ABSTRACT  To develop effective emission abatement strategies for eighteen coal-fired power plants located throughout Korea, power plant emission data and TAPM (The Air Pollution Model) were used to quantify the impact of emission reductions on primary PM$_{10}$ concentrations. TAPM was validated for two separate time periods: a high PM$_{10}$ concentration period from April 7 to 12, 2016, and a low PM$_{10}$ concentration period from June 1 to June 6 2016. The validated model was then used to analyze the impacts of five applicable power plant shut-down scenarios. The results showed that shut-down of four power plants located within the Seoul metropolitan area (SMA) would result in up to 18.9% reduction in maximum PM$_{10}$ concentrations, depending on synoptic conditions. A scenario for the shutdown of a single low stack height with highest-emission power plant located nearest to Seoul showed a small impact on averaged PM$_{10}$ concentrations (~1%) and 4.4% (0.54 μg/m$^3$) decrease in maximum concentration. The scenario for four shutdowns for power plants aged more than 30 years within SMA also showed a highest improvement of 6.4% (0.26 μg/m$^3$ in April) in averaged PM$_{10}$ concentrations, and of 18.9% (2.33 μg/m$^3$ in June) in maximum concentration, showing almost linear relationship in and around SMA. Reducing gaseous air pollutant emissions was also found to be significant in controlling high PM$_{10}$ concentrations, indicating the effectiveness of co-reduction of power plant emissions together with diesel vehicle emissions in the SMA. In addition, this study is implying that secondary production process generating PM$_{10}$ pollution may be a significant process throughout most regions in Korea, and therefore concurrent abatement of both gas and particle emissions will result in more pronounced improvements in air quality over the urban cities in South Korea.

KEY WORDS: Emission reduction, Power plants, TAPM model, Impact Assessment, South Korea

1. INTRODUCTION

High PM$_{10}$ concentrations in a particular region can be caused by the trapping of direct particle emissions and/or local secondary generation of particulate matter through photochemical reactions, and at the same time it can come from other regions through the long-range transport process in the atmosphere. Recent high
PM₁₀ concentrations observed in Korea appear to partly result from transboundary pollution from China, but also from domestic sources originating from local emissions (Jo and Kim, 2013; Kim et al., 2012a). In 2014, there were approximately 30 cases of high PM₁₀ concentration episodes (i.e., > 81 μg/m³) in the Seoul Metropolitan area (SMA). Among these episodes, 12 and 15 episodes occurred during the spring and winter, respectively. These episodes accounted for almost 90% of the episodes occurring in either spring or winter during that year (Park, 2016, 2014). Higher PM₁₀ concentrations occur generally on warm days, implying the importance of high temperatures in the atmosphere (Park, 2014). For example, PM₁₀ concentrations during 6 days from Feb. 23 to 28 ranged from 81 to 120 μg/m³, and on Feb. 25 ranged from 121 to 200 μg/m³. In 2016, an advisory by the Ministry of Environment was in effect over the SMA from April 8 to 12 in 2016 with a PM₁₀ concentration on April 9 of 241 μg/m³. Previous studies have investigated the occurrence of high PM₁₀ concentration episodes in Korea. During most episodes, the Korean peninsula is influenced by an anticyclone pattern with warm and humid air with stagnant conditions, based on surface and upper atmosphere maps during high PM₁₀ concentration episodes. The stable atmosphere, with an inversion layer and thick fog, are unfavorable conditions for transport and dispersion of particulate matter in the atmosphere (Park, 2014). Other reasons such as transboundary processes from regional sources also need to be considered for a comprehensive understanding of the occurrence of long-lasting high PM₁₀ concentration episodes. Understanding impacts of both transboundary processes and local air pollutant emissions is still an open question for developing effective emission abatement strategies in Korea.

In Korea, power plants account for nearly 65% of total electric production and emit 3,455 tons/yr of PM₁₀ (2,618 tons/yr of PM₂.₅) with much more amounts of the PM precursor emissions such as SO₂ and NOₓ (KMOE, 2017). In this context, the Ministry of Environment in Korea (KMOE) has tentatively shut down eight power plant stacks in old power plants aged more than 30 years (since June 2017). About 496 tons of PM lower was expected to be emitted compared with other PM₁₀ counter measures by a stack shut down. KMOE also plans to shut down old power plants regularly in spring beginning from 2018 (KMOE, 2017).

This studies was carried out to evaluate the impact of power plants on PM₁₀ concentrations during the periods in Korea. We report the results for a numerical study on the impacts of several reductions in emissions from power plants on air quality in both the SMA and the areas around power plants in Korea. The main objective of this study is to assess the impacts of reductions in emissions from power plants on PM₁₀ concentrations in the SMA and the areas around power plants using several emission reduction scenarios. In this study, we consider various scenarios; we investigate extremes in PM₁₀ concentrations to demonstrate the impacts of each scenario. In this approach, the implications of each shutdown scenario can be investigated. The results of this study will contribute to our understanding of the relative importance of local emission sources and transboundary air pollutant sources.

To examine the impacts of reductions in power plants on air quality, a numerical simulation model can be used with different emission characteristics but the same meteorological conditions within the same simulation domain. The modeling results can be compared between simulations excluding emissions from area and mobile sources in the same domain, and including all of the other remaining power plant emissions. The difference between these two simulations can demonstrate the impacts of the shutdown of the targeted power plants. Therefore numerical air quality models are essential tools to quantitatively estimate the impact of emission reductions. In this study, we use The Air Pollution Model (TAPM). TAPM is an integrated online model developed by CSIRO (Commonwealth Science and Industrial Research Organization) which includes coupled prognostic meteorological and air pollutant concentration components (Hurley, 2008a). Here we examine the impacts on primary PM₁₀ concentrations of various scenarios for shutdowns of 18 power plants in Korea using the modelling approach described above for two extreme synoptic conditions: April 7-12 and June 1-6, 2016.

2. MATERIALS AND METHODS

2.1 Power Plants and Emissions

The locations of eighteen power plants that are considered by KMOE for temporary shutdowns or emission reduction measures are shown in Fig. 1. Detailed
stack information such as stack height, stack radius, exit temperature and other data used in this study is listed in Table 1. As shown in Fig. 1, the power plants located in the western coastal area are distributed more densely (i.e., P03, P05, P09, P11, P08, and P12); two are located in eastern coastal area (i.e., P06 and P07), four are located in the southern coastal area (i.e., P01, P04, P14, P17, and P18); the others are in more inland areas of Korea (P13, P15, P16, and P02). Also note that Seoul, the capital of South Korea, is near the western coastal power plants, and Daejeon is located in the central inland area.

The stack heights are generally higher than 100 m, with the highest stack about 200 m height, P17 (Goseong), and P03 (Incheon), with a stack height of 199 m (Table 1). The average distance between power plant and meteorological observation site is 13.2 km, with the maximum distance of 31.8 km at P11 (Taean) among the eighteen power plants, and the shortest distance, 2.4 km, at P07 (Donghae). The average distance between the power plants and air quality station is 6.9 km, with the
maximum distance of 25.6 km at P08 (Boryeong), and the minimum 0.7 km at P02 (Daegu), respectively.

Point source emission data available from the Korean National Institute of Environmental Research were used for this study (NIER, 2016). Table 2 shows the emission rates for each of the 18 power plants. PM$_{10}$ emissions totaled 3,455 ton/year from 216 power plant stacks for the base year of 2013. As indicated in Table 2, P11 (Taean) showed the highest PM$_{10}$ emissions (835.13 ton/yr), and the second and third highest emissions were at P17, and P08, respectively. Within the SMA, the highest PM$_{10}$ emission rate was 560.94 ton/yr at P08 (Boryeong) (Table 2).

### 2.2 TAPM Model and Input Data

TAPM, employed in this study, is a PC-based fast air quality model, driven by a user-friendly graphical interface to configure inputs, run the model, and analyze outputs. TAPM is composed of two prognostic subsections: meteorological and chemical modules. The overview of TAPM is described here. More details on TAPM equations and descriptions can be found in Hurley (2008a) and Hurley et al. (2008).

Meteorological module of TAPM predicts gridded three-dimensional meteorology and air pollution concentrations. The meteorological component of TAPM is an incompressible, non-hydrostatic, primitive equation model with a terrain-following vertical coordinate for three-dimensional simulations. The model solves the primitive meteorological equations: momentum, temperature, specific humidity of water vapor, and cloud/rain/snow components. It includes parameterizations for cloud/rain/snow micro-physical processes, turbulence closure, urban/vegetative canopy and soil, and radiative fluxes (Hurley, 2008a). Turbulence closure in the mean equations uses a gradient diffusion approach with diffusivity $K$; and includes a counter-gradient correction for temperature. An $E$-$\varepsilon$ turbulence scheme is used to calculate $K$ using prognostic equations for the turbulence kinetic energy ($E$) and its dissipation rate ($\varepsilon$). Plume buoyancy, momentum, and building wake effects are also included for point sources (Hurley et al., 2008).

The chemical component of TAPM consists of an Eulerian grid-based set of prognostic equations for both gas and particulate components. The TAPM model, an Eulerian grid-based model, includes gas-phase photochemical reactions based on semi-empirical mechanism called the Generic Reaction Set (GRS) of Azzi et al. (1992) with the hydrogen peroxide modification of Venkatram et al. (1997), yielding the following 10 reactions for 13 species.

$$R_{smog} + hv \rightarrow RP + R_{smog} + \eta_{SNGOC} \quad \text{(1)}$$

$$RP + NO \rightarrow NO_2 \quad \text{(2)}$$

$$NO_2 + hv \rightarrow O_3 \rightarrow NO + O_3 \quad \text{(3)}$$

### Table 2. Emission rate (ton/yr) of power plants used in this study.

| Power plants | Emission Rate (ton/yr) |
|--------------|-----------------------|
| PM$_{10}$    | PM$_{2.5}$ | NO$_x$ | SO$_x$ |
| P01 Busan    | 12.06      | 9.73   | 455.09 | 488.25 |
| P02 Daegu    | 26.55      | 21.41  | 1042.42| 1181.48|
| P03 Incheon  | 207.76     | 167.58 | 3862.97| 5517.57|
| P04 Ulsan    | 14.04      | 11.32  | 905.46 | 847.82 |
| P05 Ansan    | 14.11      | 11.38  | 686.03 | 324.74 |
| P06 Gangneung| 29.16      | 19.40  | 2692.47| 910.16 |
| P07 Donghae  | 35.59      | 25.21  | 1086.87| 2406.16|
| P08 Boryeong | 560.94     | 452.46 | 17454.32| 11656.09|
| P09 Dangjin  | 319.95     | 111.50 | 17148.32| 7223.25|
| P10 Seocheon | 60.57      | 41.58  | 3613.69| 1317.73|
| P11 Taean    | 835.13     | 673.63 | 22168.03| 12792.28|
| P12 Gunsan   | 33.30      | 26.86  | 891.38 | 776.70 |
| P13 Iksan    | 9.97       | 7.21   | 396.49 | 500.14 |
| P14 Yeosu    | 229.13     | 178.85 | 6453.28| 4074.51|
| P15 Gimcheon | 2.48       | 2.0    | 83.68  | 69.84  |
| P16 Gumi     | 29.0       | 23.39  | 2059.47| 1860.64|
| P17 Goseong  | 564.47     | 455.32 | 23267.45| 14531.64|
| P18 Hadong   | 470.91     | 379.84 | 13524.62| 11478.44|


where $hv$ denotes photo-synthetically active, and thirteen species used here are smog reactivity ($R_{\text{smog}}$), radical pool (RP), hydrogen peroxide (H$_2$O$_2$), nitric oxide (NO), nitrogen dioxide (NO$_2$), ozone (O$_3$), Sulphur dioxide (SO$_2$), stable non-gaseous organic carbon (SNGOC), stable gaseous nitrogen products (SGN), stable non-gaseous nitrogen products (SNGN), stable non-gaseous sulphur products (SNGS). The semi-empirical GRS has been employed for photochemical analysis in numbers of previous studies (Kim et al., 2005; Venkatram et al., 1997). The concept of using $R_{\text{smog}}$ rather than volatile organic compounds (VOCs) in the reaction equations follows from the work of Johnson (1984). The concentration of $R_{\text{smog}}$ is defined as a reactivity coefficient multiplied by VOC concentration. For example, Johnson (1984) used $R_{\text{smog}} = 0.0067$[VOC] for typical 1980s. Other detailed descriptions including reaction coefficients and yield coefficients such as $\alpha$ and $\eta$ are found in Hurley (2008a) and Hurley et al. (2008).

The chemical component of TAPM has 3 modes in options: trace, gas and dust modes. The dust mode should be employed for the simulation of particulate matter. In dust mode, particle sizes are categorized in TAPM model for four size ranges: 2.5, 10, 20, and 30 $\mu$m, and the calculations of Particulate Matter concentrations are actually done for PM$_{2.5}$, PM$_{10}$, PM$_{20-20}$ and PM$_{20-30}$. Here Particulate Matter for PM$_{10}$ and PM$_{2.5}$ can be defined as sum of primary particulate matter plus secondary particulate concentrations consisting of (SNGOC), (SNGN), and (SNGS) as indicated in above equations of (1) and (7)-(10). Gas and aqueous-phase chemical reactions for sulfur dioxide and particles with the aqueous-phase reactions based on Seinfeld and Pandis (1998) are implemented. The dry deposition formulation follows the approach of Physick (1994) for gaseous pollutants, and Seinfeld and Pandis (1998) for aerosols. Wet deposition processes were considered for highly soluble gases and aerosols such as SO$_2$, and H$_2$O$_2$, PM$_{2.9}$, PM$_{10}$, PM$_{20}$, and PM$_{30}$ are considered in this model (Hurley, 2008a).

TAPM has been verified for a number of regions, industrial and urban scales in Australia, Seoul and overseas. TAPM had been used internationally for model verification studies against two US tracer experiments (Kincaid and Indianapolis), several annual US dispersion datasets (Bowline, Lovett and Westvaco), and annual meteorology and/or dispersion in various regions throughout Australia (Hurley et al., 2008; Park 2004).

The domain for TAPM model evaluation study was based on the grids of $80 \times 80 \times 25$ at three domain (12 km, 4 km, 2 km, centered at each of the 18 power point location) to evaluate the model performance for each of the 18 power plants. Therefore 18 simulations should be carried out for this case. In this way, the boundary conditions will be effectively provided for finer nested domain to simulate precisely the impact of point sources. However, for the scenario study, the model domain over Korea was centered at the center of Daejeon city (latitude 36°21’14.83” N and longitude 127°23’4.36” E) with the grid of 120 × 120 × 25 grid points was employed. For the initial conditions of the meteorological variables, LAPS (Local Administrator Password Solution) data with a resolution of 75 km × 100 km were used (ftp://ftp.csiro.au/TAPM). Surface and land use data (1 km × 1 km) from the USGS (United States Geological Survey) and initial meteorological data (75 km × 100 km) from the Local Administrator Password Solution from the Australia Meteorology Administration were used as inputs to the TAPM model (Hurley, 2008b).

2.3 Methodology and Description of Scenarios
To simulate the impacts of a reduction in emissions from power plants, we ran the TAPM model in two steps. In the first step, we carried out model performance simulations for the model validation study, prior to the impact simulations. The average concentrations of PM$_{10}$, PM$_{2.5}$, SO$_2$, NO$_2$, and O$_3$ in and around power plants during the study period were used for the initial background model conditions. The calculated initial background concentrations are listed in Table 3. Here it is noted that initial background concentrations are surface measurement only, and thus applied 4-day spin-up times to minimize the initial condition influences for both surface and non-surface concentrations. The
resultant model outputs were evaluated by comparing the simulated meteorological variables and PM$_{10}$ concentrations against measurements. The statistical evaluation parameter, the index of agreement (IOA), was used to evaluate model performance.

In the second modeling step, the emission reduction impact study was performed. We set the base case by forcing the initial background conditions to zero in this study and applied emissions of power plants only for scenario studies. Current study is a very simple approach without heavy computational costs base on semi-empirical chemical reactions of TAPM, and thus it is contrasted to the comprehensive sensitivity simulations for calculations of source-receptor relations employed by previous comprehensive studies (Baker et al., 2016; Zhou et al., 2012; Bergin et al., 2008).

We carried out five scenarios with varying reductions in power plant emissions in different areas. Table 4 illustrates the scenarios in this study: [Scenario I], complete shutdown for P08 (Boryeong); [Scenario II], complete shutdown for P03 (Incheon), P05 (Ansan), P09 (Dangjin) and P11 (Taean); [Scenario III], partial shutdown for P17 (Goseong) and P08 (Boryeong) and a complete shutdown for P06 (Gangneung), and P10 (Seocheon); [Scenario IV], halving the gas phase emissions with no reduction of PM emission; and finally [Scenario V], 20% emissions reductions of both PM and gas emissions in all power plants during October.

[Scenario I] focuses on Seoul by shutting down P08 (Boryeong), with electricity power generation (EPG) of 30,778,882 MWh (14.6% reduction among total coal-fired EPG) and the highest emission rate (560.94 ton/yr for PM$_{10}$) but lowest stack height among the power plants located within the SMA (Table 4). [Scenario II] also simulates a shutdown of the four power plants (49.7% reduction of EPG) located within the SMA. Scenarios [I] and [II] both compare Daejeon in contrast to Seoul. [Scenario III] examines the effects of the shutdown of plants more than 30 years old located over the whole south Korea (8.5% reduction of EPG), whose operation had been suspended by KMOE. [Scenario IV] estimates the contributions from secondary production, by reducing 50% of the NOx and SOx emissions of all 18 power plants. In Scenario V, the emissions of PM$_{10}$, NOx, SO2 were assigned to 20% reduction amounts of all 18 power plants in the assumption that the generated electric power is proportion to the consumed fuel amount. The Scenario V is chosen to reflect the recent PM mitigation plans of Korean MOE, among which temporary shutdown of power plants during October is included (http://www.seoul.co.kr/news/newsView.php?id=20180629018012&wlog_tag3=naver). Each of the above five scenarios are compared to quantify the impacts of the changes in each scenario. Additional details on each scenario are given in Table 4.

| Table 3. Measured mean concentrations for 18 power plants, used as an initial concentration for the validation of simulated concentrations |
|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| 7-12 April 2016 | 1-6 June 2016 | 7-12 April 2016 | 1-6 June 2016 |
| SO$_2$ (ppb) | CO (ppm) | O$_3$ (ppb) | NO$_2$ (ppb) | PM$_{10}$ (μg/m$^3$) | SO$_2$ (ppb) | CO (ppm) | O$_3$ (ppb) | NO$_2$ (ppb) | PM$_{10}$ (μg/m$^3$) |
| P01 Busan | 7.3 | 0.5 | 34.5 | 13.0 | 70.7 | 6.6 | 0.4 | 36.0 | 23.9 | 29.0 |
| P02 Daegu | 4.2 | 0.4 | 27.6 | 21.1 | 68.8 | 3.7 | 0.3 | 40.9 | 12.8 | 33.3 |
| P03 Incheon | 5.0 | 0.5 | 41.9 | 17.5 | 70.6 | 5.1 | 0.3 | 50.0 | 14.5 | 52.5 |
| P04 Ulsan | 13.2 | 0.7 | 31.2 | 32.9 | 68.6 | 9.8 | 0.4 | 39.9 | 24.3 | 36.6 |
| P05 Ansan | 5.2 | 0.5 | 27.2 | 31.1 | 68.7 | 4.2 | 0.5 | 30.2 | 29.8 | 40.8 |
| P06 Gangneung | 3.1 | 0.3 | 44.8 | 13.3 | 76.9 | 2.0 | 0.3 | 45.1 | 13.4 | 42.1 |
| P07 Donghae | 2.3 | 0.3 | 37.2 | 13.9 | 71.4 | 2.6 | 0.3 | 39.9 | 18.7 | 38.2 |
| P08 Boryeong | 3.1 | 0.5 | 46.6 | 15.4 | 62.0 | 3.9 | 0.4 | 57.9 | 14.9 | 49.0 |
| P09 Dangjin | 3.3 | 0.3 | 43.1 | 14.7 | 58.4 | 6.6 | 0.3 | 54.8 | 17.2 | 58.4 |
| P10 Seocheon | 1.7 | 0.4 | 47.1 | 8.0 | 62.8 | 1.7 | 0.3 | 53.7 | 7.2 | 31.8 |
| P11 Taean | 5.5 | 0.5 | 42.9 | 42.8 | 51.7 | 7.8 | 0.4 | 42.9 | 22.0 | 50.9 |
| P12 Gunsan | 5.1 | 0.5 | 42.1 | 18.4 | 71.1 | 5.2 | 0.4 | 52.0 | 14.0 | 50.9 |
| P13 Ikson | 6.1 | 0.5 | 44.8 | 16.9 | 90.5 | 6.6 | 0.5 | 54.7 | 13.2 | 67.7 |
| P14 Yeosu | 9.4 | 0.3 | 35.2 | 20.5 | 77.9 | 14.0 | 0.5 | 37.8 | 40.8 | 33.8 |
| P15 Gimcheon | 1.6 | 0.6 | 45.3 | 14.4 | 71.9 | 1.4 | 0.4 | 44.7 | 11.1 | 26.6 |
| P16 Gumi | 3.7 | 0.5 | 48.6 | 27.2 | 54.7 | 3.1 | 0.2 | 49.5 | 13.2 | 22.5 |
| P17 Goseong | 5.3 | 0.3 | 36.6 | 28.6 | 61.2 | 5.2 | 0.3 | 45.3 | 16.6 | 37.8 |
| P18 Hadong | 12.1 | 0.5 | 32.5 | 23.8 | 60.4 | 10.6 | 0.4 | 33.8 | 16.0 | 32.9 |
Table 4. Emission reduction scenarios for impact assessments of power plants in this study.

| Scenarios  | Powerplants | Shut-down efficiencies | Reduced generation (MWh) | Reduced emission (ton) | Target areas of impact assessments |
|------------|-------------|------------------------|--------------------------|-----------------------|----------------------------------|
|            |             | Operation rate(%)      | PM$_{10}$                | PM$_{2.5}$ | NO$_x$ | SO$_x$ |                                  |
| Scenario I | P08 Boryeong| 0.0%                   | 30,778,882 (14.6%)       | 560.94    | 452.46  | 17,454.32 | 11,656.09 | Seoul, Daejeon                   |
|            |             |                        | Subtotal 30,778,882 (MWh) (14.6%) for Scenario I |
| Scenario II| P03 Incheon | 0.0%                   | 38,610,719 (18.3%)       | 207.76    | 167.58  | 3,862.97 | 5,517.57 | Seoul, Daejeon                   |
|           | P05 Ansan   | 0.0%                   | 674,125.8 (0.3%)         | 14.11     | 11.38   | 686.03  | 324.74  | Seoul, Daejeon                   |
|           | P09 Dangjin | 0.0%                   | 32,432,355 (15.4%)       | 319.95    | 111.50  | 17,148.32 | 7,223.25 | Seoul, Daejeon                   |
|           | P11 Taean   | 0.0%                   | 32,984,153 (15.7%)       | 835.13    | 673.63  | 22,168.03 | 12,792.28 | Seoul, Daejeon                   |
|            |             |                        | Subtotal 104,701,353 (MWh) (49.7%) for Scenario II |
| Scenario III| P17 Goseong| 81.3%                  | 4,652,628 (2.2%)         | 105.73    | 85.28   | 9,497.16 | 3,275.97 | Seoul, Daejeon, P06, P17, P08, P10 |
|           | P08 Boryeong| 74.6%                  | 7,817,836 (3.7%)         | 142.37    | 114.84  | 4,935.66 | 3,549.51 | Seoul, Daejeon, P06, P17, P08, P10 |
|           | P06 Gangneung| 0.0%                | 2,102,002 (1.0%)         | 188.28    | 151.87  | 2,741.27 | 3,394.57 | Seoul, Daejeon, P06, P17, P08, P10 |
|           | P10 Seocheon| 0.0%                  | 3,370,249 (1.6%)         | 60.57     | 41.58   | 3,613.69 | 1,317.73 | Seoul, Daejeon, P06, P17, P08, P10 |
|            |             |                        | Subtotal 17942715 (MWh) (8.5%) for Scenario III |
| Scenario IV| P01–P18     | 0.00                   | 0.00                     | 58,896.02 | 38,978.72 | Seoul, Daejeon, P06, P17, P08, P10 |

Halving the emissions of NO$_x$ and SO$_x$ only with no reduction of particulate emissions for all 18 power plants

| Scenario V  | P01–P18     | 690.95               | 552.76                  | 23,558.33 | 15,591.71 | Seoul, Daejeon, P06, P17, P08, P10 |

20% reduction of PM, NO$_x$, and SO$_x$ emissions for all of 18 power plants
2.4 Case Selection and its Synoptic

Two episodes are selected as being representative for high and low aerosol episodes, respectively. The episode cannot be a perfect but suitable one for this numerical study as estimating specific sources’ contribution to local and regional air quality.

First, a long-lasting haze episode such as April 8-10 in 2016 tends to be determined by unfavorable meteorological conditions like a stagnant High pressure system accompanied with the weak boundary layer wind, which could suppress vertical mixing and ventilation, largely driven by the synoptic conditions. This kind of synoptic setting, quite typical for severe haze events, is quite consistent with the previous studies (Seo et al., 2017; Oh et al., 2015; Wang et al., 2014). The moving Low pressure system before the haze event preceded very stagnant synoptic condition and weak pressure gradient, which helped to intensify the accumulation of aerosol loadings. Fig. 2 shows spatial distributions of 850 hPa geopotential heights and wind field for April 8 to 9. Boundary layer mean wind speed (850 hPa) increased specifically around Manchuria on April 8, which facilitated transport of anthropogenic and dust aerosols from the northeastern China to Korea with strong northwesterly up to 20 m/s. Later, wind speed gradually decreased until the end of haze (Fig. 2). The first period (April 8) of the haze event characterized aerosols external transport from China by strong northwesterly. After then, relatively calm and stagnant conditions contributed to build up of domestic haze in Korea.

Meanwhile the June period from 1 to 7 is selected as a low-aerosol event. The synoptic features as shown in Fig. 2 indicate even lighter wind speed with overall lower pressure gradient. It is interesting to note that the most domain of Korea was influenced by the easterly on June 2, which shifted to southeasterly specifically in the southern peninsula later. The most striking difference between April haze and June clean periods is the boundary layer wind direction with the others largely similar. For Scenario V, impact assessment was carried out for October 1 to 11, 2017, when the prevailed wind direction was dominantly observed northeasterlies.

Fig. 2. Spatial distributions of 850 hPa geopotential heights and wind fields for (a) April 7 to 12, and (b) June 1 to 6, 2016.
3. RESULTS

3.1 Model Evaluation: Site Measurements of PM$_{10}$ Concentration around Power Plants

Measured background PM$_{10}$ concentrations during the study period were analyzed to characterize the vicinity of 18 measurement sites routinely monitored by KMOE. PM$_{10}$ concentrations at eighteen sites for both cases (April and June) are shown in the boxplots (Fig. 3). The median PM$_{10}$ concentration ranged from 35 μg/m$^3$ to 73 μg/m$^3$ in April and from 23 μg/m$^3$ to 68.5 μg/m$^3$ in June, respectively. The mean PM$_{10}$ concentration in April was 67% higher than the mean concentration in June. The mean PM$_{10}$ concentration in Seoul was 58 μg/m$^3$; in Shanghai the mean PM$_{10}$ concentration was 149 μg/m$^3$ (Wang et al., 2013).

3.2 Wind and Concentration Fields around Power Plant

Figs. 4 and 5 show the horizontal distribution of the PM$_{10}$ with the wind vector averaged for two simulated periods centered at the selected four power plants: P01 (Busan), P02 (Daegu), P07 (Donghae), and P09 (Dangjin), under the initial concentrations (Table 3) and the emission from the power plants (Table 2). PM$_{10}$ concentrations during the first simulation period are higher than that for the second simulation period because of differences in the initial concentration and meteorological conditions.

3.3 Wind and Concentration Fields over the Country

Figs. 6 and 7 show the horizontal distribution of PM$_{10}$ with the wind vector simulated on 10 April and 4 June 2016 with zero background PM$_{10}$ concentration and the emissions from the power plants, respectively. The patterns are strongly governed by the wind: upwind regions have lower concentrations while downwind regions have higher concentrations; the area where there is a confluence of wind has high concentrations and areas where the wind direction diverges have lower concentrations. Especially the overall concentration in June showed much higher due to the relatively weaker wind speed rather than in April. On 10 April 2016, northerly winds are dominant in Korea, so the high PM$_{10}$ concentration region moves southward with the maximum concentrations in the south such as P14 (Yeosu), P18 (Hadong), and P17 (Goseong). Meanwhile, on 4 June 2016, southerly and easterly winds are dominant in Korea, so the high PM$_{10}$ concentration region moves northward with the maximum concentrations in the northwest.

Fig. 8 shows the horizontal distribution PM$_{10}$ with the wind vector simulated during the two simulation period with zero background PM$_{10}$ concentration and the emissions from the power plants. The second simulation period had higher concentrations than the first simulation period by approximately 3 times. During the first simulation period, PM$_{10}$ concentrations are higher in southern Korea and lower in northern Korea. The power plant sites of P14 (Yeosu), P17 (Goseong), and P18 (Hadong) have higher PM$_{10}$ concentrations, corresponding to the wind convergence. During the second simulation period, PM$_{10}$ concentrations are higher in the west and lower in the southeast. Lower
Fig. 4. Predicted wind and concentration fields for an averaged values during 7-12 April, 2016 at four power plants (P01, P02, P07, and P09) area.

Fig. 5. Predicted wind and concentration fields for an averaged values during 1-6 June, 2016 at four power plants (P01, P02, P07, and P09) area.
PM$_{10}$ concentrations are governed by easterly winds, while higher concentrations are governed by northerly or westerly winds.

3.4 Model Evaluation
In order to validate the simulated meteorological variables and PM$_{10}$ concentrations for each power plant, data for the nearest meteorological station and the nearest air quality station were used. The index of agreement (IOA) between the simulated value at the power plant and the observed value at the nearest meteorological or air quality monitoring station for each power plant was

Fig. 6. Predicted wind and concentration fields on April 10, 2016 over the country at 00 LST, 04 LST, 08 LST, 12 LST, 16 LST, and 20 LST.
used to evaluate the simulated result. The IOA is a frequently used measure of how well the predicted variation about the observed mean are represented, with a value greater than about 0.50 considered to indicate a good prediction.

Table 5 shows the IOAs between modeled and observed PM$_{10}$ concentrations and the meteorological variables such as wind speed, wind direction, and air temperature for the study period. Temperature in June showed the highest IOA with an average of 0.89 while PM$_{10}$ concentration showed the lowest IOA with an average of 0.43. The IOA was similar to IOA found in other studies in urban areas (Hurley et al., 2008, Park et al., 2004). The IOA deviation (station IOA — station

![Fig. 7. Predicted wind and concentration fields on June 4, 2016 over the country at 00 LST, 04 LST, 08 LST, 12 LST, 16 LST, and 20 LST.](image)
averaged IOA) for two different periods shows nearly the same patterns. At P01 (Busan) and P02 (Deagu), IOAs for all variables are higher than the station-averaged value. At P12 (Gunsan) and P13 (Iksan), IOAs for the meteorological variable are higher than the station-averaged value, but those for PM$_{10}$ concentration are lower than the station-averaged IOAs.

### 3.5 Results of Scenario Studies

The results for simulated mean and maximum PM$_{10}$ concentrations to assess the contribution of each power plant in the study region, the contribution to the maximum surface concentration in April and June ranged from 3.79 µg/m$^3$ (P05: Ansan, April) to 17.00 µg/m$^3$ (P11: Taean, June) (Table 6). At P09 (Dangjin), P11 (Taean), P17 (Goseong), and P18 (Hadong), PM$_{10}$ emissions can be classified as a large power plant with regard to emissions, exceeding 300 ton/year, so that their high emissions are related to elevated maximum PM$_{10}$ concentrations (ranging from 12.84 to 17.00 µg/m$^3$ in June). At power plants such as P01 (Busan), P02 (Daegu), P04 (Ulsan), P05 (Ansan), P15 (Gimcheon),

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**Table 5.** Index of agreement (IOA) between simulated and observations of meteorological variables and PM$_{10}$ concentrations.

| Power plant | PM$_{10}$ | WS | WD | Temp. | PM$_{10}$ | WS | WD | Temp. |
|-------------|-----------|----|----|-------|-----------|----|----|-------|
| P01         | 0.55      | 0.61 | 0.91 | 0.79  | 0.56      | 0.60 | 0.69 | 0.86  |
| P02         | 0.25      | 0.70 | 0.73 | 0.92  | 0.54      | 0.80 | 0.68 | 0.88  |
| P03         | 0.39      | 0.60 | 0.68 | 0.87  | 0.51      | 0.65 | 0.73 | 0.89  |
| P04         | 0.48      | 0.58 | 0.65 | 0.82  | 0.48      | 0.65 | 0.24 | 0.90  |
| P05         | 0.33      | 0.44 | 0.80 | 0.88  | 0.60      | 0.61 | 0.77 | 0.93  |
| P06         | 0.25      | 0.47 | 0.34 | 0.89  | 0.26      | 0.33 | 0.43 | 0.92  |
| P07         | 0.21      | 0.38 | 0.45 | 0.84  | 0.35      | 0.54 | 0.50 | 0.93  |
| P08         | 0.34      | 0.37 | 0.48 | 0.89  | 0.36      | 0.34 | 0.62 | 0.90  |
| P09         | 0.42      | 0.45 | 0.67 | 0.88  | 0.47      | 0.55 | 0.63 | 0.93  |
| P10         | 0.26      | 0.26 | 0.70 | 0.80  | 0.42      | 0.32 | 0.56 | 0.84  |
| P11         | 0.37      | 0.55 | 0.59 | 0.61  | 0.34      | 0.57 | 0.79 | 0.95  |
| P12         | 0.23      | 0.72 | 0.62 | 0.89  | 0.28      | 0.67 | 0.65 | 0.90  |
| P13         | 0.23      | 0.77 | 0.58 | 0.93  | 0.28      | 0.76 | 0.45 | 0.88  |
| P14         | 0.53      | 0.54 | 0.87 | 0.78  | 0.38      | 0.61 | 0.53 | 0.88  |
| P15         | 0.43      | 0.60 | 0.72 | 0.92  | 0.45      | 0.74 | 0.42 | 0.82  |
| P16         | 0.39      | 0.28 | 0.59 | 0.93  | 0.49      | 0.23 | 0.64 | 0.91  |
| P17         | 0.60      | 0.51 | 0.49 | 0.90  | 0.46      | 0.25 | 0.17 | 0.87  |
| P18         | 0.55      | 0.63 | 0.87 | 0.80  | 0.43      | 0.68 | 0.74 | 0.89  |
P05 (Ansan), and P16 (Gumi), the maximum concentrations are lower (ranging from 3.79 to 9.59 μg/m³ in April and June). In particular, the power plant at P08 (Boryeong) had the lowest stack height (42 m) (see Table 1), but the second highest PM₁₀ emission (560.94 ton/yr) (see Table 2). Due to the lower stack height and larger emission amount, the maximum surface concentration at P08 (Boryeong) was 12.12 μg/m³, the highest in April. As considering that the locations showing the maximum concentrations were more than 100 km far from half of all stacks, it should be also mentioned the secondary production during long-range transport is also important in PM formation in addition to their contribution of the primary PM sources.

The maximum and average concentration and the location where those concentration occurred for each scenarios are shown in Table 7. The results of sensitivity experiment, such as increased/decreased concentrations, relative to BAU (Business As Usual) is shown for each scenario in Table 8. In Scenario I the maximum decrease in PM₁₀ concentrations in the SMA due to a shutdown of the P08 (Boryeong) was less than 0.00 to 0.54 μg/m³ (0.0-4.4%). There is a small impact of the P08 (Boryeong) on the SMA because the stack height is low and the SMA is distant from the plant. In scenario II, simulating a shutdown of four power plants the SMA, reduced emissions (1,320 tons/year) comprise more than one-third of the total emissions from 18 power plants (3,455 tons/year). The impact of shutting down four power plants on the decrease in PM₁₀ concentrations in the SMA was as high as 18.9% in June, and a decrease of 23.9% was also simulated in the Daejeon region, proportional to the reduced emissions in the SMA.

For scenarios III, there is a large decrease in PM₁₀ concentrations around the power plants of P17 (Goseong), P08 (Boryeong), P06 (Gangneung) from 6.4 to 31.8%, compared to the decrease in the SMA and Daejeon area from 0.9 to 7.7%, relatively far away from the power plants, even though the emission reductions of 60 to 190 tons/year in each power plant due a shutdown of aged plants are not significant compared to the total emission amount from all power plants considered in our study. The maximum PM₁₀ concentrations in in Seoul, Daejeon, P17 (Goseong), P08 (Boryeong), P06 (Gangneung) and P10 (Seocheon) decreased from 0.3 to 19.7% in scenario IV when SO₂, NOx emissions from all 18 power plants were reduced (Table 8). In Scen-
Scenario V, the maximum and averaged concentrations were higher than those in April and lower than those in June for BAU. In compared with Scenario IV, the reduction rates were higher than those in April and lower than those in June except Seoul and Gangneung.

4. DISCUSSION

There has been much debate in Korea concerning identifying sources of PM$_{10}$ pollution. Obviously, local emissions play a significant role and are often sufficient to cause PM$_{10}$ concentrations which exceed national standard levels, and transboundary sources must be considered as another important source. The National Institute of Environmental Researches (NIER) has carried out monitoring activities and has studied source-receptor relationships to estimate the long-term contributions of both local emissions and transboundary processes (Kim et al., 2012a, 2012b; Park et al., 2005). The most recent project of NIER, Korea-United States Air Quality (KORUS-AQ) campaign conducted over the Korean Peninsula (NIER, 2017), showed that more than half of the PM$_{10}$ sources are generated in Korea, with vehicles, power plants and petrochemical and chemical factories located on the west coast identified as major sources of PM$_{10}$ pollution.

The simulation results showed that high emissions and low stack height are related to higher maximum PM$_{10}$ concentrations. The location of a plant (coastal or inland) is also critical for determining how distant from the power plant the maximum PM$_{10}$ concentration will occur. In the SMA and Daejeon areas, it is apparent that directly reducing emissions is essential to decrease PM$_{10}$ concentrations. In coastal areas, the surface concentration of PM$_{10}$ and most types of air pollutants tends to rapidly increase near emission sources because PM$_{10}$ are transported into the thermal internal boundary layer (TIBL) and suddenly sink down to the surface under stable atmospheric conditions (Levitin, 2000). We found that the maximum impact on PM$_{10}$ concentrations occurred within 50 km from some of power plants located in coastal areas, i.e., P06 (Gangneung), P07 (Donghiae), P08 (Boryeong), P09 (Dan-

### Table 7. Position of PM$_{10}$ hourly maximum and averages of daily maximum concentrations of base case, and its distance from Daejeon.

| Scenarios | Case  | Max. Conc. | Direction from Daejeon | Distance from Daejeon (km) | Avg. Conc. | Direction from Daejeon | Distance from Daejeon (km) |
|-----------|-------|------------|------------------------|---------------------------|------------|------------------------|---------------------------|
| BAU       | April | 16.98      | WNW                    | 78.2                      | 2.87       | WNW                    | 78.2                      |
|           | June  | 25.64      | WNW                    | 78.2                      | 7.61       | WNW                    | 74.2                      |
| Scenario I| April | 11.81      | SSE                    | 158.6                     | 2.62       | SSE                    | 157.7                     |
|           | June  | 22.34      | SW                     | 127.9                     | 6.77       | WSW                    | 72.5                      |
| Scenario II| April | 17.03      | WNW                    | 78.2                      | 2.75       | WNW                    | 78.2                      |
|           | June  | 23.82      | WNW                    | 78.2                      | 6.73       | WNW                    | 74.2                      |
| Scenario III| April | 11.59      | WNW                    | 78.2                      | 2.54       | SSE                    | 158.6                     |
|           | June  | 21.57      | SSE                    | 127.9                     | 7.21       | W                      | 78.2                      |
| Scenario IV| April | 14.94      | WNW                    | 78.2                      | 2.69       | WNW                    | 78.2                      |
|           | June  | 20.58      | WNW                    | 78.2                      | 6.95       | WNW                    | 78.2                      |
| Scenario V| October| 17.99      | NNE                    | 119.3                     | 3.21       | NNE                    | 119.3                     |

**Fig. 9.** Daily variation of predicted mixing height in April and June in Seoul Metropolitan area.
Table 8. Results of reduced mean and maximum PM10 concentrations for five scenarios over the selected areas.

| Scenarios | Reduced Conc. (μg/m³) | Seoul | Daejeon | P06 | P17 | P08 | P10 |
|-----------|------------------------|-------|---------|-----|-----|-----|-----|
|           |                        | max.(Δfraction) | max.(Δfraction) | max.(Δfraction) | max.(Δfraction) | max.(Δfraction) | max.(Δfraction) |
|           |                        | avg.(Δfraction) | avg.(Δfraction) | avg.(Δfraction) | avg.(Δfraction) | avg.(Δfraction) | avg.(Δfraction) |
| BAU       | April max. 4.05        | 1.52  | 4.41    | 1.86 | 2.45 | 1.46 | 1.88 |
|           | avg. 1.2               | 1.82  | 4.21    | 2.35 | 2.48 | 2.48 | 2.94 |
|           | June max. 12.33        | 5.44  | 12.99   | 4.97 | 16.99| 3.78 | 16.17|
|           | avg. 4.7               | 4.97  | 12.99   | 4.97 | 16.99| 3.78 | 16.17|
|           | October max. 6.51      | 1.96  | 9.98    | 1.24 | 2.00 | 3.12 | 2.70 |
|           | avg. 1.2               | 1.24  | 9.98    | 1.24 | 2.00 | 3.12 | 2.70 |
| Scenario I| April max. 4.05        | 1.51  | 4.41    | 1.86 | 2.45 | 1.46 | 1.88 |
|           | avg. 1.2               | 1.82  | 4.21    | 2.35 | 2.48 | 2.48 | 2.94 |
|           | June max. 12.33        | 5.44  | 12.99   | 4.97 | 16.99| 3.78 | 16.17|
|           | avg. 4.7               | 4.97  | 12.99   | 4.97 | 16.99| 3.78 | 16.17|
|           | October max. 6.51      | 1.96  | 9.98    | 1.24 | 2.00 | 3.12 | 2.70 |
|           | avg. 1.2               | 1.24  | 9.98    | 1.24 | 2.00 | 3.12 | 2.70 |
| Scenario II| April max. 3.79       | 1.46  | 4.40    | 1.74 | 4.59 | 2.35 | 4.1 |
|           | avg. 1.2               | 1.74  | 4.40    | 1.74 | 4.59 | 2.35 | 4.1 |
|           | June max. 10.00        | 5.26  | 9.89    | 4.59 | 7.6 | 2.69 | 8.2 |
|           | avg. 1.2               | 4.59  | 9.89    | 4.59 | 7.6 | 2.69 | 8.2 |
| Scenario III| April max. 4.00       | 1.51  | 4.07    | 1.82 | 4.21 | 2.41 | 3.62 |
|           | avg. 1.2               | 1.82  | 4.07    | 1.82 | 4.21 | 2.41 | 3.62 |
|           | June max. 11.97        | 5.39  | 12.57   | 4.85 | 9.28 | 3.85 | 9.39 |
|           | avg. 1.2               | 4.85  | 12.57   | 4.85 | 9.28 | 3.85 | 9.39 |
|           | October max. 6.29      | 1.93  | 9.28    | 2.41 | 4.62 | 1.22 | 4.16 |
|           | avg. 1.2               | 2.41  | 9.28    | 2.41 | 4.62 | 1.22 | 4.16 |
| Scenario IV| April max. 3.79        | 1.46  | 4.35    | 1.81 | 4.05 | 1.44 | 4.35 |
|           | avg. 1.2               | 1.81  | 4.35    | 1.81 | 4.05 | 1.44 | 4.35 |
|           | June max. 11.06        | 5.27  | 11.70   | 4.63 | 8.45 | 3.75 | 8.45 |
|           | avg. 1.2               | 4.63  | 11.70   | 4.63 | 8.45 | 3.75 | 8.45 |
|           | October max. 6.29      | 1.93  | 9.28    | 2.41 | 4.62 | 1.22 | 4.16 |
|           | avg. 1.2               | 2.41  | 9.28    | 2.41 | 4.62 | 1.22 | 4.16 |
| Scenario V| October max. 6.29      | 1.93  | 9.28    | 2.41 | 4.62 | 1.22 | 4.16 |
|           | avg. 1.2               | 2.41  | 9.28    | 2.41 | 4.62 | 1.22 | 4.16 |
gjin), P11 (Taean), P12 (Gunsan), P14 (Yeosu), P17 (Goseong), and P18 (Hadong), while at P02 (Daegu), P15 (Gimcheon), P16 (Gumi) and P13 (Iksan), located in inland areas, the maximum impact on PM$_{10}$ concentrations occurred at distances more than 200 km from each power plant.

Therefore it is critical to curtail emissions from industries in Korea, especially those located in the western coastal area because sources of secondary air pollutants originate from this region. Studies on quantitative impact assessment are prerequisite for developing effective emissions abatement strategies to improve air quality. In this context, this study offers a reliable preliminary analysis to evaluate the effects of shutting down power plants with a focus on power plants in the western coastal area.

Scenario I examines a shutdown of the power plant of P08 (Boryeong) with the highest emission but lower stack height showed a negligible impact on the SMA with a maximum PM$_{10}$ concentration reduction rate of $<1\%$ in April but a reduction of 4.4\% in June, respectively (Table 8). As indicated in scenario II, a shutdown of four power plants located within the SMA is found to be more effective at reducing PM$_{10}$ concentrations with a maximum reduction rate of 6.4\% in April and 18.9\% in June, respectively (Table 8). The reduction in PM$_{10}$ concentration for scenario II is approximately proportional to the reduced emission fractions of power plants in the SMA.

Scenario III evaluated the effects of shutting down the power plants aged 30 years or older. During June 2017, this approach was tested by KMOE. Our results indicate that this scenario has a relatively insignificant effect on air quality in the SMA with a maximum concentration reduction rate of $<3\%$ for both high and low PM$_{10}$ cases, only showing an improvement in air quality near power plants with a maximum reduction in PM$_{10}$ concentration more than 31.8-21.2\% for P08 (Boryeong) and 10.5-19.3\% for P17 (Goseong), respectively, which are the highest and second highest reductions in this study. The results for scenario III therefore suggest that ceasing operations of old power plants in Korea has a small but detectable impact on the air quality in the SMA. It is clear that quantifying co-reductions of power plant PM$_{10}$ emissions together with reductions in exhaust from diesel vehicles will be needed to identify the major local sources in the SMA.

For scenario IV, where SO$_2$ and NO$_x$ emissions from the 18 power plants were reduced by 50\%, our simulation results showed that the maximum PM$_{10}$ concentrations in Seoul, Daejeon, P17 (Goseong), P08 (Boryeong), P06 (Gangneung) and P10 (Seocheon) decreased from 0.3 to 19.7\%. This implies that controlling emissions of gaseous air pollutant could have a nearly equally significant on reducing PM$_{10}$ concentrations, it also suggests that secondary production processes of PM$_{10}$ pollution might be a highly significant process generating the high PM$_{10}$ concentrations in most regions in Korea. Scenario V showed the maximum reduction rates of 3.4\% and 7.0\% for in October for Seoul and Daejeon, respectively. The averaged concentration reduction rates are 1.5\% and 3.6\% for Seoul and Deajeon, respectively, in October, indicating the intermediate values between April and June in BAU, higher than those in April and lower than those in June.

In five scenarios, the reduction is more effective in June with the higher mixing height (Fig. 9). The simulation results of curbing PM$_{10}$ emissions from industrial sectors indicate that PM$_{10}$ emissions from power plants located in the western coastal area has a small effect on the SMA but this step seems to only affect air quality around power plants. The concurrent reduction of gas phase precursors such as SO$_2$ and NO$_x$ showed a more pronounced effect. Halving emissions of gas phase pollutants only showed a nominal equivalent decrease with the shutdown of old power plants, as indicated for scenarios III and IV. As mentioned previously, this suggests that another important mechanism leading to elevated PM$_{10}$ concentrations in Korea are processes which convert gases to the particle phase. These processes are likely more complicated with non-linear effects compared to directly decreasing PM$_{10}$ emission from sources such as power plants. In this regard, further studies on the concurrent control of old power plants and restrictions on the use of older diesel vehicles will be important for effective air quality improvement in the SMA.

The current study is limited to investigating the impacts on primary PM$_{10}$ concentrations by reducing emissions from power plants in Korea, but the most effective emission abatement strategies will take into account the secondarily formed PM$_{10}$ concentrations.

5. CONCLUSION

The high PM$_{10}$ concentrations observed in Korea are
partly explained by transboundary transport from China, but frequently mixed with domestic pollution originating from local emissions. Recent studies showed that the cases of high PM$_{10}$ concentrations observed in Korea are frequently influenced by the stagnant synoptic patterns. Therefore it is worthwhile to quantify the effects of curbing emissions from local sources, and might provide valuable insights towards developing more effective air quality policies at the national level.

In this study, we carried out an impact of reduced emissions from power plants in Korea. The modeling results from this study can contribute to strategies of the power plants located South Korea. The TAPM model simulations for a high PM$_{10}$ period of April 4 to 7, and a low PM$_{10}$ period of June 1 to 6, and then carried out emission reduction simulation based on well-designed power plant shut-down scenarios.

The results yielded that all shut-down of four power plants located within the SMA (Scenario II) showed marginal effects on the air quality of Seoul with the reduction rate of 6.4 (0.26 μg/m$^3$) ~18.9% (2.33 μg/m$^3$) of maximum PM$_{10}$ concentrations, while the effect of a shut-down case of one highest-emission power plant, P08 (Boryeong) with low stack height on air quality of Seoul (Scenario I) was found to be rather lower reduction rate of only ~4.4% (0.54 μg/m$^3$) of maximum concentration. Another shutdown of the power plants aged more than 30 years, showed also insignificant effects on the air quality of Seoul. This is suggesting the effectiveness of concurrent reduction of emissions of power plants together with diesel vehicle in Seoul metropolitan area for the improvement of air quality in Seoul. Finally the scenario of 50% reduction in gaseous air pollutant emissions are found to be relatively more significant in regulating the high PM$_{10}$ concentrations then others, suggesting that the SIA (secondary inorganic aerosol) of PM$_{10}$ might be also one of the important factors in regulating the PM$_{10}$ concentrations over the nation-wide areas in Korea. In the current five scenarios, the reduction effectiveness in June under unstable condition is relatively much higher than one in April under stagnant synoptic condition.

This study mainly pertains to the results primary PM$_{10}$ concentrations from the reduction of the power plant emission. However, PM$_{10}$ as well as PM$_{2.5}$ which are emitted directly, and at the same time they are secondarily formed when emissions of gaseous precursors create particle formation. Therefore, in order to inform policies to reduce PM$_{10}$ and PM$_{2.5}$ concentrations, it is important to fully understand the particulate formation processes: both primary and secondary formations. Also long term and comprehensive monitoring would be important to analyze the assessment.

Finally, aside from the local anthropogenic emission sources, source-receptor relationship study is critical to making improvements on assessing other transboundary air pollutants. Therefore more detailed model sensitivity tests based on modeling and monitoring study will be conducted, plus the source-receptor relationship study will be carried out as a future task.

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