



Measurement report: Multi-platform greenhouse gas monitoring of a major petrochemical industrial complex in South Korea

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Abstract. Quantifying greenhouse gas (GHG) emissions from large industrial complexes remains challenging due to the coexistence of diverse source types, highly variable operational conditions, fugitive releases, and limited representativeness of bottom-up inventories. These complexities require observational approaches resolving emissions across multiple spatial and temporal scales. To address this gap, this study conducted a coordinated multi-platform observation campaign from 6–14 January 2024 at the Daesan Petrochemical Industrial Complex (DPIC), one of South Korea’s largest petrochemical hubs, which integrated in situ and ground-based column observations, mobile surveys, aircraft measurements, and satellite data across complementary spatial and temporal scales. Ground-based measurements confirmed sustained CO₂ enhancements of 27.72 ppm above background concentrations within the DPIC and observed frequent downwind transport of emissions beyond the complex boundary. Mobile measurements identified combined signatures of combustion-linked emissions and fugitive methane releases at the two largest-emitting facilities, while aircraft emission ratio characteristics corroborated these findings, revealing methane leakage concentrated in the DPIC center alongside increased combustion activity. An annual GHG emission rate of $2,595.45 \pm 333.09 \text{ GgCO}_2\text{eqyr}^{-1}$ derived from the two largest-emitting facility hotspots alone accounted for approximately 37.1 % of the nationally reported inventory values, suggesting systematic underestimation of bottom-up accounting frameworks, especially of fugitive methane. Satellite observations further identified methane enhancements in access-restricted areas consistent with ground-based measurements. This study demonstrates that coordinated multi-platform observation strategies provide critical constraints for atmospheric emission verification and a scalable framework for improving the accuracy of the quantification of greenhouse gas emissions in complex industrial environments.



1 Introduction

Anthropogenic emissions have increased rapidly over recent decades, leading to substantial rises in atmospheric greenhouse gas (GHG) concentrations and driving global warming that is now unequivocally attributed to human activities (IPCC, 2023). Atmospheric carbon dioxide (CO₂) concentrations are projected to reach 425.7 ppm in 2025, representing a 52 % increase above pre-industrial levels (Friedlingstein et al., 2025). Methane (CH₄), the second most important greenhouse gas with a global warming potential approximately 86 times more potent than CO₂ on decadal timescales, has increased at an even faster relative rate and is now approximately 2.6 times higher than pre-industrial concentrations (Jackson et al., 2024). These increases are driven primarily by fossil fuel combustion and especially from industrial activities. In 2022, the industrial sector directly emitted approximately 9.0 GtCO₂, accounting for about a quarter of global energy system CO₂ emissions (IEA, 2023). Total energy-related CO₂ emissions from fossil fuel combustion, industrial processes, and flaring increased by 0.8 % in 2024, reaching a record high of 37.8 GtCO₂ (IEA, 2025). Methane emissions from fossil fuels, industrial sources, and transport are similarly considerable, with global inventories estimating mean emissions of approximately 120 TgCH₄yr⁻¹ during 2010–2019, corresponding to about 34 % of total global anthropogenic methane emissions (Saunois et al., 2025). Given the magnitude of both CO₂ and CH₄ emissions from fossil fuel combustion and industrial activities, robust quantification and attribution of emissions from the industrial sector are critical for understanding their role in the global carbon and methane budgets and for informing effective mitigation strategies.

Efforts to quantify and monitor fossil fuel emissions from the industrial sector have relied primarily on global and regional bottom-up emissions inventories of CO₂ (Chen et al, 2020; Oda and Maksyutov, 2011; Oda et al., 2016; Gurney et al., 2019; Xue et al., 2021) and CH₄ (Lyon et al., 2015; Miller et al., 2013; Schwietzke et al., 2014). While these inventories provide a critical foundation for emissions assessment, they are inherently limited by their dependence on statistical data describing economic activities and assumed emission factors, which are subject to reporting errors, incomplete coverage, and systematic biases (Konovalov et al., 2016). Moreover, discrepancies persist among different bottom-up estimates, especially for the oil and gas sector, where inventories often underestimate actual emissions and associated uncertainties remain large (Tibrewal et al., 2024). These limitations are further compounded with factors such as the long atmospheric CO₂ lifetime, which leads to extensive spatial redistribution by atmospheric transport and complicates the attribution of localized emission sources (Åström et al., 2025). Collectively, these uncertainties underscore the necessity of independent atmospheric observations to evaluate and constrain inventory estimates and process-based models, enabling more reliable detection and attribution of industrial emissions.

Integrated measurement-based monitoring provides an essential foundation for identifying dominant emission sources in industrial areas, detecting high-emitting facilities and leaks, supporting the design of targeted policy interventions, and evaluating their effectiveness over time. Robust and accurate monitoring of GHG emissions is particularly critical for industrial



complexes, which are major emission sources and therefore key targets for effective mitigation. A wide range of observational approaches has been applied to quantify GHG emissions from industrial complexes and other regions with large anthropogenic activity, including ground-based sensors (Lelandais et al., 2022; Luther et al. 2022; Vogel et al., 2019), mobile platforms (Edie et al., 2020; Korbeň et al., 2022; Luther et al., 2019; Shi et al., 2023; von Fischer et al., 2017), aircraft campaigns (Barkley et al., 2021; Fiehn et al., 2020; Krings et al., 2018; Plant et al., 2019), and satellite observations (Irakulis-Loitxate et al., 2021; Konovalov et al., 2016; Lauvaux et al., 2022; Nassar et al., 2021; Varon et al., 2019). While each of these approaches provides valuable information, they are commonly applied using a subset of observational techniques, resulting in limitations in spatial coverage, temporal resolution, and source attribution. Consequently, a comprehensive, multi-platform monitoring framework that integrates ground-based, mobile, airborne, and satellite observations is needed to leverage their complementary strengths, fill observational gaps, reduce uncertainties, and improve transparency in anthropogenic emissions in industrial sectors.

This study presents a coordinated multi-platform campaign to characterize CO₂ and CH₄ emissions from one of the largest industrial complexes in South Korea, the Daesan Petrochemical Industrial Complex (hereafter DPIC). Located in Seosan-si, Chungcheongnam-do, DPIC is one of South Korea's three major petrochemical hubs, alongside Yeosu and Ulsan. Spanning approximately 15.3 km², DPIC hosts several major refining and chemical facilities as well as over 60 small- and medium-sized enterprises (KCIA, 2024). Situated on a coastal plain adjacent to the Daesan Port, the complex benefits from strategic logistical access for domestic distribution and international trade (Choi et al., 2007). The industrial structure of the DPIC is centered on petrochemical industries, producing basic feedstocks like ethylene and propylene in addition to various petrochemical products through oil refining and petrochemical processes (KCIA, 2024). Notably, Daesan is responsible for approximately 2 % of global ethene production (Fried et al., 2020). Reflecting this industrial concentration, total greenhouse gas emissions from Seosan-si reached 16,800.81 GgCO₂eq in 2022, ranking 13th among local governments in South Korea. Of this total, 66.3 % of emissions (11,135.98 GgCO₂eq) was emitted from chemical industry processes, accounting for roughly 35 % of the nation's total emissions from the chemical sector (GIR, 2025). The campaign integrated ground-based column measurements, in situ and mobile observations, aircraft measurements, and satellite data within and around the DPIC to observe CO₂ and CH₄ enhancements associated with industrial activities. By integrating complementary observations from multiple measurement platforms, this study aims to identify emission hotspots, assess the spatial distribution and variability of CO₂ and CH₄ within the DPIC, characterize source-specific emission behavior, and demonstrate the value of multi-platform observational strategies for industrial-scale emissions monitoring.

2 Data and methods

A coordinated multi-platform observation campaign was conducted over the DPIC from 6–14 January 2024, spanning a total of 9 days of observations, to characterize CO₂ and CH₄ emissions within the industrial complex. Seoul National University, in collaboration with the National Institute of Environmental Research (NIER), the National Institute of Meteorological Sciences (NIMS), and the Chungcheongnam-do Institute of Health and Environment, jointly planned the



100 campaign and deployed various GHG measurement instruments within and around the DPIC. To enable a comprehensive assessment, the campaign integrated ground-based column observations, in situ and mobile measurements, aircraft observations, and satellite data to capture CO₂ and CH₄ enhancements associated with industrial activities. The specifications and measurement characteristics of the deployed instruments are summarized in **Table 1**.



105 **Table 1.** Specifications and measurement characteristics of GHG measurement instruments deployed during the campaign.

Type of measurement	Instruments	EA	Description	Institute
Mobile	Kia EV6	1	Electric vehicle for mobile measurement	Seoul National University (SNU)
	Kia Carnival	1	Vehicle for mobile measurement	
	LI-7810	2	LICOR Inc. CH ₄ , CO ₂ , H ₂ O instrument	
	LI-7815	2	LICOR Inc. CO ₂ , H ₂ O instrument	
	GLA131-MEA	1	ABB Inc. CH ₄ , C ₂ H ₆ , H ₂ O instrument	
	AK770	2	ASCEN KOREA GPS instrument	
	EOLOS-IND	1	LAMBRECHT meteo GmbH Static weather sensor	
	Portable aerosol spectrometer dust decoder 11-D	1	GRIMM PM (0.253 – 35.15 µm) instrument	
	nCLD AL ²	1	Eco Physics Inc. NO, NO ₂ , NO _x instrument	
	AK940, AKA900	1	ASCEN KOREA GNSS GPS instrument	
	WPSD-9100 (HD53LS)	1	DeltaOHM anemometer	
Ground	SNUCO ₂ M (LI-850)	1	LICOR Inc. CO ₂ , H ₂ O instrument	Seoul National University (SNU)
	EM27/SUN	2	Ground-based FTIR spectrometer	National Institute for Environmental Studies, Japan (NIES)
	EM27/SUN	1	Ground-based FTIR spectrometer	
Aircraft	CRDS, AIMMS-20	1	CO ₂ , CH ₄ , CO, H ₂ O temperature, humidity, pressure, wind, longitude, latitude, altitude, speed, direction, inclination	National Institute of Meteorological Sciences (NIMS)
Satellite	EMIT	1	Hyperspectral imager onboard the International Space Station (ISS)	National Aeronautics and Space Administration (NASA)



2.1 Seoul National University CO₂ Measurement (SNUCO₂M)

The Seoul National University CO₂ Measurement (SNUCO₂M), an in situ instrument for measuring CO₂, was deployed to assess the impact of industrial activities on local CO₂ levels by capturing continuous concentration data from the core of the DPIC. SNUCO₂M consists of a widely used, low-cost non-dispersive infrared (NDIR)-based LI-850 CO₂ sensor accompanied by water vapor mixing ratio measurements, a data logger, LTE router, power supply, and a Gelman filter for removing fine particulate matter (Park et al. 2021). This instrument is calibrated periodically using the air balance zero CO₂ gas and standard span gases containing 427.13 ppm and 963.290 ppm of CO₂, in accordance with calibration standards defined by the National Oceanic and Atmospheric Administration. Previous validation studies have demonstrated that the SNUCO₂M provides CO₂ concentration measurements highly consistent with those from high-precision Picarro instruments, confirming its reliability for monitoring CO₂ variability (Park et al., 2021). During the campaign, the SNUCO₂M instrument was installed in the central area of the DPIC (37.0033° N, 126.3858° E), making 24-hour observations of CO₂ concentrations throughout the observation period.

2.2 EM27/SUN

The EM27/SUN is a ground-based, portable Fourier-transform infrared (FTIR) spectrometer developed by the Karlsruhe Institute of Technology (KIT) in collaboration with Bruker. The spectrometer records direct solar spectra in the near-infrared region, with a spectral coverage of 5500–11000 cm⁻¹ for the primary detector, and a spectral coverage of 4000–5500 cm⁻¹ for the secondary detector. The spectrometer has an optical path difference of 1.8 cm, which is equivalent to a spectral resolution of 0.5 cm⁻¹. The EM27/SUN spectrometer records double-sided, direct current (DC) coupled interferograms which make an average of 10 scans in 58 seconds. These interferograms measured from the spectrometers are processed using the PROFFAST version 2.4 retrieval algorithm developed by KIT to retrieve accurate and precise column-averaged dry-air mole fractions of CO₂ and CH₄ (XCO₂ and XCH₄, respectively) (Frey et al., 2019; Gisi et al., 2012; Hase et al., 2015, 2016; Sha et al., 2020).

Two EM27/SUNs from Seoul National University and one from the National Institute of Environmental Studies (NIES), Japan, were deployed at different sites around the DPIC throughout the campaign. All EM27/SUNs were calibrated against the KIT standard and demonstrated consistent reliable measurement performance (Ohyama et al. 2020; Park et al., 2024). An EM27/SUN was stationed at the central site of the DPIC at 37.0033° N, 126.3858° E (9 m a.s.l.), next to the SNUCO₂M and an automatic weather station operated nearby. Considering the prevailing northwesterly winds during winter in Korea, two downwind sites were selected to capture the emission plume transport under varying wind conditions. One EM27/SUN was deployed to the east of the DPIC at the Chungnam Northwestern Center for Tourism and Environmental Education (CTEE) (37.0013° N, 126.4503° E, 31 m a.s.l.), and one spectrometer was stationed to the southeast of the DPIC at the Labor Welfare Center, Daesan Branch (LWC) (36.9398° N, 126.4382° E, 65 m a.s.l.). An upwind site for comparison could not be established due to geographical constraints, as the northwest of the DPIC is a coastal area, making it difficult to

deploy a spectrometer. **Figure 1** illustrates the ground-based measurements stationed at the central and two downwind sites of the DPIC during the campaign.

We used the column-enabled Stochastic Time-Inverted Lagrangian Transport model (X-STILT) (Wu et al., 2018) with the Weather Research and Forecasting (WRF) model to simulate atmospheric transport and trace back the source regions affecting the observations. The model serves as a diagnostic tool for analyzing column-averaged trace gas concentrations by generating footprints that quantify source-receptor sensitivities to surface fluxes. This study used the WRF model version 3.9.1, with initial and boundary conditions from the fifth generation European Centre for Medium-Range Weather Forecasts atmospheric reanalysis (ERA5) data. X-STILT output footprints at each grid cell are in units of $\text{ppm } \mu\text{mol}^{-1} \text{ m}^2 \text{ s}$. For this study, 1-hour backward trajectories were calculated for hourly observations between 11:00 to 16:00 local time (LT), using a 1 km x 1 km resolution.



Figure 1. Locations of ground-based measurements deployed in the Daesan Petrochemical Industrial Complex (DPIC). The in situ instrument SNUCO₂M and an EM27/SUN are located nearby in the center of the DPIC (green triangle). As downwind sites, one EM27/SUN is located to the east of the DPIC at the Chungnam Northwestern Center for Tourism and Environmental Education (CTEE) marked as an orange circle, and one EM27/SUN is stationed to the southeast of the DPIC at the Labor Welfare Center, Daesan Branch (LWC) marked as a blue square. Pictures on the left show the SNUCO₂M and EM27/SUN instruments set up at each of their respective sites. The map imagery is from © Google Earth.



2.3 Seoul National University (SNU) mobile GHG measurement platform

Monitoring using a mobile measurement platform enables real-time detection of greenhouse gas emission sources and provides high spatiotemporal resolution concentration data. The SNU mobile GHG measurement platform consists of an electric vehicle with a GPS and in situ CO₂, CH₄, and C₂H₆ analyzers. An overview of the mobile platform is shown in **Fig. 2**, and detailed instrument specifications are provided in Joo et al. (2024). For the initial screening phase, mobile measurements were conducted across the entire DPIC at areas that were open to access for a general overview and to detect potential greenhouse gas emission hotspots. Once hotspots were identified within the DPIC, an optimized observation route was designed to conduct focused measurements for precise identification of emission sources. Depending on the prevailing wind direction of each of the observation days, the variations of CO₂ and CH₄ concentrations were observed at downwind locations of the sources. To quantify emissions from identified sources, fixed-point observations were conducted for 30 minutes downwind of the emission source, which allows for the calculation of emission rates at those locations. **Table S1** details the mobile measurement platform observation schedule during the campaign period.



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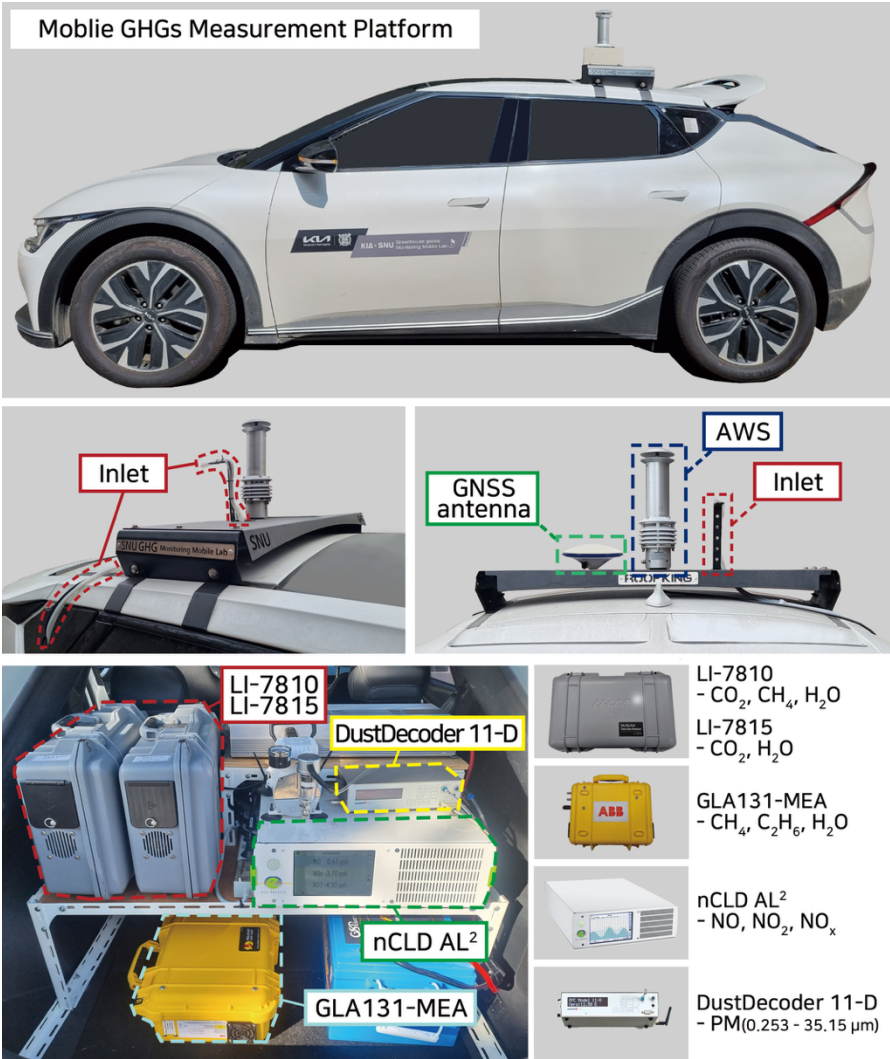


Figure 2. Instruments and layout of the Seoul National University (SNU) mobile GHG measurement platform.

Emission rates measured by the mobile platform were calculated by first using background concentrations to estimate the enhancements of CO₂ and CH₄. The background concentrations were determined using a 5-minute moving window average, employing the 5th percentile for CH₄ and the median value for CO₂. Subsequently, these background concentrations were subtracted accordingly to calculate the enhancements for each species. Using the enhancements, emission rates were then



estimated with the OTM-33A model (Korbeň et al., 2022; Thoma & Squier, 2014), which has been optimized for fixed-point measurements. The model was applied using **Eq. (1)**.

$$Q = 2\pi \cdot \sigma_y \cdot \sigma_x \cdot U \cdot C \quad (1)$$

175 The emission rate (Q) is estimated using the dispersion parameters (σ_y, σ_x) which depend on the Pasquill-Gifford stability class, which itself is determined by solar radiation and wind speed. In South Korea, daytime conditions generally correspond to stability classes A or B and are associated with windspeeds of 1–2 m s⁻¹. Under these conditions, I, J, and K coefficients were used to determine appropriate dispersion parameters from the Pasquill stability class (Seinfeld and Pandis, 2006). The average wind speed during the measurement period was used as the representative wind speed (U), and the
 180 maximum observed enhancement was used to determine concentration (C).

We used a Monte Carlo simulation approach to propagate uncertainties in three key input variables that significantly influence the Gaussian dispersion model: wind speed, source-receptor distance, and source height. Uncertainty estimates (2σ) were assigned based on the following: (1) a 20 % uncertainty in wind speed due to variability caused by surface roughness and friction; (2) a 10 % uncertainty in source-receptor distance, reflecting the ambiguity in locating emission sources within the
 185 DPIC; and (3) a 30 % uncertainty in source height, due to a lack of detailed information on emission release heights.

2.4 Aircraft measurements

Airborne observations over the DPIC were conducted using the Korea Meteorological Administration (KMA) Beechcraft King Air 350 research aircraft, modified by Weather Modification Inc. (Fargo, ND, USA). The aircraft was equipped with a Picarro CRDS 2401-m gas concentration analyzer to simultaneously measure CO₂, CH₄, CO, and water vapor
 190 through dedicated inlets. The CRDS analyzer employs a high-precision wavelength monitor with controlled pressure and temperature within the measurement cell, enabling stable, drift-free trace gas measurements with high precision over both short and extended periods. Location and meteorological data, including wind speed and temperature, were collected using a GPS and the Aircraft Integrated Meteorological Measuring System-20 (Li et al., 2020, 2022).

Airborne measurements were conducted following a predefined pattern over the DPIC on January 6, 7, and 13, 2024
 195 between 12:00 to 16:00 LT. **Figure 3** and **Table 2** detail the flight patterns performed both upwind, downwind, and across the DPIC to assess the vertical and horizontal distribution of trace gases. The aircraft departed from Gimpo International Airport (P1) and conducted spiral profiles at two locations north (P2) and south (P3) of the DPIC, each with a 2-mile radius covering altitudes from 2000 to 4000 ft. Following the spirals, approximately nine elliptical loops were flown around the complex in the order of locations P3, P4, P2, P5, and P3, gradually descending from 4000 to 2000 ft in 300 ft increments. Subsequently,
 200 straight-level transects were conducted at 2000 ft, following a series of offset crosswind transects. Aircraft observations made on clear sky days of January 6 and 13 were used in the analysis.

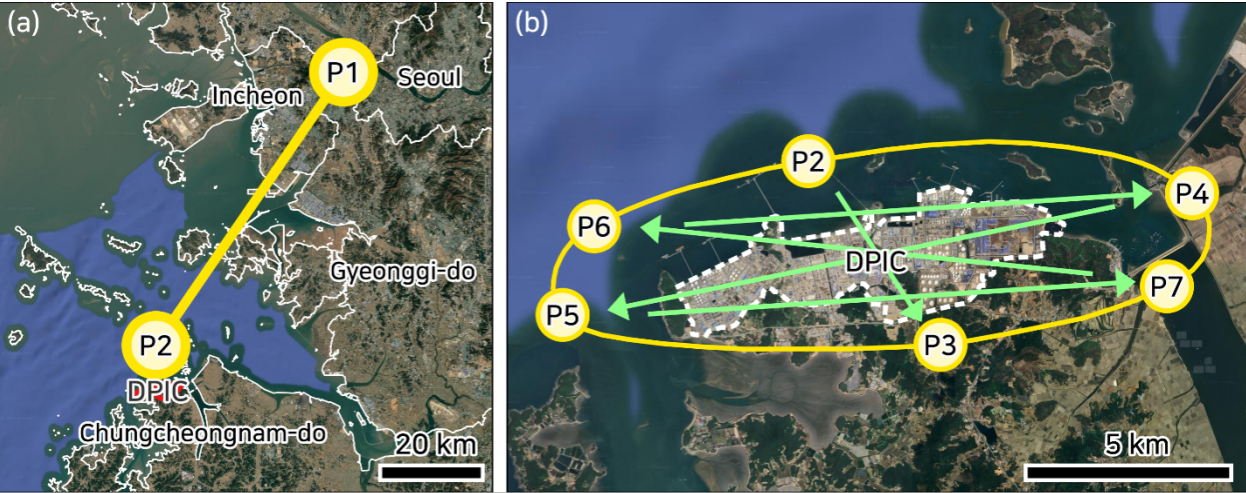


Figure 3. Flight path of aircraft observations over the DPIC during the campaign. (a) Aircraft departs from Gimpo International Airport (P1) and arrives to the north of the DPIC (P2) for the start of the observation. (b) Spiral profile observations are made at points P2 and P3. Subsequently, nine elliptical loops are flown around the DPIC in the order of locations P3, P4, P2, and P5 depicted as yellow lines. Finally, straight-level transects are conducted following a series of offset crosswind transects in the order of P7, P6, P4, P5, and P7, represented as green arrows. The dashed white line delineates the area of the DPIC. The map imagery is from © Google Earth.

Table 2. Locations of flight observation points during aircraft measurements.

Location	P1	P2	P3	P4	P5	P6	P7
Latitude, Longitude	37.5656° N, 126.8013° E	37.0239° N, 126.3670° E	36.9831° N, 126.3872° E	37.0172° N, 126.4720° E	36.9900° N, 126.3000° E	37.0097° N, 126.3092° E	36.9967° N, 126.4656° E

2.5 EMIT satellite measurements

The Earth Surface Mineral Dust Source Investigation (EMIT) is an imaging spectrometer operating on the International Space Station (ISS) that measures reflected solar radiation from the visible to shortwave infrared (381–2493 nm) at 7.4-nm spectral sampling across 285 bands. In addition to its original design to characterize the mineral composition of arid dust source regions and assess their impact on global radiative forcing, EMIT is also capable of detecting methane and CO₂, owing to its high signal-to-noise ratio, fine 60 m spatial resolution, and wide 80 km swath, which allows for a daily coverage of 1.3×10^6 km² (Green et al., 2023; Thorpe et al., 2023)

During the period of the campaign, EMIT was primarily acquiring data in the Southern Hemisphere due to low solar elevations in the Northern Hemisphere, and as a result, no observations were made over the DPIC region. Therefore, the EMIT



observation from April 7, 2024, which is the closest available observation of the DPIC region to the campaign period, was used in this study to assess methane enhancements. The EMIT observation data that was processed and distributed through the EMIT Open Data Portal did not report any methane plume detections over South Korea, most likely attributing to the high plume classification threshold set by the data provider. Therefore, raw spectral data over the DPIC were manually extracted and methane enhancement were calculated using the matched filter method as described by Foote et al. (2020). The matched filter method is a calculation method that can express the input spectral information as perturbations that occur in the average spectrum due to changes in methane concentration (Foote et al., 2020; Thompson et al., 2015). This method searches the radiance spectrum of each spatial pixel for deviations that are characteristic of the absorption spectrum of methane. In this study, we applied the matched filter method to identify localized methane enhancements and potential emission sources within the DPIC, using the publicly available code developed by Foote et al. (2020).

3 Results

3.1 Emission quantification from mobile observations

Figure 4a depicts the observation route of the mobile platform and hotspot locations within the DPIC during the campaign. Along the observation route, two hotspots were detected and marked as red circles labeled A1 and A2 where consistent enhancements of CO₂ and CH₄ concentrations were measured. Another hotspot, marked as a blue circle, was excluded as this area was undergoing construction at the time of the campaign for an underground natural gas piping. On most days of the campaign, the observations were carried out during the daytime. Nighttime observations were also made on January 11 to monitor the variations within the complex during the evening. As seen in **Figs. 4b–c**, when the underground natural gas pipeline construction was ongoing during the day, emissions were observed. However, during the night when construction was halted, no emissions were detected. Aside from such cases, a similar spatial distribution of CO₂ and CH₄ concentrations were seen throughout the DPIC both during daytime and nighttime.



Figure 4. (a) Mobile measurement platform observation route shown for CH₄ measurements with units in ppb. Red circles mark sites A1 and A2 where the largest emission hotspots were identified within the DPIC. The blue circle represents another hotspot which was later excluded as it was identified as a construction site for an underground natural gas piping. (b) Mobile CH₄ observations made during the daytime on January 7, 2024. The blue circle marks the construction site which shows enhanced CH₄ concentrations during the day. (c) Mobile CH₄ observations made in the evening of January 11, 2024. Blue circle locates the construction site which shows no emissions as construction comes to an end after operating hours. The map imagery is from © Google Earth.



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At the two locations where major emission sources were identified and labeled as sites A1 and A2 (**Fig. 5**), the mobile platform carried out 30-minute fixed-point measurements. To accurately quantify emission rates from the two sources, fixed-point measurements were conducted each day at downwind locations determined by the prevailing wind conditions, and in close proximity to the source locations. Peak CO₂ concentrations were observed to be 1,488.21 ppm at A1 and 2,802.31 ppm at A2, while peak CH₄ concentrations reached 29,833.35 ppb at A1 and 4,079.28 ppb at A2. Subsequently, we used the OTM-33A method to estimate the emission rate from the two sources. For site A1, the highest CO₂ emission rate was recorded on January 10 with a rate of $1053.37 \pm 134.30 \text{ GgCO}_2\text{eqyr}^{-1}$, and on January 6 for the highest CH₄ emission rate of $156.61 \pm 134.30 \text{ GgCO}_2\text{eqyr}^{-1}$. For site A2, the highest CO₂ emission rate was recorded on January 6 with $1290.35 \pm 164.42 \text{ GgCO}_2\text{eqyr}^{-1}$, and on January 7 for the highest CH₄ emission rate with $23.29 \pm 2.90 \text{ GgCO}_2\text{eqyr}^{-1}$. The combined emissions of CO₂ ($2343.72 \pm 212.30 \text{ GgCO}_2\text{eqyr}^{-1}$) and CH₄ ($179.90 \pm 134.33 \text{ GgCO}_2\text{eqyr}^{-1}$) from the identified hotspot sites A1 and A2, based on the measurements conducted during the campaign, yield a total annual emission of $2523.62 \pm 251.23 \text{ GgCO}_2\text{eqyr}^{-1}$. This value corresponds to approximately 37.1 % (33.4–40.8 %) of the total emissions reported as $6796.59 \text{ GgCO}_2\text{eqyr}^{-1}$ for the DPIC in the 2022 national greenhouse gas inventory compiled by the Greenhouse Gas Inventory and Research Center of Korea (GIR).

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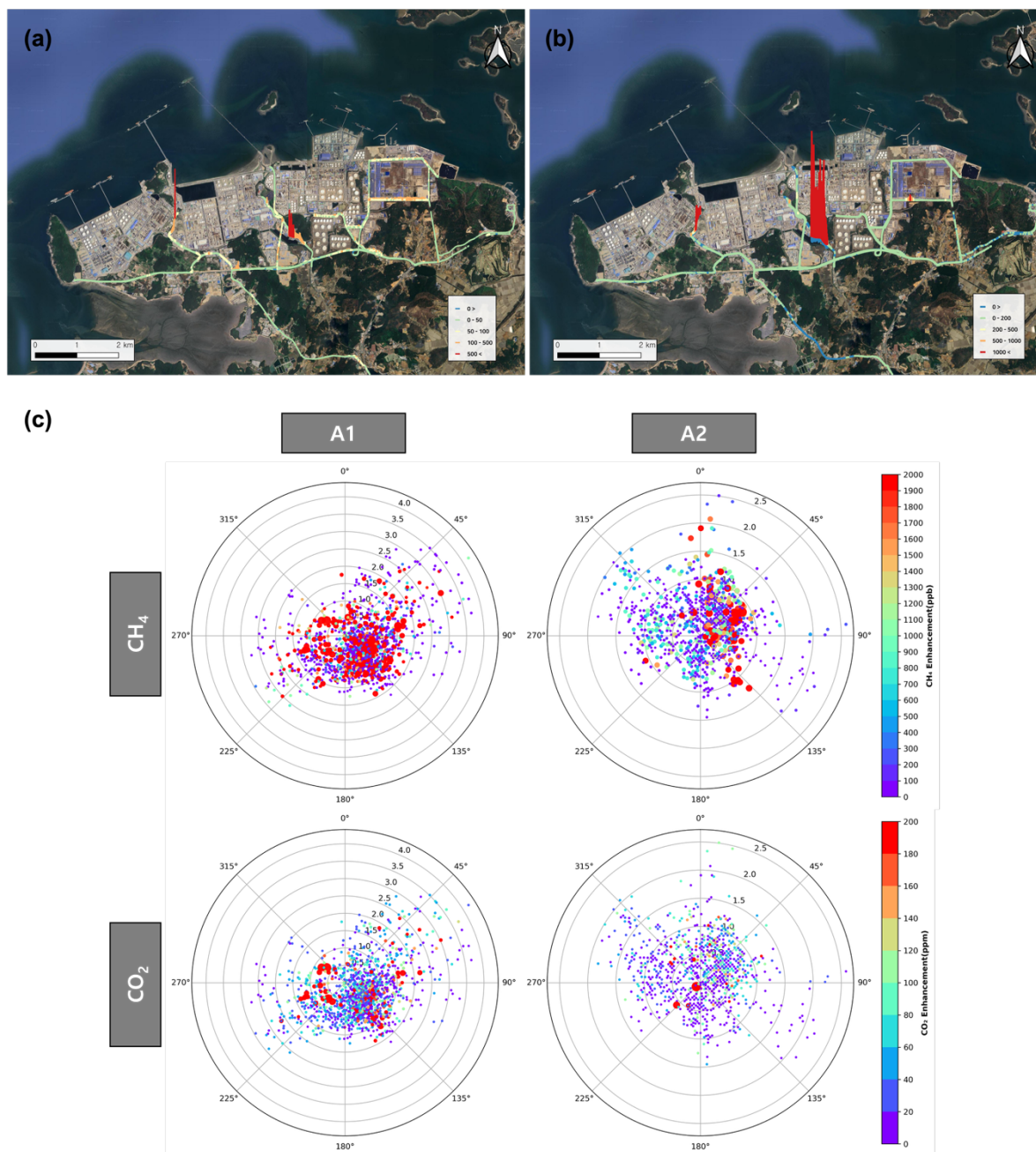


Figure 5. (a) Peak CO₂ concentrations and (b) peak CH₄ concentrations observed from the mobile measurement platform within the DPIC at sites A1 and A2. The map imagery is from © Google Earth. (c) Pollution rose analysis for sites A1 and A2 for CH₄ (top) and CO₂ concentrations (bottom) generated using simultaneously measured wind direction, wind speed, and greenhouse gas concentrations.



265 A wind vane and anemometer were installed at A1 and A2 to identify the prevailing wind conditions during periods of elevated concentrations. The pollution rose presented in **Fig. 5c** illustrates results from 30 stationary observations made from the mobile measurement platform, showing CO₂ and CH₄ enhancements projected onto wind direction–wind speed coordinates. These parameters were plotted when enhancements were observed at the site, thereby enabling inference of the direction from which the CO₂ and CH₄ concentrations were transported. A higher density of enhancements clustered within a specific wind sector indicates consistent plume inflow originating from emission sources located in that direction. At A1, both CO₂ and CH₄ exhibit pronounced clustering of enhancements in the central and southeast sector, with this pattern remaining consistent across different wind speed ranges. The proximity of facilities involved in the production of surfactants, petrochemical feedstocks, and various chemical products to the A1 site strongly suggests that these facilities are likely to be the sources of the observed enhancements. In contrast, A2 shows distinct clustering of CH₄ enhancements in the center and northeast sector, while CO₂ enhancements are relatively weaker and more scattered. The surrounding area of the A2 site contains large-scale petrochemical facilities engaging in manufacturing, storage, and transfer operations. Given the nature of such industrial operations, the observed CH₄ enhancements are consistent with non-combustion emissions, such as fugitive releases, venting, and leaks from storage tanks or transfer systems.

280 Lastly, mobile measurements of CH₄ and ethane (C₂H₆) are used to derive the proportion of observed CH₄ enhancement that is attributable to anthropogenic sources, particularly emissions from oil and gas facility operations. Ethane is widely used as a tracer to differentiate natural gas emissions from biogenic methane sources such as agriculture or landfills. Since biogenic emissions do not contain hydrocarbons like ethane, CH₄ to C₂H₆ correlations are effective for determining the non-biogenic fraction of CH₄ emissions. The methane to ethane ratio was analyzed for the sites A1 and A2 (**Fig. 6**). Both A1 and A2 sites showed positive correlations between ethane and methane ($R^2 = 0.312$ and $R^2 = 0.058$, respectively), which suggests that these emissions were sourced from non-biogenic fossil fuels. Site A1 is closely located to a manufacturer that produces high-purity carbonic acid gas and dry ice using the feed gases generated from oil refining and ethanol production processes. As a result, both the methane to ethane ratio as well as the methane to CO₂ ratio ($R^2 = 0.650$) were found to increase significantly, showing a clear correlation. Although site A2 does not have a particular manufacturer located in its vicinity as in A1, site A2 is located in between large-scale petrochemical facilities. Therefore, a weak but noticeable correlation of methane with CO₂ was also observed ($R^2 = 0.009$).

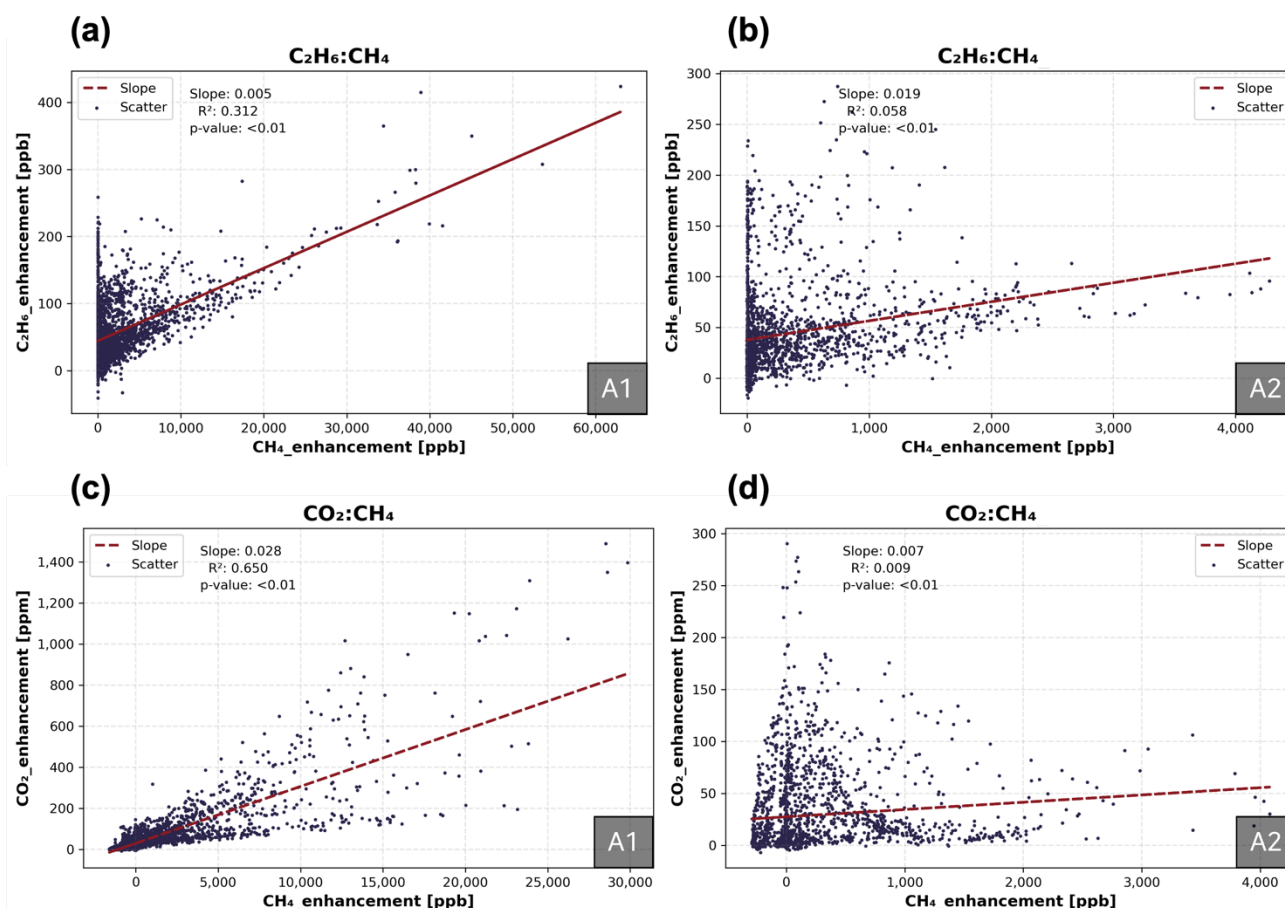


Figure 6. Ethane (C₂H₆) to methane (CH₄) ratio analysis observed by the mobile measurement platform for (a) site A1 and (b) site A2. Methane to CO₂ ratio analysis observed by the mobile platform for (c) site A1 and (d) site A2.

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3.2 GHG emission quantification from SNUCO₂M

To assess the influence of local industrial emissions on atmospheric CO₂ concentrations, the SNUCO₂M in situ instrument was deployed for continuous measurements during the campaign period in the center of the DPIC. The instrument was positioned approximately 3 m above ground level to maximize sensitivity to near-surface emissions from surrounding sources. This setup enabled detection of fine-scale variations in CO₂ concentrations attributable to local emission activity. At the DPIC site, CO₂ concentrations during the observation period averaged 469.28 ppm, with a minimum of 443.5 ppm and a maximum of 523.46 ppm. This average was approximately 27.72 ppm higher than that observed at the nearby Anmyeon-do (AMY) site, a regional background station operated by KMA under the Global Atmosphere Watch program, where the average



concentration was 441.56 ppm (**Fig. 7**). Furthermore, periodic exceedances of CO₂ concentrations above 500 ppm were also
 305 observed at DPIC. In contrast, CO₂ levels at the AMY site remained stable from 429.28 ppm to 479.42 ppm, reflecting typical
 background atmospheric conditions. In addition, CO₂ concentrations at the DPIC site exhibited concentrations that were on
 average 6.3 % higher than those at AMY, likely due to the influence of nearby emissions sources from the DPIC.

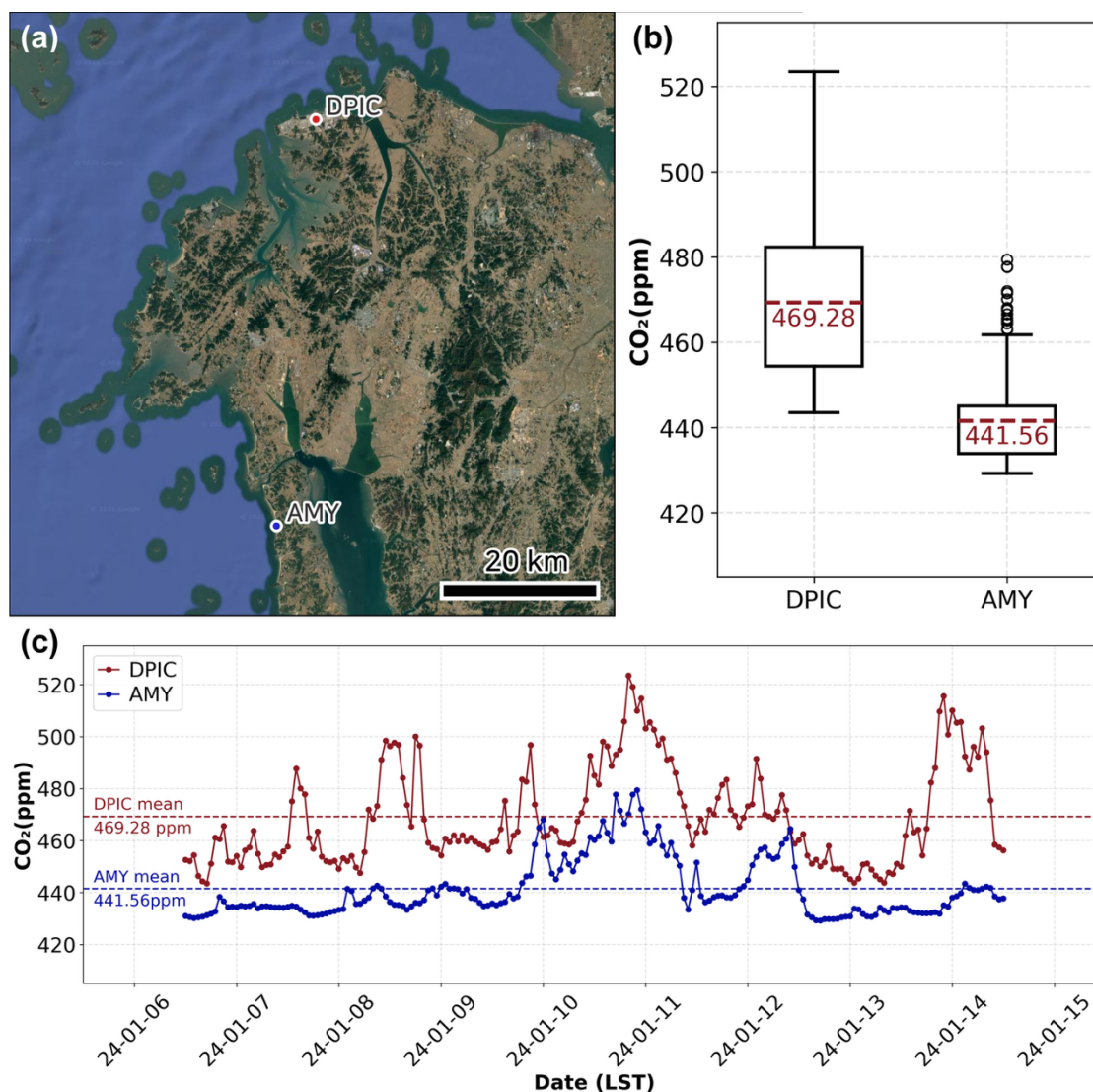


Figure 7. (a) Locations of DPIC and AMY observation sites. (b) Box and whiskers plot of mean CO₂ concentrations at DPIC and AMY, and (c) time series of CO₂ concentrations measured at DPIC (red) and AMY (blue) during the campaign period. The map imagery is from © Google Earth.



Observations from the SNUCO₂M data, in conjunction with measurements from a co-located automated weather station confirmed the presence of nearby greenhouse gas emission sources. Temporal patterns of CO₂ enhancements were found to correlate with wind speed and direction, indicating transport from adjacent industrial facilities. During the high CO₂ concentration event observed between the evening of January 11 and the early morning of January 12, southwesterly winds prevailed on the afternoon of the 11th, followed by northwesterly winds in the early morning of the 12th. Pollution roses were plotted at 6-hour intervals on different dates to illustrate concentration variations as a function of wind direction. The pollution roses identified two major emission source regions located to the north and southwest of the SNUCO₂M site (**Fig. 8**). When the prevailing wind was from the northwest, the emissions from a facility that manufactures surfactants located upwind greatly affected the in situ CO₂ measurements, and when the prevailing wind was from the southwest, the facilities manufacturing basic petrochemical materials and chemical products situated closely to the south of the SNUCO₂M impacted the observations. Finally, emission rates from these sources were quantified using the OTM-33A methodology, consistent with the method used in the mobile measurement analysis. The emission rate from the northwestern source was estimated to be 67.873 ± 8.657 GgCO₂eqyr⁻¹, while that from the southwestern source was estimated to be 44.428 ± 5.765 GgCO₂eqyr⁻¹. These findings demonstrate the utility of in situ observations for quantifying emission magnitudes and attributing them to specific industrial sectors based on meteorological conditions.

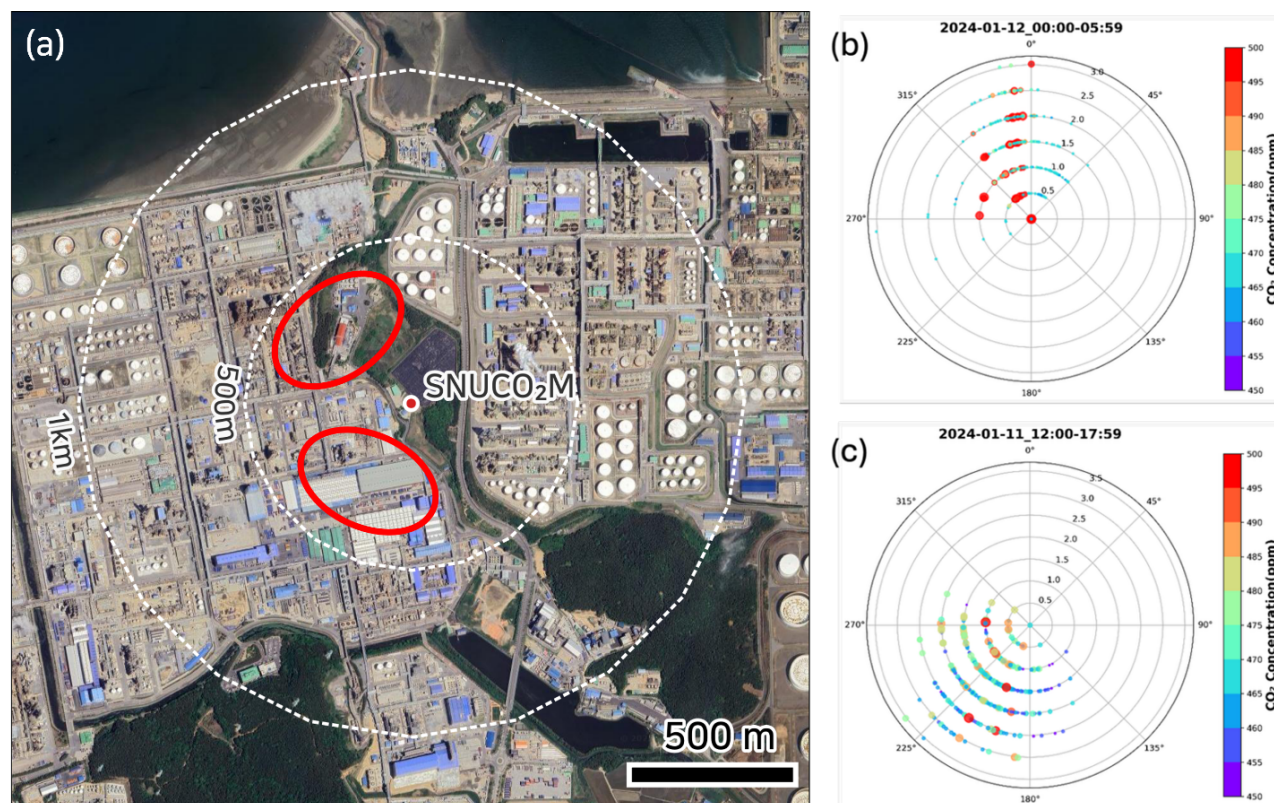


Figure 8. (a) Locations of the SNUCO₂M instrument situated in the center of the DPIC depicted as a red dot and of the two identified emission sources northwest and southwest of the measurement marked in red circles. The map imagery is from © Google Earth. Pollution rose analysis of the CO₂ concentrations emitted from the (b) northwest emission source on January 12, 2024 and (c) southwest emission source on January 11, 2024. The map imagery is from © Google Earth.

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3.3 EM27/SUN observations

A total of five days of measurements were conducted with the EM27/SUN spectrometers, with full-day observations from all three sites carried out on January 8, 12, and 13. The three deployment sites included the DPIC, the Chungnam Northwestern Center for Tourism and Environmental Education (CTEE) located to the east, and the Labor Welfare Center, Daesan Branch (LWC) located to the southeast of the DPIC. The extent to which the CTEE and LWC sites were influenced significantly or minimally by emissions from the industrial complex varied depending on the daily wind direction of each observation day.

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To isolate the anthropogenic influence of the observed GHG concentrations, enhancements of XCO₂ and XCH₄ were calculated from the EM27/SUN measurements by extracting the background concentrations (Lee et al., 2024; Ohyama et al.,



2023). To determine background concentrations, we examined the distributions of XCO_2 and XCH_4 measurements across the three observation sites during the three full observation days. As shown in **Fig. S1**, the site exhibiting the lowest concentration distribution on each day was assumed to be least influenced by local emission sources. From the site showing lowest distributions, the mode of the distribution was initially used to characterize the daily background concentration. For XCO_2 , LWC represented background concentrations on January 8, while CTEE displayed the background concentrations on January 12 and 13. For XCH_4 , DPIC showed background values on January 8, whereas CTEE exhibited the background concentrations on January 12 and 13. The background concentration at the sites also corresponded to the lowest 10th percentile concentrations recorded across all three locations on each day. Therefore, this study estimated the background concentration for each day to be the 10th percentile of all XCO_2 and XCH_4 values measured across the three sites for each day. The background XCO_2 concentrations on January 8, 12, and 13 were 424.60 ppm, 422.89 ppm, and 422.82 ppm, respectively. The background concentrations for XCH_4 were 1910.12 ppb, 1917.12 ppb, and 1918.36 ppb, respectively. Finally, daily enhancements of XCO_2 and XCH_4 (ΔXCO_2 and ΔXCH_4 , respectively) were calculated by subtracting the background concentrations from individual observations.

Figures 9–11 display the time series of ΔXCO_2 and ΔXCH_4 for January 8, 12, and 13, along with corresponding wind speed and wind direction data measured from the nearest automated weather station. On January 8, the average wind speed was 2.12 m s⁻¹, which was lower compared to other days of the campaign. Due to the weak winds, emissions were not effectively dispersed, and as a result, peak enhancements were observed in both ΔXCO_2 and ΔXCH_4 at the DPIC, with ΔXCO_2 reaching a maximum of 10.46 ppm and ΔXCH_4 reaching 22.18 ppb. Similarly, on January 13, weak winds associated with a low wind speed of 2.13 m s⁻¹ led to moderate peak enhancements in ΔXCO_2 (6.61 ppm) and ΔXCH_4 (10.84 ppb) observed at the DPIC. In contrast, on January 12, the average wind speed was higher compared to other days with a record of 3.01 m s⁻¹, which facilitated effective atmospheric dispersion of emissions. As a result, no significant peak enhancements were observed in either ΔXCO_2 and ΔXCH_4 concentrations in the DPIC. Instead, measurements at the LWC, especially for ΔXCH_4 were much higher than that of DPIC on this day.

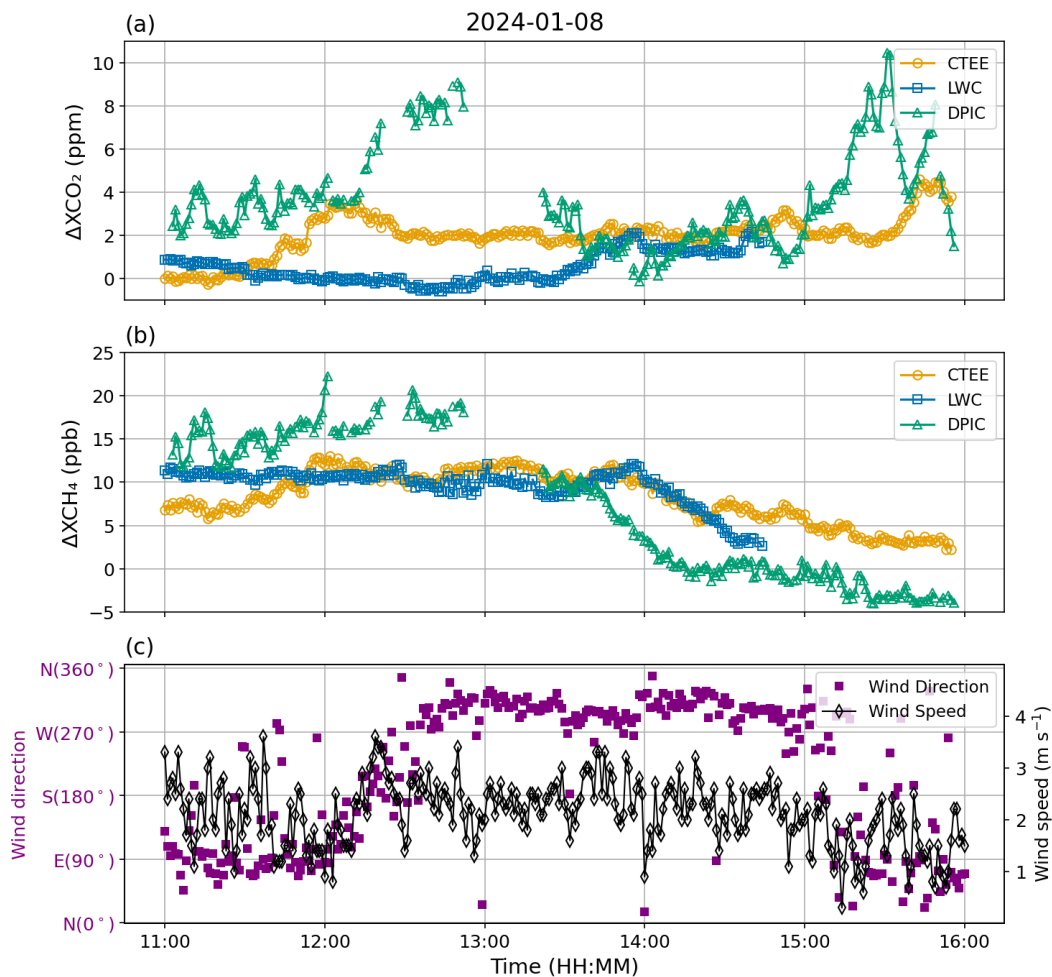


Figure 9. Measurements of (a) ΔXCO_2 and (b) ΔXCH_4 from the EM27/SUN and (c) measurements of wind speed and direction from a weather station located at each of the three sites – DPIC (green triangle), CTEE (orange circle), and LWC (blue square) – on January 8, 2024.

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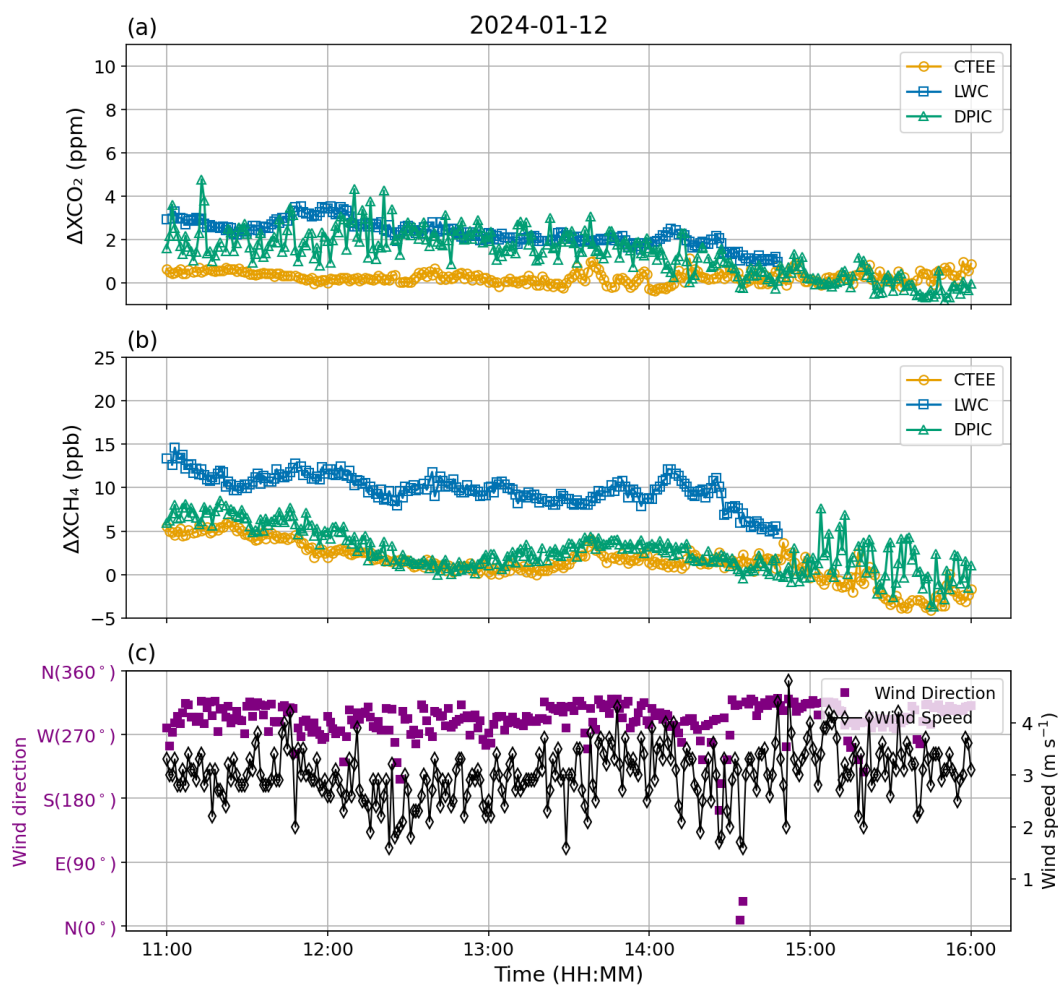


Figure 10. Measurements of (a) ΔXCO_2 and (b) ΔXCH_4 from the EM27/SUN and (c) measurements of wind speed and direction from a weather station located at each of the three sites – DPIC (green triangle), CTEE (orange circle), and LWC (blue square) – on January 12, 2024.

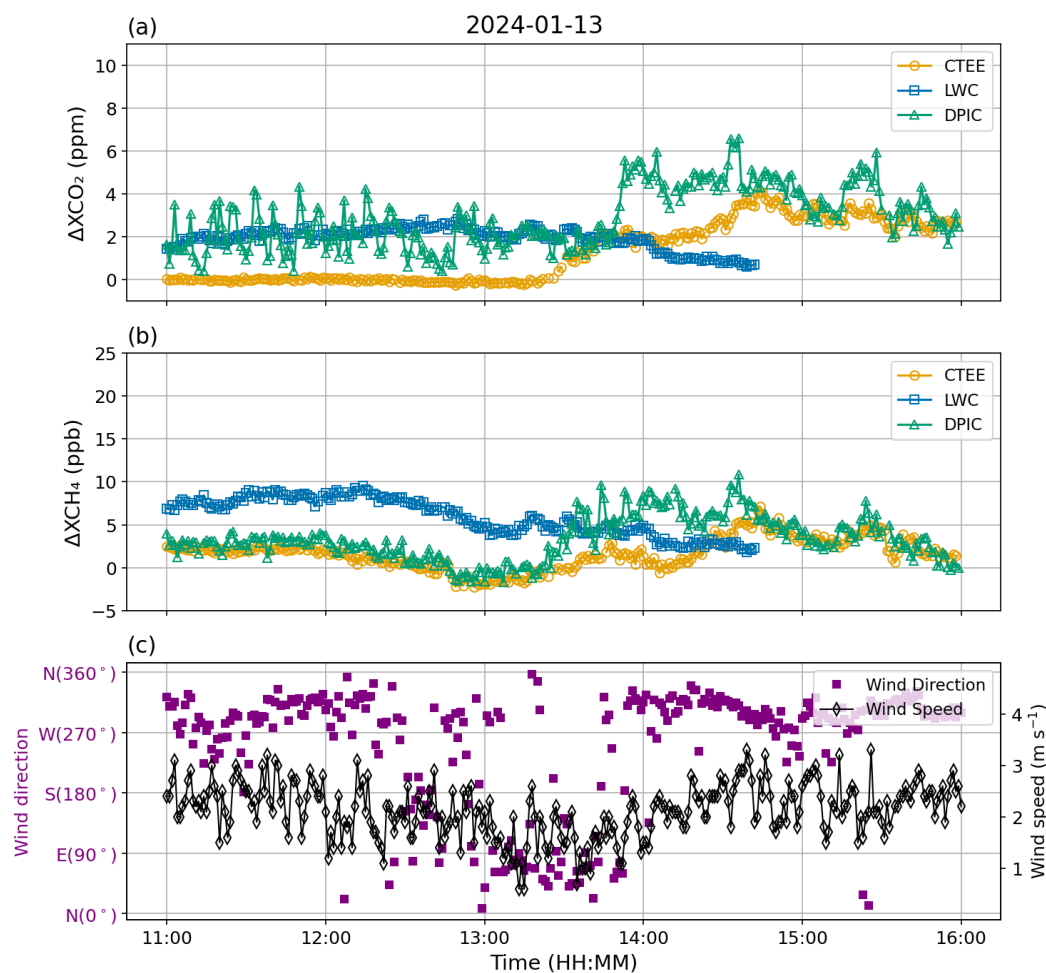


Figure 11. Measurements of (a) ΔXCO_2 and (b) ΔXCH_4 from the EM27/SUN and (c) measurements of wind speed and direction from a weather station located at each of the three sites – DPIC (green triangle), CTEE (orange circle), and LWC (blue square) – on January 13, 2024.



390 X-STILT analyses of CO₂ concentrations observed with the EM27/SUNs were carried out for January 8, 12, and 13
 to evaluate source-receptor relationships and transport pathways. One-hour back trajectories were generated for observations
 made on 12:00 and 15:00 LT of each observation day. On January 8, footprints at the DPIC site were concentrated near the
 DPIC center, indicating that air parcels were strongly influenced by emissions from within the industrial complex, consistent
 with observed peak concentrations (**Fig. 12**). CTEE was also affected by transport from the DPIC, resulting in enhancements
 395 at the site particularly at 15:00 LT. On January 12, stronger northwesterly winds led to footprint sensitivity at LWC
 concentrated over emission hotspots within the DPIC (**Fig. 13**). Consistent with the transport pattern, LWC tended to show
 higher ΔXCO_2 and ΔXCH_4 compared to the other two sites, suggesting that LWC was significantly influenced by industrial
 emissions on that day. Finally, on January 13, the footprints revealed a temporal shift in source influence. At LWC, sensitivity
 to the DPIC was initially strong but decreased from 12:00 to 15:00 LT, while CTEE showed a gradual increase of sensitivity
 400 to nearby industrial areas by 15:00 LT (**Fig. 14**). These footprint patterns align with the observed changes in GHG
 enhancements over time at both sites.

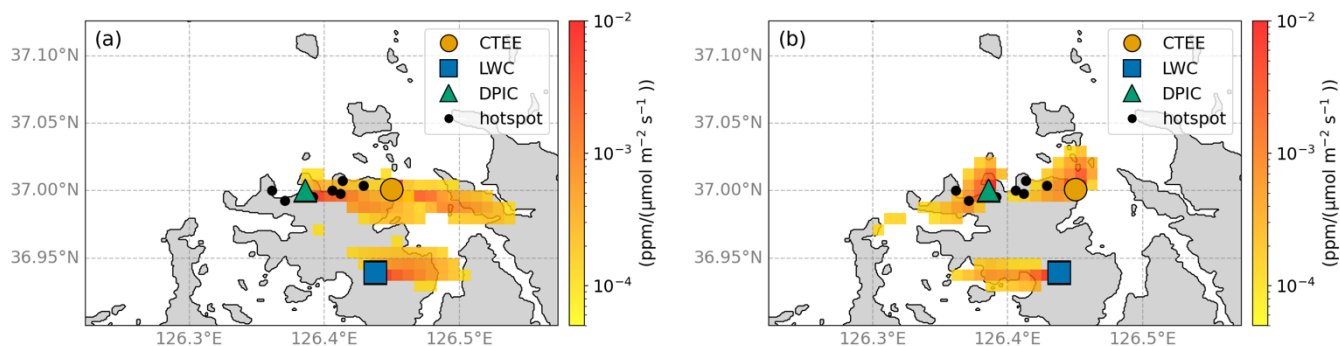


Figure 12. 1-hr back trajectory X-STILT footprints for (a) 12:00 LT and (b) 15:00 LT observed on January 8, 2024 at DPIC (green triangle), LWC (blue square), and CTEE (orange circle). Black dots represent hotspot locations identified within the DPIC.

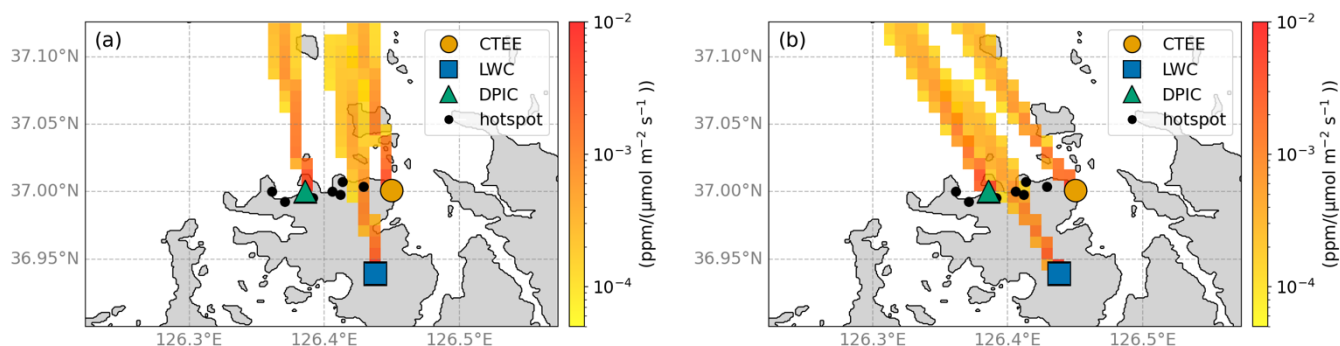


Figure 13. 1-hr back trajectory X-STILT footprints for (a) 12:00 LT and (b) 15:00 LT observed on January 12, 2024 at DPIC (green triangle), LWC (blue square), and CTEE (orange circle). Black dots represent hotspot locations identified within the DPIC.

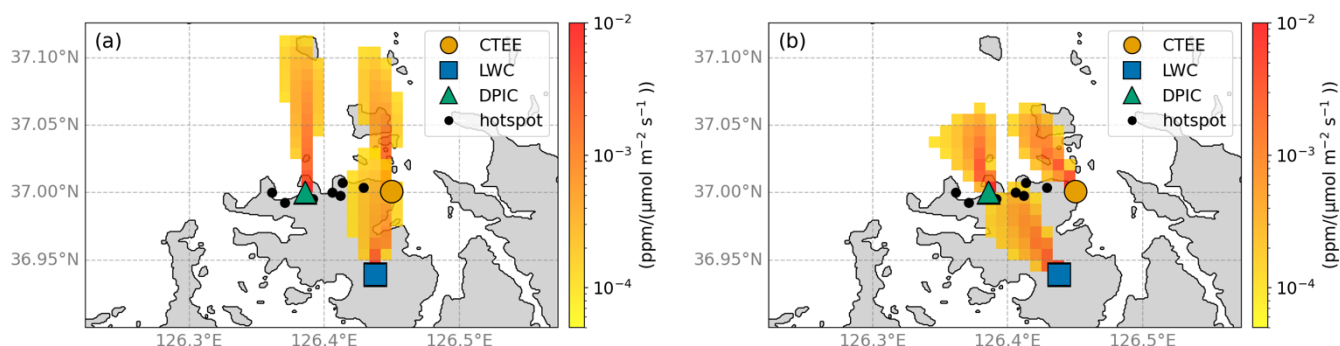


Figure 14. 1-hr back trajectory X-STILT footprints for (a) 12:00 LT and (b) 15:00 LT observed on January 13, 2024 at DPIC (green triangle), LWC (blue square), and CTEE (orange circle). Black dots represent hotspot locations identified within the DPIC.



3.4 Aircraft observations

Figure 15 displays the aircraft flight pathways and measurements of CO₂ and CH₄ made during clear sky days on January 6 and 13. Vertical profile measurements were conducted north and south of the DPIC, covering an altitude range from ~500–1200 m a.s.l. Enhancements of GHG concentrations were consistently observed downwind at the southern part of the DPIC, indicating a clear influence from emissions originating within the complex. In addition to the profiles, five circular flight loops were executed around the DPIC. Elevated concentrations of CO₂ and CH₄ were predominantly detected in the downwind region, particularly below 900 m a.s.l., highlighting the presence of emission plumes near the surface. The mean concentration recorded above 900 m a.s.l. in the free troposphere showed minimal variability with an average of 430.87 ppm and 427.53 ppm for CO₂ and 2038.25 ppb and 2019.21 ppb for CH₄ on January 6 and 13, respectively. The average concentration below 900 m a.s.l. show elevated concentrations with an average of 435.90 ppm and 440.47 ppm for CO₂, while 2047.05 ppb and 2055.86 ppb for CH₄ on January 6 and 13, respectively. Moreover, straight-line transects at a constant altitude of ~500 m a.s.l. were also conducted across the DPIC. These aircraft passes flown directly over the complex clearly captured peak concentrations of both CO₂ and CH₄. Highest concentrations reached for CO₂ is 503.56 ppm and 546.17 ppm on January 6 and 13, respectively, while CH₄ reached a maximum of 2295.80 ppb and 2338.70 ppb on January 6 and 13, respectively (**Fig. 16**).

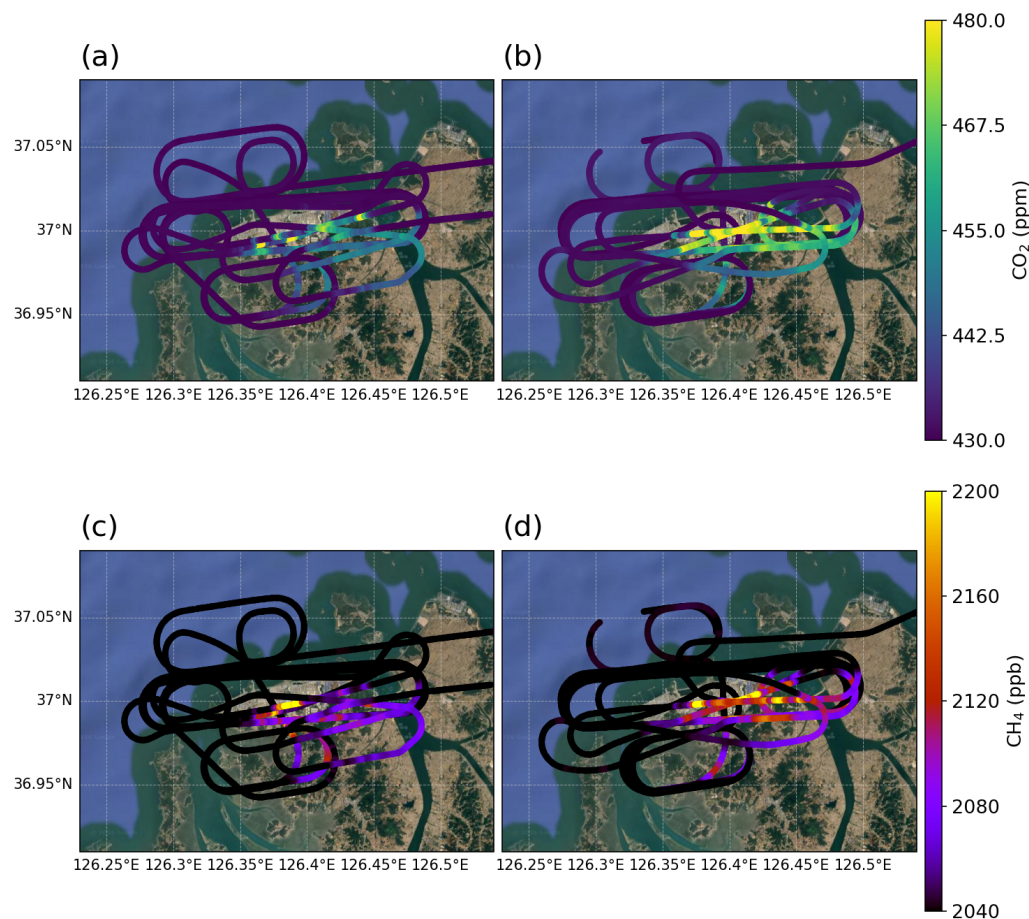


Figure 15. Aircraft observation path for CO₂ on (a) January 6 and (b) January 13, 2024, and aircraft observation path for CH₄ on (c) January 6 and (d) January 13, 2024. Base map uses OpenStreetMap tiles from © OpenStreetMap contributors, distributed under the Open Database License (ODbL).

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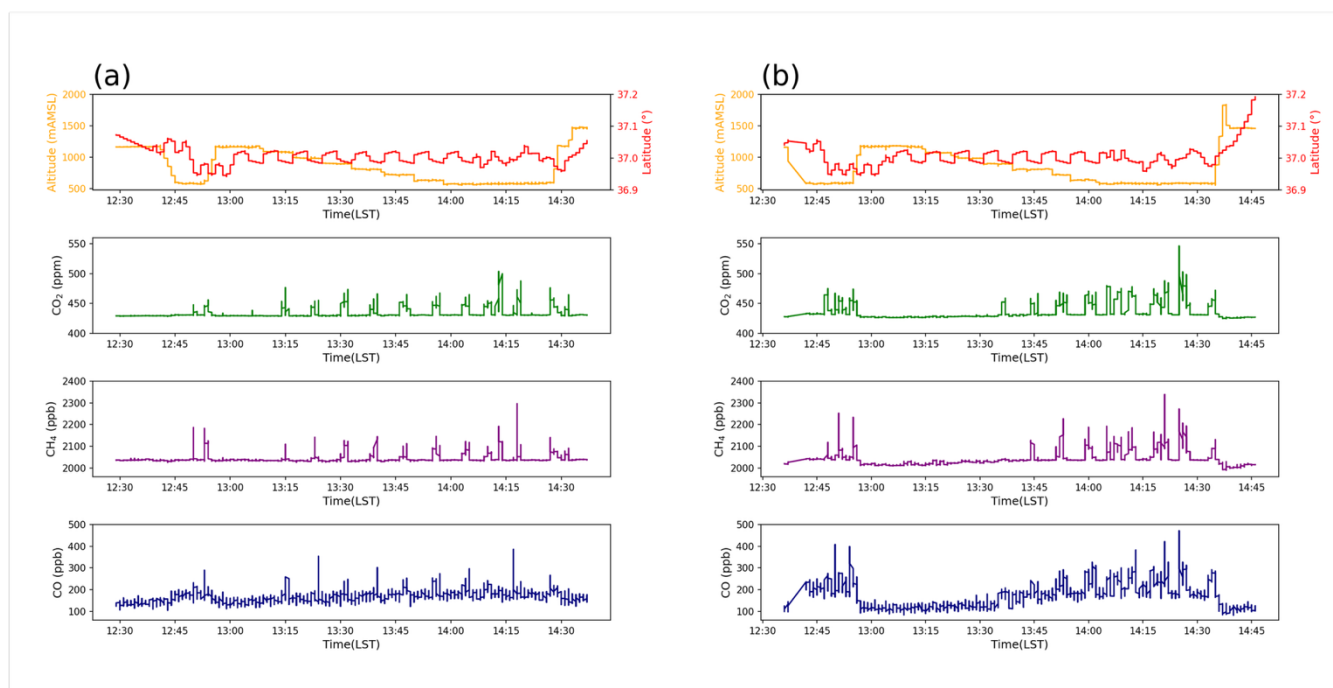


Figure 16. Flight altitude, latitude, CO₂, CH₄, and CO concentrations by time for (a) January 6, 2024 and (b) January 13, 2024 aircraft observations.

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To further investigate the emission characteristics observed from aircrafts, the enhancement ratios of CO/CO₂, CH₄/CO₂, and CH₄/CO (expressed as $\Delta\text{CO}/\Delta\text{CO}_2$, $\Delta\text{CH}_4/\Delta\text{CO}_2$, and $\Delta\text{CH}_4/\Delta\text{CO}$, respectively) were assessed along the flight transects of each latitude. Aircraft observations were first subset by altitude from 500–900 m a.s.l. to minimize vertical variability and focus on horizontally distributed plume signals closest to the sources. Background concentrations of each day were calculated to be the 10th percentile of the data and were subtracted from each observation point. The data were then grouped by latitude in increments of 0.01° (~1.1 km). We performed a least-squares linear regression between gas pairs, yielding the slope as an initial estimate of the enhancement ratio. To assess the robustness of each slope estimate, we employed a non-parametric bootstrapping method. For each latitude bin, the paired samples were resampled 500 times, maintaining the same sample size as the original dataset. The median of the bootstrap slope distribution was adopted as the best-estimate slope for each latitude bin, while the interquartile range and 95 % confidence interval were used to represent the associated uncertainty.

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Figure 17 presents the latitude-dependent enhancement ratios of $\Delta\text{CO}/\Delta\text{CO}_2$, $\Delta\text{CH}_4/\Delta\text{CO}_2$, and $\Delta\text{CH}_4/\Delta\text{CO}$, expressed as correlation slopes. The black line shows the median slope in each bin, and boxes with error bars indicate the variability and confidence intervals from 500 bootstrap resamplings. Latitude-resolved enhancement ratios derived through bootstrap regression from both flights on January 6 and January 13 show that emissions from the DPIC are composed of two distinct but spatially co-located regimes: combustion-derived CO and fugitive CH₄ releases. Elevated $\Delta\text{CO}/\Delta\text{CO}_2$ slopes reflect incomplete combustion and flare activity, while $\Delta\text{CH}_4/\Delta\text{CO}_2$ and $\Delta\text{CH}_4/\Delta\text{CO}$ slopes indicate concurrent fugitive methane releases and combustion-related CO emissions.

On January 6, the $\Delta\text{CO}/\Delta\text{CO}_2$ ratio peaks within $\sim 37.01\text{--}37.03^\circ\text{N}$ with a slope of $13.80\text{ ppb ppm}^{-1}$ (95 % bootstrap confidence interval (CI) of $12.16\text{--}15.67$, $R^2 = 0.40$), identifying the combustion core of the DPIC. In contrast, $\Delta\text{CH}_4/\Delta\text{CO}_2$ ratios exhibits a pronounced U-shaped structure with highest ratios located south (3.59 ppb ppm^{-1} with 95 % bootstrap CI: $3.13\text{--}3.93\text{ ppb ppm}^{-1}$) and north (3.19 ppb ppm^{-1} with 95 % bootstrap CI: $3.01\text{--}3.39\text{ ppb ppm}^{-1}$) of this region. At 37.00°N , the combination of low $\Delta\text{CO}/\Delta\text{CO}_2$, a pronounced dip in $\Delta\text{CH}_4/\Delta\text{CO}_2$ and moderate $\Delta\text{CH}_4/\Delta\text{CO}$ indicates the aircraft was sampling the boundary of the flare plume where CH₄ has been oxidized but CO production remain limited, reflecting relatively efficient combustion and partial mixing with surrounding methane leak air. North of 37.04°N , elevated $\Delta\text{CO}/\Delta\text{CO}_2$ and $\Delta\text{CH}_4/\Delta\text{CO}_2$ coupled with low $\Delta\text{CH}_4/\Delta\text{CO}$ (slopes ranging from $0.04\text{--}0.1\text{ ppb ppm}^{-1}$) indicate overlapping combustion and methane influences. This pattern indicates that methane leaks and combustion plumes were spatially distinct, which the aircraft sampled across latitude.

On January 13, south of 37.00°N $\Delta\text{CO}/\Delta\text{CO}_2$ remains low ($2.08\text{--}3.34\text{ ppb ppm}^{-1}$) while $\Delta\text{CH}_4/\Delta\text{CO}_2$ is modest ($1.59\text{--}2.21\text{ ppb ppm}^{-1}$) and $\Delta\text{CH}_4/\Delta\text{CO}$ exhibits two distinct peaks that reached 0.58 (95 % CI: $0.52\text{--}0.66$) and 0.90 (95 % CI: $0.84\text{--}0.97$), indicating the presence of methane-rich, CO-poor plumes unrelated to combustion. These features are consistent with intermittent or spatially localized fugitive CH₄ emissions, such as tank venting or pipeline leakage, rather than flare exhaust. North of 37.01° , both $\Delta\text{CO}/\Delta\text{CO}_2$ ($9.04\text{--}31.19\text{ ppb ppm}^{-1}$) and $\Delta\text{CH}_4/\text{CO}_2$ increase ($2.92\text{--}3.57\text{ ppb ppm}^{-1}$) while $\Delta\text{CH}_4/\Delta\text{CO}$ remains suppressed ($0.02\text{--}0.13$), indicating a CO-rich combustion plume that has additional methane present yet not co-emitted with CO. This pattern is consistent with overlapping sources of a combustion influence mixed with an independent CH₄ source. Lastly, the northward increase of $\Delta\text{CH}_4/\Delta\text{CO}_2$ enhancement ratios suggest ongoing venting beyond the combustion area and confirms that methane leakage is spatially coincident but not identical to CO emissions, which is typical of fugitive gas and combustion mixture in petrochemical complexes. The persistently low $\Delta\text{CH}_4/\Delta\text{CO}$ ($0.02\text{--}0.13$) shows that CO increases more rapidly than CH₄, suggesting decoupled origins rather than a single co-emitting process. Together, these observations indicate that Daesan's plume chemistry is dynamic, with the balance between leakage and combustion varying with facility operation and meteorological conditions.

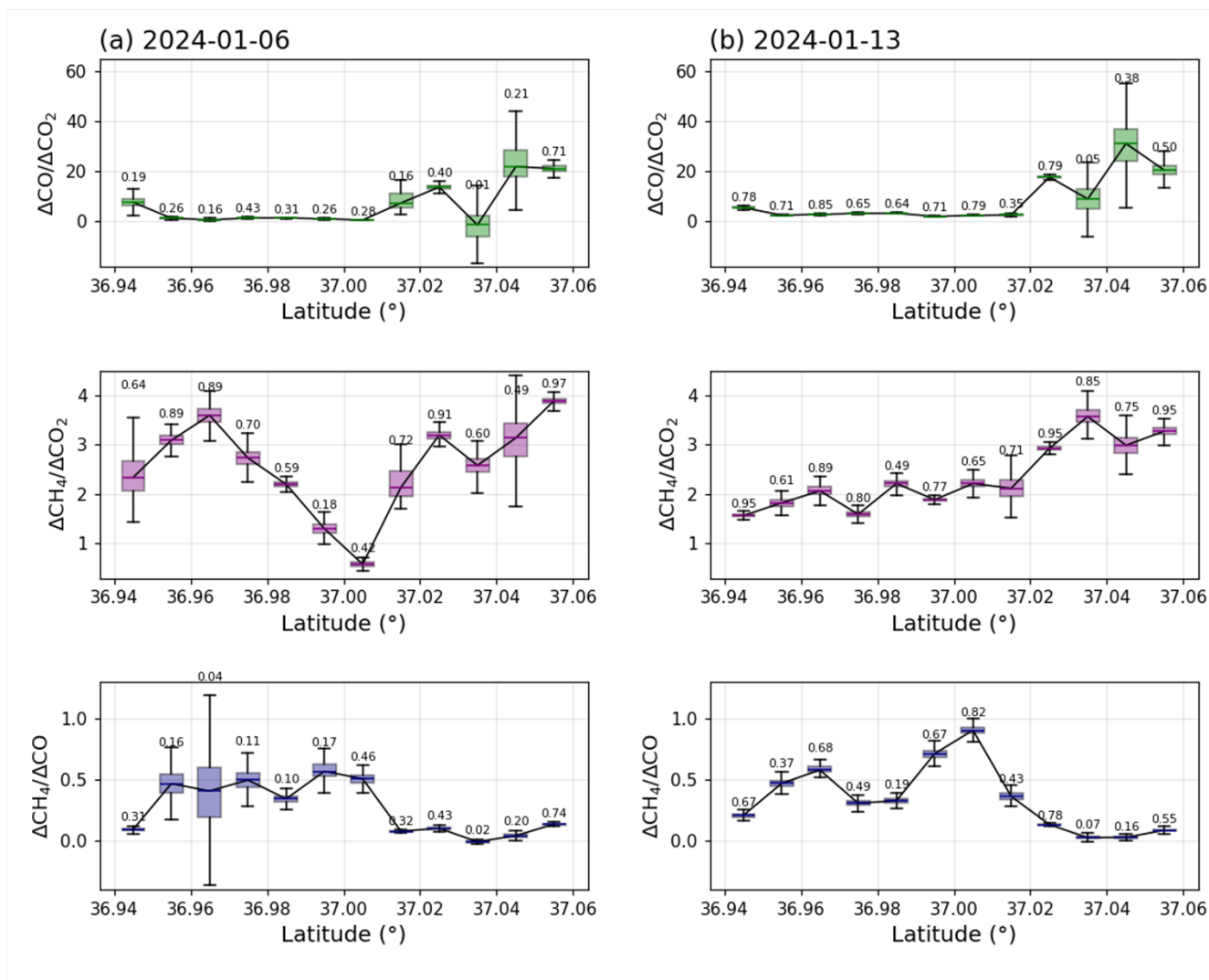


Figure 17. Latitude-resolved enhancement ratios of $\Delta\text{CO}/\Delta\text{CO}_2$ (green), $\Delta\text{CH}_4/\Delta\text{CO}_2$ (pink), and $\Delta\text{CH}_4/\Delta\text{CO}$ (purple) derived through bootstrap regression from both aircraft flights on (a) January 6 and (b) January 13 are plotted as box and whiskers plots versus latitude. Boxes indicate the IQR and whiskers represent the confidence interval. The coefficient of determination (R^2) for each slope is listed on top of each ratio.



510 3.5 EMIT observations

Due to limited satellite overpasses during the campaign period, we used post-campaign EMIT observations collected over the DPIC on April 7, 2024. The spatial distribution of methane emissions at the DPIC was assessed using EMIT observations processed with the matched filter method. The DPIC region exhibited many areas with high enhancements exceeding 2000 ppm·m, in contrast to the lower enhancements observed outside the region. As shown in **Fig. 18**, the average
515 enhancement in the DPIC region was 1153.30 ppm·m, which is 31.14 % higher than the 879.41 ppm·m observed in the area outside the DPIC.

In some areas, high enhancement values from EMIT were consistent with mobile observations from the ground. Large methane enhancements from EMIT, reaching up to 2127.56 ppm·m, were confirmed by mobile measurements, which also consistently showed elevated methane concentrations exceeding 300 ppb. These areas are identified as potential methane
520 hotspots with significantly higher concentrations than their surroundings. Additionally, EMIT detected stronger methane enhancements at an oil storage complex, supported by elevated concentrations relative to the surrounding area observed from the mobile measurements (**Figs. 18b-c**). From these hotspots, the mobile platform observed methane enhancements over 100 ppb on four days and EMIT reported values as high as 3743.49 ppm·m, suggesting emissions related to storage or operational processes. However, as urban industrial surfaces are spectrally heterogenous, EMIT enhancements can be susceptible to
525 retrieval artifacts. Therefore, agreement with independent mobile observations is critical for interpretation. Although the EMIT observations on April 7, 2024, occurred several weeks after the mobile measurements made in January, both datasets consistently captured methane enhancements at the same locations. This agreement across independent observations and timeframes reinforces the reliability of atmospheric measurements and highlights the persistent nature of methane emission from identified sources within the DPIC.

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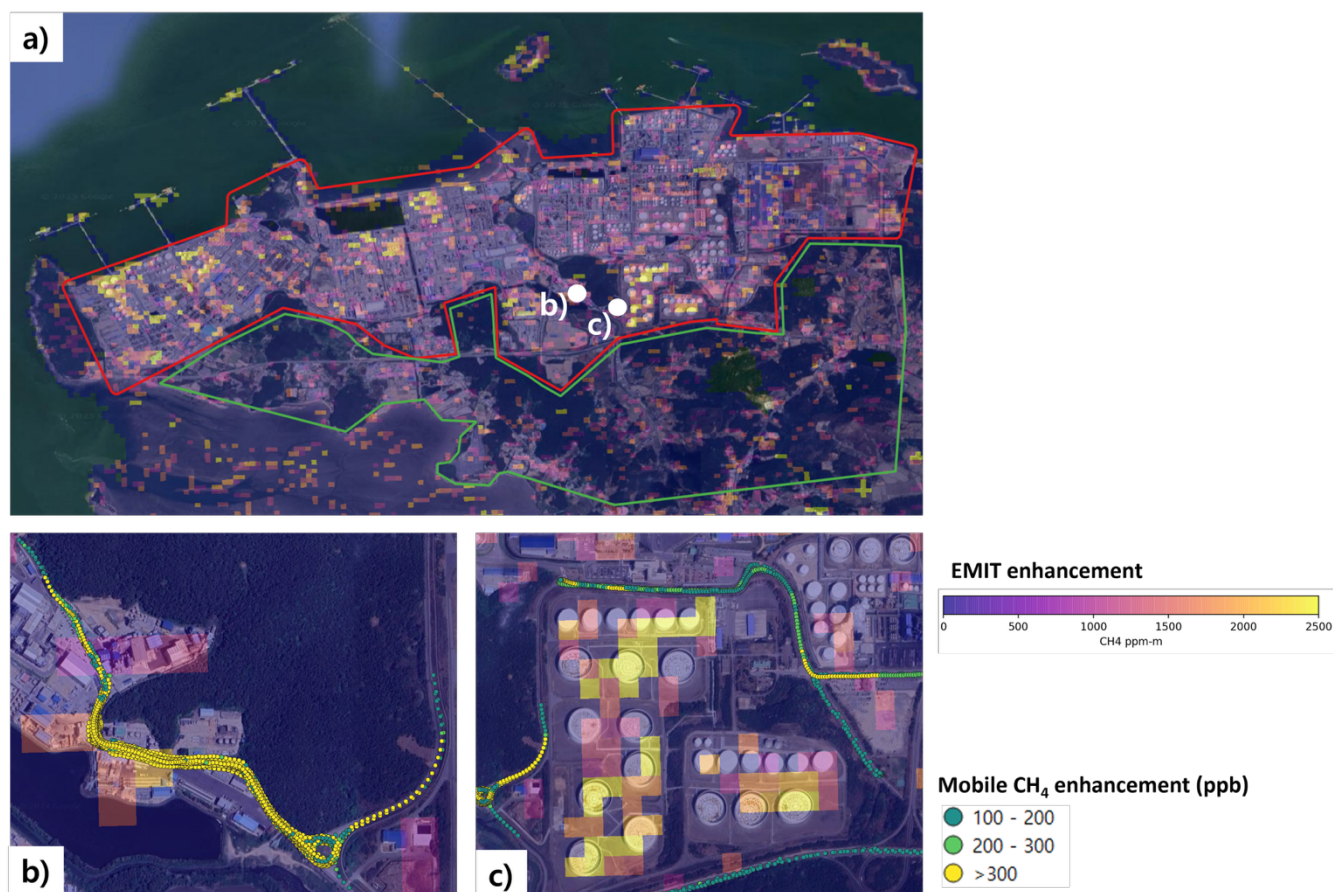


Figure 18. (a) Methane enhancements observed over the DPIC estimated with EMIT satellite data collected on April 7, 2024 and processed with the matched filter method. The red shape outlines the DPIC region, while the green shape denotes the area outside the DPIC. Satellite-based enhancements are compared with mobile observations shown in circles which show similar methane enhancements on (b) roads and (c) facilities within the DPIC. The map imagery is from © Google Earth.



4 Discussion

This study presents the results of the first multi-platform campaign to quantify greenhouse gas emissions from the Daesan Petrochemical Industrial Complex in South Korea. By integrating ground-based in situ and remote sensing measurements, mobile surveys, aircraft observations, and satellite data, we demonstrate the effectiveness of an integrated top-down approach in monitoring and characterizing CO₂ and CH₄ emissions in an industrial environment with heterogenous emission sources.

Ground-based measurements, including in situ and EM27/SUN observations, confirmed the presence of CO₂ and CH₄ from combustion-related processes as well as transport of these emissions originating from the DPIC to surrounding areas. CO₂ concentrations measured by the SNUCO₂M instrument were on average 6.3 % higher (27.72 ppm) within the DPIC compared to background levels. The EM27/SUN observations further verified that plumes frequently extended beyond the boundary of the DPIC with enhanced CO₂ and CH₄ detected from downwind sites, indicating that meteorological conditions often confine and transport emissions into surrounding regions. These results highlight the value of sustained ground-based monitoring for attributing emissions to specific industrial sectors under varying atmospheric transport.

Mobile and aircraft measurements provided additional spatial and temporal context that ground-based platforms cannot provide, revealing variability in emission strength related to industrial operating conditions and localized sources with different processes that make up the emission characteristics of the DPIC. Based on the simultaneous measurements of CH₄, ethane, and CO₂ on the mobile platform, correlations of CH₄ with ethane and CO₂ also confirmed that CH₄ enhancements observed within the DPIC are from non-biogenic fossil fuel sources. Notably, mobile measurements near two of the largest emitting facilities identified combined signatures of combustion-related CO₂ and CH₄, but also fugitive releases of CH₄ possibly from vents and leaks. Aircraft observations were able to spatially extend and support this finding across the broader complex, with emission ratio characteristics showing increased pure leakage of CH₄ emissions generated near the central part of the DPIC as well as increased combustion activity particularly in the central region of the complex, confirming that this pattern was not an artifact of localized sampling but a spatially coherent feature within the industrial complex. With the confidence of a spatial overview from aircraft observations, we used mobile observation data to estimate an annual GHG emission rate of $2,595.49 \pm 333.09 \text{ GgCO}_2\text{eqyr}^{-1}$ from the two hotspots in the DPIC sampled during the campaign. This value accounts for approximately 37.1 % of the emissions reported for the DPIC in the 2022 national GHG inventory compiled by the GIR. Given that our estimate captures only a subset of facilities within the DPIC, the substantial fraction captured by our measurements suggests that total emissions reported in the national inventory are likely underestimated. In particular, the discrepancy highlights potential setbacks in current inventory methodologies, including insufficient accounting of fugitive methane emissions and intermittent leakage events that are difficult to capture using bottom-up approaches.

Moreover, observations during the campaign were restricted to areas where site access was permitted and several regions, particularly in the western portion of the DPIC, remained inaccessible due to facility restrictions. Utilizing the advantage of satellite remote sensing, we used EMIT observations to identify methane enhancements in these areas where



ground access was not possible. In regions where EMIT detected strong methane hotspots, mobile measurements conducted outside facility boundaries showed consistent enhancement patterns. Our findings suggest certain sectors and sources unidentified during the campaign may also have emission magnitudes that could be underestimated in the national inventory. These results underscore the complementarity of satellite and ground-based approaches and the necessity of satellite remote sensing as an indispensable observation component that expands observational coverage for comprehensive and robust emission source quantification.

The multi-platform, cross-validating monitoring architecture, where in situ and ground measurements provide reference to local emissions for mobile data, mobile source attribution informs aircraft interpretation, aircraft observations confirm spatial representativeness, and satellite observations extend coverage beyond physical access constraints, demonstrates that the synergy between different measurement platforms is not only additive but recursive. Each measurement method both depends on and reinforces the reliability of the others, producing a level of emission attribution confidence that no single measurement platform could approach in isolation. The integration of multiple observational platforms enabled the characterization of emission sources, as well as identification of fugitive methane emissions, corroborated across distinct temporal and spatial scales. Furthermore, the discrepancies identified between emission estimates derived from integrated atmospheric observations and reported national inventories are further substantiated by mutually consistent signals converging across five independent observational approaches.

Consistent with our findings, a growing number of studies have demonstrated that integrated multi-platform atmospheric observation approaches yield stronger observational constraint and a more comprehensive characterization of emission sources. For example, the Upper Silesian Coal Basin, the largest coal-producing region in Poland, has been extensively studied using both bottom-up and top-down approaches. Using EM27/SUN spectrometers in combination with the Lagrangian particle dispersion model FLEXPART, Luther et al. (2022) estimated instantaneous methane emissions ranging from approximately 2,240 to 3,724 GgCO₂eqyr⁻¹. Complementary aircraft-based studies by Fiehn et al. (2020) reported annualized CO₂ emission rates of 1.21 ± 0.75 and 1.12 ± 0.38 t s⁻¹ from two selected flights, alongside CH₄ emission rates of 13.8 ± 4.3 and 15.1 ± 4.0 kg s⁻¹, underscoring the variability of emissions from industrial regions. Observation-based approaches have also been widely applied to oil and gas production regions to quantify emissions at individual facilities and point sources. Using mobile measurements, Korbeń et al. (2022) estimated a mean methane emission rate of 0.49 kg CH₄ h⁻¹ for individual oil and gas facilities in Romania. Lastly, satellite-based analyses have proven effective in identifying super-emitters where Irakulis-Loitxate et al. (2021) detected 37 extreme methane plumes with emission rates exceeding 500 kg h⁻¹ in the Permian Basin using spaceborne observations. Finally, Harris et al. (2025) estimated methane emissions from subsea pipeline leaks by integrating bottom-up pipeline rupture simulations with verifications from top-down emission estimates from airborne, satellite, and tall tower data. The combined modelled and top-down emission estimates agreed to be approximately 465 ± 20 thousand metric tons of methane emitted to the atmosphere. Their analysis highlights the value of complementary measurement approaches for quantifying methane emissions and demonstrates that incorporating top-down observations across multiple spatiotemporal domains provide a more reliable estimate of atmospheric methane emission leaks than previous



600 studies. Together, these results demonstrate that observation-based methods consistently reveal substantial emissions that are often underestimated or entirely missed by bottom-up inventories or by single observational methods, highlighting the need to integrate multi-platform observations into national inventory frameworks for industrial areas.

5 Conclusion

A multi-platform monitoring strategy, combining observations from ground-based spectrometers, in situ sampling, 605 mobile surveys, aircraft measurements, and satellite retrievals was applied to characterize CO₂ and CH₄ emissions from the DPIC during a winter field campaign in January 2024. The objective of this study was to evaluate whether the synergy of varying observational methods captures the true magnitude and spatial distribution of emissions from an industrial complex. Agreement among the five independent platforms, which differ in spatial scale, measurement sensitivity, and observational methods, provides a robust constraint on both emission magnitude and source attribution, revealing that two facility hotspots 610 alone accounted for 37.1 % of the nationally reported inventory value for the entire complex. In addition, EMIT satellite retrievals aided in identifying methane enhancements over areas where access was restricted for ground-based measurement platforms. These results indicate that reported inventory values substantially underestimate actual emissions from the DPIC, particularly with respect to fugitive and episodic sources. The consistency of this discrepancy across platforms suggests that the underestimation reflects a structural limitation of activity-based inventory construction rather than an artifact of any single 615 measurement approach. Bottom-up methodologies rely on assumed emission factors and idealized process conditions, which often fail to account for intermittent leaks and unpermitted or under-characterized emission points of the kind identified in this study. The spatial coincidence of column and in situ CO₂ and CH₄ enhancements with specific facility units further supports source attribution to identifiable processes rather than diffuse, complex-wide emission.

While this campaign provided unprecedented observational detail over the DPIC, the representativeness of these 620 findings is subject to several limitations. The campaign was restricted to nine days during a single winter period, and seasonal variability in process throughput, maintenance activity, and temperature-dependent emission rates cannot be excluded. Furthermore, due to meteorological constraints, only a fraction of campaign days yielded fully overlapping ground, mobile, and aircraft observations. Extending this multi-platform observation approach across different seasons or to annual monitoring is needed to assess the representativeness of the derived emission estimates. In addition, satellite CO₂ and CH₄ datasets from 625 greenhouse gas observation satellites such as OCO-2, OCO-3, GOSAT, GOSAT-2, and Sentinel-5P TROPOMI were excluded due to overpass timing and quality filtering at coastal areas. Also, site access restrictions prevented ground-based confirmation of the sources behind existing satellite-observed enhancements in restricted areas, so their attribution remains inferred. Finally, because the five platforms differ in spatial and temporal resolution, some of their apparent agreement may reflect shared sensitivity to the same source regions rather than fully independent confirmation.

630 Despite these limitations, the results have direct implications for the assessment of industrial greenhouse gas emissions and frameworks used to verify them. The recursive, cross-validating architecture demonstrated with the multi-



platform observation approach, in which each observational platform both contextualizes and reinforces the interpretation of the others, offers a replicable methodological model for industrial emission monitoring beyond the DPIC, applicable to other large-scale industrial source regions where emission heterogeneity, process diversity, and restricted site access present persistent challenges to accurate quantification. The coordinated use of multi-scale observations that integrate continuous ground-based measurements with repeated mobile campaigns, periodic airborne surveys, and expanding satellite data coverage will be essential for reducing emission attribution uncertainty, improving the robustness of national GHG inventories, and supporting the emission verification frameworks that effective climate policies demand.

Code, data, or code and data availability

The SNUCO₂M, mobile platform, EM27/SUN, and aircraft measurement data used for the campaign analysis is available on Zenodo at <https://doi.org/10.5281/zenodo.21201694> (Park et al., 2026). EMIT data products are publicly available from the NASA Land Processes Distributed Active Archive Center (LP DAAC) at <https://www.earthdata.nasa.gov/centers/lp-daac>.

Author contributions

HP and SJ conceptualized the research goals, and SJ supervised the study. HP, JJ, YL, HL, JK, JS, JL, DK developed the methodology and performed the measurements. Resources and instrumentation were provided by IM, MF, GM, HE, SL, SK, JY, KS. Formal analysis was conducted by HP, JJ, YL, HK, JK, JS. The original manuscript draft was prepared by HP with contributions from co-authors. The manuscript review and editing were done by SJ, JJ, DC, YL, HL, JK, JS, JL, JH, IM, MF, and SL.

Competing interests

The authors declare that they have no conflict of interest.

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