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Long-Term Trends in Greenhouse Gases in the Atmosphere over South Korea

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Abstract. Global warming is driven by rising atmospheric greenhouse gases (GHGs), yet long-term regional observational records remain limited. We analyze multi-decadal records of CO_2, CH_4, N_2O, and SF_6 measured since 1999 at four climate monitoring stations in South Korea (Anmyeondo, Gosan, Ulleungdo, and Dokdo) and compare them with datasets from East Asia, Europe, and North America. Quality-controlled daily and annual means were used to quantify trends, growth rates, and spatial and seasonal variability. In 2024, national annual mean concentrations reached 429 ± 4 ppm (CO_2), 2020 ± 26 ppb (CH_4), 339 ± 0.60 ppb (N_2O), and 12.98 ± 0.33 ppt (SF_6), generally exceeding levels in China and Japan and showing comparable or faster growth. Over the past decade, mean growth rates were 2.41 ppm yr^{-1} (CO_2), 9.30 ppb yr^{-1} (CH_4), 1.25 ppb yr^{-1} (N_2O), and 0.37 ppt yr^{-1} (SF_6). CO_2 and CH_4 exhibit pronounced winter maxima and summer minima, whereas N_2O and SF_6 show weak seasonality. South Korea's national emissions and terrestrial sink capacity alone cannot explain the elevated atmospheric burdens, implying substantial transboundary transport superimposed on rising regional backgrounds. These increases align with observed atmospheric and ocean warming around the Korean Peninsula and underscore the need for strengthened domestic mitigation, sustained monitoring, and coordinated East Asian emissions reduction and transport–climate modeling.

Keywords: Greenhouse gases, Carbon dioxide, Methane, Nitrous oxide, Sulfur hexafluoride

Short summary. Long-term observations of greenhouse gases are important for understanding regional climate change, but such records are limited. Using measurements since 1999 from four monitoring stations in South Korea, we show that atmospheric concentrations of carbon dioxide, methane, nitrous oxide, and sulfur hexafluoride have increased steadily and are higher than nearby regions. The results highlight the importance of cross-border transport and the need for monitoring and cooperation East Asia.

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1 Introduction

Global warming is primarily driven by increasing atmospheric concentrations of greenhouse gases (GHGs), which absorb and re-emit terrestrial longwave radiation, thereby warming Earth's surface and the atmosphere (Intergovernmental Panel on Climate Change; IPCC, 2021). Since the Industrial Revolution, atmospheric concentrations of GHGs have increased rapidly due to anthropogenic activities such as fossil fuel combustion and agricultural practices (IPCC, 2023). This warming has contributed to increases in the frequency and intensity of weather and climate extremes, including heatwaves, droughts, and heavy precipitation (IPCC, 2021; Zittis et al., 2022), leading to substantial socioeconomic impacts, including reduced agricultural productivity and loss of habitable land. Therefore, it is important to monitor atmospheric GHG concentrations alongside mitigation efforts aimed at reducing GHG emissions (IPCC, 2019; Fróna et al., 2021).

In response to the efforts, the international community has established a series of agreements to reduce GHG emissions. The United Nations Framework Convention on Climate Change (UNFCCC), adopted at the Rio Earth Summit in 1992, laid the foundation for subsequent climate protocols. The Kyoto Protocol, adopted in 1997, aimed to reduce GHG emissions by an average of 5.2% below 1990 levels over the 2008–2012 commitment period. More recently, the 2015 Paris Agreement set a more ambitious temperature goal of limiting global warming to well below 2 °C above pre-industrial levels, while pursuing efforts to limit the increase to 1.5 °C (Yoon, 2017). Achieving these goals will require sustained global monitoring of GHGs and the development of long-term observational records.

Among the GHGs, carbon dioxide (CO_2) is the largest contributor to anthropogenic radiative forcing as global atmospheric CO_2 concentrations have increased by approximately 51% from pre-industrial levels (approximately 278 ppm) to 419 ppm in 2023, primarily due to fossil fuel combustion, deforestation, and industrial activities (Lan et al., 2023b; IPCC, 2021). Moreover, approximately 30% of emitted CO_2 is taken up by the oceans, contributing to ocean acidification (Sabine et al., 2004).

Methane (CH_4) is the second most abundant anthropogenic GHG after CO_2 and has increased by approximately 164% since the Industrial Revolution, reaching a global annual mean of approximately 1900 ppb in 2023 (Lan et al., 2023a). While CH_4 is naturally produced in anaerobic environments such as wetlands, its recent rise is largely attributable to human activities, including agriculture (e.g., livestock and rice cultivation), waste management, and fossil fuel extraction and processing (Jackson et al., 2020; Saunois et al., 2019). CH_4 has a 20-year global warming potential (GWP20) of 80, which compares its warming effect to that of CO_2, making it a potent contributor to near-term climate change (IPCC, 2021).

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Nitrous oxide (N_2O) has also increased substantially, with the global annual mean reaching approximately 336 ppb, about 22% above pre-industrial levels, and is expected to increase further under a warming climate (Lan et al., 2023a). Major anthropogenic sources include fossil fuel combustion, the application of nitrogen fertilizers in agriculture, and various industrial processes. Its GWP20 is estimated at 273, underscoring its importance as a long-lived and potent GHG (IPCC, 2021).

Sulfur hexafluoride (SF_6) is an anthropogenic GHG and has increased rapidly since the mid-20th century (Lan et al., 2023a). It is emitted primarily from its use in electrical insulation and from industrial processes associated with semiconductor manufacturing. SF_6 is exceptionally stable in the atmosphere, with an estimated lifetime of about 3,200 years (Patra et al., 1997). Although SF_6 is present at much lower concentrations (approximately 11 ppt), its GWP20 of 16,300 underscores its disproportionate large climate impact (IPCC, 2021).

The GHGs in the atmosphere have been monitored over 30 years (since 1989) through the Global Atmosphere Watch (GAW) program operated by the World Meteorological Organization (WMO). South Korea also participates in this program through four climate monitoring stations since 1999—Anmyeondo, Gosan, Ulleungdo, and Dokdo—which continuously measure key GHGs, including CO_2, CH_4, N_2O, SF_6, and chlorofluorocarbons (CFCs). In South Korea, total GHG emissions increased by approximately 132% from 1990 to 2021 (NIMS, 2023). As such increases in emissions lead to sustained rises in atmospheric GHG concentrations, it is necessary to synthesize GHG concentration records from multiple monitoring sites across South Korea and to assess their long-term variability and trends. This synthesis can provide a critical evidence base for the formulation and evaluation of GHG mitigation policies.

Previous studies in South Korea have primarily focused on short-term (approximately five years) analyses of CO_2 and CH_4 concentrations at sites such as Anmyeondo, Gosan, and Ulleungdo (Kim et al., 2011; Lee et al., 2016; Kim et al., 2020; Kenea et al., 2021; Lee et al., 2023; Geum et al., 2024). However, analyses of long-term trends in N_2O are virtually nonexistent, and for SF_6 there is essentially only a single study based on measurements at the Gosan station in 2007 (Yoo et al., 2011).

Given these gaps, it is essential to synthesize long-term observational records from South Korea's climate monitoring stations and to assess their long-term trends and variability. This study analyzes long-term trends in the atmospheric concentrations of CO_2, CH_4, N_2O, and SF_6 at climate monitoring stations in South Korea. We compare the observed trends with those reported for neighboring East Asian countries (China and Japan), as well as Europe and North America, to characterize regional and global patterns. This comparative approach is expected

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to elucidate the extent to which GHG trends in South Korea align with or diverge from global patterns and to provide a robust evidence base for informing the design and evaluation of national GHG mitigation strategies.

2 Method and Materials

GHG measurements by NIMS are conducted at four climate monitoring stations in South Korea—Anmyeondo, Gosan (Jeju Island), Ulleungdo, and Dokdo (Figure 1; Table S1). The Anmyeondo Climate Observation Station is located within Taeanhaean National Park and adjacent to the shoreline; as a result, it is directly influenced by sea breezes, with prevailing winds from the west to northwest (Choi et al., 2006). The Gosan Global Atmosphere Watch (GAW) station on Jeju Island serves as a baseline site for background atmospheric measurements, providing fundamental data for analyses of global-scale atmospheric phenomena such as global warming and stratospheric ozone depletion (Ju et al., 2007). The Ulleungdo and Dokdo climate monitoring stations, located in the central East (Japan) Sea, experience predominantly northeasterly and southwesterly winds depending on the seasons. Owing to their remote marine setting, local anthropogenic influences are relatively small, making these sites well suited for monitoring atmospheric conditions over the eastern maritime region of the Korean Peninsula (NIMS, 2023).

A series of GHGs has been monitored since 1999, including CO_2, CH_4, N_2O, and SF_6. GHGs were monitored at different time intervals depending on instrument availability. Briefly, CO_2 was measured hourly using non-dispersive infrared (NDIR, Siemens, Germany) analyzers at Anmyeondo (1999–2011) and Gosan (2009–2013). Since 2012, hourly CO_2 measurements have been performed using cavity ring-down spectroscopy (CRDS, PICARRO, USA) at Anmyeondo, Ulleungdo, and Dokdo, and since 2014 at Gosan. CH_4 was measured daily at Anmyeondo from 1999 to 2015 using gas chromatography with flame ionization detection (GC-FID, Agilent, USA), and has been measured hourly using CRDS since 2016 at Anmyeondo, since 2015 at Gosan, and since 2012 at Ulleungdo (Table S2).

CO_2 and CH_4 measurements were periodically calibrated, and their concentrations were recalculated accordingly. Using metadata on instrument maintenance, the raw records were screened, and data likely affected by maintenance activities, as well as periods during which standard gases were introduced for calibration, were discarded. From the remaining data, time-averaged values were derived. For each gas, hourly mean concentrations and associated standard deviations were then computed and used to identify and remove outliers. Daily mean values were subsequently derived following the method of Thoning et al. (1989) (Thoning et al., 1989).

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N_2O has been monitored hourly using gas chromatography with electron capture detector (GC-ECD, Agilent, USA) at Anmyeondo (since 1999), Gosan (since 2012), and Ulleungdo (since 2019). SF_6 has also been monitored hourly using GC-ECD at Anmyeondo (since 2007), Gosan, and Ulleungdo (since 2017) (Table S2). Standard gases for N_2O and SF_6 were introduced every 6 hours during the observation period to recalibrate the instruments and re-evaluate the measured concentrations. Using information on instrument maintenance dates, the raw records were screened, and data likely affected by maintenance activities were removed. Additional quality control was performed using inter-site comparisons and concurrent meteorological information to identify valid measurements. Following this quality control, to minimize the influence of residual short-term local variability and to extract a representative atmospheric background signal, a second-order polynomial was fitted to the minimum concentrations identified within an approximately 60-day moving window. The observations were then referenced to this fitted baseline, and residuals were calculated as the difference between the observations and the fitted baseline. To suppress the influence of abnormal events and outliers, the standard deviation of the residuals was estimated using only those residuals smaller than the median value. Data with residuals less than the median plus three times this standard deviation were regarded as representative of natural background conditions, free from local pollution episodes. These background concentrations were subsequently averaged to derive daily mean values (NIMS, 2021).

To analyze long-term trends in monthly GHG concentrations, the centered moving average (CMA) method was applied using IBM SPSS Statistics (version 27, IBM, USA). The CMA is a statistical technique that smooths time series data by averaging values centered on a specified window, thereby reducing short-term fluctuations and the influence of outliers while highlighting long-term trends (Hyndman, 2025). In this study, a 12-month window was used to capture the annual seasonal cycle, enabling clearer identification of underlying trends in GHG concentrations.

Subsequently, concentrations measured at the four South Korean monitoring stations were compared with regional- and continental-scale concentrations. For international comparisons, regional averages of GHG concentrations for East Asia (China and Japan), Europe (Hungary, Italy, Germany, Switzerland, and Poland), and North America (the United States) were obtained from the World Data Centre for Greenhouse Gases (WDCGG). Comparisons were conducted at both the country level (South Korea, China, and Japan) and the continental scale (East Asia, Europe, and North America). Details of station locations and measurement periods for each GHG are provided in Tables S1 and S2.

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3 Results and Discussion

3.1 Decadal trends in atmospheric GHGs

3.1.1 Carbon Dioxide (CO_2)

In 2024, the national annual mean atmospheric CO_2 concentration in South Korea was 429 ± 4 ppm, showing minimal spatial variation across the four monitoring sites (Figure 2a; Table 1). The dominant feature of atmospheric CO_2 in South Korea is a gradual increase over time (Figure 2b). The overall growth rate of atmospheric CO_2 in South Korea was 2.41 ppm yr^{-1}, exceeding the rates observed in other countries (Table 1). Monthly atmospheric CO_2 concentrations were lowest in August and highest in December (Figure 3a). It is widely recognized that increases in atmospheric CO_2 concentrations are largely attributable to fossil fuel consumption—primarily petroleum-based fuels—in most countries, including South Korea, as well as to agricultural activities in some regions (IPCC, 2014). Fuel consumption in South Korea has increased since the 1960s (Choi and Ang, 2001; Oh and Lee, 2004; Oh et al., 2010) and typically peaks in winter according to recent energy utilization report (Korea Energy Economics Institute; KEEI, 2025). This seasonal pattern likely contributes to both the long-term rise in atmospheric CO_2 concentrations and the pronounced wintertime maxima observed in South Korea (Figure 3a). For example, during 2022–2024, winter fossil fuel consumption was 2.32 million tons, compared with 2.04 million tons in summer (KEEI, 2025), likely resulting in higher CO_2 emissions in winter. Additionally, prevailing northwesterly winds in winter facilitate the transport of air masses with elevated CO_2 concentrations from China into South Korea. In fact, Kim et al. (2020) estimated that air masses originating from China could account for approximately 32% of wintertime air masses over South Korea, suggesting that enhanced winter CO_2 levels may also be influenced by transboundary transport (Kim et al., 2020).

During summer, CO_2 is taken up by vegetation through photosynthesis, thereby reducing atmospheric CO_2 levels. For example, in 2023, CO_2 fluxes observed at the broadleaf forest tower in the Gwangneung National Arboretum were negative in summer (down to -1 mg CO_2 m^{-2} s^{-1}), indicating greater CO_2 uptake by vegetation compared to winter, when fluxes were approximately 0 mg CO_2 m^{-2} s^{-1} (NIMS, 2023). Accordingly, the seasonal reduction in atmospheric CO_2 in summer relative to winter is likely associated with enhanced vegetation activity and lower fossil fuel consumption, whereas the wintertime increase in atmospheric CO_2 is primarily driven by intensive fossil fuel use (Choi et al., 2006; Ju et al., 2007; NIMS, 2023).

In 2024, the national mean atmospheric CO_2 concentration over South Korea (429 ± 4 ppm) was higher than those over China (413 ± 8 ppm) and Japan (427 ± 3 ppm). Over the past decade, the mean annual increase in atmospheric CO_2 concentration in South Korea (2.61 ppm yr^{-1}) also exceeded those in China (2.37 ppm yr^{-1}) and

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Japan (2.59 ppm yr^{-1}) (Table 1). At the regional scale, the 2024 mean CO_2 concentration and the mean annual increase over the past decade were 432 ± 4 ppm and 2.98 ppm yr^{-1} in East Asia, and 425 ± 5 ppm and 2.54 ppm yr^{-1} in Europe and North America, respectively (Table 1). Furthermore, since the early 2000s, atmospheric CO_2 concentrations in East Asia have consistently exceeded those in Europe and North America (Figure S1). Since 2003, total CO_2 emissions from East Asia (6.62 billion tons in 2003) have exceeded those from Europe (4.31 billion tons) and North America (5.95 billion tons) (Jones et al., 2023). While CO_2 emissions in Europe and North America have plateaued or declined since the early 2000s, emissions in East Asia have continued to rise, likely contributing to the elevated atmospheric CO_2 concentrations observed in the region.

At present, the causes of the relatively high atmospheric CO_2 concentrations and rapid increase rates observed in South Korea, compared to other countries, cannot be fully constrained. While increased fossil fuel consumption and relatively less effective mitigation efforts may partly explain these patterns (e.g., IPCC, 2014), domestic emissions alone are unlikely to fully account for the observed atmospheric burdens. In addition, transboundary transport from neighboring regions, particularly China, may also contribute to the elevated atmospheric CO_2 concentrations observed over South Korea, especially during winter (Kim et al., 2020).

3.1.2 Methane (CH_4)

Annual mean atmospheric CH_4 concentration in South Korea in 2024 was 2020 ± 26 ppb, with increasing trends observed at all domestic monitoring stations (Figure 4a; Table 1). Spatial differences among sites were modest, with the highest concentrations at Anmyeondo (2030 ± 32 ppb), followed by Dokdo (2023 ± 9 ppb), Ulleungdo (2022 ± 17 ppb), and Gosan (2010 ± 35 ppb) (Figure 4a; Table 1). Over the entire observation period (1999–2024), CH_4 concentrations increased at an average rate of 5.55 ppb yr^{-1}; however, this rate accelerated to 9.30 ppb yr^{-1} after 2015, indicating a marked intensification in the growth of atmospheric CH_4 over South Korea (Figure 4b; Table 1). This accelerated trend is likely driven primarily by anthropogenic activities, including agriculture and fossil fuel use (Geum et al., 2024). Seasonally, the concentrations were lowest in summer (June–August) and highest in winter (December–February), reflecting increased fossil fuel combustion during winter (Figure 3b).

CH_4 production is typically enhanced in summer by microbial activity in rice paddies and wetlands; however, higher temperatures and stronger solar radiation also promote the formation of hydroxyl (OH) radicals—the primary atmospheric sink for CH_4—thereby enhancing CH_4 oxidation and leading to relatively lower atmospheric concentrations during this season (Geum et al., 2024). Over the past few decades, rice paddy area has declined

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(Korea Rural Economic Institute; KREI, 2021), suggesting a reduced contribution of agricultural sources to CH_4 emissions. Consequently, the observed increase in atmospheric CH_4 is more likely driven by enhanced emissions associated with natural gas production, distribution, and use. In particular, when combined with increased fossil fuel consumption during the heating season, these factors contribute to higher wintertime CH_4 concentrations (Duncan et al., 2000; Tohjima et al., 2002; KEEI, 2025). Additionally, similar to CO_2, prevailing northwesterly winds in winter transport air masses from China into South Korea, thereby contributing to elevated atmospheric CH_4 concentrations over the Korean Peninsula (Shim et al., 2013; Kim et al., 2020).

In 2024, the annual mean CH_4 concentration in South Korea was higher than that in Japan (1989 ± 29 ppb) and comparable to that in China (2003 ± 6 ppb). South Korea's CH_4 growth rate over the past decade (9.30 ppb yr^{-1}) exceeded that of China (6.83 ppb yr^{-1}) but was lower than that of Japan (10.51 ppb yr^{-1}) (Figure 4b; Table 1). At the regional scale, the CH_4 concentration in 2024 was 2004 ± 17 ppb in East Asia, with an annual growth rate 8.88 ppb yr^{-1} over the past decade (Table 1; Figure S1). In 2024, the annual mean CH_4 concentration in East Asia was lower than that in Europe (2027 ± 12 ppb) but higher than in North America (1998 ± 14 ppb). The CH_4 growth rate in East Asia over the past decade was lower than those observed in Europe (10.63 ppb yr^{-1}) and North America (10.60 ppb yr^{-1}) (Table 1; Figureure S1). Nevertheless, since the 1990s, atmospheric CH_4 concentrations in East Asia have exhibited an overall upward trend, with a pronounced acceleration since the mid-2000s that broadly mirrors trends observed in Europe and North America (Figure S1). This long-term increase is likely attributable to the global expansion of natural gas utilization as an energy source (IPCC, 2021).

At this point, the precise causes of South Korea's higher CH_4 concentrations relative to other countries in East Asia cannot be fully resolved. Given that emissions from major source sectors have continued to increase (Jones et al., 2023), the recent acceleration in atmospheric CH_4 growth is likely influenced not only by changes in source emissions but also by changes in the oxidative capacity of the atmosphere. Turner et al. (2017) showed that the global growth rate of atmospheric CH_4 slowed between the early 1990s and early 2000s as OH radical concentrations increased (Turner et al., 2017), whereas an approximately 7% decline in OH since the mid-2000s has been associated with a renewed acceleration in atmospheric CH_4 growth. Although direct OH observations for East Asia prior to the 1990s are unavailable, changes in OH radical concentrations, in combination with regional emission trends, are likely to play a key role in explaining the post-1990s increase and recent acceleration of atmospheric CH_4 across East Asia.

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3.1.3 Nitrous Oxide (N_2O)

In 2024, the annual mean atmospheric N_2O concentration in South Korea was 339 ± 0.60 ppb, corresponding to an annual growth rate of 1.25 ppb yr^{-1} over the past decade (Table 1). All three domestic monitoring stations—Anmyeondo, Gosan, and Ulleungdo—showed increasing trends over the observation period (Figure 5a). Spatial differences among sites were small, with the highest annual mean at Anmyeondo (340 ± 1.48 ppb) and Gosan (340 ± 0.54 ppb), followed by Ulleungdo (339 ± 0.43 ppb) (Table 1). In contrast to CO_2 and CH_4, N_2O did not exhibit a pronounced seasonal cycle (Figure 3c). In 2024, South Korea's annual mean N_2O concentration was lower than that in Japan (341 ± 0.22 ppb) but higher than that in China (338 ± 0.34 ppb) (Figure 5b; Table 1).

Over the full record, N_2O concentrations in South Korea have increased steadily until around 2010, followed by a temporary slowdown in the early 2010s (Figure 5b). Beginning in the mid-2000s, selective catalytic reduction (SCR) systems were increasingly deployed in the power and transport sectors to reduce nitrogen oxide (NO_x) emissions (Kurokawa et al., 2013). Consistent with this, national N_2O emissions have remained relatively stable since the 2010s, averaging approximately 14 million tons of CO_2-equivalent (CO_2eq) per year (The Greenhouse Gas Inventory and Research Center of Korea; GIR, 2023). This stabilization in emissions likely contributed to the temporary slowdown in atmospheric N_2O growth in the early 2010s. However, the subsequent resumption and persistence of N_2O increases (Figure 5a, b) suggest that additional factors—such as changes in minor sources (e.g., waste and wastewater treatment and atmospheric nitrogen deposition over land and oceans)(Tian et al., 2020), sink and removal processes (photochemical destruction in the stratosphere)(Prather et al., 2015), and atmospheric transport processes (Thompson et al., 2014)—may also be influencing recent trends and warrant further investigation.

At the regional scale, the annual mean atmospheric N_2O concentration in East Asia in 2024 was 339 ± 0.24 ppb, increasing at a rate of approximately 1.13 ppb yr^{-1} over the past decade. This concentration was comparable to those observed in Europe (339 ± 0.31 ppb) and North America (338 ± 0.17 ppb), and the annual growth rate in East Asia was broadly similar to those in Europe (1.04 ppb yr^{-1}) and North America (1.06 ppb yr^{-1}) (Table 1; Figure S1). Prior to the 2000s, N_2O concentrations in East Asia were lower than those in Europe and North America, but have increased rapidly over the past two decades, resulting in East Asian concentrations now comparable to those in both regions (Figure S1). Given that East Asia's N_2O emissions have surpassed those of North America and Europe since the mid-1990s—for example, 369.55 million tons of CO_2-eq in 1994, compared with 259.54 million tons CO_2-eq in North America and 362.01 million tons CO_2-eq in Europe (Jones et al.,

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2023)—the elevated atmospheric N_2O concentrations observed in East Asia may be attributable to higher regional emissions related to transportation sectors (IPCC, 2021).

3.1.4 Sulfur Hexafluoride (SF_6)

In 2024, the national annual mean atmospheric SF_6 concentration in South Korea was 12.98 ± 0.33 ppt with an overall growth rate of 0.37 ppt yr^{-1} (Table 1). The domestic monitoring stations—Anmyeondo, Gosan, Ulleungdo—exhibited continuous upward trends throughout the observation period (Figure 6a). Spatial differences among sites were small, with the highest annual mean at Anmyeondo (13.51 ± 0.84 ppt), followed by Ulleungdo (12.75 ± 0.31 ppt) and Gosan (12.69 ± 0.23 ppt) (Table 1). In contrast to CO_2 and CH_4, SF_6 does not display a pronounced seasonal cycle (Figure 3d), consistent with its long atmospheric lifetime.

South Korea in 2024 recorded slightly higher SF_6 concentrations than China (12.14 ± 0.16 ppt), and its overall growth rate also exceeded that of China (4.04% yr^{-1}; 0.30 ppt yr^{-1}) (Figure 6b; Table 1). At the regional scale, the annual mean atmospheric SF_6 concentration over East Asia in 2024 was approximately 12.56 ± 0.22 ppt, with an overall growth rate of 4.22% yr^{-1} (0.31 ppt yr^{-1}) (Table 1). The annual mean SF_6 concentration in East Asia in 2024 was higher than that in both Europe (12.10 ± 0.12 ppt) and North America (12.04 ± 0.12 ppt), and its overall growth rate was likewise higher than those observed in Europe (0.29 ppt yr^{-1}) and North America (0.29 ppt yr^{-1}) (Table 1; Figure S1). Across East Asia, Europe, and North America, SF_6 exhibits substantially higher growth rates than other analyzed GHGs, likely reflecting its persistent accumulation of emissions from industrial applications, particularly in the electrical power sector (NIMS, 2023).

3.2 Factors affecting regional GHG concentrations

This study analyzed long-term trends in the atmospheric concentrations of CO_2, CH_4, N_2O, and SF_6 measured at four climate monitoring stations in South Korea (Anmyeondo, Gosan, Ulleungdo, and Dokdo) and compared them with regional datasets for East Asia, Europe, and North America. The results show that GHG concentrations over South Korea are generally higher than those observed in China and Japan, and the annual growth rates are also greater than those countries (Figures 2 and 4–6; Table 1). Since the 2000s, regional annual mean GHG concentrations across East Asia have increased to levels comparable to, or exceeding, those in Europe and North America (Table 1, Figure S1), likely reflecting the combined effects of rapid industrialization, rising energy consumption, and the expansion of agricultural and livestock activities over recent decades (Tubiello et

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al., 2015; IPCC, 2021; Lamb et al., 2021). These findings highlight East Asia—and South Korea in particular—as an emerging hotspot of long-lived GHGs in the Northern Hemisphere mid-latitudes.

Among East Asian countries, a consistent elevation of the atmospheric CO_2, CH_4, N_2O, and SF_6 concentrations in South Korea could, in principle, reflect either higher emissions or weaker sinks. However, South Korea's total GHG emissions in 2023 were 627 million tons of CO_2eq (Jones et al., 2023). This value is substantially lower than those reported for China (13,968 million tons CO_2eq) and Japan (1,031 million tons CO_2eq) (Jones et al., 2023). In addition, South Korea's GHG sink capacity in 2021 was only approximately 0.5% lower than in 1990 (GIR, 2023), a modest change that alone is unlikely to explain the currently elevated atmospheric concentrations. These observations indicate that domestic sources and sinks alone are insufficient to fully explain the elevated atmospheric burdens of long-lived GHGs over South Korea.

Accordingly, the elevated atmospheric GHG concentrations over South Korea may also reflect the influence of cross-border transport of emissions from neighboring countries. For example, CO_2 and CH_4 measured at the Ganseong monitoring station in South Korea during 2012–2014 were shown to be affected by upwind emissions from China, Mongolia, Russia, North Korea, and Japan (Kim et al., 2020). In particular, wintertime atmospheric circulation transported air masses from China into South Korea, thereby influencing the observed concentrations (e.g., Shim et al., 2013; Kim et al., 2020). These findings suggest that South Korea's atmospheric GHG levels represent a superposition of domestic emissions and regional background contributions rather than purely local sources.

Importantly, although the national mean atmospheric CO_2 concentration in China has shown a noticeable slowdown since around 2015 (Figure 2b), this does not necessarily preclude continued contributions of CO_2-rich air masses to South Korea. Air masses influencing the Korean Peninsula are likely dominated by transport from eastern China, where major industrial and urban centers are concentrated, rather than reflecting national-mean atmospheric conditions (e.g., Li et al., 2024). By contrast, atmospheric CO_2 trends in Japan have been more moderate, with concentrations higher than those in China but lower than those in South Korea. Overall, these inter-country differences in atmospheric CO_2 variability across East Asia likely reflect contrasts in national energy production structures, emission intensities, mitigation trajectories, and regional atmospheric circulation patterns (e.g., Chung, 1998).

It should be noted that existing analyses of transboundary influences, including those by Kim et al. (2020), are based on relatively short observational periods. Consequently, longer-term investigations that integrate sustained observations with atmospheric transport modeling are required to better constrain the relative

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contributions of local emissions and imported air masses to the long-term evolution of atmospheric GHG concentrations over South Korea.

3.3 Impacts of atmospheric GHG increases on surface air and ocean temperatures

The long-term increases in CO_2, CH_4, N_2O, and SF_6 documented here (Figures 2–6; Table 1) are broadly consistent with the observed warming of the atmosphere over South Korea and at the global scale (Figure 7). Since the late 20th century, surface air temperatures in and around the Korean Peninsula have risen at rates comparable to those observed globally (Figure 7). The timing and magnitude of the GHG increases are qualitatively coherent with regional warming: the acceleration of CO_2 and CH_4 growth since the late 20th century parallels the intensification of the surface air temperature rise. This coherence supports the interpretation that the elevated GHG concentrations observed over South Korea contribute to ongoing regional warming.

The relationship between GHG concentrations and sea surface temperature (SST) is more complex, reflecting the ocean's role as both a heat and carbon reservoir (Bigg et al., 2003). In the marginal seas surrounding the Korean Peninsula, SSTs have increased substantially in recent decades (Figure 8), indicating enhanced ocean heat uptake under sustained GHG forcing. On interannual timescales, warm-phase events such as El Niño typically reduce oceanic CO_2 uptake and are associated with higher atmospheric CO_2 growth rates, whereas cooler La Niña conditions tend to enhance uptake and slow the growth rates (e.g., Wang et al., 2016). Such couplings have been reported in global records, where SST anomalies lead variations in CO_2 growth rates by several months. For CH_4, changes in SST can alter OH radical concentrations (Qian et al., 1995; Jankowski et al., 1999), further linking marine variability to atmospheric CH_4 trends (Zhao et al., 2020).

Increases in N_2O and SF_6 contribute to the total long-lived GHG forcing, thereby influencing both atmospheric and oceanic warming despite their relatively low abundances (Ming et al., 2014). The stabilization of national N_2O emissions in the early 2010s was likely associated with the wider deployment of selective catalytic reduction systems in the power and transport sectors, which appears to have contributed to a transient slowdown in atmospheric N_2O growth (GIR, 2023). However, the subsequent resumption of N_2O increases suggests that additional controls, such as changes in minor sources, sinks, or transport patterns, may also be important. SF_6 shows the fastest relative growth rate among the gases examined here (Table 1), consistent with its exceptional atmospheric stability and continued emissions from industrial and power-sector applications, leading to persistent accumulation in the regional atmosphere.

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4 Conclusion

The elevated GHG concentrations observed in South Korea likely reflect a combination of domestic emissions and transboundary inflow from neighboring countries, particularly China, superimposed on a broader regional trend of rising GHG forcing and associated atmospheric and oceanic warming. Effectively reducing GHG concentrations will therefore require not only robust domestic mitigation policies but also strengthened regional cooperation across East Asia on emissions inventories, long-term atmospheric and oceanic monitoring, and the development and deployment of emissions-reduction technologies. Future research should further disaggregate sectoral sources and sinks to quantify their respective contributions more precisely, and apply atmospheric transport and climate models to track the spatiotemporal evolution of source regions and associated temperature responses. Such integrated approaches will be essential for designing and evaluating mitigation strategies that simultaneously target emissions reduction, air-quality co-benefits, and climate stabilization over South Korea and the broader East Asian region.

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Author contribution

BM: Data curation, Visualisation, Conceptualization, Writing – Original Draft, Writing – Review & Editing, SP: Data curation, Visualisation, Conceptualization, Writing – Original Draft, SL: Methodology, Validation, DJ: Conceptualization, Validation, Supervision, Writing – Review & Editing, Project administration, Funding acquisition.

Code/Data availability

No code is used in this study. Data are available at the www.climate.go.kr/home**.**

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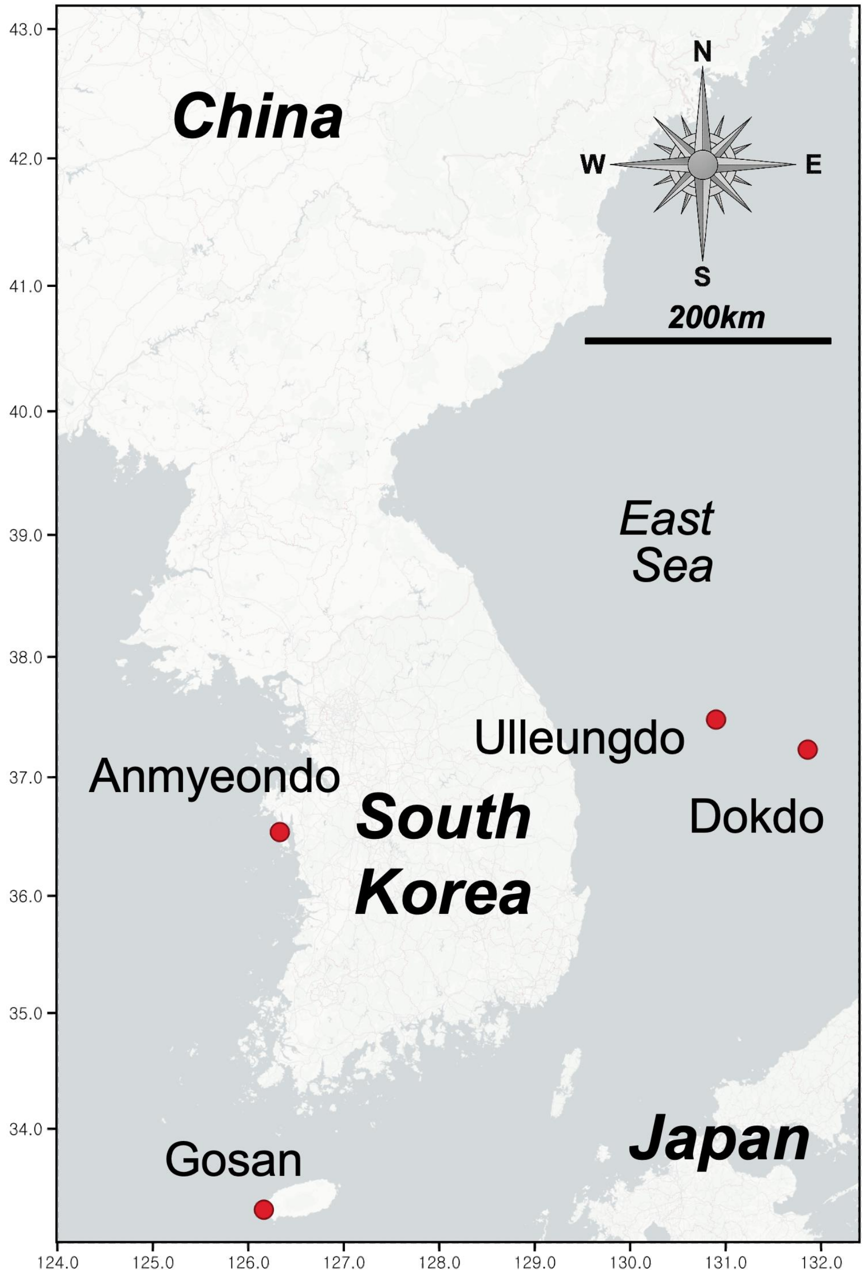

575

576 **Figure 1** Locations (latitude, longitude) of Earth and Atmospheric Monitoring Observatories located in South
577 Korea.

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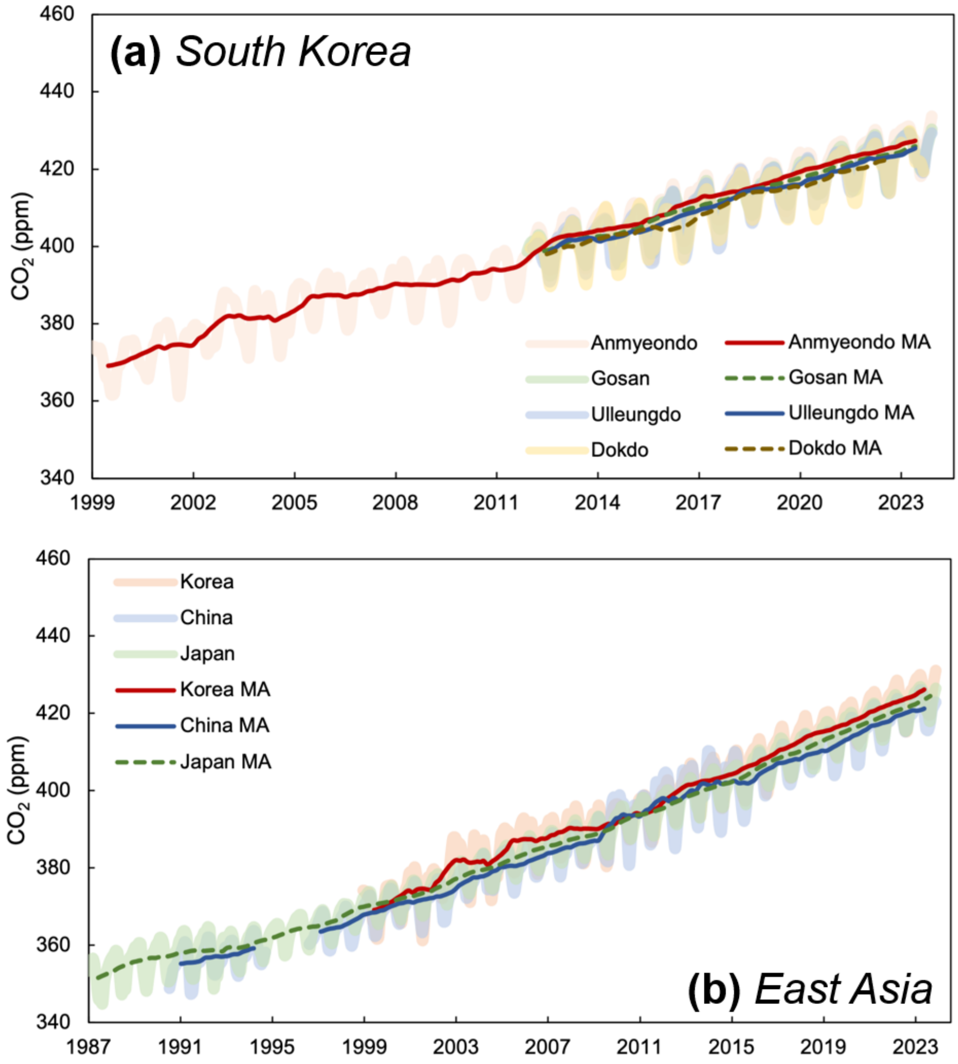

579 **Figure 2** (a) Comparison of carbon dioxide (CO_2) concentrations by region South Korea (Anmyeondo, Gosan, Ulleungdo, and Dokdo), (b) Comparison of carbon dioxide concentrations by country (South Korea, China, and Japan). MA means moving average values of the greenhouse gas.

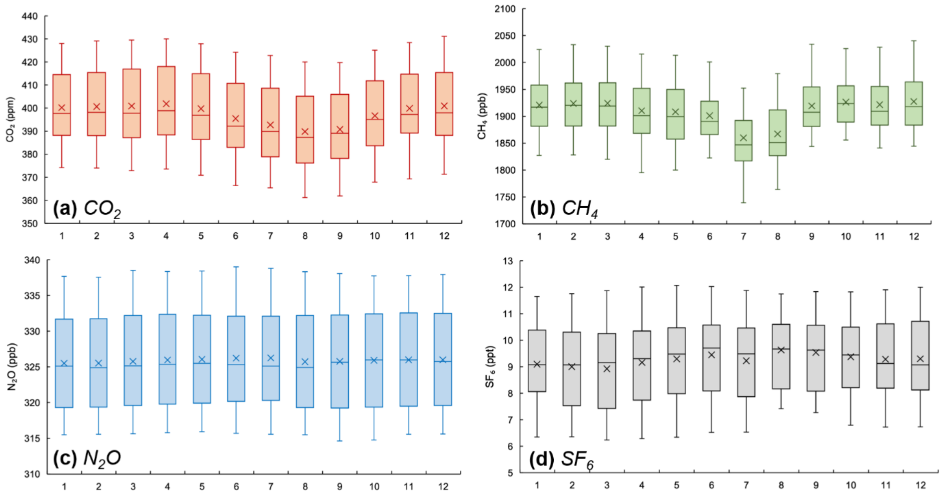

Figure 3 Monthly variations of greenhouse gases. (a) carbon dioxide (CO_2) , (b) methane (CH_4), (c) nitrous oxide (N_2O), and (d) sulphur hexafluoride (SF_6). The vertical lines at the ends of the box represent the maximum and minimum values excluding outliers, the edges of the box represent the 25th and 75th percentiles, the line inside the box represents the median, and x represents the mean.

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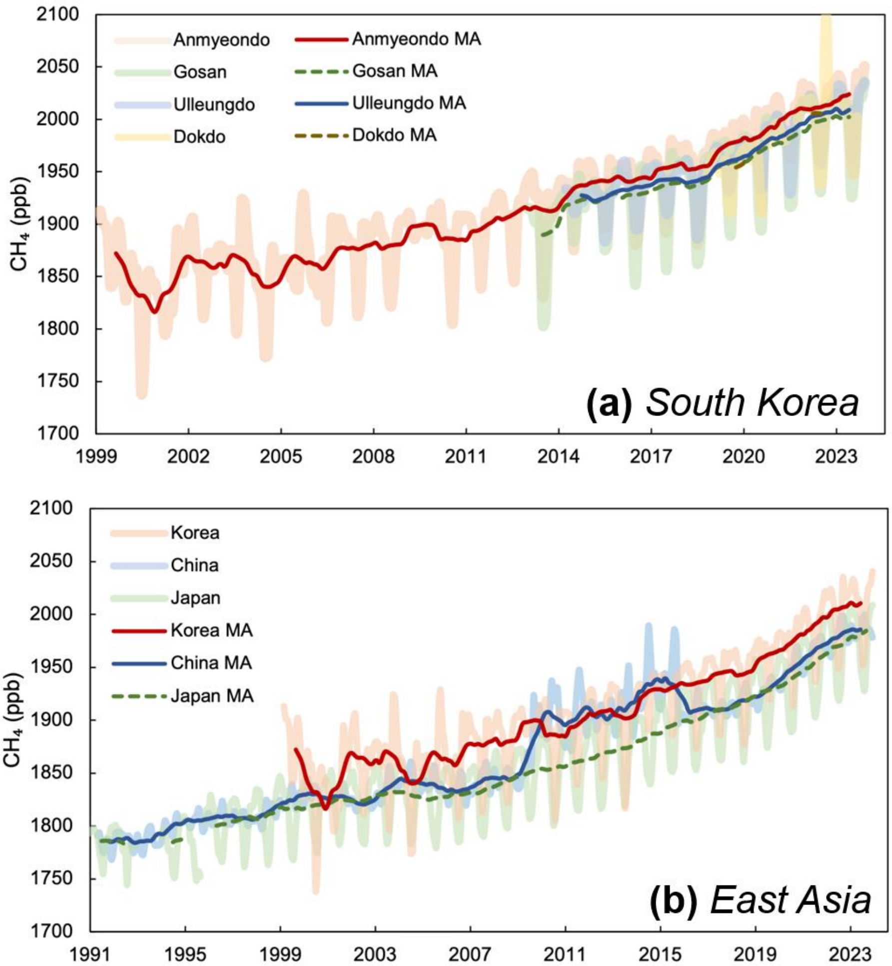

Figure 4 (a) Comparison of methane (CH_4) concentrations by region South Korea (Anmyeondo, Gosan, Ulleungdo, and Dokdo), (b) Comparison of methane concentrations by country (South Korea, China, and Japan).

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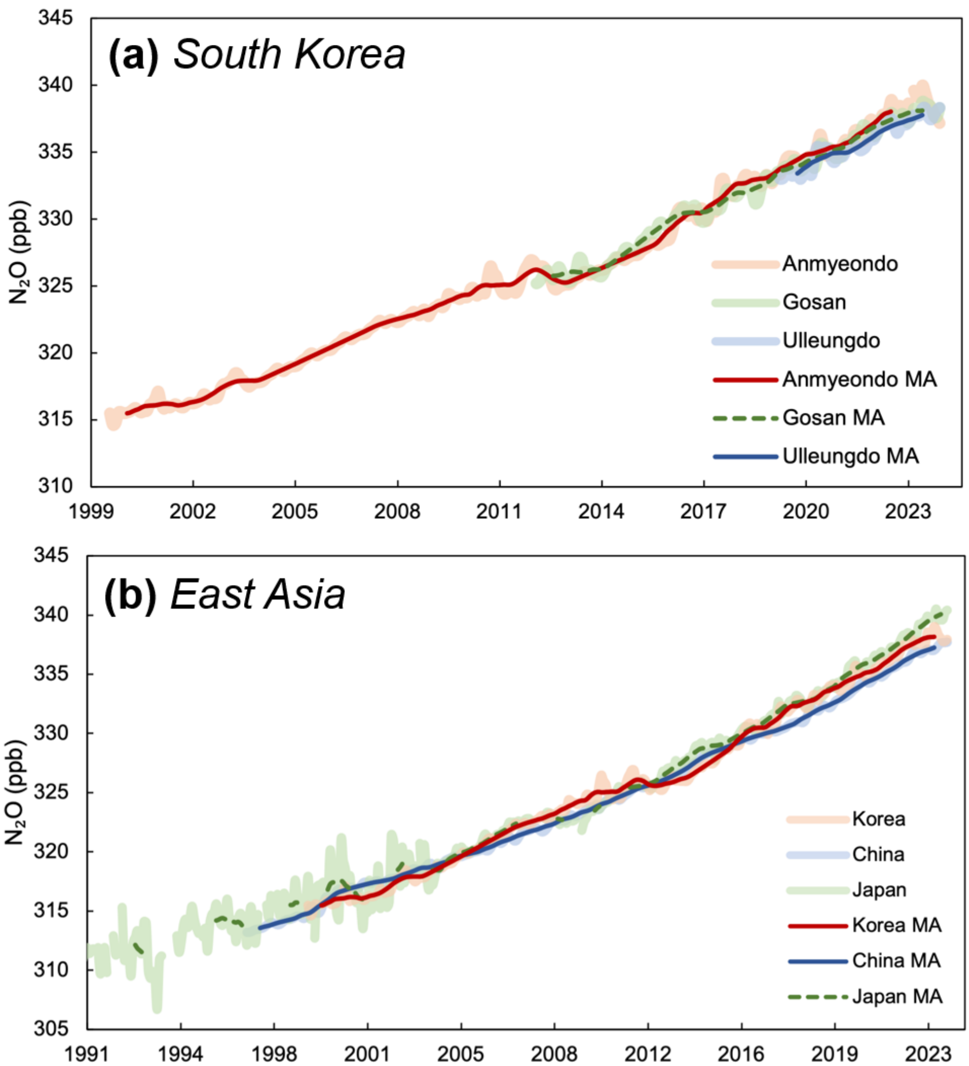

602 **Figure 5** (a) Comparison of nitrous oxide (N_2O) concentrations by region South Korea (Anmyeondo, Gosan, and
603 Ulleungdo), (b) Comparison of nitrous oxide concentrations by country (South Korea, China, and Japan).

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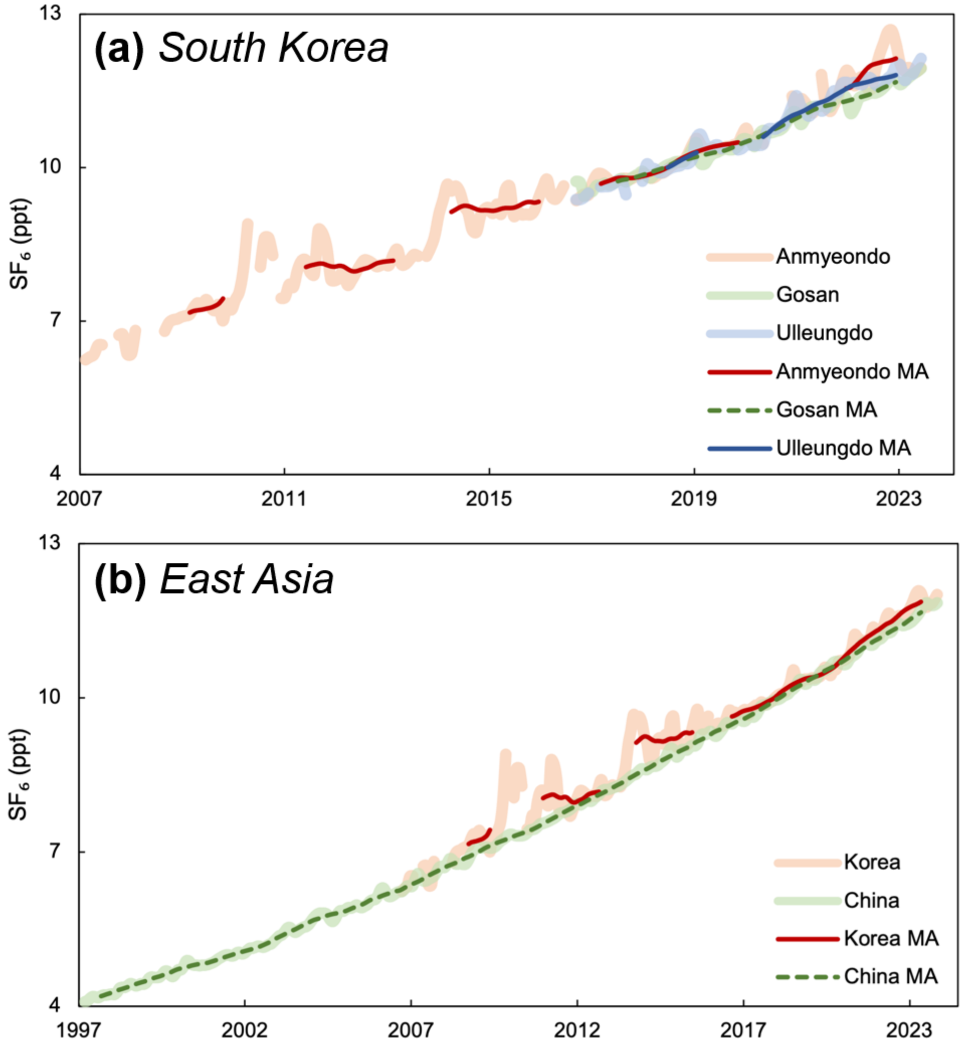

Figure 6 (a) Comparison of sulphur hexafluoride (SF_6) concentrations by region South Korea (Anmyeondo, Gosan, and Ulleungdo), (b) Comparison of sulphur hexafluoride concentrations by country (South Korea and China).

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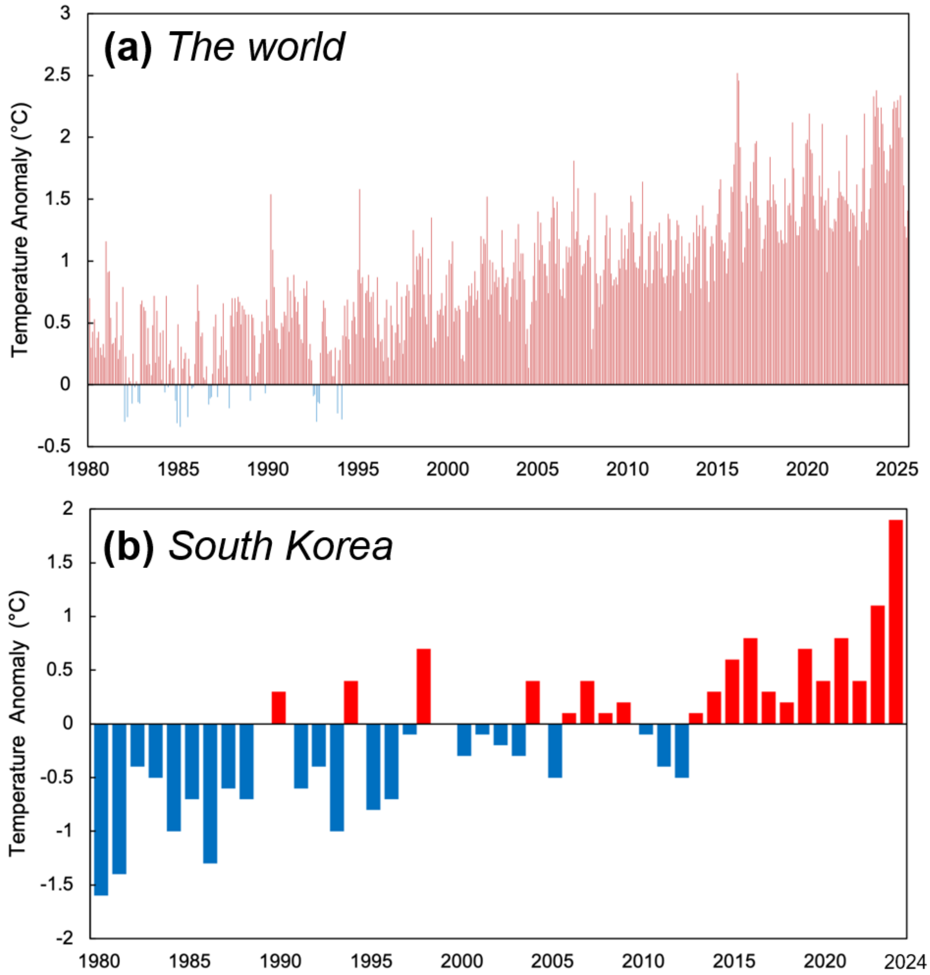

610

611 **Figure 7** Long-term variations in global (a) and South Korea (b) mean surface air temperature anomalies for
612 1980–2024. Global data are from the National Oceanic and Atmospheric Administration (NOAA, 2025), and
613 South Korea data are from the Korea Meteorological Administration (KMA, 2025).

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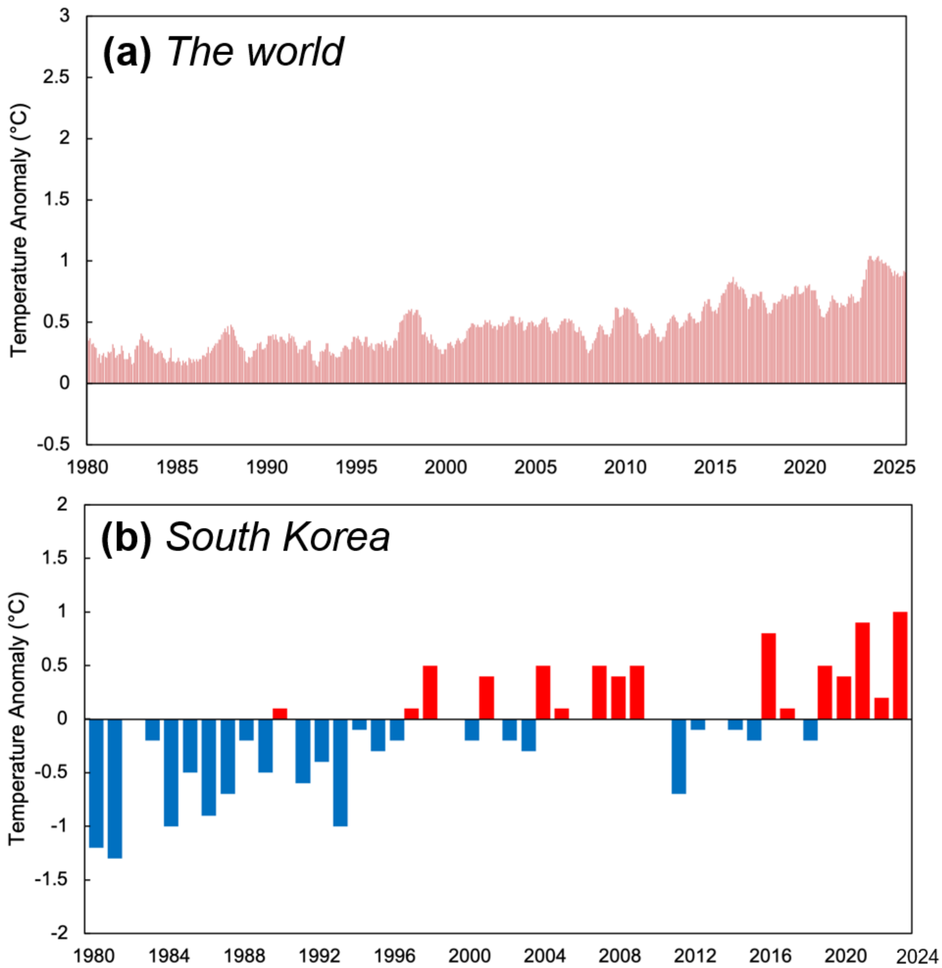

Figure 8 Long-term variations in global (1980–2024) and regional mean sea surface temperature anomalies around South Korea (1980–2023). Data sources are the same as those in Figure 7.

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Table 1. Summary of atmospheric greenhouse gas concentrations and growth rates over South Korea, including 2024 values and decadal trends.

		CO_2 (ppm)			CH_4 (ppb)		
		Concentration (2024)	Growth rate (yr^{-1})		Concentration 2024	Growth rate (yr^{-1})	
			Period of record	Past decade		Period of record	Past decade
South Korea	Anmyeondo	431 ± 4			2030 ± 32		
	Gosan	429 ± 4			2010 ± 35		
	Ulleungdo	428 ± 4			2022 ± 17		
	Dokdo	429 ± 2			2023 ± 9		
	Total	429 ± 4	2.41 (0.61%)	2.61 (0.63%)	2020 ± 26	5.55 (0.30%)	9.30 (0.47%)
China		413 ± 3	2.23 (0.58%)	2.37 (0.57%)	2003 ± 6	6.68 (0.36%)	6.83 (0.35%)
Japan		427 ± 3	2.05 (0.53%)	2.59 (0.63%)	1989 ± 29	6.52 (0.35%)	10.51 (0.55%)
East Asia		432 ± 4	2.19 (0.56%)	2.98 (0.71%)	2004 ± 17	6.59 (0.35%)	8.88 (0.45%)
Europe		425 ± 5	1.82 (0.49%)	2.54 (0.62%)	2027 ± 12	6.25 (0.33%)	10.63 (0.54%)
North America		425 ± 5	1.82 (0.49%)	2.54 (0.62%)	1998 ± 14	7.55 (0.41%)	10.60 (0.55%)

		N_2O (ppb)			SF_6 (ppt)		
		Concentration 2024	Growth rate (yr^{-1})	Concentrat ion 2024	Growth rate (yr^{-1})		
			Period of record	The past decade		Period of record	The past decade
South Korea	Anmyeondo	340 ± 1.48			13.51 ± 0.84		
	Gosan	340 ± 0.54			12.69 ± 0.23		
	Ulleungdo	339 ± 0.43			12.75 ± 0.31		
	Dokdo						
	Total	339 ± 0.60	0.97 (0.30%)	1.25 (0.38%)	12.98 ± 0.33	0.37 (4.12%)	0.10 (0.91%)
China		338 ± 0.34	0.92 (0.28%)	1.06 (0.32%)	12.14 ± 0.16	0.30 (4.04%)	0.36 (3.64%)
Japan		341 ± 0.22	0.92 (0.29%)	1.21 (0.36%)			
East Asia		339 ± 0.24	0.88 (0.27%)	1.13 (0.34%)	12.56 ± 0.22	0.31 (4.22%)	0.23 (2.11%)
Europe		339 ± 0.31	0.83 (0.25%)	1.04 (0.31%)	12.10 ± 0.12	0.29 (3.89%)	0.35 (3.50%)
North America		338 ± 0.17	0.93 (0.29%)	1.06 (0.32%)	12.04 ± 0.12	0.29 (4.00%)	0.36 (3.61%)