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Simulation of radioactive plume gamma dose over a complex terrain using Lagrangian particle dispersion model

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ABSTRACT

FLEXPART-WRF is a versatile model for the simulation of plume dispersion over a complex terrain in a mesoscale region. This study deals with its application to the dispersion of a hypothetical air borne gaseous radioactivity over a topographically complex nuclear site in southeastern France. A computational method for calculating plume gamma dose to the ground level receptor is introduced in FLEXPART using the point kernel method. Comparison with another similar dose computing code SPEEDI is carried out. In SPEEDI the dose is calculated for specific grid sizes, the lowest available being 250 m, whereas in FLEXPART it is grid independent. Spatial distribution of dose by both the models is analyzed. Due to the ability of FLEXPART to utilize the spatio-temporal variability of meteorological variables as input, particularly the height of the PBL, the simulated dose values were higher than SPEEDI estimates. The FLEXPART-WRF in combination with point kernel dose module gives a more realistic picture of plume gamma dose distribution in a complex terrain, a situation likely under accidental release of radioactivity in a mesoscale range.

1. Introduction

During the last two decades and particularly after the Chernobyl disaster the importance of emergency preparedness programme in nuclear establishments has been well recognized. Atmospheric dispersion modeling of radioactive plume is one of the important aspects of such programs to predict and assess the radiological consequences to the public. Conventional Gaussian Plume Model (GPM) is a good candidate for atmospheric dispersion of radioactive pollutants over plane and homogeneous terrain conditions. But over complex terrain, the meteorological parameters vary in space and time. There are many nuclear power plants across the world located in complex hilly areas. The dispersion of radioactive plumes over such regions is very complex because of the valley circulation, channeling of the flow, anabatic (daytime wind flow uphill), katabatic (nighttime wind flow downhill) circulations etc. Hence the employment of conventional models like GPM for radioactive pollutant dispersion over heterogeneous and complex terrain conditions is questionable. Diagnostic models (e.g. Mathew–ADPIC model; Rodriguez and Cederwall, 1991, SPEEDI; Venkatesan et al., 1997) are developed for these conditions but the accuracy lies in the density of meteorological measurements both in space and time. Due to the advent of advanced numerical weather modeling the meteorological parameters can be forecasted with sufficient accuracy over any topography by providing suitable initial and boundary conditions. These models in conjunction with particle dispersion models can simulate pollutant trajectories over complex terrain conditions. Lagrangian Particle Dispersion Models (LPDMs) are well suited for such applications. In LPDMs the results are independent of the grid resolution and hence near source dispersions can be estimated with sufficient accuracy. Therefore a LPDM driven by a meteorological model can be used as a tool for realistic dispersion estimates.

An important problem is the estimation of radioactive plume gamma dose to the ground level receptors due to exposure of the overhead plume. Methods for plume gamma dose calculation is not always available with many coupled meteorological particle models. There are methods discussed in the past to estimate the plume gamma dose to the receptor. One of them is the semi-infinite cloud model used in the MESORAD dose assessment model

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(Scherpelz et al., 1986). The drawback of this method is that it can impose large errors in the case of elevated releases and ground releases where the plume is narrow. It also assumes concentration distribution as uniform within the cloud. Another method implemented in the MESORAD model is the finite puff (short term release) model. Errors due to uniformity in concentration can be circumvented if the plume is depicted with puffs of varying concentrations. The disadvantage of this method is that it gives poor results when puff size is larger where distance between source points within the puff become of the same order of mean free path of gamma photon (Scherpelz et al., 1986). In dispersion models like RIMPUFF the semi-infinite method with correction factors proposed by Slade (1968) based on a cylindrical plume model is followed. For puff model, the dose rate is evaluated by triple integration in space by splitting the plume into tiny rectangular cells (Thykier-Nielsen et al., 1995). This method of 3D integration is time consuming and therefore a new approach is developed by Han et al. (1994). In order to reduce the computational task of evaluating a triple integral, a regular hexahedron is modeled by them as a volume equivalent sphere for simplification. All these are however approximations in representing plume concentration and hence lead to inaccurate plume gamma dose at ground level receptors. But with the availability of hyper computing, the dose can be estimated using LPDMs following a point kernel technique (Oza et al., 1999). A similar method is followed in SPEEDI but the energy of emitting isotopes are grouped into a few values and a matrix of pre-calculated dose per unit concentration in fixed sizes of numerical grid cells is used for quick assessment.

Thus the objective of this study is to incorporate a plume gamma dose module following the point kernel technique in the dispersion model FLEXPART-WRF (Stohl et al., 2005) for complex terrain and examine the dose pattern at the ground for a hypothetical release of ^{41}Ar radioactive gas. The task is divided as follows.

- The simulation of the meteorology and the shape of the plume in a complex terrain, over southeastern France as a case study.
- Calculation of plume gamma dose using point kernel technique assuming a hypothetical release of ^{41}Ar radioactivity.
- Compare the plume gamma dose simulated by FLEXPART with the SPEEDI model.

2. Description of the site

In order to simulate the meteorological condition over a hilly region and complex topography subjected to mesoscale atmospheric circulations, the Durance valley in southeastern France is chosen as the site for the study. To simulate the radioactive plume, we assume that a hypothetical source of ^{41}Ar is located in Cadarache research center which is 100 km away from the Mediterranean Sea coast at 43.69° N and 5.74° E. The dispersion of pollutants over this terrain is complicated because of the wind circulation in daytimes and stagnation of air in nighttime calm conditions. The influence of the land–sea breeze circulation also cannot be ruled out. Meteorological data are available from the ESCOMPTE experiment (Cros et al., 2004, Kalthoff et al., 2005) conducted at the Vinon sur Verdon airfield, which includes radiosonde data at 0800, 1100, 1400, 1700 GMT and data from a 10 m mast where wind, temperature, humidity and pressure sensors are installed. The mast is located at the latitude of 43.734° N and longitude of 5.785° E. The ground elevation of this location is 272 m above mean sea level. This data helps to compare simulated meteorological parameters using WRF as a case study. Brief description and configuration of WRF and FLEXPART-WRF are given in the following sections.

3. Description of the weather model

The WRF model is a sophisticated numerical weather prediction (NWP) model that solves the compressible non-hydrostatic Euler equations in flux form on a mass-based terrain-following vertical coordinate system. It computes prognostic variables such as the horizontal and vertical wind velocity components, various microphysical quantities, perturbation potential temperature, geopotential and surface pressure of dry air. The model uses the 3rd order Runge–Kutta time integration scheme and the 2nd to 6th order advection schemes in both horizontal and vertical directions. A complete description of the WRF modeling system is described in Skamarock et al. (2005).

In the present study WRF is used in a nested configuration of four domains with a grid size ratio of 1:3:3:3 (Fig. 1). The grid resolution of the mother domain is 18 km and that of the innermost domain is 0.677 km. Every domain has 100 × 100 grid cells. The terrain data used for the innermost domain is taken from the Shuttle Radar Topographic Mission (SRTM) satellite, which gives data in 90 m spatial resolution. For the land use class, Moderate Resolution Imaging Spectroradiometer (MODIS) data which has a spatial resolution of 30 s (~1 km) is used. Various PBL schemes are available with the WRF modeling system to parameterize the unresolved turbulent vertical flux of heat, momentum and constituents such as moisture within the planetary boundary layer and throughout the atmosphere. The Yonsei University (YSU) scheme (Hong et al., 2006) which calculates the vertical diffusion using K-profile is used as the boundary layer scheme in this case. The other physical parameterization schemes used in all model domains include Janjic Eta Monin–Obukhov surface layer scheme, Dudhia shortwave radiation, rapid radiative transfer model (RRTM) for long wave radiation, WRF Single-Moment 6-Class (WSM6) microphysics and the Noah land surface scheme. Cumulus scheme Grell is used for cloud microphysics in the mother domain of 18 km. All WRF domains have 35 vertical layers of non-uniformly increasing interval with height and the model top is set at 50 hPa. Out of 35 vertical levels, 13 levels are within first one km with the first model layer approximately 20 m above ground level. The National Centers

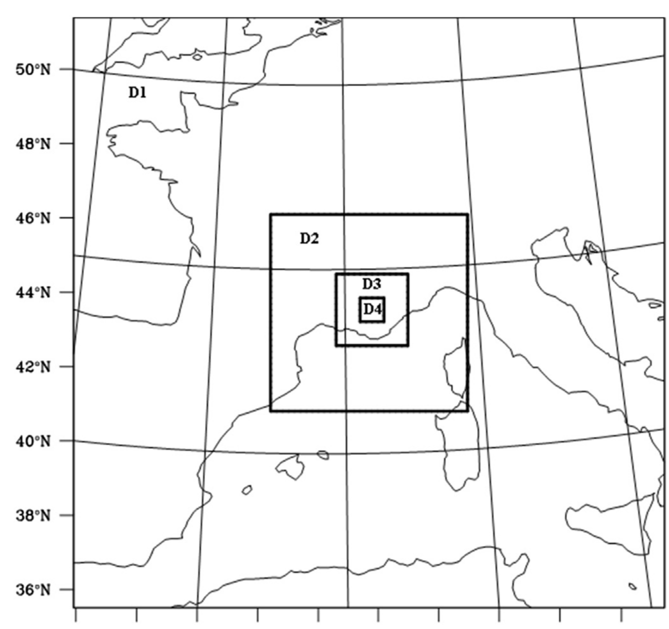

Fig. 1. WRF simulation domain.