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Air quality in Delhi during the CommonWealth Games

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Abstract

Air quality during The CommonWealth Games (CWG, held in Delhi in October 2010) is analyzed using a new air quality forecasting system established for the Games. The CWG stimulated enhanced efforts to monitor and model air quality in the region. The air quality of Delhi during the CWG had high levels of particles with mean values of $PM_{2.5}$ and PM_{10} at the venues of 111 and 238 $\mu g\, m^{-3}$, respectively. Black carbon (BC) accounted for ~ 10 % of the $PM_{2.5}$ mass. It is shown that BC, $PM_{2.5}$ and PM_{10} concentrations are well predicted, but with positive biases of ~ 25 %. The diurnal variations are also well captured, with both the observations and the modeled values showing nighttime maxima and daytime minima. A new emissions inventory, developed as part of this air quality forecasting initiative, is evaluated by comparing the observed and predicted species-species correlations (i.e., BC : CO; BC : $PM_{2.5}$; $PM_{2.5}$: PM_{10}). Assuming that the observations at these sites are representative and that *all* the model errors are associated with the emissions, then the modeled concentrations and slopes can be made consistent by scaling the emissions by: 0.6 for NO_x, 2 for CO, and 0.7 for BC, $PM_{2.5}$ and PM_{10}. The emission estimates for particles are remarkably good considering the uncertainty in the estimates due to the diverse spread of activities and technologies that take place in Delhi and the rapid rates of change.

The contribution of various emission sectors including transportation, power, domestic and industry to surface concentrations are also estimated. Transport, domestic and industrial sectors all make significant contributions to PM levels in Delhi, and the sectoral contributions vary spatially within the city. Ozone levels in Delhi are elevated, with hourly values sometimes exceeding 100 ppb. The continued growth of the transport sector is expected to make ozone pollution a more pressing air pollution problem in Delhi. The sector analysis provides useful inputs into the design of strategies to reduce air pollution levels in Delhi. The contribution for sources outside of Delhi on Delhi air quality range from ~ 25 % for BC and PM to ~ 60 % for day time ozone. The significant

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contributions from non-Delhi sources indicates that in Delhi (as has been show elsewhere) these strategies will also need a more regional perspective.

1 Introduction

Rapid industrialization and urbanization over the past few decades have led to high levels of outdoor air pollution throughout the world. This is particularly true in the megacities of Asia, where high concentrations of aerosols and other criteria pollutants have large impacts on the health and welfare of its citizens (Guttikunda et al., 2005). Small ambient particles can penetrate deeply into sensitive parts of the lungs and can cause or worsen respiratory disease, such as emphysema and bronchitis, and can aggravate existing heart disease, leading to increased hospital admissions and premature death (Drimal et al., 2010). These particles and other short-lived radiative forcing agents such as ozone also absorb and scatter solar radiation and impact weather and climate. The warming effect of all the greenhouse gases together is estimated at 2.5 watt m^{-2}, while the net cooling effect of aerosols is 0.7 $W m^{-2}$ according to the IPCC (IPCC, 2007). The high levels of black carbon (BC) in Asia are of particular interest, because of its dual role in impacting human health and in acting like a greenhouse gas, absorbing solar radiation causing warming of the atmosphere. Ramanathan and Carmichael estimate that BC is the second most important warming agent (behind CO_2) (Ramanathan and Carmichael, 2008). For these reasons there is currently mounting interest in developing strategies that will both reduce the levels of air pollutants and reduce global warming. These strategies often develop first in megacities, where air quality and energy policies respond to the rapid needs associated with the widespread urbanization. Effective management of air quality requires enhanced understanding of the sources of pollution and their effects on human health and climate.

In this paper we analyze BC and other pollutants in Delhi (28°35′ N, 77°12′ E, 217 m mean sea level (m.s.l.)), the capital city of India and the largest city by area and the second largest by population in India. It is the eighth largest megacity in the world with more than 18 million inhabitants. Delhi hosted the CommonWealth Games (CWG), a multi sport event involving 73 countries, in October 2010. This high profile event provided an opportunity to accelerate efforts to improve air quality. To support the CWG air pollution monitoring was enhanced, a new emissions inventory was developed (Sahu et al., 2011) and new air quality forecasting efforts were initiated. In this paper we use the WRF-Chem model (Grell et al., 2005) to simulate the air quality during the GWG and evaluate its performance by comparing the predicted meteorology and concentrations of BC and other criteria pollutants with observations. We present spatial patterns of BC, $PM_{2.5}$ and PM_{10}, CO, NO_x, and O_3 over Delhi and estimate the contributions from specific source sectors (Transportation, Power, Industrial, and Domestic). Such sector information is needed to help guide the development of effective pollution reduction measures. We also evaluate the emission estimates by analyzing observed and predicted species ratios.

2 Approach

2.1 WRF-Chem configuration and domain

The CMG air quality forecast system is based on the WRF-Chem model. Four nested domains were used in the analysis and they are shown in Fig. 1. The outer domain covered South Asia from 50 to 120° E and 0 to 55° N at a horizontal resolution of 45 km, with 131 × 131 grid cells. The next domain focused on the northern regions of India covering the Indo Gangetic plain at a resolution of 15 km with 127 × 127 grid cells. The two inner domains covered the Delhi region at resolutions of 5 km with 55 × 55 grid cells and 1.67 km with 75 × 75 grid cells. For all domains 27 vertical levels were used with a maximum height of ~ 20 km. The model configuration is summarized in Table 1. This configuration enables direct, indirect and semi direct aerosol radiative feedbacks to be included in the analysis. The Carbon Bond Mechanism version Z (CBMZ) with the MOSAIC aerosol module using 4 size bins was employed.

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2.2 Emissions

A new detailed emissions inventory was prepared by IITM Pune, Maharastra for the Delhi area at a resolution of 1.67 km^2. The emission inventory covered the National Capital Region Delhi (NCR) (~ 70 km × 65 km) and the surrounding areas (in total covering 115.23 km × 138.6 km). The emission data was developed for NO_x, CO, BC, $PM_{2.5}$, PM_{10}, OC, VOC and SO_2 for four sectors (i.e. power, industrial, transport, residential). This NCR area was extensively studied through a field campaign made during March–May 2010, which collected relevant primary and secondary data with high resolution. This data included vehicular along with the type of fuel used, point source locations for manufacturing industries located within Delhi, and biofuel usage from slums, hotels and street vendors (Sahu et al., 2011). For the rest of the area beyond the NCR region emissions were based on proxies as new primary data were not generated in this region.

The emission totals by species and sector for Delhi are summarized in Table 2. The transport sector accounts for the more than 40 % of the emissions for all species with the exception of SO_2 and OC. Delhi is a densely populated city and has approximately 4 million on road vehicles and the number increases at a rate of ~ 10 percent per year (Mohan et al., 2006). The $PM_{2.5}$ and PM_{10} transport sector emissions include windblown road and construction dust sources, which comprise ~ 50 % of the total transportation sector emissions. For SO_2 power generation and industrial sources are the most important sectors. The domestic sector is large for CO, OC, BC and NMOC (non-methane organic compounds).

The spatial distribution of emissions was based on roadways, and locations of power plants, slums and major industries using various Delhi data sets (Sahu et al., 2011). The emissions were transferred into the WRF-Chem modeling system using the Emission Preprocessor Model (EPRES) designed by M. Lin (Center for Sustainability and the Global Environment at University of Wisconsin-Madison) and modified by Y. F. Cheng (CGRER at the University of Iowa). EPRES does two things, first it speciates the total VOC emissions based on the chemical mechanism (i.e., CBM-Z), and second it horizontally interpolates the emission inventory onto the model grids. When interpolating the emissions, EPRES reads in the initial grid of the inventory from the WPS/WRF output and then utilizes the I/O API mass conservative interpolation subroutine to interpolate the emissions onto the WRF model grids. All the interpolated species were converted into WRF-Chem required units. After wards, the mapped emissions were distributed into vertical layers, i.e. 70 % was distributed at the surface and 30 % was uniformly distributed to the grids up to ~ 1000 m (grids 2–6 in this application). Diurnal profiles were also applied. The diurnal variability of BC emissions is shown in Fig. 7, and exhibits two peaks, one in early morning and the second in early evening associated with traffic and cooking activities.

Figure 2 shows the emission distributions of NO_x and $PM_{2.5}$ over Delhi. The emissions of all the primary species for the inner grid are shown in the Supplement Fig. S1. The spatial distribution reflects the various activities within and around the city. The NO_x and $PM_{2.5}$ emissions show intense emissions within the city and along roadways, with spatial differences reflecting different contributions by sector. Geographically Delhi is surrounded by industrially developed cities such as Gurgoan and Noida. Construction is active within and around the city and as a result many cement industries and brick kilns are situated in and around Delhi, adding to the increasing particulate emissions associated with road and construction dust. Extensive usage of wood and charcoal stoves for cooking is prevalent in the slums and in the out skirts of Delhi and high BC emissions (~ 30 % of total) occur in association with these activities (Sahu et al., 2008). The sectoral distributions of the BC emissions are shown in Fig. 3. These show clearly the locations of the power plants, industrial clusters, the distribution of slums and the major transportation networks. The venues for the CWG were clustered in the eastern half of Delhi city denoted by the completed outline in the center of the domain (see Fig. 4). These are regions most heavily impacted by domestic and industrial sources.

The INTEX-B emissions (Zhang et al., 2009) were used over the outer three domains. Biogenic emissions were calculated hourly on-line using MEGAN (Emmons

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et al., 2010). The dust emissions were turned off during the run time of the model, since the post monsoon period is a period with insignificant wind-blown soil dust impacts on Delhi. No agricultural fire emissions were included, reflecting that in this post monsoon period no harvesting takes place.

2.3 Boundary conditions and simulation procedure

To consider the influence of sources outside of the largest domain, boundary conditions from the ECMWF MACC (Monitoring Atmospheric Composition and Climate) project that operates a data-assimilation and modeling system for a range of atmospheric constituents that are important for climate, air quality and surface solar radiation (http://www.gmes-atmosphere.eu/) were used. The meteorology was initialized using NOAA FNL data using the WPS sub program and simulations were done in five day periods each with two days of spin up time.

2.4 Observations

Ten new automatic air pollution and meteorology monitoring stations were installed for the CommonWealth Games and were placed at different venues across the city (i.e., CommonWealth Games Village (CWG), IITM Delhi (IITM), Yamuna Sports Complex (YSC), Indira Gandhi Sports Complex (ISC), M.Dhyan Chand National Stadium (MDS), Jawaharlal Nehru Sports Complex (JSC), Thyagaraj Sports Complex (TSC), University of Delhi (UD), IGI-Airport (IGI) and finally Talkotaroe Garden (TG)) as shown in Fig. 4. BC, CO, NO, NO_2, O_3, and $PM_{2.5}$ and PM_{10} were measured at hourly intervals over the span of two weeks from 26 September 2010 to 15 October 2010. Similar to the air quality species, meteorology parameters (i.e., wind speed ($m\,s^{-1}$), wind direction (°), temperature (°C), and relative humidity (%)) were also measured. Ozone was measured with a photometric UV analyzer (Thermo-49i) and NO and NO_2 with chemiluminescence analyzer (Thermo-41i). BC was measured with the

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Magee Scientific aethalometer (Model AE31) and, $PM_{2.5}$ and PM_{10} using BETA attenuation analyzers (Beta Met One BAM 120).

3 Results and discussions

The WRF-Chem model was run for the period 26 September–16 October 2010. The analysis in this paper focuses exclusively on the Delhi region (the inner-most grid).

3.1 Meteorology

The CommonWealth Games were held during the post monsoon season, a transition between the summer monsoon and winter. The general situation in India is that in mid September the monsoon shifts from the Southwest Monsoon to the Northeast monsoon. This brings in air masses from the Northern parts of the country (Ghude et al., 2009). During the CWG the surface winds were most frequently from the NNW and low ($< 3\,\mathrm{m\,s^{-1}}$). Winds from the EES were less frequent but of higher speeds.

The predicted meteorology was compared with surface observations at two monitoring stations (results are typical of other sites). The statics of the comparison are shown in Table 3. The model has a dry bias (under predicts RH), slightly under predicts peak day time temperatures by 1–2° ($\sim 5\,\%$), and is biased high in wind speed. The model captures the low wind speeds, but the observations often are less than $1\,\mathrm{m\,s^{-1}}$, which the model estimates at $1–3\,\mathrm{m\,s^{-1}}$.

3.2 Air pollutants in Delhi

3.2.1 Aerosols

The predicted period mean surface concentrations of BC are shown in Fig. 5 ($PM_{2.5}$, PM_{10} and CO show a very similar spatial distribution). Black carbon concentrations exceed $25\,\mathrm{\mu g\,m^{-3}}$ in the center of the domain where emissions from the residential and

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industrial sectors are both high (see Fig. 3). $PM_{2.5}$ and PM_{10} levels are very high in this area with period mean values of 220–350 $\mu g\,m^{-3}$ and 350–550 $\mu g\,m^{-3}$, respectively, values which greatly exceed the National Ambient Air Quality standards of 60 and 100 $\mu g\,m^{-3}$, respectively.

The hourly surface concentrations from all the observation stations over the entire time period were combined and their distributions are presented in Fig. 6. The variability between the stations is shown by the bars that reflect the values at the stations that had the highest and lowest values. The mean value for BC from all the sites is 9.5 $\mu g\,m^{-3}$, with minimum and maximum site values of 4.4 and 13.1 $\mu g\,m^{-3}$. The overall mean values for $PM_{2.5}$ and PM_{10} (along with maximum and minimum site means) are: 111 $\mu g\,m^{-3}$ (77–144 $\mu g\,m^{-3}$) and 238 $\mu g\,m^{-3}$ (200–306 $\mu g\,m^{-3}$), respectively. The distributions of the calculated values are also shown in Fig. 6. In general the predicted values show a similar distribution, but with a positive bias (~ 30 %).

Further insights into the pollutant distributions in Delhi are found by analyzing the diurnal variations. The 20 day average diurnal cycle of BC observed at Dhyanchand Stadium is shown in Fig. 7, along with the diurnal emissions used in the model and the predicted PBL height. The BC observations show a strong diurnal cycle, with minimum in the mid-afternoon when the PBL is the highest and maximum in late evening when the PBL height is at a minimum and emissions are at their highest. The evening and early morning features reflect the cooking and traffic patterns and the trapping of these surface emissions by the shallow night time mixing layer. These diurnal features are well captured by the model, which suggests that the diurnal pattern used in the emissions accurately reflect these activities. The daytime values are accurately captured, while the night time values are biased high. This suggests that the daytime PBL is reasonably well predicted, but the nighttime values may be too low. The diurnal profiles of $PM_{2.5}$ and PM_{10} exhibit similar diurnal variations as BC, with minima during mid-afternoon and peak values at night, but with less asymmetry between mid-night and 6 a.m. IST values, reflecting their stronger dependency on traffic patterns.

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The predicted mean composition of $PM_{2.5}$ at Dhyanchand stadium is shown in Fig. 8. (There is only very slight variability in the percent contribution at the different monitoring stations.) BC accounts for about 8 % of the fine mode mass and is greater than that for sulfate. OC accounts for ∼ 30 % and other primary PM (from unpaved roads, construction etc.) accounts for the largest fraction. Nitrate contribution exceeds that of sulfate.

3.2.2 Gaseous pollutants

The hourly surface observations of CO, NO, NO_2, NO_x and O_3 are also shown in Fig. 6. The mean observed CO is 1.7 ppm, with station minimum and maximum of 1.1 and 2.8 ppm. The mean NO_x value is 68 ppb, with minimum and maximum station means of 28 and 139, respectively, while the station minima and maxima NO and NO_2 are 14 and 93, and 14 and 42, respectively. The mean daytime (9.30 a.m. to 6.30 p.m. IST) ozone value is 54.5 ppb, with station minimum and maximum values of 45 and 61 ppb.

The predicted distributions of these gases are also plotted in Fig. 6. Comparison with the observations shows that CO is under predicted and NO_x is over predicted. Ozone predictions are biased high, and with a much different distribution. The smaller variability among the observation sites is also captured in the predicted values of ozone and can be explained by looking at the spatial distribution of predicted daytime average surface O_3 in Delhi (Fig. 5b). The monitoring sites are all located in the eastern half of Delhi city (see Fig. 4). The ozone surface concentrations show a broader distribution over this domain than PM with weaker gradients. Due to the rapid increase in traffic, ozone is becoming a more important problem with hourly observed and predicted values exceeding 100 ppb (the India NAAQS for 8 h average is 50 ppb (100 µg m^{-3}) (CPCB Report, 2012)).

A sensitivity simulation was performed where NO_x emissions were reduced to 1/3rd of the original values in order to see the effects on the ozone distributions. These results for ozone are also plotted in Fig. 6. Under the reduced NO_x emission case the ozone distribution is much closer to that observed, as are the distributions of NO_x and NO

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and NO_2 (not shown). However the NO_x reduction is too large, as the ozone maximum values are overpredicted and the relative amounts of NO and NO_2 are now too low and high, respectively. The emissions are discussed in more detail in Sect. 3.4.

3.3 Sector contributions

We estimated the emission sector contributions to surface pollution levels in Delhi. Additional model runs were performed to isolate the contribution from specific sectors. Four different simulations were performed. An initial run was carried out to calculate the total pollution from all sources; i.e. anthropogenic, biogenic and biomass burning. Then individual runs were carried out to estimate the concentrations from each anthropogenic sector. The equations below explain the process for how the transportation sector results were determined.

$$\text{Anthropogenic (A)} = \text{Transportation (T)} + \text{Power (P)} + \text{Industry (I)} + \text{Domestic (D)} \tag{1}$$

$$\text{Initial run} = \text{I(A} + \text{Biogenic} + \text{Biomass Burning} + \text{Boundary)} \tag{2}$$

Individual run w/o Transport Sector

$$S = (\text{A} - \text{T} + \text{Biogenic} + \text{Biomass Burning} + \text{Boundary}) \tag{3}$$

$$\text{Sector contribution} = \text{I} - \text{S}, \tag{4}$$

which represents the concentrations from transport emissions only.

This process was repeated for the other three sectors and the forth sector was estimated by difference between the four simulations (base plus three sector removed runs).

Figure 9 shows the spatial distribution of the % contribution to surface concentrations from the Transportation, Power, Industry and Residential sectors for BC. In general the largest contributions are from the transport, domestic and industry sectors. The area affected by transport is the largest, but the peak contributions are larger for the domestic and industry sectors. The contributions from industry are highest in the center

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of the domain. The impact of the power sector on average surface concentrations of BC is small, but is large for SO_2, sulfate and NO_x concentrations (see Supplement Fig. S2).The sector contributions are similar for CO, $PM_{2.5}$ and PM_{10} as shown in the Supplement. The sector contributions for NO_x, SO_2 and ozone are also presented as SI.

Further insights into the sector contributions are found by looking at their diurnal variations. Figure 12 shows the 20 day average diurnal variation of the sectoral contributions to various criteria pollutants at the monitoring station at the Dhyanchand stadium. The contributions are shown in terms of percentages. In the case of BC residential and transportation sectors are most important at all times, but with maximum values in the late evening and early mornings. The industrial sector is also important at this site for BC. During the daytime as the mixing layer grows, air masses from higher altitudes, which are impacted by sources outside of Delhi, are entrained into the boundary layer, and the contribution from this process is shown by the black shading. These other contributions are from emissions that are outside of the inner most grid, and which are transported into this region through the boundaries. $PM_{2.5}$ and PM_{10} sector plots are similar to BC, with $PM_{2.5}$ showing a larger contribution from the residential sector than PM_{10}, and PM_{10} showing a larger contribution from transport, which includes the contribution from course particles from paved and unpaved roads. CO shows a larger contribution from the domestic sector and much larger daytime contribution from distant sources, which is expected due to the much longer lifetime of CO in the atmosphere than BC. In the case of NO_x, the transport sector dominates; accept for the daytime periods, where other sources become important. During the daytime the power sector also contributes to surface concentrations as the growing mixed layer entrains the NO_x emissions from nearby power plants. During the nighttime the power plant plumes are above the mixed layer and are decoupled from the surface. Ozone has the largest contributions from sources outside of Delhi. This is shown more clearly in spatial plots of the contributions of outside the domain sources to the mean surface concentrations (Fig. 11). Within Delhi the outside sources are important and contribute from 20 to

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50 % depending on species. This has important implications for control strategies and indicates the need for regional perspectives.

3.4 Evaluation of emissions

The comparisons of the observations and predictions for each species were discussed earlier. Comparison of the correlations between different species can provide further information to help evaluate the emissions inventory. Illustrative results are shown in Fig. 12, where plots of hourly surface observations from all the sites combined are presented. The observations show good correlations between BC and CO, NO_x and CO, PM_{10} and BC, and $PM_{2.5}$ and PM_{10}. Also shown are the same correlations based on the modeled surface concentrations. If the model is perfect and the emission estimates are accurate, then the correlations between the modeled concentrations should be the same as those for the observed concentrations. The model values also show strong correlation, with higher species-species correlation coefficients than the observations. The $PM_{2.5}$ to PM_{10} and the $PM_{2.5}$ to BC slopes are similar for the observations and the model concentrations. However absolute concentrations are over predicted. This suggests that the emissions are overestimated. In contrast the NO_x to CO modeled slope is too high, while the concentrations of NO_x and CO are over and under predicted, respectively. This suggest that the NO_x emissions are too high and the CO emissions too low. Assuming that the observations at these sites are representative and that all the model errors are associated with the emissions, then to make the modeled concentrations and slopes consistent with the observed values the emissions need to be scaled by the following: 0.6 for NO_x, 2 for CO, and 0.7 for BC, $PM_{2.5}$ and PM_{10}. The emission estimates for particles are remarkably good considering the wide spread of activities and technologies taking place in Delhi and the rapid rates of change.

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4 Conclusions

Stimulated by the CWG an air quality monitoring and forecasting system was established for Delhi. The monitoring program included eleven sites instrumented to obtain continuous measurements of BC, $PM_{2.5}$, PM_{10}, O_3 NO and NO_2. The air quality of Delhi during the CWG had high levels of particles with mean values of $PM_{2.5}$ and PM_{10} at the venues of 111 and 238 $\mu g\,m^{-3}$, respectively. BC accounted for ~ 10 % of the $PM_{2.5}$ mass. The model predictions were evaluated using the surface observations of meteorological parameters and the air pollution concentrations. The model showed a dry bias (under prediction in RH by ~ 10 %), slightly under predicted peak day time temperatures by 1–2° (~ 5 %), and was biased high in wind speed. The model captured the low wind speeds, but the observations often were less than 1 $m\,s^{-1}$, which the model estimates at 1–3 $m\,s^{-1}$. BC, $PM_{2.5}$ and PM_{10} were over-predicted by ~ 25 %. The diurnal variations were well captured, with both the observations and the modeled values showing nighttime maxima and daytime minima. The daytime values compared well with the observations, but the nighttime values were over predicted, suggesting that the nighttime mixing height and/or nighttime dispersion were under predicted. Further work is needed to evaluate the mixing heights in Delhi for day and nighttime periods.

A new emissions inventory was developed to support this new air quality forecasting initiative. The emission inventory was evaluated by comparing the correlations in the observations (e.g., BC : CO; BC : $PM_{2.5}$; $PM_{2.5}$: PM_{10}). The predicted $PM_{2.5}$ to PM_{10} and the $PM_{2.5}$ to BC slopes were similar to the observation-based slopes. However absolute concentrations were over predicted, suggesting that the emissions are overestimated. In contrast the NO_x to CO modeled slope was too high, while the concentrations of NO_x and CO were over and under predicted, respectively. This suggest that the NO_x emissions are too high and the CO emissions too low. Assuming that the observations at these sites are representative and that *all* the model errors are associated with the emissions, then the modeled concentrations and slopes can be made consistent by scaling the emissions by: 0.6 for NO_x, 2 for CO, and 0.7 for BC, $PM_{2.5}$ and PM_{10}. The

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emission estimates for particles are remarkably good considering the uncertainty in the estimates due to the diverse spread of activities and technologies that take place in Delhi and the rapid rates of change. A more complete evaluation of the modeling system and the emissions would benefit from additional observations including speciated NMOC, which would allow a more thorough evaluation of the photochemical oxidant cycle and ozone production.

The contribution of various emission sectors including transportation, power, domestic and industry to surface concentrations were also estimated. Transport, domestic and industrial sectors all make significant contributions to PM levels in Delhi, and the sectoral contributions vary spatially within the city. The transport sector is the main sector for ozone. Ozone levels in Delhi are already elevated, with hourly values sometimes exceeding 100 ppb. The continued growth of the transport sector is expected to make ozone pollution a more pressing air pollution problem in Delhi. The contribution for sources outside of Delhi on Delhi air quality was also estimated and was shown to vary spatially throughout the domain. The smallest contributions were found in the center of the domain, where on average the contributions ranged from $\sim 25\,\%$ for BC and PM to $\sim 60\,\%$ for day time ozone. The sector analysis provides useful inputs into the design of strategies to reduce air pollution levels in Delhi. The significant contributions from non-Delhi sources indicates that in Delhi (as has been show elsewhere) that these strategies will also need a more regional perspective.

The air quality activities established to support the CWG have been made operational, and the monitoring sites have been relocated to provide better spatial representation. Analysis of the 2 year time series of these observations will be the subject of a future paper.

Supplementary material related to this article is available online at http://www.atmos-chem-phys-discuss.net/14/10025/2014/acpd-14-10025-2014-supplement.pdf.

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Table 1. Important input settings of the WRF-Chem model used in this study.

Feature	Option	Description
Chemical Mechanism	CBMZ	Carbon Bond Mechanism v.Z with MOSAIC 4 aerosol bins (Zaveri et al., 2008)
Microphysics	Lin et al. scheme	Sophisticated scheme with ice, snow, and graupel processes.
Longwave Radiation	Rapid Radiative Transfer Model (RRTM)	Accounts for multiple bands, trace gases, and microphysics
Shortwave Radiation	Goddard shortwave	Two-stream multi-band scheme with ozone from climatology and cloud effects.
Surface Layer	MM5 similarity	Based on Monin–Obukhov with Carlson–Boland viscous sub-layer and standard similarity functions from look-up tables.
Anthropogenic Emissions	Delhi Inventory & INTEX-B	Delhi inventory at 1.67 km resolution Intercontinental Chemical Transport Experiment B (INTEX-B) data at $0.5^{\circ} \times 0.5^{\circ}$ resolution (Zhang et al., 2009).
Biogenic Emissions	MEGAN	MEGAN Model of Emissions of Gases and Aerosols from Nature, biogenic emissions online based upon the weather, land use data.
Boundary Conditions	MACC	Monitoring Atmospheric Composition & Climate, a global 3-D chemical transport model driven by offline meteorological fields.

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Table 2. Anthropogenic emissions and % sectoral contribution for Delhi.

		Contribution from each anthropogenic sector			
Species	$t\,day^{-1}$	Transportation	Power	Industry	Domestic
SO_2	81	12.9 %	48.7 %	25.2 %	13.2 %
NO_x	598.5	69.4 %	13.2 %	4.5 %	12.9 %
CO	1320.3	43.7 %	0.2 %	4.0 %	52.0 %
PM_{10}	344.8	86.8 %	7.9 %	4.6 %	0.8 %
$PM_{2.5}$	128.6	52.6 %	9.9 %	15.3 %	22.2 %
BC	36.9	58.9 %	3.0 %	6.6 %	31.5 %
OC	35.1	30.5 %	5.6 %	10.6 %	53.3 %
NMOC	852.4	58.4 %	1.2 %	5.2 %	35.3 %

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Table 3. Comparison of predicted meteorological parameters with observations at the surface monitoring sites.

	Temp (°C)	Wind speed ($m\,s^{-1}$)	RH (%)
Mean – Obs	29.0	1.3	53.5
Mean – Model	28.7	2.2	45.8
Bias Error	7.7	1.3	7.0
RMSE	13.6	2.9	33.9
R	0.9	0.5	0.7

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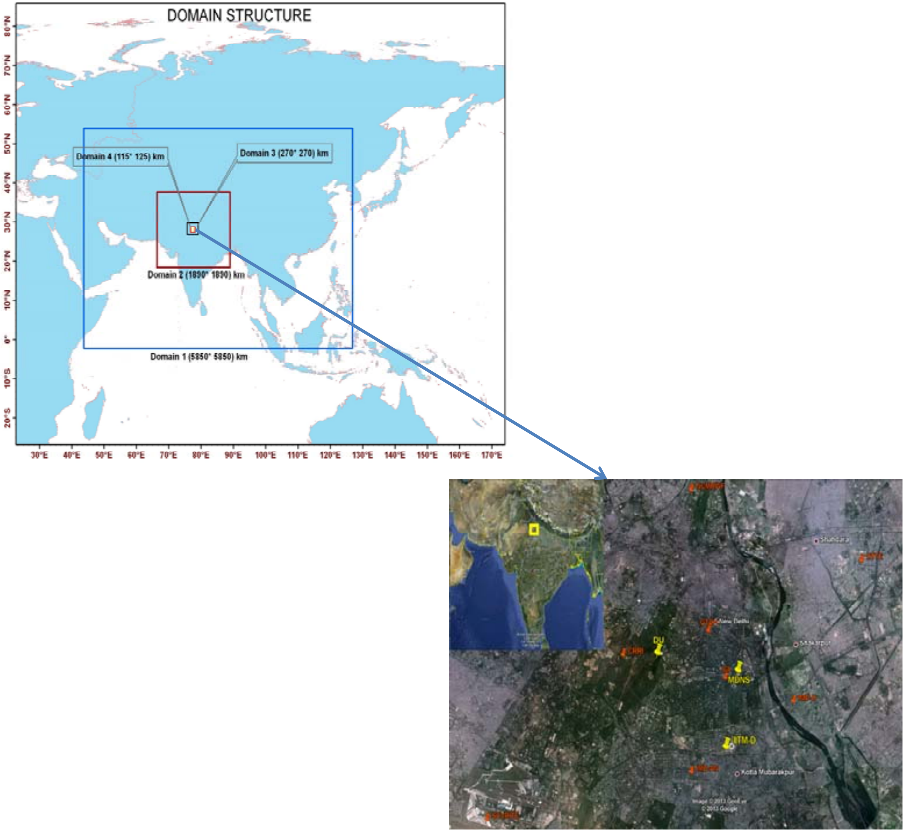

Fig. 1. Nested model domains used in the CommonWealth Games forecasts and analysis. Insert shows the locations of the observations sites.

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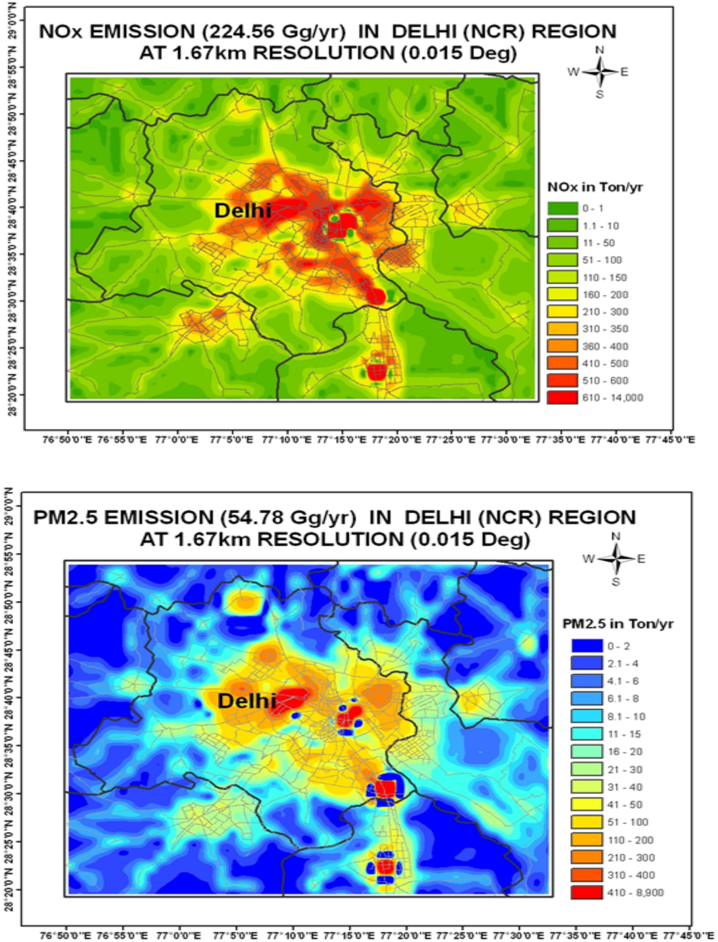

Fig. 2. Emission distributions of NO_x (top) and, $PM_{2.5}$ in $t\,yr^{-1}$ over Delhi.

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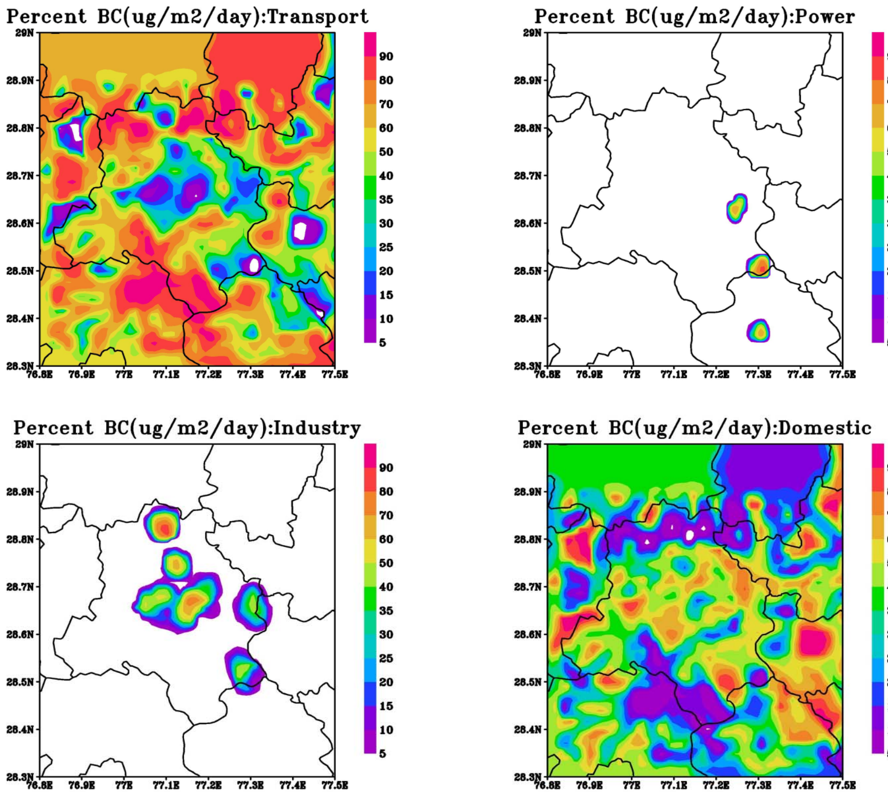

Fig. 3. Sector contributions to black carbon emissions (%) for Delhi.

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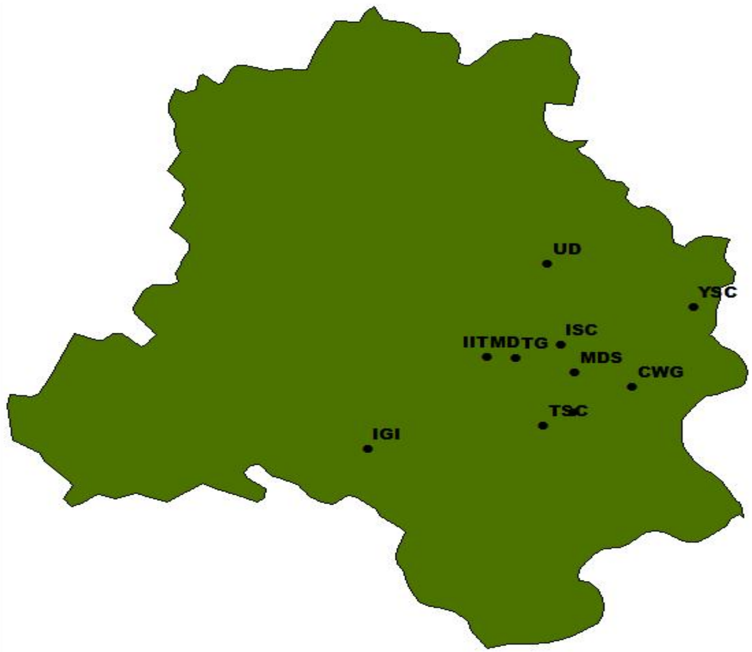

Fig. 4. Locations of the monitoring stations for the CommonWealth Games.

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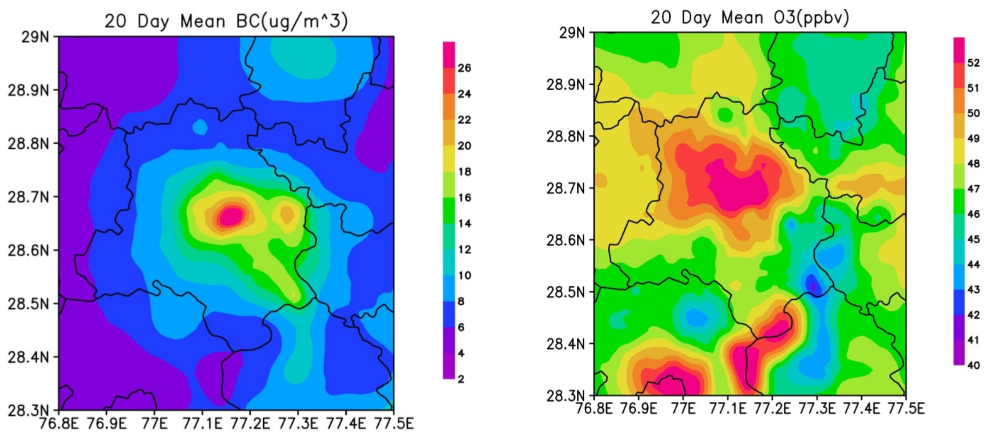

Fig. 5. Spatial distributions of calculated 20 Day mean concentrations of surface BC ($\mu g\,m^{-3}$) and daytime (9.30 a.m.–6.30 p.m. IST) ozone (ppb) over Delhi. For ozone daytime means are shown.

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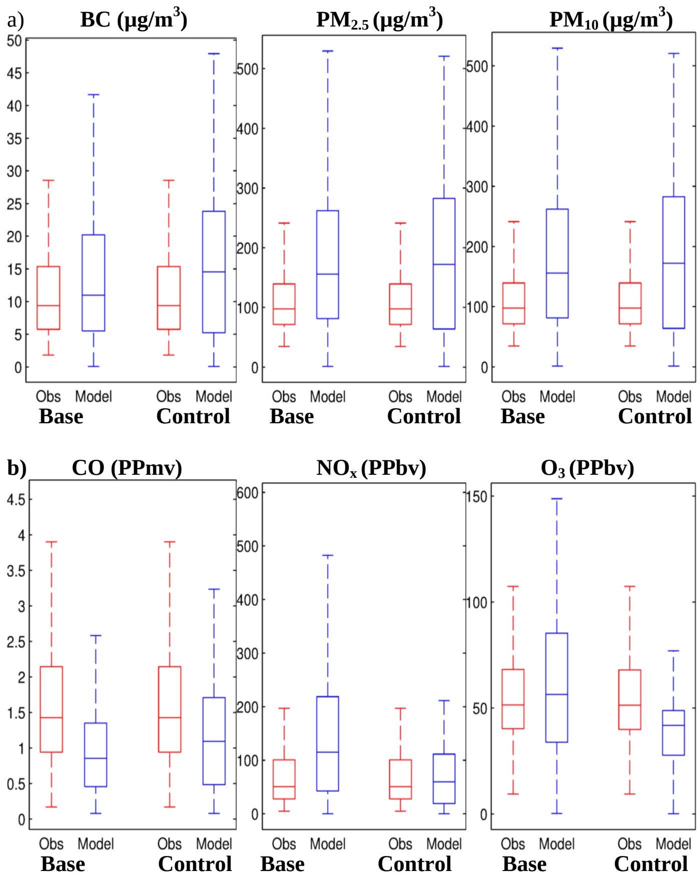

Fig. 6. Comparison of the distributions of observed and modeled hourly concentrations using data from all sites. Base corresponds to full emissions whereas control shows results where the NO_x emissions were reduced by a factor of 3.

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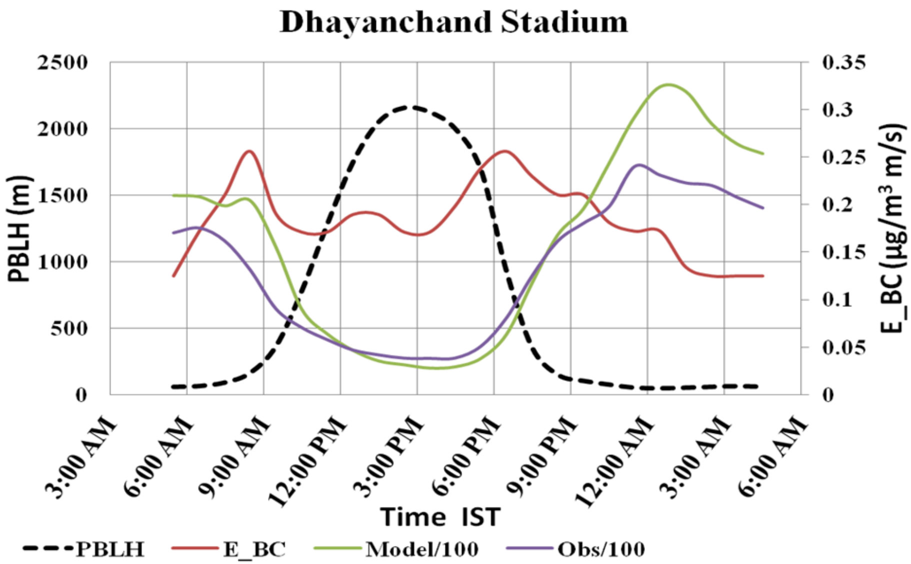

Fig. 7. Mean diurnal variation in boundary layer height, emissions and BC concentrations from model and observations at the Dhyanchand Stadium site.

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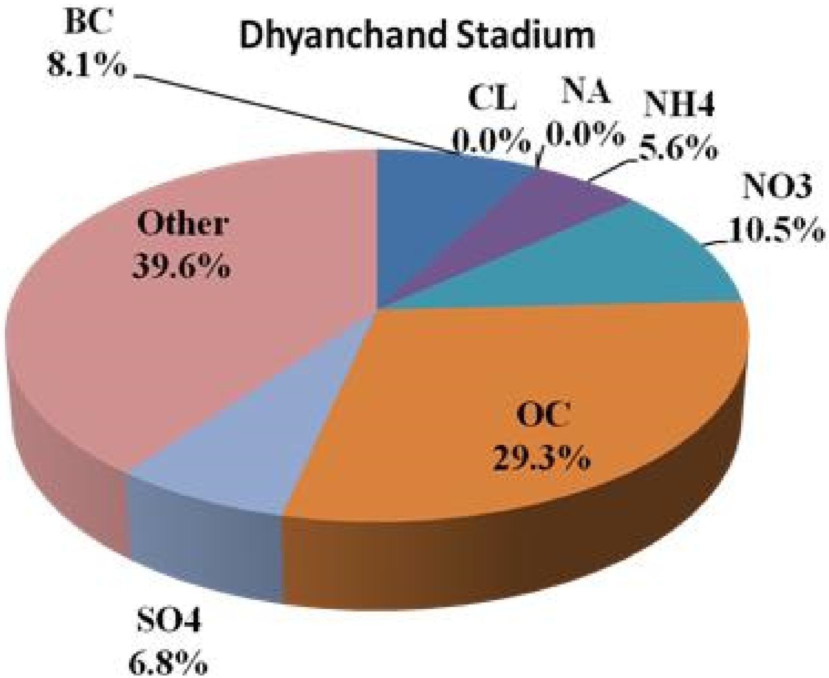

Fig. 8. Percent contribution of each species to total $PM_{2.5}$ at Dhyanchand Stadium.

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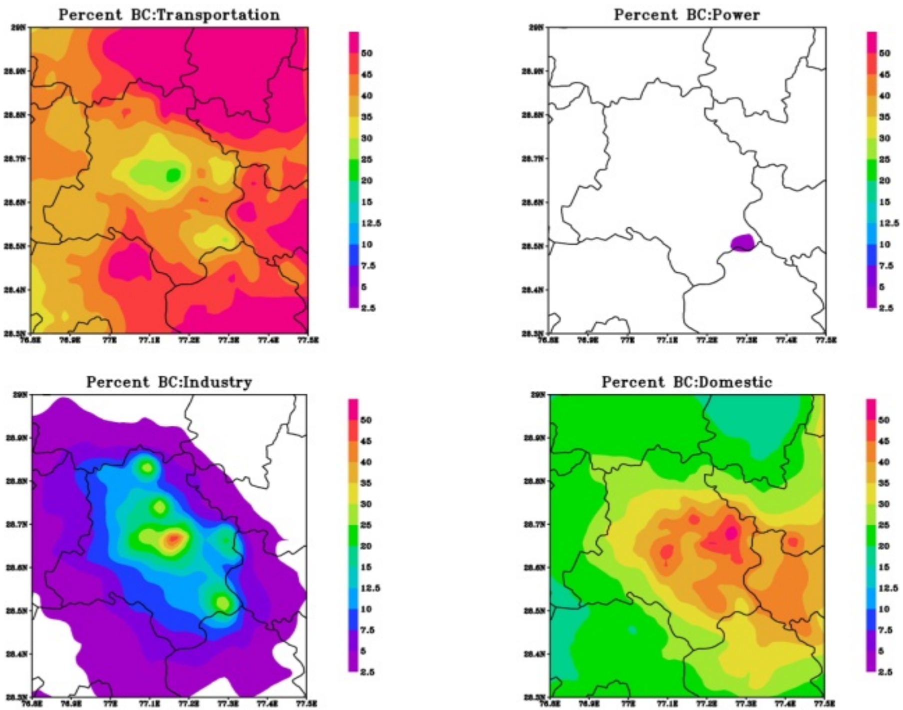

Fig. 9. Spatial distributions of sector contributions to period mean surface BC concentrations.

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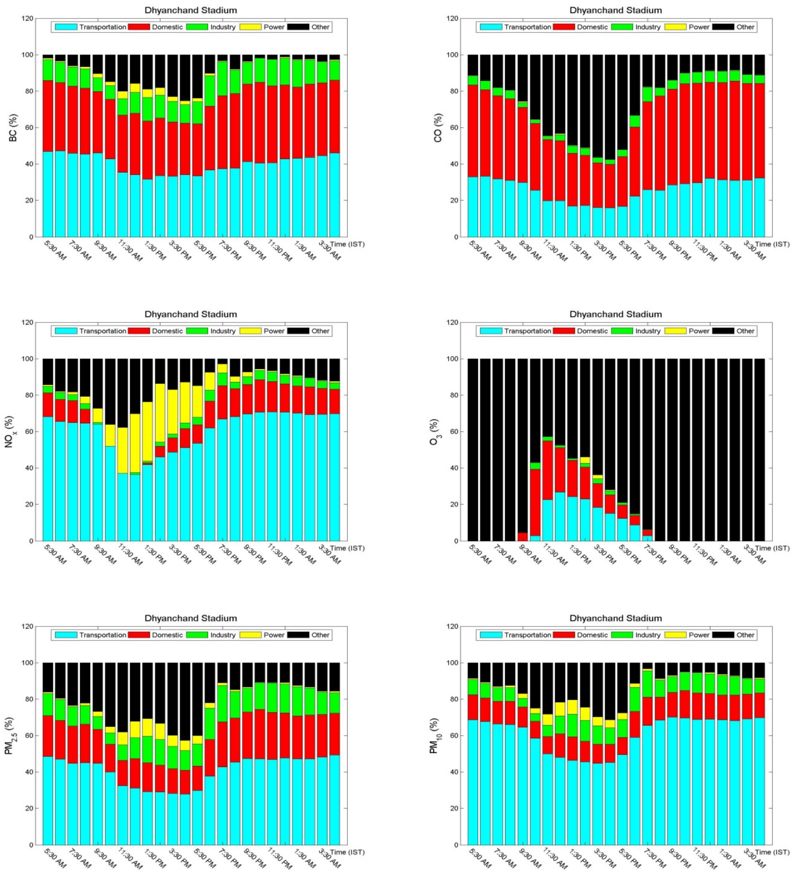

Fig. 10. Diurnal variation in the sector contribution (in %) to period mean surface concentrations of different pollutants at the Dhayanchand monitoring station.

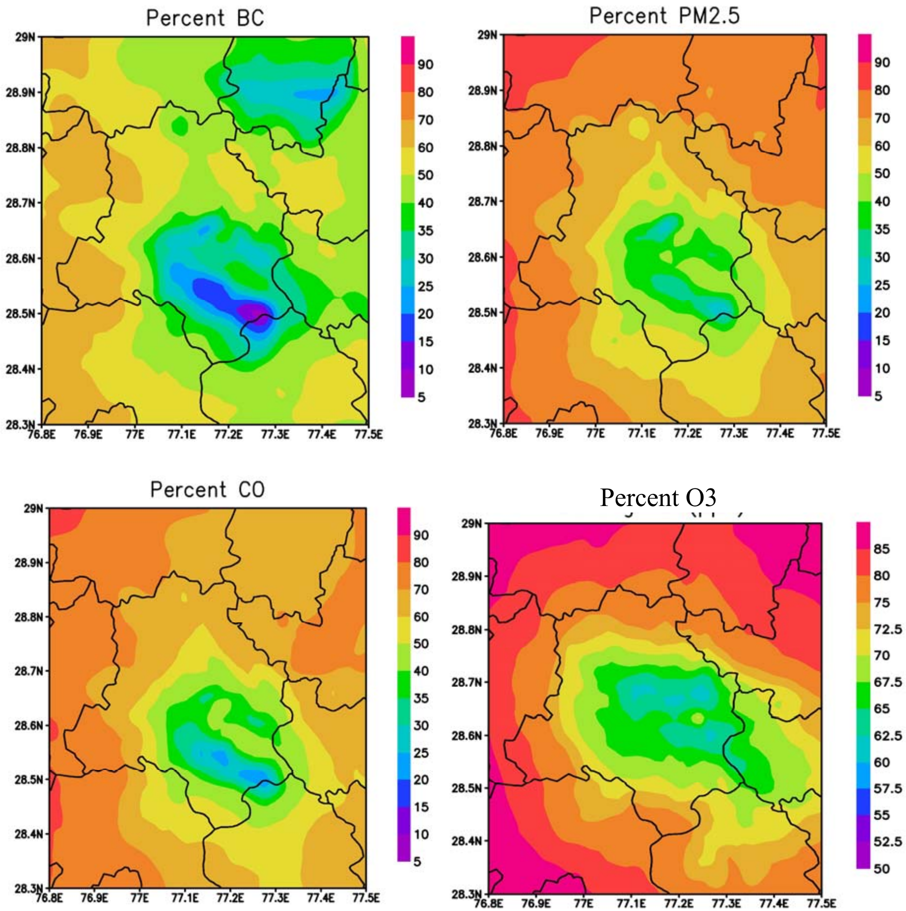

Fig. 11. 20 day mean contributions of pollutants from outside source.

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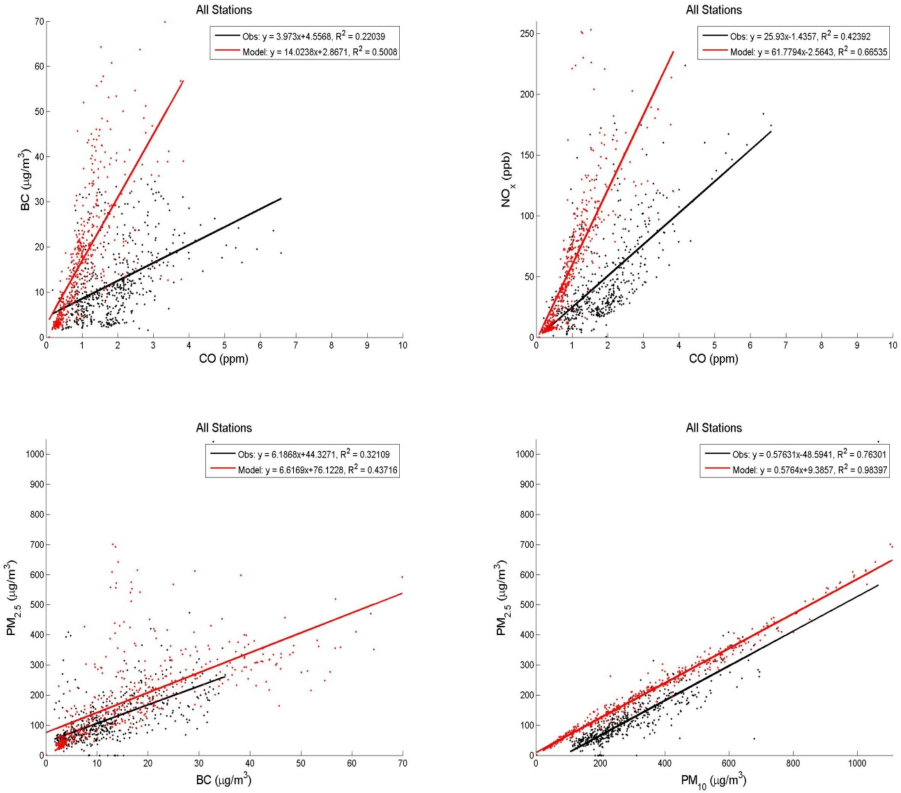

Fig. 12. Comparison of correlations between different species for all the sites combined based on observations and modeled concentrations.

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