Characteristics of Recent Severe Haze Events in Korea and Possible Inadvertent Weather Modification

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Abstract

The quantitative understanding of aerosol-cloud-precipitation interactions is still insufficient despite substantial amounts of previous efforts to solve this problem since it has inherent complexity. Probably we might need overwhelming aerosol forcings well beyond cloud and precipitation variabilities in order to identify and attribute its discernible effect on clouds and precipitation. Korea recently suffered from severe haze episodes that appear to be largely long-range transported from China, which could be made the best use of to evaluate the hypothesis of enhanced aerosol impacts on clouds and precipitation. A couple of severe hazes in January 2013 originated from eastern China were also observed in the mid-Korean peninsula. The cloud systems overlapped with aerosol plumes seemed to be modified such that drizzle-type light precipitation lasted longer within half a day than the operational weather forecast because precipitation might be extended at a less rate due to increases in number concentration of smaller cloud droplets as shown by a sensitivity test using the WRF model. This study shows a possible evidence of inadvertent weather modifications by enhanced aerosols. It also implies that Korea would be a better testbed to investigate aerosol impacts on weather.

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1. Introduction

Atmospheric haze is generally defined as visibility-impairment phenomenon whose visibility less than 10km and relative humidity less than 90\% (Wu et al. 2006). Visibility degradation mostly results from an increase in atmospheric aerosols which can scatter and absorb the sunlight. In East Asia, China has suffered from air pollution and extreme haze in the past 30 years, which could further impact not only public health but also visibility-impairment (He et al. 2002; Tie et al. 2009; Liu et al. 2013). Various kinds of aerosols have been emitted and additionally formed during their transport along with other pollutants.

Korea tends to be influenced by various air masses with different pollutant levels since Korea is located downstream of China (Oh et al. 2015; Lee et al. 2013). Several heavy haze events were recently observed in Korea from 2011 to 2013. There were more than 20 haze days in Beijing during only January 2013 with PM2.5 hourly concentration exceeding 600 \(\mu\text{g m}^{-3}\) (Tao et al. 2014; Uno et al. 2014). Certainly this heavy haze phenomenon was also detected in the whole Korean peninsula after a couple of days. Pollution aerosols would influence the meteorology by modifying the atmospheric cloud microphysics as well as radiative budget through aerosol scattering and absorbing capability. The enhanced pollution aerosols have been also known to slow down cloud drop coalescence and accretion, and thus delay the conversion of cloud water to precipitation by increasing smaller droplets (Albrecht 1989; Rosenfeld et al. 2008). Therefore, severe haze transport in accompanied with any cloud systems could modify the evolution of clouds and precipitation in terms of certain temporal and spatial scales.

Meanwhile very few studies have been done to investigate aerosol influences on synoptic weather. Ding et al. (2013) addressed weather modification of severe air pollution in China after Grell et al. (2011) demonstrated some effects of forest fires in Alaska on regional weather using a cloud-resolving model. Both cases are unusual aerosol episodes accompanied with severe haze, thus providing a better test-bed for the study of aerosol-weather relationship. In this regard, an influence of Chinese haze recently observed in Korea can be a discernible forcing, what we call, an external one from the outer domain of Korea, since both PM2.5 and PM10 mass concentrations are an order of magnitude greater than their average values. The other merit of an external forcing to the analysis domain is to reduce its masking effect by feedback mechanisms of aerosol-cloud-precipitation interactions such as aerosol scavenging by precipitation (Lee and Feingold 2010; Paimenel et al. 2015), admitting that it is impossible to completely escape from its inherent generic character.

This study briefly addresses characteristics of several dense haze episodes having recently occurred along with its regional transport from China to Korea from 2011 to 2013. Further we demonstrate a possible evidence of aerosol impacts on clouds and precipitation with a special emphasis on January 2013, and also briefly conduct numerical simulations to explain how severe hazes could modify the weather.

2. Data and method

Several Air Pollution Intensive Monitoring (APIM) Stations were established and has been managed by Korean Ministry of Environment in order to obtain comprehensive information of air quality around Korea. APIM stations of Baengnyeongdo (BN) and Seoul (SL) are the main sites used in this study. BN is located to the west about 200km far from SL and upwind region of SL in case of the dominant westerly flow (Fig. 1). PM10 is measured by beta gauge method with Metone BAM (1020 model), and PM2.5 is measured by gravitation method with a Tapered Element Oscillating Microbalance (TEOM 1400a). Aerosol light scattering...
coefficient \( (\sigma_{\text{sp}}) \) is obtained with a Nephelometer (TSI 3563). Variability in \( \sigma_{\text{sp}} \) is well known as an excellent proxy for variation in aerosol mass concentration. Unfortunately nephelometers use have neither an impactor for the specified size cut nor dehumidifier yet. But significant positive correlations were shown between \( \sigma_{\text{sp}} \) and PM2.5 with different humidity levels as displayed later. We have examined hourly particle mass concentrations and 5-min \( \sigma_{\text{sp}} \) during 3 years (2011–2013) except for earlier 4-month period.

Based on the previous experiences, we developed a procedure to classify various categories of severe haze events. First, PM2.5 and PM10 mass concentrations are used such that the events are classified as a haze if aerosol loading is greater than annual average plus one standard deviation. Next step is time lag of PM2.5 concentration between two monitoring stations (BN and SL), which have been arranged from west to east by considering the dominant westerly conditions. The long-range transported episodes are defined in case that PM2.5 and PM10 concentrations of SL increase several hours later after those of BN increase. Thirdly, we checked out whether 850 hPa backward trajectory reaching SL shows airmass coming from west or northwest. Finally the events are defined as haze ones when the ratio of PM2.5 to PM10 is larger than 0.7. The ratio value of 0.7 was arbitrary determined from previous experiences. Especially PM2.5 mass concentration substantially increases relative to PM10 in the heavy haze event, whereas PM10 increases rather than PM2.5 in case of Yellow Sand. If the ratio is less than 0.3, the events are defined as Yellow Sand, and the others are mixed haze. Yellow Sand events are generally known as coarse-mode dominant in aerosol size distribution (Chun et al. 2001; Kim and Park 2001). The following events are classified as domestic ones when PM2.5 and PM10 concentrations increase only at SL and those of BN are as low as the usual, which episodes have been excluded for the further analysis. Most analyses are limited to long-range transported haze since they are thought to be good candidates for the study of aerosol influences on weather, as emphasized in the Introduction. Examples of each haze are shown in Fig. S1.

To investigate the possible modification of clouds and precipitation during the haze episodes, we conduct a simplified sensitivity test using the Weather Research and Forecasting (WRF) version 3.4 with the Advanced Research WRF dynamic solver. The model was run in three two-way nested domains with a horizontal grid size of 30 km (61 x 62), 10 km (88 x 82), 3.3 km (166 x 73), covering East Asia, Korea, and mid-Korean Peninsula, respectively (Fig. S2) with 51 vertical sigma levels up to 50 hPa. We used the NCEP Final Operational Global Analysis (FNL) data on 1.0° x 1.0° grids, prepared every 6 h, to provide the boundary and initial conditions for the sensitivity tests. Model integration was conducted during a 24-hour period starting at every 03 Local Time (LT). WRF double-moment 6-class (WDM6) microphysics scheme is used (Linn and Hong 2010) since it can predict cloud droplet number concentrations with the explicit cloud condensation nuclei (CCN) distribution at a reasonable computational cost for the mesoscale domain. The macroscopic features of clouds and precipitation can be reasonably well represented with the WDM6 scheme in the mesoscale domain though it is not a fully bin-spec-

![Fig. 2. Histograms of 5-min average \( \sigma_{\text{sp}} \) of BN and SL for 2011 to 2013. The sample numbers of BN and SL are 252,777 and 235,203, respectively.](image)

### Table 1. Size, coverage, and basic statistics of data analyzed.

| Site | Property | Length of record (yr) | Resolution | \( N_{\text{unc}} \) | Coverage (%) | Arithmetic Mean | Arithmetic Std | Geometric Mean | Geometric Std | Median |
|------|----------|-----------------------|------------|----------------|--------------|----------------|----------------|---------------|---------------|--------|
| SL   | PM2.5 (\( \mu g \text{ m}^{-3} \)) | 3 | 1 h | 24737 | 94 | 31.1 | 22.9 | 23.8 | 2.2 | 25.0 |
|      | PM10 (\( \mu g \text{ m}^{-3} \)) | 3 | 1 h | 25088 | 95 | 46.3 | 33.8 | 37.0 | 2.0 | 40.0 |
|      | \( \sigma_{\text{sp}} \) (Mm\(^{-3}\)) | 0.33 \(^d\) | 5 min | 220908 | 79 | 143.6 | 128.5 | 98.9 | 2.5 | 102.0 |
| BN   | PM2.5 (\( \mu g \text{ m}^{-3} \)) | 3 | 1 h | 23981 | 91 | 23.1 | 20.6 | 16.6 | 2.3 | 17.0 |
|      | PM10 (\( \mu g \text{ m}^{-3} \)) | 3 | 1 h | 22140 | 84 | 41.0 | 35.1 | 31.8 | 2.1 | 31.6 |
|      | \( \sigma_{\text{sp}} \) (Mm\(^{-3}\)) | 0.33 \(^d\) | 1 h | 2880 | 100 | 99.0 | 94.6 | 71.4 | 2.2 | 63.6 |

\(^d\) Indicates period from Jan to Apr in 2011. \(^e\) Indicates period from May in 2011 to Dec in 2013.

\( N_{\text{unc}} \) is the number of data points prior to filtering. \(^f\) Geometric mean = \( \exp \{ \text{mean}[\ln(x)] \} \). \(^g\) Geometric std. = \( \exp \{ \text{std.}[\ln(x)] \} \).
is a measure of the similarity between observations as a function of time lag and degree of variability. We define e-folding time scale of autocorrelation as its temporal scale. $\sigma_{sp}$ is mainly used as aerosol temporal scale. As a result, time scale of $\sigma_{sp}$ for long-range transported haze is 6−25 hrs widely variable, which was obtained for 5 episodes (11−15 and 25−29 January, 4−8 March, 2−6 May 2012, and 10−14 January 2013) selected according to the criteria given in the previous section. It eventually corresponds to spatial scale of 120−500 km, by assuming average boundary wind speed, 5.6 m s$^{-1}$ (Anderson et al. 2003). This scale corresponds to mesoscale, consistent with the previous studies of Kim et al. (2009), and Uno et al. (2014).

Specifically time series of January haze events of 2013 shows significant increases in PM2.5 and , when time lag of event-peak of both PM2.5 and $\sigma_{sp}$ is several hours between BN and SL. Fig. 3 shows time variations of PM2.5, PM10, and $\sigma_{sp}$ at SL and BN from 10 to 18 January 2013. PM2.5 and PM10 began to increase about at 02 LT at BN, and several hours later followed by an increase in those at SL mainly in PM2.5, which was also well demonstrated by variations of $\sigma_{sp}$ (Fig. 3). Interestingly, PM2.5 and PM10 concentrations at BN decreased late afternoon of 13 January and increased again slightly at midnight until the next morning, and returned to the normal state such as 30−50 µg m$^{-3}$ of PM2.5. However PM concentrations and $\sigma_{sp}$ at SL remained at the elevated level above 100 µg m$^{-3}$ of PM2.5 and 400 Mm$^{-1}$ of $\sigma_{sp}$ until 17 Jan, largely lasting 6 days, which could represent the formation and stagnation of domestic haze after long-range transported haze. One thing to note is that the enhancement in $\sigma_{sp}$ at SL in comparison to BN could be attributable to domestic emission, less than 20% of the total value. Generally domestic haze aerosols are not good CCNs relative to aged ones because of its low hygroscopicity, which therefore seemed to be not much related with the modifications of clouds and precipitation.

On 11−12 January 2013, a trough system centered at the Manchuria passed by the northern Korean peninsula, which brought light precipitation into Korea. Figure 4 shows satellite true color image, and horizontal distributions of aerosol optical depth and cloud fraction derived from MODIS on 12 January. Satellite image showed low level cloud formation over Korea. Heavy hazes appeared to be transported together with the cloud systems, which was widely distributed from southwest to northeast over the Yellow Sea to East Sea (Sea of Japan). By taking into account surface measurements at BN and SL (Fig. 3), heavy hazes seemed to be overlapped with low-level stratiform cloud systems whose cloud top was less than ~1.5 km. However, cloud microphysics retrieved from MODIS appears to be not effective in analyzing the relationships of clouds to aerosol perturbations at smaller than mesoscale since they have poor temporal resolution such as 2 times a day.

Interestingly the operational weather forecast by Korean Meteorological Administration without considering this severe haze reported that the rain would end at noon 12 January, but actually lasted longer until the late night. The precipitation lasted even after PM concentrations began to increase around noon, which implies aerosol scavenging effect suppressed during the precipitation, since probably aerosol plume continued to be supplied as an external forcing (Fig. 3). Clearly it is expected that high aerosol loadings could have an impact on low-level clouds and precipitation pattern as well. In addition to precipitation lasting longer, horizontal distributions of the precipitation might be changed through aerosol modification of cloud microphysics such that enhanced aerosols increase number concentrations of smaller cloud droplets (Kim et al. 2012; McComiskey and Feingold 2011; Twyhow et al. 2005), and delay initiation of precipitation (Rosenfeld et al. 2008). It is worthwhile to examine how aerosols could modify weather pattern by using this episode. A WRF model is used to understand the difference in clouds and precipitation between high loading aerosols and default aerosols. Simulation period is limited to the first period of the whole haze episode because the first is the long-range transported.

The horizontal distribution of precipitation reflectivity, which is similar to the control run in the early period of simulations, begins to change with increasing CCNs as time goes by. Precipitation reflectivity represents an integrated value from rain, snow, and graupel calculated in the simulation. Figure 5 shows the horizontal distributions of reflectivity at 11 LT when the increases in PM concentrations and its overlap with lower level clouds were observed at SL. The precipitation coverage is reduced with CCN10 and CCN50 specifically in the Seoul domain (A), which is thought to be associated with cloud changes. The time series of A domain-averaged cloud fraction and precipitation rate is exhibited in Fig. 6. The cloud fraction is increased whereas precipitation rate is decreased from 10 to 15 LT with increasing CCNs, since number concentration of smaller cloud droplets increases (ref to Fig. S3), by reducing precipitation rate and extending its period about half a day. After that, the precipitation rate returns to the level-off.

Certainly we could not rule out completely the variability of large scale synoptic forcings and dynamic aspects such as urban and orographic effects in reasoning inaccurate precipitation timing. Despite these troublesome aspects, the observation of severe haze overwhelming the inherent meteorological variabilities on 12 January can be explained by the simulation result; the precipitation would end earlier as the weather forecast without enhanced aerosols, but actually the precipitation persisted longer at the weaker rate with larger cloud fraction probably by virtue of cloud microphysics modification due to substantial amounts of aerosols, because it will rain longer at a less rate than at much stronger rate in case of a specified amount of available moisture given. The response scales of aerosol effects are quite limited such as within half a day and a couple of hundreds km. It could be...
in the synoptic weather system. Certainly we hypothesize this unprecedented haze events could have an impact on the weather system. The operational weather forecast failed in precipitation timing within one-day time scale, probably because of not considering aerosol impacts on clouds and precipitation in the model.

A sensitivity study with increasing CCNs shows that both light precipitation rate and coverage decrease, corresponding to increases in cloud fraction by increasing smaller cloud droplets. In spite of a couple of episodic analyses and detailed cloud microphysics not represented, the current result would provide one possible example of inadvertent weather modifications by long range transported haze from abroad. It also implies that Korea would be a better testbed to identify and attribute aerosol impacts on weather. This study certainly claims the continuing similar efforts to look for more convincing evidences of weather modification by enhanced aerosols in East Asia.

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**Supplement**

Figure S1 indicates time variations of long-range transported haze (4–8 March 2012), Yellow Sand (10–14 May 2011), and urban domestic haze (1–5 June 2011). Figure S2 shows the model domain. The shaded area indicates the domain where the initial CCN given in the sensitivity test. Figure S3 shows horizontal distributions of cloud droplets number concentrations, same as in Fig. 5. Table S1 summarizes the statistics of 5 long-range transported haze episodes.

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**4. Conclusion**

In spite of various studies carried out, there is still uncertainty in representing aerosol-cloud-precipitation interactions since they have inherent complexity and interdependence, such as scale problems and feedback mechanisms. Recently observed long-range transported hazes along with high-loading aerosols tended to behave within the mesoscale, which was eventually embedded related to not only aerosol forcing scale but also aerosol and cloud overlapped period.

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