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Confirming anthropogenic influences on the major organic and inorganic constituents of rainwater in an urban area

K. Chon[1,2], Y. Kim[3], D. H. Bae[4], and J. Cho[5]

[1]Department of Civil and Environmental Engineering, Yonsei University, Yonsei-ro 50, Seoul 120-749, Korea
[2]Chemical Safety Division, National Institute of Agricultural Science, 166, Nongsaengmyeong-ro, Iseo-myeon, Wanju-gun, Jeollabuk-do, 565-851, Korea
[3]School of Environmental Science and Engineering, Gwangju Institute of Science and Technology (GIST), 123 Cheomdangwagi-ro, Buk-gu, Gwangju 500-712, Korea
[4]Department of Civil and Environmental Engineering, Sejong University, Neungdong-ro 209, Gwangjin-gu, Seoul 143-747, Korea
[5]School of Urban and Environmental Engineering, Ulsan Institute of Science and Technology (UNIST), UNIST-gil 50, Ulsan 689-798, Korea

Correspondence to: J. Cho (jaeweoncho@unist.ac.kr)

Abstract. Recently, rainwater composition affected by atmospheric pollutants has been the topic of intense study in East Asia because of its adverse environmental and human health effects. In the present study, the chemical composition and organic compounds of rainwater were investigated from June to December 2012 at Gwangju in Korea. The aim of this study is to determine the seasonal variation of rainwater chemical composition and to identify possible sources of inorganic and organic compounds. The volume-weighted mean of pH ranged from 3.83 to 8.90 with an average of 5.78. Of rainwater samples, 50 % had pH values below 5.6. The volume-weighted mean concentration (VWMC) of major ions followed the order $Cl^- > SO_4^{2-} > NH_4^+ > Na^+ > NO_3^- > Ca^{2+} > Mg^{2+} > K^+$. The VWMC of trace metals decreased in the order $Zn > Al > Fe > Mn > Pb > Cu > Ni > Cd > Cr$. The VWMCs of major ions and trace metals were higher in winter than in summer. The high enrichment factors indicate that Zn, Pb, Cu, and Cd originated predominantly from anthropogenic sources. Factor analysis (principal component analysis) indicates the influence of anthropogenic pollutants, sea salt, and crustal materials on the chemical compositions of rainwater. Benzoic acids, 1H-isoindole-1,3(2H)-dione, phthalic anhydride, benzene, acetic acids, 1,2-benzenedicarboxylic acids, benzonitrile, acetaldehyde, and acetamide were the most prominent pyrolysis fragments for rainwater organic compounds identified by pyrolysis gas chromatography/mass spectrometry (Py-GC/MS). The results indicate that anthropogenic sources are the most important factors affecting the organic composition of rainwater in an urban area.

1 Introduction

Rain is an efficient scavenging process for pollutants in the air and is becoming a source of pollution to the environment (Santos et al., 2011). The emission of SO_2 and NO_x from fossil fuel combustion and industrial processes has rapidly increased in East Asia due to its fast growing economy. These gases are converted into sulfuric and nitric acids before precipitating as acid rain (Lee et al., 2000; Báez et al., 2006). Consequently, there have been adverse environmental effects on aquatic, biological, and terrestrial systems (Bard, 1999; Başak and Alagha, 2004). Thus, the chemical composition of precipitation has been investigated all around the world during the last decade (Lara et al., 2001; Mouli et al., 2010; Santos et al., 2011).

Coal combustion, automobile exhaust, and industrial emissions represent the dominant anthropogenic sources of heavy metals in rainwater (Kaya and Tuncel, 1997; Hu and Balasubarmanian, 2003; Cheng et al., 2011). Heavy metals from precipitation accumulate in the biosphere and may cause adverse human health and environmental effects (Barrie et al., 1987; Báez et al., 2007). Thus, the studies of heavy metals in rainwater have increased in many countries (Pike and Moran, 2001; Al-Momani, 2003; Báez et al., 2007).

Dissolved organic carbon (DOC) is a major component of both continental (161 μM) and marine rain (23 μM) (Willey et al., 2000). DOC is a mixture of simple substances such as alkanes, carbohydrates, and fatty acids, and of complex polymeric molecules, such as aromatic, aliphatic, and carboxylic carbons (Muller et al., 2008). Rainwater DOC plays a significant role in the atmospheric carbon cycle, and the global rainwater flux of DOC is 430×10^{12} g C yr^{-1} (Willey et al., 2000). Sources of DOC compounds in rainwater are primary anthropogenic and biogenic emissions, and photochemical transformations of precursors (Klouda et al., 1996). While numerous studies have been conducted on the inorganic chemistry of rainwater, little attention has been paid to organic compounds. Kawamura et al. (1983) initiated the identification and distribution of organic compounds in rainwater. The role of organic compounds in atmospheric processes has gained much attention in the last few years, and knowledge of organic compounds has improved with various analytical methods (Kieber et al., 2002; Seitzinger et al., 2003). However, the organic compounds in the atmosphere are very complicated and chemical characterization of organic matter in precipitation requires further work (Santos et al., 2009).

Several studies have examined chemical composition of rainwater in Korea. Although many studies have been conducted on the seasonal variation of all the major ions or heavy metals in rainwater (Lee et al., 2000; Kang et al., 2004; Kim et al., 2012; Moon et al., 2012), there are few on the organic compounds and the sources and variation of DOC in precipitation (Yan and Kim, 2012).

In this study, rainwater samples were collected from June to December 2012 in an urban area of Gwangju, Korea. The objectives of this study are to investigate the seasonal variation of rainwater chemical composition and to identify possible sources of inorganic and organic compounds in rainwater.

Our framework for research design is as follows:

1. seasonal variation in chemical composition (ions and trace metals) of rainwater

2. enrichment factor analysis to evaluate the contribution of non-crustal sources

3. variation in chemical composition of initial and subsequent rainfall

4. factor analysis to investigate the influence of natural and anthropogenic sources

5. analysis of organic compounds in rainwater.

2 Materials and methods

2.1 Study site

Rainwater samples were collected at the Gwangju Institute of Science and Technology campus (35°13″ N, 126°50″ E) in Gwangju, Korea (Fig. 1), from June to December in 2012. Gwangju has an area of 501.34 km^2 and a population of around 1480 000. The annual average temperature is 13.5 °C and the average precipitation is 1368 mm per year.

2.2 Sample collection and analysis

Rainwater samples were collected per event using a Teflon-coated collector designed to manually take samples with time. Samples from initial precipitation events were collected with care not to be mixed with later precipitation samples. Initial rainwater samples were collected from a single rain event or multiple rain events in a single day. We collected initial rainwater samples until a 2 L glass jar was filled during the beginning of the rain event. All the initial and later samples were transported to the laboratory and pH and electrical conductivity (EC) were measured. The remaining samples were filtered through 0.45 μm filters (mixed cellulose ester, Advantec, Japan) and then stored at 4 °C until further chemical analyses were performed within 1 week. pH and EC were measured using a pH meter and an EC meter, respectively (Orion 3-Star, Thermo Scientific, USA).

Major ions were quantified using a suppressed type ion chromatograph (DX-120, ICS-90, Dionex, Sunnyvale, CA, USA). An IonPac AS14 and an IonPac CS12A column (Dionex, Sunnyvale, CA, USA) were used for measurements of major anions (NO_3^-, SO_4^{2-}, and Cl^-) and cations (NH_4^+, Ca^{2+}, Mg^{2+}, Na^+, and K^+), respectively. The concentrations of trace metals were measured using inductively coupled plasma mass spectrometry (ICP-MS) (7500ce, Agilent,
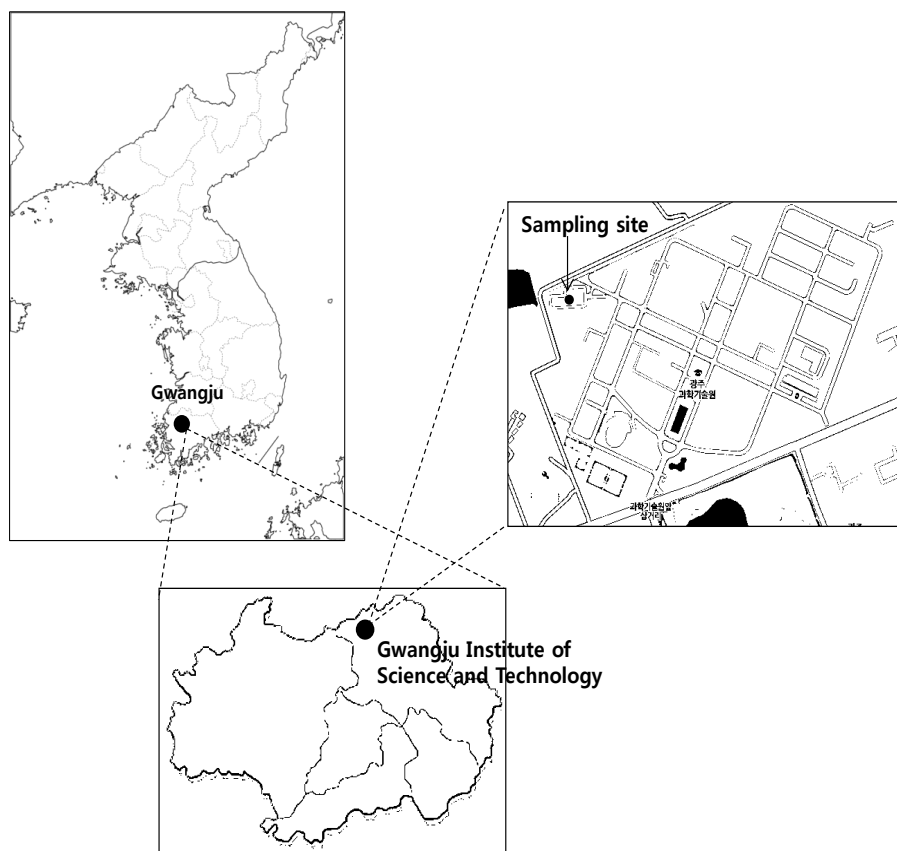
Figure 1. Location of the sampling site for this study.

Santa Clara, CA, USA). All the samples were acidified to a final nitric acid concentration of 2 % using a 70 % nitric acid solution. The levels of DOC and total nitrogen (TN) contents of rainwater samples were determined using a total organic carbon analyzer (TOC-V CPH, Shimadzu, Japan) equipped with a TN analyzer (TNM-1, Shimadzu, Japan). The UV absorbance of the samples at 254 nm (UV_{254}) was measured using a UV–vis spectrophotometer (UV-1601, Shimadzu, Japan). The specific UV absorbance (SUVA) value (an indicator of aromaticity) was calculated from the ratio of UV_{254} to DOC concentration. Rainwater samples were concentrated to a final DOC concentration of approximately $100\,\mathrm{mg\,C\,L^{-1}}$ with a rotary evaporator (Eyela, Japan). Approximately 20 mL of concentrated samples was freeze-dried using a freeze dryer (Ilshin, Korea) prior to pyrolysis gas chromatography/mass spectrometry (Py-GC/MS) analysis. Approximately 0.5–1.0 mg of freeze-dried sample powders were pyrolyzed at 590 °C for 5 s in the pyrofoil (Pyrofoil F590, Japan Analytical Industry, Tokyo, Japan) within a Curie point pyrolyzer (JCI-22, Japan Analytical Industry, Tokyo, Japan) coupled with an Agilent 7890A gas chromatograph coupled to a 5975C quadrupole mass spectrometer (ion source temperature 220 °C, scanning from 40 to 500 amu, electron energy 70 eV). Pyrolysis fragments were separated by GC equipped with a DB-5MS (Agilent Technologies, USA) column and identified using a mass spectrometer. Helium was used as the carrier gas. The temperature program of the GC oven was initially maintained at 40 °C for 5 min, then increased at $7\,°\mathrm{C\,min^{-1}}$ to a final temperature of 300 °C and remained there for 10 min, giving a total run time of 52.14 min. The interpretation of the pyrochromatograms was conducted according to the methods described in Bruchet et al. (1990).

3 Results and discussion

3.1 Variation of pH value and precipitation amount

The average monthly rainfall from June to December during 2012 was 195.4 mm and the highest amount of rainfall (473.5 mm) was observed in August 2012 (Fig. 2). Of the total rainfall, 79 % occurred during the summer (July–September). The percent frequency distribution of pH for the rainwater samples is presented in Fig. 3. The volume-weighted mean of pH was 5.78. The lowest pH value was observed on 11 July with a pH of 3.83, while the highest was on 22 August 2012 with a pH value of 8.90. Most pH values ranged between 5.0 and 5.5 (23.9 %), while about 2.6 %
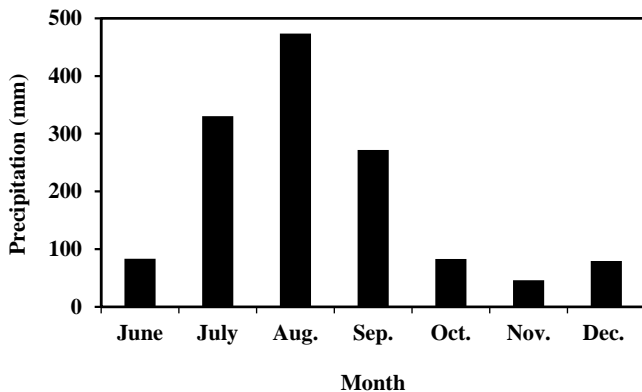
Figure 2. Monthly integrated precipitation at Gwangju during 2012.

Figure 3. Distribution of pH in rainwater samples collected from Gwangju.

of pH values were in the range of 3.5–4.5. Of the samples, 50 % had pH values below 5.6, which is the value of unpolluted water equilibrated with atmospheric CO_2 (Charlson and Rodhe, 1982). On the other hand, approximately 12 % of the samples had a pH above 7.0, suggesting strong inputs of alkaline substances to rainwater in this area.

3.2 Ionic composition of rainwater

The volume-weighted mean concentration (VWMC), standard deviation of the VWMC (SDVWMC), and minimum (Min) and maximum (Max) concentrations of the rainwater chemical components are summarized in Table 1. VWMC was calculated by the following equation:

$$VWMC = \sum_{i=1}^{n} Xi \, Pi / \sum_{i=1}^{n} Pi,$$

where Xi is the measured ion concentration, Pi is the precipitation amount, and n is the number of samples. The VWMC of major ions in rainwater follows the order $Cl^- > SO_4^{2-} > NH_4^+ > Na^+ > NO_3^- > Ca^{2+} > Mg^{2+} > K^+$. Among all the ions, Cl^- was the most abundant with an average of 123.5 µeq L^{-1}, accounting for 28.5 % of the ionic concentration. SO_4^{2-} was the second highest anion with an average of 91.9 µeq L^{-1}, accounting for 21.2 % of total ions. The contribution of NO_3 was 8.5 % (concentration of 36.8 µeq L^{-1}). The high value of SO_4^{2-} and highest of Cl^- can be attributed to emissions from fossil fuel combustion and typhoons and sea salts, respectively. As for cation species, NH_4^+ made the highest contribution at 63.0 µeq L^{-1}, accounting for 14.5 % of the total ions. Meanwhile, Na^+ was the second highest cation accounting for 13.5 % of the total ions. The concentration of Ca^{2+}, Mg^{2+}, and K^+ ions accounted for 8.5, 3.5, and 1.8 %, respectively. The high level of NH_4^+ in Gwangju was comparable to Seoul (with a mean concentration of 66.4 µeq L^{-1}; Lee et al., 2000). Wastes from agricultural and domestic activities as well as
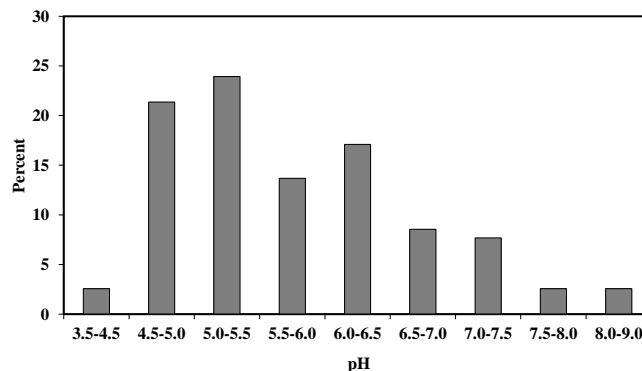
the use of fertilizers are believed to be the main sources of the emission of gaseous ammonia (Dianwu and Anpu, 1994; Panyakapo and Onchang, 2008). Ca^{2+} may originate from wind-blown dust and calcareous soil, Mg^{2+} from sea salts and dusts in the atmosphere, while Na^+ from sea salts. EC of rainwater ranged from 0.87 to 169.00 µS cm^{-1}, with a VWM (volume-weighted mean) value of 27.82 µS cm^{-1}. The VWMs of UV and SUVA in rainwater were 0.0160 and 1.09, respectively. Organic matter in rainwaters exhibit relatively hydrophilic characteristics, with SUVA values less than 2 generally indicating a high fraction of hydrophilic non-humic matter with low UV absorbance.

The VWMC of major ions in rainwater at Gwangju were compared to those reported in other urban areas around the world (Table 2). The pH value measured in our study is lower than that in Tirupati, India, but higher than those reported for other sites. The concentration of Na^+ is comparable to that in Shanghai but lower than in Istanbul and higher than other areas. The Cl^- value is comparable to that in Istanbul and much higher than those reported for other sites. The high concentration of marine elements was likely due to typhoons during summer seasons. The value of NO_3^- is higher than that in southeastern Brazil and close to that in other sites. Regarding SO_4^{2-}, its concentration is higher than that in Seoul, Mexico, and Brazil and lower than in other areas. Shanghai shows the highest values of NO_3^- and SO_4^{2-}, indicating severe air pollution problems in China. Both of these ions were mainly derived from the high coal/fuel consumption and mobile sources. The concentrations of K^+, Ca^{2+}, and Mg^{2+} are higher than those in Seoul, Mexico, and Brazil and lower than in other sites. The concentrations of these ions are comparatively higher in Istanbul than in other areas. The value of NH_4^+ is comparable to that in Seoul and higher than that in India, Turkey, and Brazil.

3.3 Seasonal variation

Figure 4 displays the monthly variation of VWM of pH, conductivity, TOC, TN, SUVA, and UV of rainwater sam-

Table 1. Volume-weighted mean concentration (VWMC), standard deviation of the VWMC (SDVWMC), and minimum (Min) and maximum (Max) concentrations of chemical composition in rainwater collected from June to December during 2012.

$n = 113$		VWMC	SDVWMC	Min	Max
pH		5.78	1.66	3.83	8.90
Conductivity	$\mu S\,cm^{-1}$	27.82	11.13	0.87	169.00
TOC	$mg\,C\,L^{-1}$	1.49	0.53	0.15	6.90
UV	cm^{-1}	0.0160	0.0061	0.0006	0.0972
SUVA		1.09	0.30	0.03	2.42
TN	$mg\,N\,L^{-1}$	1.13	0.40	N.D.	8.62
Na^+	$mg\,L^{-1}$	1.4	0.7	0.0	19.65
	$\mu eq\,L^{-1}$	58.5	30.7	1.2	854.50
NH_4^+	$mg\,L^{-1}$	1.1	0.4	0.0	5.9
	$\mu eq\,L^{-1}$	63.0	22.1	1.6	327.1
K^+	$mg\,L^{-1}$	0.3	0.1	0.0	1.9
	$\mu eq\,L^{-1}$	7.7	4.1	0.3	53.0
Mg^{2+}	$mg\,L^{-1}$	0.2	0.1	N.D.	2.5
	$\mu eq\,L^{-1}$	15.3	7.5	N.D.	208.6
Ca^{2+}	$mg\,L^{-1}$	0.7	0.4	N.D.	6.7
	$\mu eq\,L^{-1}$	36.7	17.7	N.D.	337.1
NO_3^-	$mg\,L^{-1}$	2.28	0.9	N.D.	12.4
	$\mu eq\,L^{-1}$	36.8	14.8	N.D.	199.2
SO_4^{2-}	$mg\,L^{-1}$	4.4	2.1	0.0	19.5
	$\mu eq\,L^{-1}$	91.9	42.6	0.9	405.4
Cl^-	$mg\,L^{-1}$	4.4	3.0	0.0	39.3
	$\mu eq\,L^{-1}$	123.5	83.7	1.0	1106.4

N.D.: not detected, n: number of samples. WHO (World Health Organization) drinking water guidelines: pH: 6.5–8.5, NH_4^+: 1.5 mg L^{-1}, NO_3^-: 50 mg L^{-1}, SO_4^{2-}: 250 mg L^{-1}, Cl^-: 250 mg L^{-1}.

Table 2. Comparison between the VWMC of major ions ($\mu eq\,L^{-1}$) in precipitation in Gwangju and at other sites.

Location	Period	pH	Na^+	NH_4^+	K^+	Mg^{2+}	Ca^{2+}	NO_3^-	SO_4^{2-}	Cl^-	References
This study	June–Dec. 2012	5.78	58.5	63.0	7.7	15.3	36.7	36.8	91.9	123.5	
Seoul, Korea	May 1996–Apr. 1998	4.7	10.5	66.4	3.5	6.9	10.5	29.9	70.9	18.2	Lee et al. (2000)
Tirupati, India	July 2000–June 2001	6.78	33.08	20.37	33.89	50.51	150.66	40.84	127.96	33.91	Mouli et al. (2005)
Istanbul, Turkey	Oct. 2001–July 2002	4.81	75.2	12.8	57.4	99.6	285	33.4	115.2	124.8	Basak and Alagha (2004)
Mexico City, Mexico	May 2001–Oct. 2002	5.08	7	92.35	2.16	2.46	26.44	42.62	61.94	9.56	Baez et al. (2007)
Shanghai, China	2005	4.49	50.11	80.68	14.89	29.64	203.98	49.8	199.59	58.34	Huang et al. (2008)
Piracicaba, southeastern Brazil	Aug. 1997–July 1998	4.5	2.7	17.1	2.9	2.3	5.3	16.6	18.7	7	Lara et al. (2001)

ples. pH values measured during summer seasons (June–September) with greater rainfall were higher than those during the winter season (October–December). This is consistent with previous studies (Cerón et al., 2013). Lee et al. (2000) also mentioned that the amount of rainfall influences pH. Conductivity values increased from summer to winter seasons, in agreement with the seasonal trend of major ions. Lower conductivity during the summer was caused by the dilution effect of higher rainfall. The values of TOC show similar monthly trends to TN, increasing with decreasing rainfall amounts. Similar seasonal variations of TOC have been reported in other studies (Pan et al., 2010; Yan and Kim, 2012). DOC in the atmosphere is known to vary with the seasons due to biogenic emission form vegetation. Kieber et

al. (2002) reported relatively higher levels of DOC in rainwater in warmer seasons; in contrast, Yan and Kim (2012) indicated that it was due to the prevailing anthropogenic contributions (mostly fossil fuel burning) and low precipitation in the relatively dry winter season. They also found that DOC in precipitation over Seoul was mainly produced by incomplete combustion of fossil fuel. The values of TN display similar monthly trends with TOC. They were higher in spring, fall, and winter, which are relatively dryer than summer. As expected, this is consistent with the monthly variation of NO_3^- and NH_4^+. The value of UV_{254} measured during the winter season (November–December) is higher than in the summer season (July–September). SUVA values higher than 1.4 were measured in September, November, and December, but in the
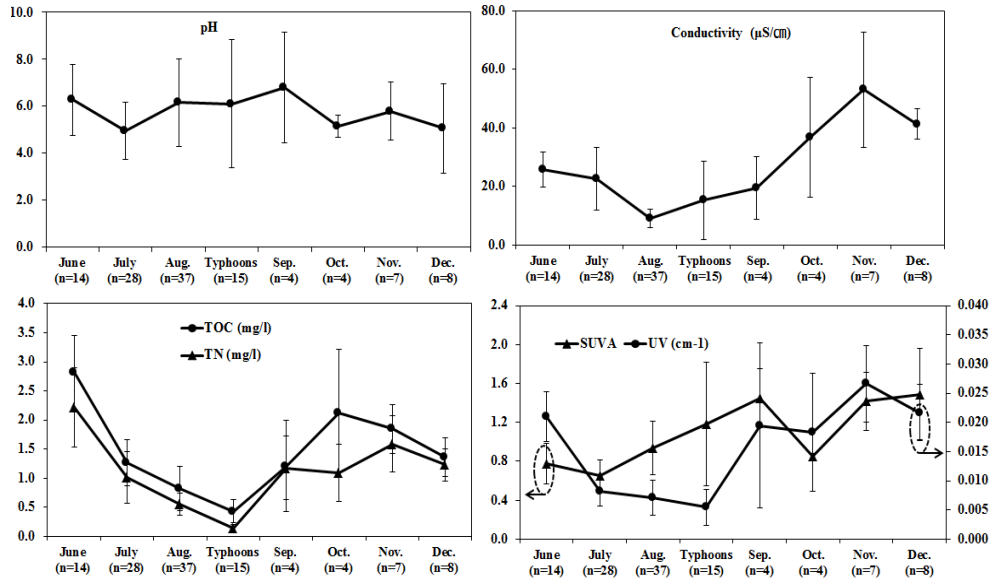
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Drink. Water Eng. Sci., 8, 35–48, 2015

Figure 4. Monthly variation of the volume-weighted mean value of pH, conductivity, TOC, TN, SUVA, and UV absorbance in rainwater samples collected in Gwangju during 2012.

Table 3. Correlation matrix between ions in rainwater samples. The Pearson correlation coefficient and the P values are shown. Bold numbers presents $R^2 > 0.6$.

Variables	Na$^+$	NH$_4^+$	K$^+$	Mg^{2+}	Ca^{2+}	NO$_3^-$	Cl$^-$
NH$_4^+$	0.19						
	0.04						
K$^+$	0.50	0.50					
	0.00	0.00					
Mg^{2+}	**0.99**	0.23	0.53				
	0.00	0.01	0.00				
Ca^{2+}	0.41	0.55	**0.67**	0.48			
	0.00	0.00	0.00	0.00			
NO$_3^-$	0.39	**0.86**	0.59	0.44	**0.78**		
	0.00	0.00	0.00	0.00	0.00		
Cl$^-$	**1.00**	0.19	0.49	**0.99**	0.39	0.38	
	0.00	0.04	0.00	0.00	0.00	0.00	
SO$_4^{2-}$	0.29	**0.82**	**0.61**	0.32	**0.66**	**0.81**	0.29
	0.00	0.00	0.00	0.00	0.00	0.00	0.00

other months they were lower than 1.0. The monthly VWMC of major ions in rainwater samples are depicted in Fig. 5. The mean concentration of major ions in samples during summer (July–September), typhoons, and winter (November–December) are illustrated in Fig. 6. More than half of the total rainfall occurs in summer, while in the winter, precipitation is less than 10 % of the total in Korea (Lee et al., 2000). Thus, seasonal variations of ionic concentration in rainwater were mainly affected by precipitation patterns and monsoonal winds (Lee et al., 2000). The major ions had relatively higher concentrations in the winter, which is a pattern opposite to the trend in rainfall. The ionic concentrations showed

decreasing trends with increasing rainfall amounts, suggesting a dilution effect of rainwater on precipitation chemistry. The lowest ion concentrations were observed during typhoon periods, except for Na$^+$ and Cl$^-$ which are typical marine components.

3.4 Correlation analysis

To investigate and identify potential correlation between major ions in rainwater samples, the Pearson correlation analysis was applied (Table 3). A strong correlation was found between Na$^+$ and Mg^{2+} ($R^2 = 0.99$) and between Na$^+$ and Cl$^-$ ($R^2 = 1.00$), suggesting a marine source. The high cor-
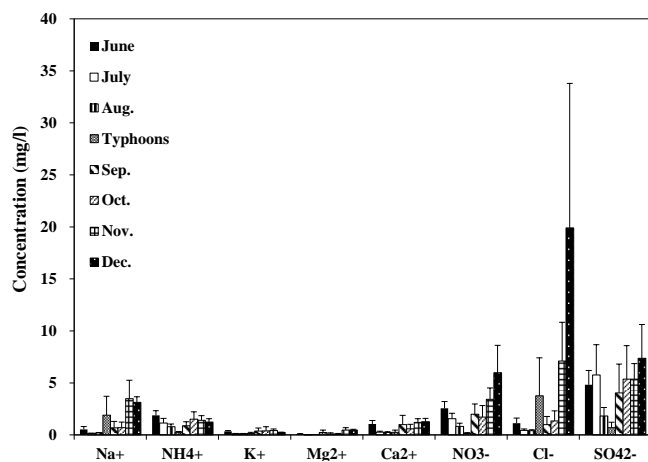
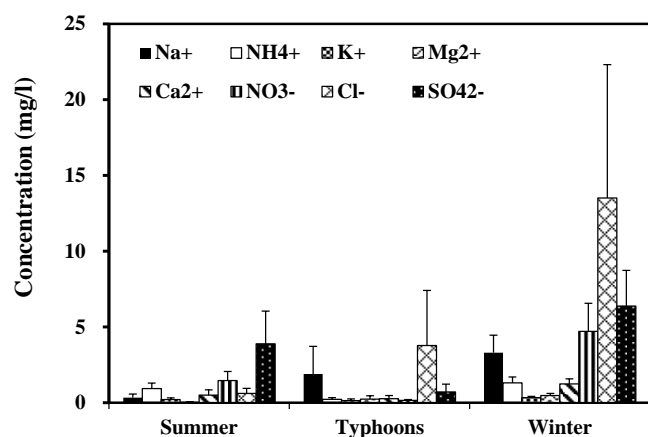**Figure 5.** Monthly variation of VWMC of major ions in rainwater samples during 2012.

Figure 6. Mean concentration of major ions in rainwater samples during summer (July–September), typhoons, and winter (November–December).

Table 4. Concentrations of trace metals in rainwater samples (ppb).

Trace metals	VWMC	SDVWMC	Min	Max
Zn	18.78	14.08	N.D.	567.20
Al	12.99	6.64	N.D.	104.60
Fe	11.00	6.55	N.D.	74.51
Mn	4.58	2.89	N.D.	33.45
Pb	3.10	1.77	N.D.	25.01
Cu	1.69	0.89	N.D.	14.70
Ni	0.28	0.18	N.D.	8.04
Cd	0.09	0.05	N.D.	1.14
Cr	0.06	0.03	N.D.	0.47

WHO drinking water guidelines: Zn: $3 \, mg \, L^{-1}$, Al: $0. \, mg \, L^{-1}$, Fe: $0.3 \, mg \, L^{-1}$, Mn: $0.5 \, mg \, L^{-1}$, Pb: $0.01 \, mg \, L^{-1}$, Cu: $2 \, mg \, L^{-1}$, Ni: $0.07 \, mg \, L^{-1}$, Cd: $0.03 \, mg \, L^{-1}$, Cr: $0.05 \, mg \, L^{-1}$.

ity of their behavior in precipitation. Correlations were also found between NO_3^- and Ca^{2+} ($R^2 = 0.78$), and between SO_4^{2-} and Ca^{2+} ($R^2 = 0.66$), suggesting that $Ca(NO_3)_2$ and $CaSO_4$ are formed from the neutralization reactions of acidity in rainwater (Zhao et al., 2013). Moderate correlation was found between K^+ and Ca^{2+}, indicating a common origin in marine aerosol. K^+ and SO_4^{2-} were somewhat correlated ($R^2 = 0.61$), suggesting the occurrence of reactions between the acid H_2SO_4 and the alkaline compounds carried into the atmosphere by windblown sea salts/dusts (Huang et al., 2008).

3.5 Trace metals

The VWMCs of trace metals in rainwater samples are presented in Table 4. The concentration of trace metals decreased in the order $Zn > Al > Fe > Mn > Pb > Cu > Ni > Cd > Cr$. Table 5 provides the comparison of trace metal concentrations in precipitation from this study with values obtained from other rural and urban regions of the world. This order of element abundance is similar to those obtained from precipitation in Chuncheon, Suwon, Mexico, and New Castle in the USA. While Al and Fe were much higher in Ankara, the authors indicate that this is due to its location in the middle of the semi-arid Anatolia Plateau. In general, the concentrations of trace metals in Gwangju are lower than those in other countries, due to the lack of industry in the city. With respect to Al, Fe, Ni, Cd, and Cr, concentrations in this study were the lowest of all the other countries. Most of the industries in Korea are located in and near Seoul and the Gyeonggi Province, but Gwangju is a city of education, culture, universities and limited industrial activity. With respect to trace metals, values measured in Ankara, Turkey, were the highest of all of the other countries with the exception of Zn.

relation between Mg^{2+} and Cl^- ($R^2 = 0.99$) also corresponds to salts of marine origin. Relatively high correlations between NO_3^- and NH_4^+ ($R^2 = 0.86$), and between SO_4^{2-} and NH_4^+ ($R^2 = 0.82$), may reveal co-occurrence of NH_4^+ with SO_4^{2-} and NO_3^- in rainwater. This was probably due to dissolution of secondary inorganic aerosols (($NH_4)_2SO_4$ and NH_4NO_3) in rainwater (Panyakapo and Onchang, 2008). Among the compounds of ammonium, ammonium sulfate is known to predominate in the atmosphere (Seinfeld, 1986). However, our study showed slightly higher correlation between NH_4^+ and NO_3^- ($R^2 = 0.86$) than between NH_4^+ and SO_4^{2-} ($R^2 = 0.82$), indicating that NH_4NO_3 dominates over ($NH_4)_2SO_4$. The dominance of NH_4NO_3 has also been reported previously (Saxena et al., 1996). The high correlation between SO_4^{2-} and NO_3^- suggests a common source origin, due to the co-emission of precursors (SO_2 and NO_x) from the same sources, such as fossil fuel burning, and the similar-

Table 5. Comparison between the VWMC of trace metals in precipitation in Gwangju and at other locations.

| Location	Zn	Al	Fe	Mn	Pb	Cu	Ni	Cd	Cr	References
This study	18.78	12.99	11.00	4.58	3.10	1.69	0.28	0.09	0.06	
Chuncheon, Korea	9.9	13.85		3.23	1.51	1.73	0.52	0.07		Kim et al. (2012)
Suwon, Korea	13.06				9.98	6.08	0.66	0.2	0.43	Jung et al. (2007)
Mexico		50.7		9.64	2.48		3.37	0.41	0.52	Baez et al. (2007)
Ankara, Turkey	0.03	980	750		19.1	6.1	4.1	9.5	3	Kaya and Tuncel (1997)
Singapore	7.23	18.44	23.91	2.78	3.37	5.58	3.86	0.33	1.62	Hu and Balasubarmanian (2003)
Jordan	6.52	382	92	2.11	2.57	3.08	2.62	0.42	0.77	Al-Momani et al. (2003)
New Castle, NH, USA	25.5	24.4	22.8		1.31	1.33	0.85	0.24	0.14	Pike and Moran (2001)
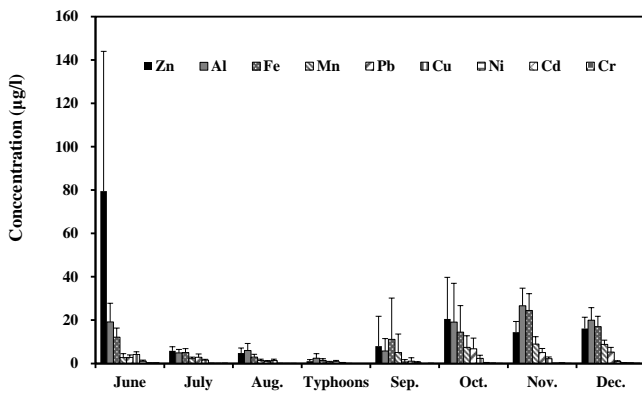
Figure 7. Monthly variation of VWMC of trace metals in rainwater samples during 2012.
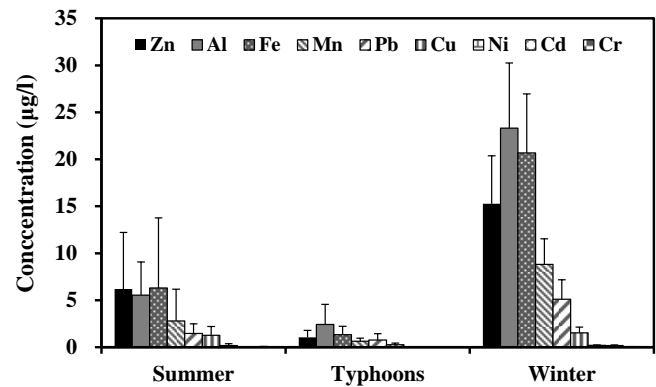

Figure 8. Mean concentration of trace metals in rainwater samples during summer (July–September), typhoons, and winter (November–December).

3.6 Variations in trace metal levels in rainwater

Monthly variations of the VWMC of trace metals in rainwater are shown in Fig. 7. As expected, the lowest concentrations of trace metals were found during typhoon periods (July–September), caused by more frequent rain events and the consequent dilution effect. The samples collected in winter had higher concentrations of trace metals than the samples in summer (Fig. 8). Similar seasonal variations have been reported in other studies (Cheng et al., 2011; Kim et al., 2012).

3.7 Correlation analysis

Table 6 lists the matrix correlation between ions and trace metals (correlation coefficients greater than 0.5 are marked in bold letters). Moderate correlation was found among the trace metals and NH_4^+, NO_3^-, and SO_4^{2-}, with the exception of Cr and Zn, suggesting the anthropogenic origin of the species. These correlations were also observed in previous studies (Garcia et al., 2006; Jung et al., 2011). Significant correlations between SO_4^{2-} and trace metals in rainwater were observed in Clarke and Radojevic (1987).

3.8 Enrichment factor analysis

An enrichment factor (EF) has been used to evaluate the contribution of non-crustal sources (Kaya and Tuncel, 1997; Kim et al., 2012). The EF values were calculated using the following relation:

$$EF = (C_X/C_{Al}\ \text{sample})/(C_X/C_{Al}\ \text{crust}),$$

where (C_X / C_{Al} sample) is the ratio of the concentration of an element X and Al in the rainwater sample and (C_X / C_{Al} crust) is the same ratio in crustal material, adapted from Wedepohl (1995).

EFs from 1 to 10 suggest crustal origin; EFs from 10 to 100 suggest moderate anthropogenic enrichment; and EFs > 100 indicate anthropogenic origin. Fig. 9 presents the bars of the EF of the trace elements. Fe and Cr with EF values of 1–10 were significantly enriched by soil. Mn and Ni with EF values in the range of 10–100 were moderately enriched by anthropogenic sources, while Zn, Pb, Cu, and Cd with EF values exceeding 100 were highly enriched by human activities. Ni and Mn are mainly emitted from manufacture of ferroalloys and from oil-fired furnaces (Báez et al., 2007). The primary sources of Zn, Pb, Cu, and Cd are industrial and traffic activities such as metal smelting and fuel combustion (Al-Momani, 2003; Cheng et al., 2011). The variation of monthly

Table 6. Correlation coefficients and P value between ions and trace metals in rainwater 1 samples from Gwangju ($n = 113$).

	Na$^+$	NH$_4^+$	K$^+$	Mg^{2+}	Ca^{2+}	NO$_3^-$	Cl$^-$	SO$_4^{2-}$
Al	0.32	**0.60**	0.44	0.36	**0.51**	**0.66**	0.33	**0.59**
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cr	0.17	0.41	0.19	0.20	0.30	0.41	0.18	0.42
	0.07	0.00	0.04	0.03	0.00	0.00	0.06	0.00
Mn	0.36	0.35	0.29	0.40	**0.52**	**0.57**	0.36	0.38
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe	0.36	**0.53**	0.39	0.41	0.49	**0.64**	0.37	**0.53**
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ni	0.02	**0.53**	0.32	0.05	0.23	0.39	0.03	0.37
	0.82	0.00	0.00	0.63	0.01	0.00	0.79	0.00
Cu	0.05	**0.67**	0.35	0.07	0.35	**0.58**	0.06	**0.58**
	0.59	0.00	0.00	0.43	0.00	0.00	0.54	0.00
Zn	0.08	0.24	0.32	0.12	0.33	0.22	0.08	0.20
	0.39	0.01	0.00	0.19	0.00	0.02	0.38	0.03
Cd	0.31	**0.59**	0.42	0.36	**0.50**	**0.61**	0.33	**0.64**
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pb	**0.50**	**0.56**	0.44	**0.54**	0.39	**0.63**	**0.51**	**0.63**
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
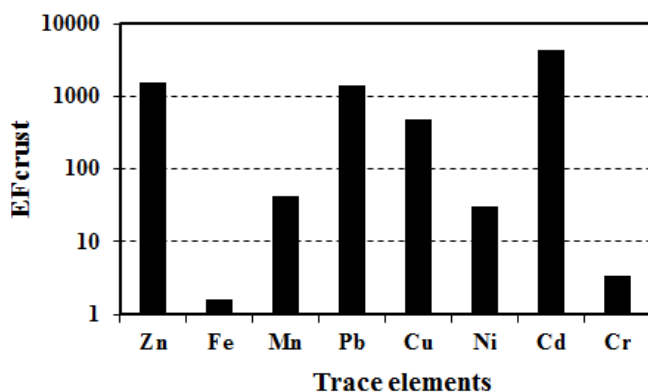
Figure 9. Average EFs of trace metals in rainwater in the Gwangju area during 2012.

Table 7. Mean values of TOC, TN, UV, SUVA, and pH and conductivity in initial ($n = 40$) and subsequent ($n = 73$) rainfall during 2012.

	Initial rainfall		Subsequent rainfall	
	Mean	SD	Mean	SD
TOC (mg C L^{-1})	2.18	1.41	1.11	0.68
TN (mg N L^{-1})	1.95	1.19	0.79	0.47
UV (cm^{-1})	0.0244	0.0135	0.0111	0.0073
SUVA	1.19	0.39	1.06	0.33
pH	5.97	0.52	5.55	0.64
Conductivity (μS cm^{-1})	38.17	25.67	25.72	19.07

SD: standard deviation.

EFs of trace metals in rainwater is depicted in Fig. 10. The monthly EFs of trace metals were relatively high during summer (from June to September). Cd and Cr were not detected during the typhoon periods or in September. The highest EF values of Fe and Mn, Pb, Cu, Cd, and Cr, and Zn and Ni were found during September, July, and June, respectively.

3.9 Comparison of chemical components in initial and subsequent rainfall

A comparison of the mean concentrations of major ions and trace metals in initial ($n = 40$) and subsequent ($n = 73$) rainfall samples is presented in Fig. 11. Greater amounts of major ions and trace metals appeared in initial rainfall samples than in subsequent samples as large amount of pollutants were dissolved in less water. Mean values of TOC, TN, UV,

SUVA, pH, and conductivity in initial ($n = 40$) and subsequent ($n = 73$) samples are shown in Table 7. Again, higher mean concentrations of TOC, TN, UV, SUVA, pH, and conductivity were observed in initial rainfall, with the values of TOC, TN, and UV in initial rainfall being twice as high as in subsequent rainfall.

3.10 Factor analysis

Factor analysis (principal component analysis) has been widely applied in previous studies to investigate the influence of different sources on the chemical components in precipitation (Báez et al., 2006; Garcia et al., 2006; Panyakapo and Onchang, 2008). A varimax-rotated principal component analysis (PCA) was performed using Minitab version 16 for Windows. Table 8 presents the result of the factor analy-
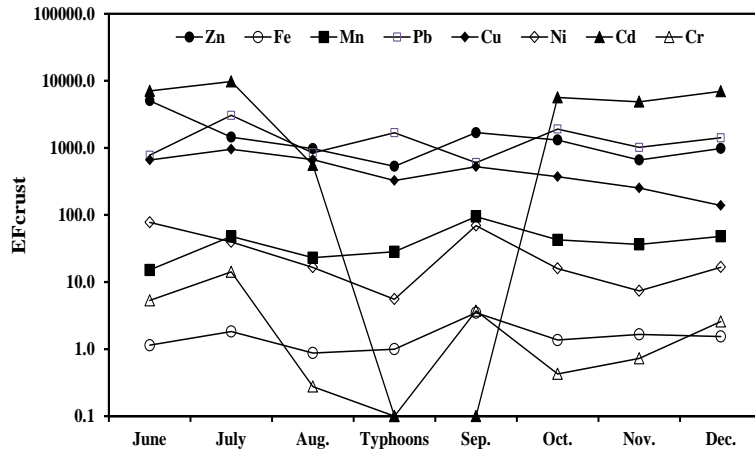
Figure 10. Monthly variation of EFs of trace metals in rainwater in the Gwangju area during 2012.
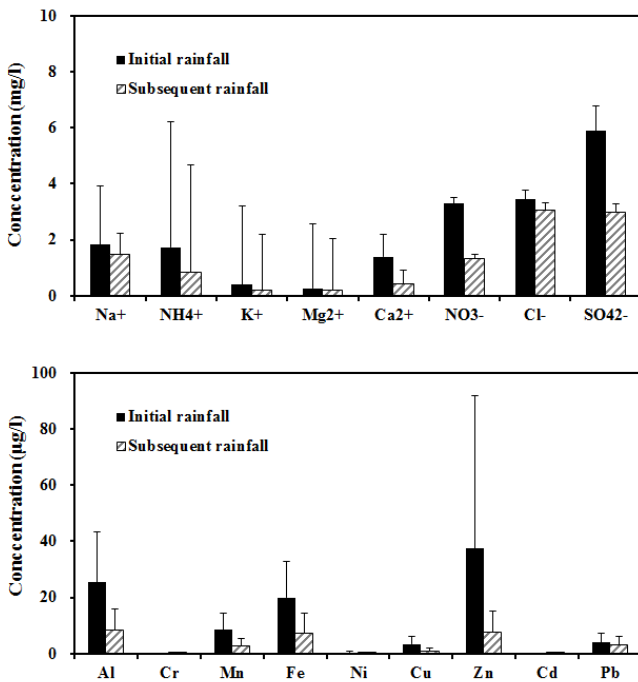

Figure 11. Comparison of mean concentration of major ions and trace metals in initial ($n = 40$) and subsequent ($n = 73$) rainfall during 2012.

Table 8. Factor analysis of chemical constituents in rainwater. Bold numbers are significant at > 0.5.

Variable	Factor 1	Factor 2	Factor 3
Na^+	0.12	**0.97**	0.10
NH_4^+	**0.88**	0.03	0.27
K^+	**0.61**	0.46	0.11
Mg^{2+}	0.15	**0.96**	0.15
Ca^{2+}	**0.67**	0.39	0.19
NO_3^-	**0.85**	0.29	0.28
Cl^-	0.11	**0.96**	0.12
SO_4^{2-}	**0.85**	0.18	0.23
Al	0.51	0.20	**0.71**
Cr	0.14	0.08	**0.79**
Fe	0.41	0.28	**0.76**
Ni	0.44	−0.18	**0.50**
Zn	0.04	0.02	**0.62**
Cd	0.47	0.24	**0.63**
Pb	0.44	0.42	**0.59**
Mn	0.36	0.35	**0.50**
Cu	**0.75**	−0.14	0.41
% total variance	28.5	22.4	22.2

sis that identified three factors that explained approximately 73.1 % of the total variance. Factor 1 explained 27.1 % of the total variance with high loadings for SO_4^{2-}, NO_3^-, and NH_4^+, and moderate loadings for K^+, Ca^{2+}, and Cu. This factor indicates marine sources for K^+ and Ca^{2+}, with an anthropogenic source for Cu, as is indicated by EF. Cu is a typical metal contaminant emitted from industrial processes (Wong et al., 2003). The loadings of SO_4^{2-}, NO_3^-, and NH_4^+ suggest that these ions come from anthropogenic sources associated with precursor gases such as SO_2 and NO_x. The co-occurrence of NH_4^+ with NO_3^- and SO_4^{2-} are caused by dissolution of aerosols and secondary pollutants containing $(NH_4)_2SO_4$ and NH_4NO_3 in rainwater. Factor 2 accounted for 22.4 % of the total variance with high loading for Na^+, Mg^{2+}, and Cl^-, indicating the influence of sea spray. Factor 3, which explained 22.2 % of the total variance, proposed moderate loadings of most of the trace metals. This factor indicates the contribution of anthropogenic sources and significant crustal contributions for Al, Cr, and Fe, as indicated by EF. Overall, the anthropogenic pollutants, sea salts, and crustal materials were the main sources of the chemical species in rainwater in Gwangju.

Table 9. Dominant pyrolysis fragments for rainwater samples as identified by Py-GC/MS.

Ranking	2 June	8 June	18 June	19 June	29 June	30 June	12 July	18 July (Typhoon Khanun)	6 Aug.	10–15 Aug.
1	Benzoic acid, 2,4-dichloro-(PHA)	Benzoic acid, 2,6-dichloro-(PHA)	Benzoic acid, 2,6-dichloro-(PHA)	Benzoic acid, 2,6-dichloro-(PHA)	Benzoic acid, 2,6-dichloro-(PHA)	Benzoic acid, 2,6-dichloro-(PHA)	Acetic acid (PS,AS)	Acetamide, 2-fluoro-(PS,AS)	1H-Isoindole-1,3(2H)-dione (Pr)	1H-Isoindole-1,3(2H)-dione (Pr)
2	1H-Isoindole-1,3(2H)-dione (Pr)	Benzoic acid, 4-chloro-(PHA)	Acetic acid (PS,AS)	Benzoic acid, 4-chloro-(PHA)	Acetic acid (PS,AS)	Phthalic anhydride (PHA)	1H-Isoindole-1,3(2H)-dione (Pr)	1,3-Benzenedicarbonitrile (Pr,PHA)	Phthalic anhydride (PHA)	Phthalic anhydride (PHA)
3	2,5-Pyrrolidinedione (Pr)	2,4-Dichlorobenzamide (PHA)	Benzenecarboxylic acid (PHA)	2,4-Dichlorobenzamide (PHA)	Benzoic acid, 4-chloro-(PHA)	1H-Isoindole-1,3(2H)-dione (Pr)	Furan, 2-methyl-(PS)	1H-Isoindole-1,3(2H)-dione (Pr)	Furan, 2-methyl-(PS)	Furan, 3-methyl-(PS)
4	Benzenecarboxylic acid (PHA)	Benzenecarboxylic acid (PHA)	Benzonitrile (Pr)	Benzene, 1,4-dichloro-(PHA)	Benzonitrile (Pr)	Acetic acid (PS,AS)	Benzonitrile (Pr)	1,2-Benzenedicarboxylic acid (PHA)	2,3-Butanedione (PS)	Acetonitrile, dichloro-(Pr)
5	Benzene, 1,4-dichloro-(PHA)	Benzonitrile (Pr)	Benzene (PHA)	Benzene, 1,4-dichloro-(PHA)	Benzene (PHA)	Benzoic acid, 2-chloro-(PHA)	Phthalic anhydride (PHA)	Benzene (PHA)	Benzenecarboxylic acid (PHA)	Benzoic acid, 2-chloro-(PHA)
6	Benzoic acid, 4-chloro-(PHA)	Benzene, 1,4-dichloro-(PHA)	Benzoic acid, 4-chloro-(PHA)	1H-Isoindole-1,3(2H)-dione (Pr)	1H-Isoindole-1,3(2H)-dione (Pr)	Dodecanoic acid (Lp)	2(5H)-Furanone, 3,5,5-trimethyl-(PS)	Benzene (PHA)	Benzonitrile (Pr)	
7	Acetamide (PS,AS)	2,5-Pyrrolidinedione (Pr)	n-Hexadecanoic acid (Lp)	Benzenecarboxylic acid (PHA)	Benzenecarboxylic acid (PHA)	Furan, 2-methyl-(Pr)	n-Hexadecanoic acid (Lp)	Acetic acid (PS,AS)		
8	Benzonitrile (Pr)	n-Hexadecanoic acid (Lp)	1H-Isoindole-1,3(2H)-dione (Pr)	Benzoic acid, 2,4-dichloro-(PHA)	Phthalic anhydride (PHA)	2,5-Pyrrolidinedione (PR)	1,2-Benzenedicarbonitrile (Pr, PHA)	1,2-Benzenedicarbonitrile (Pr, PHA)		
9	Phenol (PR,PHA)	1,4-Benzenedicarbonitrile (Pr,PHA)	2,5-Pyrrolidinedione (Pr)	Benzonitrile (Pr)	2,5-Pyrrolidinedione (Pr)	Benzene, 1-chloro-2-ethoxy-(PHA)	Furan, 2-methyl-(PS)			
10	2(5H)-Furanone, 3,5,5-trimethyl-(PS)	Octadecanoic acid (Lp)	Acetamide (PS,AS)	1,2-Benzenedicarbonitrile (Pr, PHA)	Furan, 2-methyl-(PS)	Tetradecanoic acid (Lp)	Formic acid, ethenyl ester (Lp)			

Ranking	23–24 Aug.	27–28 Aug. (Typhoon Bolaven)	30 Aug. (Typhoon Tenbin)	12 Sep.	22 Oct.	5–11 Nov.	13–26 Nov.	12 Dec.
1	1H-Isoindole-1,3(2H)-dione (PR)	Benzene (PHA)	Acetic acid (PS, AS)	Acetic acid (PS, AS)	1,2-Benzenedicarboxylic acid (PHA)	Benzonitrile (Pr)	Benzonitrile (Pr)	Acetaldehyde (PS)
2	Phthalic anhydride (PHA)	Acetic acid (PS, AS)	Phthalic anhydride (PHA)	o-Cyanobenzoic acid (PHA)	1H-Isoindole-1,3(2H)-dione (Pr)	Acetic acid (PS, AS)	Phthalic anhydride (PHA)	Acetaldehyde (PS)
3	Benzoic acid, 4-(1-methylethyl)-(PHA)	Phenol (Pr,PHA)	Benzonitrile (Pr)	1,2-Benzenedicarboxylic acid (PHA)	1,2-Benzenedicarboxylic acid (PHA)	1,2-Benzenedicarboxylic acid (PHA)	Benzonitrile, 4-[2-(methylsulfonyl)ethenyl]-(Pr)	1H-Isoindole-1,3(2H)-dione (Pr)
4	Acetic acid (PS, AS)	Benzene (PHA)	Benzene (PHA)	Benzonitrile (Pr)		Benzene (PHA)		
5	Benzoic acid, 4-chloro-(PHA)	Styrene (Pr)	2-Pentenoic acid, 4-methyl-(Pr)	Benzene (PHA)				
6	Benzoic acid, 4-methyl-(PHA)	α-D-Glucopyranose, 4-O-β-D-galactopyranosyl-(PS)	Styrene (Pr)				Furan, 2,5-dimethyl-(PS)	
7	Benzonitrile (Pr)	2,5-Pyrrolidinedione (Pr)	Pyridine (Pr)					
8	Benzenecarboxylic acid (PHA)	1H-Isoindole-1,3(2H)-dione (Pr)	Benzenecarboxylic acid (PHA)				Benzenecarboxylic acid (PHA)	
9	Furan, 2-methyl-(PS)	2H-Pyran, 3,4-dihydro-4-methyl-(PS)	Benzene, 1-methyl-4-(1-methylethenyl)-(PHA)				1,2-Benzenedicarbonitrile (Pr, PHA)	
10	Benzoic acid, 4-(1-methylethyl)-(PHA)	2-Dodecenal, (E)-(Lp)	Benzaldehyde (Lg)					

Pr: protein; PS: polysaccharides; PHA: polyhydroxy aromatics; AS: amino sugars; Lg: lignins; Lp: lipids.

3.11　Organic compounds in rainwater

Table 9 lists dominant pyrolysis fragments for rainwater organic compounds collected from June to December 2012 as identified by Py-GC/MS based on peak area percent of pyrochromatograms. Each sample could be fractionated and categorized into polysaccharides (PS), amino sugars (AS), proteins (PR), polyhydroxy aromatics (PHA), lignins (LG), and lipids (Lp) (Leenher and Croue, 2003). Benzoic acids were the most abundant compound during June, which originates from anthropogenic sources such as fossil fuel combustion. Kawamura et al. (1986) identified benzoic acids in used engine oil and motor exhaust. Benzoic acids have been found in rainfall in Los Angeles and Norway (Lunde et al., 1977; Kawamura and Kaplan, 1983). 2-Fluoro-acetamide and acetic acids were the most abundant compounds in July and September. Acetamide was one of the major pyrolysis organic compounds with precipitation in Königstein, Germany (Laniewski et al., 1998), which is a source of plasticizer and industrial solvents and normally found near industrial areas (Cho and Shin, 2013). Acetic acids originate from primary natural sources such as emissions from microbial activity and vegetation and from anthropogenic sources (biomass burning and traffic exhaust) (Avery et al., 1991). It has been found in rainwaters from both developed and remote areas (Galloway et al., 1982; Keene and Galloway, 1984). 1H-Isoindole-1,3(2H)-dione, phthalic anhydride, benzene, and acetic acids were the most abundant species during August. 1H-Isoindole-1,3(2H)-dione was one of the major pyrolysis organic compounds from precipitation in Königstein, Germany (Laniewski et al., 1998), and was found to be from tire-derived aggregates. Phthalic anhydride originates from agricultural crop burning and open burning of scrap tires (Lemieux et al., 2004). Benzene is an important aromatic compound from gasoline, automobile exhaust, and the urban atmosphere (Sigsby et al., 1987). Benzene was generally found as the major compound of volatile organic carbons in rainwater from Yokohama, Japan (Sato et al., 2006). 1,2-Benzenedicarboxylic acids were the most abundant compound in October and have been identified to come from particulate automobile exhaust emissions, cigarette combustion, degradation of plastics, and products of lignin-type material metabolized by microorganisms (Johnstone and Plimmer, 1959; Simoneit, 1985; Kawamura and Kaplan, 1987). Benzonitrile was the most abundant species during November, which has been found in accidental vehicle fires (Estrellan and Lino, 2010) and biomass combustion in improved stoves in rural China (Wang et al., 2009). Acetaldehyde was the most abundant compound in December, probably derived from primary incomplete combustion of fossil fuels and secondary photochemical reactions of hydrocarbons emitted from anthropogenic sources (Sakugawa et al., 1993). Acetaldehyde was also detected in Los Angeles (Kawamura et al., 2001) and Spain (Peña et al., 2002). Among fatty acids, n-hexadecanoic acid (C_{16}), octadecanoic acid (C_{18}),

and tetradecanoic acid (C_{14}) were found in the top 10 organic compounds during June and July. This is in agreement with previous work (Kawamura and Kaplan, 1986), where lower molecular fatty acids (C_{12}–C_{19}) are major compounds while higher molecular weight fatty acids (C_{20}–C_{30}) are minor. A major source of fatty acids ($C < 20$) is known to come from cooking and biomass combustion in urban areas (Rogge et al., 1991; Xu et al., 2008). All results in the present study indicate that anthropogenic sources were significant contributors to the organic compounds present in rainwater.

4　Conclusions

Rainwater samples collected from Gwangju, Korea, during June–December 2012 were analyzed to determine the chemical composition and organic compounds present in rainwater. Even though our study period was quite short compared to other studies, we tried to present a valuable data analysis of the chemical composition and organic compounds in rainwater between summer and winter, as there are two distinct seasons with rain in Korea. The VWM of pH was 5.78 (ranging from 3.83 to 8.90) and acid rain (pH < 5.6) frequency was 50 %. The VWMC of major ions and trace metals followed the order $Cl^- > SO_4^{2-} > NH_4^+ > Na^+ > NO_3^- > Ca^{2+} > Mg^{2+} > K^+$ and $Zn > Al > Fe > Mn > Pb > Cu > Ni > Cd > Cr$. The higher VWM values of TOC, TN, UV, SUVA, pH, conductivity, major ions, and trace metals appeared in the initial rainfall events rather than in subsequent rainfall events. The VWMCs of major ions and trace metals were relatively lower in summer due to the dilution effect. The lowest VWMCs of ions (except for Na^+ and Cl^-) and trace metals were observed during typhoons. Based on EF values, Zn, Pb, Cu, Ni, Cd, and Mn were emitted mainly from anthropogenic sources whereas Fe and Cr originated from crustal sources. The factor analysis (principal component analysis) revealed that the anthropogenic pollutants, sea salts, and crustal materials were the main sources of ionic species and trace metals in rainwaters. The most abundant pyrolysis fragments for rainwater organic compounds were benzoic acids, 1H-isoindole-1,3(2H)-dione, phthalic anhydride, benzene, acetic acids, 1,2-benzenedicarboxylic acids, benzonitrile, acetaldehyde, and acetamide, indicating that anthropogenic pollutants are significant contributors to rainwater organic compounds.

References

Al-Momani, I. F.: Trace elements in atmospheric precipitation at Northern Jordan measured by ICP-MS: acidity and possible sources, Atmos. Environ., 37, 4507–4515, 2003.

Avery Jr., G. B., Willey, J. D., and Wilson, C. A.: Formic and acetic acids in coastal North Carolina rainwater, Environ. Sci. Technol., 25, 1875–1880, 1991.

Báez, A. P., Belmont, R. D., García, R. M., Torres, M. C. B., and Padilla, H. G.: Rainwater chemical composition at two sites in Central Mexico, Atmos. Res., 80, 67–85, 2006.

Báez, A. P., Belmont, R. D., García, R. M., Padilla, H. G., and Torres, M. C. B.: Chemical composition of rainwater collected at a southwest site of Mexico City, Mexico, Atmos. Res., 86, 61–75, 2007.

Bard, S. M.: Global transport of anthropogenic contaminants and the consequences for the arctic marine ecosystem, Mar. Pollut. Bull., 38, 356–379, 1999.

Barrie, L. A., Lindberg, S. E., Chan, W. H., Ross, H. B., Arimoto, R., and Church, T. M.: On the concentration of trace metals in precipitation, Atmos. Environ., 21, 1133–1135, 1987.

Başak, B. and Alagha, O.: The chemical composition of rainwater over Büyükçekmece Lake, Istanbul, Atmos. Res, 71, 275–288, 2004.

Bruchet, A., Rousseau, C., and Mallevialle, J.: Pyrolysis-GC/MS for investigating high-molecular weight THM precursors and other refractory organics, J. Am. Water Works Ass., 82, 66–74, 1990.

Cerón, R., Cerón, J., Carballo, C., Aguilar, C., Montalvo, C., Benítez, J., Villareal, Y., and Gómez, M.: Chemical composition, fluxes and seasonal variation of acid deposition in Carmen Island, Campeche, Mexico, J. Environ. Prot., 4, 50–56, 2013.

Charlson, R. J. and Rodhe, H.: Factors controlling the acidity of natural rainwater, Nature, 295, 683–685, 1982.

Cheng, M. C., You, C. F., Lin, F. J., Huang, K. F., and Chung, C. H.: Sources of Cu, Zn, Cd and Pb in rainwater at a subtropical islet offshore northern Taiwan, Atmos. Environ., 45, 1919–1928, 2011.

Cho, Y. H. and Shin, H. S.: Determination of trace levels of acetamide, propanamide, and butyramide in surface and drinking water using gas chromatography–mass spectrometry after derivatization with 9-xanthydrol, Anal. Chim. Acta, 787, 111–117, 2013.

Clarke, A. G. and Radojevic, M.: Oxidation of SO₂ in rainwater and its role in acid rain chemistry, Atmos. Environ., 21, 1115–1123, 1987.

Dianwu, Z. and Anpu, W.: Estimation of anthropogenic ammonia emissions in Asia, Atmos. Environ, 28, 689–694, 1994.

Estrellan, C. R. and Iino, F.: Toxic emissions from open burning, Chemosphere, 80, 193–207, 2010.

Galloway, J. N., Likens, G. E., Keene, W. C., and Miller, J. M.: The composition of precipitation in remote areas of the world, J. Geophys. Res.-Oceans (1978–2012), 87, 8771–8786, 1982.

Garcia, R., del Torres Ma, C., Padilla, H., Belmont, R., Azpra, E., Arcega-Cabrera, F., and Báez, A.: Measurement of chemical elements in rain from Rancho Viejo, a rural wooded area in the State of Mexico, Mexico, Atmos. Environ., 40, 6088–6100, 2006.

Hu, G. P. and Balasubramanian, R.: Wet deposition of trace metals in Singapore, Water Air Soil Pollut., 144, 285–300, 2003.

Huang, K., Zhuang, G., Xu, C., Wang, Y., and Tang, A.: The chemistry of the severe acidic precipitation in Shanghai, China, Atmos. Res, 89, 149–160, 2008.

Johnstone, R. A. W. and Plimmer, J. R.: The Chemical Constituents of Tobacco and Tobacco Smoke, Chem. Rev., 59, 885–936, 1959.

Jung, G. B., Kim, M. K., Lee, J. S., Kim, W. I., Kim, G. Y., and Ko, B. G.: Wet Deposition of Heavy Metals during Farming Season in Taean, Korea, Korean J. Environ. Agric., 30,153–159, 2011.

Kang, G. G., Collett, J. L., Shin, D. Y., Fujita, S. I., and Kim, H. K.: Comparison of the chemical composition of precipitation on the western and eastern coasts of Korea, Water Air Soil Pollut., 151, 11–34, 2004.

Kawamura, K. and Kaplan, I. R., Organic compounds in the rainwater of Los Angeles, Environ. Sci. Technol., 17, 497–501, 1983.

Kawamura, K. and Kaplan, I. R.: Biogenic and anthropogenic organic compounds in rain and snow samples collected in southern California, Atmos. Environ. (1967), 20, 115–124, 1986.

Kawamura, K. and Kaplan, I. R.: Motor exhaust emissions as a primary source for dicarboxylic acids in Los Angeles ambient air, Environ. Sci. Technol., 21, 105–110, 1987.

Kawamura, K., Steinberg, S., Ng, L., and Kaplan, I. R.: Wet deposition of low molecular weight mono-and di-carboxylic acids, aldehydes and inorganic species in Los Angeles, Atmos. Environ., 35, 3917–3926, 2001.

Kaya, G. and Tuncel, G.: Trace element and major ion composition of wet and dry deposition in Ankara, Turkey, Atmos. Environ., 31, 3985–3998, 1997.

Keene, W. C. and Galloway, J. N.: Organic acidity in precipitation of North America, Atmos. Environ. (1967), 18, 2491–2497, 1984.

Kieber, R. J., Peake, B., Willey, J. D., and Avery, G. B.: Dissolved organic carbon and organic acids in coastal New Zealand rainwater, Atmos. Environ., 36, 3557–3563, 2002.

Kim, J. E., Han, Y. J., Kim, P. R., and Holsen, T. M.: Factors influencing atmospheric wet deposition of trace elements in rural Korea, Atmos. Res., 116, 185–194, 2012.

Klouda, G. A, Lewis, C. W., Rasmussen, R. A., Rhoderik, G. C, Sams, R. L., Stevens, R. K., Currie, L. A., Donahue, D. J., Jull, A. J. T., and Seila, R. L.: Radiocarbon measurements of atmospheric volatile organic compound: quantifying the biogenic contribution, Environ. Sci. Technol., 30, 1098–1105, 1996.

Laniewski, K., Borén, H., Grimvall, A., and Ekelund, M.: Pyrolysis–gas chromatography of chloroorganic compounds in precipitation, J. Chromatogr. A, 826, 201–210, 1998.

Lara, L. B. L. S., Artaxo, P., Martinelli, L. A., Victoria, R. L., Camargo, P. B., Krusche, A., and Ballester, M. V.: Chemical composition of rainwater and anthropogenic influences in the Piracicaba River Basin, Southeast Brazil, Atmos. Environ., 35, 4937–4945, 2001.

Lee, B. K., Hong, S. H., and Lee, D. S.: Chemical composition of precipitation and wet deposition of major ions on the Korean peninsula, Atmos. Environ., 34, 563–575, 2000.

Leenher, J. A. and Croue, J. P.: Characterizing aquatic dissolved organic matter, Environ. Sci. Technol., 37, 18–26, 2003.

Lemieux, P. M., Lutes, C. C., and Santoianni, D. A.: Emissions of organic air toxics from open burning: a comprehensive review, Prog. Energ. Combust., 30, 1–32, 2004.

Lunde, G., Gether, J., Gjùs, N., and Stùbet Lande, M. B.: Organic micropollutants in precipitation in Norway, Atmos. Environ., 11, 1007–1014, 1977.

Moon, S. H., Lee, J. Y., Lee, B. J., Park, K. H., and Jo, Y. J.: Quality of harvested rainwater in artificial recharge site on Jeju volcanic island, Korea, J. Hydrol., 414, 268–277, 2012.

Mouli, P., Mohan, S., and Reddy, S.: Rainwater chemistry at a regional representative urban site: influence of terrestrial sources on ionic composition, Atmos. Environ., 39, 999–1008, 2005.

Muller, C. L., Baker, A., Hutchinson, R., Fairchild, I. J., and Kidd, C.: Analysis of rainwater dissolved organic carbon compounds using fluorescence spectrophotometry, Atmos. Environ., 42, 8036–8045, 2008.

Pan, Y., Wang, Y., Xin, J., Tang, G., Song, T., Wang, Y. H., Li, X. R., Wu, F. K.: Study on dissolved organic carbon in precipitation in Northern China, Atmos. Environ., 44, 2350–2357, 2010.

Panyakapo, M. and Onchang, R.: A four-year investigation on wet deposition in western Thailand, J. Environ. Sci. (China), 20, 441–448, 2008.

Peña, R. M., García, S., Herrero, C., Losada, M., Vázquez, A., and Lucas, T.: Organic acids and aldehydes in rainwater in a northwest region of Spain, Atmos. Environ., 36, 5277–5288, 2002.

Pike, S. M. and Moran, S. B.: Trace elements in aerosol and precipitation at New Castle, NH, USA, Atmos. Environ., 35, 3361–3366, 2001.

Rogge, W. F., Hildemann, L. M., Mazurek, M. A., Cass, G. R., and Simoneit, B. R. T.: Sources of fine organic aerosol: 1. Charbroilers and meat cooking operations, Environ. Sci. Technol., 25, 1112–1125, 1991.

Sakugawa, H., Kaplan, R., and Shepard, L.: Measurements of H_2O_2, aldehydes and organic acids in Los Angeles rainwater: their sources and deposition rates, Atmos. Environ. B, 27, 203–219, 1993.

Santos, P. S., Otero, M., Duarte, R. M., and Duarte, A. C.: Spectroscopic characterization of dissolved organic matter isolated from rainwater, Chemosphere, 74, 1053–1061, 2009.

Santos, P. S, Otero, M., Santos, E. B., and Duarte, A. C.: Chemical composition of rainwater at a coastal town on the southwest of Europe: What changes in 20 years?, Sci. Total. Environ, 409, 3548–3553, 2011.

Sato, E., Matsumoto, K., Okochi, H., and Igawa, M.: Scavenging effect of precipitation on volatile organic compounds in ambient atmosphere, Bull. Chem. Soc. Jpn., 79, 1231–1233, 2006.

Saxena, A., Kulshrestha, U. C., Kumar, N., Kumari, K. M., and Srivastava, S. S.: Characterization of precipitation at Agra, Atmos. Environ., 30, 3405–3412, 1996.

Seinfeld, J. H.: Atmospheric Chemistry and Physics of Air Pollution, Wiley, New York, 1986.

Seitzinger, S. P., Styles, R. M., Lauck, R., and Mazurek, M. A.: Atmospheric pressure mass spectrometry: a new analytical chemical characterization method for dissolved organic matter in rainwater, Environ. Sci. Technol., 37, 131–137, 2003.

Sigsby, J. E., Tejada, S., Ray, W., Lang, J. M., and Duncan, J. W.: Volatile organic compound emissions from 46 in-use passenger cars, Environ. Sci. Technol., 21, 466–475, 1987.

Simoneit, B. R. T.: Application of Molecular Marker Analysis to Vehicular Exhaust for Source Reconciliations, Int. J. Environ. Anal. Chem., 22, 203–233, 1985.

Wang, S., Wei, W., Du, L., Li, G., and Hao, J.: Characteristics of gaseous pollutants from biofuel-stoves in rural China, Atmos. Environ., 43, 4148–4154, 2009.

Wedepohl, H. K.: The composition of the continental crust, Geochim. Cosmochim. Acta, 59, 1217–1232, 1995.

Willey, J. D., Kieber, R. J., Eyman, M. S., and Avery Jr., G. B.: Rainwater dissolved organic carbon: concentrations and global flux, Global Biogeochem. Cy., 14, 139–148, 2000.

Wong, C. S. C., Li, X. D., Zhang, G., Qi, S. H., and Peng, X. Z.: Atmospheric depositions of heavy metals in the Pearl River Delta, China, Atmos. Environ., 37, 767–776, 2003.

Xu, T., Song, Z., Liu, J., Wang, C., Wei, J., and Chen, H.: Organic composition in the dry season rainwater of Guangzhou, China, Environ. Geochem. Health, 30, 53–65, 2008.

Yan, G. and Kim, G.: Dissolved organic carbon in the precipitation of Seoul, Korea: Implications for global wet depositional flux of fossil-fuel derived organic carbon, Atmos. Environ., 59, 117–124, 2012.

Zhao, M., Li, L., Liu, Z., Chen, B., Huang, J., Cai, J., and Deng, S.: Chemical Composition and Sources of Rainwater Collected at a Semi-Rural Site in Ya'an, Southwestern China, Atmos. Clim. Sci., 3, 486–496, 2013.