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Significance of $PM_{2.5}$ Air Quality at the Indian Capital

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ABSTRACT

In New Delhi, the capital city of India, concentrations of regulated air pollutants often exceed the Indian national ambient air quality standards (INAAQS). As the sources of these pollutants differ, it is of utmost priority to understand the most dangerous air pollutant to formulate better control strategies in the city. In this study, regulated air pollutant concentrations in New Delhi during 2011 to 2014 were collected. Compared to other pollutants, $PM_{2.5}$ concentrations exceeded the INAAQS quite often. While $PM_{2.5}$ exceeded INAAQS during 85% of the days, NO_2, O_3, CO and SO_2 exceeded only on 37, 14, 11 and 0% of the days, respectively. Using air quality index approach, the most dominant pollutant was identified as $PM_{2.5}$, for 75 to 90% of the days. However, a seasonal variation in the percentage dominance of $PM_{2.5}$ was observed. For example, $PM_{2.5}$ was dominant during 95% of the winter and 68% of monsoon days. In addition to absolute concentrations, pollutants can also be ranked by studying their associated short term mortality impacts. However, such studies are rare in India. For the first time, the short term impact of $PM_{2.5}$ concentrations on non-disease specific mortality in New Delhi was assessed using Poisson regression models. Results indicated that the excessive risk associated with $PM_{2.5}$ estimated was 0.57, which was higher than the other regulated pollutants. This indicates a projected 6.2 and 6.5% decrease in mortality by meeting the $PM_{2.5}$ Indian standards and WHO set limits, respectively.

Keywords: Air quality index; New Delhi; $PM_{2.5}$; Health impact assessment.

INTRODUCTION

A world health organization (WHO) report observes that air pollution resulted in around seven million deaths globally in 2012, of which South East Asian region, dominated by India, accounted for 2.3 million (WHO, 2014a). Outdoor particulate matter (PM) was the seventh highest killer in India during 1990–2010 (IHME, 2013). According to a recently released report (WHO, 2014a) by World Health Organization (WHO), among 1600 cities surveyed, thirteen of the Indian cities were among the top twenty worst polluted cities, with New Delhi leading the list. $PM_{2.5}$ concentrations in New Delhi are atleast10 times higher than Washington DC, and 3 times higher than Beijing (WHO, 2014a). In order to construe the status of air quality in India, National Ambient Air Quality Standards (INAAQS) were adopted in 1982 by the Central Pollution Control Board, with further revisions in 1994 and 2009. Predominant sources for these regulated pollutants differ. For example in New Delhi, residential, transport and industrial sectors are major sources for $PM_{2.5}$ (Sahu *et al.*, 2011); transport sector is the major source of CO and NO_x (Aneja *et al.*, 2001); and industries are major source for SO_2 (Sadavarte and Venkataraman, 2014). So this calls for knowledge about the most dangerous pollutant in the city to formulate stricter laws and better control strategies.

As the absolute concentrations of these pollutants differ, it is necessary to bring these pollutants onto a similar scale for direct comparison. To alleviate this, Ott (1978) suggested a scheme to transform the weighted values of air pollutant concentrations into a single or set of numbers, referred to as Air Quality Index (AQI), wherein bigger the AQI greater the pollution, higher is the health risk, and vice versa. The quality of air is reported as good, satisfactory, moderate, poor, very poor or severe depending on the overall AQI, calculated using individual AQI of pollutants considered. Several developed nations in the world, including the US, UK, Australia, and Canada, have their own AQI. These vary by the range of the index, and the methodology used to estimate species specific and overall AQI. For example, UK (COMEAP, 2011) and Canada (Chen and Copes, 2013) classify AQI into four categories, with AQI ranging from 0 to 10. However, the US uses six categories, ranging from 0 to 500. Moreover, while Canada uses a non-linear aggregate of AQI of different species based on their exposure-response relationships, the US and UK use maximum AQI of different species, to estimate the overall AQI. Few studies in India, tried to analyze air quality using AQI in cities.

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For example, Sharma *et al.* (2003) used Indian NAAQS and health standards by the US, for suspended particulate matter (SPM), CO, NO_2, O_3, SO_2, and PM_{10} to estimate AQI in an Indian city. Bhaskar and Mehta (2010) used the US method to estimate AQI at thirteen different sites in Ahmadabad city in India, and observed strong seasonal effects on AQI. Banerjee and Srivastava (2011) estimated AQI proposed by Rao and Rao (1979), which uses the percentage mean of measured concentrations normalized by their corresponding NAAQS. Their analysis at an industrialized region, for PM_{10}, SPM, SO_2 and NO_2, indicated moderate to heavy air pollution, for most part of the year. Bishoi *et al.* (2009) used yearlong concentrations of CO, SO_2, PM_{10}, O_3 and NO_2, to compare AQI estimated using the US methodology and factor analysis. Results show that while both methodologies follow similar trends, the US methodology estimated higher AQI than factor analysis.

However, in order to quantify the health risk posed by a pollutant, it is essential to study the association between pollutant exposure and health outcome. These studies also aid regulatory agencies in fixing the pollution reduction targets to a level that would minimize the health risk of the exposed group. Health risk based studies are quite common in western countries. Cohen *et al.* (2005) observed that the relationship between relative risk and cardiopulmonary diseases, lung cancer, and acute respiratory infections in children was linear between $PM_{2.5}$ concentrations of 7.5 $\mu g\ m^{-3}$ to 50 $\mu g\ m^{-3}$, and flattened thereafter. Pope *et al.* (2009) observed that a nonlinear power function expressed the relationship between relative risk of ischemic heart disease, cardiovascular disease and cardiopulmonary disease mortality from cigarette smoking. Results also indicated that initially cardiovascular disease mortality increased steeply with increase in concentration of fine particulate matter and flattened out at higher exposure concentrations. In India, mainly due to lack of mortality data, there are very few studies relating health risk and pollutant concentrations. Dholakia *et al.* (2014) studied the short term association between PM_{10} concentration and mortality for five Indian cities. Balakrishnan *et al.* (2011) and Rajarathnam *et al.* (2011) did a time series study on Chennai and New Delhi respectively and obtained the risk co-efficient of PM_{10}, NO_2 and SO_2. Similarly,Guttikunda and Goel (2013) studied the health impacts of PM_{10} and $PM_{2.5}$ in New Delhi using exposure response coefficients from Atkinson *et al.* (2012). Chowdhury and Dey (2016) used satellite data for calculating nationwide $PM_{2.5}$ exposure and a risk model to estimate cause specific premature death from ambient $PM_{2.5}$ exposure. However, no short-term exposure response study of $PM_{2.5}$, which is the best indicator to the health risk levels from air pollution (WHO, 2014b), was carried out to our knowledge in India.

The objective of this study is to identify the most dangerous pollutant in New Delhi by AQI and health risk based approaches using ambient concentrations of regulated pollutants and health based mortality in New Delhi during 2011 to 2014.

MATERIAL AND METHODS

Indian AQI

CPCB set guidelines for Indian national ambient air quality standards of 12 pollutants (CPCB, 2009). Out of which 8 pollutants CO, NO_2, SO_2, $PM_{2.5}$, PM_{10}, O_3, Pb and NH_3 have short term standards. To inform people about the quality of air quickly so that people can take appropriate measures to protect themselves, IND-AQI was released in 2014. The details of IND-AQI are available elsewhere (CPCB, 2014), and only briefly summarized here. IND-AQI considers concentrations of PM_{10}, $PM_{2.5}$, NO_2, O_3, CO, SO_2, NH_3 and Pb. In a day, while maximum 8 hour running average concentrations of O_3 and CO are used, 24 hour averaged concentrations of other six pollutants are used in calculation. The concentration of each pollutant is converted to a number on a scale of 0–500. The sub AQI (AQI_i) for each pollutant (i) is calculated using Eq. (1)

$$AQI_i = \frac{I_{HI} - I_{LO}}{BR_{HI} - BR_{LO}} \times (C_i - BR_{LO}) + I_{LO} \tag{1}$$

where, C_i is the concentration of pollutant 'i'; BR_{HI} and BR_{LO} are breakpoint concentrations greater and smaller to C_i and I_{HI} and I_{LO} are corresponding AQI ranges.

The overall AQI, IND-AQI, can be estimated only if the concentrations of minimum three pollutants are available, with at least one of them being either $PM_{2.5}$ or PM_{10}. The IND-AQI is then taken as the maximum AQI_i of the constituent pollutants, denoted as dominating pollutant. The IND-AQI is divided into five categories: good, satisfactory, moderate, poor, very poor and severe depending on whether the AQI falls between 0–50, 51–100, 101–200, 201–300, 301–400 or 401–500, respectively. IND-AQI calculation can be better understood by the following example: Consider a day in New Delhi with the 24-hr concentrations of $PM_{2.5}$, SO_2, NO_2, and maximum 8-hr concentration of CO, O_3as 135 $\mu g\ m^{-3}$, 13 $\mu g\ m^{-3}$, 12 $\mu g\ m^{-3}$, 3 $mg\ m^{-3}$, and 84 $\mu g\ m^{-3}$, respectively. Using the breakpoint concentrations in Table 1 and Eq. (1), the AQI_i of $PM_{2.5}$, SO_2, NO_2, CO and O_3 are calculated as 311.75, 16.25, 15, 112.27 and 84, respectively. The IND-AQI of that day would be 311.75, and $PM_{2.5}$ would be termed as the dominant pollutant.

Health-Risk Associated with a Pollutant

This study uses excessive risk of the pollutants (ER_i) given by Cairncross *et al.* (2007), as shown in Eq. (2):

$$ER_i = \exp(\beta_i(C_i - C_{min,i})) - 1, \quad C_i > C_{min,I} \tag{2}$$

where, β_i is the exposure-response relationship coefficient, represents the increase in mortality per unit increase in concentrations.

The time series Poisson regression models are widely used to analyze the relation between pollutant concentrations and mortality (Dholakia *et al.*, 2014). The Poisson model used in this study, represented using Eq. (3), is described elsewhere (Bhaskaran *et al.*, 2013; Imai *et al.*, 2015).

Table 1. Breakpoints of different pollutants in IND-AQI (CPCB, 2014).

AQI Category (Range)	$PM_{2.5}$ 24-hr	NO_2 24-hr	O_3 8-hr	CO 8-hr	SO_2 24-hr
Good (0–50)	0–30	0–40	0–50	0–1.0	0–40
Satisfactory (51–100)	31–60	41–80	51–100	1.1–2.0	41–80
Moderate (101–200)	61–90	81–180	101–168	2.1–10	81–380
Poor (201–300)	91–120	181–280	169–208	10.1–17	381–800
Very Poor (301–400)	121–250	281–400	209–748	17.1–34	801–1600
Severe (401–500)	250+	400+	748+	34+	1600+

Note: While CO concentrations are expressed in mg m^{-3}; the other pollutants are expressed in µg m^{-3}.

$$\log(\mu_t) = \gamma + \beta C_t + \alpha K C_t + f(t) \quad (3)$$

where t denotes time; α, γ and β are the regression coefficients; μ is related to mortality; K denotes temperature; and f (t) is a smooth function of time. The spline function of time is used to remove seasonal and long term trends so that short term variation between concentration and mortality can be studied (Bhaskaran *et al.*, 2013).

In Eq. (2), C_i refers to the measured concentration and $C_{min,i}$ refers to the concentration of a pollutant below which no adverse health effects can be expected. According to WHO (2005), adverse health effects can be expected for any concentration of $PM_{2.5}$, O_3, NO_2 and SO_2. Thus, in this study $C_{min,i}$ of all pollutants except CO, is considered as 0. $C_{min,i}$ for CO is considered as 2 mg m^{-3}, as suggested by (CPCB, 2014), and shown in Table 1.

Study Area and Data Sources

New Delhi, in addition to being the capital of India, is also one of the most densely populated cities in the world. It has a population of 16.7 million with an annual average growth rate of 1.92%. The overall population density is 11,297 per sq. km. It faces extreme temperatures of as low as 7°C in winter to as high as 48°C in summer (WU, 2016). It received an average rainfall of 889.2 mm from 2011–2014. Such extreme temperatures can severely affect the already deteriorating air pollution in New Delhi. Four years data ranging from January 1st, 2011 to December 31st of 2014 was used for the analysis. The data was collected at a busiest traffic intersection, Bahadur Shah Zafar Marg (ITO) located at commercial down town of the city, as shown in Fig. 1. Hourly concentrations of CO, O_3, NO_2, SO_2, and $PM_{2.5}$ were collected by Central Pollution Control Board (CPCB). Pollutant concentrations vary across a city. However, this is the longest period for which hourly data of these species is available in any location in New Delhi. In such situations studies resort to analysis of data collected at a single location. For example, Kim *et al.* (2015) studied the association of selected components of $PM_{2.5}$ on mortality, using $PM_{2.5}$ data obtained from a centrally located residential site in Denver. Similarly, Garrett and Casimiro (2011) studied the short term effect of $PM_{2.5}$ and O_3 in Lisbon, using data obtained from a monitoring station in Olivais since this was the only station with data for both pollutants. Thus, in this study it is assumed that the concentrations observed in this location are representative of the entire city.

CO was measured using non-dispersive infrared spectroscopy, O_3 and NO_2 using Chemiluminescence, SO_2 using ultra violet fluorescence, and $PM_{2.5}$ using tapered element oscillating microbalance. As hourly PM_{10} concentrations were not available in this location, $PM_{2.5}$ is assumed to be the sole representative of particulate matter in this study. Due to unavailability of data, the percentage of days on which the IND-AQI was not calculated, was 19, 42, 41 and 60 in 2011, 2012, 2013 and 2014, respectively. The mortality data was obtained from the office of births and deaths registration in New Delhi. Due to unavailability of cause specific mortality, non-accidental mortality has been used in this study.

RESULTS AND DISCUSSION

Yearly Variation of Ambient Air Pollutant Concentrations

In INAAQS, CO and O_3 have both hourly and eight hour standards, and $PM_{2.5}$, SO_2 and NO_2 have daily and yearly standards. For comparison with INAAQS, the measured hourly data of $PM_{2.5}$, SO_2 and NO_2 were converted into daily averaged concentrations, and the hourly concentrations of O_3 and CO were used to estimate daily maximum 8 hour running average. Fig. 2 shows the change in concentrations of $PM_{2.5}$, SO_2, O_3, NO_2 and CO, from 2011 to 2014. The percentage of days for each pollutant exceeded INAAQS is also shown. Results indicate that in contrary to other pollutants, $PM_{2.5}$ had maximum median concentrations in 2013. Panel (a) in Fig. 2 shows that median $PM_{2.5}$ concentrations in all the four years exceeded the corresponding INAAQS of 100 µg m^{-3}. $PM_{2.5}$ concentrations exceeded INAAQS during 80, 82, 86 and 90% of days in 2011, 2012, 2013 and 2014, respectively.

SO_2 concentrations never exceeded INAAQS in the four years, as observed from panel (b) of the figure. Similar conclusion was derived by Goyal and Sidhartha (2003) from their air quality analysis during 1996 to 2001 at New Delhi. This indicates that SO_2 may not be a major air pollutant in New Delhi. However, the contribution of SO_2 in the formation of secondary sulfate particles might be significant, and should be explored further. Panel (c) shows that O_3 concentrations varied from 5 to 323 µg m^{-3} during the analysis period. O_3 concentrations exceeded the corresponding INAAQS of 100 µg m^{-3} for 16% in 2011, 26% in 2012, 0% in 2013, and 12% in 2014. Panel (d) shows that NO_2 concentrations exceeded the INAAQS of 80 µg m^{-3} limit 33.67% of the days in 2011, 62% of days in 2012, 15% of days in 2013, and 36% of days in 2014. CO concentrations reached a maximum of 10 mg m^{-3} during

Fig. 1. An interactive map showing the study region (Delhi) and the location of the monitoring station (ITO) in India.

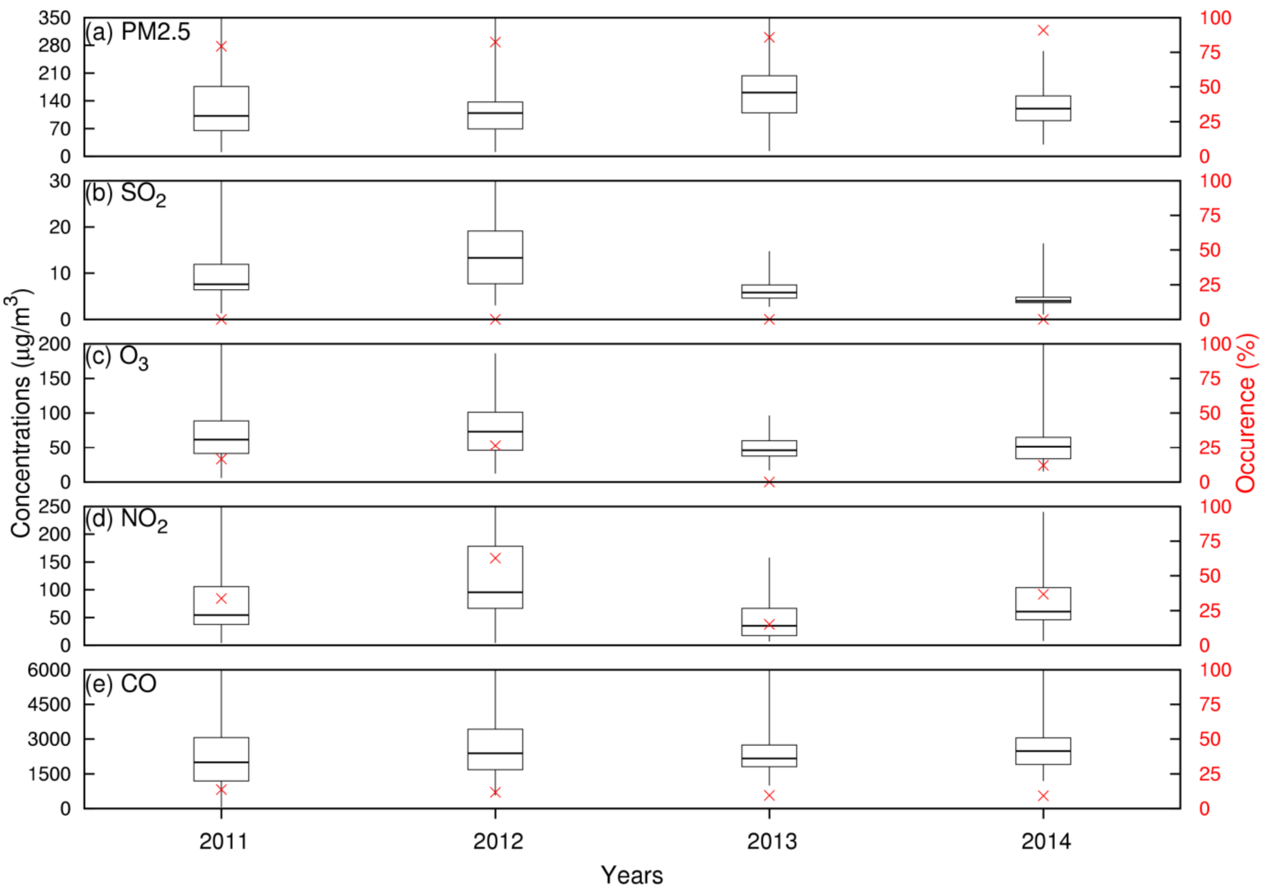

Fig. 2. Change in concentrations of CO, NO_2, O_3, SO_2 and $PM_{2.5}$ from 2011 to 2014 at New Delhi. While the left Y-axis shows the concentrations, represented using box whisker plots, the right Y-axis, represented using red crosses indicates the percentage of data which exceed the INAAQS. The box whisker plots show minimum, maximum, median, upper and lower quartiles. Note: The range of y-axis of all panels is curtailed for better representation of the figure.

the period. Panel (e) shows that CO exceeded corresponding INAAQS value of 2 mg m^{-3}; 14%, 11%, 9.4% and 9.2% of days in 2011, 2012, 2013 and 2014, respectively. This implies that $PM_{2.5}$ is the major pollutant, followed by NO_2 and CO in New Delhi. However, more studies in New Delhi where both PM_{10} and $PM_{2.5}$ concentrations are available are necessary in future to support this conclusion.

Yearly Variation of IND-AQI

The yearly variation of frequency of days falling in the six IND-AQI categories, good, satisfactory, moderate, poor, very poor and severe, during 2011–2014 is shown in Fig. 3. Due to the lack of availability of data of other pollutants only concentrations of $PM_{2.5}$, CO, NO_2, SO_2 and O_3 were used to estimate the IND-AQI in this study. The corresponding frequency of dominating species in each of those years is shown inTable 2.

$PM_{2.5}$ was the dominant species in 74 to 90% of the days in those four years. Maximum dominance of NO_2 was observed during 2011 (16%), and O_3 during 2011 (8%). While none of these years had days dominated by SO_2, CO dominance was around 9% in most of the years, except 2012. Zero dominant days of SO_2 is expected as it never violates INAAQS, as observed from Fig. 2.

Fig. 3 indicates that at least 60% of the days in all the years were poor. Moreover, 70% of days in 2013 were either very poor or severe. In comparison, 44, 53 and 52% of such days exist in 2011, 2012 and 2014, respectively. This could be due to higher $PM_{2.5}$ concentrations in 2013 as observed in Fig. 2. Only 6% of the days in all the four years were either good or satisfactory.

Weekday-Weekend Variation of IND-AQI

Data analysts have reported weekday and weekend differences in air pollutant concentrations around the world (Altshuler *et al.*, 1995; Karar *et al.*, 2006; Tiwari *et al.*, 2015). To explore this, weekdays and weekend variation of IND-AQI was analyzed, and shown in Fig. 4. $PM_{2.5}$ was the dominant pollutant during 83% and 82% on weekdays and weekends, respectively. Results indicate that air quality on weekends was only slightly better than weekdays. For example, 50% of weekends, in comparison to 52% of weekdays were in the IND-AQI category of very poor and severe. Similar conclusions were arrived by Kumar and Goyal (2011), who studied AQI, following the US methodology, at the same location during 2000 to 2006. However, these observations are in contrary to the assumption that at the sampling site, located at a busy traffic junction, where vehicle density is more on weekdays than weekends, air quality should be better on weekends.

Seasonal Variation of IND-AQI

Previous studies have shown higher concentrations of poly aromatic hydrocarbons, sulfates and nitrates in $PM_{2.5}$ in New Delhi (Pant *et al.*, 2015), which have a strong co-relation with temperature and RH (Wang *et al.*, 2005). Additionally, studies in this region showed a strong co-relation of reactive pollutants like O_3, with temperature and RH (Gaur *et al.*, 2014). To explore this, seasonal differences in IND-AQI and dominant species as a function of relative humidity (RH) and temperature were studied, and shown in Fig. 5. The seasons were categorized as winter (December–February), pre-monsoon (March–May), monsoon (June–August) and post-monsoon (September–November). Analysis indicates that concentrations of all the pollutants decreased during monsoon. This is due to wet scavenging of pollutants due to higher precipitation during that season.

Panels (a) to (d), indicate that winter had highest, around 72%, and monsoon had least, 32%, very poor and severe days. Panels (e) to (h) show a clear decreasing trend of $PM_{2.5}$ dominance from winter to post-monsoon. While, $PM_{2.5}$ was dominant in 95% of days in winter, it dominated IND-AQI during 68 and 70% of days of monsoon and post-monsoon seasons, respectively. Moreover, CO dominated during 18% of days in monsoon, and both CO and NO_2 dominated post-monsoon by around 13–14% of days each.

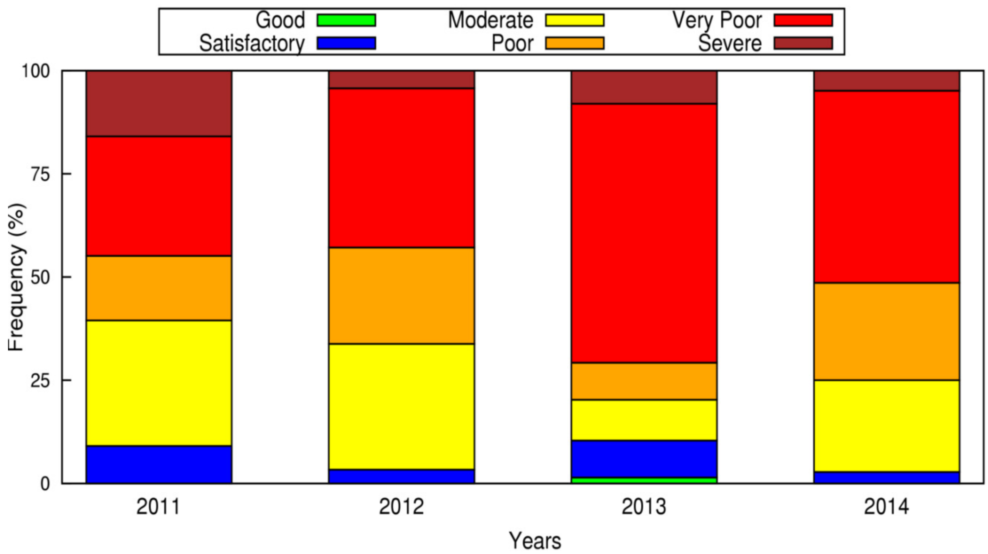

Fig. 3. Change in frequency of days (%) in various IND-AQI categories from 2011–2014.

Table 2. Variation of domination of pollutants during 2011 to 2014.

Year	SO_2	NO_2	$PM_{2.5}$	CO	O_3
2011	0	2	81	9	8
2012	0	17	75	4	4
2013	0	2	88	10	0
2014	0	0	90	9	1

Previous studies have indicated that in addition to wet deposition, variation in atmospheric mixing layer heights, air flow pattern can also be a main reason for seasonal differences of pollutant concentrations in this region (Sahu *et al.*, 2009; Bisht *et al.*, 2015). To examine this further, 24-hr back trajectories, originating from the sampling location, were generated using National Oceanic and Atmospheric Administration's Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model. Fig. S1, in the supplementary material, shows the diurnal variation in atmospheric mixing layer heights in different seasons. Analysis indicated that mixing layer heights peak in the afternoon, around 2 to 3 PM, with the least daily maximum mixing layer heights during winter.

Results in Fig. S2, in the supplementary material, show a clear seasonal pattern in air mass back trajectories in New Delhi. During winter and pre-monsoon, where more very poor and severe days are observed, air parcels might have originated in Punjab and Haryana, home of many coal-based power plants and industries. In contrary, air parcels could have originated in Rajasthan and Uttar Pradesh during monsoon, and Rajasthan and Punjab in post-monsoon. Thus, the seasonal differences and the negligible weekday-weekend difference observed in this study could be due to long range transport of air pollutants. Similar conclusions were arrived from a recent study (Ghosh *et al.*, 2015), which predicted significant influence of neighboring states in $PM_{2.5}$ concentrations, during 2008 to 2010, in New Delhi.

Estimation of Health Risk Associated with Pollutants

To estimate the potential risk associated with the

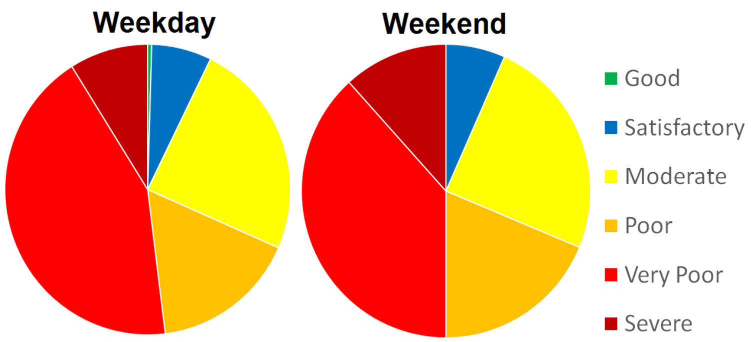

Fig. 4. Days (%) in each IND-AQI category on weekdays and weekends. Note: Data in all the four years was used in analysis.

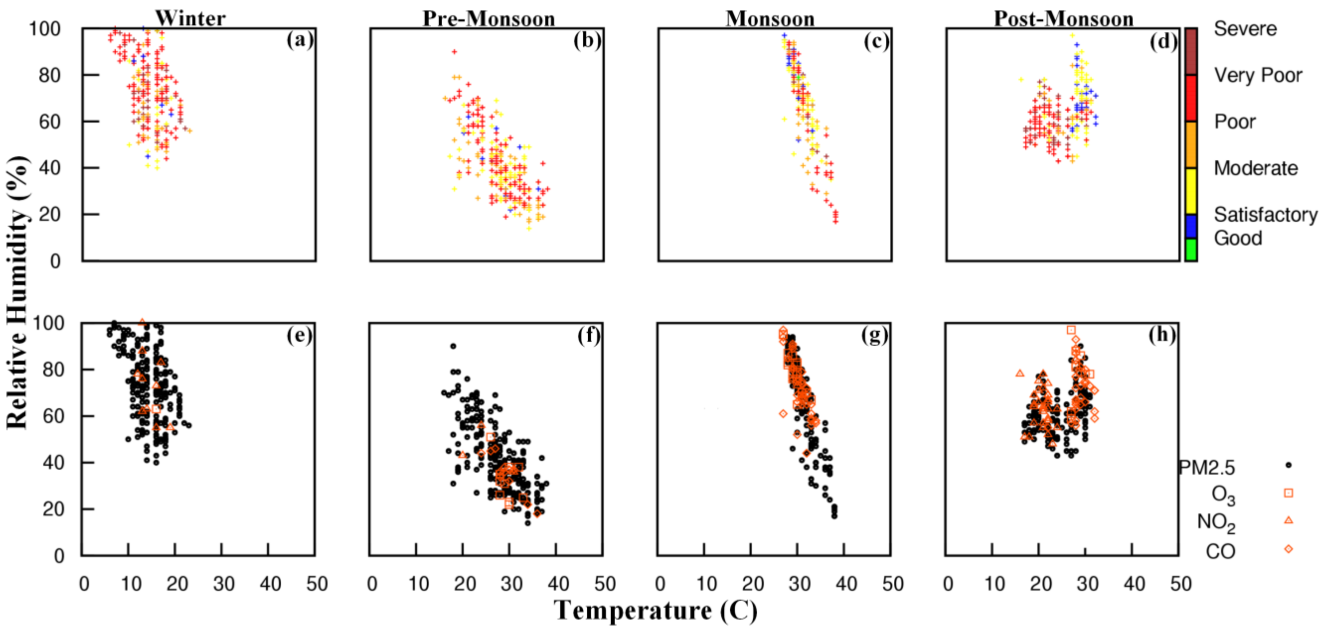

Fig. 5. Scatter plot of relative humidity versus temperature as a function of IND-AQI (panels a–d), and dominant species (panels e–h), for different seasons; winter, pre-monsoon, monsoon and post-monsoon.

concentrations of a pollutant, excessive risk associated with a pollutant was calculated using Eq. (2). Fig. 6 shows the monthly averaged $PM_{2.5}$ concentrations, temperature and non-accidental deaths at New Delhi during the analysis period. Estimated increase in non-accidental mortality, was 0.69% (95% CI: 0.17%, 1.21%), 0.88% (95% CI: 0.14%, 1.63%), and 3.77% (95% CI: –0.6%, 8.34%) per 10 µg m^{-3} increase of $PM_{2.5}$, NO_2, and 1 mg m^{-3} CO, respectively.

The ER values were obtained as 0.57 (95% CI: 0.45, 0.69), 0.36 (95% CI: 0.24, 0.46), and 0.052 (95% CI: 0.046, 0.058) for $PM_{2.5}$, NO_2, and CO, respectively. Non-significant risk factors were obtained for SO_2 and Ozone. This clearly indicates that $PM_{2.5}$ is associated with major health risk in New Delhi. Even though, Eq. (2) is commonly used (for example, see Hu *et al.* (2015)), it doesn't consider the possible non-linearities in the exposure-response curve observed by some previous studies (Cohen *et al.*, 2005; Pope *et al.*, 2009; Burnett *et al.*, 2014). Moreover, most of the health studies tend to depict the correlation between $PM_{2.5}$ concentrations and specific respiratory or heart diseases. However, in New Delhi disease specific mortality was not available during the analysis period. To study this further, the RR for average $PM_{2.5}$ concentration of 133 µg m^{-3} at New Delhi was compared to that of Burnett *et al.* (2014). While, RR was 1.57 from the Eq. (2) used in this study, it was 1.4585, 1.658 and 2.662 for COPD, lung cancer and ALRI mortality, respectively from the integrated exposure function used in Burnett *et al.* (2014). Thus the overall risk of mortality obtained in this study lies within the range of values obtained using integrated risk function.

Table 3 shows the % increase in non-accidental mortality per 10 µg m^{-3} increase in $PM_{2.5}$ concentration estimated by different studies around the world. In comparison with other major countries, no such studies were done in India. This indicates that exposure-response relation for $PM_{2.5}$ is similar in major cities in the world. This value lies in the range of global estimate by Atkinson *et al.* (2014), and closer to several studies in China (Dai *et al.*, 2004; Chen *et al.*, 2011) and the US (Ostro *et al.*, 2006).

Furthermore, to better cogitate its associated health benefits, the possible number of non-accidental deaths averted by reducing $PM_{2.5}$ concentrations, to suggested levels by WHO and INAAQS was estimated following Shang *et al.* (2013). The expected number of premature deaths (PD_i)

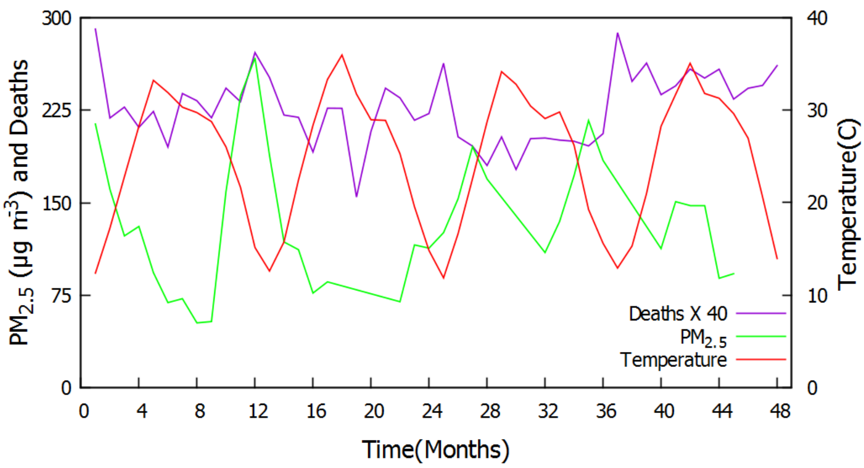

Fig. 6. Time series of monthly average $PM_{2.5}$ (µg m^{-3}) and deaths in left y-axis and temperature (C) in right y-axis.

Table 3. Increase in non-accidental mortality (%) per 10 µg m^{-3} increase of $PM_{2.5}$ at different cities around the world.

Place (Study Year)	Reference	% increase in mortality
Global Review	(Atkinson *et al.*, 2014)	1.04 (0.52–1.56)
USA (1970–1986)	(Klemm, 2003)	1.2 (0.8–1.6)
USA (1999–2005)	(Zanobetti and Schwartz, 2009)	0.98 (0.75–1.22)
USA (1997–2002)	(Franklin *et al.*, 2007)	1.2 (0.3–2.1)
USA (2000–2008)	(Levy *et al.*, 2012)	1.2 (0.5–1.9)
California (1999–2002)	(Ostro *et al.*, 2006)	0.6 (0.2–1.0)
Spain (2003–2007)	(Ostro *et al.*, 2011)	1.4 (0.6–2.3)
Australia (1996–1999)	(Simpson *et al.*, 2005)	0.9 (–0.7–2.5)
Beijing (2007–2008)	(Chen *et al.*, 2011)	0.53 (0.37–0.69)
Guangzhou (2007–2008)	(Yang *et al.*, 2012)	0.90 (0.55–1.26)
Shenyang (2006–2008)	(Chen *et al.*, 2011)	0.35 (0.17–0.53)
Shanghai (2004–2005)	(Huang *et al.*, 2009)	0.30 (0.06–0.54)
Shanghai (2002–2003)	(Dai *et al.*, 2004)	0.85 (0.32–1.89)
Xian (2004–2008)	(HOU Bin, 2011)	0.20 (0.07–0.33)
New Delhi (2011–2014)	Current Study	0.69 (0.17–1.21)

Table 4. Projected reduction in non-accidental mortality and corresponding reduction in non-acidental deaths, due to proposed reduction in $PM_{2.5}$ concentrations for New Delhi.

Proposed $PM_{2.5}$ limit ($\mu g\ m^{-3}$)	Reduction in non-accidental mortality (%)	Reduction in non-accidental deaths (per 100000 people)
40	6.20	39
35	6.52	41
25	7.17	45
15	7.80	49
10	8.12	51

due to a pollutant exposure can be calculated by Eq. (4), using mortality rate (M).

$$PD_i = M \times \frac{ER_i}{ER_i + 1} \quad (4)$$

The excessive risk (ER_i), in Eq. (4), was calculated by Eq. (2), using C_i as the averaged $PM_{2.5}$ concentration during the analysis period, and the $C_{min,I}$ as the targeted $PM_{2.5}$ limit.

Decrease of $PM_{2.5}$ concentrations from current level to 10 $\mu g\ m^{-3}$ will result in a reduction of 8826 deaths in 2011. This is similar to the estimated deaths by (Guttikunda and Goel, 2013) due to $PM_{2.5}$ in New Delhi as 7350–16200 in the year 2010. Table 4 gives the projected reduction in non-accidental mortality and number of reduction in non-accidental deaths due to decrease in current $PM_{2.5}$ concentration to the levels suggested by INAAQS and WHO. The averaged non-accidental mortality rate data for the year 2011 to 2014 was obtained from statistical handbooks of Delhi during those years (DES, 2014) as 0.625%.

Results indicate that, when the current levels are reduced to meet INAAQS annual limits of $PM_{2.5}$ i.e., 40 $\mu g\ m^{-3}$, the non-accidental mortality in New Delhi will be reduced by 6.20%, with 39 premature deaths avoided per 100000 people. Similarly, if the WHO levels of 35, 25, 15 and 10 $\mu g\ m^{-3}$ of $PM_{2.5}$ are met, the number of premature deaths per 100000 people will be reduced by 41, 45, 49 and 51, respectively.

SUMMARY AND CONCLUSIONS

This paper analyzed data collected at a busy traffic junction during 2011 to 2014 at New Delhi, to determine the most dangerous pollutant in New Delhi. AQI was used to identify the dominant pollutant while a health risk study quantified the deaths due to high concentration of the pollutant. Investigation showed that $PM_{2.5}$ was the dominant pollutant, during all the seasons, with dominant days being 24% higher in winter and pre-monsoon, than monsoon and post-monsoon. Moreover, significant differences in very poor and severe days were not observed on weekdays and weekends, with $PM_{2.5}$ being the dominant pollutant in all days. However, this conclusion might vary if PM_{10} data is included in the analysis, and more studies are needed to explore this further. Additional investigation revealed that, this could be due to long range transport of air pollutants from different regions. This shows that air quality in New Delhi can be ameliorated only due to better policies in neighboring states.

The potential health risk associated with $PM_{2.5}$ was greater than CO and NO_2. The excessive risk associated with $PM_{2.5}$, NO_2 and CO were obtained as 0.57 (95% CI: 0.45, 0.69), 0.36 (95% CI: 0.24, 0.46), and 0.052 (95% CI: 0.046, 0.058), respectively. This is in agreement with the AQI method. Finally, the impact of reducing the current $PM_{2.5}$ concentrations, the most dominant pollutant in New Delhi was investigated. Results indicated that 39 and 41 premature deaths can be avoided per 100000 by bringing down the yearly averaged concentrations of $PM_{2.5}$ to the levels suggested by INAAQS and WHO, respectively.

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SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at http://www.aaqr.org.

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