



Analysis of the Measurement Difference for the PM₁₀ Concentrations between Beta-ray Absorption and Gravimetric Methods at Gosan

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ABSTRACT

The measured mass concentrations of particulate matter less than 10 µm in diameter (PM₁₀) by β-ray absorption method (BAM) and gravimetric method (GMM) at Gosan, Republic of Korea have shown consistent difference. By using a gas/particle equilibrium model, positive error by the absorption of water at the filter in BAM during the measurements were quantified. The positive error occupied about 50% of the measurement difference. The contributions from the volatilization of ionic species to the difference were minor. However, this estimated water content difference could fully explain the concentration difference by the two methods. Multiple regression analysis was applied to the PM₁₀ mass concentration to find out the major factors that affected the concentration difference. Relative humidity, dust storm event and wind direction were identified as other major factors in addition to water absorption i.e., positive error. Still these factors could not fully account for the difference. Thus, it is advised that when using the PM₁₀ concentration at Gosan, a supersite in Northeast Asia, possible difference should be considered for the data till June 2008 by BAM.

Keywords: β-ray absorption method; Gravimetric method; Water content; Gas-particle equilibrium; Multiple regression analysis.

INTRODUCTION

Gosan is one of the six national background sites in Republic of Korea and has been used as a supersite in several international intensive campaigns since Gosan is ideally suited to study the transport and transformation of ambient trace species in Northeast Asia (Fig. 1) (Park *et al.*, 2004). Therefore, reliability of the measurement results of ambient trace species at Gosan is an important issue.

In a previous episodic measurement at Gosan, it was found that the measured particulate matter with a diameter of less than 10 µm (PM₁₀) concentration by the β-ray absorption method (BAM) was higher than the gravimetric method (GMM) and the correlation between them was low ($R^2 = 0.61$) (NIER, 2004). It was suggested that this discrepancy was caused by high relative humidity (RH) because Gosan site is located at seashore (NIER, 2004). However, supporting evidence was not presented. Thus, it was not clear what were the major factors contributing to the PM₁₀ concentration difference between the measurement methods.

BAM is the standard method for PM₁₀ measurement in

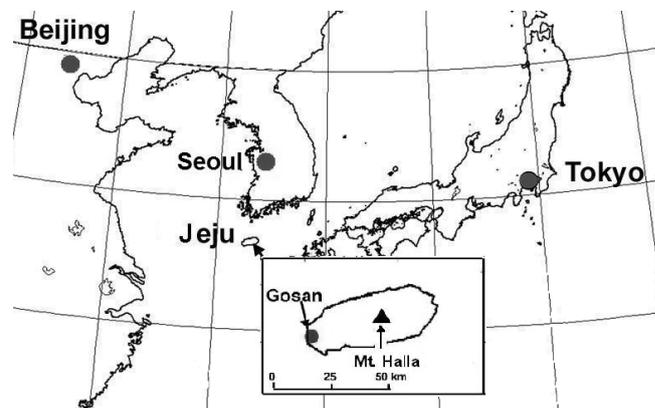


Fig. 1. The location of Gosan site in Jeju island, Korea.

Korea (NIER, 2009). Hourly PM₁₀ concentration is measured from the increase of absorption of beta-rays due to particles collected on the filter. It has been known that water absorbed in the particle is not removed in BAM if inlet air is not de-humidified. This absorbed water is called “positive error” (Gobeli *et al.*, 2008). In the US EPA, they introduced a “Smart Heater” system in which the RH of the sampled air is controlled by heating the inlet air (Gobeli *et al.*, 2008).

GMM is the reference method for PM₁₀ measurement in the USA (USEPA, 1998). In this method, a filter is weighed before and after the sampling to determine the mass change

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due to the collected particles. The filter is in a desiccator under the constant temperature and RH condition for 24 hours before and after the sampling to weigh dried particles. Also, the sampling time of GMM is usually 24 hours, longer than BAM. Thus, volatile species collected on the filter at GMM may be lost on the filter. It is called “negative error” (Turpin *et al.*, 2000).

Shin *et al.* (2010) compared the PM₁₀ concentrations by two methods at Gosan using the long-term measurement data between May 2001 and June 2008. They found that the PM₁₀ mean concentration by BAM was higher than GMM by 19.71 µg/m³. All yearly mean concentrations by BAM were higher than GMM, and the yearly discrepancies between them did not change over time (Table 1). Also, they were different within a 95% confidence interval and the correlation between them was low ($R^2 = 0.33$). As the inlet of BAM at Gosan has been heated from July 2008, the measurement data until June 2008 could be influenced by high RH. Thus, they suggested that high RH might be the main reason for the difference. However, the difference between two methods did not increase along with RH nor absolute humidity. So, they could not verify the hypothesis.

The factors that may lead to the differences between the measurement methods are the differences in the (1) cut off diameters (Tsai and Cheng, 1996), (2) flow rates, (3) materials of the filters (Lipfert, 1994; Kim, 2000), (4) water content of aerosol (Meng *et al.*, 1995; Chang *et al.*, 2001; Tsai *et al.*, 2006), (5) volatilization loss of volatile species of aerosols (Zhang and McMurry, 1992; Turpin *et al.*, 2000; Kim, 2000; Kim and Kim, 2007), and (6) conditions of measurement (Chang *et al.*, 2001; Kajino *et al.*, 2006).

Tsai and Cheng (1996) showed that the PM₁₀ concentration by a Kimoto BAM was lower than GMM because the cut off diameter of inlet at Kimoto BAM was smaller than GMM. Both BAM and GMM at Gosan have standard inlet satisfying both the Korean and US EPA standards. Thus, there should be no difference for the inlet cut off diameter. It is possible that the different flow rates of two instruments might cause the concentration difference. However, both inlets were calibrated and checked regularly at the flow rate of 16.7 L/min. Thus, it is decided that the measurement difference is not caused by the flow rate difference.

The difference of filter materials may cause the measurement difference. Teflon filter has been used for GMM while glass fiber filter has been used for BAM. The glass fiber filter has high particle collection efficiency, but might contain positive sampling difference by converting gaseous SO₂ and HNO₃ into particulate SO₄²⁻ and NO₃⁻, respectively (Lipfert, 1994). Although Teflon filter has low background concentration and is inert to the reactive ambient trace species, it is possible that volatile components such as NH₄NO₃ might evaporate (Kim, 2000). Since the exposure time at BAM (1 hr) is shorter than GMM (24 hr),

the measurement difference caused by filter material difference, if any, could occur predominantly at GMM.

When the ambient RH is high, water absorption to aerosols might lead to higher PM₁₀ concentration at BAM, especially, that without inlet heater compared to GMM (Chang *et al.*, 2001). The sum of the PM₁₀ concentrations by GMM and the water content of aerosol calculated by ISORROPIA, a gas/particle equilibrium model, were in agreement with the concentrations by BAM measured during November 1999 at four stations in Taiwan (Chang *et al.*, 2003). However, at Incheon, Korea with an inlet heater at BAM, the PM₁₀ concentration of BAM was comparable with GMM within 10% of the measurement difference and the correlation between them was high for the measurement from August to November 2006 (Jung *et al.*, 2007). The same phenomenon was observed for the PM_{2.5} concentration at several studies (APCD, 2007; Gobeli *et al.*, 2008). Recently, Jung *et al.* (2010) had shown that the concentration of PM_{2.5} by BAM without an inlet heater was higher than that by GMM, especially, in summer. However, the PM_{2.5} concentration by BAM with an inlet heater was almost same as that by GMM. Since the BAM measurement data used in this study were obtained from an instrument without an inlet heater, this kind of measurement difference might be important and will be quantified.

As mentioned in the filter difference problem, it is possible for volatile species to evaporate over the filter of GMM. Katsuyuki *et al.* (2008) have quantified this negative error for GMM at Tokyo in Japan from April 1997 to March 2004. The concentrations of volatile ion concentration (NH₄⁺, NO₃⁻, and Cl⁻) of long-term (2 weeks) sampling were smaller than short-term (1 day) sampling. It was because volatile species collected on the filter by GMM be lost during longer sampling. It could be possible that the PM_{2.5} concentrations by GMM be higher than BAM with an inlet heater. With high nitrate concentrations and low temperature case, nitrate was volatilized from the heated inlet for BAM and, thus, showed lower concentration (Hauck *et al.*, 2004). However, this result could support the fact that PM₁₀ concentration by BAM being higher than GMM at Gosan.

Lastly, the conditions of measurement caused by meteorological factors at Gosan might cause the measurement difference (Chang *et al.*, 2001; Kajino *et al.*, 2006).

In this study, to identify the major factors for the PM₁₀ concentration difference between BAM and GMM at Gosan, the positive error is quantified by using a gas/particle equilibrium model. In addition, based on the previous study results, the degree of the negative error is discussed. Since meteorological factors can also cause measurement difference, these are identified by using the multiple regression method, and the implications of this study result are discussed.

Table 1. Comparison of the statistical value of the PM₁₀ concentrations measured at Gosan (Shin *et al.*, 2010) (unit: µg/m³).

Year	2001	2002	2003	2004	2005	2006	2007	2008
BAM	35.45 ± 17.41	54.15 ± 47.83	45.77 ± 19.60	42.98 ± 24.50	62.81 ± 21.56	58.73 ± 30.10	46.05 ± 17.62	58.43 ± 23.84
GMM	26.88 ± 17.40	27.93 ± 13.31	21.52 ± 12.47	32.02 ± 11.58	35.87 ± 15.35	28.91 ± 13.43	21.58 ± 8.22	46.87 ± 24.97

DATA

In this study, PM₁₀ by GMM were collected by a low volume air sampler consisting of a Teflon-coated aluminum cyclone with a cut size 10 μm at a flow rate of 16.71 L/min (URG, USA), a Teflon filter pack for 47mm filters (Sarvillex, USA), a critical orifice (BGI, USA) and a pump (Dayton, USA). Daily mean data of PM₁₀ mass and ionic species concentrations were used. Details on the sampling and analysis procedure for the data used in this study are described in Kim and Kim (2008).

After the conventional quality control/quality assurance procedure, only the data with the ratio of the sum of the equivalent cation concentrations to the equivalent anion concentrations being within 30% were used (Park *et al.*, 2004). The number of daily data of GMM reduced from 340 to 260 after the checking process.

Hourly continuous automatic measurement data of BAM were obtained from National Institute of Environmental Research (NIER). The hourly data are converted into the daily mean data from 9 AM to 8 AM next day which was the sampling schedule of GMM. Two methods for the days with simultaneous results (GMM: 260, BAM: 2776) have 216 data sets. Thus, 216 daily data are compared for the analysis.

For identifying the measurement difference using the concentration of ionic species separated by particle size, the data of ionic species are obtained. The total suspended particulates (TSP) were collected by a high volume tape sampler (Kimoto Electric Co., Model 195A), which is an automatic sampling system with roll type PTFE filters (Sumitomo Electric, 100 mm × 10 m). Particles were collected for either 6 or 24 h and then a new clean filter surface was moved to the sampling area on which particles were collected. The flow rate was about 170 L/min. The PM_{2.5} sampler consists of a Teflon-coated aluminum cyclone with a cut size 2.5 μm at a flow rate of 16.7 L/min (URG, USA), a Teflon filter holder for 47 mm filters (Sarvillex, USA), a critical orifice (BGI, USA) and a pump (Dayton, USA). Eight ions in TSP, PM₁₀, and PM_{2.5} were analyzed. NH₄⁺ ion was analyzed by the indophenol method with a UV visible spectrophotometer (Kontron, Model Uvikon 860) and Na⁺, K⁺, Ca²⁺, and Mg²⁺ by atomic absorption spectroscopy (GBC, Model Avanta-P). Anions, SO₄²⁻, NO₃⁻, and Cl⁻ were analyzed by ion chromatography (Dionex, Model DX-500). The mean values of the data are shown in Table 2. Details on the sampling and analysis are given in Park *et al.* (2004) and Kim and Kim (2008).

EQUILIBRIUM MODEL

We quantified the positive error by using a gas/particle

equilibrium model, SCAPE2 (Simulating Composition of Atmospheric Particles at Equilibrium 2, Kim *et al.*, 1993a, b; Kim and Seinfeld, 1995; Meng *et al.*, 1998). Based on the calculated aerosol water content by SCAPE2, the effect of ambient humidity during measurement by BAM (positive error) is quantified.

For a closed multiphase system in chemical equilibrium at constant temperature T and pressure, the total Gibbs free energy of the system should be at a minimum.

$$\sum v_{ij}\mu_i = 0 \quad (1)$$

where v_{ij} is the stoichiometric coefficient of the i th species in the j th reaction, μ_i is the chemical potential of species i given in Eq. (2):

$$\mu_i = \mu_i^\circ(T) + RT \ln a_i \quad (2)$$

where $\mu_i^\circ(T)$ is the standard chemical potential for the i th species at temperature T in Kelvin, and a_i is the activity of the i th species given in Eq. (3):

$$a_i = \gamma_i m_i \quad (3)$$

where γ_i is its activity coefficient and m_i is the molality of species i . By substituting Eqs. (2) and (3) into (1), Eq. (4) is obtained:

$$\exp\left[-\frac{1}{RT} \sum v_{ij}\mu_i^\circ\right] = \prod a_i^{v_{ij}} \equiv K_j \equiv \prod_i (\gamma_i m_i)^{v_i} \quad (4)$$

where K_j is the equilibrium constant of the j th reaction. Therefore, estimating accurate activity coefficient is essential to obtain accurate equilibrium concentration of the species with the given equilibrium constants. In SCAPE2, three methods are available and the Kusik and Meissner (K–M) method is selected for calculating activity coefficient in this study.

For water content, the Stokes, Robinson, and Zdanovskii (ZSR) method is used in SCAPE2 because of simplicity.

$$W = \sum_i \frac{M_i}{m_{io}(a_w)} \quad (5)$$

where a_w is water activity, equal to the RH expressed as a fraction. And $m_{io}(a_w)$ is the molality of the binary solution at the desired water activity a_w of the multi-component solution. M_i is the molar concentration of species i in the air (mol/m³ air) and W is the mass concentration of water in the aerosol (kg water/m³ air).

Input data for SCAPE2 are total ammonia (t-NH₃ =

Table 2. The mean concentrations of inorganic ions and mass in the size-segregated aerosols measured at Gosan between May 2001 and June 2008 (unit: μg/m³).

	NH ₄ ⁺	Na ⁺	K ⁺	Ca ²⁺	Mg ²⁺	SO ₄ ²⁻	NO ₃ ⁻	Cl ⁻	Nss-Ca ²⁺	nss-SO ₄ ²⁻	Mass
TSP	1.93	2.11	0.43	0.54	0.31	7.39	2.59	1.82	0.46	6.86	–
PM ₁₀	1.85	0.47	0.22	0.19	0.08	4.88	2.05	0.37	0.18	4.76	27.69
PM _{2.5}	1.59	0.39	0.19	0.15	0.06	4.09	1.53	0.28	0.14	3.99	21.83

gaseous NH_3 + particulate NH_4^+ , t- HNO_3 (gaseous HNO_3 + particulate NO_3^-), t- HCl (gaseous HCl + particulate Cl^-), sulfate (SO_4^{2-}), carbonate (H_2CO_3), calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), sodium (Na^+), RH, and ambient temperature (T). Because we do not know gaseous species concentrations, SCAPE2 model was run in "aerosol phase only" mode.

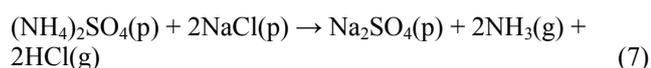
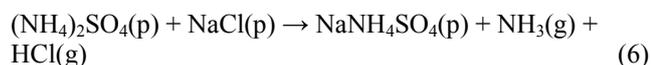
Water absorption by organic species is not treated in SCAPE2. While hygroscopic organic materials in aerosols can also take up water vapor from the air, it is hard to consider hygroscopic organic materials in estimating water content by modeling because of lack of detailed thermodynamic data (Kajino *et al.*, 2006).

RESULTS

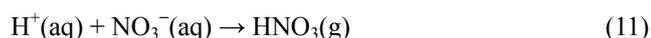
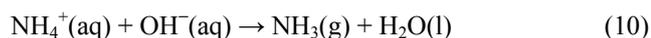
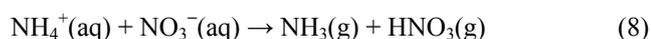
Degree of the Positive and Negative Errors

The degree of volatilization on the filter by GMM (negative error) can be quantified by comparing the measured mass concentrations and calculated mass concentrations of volatile ionic species by SCAPE2 at the thermodynamic equilibrium conditions during the sampling period. However, we run SCAPE2 in "aerosol phase only" mode without the gaseous species concentrations. For this reason, we cannot quantify the negative error but just estimate qualitatively.

Kim (2000), successfully simulated the measurement result in which the concentration of ammonium in TSP were lower than in $\text{PM}_{2.5}$ at Gosan. Since TSP includes $\text{PM}_{2.5}$, ion concentration in TSP should be higher than $\text{PM}_{2.5}$. However, with the reaction with the alkaline sea-salts species notably NaCl, ammonium might evaporate, as shown in Eqs. (6) and (7)



Since the concentration of sea-salt species is higher in TSP than $\text{PM}_{2.5}$, more ammonium ions are volatilized in TSP. In addition, following evaporation reaction are also possible:



In a humid and alkaline condition such as seashore, reaction (10) might be also important.

If the volatile alkaline ion concentration (i.e., ammonium) of PM_{10} was lower than that of $\text{PM}_{2.5}$ by GMM, the negative error for volatilization can be successfully estimated. However,

as shown in Table 2, the concentrations of ammonium decreased in descending order of particle diameter (TSP, PM_{10} , and $\text{PM}_{2.5}$). Thus, it is likely that the volatilization hardly occurred.

Next, we consider the positive error caused by water absorption at BAM. The estimated mean water content is $9.94 \mu\text{g}/\text{m}^3$ which accounts for about 50% of the discrepancy of the PM_{10} mass concentration between BAM and GMM. The positive error, water content by absorption, shows significant influence on the measurement difference. The estimated water content in summer is larger than other seasons (Spring: 10.24, Summer: 19.00, Fall: 6.58, and Winter: $7.56 \mu\text{g}/\text{m}^3$, respectively) due to high RH in summer.

However, the correlation between the measured PM_{10} concentration by BAM and the sum of the measured PM_{10} concentration and estimated water content by GMM (simulated concentration) becomes not better as shown in Fig. 2 ($R^2 = 0.33 \rightarrow R^2 = 0.25$). In Fig. 3, the yearly mean difference of the measured PM_{10} concentrations between by BAM and GMM, and between the measured PM_{10} concentration by BAM and the simulated concentration by GMM at Gosan are shown. The PM_{10} mean concentration of BAM is still higher than simulated GMM except for 2001 and 2008.

Even though considering the water content, the PM_{10} concentration difference between BAM and GMM is still large ($9.77 \mu\text{g}/\text{m}^3$) and correlation between them is low. Thus, it is hard to explain the measured concentration difference only by absorption of water at BAM. There might be other factors that influence the measurement difference. One possible reason is water soluble organic matters which are not accounted for estimating water content by using SCAPE 2. If the fraction of water soluble organic carbon (WSOC) be a significant portion of the water soluble organic matters, the error caused by it should be larger. In Hong Kong, Yu (2000) showed that the urban site (Mong Kok) had the lowest WSOC fraction whereas the rural site (Hok Tsui) had the highest WSOC. Hok Tsui is also coastal area such as Gosan. Also, according to a study of Sweden (Zappoli *et al.*, 1999), a background station for the region of mid-Sweden influenced by both marine and continental air, organic compounds accounted for 50% of the total water soluble fraction of the fine aerosol. Furthermore, 80% of the total OC was water soluble. The higher percentage of WSOC was possibly due to a higher contribution of naturally produced organic particles with a small anthropogenic contribution.

So, it is hard to estimate water content of aerosol accurately at the coastal or rural and background site like Gosan because WSOC fraction could be high. Actually, Lee *et al.* (2008) analyzed composition of water soluble aerosol at Gosan and Seoul. The fraction of WSOC in the total organic carbon mass at Gosan was higher than Seoul. Especially, water soluble organic species influenced by long-range transport of ambient trace species can occupy a large portion of the organic carbon. That is, it is possible that the total water content in aerosol could be underestimated by not considering organic fraction.

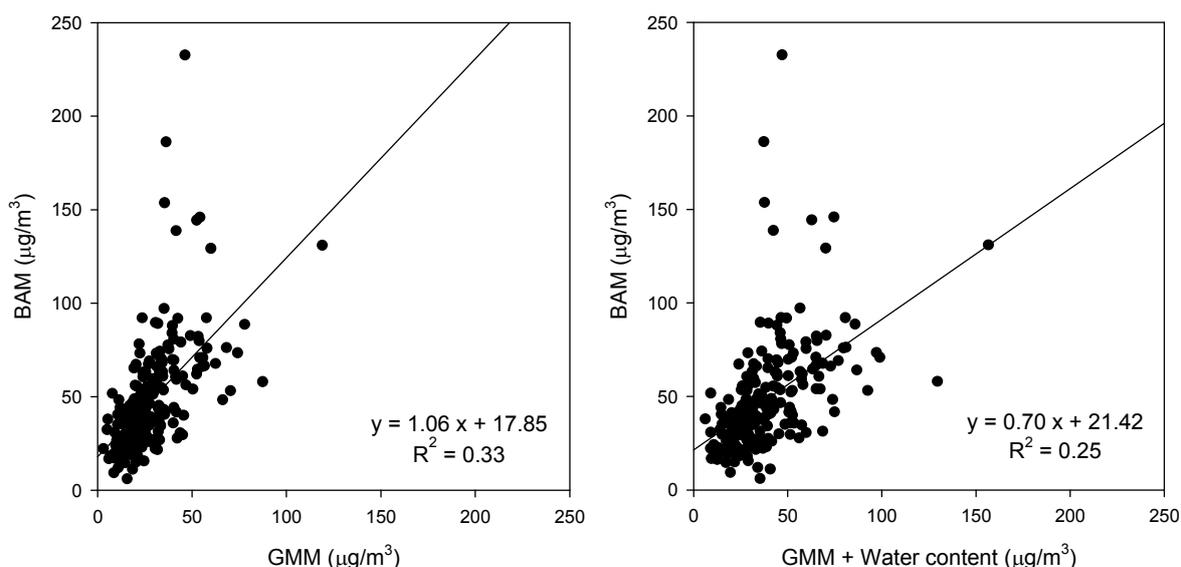


Fig. 2. Comparison of the PM_{10} concentrations between BAM and GMM, and between BAM and the sum of GMM and estimated water content (simulated GMM).

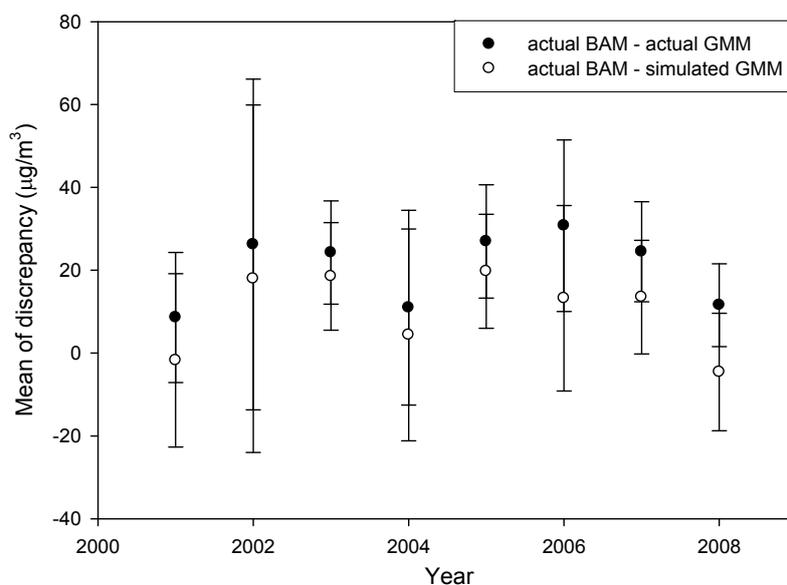


Fig. 3. The discrepancies of the PM_{10} mean concentrations between BAM and GMM and between BAM and simulated GMM measured at Gosan ($\mu\text{g}/\text{m}^3$).

Multiple Regression Analysis to Identify other Difference Sources

Since the estimated water absorption on the filter of BAM cannot fully account for the measured concentration difference, other factors that might cause the measurement difference are investigated. There are several previous studies showing that meteorological factors might influence the measured PM_{10} concentration significantly. For example, with increasing wind speed, the concentrations of PM_{10} were reported to be decreasing. On the other hand, if wind direction from source of pollution was major one, the concentration of PM_{10} could increase (Shin *et al.*, 2007). Also, when RH was very high, i.e., raining, the PM_{10} concentration becomes low because of washout by rainfall (Jung *et al.*, 2009).

In Fig. 2, it is shown that there are seven outliers of which values by BAM were much higher than by GMM. These data were for the dust storm cases. Unidentified components (heavy metals, OC, EC, and others) of this period account for 60% of PM_{10} mass concentrations compared with all data (44%). Thus, undetermined WSOC might influence some degree of the measurement difference. After these seven data points are excluded, the correlation between them is somewhat higher than the previous comparison ($R^2 = 0.33 \rightarrow 0.42$). However, the correlation is still not good.

The multiple linear regression analysis was conducted to identify the major meteorological factors such as wind direction, dust storm event, wind speed, rain, storm or fog

event, temperature, RH, and others that might affect the concentration difference significantly between BAM and GMM. The statistical program, SPSS 17 was used. The dependent variable used was the PM₁₀ concentration by GMM (PM₁₀(G)). First, each factor is linearly regressed with the PM₁₀(G) pairwise and the factor with a p-value less than 0.05 is selected for the multiple linear regression.

The obtained multiple regression equation can explain a major fraction of the concentration value by GMM with the following factors:

$$\text{PM}_{10}(\text{G}) = 37.746 + 0.292 \text{ PM}_{10}(\text{B}) + 0.861 \text{ Wat} - 23.069 \text{ Dust (dummy variable)} + 4.483 \text{ Wd (dummy variable)} - 0.482 \text{ RH} \quad (13)$$

PM₁₀(B): PM₁₀ concentration by BAM,

Wat: Estimated water content in aerosol by BAM,

Dust (dummy variable): Dummy variable for dust storm (occur '1', no occur '0'),

Wd (dummy variable): Dummy variable for wind direction (southerly wind '1', the others '0'),

RH: relative humidity.

The wind direction and dust storm factors are converted to dummy variable according to Chae *et al.* (2009). The result of multiple linear regression analysis considering each four cardinal direction variable expressed by dummy variable, the southerly wind variable is only significant with a p-value less than 0.05. So, the southerly wind was given as '1' and the others '0'. Considering the location of the Gosan station, the southerly wind could contain more water vapor than others. Thus, the southerly wind could be related with the measurement difference.

Since the factors used for the multiple regression equation have different units, it is hard to compare their relative contribution directly. Thus, t-value of each factor is estimated. If the t-value of a factor is high, it can be considered that the factor is contributing GMM significantly. The t-value of water content is higher than other factors. That is, the effect of water content occupies a larger part of the measurement difference than any other factors. In Fig 4, the value calculated by the multiple regression equation (denoted as GMM') is compared with the measured PM₁₀ concentration by GMM. The relation between them is somewhat higher than other previous comparisons ($R^2 = 0.52$). Still these variables cannot fully explain the PM₁₀ concentration difference and we need to investigate other factors to raise contribution of the multiple regression equation.

SUMMARY AND IMPLICATIONS

It was found that the PM₁₀ concentration by BAM was higher than GMM and the correlation between them was low at Gosan. Based on the previous studies, it was suggested that the major factors for the discrepancy between the BAM and GMM measurement be negative error due to the volatilization of volatile ambient species on the filter at GMM such as nitrate and ammonium and/or positive error due to the absorption of water vapor during measurement by BAM.

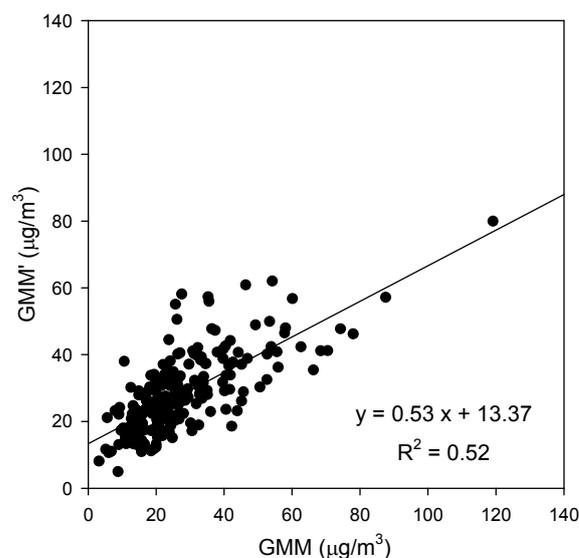


Fig. 4. Comparison of the PM₁₀ concentrations between GMM and GMM' estimated from multiple regression analysis.

It is found out that the concentrations of volatile species decreased in descending order of particle diameter (TSP, PM₁₀, and PM_{2.5}). Thus, it is likely that the volatilization hardly occurred. In other words, there was no negative error due to the volatilization of ionic species at Gosan.

The effect of water absorption is quantified by estimating the water content of PM₁₀ based on the particle composition data by GMM. The estimated water content is significant ($9.94 \mu\text{g}/\text{m}^3$) but still cannot fully explain the measured concentration difference between the two methods. It is suggested that organic hygroscopic species might play a role for that since the used gas/particle equilibrium mode, SCAPE2 cannot account for them and at Gosan. The concentration of organic species including water soluble organics were high at Gosan (Lee *et al.*, 2008).

After considering water content, discrepancy between GMM and BAM is reduced from 69% to 25%. Still, there remains discrepancy and the correlation between them is not good. Thus, to further identify the factors that might affect the measurement difference, the multiple regression analysis is carried out with the meteorological factors as independent variables. It is found that the measurement difference is mostly influenced by water content though could not fully account for the difference.

Thus, at present, the reason for the discrepancy is not fully understood, though it is certain that RH affects measurement difference significantly. Thus, to resolve the problem, the effects of other factors such as meteorological variable and unidentified hygroscopic compounds such as organic acids should be studied. It is vital that the measurement data of PM₁₀ should be accurate if we develop effective control strategy against it. As the Gosan station is one of the cleanest background areas in Korea with low emissions of anthropogenic air pollutants, the PM₁₀ concentration observed at Gosan based on a long-term data is used to establish a policy and verify modeling result. Thus, it is advised that care should be taken when using the PM₁₀ measurement

data at Gosan til June, 2008 until the reason for the measurement difference is fully identified.

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