

LAMP WRF-CHEM MODEL SENSITIVITY TO CHEMICAL SCHEMES IN SIMULATING PARTICULATE MATTER CONCENTRATIONS AND DOWNWARD SHORTWAVE RADIATION OVER GREENHOUSE-COMPLEX REGIONS IN KOREA: A CASE STUDY

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ABSTRACT. It has been reported that fine dust (particulate matter, PM) can adversely affect greenhouse crop production by reducing incoming solar radiation and near-surface temperature, potentially increasing winter–spring management costs (e.g., supplemental lighting and heating). Here we conducted WRF-Chem simulations for a high-PM episode over the Korean Peninsula (Mar. 1–8, 2019), focusing on three major greenhouse-complex regions (Haman, Hwaseong, and Buyeo). Sensitivity experiments were performed using four chemistry/aerosol configurations based on RACM-family gas-phase chemistry; the YSU planetary boundary layer (PBL) scheme was used in the five experiments analyzed here. We evaluated simulated PM₁₀ and PM_{2.5} concentrations, downward shortwave radiation, and PBL depth across experiments. All experiments reproduced the synoptic-scale long-range transport pattern from upwind China, while underestimating PM levels at the study sites. Among the tested options, the GOCART aerosol module best captured the observed temporal evolution of PM. Relative to the NO-Chem experiment, shortwave radiation decreased markedly during the peak episode (Mar. 4–7), yielding a cumulative DSWR deficit on the order of 10³ Whm^{−2} over large greenhouse complexes; shallow PBL conditions coincided with elevated PM concentrations. These results demonstrate the sensitivity of modeled PM and radiation to chemistry configurations during the event and provide a basis for future coupling with greenhouse crop models to quantify crop-growth impacts.

Keywords: WRF-Chem; Particulate matter; Greenhouse cultivation; Downward shortwave radiation; Planetary boundary layer

1 INTRODUCTION

Particulate matter (PM) is composed of organic and inorganic materials, including sulfate, nitrate, and ammonium. PM₁₀ and PM_{2.5} denote particles with aerodynamic diameters smaller than 10 μm and 2.5 μm , respectively (Li et al. 2016). Air pollution in East Asia has been associated with a wide range of impacts on weather, climate, health, and ecosystems (Lee et al. 2020a; Park et al. 2013; Streets et al. 2006; Unsworth and Ormrod 1982; Zhang et al. 2012, 2018). PM can contribute to acid deposition and associated soil and water acidification (Krug and Frink 1983; Vallero 2014). Per-

sistent air pollution can also impair plant metabolism, including stomatal function and photosynthesis (Dhir 2016), thereby inhibiting crop growth and reducing yield (Gupta et al. 2017; Zhou et al. 2018). Aerosols also influence surface shortwave radiation through direct radiative effects and through aerosol–cloud interactions (Charlson et al. 1992; Haywood and Boucher 2000; Rosenfeld et al. 2008; Twomey 1977); under polluted conditions these processes may also be accompanied by changes in haze, fog, and boundary-layer structure (Huang et al. 2014, 2018).

According to MAFRA (2019), greenhouse-crop cultivation in Korea exceeds 80,000 ha, accounting for about

5% of the total crop cultivation area. Winter and spring are important sowing, germination, and early-growth periods for greenhouse crops such as watermelon, oriental melon, and tomato, and insufficient sunlight during these periods can lead to poor early growth, fruit drop, and malformed fruit (NIHHS 2018). Low temperature and reduced sunlight can also lower fruit quality and yield and can contribute to physiological disorders related to poor water uptake. Chun et al. (2001) discussed reduced greenhouse-crop growth under low-sunlight conditions and reduced root development associated with lower soil temperature. Temperature and solar radiation are therefore important factors for winter greenhouse production, and deficits can increase management costs such as heating and supplemental lighting. High-PM episodes occur frequently in Korea during winter and spring because of regional meteorological and geographical conditions (Kim et al. 2007; Lee et al. 2011). For example, sunshine duration from January to March 2010 was about 20% below normal (KMA 2010), contributing to agricultural production losses and higher prices. RDA (2020) reported that Asian dust can reduce greenhouse transmittance and that deposition accompanied by dew or rain can further strengthen particle adhesion, reducing transmittance by 20–30%. Reduced greenhouse transmittance caused by yellow dust and fine particles has been associated with increased fruit drop in zucchini and leaf discoloration in cucumber and pepper (Chu et al. 2003).

Despite evidence that aerosol-related changes in solar radiation can affect crop growth and production, relatively few studies have examined aerosol–radiation effects over major greenhouse-production regions using an online meteorology–chemistry model that represents interactions between atmospheric composition and radiation. This study therefore evaluates the sensitivity of simulated PM concentrations and downward shortwave radiation to alternative WRF-Chem chemistry/aerosol configurations during a severe high-PM episode affecting major greenhouse complexes in Korea. The objective is to characterize relative differences among the chemistry configurations and to provide a modeling basis for future coupling with greenhouse crop models; the study is not intended as a comprehensive evaluation of absolute PM forecast skill.

Section 2 describes the observational datasets, WRF-Chem and LAMP framework, experimental configuration, and HYSPLIT analysis. Section 3 describes the selected high-PM episode. Section 4 presents the simulated PM concentrations, radiative responses, and PBL characteristics. Section 5 summarizes the conclusions and limitations.

2 METHODOLOGY

LAMP (Land–Atmosphere Modeling Package) is the operational modeling workflow of the National Center for AgroMeteorology (NCAM), integrating meteorological and chemical input preparation, WRF-Chem execution, post-processing, and database management (Lee et al. 2016). LAMP does not modify the governing equations or chemistry modules of WRF-Chem; the simulations in this study use standard WRF-Chem v3.9.1 within this workflow.

2.1 Meteorological and PM measurement dataset

Surface weather charts from the Korea Meteorological Administration (KMA) and hourly PM₁₀ and PM_{2.5} observations from urban air-quality monitoring stations operated by the Korean Ministry of Environment (MOE) were used to characterize the episode. There were 368 urban monitoring stations in March 2019, and the hourly PM data are available from AirKorea (<https://www.airkorea.or.kr>). MOE specifies that ambient air-quality monitoring inlets are installed within 20 m of the ground; this is the reason model concentrations were sampled from the model level closest to approximately 20 m above ground for site comparisons.

Figure 1 shows greenhouse-crop cultivation area by region in Korea, adapted from Statistics Korea/SGIS (Statistics Korea 2019). Gyeongsangnam-do, Chungcheongnam-do, and Gyeonggi-do are among the major greenhouse-cultivation regions, and together account for approximately 46% of the national greenhouse-crop area. We therefore selected Haman (Gyeongsangnam-do), Buyeo (Chungcheongnam-do), and Hwaseong (Gyeonggi-do) as representative study sites. Haman and Buyeo represent large greenhouse complexes outside the Seoul metropolitan area, whereas Hwaseong represents greenhouse cultivation in the metropolitan region.

2.2 WRF-Chem model and experimental design

The Weather Research and Forecasting (WRF) model is a compressible, non-hydrostatic mesoscale atmospheric model with multiple parameterization choices for physical processes (Powers et al. 2017; Skamarock et al. 2008). WRF-Chem extends WRF as a fully coupled online meteorology–chemistry model in which meteorological and chemical variables are integrated on the same grid and time step, allowing two-way interactions between atmospheric composition and meteorology for supported chemistry and physics configurations (Fast et al. 2006; Forkel et al. 2012; Grell et al. 2005; Peckham et al. 2018;

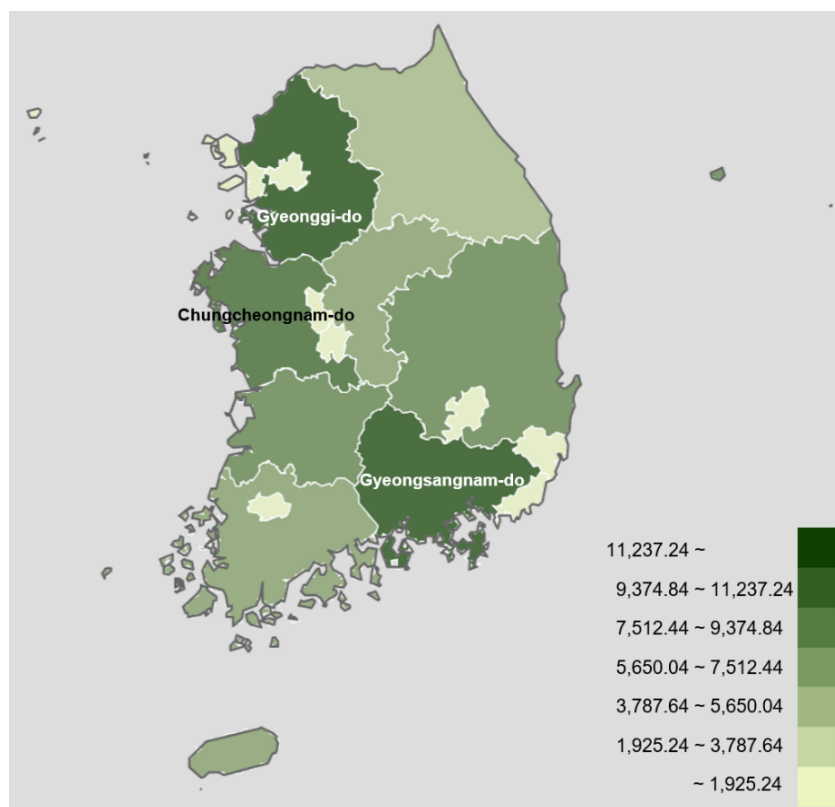


Figure 1: Regional distribution of greenhouse-crop cultivation area in South Korea (units: ha), adapted from Statistics Korea/SGIS (Statistics Korea 2019). Province names and legend classes identify the major greenhouse-producing regions used to provide national context for the three study sites.

Tuccella et al. 2012; Zhang 2008). The version used in this study was WRF-Chem v3.9.1 with KPP chemistry. Previous NCAM-LAMP studies have documented the broader performance and application of the LAMP framework for meteorological and land-surface variables (Lee et al. 2014, 2016, 2020b; So et al. 2020; Song et al. 2015).

The gas-phase mechanisms considered here are based on the Regional Atmospheric Chemistry Mechanism (RACM) and the NOAA/ESRL RACM implementation. RACM was developed for regional tropospheric chemistry (Stockwell et al. 1997), and WRF-Chem provides KPP-based RACM options with several aerosol modules (Peckham et al. 2018). MADE (Modal Aerosol Dynamics Model for Europe) represents aerosol number, size, and mass distributions using modal aerosol dynamics (Ackermann et al. 1998). SORGAM represents secondary organic aerosol formation through gas-particle partitioning of low-volatility products (Schell et al. 2001), whereas the VBS option represents secondary organic aerosol with a volatility basis set and multigenerational oxidation (Ahmadov et al. 2012). GOCART represents bulk aerosol species including sulfate, dust, sea salt, organic carbon, and

black carbon (Chin et al. 2000, 2002; Ginoux et al. 2001). The WRF-Chem v3.9.1 documentation identifies chem_opt=301 as RACM/GOCART, chem_opt=107 as RACM/MADE-SORGAM with the ESRL reaction table, chem_opt=108 as NOAA/ESRL RACM/MADE-VBS, and chem_opt=43 as RACM-ESRL/MADE-SORGAM with aqueous chemistry (Peckham et al. 2018). These documented chem_opt definitions were used to verify the experiment labels in Table 1.

Anthropogenic emissions were prepared with PREP-CHEM-SRC (Freitas et al. 2011) using EDGAR-HTAP emissions, and biogenic emissions were based on MEGAN-related inputs (Sakulyanontvittaya et al. 2008). The same PREP-CHEM-SRC/EDGAR-HTAP emissions basis was used across the chemistry experiments. The archived configuration used for this study documents that this emissions preparation was optimized for the GOCART option; consequently, species mapping and secondary-aerosol precursor representation for MADE/SORGAM and MADE/VBS are a source of uncertainty when comparing absolute PM concentrations among schemes. This limitation is considered in the interpretation of the PM underestimation.

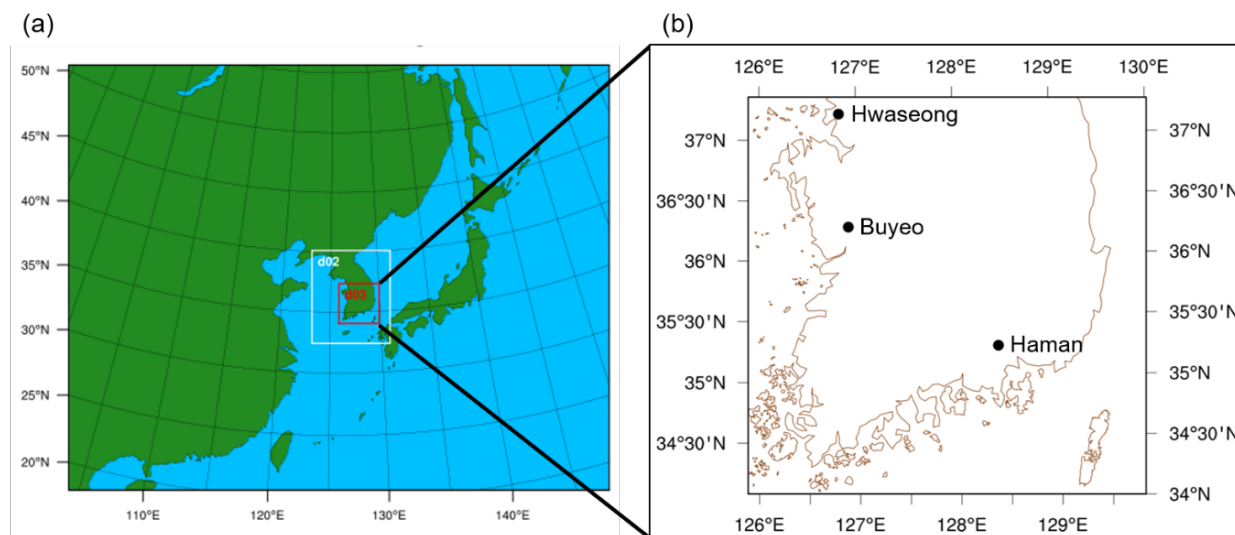


Figure 2: (a) WRF-Chem domain configuration and (b) the three study sites (black dots).

Figure 2 shows the three nested Lambert conformal domains and the study sites. Horizontal grid spacing is 27, 9, and 3 km for d01, d02, and d03, respectively, with 29 vertical levels. The model integration covers 0000 UTC Feb. 28 to 0000 UTC Mar. 9, 2019; the 96 h preceding Mar. 4 were treated as spin-up for the analysis period. Site values were collocated using the nearest d03 grid cell, and PM concentrations were taken from the model level closest to approximately 20 m above ground, consistent with the MOE monitoring-height criterion described above.

Five experiments were analyzed using four chemistry/aerosol configurations and one no-chemistry control: (1) GR, RACM with GOCART (chem_opt=301); (2) MVR, NOAA/ESRL RACM with MADE/VBS (chem_opt=108); (3) MSRE, RACM with the ESRL reaction table and MADE/SORGAM (chem_opt=107); (4) MSRE-aq, RACM-ESRL with MADE/SORGAM and aqueous chemistry (chem_opt=43); and (5) NO-Chem (chem_opt=0). In the experiment design, aerosol-radiation feedback was enabled for the four chemistry experiments and disabled in NO-Chem. Aerosol-cloud feedback and aqueous chemistry were enabled only in MSRE-aq; therefore, its cloud-related response is treated as exploratory. Table 1 summarizes the experiment settings together with the WRF-Chem v3.9.1 chem_opt definitions used to verify the chemistry/aerosol pairings (Peckham et al. 2018).

Initial and boundary meteorological fields were obtained from the 6-hourly NCEP Final (FNL) analysis. The five experiments used the same meteorological physics. The TUV/Madronich photolysis option was used (Madronich 1987); Lin microphysics and Grell 3-D cumulus parameterization were selected (Grell and

Dévényi 2002; Lin et al. 1983); the Noah land-surface model was used (Chen and Dudhia 2001); and RRTM longwave and Goddard shortwave radiation schemes were applied (Chou and Suarez 1994; Mlawer et al. 1997). A preliminary PBL sensitivity check considered the YSU and MYJ schemes (Hong et al. 2006; Janjić 1994). Only the YSU scheme was carried into the five experiments analyzed in this paper; therefore, the PBL comparison is not treated as a sensitivity result and the title and abstract refer only to chemistry-scheme sensitivity. Table 2 summarizes the physics options used in the analyzed experiments.

2.3 HYSPLIT Model

The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model is a widely used three-dimensional atmospheric transport and dispersion system (Rolph et al. 2017; Stein et al. 2015). We used HYSPLIT backward trajectories based on CDC1 global meteorological reanalysis data to identify the likely source regions of air masses reaching Korea during the high-PM episode.

3 HEAVY AIR POLLUTION EPISODE

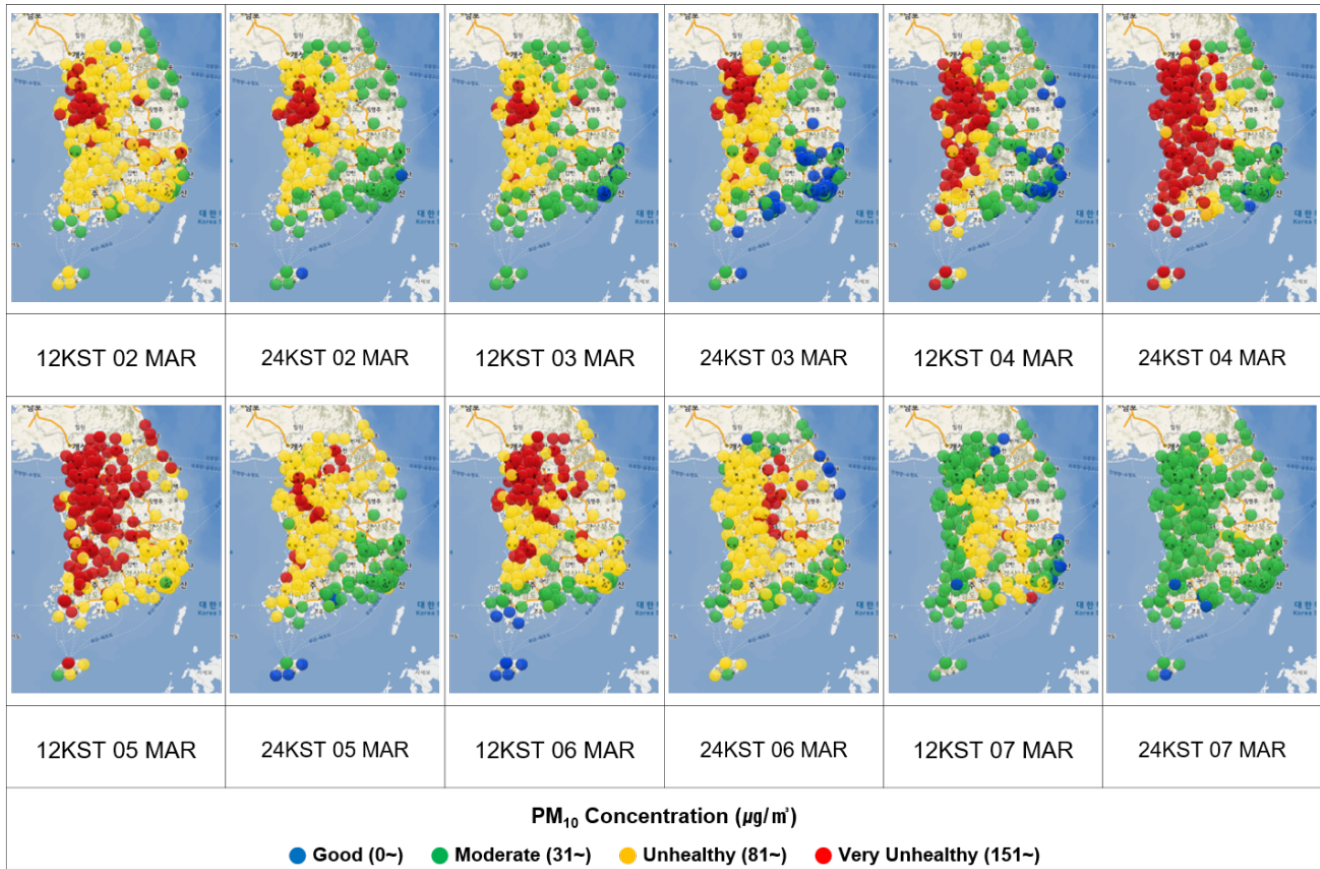
Figures 3 and 4 show observed PM₁₀ and PM_{2.5} concentrations from AirKorea stations. During Mar. 4–6, elevated PM₁₀ was widespread over western Korea, while PM_{2.5} reached the “Very Unhealthy” category over many areas. Elevated PM_{2.5} was already present in western Korea on Mar. 2. We therefore focused the model analysis on Mar. 4–7, when severe pollution af-

Table 1: WRF-Chem chemistry experiments and process settings used in the analysis.

Experiment	chem_opt	Gas chemistry	Aerosol module	Aqueous chemistry	Aerosol-radiation process	Aerosol-cloud feedback
GR	301	RACM	GOCART	No	On	Off
MVR	108	NOAA/ESRL RACM	MADE/VBS	No	On	Off
MSRE	107	RACM/ESRL reaction table	MADE/SORGAM	No	On	Off
MSRE-aq	43	RACM-ESRL	MADE/SORGAM	Yes	On	On (exploratory)
NO-Chem	0	—	—	—	Off	Off

Table 2: Physics options for all experiments

Physical Processes	WRF-Chem Option	Reference
Photolysis rate	TUV	Madronich (1987)
Microphysics	Lin	Lin et al. (1983)
Cumulus parameterization	Grell 3D	Grell and Dévényi (2002)
Land-surface physics	Noah LSM	Chen and Dudhia (2001)
Longwave radiation	RRTM	Mlawer et al. (1997)
Shortwave radiation	Goddard	Chou and Suarez (1994)
Planetary boundary layer	YSU	Hong et al. (2006)



AirKorea categories: ● Good ● Moderate ● Unhealthy ● Very Unhealthy

Figure 3: The PM_{10} concentrations and air-quality category thresholds over the Korean Peninsula between Mar. 2 and Mar. 7, 2019 (AirKorea). Blue, green, yellow, and red circles denote Good ($\geq 0 \mu g m^{-3}$), Moderate ($\geq 31 \mu g m^{-3}$), Unhealthy ($\geq 81 \mu g m^{-3}$), and Very Unhealthy ($\geq 151 \mu g m^{-3}$), respectively.

ected a large fraction of the Korean Peninsula and then began to dissipate.

Figure 5 shows the KMA surface weather charts for Mar. 4–8. On Mar. 4–5, a high-pressure system near Shanghai moved eastward toward the Korean Peninsula,

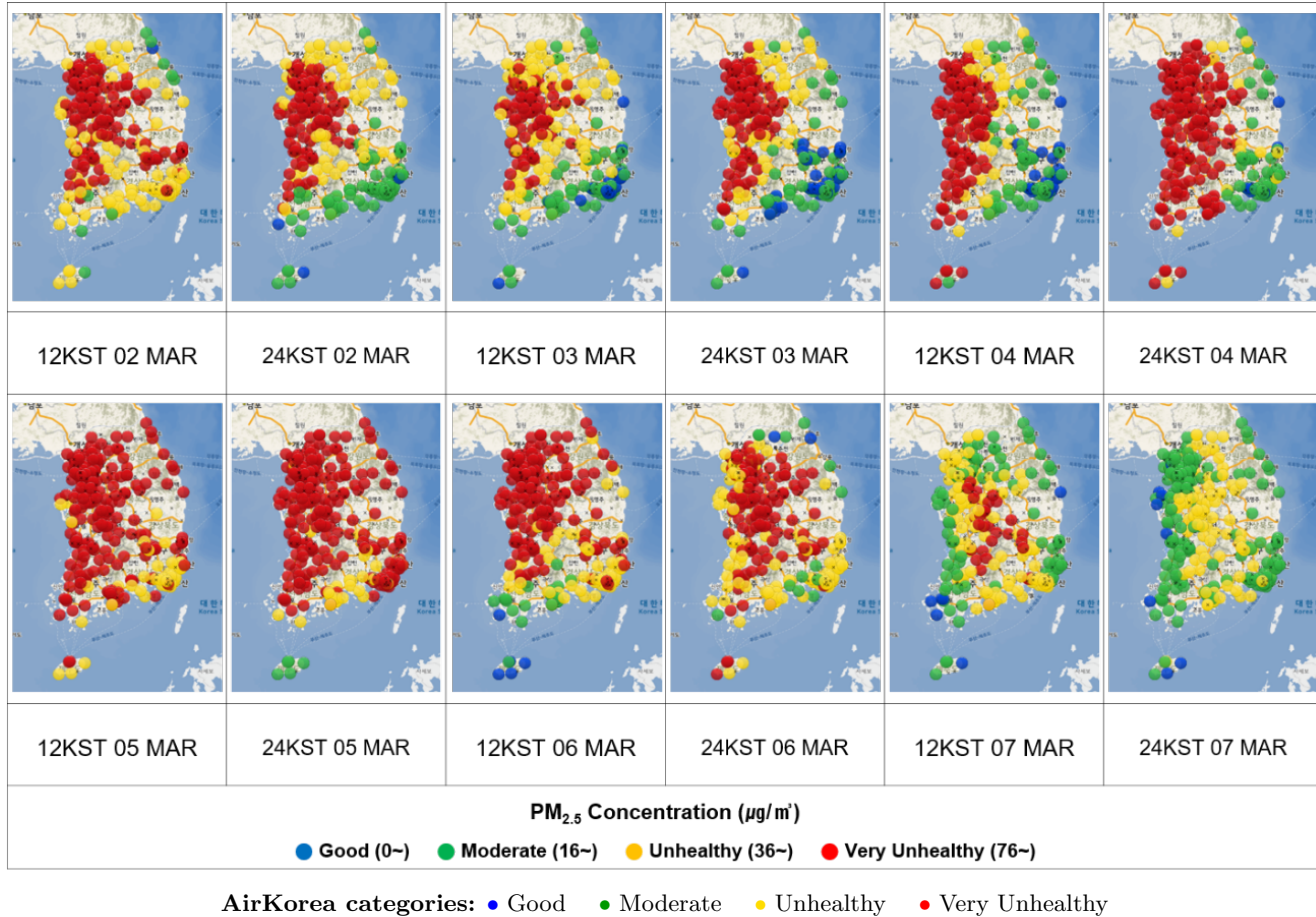


Figure 4: The PM_{2.5} concentrations and air-quality category thresholds over the Korean Peninsula between Mar. 2 and Mar. 7, 2019 (AirKorea). Blue, green, yellow, and red circles denote Good ($\geq 0 \mu\text{g m}^{-3}$), Moderate ($\geq 16 \mu\text{g m}^{-3}$), Unhealthy ($\geq 36 \mu\text{g m}^{-3}$), and Very Unhealthy ($\geq 76 \mu\text{g m}^{-3}$), respectively.

producing predominantly westerly to northwesterly flow. On Mar. 6, a low-pressure system south of the peninsula induced easterly flow and favored recirculation and stagnation over Korea. Air stagnation subsequently weakened as the synoptic pattern changed and cleaner air was advected into the region.

Figure 6 presents 72-h HYSPLIT backward trajectories for Mar. 1–6. Air masses reaching Korea on Mar. 1–4 passed over the Liaodong Peninsula and North Korea, whereas trajectories on Mar. 5–6 extended toward the Shandong Peninsula in eastern China. Previous studies have shown that anthropogenic pollutants emitted over eastern China can be transported to Korea and contribute to high-PM episodes (Chung et al. 2014; Jung et al. 2019; Wang et al. 2018).

Taken together, the synoptic charts, trajectories, and observed PM fields (Figures 3–6) indicate transport from the Liaodong Peninsula during the early part of the episode, followed by additional inflow from the Shandong Peninsula on Mar. 5–6 under stagnant conditions.

Air quality improved after Mar. 7 as the synoptic circulation changed. The WRF-Chem integration therefore covered 0000 UTC Feb. 28 to 0000 UTC Mar. 9, 2019, with Mar. 4–7 used as the principal analysis period.

4 RESULTS AND ANALYSIS

4.1 PM Comparison of chemical schemes with observation

Observations were taken from MOE air-quality monitoring stations at Haman, Buyeo, and Hwaseong. As described in Section 2, model values were collocated with the nearest d03 grid cell and the model level closest to approximately 20 m above ground. Figures 7 and 8 show daily mean spatial fields from d01, whereas Figures 9 and 10 show hourly site time series from d03.

Figures 7 and 8 show daily mean PM₁₀ and PM_{2.5} over d01 for the four chemistry experiments. GR and MVR reproduced a broad high-PM plume over eastern China

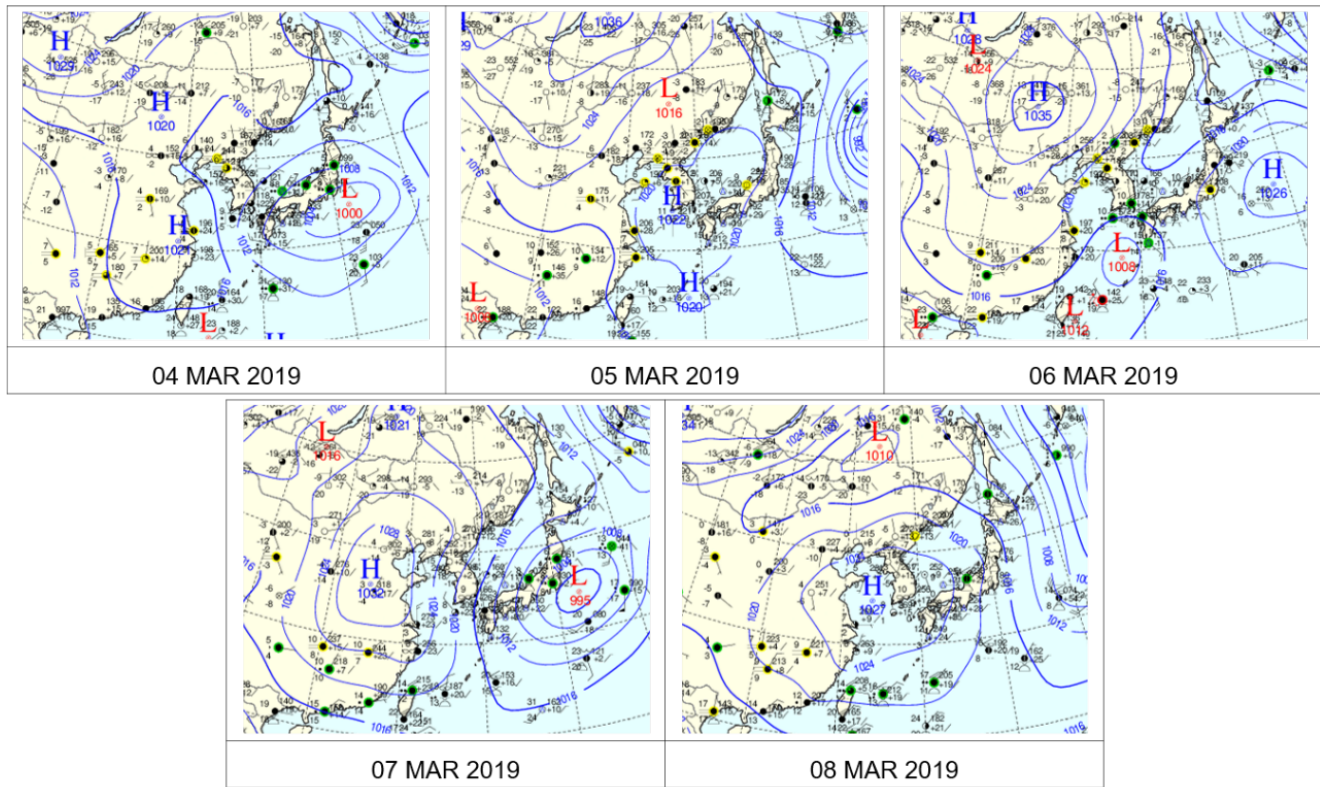


Figure 5: KMA surface weather charts at 0900 KST for Mar. 4–8, 2019. Source: Korea Meteorological Administration (KMA).

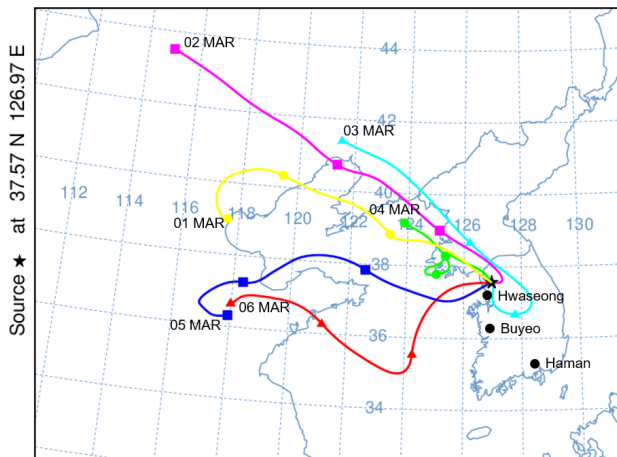


Figure 6: Seventy-two-hour HYSPLIT backward trajectories initialized at 0900 KST for Mar. 1–6, 2019. The black star indicates Seoul, and the black dots indicate the three study sites.

and its transport across the West Sea toward the Korean Peninsula, whereas MSRE and MSRE-aq produced substantially lower concentrations. The difference between the largest daily grid values in GR and MSRE exceeded

$250 \mu\text{g m}^{-3}$ for PM_{10} and $165 \mu\text{g m}^{-3}$ for $\text{PM}_{2.5}$, illustrating the strong sensitivity to the chemistry/aerosol configuration.

Hourly PM_{10} and $\text{PM}_{2.5}$ observations and simulations for Haman, Buyeo, and Hwaseong during Mar. 4–7 are presented in Figures 9 and 10 together with the AirKorea category thresholds. All four chemistry experiments underestimated PM_{10} and $\text{PM}_{2.5}$ concentrations, and simulated peaks were generally delayed relative to the observations. Because the objective is to compare relative behavior among chemistry configurations and associated radiative responses during a single event, we retain a qualitative comparison rather than presenting formal model-skill statistics. The magnitude of the underestimation is visually large, particularly for MSRE and MSRE-aq. MVR produced the largest simulated concentrations at Buyeo and Hwaseong, while GR more closely reproduced the observed temporal evolution. These results are interpreted as scheme sensitivity rather than as validation of absolute predictive skill.

Several factors may contribute to the PM underestimation. First, the anthropogenic emissions were based on the 2010 EDGAR-HTAP inventory and were processed through PREP-CHEM-SRC. A 2010 inventory should not be interpreted simply as missing later in-

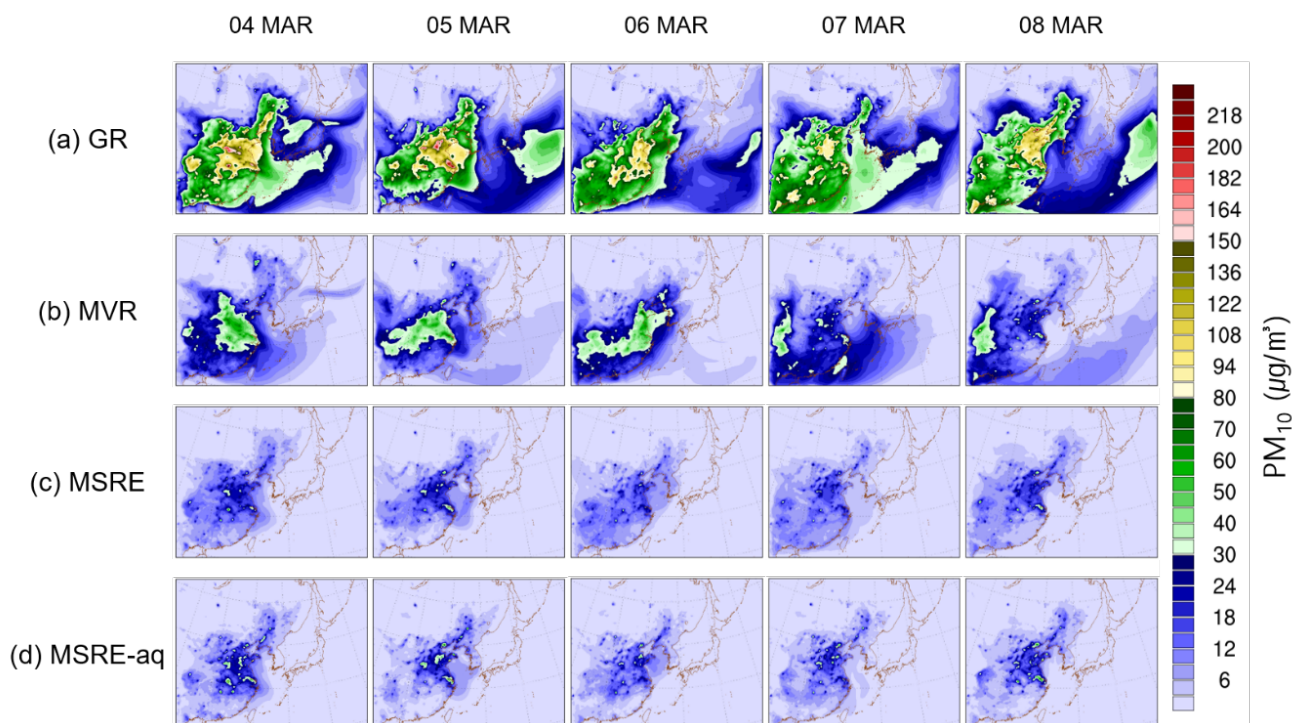


Figure 7: Daily mean PM_{10} ($\mu\text{g m}^{-3}$) in domain d01 for (a) GR, (b) MVR, (c) MSRE, and (d) MSRE-aq from Mar. 4–8, 2019. Blue, green, yellow, and red denote the AirKorea “Good,” “Moderate,” “Unhealthy,” and “Very Unhealthy” concentration categories, respectively.

creases in Chinese emissions: national Chinese emissions of SO_2 , NO_x , PM_{10} , $\text{PM}_{2.5}$, BC, and OC declined substantially between 2010 and 2017, particularly after 2013, whereas NMVOC emissions increased and NH_3 changed little (Zheng et al. 2018). Thus, use of the 2010 inventory may overstate some primary and precursor emissions relative to 2019 while still misrepresenting the spatial distribution and chemical speciation relevant to this event. In addition, the PREP-CHEM-SRC preparation used here was optimized for GOCART; applying the same emissions basis to MADE/SORGAM and MADE/VBS introduces uncertainty in species mapping and precursor availability and may contribute to the large inter-scheme differences.

Second, elevated PM was already present over East Asia before the analyzed period (Figures 3 and 4), whereas the model was initialized at 0000 UTC Feb. 28. Although 96 h were treated as spin-up before Mar. 4, the initial/background chemical state may still have been insufficient to represent accumulated regional pollution. Third, severe haze can contain a large secondary-aerosol fraction (Huang et al. 2014); insufficient secondary aerosol formation, together with uncertainties in oxidation, removal, and precursor emissions, may therefore contribute to the low simulated PM burden.

Biomass-burning emissions were not included and represent an additional source of uncertainty.

Fourth, previous WRF-Chem intercomparisons show that PM can differ substantially among aerosol modules. Gao et al. (2018) reported higher PM concentrations with GOCART than with MADE/SORGAM in some environments. Similar underestimation of PM has been reported in regional air-quality modeling studies (De Meij et al. 2015; Moon et al. 2014; Stern et al. 2008; Vautard et al. 2009; Zhong et al. 2016). SOA treatments are also important: SORGAM and VBS differ in their representation of secondary organic aerosol formation, with VBS including multigenerational oxidation and aging (Ahmadv et al. 2012; Lee et al. 2020c; Schell et al. 2001). These factors support interpreting the experiment ranking cautiously and as case-specific.

4.2 Aerosol-radiative effect

Figure 11 shows the mean DSWR difference (chemistry experiment minus NO-Chem) over d03 for Mar. 4–7. GR, MVR, and MSRE generally show lower DSWR than NO-Chem over much of Korea, including the three study regions, whereas MSRE-aq shows predominantly positive differences. Because each chemistry experiment can alter not only aerosol optical properties

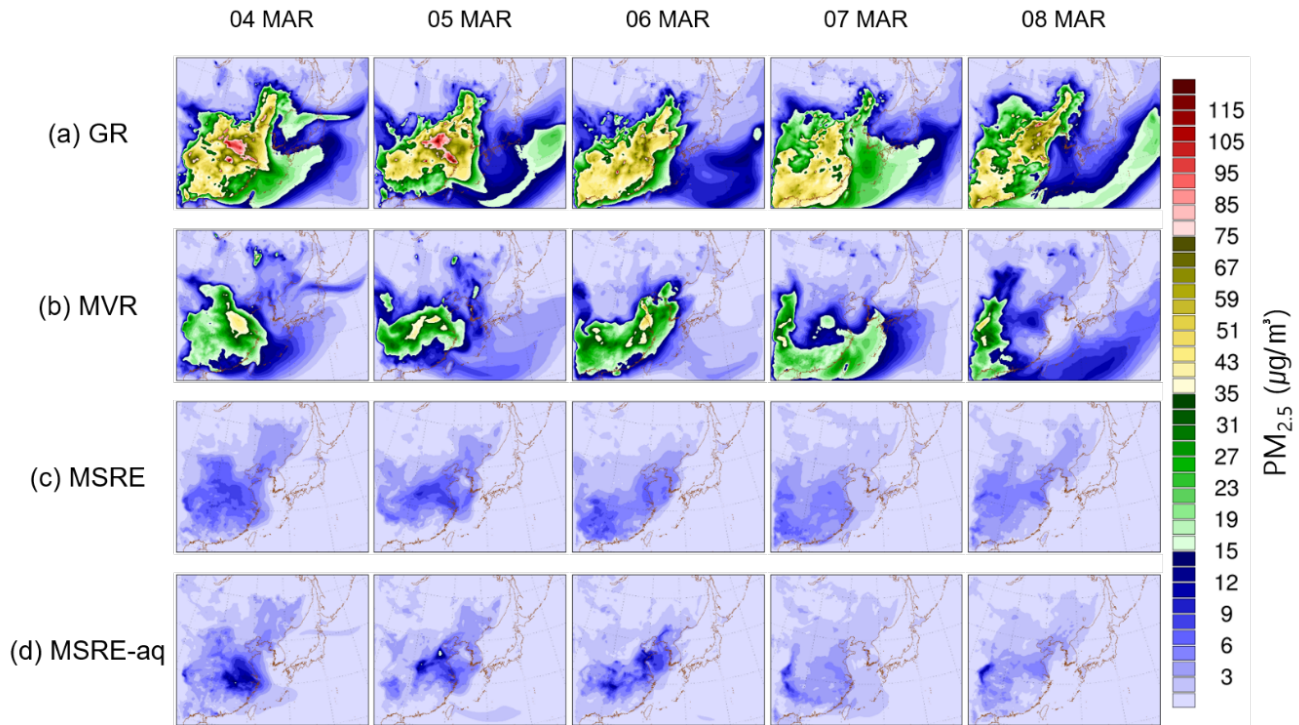


Figure 8: Daily mean $\text{PM}_{2.5}$ ($\mu\text{g m}^{-3}$) in domain d01 for (a) GR, (b) MVR, (c) MSRE, and (d) MSRE-aq from Mar. 4–8, 2019. Blue, green, yellow, and red denote the AirKorea “Good,” “Moderate,” “Unhealthy,” and “Very Unhealthy” concentration categories, respectively.

but also meteorological fields, the DSWR differences from NO-Chem may reflect both aerosol-radiative effects and experiment-to-experiment differences in clouds and weather. The MSRE-aq surplus is therefore treated as exploratory. Aerosol–cloud interactions and aqueous-phase processes could alter cloudiness, precipitation, wet scavenging, and aerosol loading, but cloud fraction, cloud water/ice, precipitation, deposition, and clear-sky DSWR diagnostics were not available for this revision. Accordingly, the positive MSRE-aq response is a hypothesis-based result rather than a confirmed aerosol–cloud mechanism.

Figure 12 shows cumulative DSWR at Haman, Buyeo, and Hwaseong, calculated by time-integrating hourly mean SWDOWN over Mar. 4–7. MVR shows the largest cumulative deficit relative to NO-Chem at all three sites. GR and MSRE are much closer to one another at Haman (-1273.96 and $-1233.81 \text{ Wh m}^{-2}$, respectively) and Hwaseong (-778.04 and $-784.81 \text{ Wh m}^{-2}$), whereas their differences are larger at Buyeo. MSRE-aq shows positive cumulative differences, reaching $+2026.98 \text{ Wh m}^{-2}$ at Hwaseong. Because the chemistry experiments can also differ in clouds and meteorology, these cumulative differences should be interpreted as inter-experiment DSWR responses rather than

Table 3: Cumulative DSWR difference relative to NO-Chem during Mar. 4–7 (units: Wh m^{-2}). Negative values indicate a deficit, whereas positive MSRE-aq values indicate an increase in DSWR.

Experiment name	Haman	Buyeo	Hwaseong
GR	-1273.96	-1834.97	-778.04
MVR	-1856.80	-2395.35	-2766.61
MSRE	-1233.81	-1280.33	-784.81
MSRE-aq	350.36	1275.31	2026.98

as aerosol-only radiative forcing or validated absolute radiation impacts.

Figure 13 compares PBL height at Haman, Buyeo, and Hwaseong. Across the five experiments, the PBL was generally shallower during the high-PM period than on Mar. 7, when pollution decreased. The PBL was particularly shallow during portions of Mar. 6, when simulated PM was elevated. Although all experiments used the same YSU PBL scheme, the chemistry configurations produced modest differences in PBL height, consistent with two-way interactions among radiation, surface heating, atmospheric stability, and air pollution. Previous studies have shown that low PBL height and

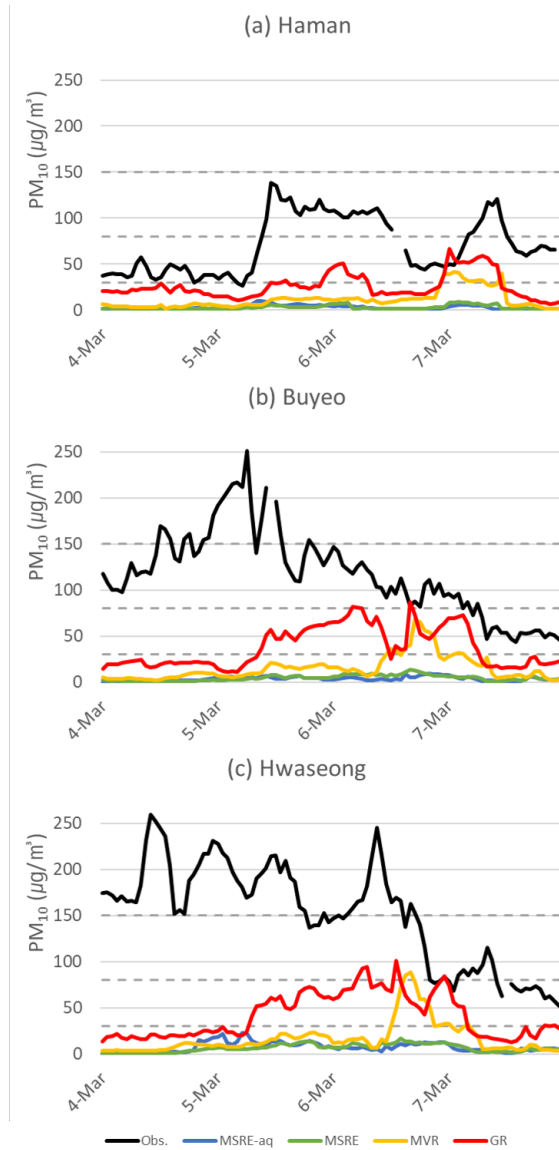


Figure 9: Observed and simulated PM_{10} concentrations at (a) Haman, (b) Buyeo, and (c) Hwaseong during Mar. 4–7, 2019. The black line denotes AirKorea observations; the colored lines denote GR, MVR, MSRE, and MSRE-aq. Model concentrations were extracted from the nearest d03 grid cell and the model level closest to approximately 20 m above ground and are shown as hourly values (units: $\mu\text{g m}^{-3}$).

enhanced stability can favor near-surface pollutant accumulation (Lee et al. 2007).

5 CONCLUSIONS AND DISCUSSION

This study examines the sensitivity of simulated PM and shortwave radiation to four WRF-Chem chem-

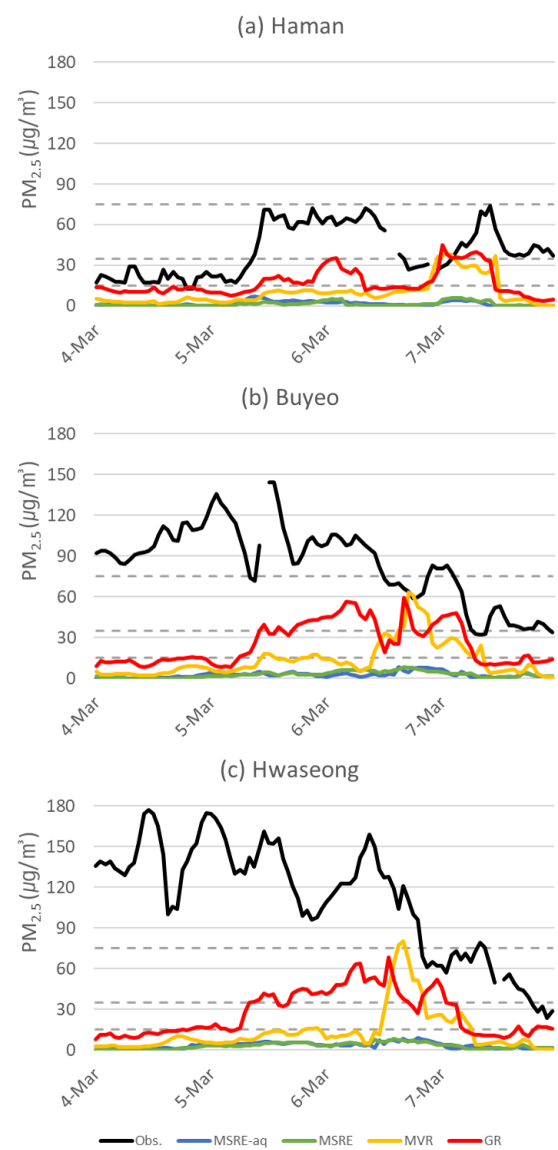


Figure 10: Observed and simulated $PM_{2.5}$ concentrations at (a) Haman, (b) Buyeo, and (c) Hwaseong during Mar. 4–7, 2019. The black line denotes AirKorea observations; the colored lines denote GR, MVR, MSRE, and MSRE-aq. Model concentrations were extracted from the nearest d03 grid cell and the model level closest to approximately 20 m above ground and are shown as hourly values (units: $\mu\text{g m}^{-3}$).

istry/aerosol configurations during the severe Mar. 4–7, 2019 high-PM episode affecting major greenhouse regions in Korea. The event involved long-range transport followed by atmospheric stagnation. The principal findings are summarized as follows:

(1) Long-range transport of PM from China to Korea was consistently simulated by all experiments, indicating

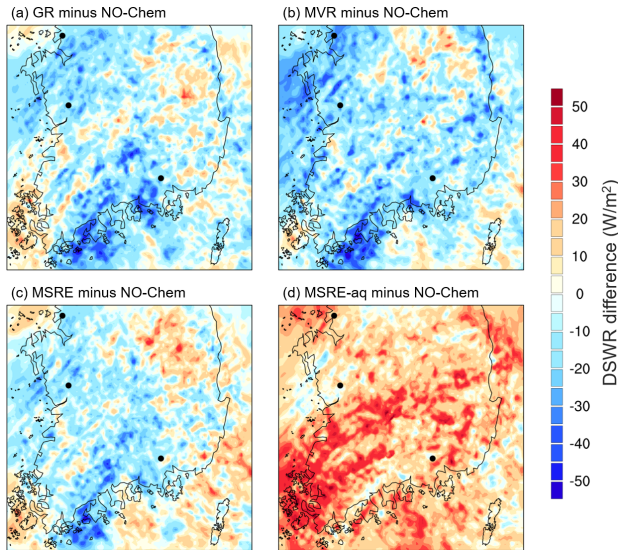


Figure 11: Mean DSWR difference (chemistry experiment minus NO-Chem; units: W m^{-2}) in d03 for Mar. 4–7, 2019: (a) GR, (b) MVR, (c) MSRE, and (d) MSRE-aq. Black dots indicate Hwaseong, Buyeo, and Haman.

that the large-scale advection feature of the event was robust across chemistry options.

(2) All four chemistry-option experiments underestimated the overall PM concentrations at the target sites. During the case period, the maximum concentration was closest to observations in the MVR experiment (chem_opt=108), while the temporal evolution of increasing and decreasing tendencies was most consistent with observations in the GR experiment (chem_opt=301).

(3) Relative to NO-Chem, GR, MVR, and MSRE generally produced lower cumulative DSWR, but the ranking was not a simple function of simulated PM concentration. MVR produced the largest deficit at all three sites, whereas GR and MSRE produced nearly equal deficits at Haman and Hwaseong. The cumulative differences were on the order of 10^3 Wh m^{-2} . MSRE-aq produced positive differences, including a large surplus at Hwaseong; this response remains exploratory because cloud, precipitation, deposition, aerosol optical depth, and clear-sky radiation diagnostics were not available to isolate the mechanism. The DSWR results therefore represent relative differences among complete experiments rather than aerosol-only radiative forcing.

(4) Simulated PBL height was generally low during the high-concentration period in all four chemistry experiments. The shallow boundary layer coincided with enhanced near-surface PM under stagnant synoptic conditions, consistent with the expected association between limited vertical mixing and pollutant accumulation.

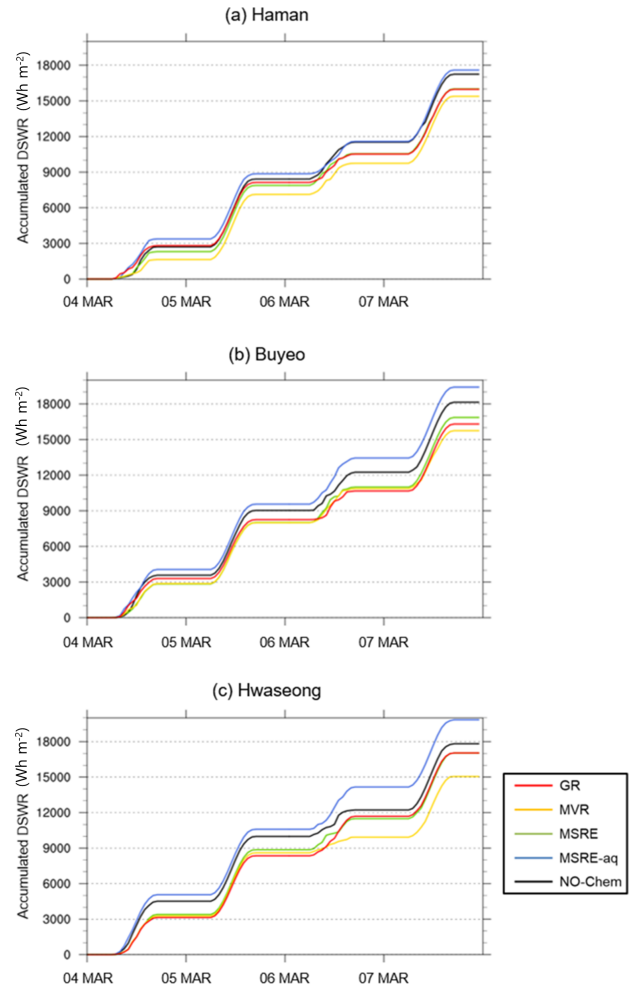


Figure 12: Cumulative downward shortwave radiation (time-integrated from hourly mean DSWR) during Mar. 4–7 in (a) Haman, (b) Buyeo, and (c) Hwaseong. The cumulative value was computed as $\sum \text{DSWR}_{\text{hour}} \times 1 \text{ h}$ and is reported in Wh m^{-2} .

This study is limited to a single high-PM episode and should therefore be interpreted as case-specific. All chemistry experiments substantially underestimated PM concentrations and generally delayed the peak timing. The use of a 2010 EDGAR-HTAP inventory, uncertainty in scheme-specific emissions mapping, incomplete representation of background pollution and biomass burning, finite spin-up, and secondary-aerosol formation may all contribute to the bias. KMA surface solar-radiation observations were not evaluated at the three study sites in this revision; therefore, DSWR impacts are interpreted as relative inter-experiment differences rather than validated absolute effects. Additional cases spanning other seasons, regions, and PM regimes, together with direct evaluation of radiation and cloud diagnostics, are required before the findings can be generalized.

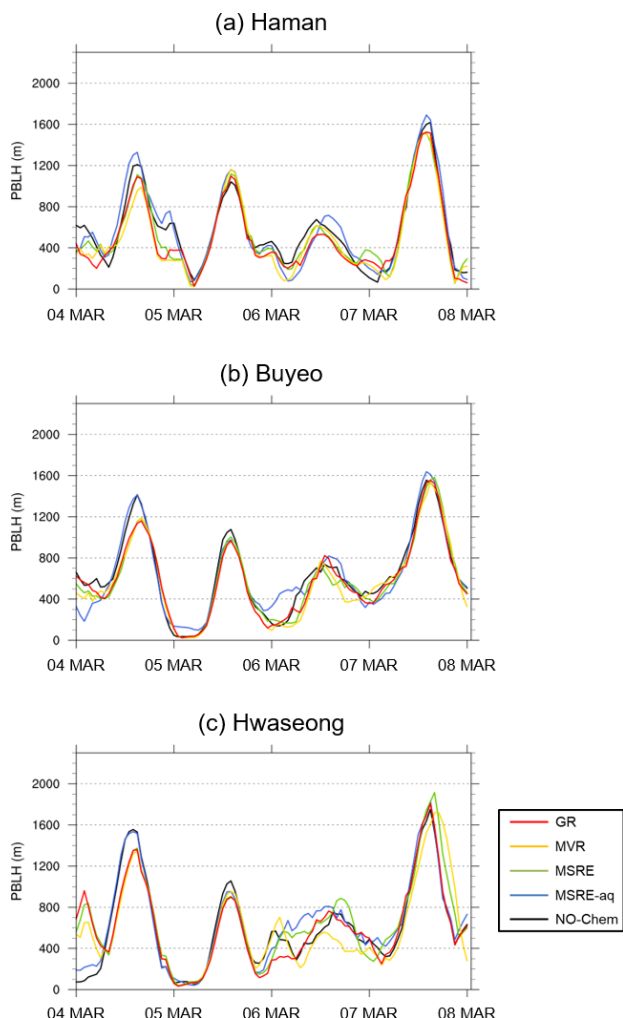


Figure 13: Planetary boundary layer height at (a) Haman, (b) Buyeo, and (c) Hwaseong during Mar. 4–8, 2019.

WRF-Chem PM performance depends on several aspects of the experimental design, including the emission inventory, chemical and aerosol mechanisms, initialization and spin-up, and model resolution. Previous sensitivity studies likewise show that no single chemistry/aerosol configuration performs best under all conditions. In the present long-range transport episode affecting the rural greenhouse regions of Haman, Buyeo, and Hwaseong, the GOCART-based GR experiment reproduced the temporal evolution more closely, whereas MVR produced the largest simulated concentrations. These case-specific differences reinforce the need to evaluate chemistry/aerosol configurations for the target phenomenon and region rather than assuming a universally optimal option.

Future work should evaluate additional episodes and seasons, incorporate direct radiation and cloud diagnos-

tics, and examine scheme performance with updated emissions. Such evaluations would provide a stronger basis for routinely producing WRF-Chem data for agricultural applications and for coupling the modeled aerosol–radiation environment with greenhouse crop models to quantify crop-growth responses.

AUTHOR CONTRIBUTIONS

Conceptualization, S. Lee and S.-J. Lee; methodology, S. Lee and S.-J. Lee; software, S. Lee and H. Lee; validation, S. Lee; formal analysis, S. Lee, S.-J. Lee, and H. Lee; investigation, S. Lee and S.-J. Lee; data curation, S. Lee; writing—original draft preparation, S. Lee; writing—review and editing, S. Lee, S.-J. Lee, H. Lee, E. Hong, and W. Choi; visualization, S. Lee; supervision, S.-J. Lee; project administration, E.-S. Jang and N.-J. Choi. All authors have read and agreed to the submitted version of the manuscript.

FUNDING

This work was carried out with the support of the Cooperative Research Program for Agriculture Science and Technology Development (Project No. RS-2025-02223519 and PJ014189032021), Rural Development Administration, Republic of Korea. This study was also supported by KISTI/KREONET.

ACKNOWLEDGEMENTS

The authors thank Dr. Hyun-Young Jo and the anonymous reviewers for their careful comments on the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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