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Research article

Impact of the 2050 carbon-neutral emission scenario on air quality in South Korea

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ABSTRACT

The 2050 Carbon Neutrality Scenario (CNS) in South Korea was developed based on greenhouse gas (GHG) emission reductions and air pollution (AP) control policies. This study evaluated its potential impact on air quality in South Korea in 2050. Implementation of cost-effective and GHG-compatible AP control policies under the 2050 CNS led to projected decreases in emissions of sulfur dioxide (SO_2), oxides of nitrogen (NO_x), fine particulate matter ($PM_{2.5}$), and ammonia (NH_3) in South Korea by 56 %, 74 %, 40 %, and 27 %, respectively, relative to 2019 levels. For China and Japan, all emissions except NH_3 were projected to decrease by 50–93 % and 37–67 %, respectively. Two contrasting AP emission scenarios were developed, coupled with IPCC Shared Socioeconomic Pathways (SSP) climate scenarios for Northeast Asia: (1) no additional control measures for energy production and AP + SSP5-85 (SSP585NMC) and (2) carbon neutrality achieved by 2050 based on a GHG-compatible AP control policy + SSP1-62 (SSP162ZERO). AP modeling through 2050 was conducted using a climate-chemistry model. By 2050, the 2050 CNS is expected to significantly reduce major air pollutants, contributing to improved air quality. However, ozone (O_3) levels exhibit complex responses under SSP585NMC, with seasonal variations leading to potential increase due to rising temperatures driven by high levels of volatile organic compounds (VOCs). This suggests that while GHG-compatible policies effectively reduce primary pollutants, a mid-to long-term strategy integrating GHS and VOC controls will be crucial to achieving sustainable air quality goals under carbon neutrality.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) (2021) reported that greenhouse gases (GHGs) emitted by human activities are driving global warming, as evidenced by a 1.09 °C increase in global surface temperatures from 1850–1990 to 2011–2020. The rate of temperature increase since 1970 has been higher than that observed in any other 50-year period over at least the last 2000 years. The IPCC predicts that, without substantial reductions in CO_2 and other GHG emissions in the coming decades, global surface temperatures will continue rising at least until the mid-21st century, with global warming likely to exceed 1.5–2 °C within the 21st century (IPCC, 2021). Against this backdrop, the IPCC Special Report (IPCC, 2019) emphasized that average global temperature increases must be limited to 1.5 °C to prevent the crossing of recoverable thresholds. To achieve this, global net CO_2 emissions from human activities must decrease by at least 45 % from 2010 levels by 2030 and reach net zero by approximately 2050 (IPCC, 2019).

To adhere to the 1.5 °C target set by the IPCC Special Report (IPCC, 2019), the South Korean government has outlined national mid-to long-term strategies and policy directions for addressing climate change effectively (The Government of the Republic of Korea, 2020). The 2030 National Greenhouse Gas Reduction Roadmap established a

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national GHG reduction target of 37 % below business-as-usual levels to meet South Korea's nationally determined contribution (NDC), with additional carbon-neutrality measures planned by 2050 (The Government of the Republic of Korea, 2021). In October 2021, South Korea reaffirmed its commitment to carbon neutrality, setting a national target to reduce GHG emissions by 40 % from 2018 levels by 2030 and enacting this commitment into law (The Government of the Republic of Korea, 2023).

In numerous previous studies, GHG reduction measures have been shown to improve air quality by decreasing pollutant emissions (Bollen et al., 2009; Zhang et al., 2016; West et al., 2013; Xie et al., 2018). Therefore, the integration of GHG reduction policies with air pollution (AP) control policies can enhance cost-effectiveness. For example, in South Korea, the long-term economic impacts of climate change mitigation under the shared socioeconomic pathway (SSP) scenario SSP2 were reported to result in a national decrease in daily average fine particulate matter ($PM_{2.5}$) concentrations in 2025 compared with 2005 levels (Kim et al., 2020). Fine particulates and their components, including sulfate, nitrate, ammonium, and organic aerosols, are generally projected to decrease over the long term under several GHG reduction scenarios (Oak et al., 2023). The reduction of anthropogenic NO_x emissions by 90 % under a carbon net-zero scenario is predicted to impact daily ozone (O_3) concentrations in diverse ways across South Korea, with changes ranging from −18 % to +36 % (Yeo and Koo, 2023). This variation is attributed to the nonlinear photochemistry of O_3 formation in certain regions, despite reductions in NO_x emissions. In Northeast Asia, the effectiveness of climate and AP emission reduction policies has been widely investigated with regard to their influence on future O_3 concentrations, considering both global climate change and air quality policies (Lee et al., 2021, 2022a).

Studies of future climate-O_3 interactions over the Korean Peninsula have been conducted under several SSP climate scenarios. These studies project air quality under different IPCC climate scenarios, showing that future global and regional O_3 concentrations are primarily influenced by the emissions of their precursors. In polluted areas, warming is expected to increase O_3 concentrations depending on the emission levels of its precursors, NO_x and volatile organic compounds (VOCs). For example, under the SSP1 scenario, O_3 concentrations over the Korean Peninsula are projected to decrease in 2045 and 2095 due to reductions in emissions in NO_x-limited environments. Under the SSP3 scenario, which lacks adequate climate change mitigation, O_3 levels may increase in the future for reasons such as higher CH_4 levels and increased biogenic VOC emissions driven by a warmer climate (Oak et al., 2023). Although these studies have provided climate-air quality projections, the results were unrelated to the 2050 carbon neutrality scenario (CNS).

Some studies on the 2050 CNS scenario in Northeast Asia have been conducted, focusing on GHG emission reductions and AP control policies. This scenario seeks to reduce GHG emissions by integrating their management with AP control policies to create synergistic effects, ultimately enhancing cost efficiency. Reports indicate that under the 2050 CNS, NO_x, SO_2, and CO emissions in Japan are projected to decrease by 50–60 %, whereas VOC and $PM_{2.5}$ emissions are expected to decrease by up to 30 % under the global RCP 4.5 scenario (Hata et al., 2023). Regional O_3 concentrations in 2050 are anticipated to decline by an average of 8.4 ppb compared with 2015, whereas $PM_{2.5}$ concentrations show a slight change, ranging from −2.2 to +1.9 μg/m^3, due to secondary $PM_{2.5}$ formation driven by increased shortwave radiation. In China, under the 2050 RCP 4.5 and Emissions for Interim Target-1 scenarios (based on Beijing's Master Plan, 2016–2035 for AP emission reduction), $PM_{2.5}$ concentrations in the Beijing–Tianjin–Hebei region are projected to decrease to half of baseline scenario levels (Li et al., 2023). Nevertheless, an analysis of the direct impact of a carbon-zero energy scenario in South Korea, based on the government's plan for reducing GHG emissions combined with AP control policies targeting pollutants such as O_3 and $PM_{2.5}$ across South Korea and the Northeast Asia region, has yet to be conducted.

Since the national 2050 CNS was developed in South Korea based on GHG emission reduction and AP control policies (The Government of the Republic of Korea, 2023), this study examined the effects of the 2050 CNS and the related AP control policies in Northeast Asia. It assessed air quality improvements in South Korea as a measure of the effectiveness of GHG reduction policies. Here, we report the improvements in air quality achieved by integrating the government's carbon-neutrality-based GHG reductions with reductions in AP emissions in South Korea. We also considered IPCC-based climate factors, including rising temperatures, which significantly influence air quality and climate policies. A coupled climate-chemistry global modeling system was used to project future air quality improvements resulting from the 2050 carbon-neutrality-driven reductions in AP emissions. The anticipated substantial improvements in air quality were analyzed quantitatively.

Previous studies have examined the interactions between climate change and air pollution; however, there is a lack of research that quantitatively assesses the direct impact of South Korea's 2050 carbon neutrality scenario on air pollutants. In particular, studies on the interaction between air pollution reduction and climate policies have primarily focused on China and Japan (e.g., Hata et al., 2023; Li et al., 2023). In contrast, this study comprehensively analyzes the effects of South Korea's carbon neutrality policies and associated air pollution control measures on air quality in Northeast Asia. This approach provides insights into how climate change mitigation policies can contribute to air quality improvement and serves as a valuable reference for future policy design and regulatory strategies.

2. Methodology

Given the complex interplay between GHG and AP emissions, achieving an effective multi-pollutant control strategy requires a well-coordinated policy framework. Future adjustments to reduction targets should consider the synergies and trade-offs between carbon neutrality and air pollution mitigation. Establishing a collaborative governance mechanism that integrates energy, climate, and air quality policies across sectors will be essential for optimizing co-benefits while minimizing unintended consequences. In this study, we comprehensively examined two extreme cases of climate change, GHG, and AP scenarios to explore the optimal scenario combination for achieving carbon neutrality. We analyzed differences between scenario combinations to derive a more effective and practical carbon neutrality policy direction. The descriptions of each scenario are provided below.

2.1. Carbon-neutral GHG and AP emission scenarios in South Korea

This study described the developed a national 2050 carbon-neutral scenario that simultaneously considered national GHG and AP reduction goals under different climate scenarios. Fig. 1 presents schematic diagrams of three future scenarios: (a) energy consumption, (b) air quality policy, and (c) climate. In Fig. 1, the energy consumption scenario pathways are categorized as BAU (Business As Usual) and NetZero (Carbon Neutrality). The BAU scenario represents the projected GHG emissions in 2050 if no additional reduction efforts are undertaken, following the current trend. The NetZero scenario aims to achieve net-zero global carbon emissions by 2050, in alignment with the 1.5 °C temperature rise limit recommended in the IPCC Special Report (IPCC, 2019). To meet this goal, South Korea must revise its 2030 NDC to a more ambitious target along with its 2050 carbon neutrality objective. The air quality policy scenario was divided into No Further Control (NFC) and Current Legislation (CLE) pathways, based on the policies currently in place or planned for implementation. The NFC pathway assumed that AP control policies implemented during the baseline year (2020) would remain unchanged without additional environmental policy measures introduced. In contrast, the CLE pathway considered the introduction of additional AP control policies through planned measures.

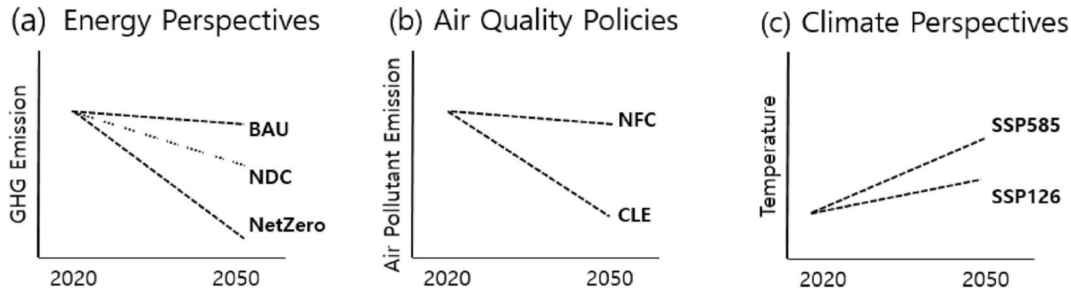

Fig. 1. Schematic diagrams of three future scenarios: (a) energy consumption, (b) air quality, and (c) IPCC SSP climate.

The future energy consumption, air quality policy, and climate scenarios were designed to be achievable by 2050. The Greenhouse gas and air pollutant Integrated Decision-support system (GUIDE) model (Jang et al., 2024) was used to develop cost-effective, GHG-compatible AP control policies and technologies for projecting Korean emissions. The GUIDE model calculates projected emissions by applying policy implementation rates and reduction efficiencies to forecast resulting emissions, enabling reduction estimates for each policy (Jang et al., 2024). To project future emissions, the baseline year was set as 2020, and scenarios were developed by incorporating future activity information along with GHG reduction and AP control policies.

The GUIDE model estimates the co-benefits of reducing GHG and AP emissions based on data from the Clean Air Policy Support System (CAPSS). The model outcomes are derived from activity data for various air pollutants and socioeconomic factors such as gross domestic product (GDP), population, oil prices, and projected energy consumption for the target year. CAPSS classifies emission sources into eight categories: power, industry, residential, on-road, non-road, agriculture, solvents, and others. It applies air pollutant emission factors specific to each source across approximately 300 activity data points from about 150 institutions, covering over 100 detailed emission sources annually (Kim et al., 2023; Yeo et al., 2019). Separate inventories were developed for CO_2, CO, NO_x, SO_2, PM_{10}, $PM_{2.5}$, VOC, and NH_3 (NIER, 2020); AP emissions were projected by applying estimated reductions from various policies. Baseline emissions data were obtained from the 2019 CAPSS inventory provided by the National Air Emission Inventory and Research Center. This inventory includes national AP emission statistics for CO, NO_x, SO_2, total suspended particulates, PM_{10}, $PM_{2.5}$, black carbon, VOCs, and NH_3. These emissions were allocated to the 17 administrative regions of South Korea (Fig. 2).

2.2. *Carbon-neutral GHS-AP emission projections over Northeast Asia*

The analysis also examined GHG emission shifts towards carbon neutrality in regions beyond South Korea. In China, emission reduction strategies have been formulated to achieve carbon neutrality by 2060. Detailed GHG emission reduction measures for specific sectors, such as transportation, have been outlined in the literature. These measures include the promotion of eco-friendly fuel vehicles and ships and the electrification of railways (KIEP, 2020). For Japan, the carbon-neutral scenario followed the government's 2021 strategy, which aims to reduce GHG emissions by 80 % from 2013 levels by 2050, thereby achieving carbon neutrality. Specific measures for individual sectors have been described in the literature, including expanding hydrogen fuel consumption to 20 million tons by 2050 and reactivating nuclear power plants through the construction of next-generation reactors with integrated zero-emission technologies. For other Northeast Asian regions, excluding Korea, China, and Japan, energy demand projections were developed using the Greenhouse gas - Air pollution Interactions and Synergies (GAINS) framework established by the International Institute for Applied Systems Analysis (IIASA)(Woo et al., 2024). This framework incorporates energy outlooks and energy mixes under different scenarios; the resulting emissions projections are applied to each region (Park, 2023; MSICT, 2023; Woo et al., 2024).

AP emission projections and scenarios for regions outside South Korea were derived from the Air Quality in Northeast Asia (AQNEA) project, which used future scaling factors relative to the 2020 baseline (MSICT, 2023). The AQNEA project includes emission inventories and air quality projection scenarios for six countries: South Korea, China, Japan, North Korea, Mongolia, and Russia. Through collaborations among regional experts and international organizations, the AQNEA project aims to establish emission levels required for achieving carbon neutrality. The 2050 carbon-neutral emissions data from the AQNEA project for regions outside South Korea served as the foundation for setting emission targets. The projected carbon-neutral emissions in China and Japan were then used to evaluate the air quality implications of emission adjustments in South Korea by 2050.

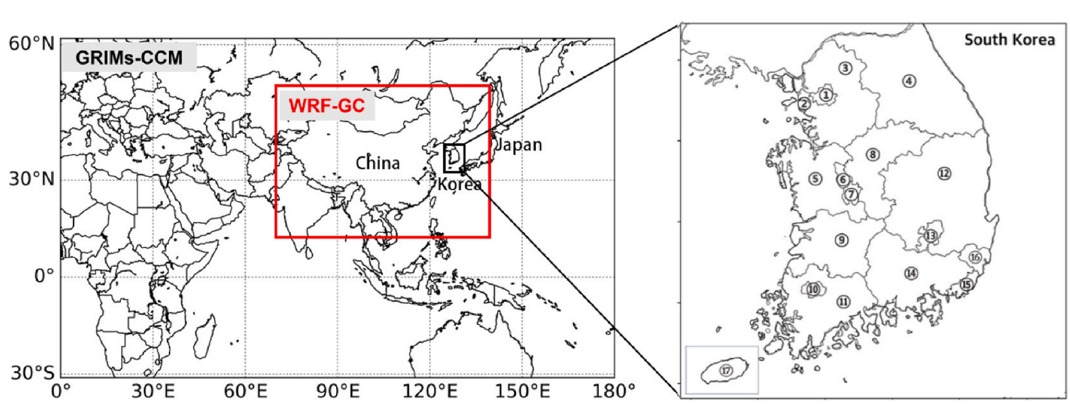

Fig. 2. Domains of the GRIMs-CCM and WRF-GC models, and the 17 administrative regions of South Korea: ① Seoul, ② Incheon, ③ Gyeonggi, ④ Gangwon, ⑤ Chungnam, ⑥ Sejong, ⑦ Daejeon, ⑧ Chungbuk, ⑨ Jeonbuk, ⑩ Gwangju, ⑪ Jeonnam, ⑫ Gyeongbuk, ⑬ Daegu, ⑭ Gyeongnam, ⑮ Busan, ⑯ Ulsan, and ⑰ Jeju.

2.3. AP emission projections under IPCC climate scenarios

The 2050 GHG and AP reduction pathways were combined with global IPCC SSP climate scenarios (Fig. 1). Two contrasting IPCC climate scenarios, SSP1-26 and SSP8-58, were used to design two GHG + AP + SSP scenarios for quantifying air quality in South Korea through 2050.

The first scenario was BAU + NFC + SSP585 (hereafter referred to as **"SSP585NMC"**). In this context, NMC represents "No More Control," indicating that the scenario adhered to the existing GHG + AP emission policies from those of 2019 through to 2050. Therefore, BAU + NFC assumes a scenario in which no additional policy efforts are implemented to reduce emissions or pollutants under the IPCC SSP8-58 climate scenario. This scenario also assumed that current air pollutant emissions and climate policies in the Northeast Asia region would remain unchanged. However, ongoing air quality improvement initiatives in China were incorporated into this scenario. These initiatives include the "Air Pollution Prevention and Control Action Plan (2013–2017)", the follow-up "Three-Year Action Plan to Win the Blue Sky Defense Battle (2018–2020)", the "Energy Development Strategy Action Plan (2014–2020)", and the "13th Five-Year Plan for Energy Development (2016–2020)", which outlines specific targets for the energy sector (NIER, 2023). Under this scenario, climate policy was modeled consistently by applying the IPCC SSP5-8.5 climate scenario. The SSP5-8.5 scenario incorporates factors such as the level of radiative forcing, efforts to reduce GHG emissions, and socio-economic shifts relevant to climate adaptation. It assumes the absence of climate policies and represents a society with low mitigation capacity, heavily reliant on fossil fuels.

The second scenario was NetZero + CLE + SSP126 (hereafter referred to as **"SSP126ZERO"**). The NetZero-CLE combination incorporated energy policies aimed at achieving net-zero carbon emissions by 2050, along with additional policies and technologies for AP reduction, resulting in a comprehensive future emission projection. The global SSP1-2.6 scenario was utilized, which assumed that emission reductions in Northeast Asia would align with efforts to achieve carbon neutrality by 2050.

However, because the calculated emissions only included the total AP by sector for each of the 17 administrative regions in South Korea (Seoul, Busan, Daegu, Incheon, Gwangju, Daejeon, Ulsan, Sejong, Gyeonggi, Gangwon, Chungbuk, Chungnam, Jeonbuk, Jeonnam, Gyeongbuk, Gyeongnam, Jeju; Fig. 2) and for neighboring East Asian countries (China, Japan, North Korea), these totals were further refined into grid-based areas. During the refinement process, the latest version of the Emissions Database for Global Atmospheric Research (EDGAR v8.1) was used as the base input data for model simulations. The sectors outlined in EDGAR v8.1 were aligned with the emissions data utilized in this study, maintaining the spatial breakdown for each sector from EDGAR v8.1.

2.4. Climate and air quality modeling system

To analyze the impact of the 2050 carbon-neutral emissions on air quality in South Korea, two systems were utilized: (1) a Global/Regional Integrated Model system Chemistry Climate Model (GRIMs-CCM) for Northeast Asia, and (2) a mesoscale integrated meteorology-air quality model, the Weather Research and Forecasting (WRF) model combined with the Goddard Earth Observing System (GEOS)-Chem model (WRF-GC), for South Korea. The model domain and spatial grid distribution are shown in Fig. 2.

The GRIMs-CCM is based on GRIMs (Hong et al., 2013) and a global climate model (Jeong et al., 2019); it was further developed via coupling with GEOS-Chem (version 9-01-02) (http://www.geos-chem.org), a 3D global atmospheric chemistry transport model. This global modeling system adjusts for feedback and interactions between climate and atmospheric chemistry by allowing aerosols and gaseous substances in the atmosphere to affect radiative processes within the climate model(Lee et al., 2022b). The model is well-regarded for its ability to simulate general global climate characteristics and its high performance in representing atmospheric aerosols and gaseous substances (Jeong et al., 2019; Lee and Park, 2022). For more detailed simulations near the Korean Peninsula, a regional-scale WRF-GC modeling system was developed (Lin et al., 2020). The integration of the WRF model with the GEOS-Chem atmospheric chemistry model has facilitated widespread use due to the community-driven nature of both models. This integration allows interactions between atmospheric and meteorological components via radiative processes, enabling comprehensive validation to be conducted for both meteorological and AP aspects (Lin et al., 2020; Xu et al., 2022; Liu et al., 2023).

The GRIMs-CCM and WRF-GC models share physical parameterization options and operate within a unified physical framework, making them suitable for global-to-mesoscale coupled simulations. Because atmospheric chemistry models in both global and regional systems are based on GEOS-Chem, they share the same chemical species framework and gas-phase chemistry processes, which enhances their applicability for this study.

Climate−air quality simulations were conducted for the SSP585NMC and SSP126ZERO scenarios, covering the period from December 2020 to 2050. In both scenarios, global boundary conditions were generated using global climate simulations based on the SSP5-85 and SSP1-26 scenarios available in the SSP database provided by IIASA (https://tntcat.iiasa.ac.at/SspDb).

2.5. Initial and boundary conditions for scenario modeling

The initial and boundary conditions for meteorological and chemical fields, including stratospheric O_3 in WRF-GC, were derived from the GRIMs-CCM results. Carbon dioxide (CO_2) and CH_4 concentrations were set to match the values in GRIMs-CCM, based on the SSP database. GRIMs-CCM is an atmospheric general circulation model that does not include an ocean model. Therefore, boundary conditions for sea and ice are required to predict climate changes. In this simulation, data from Coupled Model Intercomparison Project (CMIP6) models were used to prescribe sea surface temperature, the water equivalent of accumulated snow depth, and sea ice concentration to predict climate changes through 2050. Among the various CMIP6 models, monthly data from four models (CanESM5, IPSL-CM6A-LR, KIOST-ESM, and MIROC6), which were compatible with GRIMs without unit conversion, were ensemble-averaged through 2050. Mesoscale simulations using WRF-GC were conducted at a 45-km spatial resolution for the region surrounding the Korean Peninsula, covering the same period as the global simulations.

The global average CO_2 concentration for each year was directly prescribed in the model for both scenarios. For CH_4, average concentrations specific to the Northern and Southern Hemispheres were applied. Stratospheric O_3, a powerful greenhouse gas that significantly impacts tropospheric O_3 and other short-lived pollutants (IPCC, 2021), was simulated using the Linoz stratospheric O_3 chemistry model (McLinden et al., 2000). This model utilizes linear regression to predict existing stratospheric ozone levels and fluxes. Although effective for estimating current stratospheric ozone levels and fluxes, this approach has limitations in projecting future ozone layer recovery. To mitigate this constraint, monthly average ozone concentrations for the stratospheric ozone layer (20–25 km; 40–10 hPa) from the SSP database were calculated as a ratio against the default ozone levels in Linoz. This approach enabled consideration of potential future alterations in stratospheric ozone concentrations. The O_3 concentration ratio, used to adjust for changes in O_3 levels, was calculated as follows:

$$\text{Ratio} = \frac{mean(Input4MIPsOzone\ mixing\ ration(40-10hPa))}{mean(Original\ Linoz\ Ozone\ Logan\ Climatology(40-10hPa))} \quad (1)$$

Emissions of short-lived pollutants (e.g., carbon monoxide (CO), SO_2, NO_x, black carbon, organic carbon, NH_3, non-methane VOCs

(NMVOCs)) for the climate model were obtained from the SSP database. The SSP database emissions data were interpolated to a spatial resolution of 1° × 1° and further interpolated annually from decadal data to match the spatial resolution of the GRIMs-CCM input emissions data.

3. Results

3.1. Carbon net zero AP emissions over Northeast Asia

Projected AP emission reductions in South Korea were calculated based on the key reduction measures from various emission sources (Table S1), all of which were derived from the "2050 CNS" announced by the South Korean government (The Government od the Republic of Korea, 2021). Achieving carbon neutrality by 2050 requires the expansion of renewable energy and the adoption of new technologies, such as hydrogen gas turbines. As indicated in Table S1, the industrial sector plans include fully replacing blast furnaces in steelmaking with electric furnaces and reducing hydrogen emissions from steel production. In the cement industry, coal as a fuel will be entirely replaced with waste synthetic resin and hydrogen-based heat sources; some raw materials will transition from limestone to slag. In the road transport sector, measures will be implemented to achieve carbon neutrality, focusing on zero-emission vehicles. The adoption of eco-friendly vehicles, including electric and hydrogen-powered vehicles, is projected to significantly increase, constituting 97 % of all vehicles in use. To further reduce emissions and promote sustainable transportation practices, passenger car traffic is expected to decrease by 15 % through the expanded use of public transportation and bicycles.

Table S2 presents the GHG and AP emissions in South Korea for the baseline year (2019) and Fig. 3 illustrates annual variations in GHG and AP emissions under the two scenarios: SSP585NMC and SSP126ZERO. In South Korea, under SSP585NMC, a reduction of approximately 79 % in CO_2 emissions was observed (refer to Table S2), along with substantial decreases ranging from 86 % to 97 % for air pollutants, including CO, SO_2, NO_x, $PM_{2.5}$, and VOCs. However, NH_3 exhibited a slight increase of 1 % (Fig. 3 and Table S2). Overall, emission reductions under SSP585NMC were significantly higher (excluding VOCs and NH_3) than those under SSP126ZERO (Fig. 3). Under SSP126ZERO, which incorporated the 2050 CNS, CO_2 emissions in South Korea were projected to decrease by 83 % compared with the baseline. Because over 90 % of GHG emissions in South Korea originate from energy use, reduction measures primarily targeted energy-related emissions. Fig. 4 shows GHG and AP emissions according to source sector; Table 1 provides the ratios of GHG and AP emissions for each sector. Emissions of SO_2, NO_x, and $PM_{2.5}$ were projected to decrease by 56 %, 74 %, and 40 %, respectively, compared with the baseline under SSP126ZERO (Table 1). This decline was primarily attributed to substantial reductions in the road transport sector, driven by the widespread adoption of electric and hydrogen vehicles, which resulted in significant decreases in emissions from these sectors (Table S1). However, VOC and NH_3 emissions were projected to increase to 100.5 % and decrease to 72.8 % of the baseline, respectively. These trends were largely due to the high proportion of emissions from non-energy sources, such as solvent use and agriculture (Fig. 4).

Across the Northeast Asia region, emission reductions under SSP585NMC were greater for China (37–67 %) than for South Korea (3–13 %) and Japan (8–28 %), compared to the baseline (excluding NH_3) (see Tables S3, S4, S5, and S6). For China, under SSP126ZERO, CO_2, SO_2, NO_x, and $PM_{2.5}$ emissions in 2050 decreased by 87 %, 93 %, 90 %, and 93 %, respectively, compared with the baseline (Tables S3 and S4). However, similar to South Korea, Chinese VOC and NH_3 emissions showed lower reduction rates of 50 % and 72 %, respectively, compared with the baseline (see Tables S3 and S4). For Japan, CO_2 emissions were projected to decrease by 87 %; SO_2, NO_x, $PM_{2.5}$, VOC, and NH_3 emissions were expected to decrease by 66 %, 71 %, 51 %, 26 %, and 69 %, respectively. The reductions in VOC and NH_3 emissions were comparatively greater than those observed in South Korea and China (Tables S5 and S6).

3.2. Air quality simulations for 2050 in South Korea

3.2.1. Model performance

This study focused on O_3 and $PM_{2.5}$, which are the most hazardous air pollutants to human health and are critically important in the Northeast Asia region. The newly calculated stratospheric O_3 concentrations incorporated the Linoz stratospheric O_3 chemistry model (McLinden et al., 2000), which predicts current stratospheric O_3 levels and fluxes through linear regression. Monthly average O_3 concentrations for the stratospheric O_3 layers were calculated using data from the SSP

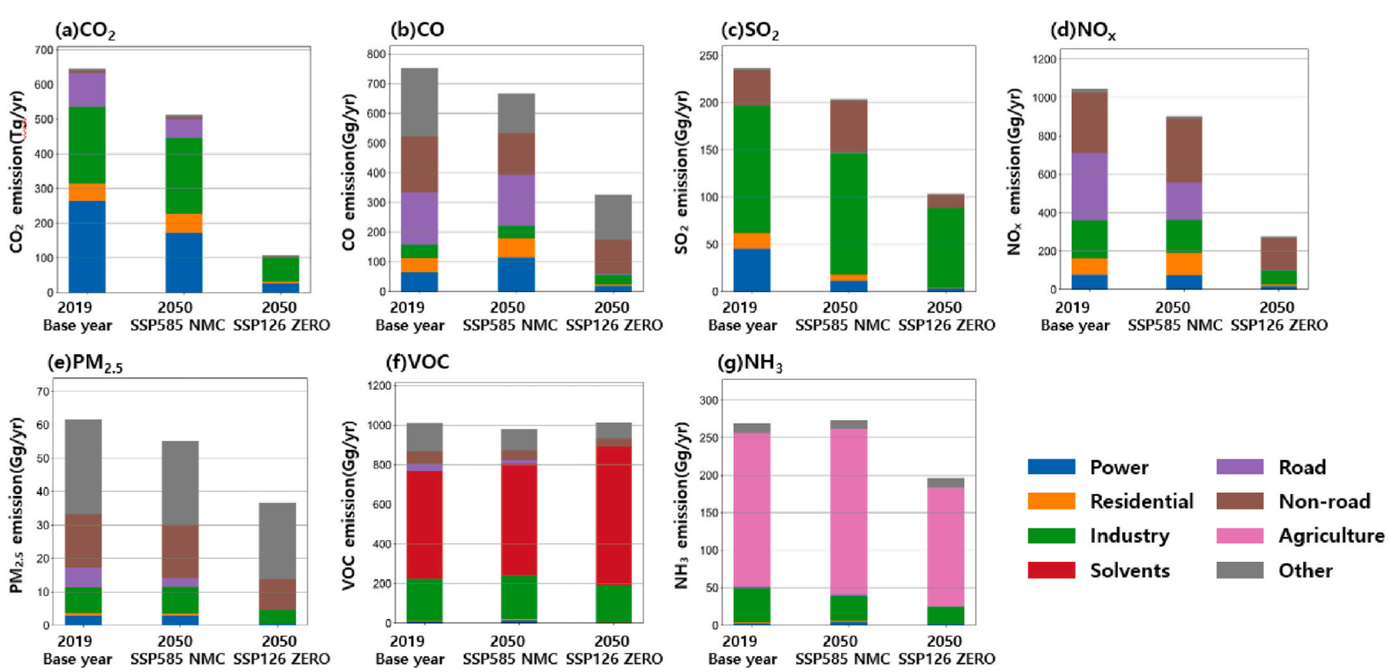

Fig. 3. Emissions according to scenario (SSP585NMC and SSP126ZERO) for (a) CO_2, (b) CO, (c) SO_2, (d) NO_x, (e) $PM_{2.5}$, (f) VOC, and (g) NH_3 in 2021.

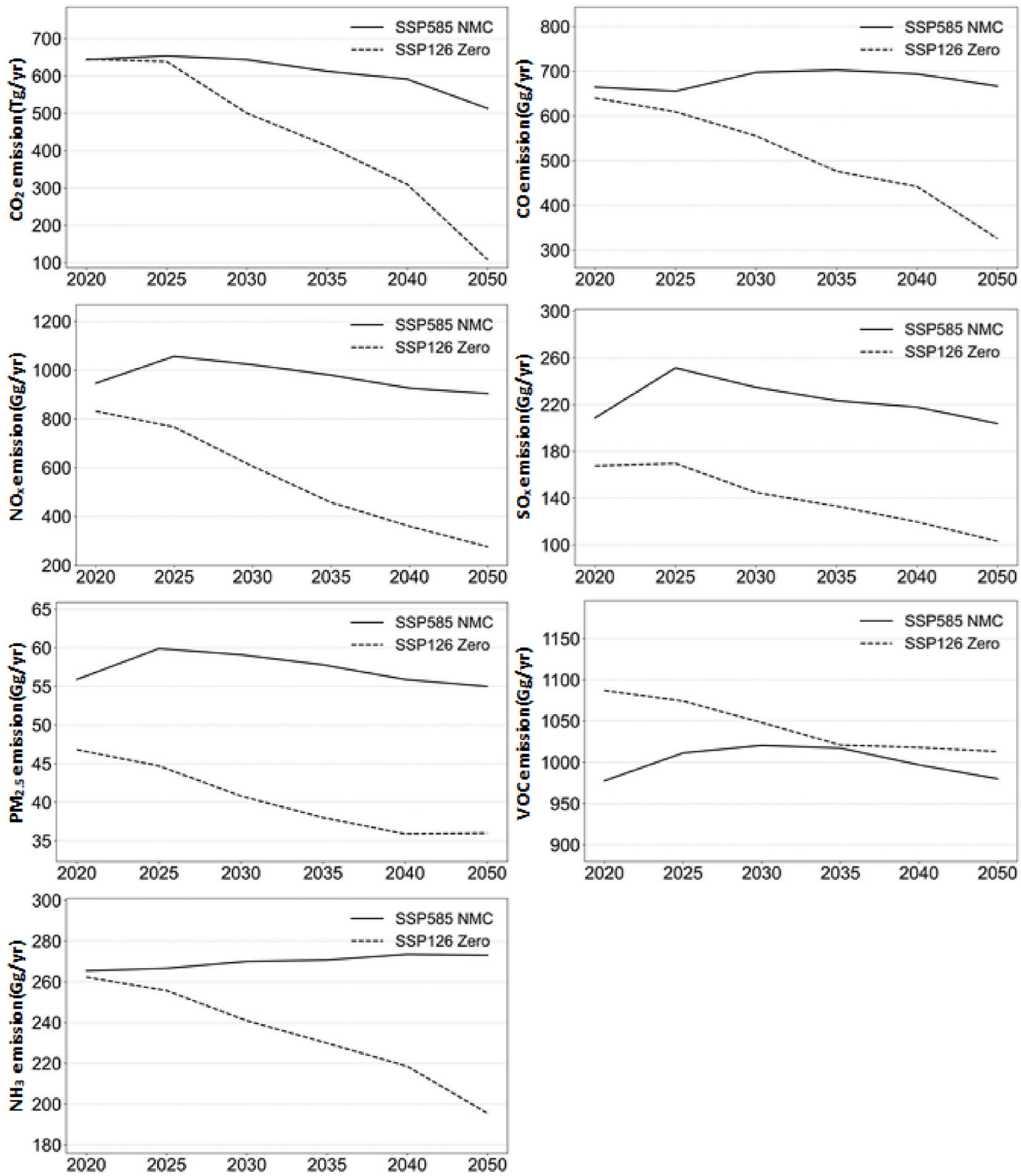

Fig. 4. Annual variations according to scenario (SSP585NMC and SSP126ZERO) for (a) CO_2, (b) CO, (c) SO_2, (d) NO_x, (e) $PM_{2.5}$, (f) VOC, and (g) NH_3 in 2021.

database and compared with stratospheric O_x ($=O_3 + NO_2$) concentrations projected by the CMIP6 models for the period 2015–2050 (Fig. S1). As shown in Fig. S1, GRIMs-CCM successfully simulated O_3 variability compared with values from the CMIP6 models, although there was a slight underestimation of the variability range.

We evaluated model performance for monthly average O_3 and $PM_{2.5}$ concentrations in South Korea from 2021 to 2022, comparing the results with observed values from selected major administrative regions: Seoul, Daejeon, Incheon, Gyeonggi, Gangwon, and Gwangju (Figs. S2 and S3). The normalized mean bias values for monthly average O_3 and $PM_{2.5}$ concentrations across the 17 administrative regions of South Korea were 21.58–30.03 % and 19.19–59.23 %, respectively. The normalized mean errors were 19.56–31.01 % and 32.88–64.23 %, respectively, while the correlation coefficients (R) were 0.37–0.81 and 0.54–0.75, respectively (Figs. S2 and S3).

3.2.2. *Projected O_3 concentrations*

Fig. 5 shows the temperature deviations in 2050 relative to 2021 under different SSP climate change scenarios. As illustrated in the figure, under SSP585NMC, temperatures increased across all four seasons. In contrast, under SSP126ZERO, South Korea experienced a slight temperature decrease in spring and summer, whereas temperatures in autumn and winter increased by 1–2 °C.

Fig. 6 shows the average O_3 concentrations simulated over the Korean Peninsula for 2021 and 2050 under the two scenarios. The highest O_3 concentrations were observed in spring under both scenarios. Under SSP585NMC, O3 concentrations were projected to increase by 6.1 ± 1.2 ppb in spring, 1.1 ± 1.4 ppb in summer, 1.4 ± 1.2 ppb in autumn, and 2.4 ± 0.8 ppb in winter compared with the base year (Table S7). Under SSP126ZERO, average O_3 concentrations in spring and summer were projected to decrease by 4.5 ± 1.0 ppb and 5.8 ± 2.5 ppb, respectively; in autumn and winter they were expected to slightly increase by 0.2 ± 1.3 ppb and 2.8 ± 2.1 ppb, respectively (Fig. 6).

The differences in O_3 concentrations projected for 2050, show distinct seasonal variations were observed under SSP585NMC, but changes in seasonal concentrations were less pronounced under SSP126ZERO (Fig. 6). Under SSP585NMC, O_3 concentrations increased across all four seasons, whereas under SSP126ZERO, concentrations

Table 1
Ratios of GHG and AP emissions according to emission source for South Korea in 2050 compared with the baseline year (2019) under the SSP585NMC and SSP126ZERO scenarios.

Pollutants	CO_2	CO	SO_2	NOx	$PM_{2.5}$	VOC	NH_3
SSP585NMC	0.79	0.89	0.86	0.87	0.89	0.97	1.01
Power	0.65	1.77	0.25	0.97	0.99	1.82	2.08
Residential	1.10	1.35	0.37	1.35	0.82	1.46	0.89
Industry	0.99	0.94	0.96	0.88	1.04	1.03	0.72
Solvents	0.00	0.00	0.00	0.00	0.00	1.04	0.00
Road	0.57	0.97	0.62	0.55	0.46	0.52	0.88
Nonroad	0.89	0.75	1.45	1.06	0.99	0.74	0.60
Agriculture	0.00	0.00	0.00	0.00	0.00	0.00	1.08
Other	1.08	0.58	0.93	0.79	0.88	0.77	0.91
SSP126ZERO	**0.17**	**0.43**	**0.44**	**0.26**	**0.60**	**1.01**	**0.73**
Power	0.10	0.30	0.06	0.23	0.16	0.30	0.63
Residential	0.10	0.11	0.05	0.11	0.11	0.12	0.21
Industry	0.32	0.68	0.63	0.36	0.52	0.89	0.50
Solvents	0.00	0.00	0.00	0.00	0.00	1.28	0.00
Road	0.01	0.02	0.01	0.01	0.01	0.01	0.02
Nonroad	0.29	0.61	0.37	0.53	0.57	0.64	0.50
Agriculture	0.00	0.00	0.00	0.00	0.00	0.00	0.78
Other	0.54	0.66	0.24	0.47	0.81	0.58	0.91

were relatively low in spring and summer but slightly higher in autumn and winter. Notably, under SSP585NMC, despite a 23 % reduction in NO_x emissions, O_3 concentrations continued to rise. Under SSP126ZERO, even with a substantial 84 % reduction in NO_x emissions, the impact on O_3 concentrations was modest; there were small decreases of less than 10 % in spring and summer, along with slight increases in autumn and winter.

3.2.3. Projected $PM_{2.5}$ concentrations

Fig. 7 shows the seasonal average $PM_{2.5}$ concentrations for 2021 and 2050 under SSP585NMC and SSP126ZERO. The highest $PM_{2.5}$ concentrations were simulated in winter, followed by spring, autumn, and summer. A substantial reduction in $PM_{2.5}$ concentrations was observed in 2050. Under SSP585NMC, $PM_{2.5}$ concentrations were projected to decrease by 18.0 ± 3.5 μg/m^3 in spring, 12.2 ± 3.1 μg/m^3 in summer, 2.9 ± 1.6 μg/m^3 in autumn, and 3.6 ± 2.7 μg/m^3 in winter compared with the baseline. Under SSP126ZERO, the reductions in $PM_{2.5}$ concentrations were generally larger, with values of 21.7 ± 1.2 μg/m^3 in spring, 5.7 ± 1.9 μg/m^3 in summer, 13.4 ± 2.1 μg/m^3 in autumn, and 31.9 ± 3.8 μg/m^3 in winter (Table S8). Under SSP585NMC, which assumed the continuation of current AP control policies in China, a regional $PM_{2.5}$ concentration reduction of 9.2 ± 0.8 μg/m^3 was projected relative to the baseline, contrasting with the O_3 trends. In comparison, the projected reduction in $PM_{2.5}$ concentrations against the baseline was substantially greater under SSP126ZERO, which incorporated carbon neutrality policies in Northeast Asian countries, reaching a maximum reduction of 18.2 ± 1.1 μg/m^3. These results indicate that $PM_{2.5}$ concentrations can be significantly reduced through carbon neutrality policies; O_3 concentrations require more robust emission reduction strategies within South Korea, as well as enhanced cooperation with neighboring countries.

3.3. Absence of a decrease in O_3 concentration despite decreasing NO_x: causes and solutions

The formation of O_3 exemplifies the nonlinear nature of the O_3–NO_x–VOC chemical reaction. Changes in O_3 levels are predominantly determined by the relative balance and interaction between reductions in anthropogenic emissions of O_3 precursors (NO_x and VOCs). The VOCs/NO_x ratio is an important diagnostic indicator widely used to assess O_3 sensitivity by distinguishing between NO_x-limited and NO_x-saturated (or VOC-limited) conditions for effective O_3 control. For example, in the NO_x-saturated (or VOC-limited) regime, a reduction in VOC emissions can lead to a decrease in O_3 formation, whereas a decrease in NO_x emissions can promote O_3 production due to a weaker NO titration effect when VOC concentrations are high (Pusede and Cohen, 2012; Pusede et al., 2014). These findings suggest that O_3 control policies in urban areas should include substantial cuts in NO_x emissions

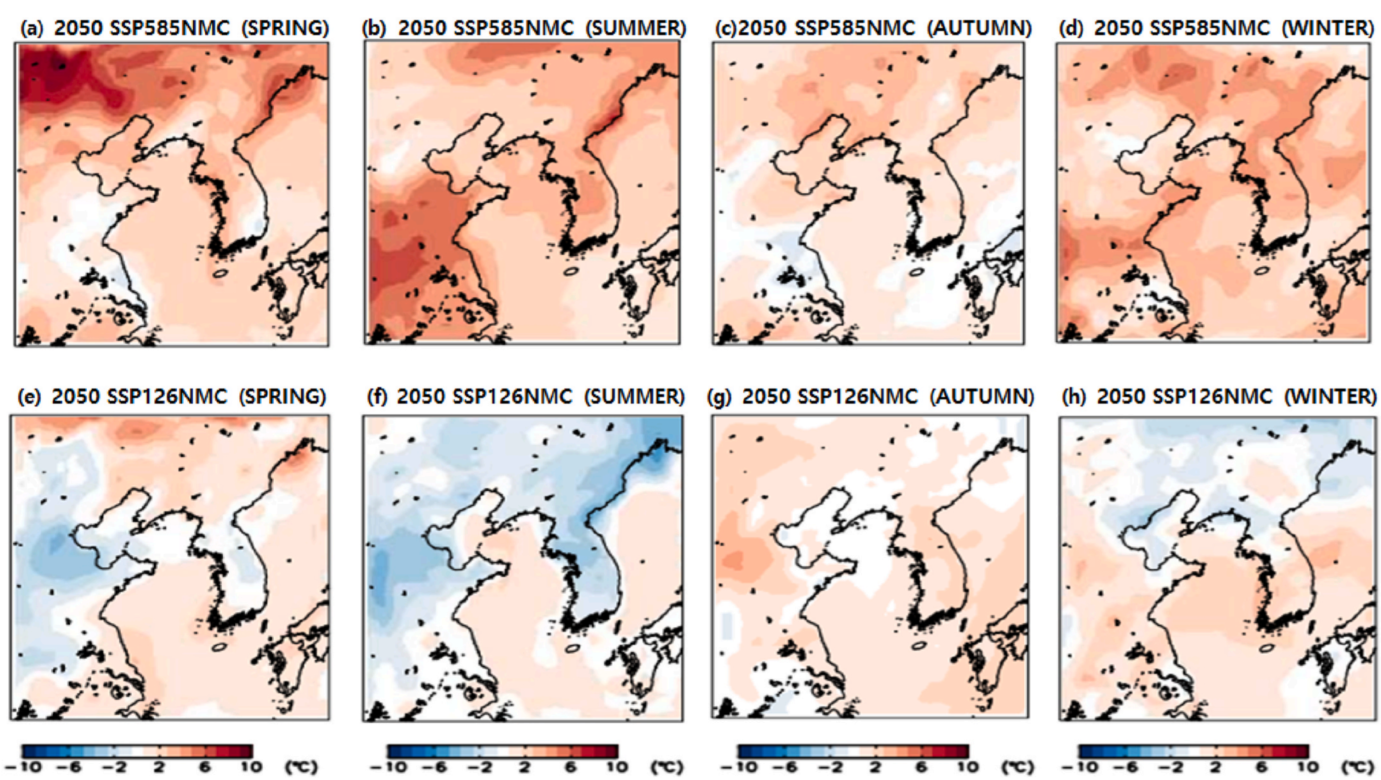

Fig. 5. The difference in daily maximum temperature relative to 2012 for SSP585NMC (top) and SSP126ZERO scenarios (bottom).

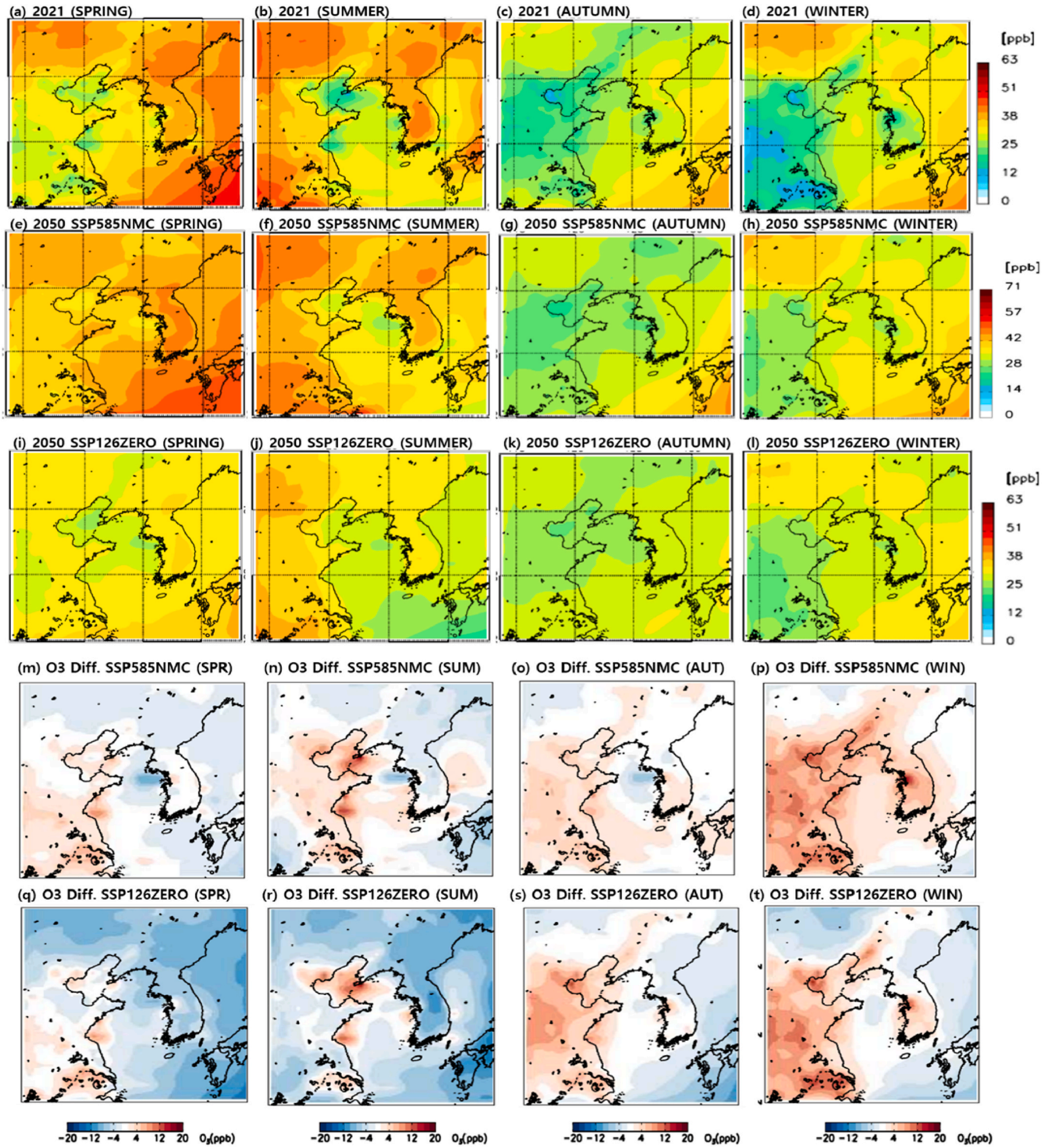

Fig. 6. Seasonal average O_3 concentrations over the Korean Peninsula for 2021 (a–d), SSP585NMC (e–h), SSP126ZERO scenarios(i-l), and the differences bewtween 2021 and the SSP585NMC and SSP126ZERO scenarios (m–u).

to transition the O_3 regime to a NO_x-limited state.

As shown in Table 1, compared to the baseline, NO_x emissions in South Korea in 2050 decreased by 87 % under SSP285NMC and by 26 % under SSP162ZERO, whereas VOC emissions remained relatively constant, decreasing to 97 % under SSP285NMC and increasing slightly to 101 % under SSP162ZERO. Thus, the scenarios represented considerable reductions in NO_x emissions under SSP285NMC and significant reductions under SSP162ZERO. However, the resulting O_3 concentrations in 2050 increased by 6.1 ppb in spring under SSP285NMC but decreased by 4.5 ppb under SSP162ZERO (Table S7 and Fig. 6). These findings suggest that reductions in NO_x emissions alone may not have a substantial positive impact on O_3 reduction in South Korea, likely due to the NO_x titration effects discussed in previous studies (Oak et al., 2023; Lee et al., 2021, 2022a). In the context of considerable NO_x emission

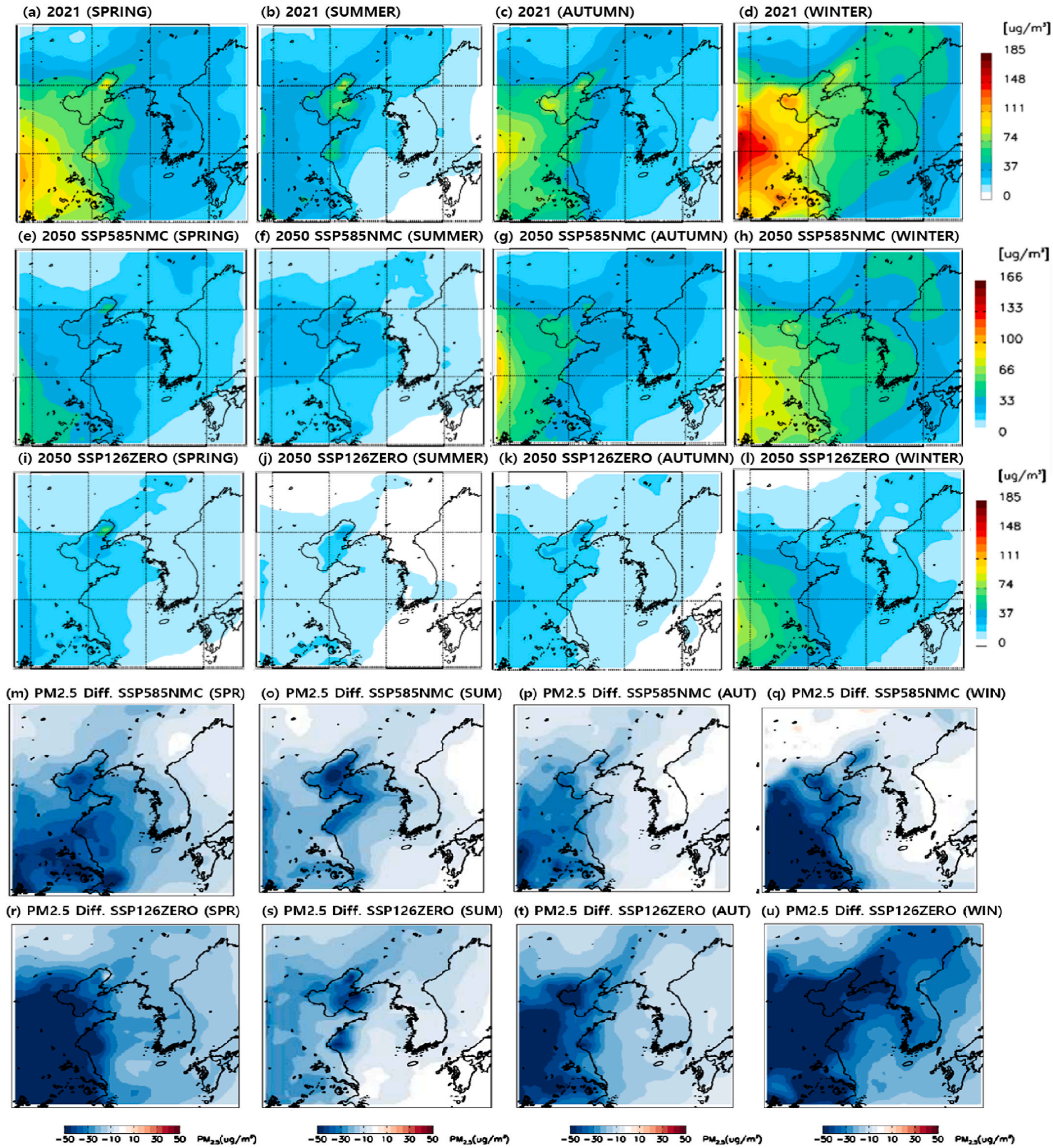

Fig. 7. Seasonal average $PM_{2.5}$ concentrations over the Korean Peninsula for 2021 (a–d), SSP585NMC (e–h), SSP126ZERO scenarios(i-l), and the differences bewtween 2021 and the SSP585NMC and SSP126ZERO scenarios (m–u).

reductions (i.e., a 23 % reduction under SSP585NMC with constant VOC emissions), O_3 concentrations increased across all four seasons (Table S7). In contrast, assuming a significant 74 % reduction in NO_x emissions under SSP162ZERO, there was a small decrease in O_3 concentrations during the high O_3 seasons (spring and summer), with reductions of 4.5–5.8 ppb (Table S7). These results indicate that the substantial reduction in NO_x emissions under SSP162ZERO enabled the O_3 regime to shift from a VOC-limited to a NO_x-limited state, resulting in only a minor decrease in O_3 concentrations. Therefore, significant NO_x reductions, such as those under SSP162ZERO, may be insufficient to mitigate O_3 pollution in urban areas in South Korea. Simultaneous control of both VOC and NO_x emissions will be critical for achieving effective, carbon-neutral O_3 control. These results also imply that GHG reduction policies alone are inadequate for controlling O_3 pollution; effective O_3 management before 2050 requires concurrent reductions in both VOC and NO_x emissions. Mid-to long-term air quality policies in

South Korea must therefore focus on VOC emission control along with GHG reduction measures to ensure effective O_3 management.

One important factor to consider is the climate penalty for O_3. The climate penalty refers to the adverse effects caused solely by rising temperatures rather than by changes in air quality driven by emission reduction policies. Studies calculating the climate penalty often focus on O_3 because its formation is highly sensitive to temperature (Bloomer et al., 2009; Jing et al., 2017; Rasmussen et al., 2013). Rasmussen et al. (2013) emphasized that, in addition to investigating policies aimed at controlling changes in O_3 precursor emissions, it is essential to adjust for the costs of mitigating increases in O_3 concentrations driven by temperature rises under future climate scenarios. In this study, temperatures in the SSP585 scenario were higher in spring than in the base year (Fig. 5), and the springtime O_3 concentration in this scenario showed the highest increase (+6.1 ppb). In contrast, O_3 concentrations in the SSP162 scenario were relatively lower, particularly during spring and summer. These results were strongly aligned with the greatest reductions in O_3 concentrations observed during the peak O_3 reduction seasons of the SSP126ZERO scenario relative to the base year. This alignment provides compelling evidence of the association between these reductions and the climate penalty, as indicated by Rasmussen et al. (2013). Our findings also suggest that in a NO_x-limited regime, NO_x control strategies alone are sufficient to both decrease the O_3–climate penalty and mitigate O_3 pollution. In contrast, in a NO_x-saturated regime, a modified emissions control plan that ensures reductions in both NO_x and VOC emissions may be necessary to eliminate the O_3–climate penalty while simultaneously reducing O_3 concentrations to the desired level. Although we did not quantitatively calculate and compare the hidden climate penalties between the two scenarios, there is a need to quantify and distinguish the effects of climate change and emission reductions. Additional research will be conducted to address this gap.

$PM_{2.5}$ concentrations over South Korea also exhibited significant seasonal variation and were strongly influenced by long-range transport across the Northeast Asia region due to the country's location downwind of prevailing westerly winds (Kim, 2019; Kim et al., 2021). The scenario incorporating carbon-neutral policies in Northeast Asia predicted greater reductions in $PM_{2.5}$ concentrations across the three countries of China, Japan, and South Korea. The results showed that the impact of carbon-neutrality emission reductions was pronounced for $PM_{2.5}$ concentrations, which decreased by 60 %, 7 %, and 49 % for South Korea, China, and Japan, respectively (Table S8 and Fig. 7). Consequently, $PM_{2.5}$ concentrations were significantly reduced across South Korea in all four seasons; the reductions were particularly prominent in winter (Fig. 7). This finding can be attributed to reduced emissions of $PM_{2.5}$ (e.g., Chinese $PM_{2.5}$ concentrations significantly decreased by 93 %), reductions in its precursors, and a decreased impact of $PM_{2.5}$ transport across Northeast Asia, which substantially affected South Korea.

Given the complex interactions between GHG reductions and AP control, achieving comprehensive air quality improvements requires a more integrated approach to policy design. While $PM_{2.5}$ reductions are expected under the 2050 carbon neutrality scenario, the projected increase in O_3 concentrations in certain regions underscores the need for targeted emission control strategies for multiple pollutants. This highlights the importance of balancing reductions in NO_x and VOC emissions to mitigate unintended consequences of climate policies on air quality. Additionally, considering the location of South Korea relative to major emission sources in Northeast Asia, transboundary air pollution management should be a key component of future policy discussions.

4. Summary and conclusion

To predict the impact of future global climate change and GHG reduction policies in Northeast Asia on air quality over the Korean Peninsula, a multi-modeling approach was adopted to simulate O_3 and $PM_{2.5}$ concentrations across the 17 administrative regions of South Korea. The scenarios were based on two assumptions: (1) current AP control policies while fully implementing 2050 net-zero GHG emission policies across Northeast Asia (SSP126ZERO), and (2) maintaining both GHG emission and AP control policies at current levels (SSP585NMC). These scenarios provided the foundational framework for emissions-related input data used in the analysis.

The results showed that changes in O_3 concentrations were primarily determined by the relative dominance between the reductions in anthropogenic emissions of O_3 precursors (NO_x and VOCs). The findings also confirmed that O_3 concentrations can increase even when NO_x levels decrease if VOC concentrations remain high. Rising temperatures were also associated with increases in O_3 concentrations. The increase in O_3 concentrations under SSP585NMC could be attributed to rising temperatures. This finding aligns with previous studies regarding the climate penalty, which indicated that surface temperature increases in polluted areas enhance chemical reactions and local emission feedbacks, thereby raising O_3 levels. Conversely, higher temperatures increase O_3 depletion in unpolluted areas, leading to reduced O_3 levels (Lu et al., 2019; Dewan and Lakhani, 2022).

Regardless of the scenario, VOC concentrations, primarily emitted from non-energy sources, remained constant or decreased less than NO_x concentrations by 2050, indicating a shift from VOC-limited to NO_x-limited conditions. Our findings, which mostly showed increased O_3 concentrations, suggest that effective O_3 management before 2050 requires simultaneous reductions in both VOC and NO_x emissions because GHG reduction policies alone are insufficient for O_3 control.

$PM_{2.5}$ concentrations over South Korea exhibited significant seasonal variation and were strongly influenced by long-range transport across Northeast Asia due to the country's location downwind of prevailing westerly winds (Lee et al., 2022; Kim et al., 2018; Park et al., 2005). The scenario incorporating carbon-neutral policies in Northeast Asia predicted greater reductions in $PM_{2.5}$ concentrations across China, Japan, and South Korea. Because $PM_{2.5}$ concentrations over the Korean Peninsula are heavily influenced by long-range transport, they can be significantly reduced by implementing policies aimed at reducing GHG emissions, whose primary source is energy use. This potential for reduction was reflected in the results of our study.

Considering these findings, there is a need to conduct a comprehensive study regarding the climate change penalty associated with O_3 concentrations. This study should distinguish the impacts of emission reduction measures from those driven by temperature increases and emphasize policy studies aimed at controlling changes in the emissions of O_3 precursors. If climate change scenarios differ, resulting in variations in future temperature trajectories, the effectiveness of AP control policies—particularly for O_3—will also vary. Consequently, the results of this study may differ depending on the climate scenario. More detailed future studies focusing on the effects of carbon-neutral emissions under various climate scenarios are necessary.

To effectively address these challenges, a multi-sectoral and multi-pollutant governance framework should be established. Coordinated reduction targets for NOx and VOCs, strengthened international cooperation on air pollution control, and adaptive policy mechanisms that consider climate change impacts on O_3 formation will be essential. Integrating these measures into South Korea's carbon neutrality strategy will enhance both environmental and public health benefits, ensuring sustainable air quality improvements in the long term.

CRediT authorship contribution statement

Hyungah Jin: Writing – original draft, Methodology, Formal analysis. **Soyoung Yeo:** Visualization, Data curation. **Jung-Hun Woo:** Writing – review & editing, Methodology, Formal analysis. **Minjoong J. Kim:** Visualization, Validation, Software, Data curation. **Miae Seong:** Validation, Data curation. **Do Hyun Seo:** Data curation. **Jiwon Baek:** Visualization. **Sang-Seok Oh:** Visualization, Data curation. **Cheol-Hee Kim:** Writing – review & editing, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.125653.

Data availability

Data will be made available on request.

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