# National Assessment on Acid Deposition in Korea

National Institute of Environmental Research

## 1.1 Basic Information on National Monitoring Activities

### 1.1.1 Outline of the activities on acid deposition and National Monitoring Plan

Korean government has taken comprehensive measures to reduce air pollutant emissions for the last six decades or so as it recognized the seriousness of air pollution caused by industrialization since the 1960's. That is why the country initiated a national air monitoring program in the middle of the 1970's. Then, photochemical assessment stations and hazardous air monitoring stations were added to the network in early 2000. In addition, atmospheric monitoring stations according to atmospheric characteristics have been added sequentially. As of 2025, there are 531 urban sites, 27 rural sites, 46 remote sites, 62 traffic sites under the national monitoring network and 43 monitoring sites for acid deposition shows that Korea is deeply aware of its importance.

Adverse effects of long range transport of air pollutants have a long history in Korea. Since its first record over six hundred years ago, the occurrence of Asian dusts and its harmful effects have been constantly reported. More importantly, North East Asia, one of the most populated regions in the world, has been experiencing extensive industrialization for the last half century and, consequently, a long range transport of air pollutants became a great public concern along with natural air pollutants and Asian dusts. As a result, rural sites and remote sites were established to evaluate the effect of long range transport on the air quality with the implementation of the acid deposition monitoring network.

Recognizing that international collaboration is required to effectively cope with trans-boundary air pollutants, Korea has actively promoted to and, if allowed, participated in regional endeavors such as NEASPEC (North East Asian Sub-regional Program of Environmental Cooperation), EANET (Acid Monitoring Network in East Asia), NOWAP (Northwest Pacific Action Plan), ACE-ASIA (Asian Pacific Regional Aerosol Characterization Experiment), KORUS-AQ(Korea-United States Air Quality study), and Asia-AQ(Airborne and Satellite Investigation of Asian Air Quality). Each of these has its own objectives and methods in addressing long range transport of air pollutants and other regional air quality problems.

EANET has become a leading acid deposition monitoring network in East Asia region since it was launched in 2001. As a founding member of EANET, Korea has been actively involved in various efforts of EANET; preparation of technical manuals; participation of QA/QC program; and regular monitoring of wet deposition, dry deposition, soil and vegetation. Monitoring data has been submitted to Network Center of EANET helping and used as the scientific information for the evaluation of both acid depositions and its impacts on ecosystems in East Asia. This year's national report covers characteristics of monitoring stations for EANET as well as preliminary analysis of monitoring data from 2000 to 2025.

### 1.1.2 Monitoring Stations

Korea selected Ganghwa, Imsil, and Jeju as the acid deposition monitoring sites for EANET. Ganghwa and Imsil were classified into "rural site", and Jeju, "remote site" according to the Technical Manual of EANET as summarized in Table 1.1.1. The locations and pictures of the stations are shown in Figure 1.1.1 and Figure 1.1.2, respectively. Ganghwa and Imsil sites are located near the coast to minimize anthropogenic emissions. Meanwhile, Jeju island site is located near the seaside, which is subjected to soil and vegetation monitoring.

With the exception for those measured by automatic instruments, as noted in Table 1.1.2, $NO_X$, $SO_2$, $O_3$ and $PM_{10}$ mass were monitored using air monitoring devices, and $PM_{2.5}$ compositions and the gaseous species, with filter pack. Together with chemical species, meteorological parameters such as wind speed, wind direction, air temperature, relative humidity, and solar radiation were observed at automatic weather stations in each site or nearby meteorological observatories.

**Table 1.1.1 The characteristics and location of monitoring sites in Korea**

| Name of sites | Site classification | Latitude | Longitude | Height above the sea level |
|---|---|---|---|---|
| Ganghwa | Rural | 37° 70' N | 126° 28' N | 102 m |
| Imsil | Rural | 35° 61' N | 127° 18' N | 50 m |
| Jeju | Remote | 33° 29' N | 126° 16' N | 67 m |

**Table 1.1.2 The selected monitoring parameters and methods in Korea**

| Name of sites | Wet dep. | Dry dep. | | | |
|---|---|---|---|---|---|
| | | Automatic | | | Filter pack |
| | | $SO_2$, $NO_2$ | $O_3$ | PM | |
| Ganghwa | O | O | O | O | O |
| Imsil | O | O | O | O | O |
| Jeju | O | O | O | O | O |

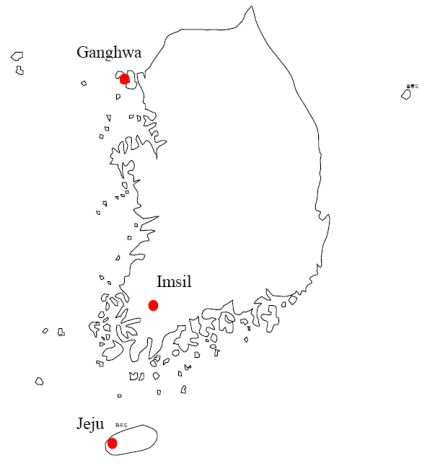



**Figure 1.1.1. The geographical Location of EANET sites in Korea.**

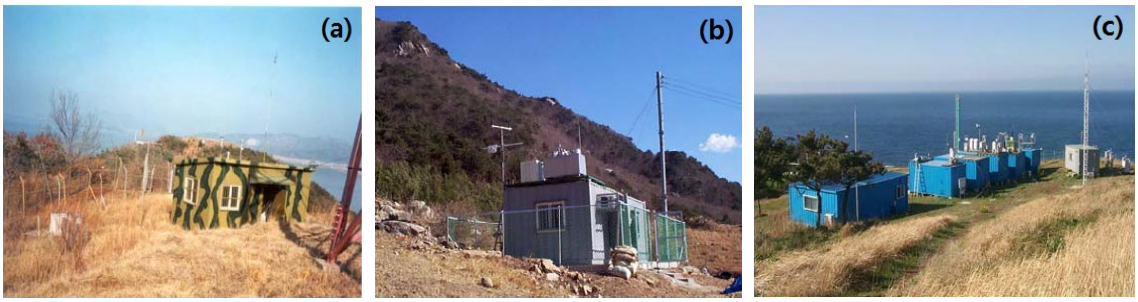



**Figure 1.1.2. Pictures of monitoring sites in Korea ((a) Ganghwa, (b) Imsil, (c) Jeju).**

### 1.1.3 Sampling and Measurements

#### 1.1.3.1 Wet Deposition Monitoring

Acid deposition monitoring in Korea has been carried out according to the common methodologies specified in the "Technical Documents for Wet deposition Monitoring in East Asia" (hereafter denoted as Manual) in order to obtain the equivalent quality of monitoring data. Figure 1.1.3 shows wet-only samplers used for monitoring work. Precipitation samples were collected on a daily basis at 3 sites as listed in Table 1.1.3. Collected samples without biocides were shipped to laboratories and stored in a cooling box to preserve the sample composition. Rainwater major constituent were analyzed in line with the Manual as shown in Table 1.1.4. Ion Chromatography is a major analytical method for chemical analysis of anions and cations. All the data were checked using ion balance and conductivity agreement by calculating ion balance (R1) and conductivity agreement (R2). If a sample or individual datum has problems including "insufficient sample volume" or "low precision", the flags corresponding to the problems were attached to the data, following "Quality Assurance/Quality Control (QA/QC) Problem for Wet Deposition Monitoring in East Asia" (2000).




**Figure 1.1.3. Wet deposition monitoring samplers.**

**Table 1.1.3 Sampling method for wet deposition monitoring in Korea**

| Name of sites | Site | Sampling frequency | Starting month |
|---|---|---|---|
| Ganghwa | Rural | Daily | March '99 |
| Imsil | Rural | Daily | April '99 |
| Jeju | Remote | Daily | January '99 |

**Table 1.1.4 Sampling method for wet deposition monitoring in Korea**

| Name of sites | Site classification | Anion analysis | Cation analysis |
|---|---|---|---|
| Ganghwa | Rural | IC | IC |
| Imsil | Rural | IC | IC |
| Jeju | Remote | IC | IC |

(Note) IC: *Ion Chromatography*

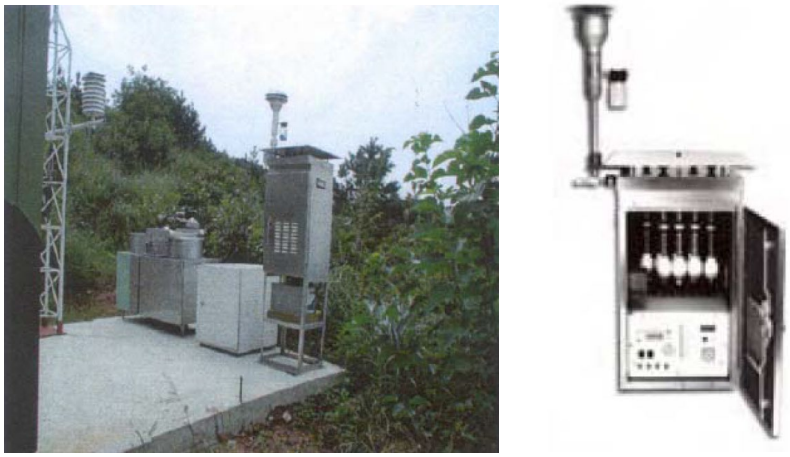
### 1.1.3.2 Dry Deposition Monitoring

$SO_2$, $NO_2$, $O_3$ - based-on the priority of the chemical species - and $PM_{10}$ mass were monitored by automatic instruments as directed by "QA/QC Program for the Air Concentration Monitoring in East Asia (2001)" as noted in Table 1.1.5. Three-stage $PM_{2.5}$ filter pack sampler, shown in Figure 1.1.4, was used to monitor gaseous acids and bases, $HNO_3$, HCl, $NH_3$, and particulate components ($SO_4^{2-}$, $NO_3^-$, $Cl^-$, $Na^+$, $K^+$, $NH_4^+$, $Ca^{2+}$ and $Mg^{2+}$).

**Table 1.1.5 Sampling method and parameter for dry deposition monitoring**

| Name of sites | Characteristics of site | Method | Parameter |
|---|---|---|---|
| Ganghwa | Rural | AT | $SO_2$, $NO_2$, $O_3$, $PM_{10}$ |
| | | FP | PMC in $PM_{2.5}$ |
| Imsil | Rural | AT | $SO_2$, $NO_2$, $O_3$, $PM_{10}$ |
| | | FP | PMC in $PM_{2.5}$ |
| Jeju | Remote | AT | $SO_2$, $NO_2$, $O_3$, $PM_{10}$ |
| | | FP | PMC in $PM_{2.5}$ |

(Note) AT: Automatic monitor, FP: Filter pack, PMC: Particulate matter components



URG (3 state $PM_{2.5}$ Sequential Sampler, USA)

**Figure 1.1.4. Instruments used for dry deposition monitoring.**

## 1.2 State of Acid Deposition in the Korea

### 1.2.1 State of wet deposition

The reliability of data was assessed based on the consistency between the measured electrical conductivity of precipitation and calculated one. If the balance of between cation and anion is not

good, it means that there are errors in sampling or conducting chemical analysis or that there is one or more missed compositions in the precipitation. As presented in Figure 1.2.1., both regression and correlation analysis showed that the slope of the regression line is 0.99, the coefficient of determination is 0.98, and the balance between cation and anion was relatively good.

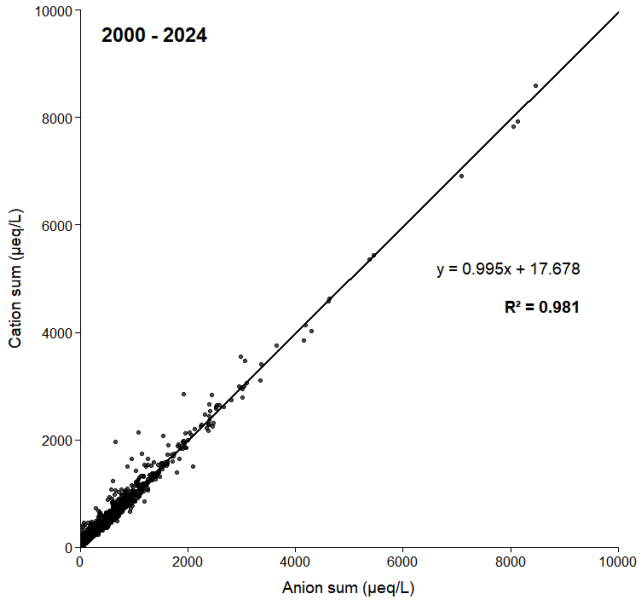



**Figure 1.2.1. Relationship between total cation and anion in precipitation.**

The EC of weak solution can be calculated using the equivalent conductance, and the result should be consistent with the EC value of samples, which can be calculated using the following equation.

ECcalc ($\mu S.cm^{-1}$) =

$\{349.7\times10^{(6-pH)} + 80.0\times2[SO_4^{2-}] + 71.5[NO_3^-] + 76.3[Cl^-] + 73.5[NH_4^+] + 50.1[Na^+] + 73.5[K^+]$

$+ 59.8\times2[Ca^{2+}] + 53.3\times2[Mg^{2+}] \} / 1000$

According to regression and correlation analyses of calculated conductivity and measured conductivity, as presented in Figure 1.2.2., the slope of the regression line is 0.89 and the coefficient of determination is 0.84.

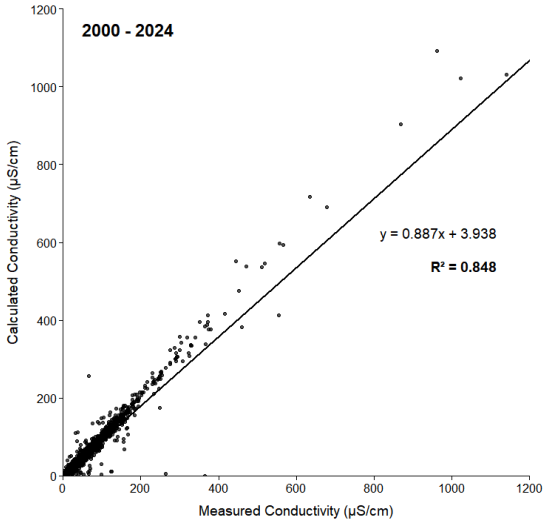
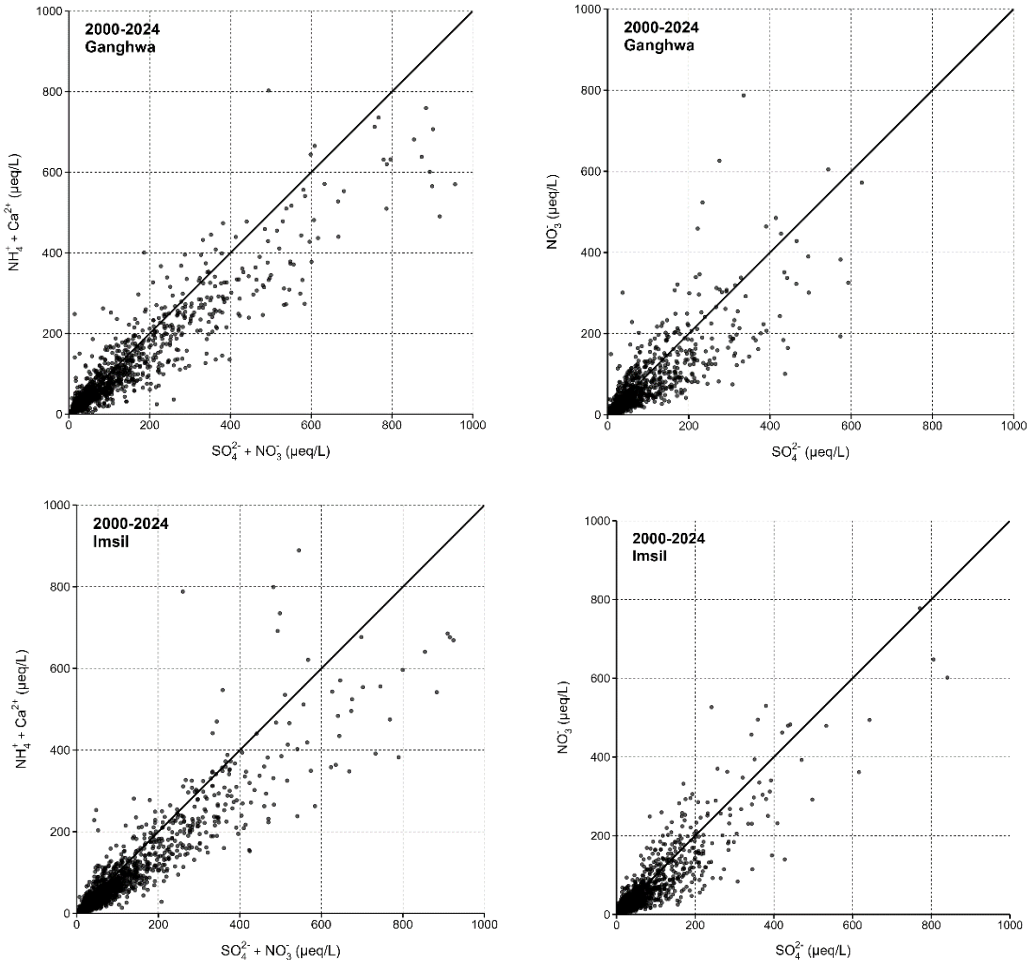



**Figure 1.2.2. Relationship between the $EC_{meas}$ and $EC_{cal}$.**

Figure 1.2.3 presents the sum of major anion and cation ratio and $SO_4^{2-}$ and $NO_3^-$ ratio (2000~2024). $NH_4^+$ and $Ca^{2+}$ were selected as major cations, and $SO_4^{2-}$ and $NO_3^-$ were selected as major anions. The sum of $SO_4^{2-}$ and $NO_3^-$ concentrations appeared to be slightly larger than the sum of $NH_4^+$ and $Ca^{2+}$. The ratios of major anions and cations were constantly checked as a key parameter for the ion balance and for rain water characteristics of sulfur and nitrogen containing species and checked together with major anion and cation ratios.



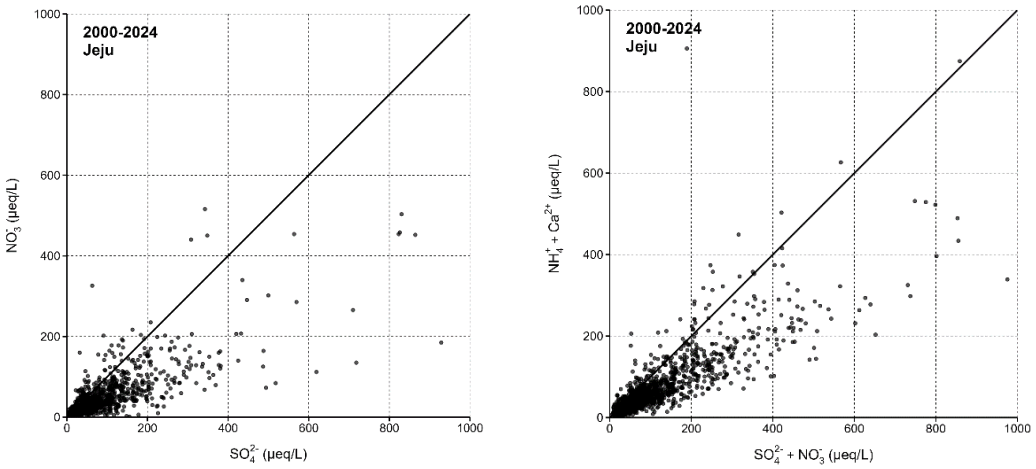
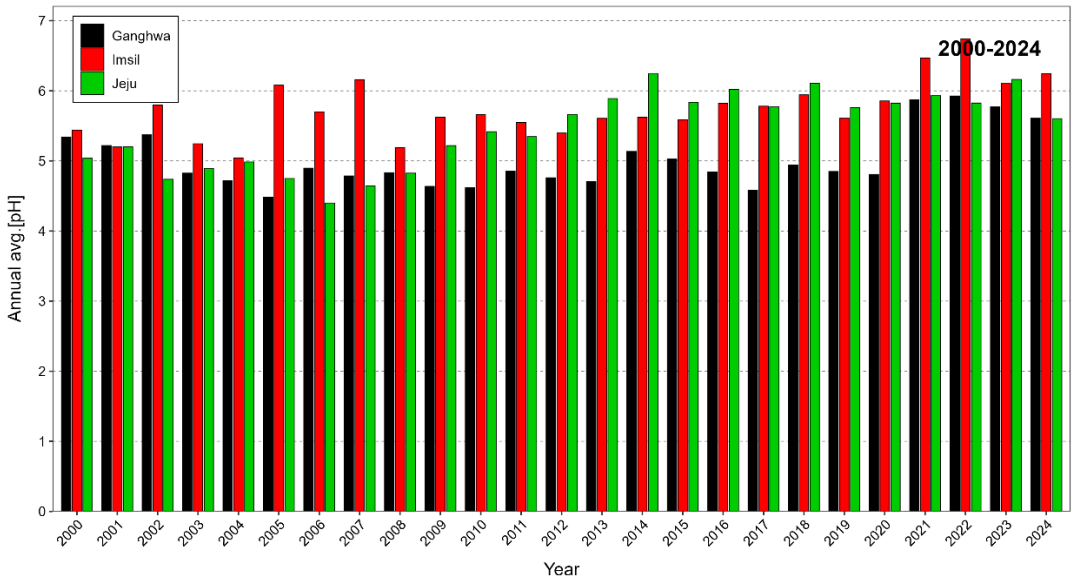



**Figure 1.2.3. Ion balance check in Ganghwa, Imsil and Jeju (Unit: μeq/L).**

pH is regarded as a major parameter characterizing acid rain mainly because it determines the acidity of rain waters. The annual mean pH was 5.2 in 2000, 5.0 in 2001, 5.0 in 2002, 4.8 in 2003, 4.7 in 2004, 4.8 in 2005, 4.8 in 2006, 5.0 in 2007, 4.7 in 2008, 4.8 in 2009, 4.8 in 2010, 4.9 in 2011, 5.0 in 2012, 5.0 in 2013, 5.3 in 2014, 5.1 in 2015, 5.2 in 2016, 5.0 in 2017, 5.5 in 2018, 5.2 in 2019, 5.3 in 2020, 5.7 in 2021, 5.9 in 2022, 5.4 in 2023 and 5.6 in 2024, while the annual precipitation was 708 mm, 976 mm, 1039 mm, 1580 mm, 1070 mm, 948 mm, 977 mm, 1157 mm, 1082 mm, 1124 mm, 1405 mm, 1483 mm, 1202 mm, 945 mm, 907 mm, 920 mm, 932 mm, 688 mm, 979 mm, 753 mm, 1078 mm, 822 mm, 633 mm, 898 mm, 1064 mm, respectively.

Figure 1.2.5 shows the frequency and volume of precipitation in the three EANET sites in Korea from 2000 to 2024. pH level of Ganghwa was most frequently at pH 4.6 ~ 5.0. Imsil showed most frequency value at pH 6.1 ~ 6.5 and Jeju was most frequently at pH 5.6 ~ 6.0.



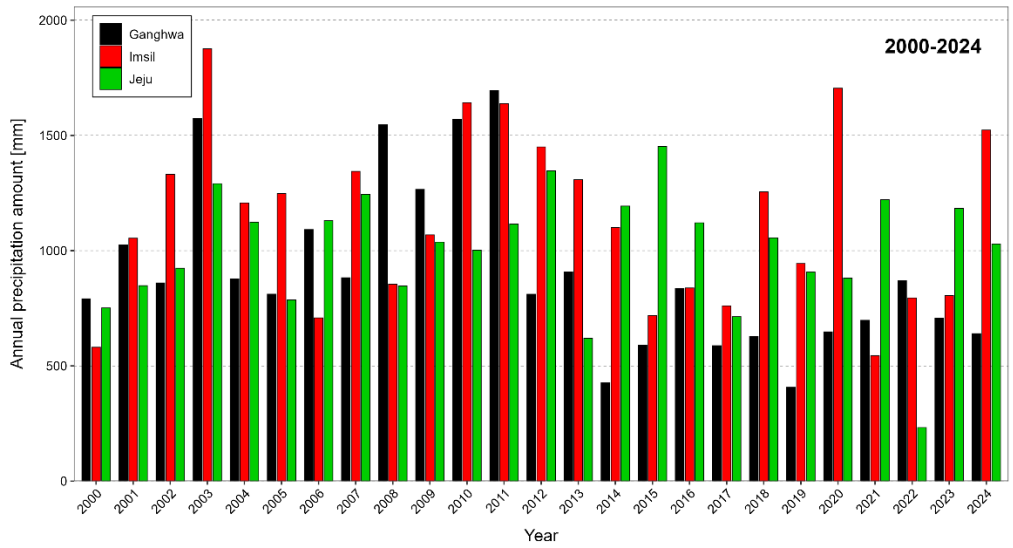



**Figure 1.2.4. The annual average pH and precipitation mount at each site (2000~2024).**

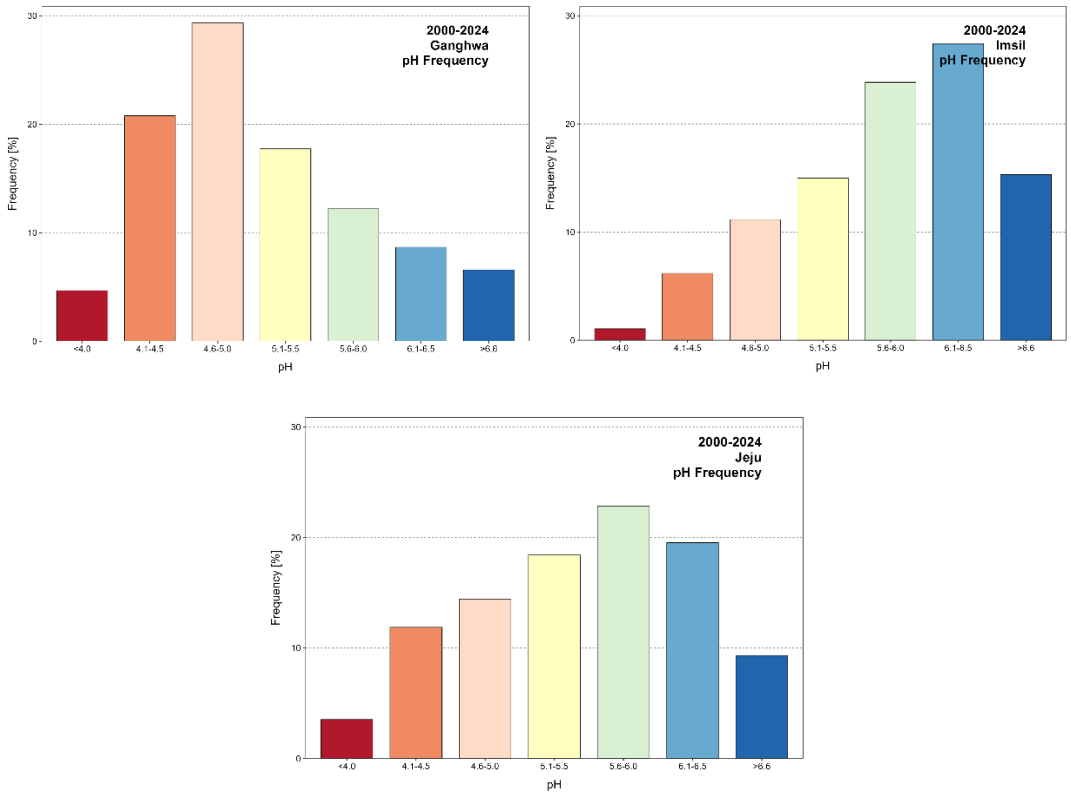



**Figure 1.2.5. pH frequency and the amount in each site (2000~2024).**

Seasonal variations of precipitation, EC, and pH are shown in Figure 1.2.6. Precipitation concentrates on summer, rainy season in Korea. In the results of the past twenty-years, summer was not always the season with the highest pH, and EC was analyzed the lowest in summer. EC concentration showed high level at the whole region in winter. And pH showed the low pH level in winter and high pH level in spring.

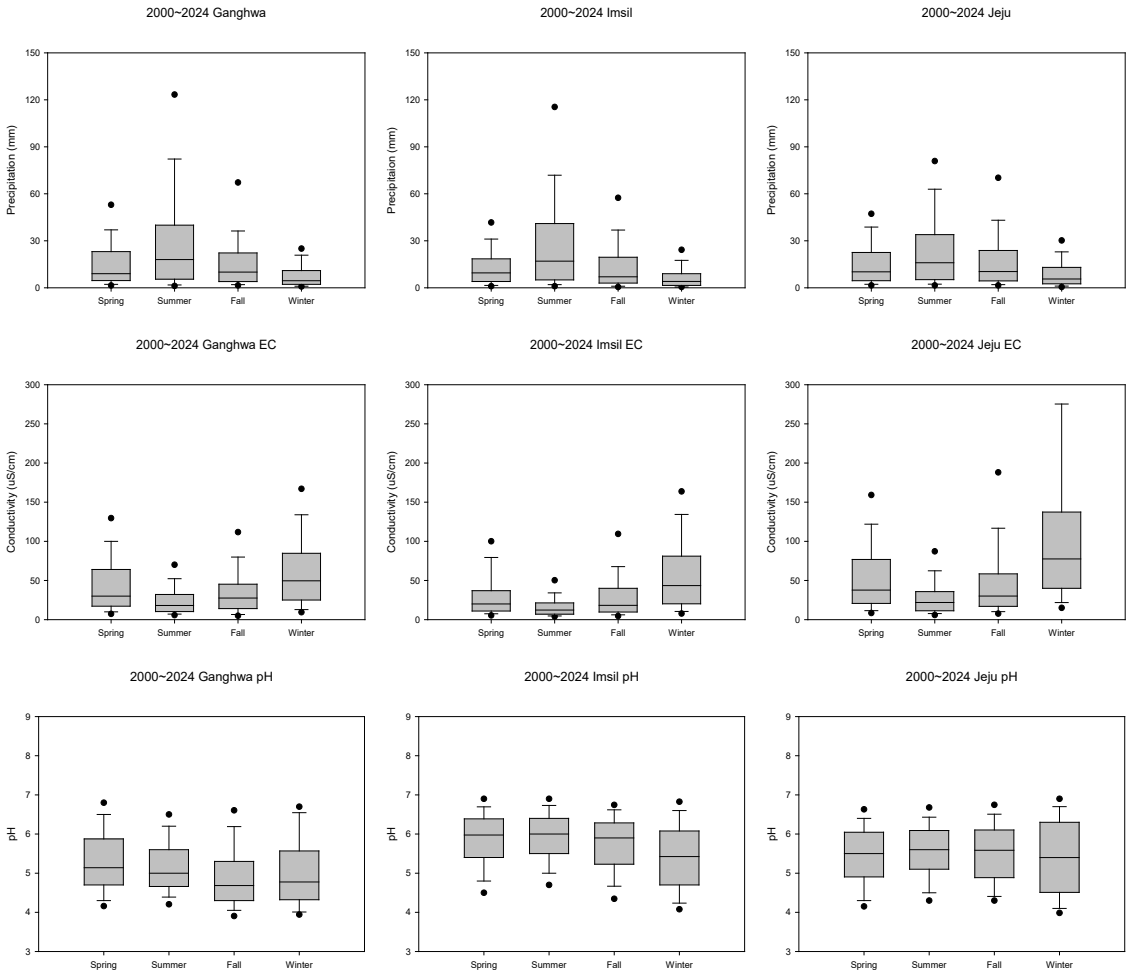
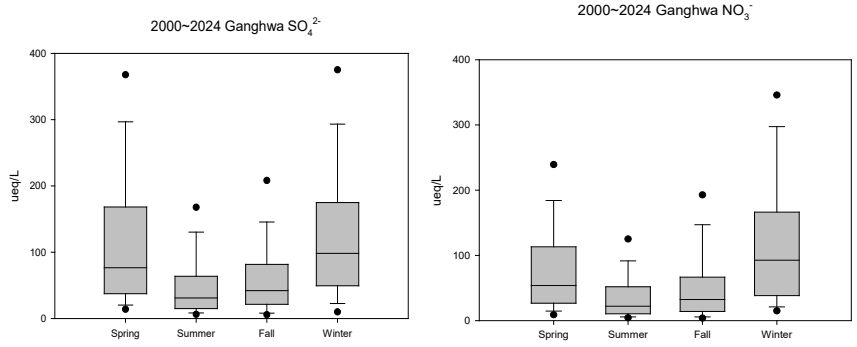



**Figure 1.2.6. Seasonal variation of precipitation, electronic conductivity and pH.**

Figures 1.2.7, 1.2.8, and 1.2.9 show seasonal variations of major ionic species concentrations and the amount of wet depositions at each site. The heavy precipitation during summer as discussed above diluted ionic species concentrations for rain waters, leading to the lowest concentration in summer. Despite the lowest ionic concentrations, the volume of wet depositions was still the largest in summer thanks to the heavy precipitation. The $SO_4^{2-}$ and $NO_3^-$ concentrations were high in winter due to high fuel demand for heating. The impact of these fuel demand was similar in Ganghwa, Imsil, Jeju. $Ca^{2+}$ concentration in spring in Gangwha and Imsil exhibited considerable variability in spring due to Asian dust as noted earlier.



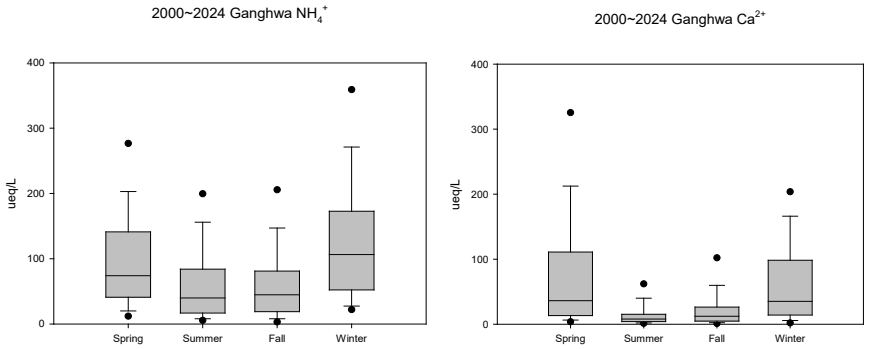



**Figure 1.2.7. Seasonal variation of wet deposition (equivalent concentration), Ganghwa**

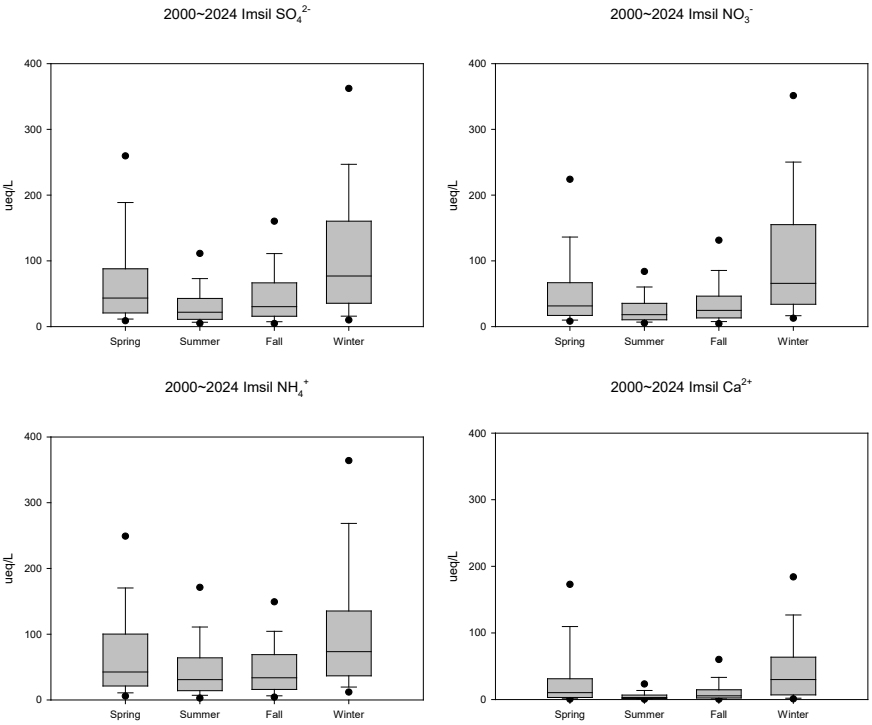
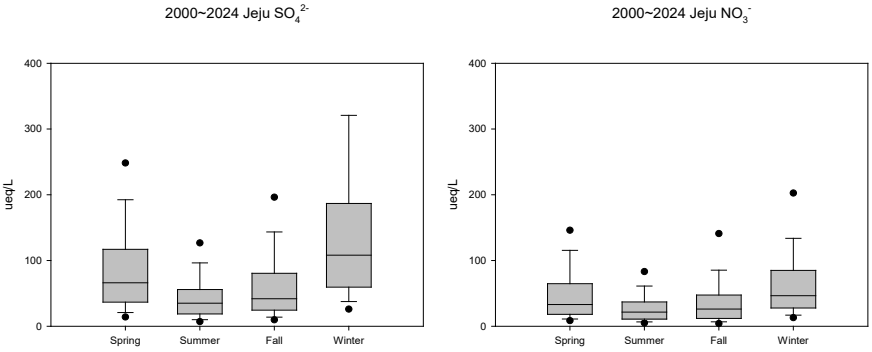



**Figure 1.2.8. Seasonal variation of wet deposition (equivalent concentration), Imsil.**



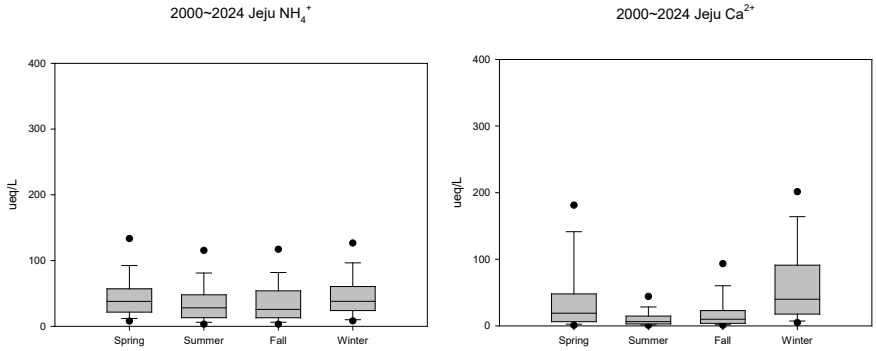



**Figure 1.2.9. Seasonal variation of wet deposition (equivalent concentration), Jeju.**

## 1.2.2 State of dry deposition

The equivalent conductance, as shown in Figure 1.2.10, was calculated using the same method for wet deposition monitoring results. The result shows that the balance between cation and anion is relatively good with 0.925 of the coefficient of determination. In this case, based-on the review of the ion balance, samples with reliability problem were reanalyzed or excluded from data analysis.

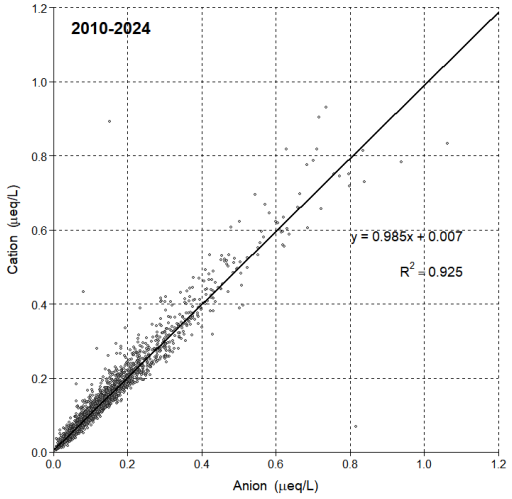
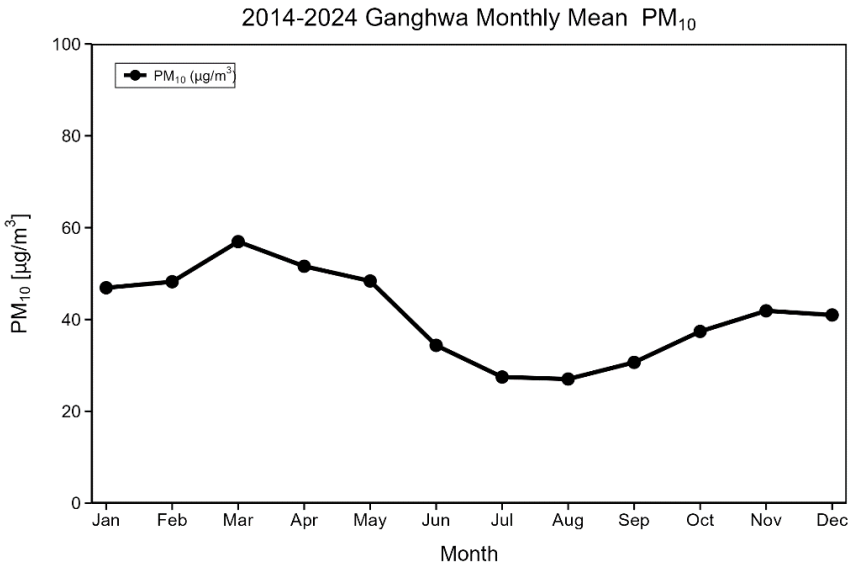
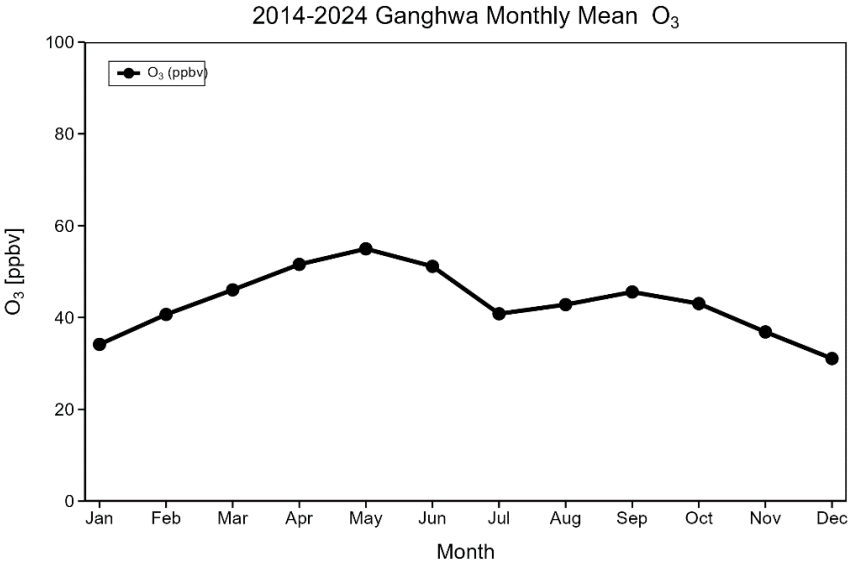
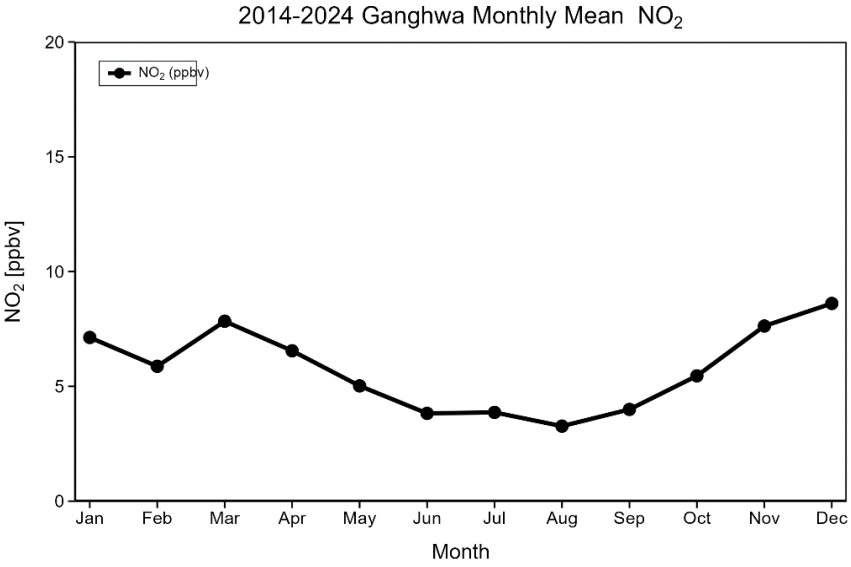



**Figure 1.2.10. Relationship between total anion and cation.**

Figures 1.2.11, 1.2.12, and 1.2.13 present the average monthly concentrations of $SO_2$, $NO_2$, $O_3$, and $PM_{10}$ mass from 2009 to 2024. The average concentration of $PM_{10}$ ranges from 31 μg $m^{-3}$ to 70 μg.$m^{-3}$. $PM_{10}$ concentrations were observed to be high mainly in March or May, a period of Asian dust. The average monthly concentration of $O_3$ measured to be high in summer. In case of $SO_2$, the increase trend in winter was observed. The highest concentration levels were Ganghwa island. But $SO_2$ and $NO_2$ levels were less than 0.75 ppbv and 4.16 ppbv in Jeju, one of the most remote sites, with one exception of January.


2014-2024 Ganghwa Monthly Mean PM10
PM10 (μg/m3)
PM10 [μg/m3]
100
80
60
40
20
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month


2014-2024 Ganghwa Monthly Mean O3
O3 (ppbv)
O3 [ppbv]
100
80
60
40
20
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month


2014-2024 Ganghwa Monthly Mean NO2
NO2 (ppbv)
NO2 [ppbv]
20
15
10
5
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month

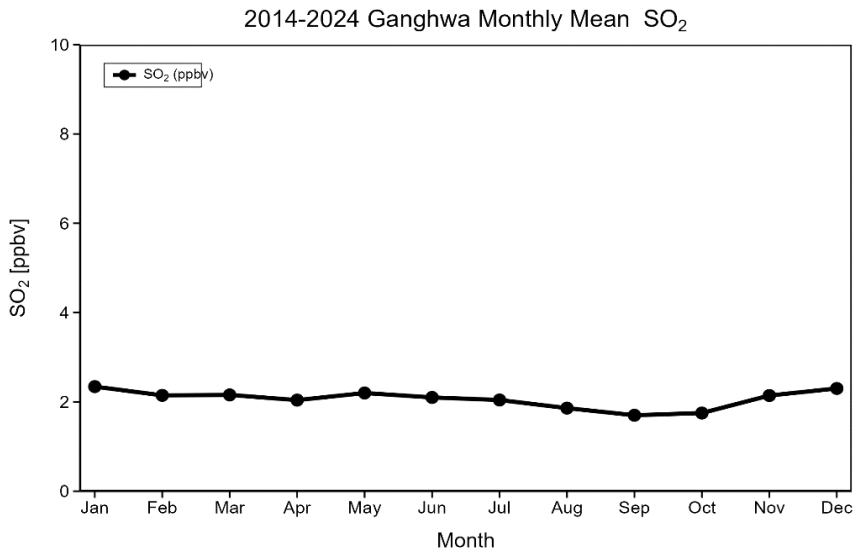
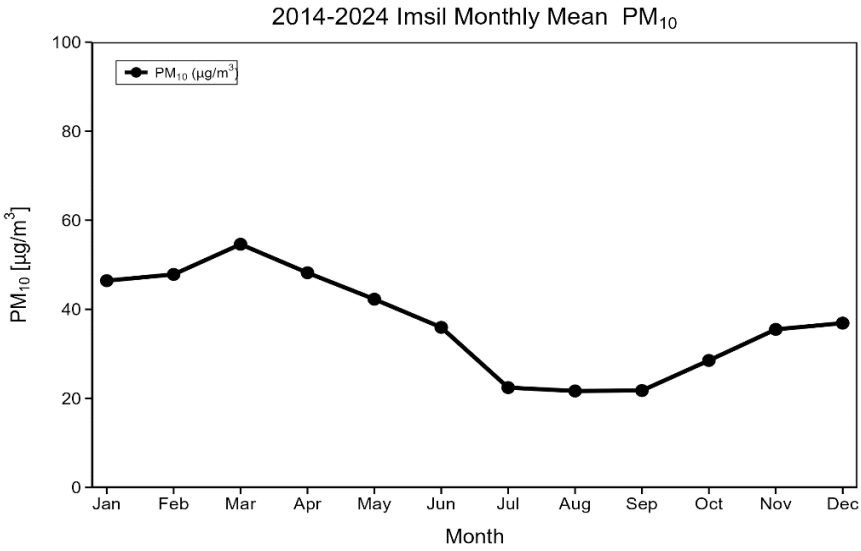
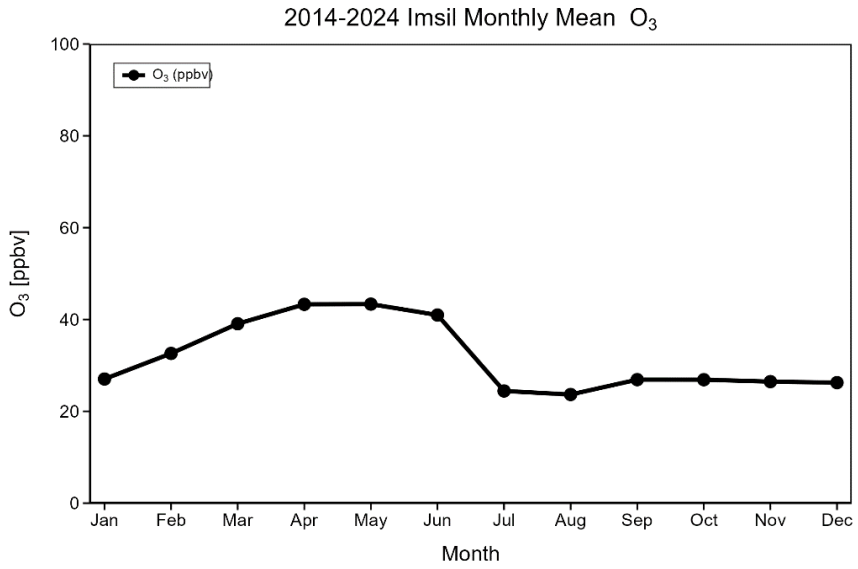



**Figure 1.2.11. Average monthly concentrations of $SO_2$, $NO_2$, $O_3$ and $PM_{10}$ at Ganghwa.**



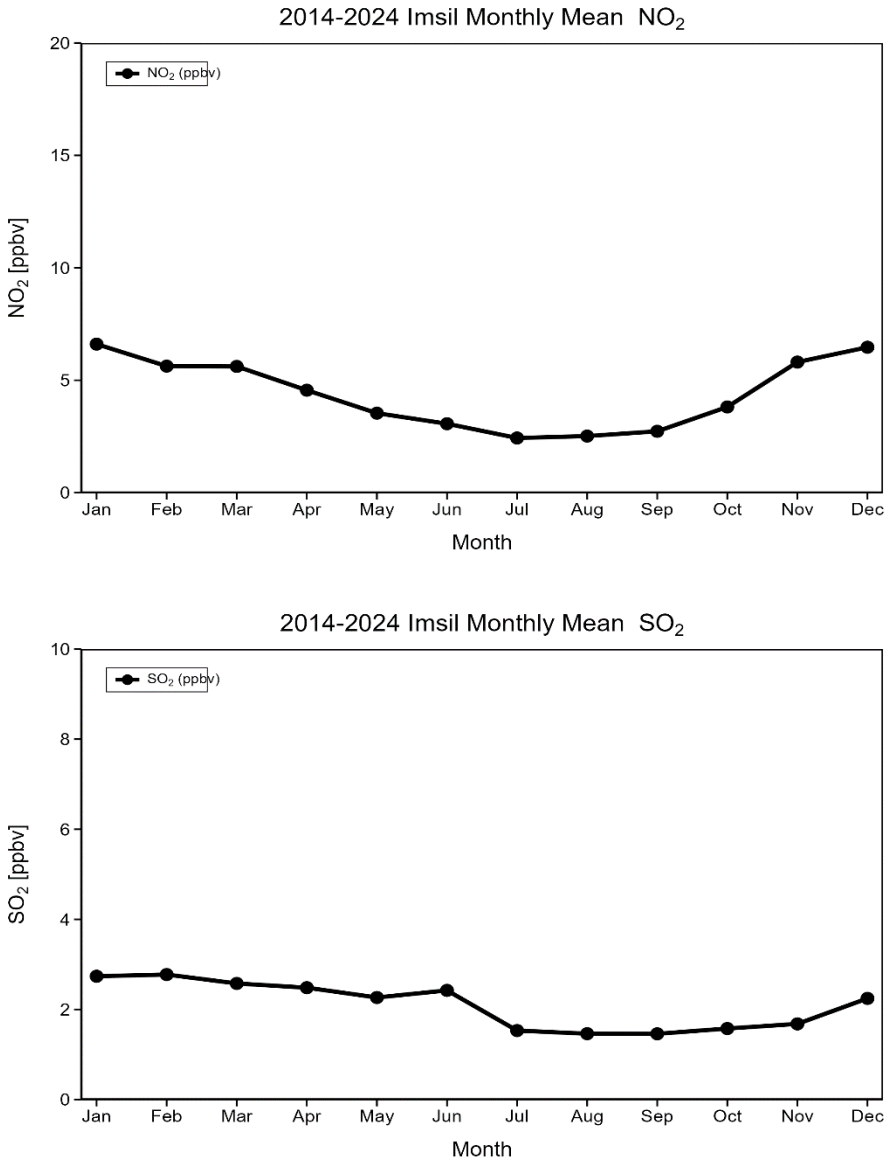
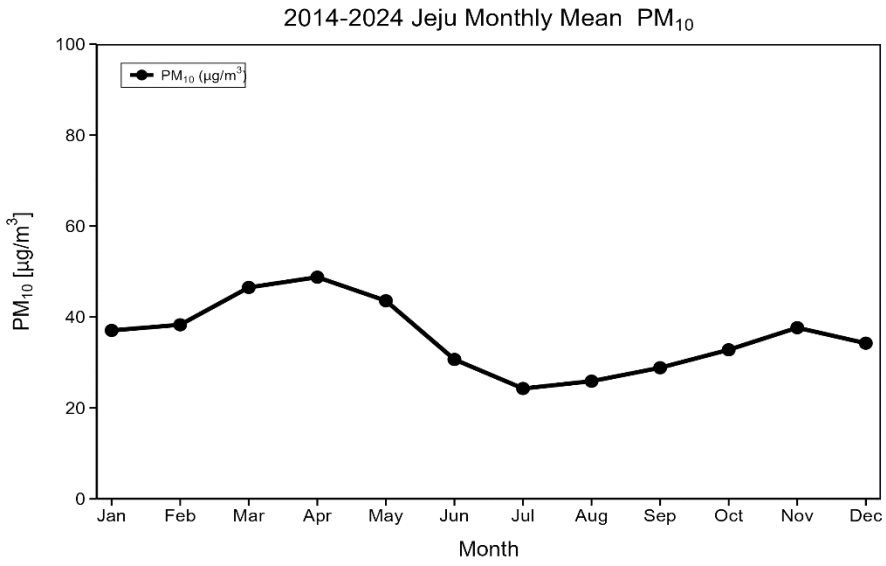
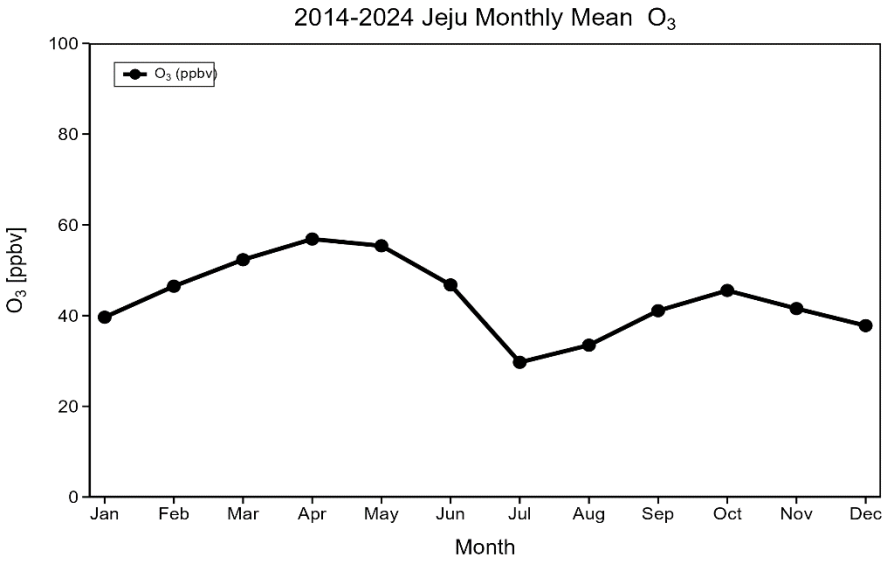
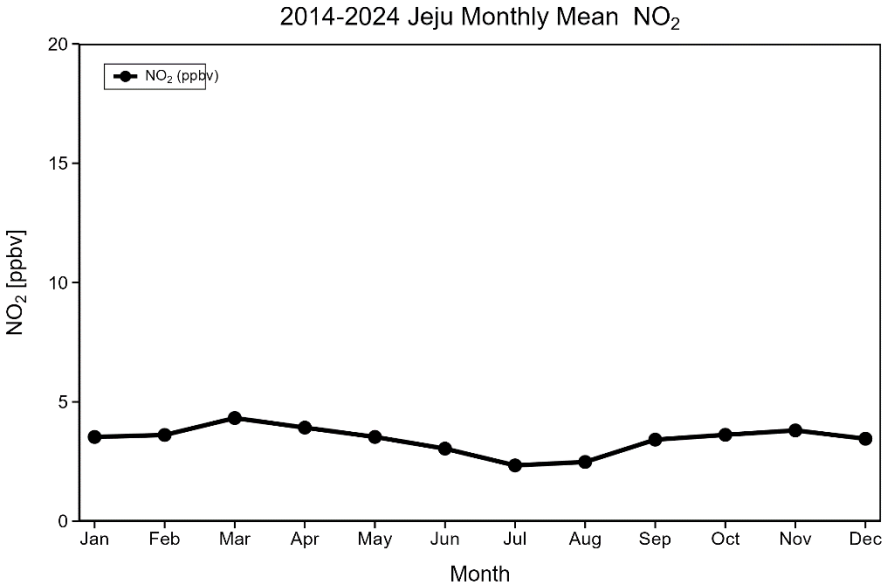



**Figure 1.2.12. Average monthly concentrations of $SO_2$, $NO_2$, $O_3$ and $PM_{10}$ at Imsil.**


2014-2024 Jeju Monthly Mean PM10
PM10 (μg/m3)
PM10 [μg/m3]
0
20
40
60
80
100
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month


2014-2024 Jeju Monthly Mean O3
O3 (ppbv)
O3 [ppbv]
0
20
40
60
80
100
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month


2014-2024 Jeju Monthly Mean NO2
NO2 (ppbv)
NO2 [ppbv]
0
5
10
15
20
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month

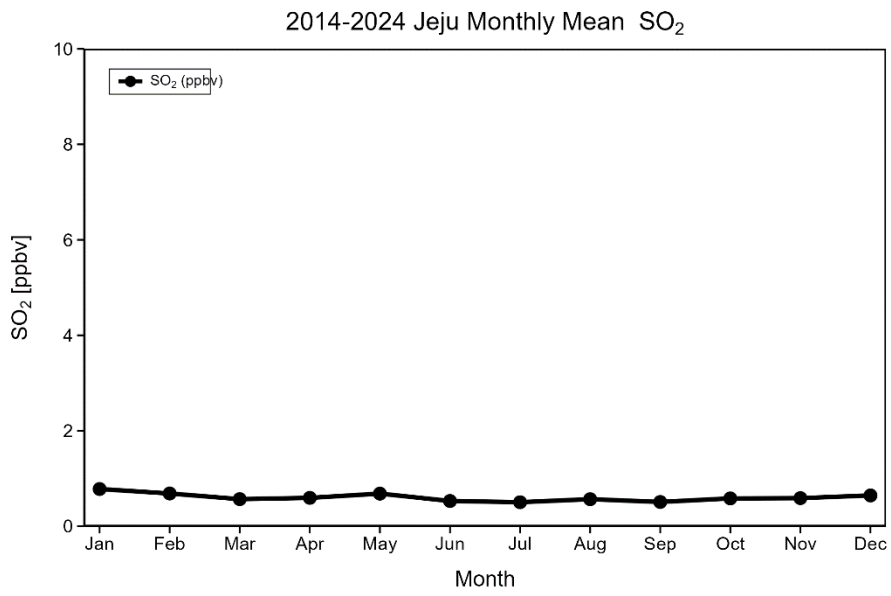
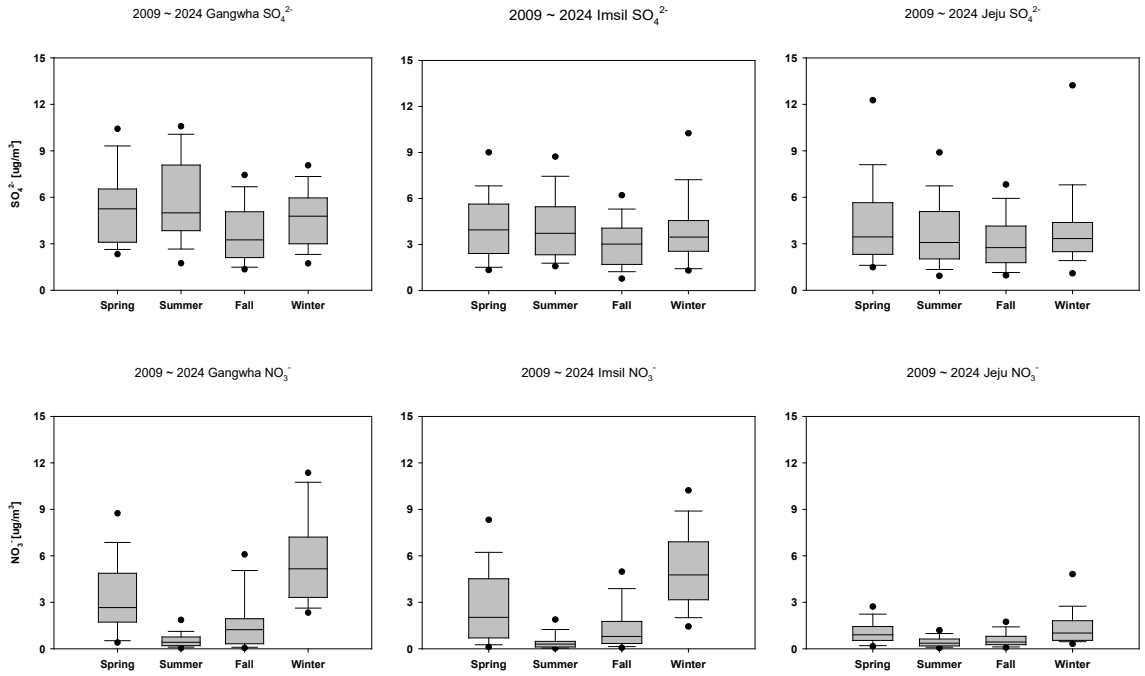



**Figure 1.2.13. Average monthly concentrations of $SO_2$, $NO_2$, $O_3$ and $PM_{10}$ at Jeju.**

Chemical composition analysis of $PM_{2.5}$ found that $SO_4^{2-}$ and $NH_4^+$ were major chemical constituents for Ganghwa, Imsil and Jeju sites. $NO_3^-$ was significantly increased in winter. But $SO_4^{2-}$ did not showed clear seasonal trend. As shown in Figure 1.2.14, the seasonal average concentrations of $SO_4^{2-}$, $NH_4^+$ and $NO_3^-$ varied among the three sites and therefore this suggests there is a need for further studies to on their causes.



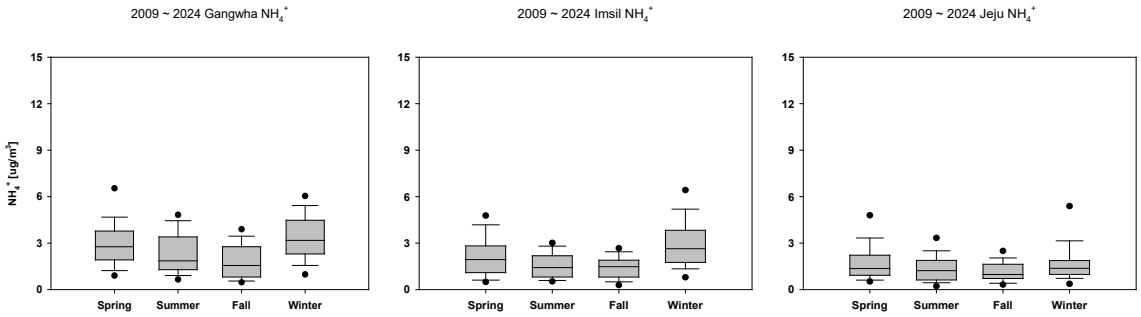



**Figure 1.2.14. Seasonal variations of major chemical species concentrations in $PM_{2.5}$ at sites.**