Contributions of economic growth, terrestrial sinks, and atmospheric transport to the increasing atmospheric CO₂ concentrations over the Korean Peninsula

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Abstract

Background: Understanding a carbon budget from a national perspective is essential for establishing effective plans to reduce atmospheric CO₂ growth. The national characteristics of carbon budgets are reflected in atmospheric CO₂ variations; however, separating regional influences on atmospheric signals is challenging owing to atmospheric CO₂ transport. Therefore, in this study, we examined the characteristics of atmospheric CO₂ variations over South and North Korea during 2000–2016 and unveiled the causes of their regional differences in the increasing rate of atmospheric CO₂ concentrations by utilizing atmospheric transport modeling.

Results: The atmospheric CO₂ concentration in South Korea is rising by 2.32 ppm year⁻¹, which is more than the globally-averaged increase rate of 2.05 ppm year⁻¹. Atmospheric transport modeling indicates that the increase in domestic fossil energy supply to support manufacturing export-led economic growth leads to an increase of 0.12 ppm year⁻¹ in atmospheric CO₂ in South Korea. Although enhancements of terrestrial carbon uptake estimated from both inverse modeling and process-based models have decreased atmospheric CO₂ by up to 0.02 ppm year⁻¹, this decrease is insufficient to offset anthropogenic CO₂ increases. Meanwhile, atmospheric CO₂ in North Korea is also increasing by 2.23 ppm year⁻¹, despite a decrease in national CO₂ emissions close to carbon neutrality. The great increases estimated in both South Korea and North Korea are associated with changes in atmospheric transport, including increasing emitted and transported CO₂ from China, which have increased the national atmospheric CO₂ concentrations by 2.23 ppm year⁻¹ and 2.27 ppm year⁻¹, respectively.

Conclusions: This study discovered that economic activity is the determinant of regional differences in increasing atmospheric CO₂ in the Korea Peninsula. However, from a global perspective, changes in transported CO₂ are a major driver of rising atmospheric CO₂ over this region, yielding an increase rate higher than the global mean value. Our findings suggest that accurately separating the contributions of atmospheric transport and regional sources to the increasing atmospheric CO₂ concentrations is important for developing effective strategies to achieve carbon neutrality at the national level.

Background

Atmospheric CO₂ concentrations have risen owing to an increase in anthropogenic CO₂ emissions, which outweigh natural CO₂ uptake [1, 2]. To mitigate anthropogenic climate change resulting from rising atmospheric CO₂ concentrations, countries around the world have...
pledged efforts to monitor and reduce their CO₂ emissions through the establishment of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992 [3]. Despite international commitment, over the last few decades, global anthropogenic CO₂ emissions have increased following the worst-case scenario, in which no action is taken to mitigate carbon emissions [4]. Numerous studies have warned that the increase in global average temperature should be limited to 1.5 °C above pre-industrial levels to avoid the risk of irreversible consequences of climate change [5]. Currently, more than 110 nations participating in the UNFCCC have committed to achieving carbon neutrality by 2050 (or 2060), including all East Asian countries, which are responsible for more than half of the global anthropogenic CO₂ emissions [6, 7]. Individual climate change mitigation policies have been adopted by considering each country’s economic and natural conditions. Therefore, understanding the characteristics of national carbon budgets and their impact on atmospheric CO₂ changes is essential for establishing effective plans to achieve this goal.

Korea is divided into the Republic of Korea (South Korea) and the Democratic People’s Republic of Korea (North Korea). These countries share similar climate conditions and natural ecosystems considering their geographic proximity, but they have different economic and social histories. In South Korea, the gross domestic product (GDP) has gradually risen since industrialization in the 1970s, and has increased by 160% in the last two decades (2000–2016) [8]. Further, forested areas, accounting for 63% of the country, remained constant with a slight decrease (0.2%) during 2001–2016 due to sustained national forest management according to remote sensing statistics [9]. Conversely, in North Korea, the GDP increased by 91% from 2000 to 2016 after an economic collapse in the 1990s; the average GDP ($25 billion) accounted for 2.3% of South Korea’s GDP ($1053 billion) during the period [10]. The previous economic collapse led to severe deforestation to secure food and fuel, causing the forested areas, accounting for 60% of the country, to decrease by 1.3% during 2001–2016 despite international efforts toward forest recovery [9, 11]. The differing changes in the economic and natural ecosystems between these countries can provide insight into the varying carbon dynamics according to human activities and national policies, despite their similar climate and environmental changes.

Spatiotemporal variations in atmospheric CO₂ concentrations reflect the regional characteristics of carbon sources and sinks [12–14]. Because of the limited spatial coverage of current tower-based surface CO₂ flux measurements [15, 16], atmospheric CO₂ has been utilized to diagnose changes in the regional carbon cycle, including both anthropogenic and natural components [17–21]. Long-term measurements show that atmospheric CO₂ concentrations in East Asia are rising faster than the global average owing to the rapid economic growth of East Asian countries [19, 22]. Satellite measurements have estimated that the column-integrated CO₂ concentrations in major cities (e.g., Seoul) could be approximately 2 ppm higher than those near non-source (or sink) regions [21, 23]. However, as atmospheric CO₂ can be significantly affected by atmospheric circulation and regional surface CO₂ fluxes, it is difficult to monitor changes in the regional carbon cycle solely based on observations. The chemical transport model (CTM) has been used to identify for the drivers of atmospheric CO₂ variations by separating the influences of regional sources and sinks on CO₂ variations [19, 24, 25]. Using CTM simulations, Fu et al. [25] estimated that terrestrial CO₂ flux and fossil fuel CO₂ emissions account for up to 14 and 17% of the interannual variations of atmospheric CO₂ over East Asia, respectively. Yun et al. [19] showed that the observed increasing seasonal difference in atmospheric CO₂ in South Korea results from enhanced terrestrial carbon uptake. Therefore, CTM simulations could provide help in the interpretation of observed atmospheric signals related to changes in regional carbon budgets.

In this study, we investigated the characteristics of atmospheric CO₂ variations over South and North Korea during 2000–2016 and identified the causes of their regional differences in the increasing rates of atmospheric CO₂ concentrations. To accomplish this, we first compared the atmospheric CO₂ variations in South Korea, North Korea, and the global mean estimated from CTM simulations. Then, changes in the national surface CO₂ fluxes and energy consumption structure in both countries were examined by analyzing statistical datasets and estimates of process-based modeling and inverse modeling. Finally, we derived the contributions of changes in atmospheric transport, as well as regional anthropogenic and terrestrial CO₂ fluxes, on increasing atmospheric CO₂ concentrations over each country based on a set of CTM simulations. The results of the analysis provided a comprehensive understanding of the role of economic activities, terrestrial ecosystems, and atmospheric transport in increasing atmospheric CO₂ concentrations at the national level.

**Results**

**Regional difference in atmospheric CO₂ trends**

The CTM modeling estimated that the global mean CO₂ concentration rose by 2.05 ppm year⁻¹ during 2000–2016, which is consistent with that computed from observations (Fig. 1a). Meanwhile, the simulated rate of
atmospheric CO₂ increase is greater than 2 ppm year⁻¹ in all regions and is more positively skewed, reaching a maximum value of 3 ppm year⁻¹ (Fig. 1b). The increasing rates of atmospheric CO₂ in South Korea (mean: 2.32 ppm year⁻¹) and North Korea (2.23 ppm year⁻¹) are greater than the global 75 percentile value. These countries also share similar monthly variations in atmospheric CO₂ (r = 0.98; p < 0.01; two tailed Student’s t-test), especially during the winter when the effect of vegetation activity is negligible (Fig. 1a). However, the variability of the monthly CO₂ concentration in South Korea was lower than that in North Korea owing to the greater CO₂ drawdown during the summer in North Korea than in South Korea. Moreover, the maximum increase in atmospheric CO₂ in South Korea (2.83 ppm year⁻¹) was greater than that in North Korea (2.40 ppm year⁻¹) (Fig. 1b).

Changes in national surface CO₂ fluxes
The national inventory reported contrasting changes in fossil fuel CO₂ (FFCO₂) emissions between the two countries from 2000 to 2016 (Fig. 2a). Specifically, in South Korea, FFCO₂ emissions increased from 128 MtC year⁻¹ in 2000–2008 to 156 MtC year⁻¹ in 2008–2016. In North Korea, however, FFCO₂ emissions decreased from 19 MtC year⁻¹ in the initial nine years of the study period to 11 MtC year⁻¹ in the final nine years. These contrasting trends are associated with different histories of changes in energy consumption and structure, as more than 90% of FFCO₂ emissions result from energy production in these countries [26]. Economic growth increased energy consumption in South Korea from 220 million tons of oil equivalent (Mtoe) in the initial 9 years to 272 Mtoe in the final 9 years. Further, the ratio of fossil (coal and petroleum) energy consumption decreased by 3% as a result of increases in natural gas and renewable energy supply, but its magnitude increased by 30 Mtoe between the two periods (Fig. 2b). Conversely, the total energy consumption in North Korea decreased from 16 Mtoe to 13 Mtoe from the initial nine to the final nine years, respectively, as the supply of domestic coal, a major energy source, sharply declined during the study period.

Unlike the FFCO₂ emissions, both the process-based models (TRENDY) and inverse modeling (Carbon-Tracker; CT) results estimated that the amount of terrestrial carbon uptake was similar in South and North Korea. These results also estimated increases in terrestrial carbon uptake in both countries during 2000–2016, although the magnitudes differed among the models (Fig. 2a). In particular, the TRENDY models simulated that terrestrial carbon uptake in South Korea increased from 3.4 ± 2.1 MtC year⁻¹ in 2000–2008 to 3.9 ± 2.7 MtC year⁻¹ in 2008–2016, which accounts for 2.5 ± 1.7% of the mean FFCO₂ emissions for the period. Similarly, the CT also estimated that the carbon uptake rose from 4.3 MtC year⁻¹ to 5.9 MtC year⁻¹ from the initial nine years to the final nine years, respectively, within an inter-model standard deviation range of the TRENDY models, suggesting that the terrestrial carbon flux in South Korea is well constrained. Similarly, the TRENDY models simulated that terrestrial carbon uptake in North Korea increased from 3.3 ± 1.8 MtC year⁻¹ in the initial nine years to 4.2 ± 1.6 MtC year⁻¹ in the final nine years of the study period, accounting for 38% ± 15% of the mean FFCO₂ emissions during this period. Further, the CT
estimated that the carbon uptake enhanced from 9.4 MtC year\(^{-1}\) to 13.3 MtC year\(^{-1}\) between these periods, which was beyond the standard deviation range of the TRENDY models. This notable discrepancy may have resulted from the absence of atmospheric measurements for constraining the terrestrial carbon flux in North Korea. Overall, these results indicate that South Korea continues to deviate further from achieving carbon neutrality, while North Korea has almost achieved carbon neutrality, even though there exist large uncertainties in the terrestrial carbon flux in North Korea.

**Causes of regional difference in atmospheric CO\(_2\) trends**

To examine the role of regional CO\(_2\) flux changes on atmospheric CO\(_2\) variations over the Korean Peninsula, a set of CTM simulations were conducted for 2000–2016 (details in the “Data and methods” section). In the ALL\(_{\text{transient}}\) simulation, wherein all variables are transient, the increasing rate of atmospheric CO\(_2\) is gradually lowering from west to east over the surrounding areas of the Korean Peninsula during 2000–2016 owing to the heavily industrialized provinces (e.g., Liaoning) in northeastern China (Figs. 3a, 4a, b) [27, 28]. In addition, distinctly different spatial patterns of atmospheric CO\(_2\) trends were present between these countries. Specifically, an increase of more than 2.4 ppm year\(^{-1}\) occurred in the outskirts of Seoul and certain industrial complexes (e.g., Yeosu and Ulsan), located in the northwest and southeast parts of South Korea, respectively. In contrast, the central and northeast regions of North Korea presented a relatively lower increase (2.2 ppm year\(^{-1}\)) than the adjacent surrounding areas.

Sensitivity simulations, which evaluate the effect of surface CO\(_2\) fluxes and atmospheric transport on atmospheric CO\(_2\) variations, revealed that the increasing FFCO\(_2\) emissions in South Korea is the major driver of regional differences in atmospheric CO\(_2\) trends between these countries. In particular, the increase in FFCO\(_2\) emissions, particularly in major cities, rose the regional and country atmospheric CO\(_2\) concentrations by more than 0.3 ppm year\(^{-1}\) and 0.12 ppm year\(^{-1}\), respectively, accounting for 5% of the net increase in national atmospheric CO\(_2\) (Figs. 3b, d, 4b). The increasing rate of atmospheric CO\(_2\) was relatively lower in Seoul than in the surrounding areas because emissions in this area have decreased owing to the government's policy to shift industrial facilities from Seoul to its outskirts (Figs. 3b, 4b). In the northeastern part of South Korea, approximately 0.2 ppm year\(^{-1}\) of the national increase appears to be caused by one strong point source. However, no possible sources of FFCO\(_2\), such as coal-burning power plants, are present in this mountainous area. Thus, this area may have been mis-allocated; hence, cautious interpretation of the spatial map is necessary. Conversely, in North Korea, decreases in FFCO\(_2\) emissions, particularly in the Pyongyang metropolitan area, which includes several primary source regions, reduced the CO\(_2\) concentrations in the region by more than 0.1 ppm year\(^{-1}\), presenting a
small nationwide impact of $-0.03$ ppm year$^{-1}$ (Figs. 3e, g, 4b). Moreover, the CT estimates, which are greater than those of the TRENDY multi-model mean, indicate that increases in terrestrial CO$_2$ uptake over widely distributed forests in the two countries decreased atmospheric CO$_2$ by up to $0.04$ ppm year$^{-1}$ (Fig. 3c, f). Although the nationwide effect of terrestrial uptake in South Korea ($-0.02$ ppm year$^{-1}$) is greater than that in North Korea ($-0.01$ ppm year$^{-1}$), its magnitude is too small to offset the increase in CO$_2$ concentrations induced by increasing FFCO$_2$ emissions (Fig. 3d, g).

The changes in transported CO$_2$ similarly rose the atmospheric CO$_2$ concentrations in both South and North Korea by 2.23 ppm year$^{-1}$ and 2.27 ppm year$^{-1}$, respectively (Fig. 5d, e). The greater increase in atmospheric CO$_2$ in North Korea is the result of its geographic proximity to major carbon sources in northeastern China and South Korea. Although the changes in transported CO$_2$ did not cause distinct regional differences in atmospheric CO$_2$ trends, they comprise more than 95% of net increases in atmospheric CO$_2$ in these countries. Specifically, the increase in FFCO$_2$ emissions in China, accounting for 65% of the global FFCO$_2$ increases in the period as derived from the national FFCO$_2$ emission inventory [26], caused South and North Korea to present greater increasing rates of atmospheric CO$_2$ than the global mean ($0.56$ ppm year$^{-1}$), rising at rates of $0.68$ ppm year$^{-1}$ and $0.70$ ppm year$^{-1}$, respectively (Fig. 5c, d, e). Nevertheless, the contribution of rising FFCO$_2$ emissions from China to the increases in atmospheric CO$_2$ over the Korean Peninsula is relatively smaller (30–31%) than the contribution of global FFCO$_2$ increases. This is because the atmospheric CO$_2$ concentration is bound to increase every year, even if global FFCO$_2$ emissions remain at 2000 levels, because FFCO$_2$ emissions have been greater than the natural carbon absorption since industrialization [1].

Discussion

Stronger actions are required in each country to mitigate climate change [29]. To support these efforts, a scientific understanding of the characteristics of national carbon budgets and the response of atmospheric CO$_2$ to budget changes is required. This study examined the causes of atmospheric CO$_2$ variations at the national level via a case study of the Korean Peninsula. The CTM simulations showed that the increasing rate of atmospheric CO$_2$ is greater in South Korea than in North Korea because of the contrasting trends of FFCO$_2$ emissions over the last two decades. These contrasting trends correspond to
the differing economic growth strategies influencing the energy structure. In particular, North Korea has created a self-reliant national economy based on its forest and mineral resources, especially coal. After the economic collapse in the 1990s, North Korea exported a significant amount of coal to China to revive its economy [30]. Because coal exports increased without the restoration of coal mine damage caused by the Great Flood in the 1990s, the domestic coal consumption and resulting CO2 emissions decreased. Conversely, South Korea has experienced successful export-led manufacturing growth since the 1960s [31]. Our results show that the efforts to reduce carbon emissions were already underway via renewable energy supply expansion, as it is common for developed countries to shift toward reducing carbon emissions after achieving a certain economic level [32, 33]. However, the increase in renewable energy was insufficient to suppress the increase in fossil energy use. Moreover, the results indicate that the regional distribution of long-term changes in atmospheric CO2 is mainly constrained by the national economic conditions in Korea.

In addition to the effect of FFCO2 emissions, terrestrial ecosystems partially contributed to changes in national atmospheric CO2 concentrations. Both inverse modeling and process-based models estimated that terrestrial CO2 uptake has not only increased in South Korea but also in North Korea, wherein a notable decrease in forest area has been observed from space [9]. We obtained insights into the causes of increased terrestrial CO2 uptake using the TRENDY sensitivity simulation results (details in the “Data and methods” section). Following the land cover change, the TRENDY models estimated that the decrease in terrestrial CO2 uptake by land-use change is greater in North Korea than in South Korea (Fig. 6). However, the effects of rising atmospheric CO2 and climate change, which have enhanced vegetation growth in mid-to-high latitude regions [34, 35], were greater than the impact of land-use changes. This indicates that terrestrial ecosystems in North Korea, where deforestation is still ongoing, also play a role in alleviating the atmospheric CO2 increase, as South Korea, wherein forest management has been conducted for a long time.

The CTM simulations showed that changes in atmospheric transport are a minor factor inducing regional differences in the annual trends of atmospheric CO2 concentrations in the Korean Peninsula. Even on a monthly scale, similar variations in atmospheric CO2 in the two countries occurred in winter, indicating that they are generally under the effect of the same atmospheric circulation system. However, changes in atmospheric transport
play a major role in differentiating the CO₂ concentrations among these countries and other regions from a global perspective. Specifically, the atmospheric CO₂ increase rate in North Korea is greater than the global mean value, even though their net carbon emissions have decreased. Previous studies reported that the greatest growth rate of atmospheric CO₂ has been observed in the Korean Peninsula, as compared with background sites in East Asia [22], especially when wind blows from China [19]. In line with the observation studies, our results show that the increase in FFCO₂ emissions in China, along with the increase in FFCO₂ emissions from South Korea, is the major drivers of rising atmospheric CO₂ concentrations in the Korean Peninsula. These results suggest that the effect of atmospheric transport should be considered when monitoring changes in regional carbon budgets via observational studies, especially when quantifying local CO₂ enhancement by comparison with other regions (e.g., [17, 21, 23]).

**Conclusions**

In this study, we discovered that different economic conditions between South and North Korea led to regional differences in their increasing rates of atmospheric CO₂ over the last two decades. However, from a global perspective, changes in atmospheric transport are the main factors causing greater increases in atmospheric CO₂ in these countries, as compared with the global average increase. Our results highlight the importance of accurately separating the influences of atmospheric transport and regional carbon budget changes on atmospheric CO₂ variations in establishing effective plans to achieve national carbon neutrality. This study, based on CTM simulations and various modeling and statistical datasets, provides directions for interpreting obtained atmospheric CO₂ data from surface and satellite measurements in relation to national economic structure, terrestrial ecosystems, and atmospheric transport, especially in main source regions. Moreover, our results show that only approximately 5% of the increase in CO₂ concentration...
can be mitigated in South Korea, even if their FFCO₂ emissions, ranked among the world’s top 10 in 2018 [7], are maintained in 2000. This indicates that the rise in atmospheric CO₂ cannot be arrested unless all countries around the world achieve carbon neutrality, despite policies for carbon neutrality being implemented individually by each country.

Data and methods

Atmospheric CO₂ measurements

Weekly atmospheric CO₂ measurements have been conducted globally by the cooperative global air sampling network. The global monthly mean surface atmospheric CO₂ concentration was computed by the National Oceanic and Atmospheric Administration-Earth System Research Laboratories (NOAA-ESRL) using global atmospheric CO₂ measurements from 2000 to 2016 [36]. To obtain the global monthly estimate, the weekly CO₂ measurements at sites less affected by local land sources and sinks were fitted to a smooth curve by applying curve fitting and filtering techniques [37]. We used the data to identify the regional characteristics of atmospheric CO₂ variations over Korea that are distinct from the global mean changes and evaluate the performance of our atmospheric transport model simulations.

Statistics of anthropogenic CO₂ emissions and energy consumption

The Emissions Database for Global Atmospheric Research version 5.0 (EDGAR v5.0; [26]) provides annual anthropogenic CO₂ emissions from 22 sectors on a per country basis on a 0.1° grid over 1970–2018 (values for 2016–2018 are obtained from fast track methodology) [38]. The dataset includes all FFCO₂ sources, including fossil fuel combustion, cement production, shipping, and aviation. The EDGAR v5.0 was used to investigate changes in FFCO₂ emissions in South and North Korea during 2000–2016 and estimate the effects of the emission changes on atmospheric CO₂ variations from atmospheric transport model simulations. In addition, the annual total primary energy consumption and composition of energy sources were investigated based on national statistics from the Korean Statistical Information Service, to understand the differing FFCO₂ emission trends between the two countries [39].

Terrestrial CO₂ flux

To estimate changes in the terrestrial CO₂ flux over Korea during 2000–2016, two types of modeling results were used: inverse modeling and process-based models. First, we investigated the monthly averaged terrestrial CO₂ flux estimated by CT (i.e., CT2017), which uses the global transport model version 5 and atmospheric CO₂ measurements from 151 surface observation sites, as well as aircraft and shipboard [40]. The CT2017 dataset has the highest spatial resolution (1°) among the widely used and publicly available inversion datasets. We then used the monthly averaged net biome production (NBP) simulated by dynamic global vegetation models involved in the TRENDY project version 6, which follow historical changes in atmospheric CO₂, climate, and land use (simulation S3; [41]). Next, we calculated the average changes in NBP over the regions and their variance simulated using nine models: CABLE, CLM4.5, ISAM, LPJ, LPX-Bern, ORCHIDEE, VEGAS, VISIT, and JULES. The TRENDY models also provided the results of sensitivity simulations. Simulation S1 was forced with increasing atmospheric CO₂ and simulation S2 was forced with increasing atmospheric CO₂ and climate change; meanwhile, simulation S0 was not forced with the annual changes of any of the factors. By comparing the simulations with or without the annual changes for each factor, we estimated the causes of changes in terrestrial CO₂ fluxes over North and South Korea.

GEOS-Chem model simulations

Goddard Earth Observing System-Chemistry model (GEOS-Chem) is a CTM that simulates the 3-D field of
the atmospheric CO₂ concentration using datasets for meteorological variables and surface CO₂ fluxes [42, 43]. We utilized a nested-grid GEOS-Chem model (version 11.2) to estimate the global mean changes in atmospheric CO₂ and its spatiotemporal variations over Korea. Results from the global simulation with a 4° × 5° horizontal resolution were prescribed as boundary conditions for the nested-grid simulations, which had a 0.5° × 0.625° horizontal resolution and 47 vertical layers over East Asia. All model simulations were conducted using datasets for hourly meteorological variables [44], annual anthropogenic CO₂ emissions (EDGAR v5.0), monthly terrestrial CO₂ flux (CT2017), climatological ocean CO₂ flux [45], and monthly biomass burning [46].

After a 10-year spin-up, a set of sensitivity simulations were conducted for 2000–2016 to evaluate the influences of changes in regional land-surface CO₂ fluxes and atmospheric transport on CO₂ concentrations over South Korea (SK) and North Korea (NK) for during 2000–2016 (Table 1). In ALLtransient, the transient meteorological variables and surface CO₂ fluxes were applied during the simulation period. In FF_SK2000, BIO_SK2000, and FFBIO_SK2000, one or both of the FFCO₂ emissions and terrestrial CO₂ flux in 2000 were repeated in South Korea while the input variable conditions were the same as in ALLtransient. These three simulations were repeated by switching the area from South Korea to North Korea: FF_NK2000, BIO_NK2000, and FFBIO_NK2000. According to the difference in the simulated surface CO₂ concentrations between ALLtransient and FF_SK2000 (FF_NK2000) and BIO_SK2000 (BIO_NK2000), the influences of regional changes in FFCO₂ emissions and terrestrial CO₂ flux on atmospheric CO₂ variations over South Korea (North Korea) were estimated. Further, based on the simulated surface CO₂ concentrations in FFBIO_SK2000 and FFBIO_NK2000, the influence of atmospheric transport changes on atmospheric CO₂ variations over the regions was estimated.

To provide an additional explanation for the effect of atmospheric transport changes, we performed the FF_CH2000 simulation, which is the same as the FF_SK2000 simulation; however, the FFCO₂ emissions in 2000 were repeated over eastern China (approximately 20–40°N, 100–125°E and 40–50°N, 100–140°E) during the simulation period. The influence of changes in FFCO₂ emissions in China on atmospheric CO₂ variations over Korea were evaluated based on the difference in simulated surface CO₂ Concentrations between ALLtransient and FF_CH2000. The modeling bias that overestimated the long-term trend of increasing CO₂ concentration was corrected by comparing the measured CO₂ concentration at Mauna Loa, which is widely used as a global (or Northern Hemisphere) background site. The bias-corrected GEOS-Chem results show a good match with the NOAA-ESRL flask CO₂ measurements in South Korea because atmospheric measurements were used to assimilate the terrestrial CO₂ flux within the CT inversion system (not shown here). The introduced model simulation set was used to identify the causes of changes in monthly variations of atmospheric CO₂ over South Korea [19].

Abbreviations
UNFCCC: United Nations Framework Convention on Climate Change; GDP: Gross domestic product; FFCO₂: Fossil-fuel CO₂; CTM: Chemical transport model; GEOS-Chem: Goddard Earth Observing System-Chemistry model; Mtoe: Million tons of oil equivalent; NBP: Net biome production; EDGAR: Emissions Database for Global Atmospheric Research; CT: CarbonTracker; NOAA-ESRL: National Oceanic and Atmospheric Administration-Earth System Research Laboratories.

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Authors’ contributions
JY performed the analysis and wrote the manuscript. SJ designed the study and provided input on the manuscript. Both authors read and approved the final manuscript.

| Simulations | Fossil-fuel CO₂ emissions | Terrestrial CO₂ flux |
|-------------|--------------------------|----------------------|
| ALLtransient | T                         | T                    |
| FF_SK2000   | FIX⁴                     | T                    |
| BIO_SK2000  | T                        | FIX⁴                 |
| FFBIO_SK2000| FIX⁴                     | FIX⁴                 |
| FF_CH2000   | FIX⁵                     | T                    |
| FF_NK2000   | FIX⁵                     | T                    |
| BIO_NK2000  | T                        | FIX⁵                 |
| FFBIO_NK2000| FIX⁵                     | FIX⁵                 |

Table 1 Model simulation configuration

Set of model simulations employed to estimate the influences of changes in regional land-surface CO₂ fluxes and atmospheric transport on CO₂ concentrations over South Korea (SK) and North Korea (NK) for during 2000–2016.

T: All variables are transient
FIX⁴, FIX⁵, FIX⁶: CO₂ flux in 2000 is repeatedly prescribed in SK, NK, and eastern China, respectively.
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Availability of data and materials
The surface atmospheric CO2 measurement datasets are available at https://www.esrl.noaa.gov/gmd/divdata/ The Emissions Database for Global Atmospheric Research v5.0 datasets are publicly available at http://geodpp.jrc.ec.europa.eu/ftp/jrc-opendata/EDGAR/datasets/v50_GHG/. The TRENDY model simulation results are available from Stephen Stich (S.A.Stich@exeter.ac.uk) or Pierre Friedlingstein (p.friedlingstein@exeter.ac.uk) upon email request. The CarbonTracker results are publicly available at http://carbontracker.noaa.gov. The datasets of primary energy supply in South Korea and North Korea are available at https://kosis.kr/statHtml/statHtml.do?orgId=101&tblId=DT_1ZGA72 (in Korean). The GEDS-Chem model simulation results that support the findings of this study are available from S.J. upon request.

Declarations

Competing interests
The authors declare no competing interests.

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