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Technical Note

Application of WRF Model for Air Quality Modelling and AERMOD – A Survey

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ABSTRACT

Meteorology plays a crucial role in air quality. The presence of uncertainties of a significant nature in the meteorological profile used during air quality model simulation has the potential to affect negatively the results of the simulations. This paper describes a most recent version of the meteorological model called Weather Research and Forecasting (WRF) model and its importance in air quality. The performance of WRF depends upon the intended application and parameterization scheme of physics options. WRF model is also applied to investigate the simulation results with various land surface models (LSMs) and Planetary Boundary Layer (PBL) parameterizations and various set of microphysics options. It predicts various meteorological spatial parameters like mixing layer height, temperature, humidity, rain fall, cloud cover and wind. The WRF results are integrated with air quality model (AQM) and the AQM depends upon the performance of WRF. It has been applied for evaluation of national pollution control policy, behaviour of plume rise, property of aerosols, prediction of Ozone, SO_2, NO_x, PM_{10}, $PM_{2.5}$ etc. using AQM for various sources. The effect of topography and different seasons on the concentration of pollutants in the atmosphere has also been studied using AQM. AQM AERMOD has also been reviewed with various other AQM models such as ADMS-Urban and CALPUFF. AERMOD has been used for different time scales, health risk assessment, evaluation of various control strategies, Environmental Impact Assessment (EIA) studies and emission factor estimation. This paper presents the importance of meteorological model to AQM as well as many applications of AQM to demonstrate various scientific questions and policies.

Keywords: Meteorological model; WRF model; Air quality modeling; AERMOD; Urban region; Atmospheric dispersion.

INTRODUCTION

Ambient concentration of air pollutants depends on emission rate and meteorology as well as morphology of geography (Seaman, 2003). Ambient concentrations are either measured or modelled. Measured concentration gives information about air quality level at a point for current scenario while modelling can give the information about air quality level for a region for current and future scenario. Air quality modelling techniques are cost effective as compared to measurement but are data intensive as modelling requires emission and meteorological data. Meteorology plays an important role for air quality because the concentration of air pollutants is governed by meteorological field (Seaman, 2000). Meteorological processes include horizontal and vertical transport, turbulent mixing and convection of pollutants. The requirement of meteorological data for air quality modelling can be accomplished by either onsite monitoring or meteorological modelling. The number of onsite meteorological measurements is severely limited in many regions of the world. Therefore, meteorological model can help to generate onsite meteorological data to use in air quality models. Meteorological and air quality models have been applied in many studies with several objectives and addressed various scientific research questions across the world. A survey of these studies has not been carried out to view all the studies together which are urgently needed. This paper is a survey article and does not present any new research or modelling studies. It includes the introduction of meteorological and air quality models and its applications. Further, numerous case studies has been incorporated category wise. The aim of this article is to support the use of WRF data in dispersion modelling of all types (AERMOD, CALPUFF, FLEXPART, CAMx, CMAQ).

Meteorological models calculate three-dimensional gridded meteorology using mathematical equations to simulate atmospheric processes like the variation in temperature and winds over time. The main purpose of the meteorological model is to forecast and simulate the weather parameters

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using current observed meteorological parameters. These models forecast meteorological parameters by solving equations of mechanics for a compressible fluid which are derived from the three fundamental physical laws governing all geophysical processes i.e., conservation of mass (for wind and moisture), momentum (Newton's laws of motion), and thermal energy (the first law of thermodynamics). The equations arising out of these three laws estimate the weather parameters from physical phenomena and strongly interact with each other. A research and development group on air quality has developed methods of meteorological forecast for predicting the atmospheric dispersion, decay and decomposition of radioactive material.

In the early nineties, mesoscale meteorological models were developed. The second edition of mesoscale meteorological modelling system was upgraded to the fifth generation of mesoscales meteorological model by Penn State University and National Center for Atmospheric Research mesoscale model (commonly referred to as MM5) in 1994 (Grell *et al.*, 1994). To modify explicit ice-phase cloud microphysics, stable boundary layer turbulence parameterization, physical parameterizations for cloud-radiation interactions, and improved treatment of heat transfer through snow and ice surfaces and implementation of a sea ice surface type were major changes. MM5 is used frequently worldwide as a meteorological model for historical episodes. This model is a limited-area based on the non-hydrostatic theory and terrain-following sigma-coordinate model. The aim of MM5 is to simulate or predict a wide range of atmospheric phenomena using nexus the complex interactions of pollutants in atmosphere at the various scales of region. Being a community model, it undergoes continuous improvement with feedback received from multiple users. Later, the MM5 model was updated to Weather Research and Forecasting (WRF) model which has been explained in next section.

WRF Model

The Weather Research and Forecasting (WRF) is a state of the art mesoscale numerical weather prediction system designed to apply to both meteorological research and numerical weather prediction needs (Henmi *et al.*, 2005). The model has the ability to simulate and forecast, followed by producing a meteorological profile that reflects either real data or ideal data of the atmospheric condition. WRF has increasingly been used in both military and private meteorological fields and has also been adopted by the NOAA's National Weather Service (NCAR, 2012).

This model configures two dynamic systems; namely, a data assimilation system and a software architecture facilitating parallel computation and system extensibility. It can simulate meteorological parameters in a wide range from meters to thousands of kilometres. It includes idealized simulations (e.g., convection, large eddy simulations, baroclinic waves), parameterization research, regional climate research, data assimilation research, forecast and hurricane research, real-time national weather prediction and coupled-model application. WRF provides operational forecasting and simulation and computationally efficient platform, and offers to research community inclusion of advances in physics, numeric, and data assimilation.

The uncertainties of meteorological model create negative impact to air quality model simulation (Sistla *et al.*, 1996). Significant errors have still been observed during the routine assessment of the performance of the next generation air quality models despite having made use of the advanced techniques for data collection and numerical modelling with high computational abilities (Russell and Dennis, 2000).

Air Quality Model: AERMOD

Air quality models provide a mathematical prediction of ambient concentration of pollutants using a simulation of physical and chemical processes of atmosphere, affecting air pollutants and determining the dispersion, reaction and behaviour of pollutants. Air quality model requires inputs such as meteorological data and source information like emission data, gas exit velocity and stack heights for predicting concentration. An important role is played by these models in air quality management as the regulatory authority widely uses these for controlling air pollution. Also, it is used for source apportionment to air pollution as well as assist in the control, design and abatement strategies to reduce air pollution levels.

There was collaboration between the American Meteorological Society (AMS) and the U.S. Environmental Protection Agency (EPA) with a goal to initiation the current planetary boundary layer (PBL) concepts into regulatory dispersion models. A research group (AMS/EPA Regulatory Model Improvement Committee, AERMIC) comprising of scientists from both agencies made a successful achievement of this collaborative effort and developed an air quality model called AERMOD.

The AERMOD (Cimorelli *et al.*, 2004) modelling system has several pre-processors (AERMET, AERSURFACE, AERMINUTE, AERMAP). The meteorological information is provided to AERMOD by the AERMIC meteorological pre-processor (AERMET) for characterization of the PBL. AERMET, like AERMOD uses the same information and surface characteristics to calculate boundary layer parameters (e.g., mixing height, friction velocity). This data must represent the meteorology in the modelling domain irrespective of the measurements done off-site or on-site. National Weather Service (NWS) generally, provides the surface input data and the upper air data. Otherwise, onsite data collection could be done for the required region. The terrain is characterised by the AERMIC terrain pre-processor (AERMAP) which also generates receptor grids. Gridded terrain data are used to model the area, where the gridded elevation data is made available to AERMAP in the form of a Digital Elevation Model (DEM) data. This data also proves useful when the associated representative terrain-influence height has to be calculated for each receptor location. Thus, elevations for both discrete receptors and receptor grids are computed by the terrain pre-processor.

This paper offers a survey of the use of meteorological in air quality models and has been applied for various purposes. It includes several applications of WRF for prediction of meteorological parameters to use in air quality modelling.

It does not present any new research or modelling studies but a survey of meteorological model like MM5/WRF and their use in air quality dispersion models like CMAQ, AERMOD and CAMx.

APPLICATION OF WRF MODEL

Currently, WRF model is most widely and frequently used for meteorological simulation and forecasting. This tool can generate gridded meteorological parameters horizontally and vertically for a region. This model is used globally to simulate weather and air quality. Generally, WRF model overestimates wind speed in dense urban regions because of building canopy and topographic structure (Kumar *et al.*, 2016). This model is being updated with a new module to address all these issues and thus the output is becoming more accurate. In many previous studies, detailed sensitivity analysis of the WRF model was carried out for the Iberian Peninsula making use of an integrated assessment modelling system (Borge *et al.*, 2008). An extensive sensitivity analysis with different user options was carried out in the meteorological model WRF–ARW (Advanced Research WRF). Borge *et al.* (2008) used "a series of common statistics to valuate over 23 alternative configurations including planetary boundary layer schemes, microphysics, land-surface models, radiation schemes, sea surface temperature and four-dimensional data assimilation". The WRF simulations were driven by the NCEP FNL input data with a spatial resolution of 1° × 1° and temporal resolution of 6 h. One-way three nested domains of WRF model were run with 81 km, 27 km and 3 km horizontal resolution including 30 vertical layers. Simulations were conducted for two periods of winter and summer episode from 19 to 28 February and from 18 to 27 June of the year 2005. The time period for sensitivity analysis was selected from analysis of observed air pollution level and the area of interest. Meteorological model was evaluated under different atmospheric as well as cold and warm conditions that were focused on results of model with correspondent model set up. The selected physics options included WRF Single-Moment (WSM) 5/6-class for microphysics, Yonsei University for Planetary Boundary Layer, Noah for Land-surface model, RRTM/Eta Geophysical Fluid Dynamics Laboratory for longwave radiation and MM5 for shortwave radiation schemes and many other combinations. Time-varying sea surface temperature and combined grid-observational nudging were also included as a best case configuration for meteorological simulation. This configuration gave more accurate results at surface level for temperature, wind and humidity parameters for the two simulated events. The model predicted data on temperature with a global index of agreement (GOI) of 0.90 and on wind speed with 0.72. Wind direction was not depicted so precisely due to measurement uncertainty. A reasonable agreement (underestimation in most of the cases) was found between the predicted planetary boundary layer heights and that estimated from usual atmospheric soundings. This study defined the best setup to fix the parameters of the WRF model to use in air quality modelling, while providing a general overview of the model's sensitivity.

WRF model was applied to test the sensitivity of the model based on the selection of parameterization schemes in the various global geographical and climatic zones. WRF was also applied for performance with various parameterization sets for Kaiga region of Karnataka state in India (Shrivastava *et al.*, 2015). The surface and upper air meteorology was simulated by WRF model (version 3.1.1) for a nuclear power plant at Kaiga. It was run for three nested domains with grid spacing varying from 27 km, 9 km, and 3 km. The meteorological measurements were done at the site from the year 2004 to 2007. Temperature and relative humidity were recorded at a height of 1.2 m, wind was recorded at a 60 m tower at multiple levels. Data from annual analysis showed that the wind sectors are West South West, West, East North East and North East with an average wind speed of 2 m s^{-1}. The summer and winter temperature were around 40°C and 14°C respectively. Around 3,700 mm of cumulative rain fall was collected from June to September. The final data analysis of the National Centers for Environmental Prediction (NCEP) with 1 × 1° spatial resolution and 6 hour temporal resolution was used as input for the model. Seven combinations of parameterizations were tested in WRF. Maxima or minima of temperature and wind were studied for a particular simulation case. However, it was concluded that the selection of parameterization depends; on the proposed application of the model and the site selected. This study shows that no single set of physics options performs best for all the meteorological parameters at this site. Hence, the selection of sets of parameterization is governed by the specific intention of the application.

An analysis of WRF was carried out for wind estimate sensitivity using selection of parameterisation in physics option in model setup (Santos-Alamillos *et al.*, 2013). Various model setup options such as microphysics, planetary boundary layer (PBL), cumulus, short and long-wave radiation were tested and wind output were compared with observed data at different spatial resolutions in southern Spain. The bias between predictions and observations concluded that prediction depended upon spatial resolution and terrain morphology. There was a high impact on wind speed with choice of PBL option and little impact on wind direction distribution with selection of physical configuration. Another study evaluated the influences of land-use data on the precision of estimated wind by WRF for southern Spain (Santos-Alamillos *et al.*, 2015). Two land-use datasets were tested in WRF model to simulate wind parameters to get more accurate results. Firstly, the Coordination of Information on the Environment (CORINE) land-use dataset with 100 m spatial resolution was used as the geographic source in WRF. Secondly, land-use data of Global Land Cover Characterization (GLCC) was used in WRF simulation. CORINE land-cover map was expected to provide description of land-use which would be more reliable than the default GLCC land-use maps. The experiments were run at 1-km spatial resolution over the study domain through the year 2009. The simulations were performed at three different places in southern Spain which had different land-use composition and topography. WRF was constructed with four nested domains with 27, 9, 3, and 1 km spatial resolutions with 36 vertical layers where all domains were configured with a total of 90 × 90 grid points for each station. Two-way interaction was used for the first three domains and one-way nesting was used for the 1-km domain. Estimated wind data (speed and direction) was compared with observed data at various elevations at these locations. Since the variation of wind speed and direction are greatly influenced by topography and land-use, the results showed that the CORINE represents appropriate land-use for wind speed and directions than GLCC.

Comparison of WRF Model Studies

WRF model has been applied in various case studies with different configuration of physics options and various land use dataset. Borge *et al.* (2008) found Yonsei University for planetary boundary layer scheme, WSM-6 for microphysics, NOAH for land surface model, Eta Geophysical Fluid Dynamics Laboratory (GFDL) and MM5 (Dudhia) for long and shortwave radiation respectively as optimum configuration. Shrivastava *et al.* (2015) concluded that a single set of physics options cannot be said to perform best for all the meteorological parameters. Santos-Alamillos *et al.* (2013, 2015) reported that prediction is dependent upon the spatial resolution and terrain morphology. The land use data set CORINE has better performance than GLLC data set. The prediction of wind speed which is highly sensitive with PBL schemes and wind direction is not much affected by physics option of WRF model configuration for these tests.

Application of WRF with CMAQ

Meteorology is extremely important for any air quality modelling system because it provides input to air quality model. A study was done to analyse the behaviour of plume rise with vertical allocations of emission and modelled air quality concentrations (Guevara *et al.*, 2014). Two air quality model simulations in CMAQ (Community Multi-scale Air Quality) were conducted where meteorological parameters were provided by WRF. Models were run with two vertical emissions allocation of point source i) fixed vertical profiles of stack height and ii) with an hourly bottom-up calculation of effective emission heights. These two simulations differ only by the allocation of emission of point source to see the impact of time-dependent effective plume heights. Results showed that emissions allocated to lower altitudes were differing significantly with fixed vertical profiles and were mainly dependent upon the source sector and air pollutant. An improvement of simulation of industrial SO_2 concentrations was leading with the hourly plume rise calculations. 22–32% concentration level was increasing with plume rise calculations for SO_2 while 2–5% for NO_2. Stack based data on real world can be used to obtain maximum precision in plume rise calculations.

Carbonaceous aerosols and radiative effects were studied during a field campaign in central California in June 2010 (Gan *et al.*, 2014). This study aimed at estimating the different types of aerosols (carbonaceous) and their optical and hygroscopic properties. Comprehensive observations of optical properties and aerosol composition were carried out at two sites on ground and overhead from instrumentation mounted on two aircrafts. It assessed the parameterization aerosol optics by conducting a single column model (SCM) of the two-way coupled WRF-CMAQ with inputs based on modelled as well as observed aerosol concentrations, compositions, and size distributions. Modelled or observed aerosol concentrations were recorded by SCM in a vertical profile of aerosol properties. The configured SCM was used with 35 layers in the vertical, extending from the surface to 50 hPA. Vertical profile of aerosol optical depth (AOD) was computed by SCM with the extinction parameterization same as that of CMAQ aerosol module algorithms. Two examined cases on June 14 and 24 (2010) displayed that the estimated aerosol extinction by coupled WRF-CMAQ were underestimated compared to vertical observations by aircraft and were well in agreement with aircraft observations. The simulated sea-salt in the accumulation mode in WRF-CMAQ was very low in both cases while the observations indicate a considerable amount of sea salt could be one of the possible causes of the WRF-CMAQ extinction errors. Also, the presence of organic carbon in significant amounts may cause difference with the observations. Though all organic carbon was reflected as insoluble in WRF-CMAQ system, most secondary organic aerosol is water soluble. Additionally, external mixing and hygroscopic effects of water soluble organic carbon on the model were not considered, which can impact the extinction calculations. Finally, this study concluded that possible causes for the underestimation of extinction were greatly underestimated accumulation, misrepresentation of water soluble organic carbon, mode sea salt and incomplete mixing state representation in the full coupled model simulation.

A coupled WRF-CMAQ modelling system was used over North America and evaluation was done for the year 2006 and 2010 (Hogrefe *et al.*, 2014). The objectives of this study were to predict ozone, $PM_{2.5}$, PM_{10} concentration and compare results with annual application of the uncoupled system which was performed during Air Quality Model Evaluation International Initiative (AQMEII) Phase 1. Simulated AOD and AOD/$PM_{2.5}$ relationship were evaluated against observations from AERONET. Subsequently, sensitivity of meteorological and air quality variables were quantified on direct feedback. Comparisons were done in observed and modelled changes in air quality and radiation from 2006 to 2010. Through operational model evaluation, the performance of WRF-CMAQ could be compared to earlier annual applications of the uncoupled WRF/CMAQ modelling system which was done in 2006 during AQMEII Phase 1. When simulated and observed AOD were compared, a tendency toward underestimation in all seasons despite a tendency to overestimate $PM_{2.5}$ during wintertime was disclosed. The summertime daily maximum 8-h ozone was underestimated. These 2010–2006 $PM_{2.5}$ decreases result in simulated increases of summer mean clear-sky shortwave radiation between 5 and 10 W m^{-2}.

The application of WRF-CMAQ was repeated to the European domain for the year 2010 under the programme AQMEII-2 (Syrakov *et al.*, 2015). The domain size of WRF-CMAQ model system was 5000 × 5000 km^2 with a horizontal resolution of 25 km. The available emissions inventory was used through AQMEII-2 for Europe. NCEP GFS data with 1° × 1° horizontal and 6 hour temporal resolution was used as input in meso-meteorological model WRF. Analysis nudging option (four-dimensional data assimilation) was switched on to the NCEP GFS data. WSM 6 scheme for microphysics, Kain-Fritsch scheme for cumulus parameterization, YSU scheme for PBL, RRTM and Dudhia scheme for longwave and shortwave radiation respectively and NOAH for Land Surface Model scheme were among the multiple physics options selected. There were 27 vertical layers structure with increasing heights where first 9 layers were from the planetary boundary layer. Further chemistry transport model CMAQ was processed with emission inventory and meteorological fields. Model was evaluated with surface observed data for ozone, nitrogen dioxide and particulate matter. There was a comparison between Simulated and observed concentrations with statistical analysis at different type of surface stations such as rural, urban, suburban as well as for selected four cities in Europe. The model over predicted for ozone and under predicted for other pollutants. Predicted concentrations were better agreed for rural than urban region and no significant difference between predicted rural and urban concentrations was observed.

Comparison of WRF-CMAQ Study

Guevara *et al.* (2014) has studied difference between fixed height emission of stack and lower altitude emission at bottom up calculation for hourly effective emission height. The concentration output by WRF-CMAQ performed better with hourly effective emission in terms of air quality. The estimated aerosol extinction (aerosol properties) by coupled WRF-CMAQ was underestimated compared to observations and agreed well with aircraft observations at a height (Gan *et al.*, 2014). The results of WRF-CMAQ were underestimated for AOD, ozone, $PM_{2.5}$ and PM_{10} concentration (Hogrefe *et al.*, 2014). Again, WRF-CMAQ was applied to European region for prediction of O_3 and other pollutants (Syrakov *et al.*, 2015). Modelling results showed that model is over-predicting for O_3 and under-predicting for other pollutants compared to observed data. In all these simulations, WRF has similar setup configuration except one or two parameters for air quality modelling.

Application of WRF-Chem

A study was carried out using online coupled air quality model "Weather Research and Forecasting with Chemical Transport Model (WRF-Chem)" for East Asian air quality with anthropogenic, biogenic, biomass burning, and volcanic emissions (TRACE-P) (Wang *et al.*, 2010). Model domain was extended in 232 and 172 horizontal grid with 30 km horizontal resolution which covers the whole Korean Peninsula, Japan and China. This simulation includes 28 vertical layers where planetary boundary layer consists of 6 layers. The National Center for Environmental Prediction (NCEP) FNL data which has 6 h temporal and 1 × 1 degree grid resolution was used to generate the initial and boundary conditions of meteorology. This simulation was carried out for vertical distributions, diurnal, seasonal and day-of-week in July 2001. The comparison of simulation results was performed with surface measurements from National Environmental Monitoring Centre of China (NEMCC) and Acid Deposition Monitoring Network in East Asia (EANET). The best simulation of WRF-Chem was with the incorporation of all types of emissions. Default emission (not diurnal or vertical distribution) gave worst results. The combined temporal simulation for the secondary pollutant O_3 was higher by 4–8 and 2–4 ppbv at night and day time respectively.

WRF-Chem was applied to study aerosol and trace gas properties in three successive summer seasons of 2008, 2009 and 2010 over the Indian domain (Michael *et al.*, 2013). The WRF model options that were selected were RRTM and Goddard for long and short wave radiation respectively, Monin-Obukhov for surface layer, NOAH for land surface model, Mellor-Yamada-Janic for boundary layer, Grell-Devenyi and Lin for cumulus parameterization and cloud microphysics, respectively. The chemistry options selected were RADM2 for Gas-Phase chemistry, MADE/SORGAM for Aerosol processes and Fast-J is Photolysis. The emission inventory of sulphur dioxide, black carbon, organic carbon and $PM_{2.5}$ at 0.25° × 0.25° grid resolution were used (Cherian *et al.*, 2013, 2012). The rest of emission was included from RETRO and EDGAR of global emission inventories. The model results showed that the optical depth of aerosol at less polluted regions had better results than high aerosol loading compared to observations. The comparison between model and observed concentration of black carbon was in good agreement at surface level as better local emission inventory was used. Also, vertical profile of model results was well comparable with observations from aircraft in 2008 and 2009. This study captured the many features of the observation that can help to understand the regional atmospheric composition.

For concentrations of O_3 and $PM_{2.5}$ (fine dust particles) over the south-eastern USA, the online-coupled WRF-Chem was used with the Model of Aerosol Dynamics, Reaction, Ionization, and Dissolution (WRF/Chem-MADRID) (Yahya *et al.*, 2014). This simulation was carried out for different seasons from May to September and December to February (winters) during 2009, 2010, and 2011. Almost similar model set up configuration was selected in this study as well (Michael *et al.*, 2013). The chemistry option includes 2005 Carbon Bond gas-phase chemical mechanism (CB05), the Carnegie-Mellon (CMU) bulk aqueous-phase chemical kinetic mechanism and MADRID1 aerosol module for this study. The forecasted results were compared with observed data at spatial and temporal resolution and performance analysis was done using statistical assessment. The model performance was well for O_3 and satisfactory for $PM_{2.5}$ but larger biases exist in PM species.

Air quality of a Swiss complex terrain region was studied using WRF-Chem for the year 1991 and 2002 at 2 × 2 km^2 horizontal resolution (Ritter *et al.*, 2013). WRF model set up was selected and Eta Ferrier scheme was selected for microphysics, Bets-Miller-Janjic for cumulus parameterization, NOAH for land surface model, Eta similarity theory for surface layer, USGS for land use dataset, Mellor-Yamada-Janjic for planetary boundary layer, RRTM and Dudhiya scheme for Long and short wave radiation. Chemistry option Model for Simulating Aerosol Interactions and Chemistry (MOSAIC) and Carbon bond mechanism version Z (CBM-Z) was selected for this study. The spatial and temporal prediction of O_3, NO_2, PM_{10}, temperature and solar radiation were compared with ground level measurements. The model performed well for temperature and solar radiation at both scales but the concentration prediction was not done well by the model and systematic bias was eliminated (reduction of RMSE) using multi-linear regression.

WRF-Chem was also implemented to estimate surface ozone concentration with different planetary boundary layer schemes over Houston/Texas region (Cuchiara *et al.*, 2014). Here, also similar set was used except PBL schemes. Yonsei University (YSU), Asymmetric Convective Model version 2 (ACM2), Mellore-Yamadae-Janjic (MYJ) and Quasi-Normal Scale Elimination (QNSE) were the four PBL schemes attempted The model results of vertical profiles for potential temperature, temperature, water vapour mixing ratio, relative humidity, u-v components of the wind and O_3 concentration were evaluated with observed data. Different PBL schemes did not show any preference for all meteorological parameters but for O_3 concentration, YSU scheme gave better comparison with observed data.

WRF/Chem was attempted to simulate secondary organic aerosol and indirect effects of aerosol for regional air quality using various chemistry options over the region of North America for July 2006 (Wang *et al.*, 2014). Two new chemistry aerosol option viz. MADE option of 2005 Carbon Bond mechanism with SORGAM and VBS modules and aqueous-phase chemistry (CB05-MADE/SORGAM and CB05-MADE/VBS) were used to simulate secondary organic aerosol (SOA). The model results with both options provide reasonable prediction of the meteorological variables, mass concentration and aerosol/cloud properties when they were compared with observed values. The new chemistry option increased the accuracy of model prediction greatly for organic carbon (OC) and $PM_{2.5}$. Sensitivity analysis of model and indirect effects of aerosol on the regional climate and air quality were also carried out in this study. This shows the importance of indirect effect of aerosol on WRF-Chem model.

RADM2 gas-phase chemistry and the MADE/SORGAM aerosol module were used to conduct eight different simulations in another study with WRF-Chem for the year 2010 to contribute in AQMEII phase2 (Forkel *et al.*, 2015). The purpose/aim of this study was to analyse the effect of direct and indirect aerosol on estimated meteorological parameters and pollutants' concentration in European region. The results show that the lower temperature and PBL heights are leaded for all seasons of the year in direct aerosol effect while temperature is highly variable in the season over Northern Europe in indirect effect. The reduction of bias was found in this study when aerosol cloud interaction was incorporated in simulation. Here also, the predicted concentration of $PM_{2.5}$ and PM_{10} were low as compared to concentration. This study concluded that the performance of WRF-Chem does not depend upon the configuration of the simulation and the selection of physics and chemistry option. Sensitivity analysis was also carried out for AQMEII phase2 program using various options of microphysics in WRF-Chem (Baró *et al.*, 2015). Two different microphysics options such as Morrison (MORRAT) vs. Lin (LINES) were tested to investigate the impact on droplet number mixing ratio, cloud water mixing ratio, shortwave radiation, temperature and precipitation. Overall, there is no significant impact on the above parameters from the selection of the microphysics option, but spatial pattern has some differences in north-south of the region. WRF-Chem model performance has been studied with changes in emissions, boundary condition of meteorology and chemistry options over the North America from 2006 to 2010 under the AQMEII Phase 2 (Yahya *et al.*, 2015).

Summary of WRF-Chem Studies

WRF-Chem was applied in many case studies with various emission datasets. A study was carried out for East Asian air quality with emission inventory of TRACE-P and simulation results showed best with all incorporation of emission and worst with default emission (Wang *et al.*, 2010).WRF-Chem model was also run with local emission of India over the Indian domain and the model results were in good agreement for black carbon. This study also helps in understanding the regional atmospheric phenomena. WRF/Chem-MADRID was applied for forecasting of O_3 and $PM_{2.5}$ and performed well for O_3 and underestimated $PM_{2.5}$ (Yahya *et al.*, 2014). WRF-Chem model performed well for temperature and solar radiation at both scales, but the concentration prediction was not good by the model. However, systematic bias was eliminated using multi-linear regression post-processing because short-term peaks of several days were not captured by the model (Ritter *et al.*, 2013). Different PBL schemes did not show any preference for all meteorological parameters but for O_3 concentration, YSU scheme gave better comparison than WRF-Chem with observed data (Cuchiara *et al.*, 2014). Two new chemistry aerosol options in WRF-Chem viz. MADE option of 2005 Carbon Bond mechanism with SORGAM and VBS modules and aqueous-phase chemistry (CB05-MADE/SORGAM and CB05-MADE/VBS) were used and increased the accuracy of model prediction greatly for organic carbon (OC) and $PM_{2.5}$ (Wang *et al.*, 2014).

Application of WRF with AERMOD

A coupling of WRF model with AERMOD has been applied for Pune city of India to assess concentration of PM_{10} (Kesarkar *et al.*, 2007). Generally, the meteorological data for many of the locations in India is not easily available. Hence, the upper air and surface layer meteorology was generated using WRF model. In this study two-way nested domains of 70 × 105 × 40 and 85 × 197 × 40 grid points with 32 km and 8 km horizontal resolutions respectively were selected. Indian subcontinent was covered by the first domain ranging from 0° to 30°N in latitude and 65° to 85°E in longitude. Western Ghats region of southern peninsular India was covered by the second domain ranging from 8° to 22°N in latitude and 72° to 78°E in longitude. NCAR-

NCEP's Final Analysis (FNL) data was used to initialize the real boundary conditions having a 1° × 1° resolution. Nested resolution was made into a ratio of 1:4 of parent domain and FNL data. This ensured that the boundary conditions maintained for the model were reliable. The results of WRF model at a resolution of 8 km were verified with observed data of meteorology. Simulated temperature and wind profile was compared with observed data. Friction velocity was used to empirically estimate the mechanical mixing heights. This study showed that WRF can generate onsite surface and upper air data which can then be used in air quality modelling because this data is unavailable for majority locations in India. Emission inventory was not advisable to quantitatively compare the simulated and observed concentrations in the absolute sense. Assuming uncertainty in the emissions and including background concentration are generally contact for short period. The predicted concentrations were evaluated at sensitive, commercial, residential and background locations. Average observed concentration at background, residential, commercial and sensitive locations were 72.6, 77.2, 108.6 and 126.6 µg m^{-3} respectively for the period, while the simulated concentrations at these locations were 25.7, 56.3, 68.2 and 37.5 µg m^{-3} respectively. The predicted PM_{10} was less than 50% of the observed PM_{10} for background and sensitive locations but the residential location was found 27% underestimation.

WRF model was also applied for vehicular pollution modelling for Chembur region in Mumbai city of India (Kumar *et al.*, 2015) . WRF model was used to provide meteorological parameters at mesoscale for input of air quality model in Chembur study. WRF model version 3.2 was operated at 25 km horizontal resolution with extension between 71°E to 81°E zone and 11°N to 21°N meridian consisting of 100 by 100 grid points. The model was run starting from 1st January to 31st December during the year 2011 at temporal resolution for 1 hour. FNL data of 1° × 1° spatial resolution with 6 hours interval of National Centers for Environmental Prediction (NCEP) was used to generate the initial and boundary conditions. Topography, geographical data as well as snow cover information were taken from United States Geological Survey. Arakawa C-grid staggering for the horizontal grid and a fully compressible system of equations was employed in WRF model. A terrain-following hydrostatic pressure coordinates with vertical grid stretching was applied. A third order Runge Kutta scheme with smaller time step was used in the time split integration for acoustic and gravity wave modes. In this study, WRF physical options were consisted of the WRF Single Moment 6-class simple ice scheme for microphysics; the Kain-Fritsch scheme for the cumulus convection parameterization, and the Yonsei University planetary boundary layer scheme. The Rapid Radiative Transfer Model has been used for long wave radiation, whereas, the Dudhia scheme has been used for the shortwave radiation. The Noah land surface model is chosen to run the WRF model in this study. The top of the model is at 10 hPa with 28 vertical levels. Vehicular emission inventory and meteorological parameters were run in AERMOD and average predicted concentrations were obtained for NO_x and PM for the month May of the year 2011. The comparisons of the simulated and observed concentration were done when model was run with all emissions. Model was underestimating by 6% and 25% for NO_x and PM respectively. It concluded that contribution of NO_x concentration in total NO_x in ambient air is about 35% from vehicles while contribution of PM concentration is very low.

Prognostic meteorological model at mesoscale provides weather input for regulatory dispersion modelling and it works as data subsection of the guideline on air quality models. Environmental Policy Agency (EPA) has updated some more flexibility to improve the facility of users. They are providing meteorological inputs for the study area where NWS station is not available. For this, an updated version of the Mesoscale Model Interface (MMIF) program has been released that convert meteorological outputs in a suitable format of dispersion model which can use the data and process the meteorological process along with simulation of air quality model. It was proposed in the mid of 2015 and now it is used in the studies. As per recommendation of regulatory authorities, the most recent data of three years can be used in model applications and the appropriate committee will review for bringing it at acceptable quality and representative of the modelling application.

Comparison of WRF with AERMOD

WRF model was used to generate onsite meteorological parameters and was applied to AERMOD to predict concentration of air pollutants. Similar setup was configured in two studies of Pune city and Chembur region of Mumbai (India). It was applied for modelling of PM_{10} in Pune city by Kesarkar *et al.* (2007) where model was well comparable for PM_{10}. Vehicular pollution modelling in Chembur was carried out to predict concentration for NO_x and PM_{10} by Kumar *et al.* (2015) where model was well comparable for NO_x but underestimated for PM_{10}.

Application of WRF with CAMx/ FLEXPART

Two different configured WRF models for air quality predictions were studied for ozone, $PM_{2.5}$ and carbon monoxide predictions using Comprehensive Air Quality Model with Extensions (CAMx) model (Baker *et al.*, 2013). The main difference between WRF configured simulations were the implementation of various land surface models (LSMs) and PBL parameterizations. Both simulations were done at 4 km horizontal resolution (253 × 334) in Lambert Conformal projection with the domain encompassing all of California, and much of western Nevada. CAMx photochemical model (version 5.41) was used to estimate concentrations for both primary and secondary pollutants using simulated meteorological fields by WRF. This photochemical model includes ISORROPIA inorganic chemistry, Regional Acid Deposition Model (RADM) aqueous phase chemistry, a semi-volatile equilibrium scheme and gas phase chemistry based on the Carbon Bond 6 mechanism (ENVIRON, 2011). It was applied from June 20th to 22nd at 4 km grid-size with a vertical layer construction same as WRF. Results showed that variability and magnitude in mixing heights were performed well by the WRF simulations. WRF system characterized well for the large scale wind flow for this time period. First configured WRF model overestimated the mixing height. $PM_{2.5}$ and carbon dioxide concentration were varying with the boundary layer on both days but the differences in boundary layer heights are directly related to model predictions was not visible. The differences in concentration are likely a combination of differences in estimated mixing layer height, temperature, and wind.

In order to assess the meteorological flow and planetary boundary layer (PBL) parameters over the complex topographic region of Jharkhand state of India, the High resolution Advanced Research WRF (ARW) mesoscale model was employed (Madala *et al.*, 2015). The generated meteorological field by WRF was used in a Lagrangian Particle Dispersion Model (FLEXPART) for simulation of air pollutant dispersion. The FLEXPART model has an ability to simulate the mesoscale transport, diffusion and dry and wet deposition of emissions using calculated trajectories of fluid particles with ARW generated meteorology. The WRF simulations were driven by the NCEP FNL input data with spatial resolution 1° × 1° and temporal resolution of 6 h. Two-way three nested domains of WRF model were run with 27 km, 9 km and 3 km horizontal resolution including 30 vertical layers. PBL schemes option was selected by Yonsei University (YSU) and Asymmetric Convective Model version 2 (ACM2). Noah land Surface Scheme was selected in surface layer parameterization, WSM-6 in microphysics, Dudhia scheme in short wave radiation and RRTM scheme in long wave radiation. Eight different seasons were selected such as winter, pre-monsoon, monsoon, and post-monsoon etc. Madala *et al.* (2015) assembled 150 × 150 horizontal grids with 3 km resolution, 13 vertical levels from the surface up to 5000 m height above ground level (AGL) with the lowest level between 0 and 25 m AGL. Results of seasonal flow-field on air pollution dispersion revealed that the low-level flow field is greatly influenced by the topography and varies extensively according to seasons. ARW-FLEXPART system disclosed that the atmosphere provided higher dilution potential in monsoon and pre-monsoon as compared to post monsoon and winter seasons over the region.

Summary of WRF with CAMx/FLEXPART

Baker *et al.* (2013) reported that the variability and magnitude in mixing heights is well captured by the WRF simulations considering differences in the definition of ACM2 PBL heights and HSRL (High Spectral Resolution Lidar) mixing layer height measurements The topography affects the Low-level flow field to a great extent and it widely varies in different seasons (Madala *et al.*, 2015). ARW-FLEXPART system revealed higher dilution potential of the atmosphere in monsoon and pre-monsoon compared to post monsoon and winter seasons over the region.

APPLICATIONS OF AERMOD

A study presented that the air quality management framework of different countries and comparisons have been attributed (Gulia *et al.*, 2015a). This article reviewed many perspectives of air quality such as air quality monitoring network in megacities and air quality management in different countries. Many countries have evaluated various plans for air quality management such as identification of air quality management areas based on monitored ambient air quality level and then developed appropriate air quality management framework. The typical plan for air quality management includes following elements like goal, air quality information system, identifying and quantifying emission sources, air quality modelling, abatement options and stakeholder participation.

Application of AERMOD for Impact Assessment

AERMOD is a local scale model which is applied for urban sources for small region because it considers single set of meteorology. Same meteorological conditions over the study region are assumed in AERMOD. If study region is big then the single set of meteorology will not be applicable over the whole region. In that case, some advanced air quality model such CALPUFF/CMAQ is used which takes multiple gridded meteorological data sets. AERMOD is an advanced version of Industrial Source Complex Short Term (ISCST3). In India, ISCST3 is a regulatory model but recently AERMOD is also being used for assessing air quality for various purposes and regulatory authority is accepting the results of AERMOD. For air quality modelling for various perspectives with measured values of concentration, AERMOD has been applied. AERMOD was used for different time scales which could help chronical exposure assessment in epidemiological studies (Kumar *et al.*, 2006; Zou *et al.*, 2010). Kumar *et al.* (2006) used AERMOD to predict concentration for the 1-h, 3-h and 24-h averaging period for Lucas county, Ohio, USA. Prediction of concentration was done for classification of convective and stable circumstances. This study was conducted at atmospheric conditions of near-neutral for both cases. Again, stability condition was isolated into two subdivisions and convective circumstance was isolated into three subdivisions. The conclusions of this study show that the model could not predict for all subdivisions of stable and convective cases. Zou *et al.* (2010) also performed AERMOD on 1-h. The concentrations were compared at temporal resolution of 3-h, 8-h and daily, monthly and annual for Texas, USA. National Emission Inventory (NEI) provided SO_2 emission data of the year 2002 for the study area. Meteorological data was collected from National Climatic Data Centre (NCDC) and National Oceanic and Atmospheric Administration (NOAA). Digital elevation datasets were collected from US geological Survey to perform AERMAP. Model was evaluated with observed concentration of SO_2 for three sites. Results of this study showed that AERMOD performed better when point and mobile sources were taken together rather than using point or mobile source alone.

For environment impact assessment (EIA) studies, AERMOD has been used for emission sources like stack of industries in Thailand (Seangkiatiyuth *et al.*, 2011). In this study, AERMOD was used for analysis of NO_2 emission from 14 stacks of four cement plants, in the north east of Bangkok. Meteorological data was obtained from the Thai meteorological department which is close to a National Park. Air quality modelling results were compared with observed data of concentration for dry and wet season. The results showed that NO_2 concentration was not exceeding the prescribed limit of National Ambient Air Quality Standards of Thailand. The maximum one hour predicted concentrations of NO_2 are 548 µg m^{-3} and 562 µg m^{-3} for dry and wet season which was above the legislation of 320 µg m^{-3}. However this study found that AERMOD prediction capability is limited for air pollutants beyond a distance of 5 km from the reference point. Also in AERMOD, reaction module should be considered for estimation of NO_2 concentrations to obtain more accurate results.

The pollutant concentration predicted from AERMOD has been used to estimate the corresponding health risk assessment for the population, and therefore the cost can be estimated for health impact from air pollution (Mokhtar *et al.*, 2014). This model is used for a critical evaluation of risk to human health for the proximity area of coal-fired power plant in Malaysia. Two pollutants SO_2 and Hg were proposed in New Environmental Quality (Clean Air, Malaysia) and introduced as non-carcinogenic species for health risk. Also, two tracer elements As and Cr were selected as carcinogenic pollutant for health risk. AERMOD predicted the ground level concentration for all pollutants for short and long term. The health risk was estimated for the population using concentration within 10 km radius. Dose response was estimated between the dose of exposure to the hazard and occurrence of adverse effects.

AERMOD was applied for vehicular pollution modelling with various control strategies in Mulund region of Mumbai city (Sonawane *et al.*, 2012). Vehicular emission inventory and meteorological parameters were run in AERMOD and average predicted concentrations were obtained for NO_x, CO and PM. Vehicles contribute 9.9, 35, 40.82, 77.6 and 0.74% of the total emission load of PM, CO, NO_x, HC and SO_2 respectively in Mulund. Initially, vehicular pollution modelling was done for the existing scenarios with observed meteorology for PM, CO and NO_x. Subsequently, various control strategies for vehicles were proposed and correspondingly emission inventory was estimated to predict the resulting concentration. Mathematical model was formulated to optimize the application of a particular strategy or a set of strategies. The difference of concentration between existing scenarios and proposed control scenario was estimated. The health impact assessment was done using BenMap for concentration changes in each scenario. Finally, cost benefit analysis was done based on the implementation of control strategies and cost of health damages by changes in air pollution level.

Comparison of AERMOD with other Air Quality Models

Many case studies throughout the world include the evaluation of AERMOD with ISCST3, ADMS, CALPUFF and other models for pollutants. AERMOD and ADMS-Urban were evaluated for Total Suspended Particulate Matter (TSPM) for the winter season of years 2000 and 2004 in Delhi, India (Mohan *et al.*, 2011). Emission inventory was prepared over a gridded area (26 × 30 km^2) with a resolution of 2 km covering most of the urban area of Delhi. Comparisons of concentration prediction of both models were done based on statistical measures. The modelled values by ADMS-Urban have higher correlations than AERMOD with observed concentrations. Daily and monthly averaged predicted concentration by both models coincided with the observed concentrations within a factor of two. Agreement of monthly average predicted concentrations with observed concentrations was better than daily predicted concentrations with observed concentrations.

Rood (2014) has evaluated Gaussian plume and Lagrangian puff models using winter validation tracer study dataset. The objectives of this study were to estimate unpaired maximum 1-h and 9-h average concentration, location of maximum plume and impacted area and concentration at arc-integrated. It was aimed to address regulatory compliance and dose reconstruction assessment questions. It concluded that Lagrangian puff models were better performers for dose reconstruction and transportation of pollutants at long range. 140 samples were collected and twelve tests were analysed for every 11 hours sample in a concentric ring of 8 km and 16 km. The performance of modelling for one-hour maximum average concentration shows a strong positive bias for the steady-state model AERMOD and nearly no bias for puff model CALPUFF. The positive bias for the steady-state model was greater at the 16-km distance. 92% of the ISC2-estimated maximum one-hour average concentrations and 83% of the AERMOD values had predicted-to-observed ratios of 0.95 or higher. Similarly, predicted maximum nine-hour average concentration was found to have a similar trend that the steady-state models revealed positive bias, while the Lagrangian puff models revealed negative bias. The plume mean deviations at 8 km distance were calculated for both models and it was found lower for AERMOD and highest for CALPUFF and ISC2. Plume width at the 8-km distance was underestimated for ISC2 and CALPUFF while it was overestimated for AERMOD.

The estimation of TSPM concentration was evaluated from quarries and open mining sources in a complex terrain for the year 2010 and 2011 (Tartakovsky *et al.*, 2013) using AERMOD and CALPUFF. Drilling, gathering, Truck loading, transportation, wind erosion and crushing (grinding) were included in emission inventory of TSPM. Meteorological data was collected from the Israel Meteorological Service (IMS) for the year 2010 and 2011. TSPM concentration on daily average was measured at three locations in the study area. Results show that AERMOD performed better than CALPUFF. The average ratio of the predicted concentration by AERMOD, and observed concentrations for complex terrain and values from previous studies for flat terrain appeared to be similar. The average ratio of the concentration predicted by CALPUFF and observed concentrations were lower than the reported previously for area sources in a flat terrain. In this case study, meteorological data was collected from IMS which was situated far away from the emission source site. Also, complexity of the topography can result in an inaccurate prediction of dispersion. With the intention to better understand the impact of quarries and open pit mining and with relatively low cost involved in data collection, it was recommended to set up a meteorological station in the study area to remove the uncertainty involved in the study.

Application of AERMOD for Building Effects, Farms and Aerosol Studies

Building effects were analysed using a comprehensive data set on two dispersion models including Danish model OML and the USEPA model AERMOD with the PRIME building algorithm (Olesen *et al.*, 2009). The observed and estimated results were carried out with the effect of building width for four scenarios. Olesen *et al.* (2009) characterized, "the parameters for the four scenarios were; the relative stack height in terms of building height is 1 (top row) and 1.5 (bottom row). The building is a cube (left column), and wide (4 times its height, right column) and the stack is placed in the middle of the building". Results of the OML model were insensitive to the building width while AERMOD results show a strong dependency on building width. Also, AERMOD overestimates by a factor of more than two at close to the building in the case of the cubic building. Recirculation region had high and uniform predictions by AERMOD while lower concentrations are estimated when building was wider. The degree of prediction was estimated with respect to maximum concentration which is less than a factor of two for both models in most of the cases. Both models had larger mispredictions for the concentration at a specific location mainly near the field.

CALPUFF and AERMOD were used for dispersion modelling of odour around a pig farm building area (Vieira de Melo *et al.*, 2012). PRIME algorithm was incorporated with both models to take into account the plume rise and effects of the building downwash. The calculations of concentrations of models did not vary. These estimations were related with pollutant concentrations for averaging time period which includes peak concentrations of short time interval. The results of wind tunnel experiments for the emission of odours at different steps of the process were used to validate the dispersion models of odours at the vicinity of a pig farm. To assess the perception of odor using AERMOD and CALPUFF, an averaging-time scaling factor was used to predict short-term peak concentrations. Overall AERMOD estimated concentrations was higher than those of CALPUFF estimated concentration mainly for maximum mean concentrations which was observed in the near field.

AERMOD was applied to estimate the ratio of 1 hr NO and NO_2 in the atmosphere (Podrez, 2015). Nitric oxide (NO) is emitted from fuel combustion in the atmosphere and reacts with ozone and other oxidising agents which form NO_2. The standard for NO_2 is provided by the Environmental Protection Agency (EPA). In this study, Ambient Ratio Method version 2 (ARM2) was taken from USEPA. ARM2 was developed to analyse the conversion rate and variation in NO_2 and NO_x concentration using 1-hour NO_2 and NO_x concentration. AERMOD was used to predict total NO_x concentration, and the ARM2 method was used to calculate the NO_2 and NO portions of the total NO_x. The performance of ARM2 and AERMOD were analysed and evaluated with independent monitored data set. This data set included NO_2, NO_x, ozone and weather parameters in the vicinity of a power plant. The ARM2 performed well as compared to other EPA conversion methods with actual ambient concentration.

AERMOD was also used to estimate the emission factor of hydrogen sulfide (H_2S) by inverse modelling for determining threshold level for ambient H_2S (O'Shaughnessy and Altmaier, 2011). This study was conducted for a region in the proximity of Concentrated Animal Feeding Operations (CAFOs) in Iowa, USA involved in livestock operations (swine feeding). These CAFOs emit H_2S from both waste lagoons and livestock housing structures. There were four air quality monitoring receptors installed at 1 km distance range of CAFOs region. An inverse approach was carried out using AERMOD to estimate the emission rate of H_2S. CAFOs building and lagoons were assumed as volume and area sources respectively. The meteorological data was collected from a nearby National Weather Service station at Mason City, Iowa, 40–60 km away from the original study area. Upper-air dataset was obtained at Omaha, Nebraska, located 260 km away from the study area. The modelled and measured concentrations were compared and adjusted to obtain the best fit model for emission rate. The adjusted emission flux rate was determined for the swine CAFOs lagoons. Three out of the four sites show a similar emission factor, however it was difficult to determine the accurate emission factor for hydrogen sulfide. Again, these emission factors were applied to CAFOs in ten monitoring stations within 7 km. Robust Highest Concentration (RHC) was used to calculate monitoring and model concentration. An average emission factor was calculated with the help of the total swine weight in kilogram of each CAFOs.

Application of AERMOD for Air Quality Management

Air quality management studies have been done across the world using AERMOD. In China, it was applied for near future air quality simulation using change in emissions based on proposed development plan to predict the concentration for the industrial city, Xuanwei of Yunan province (Ma *et al.*, 2013). The impact of emission control policy was studied for the five year (2011–2015) plan for Xuanwei. Emission reduction scenarios were prepared for the emission control policy for SO_2, NO_x and PM_{10}. Emission inventory was built based on general investigation of pollution sources and pollutant source monitoring report (2008). This included the industrial plant and six important factories around the city. In this case, average meteorological data in same time period was to be used to predict the future air quality. One-way ANOVA test was used to show effectiveness of the emission control policy. Spatial contour plots helped to identify the high concentration regions, which required the attention of the special environmental supervisors.

AERMOD was used to appraise the air quality surrounding the heritage site of Amritsar (Punjab) India (Gulia *et al.*, 2015b). Amritsar is a tourist place and religious heritage complex which is crowded during festivals. Free open kitchens operate next to the heritage structure to provide free meals to the visitors. Apart from this, coal based tandoor, diesel generators, local industries and vehicle movement are main source of emission. In this study conducted to predict concentration from June to September 2012, AERMOD was used. Various management options were discussed to decrease pollution levels at the heritage site. The cost effective approach for improving air quality included steps like identification of emission sources, assessment, inclusion of extended sources and target sources etc. are considered. The management control scenarios included introducing battery-operated vehicles, change in traffic movement and installation of air pollution control equipment in the open kitchen. The reduction for the first control scenario (battery-operated vehicles) was 14% and 21% for PM_{10} and NO_x respectively. The reduction in second control scenario (change in traffic movement) was 5% and 13% for PM_{10} and NO_x respectively. The third control scenario i.e., installation of air pollution control equipment in the kitchen, resulted in a reduction of 5% and 13% for PM_{10} and NO_x respectively.

Summary of AERMOD Studies

Zou *et al.* (2010) reported, AERMOD may not predict for all subdivisions of stable and convective cases. It can perform better with the combination of point and mobile sources together rather than using point or mobile source separately (Kumar *et al.*, 2006). The prediction of AERMOD may not be in good agreement with observation at a distance of 5 km from the reference point and reaction module should be considered for estimation of NO_2 concentrations to obtain more accurate results (Seangkiatiyuth *et al.*, 2011). Health impact assessment and cost benefit analysis can be carried out with output of AERMOD (Kumar *et al.*, 2006; Sonawane *et al.*, 2012; Mokhtar *et al.*, 2014). Mohan *et al.* (2011) concluded that ADMS-Urban performs better than AERMOD in a particular study but there is no static conclusion based on predicted concentration that any air quality model such as AERMOD, CALPUFF, ISC2 is better (Vieira de Melo *et al.*, 2012; Tartakovsky *et al.*, 2013; Rood, 2014). The development of model based emission factors and aerosols' properties can be carried out using AERMOD (O'Shaughnessy and Altmaier, 2011; Podrez, 2015). As regulatory model AERMOD is widely applied to see impact of various future scenarios at urban scale (Ma *et al.*, 2013; Gulia *et al.*, 2015b).

CONCLUSION

India and many other countries have severe lack of availability of meteorological data because they have meteorological stations at very few locations. This data may not be available at higher temporal resolution for many meteorological parameters. This limitation can be overcome by using a meteorological model. Weather Research and Forecasting (WRF) meteorological model can provide onsite meteorological data that can be applied to air quality model (AQM) and gives reasonable results for prediction. Results obtained using the WRF model has also been compared with observed data. It has been found that it gives good agreement for all parameters. Sometimes, it may not predict well wind speed and direction. It might be that WRF is not performing well to consider local and urban topography in simulation. Borge *et al.* (2008) has found physics option Yonsei University for planetary boundary layer scheme, WSM-6 for microphysics, NOAH for land surface model, Eta Geophysical Fluid Dynamics Laboratory (GFDL) and MM5 (Dudhia) for long and Shortwave radiation respectively as optimum configuration for prediction of weather parameters. There is no single set of physics options which gives best results for all the meteorological parameters (Shrivastava *et al.*, 2015). The prediction of WRF depends upon spatial resolution and terrain morphology (Santos-Alamillos *et al.*, 2013; 2015). The estimation of wind speed is sensitive with PBL schemes and no considerable sensitivity with physics option of WRF configuration.

This survey shows that WRF has been used efficiently to generate meteorological data and can be processed in air quality model such as Community Multi-scale Air Quality (CMAQ), Comprehensive Air Quality Model with extensions (CAMx). Mesoscale Model Interface (MMIF) program also can be used to convert meteorological outputs in a suitable format of dispersion model like AERMOD. CMAQ and CAMx photochemical models have been used with various objectives like the behaviour of plume rise, aerosols property and prediction of pollutant concentration. In most of the cases, CMAQ underestimates as compared to observation for AOD, ozone, $PM_{2.5}$ and PM_{10} concentration while over-prediction for O_3 (Hogrefe *et al.*, 2014; Syrakov *et al.*, 2015). AERMOD has been compared with ADMS-Urban and CALPUFF and results show AERMOD has lower as well as higher correlations than these models with various case studies. There is no static conclusion based on predicted concentration that any air quality model such as AERMOD, CALPUFF, ISC2 is better (Vieira de Melo *et al.*, 2012; Tartakovsky *et al.*, 2013; Rood, 2014). The data generation from meteorological model WRF can provide meteorological parameters to AQM and this can help to accurately estimate health risk, analysis of future impact assessment and Environment Impact Assessment (EIA) for air quality management.

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