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Effect of Precipitation on Air Pollutant Concentration in Seoul, Korea

Suhyang Kim, Ki-Ho Hong, Hwandon Jun[1], Young-Jae Park[2], Moojong Park[3], and Young Sunwoo[4],*

Department of Advanced Technology Fusion, Konkuk University, Seoul, Korea
[1]Department of Civil Engineering, Seoul National University of Technology, Seoul, Korea
[2]Seung Young Technical Corporation, Seoul, Korea
[3]Department of Civil Engineering, Hanseo University, Chungcheongnam-do, Korea
[4]Department of Environmental Engineering, Konkuk University, Seoul, Korea

*Corresponding author. Tel: +82-2-450-3541, Email: ysunwoo@konkuk.ac.kr

ABSTRACT

In this study, long-term rainfall data with irregular spatial distribution in Seoul, Korea, were separated into individual precipitation events by the inter-event time definition of 6 hours. Precipitation washout of PM_{10} and NO_2 concentrations in the air considering various complex factors were analyzed quantitatively. Concentrations of PM_{10} and NO_2 in the atmosphere were lower under condition of rainfall compared to that of non-precipitation, and a noticeable difference in average PM_{10} concentrations was observed. The reduction of concentrations of PM_{10} and NO_2 by rainfall monitored at road-side air monitoring sites was also lower than that of urban air monitoring sites due to continuous pollutant emissions by transportation sources. Meanwhile, a relatively smaller reduction of average PM_{10} concentration in the atmosphere was observed under conditions of light rainfall below 1 mm, presumably because the impact of pollutant emission was higher than that of precipitation scavenging effect, whereas an obvious reduction of pollutants was shown under conditions of rainfall greater than 1 mm. A log-shaped regression equation was most suitable for the expression of pollutant reduction by precipitation amount. In urban areas, a lower correlation between precipitation and reduction of NO_2 concentration was also observed due to the mobile emission effect.

Key words: Precipitation, Inter-event time definition, Air pollution, PM_{10}, NO_2

1. INTRODUCTION

Precipitation washout is one of the major mechanisms for removal of particulate pollutants in the air. In practice, the atmospheric concentration of particulate matter (PM) is a function of seasonal and site-specific characteristics, low in the wet season as rainfall in Korea is concentrated in summer from June to August. On the other hand, higher concentrations of PM have been observed in the spring and winter seasons (Lim *et al*., 2012).

Yoo *et al*. (2014) investigated the effect of precipitation scavenging effect on the reduction of gaseous and particulate pollutants during the wet season. The concentration of particulate matter with a diameter below 10 μm, i.e. PM_{10}, is greatly reduced. However, the reduction of gaseous pollutants such as SO_2, NO_2, CO, and O_3 was lower than that of particulate matter. Chate *et al*. (2003) also reported that the concentration of non-hygroscopic particles such as $CaCO_3$, $MgCO_3$, Zn, and Mn decreased by inertial impaction during the wet season, while the removal of hygroscopic particles such as NaCl and $(NH_4)_2SO_4$ in the air was intimately related with relative humidity.

However, many studies on precipitation washout of particulate matter in the air report only the results of a simple comparison between particulate matter concentrations under conditions of precipitation and non-precipitation (Barmpadimos *et al*., 2011; Akyuz *et al*., 2009). Other research has focused on the cloud condensation nuclei (CCN) of particulate pollutants in the air and the increment of rainfall amount by CCN formation (Qian *et al*., 2009; Choi *et al*., 2008; Jirak *et al*., 2006).

In general, the amount of the air pollutant reduction by precipitation scavenging effect can be affected by the amount, duration and intensity of rainfall. Real rainfall events have several characteristics such as rainfall volume, duration, average intensity, inter-event time (IET), peak intensity, and number of peaks. To obtain useful statistical characteristics from real rainfall data, independent events need to be identified from

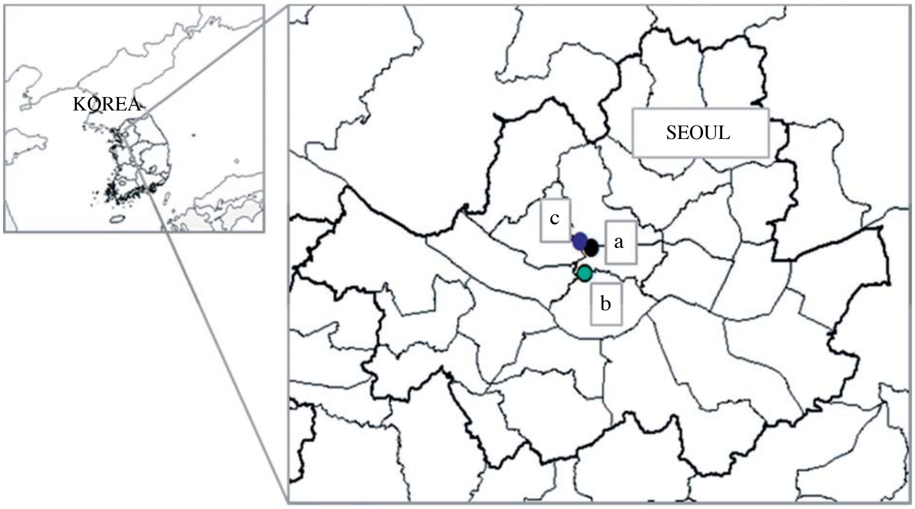

Fig. 1. Location of air and weather monitoring sites: (a) Seosomun urban air monitoring site, (b) Seoul-station roadside air monitoring site, (c) Seoul weather monitoring site.

the observed data. However, it is difficult to identify the independent rainfall events from rainfall records, which are made up of sequential pulses. There have been relatively few studies on detailed quantitative evaluation of the removal of atmospheric pollutants by rainfall in the literature because it is very difficult to understand the precipitation washout effect of particulate matter in each rainfall event. To solve problems like this, a statistical determination of Inter-event Time Definition (IETD), the minimum dry period between two rainfall pulses, is widely used in the field of hydrology, which is the study of the runoff, distribution, and quality of water on earth (Guo *et al.*, 1998).

In this study, long-term rainfall data with irregular distribution during a 10 year period in Seoul, Korea, were separated into individual precipitation events by IETD estimation. The precipitation washout of PM_{10} and NO_2 concentrations in the air were analyzed quantitatively including consideration of various complicated factors, and the reduction of PM_{10} and NO_2 concentrations by rainfall were also evaluated using regression analysis.

2. METHODOLOGY

2.1 Analysis Period and Air Monitoring Sites

Data of major pollutant concentrations such as PM_{10} and NO_2, and precipitation data were collected from national air monitoring sites and from the Korean Meteorological Administration (KMA, 2012) for the period of 1999 to 2008. PM_{10} concentration is measured by the β-ray absorption method and NO_2 concentration is measured by the chemiluminescent method at the air monitoring sites (MOE, 2012). The NO_2 data for 1999, which has a lower reliability, however, were excluded. PM_{10} data during Asian dust periods, as designated by the National Weather Service of Seoul, were also excluded to remove the effect of Asian Dust from our analysis. Asian Dust was observed for 114 days during our analysis period of ten years. Most of the precipitation patterns showed "local" characteristics such as rainfall occurring on the east side of Seoul, but not on the west. So it was determined that spatial averaging would only confuse our analysis. Therefore, for this research, the Seosomun urban air monitoring site and the Seoul-station roadside air monitoring site, which are located in the central part of Seoul and are close to the weather monitoring site about 2 km away from where we obtained the meteorological information, were selected as the target sites. The selected sites are shown in Fig. 1.

2.2 Definition of Precipitation Events

In this study, the IETD, which is obtained from serial correlation analysis (Adams *et al.*, 2000), was applied to define a precipitation event. As illustrated in Fig. 2, if the non-precipitation time duration between two rainfall events is greater than that of the determined IETD, the first and second precipitation events are considered to be independent. On the other hand, if non-precipitation time is smaller than that of the determined IETD, it is considered to be a continuous event, not two separate events.

The volume, duration, non-precipitation time interval and average intensity of rainfall can then be deter-

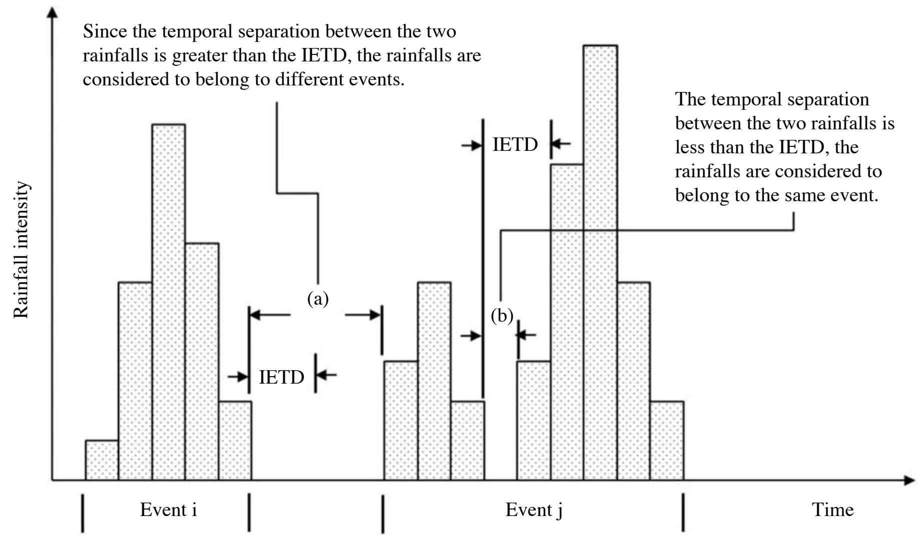

Fig. 2. Example of separation of two precipitation events.

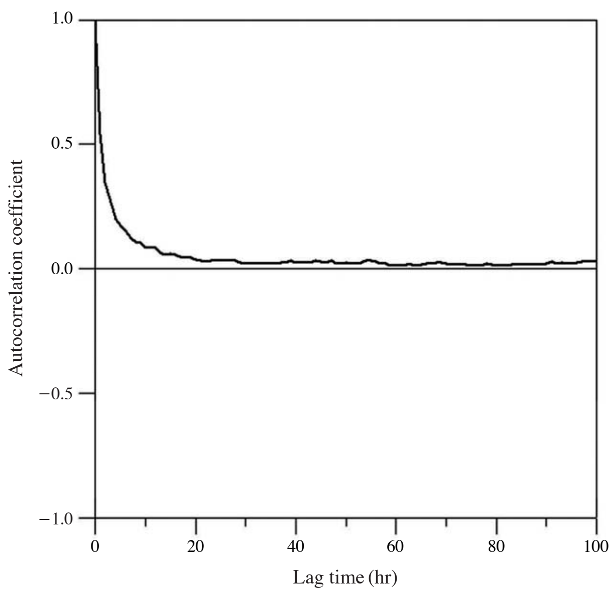

Fig. 3. Autocorrelation coefficients for Seoul weather station, Korea.

mined for the independent precipitation events. An event volume is defined as the sum of the hourly reported amount of precipitation for the separate event as determined by the IETD, and the duration of rainfall is the period from the start to the end of one precipitation event. The non-precipitation time interval is the time period from the end point of the previous precipitation event to the starting point of the next. The average event intensity can be calculated by dividing the event volume by the duration. The assumption that

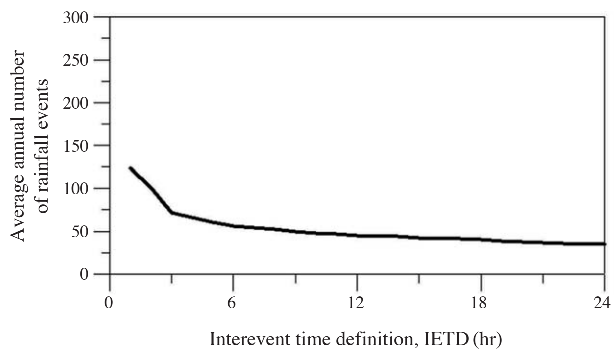

Fig. 4. Average annual number of rainfall events, in Seoul, Korea.

there is uniform rainfall volume distribution throughout the duration of an event is applied (Joksimović, 1999).

To separate out independent rainfall events from continual precipitation, the IETD needs to be defined initially. The methods used for this definition are autocorrelation, coefficient of variation (Nix, 1994), and average annual number of rainfall events (Nix, 1994; Heaney *et al.*, 1977). The autocorrelation method uses the lag time, when the coefficient of autocorrelation levels off near 0, as the IETD. The autocorrelation coefficient of Seoul weather station is close to 0.06 for a 12 hour lag time, as presented in Fig. 3. The method using average annual number of rainfall events, on the other hand, showed a relatively constant variation after the 6 hr IETD (Fig. 4).

Seoul is a megacity with a population of over 10 million, so air pollutant emissions should change dramat-

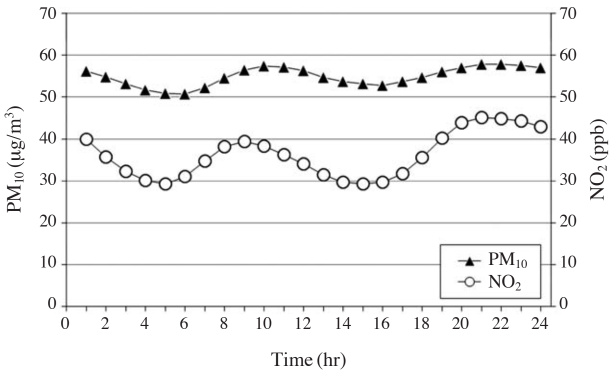

Fig. 5. Hourly variation of PM_{10} and NO_2 in Seoul in 2006, average concentrations of 27 air monitoring sites.

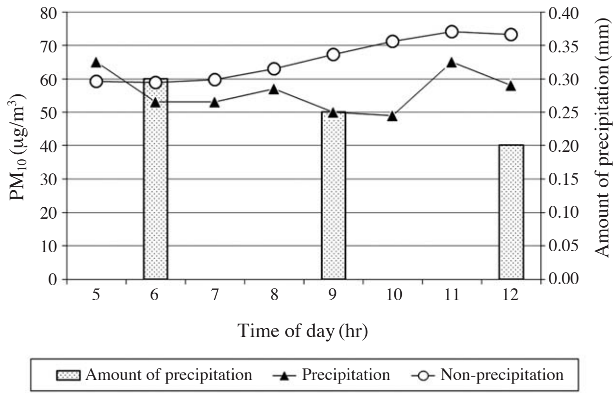

Fig. 6. Example of method for analysis of effect of precipitation scavenging on pollutant concentrations.

ically during periods of heavy commuting. Looking at the average hourly concentrations of PM_{10} and NO_2 for a sample year of 2006 measured at 27 air monitoring sites in Seoul we can see that there seems to be a fluctuation period of about six hours, as shown in Fig. 5, due to the impact of daily commuting pattern. Adams *et al.* (1986) and Kauffman (1987) also recommended that the IETD should be 6 hours for urban areas, in general. Therefore, the IETD in Seoul was determined to be 6 hours for this study.

2. 3 Method for Analyzing the Reduction Effect of Precipitation on PM_{10} and NO_2

Concentration data of PM_{10} and NO_2 for the 10 year period were separated according to conditions of precipitation and non-precipitation by using the pre-determined IETD. For a more accurate analysis, in general, concentration variation attributable to other parameters such as the emission amount, wind direction, and wind speed, should be excluded. Analyzing the reduction effect on the air pollutants due to precipitation scavenging effect only is also very difficult, as the concentration sometimes increases after the onset of precipitation. In this study, therefore, the determination of whether the concentration variation of pollutants was caused by primarily precipitation or by a variation in emission pattern was performed as follows:

1) Calculation of the "time-of-day" hourly average concentration of pollutants during non-precipitation events from the data for ten years, i.e. the 10-year concentration average for 1 am, 2 am, ⋯, 11 pm, 12 am, all 24 excluding hours with precipitation.

2) Subtraction of the concentration one hour prior to the beginning of precipitation from that at the termination of rainfall for each independent precipitation event as determined by IETD.

3) Thus, the effect of precipitation scavenging can be defined as the difference between the concentration variation under the conditions of the precipitation event calculated from Step 2 and the difference in the 10-year average concentrations calculated from Step 1 for the two times specified in Step 2.

$$CV_{pre}=C_{pre\text{-}end}-C_{pre\text{-}beg\text{-}1} \quad \text{(Eq. 1)}$$

$$ACV_{non\text{-}pre}=AC_{pre\text{-}end}-AC_{pre\text{-}beg\text{-}1} \quad \text{(Eq. 2)}$$

$$E_{pre}=CV_{pre}-ACV_{non\text{-}pre} \quad \text{(Eq. 3)}$$

where,

CV_{pre}=Concentration variation under condition of precipitation event
$C_{pre\text{-}end}$=Concentration at termination of precipitation event
$C_{pre\text{-}beg\text{-}1}$=Concentration at 1 hour prior to beginning of precipitation event
$ACV_{non\text{-}pre}$=Difference in 10-year average concentrations under condition of non-precipitation between the two times specified in Eq. 1 event
$AC_{non\text{-}pre\text{-}end}$=10-year average non-precipitation conc. for time specified by event Cpre-end
$AC_{non\text{-}pre\text{-}beg\text{-}1}$=10-year average non-precipitation conc. for time specified by event Cpre-beg-1
E_{pre}=Effect of precipitation event on PM_{10} and NO_2 concentration

The effect of precipitation scavenging on PM_{10}, as mentioned above, can also be illustrated using a sample as in Fig. 6. Precipitation was observed at 6 am, 9 am and 12 pm with an interval of 3 hours each. Therefore, the period from 6 am to 12 pm is defined as a single precipitation event, because the IETD was set to be 6 hours. The difference in the 10-year average concentrations for 12 pm and 6 am under conditions of non-precipitation ($ACV_{non\text{-}pre}$) is $+14\ \mu g/m^3$ which, by definition, is the difference between $73\ \mu g/m^3$, the 10-year

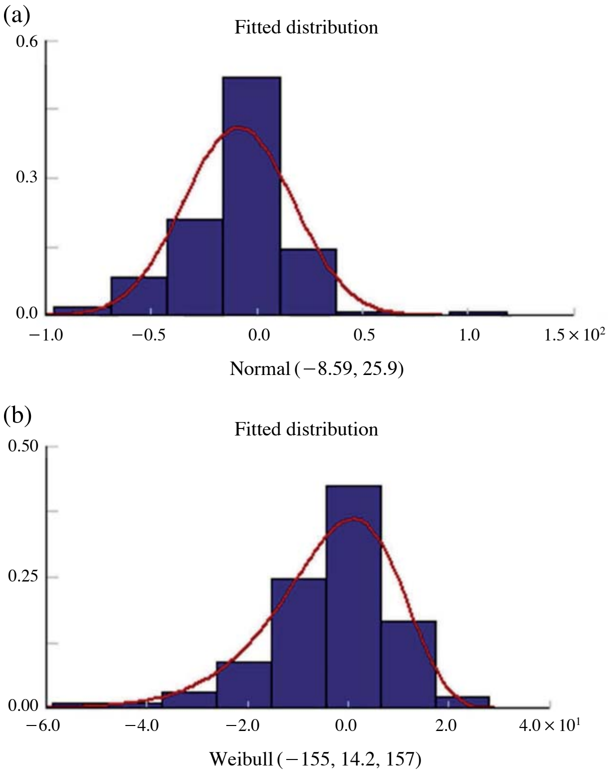

Fig. 7. Examples of CDF (Cumulative Density Function): (a) Normal distribution of Group 1 for PM_{10}, (b) Weibull distribution of Group 1 for NO_2.

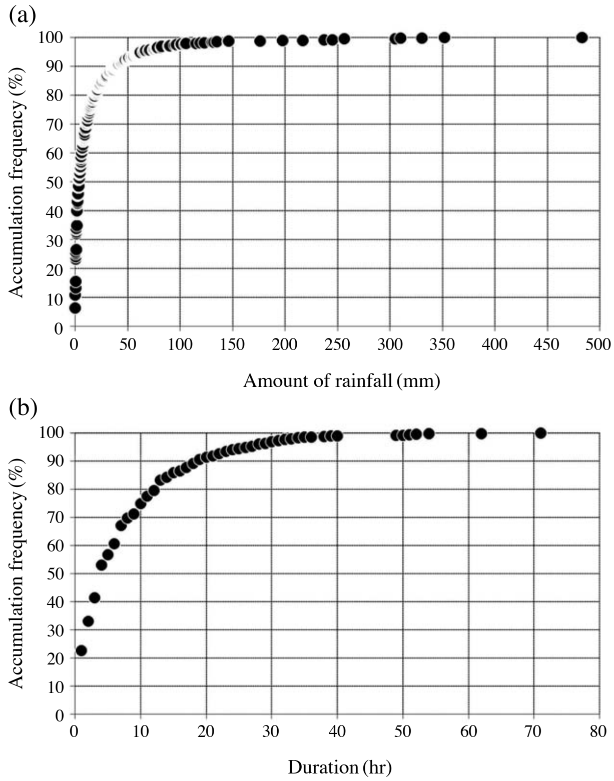

Fig. 8. Characteristics of precipitation during 10 years in Seoul: (a) amount of rainfall, (b) duration of rainfall.

average at 12 pm, signifying the time of rainfall termination of the event ($AC_{non\text{-}pre\text{-}end}$), and the concentration of 59 μg/m^3 at 5 am, representing the 10-year average one hour prior to the beginning of the event ($AC_{non\text{-}pre\text{-}beg\text{-}1}$). On the other hand, the concentration variation during the precipitation event at the monitoring site (CV_{pre}) can be calculated as $58-65=-7$ μg/m^3 (Fig. 6). Finally, the effect of precipitation on PM_{10} (E_{pre}) for this sample event can be defined as $(-7)-(+14)=-21$ μg/m^3. Such calculations were carried out for all precipitation events during the 10 year period as defined by the IETD. The utilization of long-term averages and the fact that atmospheric concentrations of most air pollutants in urban areas, including PM_{10} and NO_2, usually follow a general repetitive diurnal pattern helps validate such an approach as the one explained above.

2.4 Goodness-of-fit Test

Goodness-of-fit tests are generally used to identify the appropriate probability distribution model that best fits the data (Bentler *et al.*, 1980). In this study, the Stat::Fit software (Benneyan, 1998) was utilized for the goodness-of-fit test, and the results of the goodness-of-fit tests are shown in Fig. 7.

3. RESULTS AND DISCUSSION

3.1 Characteristics of Precipitation Events Derived by Application of IETD

The characteristics of precipitation events derived by application of the IETD in Seoul are presented in Fig. 8. Precipitation events occurred in Seoul 946 times during our ten-year period, and the duration of precipitation ranged from 1 to 71 hours. The amount of precipitation also ranged from 0.1 to 483.3 mm during the entire period. Precipitation cases with a duration of less than one hour had the highest frequency with 22.6% (214 times), and a duration of 1 to 2 hours was next with 10.4% (99 times). Overall, precipitation events with a duration of less than 12 hours occurred a total of 775 times, and this accounted for 80% of the total. Therefore, it should be noted that short duration precipitation events were much more prevalent in Seoul.

The amount of precipitation less than 1 mm had a ratio of 32.1% (304 times) while amounts between 1 to 10 mm accounted for 36.7% (347 times) during the 10-year period. Thus, precipitation events of less than

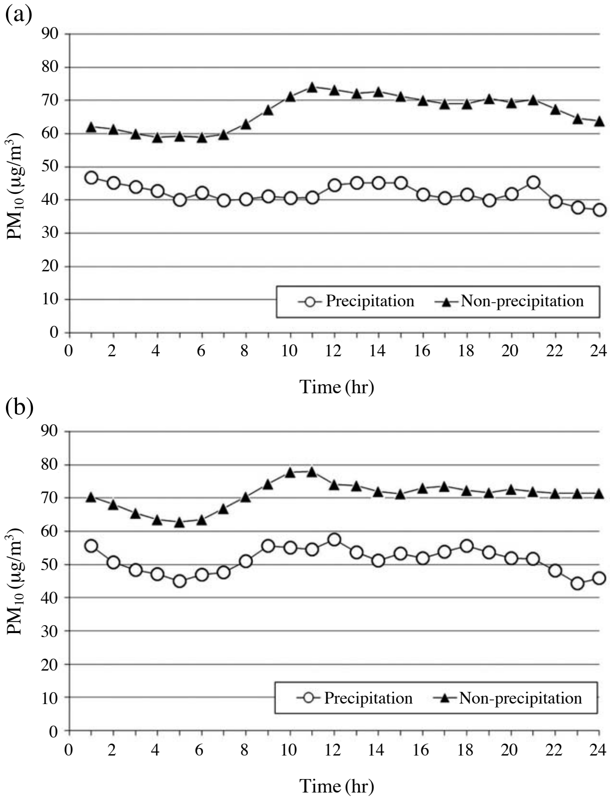

Fig. 9. PM_{10} hourly variations under conditions of precipitation and non-precipitation: (a) urban air monitoring sites, (b) roadside air monitoring sites.

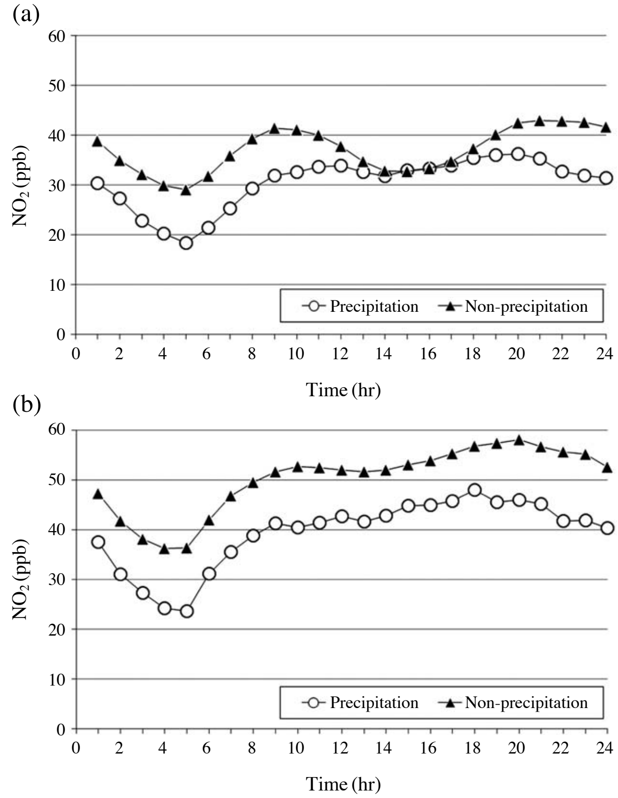

Fig. 10. NO_2 hourly variations under conditions of precipitation and non-precipitation: (a) urban air monitoring sites, (b) roadside air monitoring sites.

10 mm in Seoul over these 10 years accounted for about 70% of the total, whereas precipitation cases of over 200 mm were mainly concentrated in July, August, and September when our peninsula is affected by the monsoon season and multiple typhoons.

3. 2 Analyses of Hourly Concentration Variations of PM_{10} and NO_2

The hourly concentration variations of PM_{10} and NO_2 at urban and roadside air monitoring sites during conditions of precipitation and non-precipitation, respectively, are shown in Fig. 9 and Fig. 10. Fig. 9(a) shows that the average difference of average hourly concentrations of PM_{10} between the wet and dry cases was 24.5 $\mu g/m^3$ at our urban air monitoring sites. The average PM_{10} concentration at these sites during precipitation events was about 63% of non-precipitation conditions. The pattern of hourly PM_{10} concentration variation under non-precipitation conditions was similar with that of typical urban areas. However, PM_{10} concentrations under precipitation conditions during daytime did not increase but stayed relatively constant in spite of increasing number of vehicles. This may be explained by a combination of the following factors:

1) wash-out effect of precipitation, 2) low PM_{10} production caused by reduction of photo-chemical reactions during rainfall, and 3) activity reduction of emission sources such as construction sites.

Fig. 9(b) also shows that the average difference of average PM_{10} concentrations between precipitation and non-precipitation events were 19.9 $\mu g/m^3$ at roadside air monitoring sites. The average PM_{10} concentration at road-side air monitoring sites during precipitation events were about 72% of non-precipitation conditions. At road-side air monitoring sites, the pattern of hourly PM_{10} concentration variation under conditions of precipitation and non-precipitation were similar with each other. This may mean that the hourly PM_{10} concentration at road-side sites increase by a relatively stronger direct effect of vehicle emissions despite the rainfall. Consequently, the reduction effect of precipitation scavenging at urban sites was higher than that at road-side air monitoring sites. The ratio of wet to dry concentrations for PM_{10} at background sites in Canada was 0.66 (Veira *et al.*, 2013). This ratio was similar to our value for the urban air monitoring site while that of the road-side air monitoring site was much closer to one. This also supports the argument that on-road emissions somewhat negate the wash-out effect of precipitation.

As shown in Fig. 10(a), the average differences of average NO_2 concentration between precipitation and non-precipitation events were 7.8 ppb at the monitoring sites. The average NO_2 concentration during precipitation events was about 80% of non-precipitation conditions. Therefore, we could confirm that the reduction effect of precipitation scavenging on NO_2 was lower than that of PM_{10} at our urban and road-side sites. Under non-precipitation conditions, the NO_2 concentration at urban sites increased in proportion to the traffic in the morning, while decreasing presumably due to photochemical reaction during the daytime. NO_2 concentration variation during daytime under precipitation conditions was not observed. At road-side sites, as shown in Fig. 10 (b), the NO_2 concentration variation under the conditions of non-precipitation were similar with the case of precipitation, just like PM_{10}, because the amount of NO emissions/NO_2 production by vehicles was presumably larger than NO_2 reduction by photochemical reaction.

3.3 Reduction Probabilities of PM_{10} and NO_2 Concentrations by Precipitation

The amount of rainfall was classified into six groups; less than 1 mm, 1.1～5 mm, 5.1～10 mm, 10.1～20 mm, 20.1～50 mm, and over 50 mm. Then, distributions of concentration reduction by precipitation for each group were estimated through the goodness-of-fit test. Estimates are Maximum Likelihood Estimation (MLE), Lower Bound unknown, Interval Type equal probability, Accuracy of fit 0.0003, Level of Significance 0.05, Distribution Type continuous distributions, and the parameter is unbounded. The Normal distribution was selected in preference regardless of rank among the results of accepted distribution types. After that, a CDF (Cumulative Density Function) for each type was applied to estimate the probability that the concentration will be decrease over 0 after precipitation relative to non-precipitation times.

Table 1 presents distribution types and probabilities for the six groups of precipitation amount classification, as mentioned above. In group 1, less than 1 mm, we were not able to fit any distribution to the PM_{10} and NO_2 reductions. The "No fit" in group 1 means that the fluctuation of PM_{10} and NO_2 concentrations after precipitation changes randomly. On the other hand, the other groups showed mostly Normal distributions, except for the NO_2 in group 2 which showed a Weibull distribution.

Most cases in group 1 were drizzle events with short-term light rain averaging 2.2 hours. Because reduction mechanisms such as collision or absorption between pollutants and rain drops could not be very active, washout by precipitation appeared to have little effect on pollutant removal. When the amount of precipitation is less than 1 mm, alternatively, an increase of PM_{10} concentration in the atmosphere may be observed, because the effect of traffic and other emissions can be higher than the washout effect of the rain. Castro *et al*. (2010) also reported that if the rain intensity is about 0.6 mm/h or lower, the result may be a considerable increase in the number of aerosols measured - up to 89% more - with an increase in the number of particles smaller than 1.3 μm and a decrease in the number of particles larger than 1.3 μm.

The probability of PM_{10} concentration reduction increased with amount of rainfall with a high of 80.5% in group 6 when the amount of rainfall was greater than 50 mm. From the results of Castro *et al*. (2010), the detected number of particles decreased 20%, and large- and small-sized particles also decreased all together during rain events with intensities of over 3.2 ± 1.5 mm/h. However, correlations between the probabilities of NO_2 concentration reduction and amount of rainfall was not observed, as the probability of NO_2 concentration reduction decreased from 56.8% in group 2 to 53.9% in group 6.

Table 1. Probability and goodness of fit for concentration reduction of PM_{10} and NO_2 relative to amount of rainfall.

		Rainfall (mm)					
		Group 1 < 1	Group 2 1.1～5	Group 3 5.1～10	Group 4 10.1～20	Group 5 20.1～50	Group 6 > 50
Duration (hr)		2.2	4.9	7.1	10.6	15.4	26.2
Frequency	PM_{10}	275	200	104	102	98	68
	NO_2	268	191	102	95	87	62
Distribution type	PM_{10}	No fit	Normal	Normal	Normal	Normal	Normal
	NO_2	No fit	Weibull	Normal	Normal	Normal	Normal
Probability (%)	PM_{10}	–	63.0	61.3	71.5	71.7	80.5
	NO_2	–	56.5	58.8	52.7	58.0	53.9

Table 2. Average PM_{10} and NO_2 concentration reduction by precipitation scavenging.

		Rainfall (mm)					
		Group 1	Group 2	Group 3	Group 4	Group 5	Group 6
Average amount of rainfall (mm)		0.5	2.7	7.3	14.3	31.8	112.9
PM_{10} (μg/m^3)	Air monitoring site	−0.33	−8.59	−8.13	−19.58	−21.34	−25.55
	Road-side air monitoring site	−1.75	−3.77	−2.06	−17.50	−18.98	−30.10
NO_2 (ppb)	Air monitoring site	−1.58	−3.62	−2.74	−1.20	−2.97	−1.44
	Road-side air monitoring site	−2.19	−3.10	−2.75	−4.62	−5.08	−4.61

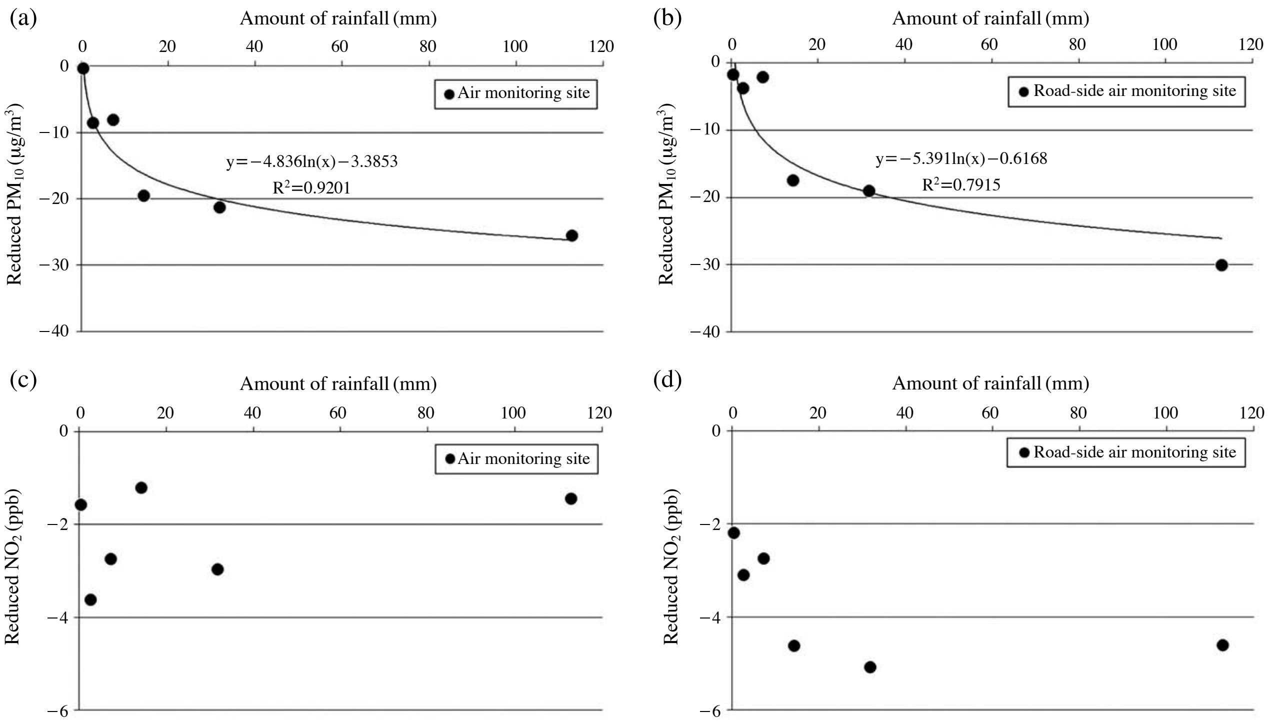

Fig. 11. Regressions of concentration reduction of PM_{10} and NO_2 according to amount of precipitation: (a) PM_{10} at urban air monitoring sites, (b) PM_{10} at roadside air monitoring sites, (c) NO_2 at urban air monitoring sites, (d) NO_2 at roadside air monitoring sites.

3. 4 Regressions Analysis of PM_{10} and NO_2 Concentration with Respect to Amount of Rainfall

The average pollutant concentration reduction of each group classified by amount of rainfall was calculated (Table 2). The PM_{10} concentration reduction, in general, increased with amount of rainfall for both urban and roadside air monitoring sites: group 1 (0.5 mm average precipitation), group 2 (2.7 mm average precipitation), group 3 (7.3 mm average precipitation), group 4 (14.3 mm average precipitation), group 5 (31.8 mm average precipitation), group 6 (112.9 mm average precipitation), had concentration reductions of −0.3 μg/m^3, −8.6 μg/m^3, −8.1 μg/m^3, −19.6 μg/m^3, −21.3 μg/m^3, −25.6 μg/m^3, respectively.

The PM_{10} concentration reductions for the two group pairs 2, 3 and 4, 5 were quite similar, even with a significant difference in the amount of average precipitation. The concentration reduction difference of PM_{10} between groups 3 and 4, however, was 11.5 μg/m^3. PM_{10} concentration reduction due to precipitation scavenging seems to have a significant critical point, maybe even a shift in dominant mechanism, around a rainfall amount of 10 mm.

The log regression equations for effect of PM_{10} concentration reduction by precipitation are as follows:

Seosomun urban air monitoring site:

$$y=-4.83ln(x)-3.385, \qquad R^2=0.920 \qquad \text{(Eq. 4)}$$

Seoul-station road-side air monitoring site:

$$y = -5.39 ln(x) - 0.616, \quad R^2 = 0.791 \quad \text{(Eq. 5)}$$

where,
y = concentration reduction of PM_{10} (μg/m^3)
x = amount of rainfall (mm)

A log-shaped regression equation was most suitable for the expression of pollutant reduction by precipitation scavenging, as can be seen by the R^2 value for the reduction of PM_{10} concentration at the urban air monitoring site being 0.920. From the estimated log-shaped regression equation, the nonlinear correlation between precipitation and reduction of PM_{10} concentration is well represented (Fig. 11(a)). It has been reported that PM_{10} levels reduce significantly for precipitation amounts up to around 5 mm/day, whereas for larger values of precipitation amounts its relative effect diminishes (Barmpadimos *et al.*, 2011).

The R^2 on the reduction of PM_{10} concentration at the road-side air monitoring site was 0.792 (Fig. 11(b)) which was lower than that of the urban air monitoring site. For NO_2 concentrations at road-side air monitoring sites (Fig. 11(d)), a much lower correlation between precipitation and concentration reduction was observed, most likely due to the mobile emission effect. Plaude *et al.* (2012) also reported that the reduction effect of precipitation scavenging on air pollutants was low due to the sources on the surface layer.

These regression equations give us a quantitative analysis regarding PM_{10} concentration reduction with increase of precipitation. Through comprehensive analysis of this and the previous section, there is greater probability of large reductions in PM_{10} concentration with increase in precipitation amount. The correlation between average concentration reduction and amount of rainfall is quite high for PM_{10}, but, there is an inherent numerical error because of using averages. The presence of this error between the actually reduced concentrations and the estimated concentration reductions using regression equations needs to be recognized.

The ranges of NO_2 concentration reduction by precipitation at urban and road-side air monitoring sites were 1~4 ppb, 2~5 ppb, respectively (Table 2). The NO_2 concentrations were reduced under precipitation but the NO_2 concentration reduction and rainfall at both site types had extremely low correlation (Fig. 11 (c) and (d)). Lim *et al.* (2013), however, analyzed that the NO_2 concentration gradually decreases with increased rainfall, and especially showed the largest reduction efficiency to be events with over 100 mm of rainfall. Finally, we need to realize that the selected sites in this study were centrally located in Seoul, so the reduction effect of precipitation should be underestimated due to the influence of emissions from the mobile sector being a major NO_2 source.

4. SUMMARY AND CONCLUSIONS

In this study, precipitation data for ten years in Seoul was categorized as independent rainfall events by using the inter-event time definition of 6 hours. The washout effects of precipitation scavenging on the removal of PM_{10} and NO_2 were evaluated quantitatively, and regression analyses of PM_{10} and NO_2 concentration reduction by effect of rainfall was also performed.

The concentrations of PM_{10} and NO_2 in the atmosphere were lower under conditions of rainfall relative to that of non-precipitation, and a noticeable difference in the average PM_{10} concentrations was observed. The reduction of concentrations of PM_{10} and NO_2 by rainfall monitored at road-side air monitoring sites was smaller than that of urban air monitoring sites due to the continuous pollutant emissions by traffic. Meanwhile, a relatively poor reduction of average PM_{10} concentration in the atmosphere was observed under the condition of light rainfall - below 1 mm, presumably because the effect of pollutant emissions was higher than that of precipitation scavenging, whereas an obvious reduction of pollutants was shown under conditions of rainfall greater than 1 mm.

A log-shaped regression equation was most suitable for the expression of pollutant reduction by precipitation scavenging effect, especially as the R-square on the reduction of PM_{10} concentration at the urban air monitoring site was 0.920. From the estimated log-shaped regression equation, the nonlinear correlation between precipitation and reduction of PM_{10} concentration was represented. In urban areas, a relatively lower correlation between precipitation and reduction of NO_2 concentration was also observed, most likely, due to the mobile emission effect.

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REFERENCES

Adams, B., Fraser, H., Howard, C., Sami Hanafy, M. (1986) Meteorological Data Analysis for Drainage System Design. Journal of Environmental Engineering 112, 827-848.

Adams, B.J., Papa, F. (2000) Urban Stormwater Management Planning with Analytical Probabilistic Models. Wiley.

Akyuz, M., Cabuk, H. (2009) Meteorological variations of $PM_{2.5}$/PM_{10} concentrations and particle-associated polycyclic aromatic hydrocarbons in the atmospheric environment of Zonguldak, Turkey. Journal of Hazardous Materials 170, 13-21.

Barmpadimos, I., Hueglin, C., Keller, J., Henne, S., Prevot, A.S.H. (2011) Influence of meteorology on PM_{10} trends and variability in Switzerland from 1991 to 2008. Atmospheric Chemistry and Physics 11, 1813-1835.

Benneyan, J.C. (1998) Software Review: Stat::Fit, OR/MS today. the Institute for Operations Research and the Management Sciences.

Bentler, P.M., Bonett, D.G. (1980) Significance tests and goodness of fit in the analysis of covariance structures. Psychological Bulletin 88, 588-606.

Castro, A., Alonso-Blanco, E., Gonzalez-Colino, M., Calvo, A.I., Fernandez-Raga, M., Fraile, R. (2010) Aerosol size distribution in precipitation events in Leon, Spain. Atmospheric Research 96, 421-435.

Chate, D.M., Rao, P.S.P., Naik, M.S., Momin, G.A., Safai, P.D., Ali, K. (2003) Scavenging of aerosols and their chemical species by rain. Atmospheric Environment 37, 2477-2484.

Choi, Y.-S., Ho, C.-H., Kim, J., Gong, D.-Y., Park, R.J. (2008) The Impact of Aerosols on the Summer Rainfall Frequency in China. Journal of Applied Meteorology and Climatology 47, 1802-1813.

Guo, Y., Adams, B.J. (1998) Hydrologic analysis of urban catchments with event-based probabilistic models: 1. Runoff volume. Water Resources Research 34, 3421-3431.

Heaney, J.P., Huber, W.C., Medina, M.A.J., Murphy, M.P., Nix, S.J., Hasan, S.M. (1977) Nationwide Evaluation of Combined Sewer Overflows and Urban Stormwater Discharges: Cost Assessment and Impacts, Vol. II. U.S. Environmental Protection Agency.

Jirak, I.L., Cotton, W.R. (2006) Effect of Air Pollution on Precipitation along the Front Range of the Rocky Mountains. Journal of Applied Meteorology and Climatology 45, 236-245.

Joksimovie, D. (1999) SCREENING MODEL FOR ADVANCED REAL TIME CONTROL (SMARTC), Graduate Department of Civil Engineering. University of Toronto.

Kauffman, G.M. (1987) A Comparison for analytical and simulation models for drainage system design: SUDS versus STORM, Dep. of Civil Eng. Univ. of Toronto, Ontario, Canada.

KMA (2012) Annual Climatological Report. Korea Meteorological Administration.

Kumar, A., Sarin, M.M. (2010) Atmospheric water-soluble constituents in fine and coarse mode aerosols from high-altitude site in western India: Long-range transport and seasonal variability. Atmospheric Environment 44, 1245-1254.

Lim, D., Lee, T.J., Kim, D.S. (2012) Quantitative Estimation of Precipitation Scavenging and Wind Dispersion Contributions for PM_{10} and NO_2 Using Long-term Air and Weather Monitoring Database during 2000～2009 in Korea. Korean Society for Atmospheric Environment 28, 325-347. (Korean)

Lim, D., Lee, T.J., Kim, D.S. (2013) Development and Validation Test of Effective Wet Scavenging Contribution Regression Models Using Long-term Air Monitoring and Weather Database. Korean Society for Atmospheric Environment 29, 297-306. (Korean)

MOE (2012) Annual Report of Ambient Air Quality in Korea. Ministry of Envionment.

Nix, S.J. (1994) Urban Stormwater Modeling and Simulation. Taylor & Francis.

Plaude, N.O., Stulov, E.A., Parshutkina, I.P., Pavlyukov, Y.B., Monakhova, N.A. (2012) Precipitation effects on aerosol concentration in the atmospheric surface layer. Russian Meteorology and Hydrology 37, 324-331.

Qian, Y., Gong, D., Fan, J., Leung, L.R., Bennartz, R., Chen, D., Wang, W. (2009) Heavy pollution suppresses light rain in China: Observations and modeling. Journal of Geophysical Research 114, D00K02.

Sanchez-Ccoyllo, O.R., de Fatima Andrade, M. (2002) The influence of meteorological conditions on the behavior of pollutants concentrations in Sao Paulo, Brazil. Environmental Pollution 116, 257-263.

Veira, A., Jackson, P.L., Ainslie, B., Fudge, D. (2013) Assessment of background particulate matter concentrations in small cities and rural locations? Prince George, Canada. Journal of the Air & Waste Management Association 63, 773-787.

Yoo, J.M., Lee, Y.R., Kim, D., Jeong, M.J., Stockwell, W.R., Kundu, P.K., Oh, S.M., Shin, D.B., Lee, S.J. (2014) New indices for wet scavenging of air pollutants (O_3, CO, NO_2, SO_2, and PM_{10}) by summertime rain. Atmospheric Environment 82, 226-237.

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