Atmospheric Environment 44 (2010) 2846–2864

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Assimilation of conventional and satellite wind observations in a mesoscale atmospheric model for studying atmospheric dispersion

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ARTICLE INFO

Article history:
Received 4 March 2010
Received in revised form
28 April 2010
Accepted 29 April 2010

Keywords:
Mesoscale
Assimilation
AWS
QuickSCAT
FDDA
Radiological dispersion

ABSTRACT

A mesoscale atmospheric model PSU/NCAR MM5 is used to provide operational weather forecasts for a nuclear emergency response decision support system on the southeast coast of India. In this study the performance of the MM5 model with assimilation of conventional surface and upper-air observations along with satellite derived 2-d surface wind data from QuickSCAT sources is examined. Two numerical experiments with MM5 are conducted: one with static initialization using NCEP FNL data and second with dynamic initialization by assimilation of observations using four dimensional data assimilation (FDDA) analysis nudging for a pre-forecast period of 12 h. Dispersion simulations are conducted for a hypothetical source at Kalpakkam location with the HYSPLIT Lagrangian particle model using simulated wind field from the above experiments. The present paper brings out the differences in the atmospheric model predictions and the differences in dispersion model results from control and assimilation runs. An improvement is noted in the atmospheric fields from the assimilation experiment which has led to significant alteration in the trajectory positions, plume orientation and its distribution pattern. Sensitivity tests using different PBL and surface parameterizations indicated the simple first order closure schemes (Blackadar, MRF) coupled with the simple soil model have given better results for various atmospheric fields. The study illustrates the impact of the assimilation of the scatterometer wind and automated weather stations (AWS) observations on the meteorological model predictions and the dispersion results.

1. Introduction

Modeling the environmental dispersion of radioactive effluents is an essential aspect in nuclear emergencies to assess the radiological consequences to the members of the public. Real-time estimates of transport and diffusion of hazardous contaminants is required for response management in such situations (Knox et al., 1981). Three-dimensional dispersion modeling tools have been developed and used for forecasting the radiological and chemical releases from normal and off-normal scenarios (Dickerson et al., 1979). Often it is needed to determine the dose rates resulting from the atmospheric transport and dispersion beyond a limited zone called the off-site range and long ranges extending up to a few hundreds of kilometers. In these ranges a numerical weather prediction model is generally used to predict the meteorological fields needed in dispersion assessment (e.g., Satomura et al., 1994; Lagzi et al., 2004). The dispersion results are influenced by the meteorological fields and the uncertainty in the estimated concentration or dose rates depends to a large extent on the accuracy of the meteorological fields apart from the uncertainty in the source term and dispersion parameters.

Essentially the physical processes of the atmospheric transport of the contaminants and their mixing, dilution and deposition need to be precisely calculated which depend on many meteorological inputs. Outputs from mesoscale atmospheric models that directly influence the dispersion simulations include the wind field, temperature profiles, water vapour mixing ratio, boundary layer depth, turbulence, surface pressure and rainfall/precipitation in the lowest 2 or 3 km (Hanna, 1994; Seaman, 2000). The performance of atmospheric models depends on the accuracy of the initial meteorological fields and the ability of the model to realistically simulate atmospheric physical and dynamical processes. Assimilation of observations through suitable methods improves the atmospheric predictions needed in air quality and emergency response systems for decision support (Seaman, 2000; Zheng et al., 2007; Kovalets et al., 2003). Several methods are developed on data assimilation in recent times, such as Four Dimensional Data Assimilation (FDDA), 3DVAR etc. FDDA is a continuous data assimilation

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doi:10.1016/j.atmosenv.2010.04.051

technique in which the model state is relaxed toward the observed state by augmenting some of the prognostic equations with forcing terms based on the difference between the observed state and the model state (Stauffer et al., 1991; Stauffer and Seaman, 1990, 1994). The land based surface automated weather stations (AWS) data on wind, temperature and humidity and the 2-D wind data from satellite platforms such as QuickSCAT over the oceanic region can be used to define the model initial conditions accurately.

A non-hydrostatic mesoscale atmospheric model MM5 developed by PSU/NCAR (Grell et al., 1995) is used for near real-time atmospheric predictions for application in a nuclear emergency response decision support system (Srinivas et al., 2006) for the Kalpakkam nuclear site situated on the southeast coast of India. The performance of this model with assimilation of observations is tested in this study for the prediction of lower atmospheric fields used in plume dispersion. In recent times more land based surface observations are becoming available over India for the purpose of precise short-range weather prediction (Rao, 2008). Assimilation of these observations needs to be tested in mesosclae models for their utility in dispersion assessment applications and emergency response systems. In the present study observations from these mesonet stations and wind observations from QuickSCAT satellite are assimilated in the MM5 atmospheric model to examine their impact on the predicted meteorological quantities and plume dispersion in a mesoscale range in the southeast coast of India. Model simulations are conducted for four cases in different seasons to study the impact of observational assimilation on the model performance. The performance of the model is also tested by conducting a few separate sensitivity experiments with two PBL and surface physics options.

2. Methodology

2.1. Description of the meteorological model

The Pennsylvania State University/National Centers for Atmospheric Research (PSU/NCAR) mesoscale model MM5 is used in the present study to generate the meteorological fields in dispersion simulations. The MM5 model has Arakawa-B horizontal grid staggering, terrain-following sigma vertical coordinate, a second-order leapfrog time integration scheme, nesting of multiple domains, and has a number of parameterization schemes for atmospheric physical processes. In the present study the model is configured with four nested domains with 36, 12, 4 and 1.33 km horizontal resolution respectively. A total of 32 vertical levels are used in all the three domains. The outer domain has 90×90 grids, the second domain has 112×112 grids, the third domain has 142×142 grids and the fourth domain has 157×157 grids, the fine mesh covers the southeast coastal Kalpakkam region and its neighboring area (Fig. 1). The inner domains 2, 3 and 4 are two-way interactive. An explicit cloud microphysics parameterization option (Dudhia, 1989) is used to predict the grid scale cloud and rain water mixing ratio and cloud water vapour. On the model outer grids (domains 1, 2) the Grell (Grell et al., 1991) cumulus parameterization scheme is used to account for the large-scale convective processes. The atmospheric radiation schemes (Dudhia, 1989) and RRTM (Mlawer et al., 1997) are used to represent the shortwave and long wave processes that interact with the atmosphere, cloud and precipitation and with the surface.

A number of parameterization schemes for PBL and land-surface physics are available in MM5. The land-surface and PBL parameterizations are influential for the simulation of winds, turbulence and other state variables in the lower atmosphere where dispersion and transport of pollutants occurs. In this study the Blackadar high resolution scheme (BK) (Blackadar, 1976; Zhang and Anthes, 1982), medium range forecast (MRF) non-local PBL turbulence diffusion scheme (Hong and Pan, 1996), Eta Mellor–Yamada (MY) level 2.5 TKE scheme (Mellor and Yamada, 1982; Janjic, 1996, 2002), Gayno–Seaman (GS) (Shafran et al., 2000), Burk and Thomson (BT) (Burk and Thomson, 1989), and Asymmetric convective model (ACM) (Pleim and Xiu, 1995) are used for PBL turbulence. The Blackadar is a high resolution PBL scheme with 5 layers. The surface fluxes of heat and moisture are computed based on standard similarity theory, where the friction velocity is derived from the wind speed and stability functions. Four stability categories viz., stable, mechanically induced turbulence, unstable (forced convection) and unstable (free convection) are considered separately, which are derived form Bulk Richardson number. The MRF scheme is a non-local first order scheme in which the vertical transfers are dependent on the bulk characteristics of the PBL and includes counter gradient transports of temperature and moisture arising from large-scale eddies. The eddy diffusivity coefficient for momentum is a function of the friction velocity and the PBL height, while those for temperature and moisture are computed using a Prandtl number relationship. The friction velocity and the surface exchange coefficients for heat, moisture and momentum are calculated through the surface layer similarity theory. The MYJ scheme includes a prognostic equation for turbulent kinetic energy (TKE), a level 2.5 turbulence closure approximation to determine eddy transfer coefficients and uses local vertical mixing within PBL. The ACM is a combination of the high resolution Blackadar model and an eddy diffusion model. It computes eddy diffusion in the stable conditions, both local and non-local transport in unstable conditions. The land-surface models (LSMs) use atmospheric information from the surface layer scheme together with the land-surface properties (defined by land use, soil type etc.) to compute eddy heat and moisture transports in the PBL. Four well-suited LSM schemes available in MM5 are chosen in the study. These are the 5-layer soil thermal diffusion (SOIL) model (Dudhia, 1996), the Noah land-surface model (NOAH) (Chen and Dudhia, 2001) and the Pleim–Xiu (PX) LSM (Xiu and Pleim, 2001). The 5-layer soil model solves the thermal diffusivity equation with 5 soil layers. The energy budget includes radiation, sensible and latent heat fluxes. It treats the snow-cover, soil moisture fixed with a land use and season dependent constant value. The Noah LSM treats explicit soil and vegetation effects. It uses the time dependent soil fields and uses a 4-layer soil temperature and moisture model with canopy moisture and snow-cover prediction. The Pleim–Xiu LSM includes a 2-layer force-restore soil temperature and moisture model and considers evapotranspiration, soil evaporation, and evaporation from wet canopies. The PX LSM is coupled to the ACM PBL. The BT scheme includes a force-restore surface temperature prediction scheme. The BK and GS schemes are used with SOIL scheme. For the control and assimilation runs the MRF PBL along with the SOIL model are used. A set of eight experiments are conducted separately to test the sensitivity of the model to different PBL and surface schemes. The sensitivity experiments are denoted as MRFSOIL, MRFNOAH, MYSOIL, MYNOAH, BKSOIL, BT, GSMSOIL, ACMPX respectively. The options used in the model are given in Table 1.

2.2. Meteorological observations

A dense mesonet is installed by the Indian Space Research Organisation (ISRO) in India to improve short-range weather prediction (Rao, 2008). This mesonet consists of a network of about 300 AWS distributed allover India and provide real-time observations on surface weather parameters of wind speed and wind direction, air temperature and relative humidity. In the present study these AWS observations, the upper-air radiosonde