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Seasonal Variation of Tropospheric Ozone and Its Association with the Chemical and Meteorological Precursors in Delhi, India

Rakhi Ghosh[1], Puja Gupta[1], Mukesh Khare[2] & Priyanka Kulshreshtha[1*]

[1] Department of Resource Management and Design Application, Lady Irwin College, University of Delhi, New Delhi, India

[2] Department of Civil Engineering, Indian Institute of Technology, New Delhi, India

[*] Priyanka Kulshreshtha, E-mail: priya.kulsh@gmail.com

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Abstract

In the present study, profile of tropospheric ozone and its variation with its chemical and meteorological precursors has been assessed in Delhi. The ambient air of Anand Vihar ISBT was found to be mainly dominated by NO_x (335 µg/m^3) and BTX (Benzene-12.2 µg/m^3, Toluene -37 µg/m^3 and pXylene -8.2 µg/m^3) amongst the selected sites of Delhi. NO_x was found to be predominately high due to high vehicular traffic, fireworks during festivals and crop burning in and around Delhi during November 2015. The concentration of benzene was exceeding the permissible standards in all the selected sites of Delhi. The study also revealed that the highest annual concentration of tropospheric Ozone (56.2 ± 23.5 µg/m^3) was reported from Punjabi Bagh among the selected sites of Delhi and was recorded primarily in summers (March 2016-June 2016). The results indicate that higher temperature, lower humidity and high intensity of solar radiation contribute to the formation of tropospheric ozone in Delhi. The minimum concentration of ozone was recorded during the monsoons (July, 2016-September, 2016). This indicates the high humidity, large cloud cover, low intensity of solar radiation which could have been the reason for slowdown of the photochemical process. A positive correlation was observed between tropospheric ozone and ambient temperature in Delhi.

Keywords

tropospheric ozone, meteorological precursors, chemical precursors, Seasonal Variation, air quality

1. Introduction

Environmental pollution is major problem in both developed and developing countries (Ghosh et al., 2005; Ahmad & Bano, 2015). It is a complex issue, fuelled by numerous sources ranging from vehicular emissions, industrial flumes, garbage burning, domestic cooking and heating and some seasonal sources such as agricultural crop burning and dust storms, etc. (Guttikunda et al., 2012).

Several cities, which are about to touch the dangerous ozone concentration levels are on the radar of World Health Organization (WHO, 2014). The rapid growth in industrial activities due to globalization has resulted in massive amount of potentially harmful gases and particles being emitted into the atmosphere (Aneja et al., 2008; Nishanth et al., 2008). Amongst the harmful gaseous pollutants like CO (Carbon monoxide), NO_x (oxides of Nitrogen), CH_4 (Methane), NMHCs (Non-methane hydrocarbons) and VOCs (Volatile organic compounds), etc., the tropospheric ozone (O_3) is particularly important because it is capable of causing adverse effects on human health (WHO, 2000; Han et al., 2011). Tropospheric ozone is a major pollutant of concern (TRS, 2008) and is now being realized as an emerging air pollution issue in India (Kumar et al., 2012; Ghude et al., 2014). Ozone (O_3) is a colourless and reactive oxidant gas which is a main constituent of atmospheric smog. It is also known as a secondary pollutant, which is formed due to photo-chemically active primary pollutants (Liu et al., 1987; World Bank Group, 1998; Royal Society, 2008; Guttikunda, 2009; Marathe & Murthy, 2015). It is not emitted directly into the air, but is formed by gases like oxides of nitrogen (NO_x) and volatile organic compounds (VOCs), which in the presence of heat and sunlight, react to form ozone (Kgabi & Sehloho, 2012). Volatile organic compounds (VOCs) are very important precursors in the formation of tropospheric ozone (IPCC, 2007). Volatile Organic Compounds react with hydroxyl radical (OH) through photochemical reactions to produce oxygenated compounds, and subsequently form ozone (Hofzumahaus et al., 2009). The relation between ozone, nitrogen oxides (NO_x) and VOCs is determined by their complex nonlinear photochemistry. Concentration of tropospheric ozone is also strongly linked to meteorological conditions (Srivastava, 2016). It plays an important role in the formation, dispersion, transport, and dilution of air pollutants (Kgabi & Sehloho, 2012). The variations in meteorological conditions such as ambient temperature, relative humidity, wind speed and wind direction have a huge great impact on the concentration of tropospheric ozone and its precursors (Elminir, 2005; Kgabi & Sehloho, 2012). The tropospheric ozone concentration is characteristic of strong seasonal, episodic, and diurnal fluctuations (Monks et al., 2015; Lang et al., 2012; Young et al., 2011; Khoder, 2009; Jasaitis et al., 2016). Kgabi and Sehloho (2012), also reported that weather conditions are critical to the formation of tropospheric ozone, which is highest during summers, when the high intensity of solar radiation and high temperatures speed up the ozone-forming photochemical reactions. The present study aimed at conducting a detailed analysis of the formation of tropospheric ozone with its chemical and meteorological precursors and establishing a correlation between ozone and its precursors.

2. Methodology

The study was conducted in Delhi, capital city of India. Delhi has been ranked as the worlds's most polluted city by the World Health Organization (WHO, 2014) as the world's most polluted city. Delhi has a population of more than 16 million, with an Air Pollution Index (API) rising rapidly from the current reading of 220 and increasing by leaps and bounds. The new index with a reading over 401 could lead to a high risk of respiratory problems in healthy people and can seriously affect those who are already ill (WHO, 2014).

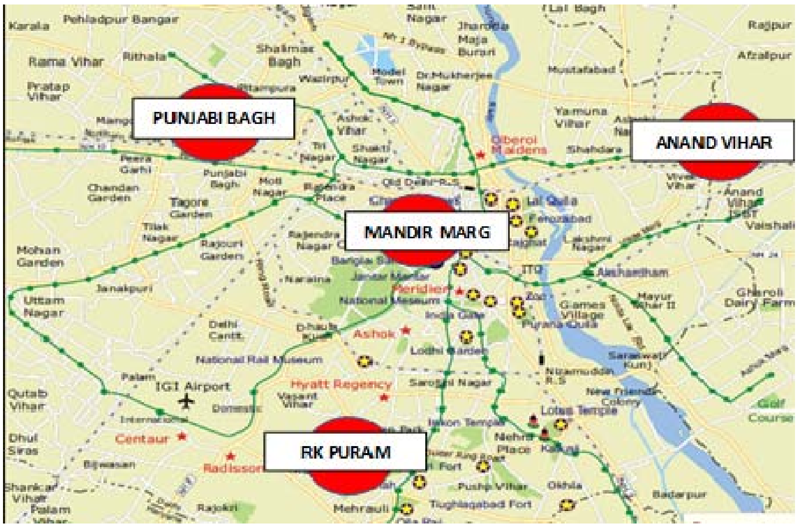


Figure 1. Map of Delhi Depicting the Selected Sites

2.1 Site Description

Delhi is located in northern India between the latitudes of 28°-24'-17" and 28°-53'-00" North and longitudes of 76°-50'-24" and 77°-20'-37" East. Delhi shares its borders with the states of Haryana and Uttar Pradesh. Delhi has an area of 1,483 sq. kms (NIDM, 2017). The average annual rainfall in Delhi is 714 mm, three-fourths of which falls in July, August and September (monsoons). During the summer months of March, April, May and June, temperatures can increase to 40°C-45°C degrees Celsius; winters are typically cold with temperatures during December and January falling to 4°C to 5°C. February, March, October and November are climatically the best months (NIDM, 2017). A purposive sample was used for the study which was collected from four selected sites of Delhi. These four selected sites were Mandir Marg (Central Delhi), Punjabi Bagh (West Delhi), Anand Vihar ISBT (East Delhi) and RK Puram (South Delhi).

2.2 Mandir Marg (Central Delhi)

Figure 2. Mandir Marg

Mandir Marg is situated in central Delhi where maximum temples are located at this area. The nearest metro station to Mandir Marg is RK Ashram Marg which is at a distance of 2km from this location. This location is well connected with buses too. Due to its location, it experiences heavy traffic and congestion throughout the day.

2.3 Punjabi Bagh (West Delhi)

Punjabi Bagh is situated in West Delhi which is primarily a residential area. The Rohtak Road crosses the area from one end and the Ring Road from another. It is well connected to various parts of the city and has a fairly good bus network and roads. It is also well connected to the Metro with 2 stations right next to the main Punjabi Bagh Chowk. The area has units ranging in furniture, electric supplies, motor parts and plastic crockery.

Figure 3. Punjabi Bagh

2.4 Anand Vihar ISBT (East Delhi)

Anand Vihar ISBT is situated in East Delhi. ISBT stands for Inter-State Bus Terminal, which connects mainly North Indian States like Haryana, Punjab, Himachal Pradesh, Jammu and Kashmir and Uttar Pradesh. Traffic activity in the study zone is very high. To ease the traffic congestion, flyovers are constructed on different roads. The study zone has very less resident population, but the floating population is very high and thus the presence of commercial activities like eateries, hotels and restaurants, etc., are also significant. Overall, the region can be defined as a very high traffic activity zone with moderate commercial activities

Figure 4. Anand Vihar

2.5 RK Puram (South Delhi)

Ramakrishna Puram popularly recognized as R.K. Puram, a Central Government Employees residential colony in South West Delhi. This location is situated between two ring roads and outer ring road. Heavy construction activities combined by traffic emissions form a lethal concoction of pollutants in the area. The emission from the heavy-duty vehicles and CO_2 emission from ready mix concrete plants are also a major source of ambient air pollution.

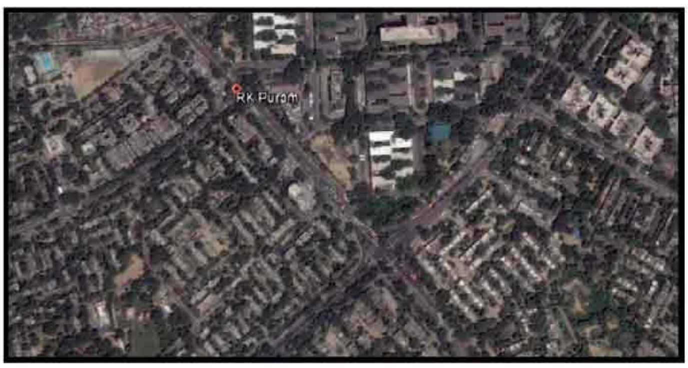


Figure 5. RK Puram

2.6 Sample

Sample for the study comprises of collection of annual data for tropospheric ozone with its chemical precursors (CO, NO_x and BTEX) and meteorological precursors (Ambient temperature, Relative humidity, Wind speed, wind direction and solar radiation). Four monitoring stations, have been selected from Delhi for data collection. From each selected site, data for tropospheric ozone and its 3 chemical precursors and 5 meteorological precursors have been collected on hourly basis for one year (October, 2015-October, 2016), thus making the total data entries of precursors to be 70,080 (8*24*365). Pearson correlation and descriptive statistics (mean, standard deviation, minimum, maximum) have been used as a statistical tool for the present study.

3. Result and Discussions

The present study assessed the variation in concentration of ozone and its precursors seasonally from Oct 2015-Oct 2016 in Delhi which are presented in Figure 7.

3.1 Mandir Marg

3.1.1 Concentration of Ozone, Its Chemical and Meteorological Precursors

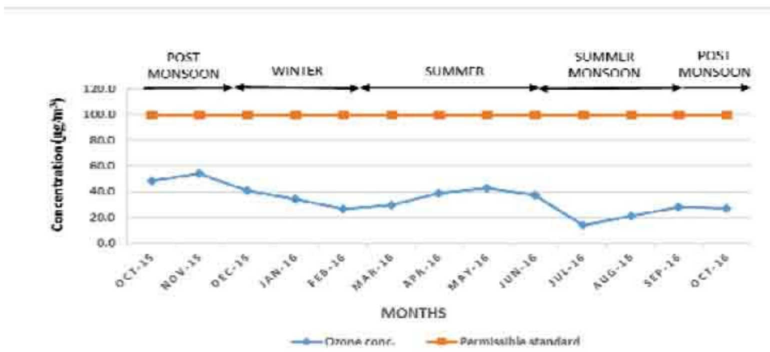


Figure 6. Seasonal Variation in Concentration of Ozone (O_3) at Mandir Marg

Figure 6 depicts that the highest concentration of ozone, i.e., 54.16μg/m^3 was observed in November 2015. It could be due to the high vehicular emission and more solar radiation. The lowest concentration (14.1 μg/m^3) has been observed in July 2016 which may be due to higher humidity in air during monsoon.

3.1.2 Summer

This season starts by early March and ends till late June (IMD, 2010). The maximum concentration of tropospheric Ozone was observed to be around 42.95 μg/m^3 in June 2016, which could possibly be due to high ambient air temperature and high intensity of solar radiation which helps in the formation of tropospheric ozone (Marathe & Murthy, 2015). The lowest concentration, i.e., 29.7 μg/m^3 was observed in March 2016. The photochemical breakdown of ozone could be the reason for this lower concentration.

			CHEMICAL PRECURSORS					
EAR	SEASONS	MONTHS	CONC.	OZONE	NOx	BENZENE	TOULENE	PXYLENE
			UNITS	[μg/m³]	[μg/m³]	[μg/m³]	[μg/m³]	[μg/m³]
2015	POST MONSOON	OCT	Avg ± S.D.	**48.62 ± 48.1**	**104.0 ± 108.6**	**3.51 ± 2.4**	**11 ± 11.2**	**6.3 ± 6.5**
			Min	7.7	7.6	0.3	1.1	0.3
			Max	265.9	716.3	16.5	95.3	39.0
		NOV	Avg ± S.D.	**54.1 ± 65.2**	**178.2 ± 160.8**	**5.7 ± 3.8**	**20.4 ± 30.4**	**10.5 ± 9.9**
			Min	0.2	13.4	1.0	1.0	0.5
			Max	355.3	887.4	26.8	238.1	55.9
	WINTER	DEC	Avg ± S.D.	**41.0 ± 42.8**	**147.5 ± 146.1**	**5.0 ± 2.87**	**14.9 ± 17.4**	**7.5 ± 7.7**
			Min	4.1	15.5	1.1	1.7	0.5
			Max	201.2	838.6	17.7	117.5	43.1
2016		JAN	Avg ± S.D.	**34.2 ± 42.8**	**154.9 ± 137.4**	**4.79 ± 2.7**	**12.8 ± 16.5**	**6.6 ± 7.1**
			Min	5.8	24.2	1.3	0.8	0.2
			Max	158.6	785.1	19.1	179.6	44.7
		FEB	Avg ± S.D.	**26.6 ± 23.0**	**121.5 ± 124.5**	**3.9 ± 2.5**	**10.0 ± 10.6**	**4.8 ± 5.0**
			Min	3.6	6.8	0.7	1.3	0.3
			Max	122.6	820.6	17.8	75.6	26.1
	SUMMER	MAR	Avg ± S.D.	**29.6 ± 20.0**	**75.1 ± 76.6**	**2.7 ± 1.9**	**6.2 ± 5.9**	**3.0 ± 3.4**
			Min	9.0	5.5	0.4	0.9	0.0
			Max	97.5	420.0	9.6	40.1	21.6
		APR	Avg ± S.D.	**39.0 ± 27.4**	**84.8 ± 109.6**	**3.06 ± 2.3**	**6.8 ± 7.5**	**3.6 ± 4.7**
			Min	7.5	8.5	0.3	0.4	0.1
			Max	125.2	751.3	13.3	60.4	28.0
		MAY	Avg ± S.D.	**42.9 ± 36.4**	**57.3 ± 53.2**	**1.7 ± 1.3**	**4.3 ± 5.1**	**2.4 ± 3.14**
			Min	1.5	0.6	0.1	0.1	0.0
			Max	189.7	368.1	11.8	64.0	27.9
		JUN	Avg ± S.D.	**37.3 ± 33.6**	**42.6 ± 34.4**	**1.2 ± 0.8**	**2.6 ± 2.3**	**1.2 ± 1.5**
			Min	5.6	8.3	0.1	0.2	0.0
			Max	242.2	243.2	8.3	15.5	9.2
	MONSOON	JUL	Avg ± S.D.	**14.1 ± 14.4**	**42.6 ± 32.2**	**1.0 ± 0.6**	**3.2 ± 2.4**	**1.6 ± 1.6**
			Min	4.3	7.9	0.1	0.4	0.0
			Max	210.9	204.9	4.6	16.9	9.2
		AUG	Avg ± S.D.	**21.1 ± 20.1**	**43.5 ± 33.2**	**1.3 ± 0.9**	**18.2 ± 6.5**	**2.2 ± 2.1**
			Min	2.6	12.3	0.1	9.5	0.2
			Max	210.9	267.1	7.1	64.3	13.7
		SEP	Avg ± S.D.	**28.2 ± 25.8**	**44.5 ± 34.3**	**1.6 ± 1.2**	**33.2 ± 10.6**	**2.7 ± 2.6**
			Min	2.6	12.3	0.1	9.5	0.2
			Max	148.3	267.1	7.1	64.3	13.7
	POST MONSOON	OCT	Avg ± S.D.	**27.3 ± 29.1**	**104.3 ± 99.0**	**4.5 ± 3.4**	**32.6 ± 20.7**	**8.06 ± 7.2**
			Min	4.9	18.5	0.5	9.0	0.4
			Max	166.7	779.2	20.5	142.0	37.4

Figure 7. Seasonal Variation in Concentration of Ozone and Its Chemical Precursors in Delhi

YEAR	SEASONS	MONTHS	METEOROLOGICAL PRECURSORS					
			CONC.	TEPERATURE	RELATIVE HUMIDITY	SOLAR RADIATION	WIND DIRECTION	WIND SPEED
			UNITS	[øC]	[% Rh]	[W/m²]	[ø]	[m/s]
2015	POST MONSOON	OCT	Avg ± S.D.	23.6 ± 6.4	56.5 ± 19.2	109.3 ± 142.4	231.7 ± 52.3	0.9 ± 0.7
			Min	10.0	18.1	5.1	62.7	0.3
			Max	36.5	88.0	392.0	315.8	3.1
		NOV	Avg ± S.D.	17.2 ± 5.9	59.9 ± 17.6	82.4 ± 114.4	232.7 ± 58.2	0.7 ± 0.5
			Min	6.6	20.5	5.0	73.8	0.3
			Max	30.5	89.1	368.7	334.0	2.9
	WINTER	DEC	Avg ± S.D.	11.9 ± 6.0	63.0 ± 18.0	74.0 ± 103.7	229.1 ± 48.6	0.9 ± 0.7
			Min	1.3	20.8	5.3	38.0	0.3
			Max	25.4	88.9	341.0	321.8	3.0
2016		JAN	Avg ± S.D.	11.8 ± 5.3	69.8 ± 15.4	60.6 ± 85.4	226.7 ± 52.6	0.9 ± 0.6
			Min	2.8	24.1	5.0	46.3	0.3
			Max	26.0	89.3	299.1	326.6	2.9
		FEB	Avg ± S.D.	15.5 ± 6.3	56.7 ± 17.8	87.9 ± 121.2	232.3 ± 52.6	1.0 ± 0.8
			Min	3.6	18.6	5.2	56.0	0.3
			Max	29.2	87.3	395.9	324.8	3.8
	SUMMER	MAR	Avg ± S.D.	23.0 ± 6.4	47.8 ± 19.3	125.2 ± 151.7	228.7 ± 56.2	1.5 ± 1.08
			Min	10.8	11.0	5.3	87.7	0.3
			Max	38.7	85.9	416.1	328.5	5.0
		APR	Avg ± S.D.	29.7 ± 6.6	24.3 ± 11.2	141.9 ± 151.8	243.5 ± 34.0	1.57 ± 1.0
			Min	16.7	3.7	16.5	89.6	0.3
			Max	42.3	58.7	413.9	329.5	4.3
		MAY	Avg ± S.D.	32.1 ± 6.1	40.4 ± 16.9	153.0 ± 155.2	188.3 ± 55.4	1.6 ± 0.94
			Min	19.8	3.7	16.5	89.1	0.3
			Max	45.5	86.9	423.0	328.2	5.8
		JUN	Avg ± S.D.	31.9 ± 4.6	51.5 ± 15.1	152.7 ± 154.3	167.3 ± 53.7	1.7 ± 0.7
			Min	22.0	16.6	16.9	4.1	0.3
			Max	44.4	81.9	409.9	315.2	4.3
	MONSOON	JUL	Avg ± S.D.	28.2 ± 3.50	72.9 ± 12.1	125.7 ± 133.5	197.3 ± 56.5	1.2 ± 0.6
			Min	21.6	37.8	15.9	89.9	0.3
			Max	37.0	90.3	411.3	336.9	3.4
		AUG	Avg ± S.D.	27.8 ± 3.8	69.9 ± 13.3	126.1 ± 138.5	213 ± 52.7	1.14 ± 0.6
			Min	20.6	34.9	4.9	79.3	0.3
			Max	38.3	90.7	411.5	323.8	3.2
		SEP	Avg ± S.D.	27.5 ± 4.2	66.9 ± 14.5	126.4 ± 143.5	228.6 ± 49.0	1.0 ± 0.6
			Min	20.6	34.9	4.9	68.6	0.3
			Max	38.3	90.7	411.5	310.7	3.0
	POST MONSOON	OCT	Avg ± S.D.	23.9 ± 6.6	59.5 ± 19.9	100.7 ± 134.2	245.9 ± 37.6	0.8 ± 0.6
			Min	12.0	19.0	4.8	103.8	0.3
			Max	37.0	89.4	386.7	335.7	2.7

Figure 8. Seasonal Variation in Concentration of Ozone and Its Meteorological Precursors in Delhi

3.1.3 Winter

Indian Meteorological Department (IMD) has categorised the months of December, January and February in winter season. This season starts in early December associated with clear skies, fine weather, light winds, low humidity and temperatures. The maximum concentration of tropospheric Ozone (41.1 $\mu g/m^3$) was observed in December 2015. This season is marked with very low temperatures, especially during the night. Since there is inadequate amount of thermal inversion in this season the pollutants tend to be trapped near the ground level. Therefore, this season also experiences high pollution episodes, which could be the reason for maximum concentration of ozone. Similar results were reported by Marathe and Murthy (2015). Whereas, the minimum concentration of Ozone, i.e., 26.7 $\mu g/m^3$ was observed in February 2016, the lower temperature and the low intensity could be the reason for lower concentration of ground level ozone.

3.1.4 Summer-Monsoon

This season starts by early July and ends till September. July is marked by high heat and relatively less rainfall and August is wettest month in Delhi (IMD, 2010). The heat is significantly reduced and it is relatively cooler for most part of the month with dense cloud formation in the sky. The minimum concentration of tropospheric ozone (14.1 $\mu g/m^3$) was observed in July 2016 and the humidity was also found to be very high (72.94%) indicating that the high humidity in air is inversely proportional to the concentration of tropospheric ozone.

3.1.5 Post Monsoon

This season starts by early October and ends till late November. The mean temperatures over north part of the country show decline from about 38°C in October to 28°C in November. Decrease in humidity levels and clear skies over most parts of north and central India after mid-October are characteristics features of this season (NATCOM, 2004; IMD, 2010). The maximum concentration of tropospheric ozone was observed to be around 54.2 $\mu g/m^3$ in November 2015. This could possibly be due to the minimal humidity, maximum temperature with high solar radiation combined with light traffic flow.

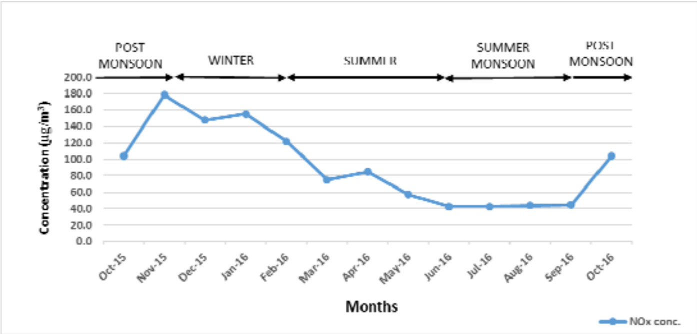


Figure 9. Seasonal Variation in Concentration of Oxides of Nitrogen (NO_x) at Mandir Marg

Figure 9 indicates that the highest concentration of Oxides of Nitrogen (178.2 $\mu g/m^3$) was observed in post-monsoon season (November, 2015) and the lowest concentration, i.e., 42.6 $\mu g/m^3$ was found in summer-monsoon season (July, 2016). The combustion of fossil fuels like coal, gas and oil used in vehicles could be the possible reasons for high concentration of NO_x. Another reason for maximum concentration of NO_x could be the occurrence of Diwali festival coupled with burning of crackers, high vehicular density and increase in emission from heavy duty vehicles.

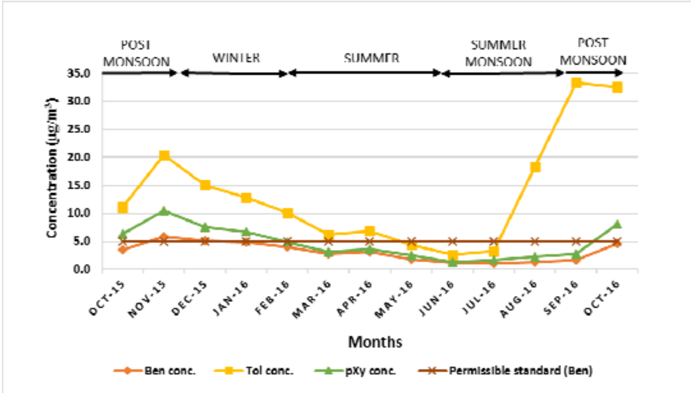


Figure 10. Seasonal Variation in Concentration of Benzene, Toluene and PXylene (BTX) at Mandir Marg

Figure 10 shows the concentration of BTX (Benzene, Toluene, & pXylene, n.d.) at Mansir Marg in Delhi. BTX have a strong influence on tropospheric chemistry of ozone. It affects the formation of tropospheric ozone and the formation of secondary organic aerosol (Hellén, 2006). The maximum concentration of benzene and pXylene was observed in November (post monsoon) and the maximum concentration of Toluene was found in September 2016 (summer monsoon). Some studies (Barletta et al., 2005; Theloke & Friedrich, 2007; Van Langenhove, 2010; Huang et al., 2011) suggested that vehicle emissions are often the main source of BTX in urban areas. The reason for high concentration of BTX could be the visitors to many old famous temples at Mandir Marg, during post monsoon and winter season which could have increased the traffic and thereby, the vehicular emissions.

3.1.6 Pearson Correlation Coefficient: Ozone and Its Chemical and Meteorological Precursors

Pearson Correlation coefficient was used to have better understanding which exists between tropospheric ozone and its chemical and meteorological precursors at Mandir Marg.

	Ozone	NOx	Ben	Temp.	RH	Solar Rad.	WS	WD
Ozone	1.00							
NOx	-0.36	1.00						
Ben	-0.26	0.72	1.00					
Temp.	0.66	-0.42	-0.44	1.00				
RH	-0.56	0.14	0.01	-0.64	1.00			
Solar Rad.	0.54	-0.34	-0.29	0.62	-0.40	1.00		
WS	0.33	-0.56	-0.54	0.41	-0.20	0.54	1.00	
WD	0.05	0.17	0.36	-0.23	-0.25	-0.16	-0.24	1.00

	Ozone	NOx	Ben	Temp.	RH	Solar Rad.	WS	WD
Ozone	1.00							
NOx	-0.29	1.00						
Ben	-0.11	0.55	1.00					
Temp.	0.59	-0.34	-0.24	1.00				
RH	-0.69	0.37	0.17	-0.90	1.00			
Solar Rad.	0.47	-0.35	-0.29	0.74	-0.63	1.00		
WS	0.30	-0.47	-0.46	0.52	-0.48	0.60	1.00	
WD	0.03	0.02	0.29	-0.20	0.06	-0.10	-0.39	1.00

	Ozone	NOx	Ben	Temp.	RH	Solar Rad.	WS	WD
Ozone	1.00							
NOx	-0.39	1.00						
Ben	-0.40	0.76	1.00					
Temp.	0.61	-0.36	-0.43	1.00				
RH	-0.68	0.41	0.45	-0.78	1.00			
Solar Rad.	0.64	-0.32	-0.33	0.70	-0.60	1.00		
WS	0.63	-0.52	-0.50	0.63	-0.58	0.75	1.00	
WD	-0.06	-0.10	0.05	-0.23	0.03	-0.25	-0.07	1.00

	Ozone	NOx	Ben	Temp.	RH	Solar Rad.	WS	WD
Ozone	1.00							
NOx	-0.33	1.00						
Ben	-0.34	0.75	1.00					
Temp.	0.54	-0.56	-0.57	1.00				
RH	-0.67	0.42	0.41	-0.72	1.00			
Solar Rad.	0.60	-0.34	-0.39	0.71	-0.64	1.00		
WS	0.54	-0.45	-0.50	0.70	-0.71	0.77	1.00	
WD	-0.17	0.08	0.24	-0.18	0.10	-0.36	-0.26	1.00

Figure 11. Pearson Correlation of Ozone and Its Chemical and Meteorological Precursors in Different Seasons (Note 1)

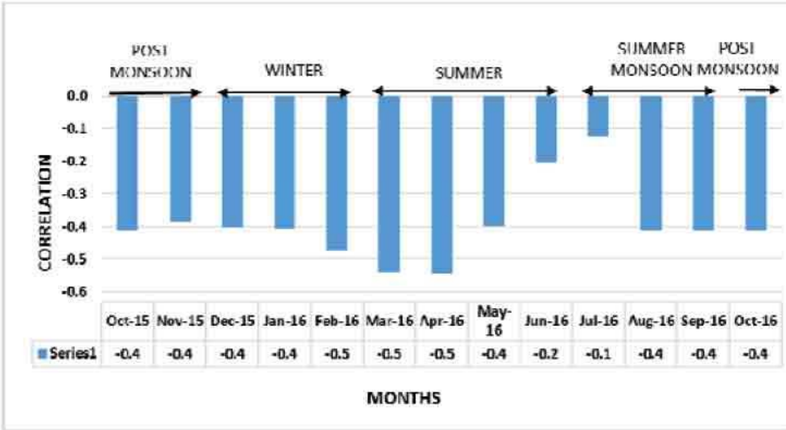


Figure 12. Pearson Correlation between Ozone (O_3) and Oxides of Nitrogen (NO_x) at Mandir Marg

Figure 12 depicts the correlation between tropospheric Ozone with NO_x in different seasons at Mandir Marg. Here, ozone and oxides of nitrogen were found to be negatively correlated in March 2016 ($r = -0.5$, $p = 0.95$). A strong negative correlation shows that concentration of precursor pollutants not only plays a significant role in the formation of ozone but also in its destruction (Marathe & Murthy, 2015). High vehicular emissions of NO_x from motor vehicles could be the reason for negative correlation between Ozone and Oxides of Nitrogen.

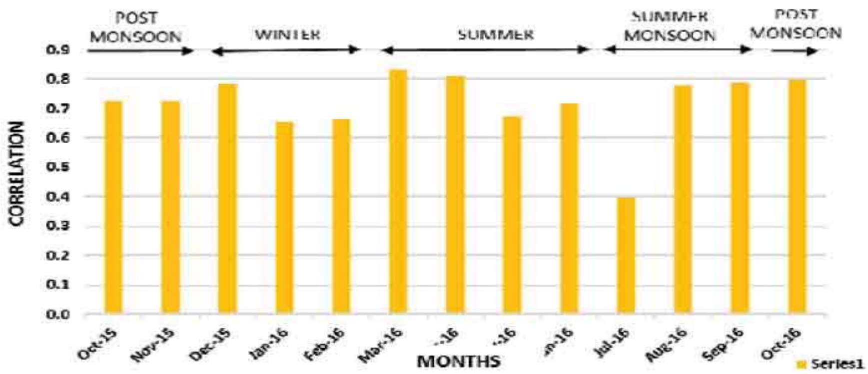


Figure 13. Pearson Correlation between Ozone (O_3) and Temperature (°C) in Different Seasons

Figure 13 shows the relation between temperature and tropospheric ozone in different seasons. A positive correlation is found in all the seasons especially in March 2016 ($r = 0.8$, $p = 0.95$). Positive correlation indicates that high tempe rature and high intensity of solar radiation boosts the production of tropospheric ozone. During the study period, the maximum average temperature (32.2°C) was recorded in May 2016.

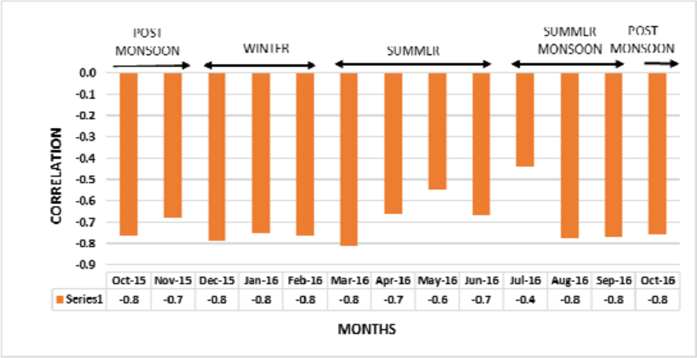


Figure 14. Pearson Correlation between Ozone (O_3) and Relative Humidity (RH) in Different Deasons

Figure 14 reveals the relationship between relative humidity and tropospheric ozone in various seasons. Though, a negative correlation was found in all seasons, a significantly negative correlation (r = -0.81, p= 0.95) was found in March 2016. Tiwari et al. (2008) stated that high relative humidity and low temperature, which explains the low O_3 concentrations during these seasons, this could be the reason for negative correlation between ozone and relative humidity.

3.2 Punjabi Bagh

3.2.1 Concentration of Ozone, Its Chemical and Meteorological Precursors

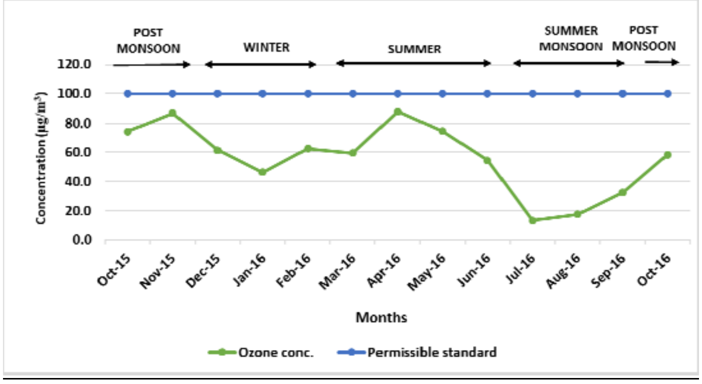


Figure 15. Seasonal Variation in Concentration of Ozone in Punjabi Bagh (O_3)

Figure 15 indicates the concentration of tropospheric ozone in various seasons at Punjabi Bagh. Ozone rose to its maximum concentration, i.e., 87.9 µg/m^3 in April 2016. This may be due to the effects of meteorological precursors like high temperature, low humidity. The minimum concentration (13.4 µg/m^3) was found in July 2016 indicating the reasons such as low intensity of solar radiation, low temperature, maximum humidity in July. The high relative humidity coupled with minimum temperature and sunshine hours, explain the low O_3 formation during monsoon (Tiwari et al., 2008).

3.2.2 Summer

Summer seasons starts from March and ends in June (IMD, 2010). The maximum concentration of tropospheric Ozone was found to be 74.5 μg/m^3 in May 2016 at Punjabi Bagh. High concentration of Ozone during the summer months can be attributed to high temperature, which favours photochemical production of O_3 (Tiwari et al., 2008). The minimum concentration, i.e., 54.7 μg/m^3 was observed in June 2016 which can be attributed to the photochemical breakdown of Ozone (Marathe & Murthy, 2015).

3.2.3 Winter

Winter in Delhi starts by early December. The maximum concentration of tropospheric Ozone (46.5 μg/m^3) was found in January 2016 at Punjabi Bagh. But the minimum concentration of Ozone, i.e., 62.8 μg/m^3 was observed in February 2016. The minimum concentration during this month could be due to greater atmospheric constancy and an increased incidence of nocturnal inversions, which may have enhanced the chemical scavenging of O_3 and dry deposition (Stephens, 1969; Tiwari et al., 2008).

CHEMICAL PRECURSORS								
YEAR	SEASONS	MONTHS	CONC.	OZONE	NOx	BENZENE	TOULENE	PXYLENE
			UNITS	[μg/m³]	[μg/m³]	[μg/m³]	[μg/m³]	[μg/m³]
2015	POST MONSOON	OCT	Avg ± S.D.	**90.1 ± 102.1**	**240.4 ± 255.8**	**1.8 ± 1.41**	**9.9 ± 9.6**	**1.9 ± 5.6**
			Min	14.9	37.7	0.5	2.4	0.8
			Max	169.4	325.2	2.9	22.0	12.2
		NOV	Avg ± S.D.	**64.6 ± 70.8**	**195.3 ± 200.9**	**1.3 ± 1.18**	**6.2 ± 6.2**	**1.3 ± 3.2**
			Min	19.7	63.6	0.7	2.8	1.3
			Max	281.5	617.7	4.4	26.8	14.5
	WINTER	DEC	Avg ± S.D.	**64.6 ± 70.8**	**195.3 ± 200.9**	**1.3 ± 1.18**	**6.2 ± 6.2**	**1 ± 3.2**
			Min	12.7	57.4	0.5	1.8	0.7
			Max	202.3	582.8	3.7	20.6	9.8
2016		JAN	Avg ± S.D.	**45.51 ± 50.7**	**200.1 ± 204.5**	**0.8 ± 0.54**	**3.8 ± 3.6**	**1.1 ± 2.2**
			Min	10.4	63.8	0.4	1.3	0.5
			Max	149.8	533.9	1.9	10.5	5.8
		FEB	Avg ± S.D.	**61.4 ± 48.8**	**153.2 ± 157.1**	**0.7 ± 0.5**	**2.9 ± 2.8**	**1 ± 1.4**
			Min	20.8	48.0	0.3	1.0	0.3
			Max	151.7	406.5	1.7	8.3	3.8
	SUMMER	MAR	Avg ± S.D.	**59.2 ± 57.4**	**137.1 ± 136.3**	**0.5 ± 0.3**	**2.2 ± 1.7**	**1.2 ± 1.0**
			Min	16.4	42.0	0.2	0.8	0.2
			Max	136.7	325.5	1.1	5.1	2.8
		APR	Avg ± S.D.	**89.9 ± 88.9**	**142.5 ± 157.0**	**0.6 ± 0.5**	**2.6 ± 2.7**	**1.1 ± 1.3**
			Min	9.9	32.1	0.2	0.7	0.2
			Max	196.4	334.7	1.6	7.3	2.9
		MAY	Avg ± S.D.	**71.5 ± 69.8**	**90.4 ± 63.9**	**0.6 ± 0.7**	**2.5 ± 3.2**	**1 ± 1.2**
			Min	12.9	35.7	0.2	0.8	0.2
			Max	172.7	215.8	1.6	8.2	3.6
		JUN	Avg ± S.D.	**54.8 ± 68.8**	**74.9 ± 47.5**	**0.7 ± 0.8**	**2.9 ± 3.6**	**2.5 ± 1.7**
			Min	9.9	33.2	0.2	0.8	0.2
			Max	182.4	162.5	2.4	10.1	4.5
	MONSOON	JUL	Avg ± S.D.	**13.42 ± 15.5**	**71.3 ± 41.8**	**0.4 ± 0.3**	**2.4 ± 1.9**	**4.6 ± 0.9**
			Min	5.9	32.3	0.2	1.0	0.3
			Max	42.6	143.6	1.1	5.9	3.0
		AUG	Avg ± S.D.	**26.8 ± 38.5**	**70.3 ± 44.6**	**0.4 ± 0.3**	**2.1 ± 1.6**	**5.6 ± 0.9**
			Min	5.9	27.3	0.1	0.7	0.2
			Max	73.2	153.3	0.9	4.9	2.7
		SEP	Avg ± S.D.	**59.7 ± 68.3**	**157.6 ± 183.6**	**1.2 ± 2.08**	**6.2 ± 9.8**	**2.8 ± 3.4**
			Min	7.7	27.0	0.2	0.9	0.2
			Max	104.3	140.6	1.2	5.6	2.6
	POST MONSOON	OCT	Avg ± S.D.	**71.5 ± 65.7**	**138.3 ± 131.3**	**1.5 ± 0.9**	**8.7 ± 8.1**	**2.8 ± 4.8**
			Min	12.3	46.1	0.3	1.5	0.6
			Max	180.2	420.9	4.2	19.0	6.8

Figure 16. Seasonal Variation in Ozone Concentration and Its Chemical Precursors at Punjabi Bagh

METEOROLOGICAL PRECURSORS								
YEAR	SEASONS	MONTHS	CONC.	TEPERATURE	RELATIVE HUMIDITY	SOLAR RADIATION	WIND DIRECTION	WIND SPEED
			UNITS	[øC]	[% Rh]	[W/m²]	[ø]	[m/s]
2015	POST MONSOON	OCT	Avg ± S.D.	**12 ± 4.5**	**66.4 ± 15.2**	**44.9 ± 91.1**	**99.4 ± 38.0**	**0.9 ± 0.5**
			Min	17.4	29.3	13.1	25.0	0.3
			Max	27.1	62.8	324.7	175.0	3.1
		NOV	Avg ± S.D.	**16.3 ± 4.9**	**54.8 ± 18.9**	**65.9 ± 72.0**	**78.5 ± 36.5**	**1.1 ± 0.6**
			Min	14.9	37.3	14.5	33.0	0.3
			Max	26.0	72.7	295.4	304.5	3.4
	WINTER	DEC	Avg ± S.D.	**23.3 ± 4.9**	**45.4 ± 18.9**	**109.2 ± 72.0**	**74.8 ± 36.5**	**1.4 ± 0.6**
			Min	8.4	40.9	14.2	33.0	0.3
			Max	19.8	78.5	237.3	304.5	3.4
2016		JAN	Avg ± S.D.	**31 ± 4.7**	**21.6 ± 14.8**	**112.8 ± 51.3**	**75.3 ± 35.5**	**1.3 ± 0.5**
			Min	7.5	42.5	14.0	0.0	0.0
			Max	17.9	80.6	180.7	175.0	2.8
		FEB	Avg ± S.D.	**32.2 ± 7.6**	**47.4 ± 16.9**	**108.6 ± 88.2**	**93.4 ± 32.2**	**1.5 ± 0.7**
			Min	10.3	32.9	14.4	20.0	0.3
			Max	27.9	74.0	279.7	150.0	3.7
		MAR	Avg ± S.D.	**32.5 ± 6.1**	**60.6 ± 16.7**	**112.4 ± 135.0**	**103.6 ± 34.2**	**1.4 ± 0.9**
			Min	15.6	25.6	14.4	23.0	0.3
			Max	29.9	66.8	391.7	142.0	4.5
	SUMMER	APR	Avg ± S.D.	**29.4 ± 5.0**	**68 ± 11.3**	**88.1 ± 131.4**	**122.8 ± 31.0**	**1.1 ± 0.8**
			Min	21.2	8.2	12.5	27.0	0.3
			Max	32.7	30.4	327.6	149.0	4.0
		MAY	Avg ± S.D.	**28.6 ± 5.1**	**70.6 ± 25.2**	**95.8 ± 127.7**	**112.6 ± 24.3**	**1.1 ± 0.7**
			Min	25.6	30.9	13.9	34.0	0.3
			Max	37.4	58.8	376.3	155.0	6.6
		JUN	Avg ± S.D.	**25.8 ± 4.1**	**53 ± 19.7**	**84.9 ± 125.7**	**96.6 ± 24.1**	**0.8 ± 0.5**
			Min	27.6	40.5	14.4	39.0	0.3
			Max	38.1	76.8	375.3	166.0	5.0
	MONSOON	JUL	Avg ± S.D.	**25.8 ± 4.0**	**50.5 ± 11.5**	**94.7 ± 103.3**	**109.6 ± 36.9**	**1 ± 0.5**
			Min	26.5	54.9	15.9	37.0	0.3
			Max	33.3	78.1	293.4	237.0	3.0
		AUG	Avg ± S.D.	**19.9 ± 2.9**	**54 ± 13.1**	**71.3 ± 119.1**	**111.2 ± 32.3**	**0.7 ± 0.5**
			Min	24.0	55.2	8.3	37.0	0.3
			Max	31.0	78.1	320.9	212.0	2.9
		SEP	Avg ± S.D.	**13.2 ± 4.4**	**59.2 ± 16.9**	**58.2 ± 118.8**	**116.6 ± 32.6**	**0.8 ± 0.6**
			Min	24.9	63.2	8.2	35.0	0.3
			Max	33.2	89.6	354.1	158.0	3.0
	POST MONSOON	OCT	Avg ± S.D.	**13.2 ± 4.6**	**59.2 ± 13.1**	**58.2 ± 123.7**	**116.6 ± 39.8**	**0.8 ± 0.7**
			Min	20.4	32.9	8.2	39.0	0.3
			Max	30.7	65.8	329.4	187.0	4.5

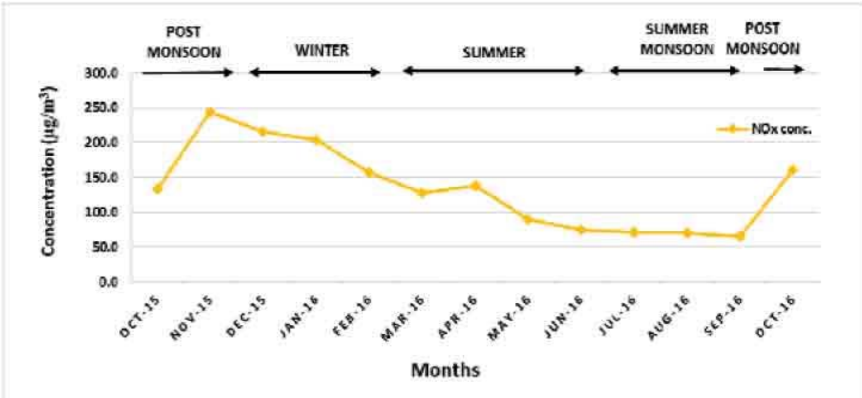
Figrue 17. Seasonal Variation of Ozone Concentration and Its Meteorological Precursors at Punjabi Bagh

3.2.4 Summer Monsoon

The monsoons in Delhi start by July and ends in late September (IMD, 2010). The minimum concentration of tropospheric ozone (13.4 µg/m^3) was observed in July 2016. This could due to high humidity and cloudy weather which leads to a decrease in the intensity of solar radiation.

3.2.5 Post Monsoon

Post monsoon starts by early October (IMD, 2010). This season ends by late November. The maximum concentration of tropospheric Ozone was found to be around 58.6 µg/m^3 in October 2016. This could be related to light traffic flow and low solar intensity which negates the chances of photo-dissociation (Marathe & Murthy, 2015).



Figuer 18. Seasonal Variation in Concentration of Oxides of Nitrogen (NO_x)

Figure 18 indicates that highest concentration of Nox, i.e., 243.9 µg/m^3 was found in November 2015. It could be due to various festivals like Diwali in November 2015 which could have increased the traffic flow on roads, thereby increasing the vehicular emissions.

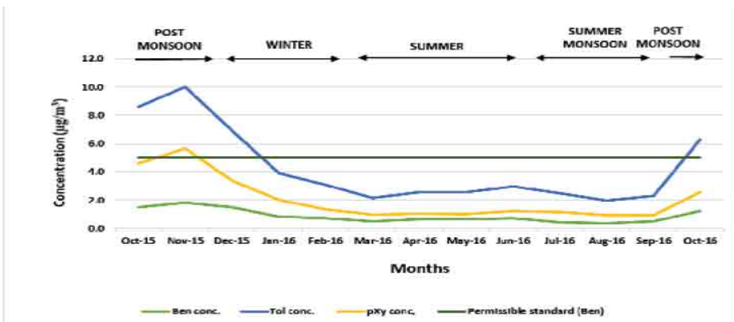


Figure 19. Seasonal Variation in Concentration of Benzene, Toluene and pXylene (BTX)

Figure 19 shows the maximum concentration of benzene (1.8 µg/m^3), Toluene (10 µg/m3) and pXylene (5.7µg/m^3) reported in November 2015. Th reason for high BTX can be attributed to high concentration of vehicular emissions in ambient air.

3.2.6 Pearson Correlation: Ozone and Its Chemical and Meteorological Precursors

	Ozone	NOx	Ben	Temp.	RH	Solar Rad.	WS	WD
Ozone	1.00							
NOx	-0.23	1.00						
Ben	-0.14	0.27	1.00					
Temp.	0.45	-0.18	0.07	1.00				
RH	-0.42	-0.06	0.07	-0.32	1.00			
Solar Rad.	0.43	-0.28	-0.12	0.41	-0.22	1.00		
WS	0.31	-0.53	-0.26	0.24	-0.09	0.41	1.00	
WD	-0.24	0.27	0.16	0.03	0.34	-0.12	-0.42	1.00

	Ozone	NOx	Ben	Temp.	RH	Solar Rad.	WS	WD
Ozone	1.00							
NOx	0.00	1.00						
Ben	-0.03	0.40	1.00					
Temp.	0.26	-0.16	-0.04	1.00				
RH	-0.26	0.07	0.15	-0.77	1.00			
Solar Rad.	0.13	-0.28	-0.11	0.54	-0.42	1.00		
WS	0.04	-0.47	-0.15	0.48	-0.36	0.54	1.00	
WD	-0.20	0.02	-0.02	0.02	-0.10	-0.13	-0.13	1.00

	Ozone	NOx	Ben	Temp.	RH	Solar Rad.	WS	WD
Ozone	1.00							
NOx	-0.30	1.00						
Ben	-0.17	0.43	1.00					
Temp.	0.55	-0.07	-0.10	1.00				
RH	-0.55	0.23	0.16	-0.45	1.00			
Solar Rad.	0.48	-0.25	-0.09	0.41	-0.37	1.00		
WS	0.53	-0.51	-0.30	0.27	-0.38	0.54	1.00	
WD	-0.29	0.34	0.41	-0.24	0.20	-0.23	-0.58	1.00

	Ozone	NOx	Ben	Temp.	RH	Solar Rad.	WS	WD
Ozone	1.00							
NOx	-0.27	1.00						
Ben	-0.13	0.67	1.00					
Temp.	0.41	-0.39	-0.29	1.00				
RH	-0.57	0.26	0.12	-0.46	1.00			
Solar Rad.	0.51	-0.30	-0.13	0.49	-0.41	1.00		
WS	0.51	-0.45	-0.29	0.50	-0.48	0.57	1.00	
WD	-0.34	0.39	0.33	-0.43	0.34	-0.32	-0.60	1.00

Figrue 20. Pearson Correlation of Ozone and Its Chemical and Meteorological Precursors in Different Seasons

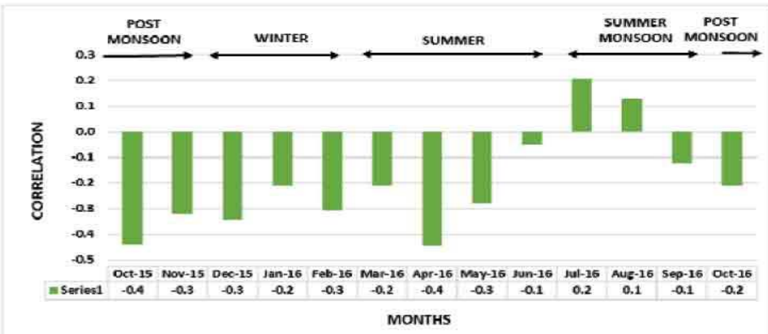


Figure 21. Pearson Correlation between Ozone (O_3) and Oxides of Nitrogen (NO_x) in Different Seasons

Figure 21 indicates the correlation between tropospheric ozone and oxides of nitrogen in different seasons in Punjabi Bagh. The weak positive correlation ($r = 0.1$, $p = 0.95$) was observed during summer monsoon, i.e., July 2016 which may be due to the low emissions from on road vehicles. Negative correlation ($r = -0.4$, $p = 0.95$) was found in April 2016 hinting at the burning of fossil fuel that emits NO_x (Russell, n.d).

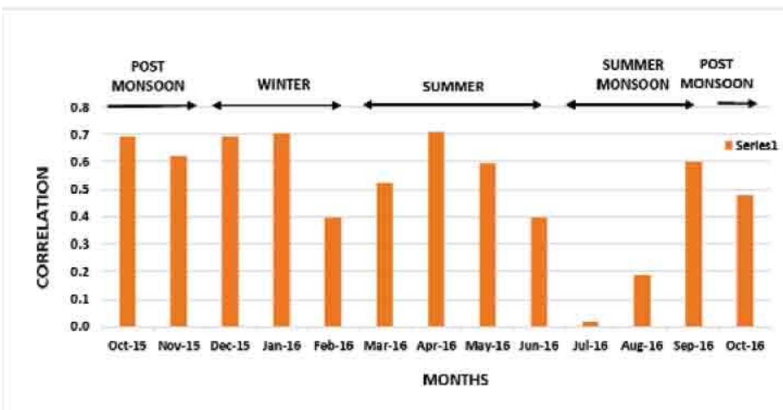


Figure 22. Pearson Correlation between Ozone (O_3) and Temperature (°C) in Different Seasons

Figure 22 depicts the correlation between tropospheric Ozone and ambient temperature in different seasons at Punjabi Bagh. A positive correlation was found in all the seasons amongst which a significant positive correlation (r = 0.7, p = 0.95) was observed in April 2016. It may be due to the maximum intensity of solar radiation and high temperature in summers.

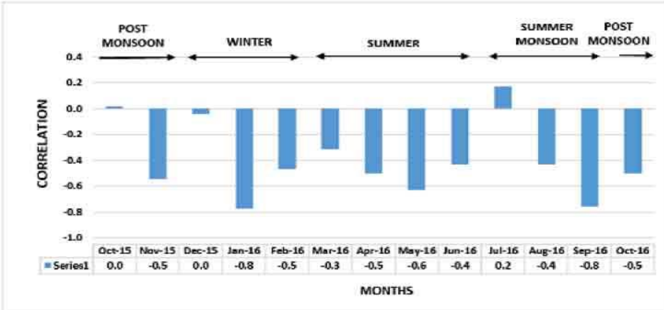


Figure 23. Pearson Correlation between Ozone (O_3) and Relative Humidity (RH) in Different Seasons

Figure 23 indicates the relationship between relative humidity and tropospheric ozone. A significantly negative correlation (r = -0.81, p = 0.95) was found in January 2016. The reason for which could be the presence of high humidity levels. A positively weak correlation (r = 0.2, p = 0.95) was found in July 2016 (Summer-monsoon). When the humidity is higher, the major photochemical pathways for removal of ozone get boosted (Selvaraj et al., 2013). Correlation between ozone and relative humidity was more noticeable in monsoons than summer in this study. Hence the ozone concentration has a strong dependence on humidity and the concentration of relative humidity is inversely proportional to concentration of tropospheric ozone (Nishanth et al., 2011).

3.3 Anand Vihar ISBT

3.3.1 Concentration of Ozone, Its Chemical and Meteorological Precursors

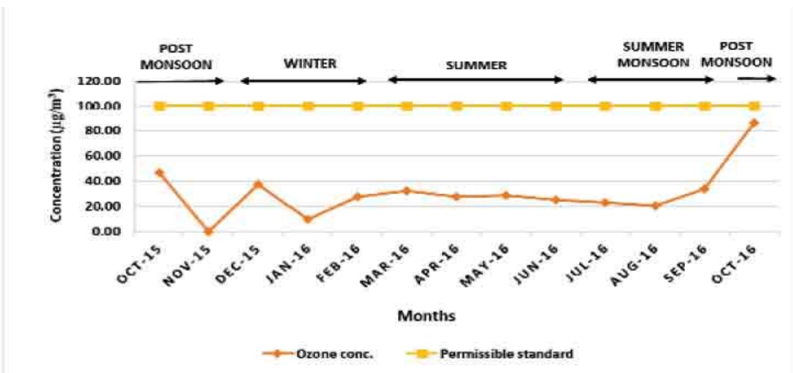


Figure 24. Seasonal Variation in Concentration of Ozone (O_3) at Anand Vihar ISBT

Figure 24 indicates the concentration of tropospheric ozone in different seasons. Maximum concentration (86.3 $\mu g/m^3$) was observed in October 2016 hinting at the reasons being heavy traffic flow which leads to the emission of gaseous pollutant from the motor vehicles and the high emissions from industries which are situated near Anand Vihar ISBT.

3.3.2 Summer

March to June is considered in a summer season in Delhi (IMD, 2010). The maximum concentration of tropospheric Ozone was found to be around 28.7 $\mu g/m^3$ in May 2016 at Anand Vihar ISBT. This may be due to the meteorological factors such as high temperature and high solar intensity which contribute in the formation of tropospheric ozone, as reported by Tiwari (2008). The minimum concentration, i.e., 25$\mu g/m^3$ was observed in June 2016.

3.3.3 Winter

According to IMD (2010), this season starts from December and ends till late February. The high concentration of tropospheric Ozone (37.14 $\mu g/m^3$) was observed in December 2016 at Anand Vihar ISBT. The season is marked with minimum temperatures, especially during the night. Since there is inadequate amount of thermal inversion in winters, the pollutants tend to be trapped near the ground level. Therefore, this season also experience the high pollution episodes (Marathe & Murthy, 2015). This could be the reason of maximum concentration of Ozone in winter season. But the minimum concentration of Ozone, i.e., 9.7 $\mu g/m^3$ was observed in January 2016 which could possibly be due to the low solar intensity and temperature.

			CHEMICAL PRECURSORS					
YEAR	SEASONS	MONTHS	CONC.	OZONE	NOx	BENZENE	TOULENE	PXYLENE
			UNITS	[μg/m³]	[μg/m³]	[μg/m³]	[μg/m³]	[μg/m³]
2015	POST MONSOON	OCT	Avg ± S.D.	**46.4 ±77.3**	**238.8 ± 205.5**	**19.0 ± 11.2**	**65.6 ± 71**	**12.5 ± 17.1**
			Min	0.4	0.4	3.4	6.5	0.0
			Max	775.1	1568.4	62.3	592.0	89.9
		NOV	Avg ± S.D.	**9.6 ± 3.2**	**456.7 ± 442.1**	**14.3 ± 8.7**	**37.6 ± 41.1**	**6.2 ± 17.1**
			Min	3.9	25.6	2.1	2.9	0.0
			Max	13.2	1873.5	54.5	364.8	74.9
	WINTER	DEC	Avg ± S.D.	**37.1 ± 88.4**	**704.2 ± 431.2**	**8.0 ± 3.8**	**21.8 ± 16**	**1.4 ± 1.9**
			Min	5.6	85.9	1.4	2.2	0.0
			Max	735.6	1832.4	21.9	117.5	13.4
2016		JAN	Avg ± S.D.	**9.6 ± 3.2**	**1368.2 ± 385.9**	**7.8 ± 2.7**	**23.5 ± 9.8**	**1.3 ± 1**
			Min	3.9	637.2	4.0	11.6	0.2
			Max	13.2	1634.6	10.8	33.6	2.7
		FEB	Avg ± S.D.	**27.5 ± 18.9**	**174.8 ± 97.5**	**20.3 ± 8.4**	**40.0 ± 25.4**	**6.0 ± 6.8**
			Min	10.6	76.8	8.4	19.3	0.7
			Max	65.3	491.2	36.4	105.4	22.0
	SUMMER	MAR	Avg ± S.D.	**32.12 ± 43.1**	**240.4 ± 223.9**	**22.2 ± 13.2**	**61.3 ± 78.5**	**11.8 ± 17**
			Min	0.0	32.1	2.9	7.6	0.0
			Max	457.1	1538.6	63.3	1267.3	112.2
		APR	Avg ± S.D.	**27.8 ± 21.6**	**317.8 ± 285.9**	**19.9 ± 14.1**	**44.3 ± 44.7**	**10.4 ± 14.1**
			Min	6.6	22.6	2.4	5.3	0.1
			Max	167.1	1711.1	128.4	420.3	82.9
		MAY	Avg ± S.D.	**28.6 ± 27.9**	**167.5 ± 156.6**	**13.3 ± 8.5**	**40.1 ± 38.6**	**6.1 ± 9.5**
			Min	0.1	20.1	2.1	3.8	0.0
			Max	457.2	1089.6	57.1	251.8	79.3
		JUN	Avg ± S.D.	**25.0 ± 35.4**	**102.4 ± 93.7**	**9.1 ± 6.6**	**34.6 ± 34**	**3.3 ± 5.9**
			Min	0.2	8.9	0.5	2.0	0.0
			Max	437.4	756.7	45.3	318.0	50.8
	MONSOON	JUL	Avg ± S.D.	**22.8 ± 28.6**	**114.7 ± 77.12**	**6.4 ± 3.4**	**31.3 ± 24.5**	**3.7 ± 4.5**
			Min	0.4	21.5	0.6	3.4	0.1
			Max	440.4	490.5	23.4	198.3	34.7
		AUG	Avg ± S.D.	**20.3 ± 25**	**69.6 ± 69.4**	**2.4 ± 2.9**	**18.1 ± 26.4**	**2.1 ± 4.7**
			Min	2.1	15.4	0.3	1.0	0.1
			Max	395.3	537.0	28.5	159.1	42.2
		SEP	Avg ± S.D.	**33.8 ± 35.6**	**147.5 ± 89**	**5.6 ± 3.8**	**24.0 ± 22**	**1.3 ± 1**
			Min	0.0	14.4	0.1	2.1	0.2
			Max	457.1	569.8	23.8	193.2	2.7
	POST MONSOON	OCT	Avg ± S.D.	**86.3 ± 167.9**	**330.1 ± 280.5**	**13.8 ± 12.4**	**48.2 ± 62.2**	**11.6 ± 15.4**
			Min	0.0	21.7	1.0	3.7	0.0
			Max	1554.9	1847.1	60.2	476.7	90.3

Table 25. Seasonal Variation of Ozone Concentration and Its Chemical Precursors at Anand Vihar ISBT

METEOROLOGICAL PRECURSORS								
YEAR	SEASONS	MONTHS	CONC.	TEPERATURE	RELATIVE HUMIDITY	SOLAR RADIATION	WIND DIRECTION	WIND SPEED
			UNITS	[øC]	[% Rh]	[W/m^2]	[ø]	[m/s]
2015	POST MONSOON	OCT	Avg ± S.D.	28.8 ± 4.9	46.8 ± 13.3	193.4 ± 193	176.8 ± 78.4	1.12 ± 0.79
			Min	17.3	19.0	12.3	28.4	0.3
			Max	39.0	75.6	451.0	285.9	4.2
		NOV	Avg ± S.D.	22.7 ± 4.3	51.9 ± 13.7	152.9 ± 185.9	175.5 ± 80.2	0.8 ± 0.6
			Min	14.5	24.8	12.2	16.4	0.3
			Max	32.5	82.8	447.2	290.5	3.9
	WINTER	DEC	Avg ± S.D.	16.3 ± 4.7	59.8 ± 11.8	102.2 ± 160.7	194.1 ± 77.4	0.6 ± 0.4
			Min	8.3	30.0	12.3	28.9	0.3
			Max	27.8	80.8	442.8	292.9	2.5
2016		JAN	Avg ± S.D.	14.1 ± 1.1	61.1 ± 3.2	12.5 ± 0.09	180.4 ± 54	0.2 ± 0.1
			Min	12.5	56.1	12.4	93.8	0.3
			Max	15.9	64.9	12.7	252.7	0.3
		FEB	Avg ± S.D.	16.8 ± 3.7	52.0 ± 17.6	166.8 ± 190.7	261.1 ± 30.3	1.1 ± 0.3
			Min	12.2	27.2	12.3	159.8	0.6
			Max	23.5	74.6	443.8	287.0	1.9
	SUMMER	MAR	Avg ± S.D.	33.4 ± 49	44.3 ± 14.9	227.8 ± 218.8	195.3 ± 83.1	3.2 ± 8.7
			Min	16.0	13.1	11.3	0.3	0.3
			Max	682.0	77.0	740.1	294.9	65.7
		APR	Avg ± S.D.	33.3 ± 5.3	24.7 ± 10.7	213.7 ± 194.4	228.8 ± 61.8	1.8 ± 1.1
			Min	21.6	4.0	12.4	51.3	0.3
			Max	44.2	54.3	457.4	293.3	5.7
		MAY	Avg ± S.D.	34.7 ± 5.3	36.2 ± 15.0	220.7 ± 193.4	163.1 ± 70.7	2.5 ± 1.4
			Min	23.5	4.2	12.0	68.7	0.3
			Max	47.5	77.3	466.1	296.9	7.3
		JUN	Avg ± S.D.	34.5 ± 4.2	49.7 ± 13.8	229.8 ± 191	143.4 ± 71.7	2.7 ± 1.1
			Min	24.9	16.6	9.9	71.0	0.3
			Max	46.6	78.1	456.1	295.9	7.4
	MONSOON	JUL	Avg ± S.D.	31.0 ± 3.1	68.5 ± 10.6	217.8 ± 184.9	155.2 ± 69.6	1.8 ± 0.9
			Min	21.5	38.4	12.7	68.2	0.3
			Max	39.8	85.7	455.3	295.4	5.7
		AUG	Avg ± S.D.	30.1 ± 3.1	69.7 ± 11.2	165.3 ± 179.9	146.2 ± 59.1	1.8 ± 1.2
			Min	24.1	45.7	2.2	76.5	0.3
			Max	41.8	87.7	459.8	317.0	6.0
		SEP	Avg ± S.D.	31.5 ± 3.1	57.3 ± 11.0	203.0 ± 192.7	188.0 ± 79.6	1.4 ± 0.7
			Min	25.6	32.3	12.8	65.0	0.3
			Max	39.2	83.8	459.5	296.3	4.7
	POST MONSOON	OCT	Avg ± S.D.	28.6 ± 4.7	52.8 ± 14.5	178 ± 185.6	186.2 ± 75.2	0.7 ± 0.56
			Min	18.7	22.3	12.4	45.1	0.3
			Max	37.5	79.1	439.2	300.2	3.7

Figure 26. Seasonal Variation of Ozone Concentration and Its Meteorological Precursors at Anand Vihar ISBT

3.3.4 Summer Monsoon

This season starts by July and ends in late September in Delhi (IMD, 2010). The minimum concentration of tropospheric ozone (20.4μg/m^3) was observed in August 2016. High levels of humidity and rainfall could be the reason behind this minimum concentration of tropospheric ozone at Anand Vihar ISBT.

3.3.5 Post Monsoon

This season starts from early October and ends by late November (IMD, 2010). The maximum concentration of tropospheric Ozone was observed to be 86.3 μg/m^3 in October 2016, the possible reasons of which could be the heavy traffic flow, emission from industries and existence of Gazipur landfill near the monitoring site of Anand Vihar ISBT.

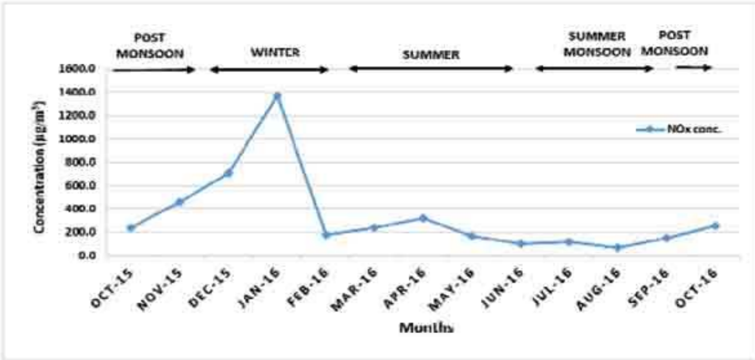


Figure 27. Seasonal Variation in Concentration of Oxides of Nitrogen (NO_x) at Anand Vihar ISBT

Figure 27 indicates the peak of concentration NO_x (Oxides of Nitrogen), i.e., 1368.2 µg/m^3 in January 2016. This area has a toxic combination of industries located in the neighbouring Sahibabad area in Ghaziabad, a busy bus terminal, railway station and the Ghazipur landfill site. Hundreds of diesel-belching interstate buses entering the terminal emit the NO_x in high amount.

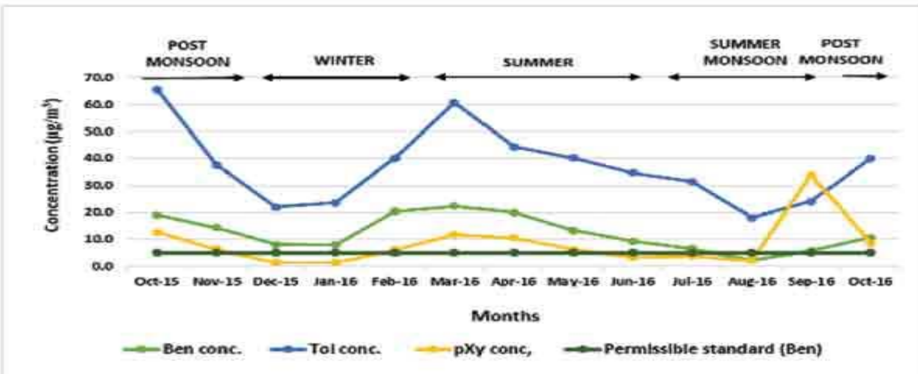


Figure 28. Seasonal Variation in Concentration of Benzene, Toluene and pXylene (BTX)

Figure 28 indicates that the maximum concentration of benzene (22.3 µg/m^3) was observed in March (summer), the maximum concentration of toluene (65.6 µg/m3) was found in October 2015 (post-monsoon) and maximum concentration of pXylene was found to be 33.8 µg/m^3 in September 2016 (summer-monsoon). The reason for high concentration of BTX could be due to the presence of industrial areas, Sahibabad and Patparganj situated close to Anand Vihar ISBT and several industrial units that use a variety of polluting fuels. National Highway (NH) 24 is also laid out close to this area. NH-24 is a heavy traffic route, used by many vehicles to enter and exit Delhi. The highway remains chronically congested and adds to vehicular emissions (CSE, 2016).

3.3.6 Pearson Correlation: Ozone and Its Chemical and Meteorological Precursors

	Ozone	NOx	Ben	Temp.	RH	Solar Rad.	WS	WD
Ozone	1.00							
NOx	0.04	1.00						
Ben	0.03	0.61	1.00					
Temp.	-0.04	-0.10	-0.04	1.00				
RH	-0.12	-0.14	0.03	-0.23	1.00			
Solar Rad.	0.07	-0.21	-0.27	0.32	-0.36	1.00		
WS	-0.07	-0.21	-0.11	0.80	-0.06	0.32	1.00	
WD	0.03	0.30	0.08	-0.15	-0.42	0.07	-0.26	1.00

	Ozone	NOx	Ben	Temp.	RH	Solar Rad.	WS	WD
Ozone	1.00							
NOx	0.09	1.00						
Ben	0.09	0.51	1.00					
Temp.	0.11	0.03	-0.08	1.00				
RH	-0.17	-0.12	0.09	-0.86	1.00			
Solar Rad.	0.09	-0.05	-0.26	0.61	-0.90	1.00		
WS	-0.08	-0.44	-0.35	0.25	-0.18	0.42	1.00	
WD	-0.03	0.53	0.13	0.20	-0.25	0.10	-0.36	1.00

	Ozone	NOx	Ben	Temp.	RH	Solar Rad.	WS	WD
Ozone	1.00							
NOx	0.13	1.00						
Ben	0.01	0.06	1.00					
Temp.	0.10	-0.44	-0.22	1.00				
RH	0.11	0.21	0.05	-0.55	1.00			
Solar Rad.	-0.02	-0.38	-0.06	0.65	-0.36	1.00		
WS	-0.13	-0.57	0.03	0.52	-0.44	0.61	1.00	
WD	-0.34	-0.24	0.05	0.19	-0.45	0.14	0.35	1.00

	Ozone	NOx	Ben	Temp.	RH	Solar Rad.	WS	WD
Ozone	1.00							
NOx	0.06	1.00						
Ben	0.15	0.39	1.00					
Temp.	-0.03	-0.48	-0.31	1.00				
RH	0.08	0.26	0.25	-0.62	1.00			
Solar Rad.	0.00	-0.31	-0.34	0.60	-0.57	1.00		
WS	-0.09	-0.48	-0.41	0.44	-0.39	0.52	1.00	
WD	-0.18	-0.09	-0.27	0.29	-0.44	0.34	0.04	1.0

Table 29. Pearson Correlation of Ozone and Its Chemical and Meteorological Precursors in Different Seasons

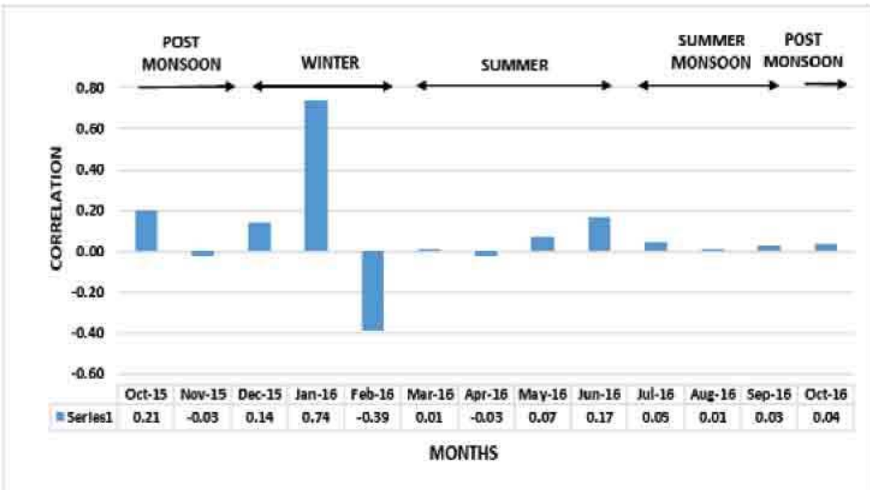


Figure 30. Pearson Correlation between Ozone (O_3) and Oxides of Nitrogen (NO_x) in Different Seasons

Figure 30 shows the correlation between Ozone and oxides of Nitrogen in different seasons. Correlation between NO_x and O_3 was found to be significantly positive (r = 0.74, p = 0.95) during winters in 2016. This may be due to the increase in combustion of fossil fuel and burning of solid waste in open. According to Humdun et al. (2015), the concentration of Ozone is inversely proportional to the NO_x.

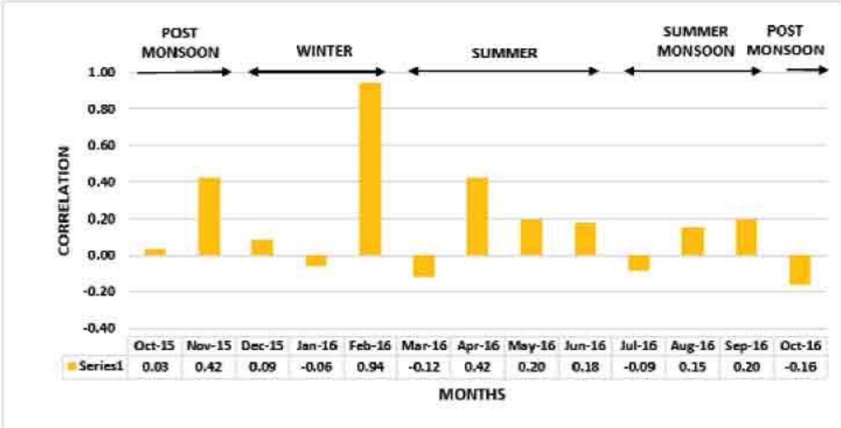


Figure 31. Pearson Correlation between Ozone (O_3) and Temperature (°C) in Different Seasons

Figure 31 depicts a strong positive correlation (r = 0.94, p = 0.95) between ozone and temperature during late winters (February, 2016). A strong positive correlation between O_3 and temperature indicates that radiation controls the temperature and hence the photolysis efficiency become higher (Nishant et al., 2012). A weak negative correlation (r = -0.16, p = 0.95) was found in October 2016, the possible reasons for which could be the fall in the ambient temperature.

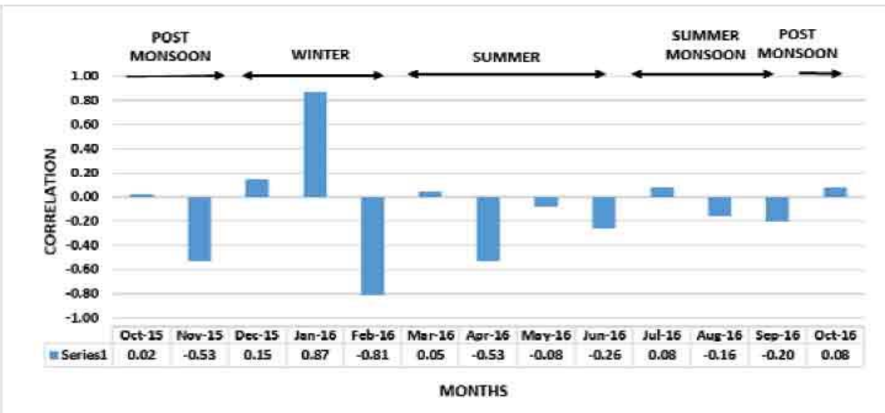


Figure 32. Pearson Correlation between Ozone ($O_{3)}$ and Relative Humidity (RH) in Different Seasons

Figure 32 shows a significant positive correlation (r = 0.87, p = 0.95) between ozone and relative humidity during winters in January 2016. Meteorological condition like relative humidity can affect ozone production and dispersion at local and regional scales. High relative humidity is associated with low O_3 levels due to wet O_3 deposition, that could be the possible reason of strong positive correlation (Humdun et al., 2015).

3.4 R.K. Puram

3.4.1 Concentration of Ozone, Its Chemical and Meteorological Precursors

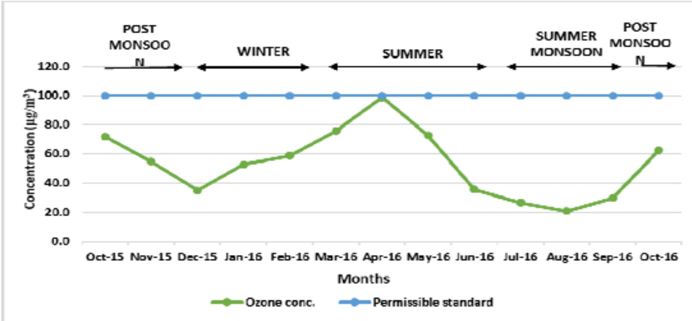


Figure 33. Seasonal Variation in Concentration of Ozone (O_3) at R.K.Puram

Figure 33 depicts the concentration of tropospheric ozone in different seasons at R.K.Puram. Maximum concentration (98.8 μg/m^3) was observed in April 2016. It could possibly be due to the heavy traffic flow and high emission of gaseous pollutant from the motor vehicles. The minimum concentration (20.9 μg/m^3) was found in August 2016, the reasons for which could cloudy weather, heavy rainfall, high levels of humidity and low intensity of Solar radiation in monsoon.

3.4.2 Summer

Summer starts from March and ends till June in Delhi (IMD, 2010). The maximum concentration of tropospheric Ozone was found to be around 98.8 μg/m^3 in April 2016. This is may be due to the high temperature and solar intensity in summer season.

3.4.3 Winter

This season starts from December and ends till late February (IMD, 2010). The maximum concentration of tropospheric Ozone (58.8 μg/m^3) was recorded in February 2016. The possible reasons could be due to minimum humidity. The highest O_3 observed in winter is attributed to a lower mixing height that results in trapping of pollutants near the earth's surface due to temperature inversion in the similar study of Nishant et al. (2012). But the minimum concentration of Ozone, i.e., 34.9 μg/m^3 was observed in December 2016 due to limited amount of thermal inversion in this season (Marathe & Murthy, 2015).

YEAR	SEASONS	MONTHS	CONC.	OZONE	NOx	BENZENE	TOULENE	PXYLENE
				CHEMICAL PRECURSORS				
			UNITS	[μg/m³]	[μg/m³]	[μg/m³]	[μg/m³]	[μg/m³]
2015	POST MONSOON	OCT	Avg ± S.D.	71.8 ± 51.3	291.4 ± 276.8	10.5 ± 4.6	29.7 ± 13.03	16.8 ± 10.3
			Min	3.1	20.5	0.8	4.5	0.3
			Max	496.9	1592.7	26.8	75.9	70.5
		NOV	Avg ± S.D.	54.8 ± 71.1	376.4 ± 257.0	13.3 ± 3.4	33.8 ± 10.6	20.51 ± 7.5
			Min	0.1	19.5	2.4	4.4	0.9
			Max	307.5	1497.7	29.3	70.8	53.6
	WINTER	DEC	Avg ± S.D.	34.8 ± 78.5	330.1 ± 224.5	11.8 ± 3.5	26.3 ± 10.6	15.0 ± 7.13
			Min	0.8	19.9	2.2	4.3	0.0
			Max	247.9	1795.9	23.8	80.2	46.9
2016		JAN	Avg ± S.D.	52.7 ± 88.6	280.9 ± 238.5	10.2 ± 3.49	22.9 ± 10.5	11.1 ± 6.7
			Min	0.0	27.6	1.5	2.5	0.4
			Max	250.5	1286.2	21.4	59.7	41.1
		FEB	Avg ± S.D.	58.8 ± 70.7	237.3 ± 124.4	6.8 ± 2.01	17.5 ± 6.9	7.8 ± 4.2
			Min	6.0	17.4	1.0	2.1	0.2
			Max	349.3	1468.7	16.6	51.5	33.4
	SUMMER	MAR	Avg ± S.D.	75.7 ± 32.3	183.5 ± 37.8	5.1 ± 0.78	14.3 ± 3.6	6.3 ± 1.5
			Min	0.9	10.1	0.3	0.4	0.0
			Max	341.9	1174.0	15.1	41.0	27.8
		APR	Avg ± S.D.	98.8 ± 27.7	187.9 ± 54.3	4.6 ± 1.0	12.7 ± 4.5	5.8 ± 2.1
			Min	6.3	13.0	0.4	1.4	0.3
			Max	404.0	1218.5	14.1	43.3	26.1
		MAY	Avg ± S.D.	72.7 ± 25.2	109.0 ± 46.3	2.6 ± 0.9	8.2 ± 3.8	3.4 ± 1.7
			Min	2.2	13.3	0.2	0.8	0.0
			Max	377.8	847.0	10.9	35.1	23.8
		JUN	Avg ± S.D.	35.5 ± 28.2	55.7 ± 101.1	1.3 ± 1.11	5.2 ± 4.51	1.6 ± 2.2
			Min	0.9	13.7	0.1	0.3	0.0
			Max	211.9	342.8	5.2	21.6	10.0
	MONSOON	JUL	Avg ± S.D.	26.5 ± 70.4	64.8 ± 294.8	1.1 ± 7.6	5.4 ± 17.4	1.9 ± 14.3
			Min	3.4	13.4	0.0	0.1	0.0
			Max	420.6	407.6	8.2	32.1	14.1
		AUG	Avg ± S.D.	20.8 ± 81.4	56.9 ± 308.4	0.9 ± 6.3	4.5 ± 16.8	1.5 ± 14.7
			Min	0.5	8.9	0.0	0.2	0.0
			Max	372.1	337.2	5.8	23.6	12.3
		SEP	Avg ± S.D.	29.6 ± 64.0	101.3 ± 357.2	1.2 ± 5.9	5.5 ± 16.6	2.1 ± 14.5
			Min	0.2	10.8	0.0	0.2	0.0
			Max	215.3	601.3	6.5	19.2	10.6
	POST MONSOON	OCT	Avg ± S.D.	60.7 ± 45.5	280.5 ± 341.5	6.1 ± 5.2	17.5 ± 15.3	10.4 ± 12.8
			Min	3.3	18.5	0.1	0.9	0.3
			Max	496.9	1592.7	33.9	81.0	70.5

Figrue 34. Seasonal Variation Ozone Concentration and Its Chemical Precursors at R.K.Puram

METEOROLOGICAL PRECURSORS								
YEAR	SEASONS	MONTHS	CONC.	TEPERATURE	RELATIVE HUMIDITY	SOLAR RADIATION	WIND DIRECTION	WIND SPEED
			UNITS	[øC]	[% Rh]	[W/m²]	[ø]	[m/s]
2015	POST MONSOON	OCT	Avg ± S.D.	**24.7 ± 5.1**	**52.7 ± 16.8**	**112.8 ± 93.2**	**210.1 ± 47.0**	**0.8 ± 0.6**
			Min	12.3	18.9	2.7	102.0	0.3
			Max	36.4	82.9	396.8	291.0	3.1
		NOV	Avg ± S.D.	**18.2 ± 5.9**	**59.5 ± 19.1**	**82.5 ± 126.7**	**219.7 ± 52.7**	**0.5 ± 0.8**
			Min	8.7	21.8	2.3	91.0	0.3
			Max	30.4	87.7	372.8	315.0	3.1
	WINTER	DEC	Avg ± S.D.	**11.8 ± 5.9**	**63.3 ± 19.7**	**65.3 ± 156.5**	**223.0 ± 54.2**	**0.8 ± 0.9**
			Min	1.9	19.3	2.4	86.0	0.3
			Max	25.6	88.0	338.5	294.0	3.0
2016		JAN	Avg ± S.D.	**11.2 ± 6.1**	**69.7 ± 12.1**	**60.4 ± 154.**	**205.1 ± 50.4**	**0.9 ± 0.9**
			Min	1.7	27.7	1.2	86.0	0.3
			Max	25.9	88.4	337.9	293.0	3.0
		FEB	Avg ± S.D.	**15.3 ± 5.7**	**56.4 ± 15.6**	**88.5 ± 155.5**	**208.3 ± 50.4**	**1.1 ± 0.9**
			Min	4.3	15.5	2.6	35.0	0.3
			Max	29.1	86.2	405.3	312.0	3.9
	SUMMER	MAR	Avg ± S.D.	**22.1 ± 4.2**	**48.9 ± 15.4**	**122.7 ± 148.8**	**204.9 ± 46.2**	**1.3 ± 0.8**
			Min	12.2	9.8	0.9	90.0	0.3
			Max	37.6	86.1	421.2	307.0	4.6
		APR	Avg ± S.D.	**30.1 ± 3.3**	**25.8 ± 12.4**	**130.0 ± 130.1**	**215.3 ± 52.6**	**1.3 ± 0.7**
			Min	18.8	6.8	2.8	87.0	0.3
			Max	45.5	66.9	406.0	306.0	4.2
		MAY	Avg ± S.D.	**32.2 ± 4.0**	**39.2 ± 11.3**	**135.3 ± 137.1**	**195.5 ± 55.1**	**1.54 ± 0.8**
			Min	20.3	7.4	2.5	105.0	0.3
			Max	44.4	82.8	404.6	310.0	5.2
		JUN	Avg ± S.D.	**30.8 ± 3.8**	**55.0 ± 13.6**	**127.4 ± 146.8**	**183.2 ± 51.8**	**1.5 ± 0.6**
			Min	21.9	22.4	2.0	112.0	0.3
			Max	42.0	86.7	399.8	315.0	4.9
	MONSOON	JUL	Avg ± S.D.	**27.9 ± 5.7**	**71.6 ± 18.0**	**99.0 ± 150.5**	**191.5 ± 46.0**	**1.1**
			Min	22.1	38.5	2.1	115.0	0.3
			Max	36.4	87.7	398.3	322.0	3.3
		AUG	Avg ± S.D.	**29.3 ± 5.7**	**69.8 ± 17.5**	**108.5 ± 147.6**	**195.7 ± 46.1**	**1.4 ± 0.6**
			Min	23.1	45.3	2.2	122.0	0.3
			Max	41.8	87.7	400.3	321.0	3.7
		SEP	Avg ± S.D.	**28.4 ± 5.2**	**60.6 ± 17.9**	**116.4 ± 119.5**	**222.5 ± 45.0**	**0.9 ± 0.4**
			Min	21.9	33.0	2.9	59.0	0.3
			Max	40.0	86.0	395.7	324.0	3.3
	POST MONSOON	OCT	Avg ± S.D.	**24.3 ± 5.6**	**50.7 ± 19.0**	**112.9 ± 99.2**	**232.6 ± 44.8**	**0.8 ± 0.6**
			Min	13.8	18.6	2.7	70.0	0.3
			Max	36.4	84.6	396.8	330.0	3.1

Figure 35. Seasonal Variation of Ozone Concentration and Its Meteorological Precursors at R.K.Puram

3.4.4 Summer-Monsoon

According to IMD (2010), this season starts by July and ends in late September in Delhi. This season is marked by high level of humidity and rainfall. The minimum concentration of tropospheric ozone (20.9 μg/m^3) was observed in August 2016 at R.K. Puram. High levels of humidity and cloudy weather condition leads to decrease in intensity of solar radiation therefore which could be the reason behind this minimum concentration of tropospheric ozone.

3.4.5 Post Monsoon

This season starts from early October and ends by late November (IMD, 2010). The maximum concentration of tropospheric Ozone was found to be 62.5 µg/m^3 in October 2016. According to Tnai et al. (2007), the increased photochemical reaction via stronger solar radiation can explain the high ozone concentration in post monsoon.

Figure 36. Seasonal Variation in Concentration of Oxides of Nitrogen (NO_x)

Figure 36 shows that maximum concentration (376.4 4 µg/m3) was recorded in November 2015. The reason could be either the festival of Diwali in November 2015 which led to the maximum emissions of NO_x from crackers or the heavy traffic flow during November 2015. But minimum concentration was found in June 2016 with concentration of 55 µg/m^3 which could be due to low vehicular emission and light traffic flow.

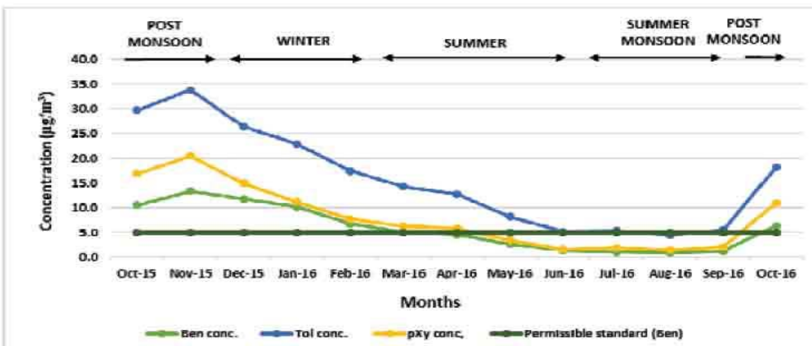


Figure 37. Seasonal Variation in Concentration of Benzene, Toluene and pXylene (BTX)

Figure 37 indicates that the maximum concentration of benzene (13.4 µg/m^3), toluene (33.8 µg/m3) and pXylene (20.5 µg/m^3) was found in November 2015. The concentration of benzene did exceed the permissible standard (5µg/m^3) NAAQS (2009). The reason of maximum concentration of BTX could be the well connectivity of DTC (Delhi Transport Corporation) buses to different part of city and existence of government & private schools at RK Puram that leads to the increase emissions from motor vehicles and buses due to heavy traffic and also the festival of Diwali in November 2015.

3.4.6 Pearson Correlation of Ozone with Its Chemical and Meteorological Precursors

	Ozone	NOx	Ben	Temp.	RH	Solar Rad.	WS	WD
Ozone	1.00							
NOx	-0.30	1.00						
Ben	0.25	0.82	1.00					
Temp.	0.52	-0.40	-0.49	1.00				
RH	-0.65	0.17	0.13	-0.67	1.00			
Solar Rad.	0.60	-0.37	-0.32	0.59	-0.47	1.00		
WS	0.38	-0.53	-0.53	0.40	-0.28	0.53	1.00	
WD	-0.23	0.44	0.46	-0.27	0.06	-0.23	-0.42	1.00

	Ozone	NOx	Ben	Temp.	RH	Solar Rad.	WS	WD
Ozone	1.00							
NOx	0.02	1.00						
Ben	0.07	0.83	1.00					
Temp.	0.18	-0.28	-0.27	1.00				
RH	-0.26	0.24	0.29	-0.78	1.00			
Solar Rad.	0.20	-0.36	-0.36	0.69	-0.68	1.00		
WS	-0.05	-0.48	[illegible]	0.38	-0.39	0.50	1.00	
WD	-0.09	0.30	[illegible]	-0.04	0.04	-0.16	-0.23	1.00

	Ozone	NOx	Ben	Temp.	RH	Solar Rad.	WS	WD
Ozone	1.00							
NOx	-0.34	1.00						
Ben	-0.47	0.78	1.00					
Temp.	0.59	-0.38	-0.54	1.00				
RH	-0.67	0.46	0.65	-0.81	1.00			
Solar Rad.	0.62	-0.40	-0.45	0.68	-0.70	1.00		
WS	0.59	-0.58	-0.62	0.51	-0.60	0.70	1.00	
WD	-0.31	0.30	0.28	-0.33	0.28	-0.35	-0.27	1.00

	Ozone	NOx	Ben	Temp.	RH	Solar Rad.	WS	WD
Ozone	1.00							
NOx	-0.42	1.00						
Ben	-0.34	0.71	1.00					
Temp.	0.66	-0.90	-0.56	1.00				
RH	-0.66	0.99	0.99	-0.81	1.00			
Solar Rad.	0.67	-0.51	-0.43	0.71	-0.70	1.00		
WS	0.51	-0.96	-0.55	0.62	-0.65	0.74	1.00	
WD	-0.43	0.41	0.24	-0.45	0.41	-0.42	-0.39	1.00

Figure 38. Pearson Correlation of Ozone and Its Chemical and Meteorological Precursors in Different Seasons (Note 2)

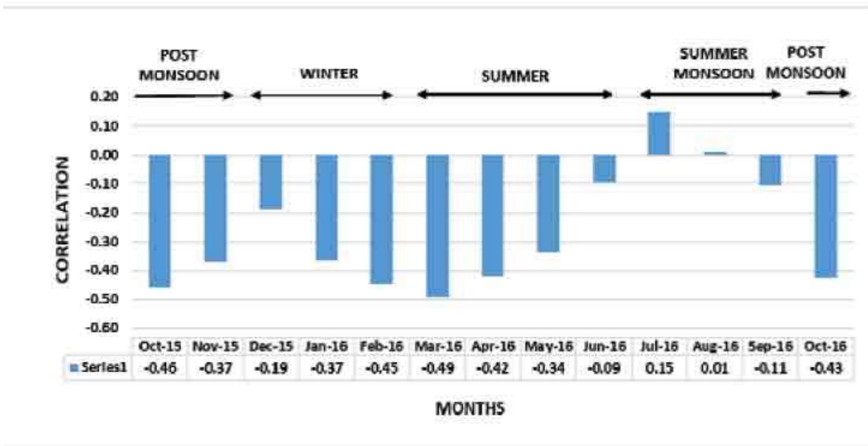


Figure 39. Pearson Correlation between Ozone (O_3) and Oxides of Nitrogen (NO_x) in Different Seasons

Figure 39 shows the correlation between tropospheric ozone and Oxides of Nitrogen in different seasons at R.K.Puram. A positive weak correlation (r = 0.15, p = 0.95) was found in July 2016 and the significant negative correlation (r = -0.49, p = 0.95) was found in March 2016. The reason for this negative relationship may be due to the light traffic flow and high emission of NO_x from vehicles and from industries.

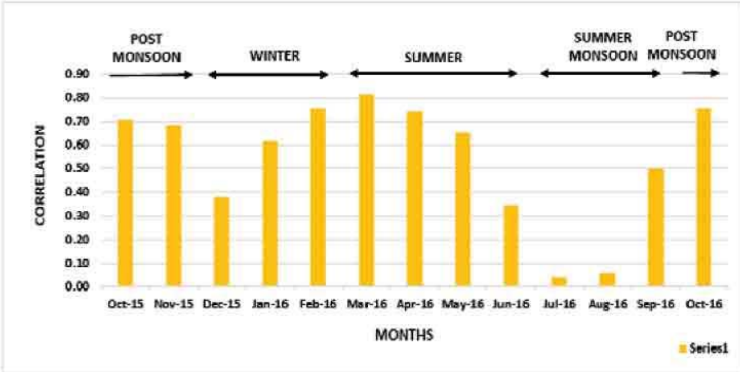


Figure 40. Pearson Correlation between Ozone (O_3) and Temperature (°C) in Different Seasons

Figure 40 indicates the correlation between ozone and temperature which in all the seasons was found to be positive. There exists a positive correlation between ozone and ambient temperature which has been proved by significantly positive correlation ($r = 0.81$, $p = 0.95$) found in March 2016.

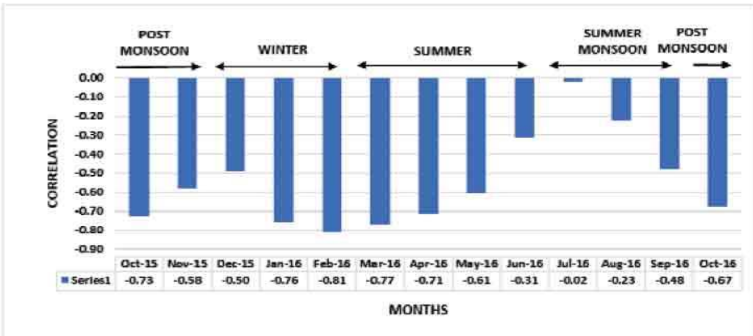


Figure 41. Pearson Correlation between Ozone (O_3) and Relative Humidity (RH) in Different Seasons in R.K. Puram

Figure 41 shows the correlation between relative humidity and tropospheric ozone. A significantly negative correlation was found during winters in February 2016. Nishant et al. (2012) reported that higher humidity levels are associated with large cloud cover and atmospheric instability, which slows down the photochemical process and the surface O_3 is depleted by deposition on water droplets in this location. Hence, the O_3 concentration has a strong dependence on the humidity levels present in the atmosphere.

3.5 Delhi-All Selected Sites

3.5.1 Concentration of Ozone, Its Chemical and Meteorological Precursors

PRECURSORS	CONC.(μg/m^3)	MANDIR MARG	PUNJABI BAGH	ANAND VIHAR ISBT	RK PURAM
OZONE	**Avg ± S.D.**	**34.2 ± 11.1**	**56.2 ± 23.5**	**33.8 ± 18.3**	**53.5 ± 23.0**
	Min	14.1	13.4	9.7	20.9
	Max	54.2	87.9	86.3	98.8
NOx	**Avg ± S.D.**	**92.4 ± 47.1**	**134.9 ± 59.8**	**197.3 ± 111.8**	**335 ± 354.2**
	Min	42.6	65.2	55.7	69.6
	Max	178.2	243.9	376.4	1368.2
BENZENE	**Avg ± S.D.**	**3.1 ± 1.63**	**0.8 ± 10.20**	**12.2 ± 2.8**	**5.8 ± 0.47**
	Min	1	0.4	2.4	0.9
	Max	5.8	1.9	22.3	13.4
TOULENE	**Avg ± S.D.**	**13.6 ± 2.71**	**4.3 ± 1.5**	**37 ± 6.45**	**15.7 ± 4.26**
	Min	2.7	2	18.1	4.5
	Max	33.3	10	65.6	33.8
PXYLENE	**Avg ± S.D.**	**4.6 ± 8.56**	**2 ± 4.41**	**8.2 ± 10.04**	**8.1 ± 6.35**
	Min	1.2	0.9	1.4	1.5
	Max	10.5	5.7	33.8	20.5

Table 42. Annual Concentration of Ozone and Its Chemical Precursors in Selected Sites of Delhi

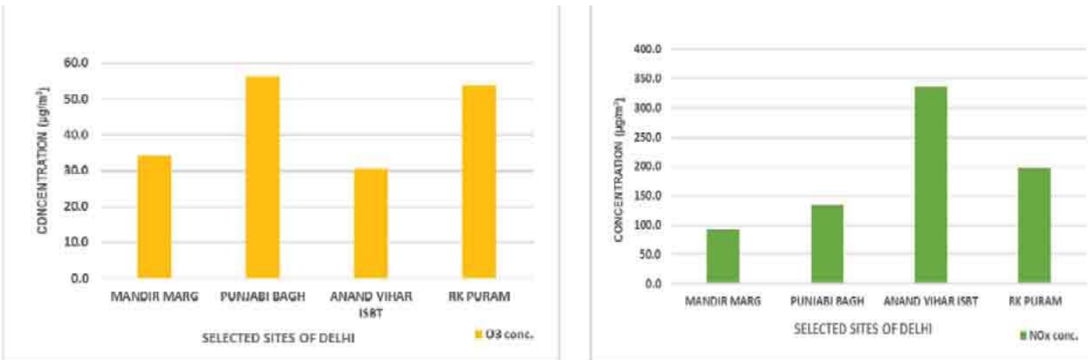


Figure 43. Annual Concentration of Ozone (O_3) in Different Monitoring Site of Delhi

Figure 43 clearly indicates the concentration Ozone in different monitoring sites of Delhi. The maximum concentration of tropospheric Ozone was observed in Punjabi Bagh among all the monitoring sites. The possible reason of maximum concentration (56.2 μg/m^3) in Punjabi Bagh may be because of the Rohtak Road crosses the area from one end and the Ring Road from another through which thousands of diesel trucks and other heavy duty commercial vehicles move and minimum concentration was found in Anand Vihar ISBT. The reason could be due to the high emission of NO_x from the on-road vehicles.

Figure 31 indicates the annual average concentration of oxide of nitrogen in all monitoring sites of Delhi. The maximum concentration, i.e., 335 μg/m^3 was observed in Anand Vihar ISBT among all the monitoring sites. The possible reason could be due the high vehicular emission from heavy duty vehicles. The minimum concentration of NO_x (92.4 μg/m^3) was found in Mandir Marg. The possible reason may be due to the low emission of NO_x from vehicles or burning of fossil fuel.

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Figure 44. Annual Concentration of Oxides of Nitrogen (NO_x) in Different Monitoring Site of Delhi

Figure 44 indicates that the annual concentration of BTX (Benzene, Toluene and pXylene) in all monitoring sites of Delhi. The maximum concentration of BTX was recorded in Anand Vihar ISBT. Anand Vihar is one of the most polluted spots of Delhi and known for being a veritable gas chamber. The maximum concentration BTX could be due to proximity of railway station where few of rails are running on coal and diesels, the Gazipur landfill, ISBT bus terminal where most of the interstate diesel based buses enter in terminal every day. These diesels based buses and the open landfill emit BTX.

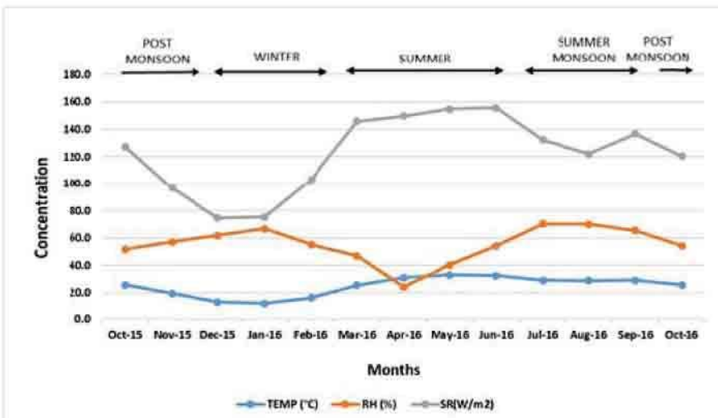

Figure 45. Seasonal Variation of Meteorological Precursors in Delhi

Figure 45 indicates the seasonal variation of meteorological precursors in Delhi. The Average temperature, i.e., 32.9° C was recorded during summers in May 2016 and the average temperature with 12.3° C during winters in January 2016. The average concentration humidity was found to be 70.32% during summer-monsoons in July 2016 in the addition of this the avenge concentration of humidity with 24.25% during summers. The maximum solar intensity was observed to be 155.66 W/m^2 during summers in June 2016 and the minimum intensity of solar radiation was recorded, i.e., 74.60 W/m^2 during winters in December 2015.

4. Discussion

In the present study, the annual seasonal variation in tropospheric ozone concentration and the correlation between its chemical and meteorological precursors was observed in Delhi.

Summers: In this season, the annual maximum concentration, i.e., 63.4 µg/m3 was observed in April. Elevated Ozone levels during the summer months can be attributed to high temperature, which favours photochemical production of tropospheric ozone (Tiwari et al., 2008). The similar findings were observed in the study of Fuentes and Dann (1994) that O_3 formation was observed to have increased during the summers when photochemical production is typically highest.

Winters: The annual average temperature (14°C) was recorded. This study revealed that the minimum annual average concentration of tropospheric ozone (35.8 µg/m^3) was observed in January.

Summer Monsoon: This season is associated with heavy rainfall, high relative humidity, cloudy weather and low intensity of solar radiation. The minimum annual average concentration, i.e. (19.2 µg/m^3) was found in July. It could be due the meteorological precursors like high humidity, low solar radiation and low temperature which are associated with large cloud cover and atmospheric instability, due to which the photochemical process is slow down and the surface O_3 is depleted by deposition on water droplets.

Post Monsoon: High concentration of ozone (60.3 µg/m^3) was observed in October 2015. The reason could be average relative humidity, heavy traffic flow and emission of chemical precursors from industries and vehicles in Delhi. These all accumulate with each other and help in the formation of tropospheric ozone in the presence of sunlight.

Inaccessibility of data was a major limitation faced during the present study. Data on chemical precursors, i.e., CO was found in interrupted format which was insufficient to be used in the present study.

It was also observed that the Ozone was negatively correlated with NO_x in most of the selected sites. It could be due to the increase in combustion of fossil fuel, burning of solid waste in open, open landfills and heavy traffic flow in Delhi. The temperature and ozone was found to be positively correlated in this study.

5. Conclusion

Based on the above findings, it can be concluded that the formation of tropospheric ozone varies seasonally and is influenced by chemical precursors under favourable meteorological conditions. During the study, the concentration of ozone was recorded highest mostly in summers (April-June 16) at all the sites. The possible reason for high concentration of tropospheric ozone could be due to the high ambient temperature, maximum intensity of solar radiation alongwith moderate concentration of NO_x and BTX in summers. The average temperature of New Delhi during summer ranges from 25º C to 44º C. The minimum concentration of ozone was recorded during the monsoons in the selected sites.

This may be due to the fact that high humidity is associated with large cloud cover, atmospheric instability, the slowdown of the photochemical process and the O_3 is depleted by deposition on water droplets. The high concentration of NO_x was found mostly in November which could be due to vehicular emissions emanating from heavy duty vehicles and industries. The concentration of benzene was exceeding the standards prescribed by NAAQS (2009) in all selected sites. The high concentration of benzene may be due to the vehicular exhaust, gasoline production, residential wood burning and fossil fuel combustion.

The maximum annual concentration of tropospheric Ozone (56.2 $\mu g/m^3$) was recorded in Punjabi Bagh as this site is less than 30 minutes away from the industrial areas in Mayapuri and Mangolpuri. The Mangolpuri industrial area has units ranging in furniture and electric supplies while Mayapuri majorly deals with motor parts and plastic crockery. Most of these units use coal chimneys for extracting metals like iron, aluminium and nickel and also, they burn solid waste in open that emit lot of gaseous pollutants. The ambient air of Anand Vihar ISBT was found to be mainly dominated by Oxides of Nitrogen (NO_x) with the value of 335 $\mu g/m^3$ and BTX (Benzene-12.2 $\mu g/m^3$, Toluene-37 $\mu g/m^3$ and pXylene-8.2 $\mu g/m^3$) amongst all the selected sites of Delhi. The reason for high concentration could be attributed to emissions from on-road vehicles, existence of Gazipur landfill near by this monitoring site, running of trains on coal and diesel, old diesel based buses in Anand Vihar ISBT.

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