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Enhanced air dispersion modelling at a typical Chinese nuclear power plant site: Coupling RIMPUFF with two advanced diagnostic wind models

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A B S T R A C T

An enhanced air dispersion modelling scheme is proposed to cope with the building layout and complex terrain of a typical Chinese nuclear power plant (NPP) site. In this modelling, the California Meteorological Model (CALMET) and the Stationary Wind Fit and Turbulence (SWIFT) are coupled with the Risø Mesoscale PUFF model (RIMPUFF) for refined wind field calculation. The near-field diffusion coefficient correction scheme of the Atmospheric Relative Concentrations in the Building Wakes Computer Code (ARCON96) is adopted to characterize dispersion in building arrays. The proposed method is evaluated by a wind tunnel experiment that replicates the typical Chinese NPP site. For both wind speed/direction and air concentration, the enhanced modelling predictions agree well with the observations. The fraction of the predictions within a factor of 2 and 5 of observations exceeds 55% and 82% respectively in the building area and the complex terrain area. This demonstrates the feasibility of the new enhanced modelling for typical Chinese NPP sites.

1. Introduction

The Risø Mesoscale PUFF model (RIMPUFF) is a Lagrangian air dispersion puff model that calculates the concentration and dose distribution for released hazardous material on a horizontal scale of up to 50 km (Thykier-Nielsen et al., 1999). It has been widely used in European emergency response systems, such as the Accident Reporting and Guiding Operational System (ARGOS) (Hoe et al., 2009) for chemical, biological, radiological and nuclear (CBRN) materials release, the Real-time Online Decision Support System (RODOS) (Ehrhardt, 1997) for radionuclide release, and the European approach to nuclear and radiological emergency management and rehabilitation strategies (EURANOS) project (Raskob et al., 2010). In China, RIMPUFF is a core part of the consequence assessment tool for nuclear accidents in: (1) the Emergency Decision Support System for Nuclear and Radiation Safety Centre (NSC) and (2) many nuclear power plant (NPP) sites (Liu et al., 2014b; Qu et al., 2001; Shi and Wang, 2003).

One critical input to RIMPUFF is the wind field over the calculation domain. However, in the operational use of RIMPUFF, only a limited amount of observational weather data can be obtained from the very sparse meteorological stations (Yao, 2011). This is insufficient to drive RIMPUFF. Consequently, it is necessary to use a diagnostic meteorological model to calculate the whole wind field based on these sparse observations (Bander, 1982).

Currently, the diagnostic meteorological model used in the Chinese consequences assessment system builds an interpolated wind field by the inverse distance weighting method and adjusts it to satisfy the mass-conservation principle (Fu and Li, 2006). This model works well for a relatively homogenous terrain. Most Chinese NPP sites are located on complex terrains with miles of mountains and include a complex of buildings. Because the above model does not have any individual module for slope flows and buildings (especially within the 10 km range), it may be inadequate for the complex terrain case and the radionuclide dispersion prediction of RIMPUFF may be biased accordingly. Similar phenomena have been reported in the simulations of a ^{41}Ar tracer experiment in the former HIFAR research reactor (Dyer and Astrup, 2012) and a "dirty bomb" attack in Frederiksberg (Andersson et al., 2008, 2009).

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In order to solve the problem, an urban dispersion model (URD) has been developed in the ARGOS system by the RISØ National Laboratory, the Danish Meteorological Institute (DMI) and Swedish Defence Research (FOI) (Andersson et al., 2008, 2009, 2011; Hoe et al., 2009), which improves prediction in a low altitude area with buildings and trees. However, for nuclear accidents of NPPs, the dispersion may occur at a higher altitude with various land-use characteristics (Brandt et al., 2002; Katata et al., 2015; NRC, 1983). In this situation, it is more appropriate to employ diagnostic models that are capable of different land-uses and altitudes. Two such candidates are the California Meteorological Model (CALMET) (Scire et al., 2000) and the Stationary Wind Fit and Turbulence (SWIFT) (Geai, 1985).

CALMET is the meteorological model of the California Puff Model (CALPUFF), which is approved by the U.S. Environmental Protection Agency (EPA). Except for the diagnostic wind field generator, the treatment models of slope flows and terrain effects are also included in CALMET. It has been evaluated through Dipole Pride 26 field experiments (Cox et al., 2005) and a typical lake-breeze event in the Chicago region (Wang et al., 2008) at meso-scale. Also, it was applied to investigate the wind energy potential over a complex terrain structure in Lantau Island, Hong Kong (Yim et al., 2007).

SWIFT (and its predecessor MINVERSE) can predict complex wind flow between packed buildings or over highly heterogeneous terrain without appreciably increasing the computation time (Cox et al., 2000). Due to this attractive feature, SWIFT has been integrated as the wind model and combined with Second-order Closure Integrated Puff (SCIPUFF) in the Hazard Prediction & Assessment Capability (HPAC) system. Together with CALMET, SWIFT alone has also been validated through Dipole Pride 26 field experiments (Cox et al., 2005). And the SWIFT-SCIPUFF combination has been validated through tracer experiments over complex terrain at meso-scale, ranging from 35 km to 120 km (Chang et al., 2003; Cox et al., 1998). However, there are few reports on the 10 km-range validation of SWIFT for an area that is characterized by both complex terrain and packed buildings.

In this study, an enhanced air dispersion modelling is proposed, in which CALMET and SWIFT are coupled with RIMPUFF for wind field calculation. Meanwhile, the diffusion coefficients corrections of the Atmospheric Relative Concentrations in the Building Wakes Computer Code (ARCON96) are adopted, in order to enhance dispersion under low wind speed conditions and in building wakes.

To evaluate the performance of the proposed modelling, a wind tunnel experiment that replicates the buildings and topography of a typical NPP site is performed. The modelling predictions are compared with the observations from the experiment both qualitatively and quantitatively.

2. Methods

The flow chart of the proposed enhanced air dispersion modelling scheme is shown in Fig. 1. It is worth mentioning that buildings can be directly modelled in SWIFT, but it is less straightforward for CALMET to handle buildings. In this study, the height of the buildings is superimposed onto the topography input data of CALMET, so that the geography input is consistent for both models. The remainder of this section will provide an outline of the various components of the enhanced air dispersion modelling scheme.

2.1. CALMET

There are two steps in CALMET to compute the wind field. In Step 1, an initial gridded wind field is computed by upper air

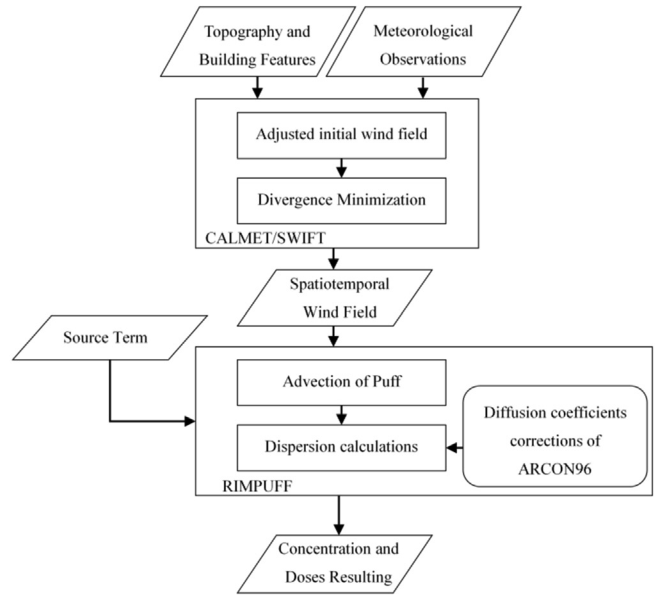

Fig. 1. Flow chart of the proposed enhanced air dispersion modelling.

sounding data and adjusted for the kinematic effects of terrain, slope flows and blocking effects. The hourly observations extended vertically by similarity theory can be additional data for the initial field. In order to satisfy the mass-conservation principle, the horizontal wind field is iteratively adjusted until the divergence at each grid point is less than a specified threshold value (Scire et al., 2000). For wind field $U(u,v,w)$, the divergence at grid point (i,j,k) is as follows:

$$D_{ijk} = \frac{u_{i+1,j,k} - u_{i-1,j,k}}{2\Delta x} + \frac{v_{i,j+1,k} - v_{i,j-1,k}}{2\Delta y} + \frac{w_{i,j,k+1/2} - w_{i,j,k-1/2}}{z_{k+1/2} - z_{k-1/2}} \quad (1)$$

where Δx and Δy are the grid sizes in the horizontal wind field and z is the height of the vertical levels. In the divergence minimization procedure, u and v are adjusted with surrounding points so that the divergence of them is zero, while the vertical velocity is held to be constant.

In Step 2, the observational data is introduced into the initial field created in Step 1. This is called the objective analysis procedure. In this processing, smoothing and O'Brien adjustment of vertical velocities are included. After that, the wind field is adjusted again by the divergence minimization scheme above.

2.2. SWIFT

In SWIFT, an initial gridded wind field $U_0(u_0,v_0,w_0)$ is first generated via spatial adjustment of the sparse meteorological observations. In this process, three different treatments are used to characterize the effects of obstacles such as buildings (Kaplan and Dinar, 1996). For separated obstacles, their effects are treated as the sum of the effects of isolated obstacles. For obstacles that are placed closer, their flow fields will interact and disturb each other. And for obstacles close to each other, the main flow will change to skimming flow. The parameter to characterize those three regions is the face-to-face space, and the threshold is a function of the height and width of those obstacles.

The initial gridded wind field may violate the mass-conservation principle and the continuity equation. Therefore the following variational approach (Kaplan and Dinar, 1996; Sasaki,