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The Characterization of Surface Ozone Concentrations in Seoul, Korea

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Abstract

This paper provides a long-term perspective for ozone concentrations at 20 national air quality monitoring sites in Seoul from 1989 to 1998, which were managed by the Korean Ministry of Environment. Ozone episodes occurred more frequently in the east areas (Bangi, Guui, Seongsu, and Ssangmun) than in the west area (Guro and Oryu). When an ozone episode happened, hourly ozone concentrations over 80 ppb continued for an average of 4.0 hours at all sites. Annual variations in daily mean and maximum ozone concentrations showed broadly consistent upward trends at Ssangmun and Gwanaksan. Monthly mean ozone concentrations were the highest from May to June and the 99^{th} and 95^{th} percentile levels appeared higher during June, July, and August. The diurnal patterns of hourly mean ozone levels in urban areas showed typical photochemical formation and destruction, while the flat diurnal shape before 1996 at Gwanaksan indicated few significant photochemical reactions due to a lack of precursors of ozone. The occurrence of ozone over 80 ppb was ascribed to meteorological conditions such as high temperature, strong solar radiation, low relative humidity, and low wind speed with winds most frequently in a westerly direction.

Key words : ozone, ozone episode, diurnal variation, urban

1. INTRODUCTION

Over the past few years, surface ozone has become a serious air pollution problem in urban areas of Korea because of frequent occurrences in concentrations sufficient to threaten human health and the environment. Ozone is an omnipresent trace gas in the atmosphere and is a secondary pollutant produced from complex photochemical reactions involving a variety of natural and anthropogenic pollutants (McKendry, 1993). In general, changes in emissions of the precursors along with meteorological conditions can alter the diurnal and seasonal variations of ozone concentrations (Komala *et al.*, 1996; Staehenlin *et al.*, 1994; Weston *et al.*, 1989). The weather conditions conducive to the generation of local high levels of ozone are subsident and strong inversions, low wind speed, abundant solar radiation, high surface temperature, and low relative humidity (Bezerra *et al.*, 1996; Ludwig *et al.*, 1995; Vukovich, 1995; Feister and Balzer, 1991). Although emissions from urban and industrialized

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areas are a major source of anthropogenic ozone precursors, the areas often experience lower concentrations than the surrounding rural locations. This may be attributed to the downwind transport of ozone and its precursors from urban or industrialized areas, and to scavenging effect of its precursors (Chan and Chan, 2000; Vecchi and Valli, 1999; Ryan *et al.*, 1998; Fuentes and Dann, 1994; Angle and Sandhu, 1989).

This paper focuses on characterizing a long-term perspective for surface ozone concentrations in Seoul from 1989 to 1998. In order to realize the purpose, we analyze 1) the episodes of high levels of ozone as well as the generalized characteristics of ozone distribution at all monitoring sites, and 2) the annual, seasonal, and diurnal patterns in ozone concentrations at the major monitoring sites. The pattern analyses will help to build a fundamental database when developing a statistical-oriented ozone forecast system for the next study.

2. DATA AVAILABILITY AND MONITORING SITES

The 142 air quality monitoring sites are linked to the telemetry system that transmit data acquired from field sites to a computerized network at Ministry of Environment (Korea Ministry of Environment, 1999). Air pollutants have been monitored at an interval of 5 minutes. The twelve readings per an hour are typically used to calculate a 1-hour average concentration (Jo *et al.*, 2000). Surface ozone is measured by the U.V. photometric method at all monitoring sites. The ozone monitoring networks in Seoul are composed of 20 sites distributed according to the types of land-use: 12 for residential area, 3 for green-space, 2 for commercial area, and 3 for semi-industrial area. The hourly ozone and nitrogen dioxide (NO_2) data used in this paper were extracted from the database of 20 sites, which have operated since the early 1980s. Figure 1 and table

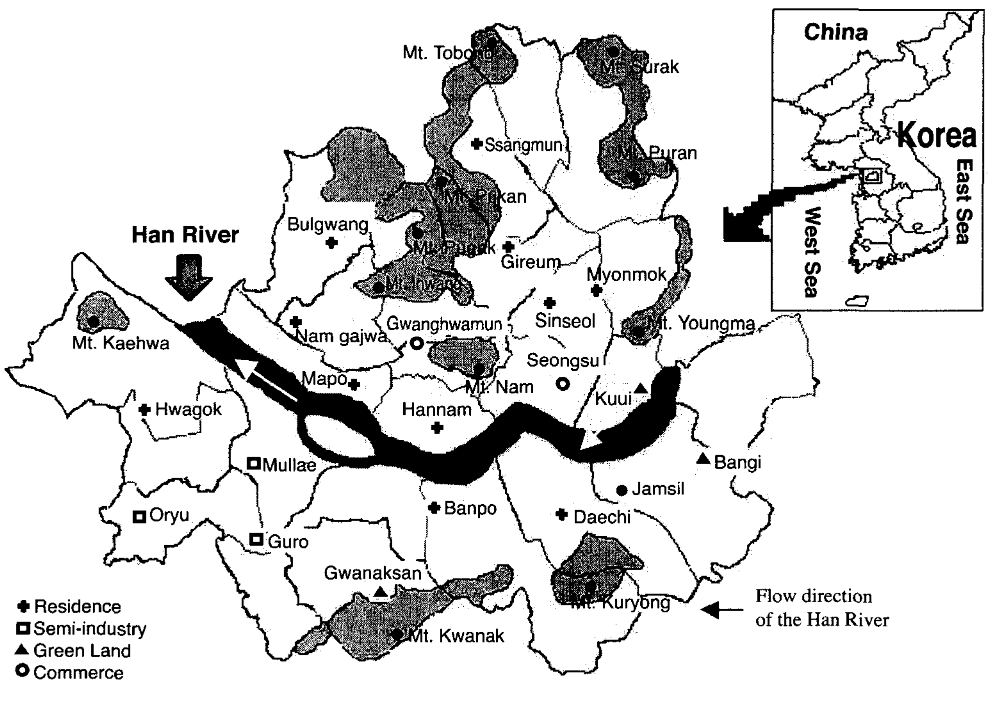

Fig. 1. The locations of 20 air quality monitoring sites in Seoul. The shaded indicates the mountainous areas.

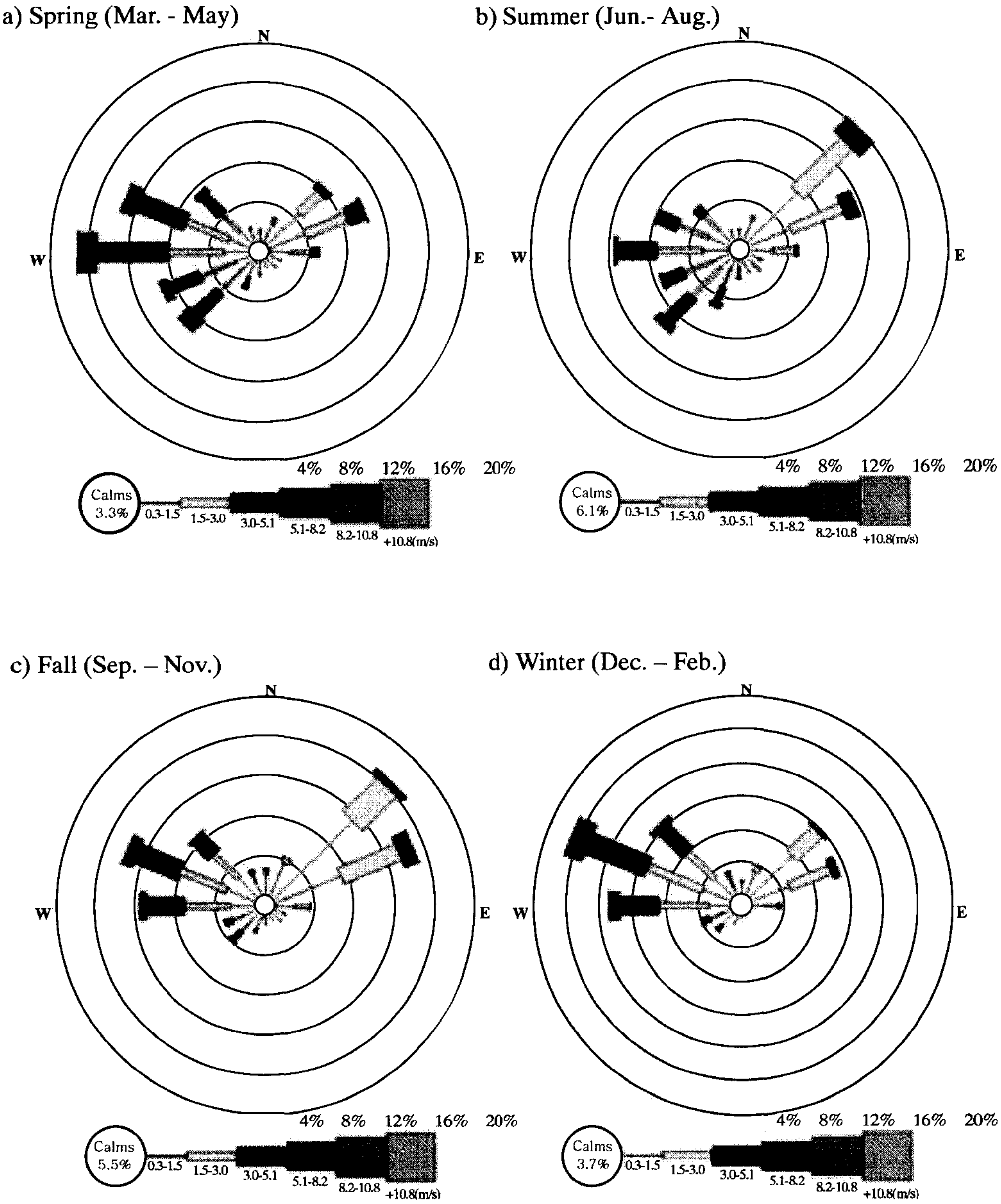

Fig. 2. Wind roses showing wind direction and speed in Seoul for 4 seasons during the periods of 1989 to 1998.

1 show the locations of air quality monitoring sites in Seoul and the site information on the land-use. We also used the meteorological data of the surface air measured by Korean Meteorological Administration. Figure 2 shows wind rose patterns representing wind direction and speed in Seoul for 4 seasons during the periods of 1989 to 1998. In general, sea breezes (i.e., westerly winds) blow from the West Sea to Seoul during the daytime and land breezes (i.e., easterly winds) blow to the West Sea at night.

Table 1. Description of 20 monitoring sites in the Seoul area.

Site name	Type of land-Use	Location	TM coordinates	
			Horizon	Ordinate
Banpo	Residence	Banpo-2 county office	199.53	444.79
Bulgwang		National Institute of Environmental Research	193.99	506.57
Jamsil		Chamsil bon county office	207.34	494.94
Hannam		A control office of Han River park	200.49	448.72
Hwagok		Hwagok-3 county office	184.56	449.57
Gireum		Gireum-3 county office	202.34	506.08
Mapo		Dongdo middle high school	195.33	499.35
Myeonmok		Chungnang elementary school	206.66	504.12
Namgajwa		Namgajwa-1 county office	192.32	452.40
Ssangmun		Ssangmun-3 county office	202.89	460.85
Sinseol		Sungin middle high school	202.08	502.26
Daechi		Daechi-1 county office	204.93	493.54
Bangi	Green land	Olympic park	210.99	446.70
Guui		Guui 164	208.15	449.28
Gwanaksan		Seoul National University	195.95	489.39
Gwanghwamun	Commerce	Tuksu Palace	197.87	201.61
Seongsu		Seongsu-3 county office	204.87	449.81
Guro	Semi-industry	The headquaters of export industrial complex	190.72	442.20
Mullae		Mullae-2 county office	190.34	495.94
Oryu		Kung 157	184.95	444.35

The city of Seoul has grown into a teeming metropolis with a population of 10.2 million (National Statistical Office of Korea, 2000) and has greatly expanded in the process of urbanization and industrialization over the past 30 years. Seoul is situated on the lower reaches of the Han River that flows through the central part of the Korean Peninsula. Seoul is also surrounded by several big and small mountains. These mountains are Mt. Pugak and Mt. Puk'an in the north, Mt. Inwang in the west, Mt. Yongma in the east, and Mt. Kwanak in the south, and Mt. Nam in the center of Seoul. These geographical situations are considered as main factors affecting the air quality in Seoul.

The five monitoring sites (Gwanghwamun, Ssangmun, Gwanaksan, Guro, and Bangi) are representative areas that can be used to interpret very well the characteristics of ozone pollution in Seoul. Gwanghwamun is a heavy traffic area in the central part of Seoul. At Ssangmun that is situated in the north-east, several surrounding big mountains inhibit atmospheric circulation, thus accumulating pollutants. Gwanaksan is located within Seoul National University amid a large tract of green land. Guro is placed downstream from the Han River in the west of Seoul. It is the semi-industrized area of Seoul with a small number of industrial plants and various commercial institutions. Bangi, located upstream on the Han River amid broad green stretches, has recorded the most frequent episodes of elevated ozone. We will especially deal with behaviors of surface ozone at the five sites presented in the following sections 3.2, 3.3, and 3.4. We will also analyze ozone episodes and their percentile distributions of hourly ozone concentrations at the 20 sites in sections 3.1 and 3.5.

3. RESULTS AND DISCUSSION

3. 1 Defining ozone episode

Definitions of so called "ozone episode", the high levels of ozone, vary. For example, Lyons *et al.* (1991) and Ludwig *et al.* (1995) defined the "ozone episode"

Table 2. The summary of ozone episodes during the1989-1998 period in Seoul. The table contains the number of episode days with ozone concentration exceeding 80 ppb for 3 consecutive hours as well as the total hours for total episode days.

Type of land-use	Monitoring Sites	'89	'90	'91	'92	'93	'94	'95	'96	'97	'98	Total episode days (Total hours)	Hours/ episode days*
Residence	Ssangmun	1 (3)	1 (3)	19 (91)	0 (0)	5 (18)	14 (59)	10 (40)	24 (107)	24 (106)	26 (123)	124 (550)	4.4
	Jamsil	0 (0)	0 (0)	0 (0)	10 (39)	2 (9)	5 (20)	5 (15)	13 (51)	3 (10)	8 (26)	46 (170)	3.7
	Banpo	1 (3)	0 (0)	6 (25)	1 (3)	3 (11)	12 (51)	1 (3)	4 (13)	11 (41)	6 (27)	45 (177)	3.9
	Hannam	0 (0)	3 (14)	6 (25)	1 (4)	1 (3)	7 (29)	1 (4)	6 (18)	7 (34)	9 (42)	41 (173)	4.2
	Bulgwang	0 (0)	0 (0)	1 (5)	2 (7)	1 (4)	4 (15)	2 (11)	11 (42)	8 (30)	9 (37)	38 (151)	4.0
	Daechi	0 (0)	3 (11)	2 (9)	1 (3)	0 (0)	2 (6)	0 (0)	9 (42)	15 (61)	0 (0)	32 (132)	4.1
	Gireum	0 (0)	0 (0)	4 (17)	6 (26)	3 (9)	4 (15)	1 (3)	4 (15)	4 (13)	2 (8)	28 (106)	3.8
	Hwagok	–	–	–	8 (36)	0 (0)	11 (41)	0 (0)	3 (13)	0 (0)	0 (0)	22 (90)	4.1
	Mapo	0 (0)	0 (0)	11 (41)	9 (34)	1 (3)	2 (8)	1 (6)	2 (9)	1 (3)	3 (10)	20 (114)	3.8
	Namgajwa	2 (9)	0 (0)	7 (29)	2 (9)	2 (7)	1 (4)	0 (0)	0 (0)	1 (3)	5 (17)	20 (78)	3.9
	Myeonmok	0 (0)	2 (6)	0 (0)	0 (0)	0 (0)	3 (10)	0 (0)	3 (10)	7 (24)	3 (10)	18 (60)	3.3
	Sinseol	0 (0)	0 (0)	0 (0)	0 (0)	4 (14)	0 (0)	0 (0)	4 (17)	0 (0)	0 (0)	8 (31)	3.9
Green Land	Bangi	9 (32)	13 (57)	1 (3)	16 (70)	7 (25)	23 (100)	10 (39)	22 (92)	14 (54)	13 (57)	128 (529)	4.1
	Guui	8 (1)	1 (3)	17 (75)	6 (26)	0 (0)	7 (25)	8 (26)	19 (79)	21 (94)	14 (58)	101 (418)	4.1
	Gwanaksan	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	8 (30)	4 (13)	3 (11)	15 (54)	3.6
Commerce	Seongsu	6 (22)	5 (17)	1 (3)	0 (0)	12 (49)	15 (71)	5 (18)	11 (51)	18 (71)	19 (91)	92 (393)	4.3
	Gwang-hwamun	0 (0)	0 (0)	25 (11)	2 (100)	11 (38)	7 (38)	0 (0)	1 (3)	9 (30)	2 (8)	57 (228)	4.0
Semi-industry	Oryu	8 (31)	5 (27)	0 (0)	0 (0)	7 (27)	17 (74)	1 (3)	3 (10)	9 (35)	3 (12)	53 (219)	4.1
	Guro	0 (0)	4 (18)	0 (0)	16 (87)	0 (0)	13 (54)	3 (11)	3 (11)	2 (7)	2 (9)	43 (197)	4.6
	Mullae	0 (0)	0 (0)	3 (10)	0 (0)	0 (0)	2 (6)	0 (0)	0 (0)	2 (9)	2 (7)	9 (32)	3.6
Total		35 (132)	37 (156)	81 (344)	102 (444)	59 (217)	149 (626)	48 (179)	150 (613)	160 (638)	129 (553)	950 (3,902)	4.0

* The average consecutive hours during an ozone episode day.

as a case exceeding 120 ppb for 1-hour NAAQS (National Ambient Air Quality Standard) in USEPA. Bower *et al.* (1994) described the "episode day" as the day in which hourly average ozone concentrations exceeded 60 ppb at two or more sites in the U.K. McKendry (1993) defined "ozone episode" as being when 82 ppb, 1-hour average maximum acceptable air quality objective in Canada, was exceeded simultaneously at two or more stations. Poulida *et al.* (1991) characterized the "ozone episode" as a case in which the hourly ozone concentration was higher than 80 ppb for at least 3 consecutive hours.

To sum up, the definition of the "ozone episode" can be explained in three ways: first, when the ozone concentration exceeds 1-hour ambient air quality standard, second, when it exceeds a standard level simultaneously at two or more sites, and third, when concentrations exceeding a standard level continue for a long-term. Many studies have reported that humans and vegetation have been harmed more by long-term exposures to levels of ozone approaching 80 ppb rather than by short-term exposures over 120 ppb (Lefohn and Foley, 1993; Lippmann, 1991; Tilton, 1989). Such considerations suggest "ozone episode" can be optimally defined as a case in which the hourly ozone concentrations exceed a long-term standard.

In this study, we consider an "ozone episode" as a case in which the hourly ozone concentration exceeds 80 ppb (ozone level for 8-hour NAAQS in USEPA) for at least 3 consecutive hours in one day. Table 2 presents the number and the continuous hours of occurrences for episodes from 1989 to 1998 at 20 sites. Throughout the ten-year period, the monitoring sites recorded 950 episodes. At Bangi, the number and duration of episodes registered, 128 instances totaling 529 hours, exceeded those of all other sites. Here, the number of episodes peaked in 1994 at 23. At Ssagmun, the episodes have increased annually. At Guui and Seongsu, the episodes numbered 101 days totaling 418 hours and 92 days totaling 393 hours, respectively. However, Oryu and Guro recorded less frequent episodes, 53 days totaling 219 hours and 43 days totaling 197 hours, than the sites illustrated above. Because the valley effect of the Han River is conducive to an increase in the general wind speed in Seoul's eastern part, precursors from western part may drift eastward and may become an important determinant of ozone formation in downwind areas (Lee and Bang, 1997; Chung and Chung, 1991). This study were similar to Chan's study (Chan *et al.*, 2000) such that elevated ozone enhanced by the channeling effect of the Pear River and by local transport of ozone and its precursors caused highest frequencies of ozone episodes in the downwind western side of China and in various remote, rural, and metropolitan districts of Hong Kong.

On the average, the episodes at all sites began to increase in frequency in 1994, decreased in 1995, again increased constantly from 1996, and decreased in 1998. The ozone episodes generated the highest frequently, 160 times totally 638 hours, in 1997. We examined the average numbers of hours for which an episode lasted. We determined the average episode's duration at all sites to be 4.0 hours. Guro averaged the highest at 4.6 hours.

3. 2 Annual variations of daily mean and maximum ozone concentrations

Air quality trends are determined by a time series analysis that may be useful for developing a long-term perspective. The ozone daily mean concentrations during the 1989-1998 period are displayed in figure 3. In this study, a data capture rate should exceed 75% for reliable statistic analysis. For this reason, the 1989-1991 ozone data at Gwanaksan, owing to a data capture rate below 60% (that is, a data missing rate over 40%), were excluded from any statistical analysis. Figure 3 shows a broadly consistent upward trend at Ssangmun and Gwanaksan. Their slopes were calculated by a simple linear regression analysis such as $+0.0043$ ppb day^{-1} at Ssangmun, and $+0.0027$ ppb day^{-1} at Gwanaksan. Ozone concentrations at Ssangmun have risen steadily since 1992. Ozone trends at Gwanghwamun, Guro and Bangi are not clearly explicable (slopes of $+0.0009$ ppb day^{-1}, -0.0006 ppb day^{-1},

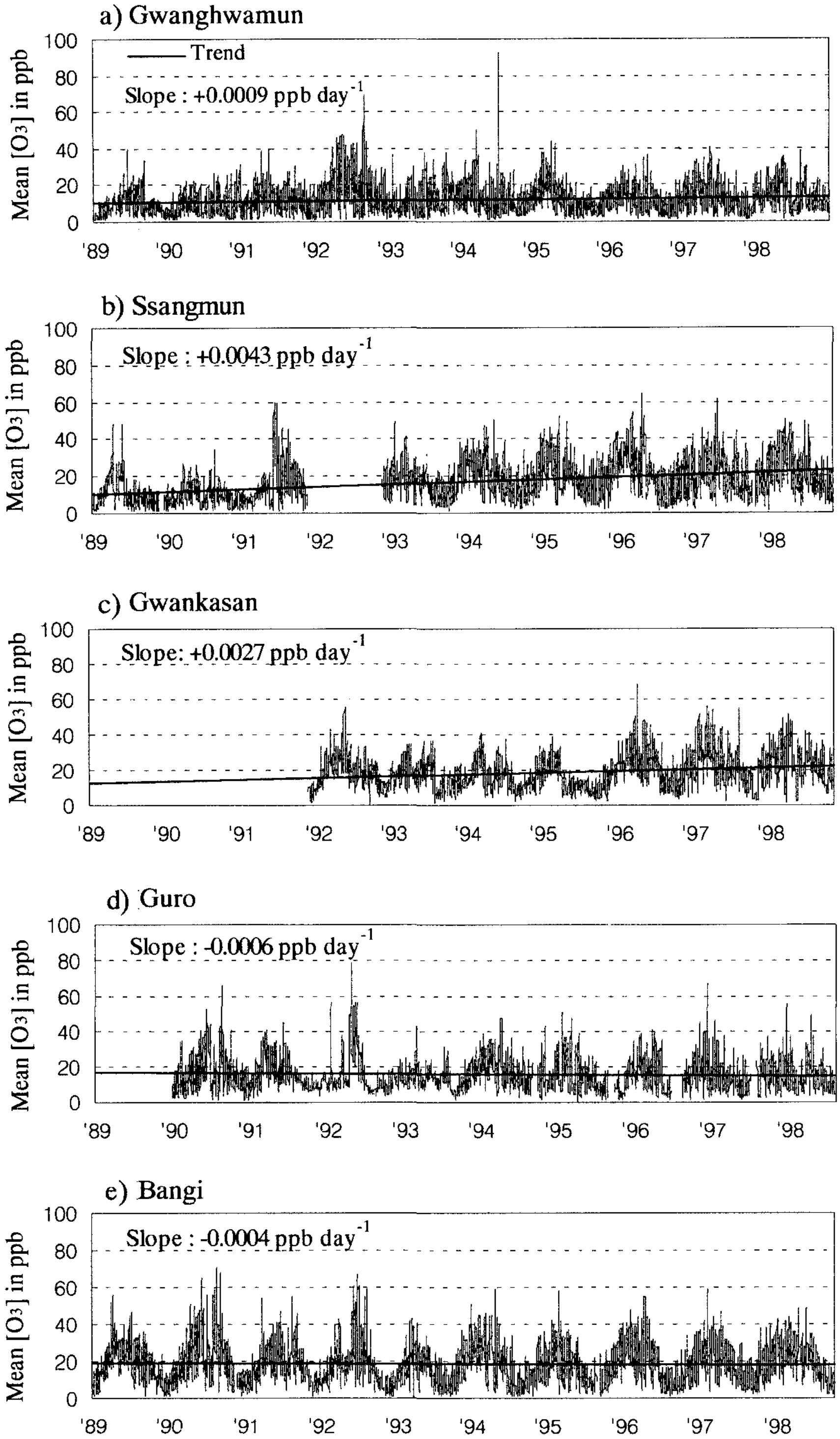

Fig. 3. Patterns of daily mean ozone concentrations at five sites in Seoul.

and −0.0005 ppb day^{-1}, respectively). Referring to Ghim ans Chang's study (2000), the annual variations of ozone in Seoul might be strongly influenced by photochemical reaction ensuing both from the downwind transport of photochemical pollutants and from local emissions.

The daily maximum ozone concentrations for the five sites were combined and the percentiles (5, 10, 25, 50, 75, 90, and 95) were computed for each year. When the data capture rate exceeded 75% every day, the daily maximum value was calculated. However, the data capture rate was not considered missing data by time zone. Box plots were produced as shown in figure 4 and a linear relationship of annual mean values were shown on a curve. For the years 1991−1993, the ozone distribution at Gwanghwamun was significantly chang-

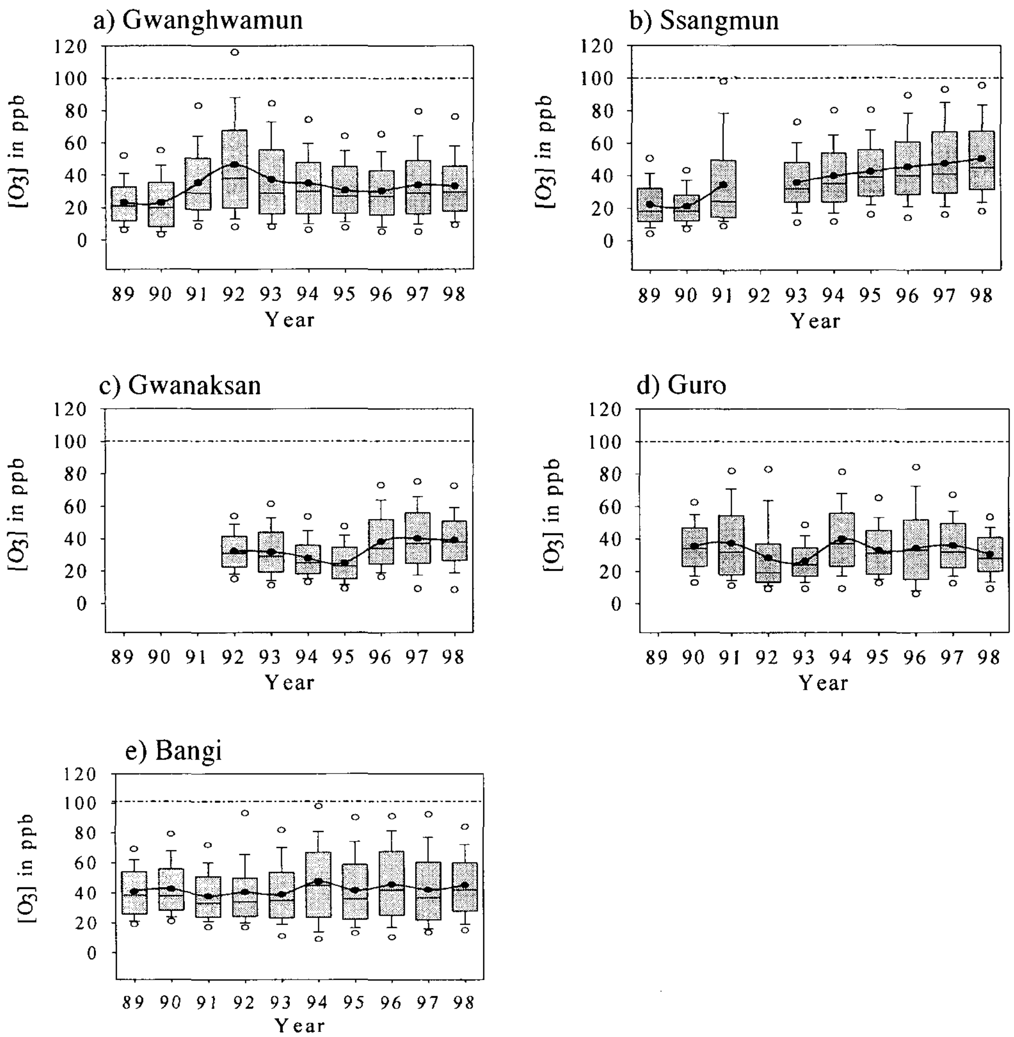

Fig. 4. Annual patterns of daily maximum ozone concentrations in Seoul for the 1989−1998 period. Each box plot represents 95, 90, 75, 50, 25, 10, and 5th percentile. Two top and bottom circles indicate 95th and 5th percentile levels, respectively. The mean values (•) are joined by lines. The dash-dot line indicates 100 ppb as the current 1 hr Korean standard.

ed from year-to-year. For the site, the 95[th] percentile concentrations were greater than 100 ppb (the current 1-hr Korean standard) in 1992, began to decrease in 1993, and increased in 1997 and 1998 (Fig. 4a). Because of many missing data, the 1992 data set for Ssangmun was omitted in these statistical analyses. Since 1991, all percentile concentrations at the site have steadily increased. However, the 95[th] percentile concentrations seldom exceed 100 ppb (Fig. 4b). For Gwanaksan, daily maximum values have risen and the differences between high and low percentile values have increased significantly since 1996 (Fig. 4c). It is obscure that such changes may be ascribed to active photochemical reactions leading to ozone formation at the site, owing to the changes in either or both local emissions of pollutants or meteorological conditions. No significant trends were observed over the ten-year period in daily maximum levels at Guro (Fig. 4d). The

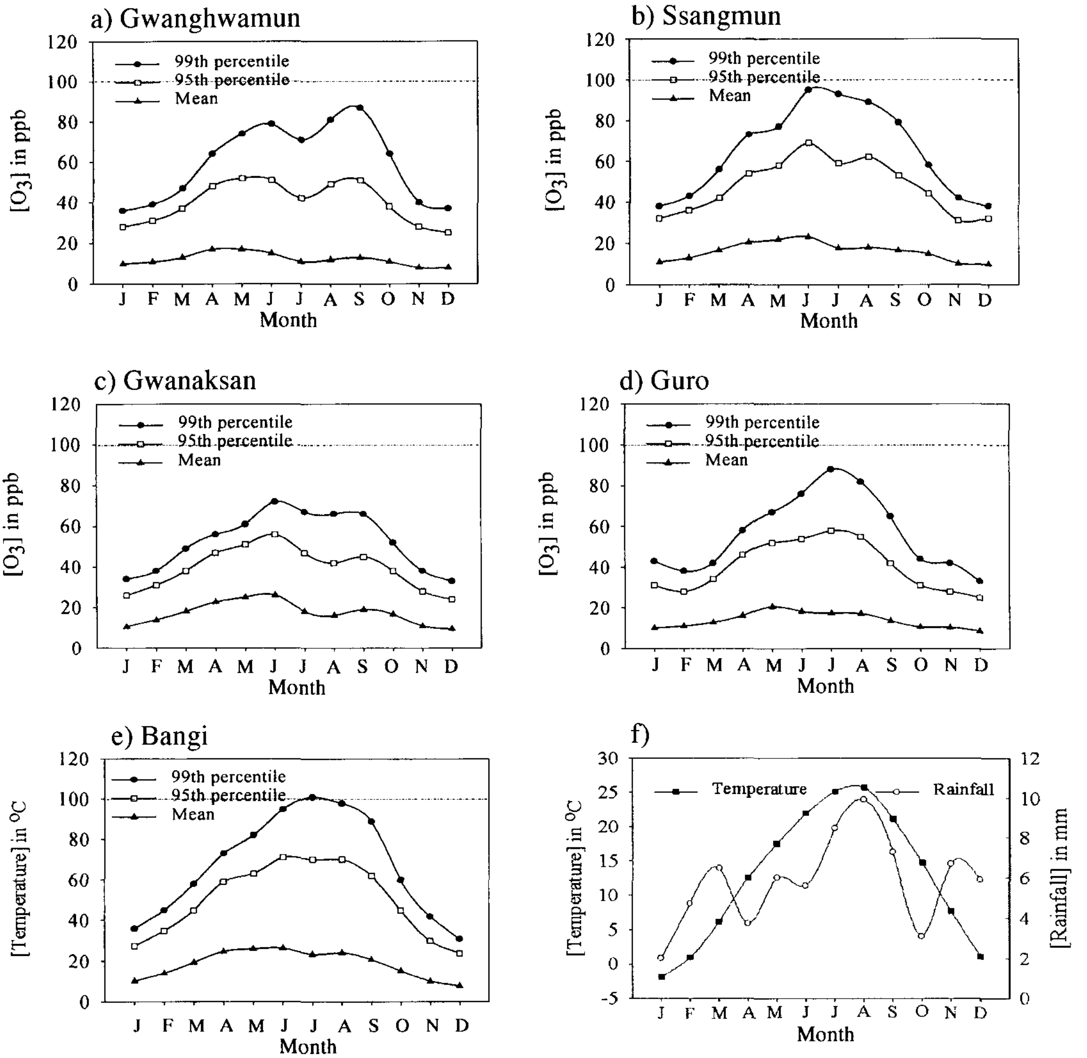

Fig. 5. a–e). Seasonal variation of monthly (99th, 95th, and mean) ozone concentrations for the 1989–1998 period. f) Seasonal variation of monthly mean rainfall and temperature at Gwanghwamun.

95th percentile levels at Bangi had begun to rise since 1992 and the level remained high to the following years (Fig. 4e). From these five sites, most of annual variations in daily maximum ozone levels should be ascribed to annual changes in the frequency of occurrence in meteorological conditions linked to ozone formation (Fuentes and Dann, 1994; Poulida *et al.*, 1991). For example, the 95th percentile levels in 1998 were dropped at all sites except Ssangmun because of unusually long rainy season in summer and twice heavy precipitation in 1998.

3. 3 Seasonal variation of ozone concentrations

Monthly means of hourly ozone concentrations can explain more clearly the seasonal trends for the ten years. Figures 5a to 5e show the trends representing the 99th, 95th percentiles, and mean values of ozone concentrations. Furthermore, figure 5f shows the variations of monthly mean rainfall and temperature for nine years (1990～1998) to illustrate the seasonal

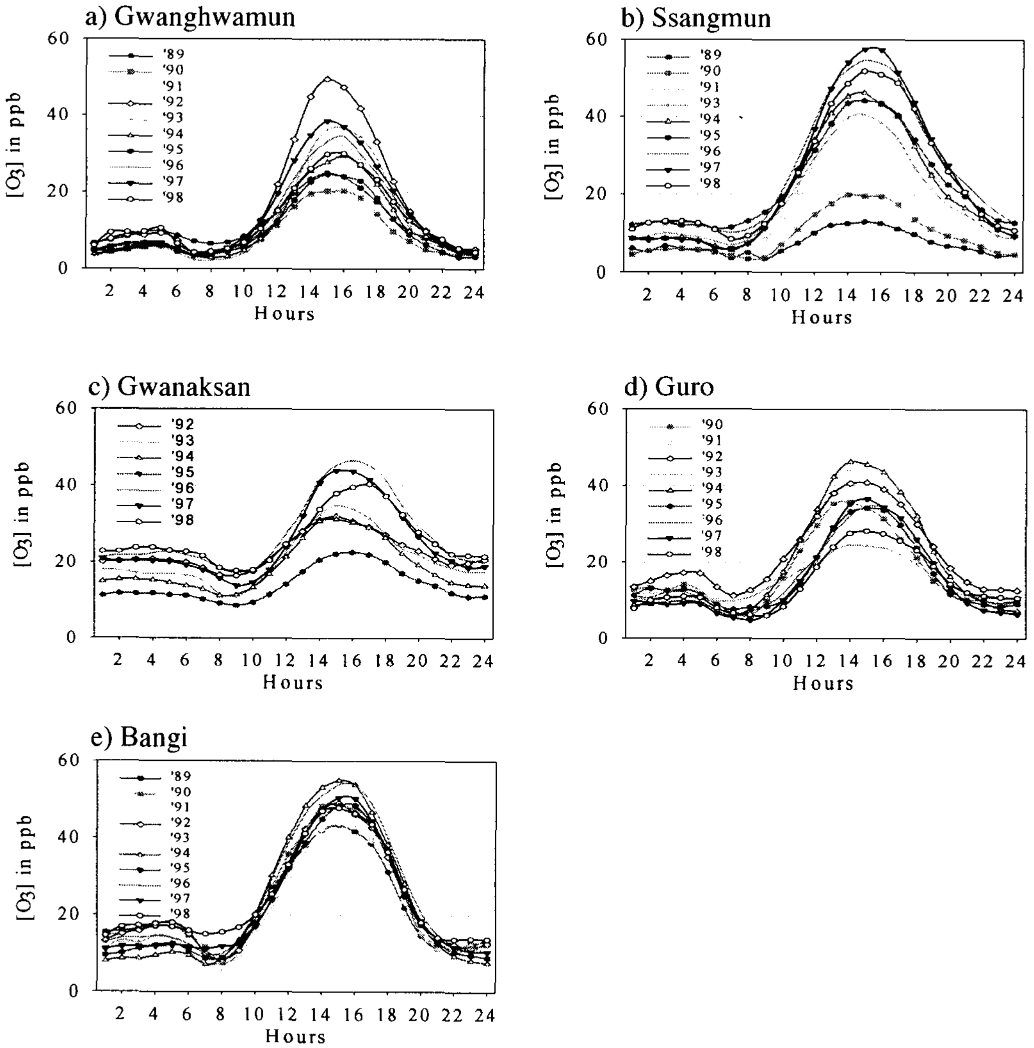

Fig. 6. Diurnal variation of hourly mean ozone concentration from June to September for the 1989-1998 period.

patterns. For the five sites, while mean values per month were the highest from May to June, the 99th and 95th percentile concentrations were the highest from June to August. Although mean concentrations during July and August were relatively lower because of scavenging effects by much rainfall for this period. These phenomena owed to rising temperature and intensifying solar radiation that enhanced the photochemical reactions (Fig. 5f). Especially, Gwanghwamun, heavy traffic area, showed higher ozone concentrations in spring and summer (Fig. 5a). In most part of Seoul, seasonal trends were similar in summer. On the other hand, relatively higher ozone was observed at Gwanaksan in spring than that at the other sites (Fig. 5c). The seasonal patterns at Bangi (eastern area) were very similar to Guro (western area) (Fig. 5d and 5e).

3. 4 Diurnal variation of hourly mean ozone concentrations in summer

Diurnal variations have been used as indicators of possible changes in the distribution of hourly mean concentrations. Diurnal patterns may provide the information on the source, transport, and chemical formation/destruction at some sites (Lefohn and Foley, 1993) and the classified patterns can be used as useful information for predicting elevated ozone episode in the next study. Figure 6 shows the diurnal variations of hourly mean ozone concentrations at the five sites from June to September for the ten-year period. Low levels of ozone may result from the abundant NO_x presence, which contributes to ozone destruction, in the urban atmosphere during the night (Fuentes and Dann, 1994). In general, the maximum hourly average concentrations at Gwanghwamun were below 40 ppb except in 1992. The ozone levels from late night to early morning of the next day were much lower than those at the other sites. Thus, the diurnal variations at this site show the typical photochemical production and destruction of ozone in NO_x concentrations remained by heavy traffic (Fig. 6a).

For Ssangmun, the pattern of diurnal variations has been changed as ozone concentrations increased since 1990 (Fig. 6b). The flat diurnal shape observed before 1996 at Gwanaksan was interpreted as indicating few pronounced photochemical reactions due to a lack of precursors (Fig. 6c). However, clear diurnal patterns were found after 1996. The peal concentrations at Guro (upwind area) were observed between 13:00 and 16:00, the ones at Bangi (downwind area) between 14:00 and 17:00 (Fig. 6d and 6e).

3. 5 General characteristics of ozone distribution

Table 3 represents the percentile distributions of the hourly ozone concentrations and the number of hours exceeding 100 ppb at all 20 monitoring sites for the ten-year period. For all sites, the infrequent occurrences below 3 ppb were highlighted by the 10th percentile; 90% of them were greater than 3 ppb. On the average, 50% of them were below 10 ppb (50th percentile), 25% of them were above 20 ppb (75th percentile), and 1% of them were higher than 53 ppb (99th percentile). On the other hand, the 25th percentile at Gwanaksan was below 9 ppb, 75% of ozone levels were less than 24 ppb (75th percentile), and their mean values were 17.6 ppb. While Gwanaksan had higher concentrations at the below 75th percentile than the other sites, it had lower concentrations at the above 75th percentile. Thus, distribution of annual ozone concentrations showed a flat-type at this site. Ghim and Chang (2000) reported that Gwanaksan reflected inclinations that were similar to the distribution of background ozone concentrations in Korea. Bangi recorded higher concentrations than the other sites at all percentiles. The 10% of hourly ozone concentrations were greater than 41 ppb and 1% of them was higher than 69 ppb. Bangi experienced less frequent occurrences over 100 ppb than Ssangmun. Although Ssangmun recorded the most frequent occurrences of ozone levels over 100 ppb, its 99th percentile values were lower than Bangi's. Thus, Bangi experienced high ozone concentrations for a long time; Ssangmun for a short while (Heo *et al.*, 1999).

Table 4 provides patterns of mean NO_2 and meteoro-

Table 3. Percentile distributions of hourly ozone concentrations, the number of hourly occurrences ≥100 ppb for 20 monitoring sites in Seoul. All concentrations are in ppb unit.

Type of land-Use	Sites	Period	No. of samples	Min.	Percentile 10	25	50	75	90	95	99	Max.	Mean	≥100
Residence	Banpo	'89-'98	63,147	1	2	3	9	20	32	40	56	227	13.6	66
	Bulgwang	'89-'98	72,129	1	3	5	12	22	32	38	53	167	15.2	47
	Jamsil	'89-'98	75,507	1	2	3	7	17	29	37	55	183	11.8	73
	Hannam	'89-'98	65,788	1	2	4	10	21	32	41	58	134	14.3	69
	Hwagok	'92-'98	52,648	1	4	6	11	20	30	37	51	170	14.5	46
	Gireum	'89-'98	68,961	1	3	4	9	19	30	37	53	152	13.4	51
	Mapo	'89-'98	73,583	1	2	3	8	15	25	31	44	189	10.8	31
	Myeonmok	'89-'98	61,624	2	4	5	9	17	26	33	46	123	12.5	11
	Namgaja	'89-'98	65,854	1	4	6	12	20	30	36	50	140	14.7	25
	Ssangmun	'89-'98	66,774	1	2	5	13	25	36	44	59	168	16.8	224
	Sinseol	'89-'98	61,543	1	3	4	8	16	25	31	44	132	11.5	11
	Daechi	'89-'98	70,634	2	3	5	9	17	27	34	48	143	12.5	48
Green land	Bangi	'89-'98	65,861	1	2	6	14	28	41	50	69	175	18.5	200
	Guui	'89-'98	70,954	1	4	7	13	23	34	42	58	157	16.6	156
	Gwanaksan	'89-'98	60,475	1	5	9	16	24	33	38	49	139	17.6	7
Commerce	Gwang-hwamun	'89-'98	77,331	1	2	3	7	17	30	39	58	322	12.0	117
	Seongsu	'89-'98	55,478	1	1	3	10	21	34	42	59	163	14.2	138
Semi-industry	Guro	'89-'98	64,296	1	2	5	11	20	32	39	55	240	14.2	100
	Mullae	'89-'98	73,729	2	4	5	10	18	27	34	46	115	13.1	4
	Oryu	'89-'98	71,281	1	2	4	11	23	34	41	56	150	15.2	70
Average				1	3	5	10	20	31	38	53	169	14.0	1,494

Table 4. Patterns of mean NO_2 and meteorological parameters according to ozone concentration at Gwanghwamun for the ozone season (April-October) from 1989 to 1998.

Range of O_3 (ppb)	No. of samples	NO_2 (ppb)	Temperature (°C)	Humidity (%)	Wind speed ($m\ s^{-1}$)	Solar ($MJ\ m^{-2}$)	Major wind direction
10	29,661	36.0±20.4	18.2±7.1	72.7±16.7	1.8±1.2	2.9±5.6	West (49.0%) East (51.0%)
11~39	15,007	28.4±19.1	18.8±8.2	58.7±18.9	2.9±1.5	8.7±9.4	West (77.6%) East (22.3%)
40~79	3,319	26.4±16.8	23.2±5.7	49.7±15.8	3.5±1.4	13.8±8.8	West (84.8%) East (5.2%)
80	334	28.2±17.2	27.0±3.8	51.3±11.9	3.3±1.1	14.7±7.6	West (99.4%) East (0.6%)

logical parameters according to ozone concentrations at Gwanghwamun during the ozone season of April to October for ten years. Ozone concentrations are classified on the basis of percentiles value in table 3, i.e. ≤10 ppb (below 50^{th} percentile), 11~39 ppb (50^{th}~95^{th} percentile), 40~79 ppb (over 95^{th}), and ≥80 ppb (ozone episode). Increased ozone concentrations are correlated with higher temperature and stronger solar radiation. High temperature and solar radiation are excellent indicators among many environmental conditions leading to the formation and accumulation of ozone. The rate constants of photochemical reactions was reported to be highly dependent on temperature (Chen *et al.*, 1998; Zaveri *et al.*, 1995). However, relative humidity and wind speed were negatively correlated with high ambient ozone concentrations (Fredericksen *et al.*, 1996). In general, a diurnal variation of hourly mean wind speed in Seoul shows that it is faster at daytime and slower at night. High ozone concentrations were mostly accompanied by westerly winds.

4. CONCLUSIONS

The aim of this study has been to analyze and offer a long-term perspective on the surface ozone concentrations in Seoul during the 1989 ~ 1998 period and to prepare a preliminary database for developing a forecast model of ozone episode in the next study. The specific geographical situation affecting the transport of air pollutants was focused on the city of Seoul in Korea. Under this state, diurnal and seasonal patterns as well as the distribution of ozone concentrations in Seoul were identified as follow:

1) Ozone episodes occurred more frequently in the east areas (Bangi, Guui, Seongsu, and Ssangmun) than in the west areas (Guro and Oryu). It is thought that the contours of the Han River valley may be conducive to the transport of ozone and its precursors from west to the east, contributing to the formation of ozone there. In general, the average duration for ozone concentrations over 80 ppb was 4.0 hours.

2) Annual variations in daily mean and maximum ozone concentration maintained broadly consistent upward trends at Ssangmun and Gwanaksan. It is thought that annual variations might be affected by photochemical reactions both from local emissions of pollutants and from those transported downwind.

3) At most sites, while mean ozone concentrations per month were the highest from May to June, the 99^{th} and 95^{th} percentile levels were higher from June to August. In general, diurnal patterns of hourly mean ozone levels at the four sites (Gwanghwamun, Ssangmun, Guro, and Bangi) explained typical photochemical formation and destruction. The flat diurnal shape observed before 1996 at Gwanaksan was interpreted as indicating few pronounced photochemical reactions due to a lack of precursors.

4) The meteorological conditions for ozone concentrations over 80 ppb were summarized as the following: high temperature, strong solar radiation, low relative humidity, and low speed winds mostly from west to east.

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REFERENCES

Angle, R.P. and H.S. Sandhu (1989) Urban and rural ozone concentrations in Alberta, Canada. Atmospheric Environment, 23D, 215-221.

Bezerra, P.C., M.A. Fagnani, H.S. Pinto, I.M. Martin, E.L.P. Da Silva, M.G. Da Silva Mello, A. Turtelli Jr, J. Lazutin, Zullo Jr, and V. Zhavkov (1996) Surface ozone study in Campinas, Sao Paulo, Brazil. Atmospheric Environment, 30, 2729-2738.

Bower, J.S., K.J. Stevenson, G.F.J. Broughton, J.E. Lampert, B.P. Sweeney, and J. Wilken (1994) Assessing recent surface ozone concentrations in the U.K. Atmospheric Environment, 28D, 115-128.

Chan, C.Y. and L.Y. Chan (2000) Effect of meteorology and air pollutant transport on ozone episodes at a subtropical coastal Asian city, Hong Kong. Journal of Geophysical Research D: Atmospheres, 105, 20,707-20724.

Chen, J.L., S. Islam, and P. Biswas (1998) Nonlinear dynamics of hourly ozone concentrations: nonparametric short term prediction. Atmospheric Environment, 32D, 1839-1848.

Chung, Y.S. and J.S. Chung (1991) On surface ozone observed in the Seoul metropolitan area during 1989 and 1990. Journal of Korea Air Pollution Research Association, 7, 169-179 (in Korean).

Feister, U. and K. Balzer (1991) Surface ozone and meteorological predictors on a subregional scale. Atmospheric Environment, 25A, 1781-1790.

Fredericksen, T.S., J.M. Skelly, K.R. Snyder, and K.C. Steiner (1996) Predicting ozone uptake from meteorological and environmental variables. Journal of Air & Waste Management Association, 46, 464-469.

Fuentes, J.D. and T.F. Dann (1994) Ground-level ozone in Eastern Canada: seasonal variation, trends, and occurrences of high concentrations. Journal of Air & Waste Management Association, 44, 1019-1026.

Heo, J.S., T.O. Kim, and D.S. Kim (1999) A comparative study on ambient air quality standard for ozone. Journal of Korean Society for Atmospheric Environment, 15, 159-173 (in Korean).

Jo, W.K., I.H. Yoon, and C.W. Nam (2000) Analysis of air pollution in two major Korean cities: trends, seasonal variations, daily 1-hour maximum versus other hour-based concentrations, and standard exceedances. Environmental Pollution, 110, 11-18.

Ghim, Y.S. and Y.S. Chang (2000) Characteristics of ground-level ozone distributions in Korea for the period of 1990-1995. Journal of Geophysical Research D: Atmospheres, 105, 8877-8890.

Komala, N., S. Saraspriya, K. Kita, and T. Ogawa (1996) Tropospheric ozone behavior observed in Indonesia. Atmospheric Environment, 30, 1851-1856.

Korea Ministry of Environment (1999) The Basic Plan of Air Pollution Monitoring Network in theYear 2000. Republic of Korea. pp. 1-104.

Lee, J.B. and S.Y. Bang (1997) Case study on the episode of ozone in Seoul metropolitan area on June 1997. Korean Society for Atmospheric Environment, For presentation at the Biannual Meeting in 1999, Naju, Cheonnam, Korea. November 14-15 (in Korean).

Lefohn, A.S. and J.K. Foley (1993) Establishing relevant ozone standards to protect vegetation and human health: exposure/dose-response considerations. Journal of Air & Waste Management Association, 43, 106-112.

Lippmann, M. (1991) Health effects of tropospheric ozone. Environmental Science & Technology, 25, 1954-1962.

Ludwig, F.L., I.J. Jiang, and J. Chen (1995) Classification of ozone and weather patterns associated with high ozone concentrations in the San Francisco and Monterey Bay Areas. Atmospheric Environment, 29, 2915-2928.

Lyons, W.A., J.L. Eastman, R.A. Pielke, C.T. Tremback, P.A. Moon, and N.R. Lincoln (1991) The meteorological of ozone episodes in the lower lake Michigan Air Quality Region. Air & Waste Management Association, For presentation at the 83th Annual Meeting & Exhibition, Vancouver, British Columbia, June 16-21.

McKendry, I.G. (1993) Ground-level ozone in Montreal, Canada. Atmospheric Environment, 27B, 93-103.

National Statistical Office, Republic of Korea (2000) http://nso.go.kr.

Poulida, O., R.R. Dickerson, B.G. Doddridge, J.Z. Holland, R.G. Wardell, and J.G. Watkins (1991) Trace gas concentrations and meteorology in rural Virginia: 1. Ozone and carbon monoxide. Journal of Geophysical Research, 96, 22461-22475.

Ryan, W.F., B.G. Doddridge, R.R. Dickerson, R.M. Morales, K.A. Hallock, P.T Roberts, D.L. Blumenthal, J.A. Anderson, and K.L. Civerolo (1998) Pollutant transport during a regional O_3 episode in the Mid-Atlantic States. Journal of Air & Waste Management Association, 48, 786-797.

Staehelin, J., J. Thudium, R Buehler, A. Voltz-Thomas, and W. Graber (1994) Trends in surface ozone concentrations at Arosa, Switzerland. Atmospheric Environment, 28, 75-87.

Tilton, B.E. (1989) Health effects of tropospheric ozone. Environmental Science & Technology, 23, 257-263.

Vecchi, R. and G. Valli (1999) Ozone assessment in the southern part of the Alps. Atmospheric Environment, 33, 97-109.

Vukovich, F.M. (1995) Regional-scale boundary layer ozone variations in the Eastern United States and their association with meteorological variations. Atmospheric Environment, 29, 2259-2273.

Weston, K.J., P.J.A. Kay, D. Fowler, A. Martin, and J.S. Bower (1989) Mass budget studies of photochemical ozone production over the U.K. Atmospheric Environment, 23, 1349-1360.

Zaveri, R.A., R.D. Saylor, L.K. Peter, L.K., R. Mcnider, and A. Song (1995) A model investigation of summertime diurnal ozone behavior in rural mountainous locations. Atmospheric Environment, 29, 1043-1065.