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Measurements and analysis of air quality in Islamabad, Pakistan

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Key Points:

- Islamabad air pollution exceeds Pakistan's NEQS
- Mobile sources are the major contributor to NO, and point sources to SO_2
- The regional background O_3 concentration for Islamabad is ~31 ppbv

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Abstract Ambient air quality of Islamabad, Pakistan, reveals that annual average mass concentration of particulate matter ($PM_{2.5}$) (~45 to ~95 μg m^{-3}) and nitric oxide (NO) (~41 to ~120 μg m^{-3}) exceeds the Pakistan's National Environmental Quality Standards (NEQS). The annual ozone (O_3) concentration is within the permissible limits; however, some of the hourly concentration exceeds the NEQS mostly during the summer months. Correlation studies suggest that carbon monoxide (CO) has a significant (p-value ≤ 0.01) positive correlation with NO and NO_y; whereas, with O_3, a significant (p-value ≤ 0.01) negative correlation is observed. The regression analysis estimates the background CO concentration to be ~300 to ~600 ppbv in Islamabad. The higher ratio of CO/NO (~10) suggests that mobile sources are the major contributor to NO concentration. On the other hand, the ratio analysis of sulfur dioxide (SO_2)/NO for Islamabad (~0.011) indicates that the point sources are contributing to SO_2 in the city. NO and SO_2 correlation indicates contribution of direct sulfur emission sources. Ratios of [CO] to [NO] and [SO_2] to [NO], based on ambient air quality measurements, provide a test for emission inventories. The ratios of these pollutants in the available Islamabad emission inventories are consistent with ambient values for these pollutants. The correlation of $PM_{2.5}$ and NO suggests that a fraction of secondary $PM_{2.5}$ is produced by chemical conversion of NO into nitrates. The regional background O_3 concentration for Islamabad has been determined to be ~31 ppbv. This study suggests that there is an increase in O_3 concentration with increases in photochemical conversion of NO to reservoir NO_y, species.

1. Introduction

Pakistan is an urbanized country in South Asia with a population of 180.71 million [*Government of Pakistan*, 2012]. Air pollution in Pakistan is on the rise as a result of rapid economic growth due to industrialization. Motor vehicles, industrial activities, and coal-fired power plants are the major sources of air pollution in the country [*Barber*, 2008]. An average Pakistani vehicle, in general, emits about 25 times higher carbon dioxide (CO_2) and carbon monoxide (CO), 20 times more nonmethane hydrocarbons (NMHCs), and 3.5 times more sulfur dioxide (SO_2) than vehicles in the United States [*Barber*, 2008]. Usage of diesel-fueled electric generators on a large scale, due to extensive power outage in the country, is a significant factor adding to the urban air pollution burden [*International Monetary Fund*, 2010]. Reliance on diesel fuel by transport sector is another factor for particulate matter ($PM_{2.5}$) pollution [*Shyamsundar et al*., 2001]. High sulfur content in the fuel, i.e., 0.5%–1% in diesel and 1%–3.5% in furnace oil, leads to higher emissions of SO_2 [*Asian Development Bank, CAI-Asia & Pakistan Clean Air Network*, 2006]. These environmental damages cost the country an annual loss of about Rs. 365 billion, of which the urban air pollution loss is approximately Rs. 65 billion [*World Bank*, 2006].

Among 18 mega cities of the world, the highest average mass concentration of $PM_{2.5}$ has been reported in Karachi as 668 μg m^{-3} [*Gurjar et al*., 2008]. *Biswas et al*. [2008] reported the average $PM_{2.5}$ mass concentration to be manyfold higher in Lahore than New York City, Hong Kong, and Seoul. In a study conducted by *Pak-EPA and JICA* [2000] in three cities of Pakistan (Rawalpindi, Islamabad, and Lahore), the concentration of NO_x and PM_{10} was found to be higher than WHO guideline. Hourly maximum concentration of CO has been reported as 3.3 ppm in Islamabad. The pollutants created a layer of smog reducing visibility, thus making Margalla Hills (a suburb) of Islamabad mostly invisible showing the severity of pollution within the city [*Barber*, 2008].

The permissible limit of ozone (O_3) under Pakistan's National Environmental Quality Standards (NEQS) for Ambient Air is 180 $\mu g\, m^{-3}$ for 1 h average. However, a revised standard value of 130 $\mu g\, m^{-3}$ is now effective from January 2013 [*Pak-EPA*, 2010]. World Health Organization has set the guideline value for O_3 levels at 100 $\mu g\, m^{-3}$ for an 8 h daily average. The annual average standard value for SO_2 is 80 $\mu g\, m^{-3}$; however, 24 h average value is 120 $\mu g\, m^{-3}$. The annual and 24 h average standard value for nitric oxide (NO) is 40 $\mu g\, m^{-3}$; however, the annual average standard value for nitrogen dioxide (NO_2) is 40 $\mu g\, m^{-3}$ and 24 h average value is 80 $\mu g\, m^{-3}$. The 8 h standard limit for CO is 5 mg m^{-3}; however, 1 h limit is 10 mg m^{-3} [*Pak-EPA*, 2010]. The 24 h limit for $PM_{2.5}$ is 40 $\mu g\, m^{-3}$, and the annual average has been set at 25 $\mu g\, m^{-3}$. A revised 24 h limit of 35 $\mu g\, m^{-3}$ and annual and hourly average of 15 $\mu g\, m^{-3}$ will be effective from 1 January 2013 [*Pak-EPA*, 2010].

The main objective of this study is to characterize the air pollutants in ambient air of Islamabad, Pakistan; examine their relationship to meteorology, and origin of air masses, i.e., back-trajectory analysis; perform a ratio analysis of the measured pollutants ([CO] to [NO], and [SO_2] to [NO]) in Islamabad to gain insight in emission sources; and compare these results with available emission inventories for these pollutants. This study would be significant for regulatory agencies to conduct monitoring and plan mitigation measures in order to improve the air quality of the city. Moreover, this data set would be of immense value to the urban, regional, and global air quality modeling community.

1.1. Description of Sampling Site

Islamabad, Federal Capital of Pakistan, is located at 33°26′N 73°02′E at the foot of the Margalla Hills with 1.21 million inhabitants. It covers an area of 906 km^2 with an extension of 2717 km^2 of Margalla Hills in the north and northeast. Variation of elevation ranges from 507 m in the plains of city to 1604 m in the hill areas of Islamabad.

Islamabad falls in semiarid zone with hot humid summers followed by monsoon and cold winter. During summer, polluted air masses are advected predominantly into Islamabad from Industrial Estate and Rawalpindi (in the southeast). Vehicular emission, energy production, and industrial processes are other major source of air pollution.

The air monitoring station (AMS) located at Pakistan Environmental Protection Agency (Pak-EPA), Islamabad, was used for data collection.

1.2. Methodology

Hourly air quality monitoring data for 5 years (2007–2011) were collected by the Federal and Provincial Environmental Protection Agencies using automated fixed and mobile AMSs for ambient concentration of six major pollutants, and meteorology. The AMSs are equipped with Combined Wind Vane, Anemometer (Koshin Denki Kogyo Co, Ltd.; Model KVS 501), Thermohygrometer (Koshin Denki Kogyo Co, Ltd.; Model HT-010), Solar Radiation Meter (Koshin Denki Kogyo Co, Ltd.; Model SR-010), and Data Logging System (Horiba, Ltd.; Model Special).

Data Logging System at Federal and each Provincial EPA retrieves the air quality data from AMSs through data processing software. The ambient air quality parameters such as CO, oxides of nitrogen (NO_x, i.e., NO and NO_2), SO_2, O_3, fine $PM_{2.5}$, and hydrocarbons (total hydrocarbons, NMHCs, and methane, CH_4) were determined using specific and prescribed analyzers in AMSs.

CO Monitor (Horiba Ltd.; Model APMA-370), using nondispersive infrared ray method (ISO4224) with detection limit of 0.1 ppm and measuring range of 0–50 ppm, was used to measure CO ambient concentration.

Chemiluminescence (ISO7996) method was used to determine NO_x, NO, and NO_2 concentrations using NO_x monitor (Horiba Ltd.; Model APNA-370) with detection limit of 0.5 ppb and range of 0–1 ppm. Thermal converter in NO_x monitor is known to introduce error in accurate concentration determination of ambient NO_2 and NO_x. As all other reactive oxidized nitrogen compounds also get converted to NO during thermal conversion, we propose using $NO_{y'}$ to denote NO_x. $NO_{y'}$ may be used as a surrogate for ambient NO_y (=$NO + NO_2$, $HONO + HNO_3 + PAN + NO_3 + \cdots$) concentration.

SO_2 was measured by SO_2 monitor (Horiba Ltd.; Model APSA-370) with detection limit of 1 ppb and range of 0–0.5 ppm through U.V. fluorescence method (ISO10498).

Ozone Monitor (Horiba Ltd.; Model APOA-370) with detection limit of 0.5 ppb, range of 0–1 ppm, and working on the principle of UV photometry method was used to determine O_3 concentration in ambient air.

$PM_{2.5}$ is measured by Dust Analyzer (Horiba Ltd.; Model APDA-370) with 0–5 mg m^{-3} range through β-ray absorption method (ISO6349).

Converter oven method applied in Hydrocarbon Monitor (Horiba Ltd.; Model APHA-370) with detection limit of 0.1 ppmC and range of 0–50 ppmC was used for hydrocarbon monitoring.

Backward air trajectories (48 h) were determined by using the Hybrid-Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model, which has been developed by the US National Oceanic and Atmospheric Administration's (NOAA) Air Resources Laboratory (ARL). Archived three-dimensional meteorological data are used by HYSPLIT model to compute the trajectories. Gridded Meteorological Data Archives from Global Data Assimilation System (GDAS) of National Center for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) was used to calculate the back trajectories. The trajectories were computed for a height of 500, 1000, and 1500 m AGL (above ground level) for different time durations. Label interval was set to be 6 h to track the path of trajectory. The back trajectories were calculated for Pakistan with a buffer zone including some part of China, India, Afghanistan, Iran, and Arabian Sea.

2. Results and Discussion

Ambient air quality data of Islamabad for 5 years (2007–2011) were analyzed for determination of average concentration of representative six air pollutants. The hourly data for each pollutant collected were analyzed for average annual, seasonal, and diurnal variation. Analysis of various pollutants has also been conducted in order to find out the role of precursors, possible emission sources, meteorology, origin of air masses (based on back-trajectory analysis), and background concentrations.

2.1. Meteorology

The climate of Islamabad has a semiarid climate with warm to hot humid summers followed by monsoon season and a cold winter. In general, May and June are the hottest months with average high temperature of ~38°C (100.4 F) observed in June. In winter season, the average low temperature of ~2°C (35.6 F) may be observed in January. Fog occurs in Islamabad during the winter season. Monsoon season brings heavy rainfall and thunderstorm during July to September. In Islamabad, temperatures vary from cold to mild, routinely dropping below zero. In the hills (Margalla Hills) there is sparse snowfall. The highest temperature recorded was 46.5°C (115.7 F) in June, whereas the lowest temperature was −4°C (24.8 F) in January. On 23 July 2001, Islamabad received a record breaking 620 mm (24 inch) of rain fell in just 10 h. It was the heaviest rainfall in 24 h in Islamabad and at any locality in Pakistan during the past 100 years [*Hameed*, 2007].

2.2. Average Concentration of Pollutants

The average annual mean concentration of pollutants in Islamabad computed for $PM_{2.5}$, NO, CO, and O_3 concentrations is presented in Figures 1a–1d. As the CO standard is either 1 h or an 8 h standard, and the O_3 is 1 h average, Figures 1e and 1f provide the numbers of exceedances of the ambient concentrations for CO and O_3 during 2007–2011. The annual average mass concentration of $PM_{2.5}$ exceeds the Pakistan's NEQS of 25 μg m^{-3} in each year (2007–2011). In Islamabad, the annual average $PM_{2.5}$ mass concentration is 81.1 ± 48.4, 93.0 ± 49.9, 47.8 ± 33.2, 79.0 ± 49.2, and 66.1 ± 52.1 μg m^{-3} during 2007–2011, respectively, and the highest hourly values observed were 303 μg m^{-3} during December 2007, 495.0 μg m^{-3} during November 2008, 259.8 μg m^{-3} during September 2009, 456.0 μg m^{-3} during October 2010, and 379.0 μg m^{-3} during January 2011. Such high mass concentrations of $PM_{2.5}$ may be attributed to primary sources such as black carbon aerosols [*Viidanoja et al*., 2002; *Husain et al*., 2007], and secondary formation (i.e., gas-to-particle conversion) also contributes to $PM_{2.5}$ [*Raja et al*., 2010]. High $PM_{2.5}$ is associated with adverse human health effects [*Petrovic et al*., 2000].

Annual mean concentration of NO is also higher than the NEQS of 40 μg m^{-3} during 2007–2010, indicating the contribution of vehicular NO emissions. The hourly average concentration of CO for all the years

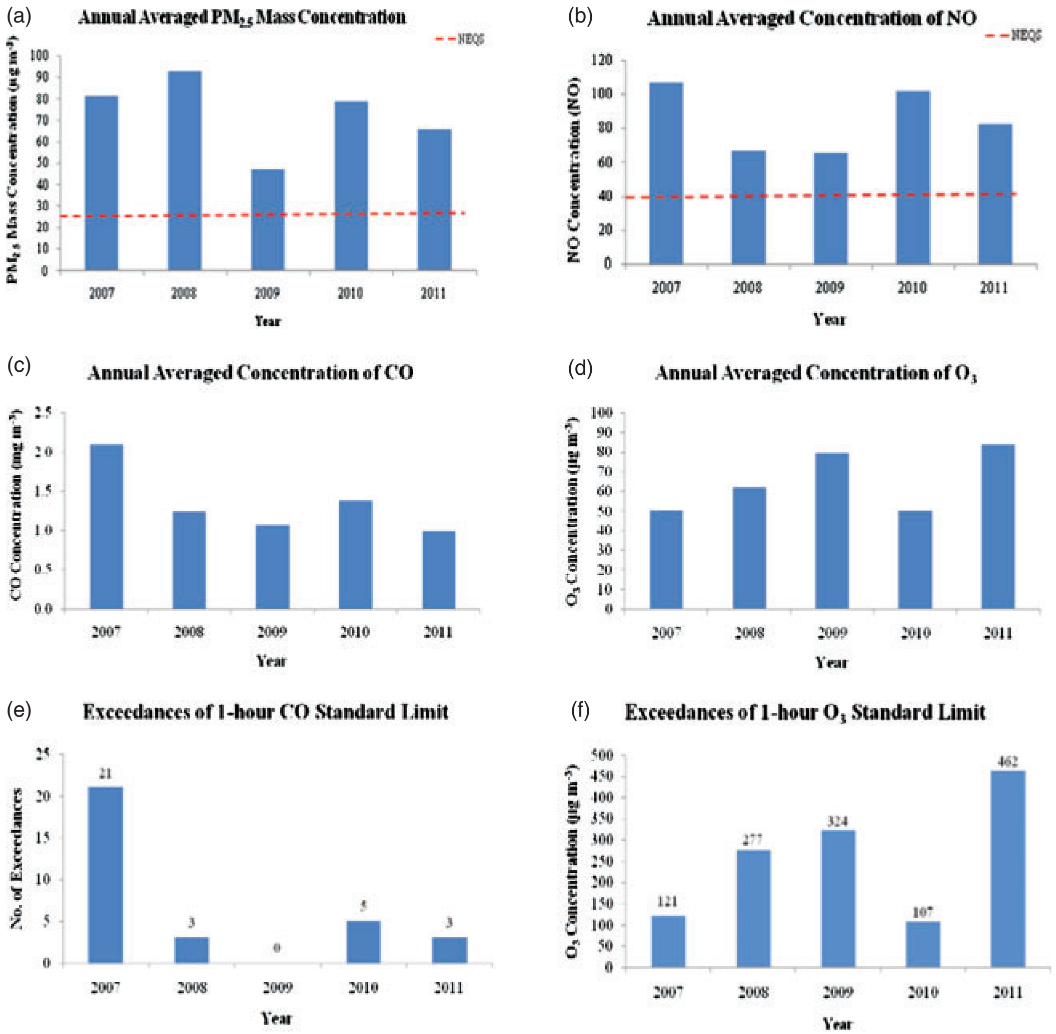

Figure 1. Annual averaged concentration of (a) PM$_{2.5}$, (b) NO, (c) CO, and (d) O$_3$, and number of exceedances of (e) CO and (f) O$_3$ in Islamabad during 2007–2011.

is below the NEQS of 10 mg m^{-3}. On some occasions, the hourly average O$_3$ concentration exceeds the NEQS primarily during the day during summer months (e.g., numbers of exceedances of O$_3$ concentrations during 2007–2011 were 121, 277, 324, 107, and 462, respectively).

2.3. Correlation of Air Pollutants

Figure 2 shows the correlation of CO with PM$_{2.5}$ during 2007–2011. As diesel combustion (from heavy duty vehicles and electric generators) is considered to be a major source of both CO and PM$_{2.5}$, the correlation between PM$_{2.5}$ and CO was used to determine the possibility of similar source for these two pollutants. Figure 2 also shows that PM$_{2.5}$ is significantly correlated ($r = 0.61$; p-value ≤ 0.01) with CO. From this plot, it may be inferred that the sources other than automobiles (i.e., electric generators) also contribute toward primary and secondary PM$_{2.5}$ in the troposphere (as CO is primarily emitted from the automobiles).

Both CO and the nitrogen oxides have many anthropogenic sources in common including mobile sources (i.e., automobiles) and point sources (i.e., energy production). It is therefore interesting to examine the relationships of these species in ambient air, especially in an urban environment where the photochemical transformations, including removal mechanisms, may be negligible, and then check these relationships against emission inventories. Mobile sources often have the characteristic of high CO/NO ratios and low SO$_2$/NO ratios, whereas higher SO$_2$/NO ratios and lower CO/NO ratios are associated with point sources (energy production). Based on ambient data, Figure 3 provides the relationship between CO and NO, and

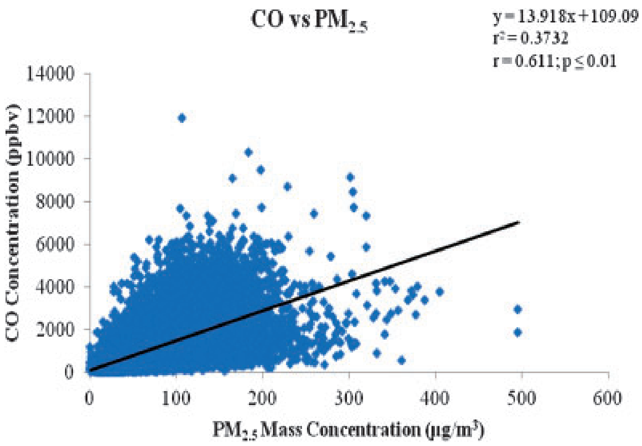

Figure 2. Correlation between ambient concentrations of CO and $PM_{2.5}$ during 2007–2011.

between CO and reactive nitrogen species, $NO_{y'}$, in Islamabad during 2007–2011. A linear regression of hourly average CO and NO, and CO and $NO_{y'}$ was performed, which shows a significant (p-value ≤ 0.01) correlation between CO and NO concentrations ($[CO] = 10.13[NO] + 511.3$; $r^2 = 0.76$) and a significant (p-value ≤ 0.01) correlation between CO and $NO_{y'}$ concentrations ($[CO] = 9.84[NO_{y'}] + 256.8$; $r^2 = 0.78$). From this ratio analysis, relative background concentrations may be determined by examining the intercept of the regression lines. The regression curves reveal a background CO concentration of ~300 to ~600 ppbv in the Islamabad urban area. This is similar to Raleigh, NC, USA, urban site value of 470 ± 52 ppbv [*Aneja et al*., 1997]; however, CO background concentration in New Delhi, India, has been observed as approximately 1693 ppbv [*Aneja et al*., 2001]. Moreover, relative source strengths like mobile sources versus point sources may also be suggested by examining the slope of the regression lines, and compared with emissions inventory. *Klimont et al*. [2013] and ECCAD (Emissions of atmospheric Compounds & Compilation of Ancillary Data, 2014, http://eccad.sedoo.fr/eccad_extract_interface/JSF/page_login.jsf, hereinafter referred to as ECCAD, online report, 2014) have provided an emissions inventory (developed for the year 2010) for CO, SO_2, and NO_x. Table 1 compares and contrasts the emissions from this inventory by examining the relationship between ambient CO and NO_x, and between ambient SO_2 and NO_x for 2007–2011 in Islamabad, Pakistan. It also compares and contrasts with CO and NO_x relationship observed in Denver, CO, USA [*Parrish et al*., 1991]; Boulder, CO, USA [*Goldan et al*., 1995]; Raleigh, NC, USA [*Aneja et al*., 1997]; and New Delhi, India [*Aneja et al*., 2001]. Based on ratio analysis of CO and NO_x, *Parrish et al*. [1991] reported values of 8.4, 7.8, and 10.2 for mobile sources in the Eastern United States, Pennsylvania area, and Western United States, respectively. Given the average ratio of about 10 (i.e., the slope of the regression line) in Islamabad, it appears that mobile sources contribute more to the concentrations of CO and NO_x than point sources.

Monthly averages of SO_2 concentration ($1\ \mu g\ m^{-3}\ SO_2 = 0.38$ ppbv) are plotted in Figure 4. Sulfur dioxide concentrations are below Pakistan's 24 h average NEQS value of $120\ \mu g\ m^{-3}$ during the measurement

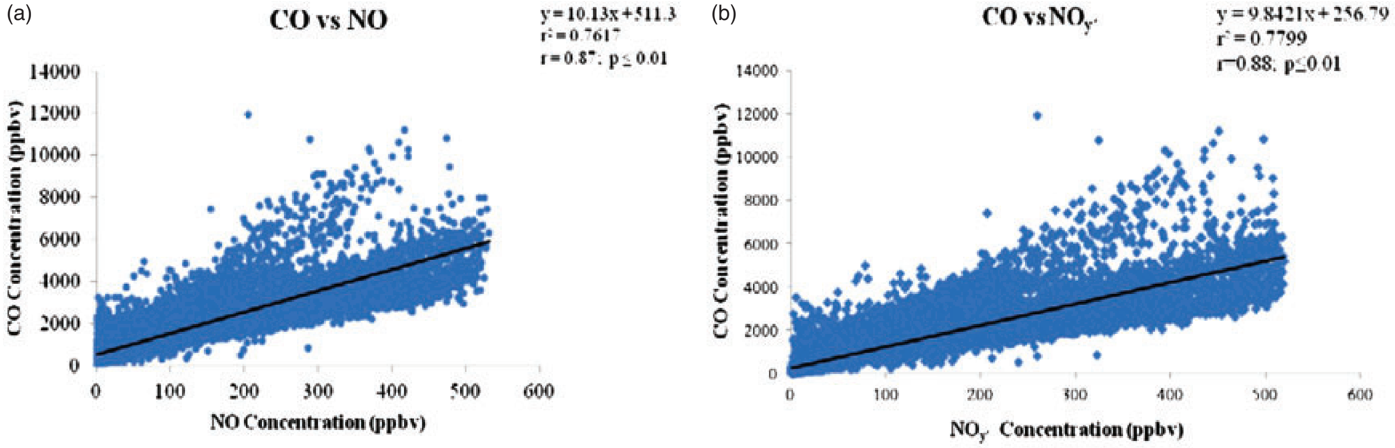

Figure 3. Correlation between (a) CO and NO, and (b) CO and $NO_{y'}$ during 2007–2011.

Table 1. Ratio Analysis Based on Average Emissions and/or Ambient Data

Region	CO/NO_x	SO_2/NO_x
Eastern United States[a] [b]	4.3	0.94
Mobiles	8.4	0.05
Point sources	0.95	1.8
Pennsylvania area[a] [c]	2.6	1.7
Mobiles	7.8	0.05
Point sources	0.8	2.3
Western United States[a] [d]	6.7	0.41
Mobiles	10.2	0.05
Point sources	1.2	1.1
Denver metropolitan area[a] [e]	7.3	0.19
Mobiles	10.5	0.05
Point sources	0.18	0.44
Raleigh, NC[f]	16.3	0.73
New Delhi, India[g]	50	0.58
This study		
Based on 2010 Emission Inventory[h] [i]		
Mobiles	4.94	0.34
Point sources	0.63	7.0
Based on ambient data	10	0.01

[a] *Parrish et al*. [1991].
[b] East of 95.5°W longitude, south of 45°N latitude.
[c] 76.5°W–81°W longitude, 39°N–42°N latitude.
[d] West of 104°W longitude, south of 49°N latitude.
[e] 104°W–105.5°W longitude, 39.5°N–41°N latitude.
[f] *Aneja et al*. [1997].
[g] *Aneja et al*. [2001].
[h] *Klimont et al*. [2013].
[i] ECCAD, online report, 2014.

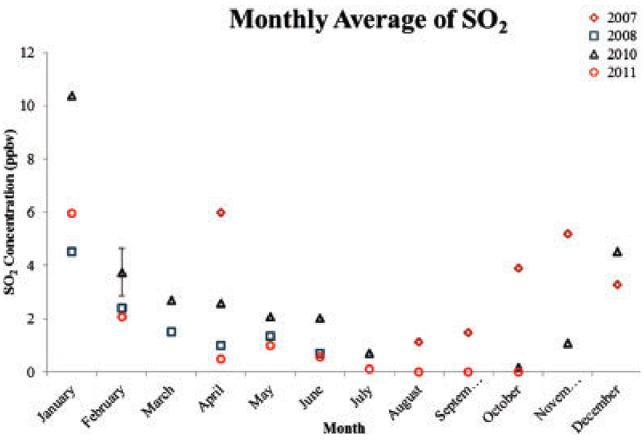

Figure 4. Monthly average of SO_2 concentration for 2007, 2008, 2010, and 2011 (I denotes ±1 SD).

period. A linear regression of hourly average SO_2 and NO concentrations (Figure 5) was performed ($[SO_2] = 0.01[NO] + 1.73$; $r = 0.4$). The ratio analysis of SO_2/NO for Islamabad (slope ~0.01) (Table 1) indicates that point sources are contributing to SO_2 in the city, also corroborated by the emissions inventory for Islamabad [*Klimont et al*., 2013; ECCAD, online report, 2014].

Figure 6 provides the correlation between $PM_{2.5}$ and NO in Islamabad. The association between $PM_{2.5}$ and NO is significantly positive (p-value ≤ 0.01; $r = 0.5$), suggesting that there is a contribution of NO in secondary production of $PM_{2.5}$. Other precursors (e.g., SO_2) and primary sources (e.g., diesel generators) also lead to the $PM_{2.5}$ burden in the city as well.

From the correlation among pollutants such as CO, NO, SO_2, and $PM_{2.5}$ (Figure 7), it may be inferred that the pollution measured in Islamabad is primary in nature having more association among species with

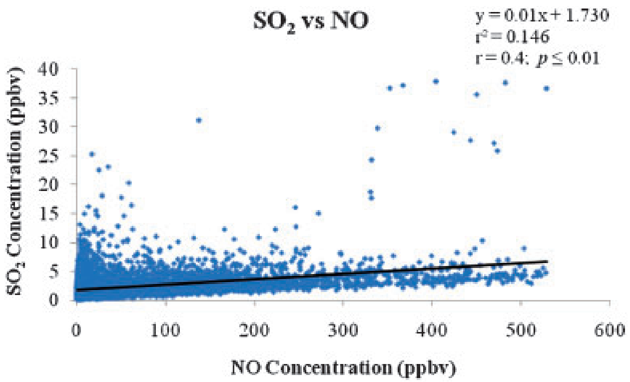

Figure 5. Correlation between SO_2 and NO in Islamabad during 2007–2011.

direct emissions. The correlation between $PM_{2.5}$ and CO concentrations is an indication of direct emissions, most likely from transport sector and fresh emissions from the industrial areas within the city (Figure 7a). The CO concentrations are also owing to the chemical conversion of volatile organic compounds (VOCs) via photochemistry, and some fraction of the $PM_{2.5}$ also originates from gas-to-particle conversion of SO_2 and NO_x. For the NO_x emissions from the transport sector, the NO is >90% of the emissions [*Vallero*, 2008] and readily converts to NO_2 in the presence of sunlight. The strong correlation between NO and SO_2 indicates the contribution of direct emission sources, such as emissions from transportation, industries, generator sets (diesel combustion), and power plants. In polluted environments, as in case of Islamabad, CO reacts with hydroxyl radicals and subsequently with NO to form O_3 through complex series of photochemical reactions (Figure 7c). Both CO and the nitrogen oxides have many anthropogenic sources in common including mobile sources (i.e., automobiles), local industries, and point sources (i.e., energy production) (Figure 7d). NO emissions are readily oxidized to NO_2 in the presence of sunlight. Its subsequent complex reactions with either VOCs and/or CH_4 lead to the formation of tropospheric O_3 (Figures 7e and 7f). Major source of VOCs is a combination of automotive exhaust owing to incomplete combustion in the vehicles because of relaxed maintenance and even adulteration of the fuel, and industries and generator sets in and around Islamabad.

2.4. Photochemistry of O_3 Formation

In the troposphere, O_3 is formed in the presence of sunlight by the precursors involving NO_x, CH_4, CO, and VOCs/volatile hydrocarbons. VOCs/volatile hydrocarbons and CO react with NO in the presence of sunlight to form NO_2, which is photolyzed to produce O_3. The correlation of O_3 with its precursors has been determined in order to find out the possible source contributions. The correlation has been done for the summer (June, July, and August) months to compare and contrast O_3 production efficiency during the summer season [*Aneja et al*., 1996]. To account for maximum photochemical activity during the day, and the degree of conversion of NO to the reservoir $NO_{y'}$ species, the time for this correlation has been set as 9:00 A.M. to 3:00 P.M. O_3 is plotted against $(NO_{y'} - NO)/NO_{y'}$ in Figure 8. This plot represents the relationship between O_3 and the degree of conversion of NO to reservoir $NO_{y'}$ species. It is observed that O_3 increases with increase in the degree of photochemical conversion of NO to reservoir $NO_{y'}$ species. O_3 concentration is expected to be low in fresh air masses because it is primarily formed by the same photochemical process that leads to the formation of $NO_{y'}$ species such as HNO_2, HNO_3, and peroxyacetylnitrate (PAN). Thus, with an increase in the ratio $(NO_{y'} - NO)/NO_{y'}$, there is a consequent increase in the ambient concentration of O_3. Results of this study show that aged air masses have higher O_3 concentration, i.e., increasing $(NO_{y'} - NO)/NO_{y'}$. An exponential fit of the data yields $[O_3] = 30.9 \exp(0.77(NO_{y'} - NO)/NO_{y'})$. The intercept of O_3 is ~31 ppbv, which represents the nominal regional background concentration of O_3 in ambient air that is not influenced by the direct emissions. The regional background O_3 concentration for Islamabad is, therefore, ~31 ppbv, i.e., air advecting into Islamabad contains ~31 ppbv of O_3. This is similar to the nominal local background O_3 concentration of ~28 ppbv for Southeastern United States, i.e., Raleigh, NC, USA [*Aneja et al*., 2000].

2.5. Diurnal Variation of Pollutants

Figure 9a shows the diurnal profile of O_3 along with its precursors in order to assess the influence of precursor pollutants on its production within the troposphere. O_3 precursors (NO_x, hydrocarbons, VOCs, and CO) build up during the morning rush hour, and the O_3 concentration starts increasing with a peak between 12:00 and 4:00 P.M. At night time, the concentration of O_3 decreases (no photochemical activity) and goes to a minimum, where as high concentration of NO and NMHCs occurs. Both NO and NMHCs increase owing to a combination of evening automobile rush hour and trucks carrying freight through the city in evening and nighttime, no formation of O_3 at night, and collapse of the planetary boundary layer. In the morning, NMHCs initiate reactions for photochemical production of O_3 resulting in their minimum concentration and an O_3 peak during mid-afternoon.

Figure 9b shows the diurnal variation of average O_3 concentration during the four seasons. The diurnal profile is

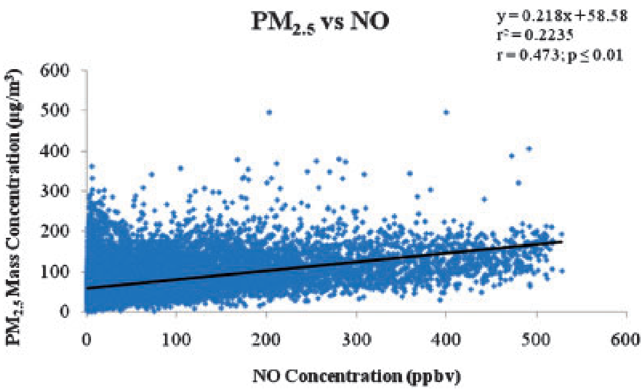

Figure 6. Correlation of $PM_{2.5}$ and NO in Islamabad during 2007–2011.

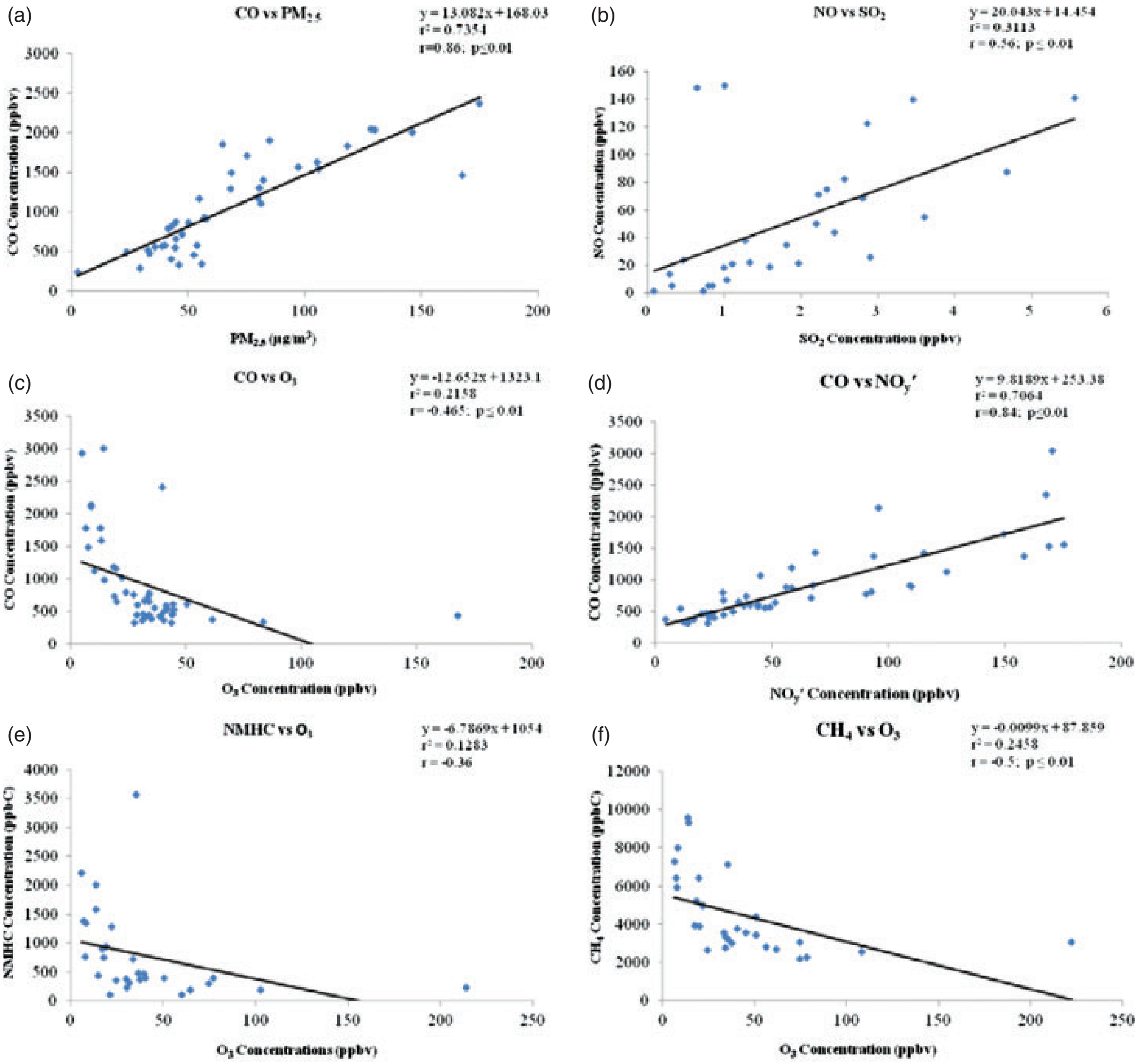

Figure 7. Correlations between criteria pollutants of measured daily averages.

similar in all the four seasons due to the fact that the tropospheric O_3 formation takes place at daytime in the presence of sunlight. The maximum O_3 concentration occurs during summer season due to high temperature and high solar intensity, and the minimum concentration levels were observed during winter season. The lower formation of O_3 in winter is because of low temperature and low solar intensity. With the beginning of spring season, the formation of O_3 increases.

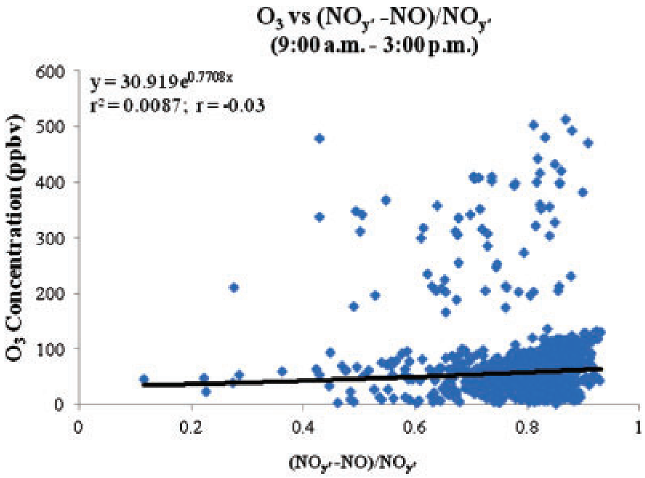

Figure 8. Variation of concentration of ozone vs. $(NO_{y'} - NO)/NO_{y'}$ in the summer months for 2007–2011 during maximum photochemical activity of the day, i.e., 9:00 A.M. to 3:00 P.M.

2.6. Effect Meteorology on Air Pollutants

The formation of tropospheric O_3 is strongly dependent on meteorological conditions especially atmospheric temperature and solar radiation [*NRC*, 1991]. Figures 10a and 10b provide the relationship of O_3 with temperature and solar radiation. O_3 has been observed to be positively correlated with temperature ($p \leq 0.01$; $r = 0.694$) and solar radiation ($p \leq 0.01$; $r = 0.601$). About 48% of variance in O_3 concentration during daytime is explained by temperature, whereas solar radiation affects about 36% of the variation in O_3 concentration. The positive correlation of O_3 with temperature and solar radiation is due to their role in photochemical formation of O_3. Similar relationship of O_3 with temperature and solar radiation has been reported by *NRC* [1991] and *Jacob and Winner* [2009].

Figures 10c and 10d represent the correlation of $PM_{2.5}$ with temperature in Islamabad. The figures show that $PM_{2.5}$ has a negative correlation ($p \leq 0.01$; $r = -0.44$) with temperature during 9:00 A.M. to 3:00 P.M. About 19% of variance in $PM_{2.5}$ can be explained by its linear relationship with temperature. The regression analysis of $PM_{2.5}$ and solar radiation shows that about 13% of variation in ambient $PM_{2.5}$ concentration in Islamabad during daytime is associated with solar radiation. There is a statistically significant correlation of $r = -0.36$ between $PM_{2.5}$ and solar radiation. *Tiwari et al*. [2013] have also reported a negative correlation of $PM_{2.5}$ with temperature, which depends on composition of the $PM_{2.5}$. This is perhaps due to the semivolatile components such as nitrate and organics that are expected to decrease as they shift from the particle phase to the gas phase at higher temperature [*Sheehan and Bowman*, 2001; *Aw and Kleeman*, 2003; *Dawson et al*., 2007; *Tsigaridis and Kanakidou*, 2007; *Kleeman*, 2008].

2.7. Back-Trajectory Analysis

The back-trajectory analysis using the NOAA HYSPLIT was conducted in order to study the atmospheric transport of air pollutants and their precursors and to find out the potential source regions for air pollution episodes in Islamabad during 2007–2011. Four pollution episodes for $PM_{2.5}$ and O_3 (Figure 11) were selected for back-trajectory analysis, which show that the important source areas (during high pollution episodes) reaching Islamabad are located in eastern Afghanistan and western India. Major pollution sources from Afghanistan, particularly Kabul and Jalalabad, include vehicular and industrial emissions, biomass burning, use of diesel electric generators, and burning of tires. The source regions in western India are located in the states of Gujarat, Rajasthan, and Punjab (i.e., southeast of Islamabad) and are known to have high concentration of industries and mechanized farming that are sources of particulate and gaseous emissions. During winter, the monsoon flow reverses and local sources of emissions in Islamabad due to burning coal and wood are more important.

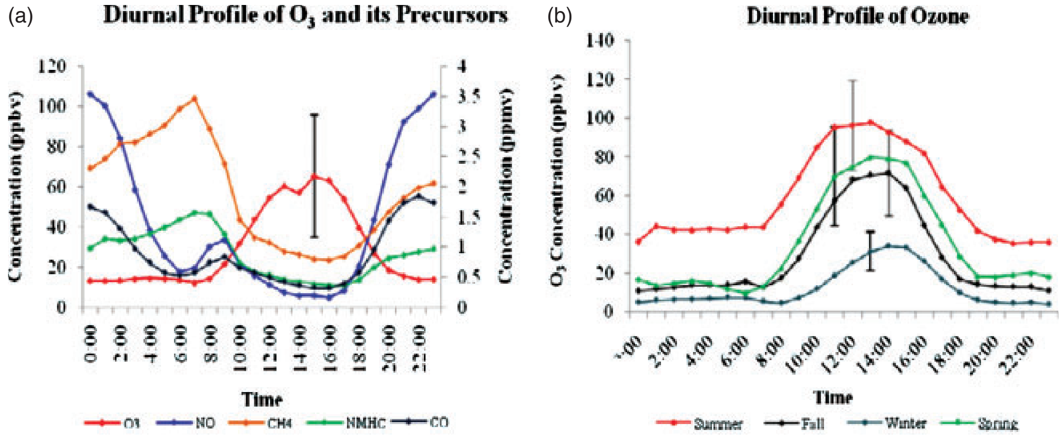

Figure 9. (a) Diurnal profile of ozone and its precursors and (b) seasonal diurnal variation of averaged ozone concentration during 2007–2011 (±1 SD is also shown in the figure).

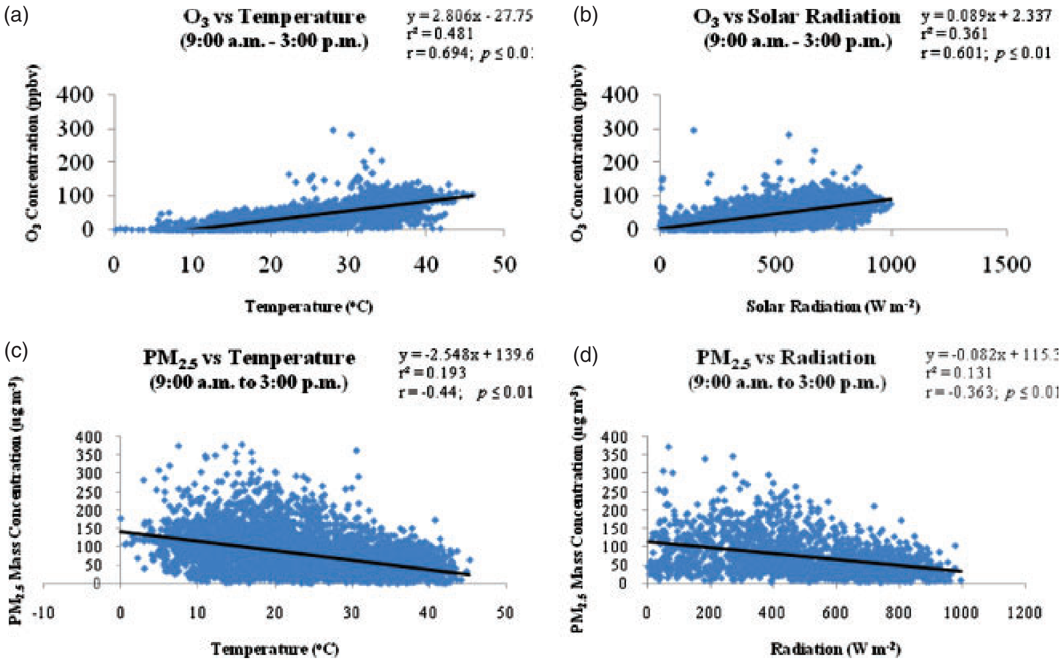

Figure 10. Correlation of ozone and $PM_{2.5}$ with temperature and solar radiation variables during 2007–2011 at 9:00 A.M. to 3:00 P.M.

3. Conclusions

The ambient air quality for criteria pollutants has been characterized for Islamabad, Pakistan, during 2007–2011. The annual and hourly average concentrations show that the annual average concentrations of $PM_{2.5}$ and NO are higher than the Pakistan's NEQS. Transportation is a major source of such high concentrations of NO. The hourly average concentrations of O_3 exceed the NEQS primarily during the summer season. CO and SO_2 are within the safe limit. Seasonal profile of O_3 concentration shows that summer is the peak season for photochemical production of O_3, whereas the winter season has the minimum concentration of O_3 among the four seasons. The back-trajectory analysis using the NOAA HYSPLIT shows that during summer months, important source areas of trajectories reaching Islamabad are located in eastern Afghanistan and western India. The source regions in the Indian states of Gujarat, Rajasthan, and Punjab (i.e., southeast of Islamabad) have high concentration of industries and mechanized farming that are sources of particulate and gaseous emissions.

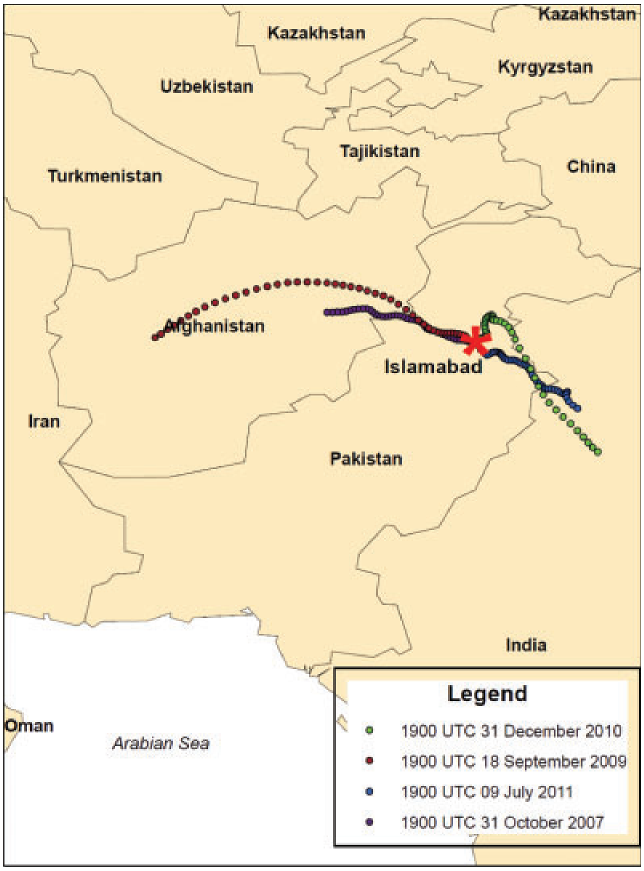

Figure 11. Air parcel 48 h back-trajectory analysis for some selected $PM_{2.5}$ and ozone high pollution episodes during 2007–2011.

This study reveals that the background concentration of CO in Islamabad (~300 to ~600 ppbv) is larger than Western U.S. background CO concentration (~200 ppbv). The ratio of CO/NO (~10) indicates that the mobile sources contribute predominantly to the ambient concentration of these compounds, whereas the ratio of SO_2/NO (~0.01) indicates that the point sources primarily contribute to SO_2 pollution within the city. The ratios of measured concentrations of [CO] to [NO], and [SO_2] to [NO] observed in Islamabad provide a test for emission inventories. The ratios of these pollutants in the available Islamabad emission inventories are consistent with ratios obtained from ambient values for these pollutants.

Keeping in view the current air quality conditions in Islamabad, Pakistan, which are degrading the atmospheric environmental conditions, there is an urgent need to develop effective strategies for pollution control. There is also a need for regulatory agency to enforce the emission standards for industries and motor vehicles in order to meet the ambient air quality standards. Extensive spatial and temporal air quality monitoring and modeling with an integrated assessment are significantly required in developing comprehensive solution to the air quality concerns of Islamabad, Pakistan.

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