Journal of Environmental Protection, 2014, 5, 408-422
Published Online April 2014 in SciRes. http://www.scirp.org/journal/jep
http://dx.doi.org/10.4236/jep.2014.55044

Scientific Research

Diurnal and Seasonal Variations of Surface Ozone and Its Precursors in the Atmosphere of Yanbu, Saudi Arabia

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Received 25 December 2013; revised 21 January 2014; accepted 18 February 2014

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Abstract

Surface ozone (O_3) and its precursor's gases (nitrogen monoxide (NO), nitrogen dioxide (NO_2), nitrogen oxides (NO_x), carbon monoxide (CO), methane (CH_4) and non-methane hydrocarbons (NMHCs), and sulfur dioxide (SO_2) were measured in Yanbu, Saudi Arabia from January 2004-December 2004. The annual average concentrations of O_3, NO, NO_2, NOx, SO_2, CO, CH_4, TNMHCs and THC were 22.51 ppb, 15.58 ppb, 17.25 ppb, 23.84 ppb, 6.66 ppb, 165.13 ppb, 3.44 ppm, 0.56 ppm and 3.88 ppm, respectively. The SO_2/NO_x and SO_2/NO_2 concentration ratios during the period of study indicate that the mobile emissions are the predominant sources in yanbu. The diurnal cycles of O_3 concentrations revealed highest levels in the daytime and lowest levels in night time. The diurnal variations of NO, NO_2, NO_x, SO_2, CO, NMHCs concentrations were similar and showed peaks concentrations linked to traffic density, boundary layer mixing processes and chemical processes in the atmosphere. The mean concentrations of O_3 in different seasons follow the order of summer > spring > autumn > winter. In contrary to O_3, NO has higher concentrations in autumn and winter than those in summer and spring seasons. The highest concentrations of NO_2, NO_x, SO_2, CO, and TNMHCs were found in autumn and spring, whereas the lowest concentrations were found in summer and winter. THC and CH_4 have no significant change over winter, autumn and summer seasons, while their concentrations decrease sharply in spring. Although the studied area does not suffer from NO_2, O_3, SO_2 and CO pollution and no health risk, comprehensive and long-term air quality management programmes are needed in order to keep air quality in a good condition.

Keywords

Ozone, Precursors, Diurnal and Seasonal, Urban, Saudi Arabia

How to cite this paper: Al-Jeelani, H.A. (2014) Diurnal and Seasonal Variations of Surface Ozone and Its Precursors in the Atmosphere of Yanbu, Saudi Arabia. *Journal of Environmental Protection*, **5**, 408-422.
http://dx.doi.org/10.4236/jep.2014.55044

1. Introduction

Anthropogenic air pollutants caused by technological progress, industrialization, and urban overpopulation had led to the deterioration of environmental air quality [1]. Toxic air pollutants emitted in close proximity of population areas have the potential to subject such population to health risks [2]. Tropospheric ozone (O_3) is an important air pollutant threatening human health and vegetation growth [3] [4]. People living in cities with high O_3 levels had an over 30% increased risk of dying from lung disease [5]. O_3 is also one of the key species affecting the chemical properties of the atmosphere where it is a precursor for the highly reactive hydroxyl radical [6] [7]. Surface O_3 and its precursors play an important role in affecting regional climates and causing adverse effects on human health and vegetation [8].

There are two sources of tropospheric O_3, viz. photochemical production [9] and downward transport of ozone from the stratosphere [10]. Ground level O_3 is a major constituent of smog in urban areas where motor vehicles are the main anthropogenic emission source of its precursors [11]. It is produced mainly by photochemistry involving pollutants that are released from various industrial and other anthropogenic activities, e.g., CH_4, CO and [12]. NO_x and hydrogen oxide radicals act as catalysts in this process. The relation between O_3 and its main precursors represents one of the major scientific challenges associated with urban air pollution [13].

Ozone concentrations depend on the absolute and relative concentrations of its precursors and the intensity of solar radiation [14]. Variations in O_3 concentration are controlled by a number of processes including photochemistry, physical/chemical removal, and transport, which occur on local, regional and global scales [15]. The variations in local meteorological conditions, such as wind direction, wind speed, temperature, and relative humidity, can affect the temporal variations in O_3 and its precursors [16]. An analysis of the influences of meteorological parameters on O_3 and its precursors at a specific site can contribute to a better understanding of the local and regional causes of O_3 pollution [8]. The seasonal and diurnal variations of surface O_3 and its precursors and the related meteorology have been extensively studied around the world [17] [18]. These studies showed that O_3 chemistry and the effects of meteorological conditions could vary depending on the characteristics of the climate and air pollutants emissions in the place of interest. The temporal variations of O_3 have been reported at many sites including rural, urban, coast and mountain sites in India [19], Japan [20], Thailand [21] and Kuwait [14].

Large quantities of non-methane hydrocarbons (NMHC) are emitted in the troposphere from vegetation and from a variety of anthropogenic sources. These anthropogenic sources include incomplete combustion sources (vehicle and fossil fueled power plant emissions), fuel storage and transport, solvent usage, emissions from industrial operations, landfills, and hazardous waste facilities [22] [23]. NO_x are also emitted, or produced in the troposphere. Nitrogen monoxide (NO) is emitted from soils and natural fires and formed in situ in the troposphere from lightning, and is emitted from combustion processes such as vehicle emissions and fossil fueled power plants [22] [23]. NO is short lived because it oxidizes to produce nitrogen dioxide gas (NO_2) and plays a major role in O_3 production. In urban areas, NMHC and NO_x, from anthropogenic sources dominate over NMHC and NO_x from biogenic sources, and the reverse is generally the case in rural and remote areas [24].

Biomass burning [25], combustion of fossil fuels, and oxidation of hydrocarbons released from automobiles and industrial solvents are the main sources of atmospheric CO [26]. Its oxidation leads to O3 formation or destruction, depending upon the NO concentration [27]. The reaction of CO with OH radicals is the primary removal process from the atmosphere. Through this mechanism, CO acts as a major precursor to photochemical ozone [9].

In order to reduce ambient ozone concentrations, anthropogenic VOC emissions, which predominantly consist of non-methane hydrocarbons ($NMHC_s$) have been the subject of extensive control programs in many countries. Accurate characterization of ozone precursors is extremely important for understanding tropospheric ozone formation and crafting effective control strategies to better address ozone air quality management issues [28]. The objective of the present study is to investigate the seasonal and diurnal variations of surface O3 and its precursors (NO, NO_2, NO_x, CO, THC, CH_4 and TNMHCs), and SO_2 in the atmosphere of yanbu Al Sinaiyah, and compare the concentrations of these pollutants with the standard limits.

2. Materials and Methods

2.1. Study Area

Yanbu Al Sinaiyah is a city in the Hejaz region of western Saudi Arabia. It has a population of more than 66,381

people. It is located about 350 km northwest of Jeddah. It is a terminal for oil pipelines and gas, which, stretching from the production areas in eastern Saudi Arabia to the west and it is the largest port on the Red Sea coast for the export of crude oil [29]. There are two types of industries in Yanbu Al Sinaiyah, which are traditional local industries and modern industries. The traditional local industries include building of sailing ships and fishing boats, furniture, traditional agricultural machinery, wicker industry, leather industry, woolens industry and jewelry industry. The modern industries include oil refining, sort of liquid natural gas, petrochemical industry, lubricants and oil additives industry.

Yanbu has a hot desert climate. The climate of Yanbu Al Sinaiyah is characterized by high temperature and dryness. The maximum temperature reaches up more than 40˚C in the summer, while temperature in the winter is between 28˚C and 15˚C. The relative humidity is between 25% (dry) and 83% (humid). The average annual rainfall is lower than 50 mm. Over the course of the year typical wind speeds vary from 0 mph to 23 mph (calm to fresh breeze), rarely exceeding 30 mph (strong breeze). The wind is most often out of the west (31% of the time). The wind is least often out of the north (3% of the time), south east (3% of the time), north east (5% of the time), south (5% of the time), and east (5% of the time).

2.2. Air Sampling

Air quality monitoring mobile station (Environment SA, France) was used to conduct the measurements of pollutants including: NO, NO_2, NO_x, O_3, CO, SO_2, THC, NMHCs and CH_4. Calibration was daily done and no data was recorded during that period. Average hourly measurements were taken in the period of January 2004 to December 2004.

3. Results and Discussion

3.1. Status of O_3 and Its Precursors

The statistical summary of daily average concentrations of O_3, NO, NO_2, NO_x, SO_2, CO, THC, CH_4 and TNMHC during the period of study (January 2004 to December 2004) are shown in **Table 1**. Seasons are defined as: spring is March, April and May; summer is June, July and August; autumn is September, October and November; winter is December, January and February. The daily average concentration ranged from 5.4 4 to 50.68 ppb (with a mean value of 22.51ppb) for O_3, 6.04 to 45.47 ppb (with a mean value of 15.58 ppb) for NO, 5.42 to 36.74 ppb (with a mean value of 17.25 ppb) for NO_2, 8.83 to 89.70 ppb (with a mean value of 32.84 ppb) for NO_x, 1.00 to 53.56 ppb (with a mean value of 6.66 ppb) for SO_2, 32.92 to 1006.67 ppb (with a mean value of 165.13 ppb) for CO, 0.76 to 6.27 ppm (with a mean value of 3.88 ppm) for THC, 0.64 to 5.65 ppm (with a mean value of 3.44 ppm) for CH_4, 0.10 to 3.45 ppm (with a mean value of 0.56 ppm) for TNMHC during the period of study.

The results of daily (24-h) minimum, maximum and average concentrations of NO_2, O_3, SO_2 and CO were compared with the available air quality standards in different countries. The concentrations of these pollutants did not exceed the available standards. Although, the studied area does not suffer from NO_2, O_3, SO_2 and CO pollution and no health risk, comprehensive, long-term air quality management programmers are needed in order to keep air quality in a good condition.

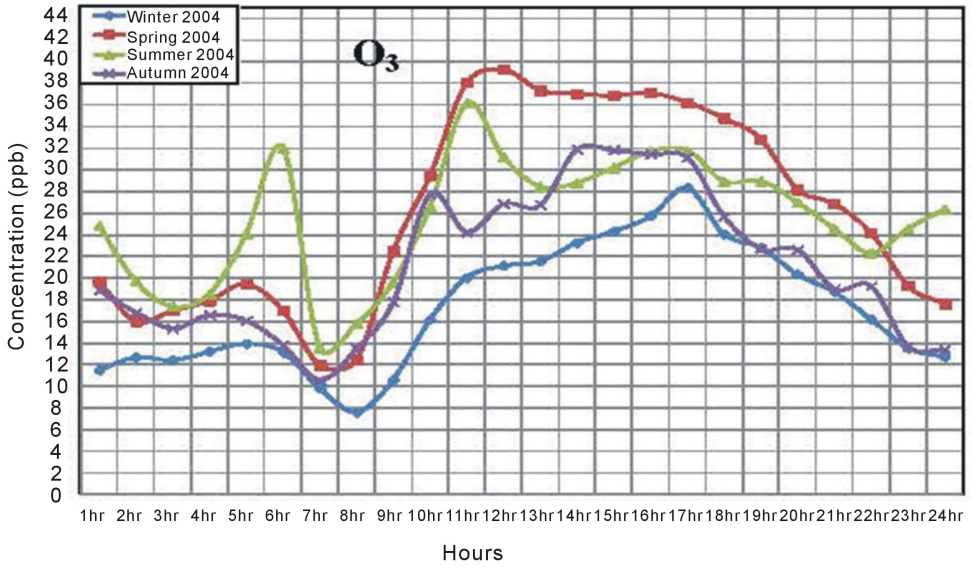
3.2. Diurnal Variations in O_3 and Its Precursors

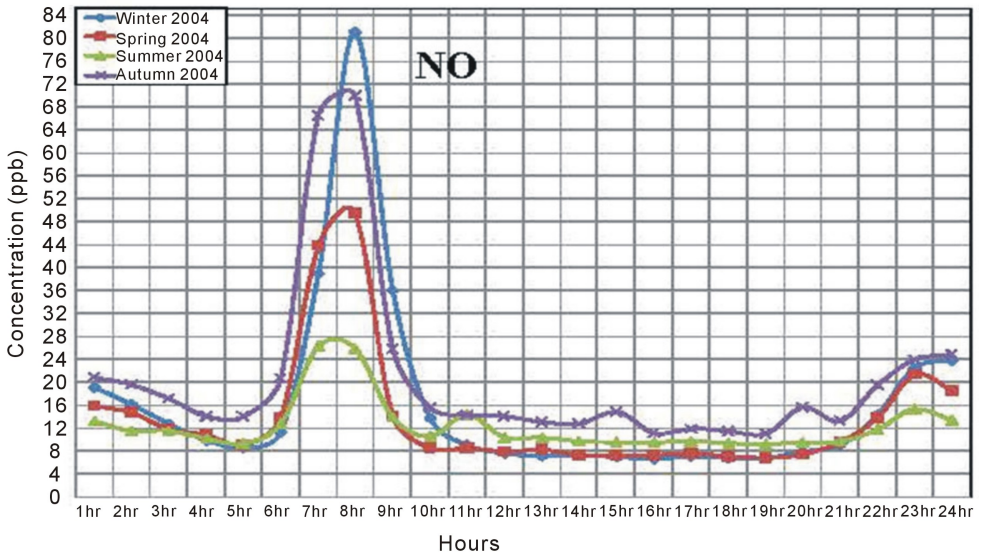
The diurnal variations in O_3, NO, NO_2, NO_x, CO, and SO_2concentrations during the period of study are represented graphically in **Figure 1**. From this figure, it can be noticed that the diurnal variation of O_3 is characterized by high concentrations during daytime and low concentrations during late night and morning. The minimum O_3 concentration appears during the morning hours (7.00 - 9.00). The maximum O_3 concentration appears at around 11.00 h in summer, at around 12.00 h in spring, at around 14.00 - 17.00 h in autumn and at around 17.00 h in winter. The increase in O_3 concentration during daytime is due to the increase in solar radiation intensity which favors the conditions to power the photochemical reactions [30]. Significant increasing O_3 values during daytime were observed at an urban site in tropical India [31]. The decrease in O_3 concentration during late night and morning is due to the absence of the photochemical reactions and the consumption of O_3 by deposition and or reaction with NO and NO_2 which act as a sink for O_3 [30].

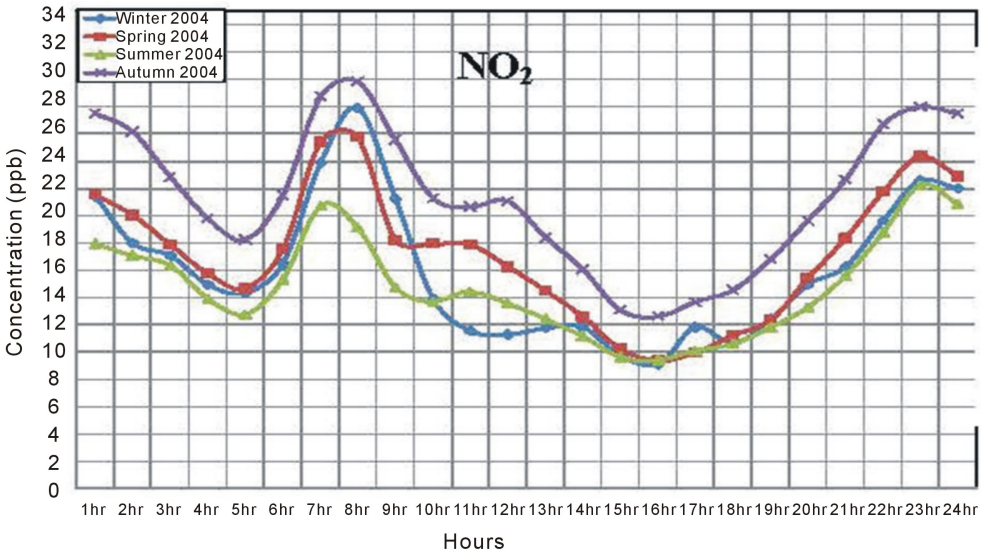
The diurnal variations of O_3 for the four seasons show a similar pattern; however, the amplitudes of the varia-

Table 1. Statistical summary of daily averaged concentrations of O_3, NO, NO_2, NO_x, SO_2, CO, THC, CH_4 and TNMHC in different seasons over the period from January 2004 to November 2004.

Pollutants	Statistics	Season				Annual
		Winter	Spring	Summer	Autumn	
O_3 (ppb)	Min.	7.96	7.40	8.05	5.44	5.44
	Max.	30.54	50.68	41.52	46.05	50.68
	Median	16.49	26.08	24.40	19.88	20.92
	Mean	17.20	25.79	24.91	20.94	22.51
	S.D.	4.10	9.93	8.87	8.45	8.97
NO_x (ppb)	Min.	15.00	16.28	19.56	8.83	8.83
	Max.	59.04	89.70	89.70	61.80	89.70
	Median	27.58	28.80	26.72	41.36	31.12
	Mean	29.16	30.41	29.26	42.53	32.84
	S.D.	9.14	9.85	9.18	8.55	9.18
NO_2 (ppb)	Min.	8.88	9.68	9.36	5.42	5.42
	Max.	23.32	36.74	25.68	31.00	36.74
	Median	15.98	16.68	14.04	21.12	16.96
	Mean	15.98	17.00	14.85	21.17	17.25
	S.D.	3.42	3.55	3.43	3.16	3.39
NO (ppb)	Min.	6.04	6.16	6.36	6.67	6.04
	Max.	34.48	25.28	27.68	45.47	45.47
	Median	14.60	12.44	11.54	18.68	14.32
	Mean	16.03	13.58	12.32	20.38	15.58
	S.D.	7.10	5.31	3.94	6.92	5.82
SO_2 (ppb)	Min.	2.44	1.00	1.23	5.20	1.00
	Max.	13.08	22.60	53.56	25.88	53.56
	Median	3.54	4.72	3.06	8.72	5.01
	Mean	4.39	6.48	5.51	10.24	6.66
	S.D.	2.17	4.53	7.14	4.50	4.59
CO (ppb)	Min.	76.00	32.92	32.92	66.67	32.92
	Max.	336.80	377.60	266.80	1006.67	1006.67
	Median	153.20	153.60	123.40	162.40	148.15
	Mean	161.42	170.86	134.00	194.25	165.13
	S.D.	57.70	69.27	52.13	132.02	77.78
THC (ppm)	Min.	3.59	1.39	1.39	0.76	0.76
	Max.	5.45	4.81	6.27	5.58	6.27
	Median	4.51	2.59	4.18	4.31	3.90
	Mean	4.55	2.90	4.01	4.05	3.88
	S.D.	0.43	0.78	1.27	0.96	0.86
CH_4 (ppm)	Min.	3.19	1.24	1.34	0.64	0.64
	Max.	4.99	4.70	5.65	4.85	5.65
	Median	4.15	2.57	3.55	3.65	3.48
	Mean	4.15	2.58	3.61	3.42	3.44
	S.D.	0.46	0.77	1.25	0.84	0.83
TNMHC (ppm)	Min.	0.31	0.10	0.22	0.42	0.10
	Max.	0.55	3.45	1.11	0.90	3.45
	Median	0.42	0.56	0.41	0.67	0.52
	Mean	0.42	0.70	0.43	0.67	0.56
	S.D.	0.05	0.65	0.14	0.09	0.23


Winter 2004
Spring 2004
Summer 2004
Autumn 2004
O3
Concentration (ppb)
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44
1hr 2hr 3hr 4hr 5hr 6hr 7hr 8hr 9hr 10hr 11hr 12hr 13hr 14hr 15hr 16hr 17hr 18hr 19hr 20hr 21hr 22hr 23hr 24hr
Hours


Winter 2004
Spring 2004
Summer 2004
Autumn 2004
NO
Concentration (ppb)
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56 60 64 68 72 76 80 84
1hr 2hr 3hr 4hr 5hr 6hr 7hr 8hr 9hr 10hr 11hr 12hr 13hr 14hr 15hr 16hr 17hr 18hr 19hr 20hr 21hr 22hr 23hr 24hr
Hours


Winter 2004
Spring 2004
Summer 2004
Autumn 2004
NO2
Concentration (ppb)
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34
1hr 2hr 3hr 4hr 5hr 6hr 7hr 8hr 9hr 10hr 11hr 12hr 13hr 14hr 15hr 16hr 17hr 18hr 19hr 20hr 21hr 22hr 23hr 24hr
Hours

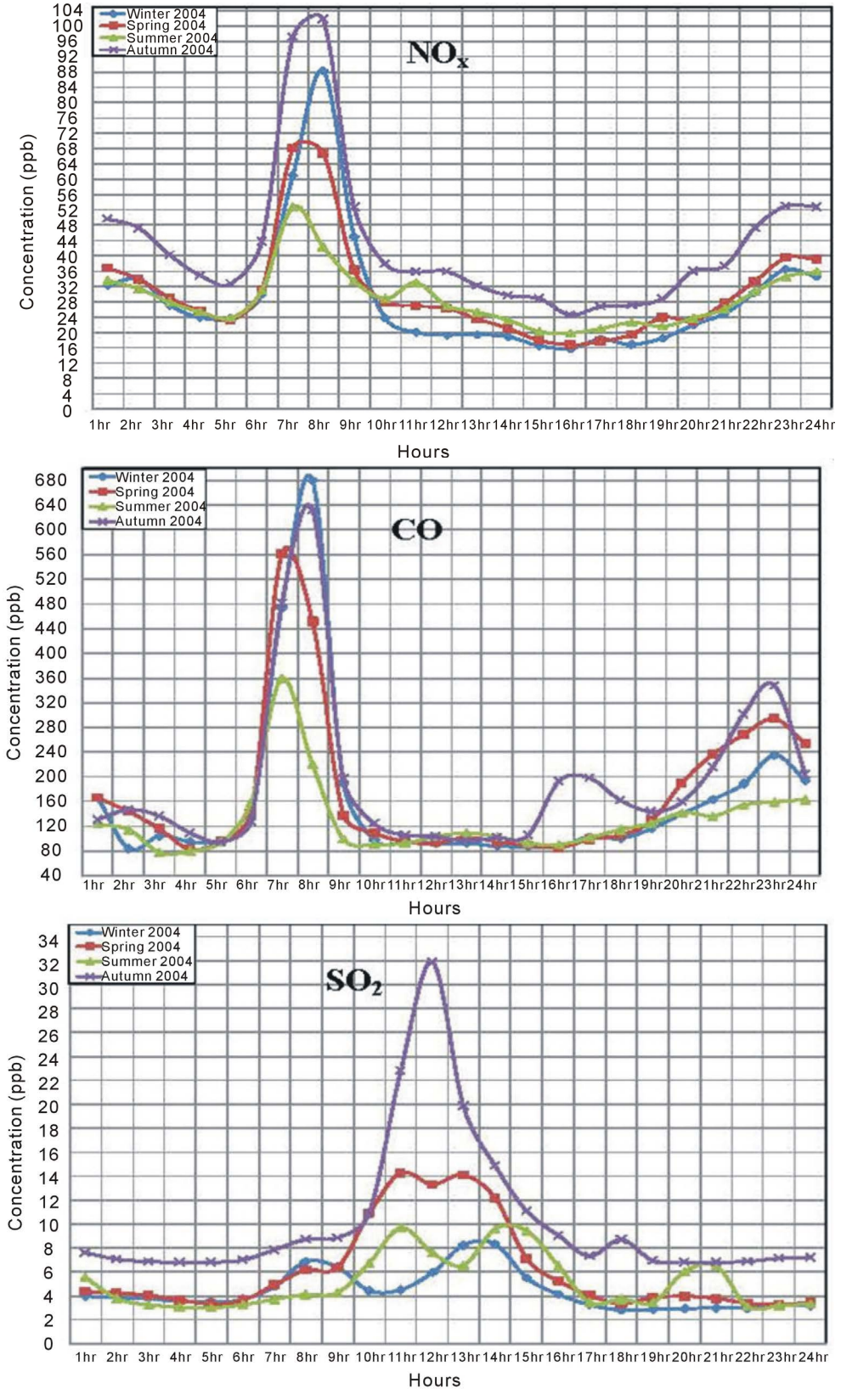


Figure 1. Diurnal variation in O_3, NO, NO_2, NO_x, CO and SO_2 concentration in Yanbu during the different seasons.

tions and position of peaks are different. The maximum amplitude is the highest in summer and spring, the second highest in autumn, and the lowest in winter. This may be attributed to the higher photochemical reactions during the summer seasons. The seasonal variation of O_3 at an urban area, Nagoya, Japan, showed that higher concentrations were observed from late spring to summer, while lower concentrations were observed in winter [32]. Elevated levels of O_3, frequently encountered in the large urban centers to exhibit variable concentration profiles [33] with maximum levels occurring during the summer months [34] are becoming a cause of global concern.

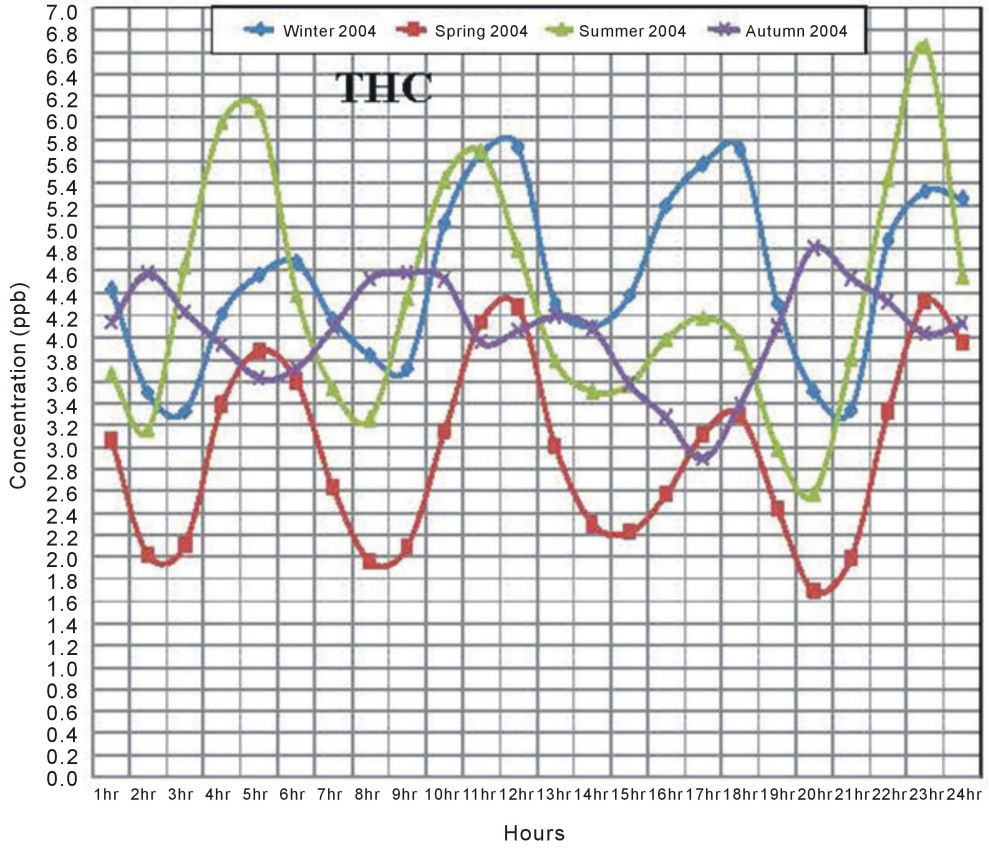
The ozone precursors, NO, NO_2, NO_x and CO, show an almost opposite diurnal variation pattern to O_3 (**Figure 1**), characterized by high concentrations during night and morning and low concentrations during daytime, especially noon and afternoon. Each pollutant has two main peak concentration levels; the first peak appears in the morning rush hours (6:00 - 9:00); the second one appears around late night (22:00 - 2:00), but for CO the second one appears around (22:00 - 24:00). The morning rush hour peak is mainly caused by traffic. These precursors reach their minimum values at around 4:00 - 6:00 and at around 15:00 - 17:00 when O_3 reaches its high values. The double peak patterns of NO, NO_2, NO_x and CO may be atypical signature of urban influence boundary layer processes, surface wind pattern, emissions, transportation/work cycle and chemical processes. During the morning time, the increase in the emission rate from traffic, accompanied with a poorer dispersive conditions and lower photochemical reaction lead to accumulate the concentrations of air pollutants. Latha and Badarinath [35] reported that high levels of NO_x during morning and late evening can be attributed to combinations of anthropogenic emissions, boundary layer processes, chemistry as well as local sources and wind patterns. In the present study, the low concentrations of NO and NO_2 during the mid-day time may be due to the high dispersion and high dilution conditions under the effect of high temperature, which increases the thermal turbulence currents. Moreover, the high temperature and solar radiation intensity during the mid-day time lead to increasing the photochemical reactions and consequently increasing the chemical loss of those pollutants. This leads todecreasing the NO_x concentrations in the mid-day time. On the other hand, during the late evening and nighttime, the boundary layer descends and remains low until early morning, thereby resisting the mixing of anthropogenic emissions with the upper layer. Hence, pollutants get trapped in a shallow surface layer resulting in raising levels of NO, NO_2 and NO_x in the present of study. This is in agreement with Rao *et al*. [36] [37] who attributed that the variations in NO_x to variations in boundary layer mixing processes, chemistry, anthropogenic emissions, and local surface wind patterns.

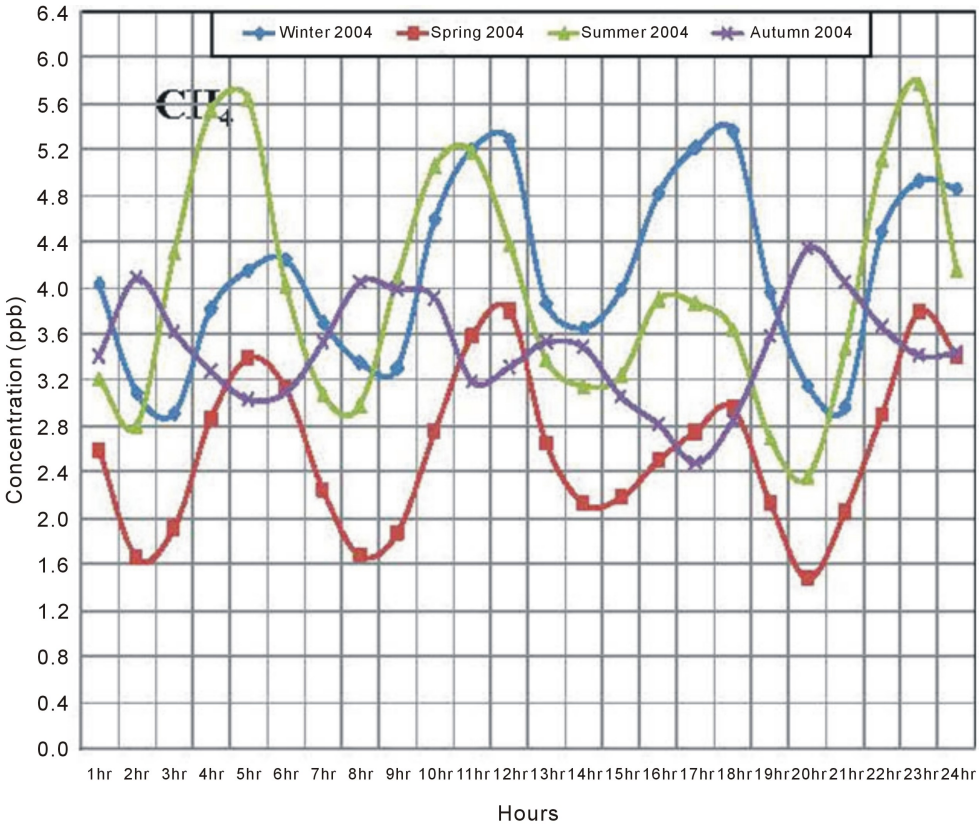
The diurnal variation of SO_2 in the present study is characterized by low concentration in early morning, evening and night and high concentration in the other time of the day (**Figure 1**). The SO_2 trend is characterized by two maxima for all seasons except for summer where it has three maxima. The maximum SO_2 concentration appears at 12.00 in autumn, at 11.00, 14.00 and 15.00 in summer, at 11.00 and 13.00 in spring and at 13.00 and 14.00 in winter. The high concentration of SO_2 in morning, noon and afternoon may be attributed to the primary emissions from factories in this industrial area.

The diurnal variations of THC, CH_4 and TNMHC during the period of study are represented graphically in **Figure 2**. From this figure, it can be noticed that the diurnal variation of THC, CH_4 and TNMHC is fluctuated along the day. THC concentration is fluctuated in the range 3.32 - 5.73 ppm in winter, 1.68 - 4.31 ppm in spring, 2.57 - 6.65 ppm in summer and 2.89 - 4.81 ppm in autumn. CH_4 concentration is fluctuated in the range 2.91 - 5.36 ppm in winter, 1.47 - 3.80 ppm in spring, 2.35 - 5.77 ppm in summer and 2.48 - 4.34 ppm in autumn. TNMHC concentration is fluctuated in the range 0.35 - 0.50 ppm in winter, 0.57 - 0.87 ppm in spring, 0.31 - 0.55 ppm in summer and 0.56 - 0.80 ppm in autumn. The trend of THC and CH_4 are the same where autumn has trend opposite to that of the other seasons of the year. This may be due to the presence of additional emission sources of THC and CH_4 in the study area. The trend of TNMHC is the same for all seasons of the year.

3.3. Seasonal Variations in O_3 and Its Precursors

The monthly and seasonal variations of O3, NO, NO_2, NO_x, CO, and SO_2 during the period of study are represented graphically in **Figure 3** and **Figure 4**. From these figures, it can be seen that, O_3 shows a well-defined seasonal variation. The low values appear in late autumn and winter (colder periods), while the high values appear in late spring, summer and early autumn (warmer periods). Studies conducted around the world reported high O_3 levels during the warmer periods [11] [14]. This common behavior of O_3 was justified by the dominant photochemical production process of O_3 due to the presence of its precursors and intense solar


Winter 2004
Spring 2004
Summer 2004
Autumn 2004
THC
Concentration (ppb)
7.0
6.8
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
4.8
4.6
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1hr 2hr 3hr 4hr 5hr 6hr 7hr 8hr 9hr 10hr 11hr 12hr 13hr 14hr 15hr 16hr 17hr 18hr 19hr 20hr 21hr 22hr 23hr 24hr
Hours


Winter 2004
Spring 2004
Summer 2004
Autumn 2004
CH4
Concentration (ppb)
6.4
6.0
5.6
5.2
4.8
4.4
4.0
3.6
3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0
1hr 2hr 3hr 4hr 5hr 6hr 7hr 8hr 9hr 10hr 11hr 12hr 13hr 14hr 15hr 16hr 17hr 18hr 19hr 20hr 21hr 22hr 23hr 24hr
Hours

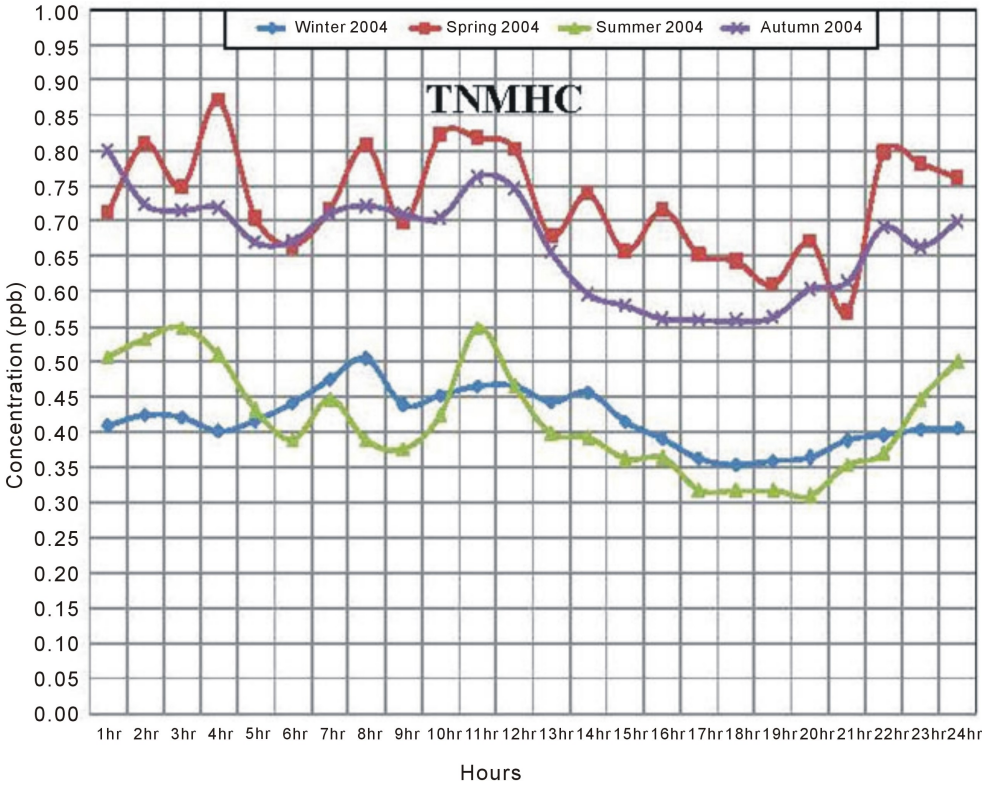


Figure 2. Diurnal variation in THC, CH_4, and TNMHC concentration in Yanbu during the different seasons.

insolation during the warmer periods. The low levels of O_3 during late autumn and winter (colder periods) is almost the same as that observed in Kuwait [11] and in urban site in China [8].

The O_3 precursors, NO, NO_2, NO_x and CO, show similar seasonal variations (**Figure 3** and **Figure 4**). The higher values appear in late autumn and winter, while the lower values appear in summer. The seasonal variation pattern of these precursors is almost opposite to that of ozone. This pattern is similar to the results of previous studies performed in many areas around the world [11] [32] [38]. One of the causes of this pattern might partly be attributed to the variation in temperature. For example, the greater photochemical reaction due to the higher solar radiation, and the stronger vertical atmospheric mixing in summer than in the other seasons, contribute to the low values of these pollutants in summer. Another cause is the increase in air pollutant emission in winter due to heating fuels consumed. The monthly and seasonal variation of SO_2 in the present study (**Figure 3** and **Figure 4**) is characterized by high concentration in autumn and early winter and the minimum concentration in winter and summer.

Figure 5 shows the seasonal variations of THC, CH_4, and TNMHC during the four seasons of year 2004. The seasonal variation of THC and CH_4 is the same, where the maximum was in summer (July) and the minimum was in spring (April). The highest concentrations of TNMHC were found in autumn and early winter, whereas the lowest levels were detected in summer (July). The photochemical removal (primarily by the hydroxyl (OH) radical) and dilution due to atmospheric mixing are two important factors that affect the seasonal variation of TNMHCs [39]. The mixing layer in summer is much higher than that in winter. The dilution for airborne pollutants from the ground source emissions in summer is stronger than that in winter. OH concentration in summer in mid-latitude is about 10 times its value in winter. High OH concentration speeds up the degradation of TNMHCs.

Mobile emission sources are predominantly characterized by high NO_x and CO concentrations, and point emission sources by high SO_2 and NO_x. So, the mobile sources have relatively low SO_2/NO_x ratios [40]. In the current study, the concentration ratios were 0.27, 0.38, 0.37, 0.48 and 0.39 for SO_2/NO_2 and 0.15, 0.21, 0.19, 0.24 and0.20 for SO_2/NO_x during the winter, spring, summer, autumn and annual, respectively. These results indicate that the mobile emissions are the predominant source within the study area. The SO_2/NO_2 concentration

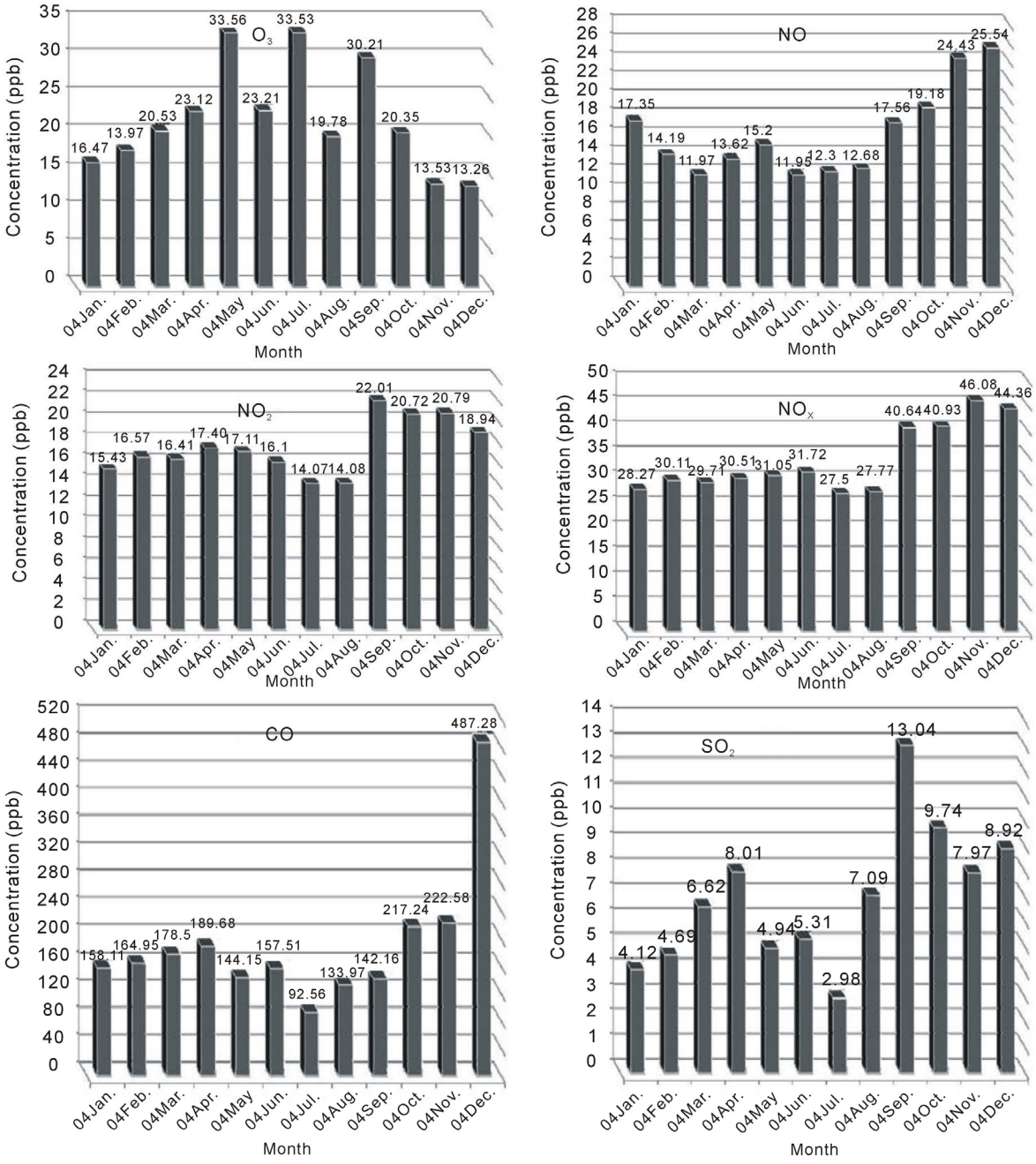


Figure 3. Monthly variation in concentrations of O_3, NO. NO_2, NO_X, CO and SO_2 in Yanbu during the period of study.

ratios at the study area during the period of study were similar to those found in Kolkata, India (ranged from 0.38 - 0.41), [41].

3.4. Comparison of O_3 and Its Precursors Levels in Yanbu Al Sinaiyah with Other International Cities

The Saudi Arabia air quality standard for hourly O_3 concentration is 150 ppb. Moreover, photochemical smog usually occurs when O3 concentration exceeds 100 ppb [42]. The frequency percentage distribution of the hourly concentrations of O_3 during the period of study is graphically presented in **Figure 6**. From this figure, it can be seen that the hourly O_3 concentrations during the period of study not exceed the maximum O_3 hourly set by

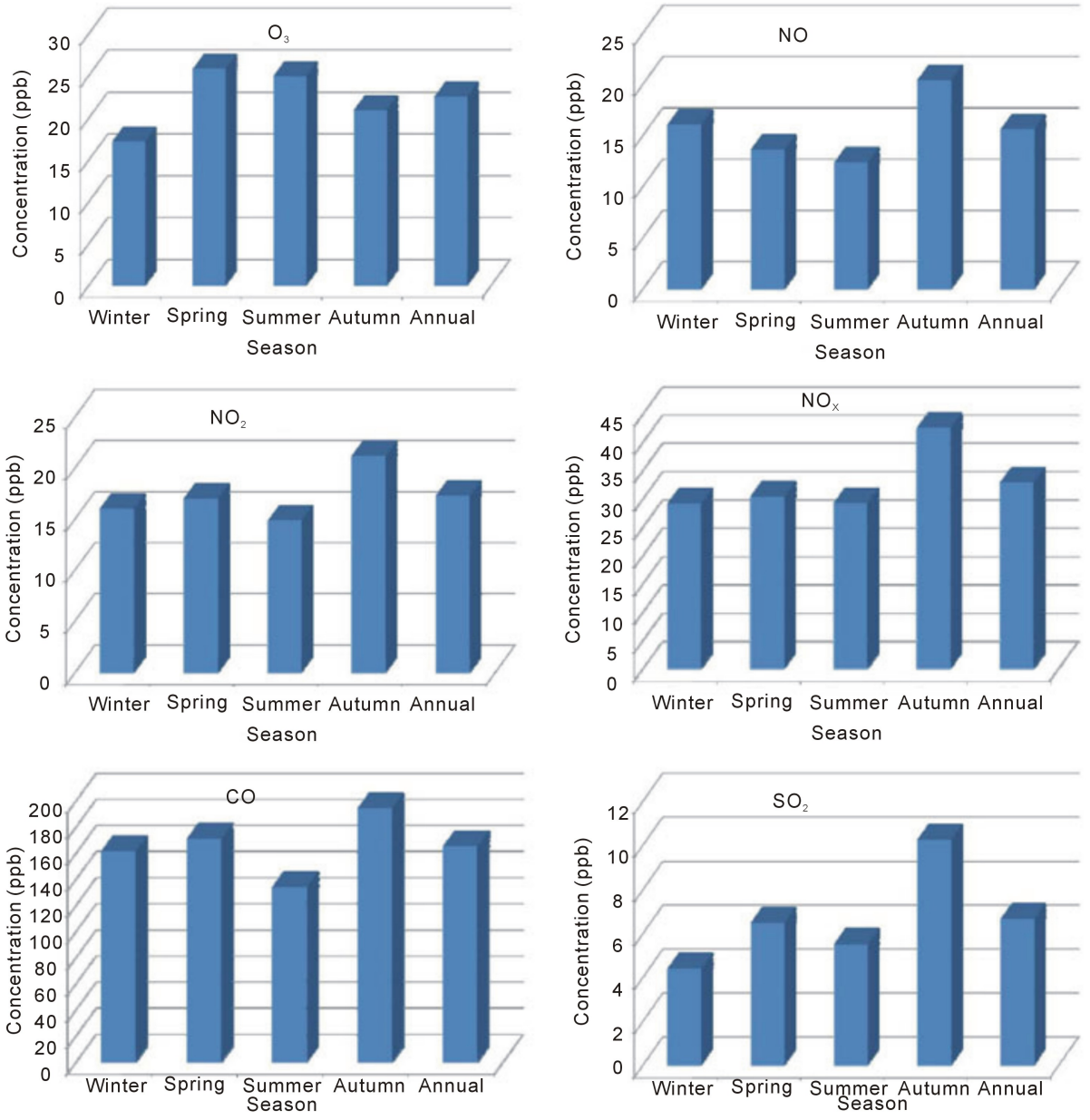


Figure 4. Seasonal variation in concentrations of O_3, NO. NO_2, NO_X, CO and SO_2 in Yanbu during the period of study.

Saudi Arabia air and the photochemical smog formation not occur during the period of study.

The annual average concentration of O_3 and its precursors in Yanbu Al Sinaiyah were compared with these found in different locations in Saudi Arabia and over the world [8] [20] [30] [41] [43]-[54]. As shown in **Table 2**, the average concentrations of NO, NO_2, NO_x, SO_2, O_3, CO, CH_4 and NMHCs in the present study were lower/higher or similar to those detected in other cities of the world. For example, the O_3 mean concentration in Yanbu Al Sinaiyah was similar to that found in Al-Taneem, KSA; Eskisehir, Turkey, and Nanjing, China, while it was higher than those found in Holy Makkah but it was lower than those found in Haram, Giza, Egypt. NO concentration was lower than those found in other locations except those found in Eskisehir, Turkey and Nanjing, China. NO_2 concentration was lower when compared with those reported in other locations. NO_x concentration was similar to that observed in Al-Taneem, Holy Makkah, KSA, while it was higher than that observed in Holy Makkah and it was lower than that recorded in Muna, KSA. SO_2 concentration was lower than those found in other locations. The CO concentration was lower when compared with those reported in other locations. CH_4

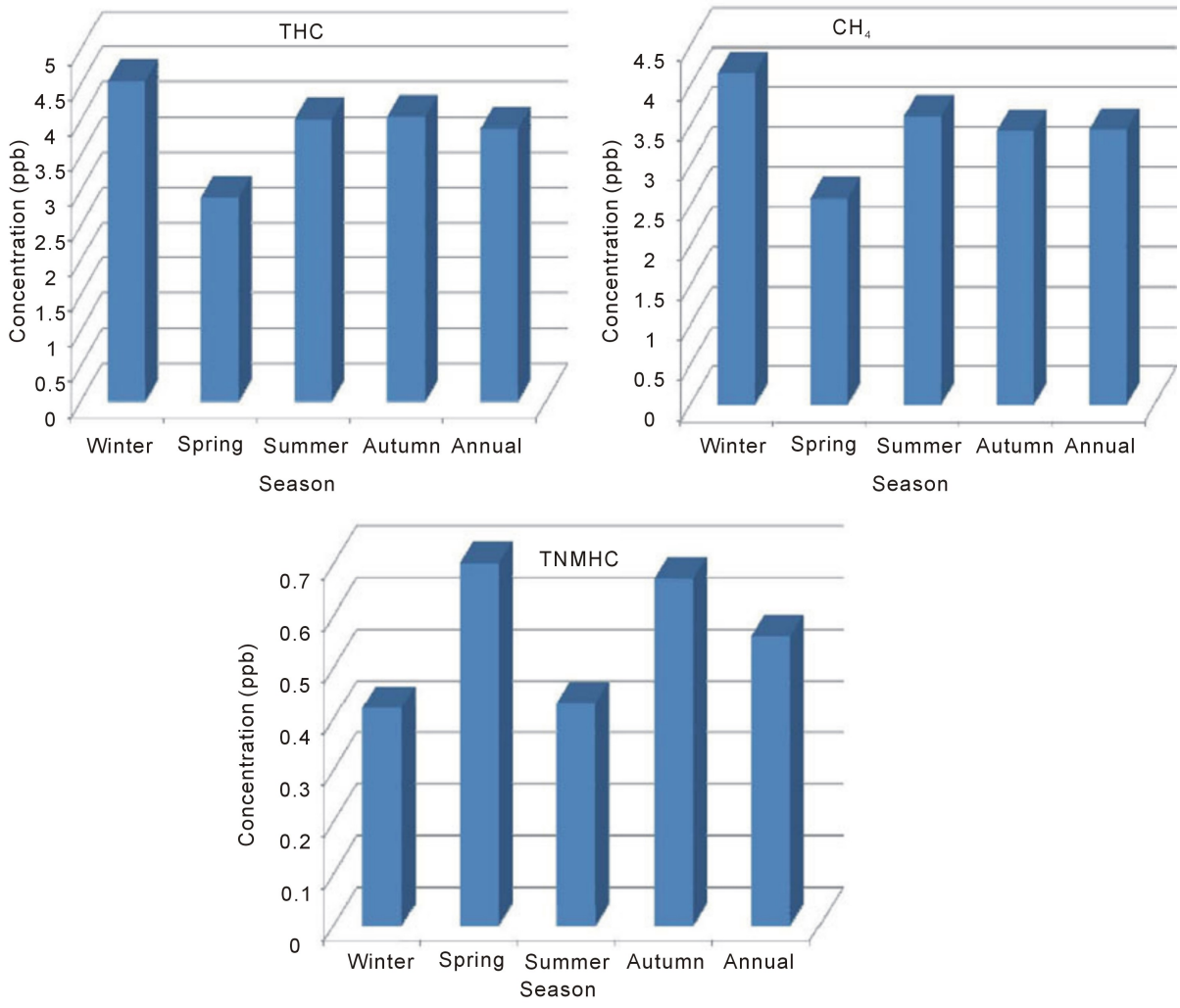


Figure 5. Seasonal variation in concentrations of O_3, THC, CH_4 and TNMHC in Yanbu during the period of study.

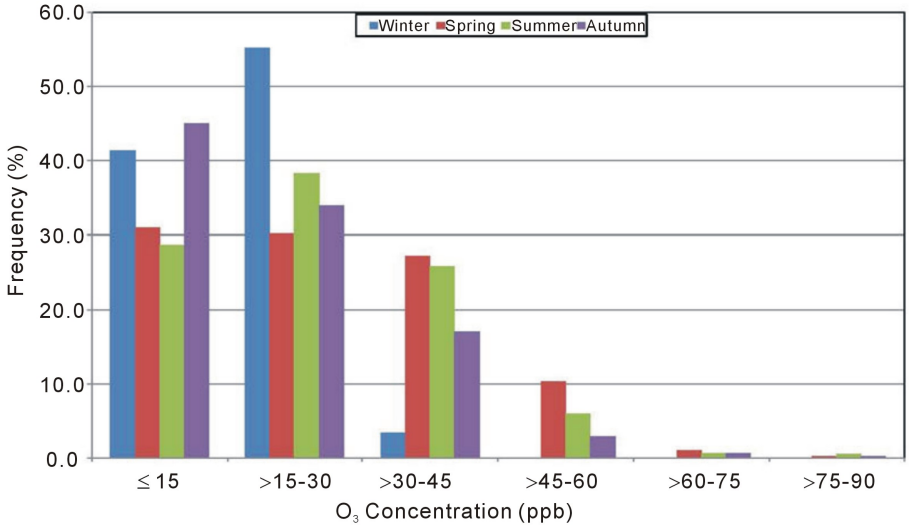


Figure 6. Frequency distribution of hourly ozone concentration during the different seasons.

Table 2. Concentration of Ozone and its precursors at different sites all over the world.

Site	O_3 (ppb)	NO (ppb)	NO_2 (ppb)	NO_x (ppb)	SO_2 (ppb)	CO (ppb)	CH_4 (ppm)	TNMHC (ppm)	Reference
Yanbu Al Sinaiyah, KSA	22.5	15.6	17.3	32.8	6.7	165.1	3.44	0.56	Present study
Al-Taneem, KSA	21.0	18.0	-	33.0	10.0	1386.0	2.15	0.39	Al Jeelani (2009a)
Holy Makkah, KSA	4.0	-	-	15.0	16.0	11300.0	-	-	Al Jeelani (2009b)
Haram, Giza, Egypt	40.0 - 79.0	-	89.0 - 137.0	-	-	-	-	-	Khoder (2004)
Haram, Giza, Egypt	30.0 - 64.0	-	-	-	-	-	-	-	Khoder (2009)
Dokki, Giza, Egypt	-	-	70.0 - 98.0	-	32.0 - 48.0	-	-	-	Khoder (2002)
Eskisehir, Turkey	19.0	8.0 - 16.0	-	-	-	-	-	-	özden *et al*. (2008)
Ankara, Turkey	-	-	-	-	11.0	-	-	-	DRSCH (2006)
Nanjing, China	20.4	10.6	18.8	-	-	1130.0	1.89	0.13	Jun *et al*. (2007)
Beijing, China	-	38.0	-	-	9.0	1970.0	-	-	Wang *et al*. (2008)
Germany	-	18.0	-	-	-	-	-	-	Lewne *et al*. (2004)
Kolkata, India	-	17.0	-	-	-	-	-	-	Gupta *et al*. (2008)
Dhaka, Bangladesh	-	-	-	-	45.0	-	-	-	Gurjar *et al*. (2008)
Nagoya, Japan	-	-	-	-	-	-	-	0.03	Saito *et al*. (2009)
London, UK	-	-	-	-	-	-	-	0.03	Derwent *et al*.(2000)
Lille, France	-	-	-	-	-	-	-	0.02	Borbon *et al*. (2002)
Seoul, Korea	-	-	-	-	-	-	-	0.05	Na and Kim (2001)

concentration was much higher than those found in other locations. The TNMHC concentration was higher than those recorded in other locations. Generally, the variation in the levels of atmospheric measured ozone and its precursors among the different locations of the world was presumably due to the difference in the traffic density, industrial activities, and intensity of human activities, land use patterns and the frequency of rainfall prior to sample collection.

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