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Environmental Benefits of Ammonia Reduction in an Agriculture-Dominated Area in South Korea

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Abstract: Agricultural activity greatly contributes to the secondary $PM_{2.5}$ concentrations by releasing relatively large amounts of ammonia emissions. Nonetheless, studies and air quality policies have traditionally focused on industrial emissions such as NOx and SOx. To compare them, this study used a three-dimensional modeling system (e.g., WRF/CMAQ) to estimate the effects of emission control policies of agricultural and industrial emissions on $PM_{2.5}$ pollution in Chungcheong, an agriculturally active region in Korea. Scenario 1 (S1) was designed to estimate the effect of a 30% reduction in NH_3 emissions from the agro-livestock sector on air pollution. Scenario 2 (S2) was designed to show the air quality under a mitigation policy on NOx, SOx, VOCs, and primary $PM_{2.5}$ from industrial sources, such as power plants and factories. The results revealed that monthly mean $PM_{2.5}$ in Chungcheong could decrease by 3.6% (1.1 μg/m^3) under S1 with agricultural emission control, whereas S2 with industrial emission control may result in only a 0.7~1.1% improvement. These results indicate the importance of identifying trends of multiple precursor emissions and the chemical environment in the target area to enable more efficient air quality management.

Keywords: NH_3; agriculture; $PM_{2.5}$; CMAQ

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1. Introduction

Particulate matter with an aerodynamic diameter of ≤ 2.5 μm ($PM_{2.5}$) is considered a serious hazard due to its adverse effects on human health and the ecosystem [1–3]. According to the State of Global Air [4], air pollution accounted for about 12% of all deaths and ranked as the fourth leading risk factor for premature death globally in 2019. Levinson [5] and Lavy et al. [6] revealed that air pollution can cause negative psychological effects on humans by lowering cognitive ability and altering emotions. Fu et al. [7] suggested that a 1 μg/m^3 increase in $PM_{2.5}$ can decrease work productivity by 0.82%. The projected increasing concentrations of $PM_{2.5}$ and ozone will lead to more hospital admissions, health expenditures, and sick or restricted activity days, resulting in labor productivity losses [8,9].

Many countries have suffered from air pollution over the past years [9–14], and South Korea ranked first among 36 OECD countries in terms of mean population exposure to $PM_{2.5}$ [15]. Lee [16] also found that Seoul, the capital of South Korea, had 27 μg/m^3 of annual average $PM_{2.5}$ concentration from November 2005 to March 2012, which is almost three times the WHO standard. Han et al. [17] estimated that more than 11,000 premature deaths were attributable to high $PM_{2.5}$ pollution in South Korea in 2015, especially concentrated in the Seoul and Gyeonggi province with high population densities.

$PM_{2.5}$ is formed through interactions between primary particles, various precursors such as NOx, SOx, VOCs, and NH_3, photochemical reactions, and meteorological processes [18–20]. The composition of $PM_{2.5}$ is various types of chemicals from primary and secondary origins, including elemental and organic carbon, ionic species (i.e., chloride, nitrates, sulfates, and ammonium), and elemental species [21,22]. Secondary inorganic $PM_{2.5}$, such as nitrate and sulfate, are formed through chemical reactions between the base gas NH_3 and acidic gas (i.e., NO_2 and SO_2). As a result, NH_4^+, SO_4^{2-}, and NO_3^- become major components of inorganic $PM_{2.5}$ [23–26].

Some studies have suggested that ammonia plays a critical role in the formulation of $PM_{2.5}$ as a precursor of secondary inorganic aerosols (SIAs) including ammonium sulfate ($(NH_4)_2SO_4$) and ammonium nitrate (NH_4NO_3) [27–29]. As shown by Aneja et al. [30] and Behera et al. [31], most ammonia is released from agricultural sources, such as animal husbandry, fertilizer use, and crop residues combustion. Moreover, in the long run, Korea's ammonia emissions are steadily increasing despite its repeating short-term up-and-down fluctuations [32,33]. However, studies on the effects of NH_3 emission mitigations in South Korea are still limited.

In this study, we conducted a modeling study to estimate the impact of agricultural ammonia emission control on $PM_{2.5}$ concentration in the Chungcheong region, which is one of the most agriculture-dominated areas in South Korea. The results were compared to other cases of industrial emission control.

2. Methods

2.1. Study Area

We carried out simulations focused on the Chungcheong area, considering its high agricultural emissions in South Korea. The study area—Chungcheong—consists of two provinces: Chungbuk and Chungnam, as shown in Figure 1. Figure 2 shows that Korea has recently emitted about 300,000 tons of NH_3 in a year, while Chungcheong accounts for more than 20% of the total since 2008 [33].

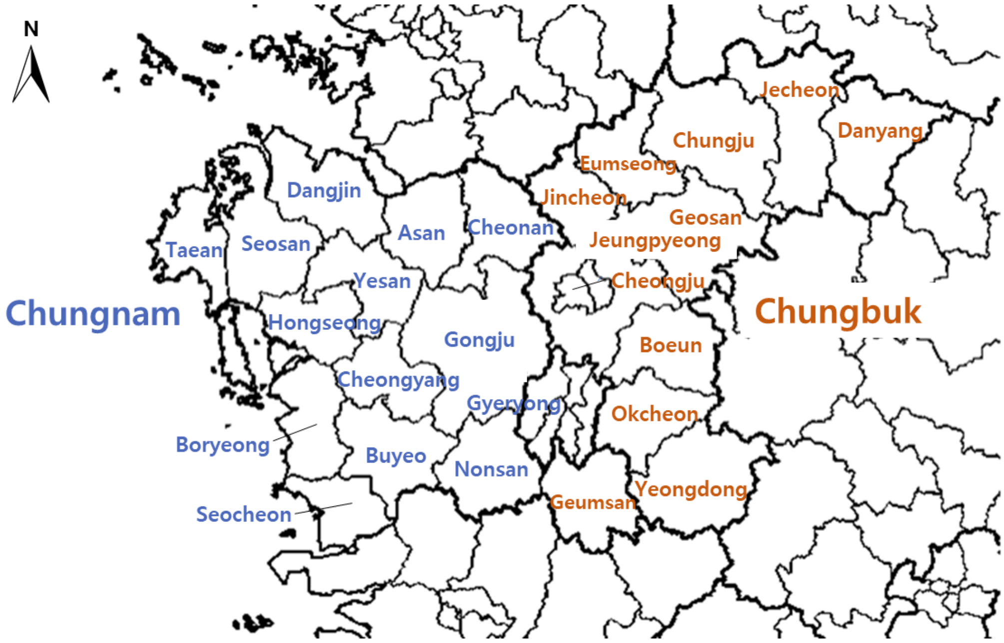


Figure 1. Administrative map of Chungcheong region.

This seems to be mainly caused by its vigorous activity of animal husbandry. According to a livestock trend survey by Korea National Statistical Office, Chungcheong accounts for 25% of the nation's livestock population and has 48,188,370 heads, the second largest in the country (Figure 3, Table 1) [34]. Particularly, Chungcheong has the second and first largest number of dairy cattle and swine, which belong to the livestock with the highest emission factors (Table 2) [35]. In the agricultural sector, Chungcheong has 3283 km^2 of farmland, accounting for 20.3% of the total (Table 3) [36].

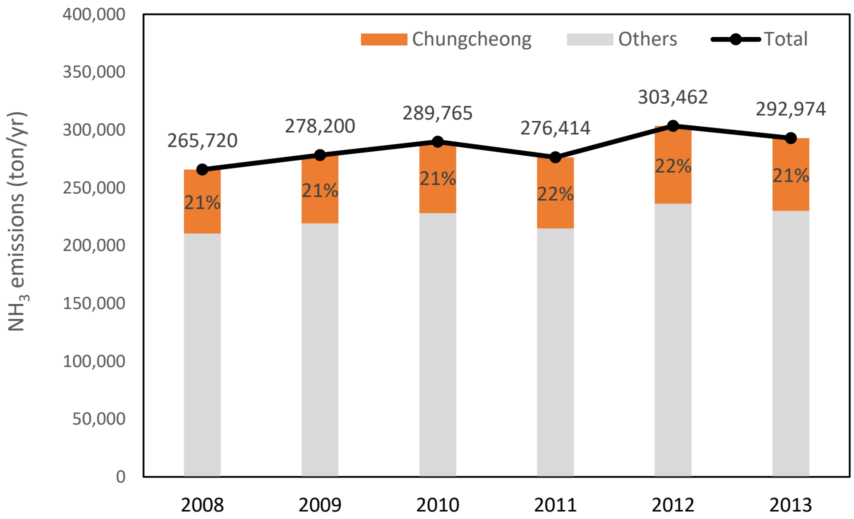


Figure 2. Trend of NH_3 emissions in South Korea (2008~2013).

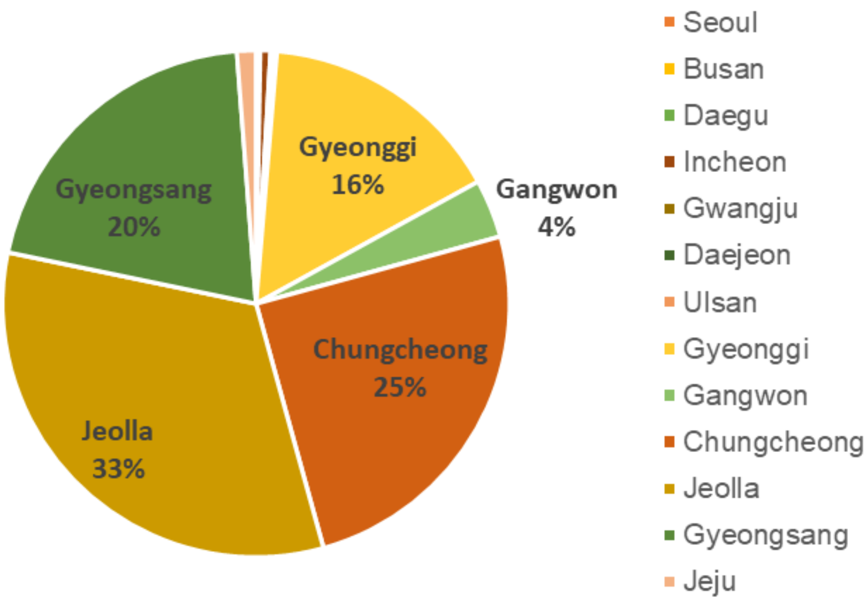


Figure 3. Livestock ratio by region (2017).

Table 1. Livestock statistics by animal type and region (2017).

Region	Beef Cattle	Dairy Cattle	Swine	Poultry	Duck	Total
Seoul	127	21	-	-	-	148
Busan	1575	378	5806	93,264	-	101,023
Daegu	18,426	1267	8114	388,500	-	416,307
Incheon	19,104	2675	40,325	1,175,700	-	1,237,804
Gwangju	6525	674	8269	141,700	-	157,168
Daejeon	6079	-	60	98,200	-	104,339
Ulsan	28,232	777	25,589	481,081	-	535,679
Gyeonggi	274,776	163,486	1,866,428	27,710,065	205,600	30,220,355
Gangwon	207,235	17,567	453,137	6,502,703	2080	7,182,722
Chungcheong	567,489	94,433	2,728,372	44,147,120	650,956	48,188,370
Jeolla	767,005	59,707	2,329,466	54,546,211	5,044,435	62,746,824
Gyeongsang	856,847	57,187	2,394,658	35,743,902	540,465	39,593,059
Jeju	32,326	4003	571,684	1,715,033	16,300	2,339,346
Total	2,785,746	402,175	10,431,908	172,743,479	6,459,836	192,823,144

Table 2. Ammonia emission factor by livestock type.

Livestock Type	Subdivision	Emission Factor (kg-NH_3/Head)
Beef cattle	Under 1 year old	11.8
	1–2 years old	14.0
	Over 2 years old	16.8
Dairy cattle	-	24.6
Swine	Nursery pig	4.4
	Glowing pig	8.7
	Fatting pig	11.4
	Sow	21.4
Poultry	Laying hen	0.37
	Broiler	0.28
Other poultry	Duck	0.92

Table 3. Area and area ratio of farmland by region (2017).

Region	Farmland (km^2)	Ratio (%)
Seoul	4	0.0
Busan	57	0.4
Daegu	81	0.5
Incheon	190	1.2
Gwangju	94	0.6
Daejeon	39	0.2
Ulsan	105	0.7
Gyeonggi	1657	10.2
Gangwon	1031	6.4
Chungcheong	3283	20.3
Jeolla	4931	30.4
Gyeongsang	4124	25.4
Jeju	611	3.8
Total	16,208	100.0

2.2. Model Description and Emission Inventory

In this study, we used Weather Research and Forecast (WRFv3.6) and Sparse Matrix Operator Kernel Emission (SMOKEv3.5) to simulate meteorological conditions and process emission data. Community Multi-scale Air Quality Modeling (CMAQv5.0.2) was applied to estimate concentrations of $PM_{2.5}$ in the Chungcheong area. Figure 4 shows a general flowchart of the WRF-SMOKE-CMAQ modeling system. This simulation was carried out for three nested domains, including Domain 1 (East-Asia)—27 × 27 km and 124 × 131 grid cells, Domain 2 (Korea)—9 × 9 km and 73 × 85 grid cells, and Domain 3 (Chungcheong)—3 × 3 km and 88 × 58 grid cells (Figure 5). The projection mode was Lambert. Carbon Bond 5 (CB5) schemes, the SAPRC mechanism, and AERO 5 module were applied for gas and aerosol chemical mechanism for CMAQ modeling. YAMO was selected for the advection scheme.

WRF was used to provide meteorological data needed by the CMAQ under conditions as follows; WSM6 for microphysics, Dudhia for shortwave radiation, RRTM for longwave radiation, Kain–Fritsch for cumulus parametrization, the Yonsei University Scheme (YUS) for planetary boundary layer, and Noah for land surface model (Table 4).

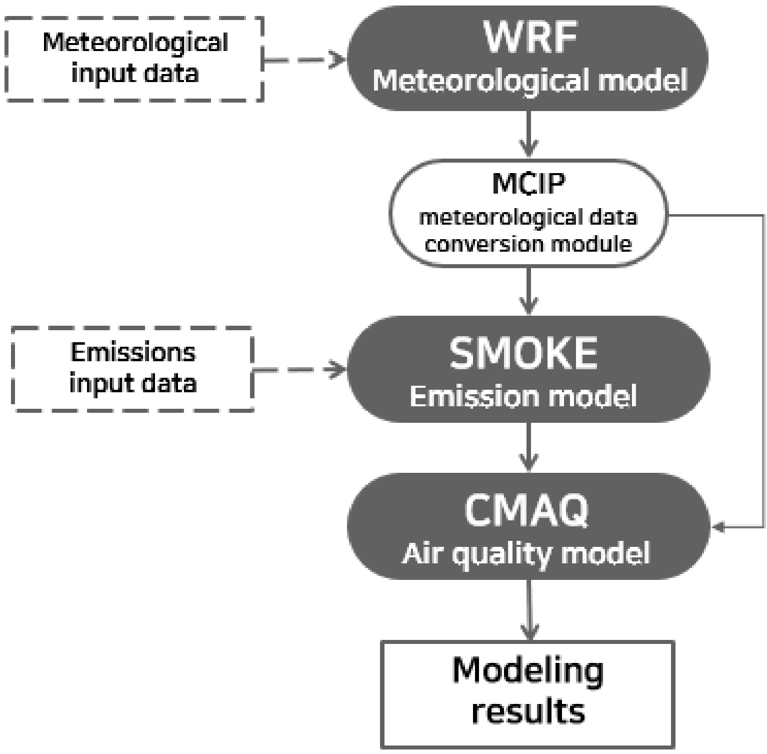


Figure 4. Flowchart of the WRF-SMOKE-CMAQ modeling system.

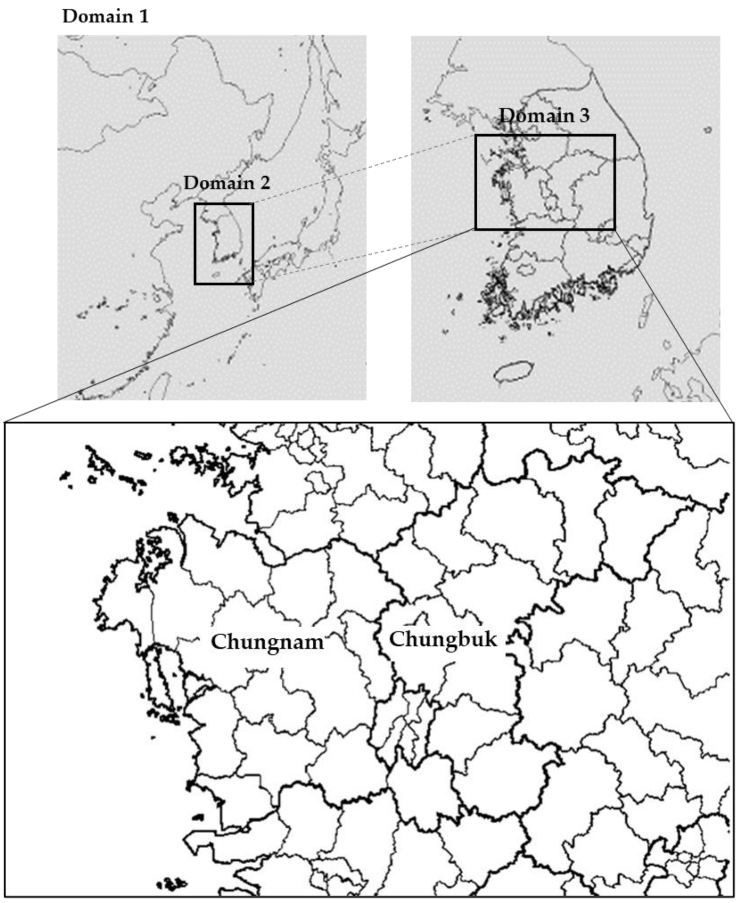


Figure 5. Simulation domain for WRF and CMAQ.

Table 4. CMAQ and WRF model conditions.

Model	Parameter	Selected Option
CMAQ	Gas-phase chemical mechanism	CB05
	Aerosol module	AERO5
	Chemical mechanism	SAPRC99
	Advection scheme	YAMO
WRF	Microphysics	WSM6
	Shortwave radiation	Dudhia
	Longwave radiation	RRTM
	Cumulus parameterization	Kain–Fritsch
	Planetary boundary layer	Yonsei University Scheme
	Land surface model	Noah

SMOKE was used as a processing model of emission data—CAPSS, which is the national emissions inventory developed by the National Institute of Environmental Research here in Korea. It uses classification categories including point, area, on-road and non-road sectors. Point sectors include industrial emissions from related sources such as "combustion in manufacturing industries", "production processes, storage and distribution of fuels", and "combustion in energy industries". Area sectors include emissions from "agriculture" and "agricultural crop residues burning" [37]. In this study, we focused only on the "agriculture" subsector. The agriculture subsector consists of two classes—"Manure management" and "Agricultural land". "Manure management" includes emissions from manure of the livestock such as cattle, swine, poultry, other poultry, sheep and lamb, perissodactyl, fur animal, and others. "Agricultural land" represents all emissions from fertilized farmland.

2.3. Emission Scenarios

We designed three types of scenarios including Base case without any control policy, Scenario 1 (S1) with agricultural emission control policy only, and Scenario 2 (S2) with industrial emission control policy only.

Base case was performed to show standard pollution conditions under no emission control. Emission data used in the Base case simulation is from CAPSS 2017, which was the latest version of national emission data in South Korea. For S1 and S2, CAPSS 2017 data were applied with modifications in agricultural or industrial emissions depending on each emission reduction policy. S1 focused only on NH_3 emissions control from agro-livestock sources such as livestock and fertilizer applications. S2 was limited to emission control of NOx, SOx, VOCs, and primary $PM_{2.5}$ from industrial sources such as power plants and factories. To design these scenarios, we referred to the latest Korean national air quality management policy, including the "Fine Dust Reduction Measures in Agro-Livestock Sector" and the "Comprehensive Plan on Fine Dust Management (2020~2024)". Each emission inventory for the respective scenarios is described in Table 5.

The Ministry of Agriculture, Food and Rural Affairs announced the "Fine Dust Reduction Measures in Agro-Livestock Sector "in 2019 in consideration of increasing concerns regarding NH_3 emissions. This policy aimed to decrease agricultural NH_3 emissions by 30% through 2022.

The "Comprehensive Plan on Fine Dust Management" was designed to decrease the national annual mean of $PM_{2.5}$ from 26 $\mu g/m^3$ in 2016 to 16 $\mu g/m^3$ in 2024. To achieve this target, different reduction rates were applied to the two provinces comprising the Chungcheong region—Chungbuk Province (Figure 3) and Chungnam Province, and the respective reduction rates are shown in Table 6.

Table 5. Emission inventories for Base case, S1, and S2.

Scenario	Point Source Emissions from Chungcheong (ton/yr)						
	CO	NOx	SOx	VOCs	$PM_{2.5}$	PM_{10}	NH_3
Base	18,611	85,449	58,270	33,910	2674	3600	11,111
S1	18,611	85,449	58,270	33,910	2674	3600	11,111
S2	18,611	53,970 (−31,479)	28,397 (−29,873)	30,747 (−3163)	2277 (−397)	3600	11,111
Scenario	**Area Source Emissions from Chungcheong (ton/yr)**						
	CO	**NOx**	**SOx**	**VOCs**	$PM_{2.5}$	PM_{10}	NH_3
Base	60,055	21,413	18,090	75,942	12,222	21,820	55,045
S1	60,055	21,413	18,090	75,942	12,222	21,820	38,859 (−16,186)
S2	60,055	21,413	18,090	75,942	12,222	21,820	55,045

Table 6. Emission reduction rates of Chungcheong for S2.

	NOx	SOx	VOCs	$PM_{2.5}$
Chungbuk	27%	17%	8%	15%
Chungnam	44%	55%	13%	15%

2.4. Target Period

In this study, we focused on evaluating the air quality improvement under emission-controlled cases in the most polluted month, which was March 2017. From the data on monthly mean air pollution in Chungcheong in 2017 [38], March showed the highest $PM_{2.5}$ concentration, reaching 36.6 $\mu g/m^3$, while the annual mean was 25.0 $\mu g/m^3$ (Figure 6).

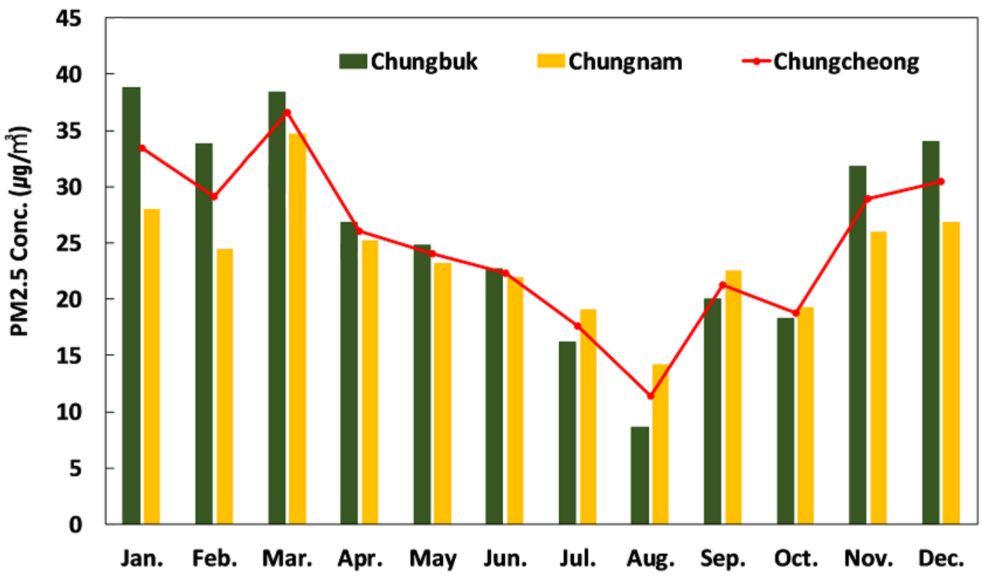
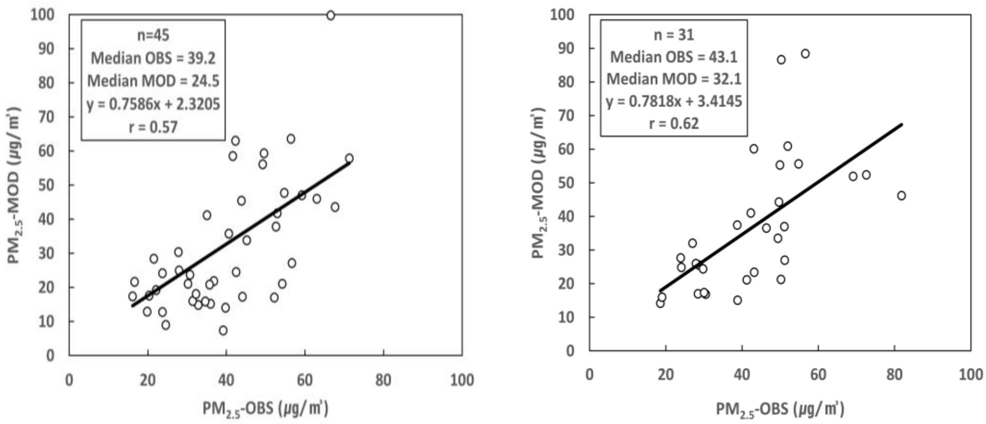


Figure 6. The 2017 monthly mean $PM_{2.5}$ concentration in Chungcheong.

2.5. Model Performance

To assess the performance of WRF-CMAQ, we compared the simulated $PM_{2.5}$ concentrations with the observation values collected in each representative station in Chungbuk province (Cheongju) and Chungnam province (Cheonan) during March 2017. Figure 7 shows the correlation analysis results of the observation data and the simulation data from CMAQ in two representative stations. Table 7 indicates the statistical values including Mean Bias (MB), Index of Agreement (IOA), fraction of predictions within a factor of two of observations (FAC2), and Correlation coefficient (R). MB was calculated as the mean difference in model estimates-observation pairings within the selected study area and period. IOA metric integrates all the differences between model estimates and observations into one statistical quantity. FAC2 was calculated by dividing model predictions by observations. From the summary statistics, we concluded that the model performed well, as the MB in both areas is relatively small with adequate IOA (0.71–0.74). FAC2 ranging from 0.82 to 0.86 is also within the acceptable range (0.5–2.0) [39]. R of 0.57–0.62 seems to be relatively low, however, we considered it is within acceptable range based on previous studies, which simulated secondary air pollutants concentration and concluded R is reasonable with similar levels (below 0.70) [40–43]. These studies have suggested that CMAQ simulates concentration trend well, but it tends to over/under-estimate concentrations during low/high concentration periods, which might be due to uncertainty in emission data and inaccuracy of meteorological model (WRF) under complex weather change conditions. In this study, the air quality model generally underestimated $PM_{2.5}$ concentration during high $PM_{2.5}$ episodes as shown in Figure 8, resulting in a lower average of predicted concentration of 32.4–36.7 μg/m^3 compared to the observed concentration of 39.7–42.6 μg/m^3 (Table 8).

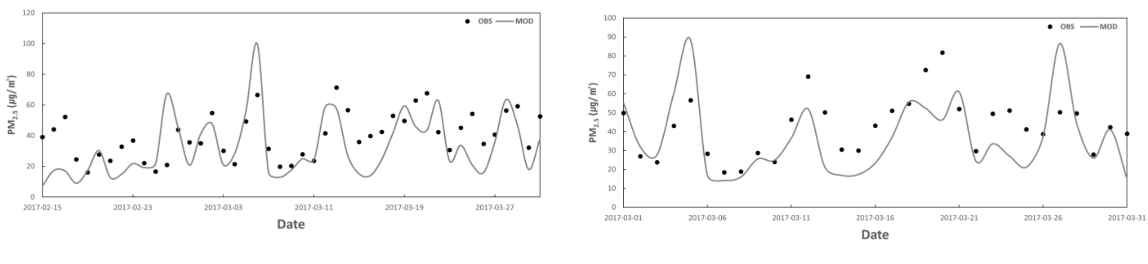


(**a**) (**b**)

Figure 7. Observed and simulated $PM_{2.5}$ concentration in March 2017 at (**a**) Cheongju station in Chungbuk province and (**b**) Cheonan station in Chungnam province.

Table 7. Statistical parameters for simulated $PM_{2.5}$ concentrations.

Statistic	Cheongju	Cheonan
MB	−7.26	−5.87
IOA	0.71	0.74
FAC2	0.82	0.86
R	0.57	0.62



(**a**) (**b**)

Figure 8. Time series of observed and simulated $PM_{2.5}$ concentrations in (**a**) Cheongju and (**b**) Cheonan.

Table 8. Observed and simulated monthly mean $PM_{2.5}$ at Cheongju station in Chungbuk province and Cheonan station in Chungnam province.

Mean (μg/m^3)	Cheongju	Cheonan
OBS	39.7	42.6
MOD	32.4	36.7

3. Results and Discussions

3.1. Base Case

Under the baseline scenario, the $PM_{2.5}$ concentration throughout Chungcheong was simulated as shown in Figure 9 and Table 9. The overall monthly mean $PM_{2.5}$ in Chungcheong was about 31.6 μg/m^3 with 31.65 μg/m^3 in Chungbuk and 31.58 μg/m^3 in Chungnam. At the city level, Cheongju in Chungbuk, and Hongseong and Cheonan in Chungnam showed comparatively severe pollution with $PM_{2.5}$ concentrations higher than 35 μg/m^3.

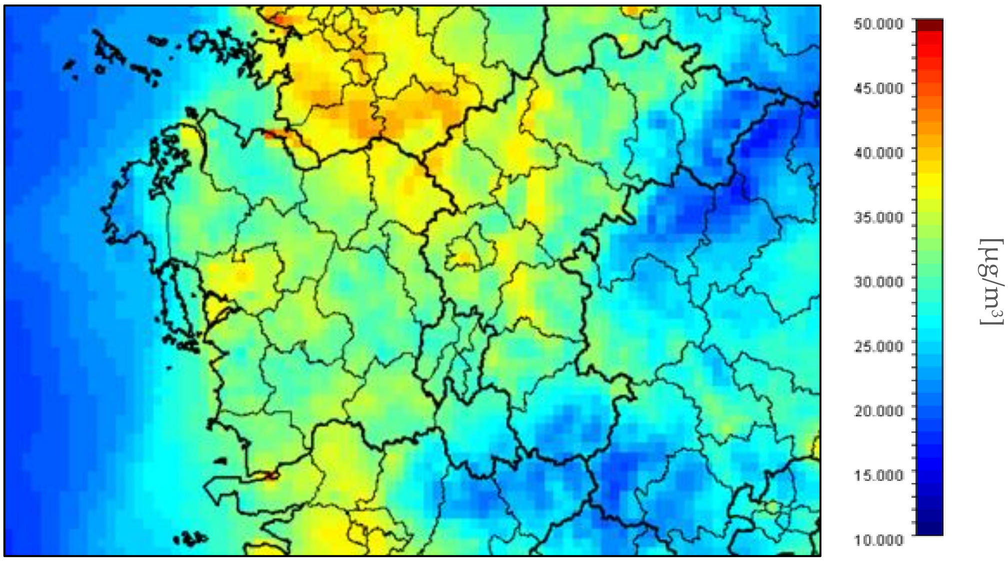


Figure 9. Monthly mean $PM_{2.5}$ concentration in Chungcheong under Base scenario.

Table 9. Predicted average $PM_{2.5}$ concentration under Base scenario in Chungcheong in March 2017.

Chungbuk		Chungnam	
City	$PM_{2.5}$ Conc. (μg/m^3)	City	$PM_{2.5}$ Conc. (μg/m^3)
Cheongju	35.8	Gongju	29.3
Goesan	30.9	Geumsan	26.3
Danyang	26.0	Hongseong	36.2
Jincheon	33.9	Nonsan	34.2
Boeun	31.8	Dangjin	28.1
Chungju	32.3	Seosan	31.5
Eumseong	34.6	Boryeong	31.8
Yeongdong	24.7	Asan	33.2
Jecheon	31.5	Cheonan	36.7
Okcheon	32.1	Buyeo	30.9
Jeungpyeong	34.7	Seocheon	31.3
		Gyeryong	31.3
		Yesan	32.8
Average	31.65	Average	31.58

3.2. Benefits of Agricultural Emission Control (S1)

Under agricultural emission reduction policy, NH_3 concentration seems to be reduced by more than 2 ppb in most regions in Chungcheong (Figure 10). The $PM_{2.5}$ concentration is also predicted to decrease, as shown in Figure 11. In short, 30% of NH_3 emission reduction from the agricultural sector may lead to more than 0.8 μg/m^3 in $PM_{2.5}$ improvement compared to the base case throughout Chungcheong. It is simulated that the average $PM_{2.5}$ decrease is 1.1 μg/m^3 and the improvement rate is about 3.6% in Chungcheong (Table 10).

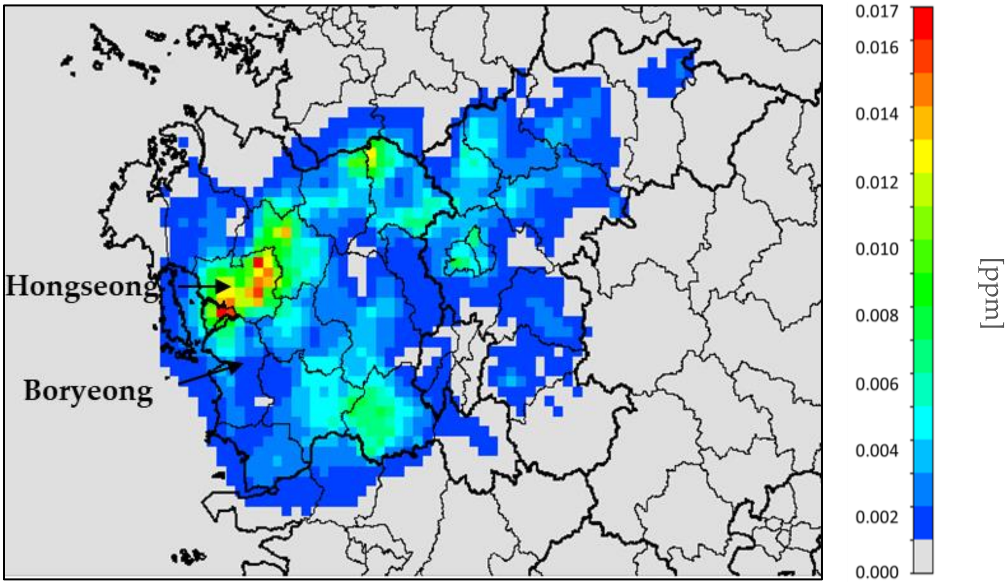


Figure 10. Monthly mean improvement of NH_3 concentration under S1.

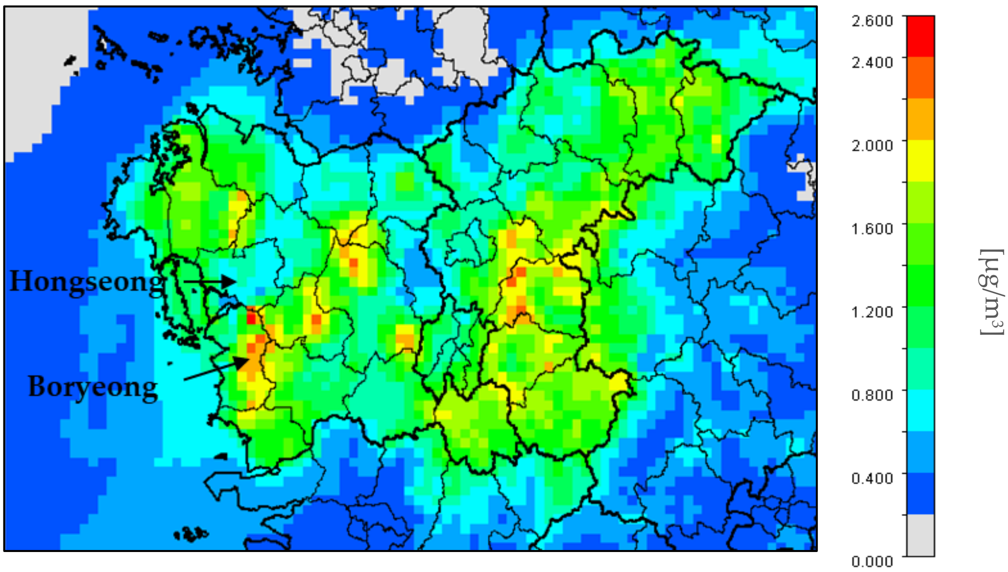


Figure 11. Monthly mean improvement of $PM_{2.5}$ concentration under S1.

Table 10. Predicted average change of $PM_{2.5}$ concentration under S1 relative to the base case in Chungcheong in March 2017.

Region	$PM_{2.5}$ Change (μg/m^3)	Improvement Rate (%)
Chungbuk	−1.1	3.6
Chungnam	−1.1	3.5

However, concentration improvements of NH_3 and $PM_{2.5}$ show spatial inconsistencies. For example, the city showing the largest improvement in NH_3 concentration under S1 is Hongseong, while the city with the largest improvement in $PM_{2.5}$ concentration is its neighbor, Boryeong. We presume that this may be caused by other major precursors of inorganic $PM_{2.5}$, such as HNO_3 and H_2SO_4 [44]. In other words, it seems that some regions, such as Hongseong, do not show $PM_{2.5}$ concentration reduction effects proportional to their NH_3 reduction amount because of their low concentration of HNO_3 and/or H_2SO_4. To verify this, we carried out a spatial prediction of HNO_3 concentration under the base scenario (Figure 12). H_2SO_4 was not considered because it is rarely found in the atmosphere since it usually reacts with ammonia instantly and forms ammonium bisulfate or ammonium sulfate [44]. Therefore, we presumed that the difference in abundance of HNO_3, which reacts with the NH_3 remaining after reaction with H_2SO_4, also affected the results of NH_3 reduction.

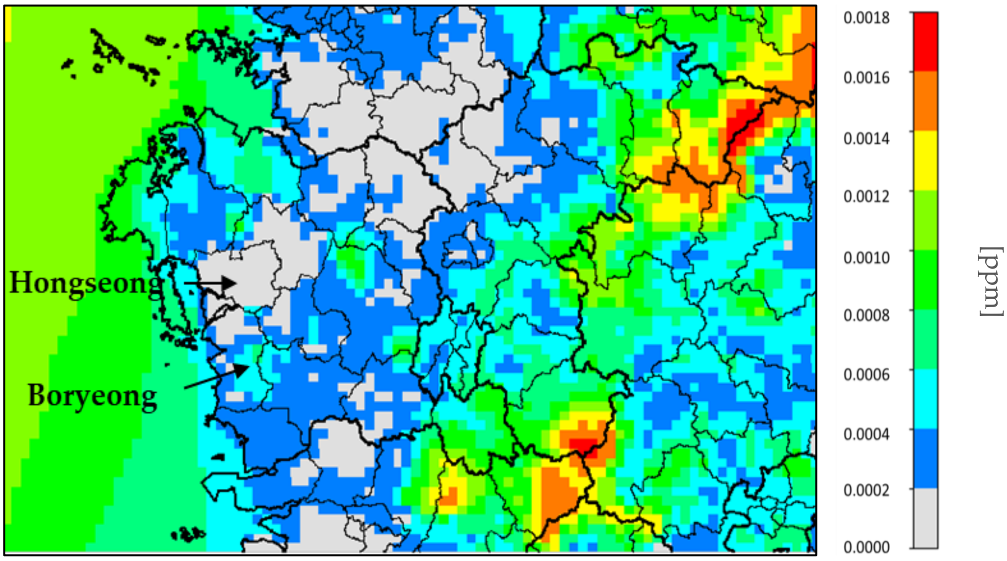
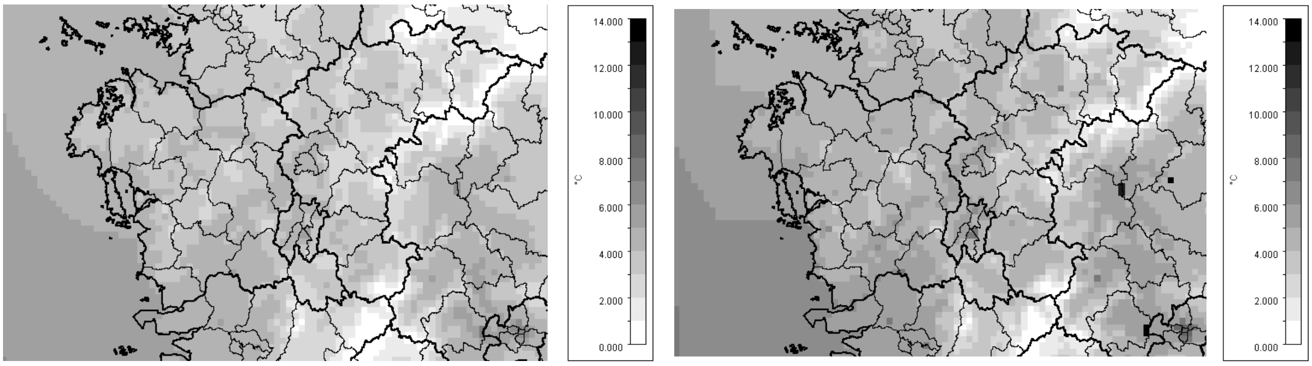


Figure 12. Monthly mean of HNO_3 concentration under Base scenario.

The results showed that the HNO_3 concentration was less than 0.2 ppb in Hongseong, the city with the highest reduction in NH_3 emissions under S1. On the other hand, Boryeong, with the most improved $PM_{2.5}$ concentration under S1, showed a relatively high HNO_3 concentration of 0.4 ppb or higher. In addition, most regions with higher HNO_3 concentrations showed larger $PM_{2.5}$ reduction effects.

We estimated that, unlike HNO_3, regional differences in meteorological factors were limited, so they did not play an important role in the spatial inconsistency between NH_3 improvement and $PM_{2.5}$ improvement. It is known that the SIAs mass has seasonal variability. While the formation of nitrate is relatively more active in the winter under lower temperature and higher humidity, sulfate formation is more active in summer due to high solar radiation and more OH radicals [45]. However, when we examined the possibility that meteorological conditions would affect the inconsistency, the results showed as "less likely". As shown in Figure 13, the spatial distribution of temperature at 2 m and surface temperature across Chungcheong indicates that it would not have played an important role due to its limited differences by region. Moreover, there is no significant difference in the temperatures of Hongseong and Boryeong, the regions with the NH_3-$PM_{2.5}$ inconsistency.



(**a**) (**b**)

Figure 13. Spatial distribution of monthly mean (**a**) temperature at 2 m and (**b**) surface temperature in Chungcheong.

3.3. Benefits of Industrial Emission Control (S2)

As shown in Figure 14, it was predicted that industrial NOx, SOx, VOCs, and primary $PM_{2.5}$ emission controls may lead to smaller $PM_{2.5}$ concentration improvements compared to S1. Under S2, $PM_{2.5}$ concentration decreased by less than 0.4 μg/m^3 in all cities in Chungcheong except Hongseong in Chungnam. The improvement rate was also limited to 0.7% in Chungbuk and 1.1% in Chungnam (Table 11).

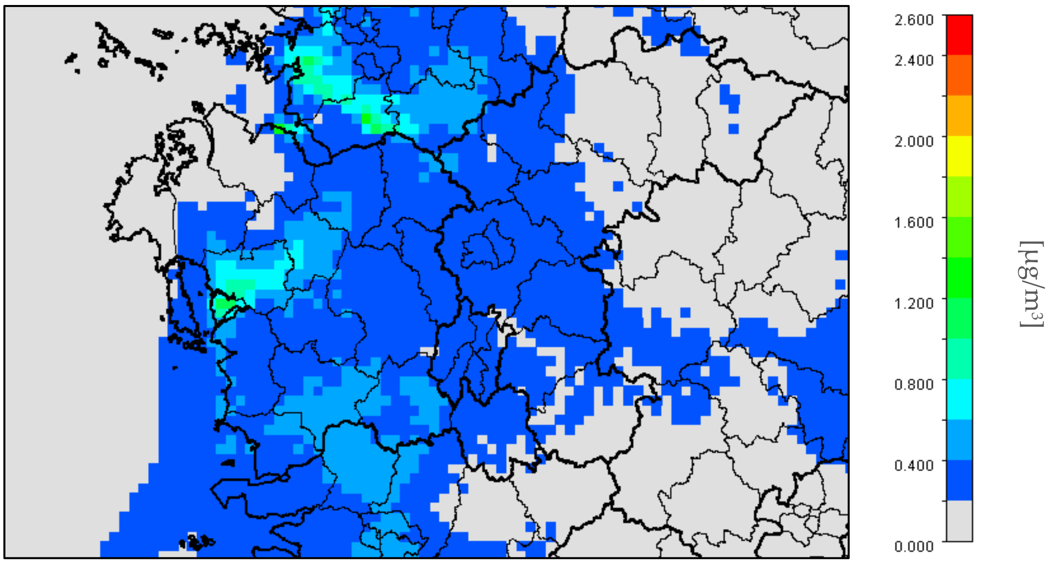


Figure 14. Monthly mean improvement of $PM_{2.5}$ concentration under S2.

Table 11. Predicted average change of $PM_{2.5}$ concentration under S2 relative to the Base case in Chungcheong in March 2017.

Region	$PM_{2.5}$ Change (μg/m^3)	Improvement Rate (%)
Chungbuk	−0.2	0.7
Chungnam	−0.3	1.1

In short, the industrial emission control policy was less effective than the agricultural emission policy despite its larger reduction of emissions and more various target pollutants. The main reason for this seems to be the non-linear formation mechanism of secondary air pollutants. For example, in a VOCs-limited (or NOx-rich) region, control of NOx may lead to increased concentration of ozone and particulate matter, which is the so-called "NOx disbenefit" [46]. To examine this case, we compared the spatial distribution of NOx and ozone concentration changes under S2, which are shown in Figures 15 and 16. As a result, it was found that the ozone concentration was higher than that of the base scenario, especially in regions with relatively large NOx reduction. As the ozone concentration increased, the atmospheric acidity was also strengthened, which seems to have led to more active formation processes of secondary $PM_{2.5}$.

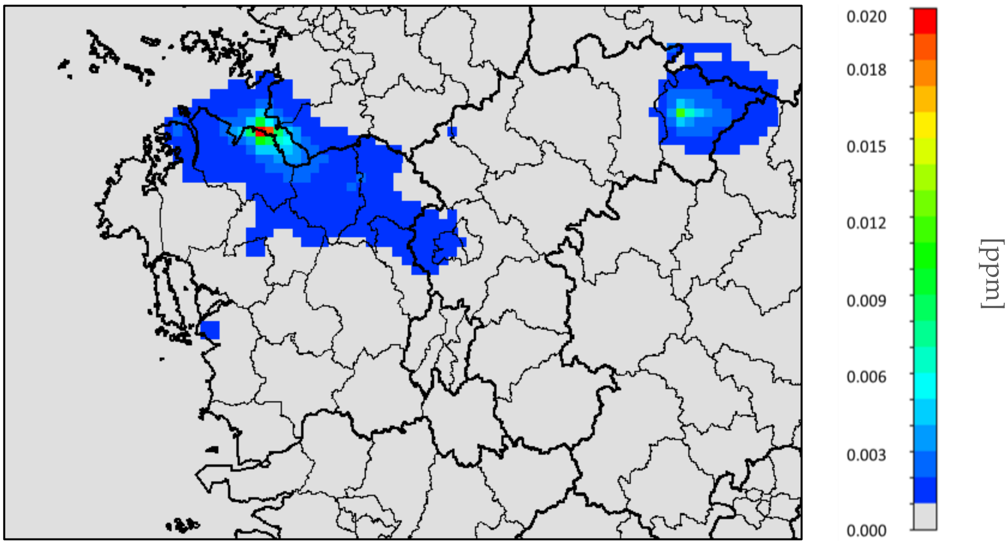


Figure 15. Monthly mean improvement of NOx concentration under S2.

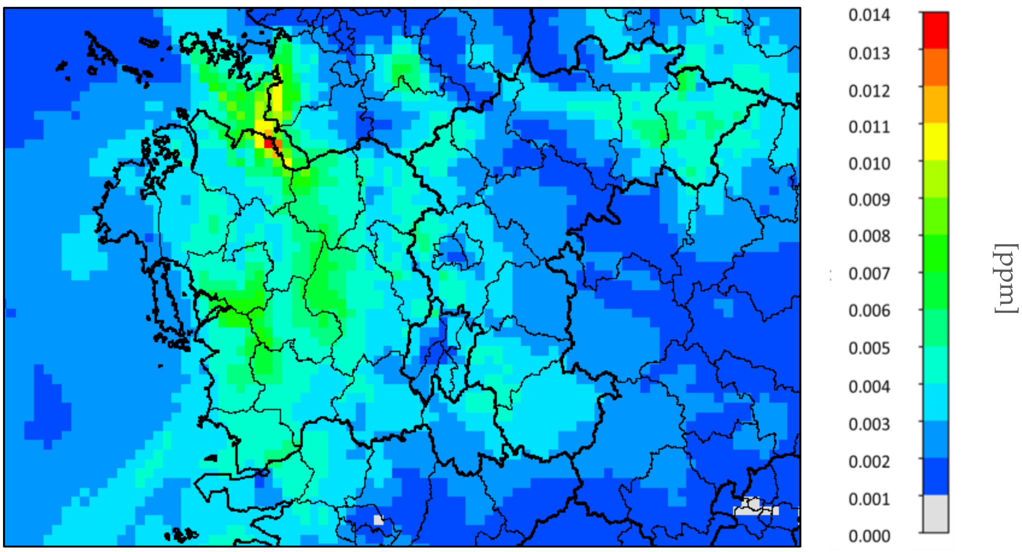


Figure 16. Monthly mean increases in maximum 8-h O_3 concentration under S2.

4. Conclusions

In this study, we carried out air quality simulations to quantify the environmental effects of agricultural NH_3 reduction versus industrial emissions reduction on $PM_{2.5}$ production. The results showed that a 30% NH_3 emission mitigation from the agro-livestock sector in Chungcheong could lead to about a 3.6% decrease in $PM_{2.5}$ concentrations compared to 32 $\mu g/m^3$ of the estimated monthly mean $PM_{2.5}$ in March 2017. In contrast, under the industrial emission reduction scenario (S2), it was predicted that the improvement ratio of the $PM_{2.5}$ concentration would be only 0.7%~1.1% despite the greater amount of reduced emissions and more target precursors including NOx, SOx, VOCs, and primary $PM_{2.5}$. Considering the predicted increases of ozone concentrations under S2, we assume that the main reason for this is that Chungcheong has a NOx-rich environment, where reducing the NOx might rather trigger the formation of ozone and secondary aerosols.

Regarding the agricultural emission control case, spatial inconsistency between the regions with the biggest NH_3 reduction and regions with the most improved $PM_{2.5}$ concentrations was observed. Given that concentrations of acid precursors could also affect the formation of secondary aerosols, we confirmed that a relatively low HNO_3 concentration caused a non-proportional effect of NH_3 reduction measures on PM pollution in this case. For example, Hongseong, the city with the largest NH_3 emission reduction, did not get the best improvement effects on $PM_{2.5}$ concentration because of its low HNO_3 concentration of less than 0.2 ppb.

In short, this study verified that the management of agricultural NH_3 emissions could be a more efficient way for reducing $PM_{2.5}$ concentrations rather than the current policy, mostly focused on industrial emissions for certain regions. In addition, to formulate effective air pollution control policies, it would be required to examine the possibility of negative and/or minimal effects of NOx emission mitigations by clarifying if the target area has a NOx-rich environment or not. In conclusion, especially in agriculture-dominated cities, this study highlights that a policy targeting ammonia management could be a safer choice and result in significant air pollution improvement effects unless the target area has a limited amount of HNO_3 Therefore, it should be considered that HNO_3 can be an important factor influencing the effectiveness of the NH_3 mitigation measures to reduce PM pollution.

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