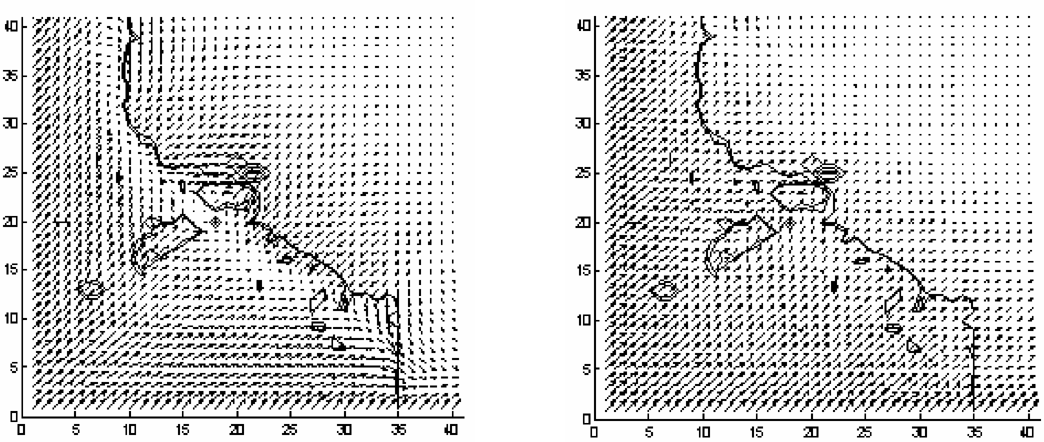
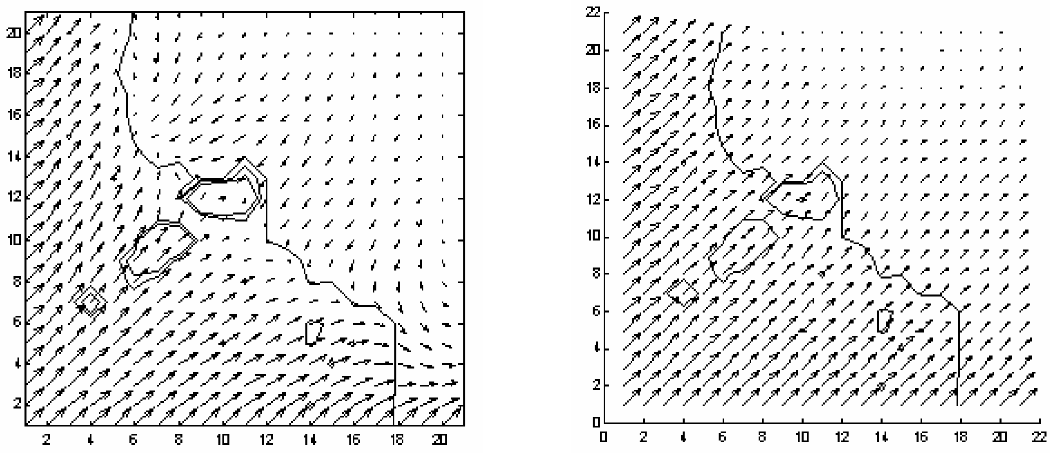


Figure 5: The wind fields predicted by near-field model at 1600 BT (left figure) and 2400 BT (right).



As for 10 releases of SF_6 tracer, the wind direction, wind speed and atmospheric stability predicted by the far-field model were compared with those from field observation. The forecasting time scale covers maximum 24 hours. **Table 1** gives the comparison for 9 stations in the simulation area. The reliability of forecasting results will decrease with the time lasting. In general, The reliability is more than 60% for the wind fields of future 9~12 hours considering the acceptability of occurring frequencies as show in **Table 1**.

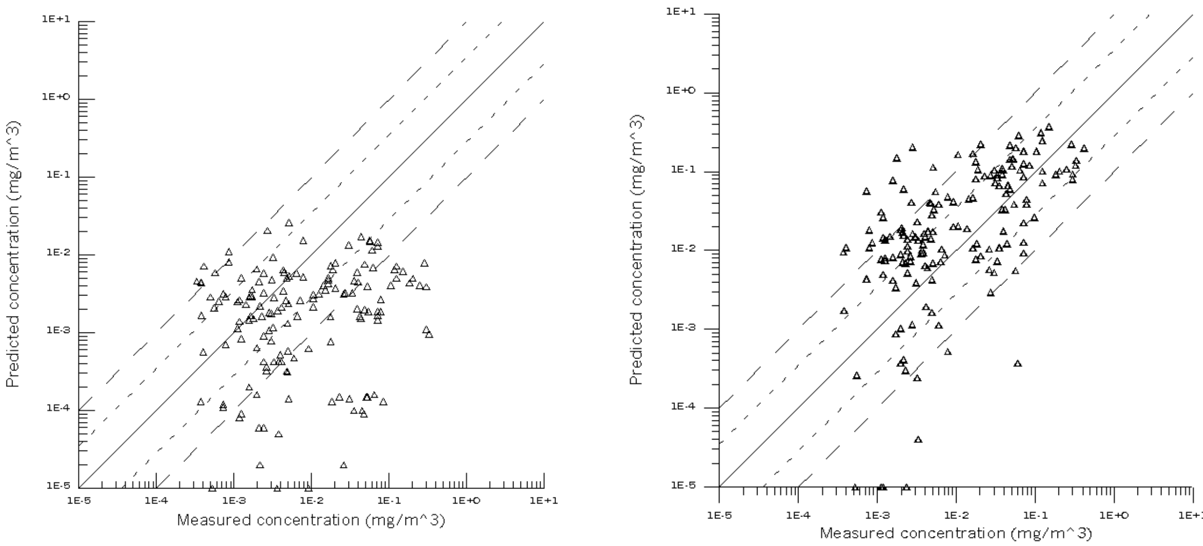
Table 1: The comparison of wind direction, wind speed and atmospheric stability from prediction with those from field observation for 9 stations during 10 releases of SF_6 tracer.

		Occurring frequencies (%) for different forecasting time					
		3 h	5 h	7 h	9 h	12 h	24 h
Difference of wind direction angles between prediction and observation (direction)	Same	39.63	36.67	33.76	31.14	27.70	22.87
	One	32.96	30.44	27.87	24.32	21.38	21.94
	Two	19.26	19.78	20.54	20.97	22.86	21.43
	Three	4.07	8.00	10.51	10.55	11.34	11.18
	Four	0.74	2.00	3.98	6.08	7.34	8.16
	Five	2.22	2.22	2.39	4.47	4.46	4.87
	Six	0	0.22	0.32	1.12	2.60	5.01
	Seven	1.11	0.67	0.64	1.12	1.30	2.50
	Eight	0	0	0	0.25	1.02	2.04
Difference of wind speed between prediction and observation (m/s)	±0~0.3	17.41	13.56	13.38	13.65	13.48	13.03
	±0.3~0.7	20.37	16.44	14.81	14.39	14.87	14.38
	±0.7~1	11.48	11.56	11.78	11.91	11.15	11.13
	±1~1.3	8.52	9.11	8.44	7.20	7.16	7.70
	±1.3~1.7	11.48	10.00	9.08	9.68	10.69	9.93
	±1.7~2	5.19	7.78	7.17	7.69	7.06	6.26
	±2~3	17.04	16.67	17.04	16.50	16.64	14.24
	±3~4	7.41	10.89	12.1	11.66	10.32	8.40
	>±4	1.11	4.00	6.21	7.32	8.64	14.94
Difference of atmospheric stability between prediction and observation (category)	Same	63.33	64.00	57.01	53.1	48.98	32.79
	One	20.00	18.00	22.93	23.45	20.91	14.61
	Two	3.33	6.00	10.03	14.52	23.42	41.74
	Three	13.33	12.00	10.03	7.82	5.86	10.02
	Four	0	0	0	1.12	0.84	0.83

4.1.3 Verification of Dispersion Model

Ten releases of SF_6 tracer experiments were used to test the ability of our modeling system to simulate microscale dispersion. Usually, the scatter diagram is a graph where predicted concentrations are plotted versus measured ones. There are 153 and 160 samples for far- and near-field simulations respectively except that the concentrations are less than 10^{-5} mg/m^3 for far-field simulations. **Figure 6** shows the distribution of ratios of predicted concentrations and measured ones, where the dot lines mean the limit of ratios of 3.5 and the broken lines of 10.

Figure 6: The distribution of ratios of predicted concentrations and measured ones.



(a) Far-field (b) Near-field

A factor, α, of goodness-of-fit is defined as the distribution function of the ratios of measured and calculated concentrations concentrated within the interval from $1/\alpha$ to α. When the ratio is invariable, the smaller the factor is and the better the goodness-of-fit is. It is good that 68% of the total number of the points in scatter diagram is concentrated within the interval from 1/3.5 to 3.5 [4].

The result analysis indicates that for far-field simulation, the percentage of predicted concentrations within factors of 3.5 and 10 of measured near-surface concentrations were 34.0 % and 62.1 %, respectively. For near-field simulation, the percentage of predicted concentrations within factors of 3.5 and 10 of measured near-surface concentrations were 50.0 % and 81.3 %, respectively. In general, the concentrations from far-field model are under-predicted and those from near-field model over-predicted. However, the goodness-of-fit for near-field simulation is better than that for far-field simulation. The main reason is that the spatial resolution of far-field simulation is low. In addition, each release continued for near one hour and time interval of meteorological observations is one hour, so that it is expected that the precision of model will be improved with higher quality meteorological data. Thus, it is viable that the Lagrangian mesoscale puff dispersion model is used in this system, especially for near-field simulation.

4.2 System-System Intercomparison

In order to further test the validity of TWNAOCAS, 4 typical cases were selected to compare the potential doses predicted by this system with those by InterRAS version 1.3, i.e. RASCAL version 2.1 [5]. **Table 2** gives the comparison results.

RASCAL—Radiological Assessment System for Consequence Analysis—was developed for use by U.S. Nuclear Regulatory Commission (NRC) staff who respond to power reactor accidents and other radiological emergencies. RASCAL, Version 2.2 (April 1998 release) estimates reactor source term, atmospheric transport, and doses resulting from radiological emergencies and can be used to assist in making protective action decisions. RASCAL 2.2 includes a "close-in" straight-line Gaussian plume model that computes doses at distances from 25 to 800 meters. A lagrangian puff model is used for longer distances.

Scenario of examples are as follows:
(a) case No.1: nuclide, ^{137}Cs; duration of release, 10 hours; height of release, 30 m; the total amount of radioactivity released during 10 h, 1×10^{18} Bq; beginning time, 0800 BT;
(b) case No.2: nuclide, ^{131}I; duration of release, 10 hours; height of release, 30 m; the total amount of radioactivity released during 10 h, 1×10^{18} Bq; beginning time, 0800 BT;
(c) case No.3: nuclide, ^{133}Xe; duration of release, 10 hours; height of release, 30 m; the total amount of radioactivity released during 10 h, 1×10^{18} Bq; beginning time, 0800 BT;
(d) case No.4a (with precipitation): nuclide, ^{137}Cs, ^{131}I, ^{133}Xe; duration of release, 10 hours; height of release, 30 m; the total amount of radioactivity released during 10 h, 1×10^{18} Bq; beginning time, 0800 BT; and
(e) case No.4b (without precipitation): nuclide, ^{137}Cs, ^{131}I, ^{133}Xe; duration of release, 10 hours; height of release, 30 m; the total amount of radioactivity released during 10 h, 1×10^{18} Bq; beginning time, 0800 BT.

It is shown that the difference of results of TW-NAOCAS and InterRAS were almost less than 10 times except case No.1. The trend of potential doses predicted by these two systems is consistent and the difference between the two systems is intelligible because of different wind field and dispersion models adopted.

Table 2: The comparison of TW-NAOCAS and InterRAS.

Scenario of case	System	1km		2km		5km	
		Potential dose (mSv)	Ratio[a)]	Potential dose (mSv)	Ratio	Potential dose (mSv)	Ratio
Case No.1	TW-NAOCAS	6.89	10.16	1.22	17.21	0.22	18.64
	InterRAS	70		21		4.1	
Case No.2	TW-NAOCAS	9.05	1.77	1.58	3.16	0.36	1.67
	InterRAS	16		5		0.6	
Case No.3	TW-NAOCAS	41.5	0.24	7.48	0.53	1.69	0.65
	InterRAS	10		4		1.1	
Case No.4a	TW-NAOCAS	15.98	6.01	2.81	10.68	0.65	8.92
	InterRAS	96		30		5.8	
Case No.4b	TW-NAOCAS	182.8	0.79	29.69	1.85	3.95	2.78
	InterRAS	145		55		11	

a) The ratio means the ratio of the value predicted by InterRAS to one by TW-NAOCAS.

5. Summary and Conclusions

Because the system is required simple to run from the point of view of operation of system, a balance should be found between selecting appropriate physical models to obtain reliable prediction and decreasing calculating time (resulting in simplifying physical models). The TW-NAOCAS system provides a mean for quickly determining the concentration distributions of radioactive materials, various dose levels and areas by dose intervention levels during the early phase of the release after accident. The results discussed above demonstrate that the numerical methods used in the TW-NAOCAS system are accurate, and that transport and dispersion of tracers was generally well simulated in the microscale and mesoscale cases studied. On the other hand, the precision of models will be improved with the increase of the temporal and spatial resolutions of the input meteorological data.

Considering that an important element for effective emergency response to an event involving radioactive airborne materials is having validated atmospheric dispersion models that can track and forecast the path of airborne materials, it will be necessary to further quantify model accuracy in future. Thus it can be seen that the preliminary model-evaluation was conducted as above. A complete evaluation of the modeling system must obviously involve comparisons to much more experimental data, and use of a wider range of space/time, meteorological conditions, and source characteristics. At the same time, several different statistical parameters should be used to test the model performance.

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