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Original article

Spatial variability of concentrations of gaseous pollutants across the National Capital Region of Delhi, India

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ABSTRACT

This study presents a systematic evaluation of a year-long, continuous, real-time measurements of gaseous pollutants including oxides of nitrogen ($NO_x = NO + NO_2$), carbon monoxide (CO), and ozone (O_3) in the National Capital Region (NCR) of Delhi. Data are available from seven air quality monitoring stations (AMS) and meteorological parameters were measured at three meteorological observatories (MO). The daily mean concentrations of NO_x and CO across NCR of Delhi (average of all seven AMSs) were 37.1 ± 11.6 ppb (NO: 18.3 and NO_2: 18.8 ppb), and 2.3 ± 0.6 ppm, respectively. The highest diurnal CO concentrations were observed during midnight (21:00 to 01:00 h LT) due to nocturnal boundary conditions. The daily mean O_3 concentration was 37.5 ± 11.0 ppb. The diurnal variations of O_3 concentrations were characterized by the high concentrations during the daytime (07:00 to 17:00 h LT: 43.6 ppb) and low concentrations during the late evening and early morning hours (18:00 to 06:00 h LT: 31.1 ppb). From 07:00 h onwards, the O_3 concentrations start increasing gradually after sunrise coinciding with the increasing solar radiation. The highest concentrations (51.7 ppb) were observed around 15:00 h. Thereafter, it is decreased. Local sources of gaseous pollutants were identified by analyzing the surface wind patterns. The annual resultant wind vector were 338° (57%) and 288° (27%) at the Hindon and Palam MOs, respectively. Local NO emissions substantially reduced the urban ozone concentrations as seen by the observed untitrated NO concentrations.

1. Introduction

Clean air is a basic necessity for sound health and the well-being of humans, animals, and plants. Unfortunately, during the past few decades, the atmosphere has become progressively more polluted particularly in developing countries. Large increases in population density, industrial development, and vehicular traffic are causing worsening air pollution and pose serious environmental threats in many urban and surrounding areas. One of the challenging issues in the ever growing industrial and urban environments is atmospheric trace gases (Wang et al., 2012). The major gaseous air pollutants are oxides of carbon (CO_x), nitrogen (NO_x) and sulfur (SO_x) that are emitted by various sources including transportation, power generation, refuse incineration, industrial and domestic fuel combustion (Smith, 2004). Extensive use of fossil fuels in urban transportation and industry has led to significant increases in gaseous pollutant concentrations (Rai et al., 2011) mostly through combustion (Khare, 2012; Andreae and Merlet, 2001). One of the other major contributors to fine particles and gaseous pollutants over the northern India is agricultural residue burning following the harvest (Awasthi et al., 2011).

The National Capital Territory (NCT) of Delhi with an area of 1483 km^2 and a population density (11,320 per km^2) (Delhi Statistical Hand Book, 2014) is a developing megacity with a very

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fast growing economy. Registered motor vehicles in Delhi as on 31 March 2014 were 8,293,167 (Transport Department, Govt. of N.C.T. of Delhi, 2015) with an annual increase of around 7%. Delhi has a high density of goods trucks and lorries during the night from five national highways (NH), NH-1, NH-2, NH-8, NH-10 and NH-24, passing through its territory. An estimated 80,000 trucks enter Delhi every night between 2100 and 0600 h. These trucks contribute more than 60% of the pollutants emitted by diesel vehicles inside Delhi (Indian Express, 2015). Petrol and diesel vehicles emit a wide variety of pollutants, including carbon monoxide (CO), oxides of nitrogen (NO_x), volatile organic compounds (VOCs) and particulate matter. Diesel emissions also have health and climate implications (Kim Oanh et al., 2010; Gupta and Kumar, 2006; Maricq, 2007; Shrivastava et al., 2013).

Oxides of nitrogen ($NO_x = NO + NO_2$) play an important role in tropospheric ozone chemistry and secondary aerosol formation, etc. They are produced by both natural (mainly lightning and microbiological processes in soil) and anthropogenic sources (fossil fuel combustion and biomass burning). The major sources of anthropogenic NO_x emissions are motor vehicles and power plants (Rai et al., 2011). The photolysis of NO_2 leads to the formation of O_3. The regional distribution of NO_x concentrations is driven by the local emissions. However, in the free troposphere, NO_x is strongly influenced by long-range transport (Kunhikrishnan et al., 2006). In the lower troposphere, the NO_x sources are anthropogenic such as combustion of fossil fuels. However, microbial emissions from agricultural soils and biomass burning can be significant contributors in non-urban (rural) regions (Van der A et al., 2008).

Carbon monoxide (CO) is a potential health threat. Its major anthropogenic sources are motor vehicles, industrial activities, heating and incinerators (Suess and Craxford, 1978). Total emission of CO indirectly contributes to global warming through the control of tropospheric ozone (Crutzen et al., 1999). The exposure to significant levels of CO reduces the blood's ability to carry oxygen to body organs thereby causing headaches and memory problems (Chelani, 2012). Facilities to measure NO_x, CO, and O_3 are very limited in India (Ghude et al., 2008; Badarinath et al., 2009; Sahu et al., 2009; Tiwari et al., 2009; Singla et al., 2011; Lal et al., 2012; CSE, 2012; Beig et al., 2013) thereby producing limited data from rural and suburban areas. Gurjar et al. (2004) presented a comprehensive emission inventory of air pollutants in Delhi for the period 1990–2000 and concluded that transport sector contributed >80% of NO_x, CO, and VOCs (volatile organic compounds). Shrivastava et al. (2013) also reported that CO is the major pollutant coming from the transport sector, contributing 90% of total emissions. The Central Pollution Control Board (CPCB) has reported that vehicular contribution to the total urban air pollution in Delhi and Mumbai is about 76–90% for CO, 66–74% for NO_x, 5–12% for SO_2 and 3–12% for PM (Gulia et al., 2015). CO and NO_x emissions from vehicular transport in Delhi were found to be 284 and 130 mg/km^2, respectively (Ramachandra and Shwetmala, 2009).

The present work offers a comprehensive statistical analysis of the seasonal and annual temporal variation in gaseous pollutant concentrations (NO_x, CO, and O_3) based on one year (2014) measurement campaign in NCR of Delhi. Measurements of the gaseous pollutants were made at seven different air quality monitoring stations (AMSs). The data were analyzed hourly, daily, monthly, and seasonally during the study period. The results were studied in view of the pollution concentrations, possible emission sources, and the meteorological conditions across the NCR of Delhi. The study contributes to a better understanding of the gaseous pollutant concentrations in the rapidly growing urban region.

2. Monitoring location, technique and meteorology conditions

2.1. Air quality monitoring stations (AMS) and meteorological observatories (MO)

The NCR of Delhi covers an area of about 34,000 km^2 in the territorial jurisdictions of four state governments, namely National Capital Territory (NCT) of Delhi, Haryana, Uttar Pradesh, and Rajasthan. The NCT of Delhi constitutes 1483 km^2 in the area whereas Haryana, Uttar Pradesh and Rajasthan contribute 13,428, 10,853, and 8380 km^2, respectively. NCR of Delhi is characterized by topographical areas like the extension of the Aravalli ridge, forests, the rivers Ganga, Yamuna, and Hindon, fertile cultivated land, and is a dynamic rural-urban region with a total population of approximately 46 million (Census of India, 2011). Seven AMSs including IGI (Indira Gandhi International) Airport, Palam (close to Haryana state border) and urban traffic industrial area of NOIDA (Uttar Pradesh) and three MOs were selected for monitoring and examining of gaseous pollutants and meteorological variables across NCR of Delhi (Fig. 1). A brief description of these AMSs and MOs is as follows:

1. **CVR Dheerpur** (28.72°N 77.20°E): It is located in the premises of Sir C.V. Raman Industrial Training Institute at Dheerpur. The institute is located on the outer ring road and lies in the northern parts of Delhi, surrounded by the different industrial areas Viz, Wazirpur, Narela, Bhawana, Naraina etc. This AMS is approximately 18 km WNW of Hindon MO in Ghaziabad and about 4 km north of Delhi University AMS.
2. **Delhi University** (**DU**) (28.68°N 77.20°E): It is located in Delhi University in north Delhi and is in a mostly residential area called Kamla Nagar. The Hindon MO is about 17 km ESE and the Safdarjung MO is approximately 14 km to the south. It is situated about 17 km NE of IGI airport Palam MO and 7 km NW of the Safdarjung MO.
3. **IITM**, **Delhi** (28.62°N 77.17°E): This AMS is located in the campus of Indian Institute of Tropical Meteorology (IITM), Rajender Nagar, New Delhi branch, lying in the central Delhi. The site is surrounded by forests and residential colony.
4. **IMD**, **Lodhi road** (28.58°N 77.22°E): It is located in the premises of India Meteorological Department (IMD) at Lodhi Road lying in central Delhi. The surrounding area is a residential and commercial with Lodhi Gardens spread over 90 acres in the close vicinity. It is situated just 2.5 km SSW of Safdarjung MO and 12 km west of IGI airport Palam MO.
5. **IGI airport**, **Palam** (28.55°N 77.09°E): This AMS is located at a distance of 30 km SW of Hindon MO and 17 km from Safdarjung MO which is spread over an area of 5106 acres (AAI, 2015) with national highway (NH-8) lying around 3 km in SE and Gurgaon rural in adjacent SW sector.
6. **CRRI**, **Mathura road** (28.55°N 77.27°E): It is an urban traffic AMS located on the campus of Central Road Research Institute (CRRI) in south Delhi. National highway (NH-2) passes from there.
7. **NCMRWF**, **NOIDA** (28.57°N 77.32°E.): This AMS is located in the campus of National Centre for Medium Range Weather Forecasting (NCMRWF), Sector 62, New Okhla Industrial Development Area (NOIDA), Gautam Budha Nagar in Uttar Pradesh State (NCMRWF, 2015). It's an industrial area with a very busy N-S oriented national highway (NH-24), connecting Delhi to the Uttar Pradesh state capital, Lucknow. Densely populated residential colonies are spread from West and NW in the close proximity of AMS. Two major industrial localities, Sahibabad industrial area and Bulandshahr industrial area, are NW and N of this AMS.

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