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Seasonal and Diurnal Trend of Carbon Dioxide in a Mountainous Site in Seoul, Korea

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ABSTRACT

In this research, the environmental behavior of carbon dioxide (CO_2) was investigated in a mountainous site in the proximity of a highly industrialized megacity, Seoul, Korea. The concentration data of CO_2 monitored routinely at hourly intervals at Mt. Gwan-Ak (GA), Seoul, Korea throughout 2009 were analyzed in several respects. The mean CO_2 value was 405 $\pm$12.1 ppm (median=403 ppm) with a range of 344 to 508 ppm (N=8548). The analysis of its seasonal trend indicated that the CO_2 levels peaked in the winter but reached a minimum in fall. If the short-term trend is analyzed, the CO_2 values generally peaked during daytime along with the presence of two shoulders; this is suspected to be indicative of strong man-made effects (e.g., traffic activities). It is seen that the general patterns of CO_2 distribution in this study area are highly comparable to those typically found in urban areas with strong signals of anthropogenic activities.

Key words: Carbon dioxide, Mountain, Continuous monitoring, Urban area, Anthropogenic

1. INTRODUCTION

Carbon dioxide (CO_2) is considered a trace gas constituting about 0.038% of the earth's atmosphere (Williams, 2009). Currently about 57% of man-made CO_2 emissions are known to be removed by the biosphere and oceans (Canadell *et al.*, 2007). However, because of various human activities (e.g., deforestation, combustion of fossil fuels, power generation, etc), the concentration of atmospheric CO_2 has been increasing gradually through the years (Colombo *et al.*, 2000; Denning *et al.*, 1995).

Keeling (1960) initiated continuous monitoring of atmospheric CO_2 at Mt. Mauna Loa, Hawaii, US since 1958. From that time on, monitoring of CO_2 has been conducted routinely in many background areas (e.g., South Pole). At present, CO_2 concentration at Mauna Loa is 392 ppm (by volume) (NOAA, 2010). This level of change corresponds to an increase of about 40% since the beginning of the industrialization age. As greenhouse gases (like CO_2) are identified to play a big role in climate change (both regionally and globally), its control is a matter of concern in many countries and societies.

According to the Fourth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC, 2007), global surface temperature increased by 0.74$\pm$0.18°C during the 20th century with much of the warming centering over the last 30 years. This warming will cause significant changes in ecosystem such as the reduction in the area of ice cover and the rise of sea level among other impacts (NASNAEIMNRC, 2008a, b). In the next 100 years, the temperature is likely to increase at least 1.1°C and possibly over 6°C, if the current trend of global warming continues (NASNAEIMNRC, 2008a, b). The cause of increases in temperature has been attributed to the rise in concentration levels of greenhouse gases.

As the concentration of CO_2 varies in diverse temporal scales (Keeling *et al.*, 1995, 1984), so does its spatial scales between urban and rural areas (Nemitz *et al.*, 2002) and between indoor and outdoor environments (Kovesi *et al.*, 2007). In South Korea, the rapid industrial growth, accompanied by socioeconomic change, has brought an immense rise in CO_2 levels to become the 9th ranked country of the global fossil-fuel consumption, i.e., nearly 130 million metric tons of carbon in 2006 (Boden *et al.*, 2009). Accordingly, South Korea needs to reduce its CO_2 emission by 55% to reach the average value for the world per capita. The statistics from the Carbon Dioxide Information Analysis Center (CDIAC) also indicate that South Korea experienced a phenomenal growth in fossil-fuel CO_2 emissions with a mean growth rate of 11.5% from 1946-1997 (Boden *et al.*, 2009). As sustainable development has become a prior obligation in the 21st century, techniques to control total energy consumption and the associated CO_2 emission will become the key issues in economic development, ecological environment, and energy technology in the coming years (Lu *et al.*, 2007). At present, South Korea is not included in the list of Annex I countries by the United Nations Framework Convention on Climate Change (UNFCCC). However, it is under the pressure to implement a schedule for reducing the emissions of Greenhouse Gases (GHG), especially CO_2 in the near future (Lim *et al.*, 2009).

In this study, the seasonal and diurnal trend of CO_2

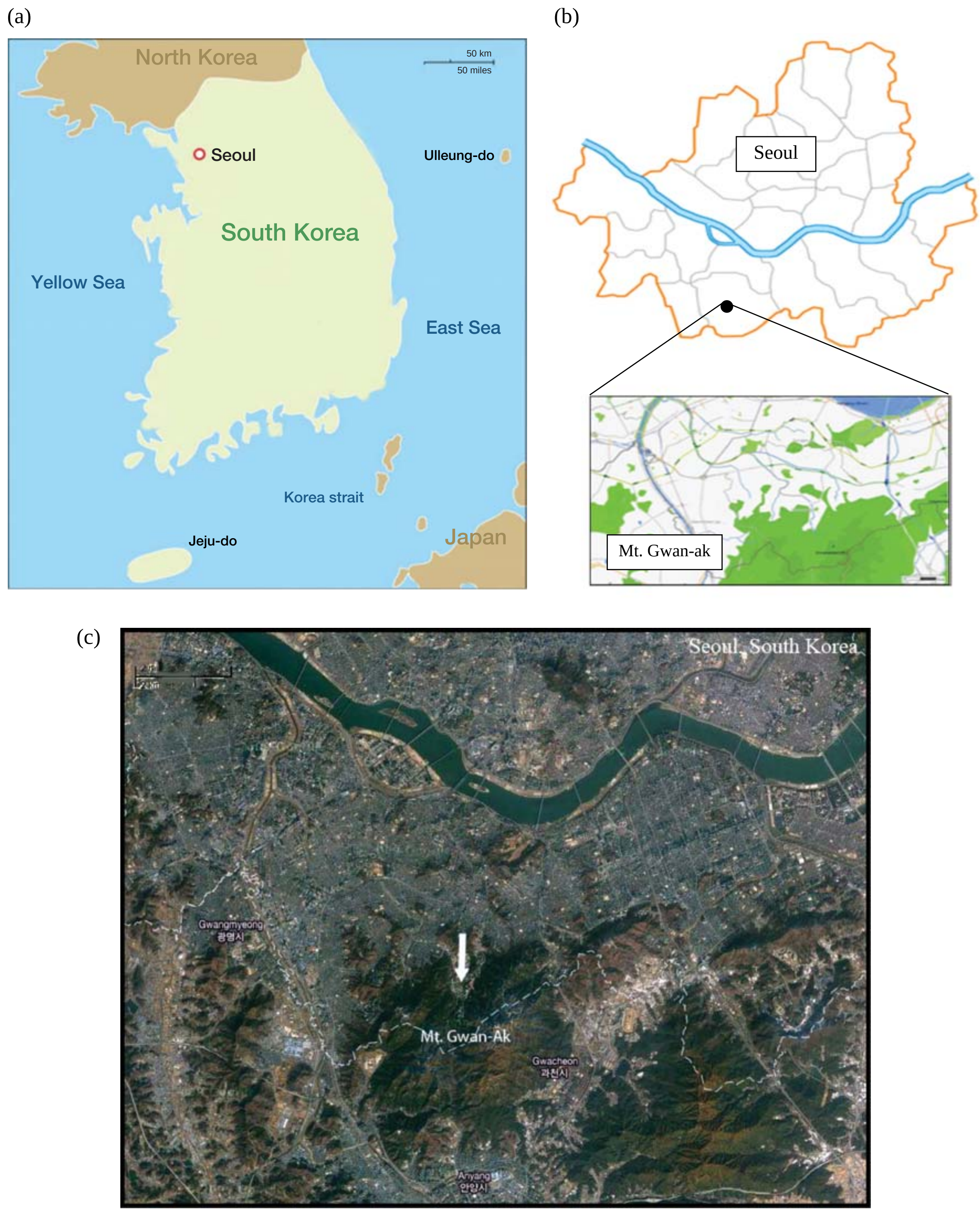

Fig. 1. Geographical location of Mt. Gwan-ak (GA) in Seoul, Korea. (a) Location of Seoul; (b) Location of Mt. Gwan-ak (GA); and (c) Topography of Mt. Gwan-ak (source: Google map).

was investigated using its hourly measurement data collected at the Mt. Gwan-Ak (GA) monitoring station (elevation: 632 m) in Seoul, Korea during the year 2009. Using these hourly measurement data, we first examined the temporal distribution of CO_2 in both diurnal and seasonal scale. These data sets were then analyzed in relation with the relevant environmental parameters to describe the fundamental factors controlling its distribution in a number of aspects. The results of this study will provide valuable insights into the factors governing the environmental behavior of CO_2 in response to various source/sink processes in the urban environment.

2. MATERIALS AND METHODS

2. 1 Site Description

As the capital of South Korea, Seoul has a carbon footprint of 1.59 metric tones per person (Sovacool and Brown, 2010). The Seoul metropolitan area has 10 million inhabitants, while occupying only 0.6 percent of the country's land area. Nonetheless, the city with 25 districts produces 21 percent of its GDP, mainly in business and financial sectors with technology firms and banking giants such as Samsung, Hyundai, Kia, and LG (Sovacool and Brown, 2010). More than 80% of the total energy used in Seoul comes from fossil fuels, mostly coal, petroleum, and natural gas (Sovacool and Brown, 2010). The city also maintains a large number of water and waste treatment plants along with landfills that can release fairly large quantities of greenhouse gases (Jo *et al.*, 2008; Kaneko and Dhakal, 2008; Jo, 2002).

In this study, the distribution pattern of carbon dioxide was investigated using the data sets collected from an air quality monitoring station on the top of Mt. GA (37° 26′44″N, and 126° 57′49″E), a relatively small mountain located at the southern district of Seoul, South Korea with the total area of 19,226,942 m^2 (Fig. 1). Mt. GA is situated to cover 4 districts in terms of the administrative zones, (1) 11,412,035 m^2 (59.4%) in Gwanak-gu, (2) 2,120,595 m^2 (11%) in Geumcheon-gu, and (3) 5,694,312 m^2 (29.6%) in both Gwacheon City and Anyang City of Gyeonggi-do. Our target study area of Mt. GA belongs to a temperate climate zone with the mean temperature of 9.53 ± 10.4°C (seasonal means of -3.2 (winter) to 20.3°C (summer)). Likewise, the UV radiation also exhibited the seasonal mean value (mWcm^{-2}) of 0.07 (winter) to 0.45 (summer). Relative humidity was significantly lower in spring (58.6%) than other seasons. Examination of the wind rose pattern indicated that during most of the time, winds were blown from WWN followed by westerlies. It is steep topographically with a ravine developed in all directions. Only a few types of needle-leaf trees (e.g., pine trees) are grown wildly while a variety of falling broadleaved trees (e.g., black oaks) can be found frequently (Gwanak-Gu, 2010).

2. 2 Data Collection

From the air quality monitoring site, the hourly CO_2 data were collected continuously to cover a whole year from January 1st to December 31st 2009 using a CO_2/CH_4/H_2O analyzer (Picarro G1301, US). An automated air pollution monitoring system (Thermo, USA) is located at a height of 620 meters above mean sea level. The vertical height of sampling inlet from the monitoring station is 14 m, while the station itself is aloft 9 m above the soil. A list of the criteria pollutants (CH_4, NO_x, O_3, SO_2, and particulate matters) were also monitored concurrently along with the meteorological parameters (air temperature, UV, humidity, wind speed, etc). The analysis of CO_2 data and all the relevant parameters can help us properly evaluate the influence of various factors and processes affecting the behavior of CO_2 in the study area.

2. 3 QA/QC Section

The instrument used to measure concentration of CO_2 is Picarro G1301 analyzer (Picarro, US). The analyzer is based on Picarro's unique Wavelength-Scanned Cavity Ring Down Spectroscopy (WS-CRDS), a time based measurement technique based on a near infrared laser. This CRDS technique is a highly precise method allowing to measure a spectral signature of the target molecule (Picarro, 2010). It is a real time, trace gas monitor capable of measuring gases at parts-per-billion (ppbv) sensitivity. The instrument is capable of measuring CO_2 in the range 0-1,000 ppmv and CH_4 in the range 0-20 ppmv. By following the procedure of Busch and Busch (1997), the measurement precision was assessed by taking a spectral scan at every 5 min with the 380 ppm CO_2 standard at room temperature. The relative standard deviation was then estimated as 0.04%.

3. RESULTS AND DISCUSSION

3. 1 The Basic Aspects of CO_2 Distribution in the Study Area

In this study, CO_2 concentration data were collected from an air quality monitoring station located on the top of Mt. GA, in the southern district of Seoul, South Korea for a one year period (January to December 2009). To explore the overall trend of CO_2, its hourly data were at first plotted as a function of time (Julian

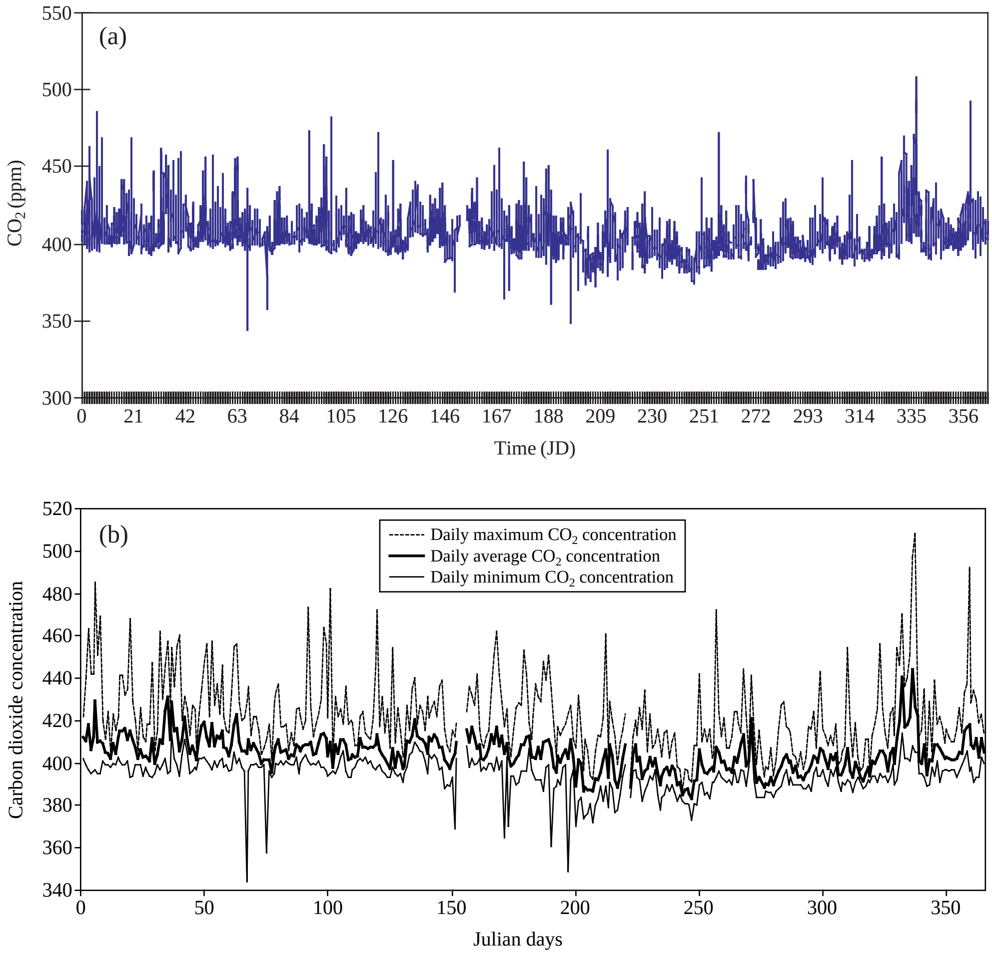

Fig. 2. Plot of daily mean concentration of CO_2 in Mt. GA, Seoul, Korea in 2009. (a) Temporal changes of CO_2 at Mt. GA using hourly data collected throughout 2009; (b) Comparison of daily parameters of CO_2 data in 2007.

day) (Fig. 2(a)). The mean hourly concentration of CO_2 for the entire study period was 405 ± 12.1 ppm (median = 403 ppm) with a range of 344 to 508 ppm (N = 8,548). The maximum hourly concentrations of CO_2 (508 ppm) was determined at 1 am on December 3rd, while its minimum value (344 ppm) at 7 am on March 8th. This observed annual concentration of CO_2 in Mt. GA was 4.55% higher than the average value of Mauna Loa (387.35 ppm) for the year 2009. The trend in CO_2 at Mauna Loa can be one of the most representative sites to predict the global trend.

3.2 Seasonal Distribution of CO_2

As shown in Table 2, the CO_2 data divided into each season show the maximum value in winter (410 ± 13.4 ppm) followed by spring (407 ± 9.56 ppm), summer (402 ± 11.3 ppm) and fall (399 ± 11 ppm). To accurately describe the temporal trend of CO_2 over a one year period, some parameters derived on daily basis (average, minimum, and maximum) were also plotted in Fig. 2(b). It is found that differences in CO_2 levels between winter (the highest) and spring (the next) are statistically significant ($P < 0.05$). The relative enhancement in wintertime CO_2 levels can be basically sought from the combined effect of such factors as the increasing consumption rate of fossil fuel (e.g., house heating), reduced photosynthesis, and more stable atmospheric conditions (Henninger and Kuttler, 2010). Our findings of relative enhancement in CO_2 during the wintertime comply well with many previous studies conducted in the background as well as in the urban region in the northern hemisphere (Henninger and Kuttler, 2010; Miyaoka *et al.*, 2007; Pataki *et al.*, 2003; Aikawa *et al.*, 1995; Woodwell *et al.*, 1978; Bolin and Keeling, 1963). It is however interesting to note that the lowest seasonal mean took place in fall. This pattern is quite unique if one considers the fact that the minimum CO_2 values were typically seen during summer in most of

Table 1. Statistical summary of CO_2 and the relevant environmental parameters measured at Mt. Gwan-ak (GA) in 2009.

		CO_2 (ppm)	CH_4 (ppm)	PM_1 ($\mu g\ m^{-3}$)	$PM_{2.5}$ ($\mu g\ m^{-3}$)	PM_{10} ($\mu g\ m^{-3}$)	NO (ppb)	NO_2 (ppb)	SO_2 (ppb)	O_3 (ppb)	a ($mWcm^{-2}$)	Humidity (%)	b (°C)	c (m/s)
All	Mean	405	1.94	17.3	23.9	42.0	4.13	15.0	4.72	38.3	0.35	66.7	9.53	4.33
	SD	12.1	0.08	13.2	18.7	41.6	6.31	10.4	3.05	20.5	0.63	20.7	10.4	3.10
	Median	403	1.93	14.0	19.0	34.0	3.00	12.0	4.00	36.0	0.02	69.0	12.0	3.50
	Min	344	1.25	0.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	−16.2	0.20
	Max	508	2.65	118	175	1014	125	110	39	135	3.59	98.0	30.3	19.7
	N	8548	8548	7772	7583	8115	8214	8209	8480	8430	6539	8731	8731	8731
Spring	Mean	407	1.92	20.1	26.3	48.9	3.21	14.7	5.02	53.6	0.44	58.6	9.08	4.96
	SD	9.56	0.06	14.7	18.5	38.2	5.21	10.5	3.60	20.5	0.71	23.7	7.25	3.12
	Median	405	1.91	17.0	22.0	40.0	2.00	12.0	4.00	49.0	0.03	55.0	10.1	4.40
	Min	344	1.25	0.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	12.0	−8.00	0.30
	Max	482	2.40	85.0	113	375	70.0	94.0	38.0	135	2.98	98.0	26.1	16.5
	N	2185	2185	1966	1768	2160	1920	1915	2184	2177	1427	2207	2207	2207
Summer	Mean	402	1.94	15.6	21.3	30.7	2.92	12.8	4.74	34.6	0.45	78.9	20.3	4.18
	SD	11.3	0.09	13.0	16.5	22.1	1.63	7.28	1.73	23.1	0.72	15.5	3.02	3.64
	Median	401	1.93	13.0	19.0	29.0	2.00	11.0	5.00	32.0	0.04	81.0	20.4	2.90
	Min	349	1.32	0.00	1.00	1.00	2.00	2.00	1.00	2.00	0.00	23.0	11.6	0.50
	Max	462	2.43	118	138	203	28.0	57.0	14.0	132	3.59	98.0	30.3	19.7
	N	2058	2058	1937	1733	2136	2198	2198	2196	2198	2205	2205	2205	2205
Fall	Mean	399	1.95	15.4	21.6	36.4	4.26	14.8	4.06	37.2	0.28	68.5	11.8	3.89
	SD	11.0	0.07	11.4	16.9	27.6	5.41	10.6	2.18	14.4	0.52	15.5	7.44	2.79
	Median	398	1.94	12.0	17.0	30.0	3.00	12.0	4.00	36.0	0.02	69.0	13.4	3.00
	Min	373	1.84	1.00	1.00	1.00	2.00	1.00	1.00	2.00	0.00	10.0	−8.00	0.50
	Max	472	2.44	73.0	110	292	79.0	110	19.0	97.0	2.88	98.0	25.9	16.4
	N	2154	2154	1902	1988	2142	2157	2157	2156	2157	2163	2163	2163	2163
Winter	Mean	410	1.96	18.0	26.1	54.6	6.28	18.2	5.08	26.3	0.07	60.8	−3.26	4.30
	SD	13.4	0.07	12.9	21.5	66.9	9.97	12.4	4.10	10.4	0.13	20.5	5.69	2.64
	Median	407	1.95	15.0	19.0	41.0	3.00	15.0	4.00	26.0	0.01	61.0	−2.30	3.80
	Min	389	1.84	1.00	1.00	1.00	1.00	1.00	1.00	2.00	0.00	1.00	−16.2	0.20
	Max	508	2.65	79.0	175	1014	125	77.0	39.0	58.0	0.65	97.0	12.8	18.9
	N	2151	2151	1967	2094	1677	1939	1939	1944	1898	744	2156	2156	2156

[a]UV; [b]Temperature; [c]Wind speed.

Table 2. The mean concentrations of CO_2 and its relative amplitude between seasons.

	All year	Summer	Fall	Winter	Spring
Mean (ppm)	404.5	401.6	399.4	410.1	406.1
Maximum (ppm)	407.6	404.5	402.9	416.3	413.1
Minimum (ppm)	402.1	397.6	396.7	404.6	404.0
RA (%)[a]	1.36	1.72	1.53	2.86	2.23

[a]Relative amplitude = (Maximum concentration − minimum concentrating)/Average × 100.

the previous studies (Pataki *et al*., 2003; Woodwell *et al*., 1978; Bolin and Keeling, 1963). Summer minimum of CO_2 concentration was also observed in urban area of Nagoya and Sapporo in the neighboring country Japan as opposed to our finding of minimum concentration in fall (Miyaoka *et al*., 2007; Aikawa *et al*., 1995). Henninger and Kuttler (2010) also found the lowest concentration of CO_2 in summer in Essan, a typical urban conurbation city of Germany. In compliance with seasonal trend, comparison of monthly mean values of CO_2 shows it's minimum and maximum in October and February, respectively. In contrast, minimum and maximum values in most of the previous studies were found most commonly in August and April, respectively (e.g., Nakazawa *et al.*, 1992).

3.3 Diurnal Variation in Carbon Dioxide Levels

To understand the short-term variability of CO_2, the mean hourly CO_2 values were examined over a diurnal cycle for both seasonal group and a whole year period (Fig. 3). For all data groups, a clear cycle is observed

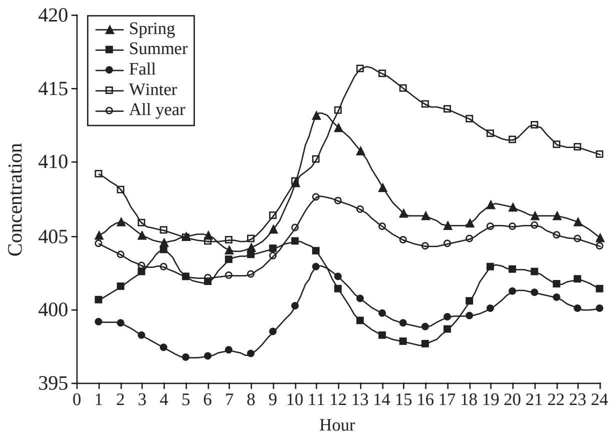

Fig. 3. Diurnal variability of CO_2: all data vs. each individual season.

with the maximum occurring in the late morning (around 11 am), while the minimum in the early morning (between 5 and 8 am). In addition, the presence of three shoulders throughout the year is also found along with the clear diurnal cycle of CO_2. This should be considered to reflect a dynamic nature of its temporal variabilities. One shoulder near midnight (around 12 am) is likely to be caused by the combined effects of respiration from soils and/or by the living organism. The other two shoulders observed earlier (9 am to 2 pm) and in the evening (6 to 10 pm) should be associated with traffic activities. The timing for these late peaks matches with the peak traffic hours in Seoul. These diurnal patterns of the CO_2 data thus clearly indicate the significance of anthropogenic activities (especially emission from automobiles) to a large extent; even at a mountainous site that is little distant from the highly urbanized sector of Seoul, one of the most populated megacities. It was also found that CO_2 concentration is immensely dependent on traffic activity in Denmark and France, respectively (Soegaard and Moller-Jensen, 2003; Widory and Javoy, 2003). In Mexico, Velasco *et al.* (2005) found the CO_2 concentration to be directly related to vehicular traffic because the transportation sector accounts for approximately 60% of emission burden.

In this study, the analysis of diurnal trend generally indicates that minimum and maximum values of CO_2 concentrations are in early morning and afternoon, respectively (Fig. 3). However, this pattern is completely opposite to what was found both in background as well as in urban areas in a number of previous studies (Anthwal *et al.*, 2010; Henninger and Kuttler, 2010; Miyaoka *et al.*, 2007; Idso *et al.*, 2002; Aikawa *et al.*, 1995). The authors commonly found its maximum in early morning and minimum in daytime. The unique diurnal trend in this study characterized by the least values in the early morning should be accounted for by the combined effect of several factors (e.g., the nighttime respiration of living organisms and soil layer emission). In contrast, a daytime minimum is suspected to be caused by the photosynthetic activities (Nasrallah *et al.*, 2003; Baez *et al.*, 1988; Spittlehouse and Ripley, 1977) and the expansion of the mixing height (Aikawa *et al.*, 1995). In addition, the appearance of CO_2 peaks near busy traffic hours, as seen in this study, should comply with those in other urban areas under strong anthropogenic activities (such as vehicular emission, and burning of fossil fuels) (Gratani and Varone, 2005; Idso *et al.*, 2002; Takahashi *et al.*, 2002; Aikawa *et al.*, 1995). Many previous studies of CO_2 reported that its concentrations in many urban areas (including Phoenix (Arizona, USA), Essen (Germany), Kuwait city (Kuwait), Taiwan, and Rome) are controlled by vehicular emission to a degree (Henninger and Kuttler, 2010; Lu *et al.*, 2007; Gratani and Varone, 2005; Nasrallah *et al.*, 2003; Idso *et al.*, 2002). As such, the observed diurnal trend of CO_2 in the study area should be accounted for by the typical activities in urban areas.

3.4 Factors Affecting the Distribution of CO_2

To examine the factors controlling the distribution of CO_2 in the studied mountain area, Pearson correlation analysis was conducted between CO_2 and the environmental parameters determined concurrently (CH_4, PM_1, $PM_{2.5}$, PM_{10}, NO, SO_2, and O_3) (Table 3a). As one of the most simplified approaches, the daily mean data for all variables were derived initially and used to assess the possible relationship between different parameters. It is now perceived that heating for industry, private automobiles, and landfill can play big roles in carbon emission in Seoul (Sovacool and Brown, 2010). As expected, a strong correlation is observed between major pollutants (like NO_x (NO_2 and NO) and SO_2). In addition, the relationship between CO_2 and CH_4 data is also evident with a correlation coefficient of 0.37 ($p=3.71E-13$, $N=361$). The particulate matter (PM) concentration also exhibited a good correlation with the CO_2 data with similar correlation coefficient (r) values between different particles of 0.441 (PM_1), 0.491 ($PM_{2.5}$), and 0.393 (PM_{10}). In contrast, CO_2 data maintained an inverse correlation with that of O_3 without meaningful significance ($p=0.46$). The highly strong correlation between CO_2 and other air quality indices suggest that there should be a close relation between the primarily measured trace elements.

All meteorological parameters (e.g., UV radiation, humidity, temperature, and wind speed) showed in-

Table 3. The results of correlation analysis between CO_2 and the basic environmental parameters

a. Relationship with concurrently measured airborne pollutants

		CO_2	CH_4	PM_1	$PM_{2.5}$	PM_{10}	NO	NO_2	SO_2	O_3
CO_2	r	1								
	p									
	N	361								
CH_4	r	0.37	1							
	p	**								
	N	361	361							
PM_1	r	0.441	0.444	1						
	p	**	**							
	N	361	361	361						
$PM_{2.5}$	r	0.494	0.494	0.939	1					
	p	**	**	**						
	N	360	360	360	360					
PM_{10}	r	0.393	0.339	0.640	0.774	1				
	p	**	**	**	**					
	N	342	342	342	341	342				
NO	r	0.546	0.482	0.212	0.302	0.209	1			
	p	**	**	**	**	**	**			
	N	346	346	346	345	335	346			
NO_2	r	0.678	0.601	0.422	0.469	0.319	0.619	1		
	p	**	**	**	**	**	**			
	N	346	346	346	345	335	346	346		
SO_2	r	0.352	0.268	0.718	0.713	0.544	0.154	0.2696	1	
	p	**	**	**	**	**	**	**		
	N	353	353	353	352	342	346	346	353	
O_3	r	−0.04	−0.16	0.41	0.27	0.22	−0.32	−0.14	0.27	1
	p		**	**	**	**	**	**	**	
	N	353	353	353	352	342	346	346	353	353

b. Relationship between CO_2 and meteorological parameters

		CO_2	UV	Humidity	Temp.	WS
CO_2	r	1				
	p					
	N	361				
UV	r	−0.27	1			
	p	**				
	N	270	270			
Humidity	r	−0.036	−0.304	1		
	p		**			
	N	361	270	361		
Temp.	r	−0.357	0.635	0.313	1	
	p	**	**	**		
	N	361	270	361	361	
WS	r	−0.075	−0.200	0.151	−0.140	1
	p		**	**	**	
	N	361	270	361	361	361

**Correlation is significant at the 0.01 level (2-tailed).

verse correlations with the CO_2 data (Table 3b). Except UV radiation, all of those meteorological parameters are not statistically significant (at p=0.05 level). However, the CO_2 data are also found to be little affected by such factors as wind speed and wind direction (Figs. 4 and 5). This observation thus signifies the trend that the increases in many meteorological variables are associated with the reduction of CO_2

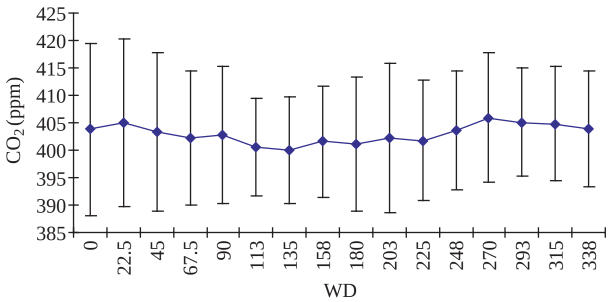

Fig. 4. A plot of CO_2 data in relation to wind direction in Mt. GA.

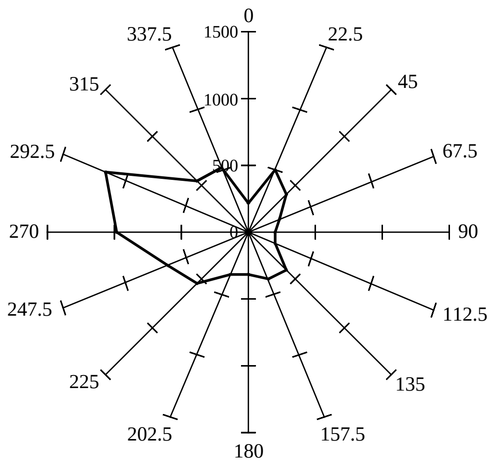

Fig. 5. Hourly wind rose pattern at Mt. GA for the year 2009.

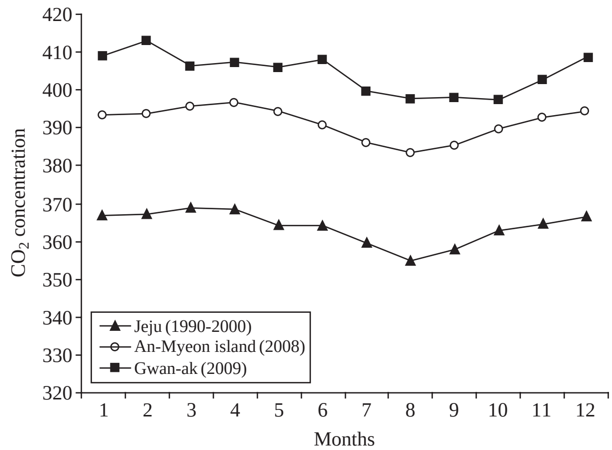

Fig. 6. Comparison of CO_2 levels between the present and previous studies. Comparison of CO_2 concentration data measured in various locations on the Korean peninsula.

levels.

The distribution of carbon dioxide in the study area can be affected not only by local sources but also by long range transport from the distant source areas. It was demonstrated previously that the distributions of relatively long lived species (e.g., atmospheric Hg and particulate matters) are influenced by long range transport from surrounding areas both in and out of Korea (Nguyen *et al.*, 2010; Nguyen *et al.*, 2009). It was also found that concentrations of NO and SO_2 in Korea are largely dependent on long range transport between Korea and East China (Shim and Park, 2004; Park and Cho, 1998). Although the main source of energy is petroleum in Japan and Korea, it is still coal for China (more than 75% of total energy source) (Hayakawa, 2009). As such, there is high possibility that the CO_2 concentration in the study area can be affected by long range transport from neighboring China. Future studies may be able to collect more direct evidence of such possibility.

3. 5 Comparison with Previous Studies

To estimate the status of CO_2 pollution in our study area, our data were first compared with those measured previously from other sites on the Korean peninsula. This comparison was extended further to cover some mountainous sites around the world and some background areas. In case of the Korean peninsula, one may refer to the continuous measurements made in Gosan, Jeju (1990-2000) (Oh *et al.*, 2001) or in An-Myeon Island (Climate Change Information Center, 2008). The site at Gosan, Jeju is on a small hill (71.2 m) above sea level near the ocean coast (33° 17′N and 126° 10′E). As seen in Fig. 6a, comparison of our data with those of two previous studies showed large differences. The average CO_2 value in Jeju (1990-2000) appears to be fairly low (363.8 ppm), whereas that for An-Myeon Island (2008) was 391.4 ppm. Because the data are taken between different years, some uncertainties in CO_2 data are expected. However, if we predict the value of Jeju by following its rate of increase (1990-2000), the value for the year 2009 is 392.7 ppm which is comparable with those of An Myon Island and Mt. GA.

The average annual CO_2 data at our study site (405 ppm) can also be compared with those values taken from World Meteorological Organization (WMO) sites (Fig. 6b). For this comparison, the 2007 annual data from WMO global atmosphere watch (World Data Centre for Greenhouse Gases (WDCGG)) were used. The CO_2 data at Mt. GA are 2.86 to 6.26% higher than all the available WMO data from various mountainous sites, eg, Sonnblick, Austria (381.1 ppm), Deuselbach, Germany (386.1 ppm), Sary Taukum, Kazakhstan (385.3 ppm), Ullan Uul, Mongolia (383.6 ppm), Mt.

Kenya, Kenya (379.63 ppm), Srinagar-Garhwal, India (393.4 ppm: Anthwal *et al.*, 2010). We cannot directly balance the difference due to the time gap between our and previous studies. However, as most of these sites are distant from cities, the concentration levels of CO_2 in those sites are lower than our data measured in the urban area. Because Mt. GA is surrounded by a densely populated urban area, its CO_2 level may reflect the man-made activities, especially traffic activities surrounding the mountainous site.

Our CO_2 data were compared further with those derived from many urban areas around the world. It is observed that our data were comparable to those in other urban areas like Rome, Essan (Germany), and Phoenix (AZ, USA). The urban area of Essen, Germany exhibited a wintertime mean value of 415 ppm which is slightly higher than our wintertime data (410 ppm). Likewise, the minimum CO_2 value in our study (mean=399 ppm) was slightly higher than that of Essan, in the summer of 2004 (mean=393 ppm) (Henninger and Kuttler, 2010). In contrast, our yearly mean concentration (405 ± 12.1 ppm) was much lower than those of urban areas in Rome, Italy where strong correlation was formed between traffic density and CO_2 (mean yearly value=477 ± 30 ppm) (Gratani and Varone, 2005). Unlike other urban areas, the CO_2 data measured from Phoenix, AZ, USA was moderately lower (390.2 ± 0.2 ppm) than other areas. Thus, we can see that the CO_2 concentrations in Mt. GA are generally comparable with those obtained from the common urban areas rather than the mountainous (or background) sites around the world.

4. CONCLUSIONS

In this study, concentration of CO_2 was measured continuously at Mt. GA air quality monitoring station in Seoul, Korea in the year 2009. To describe the basic features of CO_2 distribution, we investigated the factors affecting the environmental behavior of CO_2 in a number of respects. The concentration of CO_2 in the study area averaged as 405 ± 12.1 ppm with its peak occurrence in winter (410 ppm) followed by spring (407 ppm), summer (402 ppm), and fall (399 ppm). The occurrence of winter maximum is now explained by the combined effects of several factors (fossil fuel consumption, reduced plant activity with lower photosynthesis, and stable atmospheric conditions). According to the analysis of diurnal variation, its concentration was the highest during daytime and lowest in the early morning. This trend thus does not comply with those typically observed from clean background areas in which low concentrations are maintained during daytime.

To assess the fundamental factors affecting the environmental behavior of CO_2, we analyzed relationship between CO_2 and the basic environmental parameters measured concurrently. The CO_2 data generally exhibited strong correlations with most air pollutants, with an exception of O_3. In contrast, many meteorological parameters tended to exhibit strong inverse correlations with CO_2, while CO_2 data are affected less significantly by wind speed than others. To learn more about the status of CO_2 pollution in the study area, our results were compared with those determined in various locations in the world. The results of the comparative analysis suggest that the CO_2 levels in this study area are affected fairly sensitively by man-made processes, especially traffic activities in the surrounding areas.

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