Coupling of WRF and AERMOD for Pollutant Dispersion Modeling

Amit P Kesarkar[*1], Mohit Dalvi[1], A. Venkatram[2], A. Cimorelli[3], Akshara Kaginalkar[1] and Ajay Ojha[4]

(1) Centre for Development of Advanced Computing (C-DAC), Ganesh Khind Pune 411 007, India
(2) Dept. of Mechanical Engg., University of California at Riverside, CA, USA
(3) EPA (Region –III) Office, Philadelphia, PA, USA
(4) Air Quality Management Cell, Pune Municipal Corporation (PMC), Pune, India

1. Introduction:

In India the application of air quality models is mainly limited to regulatory applications with the Industrial Source Complex (ISC) of USEPA (ISCST3, 1998) being the model of choice. Very few cases of application of models in urban air quality management are currently available (TERI, 2005, IES, 2005, Athalye et al, 2006). Under the "Clean Air Initiative Program" being implemented in the city of Pune, India jointly by MoEF and USEPA, an integrated urban air quality modeling system is developed. For initial stage, the focus of this program is on dispersion of particulate matter since they are one of the important cause of health damage and mortality especially in the Asian countries (WHO, 2002). Under this program, it is proposed to use Gaussian air pollutant dispersion model viz. AMS/EPA Regulatory Model or AERMOD (Cimorelli et al, 2004) to understand the dispersion of Particulate Matter (PM10) over Pune. AERMOD has an improved approach for characterizing the fundamental boundary layer parameters and the vertical profile of the atmosphere alongwith better representation of plume buoyancy, penetration and urban nighttime boundary layer (Cimorelli et al, 2004) as compared to the ISC model. It provides variable urban treatment of vertical dispersion as a function of city population, and can selectively model sources as rural or urban. AERMOD requires steady and horizontally homogeneous hourly surface and upper air meteorological observations for simulating the dispersion. However, meteorological observations with such frequency are not available for Pune city (as is the case with most locations in India). To overcome this difficulty, the required meteorological parameters are derived from prognostic high resolution simulations using Weather Research and Forecasting (WRF) model developed by NCAR. An offline preprocessor required to couple WRF with the AERMOD model is developed at Centre for Development of Advanced Computing (C-DAC), Pune. This preprocessor initializes AERMOD by substituting required hourly values of surface layer and PBL parameters with those derived from WRF outputs. This paper presents a discussion on the coupling methodology used and initial results from the WRF-AERMOD simulations.

2. Air Quality Modeling Study of Pune City

As a part of the ongoing MoEF-USEPA clean air initiatives, activities related to air quality and emissions data collection targeting PM10 were initiated during the year 2003 - 04 by Pune Municipal Corporation (PMC). The main sources for PM10 emissions considered under this Program include use of biofuels for cooking, paved and unpaved road dust, vehicular exhaust, agriculture land dust, industrial and non-industrial electricity generators, trash burning and selected industrial operations. The emission inventory for PM10 has been developed for these sources and finally gridded in the form of 2kmx2km cells covering the city. The total emission load of PM10 in Pune for the year 2005 is estimated to be about 9200 tons. A short term 24 hourly ambient air quality survey for PM10 was conducted by the Air Quality Management Cell of PMC for the period 13 – 17 April 2005 at four locations (Fig. 1 a). Out of the four, three locations viz. Navi Peth, Mandai, and Koregaon Park are classified depending on surrounding landuse as residential, commercial, sensitive respectively and one location viz. Oasis club at Paud near the outskirts of the city is regarded as background. Sampling of PM10 was done using low volume samplers with teflon filters and analysis using gravimetric method. For most of the campaign period the meteorological conditions over Pune city were dry, while some convective activity associated with development of mesoscale convective system over the Western Ghats was observed in the afternoon hours of 13 and 15 April 2005. Westerly/ northwesterly winds were prevailing over Pune during this period.

3. WRF-AERMOD Modeling System:

a. WRF:

For this study, the two way nested computational domains of 70 X 105 X 40 and 85 X 197 X 40 grid points with the horizontal resolution of 32 km and 8 Km respectively are chosen (Fig. 1 b). The first domain covers most of the Indian subcontinent, ranging from 0 – 30^o N in latitude and 65 – 85^o E in longitude. The second domain covers the Western Ghats region of southern peninsular India ranging from 8 – 22^o N in latitude and 72 – 78^o E in longitude. The model is initialized by NCAR-NCEP's Final Analysis (FNL) data. The model is integrated for the period 12 – 19 April 2005 using time step of 180 seconds. The following model configuration is used for this study.

- Micro-physical subgrid processes: Lin et al., 1983
- Cumulus Parameterization: Betts Miller Janjic Scheme (Janjic, 1994, 2000)
- PBL parameterization: Yonsei University PBL scheme (Hong et al, 2006; Hong and Dudhia 2003)
- Land-surface Process: Noah land-surface model (Chen and Dudhia, 2001)

* Corresponding Author: Dr. Amit P Kesarkar, e-mail: akesarkar@cdac.in, Fax:91-020-25694004

- Short Wave Radiation parameterization: Dudhia, 1989
- Long Wave Radiation parameterization: Rapid Radiative Transfer Model (Mlawer et al., 1997)
- Surface clay Physics: Monin and Obukhov, 1954

b. AERMOD:

AERMOD has been setup for calculation of 24 hourly average concentration of PM10 using urban dispersion option. The emission profiles generated under the Pune air quality management program have been used for defining the sources. Due to unavailability of terrain elevation data for Pune at the interval (90 m) as required for AERMOD, simulations have been carried out assuming a flat terrain. The receptor grid has specified covering an area of 25 x 25 sq. km with 1.0 km resolution. The point output values at the PM10 sampling locations have been obtained to enable comparison of the simulated and observed PM10 levels.

c. Coupling:

AERMOD requires steady and horizontally homogeneous hourly surface and upper air meteorological observations. In the absence of meteorological observations at an hourly interval, the use of regional model derived meteorological parameters is well suited. The required coupler for WRF-AERMOD coupled system is developed and used for carrying out this simulation. This coupler derives the planetary boundary layer and surface layer parameters for given location from WRF model outputs and create the AERMOD meteorological input file by-passing the need for AERMET and thus any observational data requirement. Using this preprocessor friction velocity, Monin-Obukhov length, convective mixing heights, surface heat flux, wind speed and direction at 10 m height, temperature at 2.0 meter height, surface roughness, albedo at Pune are directly obtain from simulated WRF outputs with 8 Km resolution. These simulations have been carried out on the PARAM Padma, C-DAC's Tera Scale Supercomputing Facility (CDAC, 2003). The mechanical mixing heights are estimated empirically from friction velocity as described by Venkatram, 1980. The convective velocity scale is estimated from PBL height, friction velocity and Monin Obukhov length as described by Deardorff 1970. These parameters are then passed through interface present in AERMOD to calculate vertical profiles of wind speed, lateral and vertical and lateral turbulent fluctuations, and potential temperature gradient. The source profiles and ambient air quality data have been prepared under "Clean Air Initiative Program" as described earlier is used to initialized AERMOD.

4. Initial Results:

a. Validation of WRF Outputs

It is evident from this Fig. 2, the computed surface temperatures and observed temperatures show a significantly similar trend with the correlation coefficient of about 91%. The deviation of simulated surface temperature from the observed temperature ranges between -4.35^0 C to 8.35^0 C. The average deviation equals to -0.32^0 C with the standard deviation and coefficient of variation of 2.46 ^{0} C and 13% respectively. The maximum positive temperature deviation of 8.35^0 C is observed on 12 UTC of 14 April 2005 and maximum negative temperature deviation of -4.35^0 C is observed on 09 UTC of 12 April 2005. The distribution of temperature deviations show that about 31 %, 60 %, 76 % and 95 % deviations lies in the ranges of ± 1^0 C, ± 2^0 C, ± 3^0 C and ± 4^0 C respectively. Thus we can conclude that WRF model is able to simulate point surface temperatures over Pune reasonably well to initialize AERMOD.

The averaged angular distribution of wind directions for the entire period simulated by WRF and as reported in NCEP ADP dataset is as shown in Fig 3 (a) and 3 (b) respectively. As observational wind directions in this data record are reported in discrete form of 8 sectors only, the observational dataset is of coarse resolution and represents northerly and westerly winds in most of the cases. It is evident from both observations and simulations that northwesterly winds were dominated during the duration of field campaign. Simulation shows more percentage of wind directions in southwesterly direction as compare to the observations. The observed average wind speed during the period of the campaign was about 0.65 m s^{-1} while simulated wind speed is about 3.56 m s^{-1}. From above it can be conclude that the wind directions and speed are reasonably well to initialize AERMOD.

b. Comparison of Observed and Computed Concentrations of PM10

Comparison of AERMOD output with monitored air quality values at four different locations in Pune city are shown in Fig. 4. The output of AERMOD does not include the 'background' concentrations (i.e. baseline pollutant levels in absence of any emissions) and therefore it is difficult to quantitatively compare the simulated and observed concentrations. However, assuming that the background concentrations (and any uncertainty in emissions) will remain relatively constant for the short period of study, the day-to-day variation pattern of PM10 values can give an indication of the model performance. The observed concentration of PM10 averaged for the period of field campaign at residential, background, sensitive and commercial locations in Pune are 77.2, 72.6, 126.6 and 108.6 ugm^{-3} respectively, while the AERMOD simulated concentrations at these locations are 56.3, 25.7, 37.5 and 68.2 ug m^{-3} respectively. Thus, the simulated concentration of PM10 is nearer to observed for residential area while for other places it is much less as compared to the observations. This could also be attributed to lack of background level information in the model or under-representation of some source profiles in the emissions. However, the perusal of the figures also shows that the model is able to capture the day-to-day variations of the PM10 levels fairly well, especially for residential and commercial locations. At the same time the observed sudden increase in PM10 on 17th at background location is not captured in the model. This increase may be due to some local activity in vicinity of the sampler, which could not be represented in the emissions. Improvement in the emission inventory inputs along with sensitivity analysis of AERMOD to different WRF parameterization may lead to improve the predictability of this system.

5. Conclusions:

In this paper the methodology for coupling of air quality model (AERMOD) with regional weather prediction model (WRF) are discussed and initial results are presented. The comparison between simulated and observed temperature and wind fields shows that the simulations succeed in generation of meteorological inputs required for AERMOD. The comparison of observed and simulated concentrations of PM10 shows that concentrations are underestimated by the simulations except over residential area. Further, it is also shown that for almost all the days during field campaign the concentrations of PM10 pollutants are relatively high in the central locations than as compared to the outskirts of the city. This may be attributed to relatively high winds from northeasterly/ easterly directions than other wind directions in summer season and the accumulation of PM10.

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References

Athalye, V.N., Patil, R.S. and Sethi, V, 2006; "Modeling and Mapping of Air Pollution Health Benefits for an Urban Region ". Presented at National Air Quality Workshop, IIT Roorkee, February 2006.

Chen, F., and J. Dudhia, 2001: Coupling an advanced land-surface /hydrology model with the Penn State / NCAR MM5 modeling system, Part I: Model Description and Implementation. *Mon. Wea. Rev.,* **129,** 569-585.

Cimorelli, A. J., S. G. Perry, A. Venkatram, J. C. Weil, R. J. Paine, R. B. Wilson, R. F. Lee, W. D. Peters, R. W. Brode and J. O. Paumier, 2004: AERMOD: Description of model formulation, U. S. Environmental Protection Agency, EPA Rep. 454/R-03-002d, 85 pp.

Deardorff, J. W., 1970: Convective velocity and temperature scales for unstable boundary layer for Reyleigh convection. *J. Atmos. Sci.,* **27**, 1211-1213.

Dudhia, J., 1989: Numerical study of convection observed during the winter monsoon experiment using a mesoscale two-dimensional model. *Journal of Atmospheric Sciences*, **46**, 3077 – 3107.

Hong, S. Y., Y. Noh and J. Dudhia, 2006: A new vertical diffusion package with explicit treatment of entrainment processes, accepted by *Monthly Weather Review*

Hong, S. Y., and J. Dudhia, 2003: Testing of a new non-local boundary layer vertical diffusion scheme in numerical weather prediction applications, 20th Conference on Weather Analysis and Forecasting / 16th Conference on Numerical Weather Prediction, Seattle, WA.

IES, 2005; Integrated Environmental Strategies (IES) study for city of Hyderabad, INDIA, Final Report prepared by EPTRI, Hyderabad, April 2005

ISCST3, 1998; User Guide for ISCST3 model, USEPA

Janjic, Z. I., 1996: The surface layer in the NCEP Eta model, Eleventh conference on Numerical weather Prediction, Norfolk, VA, 19 – 23 August; *American Meteorological Society* Boston, MA, 354 – 355.

Janjic, Z. I., 2000: Comment on "Development and Evaluation of a convective scheme for use in climate models", *J. Atmos. Sci.*, **57**, p. 3686

Lin, Y. -L., R. D. Farley and H. D. Orville, 1983: Bulk parameterization of the snowfield in a cloud model. *Journal of Climate and Applied. Meteorology*, **22**, 1065 – 1092.

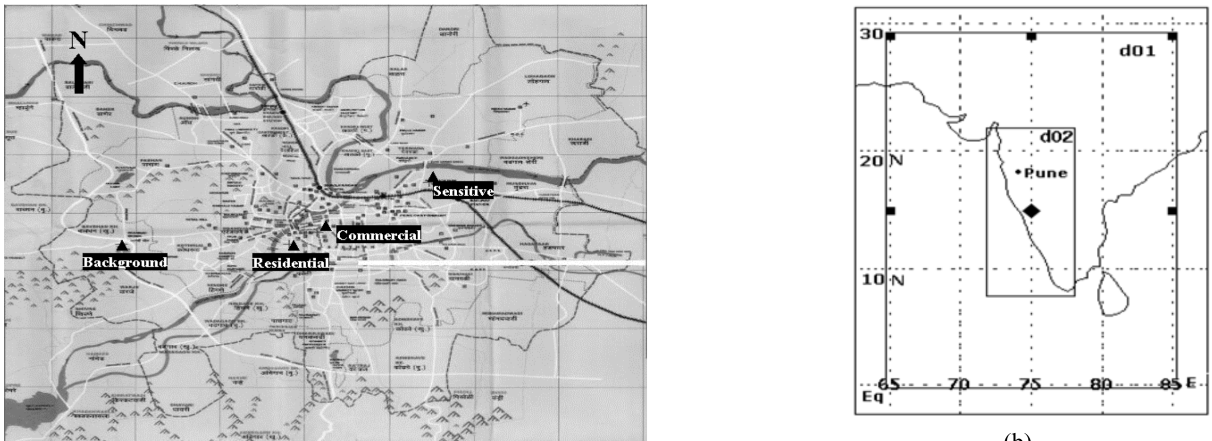
Mlawer, E. J., S. J. Taubman, P. D. Brown, M. J. Iacono and S. A. Clough, 1997: Radiative transfer for inhomogeneous atmosphere: RRTM, a validated correlated – k model for long wave. *Journal of Geophysical Research*, **102 (D14)**, 16663- 16682.

Monin, A. S. and A. M. Obukhov, 1954: Basic law in turbulent mixing in the surface layer in the atmosphere. *Contrib. Geophys. Inst. Acad. Sci.*, USSR, **151**, 163 - 187.

Venkatram, A., 1980: Dispersion in the stable boundary layer. Lectures on Air Pollution Modeling, A. Venkatram and J. C. Wyngaard, Eds., Amer. Meteor. Soc., 229-265.

TERI, 2005: Toyota and TERI initiate first 3D urban air quality study, TERI newsletter, September 2005; URL:http://static.teriin.org/teritimes/issue2/news2.htm (Accessed April 2006)

WHO, 2002: "Quantifying Selected Major Risks to Health", Chapter 4 from the World Health Report, 2002, published by World Health Organization, Geneva



(a) (b)

Fig 1: (a) Map of Pune city indicating the locations of background, residential, commercial and sensitive pollution monitoring stations (b) Location of Pune and two domains selected for the simulations using WRF

Fig 2: Comparison of simulated (obtained from WRF model outputs) and Observed surface temperatures in °C (NCEP ADP datasets) at Pune during the period of field campaign

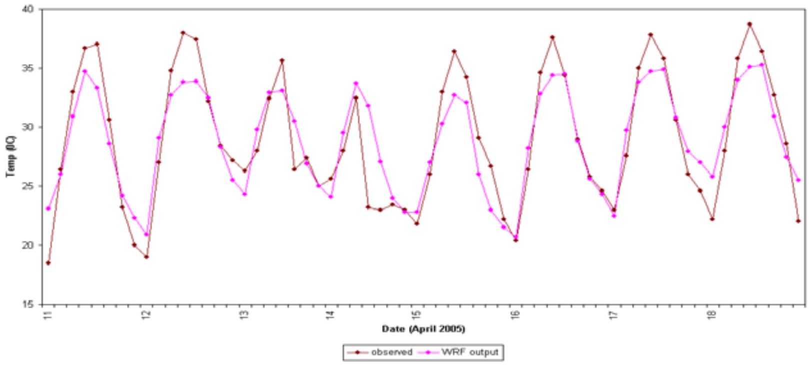


Fig 3: Averaged angular distribution of wind directions prevailing over Pune during the period of field campaign (April 12 – 17 2005) (a) as simulated by WRF (b) as observed in NCEP ADP dataset

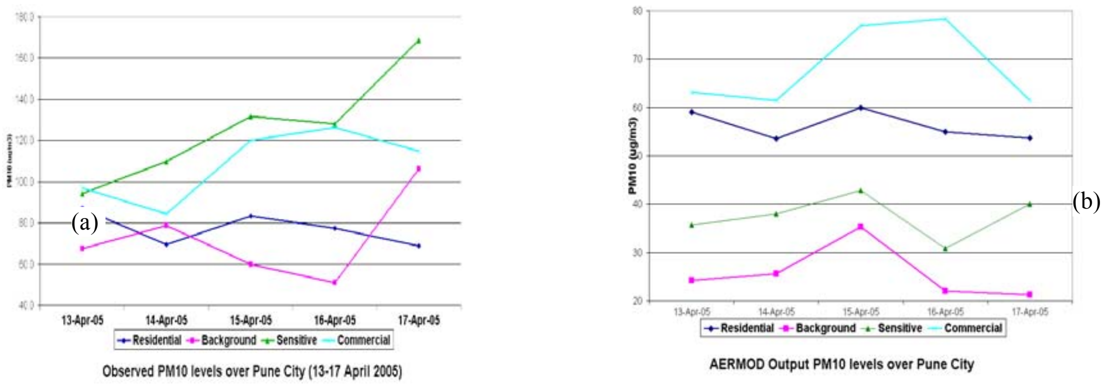


Fig. 4: Comparison of observed and simulated PM10 concentration during the period of field campaign for residential, background, sensitive and commercial locations in Pune city