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Monitoring variation in greenhouse gases concentration in Urban Environment of Delhi

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Abstract Cities across the globe are considered as major anthropogenic sources of greenhouse gases (GHG), yet very few efforts has been made to monitor ambient concentration of GHG in cities, especially in a developing country like India. Here, variations in the ambient concentrations of carbon dioxide (CO_2) and methane (CH_4) in residential, commercial, and industrial areas of Delhi are determined from fortnightly daytime observations from July, 2008 to March, 2009. Results indicate that the average daytime ambient concentration of CO_2 varied from 495 to 554 ppm in authorized residential areas, 503 to 621 ppm in the slums or jhuggies in the unauthorized residential areas, 489 to 582 ppm in commercial areas, and 512 to 568 ppm in industrial areas with an average of 541±27 ppm. CH_4 concentration varied from 652 to 5,356 ppbv in authorized residential areas, 500 to15,220 ppbv in the unauthorized residential areas, 921 to 11,000 ppbv in the commercial areas, and 250 to 2,550 ppbv in the industrial areas with an average of 3,226±1,090 ppbv. A low mid-afternoon CO_2 concentration was observed at most of the sites, primarily due to strong biospheric photosynthesis coupled with strong vertical mixing.

Keywords Greenhouse gases · Residential · Commercial · Industrial areas · Delhi · Carbon dioxide · Methane

Introduction

Urban areas contain residential, commercial, and industrial areas within their boundaries, with an ever increasing population and energy demand to sustain them. The contribution of the urban environment to the total carbon budget has been studied mostly by inventories of the emissions of greenhouse gases due to consumption of fossil fuels in these areas or sequestration by biomass estimation (Nowak 1994; McPherson and Jo 1995). To date, very few studies have monitored the ambient concentration of carbon dioxide (CO_2) and methane (CH_4) in urban environments. Most of the studies carried out in the past focused on variations in the concentration in the urban areas and the rural surrounding areas over periods ranging from 20 days to 8 months (Berry and Colls 1990a, b; Idso et al. 1998; Day et al. 2000). A few short-term studies have also been carried out in the past, which involve monitoring GHG at particular sites within the city, for example busy traffic roads (Ghauri et al. 1994) or at road intersections (Idso et al. 2000). However, to get a more accurate picture of GHG emissions from the major source areas (residential, commercial,

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and industrial areas) of any city, monitoring needs to done after carefully selecting the sites representing these areas, especially in the cities of developing countries that are densely populated with major sources for GHG emission present within its boundary.

Delhi, the capital city of India, and one of the most affluent centers, is a major source of GHG emissions. However, as with most of the cities in the world efforts to assess its carbon budget has been made through inventories, but so far, no efforts have been made to monitor ambient concentration of CO_2 and CH_4. The present study focuses on direct measurements and to create a general profile of monthly and daytime variations in the ambient concentration of CO_2 and CH_4 in residential, commercial, and industrial areas of Delhi.

Material and methodology

Description of the study area – Delhi

The National Capital Territory (NCT) of Delhi (28°61′ N and 77°23′ E) is spread over an area of 1,483 km^2 in northern India. It has a maximum length of 51.9 km and the maximum width of 48.48 km. Out of the total area, 783 km^2 is rural and 700 km^2 is urban. It is one of the fastest growing metropolises in Asia. The population increased from 0.4 million at the beginning of twentieth century to 13.8 million in 2001. In 2001, it was third most populous metropolitan Indian city after Mumbai and Kolkata. The city's population grew annually by 3.85% during the period 1991–2001 (Economics Survey of Delhi 2008–2009). It is estimated that by 2020, the population will be 22.5 million (Registrar General 2001).

Monitoring sites for CO_2 and CH_4

Onsite monitoring of GHGs (CO_2 and CH_4) was carried out in residential, commercial, and industrial areas (Table 1, Fig. 1) from July 2008 to March 2009. The major challenges faced in monitoring urban areas are the spatial variability of land cover and extreme roughness (Grimmond et al. 2002). The monitoring sites were selected to ensure that the measurements are representative.

Residential area (authorized and unauthorized colonies)

Monitoring was carried out at five authorized colonies (RA1 to RA5) and five slum or JJ settlements (Jhuggi Jhompri) within the unauthorized colonies (these are not regularized by the government, RUA1 to RUA5, in Delhi (Fig 1, Table 1). Monitoring sites were selected away from major roads to minimize contribution from vehicles. The JJ settlements were targeted as they are expected to be a major contributor of GHG due to the use of biomass as cooking fuel and burning of woods in the winter for heating.

In all the authorized colonies, monitoring was done at a height of 3 m above the ground at the center of children's parks with no buildings within the radius of 30 m. These parks are rectangular with trees on the periphery and open centers. The lanes in between the buildings beyond these parks are also lined with trees on both sides. These will act as a sink. The average green cover in 100 m^2 area around each site is 38%± 2%, which includes roadside plantations and tree cover within the parks (Table 1, Fig. 2). In the unauthorized colonies, monitoring was done on the roof tops (average height of 3.5 m) as houses are clustered together with narrow lanes (2–3 m wide) between them with no open space (like parks or playing grounds) and green cover (Table 1, Fig. 3).

Commercial area

Delhi is the largest commercial hub of north India by virtue of its geographical location and other historical factors, availability of infrastructure facilities, etc. Based on the nature of activities, the commercial areas of Delhi has been categorized into central business district (C1 and C2), district center (C3, C4, and C13), non-hierarchical commercial centers (C5, C9, and C11), local shopping center (C10 and C8), convenience shopping center, and mandi or wholesale market (C7 and C11) (Ministry of Urban Development (Delhi Division) 2007). The movement of vehicles and use of diesel generator sets for power back-up are the major source of GHG in these areas. Thirteen monitoring sites, C1 to C13 (Table 1), were selected to provide a complete profile of CO_2 and CH_4 concentration in the different categories of commercial area.

At sites C1, C3, C4, C7, C8, C9, C10, and C13, monitoring was done at 3 m with no construction

Table 1 Description of the monitoring sites

Site code	Location	Location coordinates		Height of monitoring and surrounding buildings (m)			Source characteristics
		Latitude (N)	Longitude E)	a	b	c	
Residential (authorized)							
RA1	Chitranjan Park (J-Block)	28°32′20″	77°14′50″	3.0	−(38)	13.40	Fossil fuel for cooking in houses and vehicles
RA2	Civil lines, (under hill road)	28°40′39″	77°13′16″	3.0	−(39)	13.40	Fossil fuel for cooking in houses and vehicles
RA3	Mayur Vihar (phase II)	28°37′02″	77°18′23″	3.0	−(35)	13.40	Fossil fuel for cooking in houses and vehicles
RA4	Lodhi Colony	28°35′15″	77°13′30″	3.0	−(39)	13.40	Fossil fuel for cooking in houses and vehicles
RA5	Shalimar bagh (DDA Flats)	28°42′46″	77°09′35″	3.0	−(38)	13.40	Fossil fuel for cooking in houses and vehicles
Residential (unauthorized)							
RUA1	Tuglakabad	28°30′45″	77°16′05″	3.75	3.50	3.50	Fossil fuel and biomass for cooking
RUA2	Govind puri	28°31′55″	77°15′43″	3.75	3.50	3.50	Fossil fuel and biomass for cooking
RUA3	Madanpur Khadar	28°32′05″	77°17′59″	3.75	3.50	3.50	Fossil fuel and biomass for cooking
RUA4	Sita Saran Colony	28°40′22″	77°12′12″	3.75	3.50	3.50	Fossil fuel and biomass for cooking
RUA5	Silampur	28°40′09″	77°16′16″	6.5	6.00	6.00	Fossil fuel and biomass for cooking and vehicles and burning of solid waste (e-waste) for metal extractions. Adjacent Shahdra drain serves as source of methane
Commercial							
C1	Connaught Place (Park over Palika Bazaar)	28°38′00″	77°13′13″	3.00	–	− (road at 60 m and buildings beyond that)	Vehicles, Diesel generator sets for power back up, LPG used in the kitchens of the restaurants etc.
C2	Karol Bagh (Arya Samaj Road)	28°38′54″	77°11′32″	3.75	3.50	13.40	Vehicles, Diesel generator sets, motor garages and residential units
C3	Nehru Place	28°32′55″	77°15′13″	3.00	–	10.00	Vehicles, Diesel generator sets
C4	Rajendra Place	28°38′41″	77°10′41″	3.00	–	34.00	Vehicles, Diesel generator sets
C5	Central market–Lajpat Nagar	28°34′05″	77°14′28″	3.75	3.5	13.40	Vehicles, Diesel generator sets
C6	Kamla Nagar Market	28°40′53″	77°12′25″	10.5	10.00	10.00	Vehicles, diesel generator
C7	Aazadpur mandi	28°42′43″	77°10′16″	3.00	–	6.00	Vehicles, diesel generator sets, vegetable wastes
C8	Central market Dwarka Sec- 10	28°35′01″	77°03′28″	3.00	–	13.40	Vehicles, diesel generator sets
C9	Sarojini Nagar Market	28°34′37″	77°11′45″	3.00	−(35)	6.50	Vehicles, diesel generator sets
C10	Green park Market	28°33′07″	77°12′13″	3.00	−(38)	6.50	Vehicles, diesel generator sets
C11	Laxmi Nagar Market (Vijay Chowk)	28°38′01″	77°16′45″	10.5	10.00	10.00	Vehicles, diesel generator sets and residential units
C12	Shahdra Mandi	28°40′16″	77°17′24″	10.5	10.00	10.00	Vehicles, diesel generator sets and vegetable wastes
C13	Janakpuri District Centre	28°37′44″	77°04′51″	3.00	–	20.00	Vehicles, diesel generator sets
Industrial							
I1	Okhla–Ph-I	28°31′23″	77°16′51″	3.75	3.50	3.50	Vehicles, diesel generator

Table 1 (continued)

Site code	Location	Location coordinates		Height of monitoring and surrounding buildings (m)			Source characteristics
		Latitude (N)	Longitude E)	a	b	c	
I2	Okhla–Ph-II	28°32′03″	77°16′25″	6.75	6.50	6.50	Vehicles, diesel generator sets
I3	Jhilmil	28°40′27″	77°18′39″	6.75	6.50	6.50	Vehicles, diesel generator sets
I4	Wazirpur	28°41′56″	77°09′50″	3.75	3.50	3.50	Vehicles, diesel generator sets
I5	Naraina (–Ph-I	28°37′55″	77°08′09″	6.75	6.5	6.50	Vehicles, diesel generator sets for power back up
I6	Naraina–Ph-II	28°38′29″	77°08′35″	3.00	–	6.50	Vehicles, diesel generator sets
I7	Jehangirpuri	28°43′37″	77°09′33″	3.00	–	6.50	Vehicles, diesel generator sets

Average height of sampling was 4.42 m above ground level. In 15 out of 30 sites, monitoring was done at a height of 3 m above ground with no buildings within the radius of 30 m from the monitoring sites. Buildings in the unauthorized residential (all the five sites), commercial (five sites) and industrial (five sites) areas are very close to each other leaving no scope for ground monitoring. Hence monitoring was done on the roof tops such that average height of buildings within 30 m radius is less or equal to the selected roof top

a Exact height above ground at which the monitoring was done. b Average height of the buildings within the radius of 30 m from the monitoring sites; closeness and dimension diversity of the buildings in the study area limited the criteria of height *of the surrounding buildings* for site selection to radius of 30 m only. Figures in parenthesis represent the percentage green cover within the 100 m^2 area from the monitoring sites in the authorized residential area. No green cover present near the sites in unauthorized residential, commercial, except C9 and C10 and industrial areas. c Average height of the buildings beyond the radius of 30 m from the monitoring sites

within a radius of 30 m. These sites are exclusively commercial with few trees in between the complexes. Adjacent to C9 and C10, parks are present; average green cover in the 100 m^2 area around these sites is 35% and 38%, respectively. Sites C2, C5, C6, C11, and C12 are commercial/residential areas with closely constructed buildings and narrow lanes (3–4 m wide) in between them. There are no open spaces and green cover. Monitoring was done on the roof tops after ensuring minimum disturbance from the surrounding buildings (Table 1, Fig. 4).

Industrial area

In the second half of the twentieth century, Delhi had a phenomenal growth in the industrial sector, with the number of industrial units rising from 8,160 in 1951 to 129,000 in 2001 (Economic Survey of Delhi 2007–2008). At present, Delhi mainly has a non polluting small-scale industry as the Master Plan for Delhi does not allow establishment of large-scale industries, which are the major source of pollution. As per the orders laid down by the Supreme Court of India in July 1996, all polluting units have been either closed or moved out of Delhi. Onsite monitoring of GHGs (CO_2 and CH_4) was carried out at seven (I1 to I7) sites representing major industrial areas of Delhi. Monitoring was done at the center of the industrial cluster away from major roads or residences in each of these areas to minimize the impact of traffic and residential areas on the ambient concentration of (CO_2 and CH_4) in the industrial area.

These industrial areas are characterized by blocks of buildings of equal heights adjacent to each other with 4–5 m wide lanes between them and have no green cover. Monitoring was done on the roof tops except at I6 and I7 where the vacant plots with no buildings within the radius of 30 m was used for monitoring (Table 1, Fig. 5).

Monitoring methodology

Instrumentation

Direct measurements of CO_2 and CH_4 were made using separate Aeroqual Series 500 (New Zealand) automatic analyzer comprising of a monitor fitted with gas specific sensor heads at 30 selected sites representing the residential, commercial, and industrial areas. The two sensors used for measurements are based on different technologies; CO_2 sensor is based on non-dispersive infrared technology and CH_4 based on gas-sensitive semiconductor technology. Sensors were

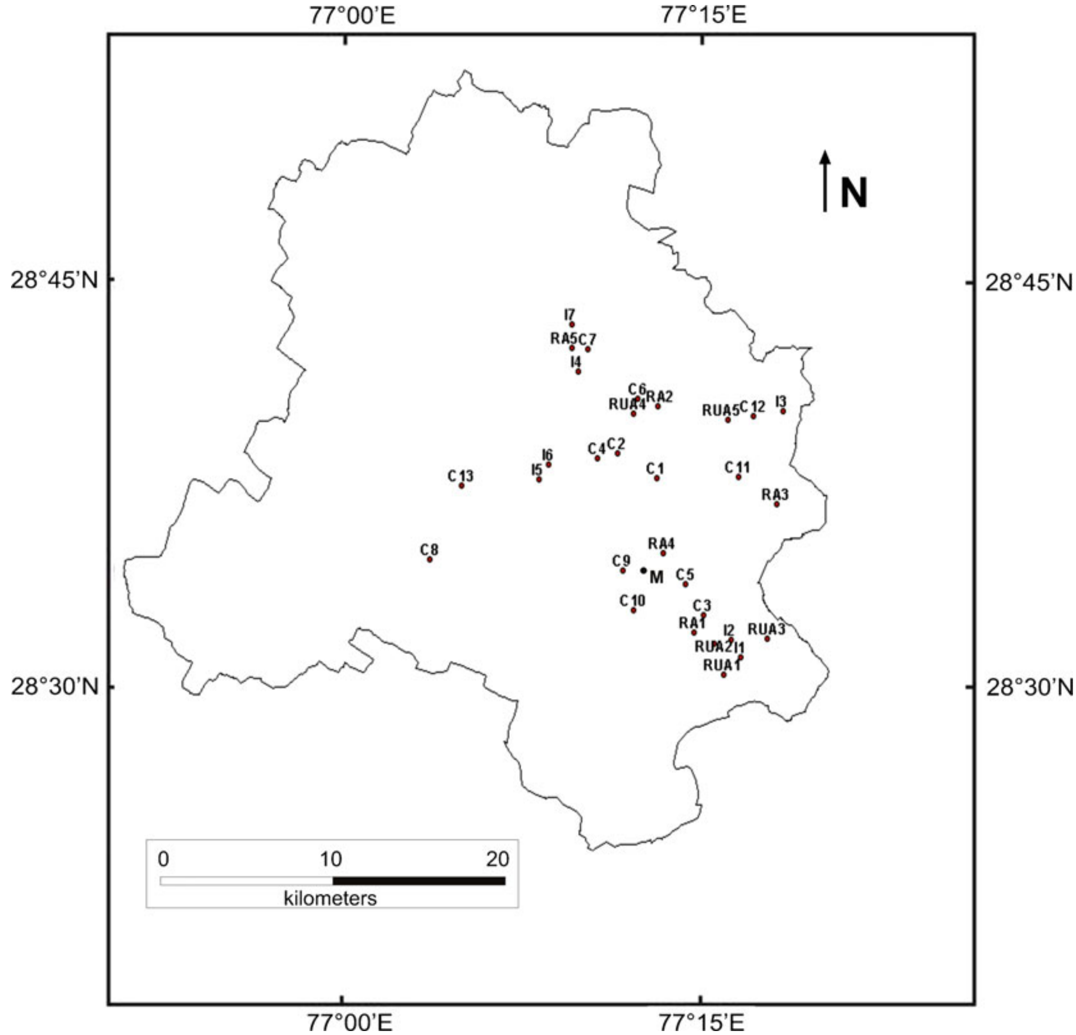


Fig. 1 Monitoring sites in the urban area of Delhi, India: authorized residential (RA) and unauthorized residential (RUA), commercial (C) and industrial (I) sites. Details of the sites are provided in Table 1. "M" represents Regional Meteorological Centre, New Delhi

factory calibrated. Both the sensors were zero calibrated in an atmosphere containing certified zero air with no cross-sensitive gases (<0.5 ppm hydrocarbons), 50 ±5% relative humidity, and 20±2°C after maintaining stable and low air flow around the monitor. The span calibration of the two sensors was done separately using the respective span gas, prepared by mixing the known concentration of sensor specific gas, 2,000 and 5,000 ppm of CO_2 and CH_4, respectively, with certified clean air. Mixing was done using calibrated mass flow controller. The calibrations by the manufacturer were done just before the start of monitoring program and were valid for 1 year; monitoring was done for 9 months.

Monitoring strategy

Measurements were taken at three different periods of the day (0800–1100, 1200–1400, and 1600–1800 hours), to capture daytime variations in the concentration due to the variations in the meteorological, height of the atmospheric boundary layer (ABL), biogenic, biospheric photosynthesis/respiration rate, and anthropological activities. This was also constrained by the battery time of 8 h. The height of ABL or the mixing height (MH) is one of the most important factors having effect on the concentrations of the pollutants in urban environment. This is proportional to the heating of the atmosphere, which results in an increase

Fig. 2 Land cover surrounding RA4 authorized residential area. Source: "Delhi" 28°35′15″ N and 77°13′30″ E. Google Earth. January 19, 2011. April 10, 2011

in the morning, peak mid-afternoon and decrease in the late afternoon (Sengupta and Ramchandran 1998). The monitoring was done to represent the three phases. Instrument values were sampled every 15 min. The values represent 1-min readings.

At the sites with no construction within a radius of 30 m, monitoring instrument (weight about 460 g) was located at 3 m above ground level on an aluminium stand. At the sites with no open spaces, the instrument was located on roof tops. Table 1 provides the height of the roof tops in different land use. The average of the monitoring heights across all the sites at which measurements were recorded was 4.42 m above the ground.

Monitoring was done from 1 July 2008 to 30 November 2008 in residential areas, 1 October 2008 to 31 December 2008 in the commercial areas, and 1 January 2009 to 31 March 2009 in industrial areas. Residential and industrial areas were monitored twice each month. Commercial sites (C1–C9) were monitored once in October 2008, C1–C10 once in November 2008, and C1–C13 twice in December 2008. All the 13 sites could not be monitored twice every month as monitoring in the residential areas was also being done during the same period on the alternate days.

The monthly daytime average is the mean of all data at all the sites by land use during that month. This is used to get the average concentration of CO_2 and CH_4 in Delhi, whereas the daytime average of the sites were calculated by taking the mean of all the readings recorded during the three periods of the day through the entire monitoring months. Standard deviations were estimated to quantify the spread or departure of the observed values from the mean. Temperature and relative humidity on the day of monitoring were recorded using a pocket weather monitor (Kestrel, USA). The instrument was placed

Fig. 3 Land cover surrounding RUA2 area unauthorized residential area. Source: "Delhi" 28°31′53″ N and 77°15′37″ E. Google Earth. January 13, 2011. April 10, 2011

Fig. 4 Land cover surrounding C2 commercial area. Source: "Delhi" 28°35′15″ N and 77°13′30″ E. Google Earth. June 06, 2010. April 10, 2011

on portable tripod near the CO_2 and CH_4 analyzers, on the same height.

Results and discussion

Diurnal and seasonal variation in CO_2 and CH_4

Atmospheric CO_2 shows diurnal and seasonal variations based on the meteorological as well as biospheric factors. CO_2 concentrations exhibit a distinct diurnal cycle with early morning peak, which decreases in the middle of the day and gradually increases thereafter. The morning peak is due to shallow mixing height and presence of air temperature inversion in the early morning, which traps the CO_2 from the nocturnal biospheric respiration and urban sources night traffic. The minimum CO_2 concentration observed around mid-day is due to solar-induced convective mixing, strong biospheric photosynthesis, mainly in the areas with dominant evergreen plantations with leaves all year around and decrease in traffic during this time of the day. The gradual increase in the late afternoon concentration is due to reduced mixing height, decrease in photosynthetic activities, and increase in traffic. Decrease in the ABL depth, very poor atmospheric mixing, biospheric respiration, and emission from urban sources result in high concentration during nights. The other meteorological factors controlling the concentration are the wind speed and its direction with respect to the measurement point. This diurnal pattern has been reported in several studies conducted at different urban centers (Tanaka et al. 1983; Nakazawa et al. 1997; Reid and Steyn 1997; Idso et al. 2002; Grimmond et al. 2002; Miyaoka et al. 2007; Chaudhari et al. 2007).

Seasonal variation in the CO_2 concentration at different times of a day measured at a residential site of Phoenix, AZ, USA has been reported by Idso et al. (2002). They observed a slight variation in the daytime

Fig. 5 Land cover surrounding I7 industrial area. Source: "Delhi" 28°43′37″ N and 77°09′33″ E. Google Earth. January 31, 2010. April 10, 2011

concentration and a distinct variation in the night time and early morning concentrations during summer and winter months. The midday concentrations were slightly higher in winter months as compared to summers due to low vertical mixing in winters. The Phoenix mean night time concentration in the winters was 53.7 ppm higher than the summers due to low heights of ABL. Miyaoka et al. (2007) in Sapporo, Japan, observed higher daytime mean CO_2 than the background value measured in discrete air samples collected at Ishikari Hama from December to February (winter) and it was nearly equal to the background from July to August (summers). Measurements were taken 34 m (1 m above the roof of 33 m high building) above the ground in the campus of Hokkaido University in Sapporo, Japan.

Diurnal variation for the CH_4 concentration measured in urban environment does not show a noticeable variation except for high night time values. The seasonal variation of CH_4 depends on the site characteristics. High mean values are observed in summers if the sources are biogenic as increase in temperature leads to anaerobic methane production, whereas emission from non-biogenic sources results in high mean values in winter due to low vertical mixing and poor dispersion (Wang et al. 2001; Nguyen et al. 2010). High values in winter can also be attributed to short day length, low solar intensity, and ambient temperature, which reduce photochemical scavenging of CH_4 (Padhy and Varshney 2000).

Meteorological conditions

The highest monthly average maximum temperature of 34.1°C in July 2008 decreased gradually to 21.59°C in January 2009 and then increased to 28.95°C in March 2009. Relative humidity was in the range of 80–90% and was highest in December 2008 (88%) and lowest in March 2009 (74.5%). Observations were similar to the data observed at the Regional Meteorological Centre, New Delhi (Fig 1); temperatures within ±1°C and relative humidity of ±3%. Maximum monthly rainfall, 245.4 mm was observed in August 2008 followed by July 2008 with 159.1 mm and September 2008 with 109.2 mm. From October to December 2008, there was no rainfall; normally, rainfall is up to 10 mm. Little rainfall (4, 5.5, and 8.4 mm) was observed in January, February, and March 2009, respectively (data from Regional Meteorological Centre, New Delhi).

Monitoring Results

Results of the on-site monitoring of CO_2 shows that the average daytime CO_2 concentration during the monitoring months (July 2008 to March 2009) varied from 495 to 554 ppm in the authorized residential areas, 503 to 621 ppm in the unauthorized residential areas, 489 to 582 ppm in the commercial areas, and 512 to 568 ppm in the industrial areas (Table 2, Fig. 6). The overall average CO_2 concentration in Delhi was 541±27 ppm. CH_4 concentration varied from 652 to 5,356 ppbv in authorized residential areas, 500 to 15,220 ppbv in the unauthorized residential areas, 921 to 11,000 ppbv in the commercial areas, and 250 to 2,550 ppbv in the industrial areas (Table 2, Fig. 7). The overall average CH_4 concentration in Delhi was 3,226±1,090 ppbv. High standard deviation for the CH_4 concentration is due to the use of values with wide range to calculate the mean.

Monthly average CO_2 and CH_4 concentration

Monthly daytime average CO_2 and CH_4 concentration at RA1 to RA5 sites (authorized residential area) varied from 495 to 554 ppm and 1,012 to 4,383 ppbv, respectively, during July to November, 2008 (Table 3). The monthly average for CO_2 was lowest at all the sites in August 2008 (Fig. 8). These residential areas are marked by dense vegetation on the roadside and inside children's parks, which serve as a sink for CO_2 (Table 1). Delhi experienced a very high rainfall (245.4 mm) in this month, which resulted in development of more sinks (adequate rainfall in the preceding months also) and washing off effect of rain leading to subsequent reduction in the ambient CO_2 concentration (Chaudhari et al. 2007). The low CO_2 concentration can also be attributed to higher mixing heights in this month due to high average maximum temperature during this month (Idso et al. 2002; Miyaoka et al. 2007).

Sites RUA1 to RUA5 (unauthorized areas) monthly daytime average of CO_2 and CH_4 concentration varies between 503 and 626 ppm and 2,431 and 8,230 ppbv, respectively (Table 3). Such high concentrations of CO_2 are mainly due to the use of biomass as a cooking fuel, congested houses, and lanes leading to accumulation, and the absence of vegetation in these areas to act as sink. Presence of open drains and open dumping of waste is the major cause for high CH_4 concentrations. The monthly daytime average of CO_2 and CH_4 concentration at C1 to C13 (commercial) ranged from

Table 2 Monthly average CO_2 and CH_4 concentrations in source sectors of Delhi

Months	Residential[a] (authorized)		Residential[a] (unauthorized)		Commercial[b]		Industrial[c]	
	CO_2 (ppm)	CH_4 (ppbv)[d]	CO_2 (ppm)	CH_4 (ppbv)[d]	CO_2 (ppm)	CH_4 (ppbv)[d]	CO_2 (ppm)	CH_4 (ppbv)[d]
July 2008	527±27	3,110±1,216 (5,234±460, 1,966±283)	569±55	42,65±2,346 (7,999±526, 1,881±499)				
August 2008	516±17	2,997±1,263 (5,198±453, 1,791±303)	567±40	4,217±2,188 (7,910±571, 2,001±496)				
September 2008	525±20	2,954±1,147 (5,044±482, 1,841±310)	554±38	4,193±2,230 (7,971±574, 1,931±401)				
October 2008	531±11	2,983±1,299 (5,100±486, 1,776±356)	554±45	4,099±1,993 (7,317±595, 2,081±422)	538±27	5,508±2,821 (9,911±860, 2,612±239)		
November 2008	530±19	3,186±1,240 (5,355±616, 2,068±475)	562±38	4,241±2,231 (7,830±466, 1,979±434)	539±28	4,756±1,905 (8,093±547, 2,784±208)		
December 2008					539±25	4,556±2,505 (8,692±567, 2,001±228)		
January 2009							530±16	1,018±766 (2,248±295, 221±60)
February 2009							536±14	1,205±840 (2,485±478, 316±141)
March 2009							545±16	1,121±900 (2,489±479, 189±121)

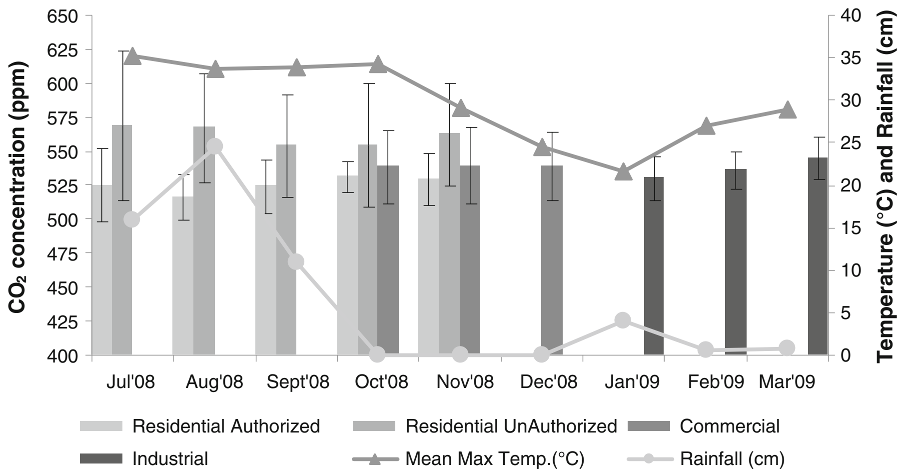
[a] Sample size (Number of readings recorded for CO_2 and CH_4). Residential (authorized and unauthorized)=280 per month (July'08–November'08)

[b] Sample size. Commercial: October'08, 252; November'08, 280; December'08, 728

[c] Sample size. Industrial=392 per month (January'09–March'09)

[d] Figures in parenthesis represent the average maximum and minimum values (mean of 5 highest and lowest values). High standard deviations for CH_4 concentrations are due to use of values of all the sites with large variation to obtain the mean value

Fig. 6 Monthly average CO_2 concentrations in three land uses and temperature and rainfall from July 2008 to March 2009



495 to 582 ppm and 350 to 14,000 ppbv and at I1 to I7 (industrial) ranged from 512 to 568 ppm and 250 to 3,000 ppbv, respectively. Except for the authorized residential area, no distinct variation in the monthly average of the CO_2 concentration was observed during the monitoring period. No well-defined variation was observed in the monthly average CH_4 concentration in all the land use.

Daytime average CO_2 and CH_4 concentration

Daytime average CO_2 and CH_4 concentration varied from 484 to 581 ppm and 522 to 5,356 ppbv in authorized residential, 486 to 644 ppm and 411 to 15,220 ppbv in unauthorized residential, 489 to 582 ppm and 100 to 14,000 ppbv in commercial, and 501 to 555 ppm and 250 to 2,100 ppbv in industrials areas (Table 4, 5, and 6).

Figure 9, 10, 11, 12, 13, 14, and 15 shows the variation in the concentration measured at the three different times of the day in the selected land use. Sites RUA2 and RUA5 recorded the highest average concentration of CO_2 across all the sites during the three monitoring period of the day. While highest CH_4 concentration across all the sites was observed at C12 in the later half of the day.

Distinct diurnal pattern of low mid-afternoon CO_2 concentrations is observed in the authorized residential, commercial (except for C5, C11, and C12), and industrial areas (except I3, I6, and I7). It was observed at all the sites in the authorized residential areas, which have vegetation cover on the roadside and children parks around the monitoring sites. Accumulation of CO_2 over night coupled with vehicular emission in the morning hours; movement of traffic within the area is very

Fig. 7 Monthly average CH_4 concentrations in the three land uses. The figure shows the monthly average measured in the three land use, monitoring plan, and the meteorological trend, and temperature and rainfall during the monitoring period

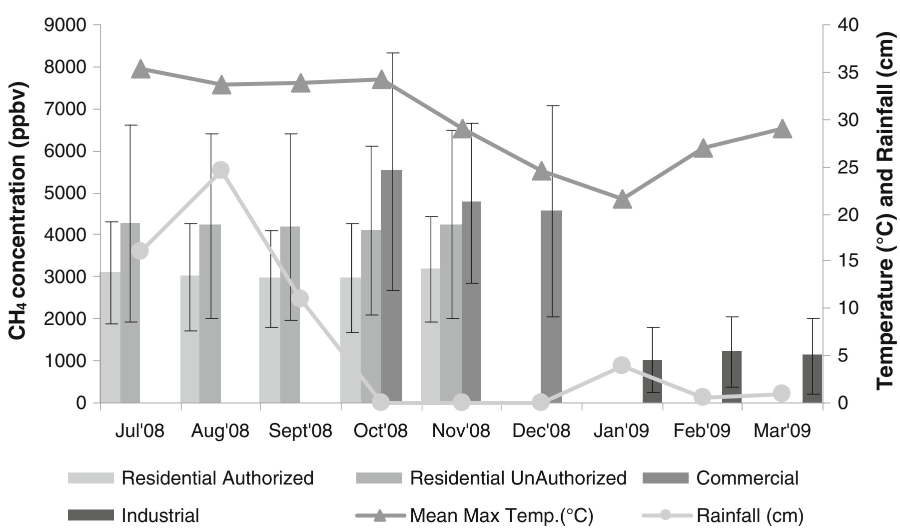


Table 3 Monthly average CO_2 and CH_4 concentrations in residential areas of Delhi

Sites	July'08		August'08		September'08		October'08		November'08	
	CO_2 (ppm)	CH_4 (ppbv)[a]	CO_2 (ppm)	CH_4 (ppbv)[a]	CO_2 (ppm)	CH_4 (ppbv)[a]	CO_2 (ppm)	CH_4 (ppbv)[a]	CO_2 (ppm)	CH_4 (ppbv)[a]
RA1	541±26	2,437±1,207 (4,701±747, 1,205±467)	526±18	2,501±1,010 (4,354±635, 1,523±543)	549±21	2,356±789 (3,868±582, 1,604±558)	544±12	2,103±985 (3,767±681, 1,226±454)	538±21	2,456±890 (4m116±682, 1,596±538)
RA2	560±22	4,383±1,093 (7,064±835, 3,307±855)	539±14	4,100±2,179 (7,786±843, 1,873±602)	542±15	4,031±1,910 (7,307±891, 2,152±620)	540±08	4,213±1,989 (7,566±923, 2,252±618)	554±19	4,561±2,078 (8,166±921, 2,519±564)
RA3	496±24	3,711±1,146 (6,266±387, 2,589±631)	495±15	3,810±1,360 (6,411±747, 2,556±634)	501±20	3,691±1,496 (6,380±748, 2,301±635)	520±16	3,854±1,740 (6,937±955, 2,285±639)	506±23	3,703±1,629 (6,452±642, 2,154±512)
RA4	512±28	1,335±1,299 (3,398±1,198, 59±36)	510 ±19	1,012±365 (1,707±548, 674±299)	512±26	1,236±390 (1,984±573, 882±456)	521±14	1,156±360 (1,865±553, 798±358)	514±21	1,425±410 (2,257±608, 1,091±519)
RA5	525±24	3,684±1,334 (6,473±915, 2,408±616)	512±21	3,564±1,399 (6,154±798, 2,214±492)	520 ±19	3,456±1,152 (5,668±721, 2,371±543)	530±07	3,589±1,421 (6,112±999, 2,186±422)	536±12	3,784±1,196 (5,926±933, 2,626±630)
RUA1	518±36	3,180±1,754 (6,266±653, 1,375±451)	529±28	3,245±1,784 (6,337±744, 1,411±451)	512±31	3,365±1,854 (6,576±860, 1,489±556)	521±48	3,100±1,581 (6,038±751, 1,502±563)	530±31	±3,012±1,486 (5,892±630, 1,507±563)
RUA2	626±72	4,494±2,514 (8,900±753, 1,874±617)	601±34	4,512±2,615 (8,980±819, 1,783±509)	595±35	4,231±2,345 (8,220±681, 1,817±510)	589±38	4,000±2,143 (7,802±563, 1,821±415)	610±29	4,521±2,376 (8,759±700, 2,111±510)
RUA3	513±44	2,369±1,354 (4,728±659, 990±386)	524±40	2,456±1,452 (5,002±702, 946±345)	520±36	2,512±1,298 (4,801±676, 1,159±519)	503±49	2,678±1,452 (5,328±571, 1,198±527)	521±41	2,431±1,293 (4,841±696, 1,097±455)
RUA4	564±56	3,050±1,754 (6,101±657, 1,210±493)	570±49	2,984±1,591 (5,765±540, 1,331±540)	554±39	2,845±1,364 (5,430±548, 1,501±455)	548±39	3,156±1,534 (6,097±514, 1,601±320)	560±42	3,250±1,748 (6,547±674, 1,451±303)
RUA5	624±65	8,230±4,356 (13,684±721, 3,711±681)	612±51	7,890±3,496 (12,468±798, 4,457±514)	588±49	8,010±4,289 (13,467±846, 3,669±569)	610±51	7,560±3,527 (11,845±752, 4,385±505)	590±48	7,990±4,251 (13,404±993, 3,657±674)

Number of readings recorded at each site for CO_2 and CH_4=56 per month

[a] Figures in parenthesis represent the average maximum and minimum values (mean of five highest and lowest values)

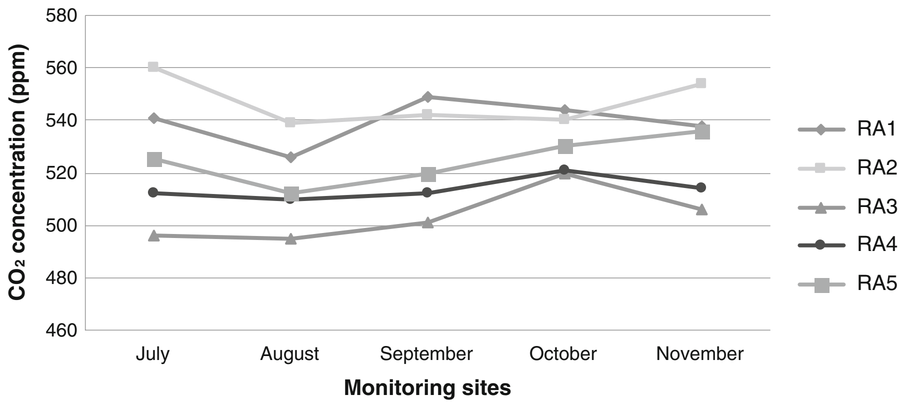


Fig. 8 Monthly mean CO_2 concentrations at the authorized residential sites

limited and mostly confined to the morning hours (rush hour extends from 0830 to 0930 hours) in these areas, when residents commute to work leads to high CO_2 concentrations during the morning hours (0800 to 1100 hours) at all the sites monitored. Commercial and industrial areas lack vegetation cover; hence; low mid-afternoon CO_2 concentration at these sites is due to vertical mixing.

Table 4 Daytime average CO_2 & CH_4 concentrations in residential areas of Delhi

Sites	9:30 AM[a]		12:30 PM[a]		17:30 PM[a]	
	CO_2 (ppm)	CH_4 (ppbv)[b]	CO_2 (ppm)	CH_4 (ppbv)[b]	CO_2 (ppm)	CH_4 (ppbv)[b]
RA1	564±22	4,881±2,111 (8,235±1,387, 2,798±709)	494±19	1,748±501 (2,862±558, 1,269±572)	566±35	684±201 (1,169±212, 511±190)
RA2	581±19	4,956±1,502 (7,767±487, 3,514±475)	559±27	2,722±600 (4,165±600, 2,173±403)	572±49	1,471±140 (4,176±473, 1,398±468)
RA3	533±16	1,527±1,023 (3,074±544, 520±275)	484±36	1,508±730 (2,908±532, 717±256)	499±38	1,000±220 (1,516±347, 792±249)
RA4	508±24	2,416±1,001 (4,433±533, 1,487±615)	490±41	1,068±540 (1,931±550, 501±382)	510±45	522±84 (752±220, 451±237)
RA5	568±29	5,356±1,853 (9,071±1,658, 3,584±409)	559±21	4,377±910 (6,784±1,299, 3,479±470)	517±29	1,320±820 (2,790±613, 459±253)
RUA1	503±41	5,660±2,001 (8,789±927, 3,781±719)	523±31	3,470±1,891 (7,197±936, 1,510±458)	529±55	411±180 (811±377, 318±213)
RUA2	600±39	6,290±1,700 (9,918±1,117, 4,779±1,048)	634±40	1,714±1,101 (2,947±797, 587±294)	644±43	5,480±480 (7,412±978, 5,103±996)
RUA3	560±47	4,460±2,150 (8,178±1,106, 2,486±706)	486±37	1,820±1,650 (4,472±638, 155±145)	493±29	827±300 (1,523±555, 607±279)
RUA4	569±27	4,490±1,100 (7,462±1,369, 3,429±712)	571±55	2,640±800 (4,572±747, 1,961±576)	583±37	2,020±920 (3,656±717, 1,189±459)
RUA5	600±35	4,050±1,260 (7,103±1,146, 2,896±722)	621±41	5,420±2,230 (9,668±982, 3,223±820)	624±41	15,220±2,600 (18,289±1,123, 12,721±1,334)

Number of readings recorded at each site for CO_2 and CH_4 during three monitoring period of the day from July 2008 to November 2008: 9:30 am – 120, 12:30 pm – 80, 17:30 pm – 80.

[a] 9:30 AM, 12:30 PM, and 17:30 PM represent the monitoring period 0800–1100 hours, 1200–1400 hours, and 1600–1800 hours, respectively. Mean value of the readings taken during this period from July 2008 to November 2008 is given in the respective column

[b] Figures in parenthesis represent the average maximum and minimum values (mean of five highest and lowest values)

Table 5 Daytime average CO_2 and CH_4 concentrations in commercial areas of Delhi

Sites	9:30 AM		12:30 PM		17:30 PM	
	CO_2 (ppm)	CH_4 (ppbv)[a]	CO_2 (ppm)	CH_4 (ppbv)[a]	CO_2 (ppm)	CH_4 (ppbv)[a]
C 1	564±31	11,000±2,001 (14,444±1,041, 9,045±978)	536±39	9,050±1,901 (12,151±996, 7,288±981)	566±29	10,000±1,740 (12,892±808, 8,322±625)
C 2	582±21	5,000±1,100 (7,460±634, 3,979±463)	559±24	4,500±1,100 (7,262±541, 3,473±476)	563±24	5,600±1,240 (8,405±413, 4,432±349)
C 3	533±29	7,000±1,050 (9,814±536, 6,142±475)	501±29	6,300±150 (7,865±159, 6,181±77)	514±29	6,800±150 (8,638±173, 6,668±86)
C 4	526±28	6,400±1,235 (9,312±417, 5,175±328)	490±28	70,00±1,035 (9,965±432, 6,043±413)	510±38	5,300±1,030 (7,736±435, 4,303±432)
C 5	536±32	1,200±990 (2,668±743, 198±170)	559±37	1,000±990 (2,531±950, 11±03)	549±37	1,900±985 (3,694±448, 891±384)
C 6	533±31	980±650 (2,136±450, 259±169)	513±21	100±50 (269±112, 42±24)	521±45	521±50 (772±224, 510±162)
C 7	531±21	890±250 (1,521±405, 691±155)	507±21	1,000±45 (1,316±370, 997±269)	501±35	2,500±50 (3,043±67, 2,481±40)
C 8	510±25	510±200 (947±95, 346±70)	489±25	780±200 (1,175±163, 595±119)	498±25	1,000±210 (1,508±138, 808±109)
C 9	546±24	546±220 (995±151, 350±95)	530±24	530±220 (937±148, 349±94)	507±24	500±230 (997±119, 301±176)
C 10	516±38	3,000±140 (3,903±426, 2,911±312)	498±38	1,900±940 (3,394±241, 907±123)	504±38	2,100±940 (3,822±376, 1,192±273)
C 11	546±39	9,000±100 (11,103±627, 8,991±464)	556±39	9,600±1,100 (12,436±551, 8,586±426)	582±39	9,300±1,100 (13,004±457, 8,285±285)
C 12	554±25	10,000±800 (13,042±765, 9,211±491)	560±36	11,500±850 (14,597±548, 10,691±482)	578±26	14,000±850 (17,299±234, 13,184±116)
C 13	554±33	8,000±1,530 (11,325±310, 6,509±268)	546±33	860±1,260 (11,677±312, 7,393±308)	569±43	9,800±1,360 (13,195±469, 8,473±332)

Values represent the mean value of the readings taken during the three monitoring periods of the day from October 2008 to December 2008. Number of readings recorded at each site for CO_2 and CH_4 during the monitoring period: 9:30 AM—48 at C1–C9, 36 at C10, and 24 at C11–C13; 12:30 PM—32 at C1–C9, 24 at C10, and 16 at C11–C13; 17:30 PM—32 at C1–C9, 24 at C10, and 16 at C11–C13

[a] Figures in parenthesis represent the average maximum and minimum values (mean of five highest and lowest values)

Low mid-afternoon CO_2 concentration has also been reported in several other studies carried out in different cities across the world: Phoenix measured at 2 m above ground level (Day et al. 2000; Idso et al. 2002), Sendai at 10 m above disturbance and 30 m above ground (Tanaka et al., 1985), Chicago at 20.7 m above the surrounding terrain ground and 27 m above ground (Grimmond et al. 2002), Sapporo at 1 m above the roof of 33 m high building (Miyaoka et al. 2007), Nagpur at 3 m above ground (Chaudhari et al. 2007), and Vancouver at 22.5 m above the surrounding terrain and 30 m above ground (Reid and Steyn 1997). High concentrations in the morning have been observed in other cities like Phoenix at 2 m above ground (Idso et al. 2000), and Kuwait at 3 m above the surrounding disturbance and 10 m above ground (Nasrallah et al. 2003).

No distinct diurnal variation was observed in unauthorized residential, commercial (C5, C11, and C12) and industrial areas. Instead of the usual trend of low mid-afternoon concentration, in unauthorized areas RUA1, RUA2, RUA4, and RUA5, the concentration started increasing in the mid-afternoon and, further, a maximum as high as 644 ppm in the late afternoon at RUA2 (Fig. 11). These areas have very little vegetation;

Table 6 Daytime average CO_2 and CH_4 concentrations in industrial areas of Delhi

Sites	9:30 AM		12:30 PM		17:30 PM	
	CO_2 (ppm)	CH_4 (ppbv)[a]	CO_2 (ppm)	CH_4 (ppbv)[a]	CO_2 (ppm)	CH_4 (ppbv)[a]
I 1	516±21	250±100 (431±95, 164±60)	510±21	400±101 (616±101, 309±82)	520±26	550±140 (849±110, 427±95)
I 2	542±19	2,000±1,100 (3,875±457, 811±290)	531±29	1,500±1,100 (3,276±296, 345±199)	555±21	1,000±120 (1,366±169, 897±141)
I 3	533±30	1,700±1,050 (3,438±334, 604±192)	520±26	2,100±850 (3,570±334, 1,297±280)	514±36	2,550±950 (4,235±372, 1,683±260)
I 4	526±30	1,100±635 (2,105±212, 379±122)	514±34	1,000±135 (1,407±271, 884±159)	536±37	1,700±1,030 (3,276±495, 633±188)
I 5	537±29	400±190 (743±130, 239±83)	512±29	353±50 (512±69, 331±29)	520±29	600±385 (1,231±164, 189±74)
I 6	533±30	300±50 (445±60, 286±51)	522±28	425±50 (584±63, 396±59)	511±38	521±50 (719±62, 498±47)
I 7	531±41	890±250 (1,402±330, 673±91)	532±31	1,000±45 (1,317±49, 989±47)	501±31	1,500±500 (2,460±409, 1,066±365)

Values represent the mean value of the readings taken during the three monitoring periods of the day from January 2009 to March 2009. Number of readings recorded at each site for CO_2 and CH_4 during the monitoring period: 9:30 AM—72, 12:30 PM—48, and 17:30 PM—48

[a] Figures in parenthesis represent the average maximum and minimum values (mean of five highest and lowest values)

thus, photosynthetic activities does not play much role in the daytime trend of CO_2 concentration. Most of these areas are inhabited by daily wage laborers who leave for their work early in the morning (around 0500 hours) and usually cook food using biomass late in the afternoon or after returning from work. High concentrations are imparted by burning of wastes for extracting metals, etc.

In the commercial areas, sites C2, C11, C12, and C13 recorded high concentrations as these are congested areas (residential/commercial) with very little vegetation, leading to accumulation of CO_2 (Fig. 13). Movement of vehicles, running of diesel generator sets for power back-ups, and other commercial activities are also responsible for the high concentrations. High concentrations at I2 in the industrial areas are related to remaining polluting units despite of the Supreme Court directives.

Maximum CH_4 concentrations were observed in the morning hours from (0800 to 1100 hours) with a

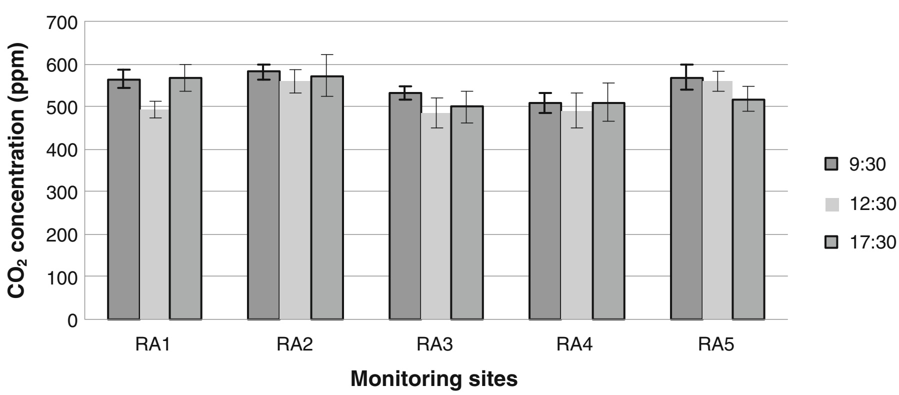
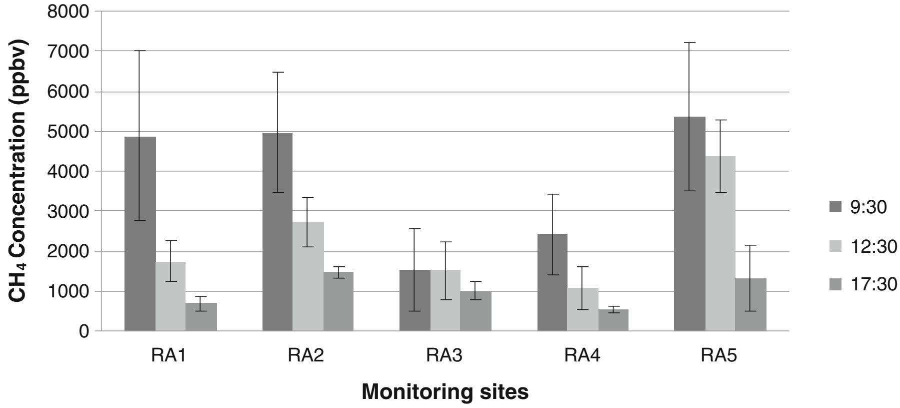


Fig. 9 Average CO_2 concentrations by time of day in authorized residential areas. Each bar represents the average concentrations measured during the three monitoring periods of the day: 0800–1100 hours, 1200–1400 hours, and 1600–1800 hours represented by 9:30, 12:30, and 17:30 respectively during the monitoring months July 2008 to November 2008

Fig. 10 Daytime average CH_4 concentrations in authorized residential areas. Each bar represents the average concentrations measured in the three monitoring periods of the day: 0800–1100 hours, 1200–1400 hours, and 1600–1800 hours represented by 9:30, 12:30, and 17:30 during the monitoring months July 2008 to November 2008



decreasing trend thereafter at all the sites in the authorized residential and at RUA1, RUA3, and RUA4 in the unauthorized residential areas (Figs. 10 and 12). Methane undergoes photochemical reactions in the atmosphere. Build-up starts early in the morning and reaches a peak around 0900–1000 hours, and thereafter, its concentration declines (Padhy and Varshney 2000). Mean maximum temperature during the monitoring period varied from 29 to 35.3°C, and high methane concentration in the urban environment is observed in the morning especially when the mean maximum temperature are on the higher side (Vinogradova et al. 2007). High traffic volume during this period inside the areas and activities like cleaning of dhalaos or kerbside waste bins, which is normally done in the morning hours, could also be one of the major sources of high concentration of methane during this period. The low boundary layer height and poor vertical mixing during this period prevents the dispersal of CH_4, leading to high concentration. No such variation was observed in the commercial and industrial areas.

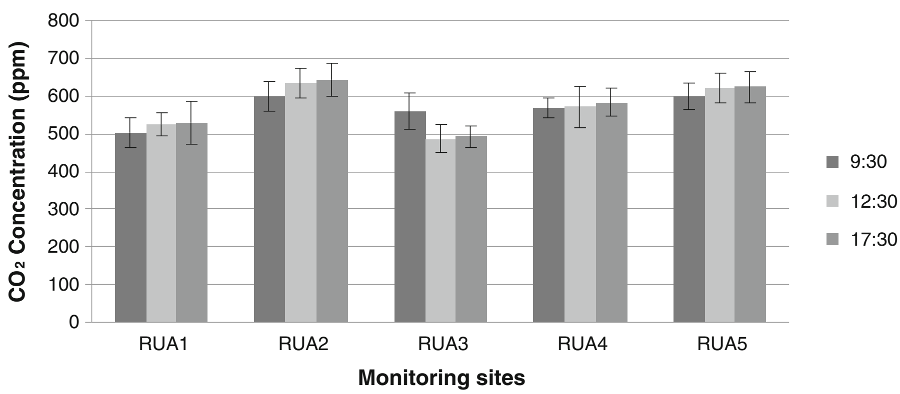
At RUA5 and C12, exceptionally high concentration (Fig. 12 and 14) was observed in the late afternoon period, which may be due to fresh discharge from several smaller drains carrying heavy sewage loads around this time of the day into the 25 m wide drain, 35 m north from the monitoring site with a discharge capacity of 158 m^3s^{-1} (sites RUA5 and C12 are located near the same drain) coupled with accumulation as they are highly congested area. Further research is required to explain this finding. Decomposition of organic wastes (vegetables, etc.) from the mandi (wholesale market) is another reason for high concentrations measured at C12. The overall low concentrations in most of the industrial area indicate that industries are not the major contributors in Delhi.

High standard deviation for the monthly mean CH_4 concentration, sometime even exceeding 50% of the mean value (Table 3), is due to the use of widespread of the daytime value recorded at these site in a month (ranging from 411 to 15,220 ppbv) to obtain the mean value.

Comparative study

The average daytime CO_2 concentration during the monitoring months (July 2008 to March 2009) varied

Fig. 11 Average CO_2 concentrations by time of day in unauthorized residential areas: July 2008 to November 2008. The time 9:30, 12:30, and 17:30 in the figure represents the three monitoring periods of the day



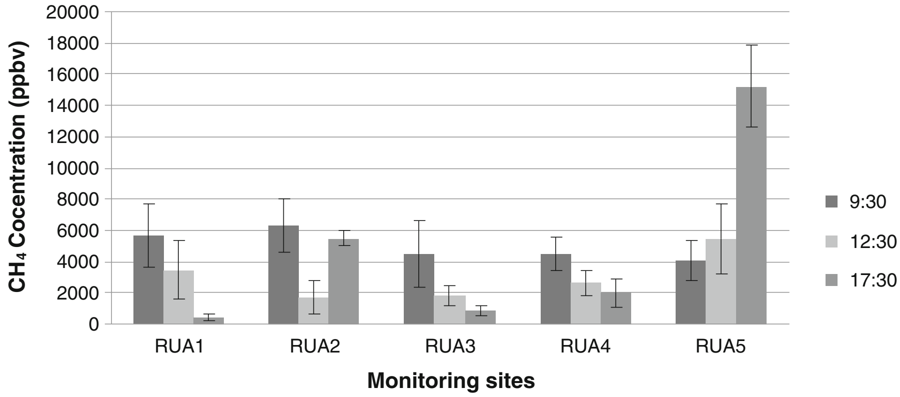


Fig. 12 Average CH_4 concentrations by time of day in unauthorized residential areas: July 2008 to November 2008. The time 9:30, 12:30, and 17:30 in the figure represents the three monitoring periods of the day

from 489 to 621 ppm in the authorized and unauthorized residential, commercial, and industrial areas with an overall average of 541±27 ppm. Compared to Chaudhari et al.'s (2007) observations in Nagpur, India, the concentrations are greater. They used the Pettenkoffer method as modified by Hess to monitor continuously for 5 months at residential, commercial, and industrial sites. The 24 hourly average concentrations varied from 197 to 526 ppm, 200 to 556 ppm, and 180 to 607 ppm in the residential, commercial, and industrial sites, respectively, with an overall average of 355 ppm, whereas the daytime concentration varied from 209 to 391 ppm, 188 to 380 ppm, and 243 to 564 ppm in the residential, commercial, and industrial sites, respectively. Compared to Delhi, low CO_2 levels were measured at the residential and commercial sites because of the low emission lifestyle of the people in these areas and higher sink potential of the vegetation cover; Nagpur has total vegetation cover of 54.9%. Total vegetation cover in Delhi is 20.20% of the total area (India State of Forest Report 2009). Relatively higher concentrations were observed at the industrial site due to lack of sink potential.

Several studies have been undertaken in the past to measure the CO_2 concentration in urban environment across different continents. Table 7 provides the comparison of our results with different studies carried out in different cities. Very limited studies have been done to measure the variations in the different land use, i.e., residential, commercial, and industrial, within a city. Nasrallah et al. (2003) measured mean CO_2 concentration at a height of 10 m (3 m tower kept on 7 m building) at the major residential and commercial area of Al-Jahra suburb of Kuwait City, from June 1996 to May 2001. The mean CO_2 concentration recorded was 369.19±11.34 ppm; values ranged from 320.64 to 741.82 ppm. The values are much lower than measured at the residential and commercial sites of Delhi because of the strong northerly winds during the day from the Kuwait bay and westerly during night; direction unchanged throughout the year, resulting in dispersion of CO_2.

Concentrations as high as 555 ppm was measured at a height of 2 m above the ground in the center of the urban metropolitan area of Phoenix, AZ, USA, during a 5-day period with low mid-afternoon values as

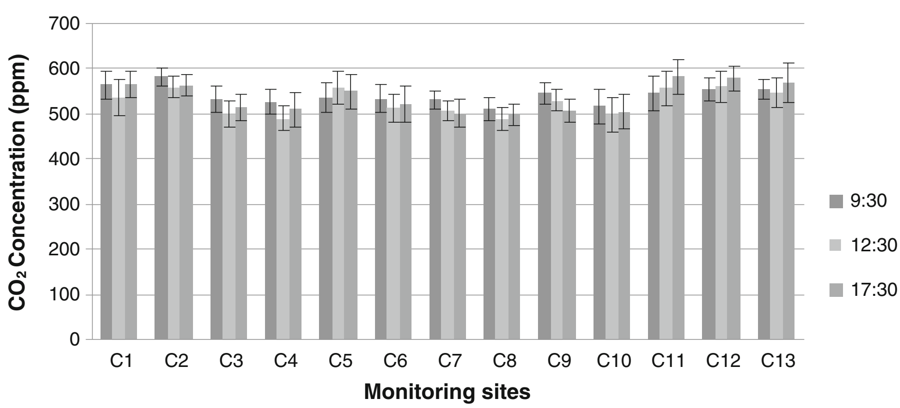


Fig. 13 Average CO_2 concentrations by time of day in commercial areas: October 2008 to December 2008. The time 9:30, 12:30, and 17:30 in the figure represents the three monitoring periods of the day

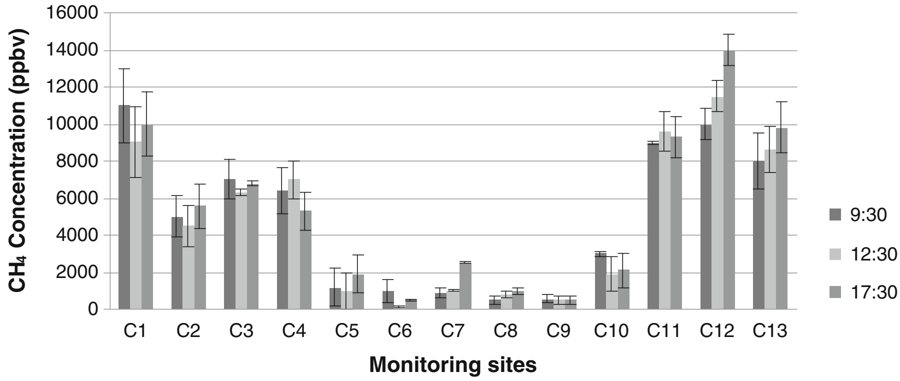


Fig. 14 Average CH_4 concentrations by time of day in commercial areas: October 2008 to December 2008. The time 9:30, 12:30, and 17:30 in the figure represents the three monitoring periods of the day

against the rural background level of 370 ppm (Idso et al. 1998). Very little variations in the concentration were observed during summer and winter (Idso et al. 1998). Since no background values for ambient CO_2 concentration are available for Delhi (no study carried out so far), establishing the difference in the concentration from the background is not possible at present.

However, continuous measurement for a year (315 days) at 2 m height in the residential area of urban Phoenix, AZ, USA, distinct diurnal and seasonal variations were observed. The daytime minimum at the mid-afternoon was 390.2±0.2 ppm with almost no variation throughout the year. The mean cold season maximum at the center of the city was estimated to 619.3 ppm (Idso et al. 2002). In the authorized residential area of Delhi, low mid-afternoon value was observed at all the sites but with variations during the monitoring months due to variation in the temperature and rainfall. Low mid-afternoon (375 ppm) and high morning CO_2 concentrations (421 ppm) have also been observed at 37 m above ground level in a densely populated city area of Mexico (Velasco et al. 2005).

Selection of the monitoring site has significant impact on the measurements. High values have been reported if monitoring sites are close to streets with heavy traffic loads, contribution from vehicular exhaust. In an experiment conducted by Widory and Javoy (2003), near surface CO_2 concentration measured in Paris, France reached as high as 950 ppm as monitoring was done close to streets with heavy traffic loads, while outside the city, it averaged 415 ppm. Gratani and Varone (2005) reported near-surface CO_2 concentration measured at different sites in Rome from 1995 to 2004 with intervals. The concentrations varied from 414 to 505 ppm at city center and showed strong correlation with the traffic density. The problem of contribution from vehicular exhaust affecting the measurements was reduced in our study as the monitoring sites were selected away from such streets.

CH_4 concentration varied from 500 to 15,220 ppbv in the authorized and unauthorized residential, commercial, and industrial areas. The overall average CH_4 concentration in Delhi was 3,226±1,090 ppbv. Earlier, Padhy and Varshney (2000) measured the ambient methane levels at different sites in the urban area of

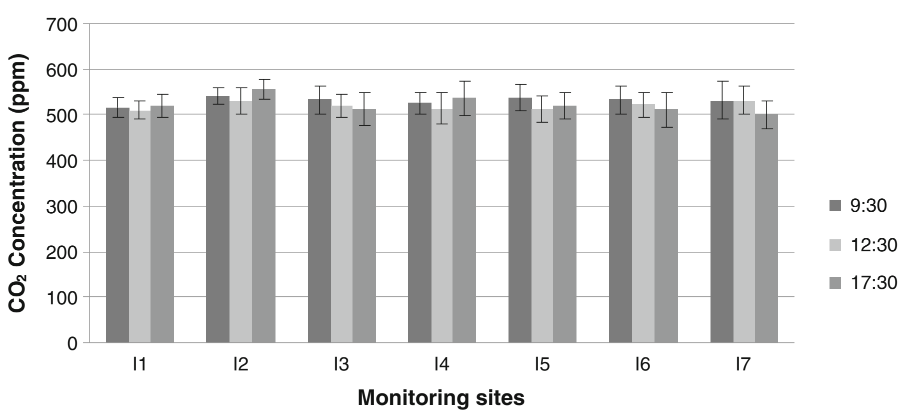


Fig. 15 Average CO_2 concentrations by time of day in industrial areas: January 2009 to March 2009. The time 9:30, 12:30, and 17:30 in the figure represents the three monitoring periods of the day

Table 7 Comparison of CO_2 and CH_4 concentrations in Delhi with results of other similar studies

Author	City/land use	Measurement height	Concentrations	Delhi[a]
CO_2 concentrations				
Chaudhari et al. (2007)	Nagpur, India/ residential, commercial, and industrial	3 m above the ground	Daytime concentration(ppm): residential, 209–391; commercial, 188–380; industrial, 243–564	Daytime concentration(ppm): residential,[b] 484–644; commercial, 489–582; industrial, 501–555
Nasrallah et al. (2003)	Al-Jahra suburb of Kuwait City/residential and commercial	10 m (3 m tower kept on 7 m building)	Range: 320.64–741.82 ppm	Range: residential,[b] 495–621; commercial, 489–582
Idso et al. 1998	Phoenix, AZ, USA/urban metropolitan area	2 m above the ground	Average: 555 ppm	Average: 541 ppm
Idso et al. 2002	Phoenix, AZ, USA/residential area	2 m above the ground	390.2–619.3 ppm	Residential:[b] 495–621
Widory and Javoy (2003)	Paris/close to streets with heavy traffic loads	–	415–950 ppm	495–621 ppm[c]
Gratani and Varone (2005)	Rome/close to streets with heavy traffic loads	–	414–505 ppm	495–621 ppm[c]
CH_4 concentrations				
Padhy and Varshney (2000)	Delhi Urban Areas	–	1,703 and 9,492 ppbv	250–15,220 ppbv[b]
Nguyen et al. (2010)	Seol, Korea/close to streets with heavy traffic loads	3.8 m above ground	Average: 2,240±420 ppbv	Average: 3,226±1,090 ppbv

[a] Average Monitoring Height in the three land use: residential, 3.65 m; commercial, 4.84 m; industrial, 4.82 m

[b] Residential includes both authorized and unauthorized areas

[c] None of the site close to streets with heavy traffic loads. Range of the values measured across all the land use

Delhi from November 1994 to June 1995 at an interval of 15 days. The CH_4 concentration varied between 1,703 and 9,492 ppbv with an average of 4,121± 354 ppbv. The average concentration in the present study was lower due to the difference in site selection, hence in the emission sources. The sampling sites selected by Padhy and Varshney comprised of open areas with vegetation intermixed with moving traffic corridors, densely populated congested residential cum commercial areas, and busy traffic intersections and roads. Samples were collected at all the sites adjacent to roads with varying traffic densities. Major sources were automobile exhaust, poorly managed solid waste dumps, and choking sewers. However, in our study, none of the site was close to roads with traffic loads, which minimized the contribution from vehicular exhausts, and the average concentration in the industrial areas was also very low resulting in lower overall average concentration.

Nguyen et al. (2010) analyzed the long-term patterns of urban CH_4 concentration in Seol, Korea. Measurements were taken at an urban site, 3.8 m above ground level and 1 m from the busy road for 11-year period. The average CH_4 concentration measured during the study period was 2,240±420 ppbv. The implementation of a nationwide air quality control policy was responsible for low values, where as in several other studies, high levels of methane in the urban environment, ranging from 2,000±20,000 ppbv (Altshuller 1968), 2,000±6,000 ppbv (Graedel et al. 1986), and 3,300±3,500 ppbv (Rowland et al. 1990) have been reported.

Conclusion

Daytime (08–18 h) measurement of ambient CO_2 and CH_4 concentration in the urban environment of Delhi provide an opportunity to compare and understand the near surface concentration of GHG in the major land uses: residential, commercial, and industrial. The average ambient CO_2 and CH_4 concentrations in the urban environment of Delhi were 541±27 and 3226±1090 ppbv during the monitoring period. Daytime average CO_2 concentration in the authorized residential areas was 526±18 ppm, lower than the other land use due to presence of vegetation serving as sink and open areas. The average concentrations in the commercial (540± 27 ppm) and the industrial areas (537±15 ppm) were almost similar with very small difference but higher than the authorized residential areas due to lack of vegetation and open space. The unauthorized areas recorded the highest average concentration of 561±30 ppm due to lack of vegetation and use of biomass as cooking fuels. All the values were higher than the values measured in the similar land use at Nagpur (Chaudhari et al. 2007).

Average CH_4 concentration was highest in the commercial areas (4,939±1,340 ppbv) followed by residential (3,624±1,715 ppbv), and industrial area (1,115± 215 ppbv). This is because CH_4 concentration depends on the site characteristics. The overall average value of 3,226±1,090 ppbv was observed in the monitored area. Delhi has an average ambient CH_4 concentration (contribution from road transport included) in the urban environment of 4,121±354 ppbv (Padhy and Varshney 2000). A distinct variation in the daytime concentration of CO_2 was observed and is in line with other similar studies exhibiting a low mid-afternoon CO_2 concentration, in authorized residential areas and a high morning CH_4 concentration with a decreasing trend thereafter.

The present study shows the impact of urbanization on the ambient concentration of GHGs. Delhi, being the capital city of India, is under constant pressure of development, which is manifested by high emission from the major land use. The lack of sink potential in the present form of land use and increasing sources is by far the major cause for high ambient concentration. The measurements are ongoing.

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