

Article

Coupled Dynamics of Aerosols and Greenhouse Gases at the Socheongcho Ocean Research Station During High-Concentration Episodes

Soi Ahn ^{1,2} , Meehye Lee ^{2,*}, Lim-Seok Chang ³  and Jin-Yong Jeong ⁴

¹ Integrated Environmental Management Research Division, National Institute of Environmental Research (NIER), Hwangyong-ro 42, Seogu, Incheon 22689, Republic of Korea; jjahn@korea.kr

² Atmosphere Environment Research, Department of Earth and Environmental Sciences, Korea University, Anam-ro 145, Seongbuk-gu, Seoul 02841, Republic of Korea

³ China-Korea Environmental Cooperation Center, No. 8 Dayangfang, Anwai, Beijing 100012, China; lschang@korea.kr

⁴ Korea Institute of Ocean Science & Technology (KOIST), 385, Haeyang-ro, Yeongdo-gu, Busan Metropolitan City 49111, Republic of Korea; jyjeong@kiost.ac.kr

* Correspondence: meehye@korea.ac.kr; Tel.: +82-02-3290-5146

Highlights

What are the main findings?

- The accuracy of aerosol optical depth (AOD) products derived from the geostationary satellites GK-2B/GEMS and GOCI-II was evaluated using ground-based observations at the Socheongcho Ocean Research Station. Both satellite products demonstrated good agreement with surface measurements; however, a systematic underestimation was identified, with coefficients of determination of $R^2 = 0.78$ for GEMS and $R^2 = 0.91$ for GOCI-II.
- An integrated analysis of satellite-observed high aerosol loading episodes and surface-observed greenhouse gas concentrations revealed distinct seasonal regimes. Aerosol variability, strongly modulated by temperature and hygroscopic growth, exerted a greater influence during dry summer conditions. Wintertime periods were characterized by stagnant boundary-layer conditions and patterns statistically consistent with regional-scale transport, during which greenhouse gases increased concurrently with $PM_{2.5}$, CO, and black carbon.

What are the implications of the main findings?

- This study highlights the necessity of an integrated analytical framework for aerosols and greenhouse gases in the Northeast Asian marine environment in which high-accuracy, ground-based observations are integrated with high spatial- and temporal-resolution satellite measurements.
- Combining satellite and in situ observations is essential for advancing our understanding of aerosol–greenhouse gas interactions and robustly assessing their modulation by meteorological and boundary-layer processes in this region.
- The proposed integrated observational approach provides a scientific basis for improving the interpretation of satellite retrievals and optimizing regional air quality and climate assessments.



Academic Editor: Yuan Wang

Received: 2 February 2026

Revised: 3 March 2026

Accepted: 5 March 2026

Published: 6 March 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

Abstract

In this study, continuous near-real-time measurements of greenhouse gases (GHGs), particularly carbon dioxide (CO₂) and methane (CH₄), and aerosol optical depth (AOD) were con-

ducted at the Socheongcho Ocean Research Station (SORS) from January 2021 to April 2022. Specifically, AOD products retrieved from the Geo-KOMPSAT-2B sensors—Geostationary Environment Monitoring Spectrometer and Geostationary Ocean Color Imager II—were compared and validated against ground-based Aerosol Robotic Network (AERONET) observations. Both satellite products exhibited overall good agreement with AERONET AOD data and showed low bias. The GHG measurements based on cavity ring-down spectroscopy indicated that CO₂ reached its highest seasonal mean in the spring of 2022, while CH₄ attained its maximum during the wet summer of 2022. Temperature, relative humidity, and evaporation were closely associated with AOD variability during the dry summer period, while elevated temperatures may have contributed to enhanced photochemical activity and modulation of CH₄ concentrations. In the cold season, concurrent increases in GHGs and combustion-related pollutants (PM_{2.5}, CO, and black carbon) were observed, suggesting reduced oxidation capacity under stable atmospheric conditions. Overall, these findings underscore the potential value of integrating satellite and in situ observations to better characterize GHG–aerosol interactions and support emission mitigation strategies in the Northeast Asian marine environment.

Keywords: aerosol optical depth (AOD); satellite; greenhouse gases (GHGs); Socheongcho Ocean Research Station (SORS); Geo-KOMPSAT-2B

1. Introduction

Anthropogenic greenhouse gases (GHGs) and aerosols are among the dominant drivers of global warming and atmospheric environmental degradation and thus are the primary targets of both ground-based observations and satellite remote sensing systems [1–3]. Compared with conventional single-parameter surface measurements, an integrated observational framework that can simultaneously monitor GHGs and aerosols is essential for enhancing spatial representativeness, distinguishing between anthropogenic and natural emission sources, and improving the accuracy of satellite-based GHG inversions [4,5].

Atmospheric aerosols originate from diverse natural and anthropogenic sources and exhibit substantial variability in chemical composition, particle size, and optical properties [6]. This complexity contributes to large uncertainties in their radiative effects and estimates of climate forcing [7–9]. Aerosol optical depth (AOD), a fundamental parameter describing column-integrated aerosol extinction from the surface to the top of the atmosphere, is widely used to quantify aerosol loading and direct radiative impacts [10,11]. Note that AOD can be retrieved from both ground- and satellite-based observations. Ground-based networks such as the Aerosol Robotic Network (AERONET) provide highly accurate measurements but have limited spatial coverage [12]. In contrast, satellite remote sensing enables regional and global monitoring of aerosol distribution and transport. However, satellite retrievals are subject to greater uncertainties due to surface reflectance effects, viewing geometry, and aerosol model assumptions, often leading to systematic biases, particularly over high-albedo surfaces and during winter [13]. Therefore, rigorous validation of satellite-derived AOD products against high-quality ground observations remains essential for reducing uncertainties in aerosol radiative assessments.

Anthropogenic GHG emissions are major drivers of climate change and enhanced radiative forcing [14]. Rapid GHG accumulation has altered the Earth's radiative balance, contributing to persistent global warming and more frequent extreme climate events, such as heatwaves, droughts, and floods [15,16]. Among GHGs, CO₂ is the dominant long-term anthropogenic forcing agent after water vapor. Its atmospheric concentration has increased

from approximately 280 ppm in the pre-industrial era to over 400 ppm since the mid-2010s. Despite extensive monitoring efforts, substantial uncertainties remain in quantifying the magnitude and temporal variability of atmospheric CO₂ due to complex interactions between natural and anthropogenic sources and sinks [17,18]. Methane (CH₄) is the second-largest contributor to anthropogenic radiative forcing. Although less abundant than CO₂, CH₄ has a much higher radiative efficiency per molecule, making accurate characterization of its sources, sinks, and atmospheric budget essential for reliable climate projections. Spaceborne observations enable continuous global monitoring of CO₂ and CH₄ and provide constraints on regional and continental-scale surface fluxes [19]. Such observations also support international climate frameworks, including the Global Stocktake under the Paris Agreement, by providing independent observation-based assessments of emission trends [20].

Therefore, accurate and spatially comprehensive monitoring of major GHGs is essential for assessing progress toward carbon neutrality. Although ground-based measurements provide high precision and long-term stability, their limited spatial coverage constrains their ability to resolve large-scale gradients and long-range transport. In response to the growing demand for robust GHG monitoring, both ground-based networks and high-resolution satellite missions have expanded, alongside continued improvements in retrieval algorithms. Continuous in situ CO₂ observations have been available since the late 1950s, and global CH₄ measurements since the late 1970s [21–23]. Advanced spectroscopic techniques, including direct absorption, FTIR spectroscopy, and cavity ring-down spectroscopy (CRDS), are widely used for high-precision CO₂ and CH₄ measurements [24,25]. In particular, CRDS analyzers have demonstrated excellent precision, accuracy, and long-term stability at ground-based and tower sites, and are commonly regarded as reliable reference instruments for atmospheric GHG monitoring [26,27].

In parallel, satellite monitoring of atmospheric CO₂ and CH₄ has rapidly progressed due to improvements in sensor technology and retrieval algorithms. Satellite GHG observations are generally categorized into thermal infrared (TIR) and shortwave infrared (SWIR) measurements. In general, TIR observations, such as the Atmospheric Infrared Sounder (AIRS) onboard NASA's Aqua satellite, primarily provide information on middle-to-upper tropospheric CO₂ and CH₄ [28]. In contrast, SWIR measurements offer greater sensitivity to near-surface concentrations and are therefore more suitable for constraining surface fluxes [29].

Since the launch of the first Greenhouse gases Observing SATellite (GOSAT) in 2009 [30], followed by the GOSAT-2 in 2018 [31] and Orbiting Carbon Observatory-2 (OCO-2) satellites in 2014 [32–35], substantial efforts have been devoted to improving the accuracy and spatial coverage of CO₂ and CH₄ products. Conventional research has primarily focused on the retrieval of column-averaged dry-air mole fractions of CO₂ (XCO₂) from SWIR measurements, as these products provide direct constraints on surface carbon fluxes. The accuracy of SWIR-based XCO₂ retrievals is strongly influenced by uncertainties in atmospheric light-path length, which are controlled by variations in aerosol scattering and surface reflectance [36]. To reduce these uncertainties, modern algorithms incorporate near-infrared (NIR) measurements, particularly the O₂ A-band, to better constrain photon path length and account for scattering by aerosols and clouds [37]. The combined use of NIR and SWIR information improves the robustness of CO₂ and CH₄ retrievals by explicitly addressing atmospheric scattering processes.

Despite these advances, meeting the accuracy and precision requirements for spaceborne XCO₂ and XCH₄ products remains challenging, and algorithm refinement and rigorous validation against high-quality ground-based observations remain critical. Accurate characterization of aerosol loading and its spatiotemporal variability are considered essential for further improving GHG retrieval performance. Geostationary observations of AOD, such as those provided by the Geo-KOMPSAT-2B (GK-2B) satellite mission, offer

high-temporal-resolution information on aerosol variability, which cannot be achieved with polar-orbiting sensors alone. Integrating GK-2B AOD products with column-averaged GHG observations can provide a promising framework for reducing retrieval uncertainties and accurately interpreting CO₂ and CH₄ variability, particularly in regions influenced by heavy aerosol loading and long-range transport.

With the aim of addressing the need for a joint aerosol and GHG observation framework, this study integrated. In many Asian regions, aerosols and GHGs originate from common anthropogenic sources and are jointly influenced by meteorology and long-range transport. Such coupling complicates the interpretation of observed GHG enhancements, particularly when distinguishing local emissions from regional or transboundary influences. Analyzing aerosols and GHGs separately may therefore lead to incomplete source attribution and biased flux estimates. Joint observations of AOD and GHGs provide a means to address these limitations. Aerosol information supports improved correction of scattering effects in GHG retrievals, while combined variability analyses offer additional constraints on shared sources and transport pathways. Coordinated satellite and ground-based observations are thus important for enhancing inversion accuracy and achieving a more physically consistent interpretation of atmospheric composition in regions affected by both local emissions and long-range transport.

This study integrated satellite-derived AOD products with continuous ground-based GHG measurements to investigate regional-scale aerosol optical characteristics and assess their influence on GHG variability. The Socheongcho Ocean Research Station (SORS)—located in the eastern Yellow Sea off the coast of the Korean Peninsula, along a major pathway of long-range atmospheric transport from Northeast Asia—provides an ideal natural laboratory for examining the coupled behavior of aerosols and GHGs. Owing to its remote marine environment, the SORS is only weakly affected by direct local emission sources; therefore, synoptic-scale meteorological influences and transboundary transport signals recorded at this station can be clearly isolated. The continuous in situ measurements of CO₂, CH₄, aerosols, and the related trace gases at the SORS offer a robust reference for the evaluation of satellite retrievals and the interpretation of GHG–aerosol interactions at the regional scale [38].

This study provides scientifically relevant information for developing effective air quality management strategies, including the seasonal fine particulate matter (PM_{2.5}) control policies implemented in South Korea, by improving the current understanding of the seasonal transport and accumulation of long-range atmospheric pollutants. The findings offer practical guidance for further refining satellite AOD products and enhancing their applicability to atmospheric composition monitoring and environmental policy development. The structure of this article is as follows: Section 2 describes the ground-based and satellite datasets and methodology used in this study. Sections 3 and 4 present the intercomparison of AOD and GHG products derived from GK-2B satellite sensors (Geostationary Environment Monitoring Spectrometer (GEMS) and Geostationary Ocean Color Imager II (GOCI-II)), discuss the characteristics of AOD and GHG variations during major aerosol episodes over Asia, and assess the consistency between satellite retrievals and ground-based observations. Section 5 summarizes the main conclusions and outlines potential future research directions.

2. Materials and Methods

2.1. Site Description and Surface Meteorological Conditions

The SORS is an offshore research platform operated by the Korea Institute of Ocean Science and Technology in the northern Yellow Sea (37°25′N, 124°44′E), approximately 37 km south of Socheong Island, at a water depth of about 50 m (Figure 1). Operational since October 2014, the station is equipped with 43 instruments, including meteorological, marine, and environmental monitoring systems [39,40], enabling multidisciplinary research

on oceanographic processes, long-range transport of atmospheric pollutants, and typhoon dynamics. The SORS can effectively characterize background aerosol conditions over the Korean Peninsula and assess variations associated with upwind source regions. In this study, we considered the surface aerosol mass concentrations, aerosol optical properties, tropospheric trace gases, and meteorological parameters observed at the SORS from January 2021 to 30 April 2022.

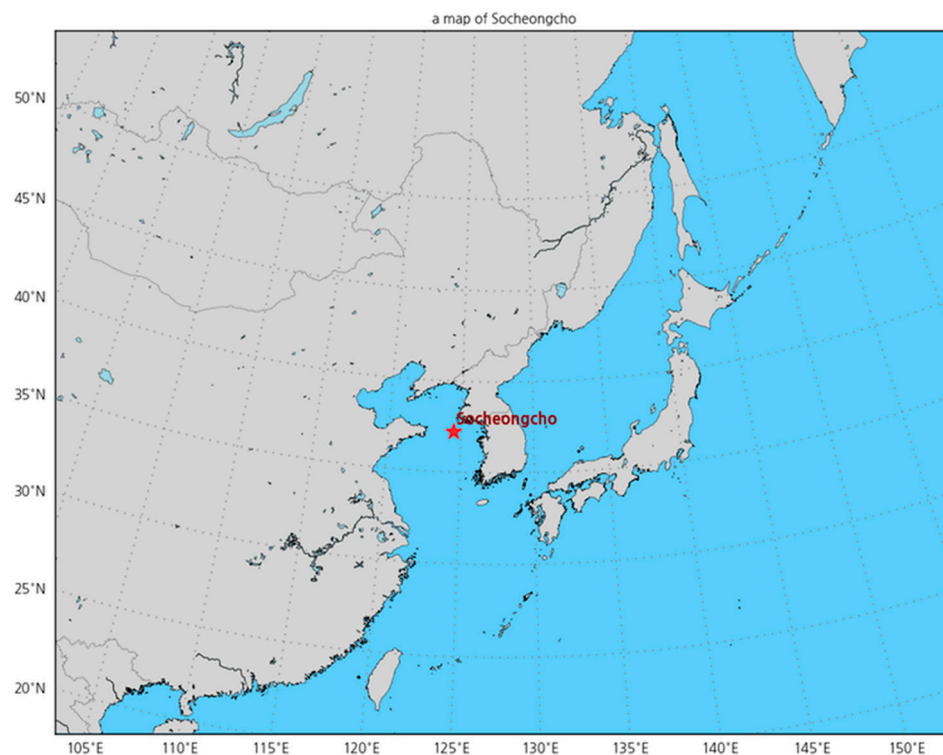


Figure 1. Location of the Socheongcho Ocean Research Station (SORS) in the Yellow Sea (red star).

2.2. Instruments and Data

2.2.1. Ground-Based Observations

- Gases

Carbon monoxide (CO), CO₂, and CH₄ concentrations were measured using a CRDS analyzer (Model G2401, Picarro Inc., Santa Clara, CA, USA). The CRDS technique is based on direct absorption spectroscopy and uses an optical resonator to effectively increase the photon path length, which substantially enhances the model's sensitivity to trace gas absorption. This configuration allows for rapid, high-precision detection of atmospheric trace gases across the sub-ppm and ppb levels, with high temporal resolution. Owing to its advantages, the CRDS method has become a standard technique for in situ monitoring of GHGs and related atmospheric trace species [41,42]. To minimize the influence of humidity under the marine conditions of SORS, the analyzer was operated with an integrated Nafion drying system installed upstream of the cavity inlet. In addition, the manufacturer-provided water vapor correction algorithm was applied to all measurements to account for dilution and spectroscopic effects of H₂O on CO₂ and CH₄ absorption features.

- Particulate matter (PM_{2.5}) and black carbon (BC)

Hourly concentrations of PM_{2.5} and BC during 2021–2022 were measured using a β -ray absorption monitor (FH62C14, Thermo Fisher Scientific, Franklin, MA, USA) and multi-angle absorption photometer (MAAP) (Model 5012, Thermo Fisher Scientific, Franklin, MA, USA; lower detection limit: 0.6 $\mu\text{g m}^{-3}$), respectively. The MAAP instrument was used to quantify

BC mass concentrations based on aerosol light absorption measurements conducted at a nominal wavelength of 670 nm. Aerosol particles were continuously collected on a fiber filter, and both the transmitted and scattered radiation signals were recorded simultaneously at multiple viewing angles (130° and 165°). These multi-angle measurements were interpreted using a radiative transfer framework that accounted for the optical properties of the filter substrate, particle-laden filter layer, and underlying absorbing layer [43,44].

- Aerosol Robotic Network (AERONET) aerosol optical depth (AOD) data

Ground-based aerosol optical properties were obtained from the AERONET website (URL: <https://aeronet.gsfc.nasa.gov>) (last accessed on 17 December 2025). Ground-based aerosol optical properties were obtained from the AERONET database [12,45,46], which provides long-term, quality-assured sun-photometer measurements of aerosol radiative and microphysical parameters. The dataset includes AOD across the near-ultraviolet (NUV)–NIR spectral range (~340–1020 nm), along with derived products such as the Ångström exponent (α), single scattering albedo (SSA), and inversion-based microphysical properties. Under cloud-free conditions, AERONET AOD uncertainties are typically ~0.01 in the visible and ~0.02 in the NUV range [47].

AERONET Version 3 AOD products were used for satellite validation. This version incorporates updated radiative transfer calculations, improved gas absorption corrections, refined surface BRDF parameterization, and enhanced atmospheric and temperature treatments [48]. The spectral dependence of aerosol extinction was further evaluated using the Ångström exponent (α), a commonly applied metric for diagnosing aerosol particle-size characteristics that provides a qualitative measure of the relative contributions of fine- ($r < 1 \mu\text{m}$) and coarse-mode ($r > 1 \mu\text{m}$) particles to the total aerosol population. Its spectral behavior is commonly used to distinguish among different aerosol types and infer changes in particle size distributions [49]. Although α is often approximated as wavelength independent, it has reportedly exhibited pronounced spectral variations under different aerosol regimes [50–52]. To account for this effect in the present study, α was calculated for two wavelength intervals, 440–870 and 440–667 nm.

$$AOD_{\lambda} = \beta \lambda^{-\alpha} \quad (1)$$

where $AOD(\lambda)$ denotes the AOD at wavelength λ , β represents the turbidity coefficient corresponding to the extrapolated AOD at $\lambda = 1 \mu\text{m}$, and α is the Ångström exponent that characterizes the spectral dependence of aerosol extinction.

2.2.2. Satellite-Based Observations

- Geostationary Environment Monitoring Spectrometer (GEMS)

The National Institute of Environmental Research operates the geostationary satellite GK-2B for continuous monitoring of atmospheric pollutants, including aerosols and trace gases, as well as episodic pollution events such as wildfires and volcanic ash emissions. The GEMS sensor onboard GK-2B is a hyperspectral ultraviolet–visible (UV–VIS) imaging spectrometer that provides high-temporal-resolution observations of atmospheric composition from geostationary orbit. GEMS covers a domain from 5°S to 45°N and 75°E to 145°E, delivering hourly measurements under daylight conditions to capture diurnal variability in aerosols and trace gases. The instrument measures Earth-reflected solar radiance across 1024 spectral channels in the 0.30–0.50 μm range, with a spectral resolution of approximately 0.6 nm and a nadir spatial resolution of about 3.5 km $\times$ 7.7 km, enabling characterization of regional-scale pollution patterns and their temporal evolution [53,54].

- Geostationary Ocean Color Imager II (GOCI-II)

The GOCI-II sensor onboard GK-2B is designed to obtain high-frequency observations of ocean color and atmospheric aerosols over East Asia and measures Earth-reflected solar radiance in 14 spectral channels spanning 375–860 nm (NUV–NIR). GOCI-II resolves fine-scale aerosol features with a spatial resolution of approximately 250 m and achieves accurate geolocation by a dedicated wideband stellar channel. A $\sim 2500 \text{ km} \times 2500 \text{ km}$ domain is centered on the Korean Peninsula; the instrument operates in a 12-subscene multi-slot scanning mode, repeating observations up to 10 times daily to capture the diurnal evolution of aerosol distributions at regional scales [55,56].

- Greenhouse Gases Observing Satellites (GOSAT and GOSAT-2)

The GOSAT series, jointly operated by Japan's Ministry of the Environment, JAXA, and the National Institute for Environmental Studies, was developed for long-term global monitoring of atmospheric greenhouse gases [30,57]. Both GOSAT and GOSAT-2, which are solely dedicated to GHG observations, carry the Thermal and Near-Infrared Sensor for Carbon Observation (TANSO), comprising a high-resolution Fourier transform spectrometer (FTS) and a cloud and aerosol imager (CAI). The FTS retrieves column-averaged dry-air mole fractions of CO_2 and CH_4 (XCO_2 and XCH_4), CO, and solar-induced chlorophyll fluorescence (SIF) from SWIR and TIR spectral measurements, while the imager provides collocated cloud and aerosol information for quality control. Operating in sun-synchronous orbit, the GOSAT series provides a consistent long-term dataset on the spatiotemporal variability of atmospheric GHGs [58–60].

- Sentinel-5 Precursor TROPOspheric Monitoring Instrument (TROPOMI)

The Sentinel-5 Precursor (Sentinel-5P), launched in 2017 under the Copernicus Earth observation program, provides high-quality global measurements of atmospheric composition. It carries a single instrument, the TROPOspheric Monitoring Instrument (TROPOMI), designed to monitor key trace gases and aerosols relevant to air quality and climate studies. Operating in a sun-synchronous orbit at $\sim 824 \text{ km}$ altitude, Sentinel-5P achieves near-global daily coverage. TROPOMI employs a wide-swath push-broom configuration with a swath width of $\sim 2600 \text{ km}$ and kilometer-scale nadir spatial resolution, enabling detailed mapping of atmospheric composition. The instrument measures backscattered solar radiation across the UV–VIS–NIR and SWIR spectral regions to retrieve column abundances of CH_4 , CO, and other trace gases, including O_3 , NO_2 , SO_2 , and HCHO, along with aerosol products. Its combination of high spatial resolution and daily global coverage supports regional-to-global analyses of emission sources and atmospheric transport processes [61–63].

- Orbiting Carbon Observatory 2 (OCO-2)

The OCO-2 delivers a continuous global record of column-averaged CO_2 (XCO_2) with high accuracy. The satellite carries a three-channel imaging grating spectrometer that measures reflected sunlight at 0.76, 1.61, and $2.06 \mu\text{m}$, targeting CO_2 and O_2 absorption features to enable robust XCO_2 retrievals while accounting for photon path length effects. Observations are acquired in nadir, glint, and target modes to improve coverage over diverse surface and illumination conditions. OCO-2 thus provides a benchmark dataset for diagnosing regional CO_2 source–sink patterns and for cross-validation of other satellite GHG products [64,65].

2.3. Methods

The satellite retrieval algorithms used in this study for aerosol optical depth (AOD), carbon dioxide (CO_2), and methane (CH_4) are summarized below, while detailed descriptions are provided in Appendix A.

2.3.1. Aerosol Optical Depth (AOD) Algorithm

- Geostationary Environment Monitoring Spectrometer (GEMS) aerosol optical depth (AOD) algorithm

The GEMS aerosol retrieval algorithm, developed by the National Institute of Environmental Research, supports near-real-time (NRT) monitoring of aerosol distributions over East Asia. GEMS provides hourly UV–VIS (300–500 nm) hyperspectral TOA radiance measurements with ~0.6 nm spectral sampling and a nadir resolution of ~3 km × 7.7 km. The inclusion of near-UV wavelengths enhances sensitivity to aerosol scattering and absorption due to generally low surface reflectance in this spectral range. The operational aerosol product (AERAOD) retrieves AOD, SSA, and aerosol layer height (ALH) using six wavelengths (354, 388, 412, 443, 477, and 490 nm). Retrieval follows a constrained inversion approach: initial AOD and SSA estimates are obtained from a two-channel UV method, consistent with NUV aerosol retrieval frameworks, and subsequently refined using an optimal estimation scheme [66]. Aerosol type classification is based on combined ultraviolet and visible aerosol indices (UVAI and VISAI), enabling discrimination among absorbing fine-mode aerosols, dust, and weakly absorbing particles. Surface reflectance is estimated using a minimum reflectance approach. Forward radiative transfer calculations are performed using lookup tables generated with the VLIDORT model [67], incorporating representative aerosol models. A priori ALH constraints are derived from climatological lidar observations [68–70]. Cloud contamination is mitigated through a multi-stage screening procedure combining reflectance thresholds, spectral ratio tests, and auxiliary infrared cloud masks. Additionally, a random forest-based post-processing correction, trained against AERONET SSA, is applied to reduce residual biases in NRT products. The integration of physics-based inversion and statistical correction enhances the stability and reliability of the operational AOD dataset.

- Geostationary Ocean Color Imager II (GOCI-II) aerosol optical depth (AOD) algorithm

The GOCI-II aerosol retrieval algorithm is an upgraded version of the heritage GOCI Yonsei Aerosol Retrieval scheme, optimized for the enhanced spectral configuration and finer spatial resolution of GOCI-II [71]. The processing begins with quality control procedures to exclude pixels affected by clouds, snow/ice, and highly reflective surfaces. Valid observations are then aggregated (10 × 10 native pixels), yielding an effective retrieval resolution of ~2.5 km. Cloud screening employs a multi-criteria approach, including NDVI-based tests over ocean regions following Ishida et al. [72]. Surface reflectance is estimated using a minimum reflectance method after classification into land, open ocean, and turbid water categories, with ocean surface effects further constrained using a wind-dependent BRDF model [73,74]. Aerosol properties are retrieved through comparison of observed TOA reflectance with precomputed radiative transfer simulations stored in LUTs generated using the VLIDORT model (v2.7) [67,75]. The LUTs incorporate six representative aerosol models derived from AERONET climatology and parameterized by SSA (440 nm) and fine-mode fraction (FMF) (550 nm). Channel selection varies by surface type: dark-target channels (380–680 nm) over land, specific visible–NIR bands over turbid water, and extended bands over open ocean. For each pixel, the aerosol model minimizing inter-channel variability in retrieved AOD at 500 nm is selected, and the corresponding parameters are used to derive the final GOCI-II AOD product.

2.3.2. Carbon Dioxide (CO₂) Algorithm

- Greenhouse Gases Observing Satellite (GOSAT and GOSAT-2) carbon dioxide (CO₂) algorithm

Satellite retrievals of atmospheric CO₂ are based on measurements of reflected solar radiation in the NIR and SWIR spectral regions, primarily exploiting CO₂ absorption bands near 1.6 and 2.0 μm . To account for atmospheric path length and surface pressure effects, the retrieved CO₂ column is normalized by the dry-air column derived from O₂ absorption in the A-band (0.76 μm), yielding column-averaged dry-air mole fractions (XCO₂). GOSAT, GOSAT-2 retrievals were primarily based on sunglint observations. For GOSAT and GOSAT-2, operational retrievals are performed using the Fast atmOspheric traCe gAs retrieval (FOCAL) algorithm [76], originally developed for OCO-2 and adapted for the GOSAT series [31,58,77]. FOCAL applies a full-physics optimal estimation framework that simultaneously constrains surface pressure, aerosol scattering, and trace gas concentrations using measurements in the O₂ A-band and CO₂ SWIR bands. Atmospheric scattering is represented by an effective aerosol layer characterized by pressure level, optical depth, and Ångström exponent. The forward radiative transfer model is embedded within an optimal estimation scheme [78] and iteratively solved using a Levenberg–Marquardt–Fletcher approach [79]. Polarization-dependent radiances (S and P components) are used to enhance sensitivity to aerosol- and cloud-induced path-length effects, which represent a major error source in SWIR retrievals. After strict cloud screening, aerosol properties and trace gas profiles are jointly retrieved, ensuring physically consistent correction of scattering effects. Retrieved vertical profiles are represented in discrete layers and vertically integrated to derive XCO₂, XCH₄, and XH₂O.

- Orbiting Carbon Observatory-2 (OCO-2) carbon dioxide (CO₂) algorithm

The Atmospheric CO₂ Observations from Space (ACOS) algorithm provides the operational Level-2 retrieval framework for OCO-2 and OCO-3, estimating column-averaged CO₂ (XCO₂) from hyperspectral observations [80]. The retrieval utilizes reflected solar radiance in three absorption bands: the O₂ A-band ($\sim 0.765 \mu\text{m}$) and CO₂ bands near 1.61 and 2.06 μm , sampled at high spectral resolution to resolve gaseous absorption features. OCO-2 observations were obtained in glint mode over ocean surfaces. ACOS applies a full-physics radiative transfer model within an optimal estimation framework [81], jointly retrieving the CO₂ profile, surface pressure, and auxiliary parameters including aerosol and cloud properties, water vapor, temperature, and surface reflectance. This simultaneous inversion mitigates biases associated with scattering-induced path-length effects. XCO₂ is calculated by normalizing the retrieved CO₂ column by the dry-air column derived from surface pressure. This column-averaged metric provides a robust constraint on surface CO₂ fluxes and is well suited for carbon cycle and source–sink analyses.

2.3.3. Methane (CH₄) Algorithm

- Greenhouse Gases Observing Satellite (GOSAT and GOSAT-2) methane (CH₄) algorithm

Satellite retrievals of atmospheric CH₄ are based on SWIR absorption features near 1.6 and 2.06 μm , from which total column CH₄ is estimated using inverse modeling. However, SWIR methane retrievals are sensitive to scattering-related path-length uncertainties arising from aerosols and surface–atmosphere radiative interactions. To reduce these effects, a proxy retrieval approach is commonly applied wherein XCH₄ is calculated from the ratio of retrieved CH₄ to CO₂ columns and subsequently scaled using an a priori estimate of XCO₂. Validation studies have reported a typical accuracy of approximately 1% for proxy-based XCH₄ derived from GOSAT observations [82]. In this study, the GOSAT CH₄ product was analyzed at an effective spatial resolution of $2.5^\circ \times 2.5^\circ$ [57].

- Sentinel-5 Precursor (Sentinel-5P) TROPOspheric Monitoring Instrument (TROPOMI) methane (CH₄) algorithm

The operational CH₄ product of Sentinel-5P is generated using a full-physics retrieval scheme based on the Remote Sensing of Trace Gases inversion system, previously applied to missions such as OCO and GOSAT [83]. The algorithm retrieves column-averaged methane (XCH₄) by jointly accounting for atmospheric scattering and surface reflectance effects within an optimal estimation framework. The TROPOMI retrieval exploits measurements from the O₂ A-band in the NIR and the CH₄ absorption band near 2.3 μm in the SWIR, providing complementary constraints on light-path length and methane absorption. Prior to inversion, NIR and SWIR spectra—acquired by separate spectrometers—are co-registered to ensure spectral consistency. With a nadir footprint of approximately 5.5 km $\times$ 7 km and near-daily global coverage, TROPOMI supports detailed analyses of CH₄ spatial and temporal variability [61,84]. Unlike proxy-based approaches that derive XCH₄ from CH₄-to-CO₂ ratios to reduce path-length errors, the TROPOMI product applies a full-physics inversion that simultaneously retrieves methane, surface reflectance, and aerosol parameters, which improves performance under heterogeneous aerosol conditions but increases sensitivity to aerosol parameterization assumptions.

2.3.4. Spatiotemporal Collocation

A strict spatiotemporal collocation strategy was applied to enable consistent inter-comparisons between satellite-derived and ground-based observations. The satellite AOD retrievals were spatially aggregated over a limited neighborhood surrounding each ground observation site and compared with point-based ground measurements. To account for the differences in native pixel geometry, the GOCI-II and GEMS AOD products were regridded to a common spatial resolution of 5 km (0.05°), using the nearest-neighbor method [56,85]. Satellite and ground-based observations were temporally collocated within a window of ± 1 h from the satellite overpass time. For each collocated case, satellite AOD values were averaged over the ± 1 h period and compared with AERONET measurements acquired within the same window. In addition, XCO₂ comparisons were performed using the OCO-2, GOSAT, and GOSAT-2 observations, while XCH₄ comparisons were conducted using the TROPOMI, GOSAT, and GOSAT-2 observations. Satellite measurements within a radius of 10 km (0.1°) of the SORS site and ground-based observations obtained on the same day within a timeframe of ± 1 h from the satellite overpass was selected for intercomparison.

3. Results

3.1. Performance of the Aerosol Optical Depth (AOD) Algorithm for Geostationary Environment Monitoring Spectrometer (GEMS) and Geostationary Ocean Color Imager II (GOCI-II)

Intercomparison was performed between satellite-based and ground-based aerosol products to assess the quantitative performance of the GK-2B/GEMS (Figure 2a) and GOCI-II AOD retrievals (Figure 2b). The AERONET station at the SORS was adopted as the reference site, and the evaluation period covered 1 January 2021 to 30 April 2022. After applying the spatiotemporal collocation procedure described in Section 2.3.2, matched datasets were used to derive the statistical indicators, including the standard deviation and coefficient of determination (R^2), for each satellite product. Both geostationary sensors reproduced the variability of ground-based AOD with high fidelity. The GEMS and GOCI-II products exhibited strong correlations with the AERONET observations, yielding R^2 values of 0.78 and 0.91, respectively, thereby confirming the robustness of the two retrieval systems under the observational conditions at the SORS site. While the performance of GEMS and GOCI-II AOD products was assessed in this study, satellite-derived AOD retrievals are subject to inherent uncertainties associated with surface reflectance characterization, aerosol model assumptions, cloud screening, and radiative transfer inversion processes.

Accordingly, interpretations based exclusively on satellite AOD signals should be made with caution.

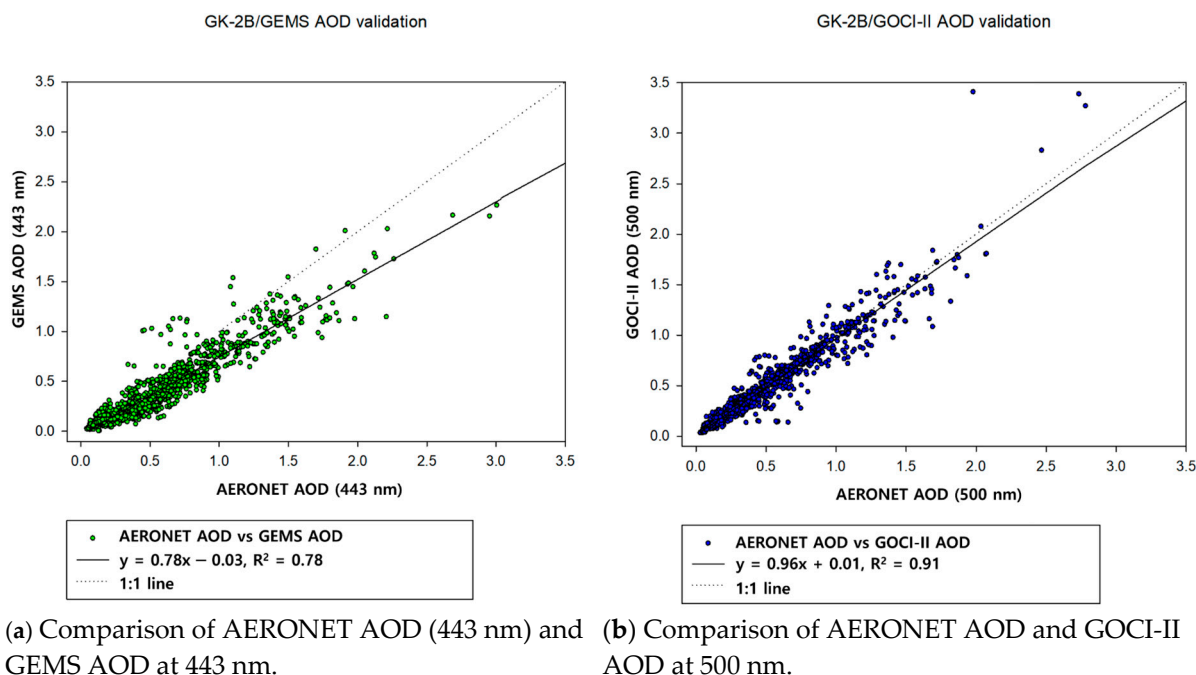


Figure 2. Aerosol optical depth (AOD) scatterplot of (a) Geostationary Environment Monitoring Spectrometer (GEMS) at 443 nm and (b) Geostationary Ocean Color Imager II (GOCI-II) at 500 nm against the reference ground-based Aerosol Robotic Network (AERONET) data for January 2021–April 2022. The dotted line indicates the linear regression, and the black line is the 1:1 line. Abbreviation: Coefficient of determination (R^2).

A seasonally stratified assessment was conducted to examine potential temporal dependencies in the performance of the GEMS AOD (443 nm) retrievals (Figure 3). The dataset was partitioned into five seasonal categories: winter, spring, dry summer, wet summer, and fall. Across winter, spring, and fall, the GEMS retrievals exhibited a systematic low bias relative to the AERONET observations, which was pronounced under moderate-to-high aerosol loading conditions. However, the linear relationship with ground-based observations remained robust, yielding R^2 values of 0.79, 0.82, and 0.92 for winter, spring, and fall, respectively. In contrast, during the dry and wet summer seasons, the retrieval performance degraded noticeably during low-AOD regime ($AOD \approx 0-0.5$), with a strong underestimation tendency. This behavior led to a reduced correspondence with the AERONET observations, as reflected by lower R^2 values of 0.64 and 0.77 for dry and wet summer seasons, respectively. The seasonal dependence suggested that the NUV-based GEMS algorithm was susceptible to uncertainties in surface reflectance and atmospheric conditions during the summer season, particularly when aerosol loading was weak [86,87].

The GOCI-II AOD (500 nm) product, which relied primarily on VIS channel measurements, showed a markedly different seasonal behavior (Figure 4). The comparison with AERONET observations indicated consistently strong and stable performance throughout the year, with R^2 values of 0.91 (winter), 0.93 (spring), 0.93 (dry summer), 0.95 (wet summer), and 0.96 (fall). However, a slight positive bias was evident in winter, a season frequently influenced by long-range transport of continental aerosols over the Korean Peninsula. This feature could be linked to enhanced multiple scattering effects and increased complexity in aerosol mixtures during such episodes [88,89].

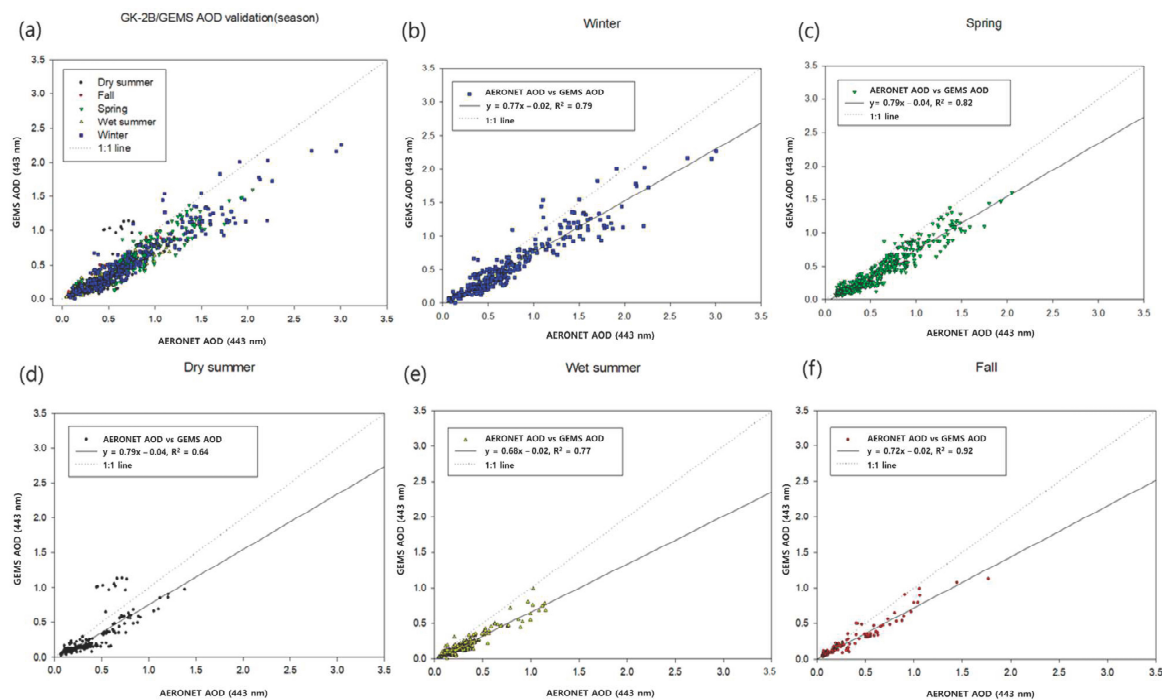


Figure 3. Seasonal aerosol optical depth (AOD) 443 nm scatterplot of the Geostationary Environment Monitoring Spectrometer (GEMS) product versus the reference ground-based Aerosol Robotic Network (AERONET) observations for January 2021–April 2022. Dotted line shows linear regression, and black line is the 1:1 line. The graphs show the data for (a) all seasons, (b) winter (December–February), (c) spring (March and April), (d) dry summer (May and June), (e) wet summer (July–September), and (f) fall (October and November). Abbreviation: Coefficient of determination (R^2).

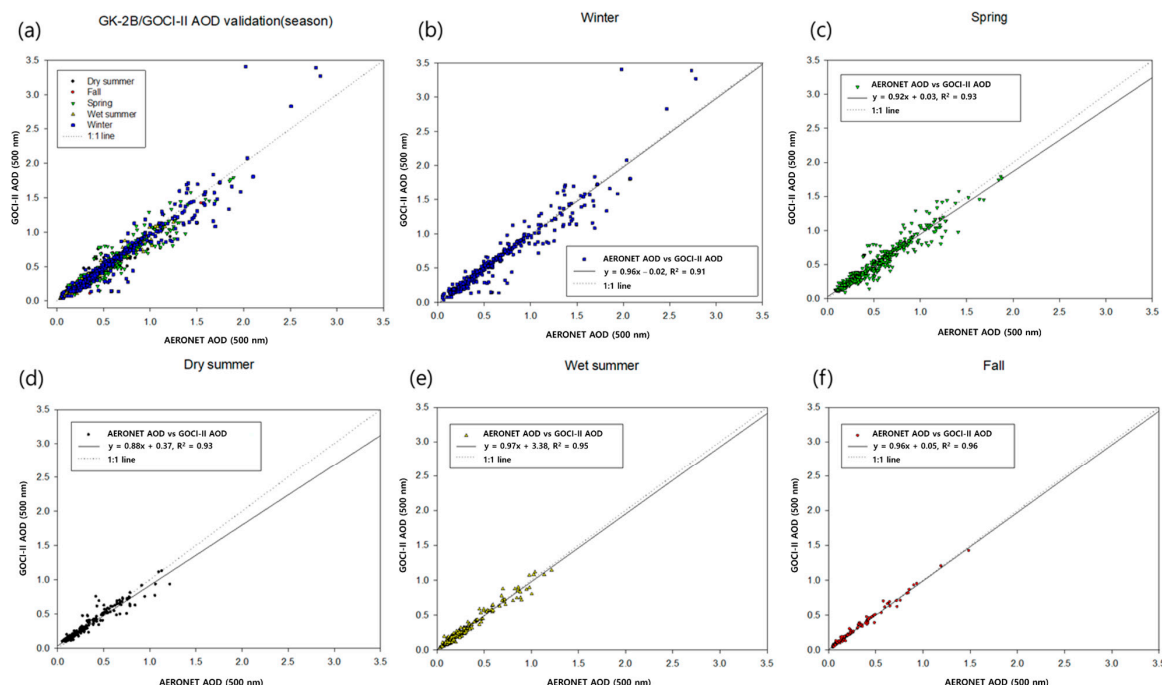


Figure 4. Seasonal aerosol optical depth (AOD) 500 nm scatterplot of the Geostationary Ocean Color Imager II (GOCI-II) product versus the reference ground-based Aerosol Robotic Network (AERONET) observations for January 2021–April 2022. Dotted line shows linear regression, and black line is the 1:1 line. Data are shown for (a) all seasons, (b) winter (December–February), (c) spring (March and April), (d) dry summer (May and June), (e) wet summer (July–September), (f) fall (October and November). Abbreviation: Coefficient of determination (R^2).

3.2. Seasonal/Monthly Distributions of Aerosol Optical Depth (AOD)

The intra-annual behavior of AOD at the SORS site, derived from the GEMS and GOCI-II products, was summarized using box-and-whisker statistics (see Figure 5a,b). Both datasets revealed a pronounced seasonal modulation characterized by enhanced aerosol loading during the cold seasons and suppressed AOD levels during the summer monsoon period. This contrast is associated with increased aerosol accumulation and long-range transport during winter and spring, as well as efficient wet scavenging under persistent precipitation in summer. The highest seasonal mean AODs were observed in spring 2022 (March–April): 0.619 ± 0.292 for GEMS and 0.682 ± 0.492 for GOCI-II. The season with the second-highest pollution was winter 2022 (December–February), with corresponding mean values of 0.563 ± 0.374 and 0.628 ± 0.329 , respectively. By comparison, substantially lower aerosol burdens were evident during fall (October–November) and spring 2021; the mean AOD values decreased to 0.305 ± 0.288 (GEMS) and 0.329 ± 0.328 (GOCI-II) in fall 2021 and 0.276 ± 0.238 (GEMS) and 0.374 ± 0.288 (GOCI-II) in spring 2021. The cleanest atmospheric conditions were observed during the summer periods, with the mean AOD values being 0.243 ± 0.248 (GEMS) and 0.314 ± 0.211 (GOCI-II) in the dry summer (May–June), which further declined to 0.182 ± 0.153 (GEMS) and 0.254 ± 0.221 (GOCI-II) during the wet summer (July–September). Monthly statistics (shown in Figure 5c,d) illustrate the temporal evolution of aerosol loading. For both sensors, the AOD value remained at relatively low levels from January to October of 2021, followed by a sharp and sustained increase beginning in November 2021 that continued into early spring in 2022. In the GEMS product, the maximum monthly mean AOD occurred in April 2022 (0.849 ± 0.298), with similarly elevated values observed in February (0.736 ± 0.310) and March (0.628 ± 0.310) of 2022. Conversely, the lowest monthly means were observed during the peak monsoon months, particularly in September (0.150 ± 0.147) and July (0.170 ± 0.148) of 2021, highlighting the dominant role of precipitation-driven aerosol removal. A comparable temporal progression was evident in the GOCI-II product, with a progressive buildup beginning in November 2021 and peak values recorded in February 2022 (0.849 ± 0.366), December 2021 (0.745 ± 0.320), and April 2022 (0.642 ± 0.352). The persistently elevated AOD levels throughout the winter-to-early spring period may reflect sustained aerosol accumulation, possibly influenced by enhanced fine-mode aerosol transport and frequent stagnant meteorological conditions typical of the cold season.

3.3. Seasonal and Monthly Variations in Mass Concentrations of Carbon Dioxide (CO₂)

During the study period, atmospheric CO₂ mole fractions measured at the SORS, varied from 407 ppm in summer to 487 ppm in spring. This variability may reflect the combined influence of regional emission sources and meteorological processes, including synoptic wind patterns, humidity conditions, long-range transport, and boundary-layer evolution. A pronounced seasonal cycle in CO₂ concentrations was evident at the SORS (Figure 6a,b), characterized by elevated levels in spring and lower levels during the wet summer season. The highest seasonal mean CO₂ concentration occurred in spring 2022 (431.56 ± 12.42 ppm), which was followed by winter 2022 (425.85 ± 6.11 ppm) and spring 2021 (425.35 ± 8.37 ppm). Comparable mean levels were observed in fall (425.06 ± 11.94 ppm) and winter (424.43 ± 8.88 ppm) of 2021. In contrast, lower seasonal averages were recorded during the dry summer (423.43 ± 11.88 ppm), with the minimum value occurring during the wet summer period (413.42 ± 3.13 ppm). Monthly CO₂ statistics (Figure 6c,d) showed that the lowest mean concentration occurred in July 2021 (413.42 ± 11.16 ppm), approximately 30 ppm lower than the maximum observed in March 2022 (443.33 ± 1.89 ppm). Both seasonal and monthly variations in CO₂ were primarily governed by an interplay between surface emissions and meteorological conditions. Enhanced

vertical mixing, increased boundary layer depth, and efficient removal processes during the summer monsoon likely contributed to the observed summertime minimum. In addition, anthropogenic CO₂ emissions from fossil fuel combustion in East Asia, particularly in China, exhibited lower and higher intensities in summer and winter, respectively, further supporting the observed seasonal contrast, with reduced CO₂ in summer and enhanced concentrations in winter and early spring [90].

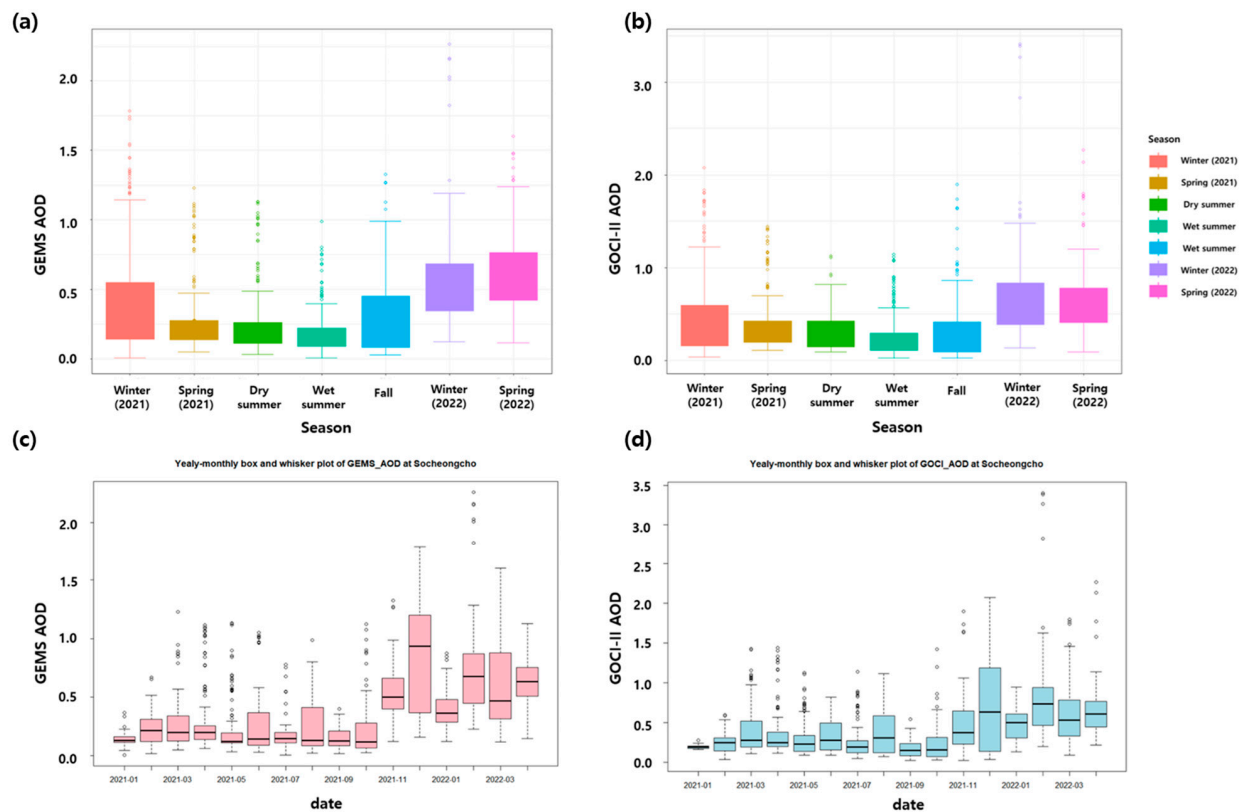


Figure 5. Seasonal and monthly variability of aerosol optical depth (AOD) at the Socheongcho Ocean Research Station (SORS) derived from (a,c) Geostationary Environment Monitoring Spectrometer (GEMS) and (b,d) Geostationary Ocean Color Imager II (GOCI-II) observations. (a,b) show seasonal and (c,d) show monthly box-and-whisker distributions. Boxes denote the interquartile range, horizontal lines indicate the medians, whiskers represent the 10th–90th percentiles, and markers denote the mean values.

In general, the CO–CO₂ relationship is used to diagnose regional emission characteristics and discriminate between combustion-related influences and background air masses [91,92]. In this study, under stagnant meteorological conditions, the initially elevated CO₂/CO slope showed a tendency to decrease in both the boundary layer and the lower free troposphere. This pattern is statistically consistent with progressive mixing of transported air masses and a relative increase in regional or local influences, as air parcels may remain over the Korean Peninsula for extended periods. However, the present analysis is based on observed co-variation and does not directly demonstrate the underlying physical mechanisms.

Data for 17 May–20 June 2021, July–October 2021, and 18 February–27 March 2022 were unavailable owing to instrument malfunction, and data continuity during July–October 2021 was further influenced by the offshore location of SORS and maintenance constraints associated with typhoons and adverse summer monsoon conditions. To evaluate the potential impact of these gaps, the CO₂–GEMS AOD correlation was recalculated using only temporally overlapping observations. The correlation coefficient decreased slightly (from

0.1575 to 0.1513; $\Delta r = -0.0062$) while remaining statistically significant ($p < 0.001$), and the 95% confidence interval exhibited only negligible variation (interval width: 0.1352 to 0.1367), suggesting that restricting the analysis to overlapping datasets does not substantially affect the statistical interpretation.

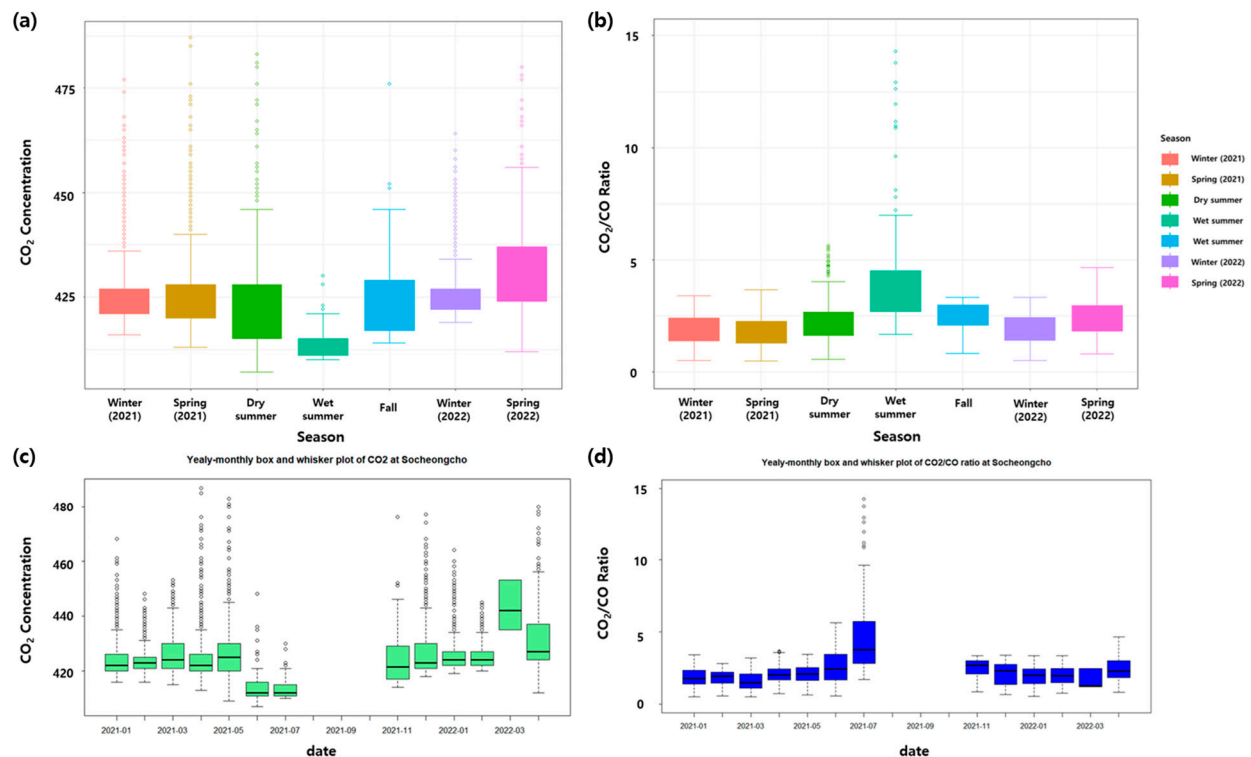


Figure 6. Seasonal and monthly variations in atmospheric carbon dioxide (CO₂) observed at the Socheongcho Ocean Research Station (SORS) during the study period. (a) box-and-whisker plots of seasonal CO₂ concentrations, (b) box-and-whisker plots of seasonal CO₂/CO ratio, (c) box-and-whisker plots of monthly CO₂ concentrations, and (d) box-and-whisker plots of monthly CO₂/CO ratio.

3.4. Seasonal/Monthly Methane (CH₄) Characterization

Atmospheric CH₄ concentrations measured at the SORS exhibited pronounced seasonal variability, characterized by elevated levels during the winter, spring, and wet summer seasons and comparatively lower concentrations during the fall and dry summer seasons. Figure 7a,b show clear seasonal patterns in the CH₄ concentrations, with the highest concentrations occurring in the wet summer season and the lowest values occurring in fall. The seasonal mean CH₄ concentrations reached 1.981 ± 0.10 ppm in the wet summer, followed by 1.956 ± 0.03 ppm in winter 2022, 1.938 ± 0.05 ppm in winter 2021, 1.936 ± 0.03 ppm in fall, 1.933 ± 0.03 ppm in spring 2022, 1.924 ± 0.04 ppm in spring 2021, and 1.922 ± 0.05 ppm in the dry summer season. The summertime enhancement of CH₄ concentrations may be associated with increased biogenic emissions from terrestrial ecosystems, including rice paddies and wetlands, which are known to emit substantial amounts of CH₄ under warm and water-saturated conditions. However, the present observations alone do not allow a quantitative attribution to specific source types. The gradual increase in CH₄ concentrations throughout 2021 was closely linked to the predominance of westerly air mass transport toward the SORS, indicating a potential influence of regional-scale transport. These air masses were likely enriched in CH₄, owing to emissions from agricultural activities, waste management, and energy-related sectors (such as coal mining) in eastern China, particularly Hebei and Shandong [93–95].

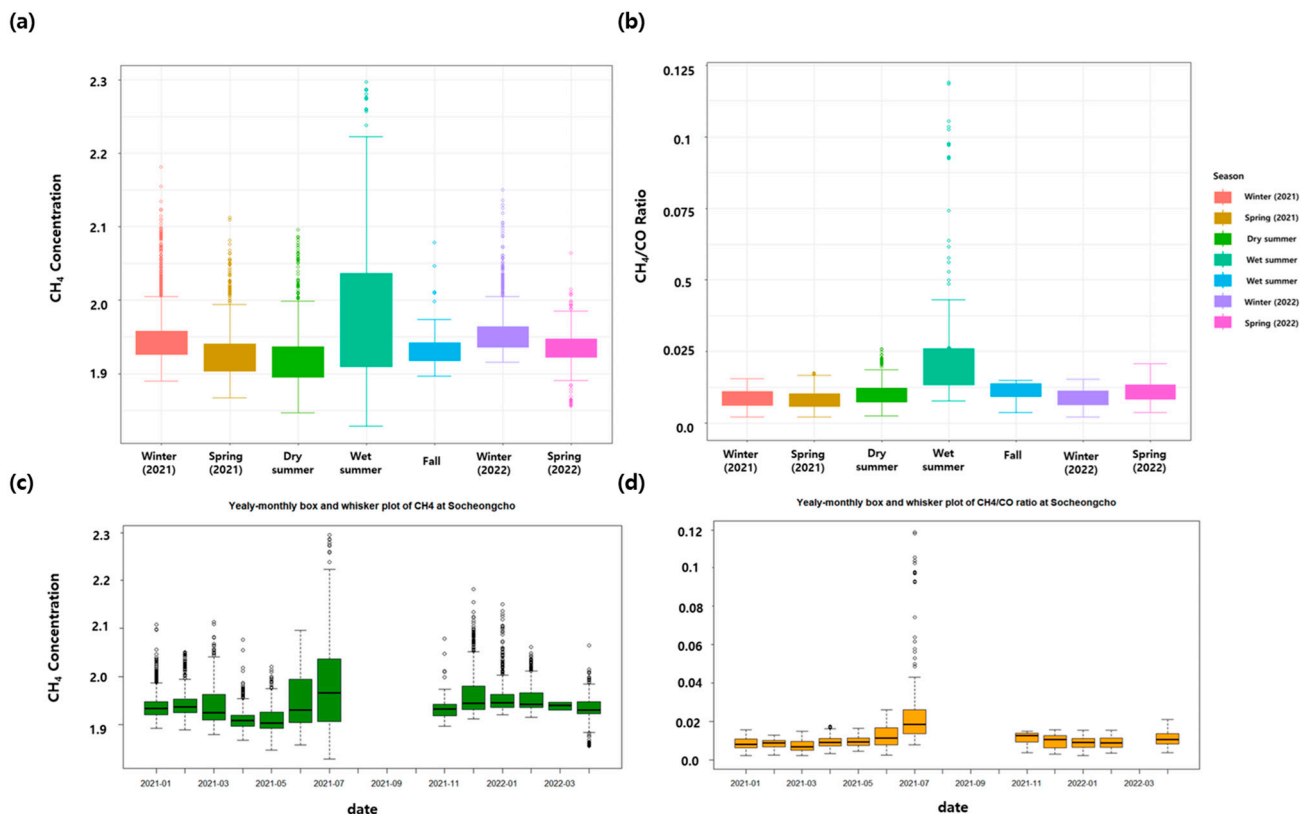


Figure 7. Seasonal and monthly variations in atmospheric methane (CH₄) concentrations and methane/carbon monoxide (CH₄/CO) ratios observed at the Socheongcho Ocean Research Station (SORS) during the study period. (a) Seasonal distribution of CH₄ concentrations; (b) box-and-whisker plots of seasonal CH₄/CO ratio; (c) monthly mean CH₄ concentrations and their temporal evolution; and (d) monthly variations in the CH₄/CO ratio, illustrating the changes in the characteristics of dominant methane sources.

To further constrain the CH₄ source characteristics, the seasonal and monthly variability of the CH₄/CO ratio was examined. In general, the CH₄/CO ratio is widely used as a diagnostic indicator of emission sources and combustion efficiency, as CH₄ and CO are emitted in systematically different proportions from fossil fuel extraction, incomplete combustion, biomass burning, and biogenic processes. The seasonal mean CH₄/CO ratios were the highest during the wet summer season in 2021 (0.026 ± 0.235), followed by fall 2021 (0.011 ± 0.019), spring 2022 (0.011 ± 0.050), dry summer 2021 (0.010 ± 0.062), winter 2021 (0.009 ± 0.093), winter 2022 (0.009 ± 0.084), and spring 2021 (0.008 ± 0.091). CH₄/CO ratio values close to ~0.01 have generally been reported in association with fossil fuel-dominated emission regimes and were more frequently observed during winter in this study, when combustion-related influences tend to be relatively stronger. In contrast, higher ratios (approximately 0.02 to 0.2) have been commonly associated in previous studies with biomass burning and biogenic emissions, which are often more active during the wet summer season. The monthly analysis (Figure 7c,d) further showed that the CH₄/CO ratio peaked in July (0.026 ± 0.077), followed by June (0.013 ± 0.055), consistent with enhanced biogenic activity during the growing season. The lowest ratios were recorded in January (0.009 ± 0.094) and February (0.009 ± 0.071) of 2022, which may reflect a comparatively greater influence of combustion-related sources during winter.

3.5. Coupled Temporal Behavior of AOD and GHGs

The time series of daily GHG concentrations and AOD derived from AERONET and GK-2B observations at the SORS site are presented in Figure 8. In situ GHG data were unavailable in July and October 2021 due to routine maintenance. Overall, GK-2B AOD values in 2022 appeared generally higher than those in 2021, with maxima observed in February 2022 and minima during July–September 2021. Although GK-2B AOD tended to underestimate AERONET measurements, it reproduced the major temporal and seasonal variability observed at the ground site. Surface CO₂ concentrations exhibited a pronounced seasonal cycle, with relatively elevated levels in spring and winter. This pattern is consistent with the possible influence of enhanced fossil fuel combustion and regional transport from upwind source areas; these areas were connected to the SORS by prevailing westerly and northwesterly airflows [96]. In contrast, CH₄ showed a distinct summertime maximum (July), which may reflect the combined effects of enhanced biogenic emissions and regional-scale transport during the wet season.

A joint analysis of AOD and GHG time series revealed both coherent and contrasting seasonal patterns. For example, winter 2021 was characterized by relatively elevated AOD and comparatively lower GHG concentrations, which may suggest aerosol-dominated transport episodes. Conversely, during spring 2022, concurrent increases in AOD and GHGs were observed, a pattern consistent with the possible co-transport of aerosols and trace gases from common anthropogenic source regions.

Seasonal scatterplots were used to examine the relationships between aerosol loading and GHG concentrations (Figure 9), showing GK-2B/GEMS and GOCI-II AOD versus surface CO₂ and CH₄ across five seasonal categories. CO₂ exhibited clear seasonal contrasts, with generally higher concentrations in winter and during the dry summer, whereas CH₄ showed comparatively weaker seasonal variability, with only modest wintertime enhancement. This pattern is consistent with previous studies reporting larger seasonal amplitudes for CO₂ than for CH₄ in East Asia [97]. The stronger variability of CO₂ may be associated with seasonal changes in combustion-related emissions [98], while CH₄ reflects contributions from both anthropogenic and biogenic sources. Distinct clustering patterns were also observed. In spring and winter (2021–2022), several cases showed elevated AOD with relatively low CO₂, which may correspond to aerosol-dominant transport conditions. In contrast, another subset displayed approximate linear co-variation between AOD and CO₂, suggesting possible combined influences of aerosol loading and anthropogenic emissions under certain synoptic settings.

The relationship between GEMS AOD and CH₄ did not exhibit a similarly coherent or seasonally consistent pattern. During the winters of 2021 and 2022, CH₄ concentrations (1.9–2.2 ppm) occasionally increased with AOD, a pattern that may reflect episodic co-occurrence of aerosol-enhanced and CH₄-enriched air masses. Similar tendencies were observed in the GOCI-II AOD relationships with CO₂ and CH₄. The GOCI-II AOD dataset showed relatively higher values in winter and lower values during the wet summer, consistent with seasonal variations in aerosol loading and monsoon-related removal processes. However, elevated CH₄ concentrations persisted even during periods of comparatively low aerosol loading in the wet summer. This apparent decoupling suggests that near-surface CH₄ variability at the SORS was not solely associated with aerosol abundance but was likely influenced by a combination of regional emissions and meteorological transport. Overall, these results demonstrated that the joint analysis of aerosol and GHG observations provided valuable constraints on source characteristics and transport regimes.

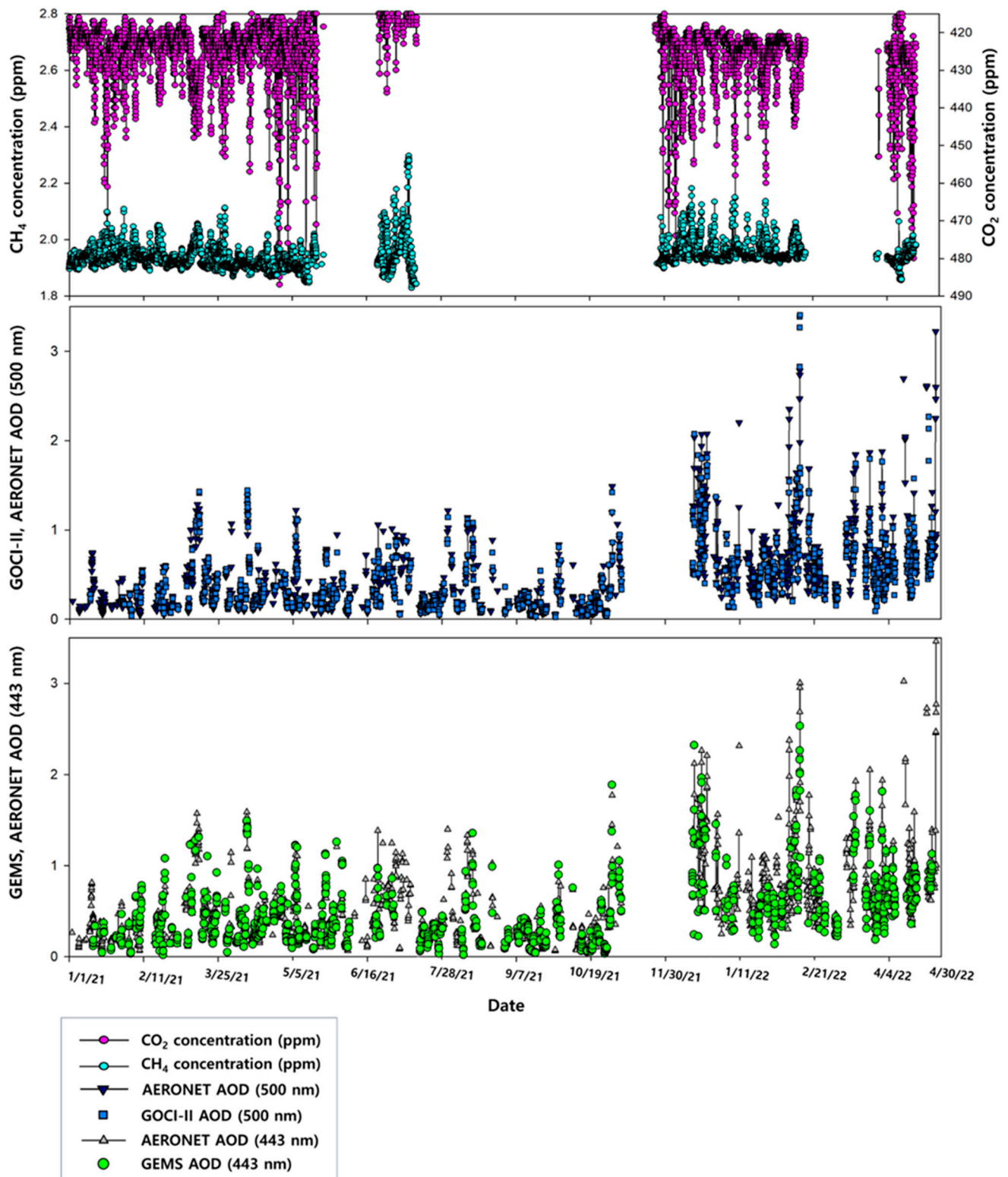


Figure 8. Time series distribution of carbon dioxide (CO_2) (pink circle), methane (CH_4) (emerald circle), aerosol optical depth (AOD) from ground (AERONET AOD at 443 nm: grey triangle up; AERONET AOD at 500 nm: navy triangle down) and satellite (GK-2B/GEMS: green circle, GK2B/GOCI-II: sky blue square) data from January 2021 to April 2022. Abbreviations: Geo-KOMPSAT-2B (GK-2B), Aerosol Robotic Network (AERONET), Geostationary Environment Monitoring Spectrometer (GEMS), Geostationary Ocean Color Imager II (GOCI-II).

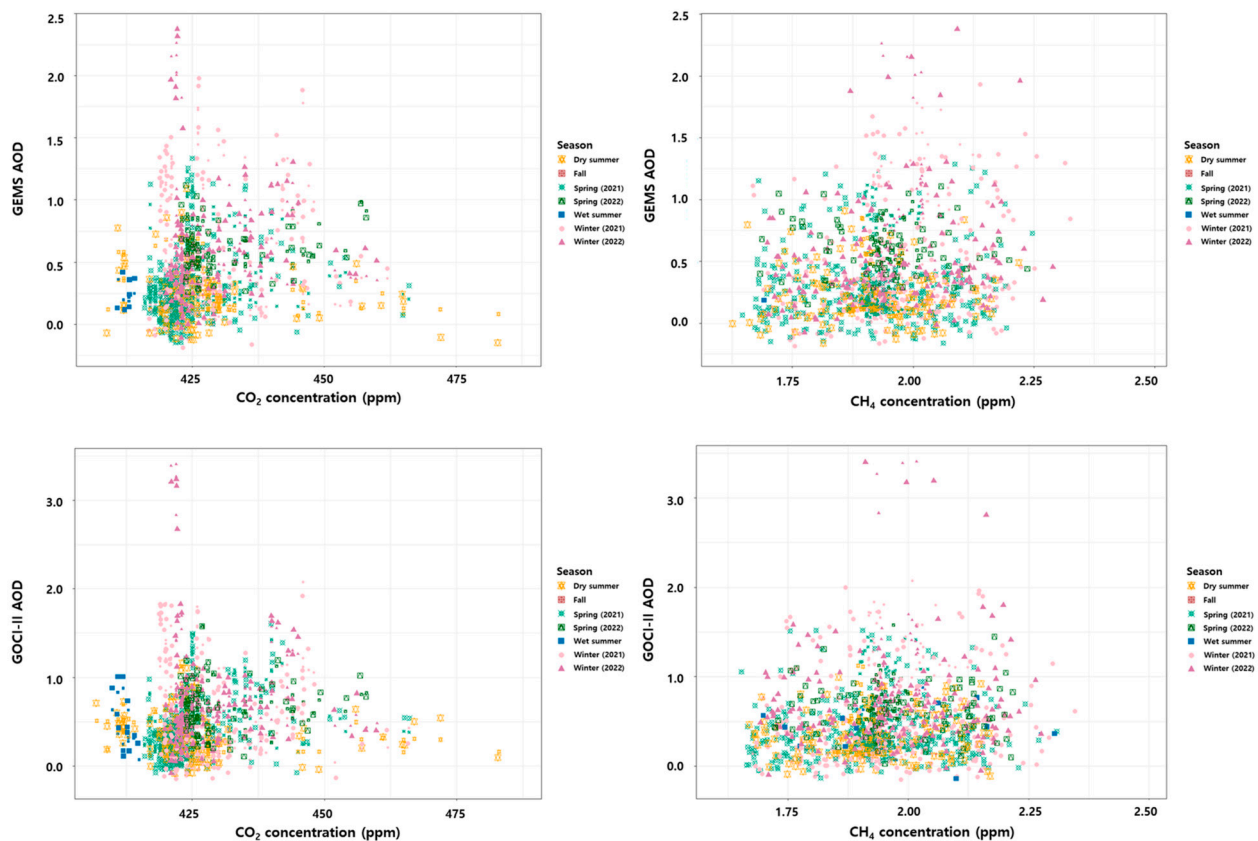


Figure 9. Seasonal scatterplots of the Geo-KOMPSAT-2B (GK-2B) aerosol optical depth (AOD) data versus the surface greenhouse gas (GHG) concentrations at the Socheongcho Ocean Research Station (SORS). Data are classified by season as follows: dry summer (May–June; yellow stars), fall (October–November; palevioletred squares), winter 2021 (January–February 2021; pink circles), winter 2022 (December 2021–February 2022; palevioletred triangles), wet summer (July–September; blue squares), spring 2021 (March–April 2021; emerald x circles), and spring 2022 (March–April 2022; forestgreen squares). Abbreviations: Geostationary Environment Monitoring Spectrometer (GEMS), Geostationary Ocean Color Imager II (GOCI-II).

4. Discussion

4.1. Comparative Analysis of Aerosol Optical Depth (AOD), Carbon Dioxide (CO_2) and Methane (CH_4) Concentrations Obtained by Satellite Remote Sensing and Surface Measurements

To properly interpret the differences between ground-based and satellite observations, a direct comparison was conducted by season and satellite sensor. In the scatterplots shown in Figure 10, ground-based measurements and satellite-retrieved values are shown on the X and Y axes, respectively, with error bars representing the variability of each dataset and highlighting the range of concentration differences. Note that instrumental characteristics differ among sensors; for example, the GEMS sensor (forest green in the figure) primarily utilizes UV channels, while the GOCI-II sensor (sky blue in the figure) relies on visible spectral bands, resulting in differences in aerosol sensitivity and retrieval behavior. The GEMS AOD product generally exhibited higher absolute values than the GOCI-II AOD product; however, the former product showed a systematic underestimation relative to the 1:1 line when compared with ground-based observations (Figure 10a). Seasonal box plots were employed to provide a complementary assessment of the consistency between ground-based and satellite observations (Figure 10b). Among all the datasets used in this study, the AERONET 443 nm data exhibited the highest values, while the GEMS data showed the lowest values, reflecting a systematic underestimation. All datasets consistently capture elevated concentrations in spring and winter of 2022, indicating that they reproduced

similar seasonal variability. Previous validation studies have reported that geostationary AOD retrievals generally exhibit coefficients of determination (R^2) on the order of 0.6–0.7 when evaluated against AERONET observations. Depending on the satellite sensor and surface conditions, reported R^2 values range from approximately 0.61–0.72 for GEMS [68] and 0.64–0.68 for GOCI-II [99]. In particular, for GEMS, roughly half of the retrievals fall within a ± 0.10 uncertainty envelope, whereas for GOCI-II, approximately 54–73% of retrievals fall within the MODIS-defined expected error range of $\pm(0.05 + 0.15 \times \text{AOD})$. These performance metrics should be interpreted with consideration of aerosol loading, surface reflectance heterogeneity, and viewing geometry, all of which can influence retrieval accuracy. Seasonal variability further modulates retrieval performance. During the rainy and summer seasons, the validation performance of GEMS-derived AOD has been reported to decline, with lower correlations against ground-based AERONET measurements compared to dry seasons. This degradation has been attributed to increased cloud cover and residual sub-pixel cloud contamination, which elevate retrieval uncertainties in UV–visible aerosol algorithms [86]. High relative humidity and complex aerosol microphysical states (e.g., hygroscopic growth and mixed modes), typical of summer environments, may also deviate from the aerosol optical models assumed in the retrieval algorithm, further contributing to seasonal biases in GEMS AOD estimates [87]. In contrast, GOCI-II AOD demonstrates mean values that are generally consistent with AERONET 500 nm observations. However, under wintertime high-pollution conditions, retrieval performance may also be affected. Elevated aerosol loadings can introduce nonlinear radiative responses, including enhanced multiple scattering and potential saturation effects, thereby amplifying retrieval uncertainties. Increased concentrations of absorbing aerosols, particularly BC, may further deviate from the assumed aerosol optical properties (e.g., single-scattering albedo and phase function) embedded in the lookup tables, leading to systematic biases. Additionally, shallow planetary boundary layer heights and strong vertical gradients during stagnation events may decouple column-integrated AOD from near-surface aerosol concentrations, increasing discrepancies in satellite–ground comparisons. Low solar elevation angles and uncertainties in surface reflectance estimation under winter conditions may further contribute to seasonal retrieval errors [88].

The comparison of CO_2 concentrations retrieved from the GOSAT, GOSAT-2, and OCO-2 sensors with the surface measurements at the SORS site is shown in Figure 10c. Despite the differences in observation geometry, spectral resolution, and retrieval algorithms, the satellite-derived CO_2 concentrations consistently exhibited lower values than the ground-based measurements, with a mean difference of approximately 5 ppm. Among the satellite products, the agreement with the 1:1 line showed the following order: GOSAT-2 (red) > GOSAT (blue) > OCO-2 (gold), with the discrepancies between them becoming more pronounced at higher CO_2 concentrations. The error bars associated with the surface observations were largest in fall, indicating enhanced temporal variability in near-surface CO_2 concentrations during this season. The seasonal CO_2 box plots (Figure 10d) revealed a clear temporal evolution, with the CO_2 concentrations increasing from winter 2021 to spring 2021 and reaching their lowest values during the wet summer period. Thereafter, the CO_2 concentrations gradually increased again, reaching their highest levels in spring 2022. Both the ground-based and satellite observations consistently captured this temporal evolution, indicating a high degree of consistency in the observed seasonal variability.

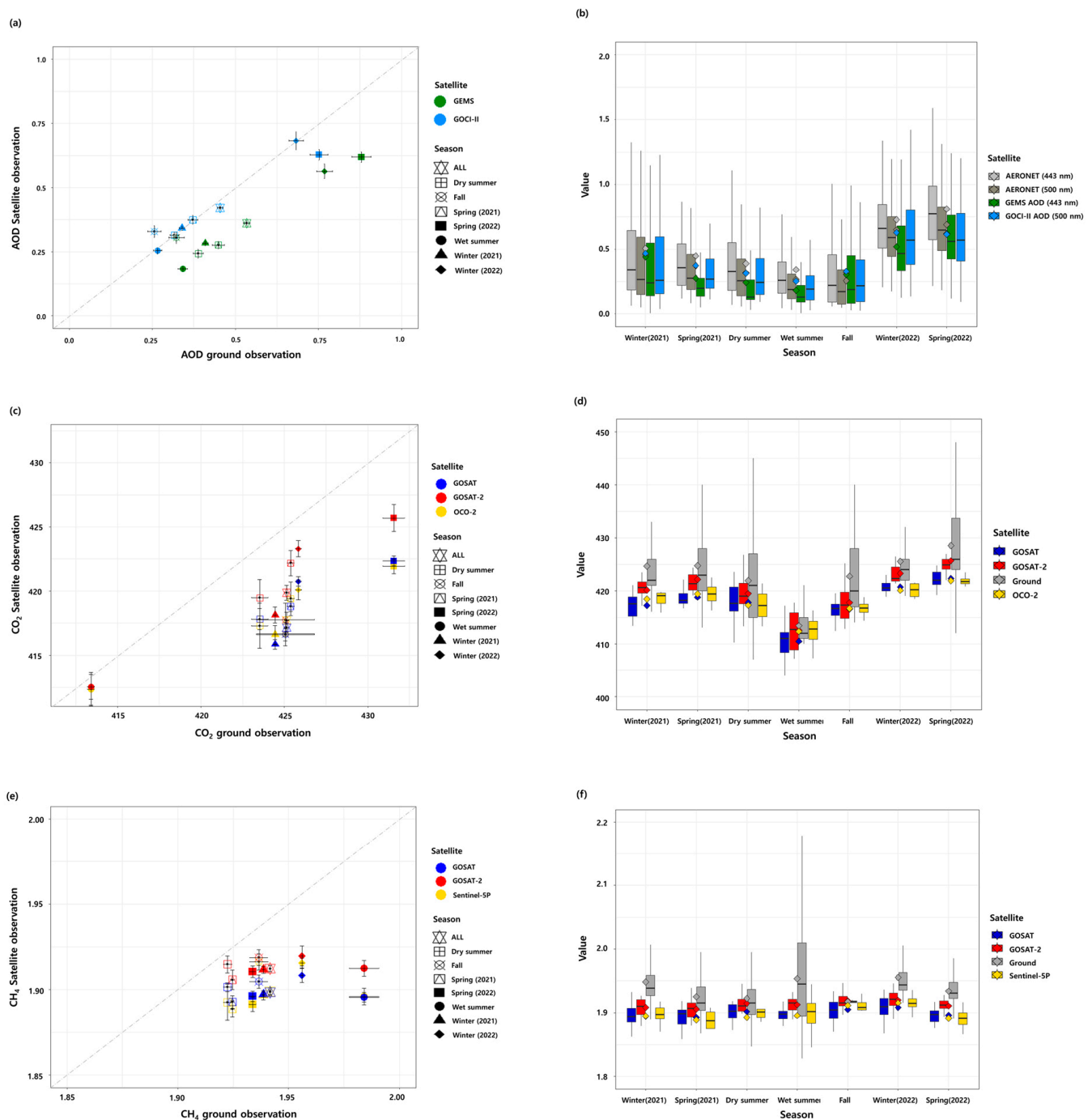


Figure 10. Comparison of aerosol optical depth (AOD), carbon dioxide (CO₂), and methane (CH₄) between ground-based and satellite observations: (a,b) AOD, (c,d) CO₂, and (e,f) CH₄. Panels (a,c,e), show scatterplots with the 1:1 reference line, and panels (b,d,f) show the corresponding seasonal box plots. Diamonds indicate mean values, and error bars represent data variability.

Figure 10e presents a comparison of the CH₄ concentrations retrieved from the GOSAT, GOSAT-2, and Sentinel-5P with the ground-based measurements conducted at the SORS site. Overall, GOSAT-2 exhibited the best agreement with the surface observations, outperforming both GOSAT and Sentinel-5P. This improved performance was largely attributable to the differences in the spectral absorption bands and retrieval strategies adopted by GOSAT and GOSAT-2. Within the concentration range of 1.88–1.92 ppm, the GOSAT-2 product retrievals closely followed the 1:1 line, while GOSAT showed a similar trend but with a systematic underestimation of 0.02 ppm. During periods of elevated CH₄ concen-

trations, particularly in the wet summer and winter seasons of 2022, both GOSAT-2 and Sentinel-5P successfully capture high-concentration events, albeit their general tendency toward underestimation.

When evaluating the overall performance of the satellite retrievals of CH₄, the proximity to the 1:1 line showed the following order: GOSAT-2 > GOSAT > Sentinel-5P, with the differences becoming more pronounced at higher concentrations. The elevated near-surface CH₄ concentrations observed in summer were primarily attributed to enhanced biogenic emissions from terrestrial ecosystems, such as rice paddies and wetlands, known to be strong methane sources under warm and humid conditions. In contrast, the satellite observations did not fully capture the summer CH₄ enhancements, instead exhibiting the highest concentrations in winter 2022 (Figure 10f). The wintertime enhancement of CH₄ may be partly associated with seasonally lower hydroxyl (OH) radical concentrations and reduced photochemical activity, which can weaken methane oxidation and thereby extend its atmospheric lifetime [100,101]. Previous studies have reported a decline in photochemical oxidation capacity over East Asian megacities during winter, largely due to reduced solar radiation and more stable boundary-layer conditions that constrain OH production [102,103]. Under such conditions, a diminished oxidative sink may contribute to the seasonal accumulation of methane.

Satellite column retrievals and ground-based in situ measurements differ fundamentally in methodology and vertical sensitivity. Satellite products (e.g., XCO₂ and XCH₄) represent vertically integrated, column-averaged mole fractions shaped by averaging kernels and a priori constraints, whereas ground-based CRDS observations reflect near-surface concentrations influenced by boundary-layer dynamics and local flux variability. Accordingly, direct quantitative equivalence between surface and column measurements is not expected. Instead, this study focuses on the inter-comparison of variability, temporal co-evolution, and episodic enhancement signals, enabling assessment of whether large-scale atmospheric perturbations are consistently captured across vertically distinct observational platforms.

4.2. Meteorological and Emission-Related Factors During a Winter Aerosol Episode

The winter haze accumulation episode observed between 10 and 20 December 2021 provides a representative example of meteorologically driven aerosol enhancement over the SORS (Figure 11a), with panels (b) and (c) showing GEMS AOD (443 nm) imagery at 02:45 and 04:45 UTC on 15 December 2021. A pronounced aerosol loading event peaked on 15 December, with AOD exceeding 1.5 and remaining elevated until 17 December. Such sustained enhancement is physically consistent with suppressed atmospheric ventilation and hygroscopic aerosol growth under increasing relative humidity (RH) and temperature conditions. The simultaneous increase in RH and temperature likely facilitated secondary aerosol formation and water uptake by existing particles, thereby amplifying column extinction. Under high-RH conditions, particle hygroscopic growth increases scattering efficiency, leading to disproportionately large increases in retrieved AOD relative to dry aerosol mass concentration. This mechanism plausibly explains the rapid amplification and persistence of AOD during this period. Beginning on 14 December, concurrent increases in surface CO₂ and CO, together with declining wind speed, suggest reduced horizontal dispersion and progressive accumulation within a shallow boundary layer. The CO₂/CO ratio remained near 0.9, a range often associated with combustion-dominated emission signatures, indicating that local and/or regional anthropogenic sources likely contributed to the buildup. In a stable winter boundary layer, such emission signals can accumulate efficiently due to weak vertical mixing. Subsequent changes on 17–18 December in temperature, RH, and the CO₂/CO ratio coincided with corresponding variations in AOD,

implying a transition in synoptic conditions or air mass origin. These coordinated shifts may indicate that the episode transitioned from a locally accumulated haze regime toward a state more influenced by transport processes, reflecting possible interactions among emission strength, boundary-layer stability, and regional circulation. Overall, this case underscores that severe winter aerosol episodes over coastal Northeast Asia are governed not solely by emission intensity but by the synergistic interaction between hygroscopic growth processes, boundary-layer suppression, and ventilation efficiency. Such meteorological modulation can substantially amplify column AOD signals even when emission rates remain relatively stable.

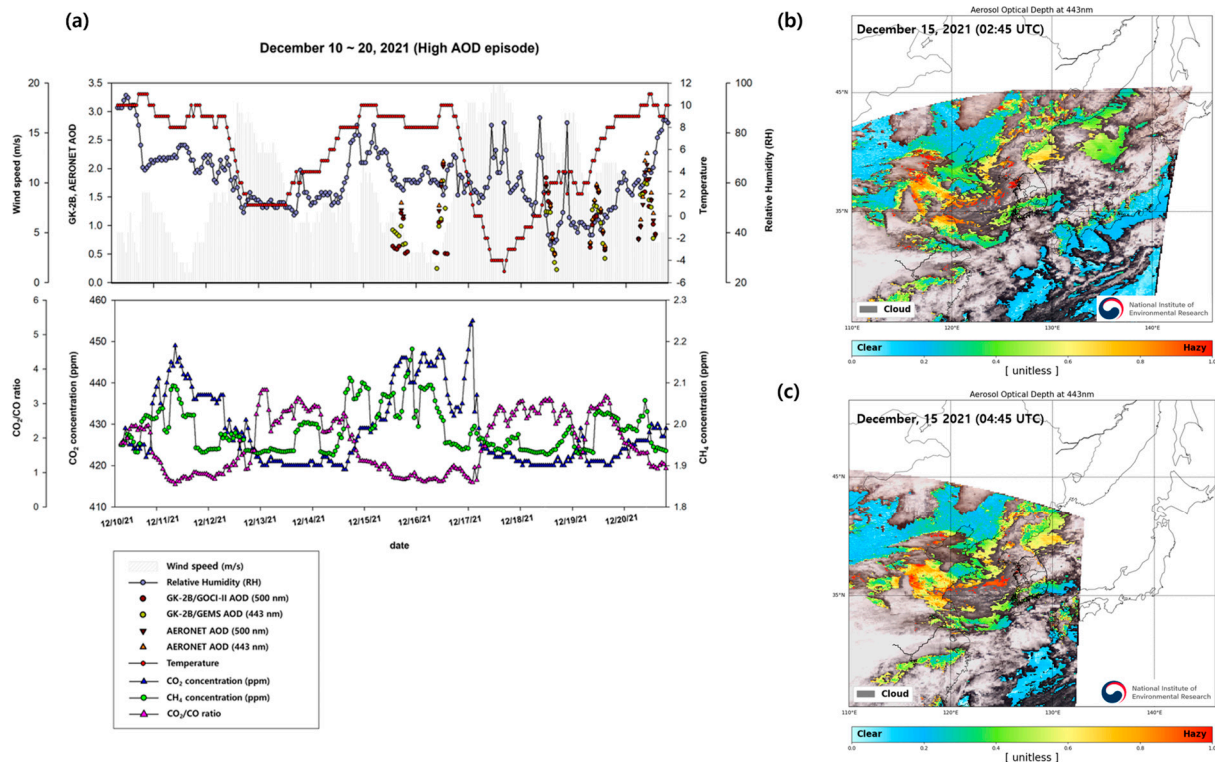


Figure 11. Time series of GK-2B AOD, AERONET AOD, and in situ carbon dioxide (CO₂) and methane (CH₄) at the Socheongcho Ocean Research Station (SORS) during a representative winter aerosol pollution episode (a), illustrating the coupled effects of haze accumulation. Wind speed is represented by gray bars; relative humidity by light steel blue circles; GOCI-II AOD by burgundy circles; GEMS AOD by gold circles; AERONET AOD (500 nm) by downward burgundy triangles; AERONET AOD (443 nm) by upward orange triangles; temperature by red circles; surface CO₂ concentration by upward blue triangles; surface CH₄ concentration by light green circles; and the CO₂/CO ratio by upward pink triangles. Panels (b,c) present GEMS AOD (443 nm) satellite images at 02:45 UTC and 04:45 UTC on 15 December 2021, respectively, highlighting the spatial evolution of aerosol loading during the episode. Abbreviations: Geo-KOMPSAT-2B (GK-2B), Aerosol Robotic Network (AERONET), Geostationary Environment Monitoring Spectrometer (GEMS), Geostationary Ocean Color Imager II (GOCI-II), relative humidity (RH), carbon dioxide/carbon monoxide (CO₂/CO) emission ratio, aerosol optical depth (AOD).

4.3. Boundary-Layer Conditions and Patterns Statistically Consistent with Transport During the High-CO₂ Episode

The high-CO₂ episode observed between 10 and 20 April 2022 illustrates variations statistically consistent with regional meteorological conditions, including boundary-layer variability and potential combustion-related influences (Figure 12a). Panels (b) and (c) show GEMS AOD (443 nm) imagery at 23:45 UTC on 14 April and 01:45 UTC on 15 April

2022. During this period, CO₂ and CH₄ concentrations increased, with the peak values for GEMS and GOCI-II being 0.916 and 1.07, indicating the influence of common source regions and large-scale transport processes rather than that of isolated local emissions. The sharp rise in surface CO₂ beginning on 17 April (reaching approximately 480 ppm on April 19), coinciding with a rapid increase in near-surface air temperature, reflects the sensitivity of CO₂ variability to boundary-layer dynamics. Under warming conditions, enhanced surface heating can initially promote vertical mixing; however, if synoptic stagnation or subsidence dominates, the effective ventilation depth may remain limited. In such scenarios, increased emissions—whether anthropogenic or ecosystem-derived—can accumulate efficiently within the lower troposphere [104,105].

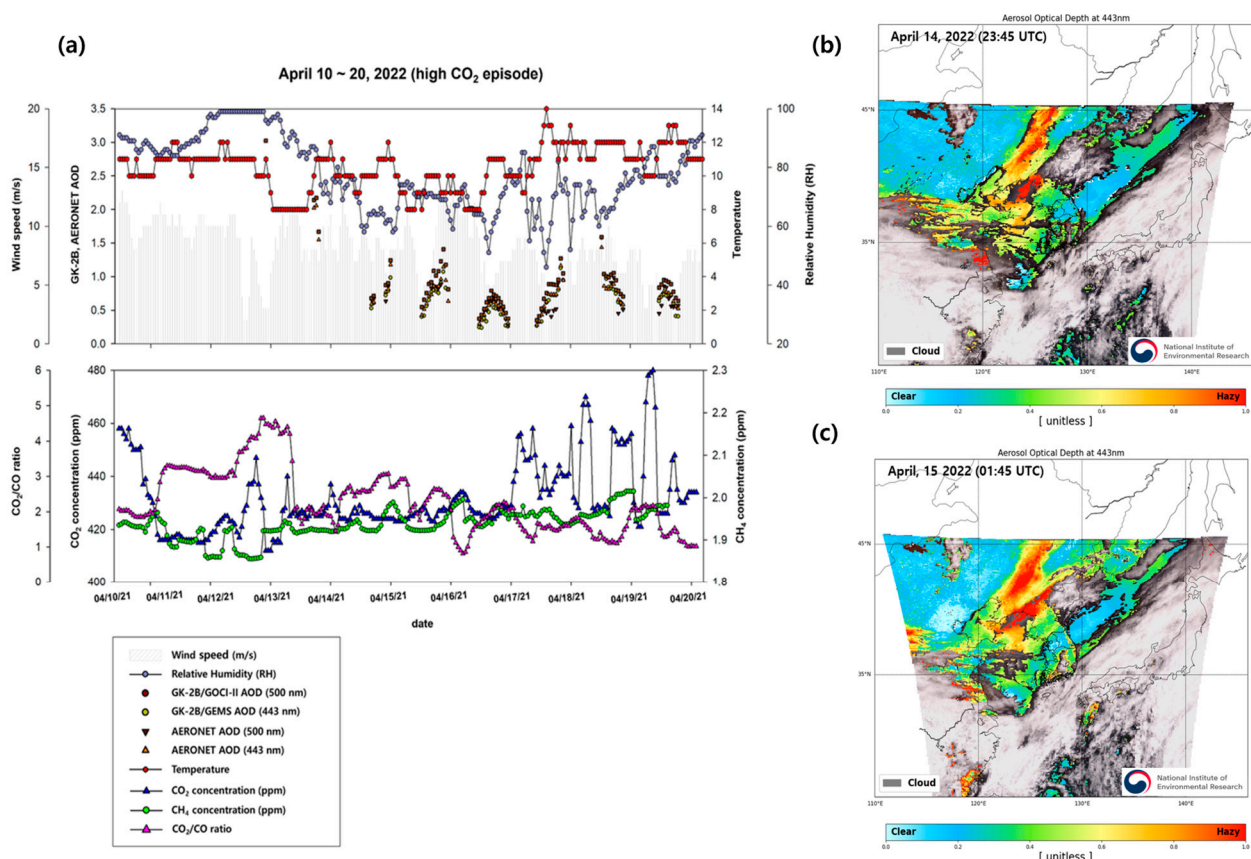


Figure 12. Time series of the GK-2B AOD, AERONET AOD, and in situ carbon dioxide (CO₂) and methane (CH₄) concentrations at the Socheongcho Ocean Research Station (SORS) during a representative CO₂ pollution episode in 11–20 April 2022 (a). Wind speed is represented by gray bars; relative humidity by light steel blue circles; GOCI-II AOD by burgundy circles; GEMS AOD by gold circles; AERONET AOD (500 nm) by downward burgundy triangles; AERONET AOD (443 nm) by upward orange triangles; temperature by red circles; surface CO₂ concentration by upward blue triangles; surface CH₄ concentration by light green circles; and the CO₂/CO ratio by upward pink triangles. Panels (b,c) display GEMS AOD (443 nm) satellite imagery corresponding to the high-CO₂ episode observed at 23:45 UTC on 14 April and 01:45 UTC on 15 April 2022, highlighting the progression of enhanced CO₂ levels during the event. Abbreviations: Geo-KOMPSAT-2B (GK-2B), Aerosol Robotic Network (AERONET), Geostationary Environment Monitoring Spectrometer (GEMS), Geostationary Ocean Color Imager II (GOCI-II), relative humidity (RH), carbon dioxide/carbon monoxide (CO₂/CO) emission ratio.

Climatologically, increasing surface temperatures after March in Northeast Asia are generally associated with enhanced photosynthetic activity and greater terrestrial carbon uptake, which often corresponds to a seasonal decline in CO₂ concentrations between

March and July [106]. However, during this episode, surface CO₂ concentrations remained relatively elevated. This pattern may reflect the combined influence of anthropogenic emissions and regional-scale transport processes, which could have offset or reduced the apparent impact of biospheric uptake during the study period. At the SORS site, relative humidity varied substantially (approximately 50–85%) and exhibited apparent co-variability with surface CO₂ concentrations. Given the coastal setting of SORS, water vapor—an important GHG in the marine troposphere—may have influenced radiative and boundary-layer thermodynamic conditions, thereby indirectly modulating near-surface CO₂ variability.

The decline in the CO₂/CO ratio during elevated CO₂ periods may reflect contributions from lower-efficiency combustion sources, with satellite fire observations indicating a possible role of regional biomass burning. However, the evidence does not allow definitive source attribution and is broadly consistent with mixed influences from anthropogenic emissions and continental transport. Overall, the ratio behavior aligns more closely with transported anthropogenic plumes than with enhanced biospheric respiration alone [107].

4.4. Potential Thermodynamic and Transport Influences During High-CH₄ Episodes

The dry summer episode observed between 20 and 30 June 2021 highlights the thermodynamic and biogeochemical controls on methane variability under humid monsoonal conditions (Figure 13a), with panels (b) and (c) showing GEMS AOD (443 nm) imagery at 00:45 and 02:45 UTC on 23 June 2021. During this period, both CH₄ and CO₂ concentrations remained persistently elevated, a pattern that may be consistent with the influence of regional anthropogenic emissions and long-range transport. Surface air temperature ranged from approximately 20 °C to 25 °C, while relative humidity frequently exceeded 90%, reflecting warm and humid meteorological conditions. Such conditions may have been conducive to enhanced CH₄ concentrations. The CH₄ concentrations increased to 2.04 ppm on 24 June 2021, reaching a maximum of 2.10 ppm on 26 June 2021. Previous studies demonstrated that CH₄ emissions are highly dependent on temperature, suggesting that the seasonal warming from late spring to summer may have enhanced the regional CH₄ flux in the study region [106,108]. Notably, temperature-related influences on CH₄ variability may be enhanced under moist conditions that favor anaerobic microbial activity in wetlands and agricultural soils. The elevated CH₄ concentrations observed at the SORS site during this episode were broadly consistent with thermally and hydrologically favorable conditions combined with atmospheric transport processes [109]. Globally, CH₄ emissions arise from both natural sources (e.g., wetlands and oceans) and anthropogenic activities, while in Northeast Asia, summertime emissions from rice paddies in eastern China are considered an important regional contributor. The high CH₄ levels observed at SORS may be consistent with, at least in part, regional transport of CH₄-enriched air masses, potentially modulated by vertical mixing associated with the East Asian summer monsoon. However, this interpretation remains indicative in the absence of detailed trajectory or source apportionment analysis. In addition, the CO₂/CO ratio began to increase on 24 June 2021, reaching a maximum value of 3.5 on 26 June 2021, which may suggest a relatively enhanced contribution from CO₂-rich combustion-related emission sources. Overall, the concurrent temporal evolution of aerosol loading and GHG concentrations observed during this episode appears to underscore the potential value of integrating satellite-derived AOD with ground-based GHG measurements to better constrain the source characteristics, transport pathways, and meteorological influences under complex summertime conditions.

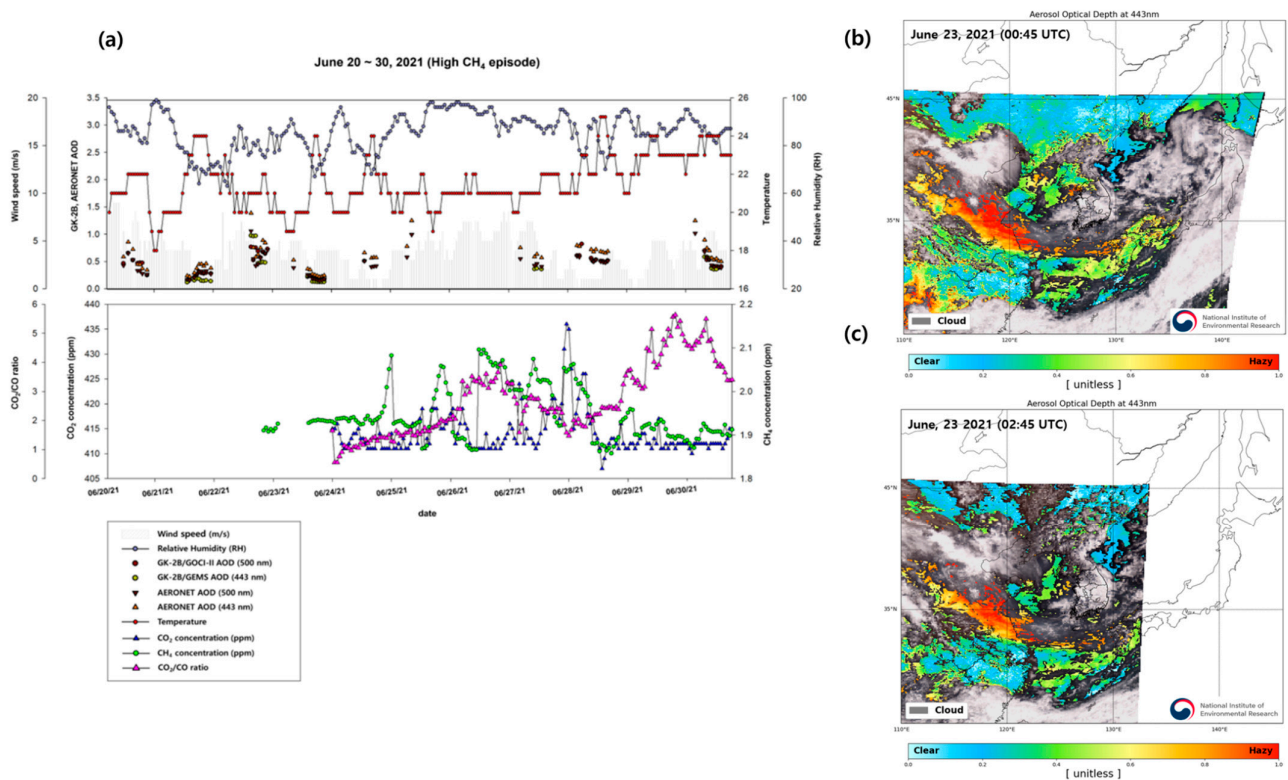


Figure 13. Time series of GK-2B AOD, AERONET AOD, and in situ CO_2 and CH_4 concentrations at the Socheongcho Ocean Research Station (SORS) during a representative dry-summer pollution episode (a), illustrating the coupled effects of monsoon-driven long-range transport and meteorological enhancement of regional emissions. Wind speed is represented by gray bars; relative humidity by light steel blue circles; GOCI-II AOD by burgundy circles; GEMS AOD by gold circles; AERONET AOD (500 nm) by downward burgundy triangles; AERONET AOD (443 nm) by upward orange triangles; temperature by red circles; surface CO_2 concentration by upward blue triangles; surface CH_4 concentration by light green circles; and the CO_2/CO ratio by upward pink triangles. Panels (b,c) show GEMS AOD (443 nm) satellite imagery corresponding to the high- CH_4 episode at 00:45 and 02:45 UTC on 23 June 2021. Abbreviations: Geo-KOMPSAT-2B (GK-2B), Aerosol Robotic Network (AERONET), Geostationary Environment Monitoring Spectrometer (GEMS), Geostationary Ocean Color Imager II (GOCI-II), relative humidity (RH).

4.5. Correlation Analysis of Aerosol, Greenhouse Gas, and Meteorological Variables

Correlation plots are used to visualize correlation coefficients among multiple variables, enabling rapid assessments of both the strength and direction of linear relationships. Correlation coefficients are generally represented using color gradients (cool and warm colors indicating positive and negative correlations, respectively), symbol size, and intensity, thereby facilitating intuitive interpretation of complex multivariate relationships. In this study, a correlation analysis was applied to ground-based and satellite-based observations of AOD, GHG, and meteorological variables across the study period (Figure 14). First, the GEMS AOD data showed a strong positive correlation with RH and exhibited correlation patterns comparable to those of the GOSAT and GOSAT-2 CO_2 products. In contrast, GEMS AOD displayed a negative correlation with wind speed, a pattern consistent with reduced ventilation conditions coinciding with elevated aerosol loading. Second, the GOCI-II AOD data showed positive correlations with CH_4 products from GOSAT and GOSAT-2, as well as with CO_2 products from OCO-2 and ground-based observations. Given that the GOCI-II AOD retrieval is based on visible (VIS) channel measurements, surface reflectance characteristics and vegetated land cover may contribute to the observed co-variation between aerosol loading and GHG concentrations. This highlights the need to carefully consider aerosol scattering

and surface reflectance effects in satellite-based GHG analyses. Third, CO₂ concentrations exhibited generally positive correlations across multiple satellite GHG products. Stronger correlations were observed between CO₂ and fine-mode aerosol indicators, including FMF and fine-mode AOD. As FMF represents the relative contribution of fine particles, this pattern is statistically consistent with CO₂ variability co-occurring with fine-mode aerosol variability, which is often associated with anthropogenic influences. Finally, ground-based CH₄ concentrations showed a positive correlation with BC and a negative correlation with temperature. These relationships are consistent with enhanced combustion-related influences during colder conditions; however, direct source attribution was not performed. Overall, the correlation patterns indicate close statistical coupling among aerosol properties, GHG variability, and meteorological conditions. The integrated AOD–GHG observations provide complementary information for examining regional atmospheric variability; however, causal interpretations should always be treated with caution.

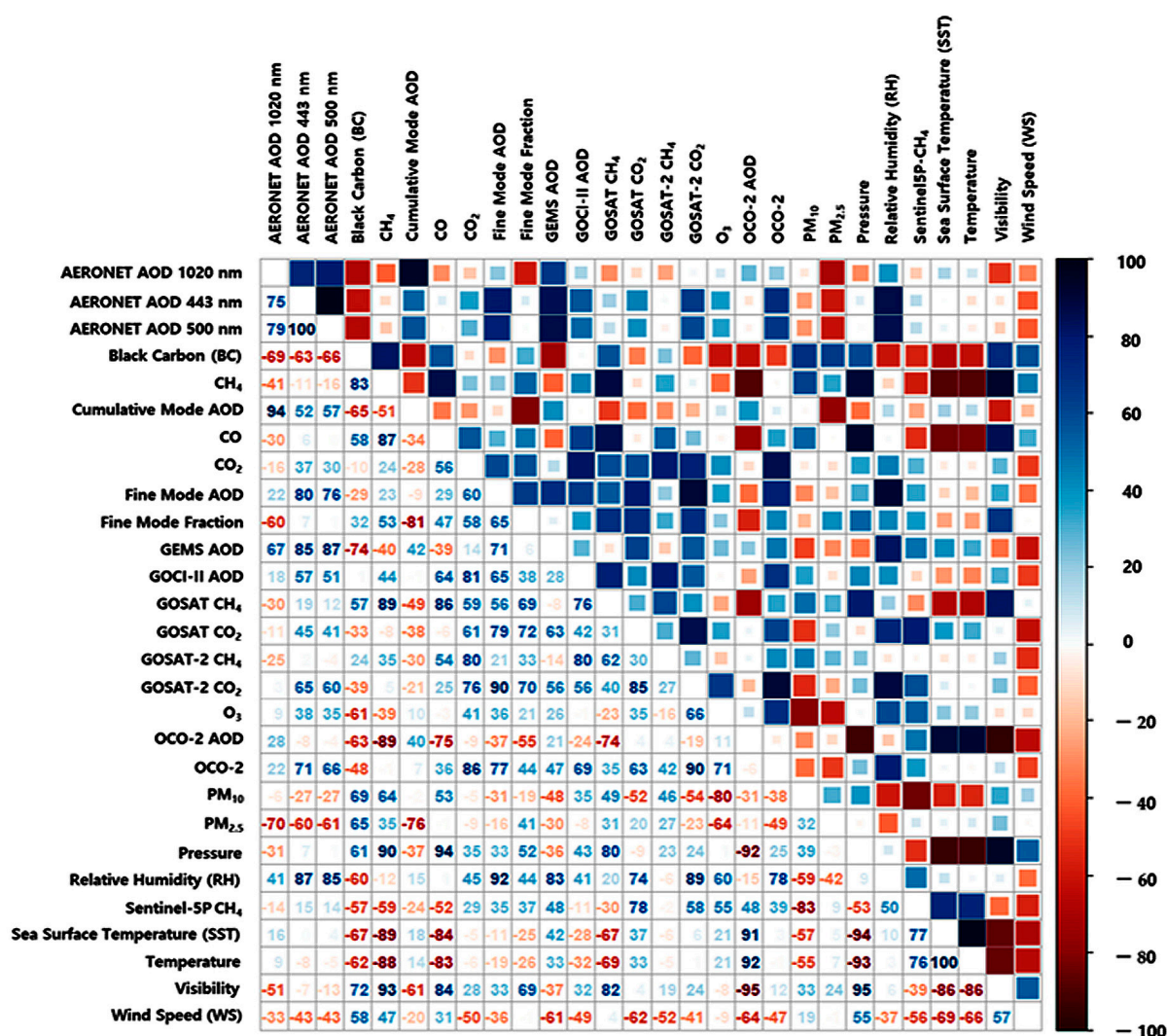


Figure 14. Correlation matrix among aerosol optical depth (AOD), greenhouse gases (GHGs), and meteorological variables derived from ground-based and satellite observations across the study period. The colors indicate the sign and magnitude of the correlation coefficients (warm colors for negative correlations and cool colors for positive correlations), and the symbol size represents the correlation strength. Abbreviations: Aerosol Robotic Network (AERONET), Geostationary Environment Monitoring Spectrometer (GEMS), Geostationary Ocean Color Imager II (GOCI-II), aerosol optical depth (AOD), sea surface temperature (SST), black carbon (BC), particulate matter (PM_{2.5} and PM₁₀), Orbiting Carbon Observatory-2 (OCO-2), relative humidity (RH), wind speed (WS).

Figure 15 presents the heatmap-based feature significance analysis for GHG concentrations and the GK-2B AOD data. To investigate the seasonal drivers across the study region in greater detail, hierarchical cluster analysis was performed based on seasonal (Figure 15a) and monthly (Figure 15b) groupings, which incorporated aerosol optical properties, gaseous constituents, and meteorological parameters. The heatmap was constructed using Pearson correlation coefficients calculated from hourly values, including only temporally overlapping data points in the analysis. Missing values were treated using pairwise complete observations, and all variables were standardized through z-score normalization prior to clustering to ensure comparability across differing units and magnitudes. Each element in the heatmap represents the relative strength of statistical association between individual features and the variability of GHG concentrations and GK-2B-retrieved AOD during the analysis period. As the heatmap framework is inherently exploratory and correlation-based, the identified patterns should be interpreted as indicative of co-variability rather than evidence of direct causal relationships.

Among the target GHGs, CH₄ exhibited a distinctly different behavior compared to the trends of GK-2B AOD and CO₂ concentrations. For CH₄, water vapor-related variables emerged as the dominant controlling factors, particularly during the wet summer season, when CH₄ concentrations reached their seasonal maxima. In addition, the FMF showed the strongest influence during the wet summer season, reflecting the predominance of fine aerosol particles. The elevated CH₄ concentrations may be associated with long-range transport of CH₄-rich air masses and the vertical transport of CH₄ from the lower troposphere to the middle-to-upper troposphere during the monsoon period [110]. Owing to the relatively long atmospheric lifetime of CH₄, satellite-observed CH₄ distributions may be influenced not only by surface emission sources but also by large-scale atmospheric circulation and transport processes. Substantially higher temperatures (e.g., surface, sea surface, and air temperatures) during summer may provide conditions conducive to enhanced biogenic methane emissions. Because CH₄ is primarily removed through reactions with hydroxyl (OH) radicals in the troposphere, the seasonal enhancement in CH₄ concentrations may be associated with a combination of emission variability, photochemical processes, and vertical exchange between the boundary layer and the free troposphere [100,101].

During the dry summer, strong associations were identified between the Ångström exponent (AE_{440–670}), RH, water evaporation, and ozone, which may indicate atmospheric conditions favorable for the formation of hygroscopic aerosols. The Ångström exponent (AE_{440–670}) appeared to reflect pronounced spectral variability in aerosol size distribution, particularly for accumulation-mode aerosols; during the dry summer, it was more strongly associated with fine particles than coarse particles. Similarly, AE_{440–870} is generally considered to characterize the relative dominance of fine-mode aerosols, with larger values suggesting a higher proportion of small particles. These findings are consistent with the possibility that aerosol composition during the dry summer was influenced predominantly by fine-mode particles. The highest GK-2B AODs during the analysis period were observed in June 2021. Although aerosol loading was elevated during the dry summer season, hygroscopic growth appeared to be enhanced during the subsequent wet summer (July 2021), driven by increased RH and evolving meteorological conditions. This seasonal transition may reflect the combined effects of aerosol accumulation and moisture-driven growth processes.

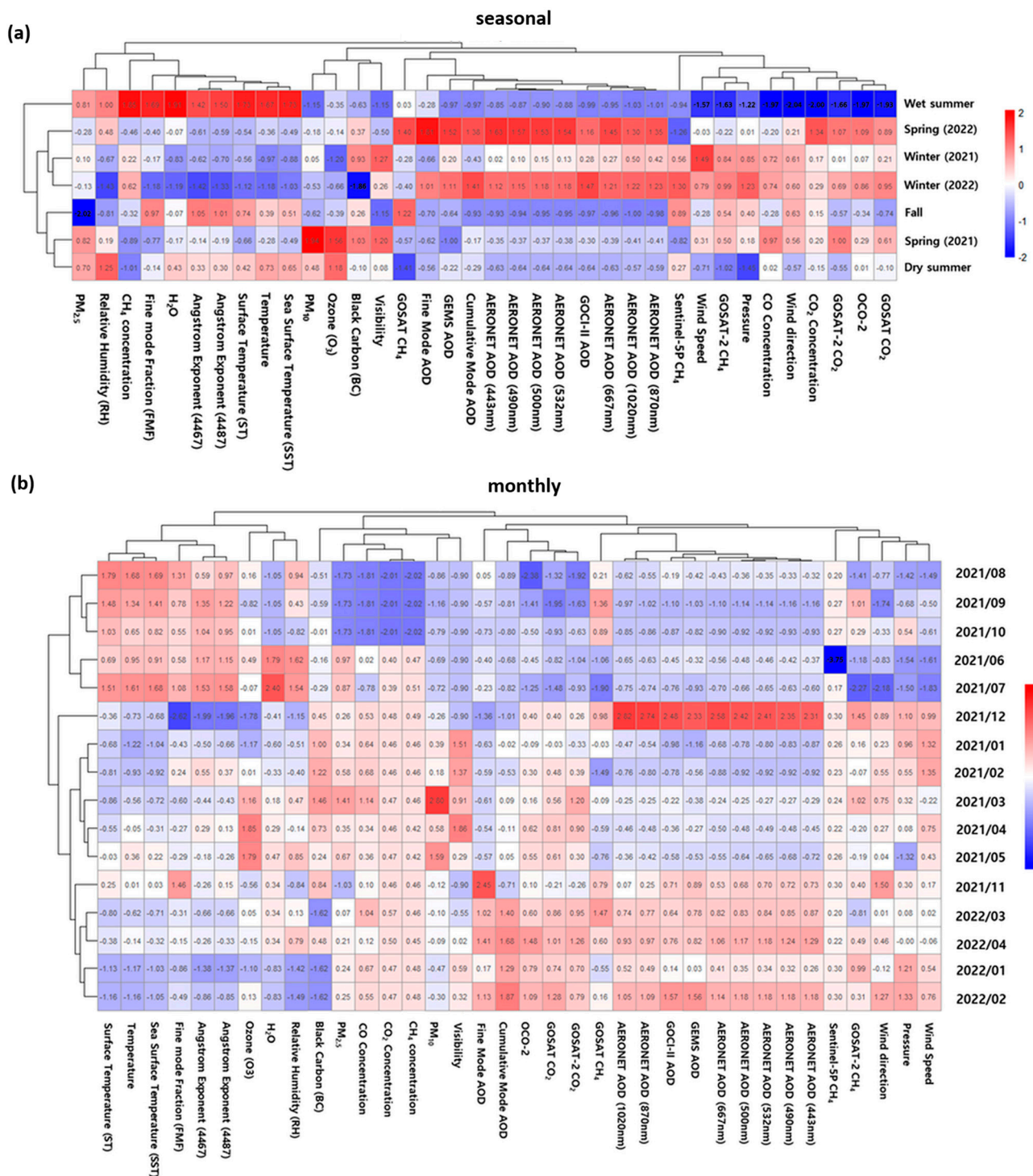


Figure 15. Heatmap-based feature significance analysis for GK-2B AOD and greenhouse gas (GHG) concentrations over the study period showing the relative contributions of aerosol, gaseous, and meteorological variables. **(a)** Seasonal and **(b)** monthly clustering results from hierarchical cluster analysis. Warmer colors indicate stronger contributions. Abbreviations: Aerosol Robotic Network (AERONET), Geostationary Environment Monitoring Spectrometer (GEMS), Geostationary Ocean Color Imager II (GOCI-II), aerosol optical depth (AOD), sea surface temperature (SST), black carbon (BC), particulate matter (PM_{2.5} and PM₁₀), Orbiting Carbon Observatory-2 (OCO-2), relative humidity (RH), surface temperature (ST), fine-mode fraction (FMF).

In contrast, during the fall season, CO₂ appeared to play a more prominent role, surpassing aerosol optical properties in importance. Among gaseous species, GOSAT CH₄

and Sentinel-5P CH₄ were also found to be strongly associated with CO₂, representing primary anthropogenic pollutant signatures. In general, these gases, largely produced by incomplete combustion processes, serve as effective tracers of anthropogenic influence on air masses. The winter season was characterized by patterns consistent with the combined influence of both CO₂ and AOD, with winter 2022 showing relatively more pronounced features compared to winter 2021. Notably, total AOD from AERONET reached its second-highest seasonal level in winter, with fine-mode aerosols appearing to exert a substantial influence. Elevated AERONET AOD values were observed across all wavelength bands, regardless of particle size classification, while CO₂ concentrations remained comparatively high in both ground-based and satellite observations. In addition, higher BC concentrations and lower wind speeds in winter 2021, relative to winter 2022, are consistent with the possible coexistence of enhanced aerosol scattering and absorption processes associated with primary combustion sources.

Spring appeared to represent the peak season for both GK-2B AOD and CO₂ concentrations. The AERONET AOD values were elevated in both fine and coarse modes, showing pronounced enhancements in 2022 than those observed in 2021, a pattern broadly consistent with the wintertime patterns. The seasonal gradient in spectral AOD variability between shorter and longer wavelengths may indicate an asymmetric aerosol size distribution and a seasonal shift in the dominance of fine- and coarse-mode aerosols. Elevated PM_{2.5} and PM₁₀ concentrations may further support the increased presence of coarse particles near the surface during spring.

5. Conclusions

The main conclusions of the study are summarized below:

- Complementary GK-2B AOD product retrieval capabilities: The GK-2B aerosol observing system provides two physically complementary AOD products. The GEMS AOD product, based on NUV hyperspectral measurements, showed strong sensitivity over high-reflectance surfaces and source regions in East Asia; meanwhile, the GOCI-II AOD product, derived from VIS channel reflectance, was particularly effective for tracking aerosol transport and evolution over the Korean Peninsula and the Yellow and East China seas.
- Validation against AERONET observations: While acknowledging inherent retrieval uncertainties, both GK-2B AOD products showed strong agreement with the AERONET observations (GEMS: $R^2 = 0.78$, slope = 0.77; GOCI-II: $R^2 = 0.91$, slope = 0.95), supporting their general applicability for regional-scale aerosol analyses.
- Pronounced seasonal contrast in aerosol loading: During spring 2022 (March–April), the GK-2B/GEMS AOD values were approximately six times (0.619 ± 0.292 for GEMS and 0.682 ± 0.492 for GOCI-II) than those observed in the wet summer season in 2021 (0.182 ± 0.153 for GEMS and 0.254 ± 0.221 for GOCI-II) at the SORS; this pattern is broadly consistent with enhanced continental outflow and episodic haze conditions in spring, whereas lower summer values may be associated with monsoon-related wet removal processes.
- Consistent seasonal behavior of CO₂ and distinct behavior of CH₄: Surface CO₂ concentrations in spring (431.56 ± 12.422 ppm) were higher than those observed in the wet summer (413.42 ± 3.13 ppm), a pattern that may be associated with enhanced anthropogenic activities and transport processes in spring. The maximum CH₄ concentrations were observed during the wet summer (1.981 ± 0.1 ppm), which may reflect enhanced biogenic emissions under warm and humid conditions.
- Different controlling factors for GEMS and GOCI-II AOD products: The GEMS AOD product was more strongly associated with RH and wind speed, highlighting the

roles of hygroscopic growth and atmospheric stagnation; the GOCI-II AOD product appeared to be more closely linked to FMF and the surface- and satellite-based CO₂ and CH₄ concentrations, which may indicate a tighter coupling with fine anthropogenic aerosols.

- Seasonally varying aerosol–GHG coupling characteristics: CH₄ variability during the wet summer season may be associated with water vapor, temperature, fine-mode fraction (FMF), and potential long-range transport influences, whereas variability in the dry summer appears more closely related to hygroscopic fine particles.
- Systematic underestimation of surface GHGs by satellites: Satellite XCO₂ and XCH₄ products generally underestimated surface concentrations, with GOSAT-2 showing the closest agreement to the 1:1 line. Discrepancies in satellite and ground-based observations increased at higher concentrations and varied seasonally, reflecting differences in vertical sensitivity and retrieval assumptions.
- Process-oriented interpretation of CH₄ seasonality: The observed seasonal cycle of CH₄ may be consistent with the combined influence of enhanced biogenic emissions during summer and seasonally reduced OH-mediated oxidation in winter, indicating possible interactions among emission variability, atmospheric chemistry, and transport processes.

This study conducted an integrated analysis of GK-2B (GEMS and GOCI-II) AOD products and in situ greenhouse gas (GHG) measurements at the SORS site to explore the coupled variability of aerosols and trace gases over Northeast Asia. The results suggest that atmospheric composition at the SORS site may be influenced by a combination of local emission sources and long-range transport of combustion-related pollutants originating from the Asian continent. These findings are consistent with the potential role of transboundary transport in modulating regional air quality and background atmospheric composition. Furthermore, strong complementarity between ground-based and satellite observations was observed.

In addition, a more robust assessment of interannual variability, long-term trends, and source–receptor relationships of aerosols and GHGs over Northeast Asia would likely require sustained long-term measurements and an expanded observational network, and future studies incorporating vertical observations. Future efforts integrating continuous ground-based observations with geostationary satellite products may provide improved constraints on source attribution and transport processes, thereby potentially strengthening the scientific utility and reliability of geostationary atmospheric composition observations. Overall, this paper proposes a framework for evaluating the coupled dynamics of aerosols and GHGs at the regional scale during high-concentration episodes, which may be applicable to other regions for environmental and atmospheric investigations.

Author Contributions: Conceptualization: S.A. and M.L.; methodology: S.A.; software: S.A.; validation: S.A.; formal analysis: S.A. and M.L.; investigation: S.A.; resources: S.A.; data curation: S.A. and J.-Y.J.; writing—original draft preparation: S.A.; writing—review and editing: M.L. and L.-S.C.; visualization: S.A.; supervision: M.L.; project administration: L.-S.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Korea Institute of Marine Science & Technology Promotion (KIMST) project (RS-2021-KS211502, “Establishment of the Ocean Research Station in the Jurisdiction Zone and Convergence Research”) and the National Institute of Environmental Research (NIER) project, “GEMS-Based Air Quality Study in Asia” (NIER-2025-04-02-114).

Data Availability Statement: The data presented in this study are available upon request from the corresponding author, subject to restrictions related to privacy or ethical considerations.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Description of Satellite Retrieval Algorithms for CO₂, CH₄, and AOD

Table A1. Comparison between GOSAT/GOSAT2 (FOCAL) and OCO-2 (ACOS) CO₂ retrieval Approaches.

CO ₂	GOSAT (TANSO-FTS)	GOSAT-2 (TANSO-FTS-2)	OCO-2
Retrieval algorithm type	Full-Physics (FP)	Full-Physics (FP)	Proxy or Full-Physics (FP)
Spectral Bands used	O ₂ A-band (0.76 μ m) SWIR CO ₂ bands 1.65 μ m, 2.06 μ m	O ₂ A-band (0.76 μ m) SWIR CO ₂ bands 1.65 μ m, 2.06 μ m + expanded bands	O ₂ A-band (0.76 μ m) SWIR CO ₂ bands 1.65 μ m, 2.06 μ m
Detection scale/resolution	10 km	9 km	1.3 $\times$ 2.3 km ²
Cloud screening	Strict pre-filtering	Strict pre-filtering	Strict pre-filtering + post retrieval quality filtering
Aerosol handling	Retrieved jointly with XCO ₂ and surface pressure	Retrieved jointly with XCO ₂ and surface pressure	Retrieved jointly (AOD, aerosol properties, cloud parameters)
Treatment of scattering	Single effective scattering layer (height, optical depth, Angstrom exponent)	Single effective scattering layer (height, optical depth, Angstrom exponent)	Explicit multi-parameter aerosol/cloud treatment
Strengths	Robust under moderate aerosol loading; Stable long-term record	Better SNR than GOSAT improved aerosol bias correction Stable long-term record	Highest spatial resolution detailed aerosol/cloud characterization
Limitations	Simplified scattering representation, coarse resolution	Simplified scattering representation, coarse resolution	Increased sensitivity to aerosol uncertainties in polluted regions
Inversion model	Optimal estimation (Levenberg–Marquardt–Fletcher)	Optimal estimation (Levenberg–Marquardt–Fletcher)	Optimal estimation

Table A2. Comparison between GOSAT/GOSAT2 (Proxy XCH₄) and Sentinel-5p (Full-Physics) retrieval Approaches.

CH ₄	GOSAT (TANSO-FTS)	GOSAT-2 (TANSO-FTS-2)	Sentinel-5P (TROPOMI)
Retrieval algorithm type	Proxy XCH ₄	Proxy XCH ₄	Proxy or Full-Physics (FP)
Retrieval concept	CH ₄ normalized by retrieved CO ₂ and scaled by a priori XCO ₂	CH ₄ normalized by retrieved CO ₂ and scaled by a priori XCO ₂	Direct physical retrieval of CH ₄ using RTM
Spectral Bands used	SWIR CH ₄ absorption near 1.65 μ m, 2.06 μ m	SWIR CH ₄ absorption near 1.65 μ m, 2.06 μ m	SWIR CH ₄ absorption near 2.3 μ m
Detection scale/resolution	10 km	9 km	7 $\times$ 7 km(early) -> 5.5 $\times$ 7 km
Treatment of scattering	Implicit (common-mode cancellation with CO ₂)	Implicit (common-mode cancellation with CO ₂)	Explicit (aerosol/cloud parameters jointly retrieved)
Aerosol influence	Reduced but not explicitly resolved	Reduced but not explicitly resolved	Explicitly modeled and retrieved
Dependence on CO ₂	Strong (accuracy depends on XCO ₂ retrieval)	Strong (accuracy depends on XCO ₂ retrieval)	Independent of CO ₂ retrieval
Strengths	reduced light-path bias Long-term stable CH ₄ record	Better SNR than GOSAT improved bias correction Long-term stable CH ₄ record	High spatial detail, explicit aerosol correction Daily global CH ₄ mapping extremely wide swath
Limitations	Limited physical interpretability, coarse resolution	Limited physical interpretability, coarse resolution	Increased uncertainty if aerosol model is inaccurate
Forward model and inversion	Line-by-line RTM, Optical Estimation (OE) inversion; multi-gas retrieval	Updated microphysical aerosol model; tighter multi-gas coupling	Nonlinear FP retrieval; PCA-based noise reduction

Table A3. Comparison between GK-2B/GEMS AOD and GEMS/GOCI-II AOD Retrieval Approaches.

AOD	GEMS	GOCI-II
Sensor type	UV-VIS spectrometer	Ocean color Imager (multispectral)
Spectral Range	300–500 nm	400–865 nm
Spectral Bands used	Continuous hyperspectral (0.6 nm resolution)	13 discrete bands
Detection scale/resolution	~7 km	250–500 m
Temporal resolution	1 h	1 h
AOD retrieval	UV spectral fitting with gas correction	Reflectance-based inversion similar to GK-2B
Forward model	UV-VIS absorption/scattering model + DOAS-like fitting	Radiative transfer + aerosol LUT
Surface reflectance treatment	Lambertian Equivalent reflectivity, UV reflectance small	BRDF + ocean surface model
Strengths	Wide coverage, UV dust detection, low surface reflectance uncertainty	Accurate land/ocean separation, fine scale AOD variability detection
Limitations	Low spatial resolution, higher noise over bright surfaces	Similar to GK-2B, retrieval failure near sunglint or coastlines

References

- Li, Z.; Xie, Y.; Shi, Y.; Li, Q.; Cohen, J.; Zhang, Y.; Han, Y.; Xion, W.; Liu, Y. A review of collaborative remote sensing observation of greenhouse gases and aerosol with atmospheric environment satellites. *Natl. Remote Sens. Bull.* **2022**, *26*, 795–816. [\[CrossRef\]](#)
- Ramana, M.V.; Chauhan, P. Global Climate Change. In *Advances in Geospatial Technologies for Natural Resource Management*; CRC Press: Boca Raton, FL, USA, 2024; pp. 439–474.
- Chin, M.; Kahn, R.; Remer, L.A.; Yu, H.; Rind, D.; Feingold, G.; Quinn, P.K.; Schwartz, S.E.; Streets, D.G.; DeCola, P.; et al. *Atmospheric Aerosol Properties and Climate Impacts*; U.S. Climate Change Science Program: Washington, DC, USA, 2009; Volume 2.
- Li, H.; Qui, J.; Zheng, B. Air-pollution-satellite-based CO₂ emission inversion: System evaluation, sensitivity analysis, and future research direction. *Atmos. Chem. Phys.* **2025**, *25*, 1949–1963. [\[CrossRef\]](#)
- Hu, K.; Feng, X.; Zhang, Q.; Shao, P.; Liu, Z.; Xu, Y.; Wang, S.; Wang, Y.; Wang, H.; Di, L.; et al. Review of satellite remote sensing of carbon dioxide inversion and assimilation. *Remote Sens.* **2024**, *16*, 3394. [\[CrossRef\]](#)
- Kondratyev, K.Y.; Ivlev, L.S.; Krapivin, V.F.; Varotsos, C.A. *Atmospheric Aerosol Properties: Formation, Processes and Impacts*; Springer: Berlin/Heidelberg, Germany, 2006.
- Lee, L.A.; Reddington, C.L.; Carslaw, K.S. On the relationship between aerosol model uncertainty and radiative forcing uncertainty. *Proc. Natl. Acad. Sci. USA* **2016**, *113*, 5820–5827. [\[CrossRef\]](#)
- Schuster, G.L.; Dubovik, O.; Arola, A. Remote sensing of soot carbon—Part 1: Distinguishing different absorbing aerosol species. *Atmos. Chem. Phys.* **2016**, *16*, 1565–1585. [\[CrossRef\]](#)
- Schuster, G.L.; Espinosa, W.R.; Ziemba, L.D.; Beyersdorf, A.J.; Rocha-Lima, A.; Anderson, B.E.; Martins, J.V.; Dubovik, O.; Ducos, F.; Fuertes, D.; et al. A laboratory experiment for the statistical evaluation of aerosol retrieval (STEAR) algorithms. *Remote Sens.* **2019**, *11*, 498. [\[CrossRef\]](#)
- Yu, H.; Kaufman, Y.J.; Chin, M.; Feingold, G.; Remer, L.A.; Anderson, T.L.; Balkanski, Y.; Bellouin, N.; Boucher, O.; Christopher, S.; et al. A review of measurement-based assessments of the aerosol direct radiative effect and forcing. *Atmos. Chem. Phys.* **2006**, *6*, 613–666. [\[CrossRef\]](#)
- Kokhanovsky, A.A. *Satellite Aerosol Remote Sensing over Land*; Leeuw, G., Ed.; Springer: Berlin/Heidelberg, Germany, 2009; Volume 111.
- Holben, B.N.; Eck, T.F.; Slutsker, I.A.; Tanre, D.; Buis, J.P.; Setzer, A.; Vermote, E.; Reagan, J.A.; Kaufman, Y.J.; Nakajima, T.; et al. AERONET—A federated instrument network and data archive for aerosol characterization. *Remote Sens. Environ.* **1998**, *66*, 1–16. [\[CrossRef\]](#)
- Sayer, A.M.; Hsu, N.C.; Lee, J.; Kim, W.V.; Burton, S.; Fenn, M.A.; Ferrare, R.A.; Kacenelenbogen, M.; LeBlanc, S.; Pistone, K.; et al. Two decades observing smoke above clouds in the south-eastern Atlantic Ocean: Deep Blue algorithm updates and validation with ORACLES field campaign data. *Atmos. Meas. Tech.* **2019**, *12*, 3595–3627. [\[CrossRef\]](#)
- Intergovernmental Panel on Climate Change (IPCC). *AR5 Synthesis Report: Climate Change 2014*; IPCC: Geneva, Switzerland, 2014; Volume 1059, p. 1072.
- Murray, V.; Kristie, L. IPCC special report on managing the risks of extreme events and disasters to advance climate change adaptation (SREX). *J. Epidemiol. Community Health* **2012**, *66*, 759–760. [\[CrossRef\]](#) [\[PubMed\]](#)

16. Masson-Delmotte, V.; Zhai, P.; Pirani, A.; Connors, S.L.; Péan, C.; Berger, S.; Caud, N.; Chen, Y.; Goldfarb, L.; Gomis, M.I.; et al. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2021. [\[CrossRef\]](#)
17. Ciais, P.; Sabine, C.; Bala, G.; Bopp, L.; Brovkin, V.; Canadell, J.; Chhabra, A.; DeFries, R.; Galloway, J.; Heimann, M.; et al. Carbon and Other Biogeochemical Cycles. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2013; pp. 465–570.
18. Reuter, M.; Buchwitz, M.; Schneising, O.; Noël, S.; Bovensmann, H.; Burrows, J.P. A fast atmospheric trace gas retrieval for hyperspectral instruments approximating multiple scattering—Part 2: Application to XCO₂ retrievals from OCO-2. *Remote Sens.* **2017**, *9*, 1102. [\[CrossRef\]](#)
19. Fraser, A.; Palmer, P.I.; Feng, L.; Bösch, H.; Parker, R.; Dlugokencky, E.J.; Krummel, P.B.; Langenfelds, R.L. Estimating regional fluxes of CO₂ and CH₄ using space-borne observations of XCH₄:XCO₂. *Atmos. Chem. Phys.* **2014**, *14*, 12883–12895. [\[CrossRef\]](#)
20. Janssens-Maenhout, G.; Pinty, B.; Dowell, M.; Zunker, H.; Andersson, E.; Balsamo, G.; Bézy, J.L.; Brunhes, T.; Bösch, H.; Bojkov, B.; et al. Toward an operational anthropogenic CO₂ emissions monitoring and verification support capacity. *Bull. Am. Meteorol. Soc.* **2020**, *101*, E1439–E1451. [\[CrossRef\]](#)
21. Keeling, C.D. The concentration and isotopic abundances of carbon dioxide in the atmosphere. *Tellus* **1960**, *12*, 200–203. [\[CrossRef\]](#)
22. Harris, D.C. Charles David Keeling and the story of atmospheric CO₂ measurements. *Anal. Chem.* **2010**, *82*, 7865–7870. [\[CrossRef\]](#)
23. Kirschke, S.; Bousquet, P.; Ciais, P.; Saunois, M.; Canadell, J.G.; Dlugokencky, E.J.; Bergamaschi, P.; Bergmann, D.; Blake, D.R.; Bruhwiler, L.; et al. Three decades of global methane sources and sinks. *Nat. Geosci.* **2013**, *6*, 813–823. [\[CrossRef\]](#)
24. McManus, J.B.; Nelson, D.D.; Zahniser, M.S. Design and performance of a dual-laser instrument for multiple isotopologues of carbon dioxide and water. *Opt. Express* **2015**, *23*, 6569–6586. [\[CrossRef\]](#)
25. Griffith, D.W.T.; Deutscher, N.M.; Caldow, C.; Kettlewell, G.; Riggenbach, M.; Hammer, S. A Fourier transform infrared trace gas and isotope analyser for atmospheric applications. *Atmos. Meas. Tech.* **2012**, *5*, 2481–2498. [\[CrossRef\]](#)
26. Miles, N.L.; Martins, D.K.; Richardson, S.J.; Rella, C.W.; Arata, C.; Lauvaux, T.; Davis, K.J.; Barkley, Z.R.; McKain, K.; Sweeney, C. Calibration and field testing of cavity ring-down laser spectrometers measuring CH₄, CO₂, and ^{δ13}CH₄ deployed on towers in the Marcellus Shale region. *Atmos. Meas. Tech.* **2018**, *11*, 1273–1295. [\[CrossRef\]](#)
27. Richardson, S.J.; Miles, N.L.; Davis, K.J.; Crosson, E.R.; Rella, C.W.; Andrews, A.E. Field testing of cavity ring-down spectroscopy analyzers measuring carbon dioxide and water vapor. *J. Atmos. Ocean. Technol.* **2012**, *29*, 397–406. [\[CrossRef\]](#)
28. Xiong, X.; Barnett, C.; Maddy, E.; Sweeney, C.; Liu, X.; Zhou, L.; Goldberg, M. Characterization and validation of methane products from the Atmospheric Infrared Sounder (AIRS). *J. Geophys. Res. Biogeosci.* **2008**, *113*, G00A01. [\[CrossRef\]](#)
29. Buchwitz, M.; Reuter, M.; Schneising, O.; Heymann, J.; Bovensmann, H.; Burrows, J.P. Towards an improved CO₂ retrieval algorithm for SCIAMACHY on ENVISAT. In *Proceedings of the Atmospheric Science Conference, Barcelona, Spain, 7–11 September 2009*; pp. 7–11.
30. Yokota, T.; Yoshida, Y.; Eguchi, N.; Ota, Y.; Tanaka, T.; Watanabe, H.; Maksyutov, S. Global concentrations of CO₂ and CH₄ retrieved from GOSAT: First preliminary results. *Sola* **2009**, *5*, 160–163. [\[CrossRef\]](#)
31. Suto, H.; Kataoka, F.; Kikuchi, N.; Knuteson, R.O.; Butz, A.; Haun, M.; Buijs, H.; Shiomi, K.; Imai, H.; Kuze, A. Thermal and near-infrared sensor for carbon observation Fourier-transform spectrometer-2 (TANSO-FTS-2) on the Greenhouse Gases Observing Satellite-2 (GOSAT-2) during its first year on orbit. *Atmos. Meas. Tech.* **2020**, *14*, 2013–2039. [\[CrossRef\]](#)
32. Crisp, D.; Pollock, H.R.; Rosenberg, R.; Chapsky, L.; Lee, R.A.; Oyafuso, F.A.; Frankenberg, C.; O'Dell, C.W.; Bruegge, C.J.; Doran, G.B.; et al. The on-orbit performance of the Orbiting Carbon Observatory-2 (OCO-2) instrument and its radiometrically calibrated products. *Atmos. Meas. Tech.* **2017**, *10*, 59–81. [\[CrossRef\]](#)
33. Massie, S.T.; Sebastian Schmidt, K.; Eldering, A.; Crisp, D. Observational evidence of 3-D cloud effects in OCO-2 CO₂ retrievals. *J. Geophys. Res. Atmos.* **2017**, *122*, 7064–7085. [\[CrossRef\]](#)
34. Crisp, D.; Fisher, B.M.; O'Dell, C.; Frankenberg, C.; Basilio, R.; Bösch, H.; Brown, L.R.; Castano, R.; Connor, B.; Deutscher, N.M.; et al. The ACOS CO₂ retrieval algorithm—Part II: Global XCO₂ data characterization. *Atmos. Meas. Tech.* **2012**, *5*, 687–707. [\[CrossRef\]](#)
35. O'dell, C.W.; Eldering, A.; Wennberg, P.O.; Crisp, D.; Gunson, M.R.; Fisher, B.; Frankenberg, C.; Kiel, M.; Lindqvist, H.; Mandrake, L.; et al. Improved retrievals of carbon dioxide from Orbiting Carbon Observatory-2 with the version 8 ACOS algorithm. *Atmos. Meas. Tech.* **2018**, *11*, 6539–6576. [\[CrossRef\]](#)
36. Aben, I.; Hasekamp, O.; Hartmann, W. Uncertainties in the space-based measurements of CO₂ columns due to scattering in the Earth's atmosphere. *J. Quant. Spectrosc. Radiat. Transf.* **2007**, *104*, 450–459. [\[CrossRef\]](#)
37. Frankenberg, C.; O'Dell, C.; Guanter, L.; McDuffie, J. Remote sensing of near-infrared chlorophyll fluorescence from space in scattering atmospheres: Implications for its retrieval and interferences with atmospheric CO₂ retrievals. *Atmos. Meas. Tech.* **2012**, *5*, 2081–2094. [\[CrossRef\]](#)

38. Ahn, S.; Lee, M.; Kim, H.S.; Sohn, E.H.; Jeong, J.Y. Near-time measurement of aerosol optical depth and black carbon concentration at Socheongcho Ocean Research Station: Aerosol episode case analysis. *Remote Sens.* **2025**, *17*, 382. [\[CrossRef\]](#)
39. Lee, D.; Jeong, J.Y.; Jang, H.K.; Min, J.O.; Kim, M.J.; Youn, S.H.; Lee, T.; Lee, S.H. Comparison of particulate organic carbon to Chlorophyll-*a* ratio based on the ocean color satellite data at the Jeodo and Socheongcho ocean research stations. *J. Coast. Res.* **2019**, *90*, 267–271. [\[CrossRef\]](#)
40. Lee, G.H.; Chang, J.; Kang, K.; Jeong, J.Y. Hydrodynamics and sediment transport at Socheongcho Ocean Research Station, Korea, in the Yellow Sea. *Water* **2024**, *16*, 23. [\[CrossRef\]](#)
41. Chen, H.; Winderlich, J.; Gerbig, C.; Hofer, A.; Rella, C.W.; Crosson, E.R.; Van Pelt, A.D.; Steinbach, J.; Kolle, O.; Beck, V.; et al. High-accuracy continuous airborne measurements of greenhouse gases (CO₂ and CH₄) using the cavity ring-down spectroscopy (CRDS) technique. *Atmos. Meas. Tech.* **2010**, *3*, 375–386. [\[CrossRef\]](#)
42. Yver Kwok, C.; Laurent, O.; Guemri, A.; Philippon, C.; Wastine, B.; Rella, C.W.; Vuillemin, C.; Truong, F.; Delmotte, M.; Kazan, V.; et al. Comprehensive laboratory and field testing of cavity ring-down spectroscopy analyzers measuring H₂O, CO₂, CH₄ and CO. *Atmos. Meas. Tech.* **2015**, *8*, 3867–3892. [\[CrossRef\]](#)
43. Joo, H.S.; Han, S.W.; Han, J.S.; Ndegwa, P.M. Emission characteristics of fine particles in relation to precursor gases in agricultural emission sources: A case study of dairy barns. *Atmosphere* **2023**, *14*, 171. [\[CrossRef\]](#)
44. Zalakeviciute, R.; Lopez-Villada, J.; Ochoa, A.; Moreno, V.; Byun, A.; Proaño, E.; Mejía, D.; Bonilla-Bedoya, S.; Rybarczrk, Y.; Vallejo, F. Urban air pollution in the Global South: A never-ending crisis? *Atmosphere* **2025**, *16*, 487. [\[CrossRef\]](#)
45. Giles, D.M.; Sinyuk, A.; Sorokin, M.G.; Schafer, J.S.; Smirnov, A.; Slutsker, I.; Eck, T.F.; Holben, B.N.; Lewis, J.R.; Campbell, J.R.; et al. Advancements in the Aerosol Robotic Network (AERONET) Version 3 database—Automated near-real-time quality control algorithm with improved cloud screening for Sun photometer aerosol optical depth (AOD) measurements. *Atmos. Meas. Tech.* **2019**, *12*, 169–209. [\[CrossRef\]](#)
46. Zhang, Z.; Li, J.; Che, H.; Dong, Y.; Dubovik, O.; Eck, T.; Gupta, P.; Holben, B.; Kim, J.; Lind, E.; et al. Long-term trends in aerosol properties derived from AERONET measurements. *EGU sphere* **2024**, *25*, 4617–4637. [\[CrossRef\]](#)
47. Dubovik, O.; Smirnov, A.; Holben, B.N.; King, M.D.; Kaufman, Y.J.; Eck, T.F.; Slutsker, I. Accuracy assessments of aerosol optical properties retrieved from Aerosol Robotic Network (AERONET) Sun and sky radiance measurements. *J. Geophys. Res. Atmos.* **2000**, *105*, 9791–9806. [\[CrossRef\]](#)
48. Sinyuk, A.; Holben, B.N.; Eck, T.F.; Giles, D.M.; Slutsker, I.; Korkin, S.; Schafer, J.S.; Smirnov, A.; Sorokin, M.; Lyapustin, A. The AERONET Version 3 aerosol retrieval algorithm, associated uncertainties and comparisons to Version 2. *Atmos. Meas. Tech.* **2020**, *13*, 3375–3411. [\[CrossRef\]](#)
49. Eck, T.F.; Holben, B.N.; Reid, J.S.; Dubovic, O.; Smirnov, A.; O’Neil, N.T.; Slutsker, I.; Kinne, S. Wavelength dependence of the optical depth of biomass burning, urban, and desert dust aerosols. *J. Geophys. Res. Atmos.* **1999**, *104*, 31333–31349. [\[CrossRef\]](#)
50. Reid, J.S.; Eck, T.F.; Christopher, S.A.; Hobbs, P.V.; Holben, B.N. Use of the Ångström exponent to estimate the variability of optical and physical properties of aging smoke particles in Brazil. *J. Geophys. Res. Atmos.* **1999**, *104*, 27473–27489. [\[CrossRef\]](#)
51. Smirnov, A.; Holben, B.N.; Kaufman, Y.J.; Dubovic, O.; Eck, T.F.; Slutsker, I.; Pietras, C.; Halthore, R.N. Optical properties of atmospheric aerosol in maritime environments. *J. Atmos. Sci.* **2002**, *59*, 501–523. [\[CrossRef\]](#)
52. Kaskaoutis, D.G.; Kambezidis, H.D.; Hatzianastassiou, N.; Kosmopoulos, P.G.; Badarinath, K.V.S. Aerosol climatology: Dependence of the Angstrom exponent on wavelength over four AERONET sites. *Atmos. Chem. Phys.* **2007**, *7*, 7347–7397. [\[CrossRef\]](#)
53. Choi, W.J.; Moon, K.J.; Yoon, J.; Cho, A.; Kim, S.K.; Lee, S.; Ko, D.H.; Kim, J.; Ahn, M.H.; Kim, D.R.; et al. Introducing the geostationary environment monitoring spectrometer. *J. Appl. Remote Sens.* **2018**, *12*, 044005. [\[CrossRef\]](#)
54. Kang, M.; Ahn, M.H.; Liu, X.; Jeong, U.; Kim, J. Spectral calibration algorithm for the geostationary environment monitoring spectrometer (GEMS). *Remote Sens.* **2020**, *12*, 2846. [\[CrossRef\]](#)
55. Lim, H.; Go, S.; Kim, J.; Choi, M.; Lee, S.; Song, C.K.; Kasai, Y. Integration of GOCI and AHI Yonsei aerosol optical depth products during the 2016 KORUS-AQ and 2018 EMeRGe campaigns. *Atmos. Meas. Tech.* **2021**, *14*, 4575–4592. [\[CrossRef\]](#)
56. Kim, M.; Kim, J.; Lim, H.; Lee, S.; Cho, Y.; Lee, Y.G.; Go, S.; Lee, K. Aerosol optical depth data fusion with Geostationary Korea Multi-Purpose Satellite (GEO-KOMPSAT-2) instruments GEMS, AMI, and GOCI-II: Statistical and deep neural network methods. *Atmos. Meas. Tech. Discuss.* **2024**, *17*, 4317–4335. [\[CrossRef\]](#)
57. Kuze, A.; Suto, H.; Shiomi, K.; Nakajima, M.; Hamazaki, T. On-orbit performance and level 1 data processing of TANSO-FTS and CAI on GOSAT. In *Sensors, Systems, and Next-Generation Satellites XIII*; SPIE: Bellingham, WA, USA, 2009; pp. 151–158. [\[CrossRef\]](#)
58. Imasu, R.; Matsunaga, T.; Nakajima, M.; Yoshida, Y.; Shiomi, K.; Morino, I.; Saitoh, N.; Niwa, Y.; Someya, Y.; Oishi, Y.; et al. Greenhouse gases observing SATellite 2 (GOSAT-2): Mission overview. *Prog. Earth Planet. Sci.* **2023**, *10*, 33. [\[CrossRef\]](#)
59. Nakajima, M.; Kuze, A.; Suto, H. The current status of GOSAT and the concept of GOSAT-2. In *Sensors, Systems, and Next-Generation Satellites XVI*; SPIE: Bellingham, WA, USA, 2012; pp. 21–30. [\[CrossRef\]](#)
60. Nakajima, M.; Suto, H.; Yotsumoto, K.; Shiomi, K.; Hirabayashi, T. Fourier transform spectrometer on GOSAT and GOSAT-2. In *International Conference on Space Optics—ICSO*; ICSO: Tenerife, Spain, 2014; Volume 10563, pp. 1354–1362. [\[CrossRef\]](#)

61. Veefkind, J.P.; Aben, I.; McMullan, K.; Förster, H.; De Vries, J.; Otter, G.; Claas, J.; Eskes, H.J.; de Haan, J.F.; Kleipool, Q.; et al. TROPOMI on the ESA Sentinel-5 Precursor: A GMES mission for global observations of the atmospheric composition for climate, air quality and ozone layer applications. *Remote Sens. Environ.* **2012**, *120*, 70–83. [\[CrossRef\]](#)
62. de Vries, J.; Voors, R.; Ording, B.; Dingjan, J.; Veefkind, P.; Ludewig, A.; Kleipool, Q.; Hoogeveen, R.; Aben, I. TROPOMI on ESA's Sentinel 5P ready for launch and use. In Proceedings of the Fourth International Conference on Remote Sensing and Geoinformation of the Environment, Paphos, Cyprus, 4–8 April 2016; Volume 96880B, pp. 86–97. [\[CrossRef\]](#)
63. Reshi, A.R.; Pichuka, S.; Tripathi, A. Applications of Sentinel-5P TROPOMI satellite sensor: A review. *IEEE Sens. J.* **2024**, *24*, 20312–20321. [\[CrossRef\]](#)
64. Frankenberg, C.; Pollock, R.; Lee, R.A.M.; Rosenberg, R.; Blavier, J.F.; Crisp, D.; O'Dell, C.W.; Osterman, G.B.; Roehl, C.; Wennberg, P.O.; et al. The Orbiting Carbon Observatory (OCO-2): Spectrometer performance evaluation using pre-launch direct sun measurements. *Atmos. Meas. Tech.* **2015**, *8*, 301–313. [\[CrossRef\]](#)
65. Crisp, D.; Atlas, R.M.; Breon, F.M.; Brown, L.R.; Burrows, J.P.; Ciais, P.; Connor, B.J.; Doney, S.C.; Fung, I.Y.; Jacob, D.J.; et al. The Orbiting Carbon Observatory (OCO) mission. *Adv. Space Res.* **2004**, *34*, 700–709. [\[CrossRef\]](#)
66. Kim, M.; Kim, J.; Torres, O.; Ahn, C.; Kim, W.; Jeong, U.; Go, S.; Liu, X.; Moon, K.J.; Kim, D.R. Optimal estimation-based algorithm to retrieve aerosol optical properties for GEMS measurements over Asia. *Remote Sens.* **2018**, *10*, 162. [\[CrossRef\]](#)
67. Spurr, R.J.D. VLIDORT: A linearized pseudo-spherical vector discrete ordinate radiative transfer code for forward model and retrieval studies in multilayer multiple scattering media. *J. Quant. Spectrosc. Radiat. Transf.* **2006**, *102*, 316–342. [\[CrossRef\]](#)
68. Go, S.; Kim, J.; Park, S.S.; Kim, M.; Lim, H.; Kim, J.Y.; Lee, D.W.; Im, J. Synergistic use of hyperspectral UV-visible OMI and broadband meteorological imager MODIS data for a merged aerosol product. *Remote Sens.* **2020**, *12*, 3987. [\[CrossRef\]](#)
69. Cho, Y.; Kim, J.; Go, S.; Kim, M.; Lee, S.; Kim, M.; Chong, S.; Lee, W.J.; Lee, D.W.; Torres, O.; et al. First atmospheric aerosol monitoring results from Geostationary Environment Monitoring Spectrometer (GEMS) over Asia. *Atmos. Meas. Tech.* **2024**, *17*, 4369–4390. [\[CrossRef\]](#)
70. Kim, S.; Cho, Y.; Ki, H.; Park, S.; Oh, D.; Lee, S.; Cho, Y.; Kim, J.; Lee, W.; Park, J.; et al. Improved mean field estimates from the Geostationary Environment Monitoring Spectrometer (GEMS) Level-3 aerosol optical depth (L3 AOD) product: Using spatiotemporal variability. *Atmos. Meas. Tech.* **2024**, *17*, 5221–5241. [\[CrossRef\]](#)
71. Fan, Y.; Sun, L.; Liu, X. GOCI-II geostationary satellite hourly aerosol optical depth obtained by data-driven methods: Validation and comparison. *Atmos. Environ.* **2023**, *310*, 119965. [\[CrossRef\]](#)
72. Ishida, H.; Nakjima, T.Y.; Yokota, T.; Kikuchi, N.; Watanabe, H. Investigation of GOSAT TANSO-CAI cloud screening ability through an intersatellite comparison. *J. Appl. Meteorol. Climatol.* **2011**, *50*, 1571–1586. [\[CrossRef\]](#)
73. Hsu, N.C.; Tsay, S.C.; King, M.D.; Herman, J.R. Aerosol properties over bright-reflecting source regions. *IEEE Trans. Geosci. Remote Sens.* **2004**, *42*, 557–569. [\[CrossRef\]](#)
74. Cox, C.; Munk, W. Measurement of the roughness of the sea surface from photographs of the Sun's glitter. *J. Opt. Soc. Am.* **1954**, *44*, 838–850. [\[CrossRef\]](#)
75. Spurr, R.; Christi, M. The LIDORT and VLIDORT linearized scalar and vector discrete ordinate radiative transfer models: Updates in the last 10 years. In *Springer Series in Light Scattering*; Kokhanovsky, A., Ed.; Springer: Cham, Switzerland, 2026. [\[CrossRef\]](#)
76. Noël, S.; Reuter, M.; Buchwitz, M.; Borchardt, J.; Hilker, M.; Schneising, O.; Bovensmann, H.; Burrows, J.P.; Di Noia, A.; Parker, R.J.; et al. Retrieval of greenhouse gases from GOSAT and GOSAT-2 using the FOCAL algorithm. *Atmos. Meas. Tech.* **2022**, *15*, 3401–3437. [\[CrossRef\]](#)
77. Eldering, A.; Wennberg, P.O.; Crisp, D.; Schimel, D.S.; Gunson, M.R.; Chatterjee, A.; Liu, J.; Shwandner, F.M.; Sun, Y.; O'Dell, C.W.; et al. The Orbiting Carbon Observatory-2 early science investigations of regional carbon dioxide fluxes. *Science* **2017**, *358*, eaam5745. [\[CrossRef\]](#) [\[PubMed\]](#)
78. Rodgers, C.D. *Inverse Methods for Atmospheric Sounding: Theory and Practice*; World Scientific: Singapore, 2000; Volume 2.
79. Fletcher, R. *A modified Marquardt Subroutine for Non-Linear Least Squares*; United Kingdom Atomic Energy Authority: Oxford, UK, 1971.
80. Thompson, D.R.; Benner, D.C.; Brown, L.R.; Crisp, D.; Devi, V.M.; Jiang, Y.; Natraj, V.; Oyafo, F.; Sung, K.; Wunch, D.; et al. Atmospheric validation of high accuracy CO₂ absorption coefficients for the OCO-2 mission. *J. Quant. Spectrosc. Radiat. Transf.* **2012**, *113*, 2265–2276. [\[CrossRef\]](#)
81. Taylor, T.E.; O'Dell, C.W.; Baker, D.; Bruegge, C.; Chang, A.; Chapsky, L.; Chatterjee, A.; Cheng, C.; Chevallier, F.; Crisp, D.; et al. Evaluating the consistency between OCO-2 and OCO-3 XCO₂ estimates derived from the NASA ACOS version 10 retrieval algorithm. *Atmos. Meas. Tech.* **2023**, *16*, 3173–3209. [\[CrossRef\]](#)
82. Butz, A.; Guerlet, S.; Hasekamp, O.; Schepers, D.; Galli, A.; Aben, I.; Frankenberg, C.; Hartmann, J.M.; Tran, H.; Kuze, A.; et al. Toward accurate CO₂ and CH₄ observations from GOSAT. *Geophys. Res. Lett.* **2011**, *38*, 14. [\[CrossRef\]](#)
83. Lindqvist, H.; Kivimäki, E.; Häkkinen, T.; Tsuruta, A.; Schneising, O.; Buchwitz, M.; Lorente, A.; Velarte, M.M.; Borsdorff, T.; Alberti, C.; et al. Evaluation of Sentinel-5P TROPOMI methane observations at northern high latitudes. *Remote Sens.* **2024**, *16*, 2979. [\[CrossRef\]](#)

84. Schneising, O.; Buchwitz, M.; Reuter, M.; Bovensmann, H.; Burrows, J.P.; Borsdorff, T.; Deutscher, N.M.; Feist, D.G.; Griffith, D.W.T.; Hase, F.; et al. A scientific algorithm to simultaneously retrieve carbon monoxide and methane from TROPOMI onboard Sentinel-5 Precursor. *Atmos. Meas. Tech.* **2019**, *12*, 6771–6802. [\[CrossRef\]](#)
85. McRoberts, R.E. Diagnostic tools for nearest neighbor techniques when used with satellite imagery. *Remote Sens. Environ.* **2009**, *113*, 489–499. [\[CrossRef\]](#)
86. Jang, B.; Stratoulas, D.; Aekakkararungroj, A.; Towashiraporn, P. Validation and analysis of GEMS aerosol optical depth product against AERONET over mainland Southeast Asia. *Aerosol Air Qual. Res.* **2025**, *25*, 22. [\[CrossRef\]](#)
87. Kang, Y.; Kim, M.; Kang, E.; Cho, D.; Im, J. Improved retrievals of aerosol optical depth and fine mode fraction from GOCI geostationary satellite data using machine learning over East Asia. *ISPRS J. Photogramm. Remote Sens.* **2022**, *183*, 253–268. [\[CrossRef\]](#)
88. Levy, R.C.; Mattoo, S.; Munchak, L.A.; Remer, L.A.; Sayer, A.M.; Patadia, F.; Hsu, N.C. The Collection 6 MODIS aerosol products over land and ocean. *Atmos. Meas. Tech.* **2013**, *6*, 2989–3034. [\[CrossRef\]](#)
89. Sayer, A.M.; Munchak, L.A.; Hsu, N.C.; Levy, R.C.; Bettenhausen, C.; Jeong, M.J. MODIS Collection 6 aerosol products: Comparison between Aqua's e-Deep Blue, Dark Target, and "merged" data sets, and usage recommendations. *J. Geo-Phys. Res. Atmos.* **2014**, *119*, 13–965. [\[CrossRef\]](#)
90. Feng, S.; Jiang, F.; Wang, H.; Liu, Y.; He, W.; Wang, H.; Shen, Y.; Zhang, L.; Jia, M.; Ju, W.; et al. China's fossil fuel CO₂ emissions estimated using surface observations of coemitted NO₂. *Environ. Sci. Technol.* **2024**, *58*, 8299–8312. [\[CrossRef\]](#)
91. Newman, S.; Jeong, S.; Fischer, M.L.; Xu, X.; Haman, C.L.; Lefer, B.; Alvarez, S.; Rappenglueck, B.; Kort, E.A.; Andrews, A.E.; et al. Diurnal tracking of anthropogenic CO₂ emissions in the Los Angeles basin megacity during spring 2010. *Atmos. Chem. Phys.* **2013**, *13*, 4359–4372. [\[CrossRef\]](#)
92. Silva, V.; Monteiro, E.; Couto, N.; Brito, P.S.D.; Rouboa, A. Experimental and numerical analysis of coffee husks biomass gasification in a fluidized bed reactor. *Energy Procedia* **2013**, *36*, 591–595. [\[CrossRef\]](#)
93. Zhang, B.; Chen, G.Q. China's CH₄ and CO₂ emissions: Bottom-up estimation and comparative analysis. *Ecol. Indic.* **2014**, *47*, 112–122. [\[CrossRef\]](#)
94. Peng, S.; Piao, S.; Bousquet, P.; Ciais, P.; Li, B.; Lin, X.; Tao, S.; Wang, Z.; Zhang, Y.; Zhou, F. Inventory of anthropogenic methane emissions in mainland China from 1980 to 2010. *Atmos. Chem. Phys.* **2016**, *16*, 14545–14562. [\[CrossRef\]](#)
95. Wang, K.; Zhang, J.; Cai, B.; Yu, S. Emission factors of fugitive methane from underground coal mines in China: Estimation and uncertainty. *Appl. Energy* **2019**, *250*, 273–282. [\[CrossRef\]](#)
96. Kim, H.K.; Song, C.K.; Hong, S.C.; Shin, M.H.; Seo, J.; Kim, S.K.; Lyu, Y. Source characteristics of atmospheric CO₂ and CH₄ in a northeastern highland area of South Korea. *Atmosphere* **2020**, *11*, 509. [\[CrossRef\]](#)
97. Wei, C.; Wang, M.; Fu, Q.; Dai, C.; Huang, R.; Bao, Q. Temporal characteristics of greenhouse gases (CO₂ and CH₄) in the megacity Shanghai, China: Association with air pollutants and meteorological conditions. *Atmos. Res.* **2020**, *235*, 104759. [\[CrossRef\]](#)
98. Zhao, H.; Yang, G.; Tong, D.Q.; Zhang, X.; Xiu, A.; Zhang, S. Interannual and seasonal variability of greenhouse gases and aerosol emissions from biomass burning in northeastern China constrained by satellite observations. *Remote Sens.* **2021**, *13*, 1005. [\[CrossRef\]](#)
99. Lee, S.; Choi, M.; Kim, J.; Park, Y.J.; Choi, J.K.; Lim, H.; Cho, Y. Retrieval of aerosol optical properties from GOCI-II observations: Continuation of long-term geostationary aerosol monitoring over East Asia. *Sci. Total Environ.* **2023**, *903*, 166504. [\[CrossRef\]](#)
100. Lelieveld, J.; Evans, J.S.; Fnais, M.; Giannadaki, D.; Pozzer, A. The contribution of outdoor air pollution sources to premature mortality on a global scale. *Nature* **2015**, *525*, 367–371. [\[CrossRef\]](#)
101. Montzka, S.A.; Krol, M.; Dlugokencky, E.; Hall, B.; Jöckel, P.; Lelieveld, J. Small interannual variability of global atmospheric hydroxyl. *Science* **2011**, *331*, 67–69. [\[CrossRef\]](#) [\[PubMed\]](#)
102. Tan, Z.; Lu, K.; Jiang, M.; Su, R.; Wang, H.; Lou, S.; Zhang, Y. Daytime atmospheric oxidation capacity in four Chinese megacities during the photochemically polluted season: A case study based on box model simulation. *Atmos. Chem. Phys.* **2019**, *19*, 3493–3513. [\[CrossRef\]](#)
103. Whalley, L.K.; Slater, E.J.; Woodward-Massey, R.; Ye, C.; Lee, J.D.; Squires, F.; Heard, D.E. Evaluating the sensitivity of radical chemistry and ozone formation to ambient VOCs and NO_x in Beijing. *Atmos. Chem. Phys.* **2021**, *21*, 2125–2147. [\[CrossRef\]](#)
104. Dong, Y.; Li, J.; Guo, J.; Jiang, Z.; Chu, Y.; Chang, L.; Yang, Y.; Liao, H. The impact of synoptic patterns on summertime ozone pollution in the North China Plain. *Sci. Total Environ.* **2020**, *735*, 139559. [\[CrossRef\]](#) [\[PubMed\]](#)
105. Faraday, E.T.; Oluwabunmi, O.A. Greenhouse gas levels (CH₄ and CO₂) in Lagos state and Oyo state, Nigeria. *Discov. Environ.* **2024**, *2*, 4. [\[CrossRef\]](#)
106. Guo, M.; Wang, X.; Li, J.; Wang, H.; Tani, H. Examining the relationships between land cover and greenhouse gas concentrations using remote-sensing data in East Asia. *Int. J. Remote Sens.* **2013**, *34*, 4281–4303. [\[CrossRef\]](#)
107. Streets, D.G.; Bond, T.C.; Carmichael, G.R.; Fernandes, S.D.; Fu, Q.; He, D.; Klimont, Z.; Nelson, S.M.; Tsai, N.Y.; Wang, M.Q.; et al. An inventory of gaseous and primary aerosol emissions in Asia in the year 2000. *J. Geophys. Res. Atmos.* **2003**, *108*, 8809. [\[CrossRef\]](#)

108. Keppler, F.; Hamilton, J.T.G.; Brass, M.; Röckmann, T. Methane emissions from terrestrial plants under aerobic conditions. *Nature* **2006**, *439*, 187–191. [[CrossRef](#)]
109. Yang, W.; Song, C.; Zhang, J. Dynamics of methane emissions from a freshwater marsh of northeast China. *Sci. Total Environ.* **2006**, *371*, 286–292. [[CrossRef](#)] [[PubMed](#)]
110. Ding, W.; Cai, Z.; Tsuruta, H. Methane concentration and emission as affected by methane transport capacity of plants in freshwater marsh. *Water Air Soil Pollut.* **2004**, *158*, 99–111. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.