

The Temporal and Spatial Distribution of Volatile Organic Compounds (VOCs) in the Urban Residential Atmosphere of Seoul, Korea

Ashish Anthwal, Chan-Goo Park¹⁾, Kweon Jung¹⁾, Min-Young Kim¹⁾ and Ki-Hyun Kim*

Department of Earth & Environmental Sciences, Sejong University, Seoul 143-747 Korea

¹⁾Seoul Metropolitan Institute of Public Health and Environment, Seoul 137-734 Korea

*Corresponding author. Tel: +82-2-499-9151, E-mail: khkim@sejong.ac.kr

ABSTRACT

Automobile emissions have caused a major hydrocarbon pollution problem in the ambient air of many cities around the world. This study was conducted to measure the pollution status of volatile organic compounds (VOCs) in some urban residential areas in Seoul, Korea. A total of 20 VOCs (11 aromatic and 9 chlorinated species) were identified at 4 urban residential sites in Seoul, Korea from February 2009 to July 2009. Comparison of total VOC (TVOC) concentration data indicated the dominance of the aromatic species with the maximum (72.2 ppbC) at Jong Ro (JR) and the minimum at Yang Jae (33.4 ppbC). The peak concentration of TVOC occurred during spring at all sites with an exception at Gang Seo (GS), where it was recorded during winter. The distribution of individual VOCs at the study sites was characterized by high toluene concentration. A strong correlation of benzene was also observed with other VOCs and criteria pollutants at all sites (except YJ). The overall results of this study suggest that vehicular emissions have greatly contributed to the increase in VOC pollution at all the study sites.

Key words: Urban air pollution, VOC, Aromatic, Vehicular, Residential

1. INTRODUCTION

Volatile organic compounds (VOCs) are an important group of air pollutants to be monitored in the ambient air, because of their versatile roles in environmental chemistry and the associated environmental impacts on the ecological systems. A number of VOCs are involved in tropospheric chemistry through the interaction with the OH radical or by the formation of photochemical oxidants (Wang and Zhao, 2008; Srivastava *et al.*, 2006; Atkinson, 2000). Some VOCs are also

reported to have toxic and carcinogenic health effects (Guo *et al.*, 2004).

VOCs are released into the atmosphere from both biogenic (mainly vegetation) and anthropogenic sources. Anthropogenic sources include vehicle exhaust, gasoline evaporation, natural gas, and combustion of fossil fuels (Nguyen *et al.*, 2009; Wang and Zhao, 2008). A large amount of VOCs are released in both a local and regional scale, while the patterns of their emissions vary depending on source characteristics. Emissions of aromatic hydrocarbons come from diesel and gasoline engine vehicles (Abrantes *et al.*, 2004; Tavares *et al.*, 2004; Broderick and Marnane, 2002). In the urban areas, aromatic VOCs such as benzene, toluene, ethylbenzene, and xylene (collectively called as BTEX) constitute up to 60% of non-methane VOCs (e.g., Lee *et al.*, 2002). Hence, BTEX compounds can be considered an indicator of organic compound pollution from road traffic (Hoque *et al.*, 2008). The use of unleaded gasoline and diesel fuel has increased worldwide due to increases in traffic volume. As these fuels contain a large fraction of aromatic hydrocarbons, their monitoring in urban areas has become one of the prior tasks in air quality management.

The US EPA has classified benzene as a group A human carcinogen (US EPA, 1993), as leukemia has been observed in humans occupationally exposed to benzene. As toluene, xylene, and ethylbenzene can form secondary organic aerosol, they have also been the subject of several investigations (Cocker *et al.*, 2001; Odum *et al.*, 1997). The secondary organic aerosols can affect lung function (Seaton *et al.*, 1995), while contributing to visibility degradation (Appel *et al.*, 1985). Hence, a proper evaluation of traffic related contribution to regional VOC emissions is of great interest (Barletta *et al.*, 2002; Kim *et al.*, 2001).

As the capital of Korea, Seoul has an area of 605.5 km² and a population of about 10.3 million with about 2.8 million motor vehicles (City of Seoul, 2010). As considerable amounts of airborne pollutants are postu-

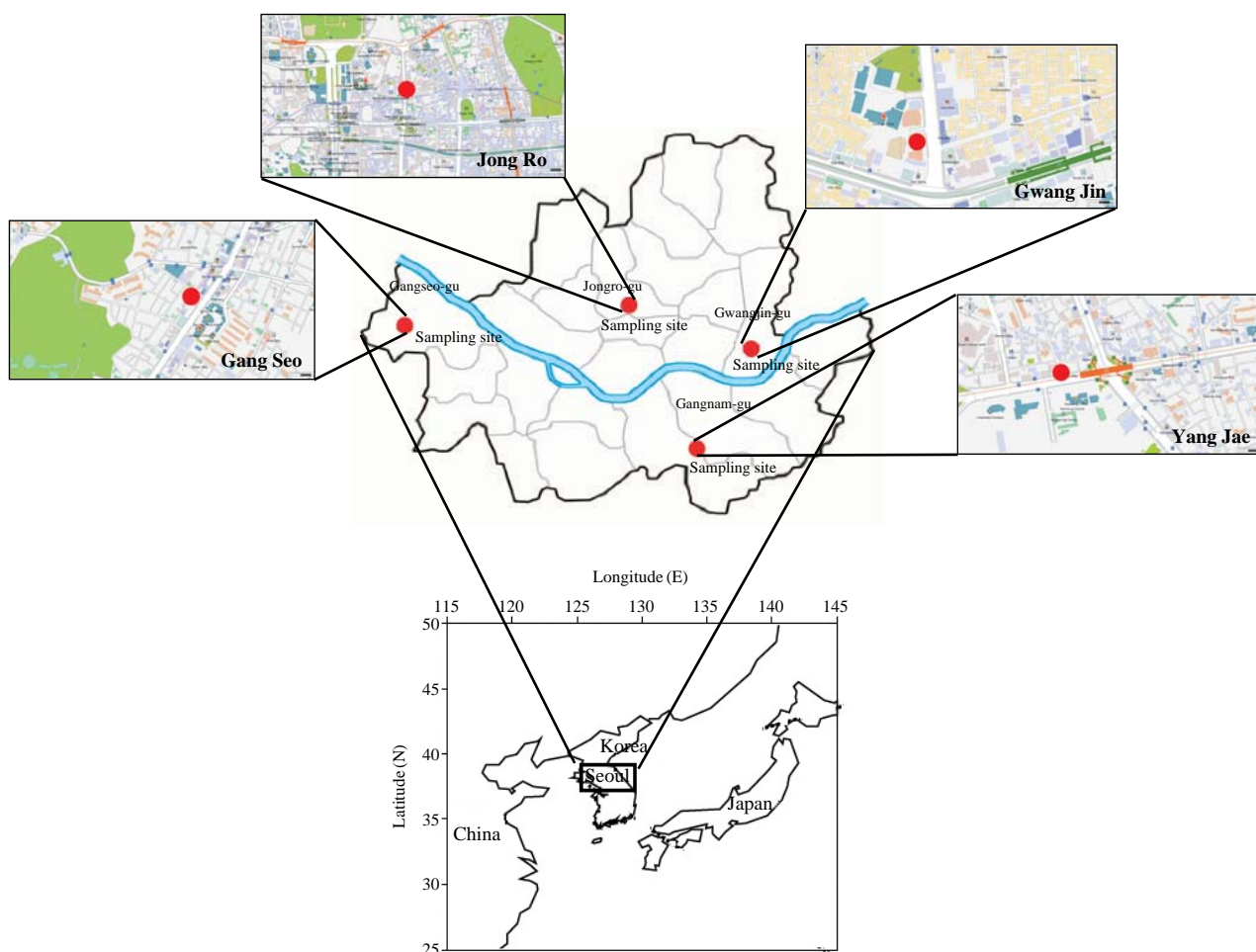


Fig. 1. Geographical location of four study sites in Seoul, Korea: Jong Ro (JR), Gwang Jin (GJ), Gang Seo (GS), and Yang Jae (YJ).

lated to be emitted, it is very important to describe the concentration, composition, sources, and behavior of VOCs for the development of their abatement strategies. The main objectives of this study were: (1) to describe the spatial and temporal distribution patterns of VOC in the ambient air; (2) to assess the status of VOC pollution in the ambient air of megacity; and (3) to identify the major factors and processes affecting the behavior of VOC in the urban air. For reader's reference, polycyclic aromatic hydrocarbons measured from the same study sites have been reported elsewhere (Anthwal *et al.*, in press).

2. MATERIALS AND METHODS

2.1 Field Site and Sampling

In this study, the measurements of VOC in ambient air and the relevant environmental parameters were undertaken at four residential locations in Seoul which

include Jong Ro (JR), Gwang Jin (GJ), Gang Seo (GS), and Yang Jae (YJ) (Fig. 1). GS might be affected due to road traffic, whereas GJ site was located near water purification plant under the direct effect of road traffic. All of these sampling sites represent air quality monitoring stations in residential areas where the basic air quality criteria have been monitored on a routine basis. None of the local emission sources were found near the sampling location. Thus, it can be postulated that the air samples collected at these sampling locations are influenced mainly by the common man-made activities in the urban area without any identifiable strong source activities. General aspects of these sampling sites have been described in our previous report of PAH study (Anthwal *et al.*, in press).

The collection of VOC samples for this study was carried out from Feb to July 2009. During the study period, daily samples were collected for 30 minutes between 3-3:30 pm (over 3 consecutive days per month intervals). A list of VOCs selected and analyzed

Table 1. Basic information of the volatile organic compounds (VOCs) monitored in this study.

S. No	VOC species	Short name	CAS number	Molecular weight g mol ⁻¹	Chemical formula
Aromatic VOCs					
1	Benzene	B	71-43-2	78.11	C ₆ H ₆
2	Toluene	T	108-88-3	92.14	C ₇ H ₈
3	Styrene	STY	100-42-5	104.15	C ₈ H ₈
4	Ethylbenzene	EB	100-41-4	106.17	C ₈ H ₁₀
5	m,p-Xylene	MPX	108-38-3	106.16	C ₈ H ₁₀
6	o-Xylene	OX	95-47-6	106.17	C ₈ H ₁₀
7	1,2,4-Trimethylbenzene	1,2,4-TMB	95-63-6	120.19	C ₉ H ₁₂
8	Dichlorodifluoromethane	DCDFM	75-71-8	120.91	CCl ₂ F ₂
9	Trichlorofluoromethane	TCFM	75-69-4	137.37	CCl ₃ F
10	Dichlorotetrafluoroethane	DCTFE	76-14-2	170.92	C ₂ Cl ₂ F ₄
11	1,1,2-Trichlorotrifluoroethane	1,1,2-TCTFE	76-13-1	187.37	C ₂ Cl ₃ F ₃
Chlorinated VOCs					
12	1,1-Dichloroethane	1,1-DCE	75-34-3	98.96	C ₂ H ₄ Cl ₂
13	Chloroform	CF	67-66-3	119.38	CHCl ₃
14	Methyl chloride	MC	74-87-3	50.49	CH ₃ Cl
15	Trichloroethylene	TCE	79-01-6	131.39	C ₂ HCl ₃
16	Perchloroethylene	PCE	127-18-4	165.8	C ₂ Cl ₄
17	1,1-Dichloroethylene	1,1-DCEY	75-35-4	96.94	C ₂ H ₂ Cl ₂
18	Vinyl chloride	VC	75-01-4	62.498	C ₂ H ₃ Cl
19	1,2-Dichloroethane	1,2-DCE	107-06-2	98.96	C ₂ H ₄ Cl ₂
20	1,1,1-Trichloroethane	1,1,1-TCE	71-55-6	133.4	C ₂ H ₃ Cl ₃

throughout this study can be extended to cover a total of 20 compounds (Table 1). They consist of eleven aromatic compounds including BTEX and nine chlorinated VOCs.

2.2 Collection of Air Samples and VOC Analysis

For the collection of VOC samples, adsorption trap was made using stainless steel tube. These tubes were packed with a solid sorbent Carbotrap 300 (a combination of Carbotrap C, Carbotrap B, and Carbosieve S-III). The former two types of Carbotraps are efficient to adsorb VOCs with C₄-C₁₄, while the latter Carbosieve is considered an optimal choice for low-weight VOCs with C₂-C₆. These sampling traps were conditioned for 1 h at 350°C with the constant supply of N₂ at 50 mL min⁻¹. They were then sealed by both Swagelok fitting and PTFE ferrules. The collection of VOC samples on the carbotrap 300 was made from 3 PM for each measurement date for 30 mins duration with flow rate of 100 mL min⁻¹ using a hand held pump (SIBATA Σ30, Japan). The stainless steel tubes were stored at 4°C and brought to the laboratory for analysis.

The VOC samples collected in adsorption traps were analyzed with the laboratory GC/MS system (Agilent GC/MSD, model 6890/5975B) via thermal desorption unit (Markes Unity Ltd., UK) on the following sequence: (1) thermal desorption of tubes at 280°C for 10 mins, (2) focusing of VOCs on cold trap at -10°C, and

(3) subsequent transfer of VOCs into the GC/MS system. The separation of VOC compounds was made by a capillary column (DB-1, 60 m × 0.25 mm × 1 μm film thickness). The mass selective detector was operated in electron impact mode (70 eV). The temperature program was conducted as follows: 40°C for 5 min, 50-230°C ramping at 7°C min⁻¹, and 230°C for 10 min. The flow rate of carrier gas (helium) was maintained at 1.3 mL min⁻¹. The method detection limits (MDL), if determined based on the instrumental detection limits for the VOC analysis, was in the range of ~ < 1.0 pg m⁻³ or 0.24 ppb (0.15 (vinyl chloride)-1.0 ng (m,p-xylene) in absolute mass).

3. RESULTS AND DISCUSSION

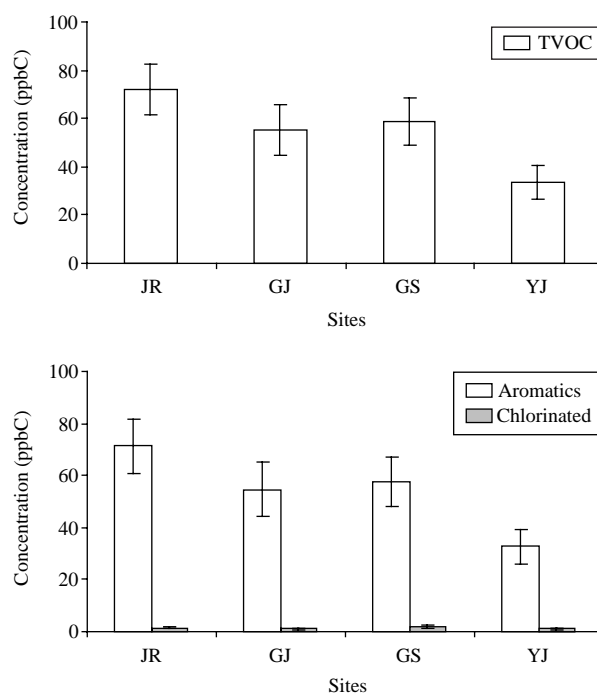
3.1 Distribution Characteristics of VOC

A statistical summary of the relevant parameters measured at four urban locations during the study period is given in Table 2. Table 2 summarizes the sum concentration of aromatic and chlorinated VOC, criteria pollutants, and meteorological parameters measured during the study. In Fig. 2, concentrations of TVOC determined at four urban locations are compared along with the sum of aromatic and chlorinated VOC. The mean concentration of TVOC (ppbC) was seen in the order of 72.2 (18.1-149) at JR, 55.2 (12.1-157) at GJ, 59.0 (18.6-165) at GS, and 33.4 (9.8-123)

Table 2. A statistical summary of relevant environment parameters measured at 4 urban locations in Seoul.

	Jong Ro (JR)	Gwang Jin (GJ)	Gang Seo (GS)	Yang Jae (YJ)
A. Criteria pollutants				
SO ₂ (ppb)	7.83 ± 3.167 (7.0)	4.28 ± 2.54 (4)	7.72 ± 4.31 (6.0)	5.06 ± 3.44 (4)
NO (ppb)	15.61 ± 11.64 (11.0)	17.1 ± 13.8 (13.5)	15.9 ± 16 (9.5)	21.7 ± 17.2 (16)
NO ₂ (ppb)	41.3 ± 17.4 (35.5)	40.8 ± 15.5 (37.5)	39.7 ± 18 (32.5)	41.8 ± 16.6 (38.5)
NO _x (ppb)	57.2 ± 27 (46)	57.6 ± 27.4 (47)	55.4 ± 31.9 (41.0)	63.2 ± 31.2 (54.5)
CO (ppb)	772 ± 267 (700)	750 ± 182.3 (700)	517 ± 206.5 (450)	600 ± 208.6 (550)
O ₃ (ppb)	2.3.5 ± 9.71 (24)	27.7 ± 12.4 (26.5)	26.3 ± 11.9 (27.0)	22.6 ± 11.9 (20)
TSP (μg m ⁻³)	118.2 ± 44.6 (106)	79.1 ± 38.2 (67)	103 ± 58.4 (81.0)	88.5 ± 45.53 (78.5)
PM ₁₀ (μg m ⁻³)	61.9 ± 29.1 (51.5)	58.8 ± 29.5 (50)	65.2 ± 38.5 (54.5)	62.4 ± 33.7 (54)
PM _{2.5} (μg m ⁻³)	27.9 ± 13.4 (24.5)	29.7 ± 14.5 (24)	32.2 ± 18.9 (25.5)	30.1 ± 18.6 (22.5)
CH ₄ (ppm)	2.23 ± 0.35 (2.26)	1.99 ± 0.14 (2.01)	2.13 ± 0.13 (2.15)	2.09 ± 0.15 (2.05)
NMHC ^a (ppm)	0.32 ± 0.07 (0.3)	0.25 ± 0.11 (0.25)	0.34 ± 0.05 (0.35)	0.28 ± 0.09 (0.28)
THC ^b (ppm)	2.55 ± 0.37 (2.56)	2.24 ± 0.22 (2.22)	2.47 ± 0.15 (2.5)	2.38 ± 0.23 (2.36)
B. Meteorological parameter				
TEMP (°C)	22.8 ± 8.09 (22.4)	19.0 ± 7.75 (21.25)	18.9 ± 7.33 (20.5)	22.7 ± 6.77 (24.8)
HUM (%)	53.2 ± 19.4 (47.5)	52.8 ± 19.2 (45.5)	52.1 ± 16.2 (47)	50.8 ± 16.6 (45)
WS (m s ⁻¹)	1.35 ± 0.33 (1.3)	2.04 ± 0.46 (1.95)	1.07 ± 0.1 (1.1)	0.9 ± 0.22 (0.85)
UV (mW cm ⁻²)	0.49 ± 0.27 (0.42)	0.43 ± 0.19 (0.43)	0.36 ± 0.18 (0.32)	0.4 ± 0.22 (0.35)
Solar (W m ⁻³)	181 ± 78.6 (192)	158 ± 75.2 (168)	172 ± 75.7 (185)	164 ± 72.3 (173)

Superscript a denotes non-methane hydrocarbon which is deduced from difference between THC and CH₄ concentrations. Superscript b denotes total hydrocarbon (THC).


Fig. 2. Ambient concentration of VOC measured at 4 urban residential locations in Seoul.

at YJ. The data presented in Table 3 indicate the dominance of aromatic VOCs at all sites with the highest concentration at JR site (71.3 ± 39.9 ppbC) and lowest at YJ (32.6 ± 27.9 ppbC). Among all these sites, the highest mean concentration (ppbC) of Σ BTEX was seen from JR (69.5 ± 38.9) followed by GS (53.3 ± 42.1), GJ (55.0 ± 38.2), and YJ (31.9 ± 27.7). A summary of individual VOC data shows that the seven VOC species (including benzene, toluene, ethylbenzene, m/p-xylene, o-xylene, dichlorodifluoromethane, and trichlorofluoromethane) were quantified consistently at all the sampling sites. Because of low abundance of chlorinated VOC data, major aromatic VOCs including BTEX were examined most extensively as the target pollutants of our study. These compounds have been listed as toxic organic pollutants by the United States Environmental Protection Agency (EPA) with adverse effects on human health, as aromatic VOCs can contribute to the formation of photochemical smog (Han and Naehar, 2006). Most Aromatic VOCs can be emitted from fossil fuel combustion, vehicular exhaust, and industrial processes (Ferrari *et al.*, 1998). According to a previous report, the proportion of aromatic VOCs in fossil fuels ranged from 41-51% and was larger than the paraffins (28-47%) and the olefins (7-12%) (Tsai *et al.*, 2004).

The concentrations of the 20 most abundant species based on the identified VOC at 4 urban locations are

Table 3. The concentration of volatile organic compounds (ppb) measured in ambient air at 4 sites in Seoul, Korea (unit: ppb and ppbC).

	Jong Ro (JR)		Gwang Jin (GJ)		Gang Seo (GS)		Yang Jae (YJ)	
A. Individual VOC species (ppb)^a								
(1) Aromatic VOCs								
Dichlorodifluoromethane	0.42±0.15 (0.47)	0.13-0.60 (12)	0.35±0.16 (0.35)	0.14-0.68 (14)	0.49±0.17 (0.50)	0.12-0.78 (16)	0.39±0.15 (0.41)	0.15-0.61 (15)
Trichlorofluoromethane	0.35±0.21 (0.27)	0.08-0.88 (15)	0.73±1.25 (0.35)	0.12-5.44 (17)	0.89±0.70 (0.68)	0.14-2.50 (18)	0.19±0.09 (0.21)	0.06-0.34 (17)
Benzene	0.66±0.27 (0.65)	0.26-1.14 (14)	0.53±0.25 (0.44)	0.26-0.93 (14)	0.62±0.33 (0.51)	0.25-1.29 (16)	0.51±0.21 (0.44)	0.28-0.86 (12)
Toluene	7.04±3.93 (5.80)	1.84-14.93 (15)	5.60±4.23 (4.16)	1.49-15.29 (17)	5.4±3.6 (3.6)	1.65-13.9 (18)	3.5±2.8 (2.61)	1.04-11.9 (18)
Ethylbenzene	0.84±0.61 (0.69)	0.20-2.32 (15)	0.77±0.64 (0.57)	0.19-2.08 (14)	0.76±0.58 (0.53)	0.23-2.28 (18)	0.49±0.45 (0.28)	0.17-1.64 (11)
m,p-Xylene	0.98±0.59 (0.97)	0.27-2.35 (14)	0.79±0.54 (0.65)	0.29-2.15 (13)	0.91±0.71 (0.71)	0.26-2.94 (15)	0.58±0.41 (0.45)	0.25-1.44 (8)
Styrene	–	–	–	0.23-0.23 (1)	0.45±0.13 (0.45)	0.28-0.61 (4)	–	0.17-0.17 (1)
o-Xylene	0.35±0.22 (0.29)	0.15-0.86 (13)	0.31±0.20 (0.28)	0.14-0.79 (11)	0.42±0.27 (0.37)	0.14-1.10 (10)	0.30±0.17 (0.26)	0.16-0.58 (5)
1,2,4-Trimethylbenzene	0.27±0.04 (0.26)	0.22-0.32 (6)	–	–	–	0.46-0.46 (1)	–	–
Dichlorotetrafluoroethane	0.33±0.14 (0.33)	0.23-0.43 (2)	0.22±0.13 (0.16)	0.13-0.37 (3)	0.30±0.22 (0.25)	0.12-0.54 (3)	0.46±0.15 (0.46)	0.35-0.57 (2)
1,1,2-Trichlorotrifluoroethane	0.10±0.02 (0.11)	0.07-0.13 (6)	0.11±0.03 (0.10)	0.08-0.16 (5)	0.09±0.02 (0.09)	0.07-0.13 (11)	0.09±0.02 (0.09)	0.07-0.13 (5)
(2) Chlorinated VOCs								
Dichloroethane	0.14±0.05 (0.14)	0.11-0.17 (2)	–	0.15-0.15 (1)	0.24±0.06 (0.23)	0.19-0.31 (3)	–	–
Chloroform	0.11±0.05 (0.09)	0.07-0.22 (8)	0.15±0.14 (0.09)	0.08-0.57 (12)	0.16±0.08 (0.12)	0.08-0.29 (7)	0.25±0.17 (0.17)	0.09-0.51 (7)
Methyl chloride	–	0.43-0.43 (1)	–	–	0.52±0.005 (0.52)	0.51-0.52 (2)	–	–
TCE	0.44±0.24 (0.34)	0.17-0.86 (7)	0.49±0.29 (0.41)	0.17-0.85 (7)	0.63±0.44 (0.37)	0.23-1.40 (11)	0.40±0.26 (0.31)	0.17-0.82 (8)
PCE	–	–	–	–	–	0.17-0.17 (1)	–	–
1,1,1-Trichloroethane	0.21±0.15 (0.21)	0.10-0.31 (2)	0.11±0.02 (0.11)	0.10-0.13 (2)	0.18±0.04 (0.19)	0.13-0.23 (5)	–	–
1,1-Dichloroethylene	0.51±0.32 (0.38)	0.19-0.88 (5)	0.48±0.36 (0.34)	0.21-0.89 (3)	0.70±0.59 (0.54)	0.22-1.82 (6)	0.55±0.38 (0.39)	0.24-1.22 (6)
Vinyl chloride	–	–	–	–	0.14±0.02 (0.14)	0.13-0.16 (2)	–	0.086-0.086 (1)
1,2-Dichloroethane	0.04±0.01 (0.04)	0.03-0.04 (4)	0.03±0.01 (0.03)	0.02-0.04 (6)	0.05±0.02 (0.04)	0.02-0.09 (6)	0.04±0.01 (0.03)	0.03-0.05 (4)
B. Summation terms (ppbC)								
ΣAromatics	71.3±39.9 (58.0)	17.9-147 (15)	54.5±43.1 (39.5)	12.1-154 (17)	57.4±40.3 (41.2)	18.6-161 (18)	32.6±27.9 (22.0)	9.6-118 (18)
ΣChlorinated	1.28±1.08 (1.11)	0.21-3.89 (11)	0.97±1.20 (0.51)	0.08-3.74 (13)	1.94±1.61 (1.39)	0.52-6.07 (15)	1.17±1.30 (0.49)	0.10-4.15 (13)
TVOC	72.2±40.8 (58.4)	18.1-149 (15)	55.2±44.0 (39.5)	12.1-157 (17)	59.0±41.6 (41.5)	18.6-165 (18)	33.4±29.0 (22.9)	9.8-123 (18)

^aAll individual VOC species in ppb unit; ^bMean ±SD (median); ^cRange (number of data)

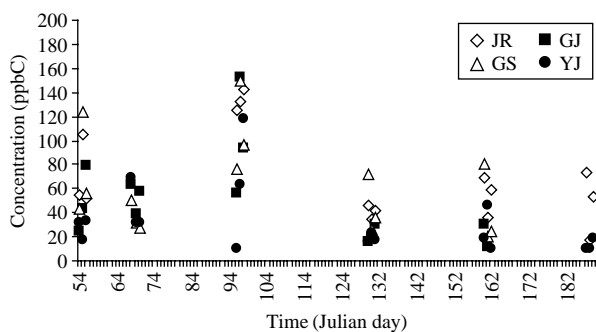


Fig. 3. The concentration of all aromatic VOC (Σ Aromatic (ppbC)) measured at 4 urban sites in Seoul during the study period.

shown in Table 3. Results presented in the Table 3 clearly indicate the dominance of toluene among all the VOC species investigated at all the study sites. The highest concentration of toluene was recorded at JR site with a mean concentration of 7.04 ppb followed by m, p-xylene (0.98 ppb). In the urban atmosphere, toluene is the most abundant aromatic species, as reported from many of previous studies (Wang and Zhao, 2008; Ho *et al.*, 2004; Kim and Kim, 2002; Kourtidis *et al.*, 2002). The proportions of aromatic VOCs may vary by locations due to differences in traffic and industrial activities, emissions patterns, and meteorological conditions (Lai *et al.*, 2004). The concentration of toluene is typically 2-4 times that of benzene (Borbon *et al.*, 2002; Na and Kim, 2001; Brocco *et al.*, 1997). The mean concentrations of most aromatic VOCs (except toluene) were seen in the range of 0.5-2 ppb. It is also noted that BTEX exhibited fairly strong variabilities, as the coefficient of variation (CV) values generally ranged from 40 to 90%.

In Fig. 3, the mean concentrations of aromatic VOCs (mainly BTEX) determined during the study period are compared across 4 sites. The relative dominance of toluene may be accounted for by the effect of traffic activities, as it is used as the major component of gasoline or solvents (Brocco *et al.*, 1997). Due to the high reactivity of toluene and other aromatic hydrocarbons, their presence at high concentration levels can lead to the production of toxic products through atmospheric oxidation (Liu *et al.*, 2000). In addition, benzene is mainly emitted from automobile emissions. Amongst the aromatic hydrocarbons, toluene and benzene are often treated as the main indicators of VOC pollution, while their reactivities are significantly different from each other. Toluene is 5 times more reactive than benzene in its reaction with OH radicals. Hence, changes in their relative concentration ratio can be used to assess their relative behavior (Gelencsr *et al.*, 1997).

In some previous studies, toluene to benzene (T/B) ratio was computed to infer their source properties (Barletta *et al.*, 2005; Wang *et al.*, 2005; Chan *et al.*, 2002; Lee *et al.*, 2002). Considering that toluene and benzene are the main fuel constituents, T/B ratio can be a useful marker for road traffic emissions (Kelessis *et al.*, 2006; Rappengluck *et al.*, 2005; Brocco *et al.*, 1997; Gelencsr *et al.*, 1997). As one good example of such applications, the T/B ratios can be examined as a function of distance to the road (Gelencsr *et al.*, 1997). In this study, the median value of T/B ratios at 4 sites (5.9-9.4) were much higher than those reported in many other urban areas like Rome, Changchun (China), Kaohsiung (Taiwan), and Thessaloniki (Greece) (Hong *et al.*, 2006; Kelessis *et al.*, 2006; Lai *et al.*, 2004; Liu *et al.*, 2000; Brocco *et al.*, 1997). However, these values are rather comparable to those in most of Asian countries such as: Bangkok (10.22), Hong Kong (7.74), and Osaka (7.19) (Lee *et al.*, 2002; Gee and Sollars, 1998; Tsujino and Kuwata, 1993). The higher T/B ratio in the urban air should be associated with highly diversified sources of toluene or with major differences in the fuel and vehicle types (Hoque *et al.*, 2008; Gee and Sollars, 1998).

3.2 Temporal Variations in VOC Concentration

Temporal variations in the TVOC concentration and individual VOCs are examined by their daily values at the 4 study sites, as shown in Fig. 4. According to this analysis, the patterns of TVOC and individual VOCs showed good similarities between different sites. TVOC values at all sites peaked in April and then decreased till July. In case of individual VOC, toluene concentration at the JR site recorded the maximum of 14.9 ppb in April, while a vivid dropdown was recognized in July with 1.84 ppb.

The seasonal mean values of TVOC and BTEX are also plotted in Fig. 5. TVOC and BTEX species exhibit very clear seasonal characteristics at all study areas. At JR, GJ, and YJ, TVOC showed maximum values during the spring and minimum during summer. However, the pattern of GS was slightly modified with the winter maximum. If the individual VOCs are compared by the seasonal mean values, the results are fairly consistent in most cases (Fig. 5). In many previous studies, seasonal variations in the VOC were generally characterized by high concentration of VOC during winter (Nguyen *et al.*, 2009; Hoque *et al.*, 2008; Na and Kim, 2001; Liu *et al.*, 2000; Brocco *et al.*, 1997). However, there is also contrasting evidence such as higher concentration of aromatic VOC components during summer (Nguyen *et al.*, 2009). Cheng *et al.* (1997) also reported high concentrations of aromatics in two downtown sites in Edmonton, Canada during

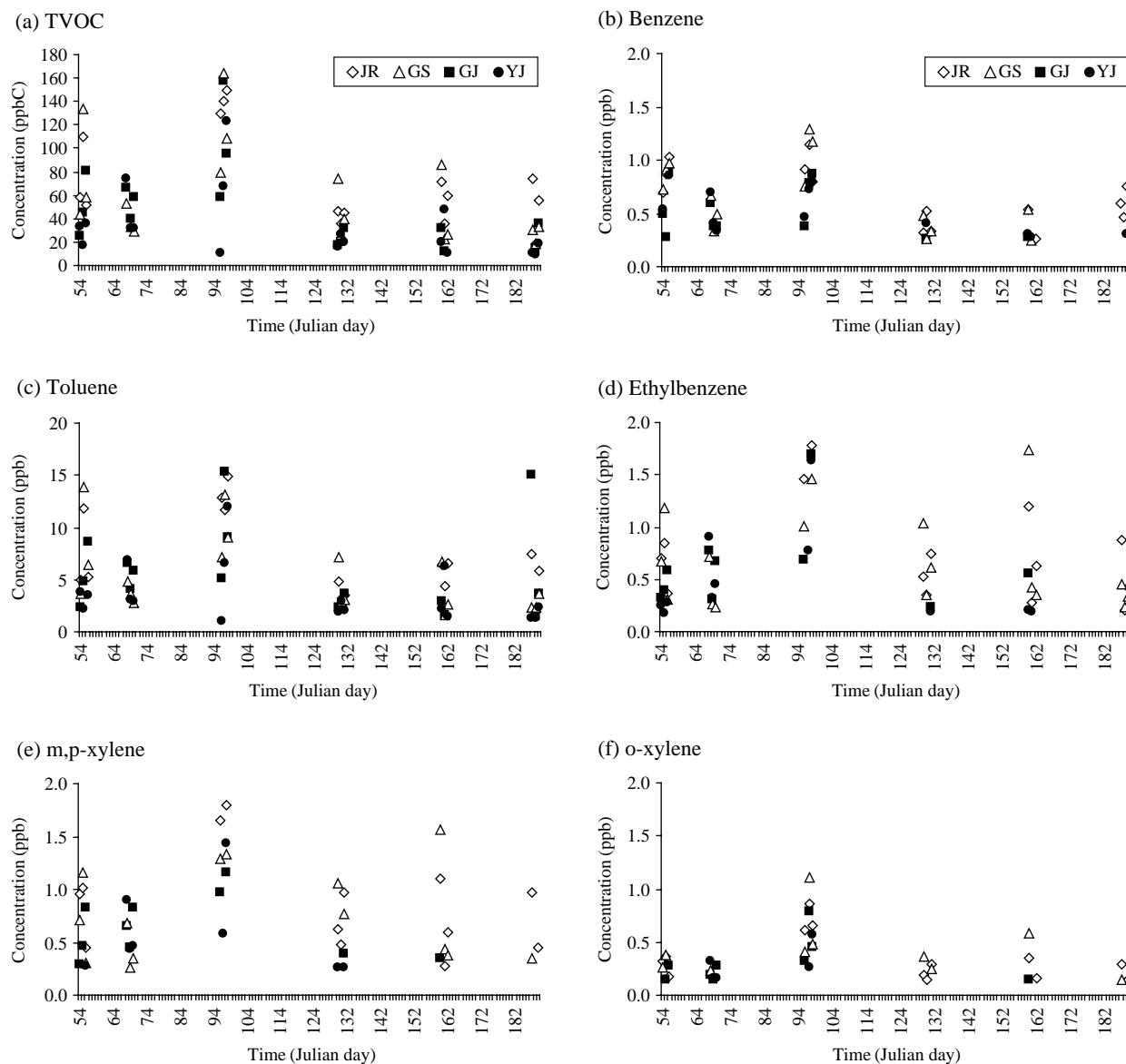


Fig. 4. Temporal variation in the TVOC concentration and five individual components (BTEX) at 4 urban sites in Seoul during the study period.

spring and in the industrial area during winter. Observed seasonal trends can be explained by the combined effects of various factors including variations in source strength and the meteorological conditions. In addition, the availability of OH radical and/or insolation can also be important, as those factors can influence the efficiency of the removal process of the VOC species from the atmosphere (Singh and Zimmerman, 1992).

3.3 The Factors Affecting VOC Distributions

To elucidate the potential roles of different sources controlling the behavior of the aromatic VOCs, corre-

lation analysis had been employed by several workers (Hoque *et al.*, 2008; Na and Kim, 2001; Brocco *et al.*, 1997). In this study, correlation analysis was conducted among the concentration data of BTEX, TVOC, criteria pollutants, and meteorological parameters (Table 4). A strong positive correlation was observed between TVOC, SO_2 , NO_2 , and CO at all the study sites. The cases of the strongest correlation of TVOC were found most abundantly at JR with such variables as with SO_2 ($r=0.85$, $p<0.01$) or CO ($r=0.817$, $p<0.01$) or NO_2 ($r=0.778$, $p<0.01$). In accordance with our observations, Smith *et al.* (2001) suggested that CO and SO_2

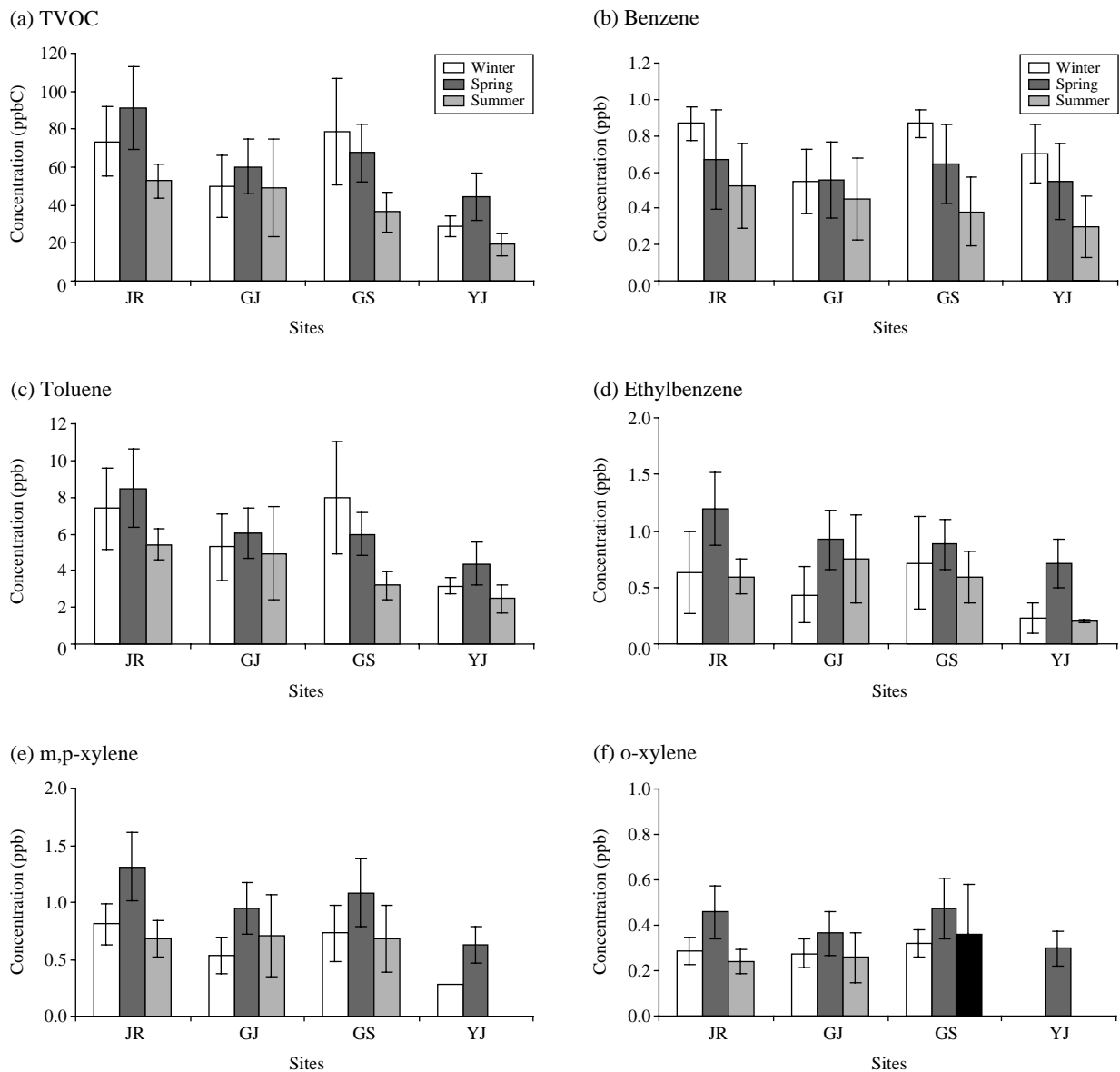


Fig. 5. Seasonal changes in the concentrations of TVOC and individual aromatic VOC at 4 study sites.

should originate from motor vehicles along with NO_x . The existence of strong correlations among most VOC species (e.g., between ethylbenzene and xylene) suggests that they should share the same source properties (Balasano *et al.*, 1998; Wang *et al.*, 1993). The results also indicate that most meteorological parameters (e.g., wind speed, relative humidity, and air temperature) do not exhibit strong correlations with the VOC concentration data. Benzene, well-known as tracer for automobile exhaust, showed a good correlation ($p < 0.01$, $p < 0.05$) with other VOCs and criteria pollutants at JR, GJ, and GS. However, no such correlation was evident at YJ (Hoque *et al.*, 2008; Hong *et al.*, 2006; Rudd,

1995; Chan *et al.*, 1991). The lack of correlation between benzene and other VOC species in the YJ site suggests that the sources of VOCs in YJ are more complicated in Seoul relative to the other study areas.

3.4 Comparison of BTEX Levels in Seoul with Previous Studies

To learn more about the spatial variability of VOC, the average concentrations of BTEX in the four urban locations in Seoul can be evaluated in relation with those measured previously in other urban areas (Nguyen *et al.*, 2009; Wang and Zhao, 2008; Khoder, 2007; Lee *et al.*, 2002; Na and Kim, 2001; Gee and Sollars,

Table 4. Results of correlation analysis between BTEX compounds, criteria pollutants, and meteorological parameters at four urban locations in Seoul.

	B	T	EB	MPX	OX	TVOC	SO ₂	NO ₂	CO	O ₃	T	RH	WS
(a) Jong Ro													
B	1												
T	0.611*	1											
EB	0.535*	0.816**	1										
MPX	0.53	0.787**	0.985**	1									
OX	0.607*	0.807**	0.977**	0.994**	1								
TVOC	0.65*	0.979**	0.908**	0.899**	0.913**	1							
SO ₂	0.584*	0.845**	0.715**	0.778**	0.795**	0.852**	1						
NO ₂	0.467	0.686**	0.844**	0.892**	0.881**	0.778**	0.822**	1					
CO	0.587*	0.733**	0.859**	0.909**	0.921**	0.817**	0.862**	0.958**	1				
O ₃	-0.182	0.054	-0.058	-0.093	0.036	-0.018	-0.007	-0.149	-0.176	1			
Temp	-0.237	-0.021	0.136	0.182	0.172	-0.006	0.071	0.238	0.217	0.432	1		
RH	-0.437	-0.367	-0.375	-0.393	-0.394	-0.416	-0.319	-0.293	-0.255	-0.152	0.369	1	
WS	-0.366	-0.204	-0.427	-0.56*	-0.469	-0.311	-0.382	-0.56*	-0.618**	0.636**	-0.128	-0.099	1
(b) Gwang Jin													
B	1												
T	0.83**	1											
EB	0.72**	0.927**	1										
MPX	0.767**	0.929**	0.921**	1									
OX	0.723*	0.89**	0.918**	0.99**	1								
TVOC	0.838**	0.997**	0.948**	0.947**	0.914**	1							
SO ₂	0.537*	0.483*	0.497	0.504	0.471	0.521*	1						
NO ₂	0.511	0.543*	0.62*	0.626*	0.796**	0.573*	0.772**	1					
CO	0.396	0.505*	0.641*	0.614*	0.707*	0.544*	0.565*	0.754**	1				
O ₃	0.009	-0.079	0.232	0.243	0.134	-0.061	-0.119	-0.33	0.035	1			
Temp	-0.12	0.043	0.251	0.208	0.269	0.065	-0.22	0.016	0.42	0.602**	1		
RH	-0.239	-0.22	-0.09	-0.207	-0.191	-0.217	-0.511*	-0.342	0.19	0.199	0.593**	1	
WS	0.043	-0.08	0.042	0.061	-0.13	-0.106	-0.035	-0.277	-0.382	0.567*	0	-0.281	1
(c) Gang Seo													
B	1												
T	0.808**	1											
EB	0.677**	0.807**	1										
MPX	0.647*	0.772**	0.965**	1									
OX	0.704*	0.708*	0.954**	0.995**	1								
TVOC	0.832**	0.975**	0.908**	0.889**	0.847**	1							
SO ₂	0.622*	0.453	0.501*	0.47	0.335	0.521*	1						
NO ₂	0.718**	0.517*	0.597**	0.624*	0.55	0.615**	0.774**	1					
CO	0.406	0.291	0.23	0.231	0.291	0.322	0.29	0.575*	1				
O ₃	-0.301	-0.384	-0.285	-0.188	-0.039	-0.369	0.155	-0.325	-0.513*	1			
Temp	-0.247	-0.212	0.092	0.31	0.144	-0.129	0.023	0.022	-0.511*	0.358	1		
RH	-0.308	-0.006	0.149	0.123	-0.18	-0.004	-0.421	-0.36	-0.398	-0.109	0.468	1	
WS	-0.638**	-0.447	-0.378	-0.401	-0.392	-0.469*	-0.248	-0.633**	-0.609**	0.736**	0.252	0.292	1
(d) Yang Jae													
B	1												
T	0.566	1											
EB	0.596	0.907**	1										
MPX	0.347	0.965**	0.984**	1									
OX	0.827	0.987**	0.995**	0.989**	1								
TVOC	0.640*	0.989**	0.960**	0.969**	0.988**	1							
SO ₂	0.448	0.417	0.873**	0.861**	0.906*	0.465	1						
NO ₂	0.520	0.500*	0.703*	0.599	0.646	0.553*	0.654**	1					
CO	0.596*	0.516*	0.619*	0.52	0.49	0.560*	0.738**	0.902**	1				
O ₃	-0.391	-0.074	-0.03	0.375	0.487	-0.14	0.111	-0.392	-0.374	1			
Temp	-0.366	0.092	0.362	0.464	0.757	0.037	0.002	0.189	-0.06	0.488*	1		
RH	-0.543	-0.344	-0.421	-0.272	0.318	-0.422	-0.506*	-0.379	-0.466	0.116	0.41	1	
WS	-0.113	0.079	-0.2	-0.101	-0.341	0.044	-0.185	-0.559*	-0.431	0.431	-0.152	-0.23	1

* Correlation is significant at the 0.05 level; ** Correlation is significant at the 0.01 level

Table 5. Comparison of aromatic VOCs concentrations (ppb) in air among various locations in the world.

Compound	Seoul	Seoul	Seoul	Seoul	UK	China	Hong Kong	Bangkok	Mamila	Sao Paulo	Greater Cairo
Reference	This study	Nguyen <i>et al.</i> , 2009	Kim and Kim, 2002	Na and Kim, 2001	Derwent <i>et al.</i> , 2000	Wang and Zhao, 2008	Lee <i>et al.</i> , 2002	Gee and Sollars, 1998	Gee and Sollars, 1998	Gee and Sollars, 1998	Khoder, 2007
Country	Korea	Korea	Korea	Korea	UK	China	Hong Kong	Thailand	Philippines	Brasil	Cairo
Land use	Urban residential	Commercial	Urban landfill	Residential and commercial	Urban background and rural	Roadside	Urban residential	Unknown	Unknown	Unknown	Urban
Measurement year	February 2009 to July 2009	January 2004 to December 2004	22 March to 4 April 2004 20 Sept to 4 Oct 2004	August 1998 to July 1999	January 1996 to December 1996	April 2006 to January 2007	September 1997 to September 1999	Unknown	Unknown	Unknown	June 2004 to August 2004
Number of measurement data	5-18	17-8656	165-217	Unknown	4411-7525	10	20	Unknown	Unknown	Unknown	12
Benzene	0.58	0.82	1.65	1.00	1.10	2.48	4.73	5.70	3.95	5.23	27.3
Toluene	5.39	39.8	9.62	6.40	2.12	5.80	36.4	49.4	44.6	7.46	56.8
Ethylbenzene	0.72	4.35	1.17	0.70	0.46	0.72	2.68	8.43	5.05	1.38	9.98
m-p, xylene	0.82	5.25	1.84	2.30	1.35	0.95	5.17	18.7	12.7	4.26	32.5
o-xylene	0.35	2.08	0.83	0.80	0.55	0.62	2.45	6.66	3.87	1.43	16.9
Σ BTEX (ppbC)	56.3	377	108	81.2	40.3	73.8	366	650	509	140	1036

1998). In order to assess the relative dominance of BTEX, their concentration data were collected from different studies and compared in Table 5. To facilitate this comparison, the original data for aromatic VOCs (mainly BTEX) reported in other studies (in ppb unit) were also bound together for the derivation of Σ BTEX (ppbC). The concentration of Σ BTEX measured in this study (56.3 ppbC) was higher than that of UK (40.3 ppbC) but significantly smaller than others such as Cairo, Thailand, Philippines, Hong Kong, and China. The Σ BTEX levels (ppbC) can also be compared on the basis of the land use type. The highest mixing ratio of the Σ BTEX was 1,036 ppbC in Cairo (Khoder, 2007), while the lowest value (40.3 ppbC) was recorded in 12 cities in UK (Derwent *et al.*, 2000). The results of this study are lower by a factor of 1.4 times than previous one measured in other locations of Seoul (Na and Kim, 2001) and 6.5 times than those of Hong Kong (Lee *et al.*, 2002).

A comparison of the individual BTEX component indicated that toluene levels were consistently the highest of all VOC in all the studies (Table 5). As shown in Table 5, the concentration of benzene and toluene was low compared to the previous studies conducted in Seoul (Nguyen *et al.*, 2009; Kim and Kim, 2002; Na and Kim, 2001). If the toluene data are compared with those seen in the other Asian cities, our values appear to be most comparable to that of China (5.80 ppb) (Wang and Zhao, 2008). However, our data are lower by 1-9 times than those measured previously in Seoul (Nguyen *et al.*, 2009; Kim and Kim, 2002; Na and Kim, 2001) as well as other Asian cities like Hong Kong (Lee *et al.*, 2002) and Thailand/Philippines (Gee and Sollars, 1998). The concentration level of toluene in the present study (5.39 ppb) is however still much higher than that of UK (2.12 ppb, Derwent *et al.*, 2000) but was lower than that reported from Sao Paulo (7.46 ppb, Gee and Sollars, 1998) and Greater Cairo (56.8 ppb, Khoder, 2007). It is also interesting to note that benzene levels were lower by 1.4-2.8 times than those measured previously in Seoul (Nguyen *et al.*, 2009; Kim and Kim, 2002; Na and Kim, 2001). Our findings of generally reduced BTEX levels relative to previous studies in Seoul may reflect the effect of the stringent regulations enforced by the Korean government, e.g., less than 2% of benzene in gasoline fuel (Na *et al.*, 2002).

3.5 VOC Pollution and Human Exposure

As the major components of aromatics, BTEX are well known for toxic and carcinogenic health effects. The concentration data of BTEX measured in this study were compared with those set by current regulations, advisories, and guidelines, as recommended in a

Table 6. Regulations and guidelines for volatile organic compounds by international and national agencies.

Compound	Regulations and guidelines ^a (ppm)								
	AQG	Inhalation MRL		TLV	STEL		REL (10-h TWA)	PEL (8-h TWA) ^b	IDLH
		Acute	Chronic						
	WHO	ATSDR	ATSDR	ACGIH	ACGIH	NIOSH	NIOSH	OSHA	NIOSH
B	6×10^{-6}	0.009	0.003	0.5	2.5	1.0	0.1	1.0	500
T		1.0	0.08	50		150	100	200	
EB		10	0.3	100	125	125 ^c	100	100	800
X		2.0	0.05	100	151	151	100 ^d	100	900
STY	0.016	2.0	0.2	20	40	100	50	100	686
MC		0.5	0.05					100	
1,1-DCE				200	250			99	4,000
CF		0.1	0.02					50	
TCE	25.12	2.0						100	
PCE		0.2	0.04					100	
1,1-DCEY								1.0	
VC	0.0004	0.5		1.0				1.0	
1,2-DCE					10		2.0	1.0	50
1,1,1-TCE		2.0		350	450		350	350	700

^aDefinitions for acronyms: AQG: air quality guideline; TLV: threshold limit values; STEL: short-term exposure limit; REL: recommended exposure limit; PEL: permissible exposure limit; IDLH: immediately dangerous to life or health; TWA: time-weighted average, ^bFor general industry, ^c15-minute TWA, ^d15-minute ceiling limit

number of reports made by the US-Agency for Toxic Substances and Disease Registry (ATSDR) (Table 6). Because all our measurements were made in the urban ambient air, our data should be significantly lower than those regulation values such as: (1) the World Health Organization air quality guideline (WHO AQG), (2) the threshold limit values (TLV) set by the American Conference of Governmental Industrial Hygienists (ACGIH), (3) the recommended exposure limits (REL) of the National Institute for Occupational Safety and Health (NIOSH), (4) the permissible exposure limits (PEL) set by the Occupational Safety and Health Administration (OSHA), and (5) immediately dangerous to life or health (IDLH) value of NIOSH. It should be more meaningful to compare with such criteria as the national air quality standard of benzene (1.54 ppb) in Korea, although our benzene data measured at all study sites were still well below such criterion. Our benzene data are however found to be higher than the criteria established by the WHO in which a lifetime exposure of $1 \mu\text{g m}^{-3}$ (0.31 ppb) of carcinogenic benzene can lead to about six cases of leukemia per million inhabitants (WHO, 1999). Thus, in a city like Seoul with a population of about 10.3 million and an average benzene level of $1.85 \mu\text{g m}^{-3}$ (0.57 ppb), one may expect about 114 cases of leukemia in the city. It is thus necessary to apply pollution control measures on VOC emission in the city by considering the toxic health effects caused due to benzene.

4. CONCLUSIONS

To assess the level of VOC pollution in Seoul, samples were collected for VOC analysis for 3 consecutive days per month basis from February 2009 to July 2009. In this study, a total of 20 VOCs (11 aromatic and 9 chlorinated species) were measured at the 4 urban residential locations in Seoul, Korea. The TVOC concentration was recorded to be the highest at JR (72.2 ppbC) and lowest at YJ (33.4 ppbC). Among the BTEX components, toluene consistently showed the maximum at all the sites with the highest mean value at JR (7.04 ppb), while the lowest value was found from 1,2-dichloroethane at GJ (0.03 ppb).

If the temporal variation is examined using the TVOC and individual BTEX data, the results showed large similarities with the maximum concentration typically occurring on the Julian days 95-97 at all the sites. Examination of the seasonal data sets indicated that TVOC concentration generally peaked during spring at JR, GJ, and YJ site, whereas those in the GS site peaked during winters. The concentration of toluene tended to peak during spring at JR, GJ, and YJ site, whereas winter time peak was noticed in the GS site. In contrast, benzene generally recorded maximum concentration during winter at all the sites. The results of correlation analysis at JR, GJ, and GS site indicated strongly correlated cases of benzene with TVOC and other VOCs, while it showed strong correlation with

TVOC at YJ.

If a comparison of the VOC data is made mainly in terms of BTEX levels between different studies, the emissions due to automobile exhaust and evaporative losses appeared to be the main cause for the high concentration of VOCs in certain countries. The results of the present study suggest that vehicular emissions should have contributed to the VOC pollution at all the study sites. Considering the importance of VOC pollution in the urban environment, much more elaborated efforts are needed to place limits on VOC distribution, particularly aromatic hydrocarbons among the hazardous air pollutants.

ACKNOWLEDGEMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Ministry of Education, Science and Technology (MEST) (No. 2009-0093848).

REFERENCES

- Abrantes, R.D., de Assuncao, J.V., Pesquero, C.R. (2004) Emission of polycyclic aromatic hydrocarbons from light-duty diesel vehicles exhaust. *Atmospheric Environment* 38, 1631-1640.
- Anthwal, A., Jung, K., Kim, H.J., Bae, I.-S., Kim, K.H. Polycyclic aromatic hydrocarbons in ambient air at four urban locations in Seoul, Korea. *Fresenius Environmental Bulletin* In Press.
- Appel, B.R., Tokiwa, Y., Hsu, J., Kothny, E.L., Hahn, E. (1985) Visibility as related to atmospheric aerosol constituents. *Atmospheric Environment* 19, 1525-1534.
- Atkinson, R. (2000) Atmospheric chemistry of VOCs and NO_x. *Atmospheric Environment* 34, 2063-2101.
- Baldasano, J.M., Delgado, R., Calbó, J. (1998) Applying receptor models to analyze urban/suburban VOCs air quality in Martorell (Spain). *Environmental Science and Technology* 32, 405-412.
- Barletta, B., Meinardi, S., Rowland, F.S., Chan, C., Wang, X., Zou, S., Chan, L.Y., Blake, D. (2005) Volatile organic compounds in 43 Chinese cities. *Atmospheric Environment* 39, 5979-5990.
- Barletta, B., Meinardi, S., Simpson, I.J., Khwaja, H.A., Blake, D.R., Rowland, F.S. (2002) Mixing ratios of volatile organic compounds (VOCs) in the atmosphere of Karachi, Pakistan. *Atmospheric Environment* 36, 3429-3443.
- Borbon, A., Locoge, N., Veillerot, M., Galloo, J.C., Guillermo, R. (2002) Characteristics of NMHCs in a French urban atmosphere: overview of the main sources. *The Science of the Total Environment* 292, 177-191.
- Brocco, D., Fratarcangeli, R., Lepore, L., Petricca, M., Ventrone, I. (1997) Determination of aromatic hydrocarbons in urban air of Rome. *Atmospheric Environment* 31, 557-566.
- Broderick, B.M., Marnane, I.S. (2002) A comparison of the C2-C9 hydrocarbon compositions of vehicle fuels and urban air in Dublin, Ireland. *Atmospheric Environment* 36, 975-986.
- Chan, C.C., Spengler, J.D., Ozkaynak, H., Lefkoulou, M. (1991) Commuter exposure to volatile organic compounds in Boston, Massachusetts. *Journal of Air and Waste Management* 41, 1594-1600.
- Chan, C.Y., Chan, L.Y., Wang, X.M., Liu, Y.M., Lee, S.C., Zou, S.C., Sheng, G.Y., Fu, J.M. (2002) Volatile organic compounds in roadside microenvironments of metropolitan Hong Kong. *Atmospheric Environment*, 36, 2039-2047.
- Cheng, L., Fu, L., Angle, R.P., Sandhu, H.S. (1997) Seasonal variations of volatile organic compounds in Edmonton, Alberta. *Atmospheric Environment* 31, 239-246.
- City of Seoul (2010) <http://english.seoul.go.kr/gtk/about/fact.php>.
- Cocker, III D.R., Mader, B.T., Kalberer, M., Flagan, R.C., Seinfeld, J.H. (2001) The effect of water on gas-particle partitioning of secondary organic aerosol: II. m-xylene and 1,3,5-trimethylbenzene photooxidation systems. *Atmospheric Environment* 35, 6073-6085.
- Derwent, R.J., Davies, T.J., Delaney, M., Dollard, G.J., Field, R.A., Dumitrescu, P., Nason, P.D., Jones, B.M.R., Pepler, S.A. (2000) Analysis and interpretation of the continuous hourly monitoring data for 26 C2-C8 hydrocarbons at 12 United Kingdom sites during 1996. *Atmospheric Environment* 34, 297-312.
- Ferrari, C.P., Kaluzny, P., Roche, A., Jacob, V., Poster, P. (1998) Aromatic hydrocarbons and aldehydes in the atmosphere of Grenoble, France. *Chemosphere* 37, 1587-1601.
- Gee, I.L., Sollars, C.J. (1998) Ambient air levels of volatile organic compounds in Latin American and Asian cities. *Chemosphere* 36, 2497-2506.
- Gelencsr, A., Siszler, K., Hlavay, J. (1997) Toluene-benzene concentration ratio as a tool for characterizing the distance from vehicular emission sources. *Environmental Science and Technology* 31, 2869-2872.
- Guo, H., Wang, T., Simpson, I.J., Blake, D.R., Yu, X.M., Kwok, Y.H., Li, Y.S. (2004) Source contributions to ambient VOCs and CO at a rural site in eastern China. *Atmospheric Environment* 38, 4551-4560.
- Han, X., Naeher, L.P. (2006) A review of traffic-related air pollution exposure assessment studies in the developing world. *Environment International* 32(1), 106-120.
- Ho, K.F., Lee, S.C., Guo, H., Tsai, W.Y. (2004) Seasonal and diurnal variations of volatile organic compounds (VOCs) in the atmosphere of Hong Kong. *Science of the Total Environment* 322, 155-166.
- Hong, Y.J., Jeng, H.A., Gau, Y.Y., Lin, C., Lee, I.L. (2006) Distribution of volatile organic compounds in

- ambient air of Kaohsiung, Taiwan. *Environmental Monitoring and Assessment* 119, 43-56.
- Hoque, R.R., Khillare, P.S., Agarwal, T., Shridhar, V., Balachandran, S. (2008) Spatial and temporal variation of BTEX in the urban atmosphere of Delhi, India. *Science of the Total Environment* 392, 30-40.
- Kelessis, A.G., Petrakakis, M.J., Zoumakis, N.M. (2006) Determination of benzene, toluene, ethylbenzene, and xylenes in the urban air of Thessaloniki, Greece. *Environmental Toxicology* 21(4), 440-443.
- Khoder, M.I. (2007) Ambient levels of volatile organic compounds in the atmosphere of Greater Cairo. *Atmospheric Environment* 41, 554-566.
- Kim, K.H., Kim, M.Y. (2002) The distributions of BTEX compounds in the ambient atmosphere of the Nan-Ji-Do abandoned landfill site in Seoul. *Atmospheric Environment* 36, 2433-2446.
- Kim, Y.M., Harrad, S., Harrison, R.M. (2001) Concentrations and sources of VOCs in urban domestic and public microenvironments. *Environmental Science and Technology* 35, 997-1004.
- Kourtidis, K., Ziomas, I., Zerefos, C., Kosmidis, E., Symeonidis, P., Christophilopoulos, E., Karathanassis, S., Mploutsos, A. (2002) Benzene, toluene, O₃, NO₂ and SO₂ measurements in an urban street canyon in Thessaloniki, Greece. *Atmospheric Environment* 36, 5355-5364.
- Lai, C.H., Chen, K.S., Ho, Y.T., Chou, M.S. (2004). Characteristics of C₂-C₁₅ hydrocarbons in the air of Urban Kaohsiung, Taiwan. *Atmospheric Environment* 38, 1997-2011.
- Lee, S.C., Chiu, M.Y., Ho, K.F., Zou, S.C., Wang, X. (2002) Volatile organic compounds (VOCs) in urban atmosphere of Hong Kong. *Chemosphere* 48, 375-382.
- Liu, C., Xu, Z., Du, Y., Guo, H. (2000) Analyses of volatile organic compounds concentrations and variation trends in the air of Changchun, the northeast of China. *Atmospheric Environment* 34, 4459-4466.
- Na, K., Kim, Y.P. (2001) Seasonal characteristics of ambient volatile organic compounds in Seoul, Korea. *Atmospheric Environment* 35, 2603-2614.
- Nguyen, H.T., Kim, K.H., Kim, M.Y. (2009) Volatile organic compounds at an urban monitoring station in Korea. *Journal of Hazardous Materials* 161, 163-174.
- Odum, J.R., Jungkamp, T.P.W., Griffin, R.J., Forstner, H.J.L., Flagan, R.C., Seinfeld, J.H. (1997) Aromatics, reformulated gasoline, and atmospheric organic aerosol formation. *Environmental Science and Technology* 31, 1890-1897.
- Rappengluck, B., Schmitz, R., Bauerfeind, M., Cereda-Balic, F., von Baer, D., Jorquera, H., Silva, Y., Oyola, P. (2005) An urban photochemistry study in Santiago de Chile. *Atmospheric Environment* 39, 2913-2931.
- Rudd, H.J. (1995) Emissions of Volatile Organic Compounds from Stationary Sources in the United Kingdom: Speciation, AEA Technology Report, AEA/CS/16419-033/REMA029/Issue 2, NETCEN, Culham Laboratory, Oxfordshire.
- Seaton, A., MacNee, W., Donaldson, K., Godden, D. (1995) Particulate air pollution and acute health effects. *The Lancet* 345, 176-178.
- Singh, H.B., Zimmerman, P.B. (1992) Atmospheric distributions and sources of nonmethane hydrocarbons. In *Gaseous Pollutants: Characterization and Cycling* (Nriagu, J.O. Ed), Wiley, New York, USA, pp. 177-225.
- Smith S., Stribley, F.T., Milligan, P., Barratt, B. (2001) Factors influencing measurements of PM₁₀ during 1995-1997 in London. *Atmospheric Environment* 35, 4651-4662.
- Srivastava, A., Joseph, A.E., Devotta, S. (2006) Volatile organic compounds in ambient air of Mumbai-India. *Atmospheric Environment* 40, 892-903.
- Tavares, M. Jr., Pinto, J.P., Souza, A.L., Scarminio, I.S., Solci, M.C. (2004) Emission of polycyclic aromatic hydrocarbons from diesel engine in a bus station, Londrina, Brazil. *Atmospheric Environment* 38, 5039-5044.
- Tsai, J.H., Hsu, Y.C., Yang, J.Y. (2004) The relationship between volatile organic profiles and emission sources in ozone episode region-a case study in Southern Taiwan. *Science of the Total Environment* 328, 131-142.
- Tsujino, Y., Kuwata, K. (1993) Sensitive flame ionization detector for the determination of trace of atmospheric hydrocarbons by capillary gas chromatography. *Journal of Chromatography* 642, 383-388.
- US EPA (1993) Integrated Risk Information System (IRIS) on Benzene, Environmental Criteria and Assessment Office, Office of Health and Environmental Assessment, Office of Research and Development, Cincinnati, OH.
- Wang, X.M., Sheng, G.Y., Fum, J.M., Chan, C.Y., Lee, S.C., Chan, L.Y., Wang, Z.S. (1993) Urban roadside aromatic hydrocarbons in three cities of the Pearl River Delta, People's Republic of China. *Atmospheric Environment* 36, 5141-5148.
- Wang, P., Zhao, W. (2008) Assessment of ambient volatile organic compounds (VOCs) near major roads in urban Nanjing, China. *Atmospheric Research* 89, 289-297.
- Wang, T., Guo, H., Blake, D.R., Kwok, Y.H., Simpson, I.J., Li, Y.S. (2005) Measurements of trace gases in the inflow of South China sea background air and outflow of regional pollution at Tai O, Southern China. *Journal of Atmospheric Chemistry* 52, 295-317.
- World Health Organization (WHO) (1999) Air Quality Guidelines for Europe. WHO Regional Publication, European Series. World Health Organization. Regional Office for Europe, Copenhagen.

(Received 30 March 2010, accepted 7 May 2010)