



Assessment of contribution to PM₁₀ concentrations from long range transport of pollutants using WRF/Chem over a subtropical urban airshed

Medhavi Gupta, Manju Mohan

Centre for Atmospheric Sciences, Indian Institute of Technology Delhi, Hauz Khas, New Delhi–110016, India

ABSTRACT

A regional chemical transport model was implemented to simulate the Respirable Suspended Particulate Matter (PM₁₀) concentration in order to study the impact of long-range transport of air pollutants over megacity Delhi with due consideration to different geographical domains extending up to entire Asia and corresponding emissions. PM₁₀ concentration levels over megacity Delhi remain persistently high, often exceeding the ambient air quality standards. A chemical transport model namely Weather Research and Forecasting (WRF) model Version 3.2 coupled with chemistry module (WRF/Chem) was utilized with nested domains for this purpose, subsequent to model evaluation for the period during June, 2010 that includes extremely high PM₁₀ concentrations. A highly satisfactory model performance was interpreted based on the several statistical parameters as per the current state of the science and their recommended values. Based on model simulations representing different geographical domains encompassing Asia, India, North India and Delhi and their corresponding emissions, it was clearly reflected that contributions due to emissions of the megacity Delhi alone is 11%–41% and thus remaining (59%–89%) proportion is expected to be contributed from the sources outside of the Delhi region which is significant. It is demonstrated that the WRF/Chem model performs well for a sub-tropical urban airshed though there is scope of improvement for the consistent under-prediction with more refined emission inventories. Nevertheless, this model could be implemented to assess the long-range transport of pollutants so as to adequately address the influence of the remote sources outside the urban airshed. This can serve as an important tool towards planning and implementing the regulatory policies for air pollution control for more effective outcomes.

Keywords: WRF/Chem, long range transport, PM₁₀, air pollution control, megacity Delhi

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Corresponding Author:

Manju Mohan

☎ : +91-11-2659-1313

☎ : +91-11-2659-1386

✉ : mmohan6@hotmail.com

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1. Introduction

Long-range transport (LRT) of pollutants can significantly result in air-quality degradation (Kallos et al., 2007). Pollutants emitted cross geopolitical boundaries or migrate across several geographic zones, the pollution is designated as transboundary even if the physical distance of the boundary from the emitting pollutant source is quite short (DiGiovanni and Fellin, 2013). For several decades LRT of air pollution has been the topic of scientific research (Pongkiatkul and Oanh, 2007). Particulate matter (PM) is defined by size and measured as the mass concentration of particles within certain size classes such as, Respirable Particulate Matter (PM₁₀) and Fine Particulate Matter (PM_{2.5}). Among the monitored pollutants, PM₁₀ and PM_{2.5}, show the highest percentage of exceedance (Gupta et al., 2006; Oanh et al., 2006; Tsai and Chen, 2006; Hopke et al., 2008; Hai and Oanh, 2013). PM₁₀ can be transported in the atmosphere for hundreds or even thousands of kilometers, implying that pollutants emitted in one country can affect PM₁₀ concentrations in neighboring countries and even countries far distant from the source (WHO, 2006). Kerschbaumer and Lutz (2008) studied how 70% urban PM₁₀ concentrations of Berlin were influenced by LRT from remote source areas using the Aerosol Chemistry Transport Model. Amodio et al. (2011) used an integrated approach to distinguish local and long-range transport to PM₁₀ concentrations at Apulia Region. Intercontinental transport of Asian aerosols is considered as an important issue for air quality and climate concerns (Wuebbles et al., 2007).

Due to the fast economic development in Asia, some countries generate high levels of air pollution (Pongkiatkul and Oanh, 2007). Rapid urbanization and industrialization have resulted in highly polluted Indian cities (Ghude et al., 2008; Mohan et al., 2012; Mohan et al., 2013). Consequently, megacity Delhi is ranked as one of the most polluted cities in the world (Mohan and Kandya, 2007; Gurjar et al., 2008; Incecik and Im, 2012) as far as PM₁₀ pollution is concerned. According to air quality monitoring carried out by Central Pollution Control Board (CPCB) the Capital's particulate pollution has increased steadily since 2005 despite the Delhi government building several flyovers to reduce traffic congestion at important intersections. PM₁₀ pollution has been rising in Delhi's neighbor since 2008, reaching 290 µg/m³ over Ghaziabad as compared to 261 µg/m³ over Delhi (Hindustan Times, 2013).

There are various factors that contribute to PM₁₀ in ambient air besides anthropogenic emissions such as frequent dust storms that prevail in Delhi (Chelani and Devotta, 2005) and varying meteorological conditions such as wind direction, wind speed etc. Both summer and winter in Delhi are severe with June being the hottest month (NSR, 2010). According to Zannetti (1990), depending on the distance from the emitting source, five types of scales can be distinguished as, near-field phenomena (<1 km from source); short-range transport (<10 km from source); intermediate-range transport (between 10 to 100 km from source); long-range transport (>100 km from source) and global effects. The main objective of this study is to understand the impact of different geographical domains on PM₁₀ concentration and thereby

assess contributions due to long range transport over a highly polluted subtropical urban airshed i.e., megacity Delhi. Weather Research and Forecasting (WRF) model coupled with chemistry module (WRF/Chem) version 3.2 was implemented for this purpose.

2. Model Description

WRF/Chem constitutes of a mesoscale non hydrostatic meteorological model coupled with chemistry module. WRF/Chem is an “online” model (Grell et al., 2005; Fast et al., 2006) that predicts meteorological and chemical components simultaneously. WRF/Chem version 3.2 has been selected for this study as being a coupled weather prediction/dispersion model it allows to simulate release and transport of PM_{10} . Meteorological model WRF version 3.1 has been validated along with the model sensitivity for various physical schemes over Delhi region by Mohan and Bhati (2011). Their study employed various physical schemes and concluded that a combination of Lin et al. (1983) microphysics; Noah Land Surface Model (Chen and Dudhia, 2001); the YSU PBL scheme (Hong and Lim, 2006); Kain–Fritsch cumulus parameterization scheme (Kain, 2004) and Rapid Radiative Transfer Model (RRTM) long-wave radiation scheme (Mlawer et al., 1997) performs best for Delhi region. Accordingly, these schemes were used in the present study also. The Goddard scheme (Chou and Suarez, 1994) was used to compute atmospheric shortwave radiation since it is more compatible with the chosen gas–phase chemical, aerosol mechanism and the photolysis scheme. The Regional Atmospheric Chemistry Mechanism (RACM) (Stockwell et al. 1997) based upon the earlier Regional Acid Deposition Model, Version 2 (RADM2) mechanism (Stockwell et al., 1990) was selected for predicting gas–phase chemistry. There are three different gas–phase mechanisms, one can choose from in the WRF/Chem model, namely RACM, RADM2 and CBMZ. A sensitivity study by carrying out simulations for each of these mechanisms and their impact on simulated concentrations in relation to observed concentrations were analyzed. Consequent to this sensitivity analysis the model option was chosen as RACM. The percentage error calculated for gas–phase chemical mechanisms were 9.39% for RADM2 mechanism, 15% for CBMZ mechanism and about 5.4% for RACM mechanism. Hence RACM mechanism was chosen as the % error was minimum in this case. The Madronich photolysis scheme (Madronich, 1987) and MADE/SORGAM (Ackermann et al., 1998 and Schell et al., 2001) aerosol module were selected for this study.

3. Model Inputs and Simulation Details

3.1. Model inputs

The land–use data used for interpolating topography was U.S. Geological Survey (USGS) 24– category data of spatial resolution of $30''$. The territory of Delhi is stretched over an area of $1\,483\text{ km}^2$, is located between the mountain ranges of the Great Himalayas and Aravalis. Delhi lies around 200 to 300 meters above the sea level. The topography of Delhi can be divided into three different parts, the plains, the Yamuna flood plain, and the ridge. As per the topography, Delhi is located on the western fringes of the Gangetic Plains. The other topographical feature is the Ridge, which reaches the height of 318 m above sea level, and is the highest point in Delhi. The ridge originates in the south and surrounds its western, the northwestern and northeastern part. It is a part of the Aravalli Hills (Delhi, 2013). National Centre for Environmental Prediction (NCEP) final analysis data (FNL) of resolution 1° was used as meteorological input for initial and boundary conditions to the model. The output has been retrieved and analyzed at every 60 minutes for the given simulation period. Anthropogenic emissions obtained from Emission Database for Global Atmospheric Research (EDGAR) are annually averaged with spatial resolution of 0.1 degree. The emissions that are input in the model were processed by prep_chem_sources program (Freitas et al., 2011) developed at CPTEC, Brazil. The program maps the global anthropogenic

emissions data obtained from EDGAR to a WRF–forecast domain. To interpolate the emission fields to the model grids, Mercator projection was used.

3.2. Simulation details

Subtropical climate conditions categorize summers as hot and humid, and winters as cold and dry. Megacity Delhi experiences subtropical climatic conditions, where months of May–June mark the summer season in Delhi where the maximum temperature ranges from $41\text{--}45^\circ\text{C}$. PM_{10} episodes are linked to typical autumn–winter episode due to stagnant meteorological conditions (Mohan and Bhati, 2011) but high concentrations of PM_{10} are also related to long–range transport process that usually takes place in summer (Artinano et al., 2003). The PM_{10} observations over Delhi during the year 2010 were scrutinized for the entire year and it was found that summer months especially June showed the highest concentration values. Thereby, the simulations were carried out for the period 1–7 June 2010 when high concentrations of about $1\,000\text{ }\mu\text{g}/\text{m}^3$ were observed. In this study, influence of geographical regions in terms of domain size and as a consequence the emissions was also examined for an episode when PM_{10} level was particularly high as by reducing the domain size, we have also reduced the emissions and vice–versa. This has been described in detail in the following sections. The simulations consisted of a parent domain and three nested domains with resolutions of 90 km, 30 km, 10 km and 3.3 km respectively. The parent domain, Domain 1 included Asia covering $506\,340\text{ km}^2$. The maximum size of the domain (Asia) is chosen such that any further increase in the domain size does not influence the results. Domain 2 consisted of India covering $290\,460\text{ km}^2$ and Domain 3 consisted of North India covering $147\,340\text{ km}^2$. The third nested domain, Domain 4 included Delhi region and surroundings covering $7\,016\text{ km}^2$. The simulation domains and stations selected in Delhi for validation are shown in Figure 1. The monitoring stations selected in Delhi are ITO which is a traffic junction and Dwarka, Shadipur and Dilshad Garden which are categorized as residential areas. The selection of stations is based on the availability of PM_{10} data obtained from CPCB, which is a statutory organization that monitors air quality over entire India.

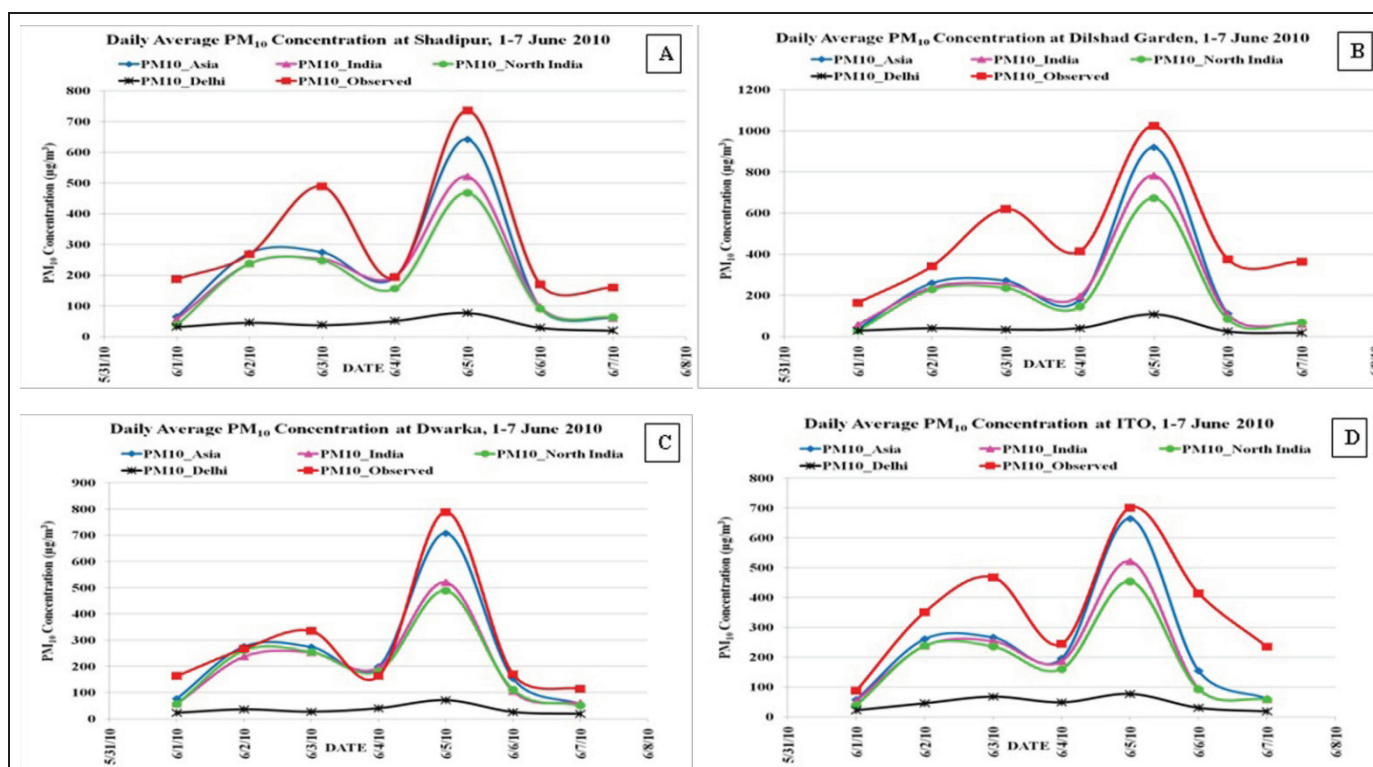
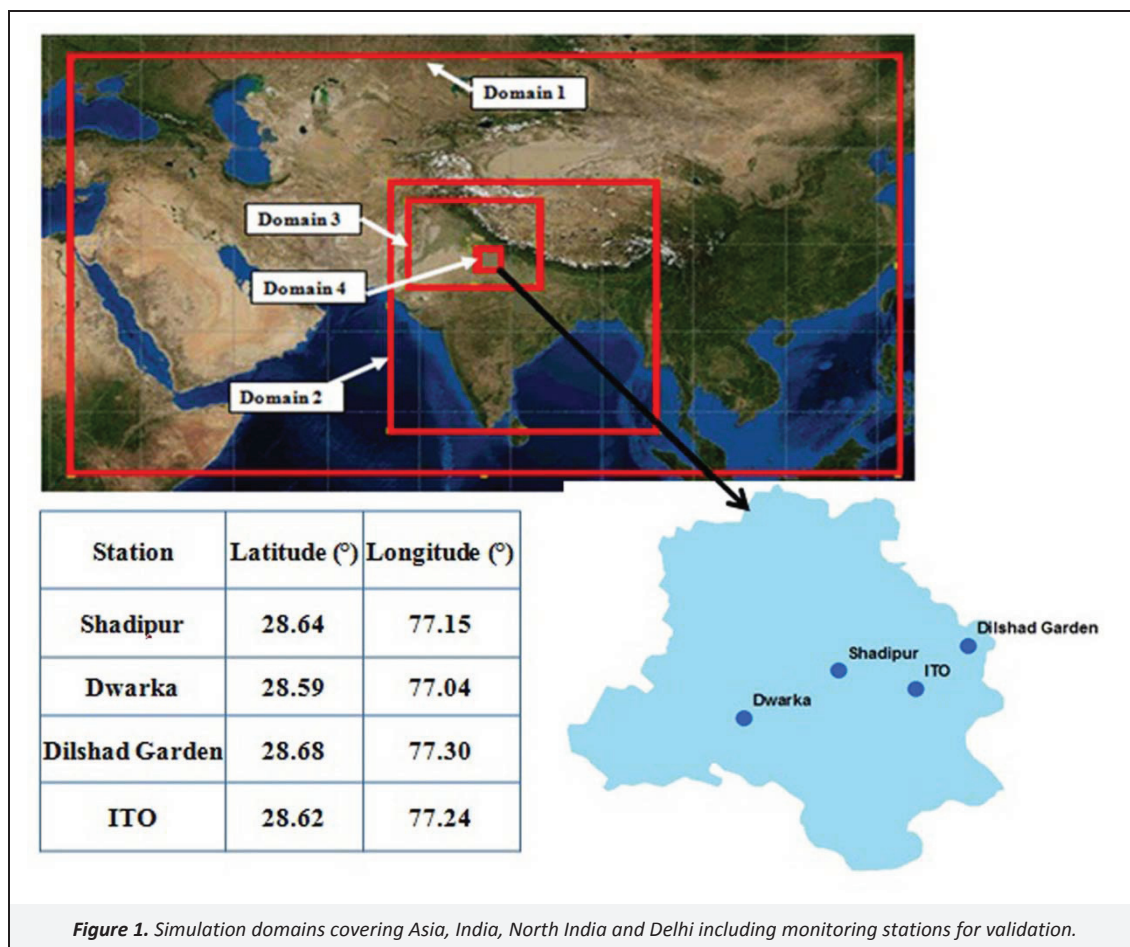
4. Results and Discussions

Figure 2 displays daily averaged time series of the observed and simulated PM_{10} concentrations obtained at 2 m height for Delhi at monitoring locations (A) Shadipur, (B) Dilshad Garden, (C) Dwarka and (D) ITO. PM_{10} was not simulated well when the model domain was confined to Delhi region only. However, an increase in PM_{10} concentration was observed when the simulated model domain was expanded progressively from Delhi region to North India and so on to whole Asia region, thereby including emissions of the larger region as well.

It is appropriate to compare model predictions with the observations using various statistical parameters as a confidence building measure towards model applications. Statistics for model evaluation is scrutinized in the light of papers such as Chang and Hanna (2004), WMO (2008), Zhang et al. (2006) and Spak and Holloway (2009). The statistical indices selected are normalized mean square error (NMSE), index of agreement (IOA), the fraction of predictions within a factor of two of observations (FAC2), fractional bias (FB), mean normalized gross error (MNGE), correlation coefficient (R) and mean normalized bias (MNB). These are standardized measures of the degree of model prediction error. The formulae of the mentioned statistical parameters are given below:

$$NMSE = \overline{(Co - Cp)^2} / \overline{CoCp} \quad (1)$$

$$FB = (\overline{Co} - \overline{Cp}) / 0.5(\overline{Co} + \overline{Cp}) \quad (2)$$



$$FAC2 = \text{fraction of data that satisfy } 0.5 \leq C_p/C_o \leq 2.0 \quad (3)$$

$$IOA = \sum (C_p - C_o)^2 / \sum (|C_p - \bar{C}_p| + |C_o - \bar{C}_o|)^2 \quad (4)$$

$$MNGE = \overline{(C_p - C_o)} / C_o \quad (5)$$

$$R = \overline{(C_o - \bar{C}_o)(C_p - \bar{C}_p)} / \sigma_{C_p} \sigma_{C_o} \quad (6)$$

$$MNB = \overline{(C_p - C_o)} / C_o \quad (7)$$

where C_p is the model predictions, C_o is the observations, and \bar{C} is the average over the dataset.

Table 1 shows the statistical evaluation of model for the simulation of Asia region which is the maximum domain size of the model, as it was evident from the time series plot that concentration resulting from Asia region takes into account the contribution of all the possible emission sources including the ones contributing towards the long-range transport. The value of $NMSE$ calculated for Shadipur is 0.11, 0.28 for Dilshad Garden, 0.03 for Dwarka and 0.19 for ITO. According to Tewari et al. (2005) the accepted value of $NMSE$ is <4 . The FB indicates the measure of over or under estimation of simulated value. Spak and Holloway (2009) reported that for an average performance by the model, FB for PM_{10} concentration is ± 0.6 , ± 0.3 for good performance and ± 0.15 for excellent performance of model. As observed from the Table 1, the value of FB falls under excellent performance criteria for Dwarka, good performance for Shadipur and average performance for Dilshad Garden and ITO. The positive FB values indicate that there is under-prediction by the model. $FAC2$ is the most robust measure, as it is not overly influenced by outliers (Chang and Hanna, 2004). The value of $FAC2$ is 0.72 for Delhi at all monitoring locations except for Dilshad Garden where it is comparatively less. The accepted value of $FAC2$ is >0.5 (Tewari et al., 2005). The ideal value for IOA is 1. According to Zawar-Reza et al. (2005) IOA should be ≥ 0.5 for good model performance. The value of IOA for Shadipur is 0.92, 0.9 for Dilshad Garden, 0.98 for Dwarka and 0.94 for ITO. The value of $MNGE$ ranges from 0.24 to 0.54. This is reasonable considering the Zhang et al. (2006), study that indicated the value of $MNGE$ for PM_{10} to be ≤ 0.56 . The correlation coefficient, R , reflects the linear relationship between observed and predicted concentrations. The value of R for the monitoring stations is observed to be between 0.9 and 0.98. This can be considered reasonably good, as even Spak and Holloway (2009) study also reported value of R for $PM_{10} > 0.57$. The value of MNB for PM_{10} for Shadipur is -0.33 , -0.54 for Dilshad Garden, -0.17 for Dwarka and -0.38 for ITO. Overall these are reasonable considering study by Zhang et al. (2006) that reported the value of MNB for PM_{10} between -0.38 and 0.35 . The negative sign in MNB indicates that the PM_{10} concentrations are under-predicted. Based on chosen statistical indices and the reference value provided by

the reported studies the model performance is considered highly satisfactory.

Simulations were performed for estimation of PM_{10} concentration when only Delhi emissions were included to understand the impact of local sources on PM_{10} concentration. The percentage contribution to daily averaged PM_{10} concentration was analyzed. It was observed that when low concentrations were simulated the percentage distribution due to Delhi region was 41.5%, 34.7% due to India and North India region put together and remaining 23.8% was contributed from outside India. Whereas for days when high concentrations were simulated the contribution from Delhi changed to 11.2%, 69.2% was due to India and North India combined; and 19.6% PM_{10} concentration resulted from outside India. Thus contribution due to Delhi region ranged from about 11% to 41% and the remaining approximately 59% to 89% was estimated to be from outside the urban airshed depending upon the PM_{10} concentrations. However, contribution from sources outside India was assessed approximately in the range of 20% to 24%. It is interesting to note that % contribution due to Delhi decreases when high concentrations are observed and vice-versa indicating that there is greater degree of long-range transport from outside Delhi region and vice-versa. Performance of model is good but there is marked underestimation in the simulated concentration which can be improved perhaps with better emission inventories. Further, it is stated that overcoming under-prediction may change these contributions; however relative percentage distributions may still be significant. Moreover, the model evaluation discussed above indicate by and large a reasonable model performance such that improving further model performance may not drastically undermine the importance of long-range transport from outside the urban airshed and its usefulness to contribute towards planning and implementing air pollution control strategies.

5. Conclusions

- The influence of geographical domain on PM_{10} based on model simulations revealed that the contributions due to long range transport outside Indian domain can be as high as 20% to 24%. Contribution due to Delhi ranged from 11% to 41% and 34.7% to 69.2% was contributed by North India and India together. It can be inferred that the high levels of PM_{10} concentration is not only due to local pollution but is also highly influenced by remote sources.
- Model evaluation shows a highly satisfactory model performance. As the under-estimation is consistent we assume that relative percentage may still be significant on further refinement of the model performance.
- When the model domain is confined only to Delhi region the model performance is not good. This further emphasize that regional and long-range transport is significantly contributing towards assessment of PM_{10} concentrations.

Table 1. Model evaluation for PM_{10} concentration over Delhi

Statistical Parameter	Shadipur	Dilshad Garden	Dwarka	ITO	Reported values from other studies	Reference
NMSE	0.11	0.28	0.03	0.19	<4	Tewari et al. (2005)
FB	0.32	0.57	0.14	0.41	± 0.15 for excellent, ± 0.30 for good and ± 0.60 for average performance by model	Spak and Holloway (2009)
FAC2	0.72	0.29	0.72	0.72	>0.5	Tewari et al. (2005)
IOA	0.92	0.9	0.98	0.94	≥ 0.5	Zawar-Reza et al. (2005)
MNGE	0.33	0.54	0.24	0.38	≤ 0.56	Zhang et al. (2006)
MNB	-0.33	-0.54	-0.17	-0.38	-0.38 to +0.35	Zhang et al. (2006)
R	0.94	0.94	0.98	0.9	>0.57	Spak and Holloway (2009)

- In megacity Delhi, particulate matter levels remain persistently high. It is therefore recommended that regulatory measures should duly incorporate regional and long-range transport in policy formulations.

References

- Ackermann, I.J., Hass, H., Memmesheimer, M., Ebel, A., Binkowski, F.S., Shankar, U., 1998. Modal aerosol dynamics model for Europe: development and first applications. *Atmospheric Environment* 32, 2981–2999.
- Amodio, M., Andriani, E., Angiuli, L., Assennato, G., de Gennaro, G., Di Gilio, A., Giua, R., Intini, M., Menegotto, M., Nocioni, A., Palmisani, J., Perrone, M.R., Placentino, C.M., Tutino, M., 2011. Chemical characterization of PM in the Apulia Region: local and long-range transport contributions to particulate matter. *Boreal Environment Research* 16, 251–261.
- Artinano, B., Salvador, P., Alonso, D.G., Querol, X., Alastuey, A., 2003. Anthropogenic and natural influence on the PM₁₀ and PM_{2.5} aerosol in Madrid (Spain). Analysis of high concentration episodes. *Environmental Pollution* 125, 453–465.
- Chang, J.C., Hanna, S.R., 2004. Air quality model performance evaluation. *Meteorology and Atmospheric Physics* 87, 167–196.
- Chelani, A.B., Devotta, S., 2005. Impact of change in fuel quality on PM₁₀ in Delhi. *Bulletin of Environmental Contamination and Toxicology* 75, 600–607.
- Chen, F., Dudhia, J., 2001. Coupling an advanced land surface–hydrology model with the Penn State–NCAR MM5 modeling system. Part I: model implementation and sensitivity. *Monthly Weather Review* 129, 569–585.
- Chou M.–D., Suarez, M.J., 1994. An Efficient Thermal Infrared Radiation Parameterization for Use in General Circulation Models, NASA Technical Memorandum 104606, 85 pages.
- Delhi, 2013. <http://www.maharashraweb.com/India/union%20territories/delhi/newdelhigeography.htm>, accessed in 2013.
- DiGiovanni, F., Fellin, P., 2013. Transboundary Air Pollution, Environmental Monitoring, Encyclopedia of Life Support Systems, EOLSS Publishers Co., UK, 12 pages.
- Fast, J.D., Gustafson, W.I., Easter, R.C., Zaveri, R.A., Barnard, J.C., Chapman, E.G., Grell, G.A., Peckham, S.E., 2006. Evolution of ozone, particulates, and aerosol direct radiative forcing in the vicinity of Houston using a fully coupled meteorology–chemistry–aerosol model. *Journal of Geophysical Research – Atmospheres* 111, art. no. D21305.
- Freitas, S.R., Longo, K.M., Alonso, M.F., Pirre, M., Marecal, V., Grell, G., Stockler, R., Mello, R.F., Gacita, M.S., 2011. PREP–CHEM–SRC–1.0: a preprocessor of trace gas and aerosol emission fields for regional and global atmospheric chemistry models. *Geoscientific Model Development* 4, 419–433.
- Ghude, S.D., Jain, S.L., Arya, B.C., Beig, G., Ahammed, Y.N., Kumar, A., Tyagi, B., 2008. Ozone in ambient air at a tropical megacity, Delhi: characteristics, trends and cumulative ozone exposure indices. *Journal of Atmospheric Chemistry* 60, 237–252.
- Grell, G.A., Peckham, S.E., Schmitz, R., McKeen, S.A., Frost, G., Skamarock, W.C., Eder, B., 2005. Fully coupled "online" chemistry within the WRF model. *Atmospheric Environment* 39, 6957–6975.
- Gupta, P., Christopher, S.A., Wang, J., Gehrig, R., Lee, Y., Kumar, N., 2006. Satellite remote sensing of particulate matter and air quality assessment over global cities. *Atmospheric Environment* 40, 5880–5892.
- Gurjar, B.R., Butler, T.M., Lawrence, M.G., Lelieveld, J., 2008. Evaluation of emissions and air quality in megacities. *Atmospheric Environment* 42, 1593–1606.
- Hai, C.D., Oanh, N.T.K., 2013. Effects of local, regional meteorology and emission sources on mass and compositions of particulate matter in Hanoi. *Atmospheric Environment* 78, 105–112.
- Hindustan Times, 2013. <http://www.hindustantimes.com/India-news/NewDelhi/Ghaziabad-air-more-polluted-than-Delhi-Noida-safer/Article1-1022958.aspx>, accessed in April 2013.
- Hong, S.–Y., Lim, J.–O., 2006. The WRF single–moment 6–class microphysics scheme WSM6. *Journal of the Korean Meteorological Society* 42, 129–151.
- Hopke, P.K., Cohen, D.D., Begum, B.A., Biswas, S.K., Ni, B.F., Pandit, G.G., Santoso, M., Chung, Y.S., Davy, P., Markwitz, A., Waheed, S., Siddique, N., Santos, F.L., Pabroa, P.C.B., Seneviratne, M.C.S., Wimolwattanapun, W., Bunprapob, S., Vuong, T.B., Hien, P.D., Markowicz, A., 2008. Urban air quality in the Asian region. *Science of the Total Environment* 404, 103–112.
- Incecik, S., Im, U., 2012. *Air Pollution in Mega Cities: A Case Study of Istanbul, Air Pollution - Monitoring, Modelling and Health*, edited by Khare, M., InTech, pp. 77–116.
- Kain, J.S., 2004. The Kain–Fritsch convective parameterization: an update. *Journal of Applied Meteorology* 43, 170–181.
- Kallos, G., Astitha, M., Katsafados, P., Spyrou, C., 2007. Long-range transport of anthropogenically and naturally produced particulate matter in the Mediterranean and North Atlantic: current state of knowledge. *Journal of Applied Meteorology and Climatology* 46, 1230–1251.
- Kerschbaumer, A., Lutz, M., 2008. Origin and influence of PM₁₀ in urban and in rural environments. *Advances in Science and Research* 2, 53–55.
- Lin, Y.L., Farley, R.D., Orville, H.D., 1983. Bulk parameterization of the snow field in a cloud model. *Journal of Climate and Applied Meteorology* 22, 1065–1092.
- Madronich, S., 1987. Photodissociation in the atmosphere: 1. Actinic flux and the effects of ground reflections and clouds. *Journal of Geophysical Research – Atmospheres* 92, 9740–9752.
- Mlawer, E.J., Taubman, S.J., Brown, P.D., Iacono, M.J., Clough, S.A., 1997. Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated–k model for the longwave. *Journal of Geophysical Research – Atmospheres* 102, 16663–16682.
- Mohan, M., Kikegawa, Y., Gurjar, B.R., Bhati, S., Kolli, N.R., 2013. Assessment of urban heat island effect for different land use–land cover from micrometeorological measurements and remote sensing data for megacity Delhi. *Theoretical and Applied Climatology* 112, 647–658.
- Mohan, M., Kikegawa, Y., Gurjar, B.R., Bhati, S., Kandya, A., Ogawa, K., 2012. Urban heat island assessment for a tropical urban airshed in India. *Atmospheric and Climate Sciences* 2, 127–138.
- Mohan, M., Bhati, S., 2011. Analysis of WRF model performance over subtropical region of Delhi, India. *Advances in Meteorology* 2011, art. no. 621235.
- Mohan, M., Kandya, A., 2007. An analysis of the annual and seasonal trends of air quality index of Delhi. *Environmental Monitoring and Assessment* 131, 267–277.
- NSR (National Summary Report), 2010. Air Quality Monitoring, Emission Inventory and Source Apportionment Study for Indian Cities, Central Pollution Control Board, India, 290 pages.
- Oanh, N.T.K., Upadhyaya, N., Zhuang, Y.H., Hao, Z.P., Murthy, D.V.S., Lestari, P., Villarin, J.T., Chengchua, K., Co, H.X., Dung, N.T., Lindgren, E.S., 2006. Particulate air pollution in six Asian cities: spatial and temporal distributions, and associated sources. *Atmospheric Environment* 40, 3367–3380.
- Pongkiatkul, P., Oanh, N.T.K., 2007. Assessment of potential long-range transport of particulate air pollution using trajectory modeling and monitoring data. *Atmospheric Research* 85, 3–17.
- Schell, B., Ackermann, I.J., Hass, H., 2001. Modeling the formation of secondary organic aerosol within a comprehensive air quality model system. *Journal of Geophysical Research* 106, 28275–28293.
- Spak, S.N., Holloway, T., 2009. Seasonality of speciated aerosol transport over the Great Lakes region. *Journal of Geophysical Research – Atmospheres* 114, art. no. D08302.

- Stockwell, W.R., Kirchner, F., Kuhn, M., Seefeld, S., 1997. A new mechanism for regional atmospheric chemistry modeling. *Journal of Geophysical Research – Atmospheres* 102, 25847–25879.
- Stockwell, W.R., Middleton, P., Chang, J.S., Tang, X., 1990. The second generation regional acid deposition model chemical mechanism for regional air quality modeling. *Journal of Geophysical Research – Atmospheres* 95, 16343–16367.
- Tewari, M., Warner, T.T., Coirier, W.J., Kim, S., 2005. Numerical modeling study of wind flow over the Salt Lake City region using integrated WRF–Noah–UCM model at Meso–Gamma scale, <http://www.mmm.ucar.edu/wrf/users/workshops/WS2005/presentations/session4/3–Tewari.pdf>, accessed in August 2003.
- Tsai, Y.I., Chen, C.L., 2006. Atmospheric aerosol composition and source apportionments to aerosol in southern Taiwan. *Atmospheric Environment* 40, 4751–4763.
- WHO (World Health Organization), 2006. Health Risks of Particulate Matter from Long–Range Transboundary Air Pollution, European Centre for Environment and Health, Copenhagen, 113 pages.
- WMO (World Meteorological Organization), 2008. Overview of Tools and Methods for Meteorological and Air Pollution Mesoscale Model Evaluation and User Training, Joint Report of COST Action 728 and GURME, Geneva, 116 pages.
- Wuebbles, D.J., Lei, H., Lin, J.T., 2007. Intercontinental transport of aerosols and photochemical oxidants from Asia and its consequences. *Environmental Pollution* 150, 65–84.
- Zannetti, P., 1990. *Air Pollution Modelling*, Van Nostrand Reinhold, New York, 444 pages.
- Zawar–Reza, P., Kingham, S., Pearce, J., 2005. Evaluation of a year–long dispersion modelling of PM₁₀ using the mesoscale model TAPM for Christchurch, New Zealand. *Science of the Total Environment* 349, 249–259.
- Zhang, Y., Liu, P., Pun, B., Seigneur, C., 2006. A comprehensive performance evaluation of MM5–CMAQ for the Summer 1999 Southern Oxidants Study Episode–Part I: evaluation protocols, databases, and meteorological predictions. *Atmospheric Environment* 40, 4825–4838.