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Role of meteorology in seasonality of air pollution in megacity Delhi, India

Sarath K. Guttikunda · Bhola R. Gurjar

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Abstract The winters in megacity Delhi are harsh, smoggy, foggy, and highly polluted. The pollution levels are approximately two to three times those monitored in the summer months, and the severity is felt not only in the health department but also in the transportation department, with regular delays at airport operations and series of minor and major accidents across the road corridors. The impacts felt across the city are both manmade (due to the fuel burning) and natural (due to the meteorological setting), and it is hard to distinguish their respective proportions. Over the last decade, the city has gained from timely interventions to control pollution, and yet, the pollution levels are as bad as the previous year, especially for the fine particulates, the most harmful of the criteria pollutants, with a daily 2009 average of 80 to 100 $\mu g/m^3$. In this paper, the role of meteorology is studied using a Lagrangian model called Atmospheric Transport Modeling System in tracer mode to better understand the seasonality of pollution in Delhi. A clear conclusion is that irrespective of constant emissions over each month, the estimated tracer concentrations are invariably 40% to 80% higher in the winter months (November, December, and January) and 10% to 60% lower in the summer months (May, June, and July), when compared to annual average for that year. Along with monitoring and source apportionment studies, this paper presents a way to communicate complex physical characteristics of atmospheric modeling in simplistic manner and to further elaborate linkages between local meteorology and pollution.

Keywords Air quality in Delhi · Particulates pollution · Winter highs · Mixing layer height · Role of meteorology

Introduction

Delhi, one of the largest megacities of South Asia and the capital of India, is located at 28.5° N latitude and 77° E longitude and 216 m above mean sea level. Delhi lies almost entirely on the Gangetic plains with the Thar Desert in the West, central hot plains in the South, and hills in the North and East. The river Yamuna forms the eastern boundary passing through the city. The city lies in a semi-arid climate zone, with long summers (early April to October), monsoon season in between, and notorious winters (October to January) with heavy fog (Ali et al. 2004). In the last two decades, the city grew from being Delhi to

S. K. Guttikunda (✉)
Division of Atmospheric Sciences,
Desert Research Institute,
2215 Raggio Parkway,
Reno, NV 89512, USA
e-mail: sguttikunda@gmail.com

B. R. Gurjar
Associate Professor, Department of Civil Engineering,
Indian Institute of Technology, Roorkee,
Roorkee 244667, India

National Capital Region (NCR) of Delhi, covering an area of ~1,500 km^2, including 165 villages and 9 districts (SoE-Delhi 2010). The NCR now includes new townships and satellite centers such as Noida, Gurgaon, Ghaziabad, and Faridabad, all of which are a combination of information technology firms and industrial clusters (the spatial spread of the city is presented in Fig. 1). In 2007, the population of NCR was estimated at 16 million. It is expected to reach 22.5 million in 2025 (UN-HABITAT 2008).

Rapid population growth followed by intensive infrastructure development led to heightened demand in energy from domestic, transport, and industrial sectors, resulting in an increase in the air pollutant emissions of particulate matter (PM), sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), and hydrocarbons. From 1971 to 2001, the road length in Delhi increased from 8,400 to 28,500 km (3.4 times), whereas the number of vehicles increased from 0.2 to 3.5 million (20 times) (Gurjar and Lelieveld 2005). For mid-2010, the in-use vehicle population is estimated at ~5.6 million and the number of industrial units at ~7,000 (SoE-Delhi 2010).

Air pollution in Delhi

As a result of rapidly expanding city with growing pollutant emissions, an increase in pollution levels for all criteria pollutants was observed, except for SO_2, resulting in health and respiratory impacts. According to a local survey, 30% of Delhi's population was found suffering from respiratory disorders due to air pollution and the number of cases were ~12 times the national average (Kandlikar and Ramachandran 2000), following which in 2009, Delhi was characterized as the "asthma capital" of India (Dubey 2009). A summary of measured daily averages by month for the period of 2006–2010 for PM_{10}, $PM_{2.5}$, SO_2, ozone, CO, and NO_2 concentrations are presented in Fig. 2, along with a thick line indicating the new national ambient standard (CPCB 2010) and error bars indicating the standard deviation among the daily averages for each month. This is an average of

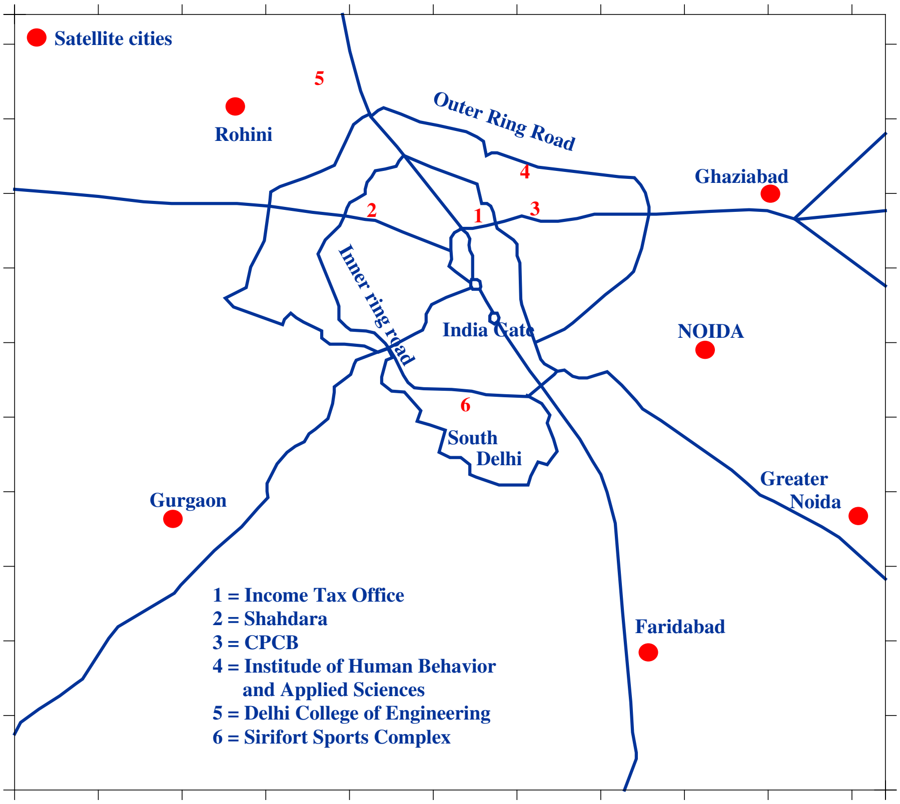

Fig. 1 A map of Delhi representing the ring roads and the approximate location of the continuous monitoring stations

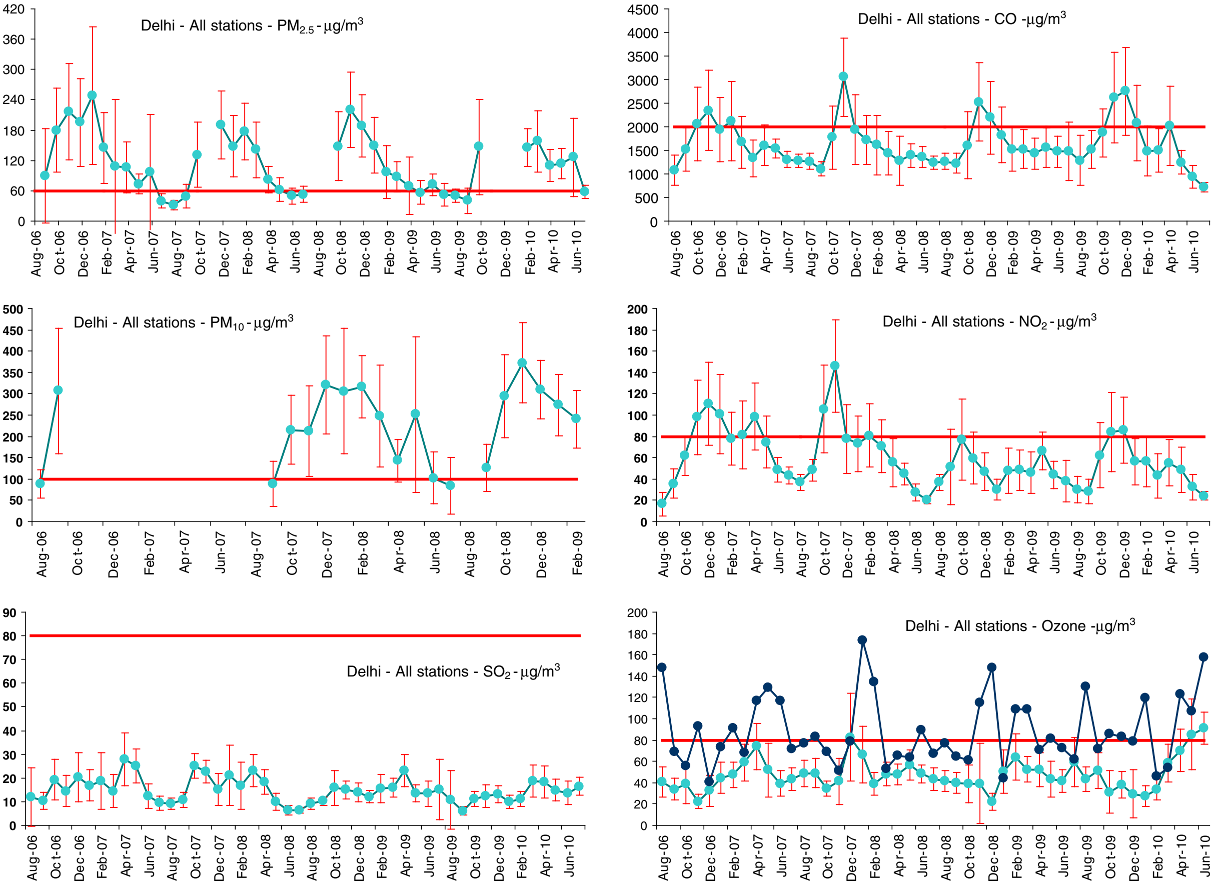

Fig. 2 Average of monitoring data from six stations in Delhi, India; *thick line* indicates the national ambient standard; *error bars* indicate standard deviation in data for that month; for ozone, the *dark dots* indicate daily maxima (source: CPCB 2010)

monitoring data collected from six continuous air monitoring stations (Fig. 1) in Delhi (CPCB 2010), which is lower than what is typically observed at a heavy traffic junction like Income Tax Office (ITO) station. Due to inconsistencies in the measurements, there was limited data available for PM_{10}. On an average, the PM pollution exceeded two to three times the daily ambient standard of 100 µg/m^3 for PM_{10} and 60 µg/m^3 for $PM_{2.5}$. These exceedances were severe in the winter months. For ozone, the plot also includes the daily maxima, which exceeded the standard for 50% of the year. The daily average CO concentrations also remained low for most of the year. However, it is important to note that the hourly averages spread from 3,000 to 5,000 µg/m^3, and these acute spurts of exposure, especially along the road corridors where congestion times are increasing, are very unhealthy (Gómez-Perales et al. 2007; Zhao et al. 2004).

What worked in Delhi?

Aneja et al. (2001) measured the ambient concentrations of CO, NO_x, SO_2, and total suspended particulates (TSP) from January 1997 to November 1998 at ITO station. The yearly average concentrations for CO, NO_x, SO_2, and TSP for years 1997 and 1998 were found to be 4,810±2,287 and 5,772±2,116 µg/m^3, 83 ±35 and 64±22 µg/m^3, 20±8 and 23±7 µg/m^3, and 409±110 and 365±100 µg/m^3, respectively—at least twice the current air quality levels.

The drop in the concentrations over the last decade is primarily due to a number of interventions that were introduced to control air pollution and better urban planning by the local government. In 1998, the Supreme Court ruled that the city of Delhi should take concrete steps to address air pollution in the transport and industrial sectors. The timeline of implementation (in the transport and industrial sector) and the experience for instituting change which has become a model for other Indian cities is described in detail in Narain and Bell (2005). For the transport sector, this ruling led to largest ever compressed natural gas (CNG) switch in the world for public transport vehicles. More than 100,000 vehicles (including the three wheelers and taxis) were converted to CNG over five years (DTC 2010). This resulted in significant decrease in the PM pollution—largest improvement came from retrofitting ~3,000 diesel buses to CNG (DTE 2002). Kandlikar (2007) attributes the following changes to the introduction of CNG: a dramatic drop of 40% in the CO concentrations for the calendar year 2002 from 5,000 to 3,000 $\mu g/m^3$ and the NO_x concentrations showed an increase of 50% from 63 to 95 $\mu g/m^3$ from January 2001 to January 2004 followed by a slow decrease to 82 $\mu g/m^3$ by January 2006. Kandlikar (2007) concludes that the reverse trend in NO_x concentrations is linked more to the rapid changes in the vehicle fleet, which quickly negated the benefits of CNG conversion. The concentration of SO_2 showed a decline of about 33%, from 15 to 10 $\mu g/m^3$, which is a result of the conversion to CNG and reduction in diesel fuel sulfur content introduced in 2001–2002 (Badami 2005). Delhi has, since 2000, also enforced Euro II emission standards, 5 years ahead of schedule, Euro III in 2005 for all passenger vehicles, and Euro IV fuel standards in April 2010 (in Delhi and 11 other cities).

Other significant fallout of the ruling was in the industrial sector—approximately 500 heavy industries were either shut down or relocated to areas outside the Delhi administrative boundaries, which the industries took the opportunity to upgrade (while relocating) their energy systems to improve energy efficiency and consumption levels.

Yet, there remains a tremendous amount of potential to reduce the air pollution impacts in Delhi as the demand rises for infrastructure and services. Reynolds and Kandlikar (2008) examined the opportunities for combined benefits of Delhi's fuel switching strategy—not only for local air pollution but also for climate-related affects—and evaluated the potential for extending such services to other cities.

Scope of this paper

While there is no single sector that is solely responsible for Delhi's air pollution, rather a combination of sources including industries, power plants, domestic combustion of coal and biomass, and transport (direct vehicle exhaust and indirect road dust) contribute to air pollution (CPCB 2010; Chowdhury et al. 2007; Mohan and Kandya 2007; Garg et al. 2006; Gurjar et al. 2004; Reddy and Venkataraman 2002; Shah et al. 2000), though the sectoral contributions vary considerably from season to season. Seasonal changes in demand for fuel and natural pollution result in differing source contributions during the summer and the winter months. This needs further evaluation for not only the emission trends but also the changing meteorological conditions from season to season in order to maximize the effectiveness of anti-pollution initiatives (Guttikunda 2009; Gurjar et al. 2004, 2008; Mohan and Kandya 2007).

It is generally believed that the air pollution can only be controlled at the source, and the limiting factor is most often the balance sheet of costs and associated benefits (like health). However, in some cases, possible reduction in emissions is a direct function of the geographical location and prevalent meteorological conditions. For example, in cities like Los Angeles or Ulaanbaatar, which form a valley terrain, irrespective of the wind patterns, the emissions tend to stay in the area longer and contribute more to the local air pollution problems. On the other hand, in cities like Bangkok, Beijing, Delhi, Dhaka, and Manila, with flat terrains, the meteorology tends to have higher impact on dispersing the air pollution. In this regards, a study of air movement over urban areas can help us better understand the movement of pollutants and their respective impact on pollution planning. In this paper, in combination with monitoring data from the Pollution Control Board and particulate pollution source apportionment analysis in the literature, we assess the role of meteorology for the period of 2000s as a diffusing or non-diffusing agent of air pollution in megacity Delhi, India.

Study methodology

The fundamental parameter in the movement of contaminants is the wind, its speed and direction, which in turn is interlinked with vertical and horizontal temperature gradients. In other words, the greater the wind speed, the greater the turbulence and the more rapid and complete the dispersion of contaminants in the air. Previously, models were utilized under varying conditions to evaluate air pollution at regional and urban scale. For example, air pollution assessment linked to meteorology in Milan (Cogliani 2001), dust storms in China (Qian et al. 2004), numerical modeling of photochemical smog in Hong Kong (Jiang et al. 2008), and air pollution forecasting systems for events like Shanghai Expo 2010 (SEPB 2010). Interestingly, the recent study by Tandon et al. (2010) focused on coupling between meteorological factors and ambient aerosol load in Delhi, which found that the undulation observed in both (coarser and respirable) size fractions of aerosol load from the local crust was affected by the meteorological factors. However, effects of meteorology or seasonal change on other pollutants were not assessed in that study. Sharma et al. (2010) studied seasonal variability of ambient NH_3, NO, NO_2, and SO_2 over Delhi. In the present study, we evaluate the impact of meteorology on primary pollutants, released in a dispersion model as a tracer. In this analysis, the movement of the tracer is diagnosed as monthly averages along with the synopsis of local meteorological conditions.

Also, it is important to keep in mind that the methodology

- Is limited to qualitative assessment of impacts using some quantitative inputs, and no attempt is being made to list any working formulae for assessment
- Does not compare with theoretical approaches to analyzing atmospheric diffusion
- Is limited to primary pollutants only. The tracer modeling is conducted assuming no chemical reactions and to study the impact of meteorology only. The pollutant of concern is limited to PM and dispersion characteristics (dry and wet deposition) used are of PM, though the calculations were conducted in two bins to account separate characteristics for coarse- and fine-mode PM
- Cannot be extended to secondary pollutants like ozone, which follow a very complex path of chemical reactions between NO_x and VOCs
- Is limited to urban scale and does not attempt to estimate the impact of long-range transport.

ATMoS dispersion model

The modeling was conducted for a period of 19 years from 1990 to 2008 (however, results only from the 2000s are discussed in this paper), using the Atmospheric Transport Modeling System (ATMoS) dispersion model—a UNIX/Linux-based meso-scale three-layer forward trajectory Lagrangian puff transport model (Calori and Carmichael 1999). The model was previously utilized to study regional- and urban-scale pollution management in Asia for sulfur, nitrogen, and PM pollutants (Arndt et al. 1998; Streets et al. 2000; Guttikunda et al. 2001, 2003; Holloway et al. 2002; Carmichael et al. 2008). The model is a modified version of the US National Oceanic Atmospheric Administration, Branch Atmospheric Trajectory model (Heffter 1983). The layers include a surface layer, boundary layer (designated as the mixing layer height), and a top layer. The multiple layers allow the model to evaluate and differentiate the contributions of diffused area sources like transport and domestic combustion emissions and points like industrial and power plant emissions. The model has flexible temporal and spatial resolution and can be run for periods ranging from a month to a year and from regional to urban scales (Guttikunda et al. 2003). The model produces monthly average concentrations as output and then converted to seasonal and yearly averages for further analysis.

Meteorological data

The meteorological data for this analysis come from the NCEP/NCAR reanalysis data (Kalnay et al. 1996). In the model, the NCEP data are re-gridded and multiple parameters are utilized to establish the mixing layer height for the city domain. The meteorological parameters utilized are global 3D wind and temperature, surface wind, temperature, and pressure, surface heat flux, and precipitation fields. The meteorological processing is conducted before the dispersion modeling. Figure 3 presents the model calculated mixing layer height (in meters) along with a moving average for years 2001 to 2008. The summer time heights are as high as

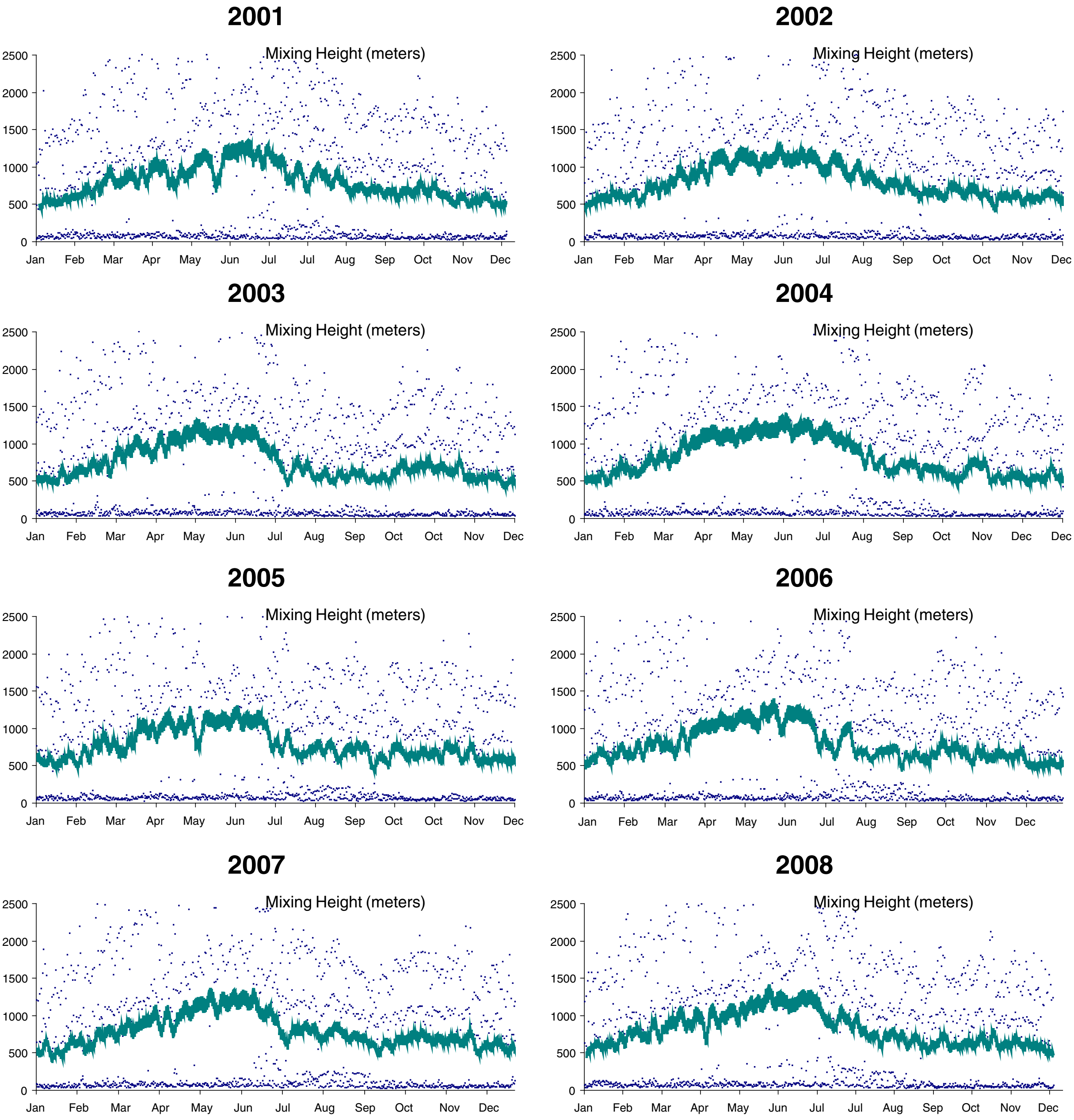

Fig. 3 Mixing layer height in Delhi, estimated from NCEP reanalysis data (*thick line* indicates a 15-day moving average)

2,500 m during the daytime compared to the lows of less than 100 m in the winter months.

Modeling domain

The modeling domain is presented in Fig. 4. The modeling domain consists of a 2×2° box ranging from 76° E to 78° E in longitude and 27.5° N to 29.5° N in latitude. The square indicates the domain represented in Fig. 1, the domain in which the tracer emissions were released for forward advection. The 2×2° box is sub-divided into 40×40 grid cells of which the tracer domain consists of 8×8 grid cells, i. e., 64 cells were assigned tracer emissions. The tracer emissions of 1,000 tons/year were released as a puff every 3 h and advected following Lagrangian

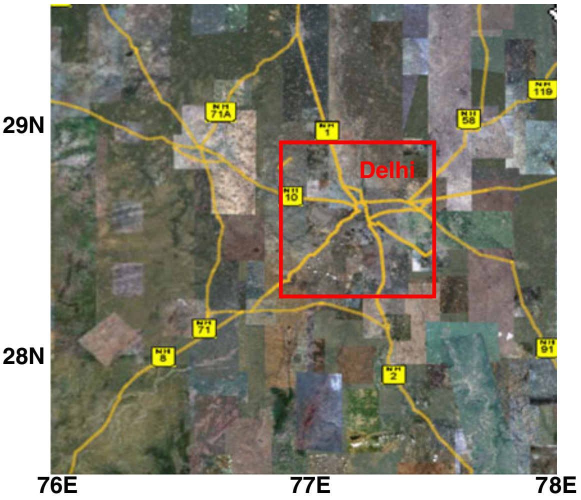

Fig. 4 The modeling domain for the tracer simulations (the *thick square* represents the city domain from Fig. 1)

puff transport formulation in ATMoS modeling system.

Results and discussion

Tracer model results

For the tracer emissions domain (8×8 cells represented by a box in Fig. 4), a summary of the percentage variation of the monthly tracer concentrations compared to the annual average for that year is presented in Fig. 5. For convenience, only the results from 2001 to 2008 are presented in this paper. An important observation is the similarity in the dispersion patterns over the years. A clear conclusion is that irrespective of the constant emissions over each month, the observed concentrations are invariably 40% to 80% higher in the winter months (November, December, and January) and 10% to 60% lower in the summer months (May, June, and July). The pattern is consistent over the years, and the shift is primarily due to the variability in the mixing layer heights and wind speeds between the seasons (and years). During the day, similar patterns are also evident, when the mixing height is routinely lower during the night time compared to the day, irrespective of the seasons.

Mathematically, assuming a box model, by definition, the ambient concentration is defined as mass over volume. Assuming that the emissions are equally mixed in an urban air shed under the mixing layer, for the same emissions, a lower mixing height means higher ambient concentrations. Similar to the mixing layer height (presented in Fig. 3), the wind speed is also very relevant. Figure 6 presents a summary of the surface layer wind speeds in 2008 from NCAR/NCEP reanalysis for Delhi. The summer time wind speeds averaged 3 to 6 m/s, while the winter time averaged 1 to 3 m/s. The higher wind speeds are responsible for driving part of the pollution out of the city limits, as evident from lower shares of tracer concentrations for the summer months of June, July, and August (Fig. 5).

Comparisons with monitoring data

The variations in measured daily average $PM_{2.5}$ levels for each month (Fig. 2) are then compared to the variations observed in the tracer model runs; the percentage changes for the two compared to their respective annual averages are presented in Fig. 7. The monthly variations in monitoring data (higher for the winter months and lower for the summer months compared to annual average) are prominently similar to the estimated meteorological influence. The difference between the two results is mainly due to not substituting the tracer emissions with an absolute emissions inventory to match the seasonal trends, along with the meteorological conditions. A good qualitative agreement between the measurements and tracer calculations is evidence that emphasis is needed on introducing seasonal specific control measures in order for the pollution to stay at the summer time low levels.

Seasonal pollution sources

The winters in Delhi are harsh, foggy, and more polluted than any other season. The recurring impacts include heavy persistent smog and fog in the months of November to February, higher pollution levels for all criteria pollutants, frequent delays or cancelations of flights (domestic and international), and reduced visibility causing minor and major accidents along the roads (Ali et al. 2004). Chowdhury et al. (2007) summarized the contribution of major sources, via particulate matter source apportionment study, for four seasons based on measured $PM_{2.5}$ pollution at various locations in Delhi. A summary of the source apportionment results from the four seasons is presented in Table. 1. A caution is advised, as these

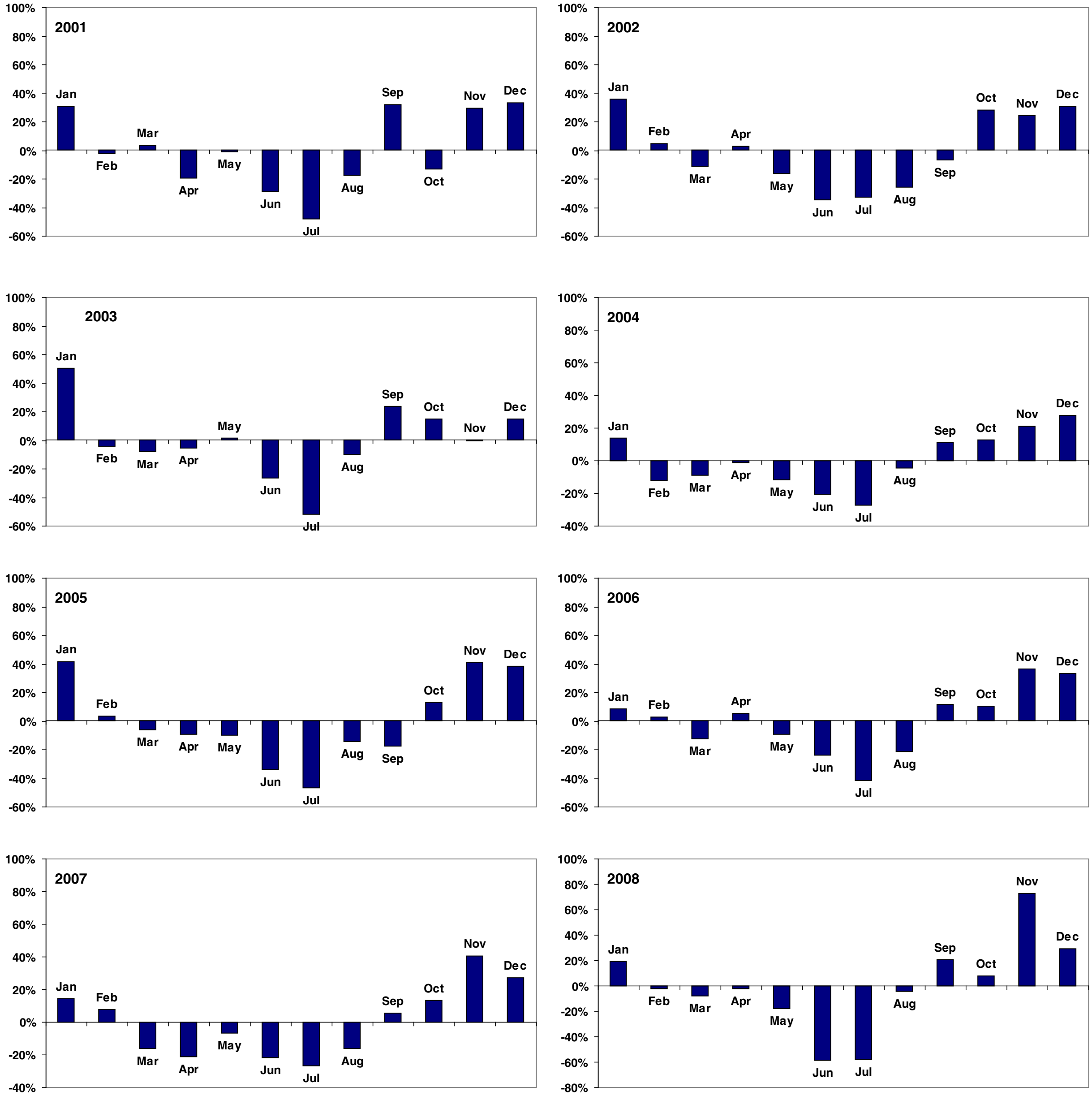

Fig. 5 Percentage change in monthly average tracer concentrations compared to the annual average concentration for the emission domain

results are based on measurements, chemical analysis, and receptor modeling, which come with certain limitations in assigning source contribution percentages (Johnson et al. 2011). However, these studies are very useful in highlighting pollution sources which need immediate attention for air quality management. In summer, with an average $PM_{2.5}$ of ~60–90 μg/m^3 during the study period, in addition to the road dust already present on Delhi roads, dust storms from the Thar Desert, to the southwest, contribute to increased fugitive dust. This is exacerbated by the low moisture content in the air, leading to higher resuspension (40% of PM in summer, compared to 4% in winter). In the winter months, with an average $PM_{2.5}$ of ~200 μg/m^3 during the study period, the pollution sources changed dramatically. The use of biomass,

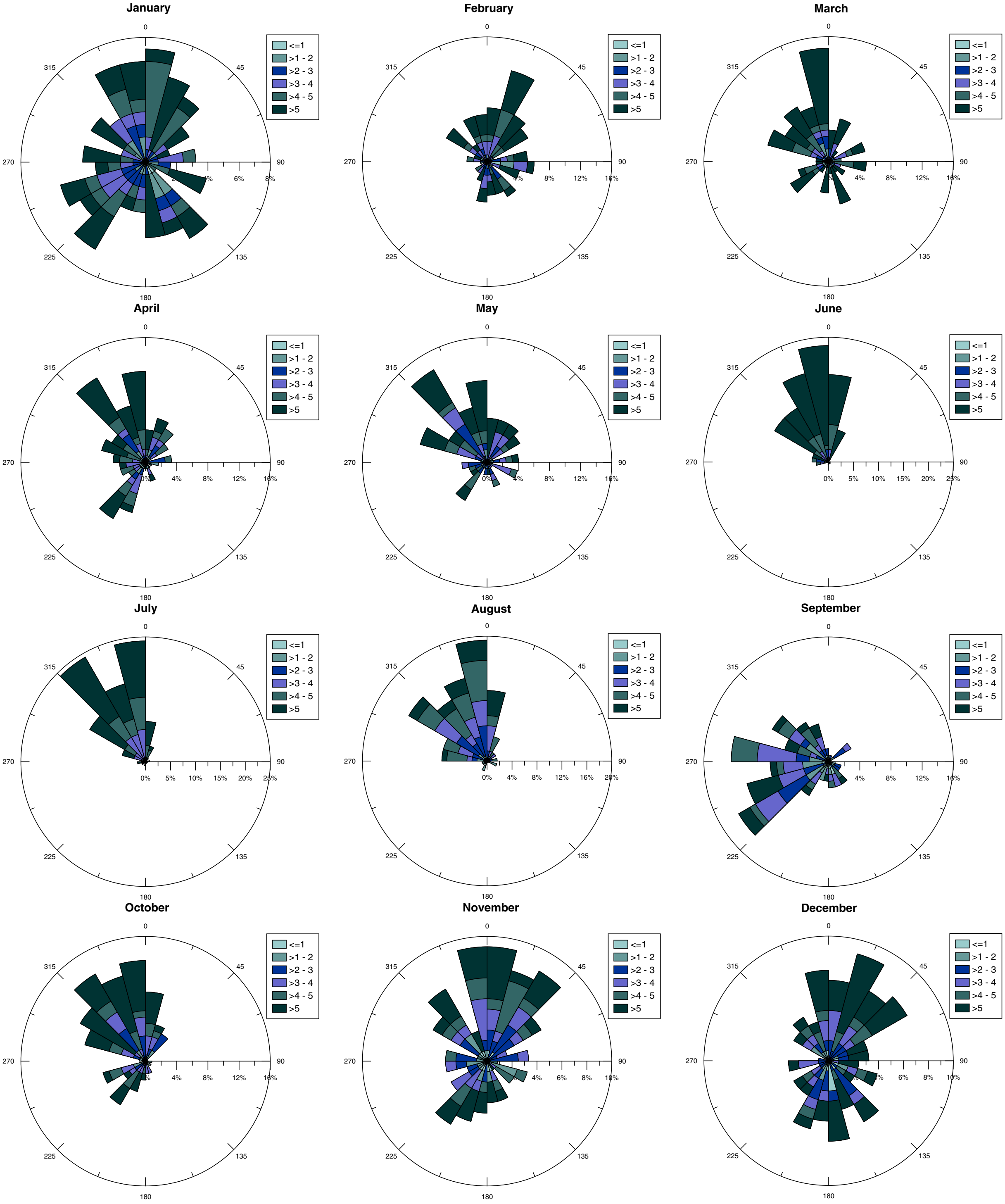

Fig. 6 Wind speed and wind direction for the Delhi domain at 6-h interval, estimated from NCAR/NCEP reanalysis data for year 2008

primarily for heating contributes to ~30%—with most of the burning taking place at night, when the “mixing layer height” is low and further worsening the ambient concentrations. In summer, biomass accounts

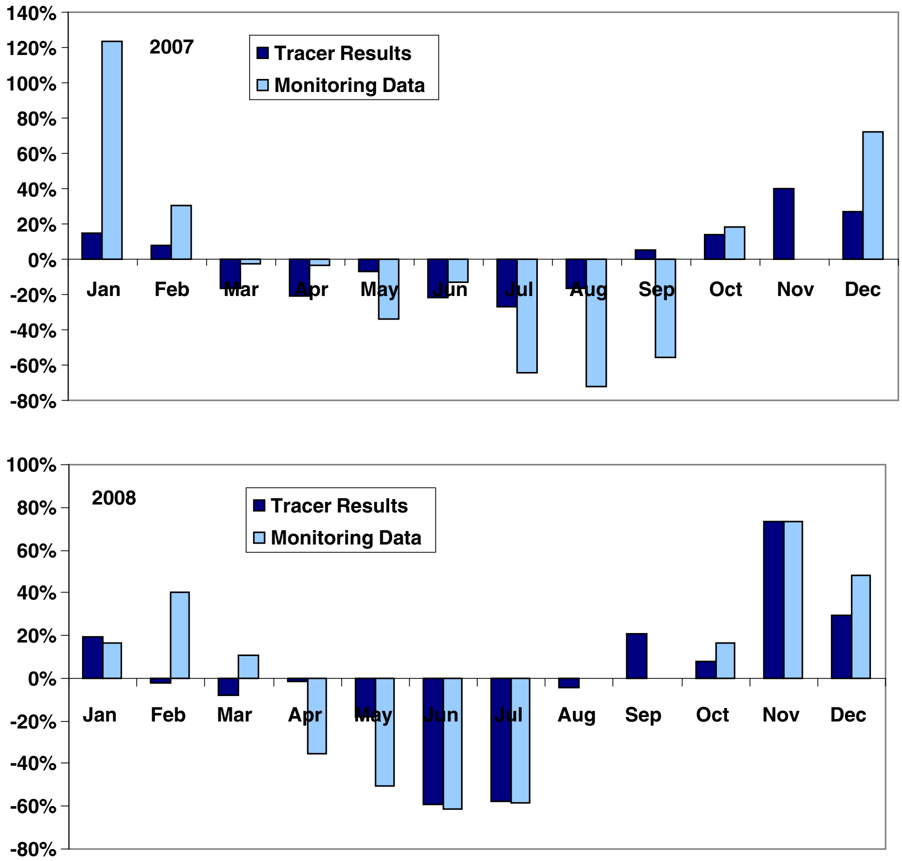

Fig. 7 Percentage change in monitored monthly average $PM_{2.5}$ concentrations (average of six stations) compared to the monitored annual average concentration and percentage change in estimated monthly average compared to annual average tracer concentration (Fig. 5) over the emissions domain in Delhi, India

for only 9% of particulate pollution. According to Sharma et al. (2010) in the year 2008, the ammonia concentrations during the winter months ranged from ~1.0 to 46.2 ppb with average mixing ratio of 20.2± 9.4 ppb. Whereas, during the summer months, concentrations were approximately one third.

Though seasonal, after crop harvests, clearing agricultural land is a common practice in the surrounding (largely agricultural) states, and the smoke reaches Delhi contributing to substantial smog formation and PM and ozone pollution (NASA 2008). Note that the dust storms and biomass burning are not

Table 1 $PM_{2.5}$ source apportionment results for Delhi, India

Source type	Season			
	Summer (%)	Autumn (%)	Winter (%)	Spring (%)
Road dust	40.7	17.9	4.1	16.1
Gasoline	1.8	3.2	7.4	3.8
Diesel	23.1	15.7	16.3	17.8
Coal burning	0.7	2.4	8.8	1.6
Biomass burning	9.5	20.9	28.6	22.2
Secondary sulfates	9.7	5.8	7.7	7.9
Secondary nitrates	2.8	2.1	7.2	2.0
Secondary ammonium	2.9	2.1	4.8	5.7
Others	8.8	29.9	15.2	22.9

Source: Chowdhury et al. (2007)

necessarily natural phenomena. Desert crusts and vegetation can be destroyed via construction activities in the cities, thereby creating a reservoir of suspendible dust during high winds. These with anthropogenic activities compound the impact of what might otherwise be viewed as purely natural phenomena, and they may change the importance of these pollution sources within the context of an air quality management program. The dust events or the fires can only be predicted using satellite and modeling data but cannot be prevented. However, the dust from the storms or the smoke from forest fires can be detected in advance and provide public pollution alerts based on the meteorological tracer or chemical transport modeling in forecast mode.

Conclusion

It is important to note that while the modeling is conducted using the meteorology pertinent to the city area, the tracer emissions are not. While the simulations provided a better understanding of the dispersion and seasonality of air pollution in the city, the pollution patterns are best studied using a local emissions inventory, including the contributions of emissions originating outside the city (transboundary pollution). For example, in case of Delhi, a constant traffic between Delhi and its satellite cities (Gurgaon and NOIDA) is a growing emission source, along with all the industrial estates in the northeast and northwest sectors.

Studying the role of meteorology is crucial also from mega event management perspective. For example, air pollution in Beijing received significant attention in 2008 before (and after) the 2008 Olympic Games (Streets et al. 2007). A number of interventions were implemented in domestic, industrial, and transport sectors to achieve the target air pollution reductions and improve the number of clean air (blue sky) days in Beijing (UNEP 2009). During the Olympic Games, the traffic was restricted to only 50% of the passenger vehicles (depending on the registration number) every day. And at the industrial level, a number of small and large scale units were shut down. Most importantly, a number of industries were also shut down in the neighboring cities to cut down the long-range transport (due to meteorological advection) of pollutants. With the interventions in place, the levels of NO_x (primarily from the cars, trucks, and power plants) plunged ~50%. Likewise, levels of PM fell ~20% (UNEP 2009). Similar steps, with lesser intensity, were implemented in Delhi during the 2010 Commonwealth Games in October 2010, such as separate lanes for public and athletes, closing down of coal-based power plant in the city, and varying the working hours of public offices to avoid some congestion on the roads.

The linkages between pollutant emissions, meteorology, and health impacts are complex, and to formulate an integrated multi-pollutant strategy, one needs better understanding of these linkages (Hidy and Pennell 2010). For air quality management in Delhi and in other cities of India, the proposed methodology to study the movement of local emissions and the role of meteorology in either advecting or trapping the pollution in the city, along with any top-down source apportionment study like Chowdhury et al. (2007), can play a vital role in communicating complex physical characteristics of atmospheric modeling in simplistic manner—and to further elaborate pollution parameters and potential health risks.

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