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Special session

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Moderators: Hiroshi Suto (JAXA), Tsuneo Matsunaga (NIES)

Status of NIES GOSAT and GOSAT-2 Projects

Tsuneo Matsunaga[1], Isamu Morino[1], Yukio Yoshida[1], Makoto Saito[1], Hibiki Noda[1], Hirofumi Ohyama[1], Yu Someya[1], Tazu Saeki[1], Yosuke Niwa[1], Hiroshi Tanimoto[1], Akihide Kamei[1], Fumie Kawazoe[1], Yukitomo Tsutsumi[1], Jiye Zeng[1], Shamil Maksyutov[1], Rajesh Janardanan[1], Fenjuan Wang[1], and Lorna Nayagam[1]

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Greenhouse gases Observing SATellite (GOSAT) launched in 2009 and GOSAT-2 launched in 2018 are Japanese satellite missions jointly promoted by Ministry of the Environment, Japan Aerospace Exploration Agency (JAXA), and National Institute for Environmental Studies (NIES), for global observation of major greenhouse gases, carbon dioxide (CO_2) and methane (CH_4). NIES is responsible for generation, validation, distribution, and archiving of higher level products such as (L2) column average concentrations and (L4) fluxes of CO_2 and CH_4. L2 products are being updated when updates on L1B spectral radiance products, L2 processing algorithms, and reference data occurred. Latest L2 standard products from NIES, V03.00/03.05 for GOSAT and V02.10 for GOSAT-2 are validated using data from the global networks of ground-based Fourier transform spectrometers such as Total Carbon Column Observing Network (TCCON).

Although the design lifetimes of two satellites, five years, have already passed, they are mostly in healthy conditions and providing CO_2 and CH_4 data for more than 16 years. During 16-year period, two El Nino events have been occurred, the one around 2016 and the other in 2023/2024. GOSAT data clearly showed the coincident between El Nino event and high CO_2 annual growth as presented in our latest press release (https://www.nies.go.jp/whatsnew/20250214/20250214-e.html). The sudden surge and decline of CH_4 concentration growth were also captured by GOSAT around 2021 (https://www.nies.go.jp/whatsnew/20220323/20220323-e.html). Inversion studies using GOSAT data to clarify the mechanisms of such global phenomena are ongoing.

In addition to the inversion system used for the generation of GOSAT L4 and GOSAT-2 L4 standard products, we have developed a higher resolution experimental global atmospheric transport and inverse model. This systems is being used for country-level estimation of sector-wise emissions of CO_2 and CH_4. Some of results using this model and long-term GOSAT data were compared with global gridded emission inventories and national reports to United Nations Framework Convention on Climate Change (UNFCCC). Such results were presented at several UNFCCC conferences and attracted global attentions.

Long-term Global Greenhouse Gas Observation by GOSAT and GOSAT-2 and Local Emissions/Removals Observation by GOBLEU

Hiroshi SUTO[1], Kei SHIOMI[1], Nobuhiro KIKUCHI[1], Shin ISHIDA[1], Rio KAJIURA[1], JAXA GOSAT/GOSAT-2 team, and ANA-JAXA GOBLEU team.

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GOSAT is the Japan's first greenhouse gases observation dedicated satellite, launched in 2009, and now over 16 years on-orbit. The instrument and satellite are healthily, and continuously monitoring the global greenhouse gases. Also, it has enough fuels and healthy batteries to operate for another decade. To estimate the radiance degradation factor of satellite instruments, the joint vicarious calibration campaign with OCO, TROPOMI, TEMPO and GOSAT teams are annually performed, and the results are supported to update the L1 products.

GOSAT-2 is the follow-on satellite of GOSAT and launched in 2018. GOSAT-2 has extended functionally such as the monitoring of CO, large latitudinal coverage of glint observation. GOSAT-2 is also continuously observing the global greenhouse gases, and now over 6 years in space. The instrument and satellite are also healthy, and system has enough fuels and healthy batteries to operate for another decade. The new L1 products of GOSAT-2 is developed and validated with the forward calculation, and will be released.

GOSAT and GOSAT-2 can simultaneous observation both SWIR and TIR, its unique functionality. JAXA developed the original L2 algorithm, which taken account two-orthogonal polarization spectra of solar reflected light and thermal emissions from GOSAT and GOSAT-2. The JAXA/GHG products contain not only the total column concentration but also the partial column concentration of upper and lower troposphere (approximately 0-4 km and 4-12 km respectively). The JAXA/GHG products are compared with TCCON, other satellite products, model results. The products are available from JAXA's website.

JAXA and ANA holdings have started the Greenhouse gas Observations of Biospheric and Local Emissions from the Upper sky (GOBLEU) mission to visualize the local (city-level) anthropogenic emissions and removals. To make a frequent observation, the firstest round-trip observation flight was started with updated instruments. We will summarize the latest status of operation, calibration, and analysis results.

The OCO-2 and OCO-3 Missions: Status, Results and Plans

Vivienne Payne*[1], Abhishek Chatterjee[1], Junjie Liu[1]
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Session: Status of current missions
Preference: Oral

The Orbiting Carbon Observatory 2 (OCO-2) was successfully launched into a sun-synchronous polar orbit in July 2014, has been providing science measurements in nadir, glint and target modes since September 2014. The OCO-2 instrument and spacecraft remain in excellent health. In May 2019, the OCO-3 instrument was installed on the International Space Station (ISS) and has provided science measurements across varying times of day in the latitude range 52S-52N from that inclined orbit starting in August 2019. In addition to nadir, glint and target observations, an agile pointing mirror assembly allows the OCO-3 instrument to collect Snapshot Area Maps (SAMs), which are data collections over ~80km by 80km in 2 minutes. Following storage on the ISS from November 2023 to July 2024 to allow another payload to complete their nominal mission, OCO-3 was successfully reinstalled in its original location on the ISS and resumed science observations in July 2024. Together, the long-term, high quality XCO2 and SIF measurements from these missions are enabling advances in our understanding of the global, regional and local-scale carbon cycle and their response to changing human activities, natural climate variability, climate change and extreme events.

The stability and quality of the OCO-2 and OCO-3 data products have been made possible by sustained efforts in calibration, validation and Level 2 algorithm development. We will present a high-level overview of status, results and plans in these areas. We will discuss the OCO-2 v11.2 and OCO-3 v11 datasets and opportunities for synergistic use of the complementary sampling and capabilities of OCO-2 and OCO-3. We will reflect on lessons learned over the lifetimes of these two pathfinder missions so far and on how these can help to inform efforts for OCO-2, OCO-3 and other greenhouse gas missions going forward into the future.

The New Progress of DQ-1 and the Pre-research of DQ-2

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After two years of operation in orbit with DQ-1, the performance of its LiDAR system has been comprehensively evaluated. The LiDAR measurements were compared with TCCON, and 70 valid synchronous observations were selected (within 1° of latitude/longitude from each TCCON site and within a one-hour observation window). The R^2 between the XCO_2 values from ACDL and TCCON sites is 0.92, and the root mean squared error (RMSE) is 0.95 ppm. For SNO, comparisons were made with OCO-3. For the DQ-1 satellite, we leveraged its observational capabilities to compare nighttime and daytime CO_2 measurements while excluding diurnal variations unrelated to CO_2 concentration changes (e.g., differences in the diurnal boundary layer, temperature, and humidity). Our results indicate that the diurnal differences in CO_2 observations can effectively quantify the strength of terrestrial vegetation sinks. Due to limitations in the active and passive observation mechanisms, we analyze the differences between these measurements to explore their ability to quantify CO_2 sources and sinks. This approach represents a very promising observation method for the forthcoming DQ-2 satellite, which will be equipped with both active and passive instruments. Consequently, an active–passive collaboration technology has been developed. However, we are currently employing simulation techniques to verify the feasibility of this technology prior to launch, and its viability has been preliminarily confirmed through external SNO observations from DQ-1 and other satellites.

GHGSat in 2024: Performance, Global Emissions Insights, and Constellation Expansion

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We present an update on the performance and methane emissions observed in 2024 with the 10-satellite GHGSat methane constellation. GHGSat instruments retrieve the methane column density over approximately 100,000 square km per day at 25 m spatial resolution and 100 kg/hr emission rate detection sensitivity. The GHGSat constellation currently detects approximately 17,500 methane plumes per year, a rate ~8x greater than currently reported from any other individual satellite mission and ~3x greater than all other satellite missions combined.

In 2024, we spatially attributed plumes to approximately 4,700 unique sites. Each emitting site was observed an average of 20 times with plumes detected in 15% of O&G site observations, 55% of Mining site observations, and 75% of Waste site observations, without significant continental variation. We estimate that 18.1 Mt/yr of methane was being emitted from these sites (O&G: 9.7 Mt/yr; Mining: 2.5 Mt/yr; Waste: 5.4 Mt/yr; Other sectors: 0.5 Mt/yr), an amount that represents approximately 12% of the global total from the O&G, Mining and Waste sectors combined. We observe only weak correlation with spatially resolved inventory estimates. These findings highlight that GHGSat's high-resolution satellite observations can be used to refine global methane inventories and provide actionable insights for targeted mitigation efforts at scale.

Finally, we provide an update on our four newest methane satellites, GHGSat-C12 to GHGSat-C15, that are scheduled for launch in 2025, adding 50% more observational capacity to the GHGSat constellation. This will be followed by an additional five more satellites scheduled for launch in 2026. We note that GHGSat's methane data is available for free to the scientific community for research and non-commercial application development through the NASA Commercial Satellite Data Acquisition program, the ESA Third Party Missions program, and the U.K. Satellite Applications Catapult.

The MethaneSAT mission: current status and future direction

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The emissions-monitoring satellite MethaneSAT – successfully launched into a sun-synchronous orbit on 04 March 2024 – was designed to help motivate and enable reduction of methane emissions. Commissioned by MethaneSAT LLC, a subsidiary of the Environmental Defense Fund, MethaneSAT is now actively mapping and quantifying CH4 emissions from regions accounting for over 80% of global oil and gas production. MethaneSAT's target observations consist of a wide observing swath (~220 km @ nadir), high spatial resolution (~140 m x 400 m), and low detection threshold (2 ppb precision @ 4 km2 as determined on orbit), enabling quantification of both concentrated as well as diffuse area-aggregate emissions associated with oil and gas production regions.

MethaneSAT's two imaging spectrometers (CH4/CO2: 1598-1683nm; O2: 1249-1305nm) were built by Ball Aerospace (now BAE) and integrated onto a spacecraft bus provided by Blue Canyon Technologies. Extended commissioning and initial on-orbit calibration activities were performed during Q2-Q3 2024, and we continue to ramp up observations to our nominal ~20 targets per day. Ongoing validation activities include regular targeting of Total Carbon Column Observing Network stations, coordination with controlled-release sites, and deployments of the airborne precursor instrument, MethaneAIR. In this presentation we will demonstrate the performance and stability of the MethaneSAT sensor during its first year on orbit, and will highlight our operationally produced L4 dispersed area source emission product.

Carbon Mapper updates and preliminary Tanager-1 greenhouse gas measurement performance

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Efforts to mitigate methane (CH_4) and carbon dioxide (CO_2) emissions are complicated by inconsistencies between estimates derived from atmospheric measurements, greenhouse gas inventories, and self-reporting programs. Contributing to these discrepancies are a relatively small number of industrial facilities that emit anomalously high amounts of greenhouse gases, in some key sectors in an unpredictable and intermittent fashion. Lack of transparency, spatio-temporal completeness, measurement sensitivity and costs are barriers to diagnosing and mitigating point-source emissions at scale across geographically dispersed infrastructure. This motivated the establishment of the non-profit organization Carbon Mapper and an innovative public-private partnership that includes Planet Labs and JPL to characterize and monitor the global distribution of super-emitter point sources in the oil & gas, coal, waste, and livestock sectors for priority regions at 30m spatial resolution using visible-infrared imaging spectrometers. To support those objectives, the Tanager satellite constellation is being developed with an ultimate goal of providing daily or higher frequency monitoring to support emission mitigation efforts at facility scale.

We summarize Carbon Mapper status and plans including a representative global CH_4 monitoring strategy using a constellation of 4 Tanager satellites. We present a preliminary assessment of Tanager-1 CH_4 and CO_2 emissions detection and quantification performance including intercomparison with contemporaneous aircraft under-flights and controlled release testing based on observations collected during and following Tanager-1 commissioning. Finally, we provide an update on Carbon Mapper efforts to support CH_4 regulatory programs in key jurisdictions.

Interface with users of GOSAT-GW TANSO-3 observation: observation requests, product downloads, and acquisition of information

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We have almost reached the launch time of the Global Observing SATellite for Greenhouse gases and Water Cycle (GOSAT-GW). The satellite has a design life of seven years, during which the Total Anthropogenic and Natural emissions mapping SpectrOmeter-3 (TANSO-3) is used to observe carbon dioxide (CO_2) and methane (CH_4), nitrogen dioxide (NO_2), solar-induced fluorescence (SIF), etc., by switching between two observation modes (wide mode and focus mode). Based on the TANSO-3 data policy, we will distribute Level 1B products, which are spectral data, and Level 2 products, which include concentration information of CO_2 and CH_4, through a website GOSAT-GW TANSO-3 Product Archive (G3PA). G3PA also provides users with information such as product formats and processing algorithms and accepts requests for focus mode observations from specific users. These functions are provided by three ground systems that NIES has completed developing: 1) GOSAT 3rd generation Data Processing/operating System (G3DPS), which manages product process/archive/distribution as a core system, 2) GOSAT-GW NO2 Data Processing System (GNDPS), which is responsible for processing the Level 2 products related NO2 concentration on the public cloud, 3) GOSAT operational and research Computing Facility (GOCF), which is the supercomputer used for processing the Level 2 products related CO_2/CH_4 concentration and algorithm development. GOSAT-GW has a revisit time of 3 days and orbits the Earth's daylight region approximately 14-15 times per day. For Level 2 products, wide mode observation data is aggregated into one file for one day and provided. On the other hand, focused mode observation results are provided as a product file per observation request. We designed the observation area for one focused mode to be a maximum of 90km x 90km. Few glint observations over the ocean can be obtained in wide area mode, so planned observations over the ocean using focused mode are necessary.

Sub-Kilometer Hyperspectral Carbon Monitoring: Joint Radiance-Wavelength Calibration and Bayesian Spatiotemporal Collaborative Retrieval

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This study developed a novel spaceborne hyperspectral imaging carbon monitoring technology, overcoming the spatial resolution and accuracy limitations inherent in traditional greenhouse gas remote sensing. The greenhouse gas imager achieves a 30-km observation swath with 400-m spatial resolution. To address noise interference in sub-nanometer spectral detection, we proposed a joint radiance-wavelength correction model that integrates onboard calibration parameters with atmospheric radiative transfer simulations, establishing a multidimensional noise suppression matrix to enhance channel signal-to-noise ratio (SNR) and spectral positioning accuracy. At the inversion algorithm level, an innovative maximum a posteriori estimation method under a Bayesian spatiotemporal collaborative framework (ST-MAP) was developed. This approach incorporates 1-km resolution global land cover data and atmospheric chemical transport models to construct a dual-constrained objective function, effectively resolving retrieval biases in heterogeneous surface areas through spatial continuity regularization optimization. Experimental results demonstrate CO_2/CH_4 retrieval accuracies better than 5.0 ppm and 40 ppb respectively, representing over 20% improvement compared to conventional optimal estimation methods. The algorithm shows strong spatial consistency with ground-based observations from global TCCON stations, significantly enhancing spatial-scale identification of urban emission hotspots.

This research achieves a technological leap from "column-averaged concentration statistics" to "sub-kilometer distribution analysis" in greenhouse gas monitoring. The established technical framework encompassing "radiometric calibration-noise suppression-collaborative inversion" provides a core solution for carbon satellite constellation development. It offers critical technical support for refined emission verification under the Paris Agreement's Global Stocktake mechanism, advancing the implementation of nationally determined contributions (NDCs) through enhanced quantification of anthropogenic carbon fluxes.

Detection of spatio-temporal variations of atmospheric chlorofluorocarbons and hydrochlorofluorocarbons using ground-based technology of Fourier transform infrared spectroscopy (FTIR) and application

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Synthetic halogenated hydrocarbon Freon, due to its stable and non-toxic chemical properties, has widely used in industry as refrigerants, foamblowing agents and propellants. However, the two types of gases, chlorofluorocarbons and hydrochlorofluorocarbons in Freon, can seriously destroy stratosphere ozone and contribute significantly to global warming trends. Therefore, studying the spatio-temporal distribution and variation of atmospheric chlorofluorocarbons and hydrochlorofluorocarbons is of great significance for global ozone hole recovery and greenhouse gas emission control. As high precision detection technology of atmospheric trace gas, Ground-based high-resolution Fourier transform infrared (FTIR) spectroscopy technology can observe and study the long-term time series of column concentration and vertical profiles of trace gases in the atmosphere, providing important support for understanding the distribution and changes of atmospheric chlorofluorocarbons and hydrochlorofluorocarbons.

In the paper, based on the mid-infrared spectra measured by ground-based FTIR spectrometer at Hefei station, the vertical profiles and columns of atmospheric chlorofluorocarbons CFC-11(CCl_3F), CFC-12(CCl_2F_2) and hydrochlorofluorocarbons HCFC-22(CHClF2) were obtained. The seasonal and annual variation of three gases were analyzed, and the ground-based FTIR data at Hefei station were compared with other independent data, including satellite data, model data and other station data. A source analysis of airmass was conducted for chlorofluorocarbons and

hydrochlorofluorocarbons gas, and the emissions of HCFC-22 and CFC-11 in the Yangtze River Delta region from 2017 to 2022 were estimated.

The atmospheric column concentration retrieval method for CFC-11 fluorocarbons was studied based on the mid infrared spectra observed by the ground-based FTIR spectrometer. The spectral retrieval parameter were set, and the systematic and random errors of the retrieval results were calculated. The vertical profile distribution of atmospheric CFC-11 were obtained and the characteristics were analyzed. An analysis was conducted on the time series of atmospheric CFC-11 column at Hefei from 2017 to 2022, and it was found that CFC-11 has an annual decreasing trend with an annual rate of -1.40% year $^{-1}$. CFC-11 has the highest total column in summer and the lowest in spring. By comparing the ground-based FTIR observation results at Hefei with ACE-FTS satellite data, atmospheric model WACCM, and observations from three other ground-based remote sensing stations, the average relative difference in CFC-11 vertical profile concentration between ACE-FTS satellite data and ground-based FTIR data was -6.29±4.19%, indicating high consistency between the two data. The total columns of CFC-11 at the four sites showed consistent seasonal variations.

The spectral retrieval method of CFC-12 gas was studied, and the column time series of atmosphere CFC-12 at Hefei station from 2015 to 2022 were obtained. The results showed total columns of atmosphere CFC-12 at Hefei decreased with an average annual rate of -0.70% year $^{-1}$. The comparison between ground-based FTIR observation data and ACE-FTS satellite data shows good consistency, with an average relative difference of

3.95±2.12% for vertical profiles. Compared with the observation data of other ground-based FTIR remote sensing stations, the seasonal variation of CFC-12 at the four stations was consistent.

The spectral retrieval method for atmospheric hydrochlorofluorocarbons (HCFC-22) was studied. The time series of HCFC-22 were analyzed from 2017 to 2022. The total columns of HCFC-22 over Hefei increased from 2017 to 2018, with an annual change rate of 5.98% year $^{-1}$, and gradually decreased from 2018 to 2022, with an annual change rate of -1.02% year $^{-1}$. By comparing ground-based FTIR observation data with ACE-FTS satellite data, the average relative difference in vertical profile between the two datasets was -4.38±0.62%, indicating good consistency. Comparing the observation data at Hefei station with the ground-based remote sensing data at St. Petersburg, the seasonal variation rate at Hefei station was significantly higher than that of St. Petersburg station. The HCFC-22 column at two stations had similar monthly variations from September to next March. The reasons for the differences in gas variation at the two stations were analyzed.

Based on the atmospheric transport models FLEXPART and HYSPLIT, the source of surface and air masses of chlorofluorocarbons and hydrochlorofluorocarbons was analyzed. In summer with high concentrations of chlorofluorocarbons and hydrochlorofluorocarbons, most of the air masses came from southern provinces and cities in China and the Yangtze River Delta region. The emissions of HCFC-22 and CFC-11 in the Yangtze River Delta region were estimated using the atmospheric transport model FLEXPART and the Bayesian algorithm. It was found that the emissions of HCFC-22 in the Yangtze River Delta region were relatively high in 2017 and 2018, about 34.3±15.4 kt/year and 34.9±16.7 kt/year, respectively. The emissions decreased significantly from 2019 to 2022, and the lowest value in 2022 was 29.3±12.9 kt/year, which is close to the values calculated by the interspecies correlation method. The emissions of CFC-11 in the Yangtze River Delta region show a significant decrease trend, with the highest value of 2.91±1.52 kt/year in 2017 and the lowest value of 2.15±1.07 kt/year in 2022.

This study demonstrates the ability of ground-based high-resolution Fourier transform infrared spectroscopy technology to accurately detect the vertical profiles and column concentrations of atmospheric chlorofluorocarbons and hydrochlorofluorocarbon CFC-11, CFC-12 and HCFC-22, and provides reliable data and technical support for study of the changes, emissions and distribution of source and sink for atmospheric halogenated hydrocarbon compounds.

Long-term XCO_2 from GOSAT observations with IAPCAS retrieval algorithm

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Carbon dioxide (CO_2) is one of the primary greenhouse gases in the atmosphere. Over the past few decades, anthropogenic emissions have led to a sharp increase in atmospheric CO_2 concentrations, profoundly influencing and altering global carbon cycle processes. To understand and mitigate the progression of global climate change, it is particularly urgent to obtain accurate long-term date sets of atmospheric CO_2 concentrations.

The Greenhouse Gases Observing Satellite (GOSAT), launched in 2009, is the world's first satellite dedicated to measuring greenhouse gas concentrations from space. To date, it has accumulated over 15 years of measurements, enabling the characterization of global XCO_2 variability. Its data have proven invaluable in climate change research and have made significant contributions to global carbon stoke take.

The retrieval algorithm IAPCAS (Institute of Atmospheric Physics Carbon dioxide retrieval Algorithm for Satellite remote sensing) was established for space-based satellite measurement of greenhouse gases. In IAPCAS, XCO2 is retrieved using the Optimal Estimation Method (OEM) by iteratively analyzing and optimizing the spectrum residual between the simulation and measurement. The application of this retrieval algorithm to TanSat retrieval has yielded the TanSat XCO_2 product, characterised by an accuracy of −0.08 ppm and a precision of 1.47 ppm.

In this study, the IAPCS algorithm was employed to retrieve XCO_2 from GOSAT L1b spectra measurements (v300.300), thereby yielding XCO_2 data spanning a period exceeding 15 years (from April 23, 2009 to December 31, 2024). To validate the long-term XCO_2 data, we also made a comparison of the retrieved XCO_2 against the ground-based accurate and precise column-averaged measurements of XCO_2 from the Total Carbon Column Observing Network (TCCON).

NASA's GHG Observation Plans Over the Next 4 Years

Ken Jucks

NASA has had a significant role to play in remote sensing Greenhouse Gas observations from satellites and the surface for two decades. We initiated the TCCON network based on the original funding from the original Orbiting Carbon Observatory mission. When that failed to achieve orbit, NASA worked with our JAXA/NIES partners to analyze GOSAT data until we could develop OCO-2, then OCO-3. Both of those missions are still operating and producing top tier science data used by researchers all over the world. And TCCON has continued to expand internationally and spawned the COCCON network. NASA also selected the GeoCarb mission that has completed instrument build and initial demonstration of its capabilities. Access to space is the primary reason that mission has not gone forward at this time. NASA has also implanted the Carbon Monitoring System to improve the useability of all forms of Carbon Cycle data from space into products that can be deployed by end users. How all this will develop with the current political priorities in the United States has yet to determined. I will discuss these implications to the best of my ability at the time of this presentation.

The greenhouse gas observation mission with Global Observing SATellite for Greenhouse gases and Water cycle (GOSAT-GW): Updates

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The Japanese Global Observing SATellite for Greenhouse gases and Water cycle (GOSAT-GW) will be an Earth-observing satellite to conduct global observations of atmospheric carbon dioxide (CO_2), methane (CH_4), and nitrogen dioxide (NO_2) simultaneously from a single platform. GOSAT-GW is the third satellite in the series of the currently operating Greenhouse gases Observing SATellite (GOSAT) and GOSAT-2. It will carry two sensors, the Total Anthropogenic and Natural emissions mapping SpectrOmeter-3 (TANSO-3), and the Advanced Microwave Scanning Radiometer 3 (AMSR3), with the latter dedicated to the observation of physical parameters related to the water cycle. TANSO-3 is a high-resolution grating spectrometer designed to measure reflected sunlight in the visible to short-wave infrared spectral ranges. It aims to retrieve the column-averaged dry-air mole fractions of CO_2 and CH_4 (denoted as XCO_2 and XCH_4, respectively), as well as the vertical column density of tropospheric NO_2. The TANSO-3 sensor onboard GOSAT-GW will utilize the wavelength bands of 0.45, 0.76, and 1.61 µm for NO_2, O_2, and CO_2 and CH_4 retrievals, respectively. GOSAT-GW will fly in a sun-synchronous orbit with a local overpass time of approximately 13:30 and a 3-day ground-track repeat cycle. The TANSO-3 sensor has two observation modes in the push-broom operation: Wide Mode, which provides globally covered maps with a 10-km spatial resolution within 3 days, and Focus Mode, which provides snapshot maps over targeted areas with a high spatial resolution of 1–3 km. The objectives of the GOSAT-GW mission include (1) monitoring atmospheric global-mean concentrations of greenhouse gasses (GHGs), (2) verifying national anthropogenic GHG emissions inventories, and (3) detecting GHG emissions from large sources, such as megacities and power plants. A comprehensive validation exercise will be conducted to ensure that the sensor products' quality meets the required precision to achieve the above objectives. With a projected operational lifetime of seven years, GOSAT-GW will provide vital space-based constraints on both anthropogenic and natural GHG emissions. These measurements will contribute significantly to climate change mitigation efforts, particularly by supporting the Global Stocktake (GST) mechanism, a key element of the Paris Agreement.

Reference: Tanimoto et al. (2025), The greenhouse gas observation mission with Global Observing SATellite for Greenhouse gases and Water cycle (GOSAT-GW): Objectives, conceptual framework and scientific contributions", Prog. Earth Planet. Sci., 12, 8, https://doi.org/10.1186/s40645-025-00684-9.

The Chinese GHG Status and Plan

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In recent years, China has launched several greenhouse gas satellites—including the TanSat-1, Gaofen-5, and Fengyun 3D, and currently has DQ-1 in orbit. And, China plans to launch several remote-sensing satellites dedicated to greenhouse gases in the future. China's planned satellite portfolio includes large dedicated GHG satellites (i.e., next-generation carbon satellites); satellite platforms equipped with GHG detection payloads (e.g., Fengyun 3H, DQ-2, BK, et al.); and small satellites launched by commercial companies targeting methane point sources (e.g., XiGuang-xx). Moreover, these satellites are operated by different authorities. This report outlines China's future plans for greenhouse gases and introduces the concept of a multi-satellite network.

Carbon-I, a NASA Earth System Explorer Mission Concept for Global Carbon Cycle Science

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The past two decades have seen tremendous improvements in greenhouse gas (GHG) remote sensing from space, including global area flux mappers like SCIAMACHY, GOSAT, OCO-2, GOSAT-2, TROPOMI and OCO-3 among others, with more missions planned, such as CO2M. In the past decade there has also been an increase in GHG point source imagers, a field that has grown rapidly after initial successes using AVIRIS-NG and subsequent VSWIR spectrometers (coarser spectral resolution over a broader range). While area flux mapper missions have been effective at measuring GHG with high accuracy, fundamental gaps persist in the humid tropics, where data yields are 2-3 orders of magnitude lower than elsewhere.

Here, we discuss the Carbon Investigation (Carbon-I), which was selected for a Phase A mission concept study within NASA's Earth System Explorer call. Carbon-I provides a unique combination of global land coverage, high spatial resolution, and very high sensitivity required to quantify CH_4, CO_2, and CO emissions at both the area and point source scale. Given the importance of the tropics for global carbon budgets and in particular natural methane emissions, Carbon-I specifically targets the remaining data and knowledge gaps within the tropics, enabling a step change in our capabilities of observing the tropics with more even temporal and spatial sampling.

Carbon-I is a single-band spectrometer covering the 2040 to 2380 nm spectral range with 0.7nm spectral sampling and spatial sampling ranging from ~30m in a local target mode to ~300m for global land mapping. We will discuss the sweet spot in the tradeoff between spatial and spectral resolution, the multi-species trace gas capabilities (CH_4, CO_2, CO, HDO, H_2O, N_2O, potentially Ethane), the capabilities to measure GHG area fluxes and point sources while minimizing surface interferences and our approach to account for atmospheric scattering effects.

The Twin Anthropogenic Greenhouse Gas Observers Mission

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The Twin Anthropogenic Greenhouse Gas Observers (TANGO) mission is a new ESA mission that is realized within the SCOUT program with an envisaged launch in 2028. Complementing the Copernicus atmospheric monitoring missions Sentinel-5 Precursor, Sentinel 4/5, and the CO2M carbon dioxide monitoring mission, TANGO will measure carbon dioxide and methane emissions from human activity to help verify the Paris Agreement. Tango will provide about 10.000 emission estimates per year from large industrial facilities and power plants. It will deliver high-resolution images of emission plumes with sufficient accuracy to determine emissions from single observations. The Tango mission will comprise two 25-kg 16 U satellites, TANGO-Carbon and TANGO-Nitro, orbiting in tandem: one configured to measure methane and carbon dioxide and one to measure nitrogen dioxide to support plume and emission specifications. TANGO will pave the way to innovative high-resolution spectral imaging of greenhouse gas (GHG) emissions based on European CubeSat technology. In this contribution, we will present the concept and status of the TANGO mission.

CO_2 is emitted into the atmosphere by mankind through the combustion of fossil fuels (coal, natural gas, and oil), solid waste, and due to certain chemical reactions (e.g., cement manufacturing). It is removed from the atmosphere when it is taken up by the biosphere as part of the biological carbon cycle and absorbed by the oceans. Ideally, the carbon cycle would keep atmospheric CO_2 in balance between its different reservoirs, but due to mankind, we have seen a steady increase in CO_2 for decades. CH_4 is the second most important greenhouse gas with anthropogenic emissions from livestock, the oil and gas industry, coal mines, and waste treatment. Its atmospheric lifetime is 8-10 years and has a global warming potential of 28-36 times that of CO_2. To predict the impact of the recent increase of CO2 and CH4 concentration on near-surface temperature and to evaluate the potential effect of possible climate change mitigations, the complete Earth's climate system needs to be better understood, including the cooling effect by aerosols and complex feedback mechanisms. A large fraction of anthropogenic GHG emissions is due to localized point sources, causing distinct plume signatures in its atmospheric abundance on top of a large background concentration. To derive emission estimates from plume observations, accurate and precise measurements of the total column amount of GHG are required; the lower the spatial resolution of the sensor, the more precise and accurate. From that perspective, high-resolution sensors are favorable for mission design, presenting the challenge of sufficient data coverage. This leads to an exciting synergy between global survey missions like Sentinel-5 and CO2M with spatial resolutions of 7×7 km^2 and 2×2 km^2 and a targeted mission like TANGO which measures CO_2 and CH_4 in preselected target areas of 30 ×30 km^2 but with a spatial resolution 50 times higher than CO2M. TANGO senses solar-reflected radiances in the 1.6 µm spectral range with a spectral resolution of 0.45 nm to detect moderate to strong emissions of CH_4 (≥5 kt/yr) and CO_2 (≥2.5 Mt/yr). The TANGO-Nitro instrument yields

collocated NO_2 observations from radiance measurements in the visible spectral range with a spectral resolution $\leq$ 0.6 nm, supporting plume detection and exploiting the CO_2/NO_2 ratio for emission specification.

The TANGO spectrometers are carried by two agile satellite buses flying in close formation with a time difference of less than 1 minute. Platform agility is achieved by controlled 3-axis reaction wheels. This allows flexible pointing of the spectrometer on a roll of ± 30° and with forward motion compensation that improves the integration time by a factor of up to 5, resulting in better data coverage and precision of the observations. As part of the mission implementation, a ground segment will be established providing the scientific user community with open and free data including calibrated radiance measurements (level-1b data), the dry air mole fraction column densities XCO_2 and CH_4, and tropospheric columns of NO_2 (level-2data). Furthermore, CO_2, CH_4, and NO_2 emission estimates will be provided operationally for each successful target observation (level-4 data).

The MicroCarb CO2 mission: imminent launch!

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MicroCarb will be the first European mission dedicated to the monitoring of CO2 surface fluxes from space. MicroCarb is developed as a partnership led by CNES with major contributions from UKSA, EUMETSAT and EU through H2020 IOD-IOV program operated by ESA.
The main objective of MicroCarb is the monitoring of CO2 fluxes for a better understanding of the carbon cycle mechanisms. For this objective, the platform will acquire relevant spectra in nadir or glint observation modes. An imagery mode (footprint size 2x2km, swath 40km) is also implemented as a demonstrator for anthropogenic emission estimates. MicroCarb measurements will allow estimates of the atmospheric CO2 column integrated concentrations at high accuracy (requirement for random error <1ppm, regional bias <0.2ppm) from an affordable micro satellite (Myriade series, ~200kg).
The satellite will fly on a sun-synchronous 10:30 am (descending node) orbit. The MicroCarb instrument is a compact grating spectrometer based on a unique telescope, spectrometer and detector instrument concept. The instrument will measure high-resolution radiance spectra (resolving power 25,000) of the Earth during daylight in four short-wave infrared spectral bands: CO2 centered at 1.61 and 2.04 µm, O2 at 0.76 and 1.27 µm. This latter band is specific to the MicroCarb mission to mitigate aerosol-related biases, and the retrieval algorithms shall account for the airglow emission. The XCO2 retrievals will be performed by the 4ARTIC full physics optimal estimation code, developed specifically for MicroCarb and currently tested on OCO-2 and EM27/SUN spectra. An imager is also embedded for geolocation and cloud detection.
The MicroCarb launch is imminent, with a planned launch date for July 2025 on Vega-C. Both space and ground segments are ready. TVAC performance tests have been mostly successful, with an ongoing analysis to finalize the instrument model necessary for measurement calibration.
CNES and its partners are now ready for Cal/Val activities, which are planned to last one year. Cal/Val for L1 will be performed with on-board sources (Shutter, Lamp) as well as natural sources (Cold Space, Sun, Moon and terrestrial scenes). Cal/Val for L2 will be based mostly on comparison with ground-based TCCON, EM27/SUN, AirCore and CO2 atmospheric modeling results.

We will present:
- A quick reminder of the mission
- The current status of the program.
- The algorithms, from raw measurements to XCO2
- An estimate of the L1 and L2 products performances before launch
- The cal/val plan

The Copernicus anthropogenic CO2 Monitoring (CO2M) mission – status and results from product development

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As part of the Copernicus Programme, the European Commission and the European Space Agency (ESA), are expanding the Copernicus Space Component and are implementing satellite remote measurements for supporting anthropogenic CO_2 (and CH_4) emission monitoring. The European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) is responsible of the development of the operational ground segment (with contributions from ESA) and the CO2M system operations in system commissioning and routine phase. Satellite measurements of atmospheric CO_2 and CH_4, complemented by in-situ measurements and bottom-up inventories will be operationally assimilated in the Copernicus GHG Monitoring and Verification Support Capacity (MVS) of the European Commission developed by the Copernicus Atmosphere Service (CAMS) at the European Centre for Medium-Range Weather Forecast (ECMWF). The GHG MVS will provide CO_2 and Methane emission inventories at a regional, national, and global scale to users and stakeholders.

This presentation will provide an update on the mission and instrument development status at ESA and will present the status and first results from the CO2M operational processing system developments ongoing at EUMETSAT. The latter will include first simulations of dedicated CO2M aerosol, cloud, and NO_2 products, as well as results from the three retrieval algorithms for greenhouse gases (GHG) used for CO2M.

We show the concept of how the measurements from the three instruments on-board CO2M (the CO_2/NO_2 push-broom grating spectrometer (CO2I/NO2I), the Multi Angle Polarimeter (MAP), and the Cloud Imager (CLIM)) will be combined into one “hyper-instrument” processing system by a common multi-instrument data processing architecture. This includes the centralized and harmonized provision of auxiliary and a priori information to all level-2 processors in order to ensure maximum consistency between all of parts of the processing system. Such harmonization requires elaborate techniques of co-registration, bridging different scales of instrument input and auxiliary information. Latest results presented are based on realistic simulations of orbits for a constellation of three platforms, including one which is continuously following the sun-glint spot instead of looking in the nadir direction.

Keywords: CO2M, CO_2, CH_4, SIF, Aerosol, NO_2, constellation, instruments, monitoring, products, processing, validation.

Greenhouse gas observations from the proposed Arctic Observing Mission (AOM)

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The Arctic Observing Mission (AOM) is a satellite mission concept completing a pre-formulation study (PFS) for the Government of Canada (GOC) in 2025. The baseline AOM plan is to use two satellites in a Highly Elliptical Orbit (HEO) to make geostationary-like observations of greenhouse gases (GHGs) and other Earth observations over northern regions. AOM would observe GHGs using an Imaging Fourier Transform Spectrometer (IFTS). When coupled with cloud data from AOM's meteorological imager in an intelligent pointing approach, the IFTS could deliver unprecedented hourly XCO_2, XCH_4, XCO and SIF observations during daylight over cloud-free land from ~40-80°N (https://doi.org/10.3389/frsen.2023.1233803). In AOM's recently-completed mission design contract (MDC), an industry team assessed payload and orbit options, updated the IFTS conceptual design and estimated mission costs. The study found that a new focal plane array option and flexibility in pixel binning could potentially enable XCO_2, XCH_4, XCO and SIF imaging with an orbit-averaged spatial resolution of ~1.0 km for applications where spatial resolution takes priority over precision. AOM's new GHG observations would improve our ability to detect and monitor changes in Arctic and boreal carbon cycles, including CO_2 and CH_4 emissions from forests, wetlands, permafrost thaw or anthropogenic sources. This presentation will give an update on AOM's progress and status, international partnership scenarios, the GHG IFTS design and potential enhancements, related AOM studies and next steps for the mission.

Towards a remote sensing solution to quantify N_2O emissions by integrating shortwave and longwave infrared bands

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Nitrous oxide (N_2O) has profound implications for the Earth's environment, serving as a potent greenhouse gas and a key driver of stratospheric ozone depletion. Despite its critical role in climate change and ozone depletion, accurately measuring N_2O emissions at the most relevant spatiotemporal scales remains a challenge. Ground-based networks such as TCCON and NDACC provide precise X_{N2O} measurements but lack spatial coverage. In contrast, spaceborne observations offer global coverage but struggle to resolve N_2O enhancements even over strong emission sources.

In our research, we integrate shortwave (2-µm) and longwave (7-µm) infrared bands of N_2O to reduce the X_{N2O} uncertainty and enhance overall total column sensitivity. SPLAT-VLIDORT radiative transfer model is used as a forward model to simulate radiance and Jacobians. Originally developed for MethaneSAT, SPLAT was designed to handle only shortwave infrared radiation. However, in our work, SPLAT capabilities are expanded to incorporate longwave thermal infrared radiation, enabling a more comprehensive multispectral remote sensing approach.

Linear sensitivity analysis (LSA), a Bayesian framework, is utilized to calculate X_{N2O} posterior error and sensitivity of the posterior to the true state. Results indicate that the integration of 2-µm and 7-µm band provides a balance between retrieval accuracy and total column sensitivity. It especially improves sensitivity in the near surface layers, allowing for better detection of N_2O enhancements. We also analyze errors and sensitivities under different scenarios of thermal contrast and inflation to the prior error. We apply LSA to a large number of pixels to obtain statistically significant results.

Additionally, we introduce a dimensionless detectability metric Q to assess the conditions under which the instrument can provide reliable emission estimates, where Q is the ratio between the emission-induced enhancement ($\Delta\Omega$) and the measurement uncertainty ($\sigma\Omega$). Using this metric, we explore the feasibility of airborne and spaceborne missions for N_2O detection. The results suggest that with a flux of 8 mol $m^{-2}s^{-1}$, the spatial variability of X_{N2O} can be detected at about 2.5 km resolution by an airborne instrument and at about 6 km by a spaceborne instrument, facilitating both localized emission hotspot detection and large-scale emission monitoring.

The greenhouse gas emission monitoring spectrometer onboard CubeSat platforms: current status and plans in Korea

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Effective monitoring of greenhouse gas (e.g., methane, and carbon dioxide) emissions is essential for achieving carbon neutrality. Although ground-based observations provide accurate data, their spatial coverage remains a key uncertainty for quantifying emissions from various sources (e.g., rural areas and over the ocean). To complement such limitations, The Environment Satellite Center (ESC) of the National Institute of Environmental Research (NIER) of South Korea plans to launch 5 Cubesat instruments to monitor greenhouse gases (e.g., CH_4, CO_2) by 2028. In this presentation, we summarized the current status and future plans of developments for monitoring CH_4 and CO_2 emissions onboard the CubeSat platforms. We will also demonstrate the required precision of the inversion products and application plans for the data.

Overview of Greenhouse gases Absorption Spectrometer (GAS) onboard FengYun-3H satellite

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The Greenhouse gases Absorption Spectrometer (GAS) onboard FY-3H satellite is a push-broom imaging grating spectrometer designed to measure global CO2 and CH4 consentrations (XCO2 and XCH4) with sufficient accuracy to detect greenhouse gas sources and sinks and distinguishing anthropogenic from biogenic emissions. The GAS instrument measures Earth-reflected solar spectral radiance on Top-Of-Atmosphers (TOA) in four spectral channels: the O2 A-band (ABO2) at 0.76 μm, the "weak" and "strong" CO2 bands (WCO2 and SCO2) at 1.61 and 2.06 μm, and the CH4 absorption band (ABCH4) at 2.3 μm. The light in each channel is measured by a separated spectrometer, and all the four spectrometers use similar optical designs, and are integrated into a common optical optical bench and share a common, 135 mm focal length, F/3 three-mirror anastigmat (TMA) telescope. So, the instrument can collect collocated and simultaneous observations in all spectral channels. In order to span the swath to 100 km, a curved-slit is used to correct the image distortion. The diffraction gratings spectrally disperse the slit images onto the 2-dimensional focal plane array (FPA). The spectrum in different channel is dispersed various columns of FPA in the direction perpendicular to the long axis of the slit (spectral direction), while the spatial field of view is imaged onto 456 pixels in the dimension orthogonal to the direction of dispersion (spatial direction). To reduce the downlink data volume and increase the signal-to-noise ratio (SNR), 12 adjacent pixels along the spatial direction are summed together on board to produce a "super-pixel" and is referred to as a spectral sample. Thus, the 440 of 488 rows are illuminated by the slit are divided into 34 footprints with each being defined by the field of view of the spectral sample. Since it takes 440 ms to record one frame of spectrum image, and the spacecraft is moving about 3.2 km downtrack over the time, a footprint is shaped with dimensions of ~3.2 km by 3 km at nadir when the instrument is operated in push-broom fashion from an 836 km orbit. The instrument has three observation modes under different geometric conditions. One is the nadir sounding mode, in which the field-of-view of instrument is directed towards the sub-satellite point, yielding XCO2/XCH4 estimation over land. The second is Sun-glint sounding mode, in which light is specularly reflected by the Earth's surface and the observations collected near the apparent glint spot are used to eatimate XCO2/XCH4 over the ocean. Due to the very low reflectance of water bodies in the SWIR channel, measurements over oceans are only possible in Sun-glint mode. In addition, Sun-glint observations over land is also useful, especially over lakes and snow-covered or poorly illuminated regions. The third is Target sounding mode, in which the field-of-view of instrument is directed towards the targets of interest on Earth that has greenhouse gas emissions. The GAS flight model is currently undergoing pre-flight testing and is expected to launch in Quarter-3 of this year.

Hyperspectral imaging detection technology for greenhouse gases with variable spatial resolution based on DMD coding

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As the largest-scale organized human activity in the 21st century, "carbon neutrality" urgently calls for a scientific response. The Sixth Assessment Report of IPCC once again pointed out that "due to the continuous increase in greenhouse gas emissions, the pace and scale of the work carried out so far, as well as the current plans, are not sufficient to address climate change." The emission characteristics of greenhouse gases and the emission reduction pathways in industrial sectors where anthropogenic carbon emissions are concentrated are cutting-edge issues that have attracted great attention in relevant research fields. Therefore, high-precision and highly time-efficient carbon monitoring data serve as an objective criterion for measuring the effectiveness of emission reduction. The current problems of satellite remote sensing carbon monitoring are mainly manifested as follows: 1) The existing large and medium-sized satellite payloads mainly serve climate change research. Their insufficient spatial resolution fails to meet the demand for high-precision inversion of the emission flux of regional and point-source carbon emission targets. 2) In the face of illegal emissions from point-source targets such as enterprises and factories, and in emergency situations like sudden leakage and explosion accidents in coal-fired power plants, gas pipelines, and mines, there is a lack of refined carbon monitoring capabilities (including CO_2 and CH_4).

There are still some technical challenges in developing satellite for carbon emission monitoring in hotspot areas with high spatial resolution and high-performance payload detection technology:

(1) To improve the spatial resolution, it is necessary to reduce the spectral resolution to ensure the luminous flux. Limited by the spectral resolution (approximately 10nm), the minimum detection threshold of the payload is affected to a certain extent (e.g. Sentinel-2 and PRISMA). (2) In the observation scenarios with high spatial resolution in hotspot areas such as cities, in order to improve the signal-to-noise ratio, the satellite needs to perform staring compensation, which places extremely high demands on the attitude of the satellite platform. (3) When the flight trajectory of the satellite's sub-satellite point is in a non-urban area (non-anthropogenic greenhouse gas emission concentrated areas account for more than 97% of the land area), the payload has no observation data, and the detection efficiency is seriously insufficient.

To address the above challenges, a novel technology for hyperspectral imaging detection of greenhouse gases with variable spatial resolution based on DMD (Digital Micromirror Device) coding regulation is proposed. Firstly, based on the research of the spatial heterodyne interferometric imaging spectroscopy technology (SHIS) and the spatial light modulation mechanism of the digital micromirror device (DMD), the functional relationship from the radiation source “end” to the spectral quality “end” in complex application scenarios and its main influencing factors are obtained through simulation. Secondly, an experimental device of an imaging spectrometer with programmable regulation of spatial resolution is designed and built, and research is carried out on methods such as the calibration of the spatial coordinate transformation matrix of the conjugate plane of the DMD micromirror array and the imaged target, the localization plane of the interference fringes and the detector image plane, and the programming regulation of the spatial resolution. Correspondingly, research is carried out on the interference image reconstruction and spectral information demodulation algorithms of the

experimental device. By conducting detection case studies in different application scenarios, the rationality and scientificity of this method are verified. It is expected to resolve the problem that existing payloads are unable to balance high - resolution target observation and low - resolution atmospheric background observation simultaneously. Specifically, it can solve the problem of high - spatial - resolution and accurate detection of CO_2, thus providing a new and efficient technical approach for satellite remote sensing carbon monitoring.

OCO-3 Version 11 Snapshot Area Mapping (SAM) Mode Observations

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The NASA Orbiting Carbon Observatory-3 (OCO-3) data record has recently been reprocessed using the latest v11 Atmospheric Carbon Observations from Space (ACOS) dry-air mole-fraction of carbon dioxide (XCO_2) retrieval. Major changes relative to v10 include an updated Digital Elevation Model (DEM), switching from GEOS FP-IT to GEOS-IT for the meteorological and aerosol priors, a new ocean surface treatment, ABSCO updates, and geolocation improvements. Here, we analyze observations from OCO-3 in its Snapshot Area Mapping (SAM) mode, which scans an ~80 km by ~80 km region over the span of about two minutes, processed through the new v11 retrieval. These v11 SAM observations represent a clear improvement over v10. We investigate the impact of switching to a different DEM, the bias correction and quality filter choices made when creating the v11 Lite product, and several spatial features of interest seen in both individual v11 SAMs and site-average plots comprised of multiple SAMs.

MethaneSAT XCH_4 retrieval

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Session: 3) Retrieval algorithms, priors, and products

The area-mapping MethaneSAT satellite, launched on March 4 2024, aims to estimate CH_4 oil & gas emissions over regions that account for 80% of O&G onshore production. It uses one spectrometer to record CH_4 absorption from a window centered at 1.66 µm, and CO_2 absorption from a window centered at 1.61 µm, and a second spectrometer to record O_2 absorption from the $^1\Delta$ band at 1.27 µm. With its first light measurement taken in May 2024, MethaneSAT has collected data for over a year (at the time of IWGGMS), ramping up to its operational ~20 targets per day in fall 2024.

We present our processing steps for retrieving XCH_4 from the measured spectra. The MethaneSAT operational retrieval algorithm is the Smithsonian PLanetary ATmosphere retrieval (SPLAT). The operational retrieval does not account for light scattering, it instead relies on the CO_2 proxy method to derive XCH_4 as light path effects and other systematic forward model errors will in part cancel when taking the ratio of the retrieved CH_4 and CO_2 columns. We also present XCH_4 maps over a set of targets acquired during this first year of MethaneSAT operations.

First quantification of atmospheric carbon dioxide from the Geostationary Operational Environmental Satellite (GOES East)

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The need for characterizing global variability of atmospheric carbon dioxide (CO2) is quickly increasing, with a growing urgency for tracking greenhouse gasses with sufficient resolution, precision and accuracy so as to support independent verification of CO2 fluxes at local to global scales. The current generation of space-based sensors, however, can only provide sparse observations in space and/or in time, by design. While upcoming missions may address some of these challenges, most are still years away from launch. This challenge has fueled interest in the potential use of data from existing missions originally developed for other applications for inferring global greenhouse gas variability.

The Advanced Baseline Imager (ABI) onboard the Geostationary Operational Environmental Satellite (GOES-East), operational since 2017, provides full coverage of much of the western hemisphere at 10-minute intervals from geostationary orbit at 16 wavelengths. We leverage this high temporal resolution by developing a single-pixel, fully-connected neural network to estimate dry-air column CO2 mole fractions (XCO2). The model employs a time series of GOES-East's 16 spectral bands, which aids in disentangling atmospheric CO2 from surface reflectance, alongside ECMWF ERA5 lower tropospheric meteorology, solar angles, and day of year. Training used collocated GOES-East and OCO-2/OCO-3 observations (2017-2020, within 5 km and 10 minutes), with validation and testing performed on 2021 data.

The model successfully captures monthly latitudinal XCO2 gradients and shows reasonable agreement with ground-based TCCON measurements. Furthermore, we demonstrate the model's ability to detect elevated XCO2 signals from high-emitting power plants, particularly over low-reflectance surfaces. We also confirm that removing bands 5 (1.6 µm) and 16 (13.3 µm) substantially decreases performance, indicating that the model is able to extract useful information from these bands.

Although GOES-East derived XCO2 precision may not rival dedicated instruments, its unprecedented combination of contiguous geographic coverage, 10-minute temporal frequency, and multi-year record offers the potential to observe aspects of atmospheric CO2 variability currently unseen from space, with further potential through spatio-temporal aggregation.

Correlated albedo and elevation variability leading to retrieval artefacts

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This study was motivated by a report compiled for an environmental group that showed large positive anomalies in column-integrated methane (XCH_4) measurements from TROPOMI, averaged over two years, over open-pit coal mines in Germany. The anomalies were much larger (up to 40 ppb) than what would be expected based on reported emission factors from this kind of mining, and the suggestion was that the emissions were being systematically underreported. A closer look at the data found that these anomalies did not behave as we would expect true point sources to behave, as no plume was visible. Instead, it appeared to be related to the high albedo of the pits themselves in the shortwave infrared (SWIR). Albedo-related artefacts have been previously reported in retrievals of XCH_4 from TROPOMI, but these were related to the representation of the spectral dependence of the Lambertian albedo, and were largely alleviated by switching to a third-order polynomial rather than a quadratic function. The cause of these new anomalies is found to be the spatial correlation of sub-pixel-scale albedo variability with sub-pixel-scale elevation variability. The issue is not just that the coal mines are bright, but rather that they are deep, bright holes. As such, proportionally more light is reflected from the part of the pixel in the hole. The interplay with elevation comes through the calculation of the dry air column, which is used to calculate XCH_4. This is based on surface pressure taken from a numerical weather prediction model, corrected to the pixel using a highly-resolved digital elevation map. This average is weighted by area across the pixel. However, because more of the signal measured at the satellite is coming from the deep, bright section of the pixel, the "effective" elevation measured by the satellite is actually lower. As a result, the effective dry air mole fraction is underestimated, and the resulting retrieved XCH_4 is biased high. By analyzing high-resolution reflectances measured in Band 12 of Sentinel-2, close to the 2.3-µm methane band of TROPOMI, and convolving these with the high-resolution Copernicus DEM, we are able to show that this sub-gridscale correlated variability can explain the observed artefacts. Furthermore, by applying the same albedo-weighting using Sentinel-2 reflectances from Band 7, which corresponds to the O_2 A-band, we show that deriving the dry air column from this band would not solve the problem. This is because the albedo anomalies have a high spectral dependency. We further extended our analysis to include Band 11 reflectances, corresponding to the 1.6-µm SWIR band, which is used for retrieval of both XCH_4 and XCO_2. We used this approach to predict other areas where similar artefacts would be expected, based purely upon the local spectral albedo and elevation variability, and then assess the measured XCH_4. The presence of water over part of a pixel is found to have the opposite effect, as the lowest elevation (i.e. the surface of the water body) has a systematically lower reflectance than the rest of the pixel (i.e. land) in the SWIR. Simple approaches to correct this bias, using albedo-weighted elevations, are suggested.

Impact of Raman scattering on XCO2 and SIF retrievals by OCO-2/3

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Rotational Raman scattering (RRS) was long neglected in hyperspectral retrievals involving the O2 A-band and its spectral neighborhood, such as XCO2 and SIF retrievals from OCO-2/3 observations. Recent modeling advances (Sanghavi 2022, Sanghavi & Frankenberg 2023) have allowed us to simulate the exact contribution of Raman scattering to the measured spectrum. We find a non-negligible contribution that varies with surface brightness, topography, and viewing geometry, that introduces significant variable biases in both XCO2 and SIF retrievals. We present an analysis of the RRS contribution, quantify its dependence on the aforementioned parameters both in clear sky and hazy conditions, and determine the resulting biases in the retrieved state parameters. We introduce a generally applicable look-up table-based correction strategy that is relevant to hyperspectral retrievals by OCO-2/3 as well as other instruments like GOSAT, TROPOMI, etc.

Development of a principal components-based radiative transfer model and its application to IASI CH_4 retrievals

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Methane (CH_4) retrievals in the thermal infrared (TIR) can be computationally demanding: spaceborne instruments such as IASI produce a considerable volume of high-resolution spectral observations demanding accurate radiative transfer modelling (RTM). This aspect, coupled with the large number of species to consider in the CH_4 retrieval spectral region dictate that the radiative transfer modelling needs to be carried out on a fine spectral and vertical grid. These constraints lead to substantial processing time when using full-physics RTMs. Fast RTM alternatives such as RTTOV exist, but they are often impossible or difficult to customize when it comes to aspects such as the atmospheric species considered, spectroscopy, vertical discretization, and spectral resolution.

In order to perform faster CH_4 retrievals from IASI data, an algorithm based on the Principal Component-based Radiative Transfer Model (PCRTM) approach (Liu et al., 2006) has been developed. The main idea behind the PCRTM method is to compress the spectral information in a limited number of Principal Components (PC) and parameterize the PC scores based on a relatively small number of monochromatic radiative transfer simulations, resulting in a significant reduction of the necessary computations. The model produces the top-of-atmosphere (TOA) IASI channel radiances as well as the Jacobians for all species of interest in the spectral region used for the retrieval (1190 – 1350 cm^{-1} in case of CH_4). PCRTM is a great framework to develop a customized, accurate and fast RTM, based on full-physics radiative transfer calculations.

In this presentation, we will detail the general approach taken for the development of a PCRTM for the specific spectral region of CH_4 in the TIR, how the Jacobians were derived, its implementation in an optimal estimation inversion scheme for CH_4. We will also describe the various techniques that were tested and used to find an optimal set of wavenumbers at which the radiative transfer calculations should be carried out for the parameterization of the PC scores for the IASI channel radiances and Jacobians. We will compare the TOA radiances and Jacobians produced by the customized PCRTM and the full-physics RTM on which it was based, as well as the retrieved quantities from the CH_4 retrieval scheme driven by both the Full-Physics and the Principal Component RTMs.

Retrieval of GHG from interferogram : exploration, comparison with spectra from spectra

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ABSTRACT

Onboard MetOp satellite series, Infrared Atmospheric Sounding Interferometer (IASI) is a Fourier Transform spectrometer based on the Michelson interferometer. IASI acquires interferograms from which high-resolution atmospheric emission spectra are provided, enabling the derivation of temperature and humidity profiles (among other things) with exceptional spectral resolution. In this study, we will use the IASI archive to evaluate a retrieval approach in the interferogram domain, which we anticipate will be well-suited for near-real-time (NRT) analysis of extensive spectral datasets expected from next-generation tropospheric sounders like IASI-NG, GOSAT-GW, or MTG-IRS. The Partially Scanned Interferograms (PSI) method, applied to the retrieval of trace gases from IASI, has only rarely been studied. However, existing studies suggest its potential for specific gases, including CO, CO_2, CH_4, and N_2O, which could enable highly accurate trace gas column density retrievals at the resolution of a single IASI footprint.

We will present the interferogram retrieval approach of CO_2 and CH_4 from IASI simulations. These results are based on the set of simulations of IASI interferograms for which the identified regions (optical path differences), sensitive to the target species, are noised and then used for retrievals. Furthermore, the study which aims to compare the performance of the interferogram retrieval approach compared to the conventional (i.e. from the spectral domain) will also be presented. The expected advantage compared to the usual methods is an efficient use of the information contained in all IASI channels that are available in the absorption bands of a specific gas species.

The simulation of IASI spectra was conducted using the LATMOS Atmospheric Retrieval Algorithm (LARA), a robust and validated radiative transfer model based on Least Squares estimation [Segonne et al., 2021]. The climatological library TIGR [Chédin et al., 1985; Chevallier et al., 1998] was used to generate the IASI inteferograms with LARA. TIGR comprises 2311 atmospheric scenarios, each characterized by temperature, water vapor, and ozone concentration values across a specified pressure grid from the surface to the top of the atmosphere. The present study focuses on carbon dioxide and methane. This both gases exhibit a characteristic “comb” absorption pattern within the IASI wavenumber Simulations were performed for surface temperatures ranging from -15 to +15 K, in 5 K increments from the base temperature, to assess the impact of thermal contrast [Baudin et al., 2016]. Additionally, the study explores the potential of correlating interferogram characteristics (e.g. with surface temperature and H_2O content) aiming to enhance the accuracy of CO_2 or CH_4 column retrievals.

Release and demonstration of a new open retrieval algorithm toolset

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The University of Maryland and NASA Goddard Space Flight Center are happy to announce the upcoming public release of their new open retrieval toolset. This software is capable of supporting various greenhouse gas retrieval tasks, including the commonly used multi-band approach to obtain estimates for XCO2 based on measurements from platforms such as GOSAT(-2) and OCO-2(3).

We place a strong emphasis on ease-of-use and documentation to allow researchers to focus on the science questions at hand. In addition, we will also provide self-guided tutorials to introduce and explain the important concepts of the software to new users. These tutorials are hosted online, and researchers are encouraged to engage with that training material.

For this poster presentation at IWGGMS-21, we implemented NASA's ACOS algorithm with our toolset and used it on a number of case studies. These case studies include plumes from power plants seen by OCO-3 SAM mode measurements and OCO-2 target observations. This exercise shows how even the more challenging but crucial features of a physical retrieval algorithm (e.g., polarized, multiple-scattering radiative transfer), are firmly implemented and easily configurable.

Our software will be released under an open source license, and we want to encourage researchers from the global greenhouse gas community to try our tools and see if they can assist in your retrieval-related research!

Latest topics about the GOSAT-2 SWIR L2 products

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The Greenhouse gases Observing SATellite-2 (GOSAT-2; 2018-current), the successor to the GOSAT (2009-current) has been operating for more than 6 years. The column-averaged dry air mole fractions of carbon dioxide, methane, carbon monoxide, and water vapor (XCO_2, XCH_4, XCO, and XH_2O, hereinafter called Xgas), have been retrieved from Short-Wavelength InfraRed (SWIR) spectral data (Band 1, 2, and 3 at 0.75-0.77, 1.56-1.69, and 1.92-2.33 µm, respectively) observed with Thermal And Near-infrared Sensor for carbon Observation Fourier Transform Spectrometer-2 (TANSO-FTS-2) onboard GOSAT-2. Xgas are simultaneously retrieved using a so-called full-physics retrieval method and released as the "GOSAT-2 TANSO-FTS-2 SWIR L2 Column-averaged Dry-air Mole Fraction Product (hereinafter called SWFP)". Retrieval uncertainties of Xgas are evaluated primarily by comparing with the Total Carbon Column Observing Network (TCCON) data. The latest version of SWFP, V02.10, was released in February 2025. In SWFP V02.10, the a priori variance-covariance matrix for CO_2 profile was modified to relax the constraint on the a priori values. This resolved the reduction in the number of XCO_2 data over the ocean that occurred in the previous version of SWFP V02.00. In addition to SWFP V02.10, further updates are planned. Since the update of the Japanese 55-year reanalysis (JRA-55) data, the meteorological data used in the SWFP retrieval processing, was terminated on February 1, 2024, SWFP V02.10 processing could only go so far. To extend the processing period, the meteorological data will be switched to the succeeding product of JRA-55, the Japanese reanalysis for three quarters of a century (JRA-3Q), in the next version of SWFP V02.20. Also, JAXA is preparing the next version of the TANSO-FTS-2 L1B SWIR product, and the preliminary evaluation of the L1B sample product provided by JAXA is undergoing. We will show these latest topics about the GOSAT-2 SWIR L2 products in the session.

Improved CO2 retrievals with modified aerosol information using GOSAT measurements over East-Asia

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The Yonsei CArbon Retrieval (YCAR) algorithm, developed by Yonsei University, retrieves the column averaged dry-air mole fraction of carbon dioxide (XCO_2), which is based on optimal estimation method using shortwave infrared (SWIR) channels. In sensitivity analysis using simulated radiance spectra at difference surface and atmospheric conditions, the aerosol-related parameters representing the vertical distribution and optical properties of aerosols are important factor in XCO_2 retrievals, resulting in errors up to 2.5 ppm due to inaccurate aerosol optical information. As aerosols in the atmosphere are highly variable in their amount, vertical distribution and optical properties, their effect can be under-constrained (Frankenberg et al., 2012). These errors are caused by the simplified or inaccurate aerosol assumptions in the forward model and can be also increased in CO_2 retrieval using real spectra. To reduce the errors caused by the simplified aerosol assumptions, the YCAR algorithm are modified by using 12 parameters, representing aerosol vertical distribution and its optical properties instead of AOD profiles used in previous version. The XCO_2 retrievals with two different approaches in handling aerosol information analyzed using the Greenhouse Gases Observing SATellite (GOSAT) spectra over East-Asia and evaluated through the comparison with collocated ground-based observations at several Total Carbon Column Observing Network (TCCON) sites. These results can improve the accuracy of CO_2 retrieval algorithm taking into account aerosol information and provide useful information to reduce uncertainty and increase data availability.

A machine learning approach to fill the gap in global XCO_2 using multiple satellite measurements

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Accurate monitoring of atmospheric carbon dioxide (CO_2) concentrations is essential for understanding the global carbon cycle. Satellite remote sensing enables global CO_2 monitoring by providing column-averaged dry air mole fractions of CO_2 (XCO_2). Current missions such as the Orbiting Carbon Observatory-2 (OCO-2) and Greenhouse gases Observing SATellite (GOSAT) series provide high-quality XCO_2. However, these missions are limited by many observation gaps due to their narrow swath widths or cloud interference. To fill the observation gaps in XCO_2, we present a machine learning (ML) approach to estimate daily XCO_2 (ML XCO_2) at a 0.25° resolution using OCO-2, Sentinel-5 Precursor TROPOspheric Monitoring Instrument, and ERA5 reanalysis data from May 2018 to December 2024. Our ML XCO_2 estimates show high agreement with the Total Carbon Column Observing Network XCO_2 measurements. Additionally, we compared ML XCO_2 with other satellite measurements, including OCO-2, OCO-3, and GOSAT, as well as model-based products such as CarbonTracker and Copernicus Atmospheric Monitoring Service (CAMS). The spatiotemporal distributions in ML XCO_2 are generally consistent with publicly available XCO_2 products. Notably, during the Coronavirus disease 2019 (COVID-19) pandemic in 2020, ML XCO_2 estimates were more consistent with other XCO_2 products than CAMS XCO_2, which was overestimated due to unadjusted COVID-19-related CO_2 emission reductions. Finally, we estimated the annual mean CO_2 growth rates from ML XCO_2, which also consistent with estimates from OCO-2 and the National Oceanic and Atmospheric Administration surface CO_2 measurements, indicating the robustness of our approach. Our study demonstrates that the synergy between multiple-satellite measurements enhances the spatial coverage of XCO_2 with high accuracy and improves our understanding of the global carbon cycle. In this presentation, we will provide details on our ML approach, validation results, applications, and key findings. This work was supported by Korea Environmental Industry & Technology Institute (KEITI) through "Project for developing an observation-based GHG emissions geospatial information map", funded by Korea Ministry of Environment(MOE)(RS-2023-00232066).

Updates of retrieval algorithm for GOSAT-2/TANSO-FTS-2 TIR bands

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We had retrieved vertical profiles of GHG (CO_2, CH_4, N_2O, H_2O, and O_3) concentrations and temperature from GOSAT-2/TANSO-FTS-2 TIR spectra by adopting a non-linear maximum a posteriori (MAP) method with linear mapping [Rodgers, 2000] and released them as the TIR L2 V01.06 products. Overall accuracy of the initial released version of TANSO-FTS-2 TIR L2 CO_2 product was about 0.5-1% in the lower and middle troposphere, judging from comparisons with aircraft observations. However, data quality of the TANOS-FTS-2 TIR L2 V01.06 products varied depending on scenes, which might reflect from spectral bias of each of the observations. Such spectral biases should be also inherent to the TANSO-FTS-2 TIR L1B versions. Besides, there are several factors that would affect the quality of the retrieval profiles, such as uncertainties in surface emissivity, line parameters, and radiative transfer calculations.

We have improved our retrieval algorithm to reduce the influence of such spectral biases and uncertainties of other parameters on the retrieval quality; we have introduced eigenvectors obtained through a principal component analysis of spectral residuals, defined as differences between theoretical forward spectra and observed spectra, as one of the state vectors of the retrieval processing, and estimated them simultaneously with temperature and gas concentrations. To perform a principal component analysis considering various measurement conditions, we extracted TANSO-FTS-2 observation scenes with relatively large variations in latitudes, zenith angles, and azimuth angles and then calculated the spectral residuals for each of the different L1B versions. In addition, the improved algorithm has estimated five major GHG gases (CO_2, CH_4, N_2O, H_2O, and O_3) simultaneously, whereas the previous algorithm performed the retrieval processing of CO_2 (H_2O and O_3) and CH_4 (H_2O and N_2O) independently. In the retrieval processing of the five major GHG gases, we have set 13 micro-windows by carefully examining the absorption lines of each of the molecules, and retrieved multiple molecules and temperature simultaneously for each of the 13 micro-windows; this enables more accurate consideration of the effects of absorptions of molecules which spread over a wide range of wavelengths, such as H_2O. We evaluated performance and validity of the improved algorithm by comparing the retrieval GHG profiles with aircraft data, sonde data, and other in-situ observations.

Sensitivity Analysis of XCH_4 Retrieval Algorithm for the Narsha Microsatellites

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Methane (CH_4) is a potent greenhouse gas with a high global warming potential and a relatively short atmospheric lifetime, making it a crucial focus for emission reduction strategies. The Narsha project aims to develop a constellation of microsatellites for high-resolution methane monitoring. This study outlines the development of the satellite instrument, the methane retrieval algorithm, and its preliminary validation through simulation-based experiments.

First, a sensitivity analysis was conducted to examine how key instrumental parameters, such as spectral resolution and signal-to-noise ratio, influence retrieval accuracy. By evaluating the information content of observations, the study provides insights into potential retrieval precision under varying conditions, guiding the optimal instrument design.

Second, an XCH_4 (column-averaged dry air mole fraction of atmospheric methane) retrieval algorithm has been developed using the Optimal Estimation approach. The algorithm has undergone preliminary validation within an Observation System Simulation Experiment (OSSE) framework. Synthetic observations, generated from a radiative transfer model incorporating realistic atmospheric and instrumental conditions, were processed through the retrieval algorithm, demonstrating its effectiveness in accurately reconstructing methane concentrations. Future efforts will focus on refining error quantification and expanding validation through airborne observations.

This research lays the foundation for the Narsha mission to enhance global methane monitoring, ensuring the accuracy and reliability of satellite-derived XCH_4 data for emission assessment and climate policy development.

Advances on the emission estimation using the divergence method for individual satellite overpasses with noise reduction

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With ongoing climate change and rising global temperatures, quantifying greenhouse gas (GHG) emissions has become increasingly critical. One of the primary uses of remote sensing tools is to observe greenhouse gases, such as CO2 and CH4. Over the past decade, advancements in Earth observation (EO) and remote sensing have enabled the development of instruments with superior spatial and spectral resolution, accuracy, and coverage, which are essential for accurately monitoring these emissions. Combining satellite observations with inverse modeling has further strengthened our capacity to detect and quantify diverse GHG sources, from urban centers to natural environments.

To meet the requirements for monitoring CO2 emissions, the European Copernicus programme is preparing a dedicated CO2 Monitoring (CO2M) satellite constellation, scheduled for launch in 2026. This mission will deliver carbon dioxide (CO2) and nitrogen dioxide (NO2) observations with both along-track and cross-track pixel resolution of 4 km and a swath width of 250 km. Compared to other public satellite data products, such as TROPOMI on board of Sentinel-5P, CO2M will produce observations with improved spatial resolutions on regional and global scales.

Supporting the CO2M mission, there have been ongoing methodological advances on how to convert total column observations into emission estimates. One related project was the ESA-funded COCO2 project, conducted from 2021 to 2023, which developed the data-driven emission quantification (ddeq) Python library Kuhlmann et al. (2024). The ddeq library includes various inversion methods for converting satellite observations into emissions, such as the cross-sectional flux method, Gaussian plume model, integrated mass enhancement and divergence method.

In our study, we aim to improve the ddeq library, especially focusing on the implementation of the divergence method Beirle et al. (2019) Beirle et al. (2021) Hakkarainen et al. (2022). In the ddeq version 1.0, the divergence map over the area of interest is computed by gridding and averaging fluxes over longer time periods using multiple overpasses. This reduces the background noise but makes comparing and cross validating the divergence method with other methods in v1.0 challenging since other methods perform emission estimations using individual overpasses. The divergence can be computed for individual overpasses, but numerical differentiation combined with the noisy background resulted in significant noise in the divergence map, especially for CO2.

Our goal is to explore various methodologies for reducing noise prior to applying numerical divergence computation. By implementing effective techniques, we aim to achieve a significant reduction in noise during the differentiation, resulting in smoother divergence maps. We also plan to compute the divergence and estimate the emission rates from single overpasses using satellite coordinates (along and cross track), omitting the regridding step of the divergence map, thereby saving computational time.

Monitoring formic acid emissions from GOSAT-2 satellite observations

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Formic acid (HCOOH) plays a critical role in atmospheric acidity, yet the understanding of its budget remains incomplete. In regions affected by biomass burning, the precision of HCOOH profiles simulated by chemical transport models (CTMs) is significantly compromised, leading to underestimated emissions. Satellite observations provide a promising method for creating global maps of formic acid and for correcting the underestimation of carbon sources and sinks in local areas from a space-based perspective.

In this study, we utilized GOSAT-2 satellite spectra to retrieve HCOOH profiles and columns from the thermal infrared (TIR) band. Given the presence of other strong absorbing gases such as water vapor and ozone within the same absorption range as HCOOH, we developed a radiative transfer model (RTM) for mixing gases to accurately simulate the GOSAT-2 TIR band within the spectral range from 650 to 1450 cm^{-1}. The inversion process employed the Maximum a posteriori (MAP) estimation to achieve the best fit for HCOOH profiles by minimizing the discrepancy between simulated spectra and GOSAT-2 observations. The validation of the retrieved results for other profiles, such as temperature, water vapor, and ozone, were compared with OzoneSonde measured data, using the Japanese 55-year Reanalysis (JRA55) and MIPAS O_3 dataset as a priori values.

For HCOOH emissions during biomass burning events, we conducted an in-depth retrieval analysis for December 2019, focusing on the peak period of the Australian bushfires. The GOSAT-2 retrievals were compared with co-located HCOOH observations from the IASI satellite sensor, showing consistent enhancements in emission regions. Additionally, we validated the HCOOH distributions with active fire detections from the FIRMS dataset, revealing strong spatial correlations with fire hotspots. These results further confirm the significant role of biomass burning in HCOOH emissions and provide refined estimates of its atmospheric distribution. The posterior results offer robust constraints on HCOOH concentrations, distributions, and emission estimates.

Comparative validation of satellite-based GHG observations using FTS

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A ground-based Fourier Transform Spectrometer (FTS) is used as reference data for validating satellite-based greenhouse gas (GHG) observations. In particular, the IFS125HR, with its high spectral resolution of $0.02\ cm^{-1}$, is widely utilized for satellite data validation due to its high accuracy and reliability. However, as a stationary instrument, the IFS125HR is limited to retrieving the concentration of GHG at a single location, making it less suitable for large-scale validation. Therefore, to effectively validate satellite instruments that monitor GHGs over broad areas, it is essential to utilize mobile instruments capable of measuring greenhouse gases at multiple sites. In this regard, the Korea National Institute of Meteorological Sciences (NIMS) introduced the EM27/SUN in September 2022. While the EM27/SUN has a lower spectral resolution of $0.5\ cm^{-1}$, it offers the advantage of mobility. This study conducts a comparative analysis of CH4 retrievals from the two FTS instruments and Sentinel-5P (S5P) TROPOMI satellite data, based on measurements taken in 2024. The EM27/SUN performed observations at Ewha Womans University (EW) in Seoul from February to May 2024, while during the remaining period, it was deployed at Anmyeondo (AMY), where it operated alongside the IFS125HR. For the comparison, TROPOMI data within a 100 km radius of the FTS observation sites were selected, and FTS measurements taken within ± 1 hour of the satellite observation times were used. The results showed that the correlation coefficients between the satellite data and the two FTS instruments at the same site (AMY) were 0.95 for EM27/SUN and 0.93 for IFS125HR, with EM27/SUN showing a slightly higher correlation. Both instruments exhibited a bias of less than 2%, and the EM27/SUN demonstrated accuracy comparable to that of the IFS125HR when compared to TROPOMI. However, the correlation coefficient between the EM27/SUN and TROPOMI at EW was 0.68, which was lower than the result from AMY, though the bias was within 1%. During the same period, the correlation coefficient between the IFS125HR and TROPOMI at AMY remained high at 0.94, with a bias of less than 1.5%. This study presents an analysis of the temporal and spatial characteristics through a comparison between the satellite data and the FTS instruments, and assesses the potential of the EM27/SUN as a reference for validating satellite-based GHG observations.

Air mass factor calculation using deep neural network

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We conducted a feasibility study on using a deep neural network (DNN) to calculate the air mass factor (AMF) for NO_2 retrieval in the GOSAT-GW satellite mission. AMF is crucial for converting slant column density (SCD) to vertical column density (VCD) and is a major source of uncertainty in NO_2 measurements, particularly in polluted regions. Traditional lookup table (LUT)-based methods, while commonly used, involve a trade-off between computational efficiency and accuracy, often leading to significant errors. To address these limitations, we developed two DNN models: Trop-AMF-Net, which predicts tropospheric AMF, and Box-AMF-Net, an encoder-decoder model incorporating LSTM for altitude-dependent box-AMF calculations. Our models were trained and tested on datasets under three different atmospheric conditions: clear-sky, aerosol and cloud. The datasets were further divided into two distributions: one based on actual NO_2 observations and the other uniformly distributed. The results demonstrate that our DNN-based approach achieves RMSPE values as low as 0.123% for Box-AMF-Net in tropospheric AMF calculations under cloud conditions, approximately 3 times more accurate than LUT-based methods. Similar improvements were observed in clear-sky and aerosol conditions, with RMSPE reductions of 30–40 times. Additionally, the computation time for 10,000 samples is reduced to 3.7 seconds, five times faster than the LUT method, meeting the real-time processing requirements of the GOSAT-GW mission. These findings highlight the potential of DNNs to significantly enhance both the accuracy and efficiency of AMF calculations across different atmospheric conditions in satellite-based NO_2 retrieval.

Reprocessing the GOSAT TANSO-FTS record via ACOS v11 full physics retrieval algorithm

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The Japan Aerospace Exploration Agency's (JAXA's) Thermal And Near infrared Sensor for carbon Observations – Fourier Transform Spectrometer (TANSO-FTS) on the Greenhouse gases Observing SATellite (GOSAT) was the first dedicated greenhouse gas sensor [Kuze, Applied Optics, 2009], predating NASA's OCO-2 [Eldering, Atmos. Meas. Tech., 2017] by more than five years. The TANSO-FTS sensor has been making useful observations of reflected solar spectra in the shortwave infrared since April 2009. These spectra, along with necessary ancillary information such as meteorologic conditions, carbon dioxide (CO2) priors and aerosol priors, can be used in a Bayesian optimal estimation retrieval to produce estimates of the total column dry-air mole fraction of carbon dioxide (XCO2). The long observational record of GOSAT (April 2009 to the present) is of high utility to the science community.

NASA's Atmospheric Carbon Observations from Space (ACOS) level two full physics (L2FP) retrieval algorithm is used for the operational processing of the OCO-2 and OCO-3 sensors to provide estimates of XCO2 [O'Dell, AMT, 2018]. Historically, the ACOS team has also applied the L2FP algorithm to the GOSAT observations, most recently for version 9 (v9) [Taylor, Earth System Science Data, 2022]. A new funding stream through the United States Greenhouse Gas Center has allowed the resources for a full reprocessing of the GOSAT record using the most newest version 11 ACOS L2FP retrieval algorithm.

In addition to providing a data record beginning in 2009, the GOSAT ACOS v11 product will provide a consistent dataset that complements OCO-2 and OCO-3 in both space and time. After reprocessing of the retrospective GOSAT data, the nominal plan is to implement a low latency forward-processing data stream to provide a continuous XCO2 data set that may be used for assimilation into operational carbon inversion systems.

This work provides a progress report on the key steps required to process the GOSAT data, including repackaging of the JAXA measured spectra into ACOS Level 1b radiance files, generation of meteorology and CO2 prior files, and running preprocessors used for cloud and aerosol screening. All of these steps are necessary to provide the inputs to the L2FP retrieval, which generates raw estimates of XCO2. The raw results are subsequently quality filtered and bias corrected to provide final estimates of XCO2. Some initial XCO2 estimates are shown. Ultimately the data product will be delivered to the NASA GES-DISC in the form of daily LiteCO2 files, which will be publicly available to all science users hopefully by the end of 2025.

Retrieving the Vertical Profiles of Carbon Dioxide (CO_2) and Methane (CH_4) Using TCCON Fourier Transform Spectrometer (FTS)

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The Total Carbon Column Observing Network (TCCON) utilizes Fourier Transform Spectrometers (FTS) to provide atmospheric column-average concentrations of greenhouse gases. While the retrieval process scales a priori gas profiles as input parameters, the FTS data itself enables the derivation of vertical profiles for these gases. This study focused on deriving and validating the vertical profiles of carbon dioxide (CO_2) and methane (CH_4) concentrations from FTS measurements at TCCON's Anmyeondo observation site.

Accurate CO_2 and CH_4 profiles require improving the precision of a priori profiles, as their vertical structure persists through the retrieval algorithm. The a priori profiles of CO_2 and CH_4 currently employed by TCCON were found to inadequately represent local emissions, exhibiting weak diurnal variations, especially within the boundary layer. To address this limitation, this study adopted a new a priori profile simulated by the Goddard Earth Observing System Chemistry (GEOS-Chem) model instead of the standard TCCON-provided profiles.

Although the GEOS-Chem a priori CO_2 profile exhibited greater differences from the TCCON profile when compared with airborne observations, its overall vertical shape appeared more representative of actual conditions. When the GEOS-Chem a priori profiles were employed, the retrieved CO2 profiles achieved much better agreement with both surface in-situ measurements and airborne observations, particularly in the lowermost atmospheric layers near the ground. Notably, the discrepancy between the derived surface CO2 values and in-situ readings was significantly reduced to 6.4±8.7 ppm using the GEOS-Chem a priori profile, compared to 12.6±9.5 ppm with the standard TCCON a priori profile.

CH_4 profiles simulated by the GEOS-Chem model displayed distinct diurnal fluctuations near the surface and demonstrated better agreement with surface in-situ measurements. Interestingly, the column-averaged methane concentrations retrieved using the TCCON and GEOS-Chem a priori profiles differed only slightly, within 1~2 ppb, suggesting negligible influence of the a priori's vertical distribution on CH_4. However, employing the GEOS-Chem a priori profiles markedly improved the retrieved vertical profiles of CH_4 compared to using the standard TCCON a priori. When the GEOS-Chem profiles were utilized, the discrepancy between the derived surface methane values and in-situ measurements was halved. Moreover, the GEOS-Chem retrieved profiles exhibited better agreement with airborne measurements, particularly within the boundary layer.

These findings highlight the importance of using representative a priori profiles that adequately capture local emissions and boundary layer dynamics to accurately retrieve greenhouse gas vertical distributions from ground-based remote sensing data.

Satellite Multi-Band Multi-Path Approaches for Methane Quantification

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Greenhouse gases play a vital role in regulating Earth's climate, but their increasing concentrations pose a major threat by accelerating global warming. Among these gases, methane stands out due to its far greater global warming potential compared to carbon dioxide. Accurate observation of methane emissions and concentrations in global scale, however, remains challenging, creating uncertainties that complicate our understanding of climate change and hinder effective mitigation efforts. Enhancing methane monitoring techniques is therefore critical for developing informed strategies to combat global warming.

In this study, we focus on the Multi-Band-Multi-Pass (MBMP) approach for retrieving methane concentrations from super emitters. Using data from the Himawari 9 satellite, specifically at the 1.6µm and 2.3µm bands, as well as applying the same procedure to LandSat data, we evaluate and compared the performance of MBMP. This method combines multiple spectral bands and reference observations, aiming to improve the accuracy of methane concentration retrieval. To strengthen the reliability of our findings, we compare the MBMP-derived methane concentrations against observations from the TROPOMI satellites.

Our results indicate that the MBMP technique demonstrates the capability to detect and quantify methane emissions, particularly when monitoring major emission sources frequently. Moreover, by integrating satellite measurements with ground-based data and emission inventory database from the EDGAR database, we refined our methane estimates with improved detection accuracy. This underscores the value of consolidating diverse data sources for more precise and actionable insights.

Dual-domain injection network for methane plumes segmentation

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The automated detection and segmentation of methane plumes is a significant component of the implementation of emission reduction strategies. However, the challenge of false positive rates in the matched filter method remains a significant concern.

We have just published a paper describing the scientific contribution of the proposed network to the methane observation mission. The paper, entitled “Frequency and Spatial Domain Injection Network for Methane Plumes Semantic Segmentation”, was published in IEEE Transactions on Geoscience and Remote Sensing (Liu et al., 2024). Its abstract is pasted below or click here for a full access, https://ieeexplore.ieee.org/document/10816439.

Methane, a powerful greenhouse gas, significantly influences climate change. Estimating methane emission fluxes is critical for implementing emission reduction strategies, and plumes segmentation is an important technique for accurate quantification. However, existing methane plumes segmentation studies focus on pixel-level localization of spatial and spectral features, which makes it difficult to capture global contextual information of remote sensing images. To tackle these challenges, we propose a novel frequency and spatial domain injection network (FSDINet) for methane plumes segmentation. FSDINet introduces three blocks that process spectral features utilizing the frequency domain to capture global contextual information and supplement local information with pixel values in the spatial domain, thus allowing for precise localization and segmentation. We conduct extensive experiments on hyperspectral and multispectral datasets. On the Airborne Visible InfraRed Imaging Spectrometer—Next Generation (AVIRIS-NG) hyperspectral dataset, the majority of our model evaluation scores exceed those of existing methods in a range of conditions, including both strong and weak plumes, with the highest precision and intersection over union (IOU) of 87.75% and 65.56%, respectively. On the WorldView-3 multispectral dataset, precision and IOU improved up to 8.76% and 4.04% over methods utilizing spatial and spectral features. Furthermore, the zero-shot experiments on the Earth Surface Mineral Dust Source Investigation (EMIT) dataset confirm the robust generalization capacity of our model when confronted with different sensor data.

Evaluating satellite-based X_{CO2} measurements from v11.2 OCO-2 and v11 OCO-3 against ground-based measurements from TCCON and COCCON, and airborne measurements from ATom

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Carbon dioxide (CO_2) is naturally present in Earth's carbon cycle but is also emitted into the atmosphere in large amounts due to anthropogenic activities. Such activities strongly influence and alter the carbon cycle by impacting the ability of natural sinks to reduce atmospheric CO_2, necessitating precise, accurate, and long-term measurements of CO_2.

The Orbiting Carbon Observatory-2 (OCO-2) was launched in 2014 and is NASA's first Earth-orbiting satellite dedicated to making observations of atmospheric CO_2. The Orbiting Carbon Observatory – 3 (OCO-3), installed on the International Space Station (ISS) in May 2019, was developed to build upon and enhance the capabilities of its predecessor, OCO-2. OCO-2 and OCO-3 (collectively termed OCO, hereafter) measure the column-averaged dry-air mole fraction of CO_2 (X_{CO2}). The OCO missions aim to provide sufficiently precise and accurate X_{CO2} measurements to aid the quantification of carbon cycle fluxes at regional scales and understand its seasonal and interannual variability.

With the long-standing data record of the OCO missions, we evaluate the new and improved version 11.2 (v11.2) of OCO-2 and version 11 (v11) of OCO-3 X_{CO2} data against ground-based measurements from the Total Carbon Column Observing Network (TCCON) and the COllaborative Carbon Column Observing Network (COCCON). TCCON data have been historically used as the primary validation source for the OCO missions. When compared over selected sites, the TCCON data indicate absolute average bias values close to 0 ppm in the Land Nadir/Glint mode against the OCO datasets and the Target mode against OCO-2. COCCON uses portable Fourier-Transform InfraRed (FTIR) spectrometers (EM27/SUN) to provide precise and accurate column-averaged measurements of X_{CO2} and is highly advantageous in locations that TCCON does not access. Global comparisons against COCCON indicate bias values less than 0.30 ppm and 0.90 ppm in the Land Nadir/Glint and Target modes, respectively, for OCO-2 and less than 0.60 ppm for both these observation modes for OCO-3. Note that COCCON data, in the latest data version, are currently available for limited sites. Further, we evaluate specific sites of interest to understand the underlying factors that introduce the biases.

Lastly, this work provides preliminary analysis by comparing coincident OCO-2 measurements to the airborne Atmospheric Tomography Mission (ATom) when ATom conducted around-the-world flights in each of the four seasons between 2016 and 2018. This study aims to bridge the gap between satellite, ground-based, and airborne X_{CO2} measurements and aid the improvement of the OCO data products. It provides the latest validation analysis for the OCO missions and the most up-to-date information on biases and uncertainty in the OCO datasets, establishing their robustness for use by the scientific community.

Validation of satellite data of greenhouse gases based on observations of TCCON Hefei Site, China

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A ground-based high-resolution Fourier transform spectrometer (FTS) station has been established in Hefei, China since 2014, to remotely measure CO_2, CH_4 and other greenhouse gases based on near-infrared solar absorption spectra. Total column measurements of atmospheric CO_2 and CH_4 were successfully obtained from 2015 to 2024. The characteristics of the seasonal variation and the driving factors of the greenhouse gases variation were analyzed. The interannual variation and the growth rate were given. The observations based on the high-resolution FTS were used to compared with the temporally coinciding measurements taken with satellite, such as GOSAT, GOSAT-2, OCO-2, OCO-3 and Chinese TanSat, to evaluate the performance of carbon dioxide and methane observations from carbon-monitoring satellite products over China

The COllaborative Carbon Column Observing Network COCCON: Recent updates

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Greenhouse gases (GHGs) are a major contributor to global warming. Therefore, precise and accurate observations of GHGs, especially carbon dioxide and methane, are of utmost importance for the estimation of their emission strengths, flux changes and long-term monitoring. Satellite observations and global atmospheric models are well suited for this task as they provide global coverage. However, they need to be validated.
The COllaborative Carbon Column Observing Network (COCCON) performs ground-based solar-absorption observations to retrieve column-averaged dry air mole fractions of GHGs (XGAS). The instrument mostly used by the network is the EM27/SUN, a Fourier Transform infrared (FTIR) spectrometer. COCCON uses species dependent airmass-independent and airmass-dependent adjustments for tying the XGAS products to TCCCON (Total Carbon Column Observing Network) and thereby to the World Meteorological Organization (WMO) reference scale to achieve high accuracy and precision. Moreover, instrument specific characteristics are measured for each individual COCCON spectrometer and taken into account in the data analysis.
After an introduction of the COCCON network in general, we highlight its capabilities for various applications including satellite validation, long-term observation of GHGs, and local and regional GHG source emission strength estimations. We further discuss recent updates within the COCCON network.
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What Are Fiducial Reference Measurements for Greenhouse Gases and How Reliable Are They For The Satellite Validation?

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The Quality Assurance Framework for Earth Observation (QA4EO) provides a set of principles, guidance, and specific tools to encourage provision of internationally consistent quality indicators on the delivered data. Fiducial reference measurements (FRM) are fully characterized and documented sets of independent data, their associated uncertainties being in compliance with the QA4EO principles. Calibration and validation form an integral part of the global integrated Earth observation data system for ensuring provision of reliable information on the measured variable. The European Space Agency initiated the FRM4GHG project in 2016 to create high quality FRM data of greenhouse gas (GHG) for supporting satellite validation. Several portable low-spectral resolution spectrometers have been tested and some of them were found to meet FRM requirements. These spectrometers are useful to achieve a denser distribution of the ground-based stations, cover geographical gaps for various atmospheric conditions, source regions of special interest, emission verification, and to create a large latitudinal distribution of stations. In the current phase of the project the focus is on bringing the instruments capable of providing GHG data of FRM quality under the umbrella of the COllaborative Carbon Column Observing Network (COCCON) led by KIT, improvements in the data processing software to ingest and analyze the measurements from various spectrometers, and analysis of further trace gases which complement the GHG observations by extending the measurement spectral range.

In this presentation, we will show latest results of the FRM4GHG project highlighting the benefits of the selected set of instruments under test for providing the high-quality reference data and describe how the data are tied indirectly to WMO standards and the updates and further improvements in data analysis. Finally, we show how such a suite of independent, fully characterized and traceable measurements can be used for the validation of greenhouse gases measured by traditional satellite missions.

Status and upcoming plans of ground-based FTS measurements for evaluating space-based greenhouse gas measurements and carbon cycle studies at the National institute for Environmental Studies

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The Total Carbon Column Observing Network (TCCON), established in 2004, is a ground-based high-resolution Fourier transform spectrometer (FTS, Bruker IFS 125 HR or 120/5 HR) network dedicated to the precise remote sensing measurement of column-averaged dry-air mole fractions (DMF) of CO_2, CO, CH_4, N_2O, HF, HDO and H_2O. Column-averaged DMF of gases (denoted as XG for gas G, e.g. XCO_2) can be used in combination with in-situ measurements to disentangle the effects of atmospheric mixing and surface exchange of atmospheric gases, playing critical roles in evaluations of current and future space-based observation systems like GOSAT, GOSAT-2, GOSAT-GW, OCO-2/3, and TROPOMI, and providing a better understanding of the regional-scale fluxes.

We initiated ground-based FTS measurements in Tsukuba, Ibaraki, Japan in 2009, marking the first TCCON site in Asia. This was followed by a second site in Rikubetsu, Hokkaido, Japan in 2013. Both sites were established as part of the GOSAT validation activities. In 2017, we expanded our network by establishing a new TCCON site in Burgos, Ilocos Norte, the Philippines, the first TCCON site in South-Asia, as part of the GOSAT-2 validation activities.

To address the observational gaps of TCCON, the COllaborative Carbon Column Observing Network (COCCON) was established in 2016, based on the low-resolution FTS (Bruker EM27/SUN) developed by the Karlsruhe Institute of Technology (KIT) in cooperation with Bruker Optics. The low-resolution FTS delivers precision and accuracy comparable to that of TCCON.

We have deployed a low-resolution FTS as a COCCON site at NIES in Tsukuba since 2016, where Tsukuba TCCON FTS is also operating. Recently, we have established three new COCCON sites in Tokyo metropolitan region as part of the GOSAT-GW validation activities: at Sophia University in the central Tokyo, at Japan Agency for Marine-Earth Science and Technology in Yokosuka, south of the central Tokyo, and at Tokyo University of Agriculture and Technology in Fuchu, west of the central Tokyo.

Furthermore, we have started a new ground-based FTS measurement project focusing on India together with the Royal Belgian Institute for Space Aeronomy (BIRA-IASB) and Indian research organizations with the aim to have the first measurements starting in 2026.

In this presentation, we will show the status of ground-based FTS measurements from TCCON and COCCON operated by NIES, scientific achievements, and upcoming plans for Indian ground-based FTS project.

The Copernicus anthropogenic CO_2 Monitoring (CO2M) mission – operational product validation and monitoring

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As part of the Copernicus Programme, the European Commission and the European Space Agency (ESA), are expanding the Copernicus Space Component and are implementing satellite remote measurements for supporting anthropogenic CO_2 (and CH_4) emission monitoring. The European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) is responsible for the development of the operational ground segment (with contributions from ESA) and the CO2M system operations in the system commissioning and routine phases. Satellite measurements of atmospheric CO_2 and CH_4, complemented by in-situ measurements and bottom-up inventories, will be operationally assimilated into the Copernicus GHG Monitoring and Verification Support (MVS) Capacity of the European Commission developed by the Copernicus Atmosphere Service (CAMS) at the European Centre for Medium-Range Weather Forecast (ECMWF). The GHG MVS will provide CO_2 and methane emission inventories at regional, national, and global scales to users and stakeholders.

We will present an update on the status of developments and planning for the product commissioning, as well as the future operational continuous validation and monitoring.

CO2M will require co-located ground-based reference measurements, not only of XCO_2 and XCH_4, but also of aerosol optical depth and NO_2 at the same locations, both for polluted (close to the source) and for background conditions, and at a representative set of locations around the globe. The continuous and timely provision of ground-based reference data from all relevant networks (including TCCON, COCCON, Pandonia, NDACC, and AERONET) will play a key role in all activities concerning product validation and monitoring. Following the dedicated CO2M & MicroCarb Cal/Val workshop held after IWGGMS 2023 and subsequent iterations with network data providers, we will summarise the status and the way forward.

Keywords: CO2M, CO_2, CH_4, SIF, Aerosol, NO_2, constellation, instruments, monitoring, products, processing, validation.

Assessing the Effect of HITRAN Updates on Cross-Platform Calibration and Validation for Satellite-Based GHG Retrievals

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Preference: Oral

GOSAT, Japan's first satellite dedicated to greenhouse gas observations, was launched in 2009 and has been monitoring global GHG concentrations for over 16 years. Following its success, the OCO-2, OCO-3, TROPOMI (Sentinel-5P), and GOSAT-2 instruments were launched and remain operational at the present time. The TEMPO geostationary instrument, designed to monitor air quality and anthropogenic emissions in the United States, was launched in April 2023. These satellites provide global GHG and AQ datasets, contributing to climate change research. Satellite-based GHG observations are essential for tracking emission reductions and predicting climate scenarios for 2050.

To enhance scientific understanding, high-accuracy GHG monitoring products are required. Our recent study has identified spatial and temporal biases in existing GHG and AQ products. To reduce these biases and ensure consistency across multiple GHG instruments, we have conducted cross-platform calibration and validation campaigns. In this regard, we have examined the effect of updating spectroscopic data (to HITRAN2020+updates) on radiative transfer calculations. With LIDORT (V3.6) as the radiative transfer model, we have updated the calculation of input molecular absorption optical properties needed to run the RT model, to assess whether improved absorption cross-sections enhance agreement between simulated and observed radiance. Specifically for this update, we migrated from the HITRAN 2012 line spectroscopy data base to the more recent HITRAN 2020 data.

In this work, we have focused on the vicarious calibration campaign dataset acquired over the Railroad Valley (RRV) playa in the United States between June 9 and June 26, 2024. With the more recent HITRAN database as input, we performed radiative transfer calculations with LIDORT and assessed changes in computed spectral radiances compared with earlier results using older HITRAN data.

Comparison of the TIR spectral radiance between GHG satellite-based multi-sensors (GOSAT, GOSAT-2, AIRS, IASI, and CrIS) and aircraft-based S-HIS

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The Greenhouse Gases Observing SATellite (GOSAT) and GOSAT-2 have unique greenhouse gas (GHG) sensors, which observe not only the solar radiation reflected from the Earth's surface in the shortwave-infrared (SWIR) region, but also thermal infrared (TIR) radiation emitted from the ground and the atmosphere. To provide multi-layer retrievals of GHG, the TIR spectral radiance calibration is essential.
Therefore, we demonstrated the comparison of coincident measurements between GHG satellite-based TIR multi-sensors and the Scanning High-resolution Interferometer Sounder (S-HIS) on the NASA ER-2 aircraft by adopting the double difference method (e.g., Tobin et al. 2006; Kataoka et al. 2014). The S-HIS is a cross-track scanning interferometer sounder and measures upwelling TIR radiation at high spectral resolution. For the S-HIS, we used the preliminary data of S-HIS Westcoast & Heartland Hyperspectral Microwave Sensor Intensive Experiment (WHyMSIE) 2024 flight at an altitude of 20 km. As an example, we evaluated the coincidence between GOSAT-2/FTS-2 and S-HIS near Lamont in north-central Oklahoma on October 22, 2024. At this coincidence, we utilized coincident radiosonde profiles from the Atmospheric Radiation Measurement (ARM) as one of the input parameters for our forward calculation. The satellite-based sensors include GOSAT/FTS, Atmospheric Infrared Sounder (AIRS), Infrared Atmospheric Sounding Interferometer (IASI), and Cross-track Infrared Sounder (CrIS) as well as GOSAT-2/FTS-2. The double difference method analyzes residuals between observed and calculated spectral radiances, reducing the effect of differences in input parameter errors and observation geometry such as altitude and viewing angle.

MethaneSAT L0 to L1B Processor and in-Flight Calibration and Performance

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MethaneSAT was launched on March 4, 2024, to monitor methane emissions from over 80% of global oil and gas production, as well as from agricultural sources and calibration targets, with high precision and fine spatial resolution.

We present the MethaneSAT Level 0 (L0) to Level 1B (L1B) processor and its Quality Assurance and Quality Control (QAQC) framework. The processing pipeline consists of four main stages: (1) L0-L1A, which converts raw digital number counts into radiometrically and wavelength-calibrated spectra using pre-launch instrument calibration data and correction steps such as residual image correction, dark current subtraction, nonlinearity and gain adjustments, straylight correction, noise estimation, radiometric calibration, and wavelength assignment; (2) L1A-L1B, which geolocates the L1A data and calculates the viewing geometry through orthorectification; (3) an optional GeoAkaze correction, which refines geolocation accuracy by aligning L1B data with cloud-free Sentinel-2 MSI imagery via feature mapping; and (4) a QAQC process which evaluates L1B data quality, selecting high-quality targets for further analysis. We will also present examples of L1B data and report on the in-flight calibration and performance monitoring of the MethaneSAT CH_4 and O_2 spectrometers.

Inverse modeling of GOSAT observations and machine learning predictions highlight the role of wet tropics in driving the 2020-2022 methane surge

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Atmospheric methane concentrations rose rapidly over the past decade and surged in 2020-2022 but the causes have been unclear. We find from inverse analysis of GOSAT satellite observations that emissions from the wet tropics drove the 2010-2019 increase and the subsequent 2020-2022 surge, while emissions from northern mid-latitudes decreased. The 2020-2022 surge is principally contributed by emissions in Equatorial Asia (43%) and Africa (30%). Wetlands are the major drivers of the 2020-2022 emission increases in Africa and Equatorial Asia because of tropical inundation associated with La Niña conditions, consistent with trends in the GRACE terrestrial water storage data. In contrast, emissions from major anthropogenic emitters such as the US, Russia, and China are relatively flat over 2010-2022. Concentrations of tropospheric OH (the main methane sink) show no long-term trend over 2010-2022, but a decrease over 2020-2022 that contributed to the methane surge. To improve predictions of tropical wetland methane emissions and support climate projections, we trained a machine learning model using ENSO index and meteorological variables as inputs. The model's predictions capture the increase in wetland emissions, including the 2020-2022 surge in Africa, demonstrating its capability to represent how these variables influence natural greenhouse gas emissions.

Establishing an Arctic-Boreal Earth Science, Cal/Val Supersite at the FMI Arctic Space Centre in Sodankylä

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Finnish Meteorological Institute's Arctic Space Centre (FMI-ARC) in Sodankylä, Finland has undergone systematic development and expansion for the past 15 years. Now, in collaboration with the European Space Agency (ESA), the Sodankylä site will be expanded and developed into an ESA Arctic-Boreal Earth Science, calibration and validation supersite that will help EO satellite missions achieve their full potential to monitor the changing Arctic environment reliably. Three scientific focus areas guide the development and investments: (a) boreal forest ecosystems, (b) hydrology and snow, and (c) greenhouse gases (GHG) and atmospheric composition. The goal of the supersite is to provide reference data for current and forthcoming Earth Observation satellite sensors to validate their measurements and products for Arctic-Boreal and global applications.

In this poster, we will introduce the current suite of FMI-ARC ground-based instruments that enable versatile Cal/Val activities both regarding quasi-continuous monitoring and ad hoc campaigns. With the focus on GHG and SIF missions, we will review the challenges and development needs for our ground-based Cal/Val measurements to best support upcoming missions, e.g. European missions Sentinel-5, CO2M, and FLEX. Furthermore, we will highlight the specific advantages of our measurement setup where the cryospheric and atmospheric monitoring is intertwined. We will show examples of our ongoing and recent high-latitude satellite and model validation work, including novel instrument development, EM27/SUN gradient observation experiment, and the use of high-resolution atmospheric transport models to improve GHG satellite validation.

Beyond routine satellite Cal/Val activities, the ground-based measurements have high scientific value for identifying algorithm improvements to space mission data products, developing new data products, advance process understanding through multisource data analysis or model evaluation, and testing preliminary instrument or operation concepts of future missions. The measurements at the site have also potential to support the testing of innovative mission operation concepts.

Pre-launch and on-orbit spectral calibration of MethaneSAT

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MethaneSAT is a push-broom, area-mapping satellite launched into sun-synchronous orbit on March 4, 2024. The MethaneSAT mission aims to accelerate methane (CH_4) emission reductions by mapping, quantifying, and tracking oil and gas CH_4 point and area emission sources. MethaneSAT has two spectrometers on-board. One spectrometer covers carbon dioxide (CO_2) and CH_4 absorption windows centered at 1.61 µm and 1.66 µm, respectively, with 0.08 nm per pixel dispersion and 0.23 to 0.25 nm full width at half maximum (FWHM). A second spectrometer covers an oxygen absorption window centered at 1.27 µm, with 0.06 nm per pixel dispersion and 0.16 nm FWHM. We present novel methods for pre-launch and on-orbit spectral calibration of both MethaneSAT spectrometers. We derive and compare instrument spectral response functions (ISRFs) collected during ground calibrations on individual spectrometers (sensor level) collected at three temperatures and on the integrated flight system. Novel methods robustly merge ISRFs at three overlapping slit illumination fields of view and identify bad ISRF positions for gap filling. We evaluate four distinct ISRF data sets for on-orbit calibration by examining scaling the tabulated ISRF wavelength grid by a fitted squeeze factor. ISRFs measured at temperatures closest to those observed on-orbit produce ISRF squeeze factors close to unity. We also test the sensitivity of retrievals on thermal ISRF variations using pure CH_4 gas cell calibration exposures. We derive in-band stray-light kernels for the far-field and main reflection (ghost) based on pre-launch, sensor-level point spread function measurements. The stray-light correction is a redistribution of stray-light using an iterative deconvolution with the far-field kernel followed by deconvolution with the ghost kernel. Based on CH_4 gas cell measurements, 3% of detectable radiance signal in illuminated gas cell across-track pixels is correctable in-band stray-light, consistent with the integrated far-field stray-light kernel. Our results have important implications for validating on-orbit level 1 radiance calibration and the level 2 retrieval performance of MethaneSAT.

Validation plan for GOSAT-GW TANSO-3 Level 2 products

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The GOSAT-GW (Global Observing SATellite for Greenhouse gases and Water cycle) is the third satellite of the Japanese greenhouse gases observing satellite series and will be launched in the first half of Japanese fiscal year 2025. GOSAT-GW will carry two mission instruments: TANSO-3 (Total Anthropogenic and Natural Emission Mapping Spectrometer-3) and AMSR3 (Advanced Microwave Scanning Radiometer 3). TANSO-3 is an imaging grating spectrometer that measures backscattered sunlight spectra in three spectral bands of 0.45, 0.76, and 1.6 μm. TANSO-3 will have two observation modes (Wide Mode, with a ~900 km swath width and a ~10 km footprint size; Focus Mode, with ~90 km x 90 km observation areas and a <3 km footprint size), allowing observations of carbon dioxide (CO_2), methane (CH_4), and nitrogen dioxide (NO_2) from local to global scales. The NO_2 measurements will help to identify anthropogenic CO_2 emission sources and quantify the CO_2 emissions.

The TANSO-3 Level 2 products will be validated primarily using ground-based remote sensing data from global observation networks. The Total Carbon Column Observing Network (TCCON) and COllaborative Carbon Column Observing Network (COCCON) data will be used for validation of the column averaged dry-air mole fractions of CO_2 and CH_4 (Xgas), and the Pandonia Global Network (PGN) and Multi AXis Differential Optical Absorption Spectroscopy (MAX-DOAS) data will be used for the total and tropospheric NO_2 vertical column densities (VCDs). Air-borne in-situ measurements, satellite measurements (GOSAT/GOSAT-2, OCO-2/3, TROPOMI, etc.), and simulated concentration fields from atmospheric transport models will complement the ground-based data. For the validation of the Focus Mode data in urban areas, it is crucial to evaluate small-scale spatial gradients in Xgas and NO_2 VCDs. We are developing urban operational observing sites in the Tokyo metropolitan area, Japan, and its surroundings by deploying EM27/SUN spectrometers (COCCON instrument) and Pandora spectrometers (PGN instrument) close to each other. These observations will be complemented by ship-based EM27/SUN and DOAS observations along Japan's east coast. In this presentation, we will show the results of our preliminary studies using Xgas and NO_2 VCDs from the ground-based observing networks and other satellite observations, and discuss how we will effectively implement the validation of the TANSO-3 Level 2 products.

Greenhouse Gases Validation and Monitoring over the East Asia by Satellite-based Observation

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Abstract:
According to the 6th IPCC report, the concentration of greenhouse gases has increased about 20% since pre-industrial revolution, and 17% of them have increased over the last 10 years. The Korea Metoeorological Administration has analyzed satellite-based greenhouse gases to monitor climate change and support government's achievement of net zero.
The KMA has validated satellite-based greenhouse gases using CO_2 observed in situ and retrieved TCCON in Anmyeon, the South Korea which is a GAW site.
Both ground- and satellite-based CO_2 showed a good agreement in their increasing trends with seasonal variations. However, satellite-based CO2 observed total column appear smaller than in situ observations affected by local sources due to observe near the surface, but agree well with TCCON observed the total column. The RMSD of GOSAT, and OCO2 with in situ and TCCON is estimated about 14.85, 16.93 and 2.81, 2.01ppmv for a 1.0degree × 1.0degree spatial resolution on a daily time scale from January 2014 to December 2018. The results show that satellite-based products could be used greenhouse gases monitoring, but it needs to be verified more validation data.
We will present the detailed methods and results in the conference.

Bridging the Gap: Ground-Based and Airborne Measurements of CO_2 and CH_4 over the Tibetan Plateau for Satellite Validation

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Current ground-based observation networks for atmospheric greenhouse gases (GHG) volume mixing ratios remain sparse over the TP, where satellites have been the primary data source. However, the trueness of satellite observations over the TP remains unverified due to a lack of *in-situ* and ground-based remote sensing validation systems. To address this gap, we conducted a series of campaigns under the Second Tibetan Plateau Scientific Expedition Program (STEP), combining ground-based remote sensing, tethered balloon-based and helicopter-based *in-situ* measurements. Our findings reveal three critical limitations in current satellite retrievals: (1) substantial biases in *a priori* vertical profiles used by retrieval algorithms, (2) significant individual retrieval errors exceeding reported uncertainties, and (3) failure to resolve near-surface spatial gradients of GHG concentrations. We therefore propose establishing a standardized and long-term observational network combining *in-situ* and ground-based remote sensing measurements to enhance satellite retrievals over this climate-sensitive region.

What to expect from the HITRAN2024 database?

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This poster summarizes the 2024 quadrennial edition of the HITRAN molecular spectroscopic database. The HITRAN compilation is composed of six major components. The already existing (but updated in this edition) include the line-by-line spectroscopic parameters required for high-resolution radiative-transfer codes, experimental infrared absorption cross-sections (for molecules where it is not yet feasible for representation in a line-by-line form), collision-induced absorption data, aerosol indices of refraction, and general tables (including partition sums) that apply globally to the data. For the HITRAN2024 the water vapor continuum model has also been added in response to the multiple requests from the community.

The HITRAN2024 edition takes advantage of recent experimental and theoretical data that were meticulously validated, in particular, against laboratory and atmospheric spectra. The new edition replaces the previous HITRAN edition of 2020 (including its updates during the intervening years).

The extent of the updates of the line-by-line section in the HITRAN2024 edition ranges from updating a few lines of specific molecules/isotopologues to complete replacements of the lists, and also the introduction of additional isotopologues and new (to HITRAN) molecules: H_3^+, CH_3, S_2, COFCl, HONO, $ClNO_2$. Many new vibrational bands were added, extending the spectral coverage and completeness of the line lists. In addition, the accuracy of the parameters for major atmospheric absorbers has been increased substantially, often bringing uncertainties to unprecedented level below 0.1 %.

Over 300 new (to HITRAN) molecules were added to the section with experimental cross-sections.

An Overview of the Multi-instrument Dataset Collected during the 2023 AEROMMA Campaign

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The 2023 Atmospheric Emissions and Reactions Observed from Megacities to Marine Areas (AEROMMA) campaign, led by NOAA's Chemical Sciences Laboratory, investigated atmospheric emissions driving air quality and climate change in and around multiple cities within the United States. A key target was the Los Angeles Basin, where flights spanned multiple times of day and provided robust spatial coverage of the area. To better understand the distribution of carbon dioxide (CO_2) over urban areas, multiple observing platforms, spanning in-situ to space-based technologies, were coordinated to collect observations during these flights. In total, three EM27/SUNs were deployed in the study domain to run continuously during daytime hours, NASA's space-based Orbiting Carbon Observatory missions (OCO-2 and OCO-3) prioritized the Los Angeles area along with JAXA's GOSAT and GOSAT-2 platforms. Two stations of the Total Carbon Column Observing Network (TCCON) were also of use. One within the basin, and one just outside the basin. Presented here are preliminary findings from the ongoing investigation of urban CO_2 gradients with multiple instruments along with insights into coordinating future multi-instrument campaigns.

Aircraft-based CO_2 and CH_4 vertical distributions at the Anmyeon-do GAW site and the Yellow Sea in Korea for satellite retrievals validation

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Airborne greenhouse gas (CO_2, CH_4) observations have been conducted over Korea since 2018 using Picarro CRDS 2401m mounted on the King Air 350HW, under the Korea Meteorological Administration (KMA) and the National Institute of Meteorological Sciences (NIMS). This study presents the vertical distribution of CO_2 and CH_4 over the Yellow Sea and the Anmyeon-do (AMY, 36.54˚N, 126.33˚E) station, along with validation of satellite retrievals. AMY serves as both a Global Atmosphere Watch (GAW) regional background station for greenhouse gases (GHGs) and part of the Total Carbon Column Observing Network (TCCON). Located on the western coast of Korea, AMY is in a region where satellite-derived uncertainty is high, making validation efforts crucial for improving satellite accuracy. The vertical profiles observed at AMY and the Yellow Sea display distinct seasonal characteristics. High-concentration greenhouse gases in the Yellow Sea were primarily observed at higher altitudes, while at AMY, located along the coast, greenhouse gases were predominantly present in the lower troposphere. This suggests that the vertical transport mechanisms of greenhouse gases differ between these regions. Since the Yellow Sea has no direct emissions, it is likely more influenced by long-range transport through the middle troposphere. Long-term observations are expected to provide a clearer understanding of the vertical seasonal characteristics of greenhouse gases across different regions of Korea. Over five years, approximately 40 profiles of CO2 and CH4 were observed at AMY. Smoothed XCO2 and XCH4 values were calculated to validate satellite retrievals. A comparison of XCH4 concentrations observed at AMY and the Yellow Sea by aircraft with XCH4 values derived from the TROPOMI sensor on the Sentinel-5P satellite revealed that the bias-corrected XCH4 concentrations significantly reduced discrepancies, confirming an improvement in the satellite-derived values. Additionally, vertical spiral observations at AMY were compared with targeted measurements from OCO-3 during October 2019, with the mean bias falling within the expected uncertainties. It is anticipated that airborne observational data will play a significant role in validating various satellites and models in the future.

Short- and long-term ground-based FTIR GHG measurements at the Qinghai-Tibetan Plateau and contributes to satellite validation

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The Qinghai-Tibetan Plateau (QTP) is a key system that impacts the global carbon balance, but greenhouse gases (GHGs) mole fraction measurements in this region are limited due to the tough environment. In recent years, our team has carried out several short-term ground-based FTIR measurement campaigns at QTP. Since August 2024, we have installed one Bruker EM27/SUN instrument at Naqu, Tibet. The FTIR at Naqu is continuously operating and we plan to keep the measurements at least for another year. This study will give an overview about the these short- and long-term ground-based FTIR measurements at QTP. In addition, satellite validations will also be presented and discussed.

Validation of the latest GOSAT series L2 products

~ Ver. 03.10 for GOSAT product and Ver. 2.10 for GOSAT-2 product ~

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Space-based measurements of greenhouse gases (CO_2 and CH_4) are important to elucidate the Earth's carbon cycle. The Greenhouse Gases Observing Satellites (GOSAT and GOSAT-2) are the spacecrafts with Thermal And Near-infrared Sensor for carbon Observation Fourier Transform Spectrometer (TANSO-FTS/TANSO-FTS-2) onboard to measure the column-averaged dry air mole fractions of greenhouse gases from space. The L2 products measured by the GOSAT and GOSAT-2 have been released to the public. In the 19th IWGGMS, we presented the validation results of version 03.00 of GOSAT L2 product and version 02.00 of GOSAT-2 L2 PROXY product. Here, we present the latest validation result of GOSAT L2 product (Ver. 03.10) and GOSAT-2 L2 product (Ver. 02.10). The GOSAT series L2 products obtained within ±2°at each TCCON site are compared with the TCCON data. TCCON data are averaged over within ±30 min of GOSAT or GOSAT-2 overpass time.

Table 1. Mean biases and standard deviations of GOSAT-2 Full Physics product (Ver.02.10, land) against ground-based FTS observations at all TCCON sites（March 2019 — January 2024）

XCO_2		XCH_4		XCO		XH_2O	
Bias [ppm]	Std. [ppm]	Bias [ppb]	Std. [ppb]	Bias [ppb]	Std. [ppb]	Bias [ppm]	Std. [ppm]
3.52	2.16	0.75	12.61	6.92	11.27	-38.47	399.01

Table 2. Mean biases and standard deviations of GOSAT-2 PROXY product (Ver.02.10, land) against ground-based FTS observations at all TCCON sites（March 2019 — January 2024）

XCH_4		XCO	
Bias [ppb]	Std. [ppb]	Bias [ppb]	Std. [ppb]
-3.93	13.72	4.59	12.45

Table 3. Mean biases and standard deviations of GOSAT product (Ver.03.10, land) against ground-based FTS observations at all TCCON sites（April 2009 — December 2022）

XCO_2		XCH_4		XH_2O	
Bias [ppm]	Std. [ppm]	Bias [ppb]	Std. [ppb]	Bias [ppm]	Std. [ppm]
-0.78	2.31	-3.86	12.02	-100.06	410.53

For the GOSAT-2 Full Physics product, the absolute bias of this product (Ver. 02.10) was larger than that of the previous product (Ver. 02.00) for all constituents. For the GOSAT-2 PROXY product (Ver. 02.10), the absolute

mean bias of this product for XCH_4 was smaller than that of the previous product (Ver. 02.00), and the signs of the biases were reversed from positive to negative.
For the GOSAT product, the mean absolute bias of this product (Ver. 03.10) for XCO_2 increased compared to the previous product (Ver.03.00). For XCH_4 and XH_2O, the absolute biases decreased compared to the previous product.

Calibration and performance of MethaneSat and GeoXO-ACX at BAE Systems Inc.

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BAE Systems Space & Missions Systems Inc. has extensive heritage in developing science mission remote sensing technology with exquisite calibration. Our experience in developing trace gas instruments spans the UV to the IR. With recent successes in the deployment of MethaneSat and new developments for the NOAA GeoXO suite of instruments, we are continuing our legacy partnering with science teams to create sensitive instruments with traceable calibration and strong heritage. We will share our methods of calibration and instrument design for the MethaneSat spectrometers as well as discuss developments being made for the GeoXO Atmospheric Composition (ACX) instrument.

MethaneSAT is an observatory with the payload designed and built by BAE Systems, Inc., formerly Ball Aerospace, for MethaneSAT LLC, a wholly owned subsidiary of the Environmental Defense Fund. The MethaneSAT observatory is designed to locate and quantify anthropogenic methane emissions, specifically oil and gas emissions, throughout the world. BAE conducted characterization and calibration of the sensors throughout development demonstrating excellent performance. The sensors were then integrated to a customer-furnished bus and final characterization and calibration of the Flight System was conducted prior to launch. MethaneSAT was successfully launched on March 4th, 2024, and is delivering data to stakeholders.

The ACX instrument leverages significant design heritage from Tropospheric Emissions: Monitoring of Pollution (TEMPO) and The Geostationary Environment Monitoring Spectrometer (GEMS). BAE applied lessons learned from these heritage programs to improve performance and “operationalize” the ACX design. These UV/Vis instruments conduct hourly measurements of atmospheric trace gases and aerosols critical to understanding atmospheric composition and air quality. The high spatial and temporal resolution of these instruments allow for measurements and analyses of the complex diurnal cycle of pollution, driven by the combination of photochemistry, chemical composition, and the dynamic nature of the atmosphere. Improvements from GEMS and TMEPO include calibration methods, dynamic range, and SNR.

The HITRAN2024 methane update

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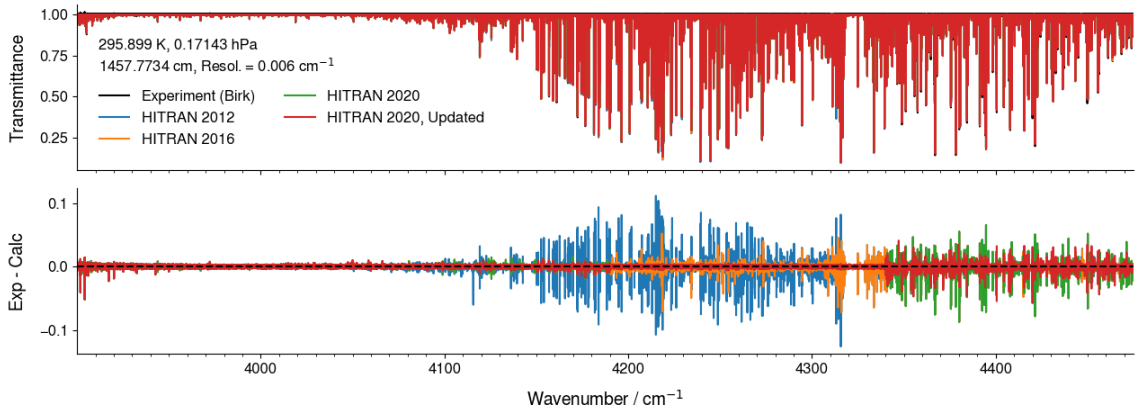
Knowledge of accurate spectral parameters of methane transitions is very important in atmospheric and planetary sciences. With that, in many spectral regions reliability of reference spectra for methane remain limited by a lack of data. The HITRAN[1] database sources its methane line parameters from many different studies, impacting remote observations with varying modeling accuracy throughout the spectrum. For instance, lines could be missing, shifted from their real position, unassigned, or lack traceability limiting its applicability. Gathering several new line lists of CH_4 and its isotopologues, and collisional data from theory and experiments, this work aims to improve the transitions wavenumbers, intensities, assignments and pressure-induced line-shape parameters in HITRAN.
The line positions and intensities from these line lists were compared to different low-pressure experimental spectra. Parts of these lists then replaced HITRAN 2020 in places where a clear improvement could be seen in the spectra residuals (see example below). The talk will be dedicated largely to the updates in the pentad and octad regions but other spectral regions have been updated as well.
The pressure-induced parameters were directly compared between work done in the ν_3 band considering its wealth of data. The parameters were separated according to their rotational symmetry, ranking index, branch, and line profile used and fit to an empirical Padé approximant. We present the final residuals from these line lists, the resulting fits, as well as a comparison of the predictions with theoretical calculations. Having a consistent set of parameters per profile allows for better parametrization of line mixing as the next step.



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Studying the Carbon Cycle Dynamics in Semi-arid Regions of the Southern Hemisphere from Space

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Semi-arid regions of the Southern hemisphere contribute substantially to the inter-annual variability of the global carbon sink. Processes driving the terrestrial carbon fluxes in these regions are not well understood due to limited availability of in situ and flux tower measurements. In order to obtain an understanding of the terrestrial processes, Dynamic Global Vegetation Models (DGVMs) can be used as they represent the biogenic carbon cycle and its dynamics given environmental conditions. However, model results for net CO_2 exchange vary considerably between different models as they include different processes, interactions and parametrizations. We present a comprehensive analysis of CO_2 flux dynamics in Southern Hemisphere semi-arid regions over a decade (2009–2018), including the South American Temperate (SAT) region (Vardag et al., 2025), Southern Africa (Metz et al., 2025), and Australia (Metz et al., 2023). We leverage multiple data products (in-situ, OCO-2, GOSAT) in combination with DGVMs. By identifying the process models that closely align with observational data, we pinpoint the processes driving the seasonal and interannual land-atmosphere CO_2 exchange.

We reveal that in semi-arid regions the onset of rainfall triggers an early increase in heterotrophic respiration while autotrophic respiration and gross primary production (GPP) are delayed. This dephasing leads to an increase in net ecosystem exchange shaping the seasonal cycle. While we find that this effect also shapes interannual variability (IAV) over Australia, while the IAV in Southern Africa is mainly influenced by year-to-year variations in GPP. We argue that soil rewetting processes in semi-arid areas need to be accurately represented in global carbon cycle models to improve the global carbon budget. Our study demonstrates the potential of satellite measurements to study biogenic processes in remote areas.

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Advance in understanding of the changes in the carbon cycle and its linkage to the water cycle during the 2023-2024 El Niño in Amazon region

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The Amazon forest is crucial to the global carbon cycle, and even minor disturbances — whether from human activity or climate variability — can significantly impact the global climate and South America's hydrological cycle. The ongoing 2023-2024 El Niño is accelarating atmospheric CO2 growth rate, yet the underlying regional drivers and controling processes remain challenging to quantify due to the complex coupling of carbon-water-energy interactions and their spatial variations.

To address these challenges, we employed a hybrid machine learning (ML) approach that integrates ML techniques with a data assimilation framework to improve our understanding of terrestrial carbon cycle and its interaction with the water cycle, particularly through the coupling of photosynthesis and transpiration fluxes. Unlike conventional models that generatalize plant behaviours into broad categories, our approach incorporates diverse environmental factors, including climate, forest age, and soil properties, allowing for more accurate predictions of plant responses at various locations.

Training our hybrid ML model on satellite observations in the Amazon region resulted in relatively high Nash-Sutcliffe Efficiency scores across multiple indicators, paticularly for leaf area index and net biome exchange (NBE). The model retained strong predictive performance even under drought and extreme heat conditions induced by El Niño. Further explainable artificial intelligence (XAI) analysis – using integrated gradients (IG) – indentified distinct carbon-climate interactions in wet vs. dry regions. XAI revealed that radiation dominates carbon uptake in wet regions while precipitation and temperature exert stronger controls in dry region. Additonally, XAI enabled us to decompose predictor effects into memory effects (past anomalies influencing current conditions) and concurrent effects (real-time responses). Notably, precipitation and temperature anomalies exhibited stronger memory effects in dry regions, likely due to deeper rooting systems and prolonged water stress.

Overall, our findings demostrate that DiffLand effectively captures key Amazonian ecosystem processes and aligns well with statellite observations. The incorpratation of XAI techniques enables precise attributions of satellite observed anomalies to underlying ecosystem processes, enhancing our ability to model and predict Amazonian responses to climate extremes.

Keywords: Amazon, El Niño, extreme events, machine learning, data assimilation

Inverse analysis with in-situ/flask and GOSAT observations to disentangle regional and sectoral emission contributions to the surge of atmospheric CH_4 for 2020–2022

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Atmospheric methane (CH_4) growth rates reached unprecedented values in the years 2020–2022. To identify the main drivers of this increase, an inverse modeling study estimated regional and sectoral emission changes for 2016–2022. The inversion system we used is NICAM-based Inverse Simulation for Monitoring CH_4 (NISMON-CH_4), which uses the four-dimensional variational (4D-Var) method to optimize CH_4 emissions. Using NISMON-CH_4, we performed inversions based on three different sets of atmospheric CH_4 observations: surface observations only, surface and aircraft observations, and GOSAT observations. The GOSAT observations are derived from the NIES full physics product (V02.95/V02.96). The three different inversions consistently suggest notable emission increases from 2016–2019 to 2020–2022 in the tropics (15°S–10°N) (10–18 Tg CH_4 yr^{-1}) and in northern low-latitudes (10–35°N) (ca. 20 Tg CH_4 yr^{-1}), the latter of which likely contributed to the growth rate surge from 2020. The emission increase in the northern low-latitudes is attributed to emissions in South Asia and northern Southeast Asia, which abruptly increased from 2019 to 2020, and elevated emissions continued until 2022. Meanwhile, the tropical emission increase is dominated by tropical South America and central Africa, but they were continuously increasing before 2019. Agreement was found in the sectoral estimates of the three inversions in the tropics and northern low-latitudes, suggesting the largest contribution of biogenic emissions. However, posterior mole fractions of the GOSAT inversion showed persistent deviations from the surface observations in the tropics and the southern latitudes, which can also be seen to a lesser extent in the comparison with the aircraft observations. Furthermore, a sensitivity test using a different GOSAT

product (by a proxy method) showed different estimates for the emission increases (a predominant role of African emissions). To investigate these satellite data characteristics, we need more elaborate networks of high-precision in-situ and flask observations not only at the surface but also in the upper-air (by aircraft); these observations are specially needed in the tropical and low-latitude areas of Africa, South America, and Asia.

Nitrous oxide (N_2O) surface fluxes derived from IASI space-borne observations

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Nitrous oxide (N_2O) is the third most important long-lived greenhouse gas (GHG) after carbon dioxide (CO_2) and methane (CH_4) contributing to global warming. It has a global warming potential 298 times higher than that of CO_2 on a mass basis and for a 100-year horizon. N_2O emissions increased by 0.25-0.30% yr^{-1} over the past 10 years and keep increasing until 2100 in the majority of socio-economic scenarios. Emissions of N_2O are largely driven by the microbial processes of nitrification and denitrification occurring in soils, the ocean and freshwater systems. Of the global total emission (~17 TgN yr^{-1}), ~57% is naturally occurring and the remaining ~43% is anthropogenic. Anthropogenic emissions are dominated by agriculture (~52%) and are due to the perturbation of the nitrogen cycle through the addition of nitrogen from synthetic fertilizers and manure, while industrial and fossil fuel combustion contribute ~27%. The N_2O surface emissions show huge temporal and spatial variabilities. The spatial variability on the global scale is estimated to be greater than a factor 10 over land and greater than a factor 5 over the ocean. For anthropogenic emissions, East and South Asia, Europe and North America are the most emitting regions, while for natural soil emissions, Equatorial and South Africa and South America are the most emitting regions. The N_2O emissions and sources are highly uncertain both over land and ocean. Quantifying N_2O emissions through a "top-down" approach relies on sparse surface observations. Our aim is to develop a tool based on space-borne observations of N_2O to derive N_2O surface fluxes at global scale. Observations of N_2O from the Infrared Atmospheric Sounding Interferometer (IASI/Metop A) space-borne instrument over the year 2011 have been processed using the Toulouse N_2O Retrieval (TN_2OR) tool showing a high (significant) sensitivity around 300 hPa. The retrievals are based on the RTTOV radiative transfer model coupled with the optimal estimation method. They have been validated against airborne (HIPPO) and ground-based (NDACC) observations. We have used the Community Inversion Framework (CIF) model to invert N_2O global surface flux. The CIF configuration was based on the LMDz model coupled with a 4DVAR assimilation technique to minimize the forecast model outputs and the IASI observations at 300 hPa. Surface fluxes on the global scale are difficult to validate. Thus surface mixing ratios are used instead. Considering more than 50 stations around the world, the N_2O surface mixing ratio assimilated with CIF over 2011 is consistent with surface observations to within ±0.5 ppbv despite an initial bias of 10 ppbv in the model initialization. Our study is able to highlight the seasonal evolution of N_2O surface fluxes within different regions of the globe. Two areas show the greatest seasonal amplitudes in the assimilated surface fluxes with Africa (60%) and South America (80%) maximizing in September whilst the forecast surface fluxes reach only 10% amplitude for these two areas. The assimilated yearly fluxes are consistent with literature (Tian et al., 2024) although the regions of Africa and South America show a significant greater value by 40% and 20%, respectively.

Progress in understanding natural carbon fluxes with decade-long OCO-2/3 observations

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Session: Global to regional flux estimates and validation
Preference: oral

The natural carbon cycle acts as an important buffer for atmospheric CO_2 increases by absorbing ~56% of fossil fuel emissions up to now (IPCC AR6). Where emitted carbon has been absorbed and why, and how this carbon sink will change in the future are core questions that have driven carbon cycle research during the last few decades. Answering these questions is also crucial to choosing the most likely emission pathways that limit the global temperature increase to < 2.0°C by the end of this century. With much greater global coverage, satellite remote sensing of column CO_2 and solar induced chlorophyll fluorescence (SIF) provides a vantage point to quantify CO_2 sources and sinks as well as component fluxes, providing insights on how the carbon cycle interacts with climate across the globe. In this talk, we will review the progress that has been made in quantifying regional CO_2 sources and sinks and understanding carbon-climate interactions during the last decade with insitu and OCO-2/3 observations. We will highlight robust signals inferred from the decade-long top-down flux inversion results, insights on carbon-climate interactions, and country carbon stock changes due to climate variations. We will conclude by discussing the remaining sources of uncertainty in flux estimates based on satellite observations. We will also discuss opportunities available with the extension of the column CO_2 records, the expansion of surface and aircraft CO_2 observing networks, and upcoming space-based CO_2 observations.

Progress in multiresolution flux inversions in support of OCO2-MIPv2

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Session : GHG Flux estimates
Preference : Oral

Inverse modeling of space-based measurements of carbon dioxide (CO_2) is the principal means to infer spatially-resolved fluxes from variations in atmospheric concentrations owing to transport and surface-atmosphere carbon exchange. Variational approaches such as 4D-variational assimilation used in CMS-Flux have become the benchmark for high-resolution flux estimates globally through efficient adjoint calculations and inherent mass conservation. However, these approaches have limitations in computing flux uncertainty, the flux resolution, and the information content of observations. These quantities are critical for communicating results for both scientific and policy-relevant applications. We introduced the Carbon Monitoring System Multiresolution Flux (CMS-MFlux) approach to estimating carbon fluxes that can compliment existing approaches. In this methodology, fluxes are decomposed into successive, but orthogonal, resolutions that are adapted to the information content of the observing system. We apply this approach to estimate fluxes as part of the OCO2-MIPv2 activity. We show preliminary results and how they integrate more tightly with 4D-var solutions from CMS-Flux. From this standpoint, we show how this approach provides a “best-of-both worlds” for atmospheric inversions.

Regional carbon sink estimates by NTFVAR inverse model with surface and satellite observations.

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We present top-down regional carbon dioxide flux estimates using CO_2 observations from the GOSAT satellite and surface in-situ sites from 2010 to 2023. We use the NTFVAR (NIES-TM-FLEXPART-variational) global inverse model that is based on a 0.1° high-resolution transport. The prior emissions are prescribed using ODIAC or GridFED (fossil) and GFAS (fire). We also use data-driven products for land biosphere and oceanic fluxes. The estimated fluxes are provided to the Global Carbon Budget comparison and evaluated against results from other participating models and independent data. Annual mean regional fluxes show a good balance with modest tropical source combined with modest boreal sink, but some improvement in interannual variability is needed. A need for further improvement in flux estimates for South Asia and Amazonia is indicated by a comparison with independent airborne observations, and it can be achieved by adding surface observations to supplement a lack of satellite observations during rainy seasons. To accommodate future wide-swath CO_2 satellite observations, an increase in resolution of the transport model, wind fields and prior fluxes are considered. A new prior CO_2 flux data set based on MODIS GPP is tested in a 0.025° resolution inversion with surface data, and a good fit of the optimized simulation to the observed data is confirmed.

Investigating anomalous growth of atmospheric CO2 in 2023–2024 using GOSAT XCO2-constrained inverse modeling

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The global atmospheric CO_2 growth rate in 2023–2024 observed by Greenhouse gases Observing SATellite (GOSAT) has surged to an unprecedented level, surpassing all historical records, as reported by National Institute for Environmental Studies (NIES). While fossil fuel emissions drive the long-term rise of atmospheric CO_2, its interannual variations are largely governed by natural carbon fluxes in response to climate variations, particularly ENSO. The strong 2023–2024 El Niño event likely played a central role in modulating terrestrial carbon fluxes, suppressing tropical biospheric uptake, and intensifying fire emissions.

To investigate the mechanisms behind this anomalous growth, numerical experiments are conducted using top-down inversion framework NISMON-CO_2, constrained by column-averaged dry air mole fraction data of atmospheric CO_2 (XCO_2). The XCO2 data are provided from NIES as Level 2 product of GOSAT measurements. NISMON-CO_2 incorporates NICAM-TM (Nonhydrostatic ICosahedral Atmospheric Model-based Transport Model) for forward and adjoint simulations, coupled with a four dimensional variational (4D-Var) data assimilation system for inverse computations. Our analysis reveals that in 2023–2024, net average carbon flux anomalies were -0.1, 2.4 and -0.1 PgC yr-1 in the northern mid-latitude (90°N–30°N), tropics (30°N–30°S) and southern mid-latitude (30°S–90°S) respectively, relative to 2017–2022. Despite of having large-scale fire in 2023–2024 (e.g., Canada), northern mid-latitude remained net carbon sinks (southern mid-latitude as well), while tropics continued as a net source, with an increasing trend, suggesting that rising tropical emission dominated the global atmospheric CO2 increase in 2023–2024. These findings provide key insights into the sensitivity of the global carbon cycle to climate extremes, with implications for predicting future atmospheric CO_2 trajectories in a warming world.

Keywords: CO_2 inversion, 4D-Var, GOSAT, XCO_2, NICAM, El Niño, Transport Model.

Constraining shoulder season carbon fluxes (CO_2 and CH_4) from the Arctic-Boreal zone using remote-sensing observations

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One of the largest uncertainties in projected greenhouse gas concentrations and temperature trends is the impact from terrestrial and marine carbon-climate feedbacks in the northern high latitudes (i.e., circumpolar Arctic and Boreal region North of approximately 50° latitude). While evidence is emerging about changes to various terrestrial and marine ecosystem processes, a comprehensive and integrated understanding of Arctic-Boreal carbon cycle dynamics and its interaction with the global carbon cycle remains elusive. Of particular concern are the "shoulder season" (March–May and September–November) carbon emissions, both CO_2 and CH_4, which are now known to contribute a significant portion of the annual carbon budget in these ecosystems.

In this presentation, I will cover some of the recent advancements that have been made to improve both the quantity and quality of retrievals from space-based sensors (such as OCO-2 and TROPOMI) and their subsequent impact on constraining Arctic-Boreal carbon fluxes during the shoulder seasons. Novel machine-learning based approaches have allowed us to refine the filtering and bias correction approach, accounting for high airmasses, aerosol burdens and different surface albedos to better capture characteristics of retrievals over snow and ice-covered surfaces. These innovations have allowed us to use the space-based vantage point to better quantify Arctic-Boreal carbon fluxes, diagnose its current state (net source or net sink or approximately carbon neutral) & spatiotemporal patterns. Our ability to monitor the shoulder season carbon fluxes is also providing new insights into the processes and factors controlling temperature, oxygen availability, and carbon substrates that regulate the release of CO_2 and CH_4 fluxes during spring thaw and fall senescence.

Finally, I will use these results, along with findings from NASA's ABoVE campaign and the international RECCAP-2 Permafrost effort, to discuss the potential for space-based observations for providing new insights into Arctic-Boreal carbon cycle dynamics. This is of high interest to the carbon cycle community, especially as we prepare to utilize high-density data from ESA's CO2M satellite constellation and JAXA's GOSAT-GW mission. I

will conclude with a discussion on the need for integrating these remote-sensing observations with other environmental datasets in order to obtain a truly integrated picture of the Arctic-Boreal system, identify its most sensitive parts and significantly reduce uncertainties related to Arctic-Boreal carbon processes and budgets in current and future climates.

Can we detect CH_4 emissions from permafrost with TROPOMI XCH_4?

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Some fraction of the carbon in northern circumpolar permafrost will be released as CH_4 or CO_2 as permafrost thaws in the coming years. Column-averaged methane (XCH_4) observations (2018-2023) from the Tropospheric Monitoring Instrument (TROPOMI) are assessed for evidence of CH_4 emissions from permafrost regions. Using Weighting Function Modified Differential Optical Absorption Spectroscopy (WFMD) v1.8 TROPOMI XCH_4 data, XCH_4 anomalies north of 50°N are calculated and averaged bi-monthly onto a high spatial resolution (0.09°x0.18° ≈ 10 km) grid. Soil temperature anomaly maps (down to 1.5 m depth) are also generated from reanalysis data. A region that stands out is Canada's Hudson Bay Lowlands (HBL), which exhibits a strong correlation between XCH_4 and soil temperature anomalies over the 6-year period indicating increasing CH_4 emissions over time. The HBL is an area of wetlands and peat underlain by continuous through to isolated permafrost, containing very high soil carbon content and wind conditions that are favorable detecting localized emissions. We will discuss whether such CH_4 emissions can be linked to permafrost, a comparison to some other published findings and the potential for detection of permafrost CH_4 or CO_2 emissions from future satellite missions.

Evaluating the consistency of the emissions estimated from atmospheric inversions using three methane TROPOMI products at the regional and global scales

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Satellite observations of total column methane atmospheric mixing ratios (XCH_4), combined with atmospheric transport inverse modeling, enhance our ability to monitor methane (CH_4) emissions at global and regional scales. Their extensive coverage provides a valuable source of observations for refining top-down emission estimates, particularly in regions with sparse monitoring networks.

The TROPOspheric Monitoring Instrument (TROPOMI) on board the Sentinel-5 Precursor (S5P) satellite provides XCH_4 with global daily coverage and a relatively high (5.5×7 km²) horizontal resolution. Three XCH_4 products, retrieved using different algorithms, are available from TROPOMI Level 1 data: (1) the official reprocessed product (SRON, v2.04) based on the RemoTeC full-physics algorithm; (2) the BLENDED product (v1.0, Harvard University), a machine-learning-corrected version of the official product with respect to GOSAT-TANSO retrievals; and (3) the WFMD product (University of Bremen, v1.8) based on the WFM-DOAS algorithm. These products differ in quality filtering, sampling, observed XCH_4 values and associated uncertainties, leading to discrepancies in the posterior emission estimates derived from inversions.

This study aims at comparing the CH_4 emissions inferred from atmospheric inversions assimilating the three TROPOMI products. We perform inversions at multiple spatial scales to provide a synthetic analysis of the differences, using the flexibility of the Community Inversion Framework (CIF). **Regional inversions** over Europe use the chemical transport model (CTM) CHIMERE at a **0.5° × 0.5° resolution**, while **global inversions** are performed using the CTM LMDz on a **96 × 96 horizontal grid (3.8° x 1.9°)**. We explore the key drivers of the inter-product differences, including observation density, retrieval errors, surface albedo and aerosols. We perform Observing System Simulation Experiments (OSSE) with synthetic pseudo-observations and known prior fluxes to identify and quantify the impact of individual drivers on the inversion results and to assess the sensitivity of the system to these factors. Emissions estimated from the assimilation of real observations are reported and compared at pixel, country and regional scales, providing insights into the consistency of TROPOMI-based inversions.

European Methane Flux Estimates Using the Community Inversion Framework

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Methane (CH_4) is a potent greenhouse gas, and accurately quantifying its emissions is essential for climate mitigation efforts. Leveraging the Community Inversion Framework (CIF), we estimate monthly CH_4 fluxes across Europe (-12^0E to 37^0E, 35^0N to 73^0N) for the period 2017–2022 at a $0.2^0 \times 0.2^0$ resolution. The inversion system integrates the Lagrangian Particle Dispersion Model (FLEXPART) driven by ECMWF meteorology to compute surface flux footprints. We assimilate data from 40+ in-situ measurement sites, including ICOS and non-ICOS stations, using a 4D-Var approach to optimize high-resolution prior flux estimates. The prior CH_4 flux is derived from multiple sources: EDGARv8.0 and GAINS (anthropogenic emissions), GFAS (biomass burning), JSBACH-HIMMELI (wetlands, peatlands, and mineral soils), and T. Weber et al. (2019) (air-sea exchange), alongside additional contributions from geological and termite emissions. Our posterior CH_4 concentration estimates show reduced bias and RMSE, with improved correlation against in-situ observations. Compared to the prior, the posterior achieves a lower mean bias (13.69 ppb vs. 19.54 ppb), lower RMSE (24.67 ppb vs. 34.84 ppb), and a higher R^2 (0.77 vs. 0.58), with the strongest agreement at Nordic stations. Major CH_4 emitters (France, Germany, Italy, Spain, Poland, and the UK) contribute 72% of total emissions. At the EU27+3 scale, the six-year mean emissions increase from 21.8 Tg/yr (prior) to 23.3 Tg/yr (posterior) (+6.5%). Prior anthropogenic fluxes for EU27+3 were aggregated to 15.5 Tg/yr, while the posterior estimates indicate 16.7 Tg/yr (+7.5%), aligning more closely with the UNFCCC five-year (2017–2021) mean reported value of 17.1 Tg/yr. The BENELUX region shows a >35% correction, suggesting GAINS may underestimate anthropogenic emissions of the region. Conversely, Italy exhibits a notable posterior reduction, likely due to inflated geological emissions in the prior flux. Across the study domain, total emissions show a modest increase from 36.11 Tg/yr to 36.72 Tg/yr (+1.69%). Our results highlight the crucial role of data assimilation in reducing CH_4 flux uncertainties for regions with dense observational networks, while minimal corrections occur in regions with sparse coverage like the Iberian Peninsula and Eastern Europe. This underscores the need for enhanced in situ networks and satellite observations to improve methane flux estimates, particularly in regions with sparse ground-based measurements. To address this, we have begun assimilating TROPOMI CH_4 retrievals, leveraging their extensive spatial coverage and high-frequency observations to refine flux estimates. This integration is expected to enhance the accuracy and spatial distribution of methane emissions, complementing ground-based networks and improving our understanding of regional CH_4 sources. A comparison of our results with WFMD retrievals for the summer months (June, July, and August) of 2021 reveals significant differences between surface-based and satellite-derived CH_4 concentrations, highlighting the need for further investigation and optimization of data assimilation strategies.

Assessing South Asia's Methane Budget Using Satellite Observations and Inverse Modeling

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Methane (CH_4) is a potent greenhouse gas with a global warming potential significantly higher than carbon dioxide over a 20-year period. Its major sources in South Asia include agriculture, wetlands, waste management, and fossil fuel. Despite its importance, the region faces significant challenges in accurately quantifying CH_4 emissions due to the sparse observational network and high uncertainties in bottom-up emission inventories.

This study leverages high-resolution TROPOMI satellite observations in combination with the Lagrangian transport model FLEXPART and the Bayesian inversion framework FLEXINVERT to constrain methane fluxes over South Asia for the year 2020. By integrating multiple bottom-up inventories, we estimate total methane emissions at 66.3 Tg/yr over the study domain, with India contributing 38.6 Tg, Pakistan 8.0 Tg and Bangladesh 7.6 Tg. Our inversion results suggest that the actual emissions vary significantly across the region, with a higher posterior estimate over eastern India and Bangladesh. Significant discrepancies are observed in agricultural and wetland emissions, particularly during the monsoon season, highlighting gaps in current inventories. The study employs a comprehensive sectoral methane inventory and a variable grid approach for assimilating satellite observations, enhancing computational efficiency and improving the accuracy of emission estimates. These findings provide a more accurate representation of regional methane fluxes, crucial for improving emission mitigation strategies, aiding in the development of effective policies and verifying national greenhouse gas reporting in line with international climate agreements.

Estimating methane emissions consistent with both satellite and isotope constraints

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The increase of atmospheric methane (CH_4) over the past decades has posed a puzzle with many possible solutions. The puzzle is made tricky by the many sources of CH_4, anthropogenic and natural, that respond in different ways to human activity and climate variations. Methane sinks add a layer of complexity; while weak (they consume ~10% of the CH_4 burden every year), they do vary with changes in climate.

Atmospheric inverse modeling estimates CH_4 sources given observed atmospheric gradients and a model of atmospheric circulation. The TROPOMI satellite, launched in 2017, is the latest in a series of CH_4-observing satellites with sensitivity to the ground. With ~400,000 retrievals of column CH_4 each day, TROPOMI provides the information to estimate total CH_4 sources over relatively small time and space scales. Attributing these to specific sources, however, is left to prior constraints.

The isotopic composition of CH_4 depends on the history of CH_4 formation and oxidation, and therefore provides a way to distinguish between different sources of CH_4. For example, in the isotope world, CH_4 from leaks in high northern gas wells looks very different from wetland CH_4 at the same latitudes.

Methane isotopic measurements are considerably more difficult to make than CH_4 measurements and are limited (so far) to in situ measurements. However, in concert with a sampling platform such as TROPOMI that provide a tight constrain on total CH_4, these isotope measurements provide a way to estimate source-specific CH_4 emissions, and potentially a way to distinguish sources from sinks.

Here we describe an atmospheric inversion framework that can simultaneously assimilate remotely sensed total CH_4 and in situ isotope measurements to provide source-specific CH_4 emissions. We present initial results from a joint assimilation of TROPOMI CH_4 retrievals and in situ measurements of $\delta^{13}CH_4$. We show that discrepancies between the source attribution suggested by TROPOMI and $\delta^{13}CH_4$ data come mainly from deficiencies in our prior CH_4 emission maps, and suggest ways of improving the prior flux maps to be able to simultaneously assimilate TROPOMI CH_4 and in situ $\delta^{13}CH_4$ data.

The MethaneSAT CORE algorithm: quantification of diffuse sources from oil and gas production regions

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MethaneSAT is a spaceborne imaging spectrometer that bridges the gap between area flux mappers and point source imagers. Observing methane in the 1.65 µm band and oxygen in the 1.27 µm band, it combines high spatial resolution (100 m x 400 m native pixel at nadir), a wide swath (210 km), and high precision (~3ppm at 1 km x 1km) to simultaneously measure discrete, high-emission point sources and dispersed area sources. Discrete source quantification methods are outlined in Chulakadabba et al., 2023 and Chan Miller et al., 2023. Here, we describe the MethaneSAT Level 4 Conserved and Optimized Retrieval of Emissions (MSAT L4-CORE) algorithm that optimizes the dispersed area source emissions and show results from oil and gas production regions around the world. MSAT L4-CORE uses the Stochastic Time-Inverted Lagrangian Transport (STILT) model driven by operational meteorology to model transport, a hybrid modeled/empirically fit background concentration, and Markov Chain Monte Carlo simulations using the Stan software for Bayesian data analysis to optimize the boundary inflow and dispersed sources simultaneously. Emissions estimates from MSAT L4-CORE show good agreement with estimates from independent analyses and MethaneSAT's airborne precursor, MethaneAIR. These data will contribute powerfully to emissions mitigation frameworks that rely on timely, empirical data, and is a huge step towards radical transparency in the industry.

Methane Budgets of East, Southeast and South Asia (2010–2021): An Inversion Inter-Comparison for Asia (MICA)

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Methane emissions from East, Southeast, and South Asia significantly impact the global methane budget, driven by diverse agricultural, industrial, and natural sources. Accurate quantification of these emissions is essential for developing effective mitigation strategies. This study presents the first comprehensive quantification of methane budgets for these regions from 2010 to 2021, derived from an intercomparison of seven inverse models. These models utilized a consistent set of prior emission estimates and atmospheric methane observations, including data from the GOSAT satellite, the NOAA ObsPack CH_4 dataset, and additional in-situ measurements from Asian sites. Our analysis revealed consistent downward corrections of prior emission estimates in East Asia, contrasting with regional variations in South and Southeast Asia. While prior total emission trends showed significant increases across all three regions, posterior trends indicated a significant increase only in South Asia. Sectoral emissions were also analized. Notably, discrepancies between prior and posterior trends in South Asian agricultural emissions, potentially influenced by ENSO, underscore the complexities of regional methane dynamics. We observed consistent and significant increases in waste emissions across all regions, alongside a marked rise in coal emissions specifically in South Asia. Furthermore, we estimated national-scale methane budgets and attributed emissions to key sources, providing critical information for targeted emission reduction strategies. This work will serve as an independent evaluation for the Global Stocktake, contributing to a more robust assessment of global methane emissions.

Benchmarking USA Methane Inventories using GOSAT based Methane Fluxes

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Testing bottom-up (BU) methane emission inventories and their changes, using satellite methane concentration data (Top-Down or TD) for the purpose, requires characterizing uncertainties related to atmospheric concentration data, the chemistry and transport model used to relate emissions to concentrations, and the convolved effects of spatial resolution and prior uncertainty (or smoothing error). In this study, we demonstrate an optimal estimation framework that explicitly quantifies yearly emissions by sector using GOSAT XCH4 data. This approach enables us to account for the choice of a priori and inversion sensitivity to the emissions, thereby mitigating smoothing error when comparing these TD emissions estimates to other inventories. We evaluate USA emissions and trends from 2012 to 2020 from three state-of-the-art inventories (EDGAR v8, GRAPES (fossil only), and GHGI) with the GOSAT-based emissions and demonstrate: 1) that not accounting for smoothing error results in poorly informed comparisons, and 2) where the inventories may need additional scrutiny due to robust differences (differences larger than calculated uncertainty) between inventory and satellite-based estimates. In particular, we find that the activity based fossil emissions (EDGAR and GHGI) are significantly smaller than the satellite based emissions whereas the GRAPES (a hybrid atmospheric / activity model) is consistent, suggesting that spurious emissions not accounted by activity metrics are a significant source of methane. On the other hand, trends in emissions between the three inventories and the satellite data are broadly consistent and indicate that USA emissions are not observably changing during this time period.

Capacity of observing systems to estimate CH4 fluxes at regional and sectorial scales through OSSEs

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Top-down methane (CH_4) flux estimates involve important uncertainties stemming from three main sources: (1) the coverage of the observing system, (2) systematic and random errors in the data and (3) errors in the atmospheric transport model linking concentrations to fluxes. Quantifying these uncertainties is challenging, and recent studies suggest they can be substantial. While global-scale uncertainties in total CH_4 emissions are relatively constrained (±5%), they increase significantly at regional scales exceeding ±20% in high latitudes. Differences in satellite and in-situ measurement uncertainties, as well as variations in data density, further influence the precision of CH_4 flux estimates. Distinguishing uncertainties by emissions sector is especially critical in high-emission regions, as it plays a key role in refining flux estimates at the regional scale.

This study aims to assess the capacity of different observing systems to estimate CH_4 surface fluxes at regional and sectorial scales using Observing System Simulation Experiments (OSSEs), assuming a perfect atmosphere and accurate prior emissions. The experiments are conducted within the Community Inversion Framework (CIF) over the period from June 2018 to June 2020, to assess the capacity of each observing system to retrieve true fluxes and estimating the uncertainties reduction on the inversion. The CIF integrates the atmospheric transport model LMDZ, coupled with SACS (Simplified Atmospheric Chemistry Assimilation System), where a Bayesian approach optimally combines CH_4 observations, fluxes, covariance matrices, and input parameters. LMDZ operates at a 2.5° × 1.27° horizontal resolution with 79 vertical levels and a 30-minute time step. CH_4 fluxes are perturbed using a Monte Carlo method, generating a 10-member ensemble. OSSEs were conducted over 18 regions in two phases using: (1) aggregated sectorial fluxes and (2) separated sectorial fluxes. Assimilated observations include GOSAT-1-NIES, GOSAT-1-Leicester, IASI-Metop-A, TROPOMI-WFMD and in-situ measurements, together with their combinations. OSSE results were analyzed at both regional and sectorial scales. Uncertainty reduction was quantified as the posterior-to-prior standard deviation ratio across ensemble members, while comparing posterior and prior values to true fluxes assessed the relative improvement in flux estimates.

Overall, we observe a heterogeneous reduction in uncertainty depending on the satellite, region, and sector. When considering aggregated fluxes, uncertainty reduction is mainly concentrated in the Northern Hemisphere, reaching up to 50% in some regions using in-situ data alone or combined with GOSAT-1 observations. For sectorial flux inversions, uncertainty reductions are most significant in high-emission areas. Regarding flux estimate improvements, the results align with uncertainty reduction, following similar spatial distribution. Our findings highlight the importance of the accuracy and spatial distribution of the data to reduce the inversion uncertainties and enhance the CH_4 flux estimations.

The Community Inversion Framework: A Flexible and Scalable Data Assimilation Framework for Satellite Greenhouse Gas Observations

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Accurate greenhouse gas (GHG) emission monitoring is essential for advancing our understanding of climate change and supporting effective mitigation strategies. For the past two decades, satellite-based platforms have played a significant role in monitoring atmospheric composition of GHG, and new generation of satellite platforms will enhance this capability in the coming years. The process of comparing satellite-based observational products, particularly total or partial columns, to chemistry-transport models, in order to evaluate 3D simulation fields and to monitor fluxes, has proved tedious and human-resource intensive in the past, with numerous different approaches and ways of reporting satellite-based datasets (averaging kernels, priors, instrumental and retrieval uncertainties, etc.). Significant standardization efforts have been dedicated to satellite products by the community over the past few decades. However, legacy GHG monitoring systems have demonstrated limited flexibility and ability to rapidly integrate new satellite missions. This has impeded the capacity of the GHG quantification community to leverage the full potential of satellite-based products, particularly by postponing the integration of new satellite missions widely into the monitoring community.

The Community Inversion Framework (CIF) is a flexible and open-source tool that integrates various inversion methods and interfaces seamlessly with chemistry-transport models (CTM) and various observation streams, including satellite products, into a unified framework. Thanks to its very flexible design, CIF can be easily adapted to read various data-streams, such as emission inventories or observations, directly from the data provider file format, with several products already implemented.

For satellite applications, CIF offers end-to-end capabilities to transform 4D atmospheric concentration fields, sourced from widely available products or user-made CTM simulations, into satellite-comparable quantities through automatic temporal, horizontal, and vertical interpolation and the flexible application of satellite averaging kernels. CIF processes disparate datasets from various providers into a standardized format, thereby enabling robust inter-comparisons of satellite observations, either through CTM simulations or full inversions. This process yields reliable estimates of greenhouse gas fluxes at regional or global scales. This integrated approach enhances our capacity to evaluate atmospheric composition in a rigorous and reproducible manner, supporting improved climate monitoring and informing targeted mitigation strategies.

We present the general approach of satellite integration in the Community Inversion Framework and some examples relatable to the GHG community (GOSAT, TROPOMI, IASI, CO2M, OCO-2).

Localized CO_2 enhancements observed by the GOSAT satellite and their relation to country-level anthropogenic emissions

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Emissions from fossil fuel combustion primarily cause the growth of atmospheric CO_2 abundance, the major part of which happens in large power plants and megacities. A satellite-based capability of remotely observing CO_2 enhancement due to anthropogenic emissions should help detect potential biases in reported emission inventories. We utilized a high-resolution atmospheric transport model to simulate fossil fuel emission signals in XCO_2 observed by Greenhouse gases Observing SATellites (GOSAT NIES L2 v03.05; 2009-2022). This allows us to relate emissions to observed XCO_2 anomalies around large point sources such as power plants or a cluster of such sources like megacities. These anomalies are calculated as deviations from a monthly background value, which is a 10°×10° box-average of GOSAT observation having weak fossil signal (<0.1 ppm simulated XCO_2). Regression analysis of model-simulated fossil-XCO_2 and GOSAT-observed anomalies show that they agree well in regions with large volumes of observations. For the global average, we found a slope value close to unity (0.98±0.06), while for North America and East Asia, the simulated and observed XCO_2 enhancements have regression slopes (0.84±0.07, 1.17±0.09 respectively) reflecting potential regional biases in the inventory. On analysis at the country level, we were able to select large countries, such as China, India, the USA, etc., that had sufficient observations to establish a linear relation between simulated and observed enhancements. We will discuss the country-level regression and the implications for regional analysis. Our results indicate that by increasing the number of observations around emission sources, satellites like GOSAT can be used for anthropogenic emission monitoring for independent verification of reported emission inventories.

Global carbon dioxide and methane flux estimates based on GOSAT-2 observations

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Carbon dioxide (CO2) and methane (CH4) are greenhouse gases that have a major impact on climate change. While ambitious efforts to combat climate change are undertaken by all nations, anthropogenic greenhouse gas emissions have been increasing due to energy demand growth even after Paris Agreement that was adopted at COP21 in December 2015. A detailed understanding of sources and sinks of greenhouse gases is required to answer scientific and political questions for keeping a global temperature rise this century well below 2 degree Celsius above pre-industrial levels.

Greenhouse gases Observing SATellite-2 (GOSAT-2) was launched in October 2018 as a successor of GOSAT launched in 2009. The GOSAT-2 mission was motivated by an urgent need for improved observation data sets that characterize the global distribution of major greenhouse gases, CO2 and CH4, from spaceborne measurement to promote climate change studies and decision making. This study uses TANSO-FTS-2 Column-averaged Dry-air Mole Fraction Product (GOSAT-2 SWFP Level 2 Product V02.10), which is retrieved from the radiance spectra acquired by the GOSAT-2, to estimate global distribution of CO2 and CH4 sources and sinks. For the net sources and sinks estimate, an inverse analysis system NICAM-based Inverse Simulation for Monitoring CO2 /CH4 (NISMON-CO2/CH4) is used. In this presentation, we evaluate and compare our results, monthly global net sources and sinks estimate with a 2.5 deg. spatial resolution, with our previous estimates, atmospheric observations and other inverse analysis results, and show associated seasonal and interannual patterns of the global net CO2 and CH4 sources and sinks estimated based on GOSAT-2 observations.

Quantifying Indian terrestrial biospheric CO_2 flux using observations from ground-based network and GOSAT

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We estimate the Indian terrestrial biospheric CO_2 fluxes using a global inverse model, NIES-TM-FLEXPART-VAR (NTFVAR), utilizing the observations from an Indian local surface network, the global reference surface network, and the GOSAT satellite. The inverse model is an Eulerian-Lagrangian coupled model that optimizes terrestrial biosphere and the ocean-atmosphere exchanges separately, while the fossil fuel fluxes are prescribed. The estimated fluxes for the land and ocean regions are found comparable to the results from the OCO2-Model Intercomparison Project (MIP). The sensitivities of the estimated regional fluxes to the observations are also examined. Our result show that the Indian region act as a sink (-0.147 ±0.094 PgC yr^{-1}) when the model is constrained by all the available observations. However, the sink gets weaker (-0.040 ±0.133 PgC yr^{-1}) without the Indian surface observations or by using filtered GOSAT observations. Our result suggests that the model is largely constrained by the observations from the Indian local surface networks and GOSAT. Though the constrain from the GOSAT observations is significant, obtaining robust estimates only by using the GOSAT data is difficult, as the data yield is low especially in the summer season.

Development of the OCO-2 inverse analysis system introducing independent bias correction method

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The World Meteorological Organization has officially launched its Global Greenhouse Gas Watch (G3W) plan for 2024. This ambitious plan aims to provide the concentration and flux of carbon dioxide and other greenhouse gases with a horizontal resolution of one degree and a time resolution of one month with a one-month delay. Considering the current greenhouse gas observation network, the use of satellite observation data is indispensable to realize this project. Currently, several greenhouse gas observation satellites have been operated in Europe, the U.S., Japan, and other countries, and more are planned for launch in the future. In order to make effective use of these valuable observation data, the spatiotemporal biases of each satellite must be corrected appropriately, otherwise, the estimated GHG flux and concentrations will be greatly affected. The authors have succeeded in estimating and correcting the biases of satellite observation data from the independent inverse analysis of GOSAT using only in-situ observations into the inverse analysis while correcting for them (Maki et al., 2023), and were able to use this method for OCO-2 in this study. In comparison with the independent inverse analysis, no significant trend of the bias was observed in the data from both satellites (GOSAT and OCO-2). The OCO-2 observation data has a wider observable range and smaller bias than the GOSAT data. The introduction of the OCO-2 observational data in our inversion system greatly improved the carbon dioxide flux uncertainty for the south America and the Africa. At the meeting, we will report on the bias evaluation using OCO-2 and GOSAT, a summary of the inverse analysis results from 2014 to 2023, and the validation results using independent observation data.

Preliminary CO_2 flux inversion results from the OCO-2 v11 MIP

David Baker and the OCO-2 v11 MIP flux inversion modeling team

Abstract:
A variety of error sources affect global flux inversions of satellite CO_2 data, some springing from the retrieval of CO_2 mixing ratios from the satellite radiances, others from inferring surface fluxes from the retrieved CO_2 fields using atmospheric transport models and inversion methods. To disentangle these errors from the fluxes of interest,
global inverse modelers have worked together to interpret the OCO-2 data as part of a model intercomparison project (MIP). Controlled experiments were run in which all groups use the same data and data uncertainties: these can be used to quantify
systematic errors (biases) between the different data types (e.g., ocean glint (OG) versus land nadir (LN) or land glint (LG)). The impact of transport model differences may be minimized by viewing results across the full suite of models.

In the most recent version of the OCO-2 MIP ('version 10'), a bias in the OG data relative to the LN/LG proportional to airmass/path length (and also related to scatterer optical depth) was detected. This caused large, unrealistic effects on the fluxes, so the OG results were not used – only the LNLG data were used, along with *in situ* (IS) CO_2 data, for science work. One key finding was a large release of CO_2 from Africa north of the equator, the realism of which has been debated.

A variety of changes have been made to the OCO-2 v10 retrieval scheme in moving to the latest version (v11), released last year. In addition, the methods used to process the TCCON column CO_2 data, used to screen and bias-correct the OCO-2 data, have also changed significantly over the past couple years. How have these changes filtered through to affect the CO_2 fluxes estimated by the inversions? Here we show some preliminary results from the OCO-2 v11 MIP to see. In particular, is the airmass-related OG bias still seen? Is the carbon release from tropical North Africa still there? We also assess the impact of inverting OCO-3 data along with OCO-2. Finally, we look at new forward run experiments of CO_2 tracers to better assess transport behavior of the models used in the v11 MIP.

Integrating Isotopic, Satellite, and Modeling Techniques for Enhanced Methane Flux Estimation in Global CH_4 Monitoring

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The Global Methane Pledge (GMP) aims to reduce CH_4 emissions by 30% below 2020 levels by 2030, but achieving this goal requires frequent, high-resolution monitoring, as highlighted by the World Meteorological Organization's Global Greenhouse Gas Watch (G3W) program.

This study addresses these challenges by developing an advanced system for accurate and near real-time estimation of CH_4 fluxes that integrates multiple isotopic observations, satellite datasets, and atmospheric model. The isotopic composition of CH_4 provides critical information on its atmospheric sources, as different emission sectors (microbial, thermogenic, biomass burning) exhibit distinct stable carbon isotopic signatures. By incorporating relatively sparse but highly accurate isotopic measurements, the proposed system improves the attribution of CH_4 emissions to specific sources, thereby enhancing sector-specific emission tracking and trend analysis.

Satellites equipped with advanced sensors offer significant advantages for global CH_4 monitoring, providing continuous coverage, high temporal resolution, and reduced data latency compared to conventional ground-based methods. The atmospheric transport model MIROC4-ACTM is used to efficiently assimilate and analyze large observational data sets. This high-performance computing framework facilitates the rapid evaluation of different satellite datasets, ensuring near real-time flux estimates to support global monitoring initiatives under G3W and the Global Carbon Project. Long-term variations are inferred by an isotopic composition-based inversion, while short-term updates are derived using the CH_4 burden approach with satellite XCH_4 data.

GOSAT XCH_4 data were integrated into the developed system following the method of Patra et al. (Scientific Reports, 2017). A key advantage of this analysis is the nearly uniform data coverage over tropical Asia, Australia, South America, and Africa, regions that are sparsely monitored by in situ measurement networks. This capability provides a truly global CH_4 flux signal. In contrast, traditional analyses based on ground-based observations focus primarily on individual sites, which are often influenced by regional or local flux signals.

Differentiable Land Model Reveals Global Environmental Controls on Latent Ecological Functions

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Accurate modeling of terrestrial carbon and water exchange requires robust ecological parameters that capture vegetation responses and adaptations to the local environment. The current generation of land models use Plant Functional Types (PFTs) to discretize vegetation functional diversity, but these coarse categorizations often overlook fine-scale variations shaped by local climate, soil, and forest age factors. The lack of governing equations for plant adaptation demands a paradigm shift in how we integrate diverse Earth observations to uncover ecological functional dependence on changing environments. To address this challenge, we developed DifferLand, a differentiable, hybrid physics and machine learning model that infers the spatial distributions of ecological parameters and their relationships with environmental factors constrained by both satellite and in-situ observations. Our model unifies top-down (i.e., CMS-Flux net biosphere exchange inversion) and bottom-up observational constraints (i.e., eddy covariance measurements) of carbon fluxes with process-based knowledge to generate a global analysis of ecological functions and their adaptation to environmental gradients. By integrating multiple streams of satellite observations, DifferLand enables attribution of satellite-observed anomalies to underlying ecosystem processes and derives unique information on ecosystems as latent ecological functions. Crucially, we demonstrate that hybrid modeling allows us to identify novel ecological functional relationships across space that cannot be directly observed or retrieved through pure machine learning or conventional model-data fusion. We found PFTs account for less than half of the explainable spatial parameter variations controlling carbon fluxes and vegetation states. The remaining parameter variability is largely driven by local climate and forest demography factors, and the learned environment-parameter relationships lead to enhanced spatial generalization at unseen locations. DifferLand identified growing season length, leaf economics, and agricultural intensity as the three orthogonal spatial gradients underlying parameter variations. Our novel framework can lead to new insights on global carbon cycling by learning directly from satellite observations and expanding our understanding of local ecosystem responses to environmental drivers.

Key Words: differentiable modeling, hybrid modeling, adaptation, model-data fusion

Investigating the causes of increasing methane emissions from Africa using inverse analysis of TROPOMI satellite observations

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Over the past two decades, much of the increase in global atmospheric methane concentrations has been attributed to increasing emissions from Africa. We use inverse analysis of TROPOMI methane observations to investigate the causes of this increase, inferring monthly methane surface fluxes from Africa at a spatial resolution of 0.5° × 0.625° from May 2018 to present. Relative to previous work, this spatial resolution better allows us to separate co-located sources. We use an analytical inversion to infer these fluxes, using the information provided by TROPOMI to update estimates from process-based flux inventories. We examine the sensitivity of our results to the TROPOMI data product and prior wetland emission inventory that we use.

Understanding Fire dynamics and its contributions to carbon flux variability in South Asia

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Abstract:
South Asia (SA) is an important part of the global carbon cycle and has experienced anomalous forest fire events in addition to seasonal forest fires, including the recent 2021 fire event. We have analyzed regional fire dynamics and carbon flux variability over three fire-prone regions in SA namely Region-1 (southwestern Nepal, Uttarakhand), Region-2 (central India), and Region-3 (northeast India) from 2010 to 2021, especially focusing on the significant February, March, and April or FMA 2021 forest fires. We find high forest burned areas (5000-10,000 km^2), and large fire emissions (6 TgC/season) across RGs in FMA, 2021 as compared to 2010-2020. The strong linear co-variation between snow cover, soil moisture, and gross primary production (GPP) observed in Region-1 suggests snow-driven reductions in soil moisture likely created fire-conducive conditions, leading to increased fire activity and consequent large drawdown in GPP. In Region-2 and Region-3, the influence of environmental drivers was elusive, largely due to region-specific factors such as higher rainfall and lesser variation in GPP, particularly in RG-3. During FMA, 2021, Region-1 showed a total fire emissions (~ 4 TgC) more than total fossil emissions (~ 2.2 TgC), whereas the fire emissions in RG-2 remained below fossil emission but with RG-3 fire emissions occasionally exceeding fossil emissions (e.g., 2012–2014). This result highlights the importance of wildfire events in shaping the carbon budget. More results with greater detail will be presented.

CH_4 emissions estimates and sensitivity analysis using STILT-inversion over South Korea (2010-2021)

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Abstract

Accurate methane (CH_4) emission estimates are essential for tracking progress toward reduction targets, yet significant uncertainties remain. In South Korea, CH_4 emissions are predominantly anthropogenic. This study employs a Bayesian inversion framework coupled with the STILT model to estimate national CH_4 emissions at monthly and yearly scales using in-situ near surface observations from 2010 to 2021. Prior emissions consist of both anthropogenic and natural sources. Anthropogenic emissions—including those from agriculture, coal, waste, biofuels, oil, gas, and industry—are derived from the EDGAR v7 inventory dataset. Our results indicate a decline in posterior yearly total emissions from 1.61 Tg yr^{-1} in 2010 to 1.52 Tg yr^{-1} in 2021, consistently lower than prior estimates. The most significant reductions relative to the prior occurred in spring, primarily driven by agricultural emissions, suggesting that this source is overestimated in the prior inventory. We also compare our estimates with regional inversion results from NIES, Japan, as part of the CH_4 Inversion Inter-Comparison for Asia (MICA) project. Sensitivity analyses are conducted to assess the impacts of the observation network, prior emissions, and prior uncertainty. Additionally, we explore discrepancies arising from the use of different meteorological datasets in transport model, providing insights into their influence on CH_4 emission estimates.

Using satellite data and atmospheric inversion modelling to estimate global and high resolution CO2 budgets: project FICOCOSS

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Nations are accountable for their GHG emissions, and since the Paris Agreement, progress towards national emission reductions is tracked. To facilitate this, atmospheric inversion modelling is employed as the state of-the-art means to collect information from GHG observations to quantify global and regional sources and sinks. High-resolution estimation of GHG fluxes for needs of national-scale emission verification greatly benefits from developments in satellite data analysis and computational methods. FICOCOSS project develops these methods and assimilates OCO-2 satellite data in atmospheric inversion models (CIF-FLEXPART, CIF-TM5-MP) to estimate CO2 sources and sinks. We prepare for the high intensity CO2M satellite by developing more efficient computational methods related to e.g. large error covariance matrix operations and satellite retrieval processing. Preliminary findings indicate that more efficient methods can be developed for using satellite CO2 data in high resolution inversions.

Global Methane Flux Estimates Using the GOSAT Partial Column Retrievals and CTE-CH_4 Atmospheric Inverse Model

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Satellite retrievals have provided various opportunities and insights in quantifying global and regional greenhouse gas budgets. However, challenges in assimilating the satellite data into atmospheric inverse models remain. In this study, we examine the use of newly developed JAXA/EORC partial column data from GOSAT in estimation of regional and global methane (CH_4) budgets using the CarbonTracker Europe-CH_4 atmospheric inverse model. The partial column CH_4 is retrieved from radiance in the short wave infrared (SWIR) and thermal emission in the thermal infrared (TIR) by minimizing contamination by highly-polarized radiation scattered by aerosols and thin clouds. The flux inverse model simulations were carried out by assimilating the 1) JAXA/EORC lower tropospheric partial column data, 2) JAXA/EORC total column data and 3) ground-based surface data mainly from NOAA ObsPack. The results showed that the CH_4 fluxes for the Northern Hemisphere agreed well in the inversions assimilating the lower tropospheric partial column data and ground-based data, while the estimates using the total column data were significantly lower. The Southern Hemispheric emissions were larger in the both GOSAT inversions compared to the ground-based inversion. The evaluation against ground-based surface and TCCON data and aircraft data from Atmospheric Tomography Mission showed that the lower tropospheric North-South gradients agreed well with the posterior estimates from the inversions using the lower tropospheric partial column data and ground-based data. Overall, we found the GOSAT JAXA/EORC lower tropospheric partial column data provides a good potential in estimating global and regional CH_4 fluxes and advancing our understanding of the CH_4 budgets.

The integrated Land Ecosystems Atmospheric Processes Study (iLEAPS)

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The integrated Land Ecosystems Atmospheric Processes Study (iLEAPS) was formed in March 2004 to build an international community of practice to investigate the interactions between terrestrial ecosystems and the atmosphere. Originally part of the International Geosphere-Biosphere Programme, iLEAPS became a global research network of Future Earth in 2014.

The first decade of iLEAPS had an emphasis on creating new ways to observe and model the land–atmosphere continuum. The iLEAPS contribution to the support and development of networks of long-term flux stations and large-scale land–atmosphere observation platforms. iLEAPS promoted the integration of data from remote sensing, ground-based observations, and other sources into data cubes and products. The understanding gained contributed to advances in land–surface models that represent the role of land cover changes and land–atmosphere feedback processes in the Earth system. In this second decade, the focus has shifted to the human influence on these ecosystem–atmosphere interactions and the implications for resource use and sustainable development. While the impact on the natural environment is still being investigated, socio-economic aspects are also needed to cover mitigation and adaptation to climate change.

iLEAPS has hosted the iLEAPS Open Science Conference (OSC), every 3-4 years. This conference marks the seventh time since the first conference in 2006 and is the most authoritative international conference in the interdisciplinary field of atmosphere-land interactions and climate change. After careful consideration, the iLEAPS Scientific Steering Committee decided that the 7th iLEAPS Open Science Conference would be held in Hiroshima, Japan in March 2027 (this is the first time that the conference will be held in Japan). The aim of the conference is to bring together world-class researchers to discuss and present the latest research results, and to promote the development of atmosphere-land interactions and their applications. Please join us!

Global carbon budgets estimated from atmospheric O_2 and CO_2 observations in the western Pacific over a 20-year period

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We estimated global carbon sinks of the ocean and land biosphere from secular changes in the atmospheric O_2/N_2 ratio and CO_2 mole fraction of air samples obtained from the National Insitutute for Environmental Studies' (NIES's) flask sampling network. The network includes three ground stations, Hateruma Island (HAT; lat. 24.1°N, long. 123.8°E), Cape Ochi-ishi (COI; lat. 43.2°N, long. 145.5°E), and Minamitorishima (MNM ; lat. 24.3°N, long. 154.0°E), and cargo ships regularly sailing in the western Pacific. The air samples collected in glass flasks were sent back to NIES's laboratory, then the O_2/N_2 ratio and CO_2 mole fraction of the samples were determined by using a GC/TCD and NDIR analyzers, respectively. From the observed O_2/N_2 ratio and CO_2 mole fraction, we computed a tracer of atmospheric potential oxygen (APO), which is defined as $APO=O_2+1.1\times CO_2$. Based on annual fossi-fuel-derived CO_2 emission rates estimated from enegy statistics and tempral increasing rate of the global atmospheric CO_2 evaluated from global observations by NOAA/GMD as well as APO decreasing rates of this study, the global carbon sinks of the ocean and land biosphere for a period of more than 20 years were evaluated. Here, we applied a correction for the time-varying ocean O_2 outgassing effect with an average of 0.56 PgC yr^{-1} for 2000-2023 to the sink calculations. In addition, we also addopted recrently reported corrections for the effective O_2 emissions associated with industrial metal refining processes with an average of 0.20 PgC yr^{-1} for 2000-2023 and for the O_2 scale deviation of about 3% from a gravimetric scale.

The resulting oceanic and land biotic carbon sinks were 3.0 ± 0.7 PgC yr^{-1} and 1.2 ± 0.9 PgC yr^{-1}, respectively for a 24-year period (2000-2023), 2.7 ± 0.6 Pg-C yr^{-1} and 1.2 ± 0.8 Pg-C yr^{-1}, respectively for a former 12-year period (2000-2011), and 3.3 ± 0.8 Pg-C yr^{-1} and 1.2 ± 1.0 Pg-C yr^{-1}, respectively for a latter 12-year period (2012-2023). Compared with the process based-model estimations reported by the Global Carbon Project (GCP), the ocean and land sinks of this study were by 0.3-0.4 Pg-C yr^{-1} larger and by 0.3-0.8 Pg-C yr^{-1} smaller, respectivly, and the descrepancy was enhanced for the latter period, although there were still large uncertainties in our estimations. To examine the temporal changes in the oceanic and land biotic sinks over the 20-year period, we conducted the carbon budget calculations for for an interval of 5 years under the assumption that the 5-year interval effectively reduce the apparent errors caused by the inter annual variations ocean outgassing effect. The pentad (5-year) ocen sinks showed an increaing trend at a rate of 0.08 ± 0.01 Pg-C yr^{-2} during 2001-2021, which is larger than that for the GCP ocean sinks (0.039 ± 0.002 Pg-C yr^{-2}). The pentad land sinks showed substantial decrease during 2009-2014 at a rate of -0.24 ± 0.04 Pg-C yr^{-2}, which were not reproduced GCP estimation.

Advanced Methane Plume Detection and Inversion Using GF-5B AHSI: A Statistical-Physical Coupling Approach

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Methane (CH_4) emissions from point sources, such as coal mines and oil and gas facilities, significantly contribute to atmospheric greenhouse gas concentrations. This study develops a full-physical CH_4 inversion method for hyperspectral satellite observations using the Gaofen-5B (GF-5B) Atmospheric Hyperspectral Imager (AHSI). We integrate statistical and physical retrieval techniques, including the Matched-Filter method for statistical detection and an Iterative Maximum A Posteriori approach for physical inversion, to quantify CH_4 plumes accurately.

The methodology is applied to methane point source emissions in Shanxi, China, and the west coast of Turkmenistan, comparing GF-5B/AHSI data with PRISMA and TROPOMI observations. Our results show that heterogeneous surface conditions significantly affect CH_4 retrieval accuracy, introducing uncertainties in inversion results. We also validate our approach using controlled release experiments in Arizona, demonstrating consistency between statistical and physical methods in quantifying emission rates.

The study highlights the importance of surface reflectance and atmospheric corrections in CH_4 retrieval and proposes an optimized framework for improved satellite-based methane monitoring. Our findings provide a basis for more accurate detection and quantification of methane super-emitters, aiding climate change mitigation efforts.

Methane emission estimates of localized sources from Sentinel-5 Precursor, PRISMA, EnMAP and EMIT using a cross-sectional-flux method

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Releases of methane (CH4) by man are after those of carbon dioxide (CO2) the second most important anthropogenic sources of greenhouse gasses and are important drivers of climate change. Satellite retrievals of the atmospheric column-averaged CH4 dry mole fractions (XCH4) in combination with appropriate data analysis are used to assess the magnitudes of anthropogenic and natural methane sources. Significant progress in this area has been made since the launch of the Sentinel-5 Precursor (S5P) satellite with its TROPOMI instrument thanks to its unique combination of daily coverage (swath width approximately 2600 km), dense spatial sampling, and moderate spatial resolution (about 5.5x7 km2). We are continuously improving our scientific WFMD retrieval algorithm to generate high-quality scientific XCH4 data products from S5P. Here we present latest results obtained with WFMD version 2.0. In addition, we now also retrieve local XCH4 anomalies at high spatial resolution from PRISMA, EnMAP and EMIT radiance images. These sensors provide much higher spatial resolution (30-60 m depending on sensor) compared to that of TROPOMI/S5P but have poorer spatial coverage. To obtain emission estimates of localized emission sources from these sensors, we have developed a Cross-Sectional-Flux (CSF) algorithm. These activities are carried out in the context of several methane related ESA (GHG-CCI, MEDUSA, SMART-CH4) and EU (EYE-CLIMA) projects. Selected results from the application of this emission estimation algorithm to S5P, PRISMA, EnMAP and EMIT will be presented. This will also include initial results from the ongoing methane release experiment as conducted by teams from Stanford University and University of Michigan.

Methane Discrete Source Detection and Quantification Using MethaneSAT

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MethaneSAT is a satellite that provides a comprehensive characterization of methane emissions from whole oil and gas production regions by detecting and quantifying discrete point sources and dispersed area sources simultaneously. MethaneSAT seeks to automate data production to improve throughput, but automated detection and quantification of discrete point sources is challenging due to nuances like background interference and variability in plume shape. This study summarizes the progress in algorithm development for discrete source detection and quantification in the MethaneSAT mission. Given an image of retrieved methane concentrations, two plume identification methods are employed in parallel: divergence integral thresholding and wavelet denoising. The divergence integral thresholding method calculates flux divergence over tiled grids across the scene, producing a flux map with hot spots at plume origins. Plume masks are generated using thresholding of both the flux map and XCH_4. The wavelet denoising method removes high-frequency noise from image using a 2D discrete wavelet transform, followed by XCH_4 thresholding to create plume masks. In both approaches, thresholds are dynamically determined based on the local background rather than fixed values. Plume origins are determined based on plume shape and wind direction, and flux rates are estimated using the divergence integral method. Applying these techniques to over 40 MethaneSAT scenes, over 120 plumes were identified with flux rates ranging from 0.5 t/hr to 100 t/hr. Ground validation campaigns are underway to assess and potentially improve algorithm performance. These methods will allow MethaneSAT to operationalize plume detection and quantification, facilitating the detection of a large volume of plumes and aid its mission to support global methane mitigation efforts.

Quantifying agricultural CH_4 emissions using MethaneSAT, MethaneAIR and ground-based data

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The MethaneSAT satellite, launched in March 2024, is a joint American and Aotearoa-New Zealand initiative, involving a partnership between Environmental Defense Fund's (EDF) subsidiary MethaneSAT LLC, and the New Zealand government. The satellite's core mission is to support CH_4 emission reductions around the world by measuring atmospheric CH_4 with an unprecedented combination of precision, resolution, and imaging area. While MethaneSAT was designed to detect emissions from oil and gas infrastructure, it can also be used to measure agricultural methane emissions. We will present preliminary results demonstrating MethaneSAT's capability to detect and quantify both dispersed emissions from pastoral agriculture and discrete emissions from intensive agriculture using ground-based data, aircraft measurements, and model simulations.

New Zealand is the ideal test case for dispersed pastoral agricultural emissions, due to its high CH_4 emissions, approximately 85% of which are from agriculture. We will show preliminary results comparing MethaneSAT data with observations from ground-based and aircraft data collected during two month-long field campaigns in key agricultural regions of New Zealand. During the field campaigns, we deployed four EM27/SUN portable Fourier transform spectrometers within a MethaneSAT target and made in situ CH_4 measurements on light aircraft using a LiCor analyser. These measurements are in close agreement with modelled XCH_4 modelled using 1.5 km spatial resolution, New Zealand specific bottom-up CH_4 fluxes and the Numerical Atmospheric dispersion Modelling Environment (NAME III), driven by meteorological input from the New Zealand Convective Scale Model (NZCSM, 1.5 km spatial resolution) Numerical Weather Prediction (NWP) model. Then, we will show XCH_4 measurements and emissions estimates from intensive agricultural systems in the US (e.g. dairies and feedlots) from MethaneAIR, an airborne precursor instrument. MethaneAIR data collected over more than 178 individual scenes have been processed using wavelet analysis and emissions have been quantified using a divergence integral approach. 68% of all agricultural scenes were found to have at least one agricultural plume present and 40% of all agricultural scenes have robustly detected plumes. MethaneAIR and MethaneSAT observations will be compared for facilities observed by both instruments.

Global Distributions of Super-Emitting Methane Sources

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IWGGMS Session: Urban/local/facility scale emissions – quantification and validation

Abstract:

Detection, quantification, localization, and attribution of methane emitters provides actionable information for methane mitigation, inventory development, and sector apportionment of methane budgets. Carbon Mapper, using primarily the Tanager-1 satellite, aims to improve understand for each of these use cases through deliberate satellite tasking, plume detection, emission quantification, and infrastructure-level attribution. Here we present an interim analysis on 6 months of initial global tasking of Tanager-1 across oil&gas basins (both on and off-shore), waste sites, and coal production sites and show distributions of super-emitters across these regions and sectors. Emission distributions by basin are a key component of quantifying methane intensities across the global energy supply chain. In particular, we show routine detection performance (<1000 kg/h plume detection) in high-latitude regions (>65N) during winter months, showing the capability of Tanager-1 to quantify emissions in remote regions that are generally considered difficult to detect and quantify with passive sensors. For the waste sector, in addition to showing global distributions of emissions by country, we highlight how the high sensitivity mode for Tanager (increased signal-to-noise due to oversampling) can detect new emission sources from informal dumpsites in the global south. For the coal sector, we show distributions of ventilation shaft emissions across major basins, and roadmap how these observations can be used to constrain emission factors for IPCC-grade inventories. As the Tanager constellation grows, routine data, combined with other orbital and sub-orbital observations will continue to provide relevant and actionable data across a diversity of use-cases.

Detection and Quantification of CH_4 and CO_2 Emissions at the Facility Scale with the GHGSat Constellation

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GHGSat operates a constellation of small satellites for detecting and quantifying greenhouse gas emissions at the single-facility scale. We have primarily focused on methane since the first demonstration satellite was launched in 2016 – our fleet of ten commercial methane satellites will see its capacity doubled over the next two years. In late 2023 we also launched our first satellite designed to measure carbon dioxide. This presentation will discuss the latest results on the performance for both species in terms of detection limit and quantification accuracy.

Controlled releases continue to be the primary means to measure the performance of methane point source imagers on satellites and aircraft. We release a known, steady flux of methane from a point-like source, with timing coordinated with a satellite overpass. By repeating this many times with different rates above and below the detection threshold, we can (a) fit a wind-speed dependent probability of detection (PoD) model to the binary detection results and (b) assess the accuracy of our source rate retrievals (quantification accuracy).

For the case of methane, we present our latest detection limit analysis with an updated PoD model and additional data points, including from our newest satellites. The inferred detection limit has consistently been close to 100 kg/hr (PoD=50%, wind speed 3 m/s) for the past several years even as data points have been added from new satellites and as minor adjustments are made to the PoD model.

For the case of CO_2, we have now amassed a sufficient number of detection events to produce initial assessments of these metrics. However, since the detection limit is much higher than the methane case (> 100 t/hr), controlled releases are not practical. Instead, we make use of facilities with publicly reported ground truth emissions. We also discuss some other CO_2-specific challenges we have encountered, such as co-emission of aerosols, multiple release points at a given facility and the high elevation of the release points.

Scale dependencies in urban CO_2 inversions constrained by satellite remote sensing measurements

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Urban areas are significant contributors to global CO_2 emissions, and accurately simulating CO_2 dispersion in these regions, particularly near emission hotspots, presents substantial challenges due to complex dynamics at small scales. High-resolution simulations are crucial for accurately capturing CO_2 dispersion, especially as satellite-based observations, despite their growing use in monitoring greenhouse gases (GHGs), can be limited by factors such as spatial resolution, cloud cover, and temporal frequency. As part of the CATRINE project, which aims to evaluate and improve numerical schemes for tracer transport in the Copernicus anthropogenic CO_2 emissions monitoring and verification support capacity, we employ the Weather Research and Forecasting model in Large-Eddy Simulation (WRF-LES) mode to simulate CO_2 concentrations over the Paris area and to examine the sensitivity of CO_2 plume structures to model resolution. A series of simulations using five nested domains, with resolutions ranging from 8.1km to 100m, were conducted. The study also bridges the gap between high-resolution simulations and satellite-based observations by running a pseudo-data CO_2 inversion using 100m resolution WRF outputs but performing atmospheric inversions at coarser resolutions (300m and 900m). This investigation explores how model resolution influences inversion results and quantifies errors introduced when aggregating higher-resolution outputs to coarser resolutions. The results are compared with satellite-based CO_2 measurements from the NASA OCO-3 mission. Additionally, WRF model outputs are validated against ground-based observations from various sources, including the Paris ICOS-City Mid-cost CO_2 sensor network (>20 sensors deployed across Paris), total column CO_2 measurements from two EM27 and the Jussieu TCCON station (Total Carbon Column Observing Network) and wind LIDAR profiles from six stations across Paris and Île-de-France collected during the URBISPHERE project, providing a comprehensive comparison between model outputs and observations.

Investigating the Potential for Detecting Urban Methane Point Sources over South Korea Using EMIT Observations

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Methane is a key greenhouse gas contributing to global warming, making it essential to identify its point sources accurately. sources. Recently, high-resolution imaging spectrometers onboard satellites have been increasingly utilized to estimate methane emissions. This study evaluates the capability of satellites to detect methane sources in urban industrial areas in South Korea using the Earth Surface Mineral Dust Source Investigation (EMIT) imaging spectrometer onboard the International Space Station (ISS). To assess the effectiveness of satellite detection, methane enhancements observed by EMIT were compared with ground-based mobile measurements conducted in urban and industrial complexes. It was found that locations with high methane enhancements estimated from EMIT (2061 ppm·m on average) also exhibited high methane concentrations in ground-based mobile observations (697 ppb on average), demonstrating the potential of satellites for detecting urban point sources. In addition, this study explores the potential for quantifying methane emissions from detected sources, highlighting the role of satellite-based observations in emission estimation. Despite the challenge of satellite observations due to surface heterogeneity, the integration of ground-based validation methods and domain knowledge highlights the feasibility of satellite-based methane source detection within complex urban environments. This approach underscores the value of hyperspectral satellite data in supporting methane emission detection and monitoring efforts.

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A network of EM27 FTS for urban measurements of XCO2, XCH4, and XCO across the city of Toronto

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The Toronto Atmospheric Monitoring of Emissions (TAME) project was started in 2023 to determine whether Toronto is meeting emissions reduction targets by developing a city-wide network that measures greenhouse gases and air quality. As part of this project, we are maintaining a network of four EM27 Fourier Transform Spectrometers (FTS) around the city of Toronto with a fifth site to the north that records concentrations outside the city. This network of EM27 FTS will be used to determine gradient enhancements in column averaged dry air mole fractions of CO_2, CH_4, and CO (referred to as X_{CO2}, X_{CH4}, and X_{CO}) across the city of Toronto.

In this presentation, we will show results from on-going use of modified fibre optic solar tracking systems with our EM27 FTS, installed at all sites since September 2024. The new tracking system uses a telescope and fibre optic mounted on the Eko Suntracker, allowing for full site automation. We will show comparisons between EM27 GGG2020 retrievals and collocated satellite-based retrievals from OCO-2/3 and TROPOMI. Finally, a preliminary analysis of EM27 enhancement ratios of X_{CH4}/X_{CO2}, X_{CO}/X_{CO2}, and X_{CH4}/X_{CO} across Toronto will be presented.

Regional and Socioeconomic Characteristics in C40 Cities' CO_2 Emissions Revealed from Space

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Cities play a crucial role in reducing global greenhouse gas emissions. While activity-based ("bottom up") emission estimates are widely used for global cities, they often lack independent verification. In this study, we use spaceborne CO_2 observations from the Orbiting Carbon Observatory-3 (OCO-3) to "top-down" estimate CO_{-2} emissions for 54 global cities. This global-scale analysis is enabled by a computationally efficient Cross-Sectional Flux (CSF) approach, which constrains urban plume shape using NO_2 observations from TROPOMI and trajectory simulations from HYSPLIT. Our satellite-based emission estimates for 54 global cities agrees within 7% to two widely used bottom-up datasets but reveal regional discrepancies. Bottom-up estimates tend to overestimate emissions for cities in Central East Asia and South and West Asia, while underestimating emissions in Africa, East and Southeast Asia & Oceania, Europe, Europe, and North America. Additionally, our satellite-based socioeconomic analysis shows that 1) high-income cities tend to have less carbon-intensive economies: North American cities emit 0.1 kg CO_2 per USD of economic output, while African cities emit 0.5 kg CO_2 per USD, and 2) per capita emissions decrease with increasing population size, from 7.7 tCO_2/person for cities under 5 million residents to 1.8 tCO_2/person for cities over 20 million residents. This study highlights the potential of satellite data to bridge gaps between top-down and bottom-up emission estimates, enhancing the robustness and transparency of emissions monitoring. Our findings emphasize the growing role of satellite data in verifying urban CO_2 emissions and supporting efforts to mitigate emissions for global cities.

Assessing Methane Detection Capabilities of Operational Satellite Sensors using Controlled Release Experiments

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Detecting, reporting, and mitigating fugitive methane leaks has been identified as one way of lowering national methane emissions in the United States. To that effect, the United States Environmental Protection Agency has launched a new super emitter program that relies on technologies that can detect and report methane leaks for mitigation. NOAA is exploring the option of utilizing its fleet of geostationary and polar-orbiting satellite sensors to operationalize the short wave infrared Multi Band Multi Pass methane detection algorithm developed by Harvard University. Prior to transitioning the technology to NOAA operations, a careful evaluation of retrievals from the two sensors, Advanced Baseline Imager on GOES-R series and Visible Infrared Imaging Radiometer Suite on JPSS series is needed. NOAA satellites can detect only large methane plumes (tons per hour) and benchmarking the capability is critical to work with stakeholders such as the EPA. To do that, NOAA is partnering with facility operators that conduct timed large methane releases during pipeline blowdown events to validate satellite methane detections and quantification of emissions. NOAA, in partnership with the Pipeline Research Council International, conducted its first pipeline blowdown experiment on October 8, 2024, deploying methane-monitoring technologies across ground, air, and space to track a controlled methane release. Three NOAA geostationary satellites viewing the plume from different geometries detected the plume along with various ground and airborne instruments - all systems reported methane flux estimates that are closer to the values reported by the pipeline operator. Results of this controlled release experiment will be presented along with plans to conduct additional experiments, jointly with NASA, to validate methane plumes from civilian satellite data as well as those detected by commercial plume mappers such as GHGSat, CarbonMapper, and MethaneSat.

Common Practices For Quantifying, Reporting, Validating and Assessing Facility Scale Methane Emissions Using Remote Sensing

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We present an update on the Common Practices for the Identification of Methane Plumes and Quantifying Emissions at the Facility Scale initiative currently underway within the CEOS WG climate GHG task team.
The activity aims at identifying community-accepted practices for generating, validating, reporting, and quality assessment of facility-scale methane emission plumes and estimates derived from spectroscopic remote sensing radiances. These best practices are being prepared by subject matter experts with comprehensive knowledge of all stages involved in these types of measurements. The recommendations presented have been developed through the analysis of existing practices in each area and the identification of key methods required to produce uniform, interoperable products, regardless of the data source as it relates to emissions from specific sites, it does not address emissions from dispersed sources that account for a large percentage of total methane emissions, at this time. The best practices document is intended for both data producers and data users of remotely sensed facility-scale methane emission identification and quantification products. Data producers can use it as a guide to understand the standards expected by community practitioners, ensuring their data meets reliability criteria. Data users can refer to it to identify key data elements and considerations that may guide their expectations and support a balanced assessment of whether a dataset is fit for their specific purpose.
The initiative was initiated in 2023. A draft v0.3 was open for community review to the end of March 2025, with the intention to have a v1.0 for July 2025. Later in 2025 engagement with the community, user and key stakeholder, e.g. Global Methane Pledge, UNEP IMEO, WMO G3W, will continue towards a wider representation at COP 30.

Utilization of GEMS and OCO-3 data on the identification of CO2-NO2 relationship and CO2 emission estimation in Asian Urban areas

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Urban areas in Asia emit large amounts of greenhouse gases and air pollutants due to anthropogenic activities for socio-economic development. The relationship between greenhouse gases and air pollutants concentrations varies across regions depending on various factors such as fuel type, combustion, and combustion efficiency. This study investigated the relationship between carbon dioxide (CO_2) and nitrogen dioxide (NO_2) in several urban areas in Asia using measurements from the Geostationary Environmental Monitoring Spectrometer (GEMS) and the Orbital Carbon Observatory-3 (OCO-3). Combining GEMS NO_2 measurement in high temporal resolution with OCO-3 CO_2 measurement (CO_2 column-averaged dry air mole fraction) of city-scale (measurement from Snapshot Area Map mode) can be used to derive regionally specific NO_2-CO_2 relationships. The NO_2-CO_2 relationship (CO_2-to-NO_2 slope in this study) for each region was obtained by sampling co-observation cases of the GEMS and OCO-3. The regionally characterized CO_2-to-NO_2 slopes were used to estimate CO_2 fields from the NO_2 measurement, and CO_2 emissions were estimated for the urban areas in Asia based on the estimated CO_2 fields and a mass balance method. This study emphasizes that GEMS data can be usefully used to qualitatively and quantitatively understand urban emissions in conjunction with OCO-3 data.

High resolution CO_2 simulation over Kanto region in Japan

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The Kanto region in Japan is one of the world's largest economic zones, characterized by high anthropogenic emissions, varied topography, and intricate coastlines. It is home to both ground and airborne measurements that are essential for tracking greenhouse gas (GHG) emissions. To analyze these observations, we developed a high-resolution CO_2 model at smallest grid size of 1×1 km^2 using the Weather Research and Forecasting model coupled with GHGs fluxes (WRF-GHG). The model used three different anthropogenic emission inventories: EAGrid (Japan region, 1×1 km^2), EDGAR ($0.1^o\times0.1^o$), and EDGAR-downscaled ($0.01^o\times0.1^o$), and was run for February and May 2018, and February 2020. At 1×1 km^2 resolution, simulations resolve point-source emission, which gradually attenuate as the model resolution is coarsened to 3×3, 9×9 or 27×27 km^2; however, at surface sites, the 1×1 km^2 model introduces transport errors, weakening the correlation with observations compared to the 27×27 km^2 model. We assess the sensitivity of Planetary Boundary Layer (PBL) schemes in CO_2 modeling by comparing WRF-GHG simulations with two local closure schemes to ground-based observations. CO_2 simulations are found to be sensitive to PBL dynamics on event basis. The 1×1 km^2 model better reproduced the CO_2 aircraft observations between 0-3 km, compared to 27×27 km^2 model, highlighting the importance of fine-scale emission patterns and transport processes. We also show that neglecting lateral and top boundary conditions in WRF-GHG introduces a systematic bias in the CO_2 vertical distribution in the mid-to-upper troposphere (altitudes > 3 km). These vertical biases can significantly affect comparisons with remote sensing observations of total columns.

The role of satellite observations in constraining urban CO_2 emissions

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Urban areas account for over 70% of global anthropogenic CO_2 emissions, making them critical targets for emission reduction strategies. Accurate and high-resolution CO_2 emission estimates are essential for assessing climate policies and guiding mitigation efforts. In this study, we improve CO_2 emission estimates over Seoul, a megacity with high emissions and an extensive monitoring network, using a Bayesian inverse modeling approach. We integrate ground-based in situ CO_2 observations, which provide high-temporal-resolution data on surface emissions, with satellite-based column-averaged CO_2 (XCO_2) observations that offer broader spatial coverage. This combination allows for a more comprehensive constraint on urban CO_2 fluxes, addressing the limitations of previous studies that relied on single observation types. Our inverse modeling framework has a spatial resolution of 0.01° and a temporal resolution of 1 hour, incorporating anthropogenic CO_2 emissions, biogenic CO_2 fluxes, atmospheric CO_2 measurements, a Lagrangian transport model (WRF-STILT and WRF-XSTILT), and prior and observational error covariances. Particularly, we utilize satellite data from both OCO-2 and OCO-3, selecting good quality retrievals from the OCO-2 and OCO-3 V11r files. We then construct a weighted average of key variables, including latitude, longitude, XCO_2, averaging kernel vector, and pressure weighting function, among others. We apply this framework to estimate the optimal spatiotemporal distribution of CO_2 emissions in Seoul throughout the entire year of 2021. The effectiveness of the inversion is evaluated by comparing observed and simulated CO_2 enhancements using prior and posterior emissions. Additionally, sensitivity tests are conducted to assess the impact of different observational datasets on emission estimates. We compare the CO_2 emissions in Seoul, derived from both ground-based and satellite observations, with the bottom-up estimates provided by the South Korean Ministry of Environment to assess whether our results properly constrain urban CO_2 emissions. Given Seoul's commitment to carbon neutrality and its participation in global climate initiatives, our study provides valuable insights for improving urban CO_2 monitoring and refining emission inventories. The findings contribute to enhancing the accuracy of urban CO_2 estimates and informing future climate policies aimed at achieving net-zero emissions.

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Estimating Urban CH_4 Emissions from Satellite-Derived Enhancement Ratios of CH_4, CO_2, and CO

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Urban centres are an important source of anthropogenic methane emissions and the focus of recent policy efforts aimed at emissions reductions. However, emissions from urban areas are poorly characterized except in the few cities with robust measurement infrastructure. Satellite measurements offer a promising means for monitoring urban emissions. We use co-located measurements of methane (CH_4) and carbon monoxide (CO) from the TROPOspheric Monitoring Instrument (TROPOMI) and carbon dioxide (CO_2) from the Orbiting Carbon Observatory 2 and Orbiting Carbon Observatory 3 (OCO-2/3) to calculate CH_4:CO_2, CH_4:CO, and CO:CO_2 enhancement ratios over 85 cities across the globe. These satellite-based enhancement ratios are compared to those computed from bottom-up globally gridded emission inventories. We find EDGARv8 to best represent CH_4 emissions in urban areas with mean error of 30% compared to CAMS-GLOB-ANTv6.2 (based on EDGARv6.1), and CEDSv2021, with mean errors of 42% and 48%, respectively. We also find that EDGARv8 and HTAPv3 underestimate CO emissions by a factor of 2-5 for cities in Iran, Turkmenistan, and Argentina. And we find that CO emissions in EDGARv8 are overestimated in some cities in Europe by a factor of $\sim$2. Finally, we see noticeably higher methane emissions per capita in Northern American and South-Central Asia compared to those in Europe, Western Asia, or Eastern Asia.

Maximizing the Use of Spatial Information in Dense XCO_2 Observations for Bayesian Inversions

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Bayesian inversion schemes are an established method of updating "prior" spatially explicit local, regional, and global estimates of carbon dioxide (CO_2) fluxes by incorporating atmospheric measurements to produce optimized "posterior" distributions. Early studies using these methods incorporated in-situ and aircraft CO_2 observations, which provide limited coverage in both space and time. However, the launch of multiple Earth-focused space-based observing instruments (GOSAT, GOSAT-2, TanSat, OCO-2, OCO-3) provides near-global coverage of atmospheric CO_2 concentrations with 3-16 day revisit times over areas. While many studies aggregate these observations to focus on the optimization of regional/global CO_2 flux distributions, the mechanics of the OCO-3 instrument provide collections of spatially dense (2km x 2km) column-averaged CO_2 observations that fill domains of 80km x 80km over targeted cities. The spatial structure of city-level influences on the atmosphere are revealed by these observations and provide additional information for Bayesian inversion schemes. This work compares multiple statistically driven approaches for incorporating spatial structure in dense column-averaged CO_2 observations and posits a new method based on a series of spatial sensitivity analyses. This is an ongoing effort and results are preliminary.

High resolution methane modelling using satellite observations: a case study of the coal mining region in New South Wales in Australia

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The coal mining sector is the second most important contributor in Australia's national methane inventory. However, uncertainties in the reported (bottom-up) emission estimates are high, and there are concerns about potential underreporting of these sources. Inversion of atmospheric observations has the potential to refine methane emissions and provides an independent constraint on methane emissions from coal mines.

We use the Community Multiscale Air Quality (CMAQ) transport model driven with a 2km x 2km spatial resolution in the New South Wales coal mining region of Australia. The transport model requires meteorological simulations and emission inventories. Simulated meteorological data is obtained using the Weather Research Forecasting (WRF) model. The capability of WRF in simulating met data is assessed using observations from Australian Bureau of Meteorology weather stations. The comparison shows strong agreement between modelled and observed wind field data. In addition to the meteorological input data, spatially gridded emission inventories are essential. As there are no high-resolution gridded methane inventories representing the coal mining region in NSW, we need to build the emission data by combining the available datasets and information. Here we develop an appropriate spatially resolved inventory using the classification of active mining areas and re-distributing the gridded national inventory derived from OpenMethane platform to the identified areas for each coal mine. Using this inventory, we compare the modelled mixing ratios (concentrations) with the observed data obtained from the TROPOspheric Measurement Instrument (TROPOMI), and ground-based EM27/SUN spectrometers. Results of this forward-model run will be used as a basis for the inversion framework.

COCCON-Spain: Toward an Integrated Greenhouse Gas Observation System in Spain

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Availability of atmospheric greenhouse gas (GHG) information is crucial to develop effective mitigation policies, to monitor progress towards emission reductions targets, and to support the adaptation actions needed to tackle the increasing global warming effects. Integrated and multidisciplinary observation systems are a necessary tool for an improved knowledge of carbon cycles at different temporal and spatial scales. In this context, this work gives an overview of an integrated GHG observation system in Spain, COCCON-Spain, which is being currently designed and developed. The foreseen observation system aims to partially overcome the current gap of continuous atmospheric GHG measurements in Spain, including estimations of GHG emissions in the main urban-industrial hot spots at national scale (Madrid and Barcelona metropolitan areas).

COCCON-Spain will be the first permanent infrastructure at national scale to monitor atmospheric GHG concentrations and emissions using ground-based remote sensing observations. It will collaborate closely with other GHG initiatives such as ICOS-Spain, as well as regional and local GHG monitoring networks in order to build an integrated GHG observation system in Spain. The resulting integrated system will be an indispensable

tool for the verification of the emission inventories and mitigation actions adopted at a national scale, as well as for the validation of current and foreseen GHG satellite missions.

As an example of COCCON-Spain's potential, this work will also provide an overview of short-term field campaigns conducted to monitor GHG column amounts and derive corresponding emission fluxes in specific case studies. These include the 2021 volcanic eruption of the Tajogaite volcano in the Canary Islands, as well as biogenic and urban emissions in Santa Maria, Brazil, and the Aosta Valley, Italy, respectively.

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CO_2 emissions from China and their impact on Japan's coastal regions inferred from $\Delta XCO_2/\Delta XCH_4$ of GOSAT and GOSAT-2 observations

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We have analyzed XCO_2 and XCH_4 data obtained from GOSAT and GOSAT-2 satellite observations in the three land regions in China (East China, North China, and South China) and East China Sea and Japan Sea to assess the impact of China's fossil fuel emissions on Japan's coastal regions. We calculated excess concentrations of XCO_2 and XCH_4 relative to their background concentrations (ΔXCO_2 and ΔXCH_4), and then calculated Enhancement Ratio (ER), which includes information on emission sources, by taking the ratios of ΔXCO_2 and ΔXCH_4. We compared the calculated ER values with EDGAR CO_2 and CH_4 inventory data to investigate the emission source of CO_2 in Mainland China.

In North and East China, the calculated ER values and correlation coefficients were higher in winter and summer and higher ΔXCO_2 contributed to the high ER values. The seasonal variation of ER was consistent with the seasonal variation of CO_2 emissions from the power industry, which suggests that the high ER values were attributed to CO_2 emissions from the power industry. In South China, the ER values were higher in winter, suggesting the influence of CO_2 emissions from the power industry. In summer, in contrast, the ER values were lower because of higher ΔXCH_4, which indicates that agriculture emission affected characteristics the ER values in South China.

Over the ocean regions where there are no major CO_2 and CH_4 emission sources, the monthly ER values were the highest in February and March. Judging from the absence of major CO_2 emission sources in the ocean regions and the consistent high ER values throughout a year in North and East China, CO_2 enhancements over the Japan's coastal regions can be attributed to airmass with high CO_2 concentrations emitted by fossil fuel combustion on Mainland China and transported by the East Asian winter monsoon. Backward trajectory analysis for February showed that airmasses were transported from North and East China to East China Sea and from North China to Japan Sea, which suggests the possibility of the transport of fossil fuel CO_2 emitted from North and East China and North China to East China Sea and Japan Sea. Seasonal variations of $\Delta XCH_4/\Delta XCO_2$ over the ocean regions based on GOSAT and GOSAT-2 observations showed good agreements to those based on surface observations over Hateruma Island by Tohjima et al. [2014], which indicates that our satellite-based ER analysis can also discuss the characteristics of the transport of fossil fuel CO_2 from Mainland China to Japan, as done in the previous study.

Carbon dioxide emission quantification and validation for the Carbon Mapper Coalition/Tanager-1 satellite

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Carbon dioxide (CO_2) emissions from major point sources constitute a significant portion of global greenhouse gas emissions, with considerable uncertainties persisting in bottom-up estimates. Monitoring facility-scale CO_2 emissions is essential for reducing emissions from large point sources and minimizing their associated uncertainties. Imaging spectrometers that measure solar backscattered radiance at shortwave infrared (SWIR) wavelengths have been widely used for detecting methane (CH_4) point sources and quantifying emissions. These instruments are also sensitive to absorption from elevated CO_2 concentrations and therefore are also capable of CO_2 emission detection and quantification. Here, we present the performance of the first Carbon Mapper Coalition satellite (Tanager-1) for CO_2 detection and emission quantification. Tanager-1, launched in August 2024, is capable of providing high spectral resolution (5 nm) and high spatial resolution (30 m) observations of CO_2. We validate our estimated emissions by comparing it to in-stack continuous emissions monitoring systems (CEMS) emission rates reported by the U.S. Environmental Protection Agency (EPA). Finally, we compare the performance of Tanager-1 CO2 detection to the NASA Earth Surface Mineral Dust Source Investigation (EMIT) CO2 detection showing lower detection limit of Tanager-1.

Characteristics of methane in South Asia inferred from enhancement ratios of greenhouse gas concentrations based on satellite observations

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CH_4 emissions from South Asia significantly contribute to global CH_4 emissions. We have analyzed XCH_4 and XCO data over South Asia, which were obtained from Thermal And Near infrared Sensor for carbon Observation-Fourier Transform Spectrometer-2 (TANSO-FTS-2) on board Greenhouse gases Observing Satellite-2 (GOSAT-2). We first calculated ΔXCH_4 and ΔXCO, which were defined as excess concentrations of XCH_4 and XCO relative to their background concentrations. Then, we determined the Enhancement Ratio (ER) by taking the ratios of ΔXCH_4 and ΔXCO. In this study, we have divided South Asia, mainly India, into 10 regions: high CH_4 emission land areas (three regions), low CH_4 emission land areas (five regions), and ocean areas (two regions), and calculated monthly ER values of $\Delta XCH_4/\Delta XCO$ in each of the 10 regions. We compared the calculated monthly ER with monthly emission data of CH_4 and CO from various emission sources based on EDGAR (Emissions Database for Global Atmospheric Research) database to evaluate dominant emission sources for each region. In high CH_4 emission land areas, the calculated monthly ER values and their correlation coefficients reached the highest level in September. The corresponding EDGAR emission data showed that CH_4 emissions from agricultural sources were high, while agricultural CO emissions were not much high in September. This indicates that higher ER in September there could be attributed to agricultural emissions. In the low CH_4 emission land areas, especially in southern India, the monthly ER values and their correlation coefficients were higher from September to November. Judging from the EDGAR emission data, agricultural CH_4 emissions were considerably elevated during this period, which leads to the higher ER values, indicating agricultural origin is a predominant factor to characterize CH_4 concentrations there. The timing of high ER values due to agriculture-origin high CH_4 in the high CH_4 emission land area (northern region) differed from that in the low CH_4 emission land area (southern region). This could be attributed to the difference in the timing of the two cropping seasons, the kharif and rabi seasons [Kavitha et al., 2017].

Deep-learning-based point source emission estimation for future satellite missions

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To support the goals of the Paris Agreement, monitoring and verification support (MVS) capacities focussing on anthropogenic greenhouse gas emissions are being developed, such as the EU's emerging Copernicus CO_2 Service and Germany's ITMS (*Integriertes Treibhausgas-Monitoringsystem*). Satellite concepts capable of measuring atmospheric CO_2 and CH_4 concentrations on small spatial scales (10s of meters) have emerged as potential contributors to such MVS systems, through their ability to image the exhaust plumes of individual facilities. To quantify emissions based on these plume images, traditional mass balance methods require an accurate knowledge of the effective speed of the wind that transports the detected CO_2 or CH_4 plume. Uncertainty in the wind speed is the largest source of uncertainty in the estimated emissions. It has been proposed, however, that machine learning approaches might be able to estimate emission rates directly from the turbulent plume images without the need to impose wind speeds from external sources.

Here, we present our progress on developing a deep-learning-based emission rate estimator for plume images using convolutional neural networks. Our main focus lies on the improvement of the quality and certainty of deep learning models. Therefore, we provide a model that is capable of providing estimates with, on average, little to no bias over a large scale of flux rates. In addition, our model provides error estimates alongside its flux predictions, making a first step towards improving the certainty of estimated predictions. Further, we present our progress on improving the performance of our model by adapting the network architecture, allowing us to incorporate knowledge about auxiliary information into the model during the training process. This makes the predictions more stable across different wind speed situations and also allows us to potentially extract effective wind speed information directly from image data. Thus, we are working towards applying deep-learning-based methods in a more stable and powerful approach that is capable of efficiently analyzing large amounts of incoming data.

Urban CO_2 simulations for the Greater Tokyo Area based on high-resolution modeling and comparison with tower observation network

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Urban areas are a major contributor to global anthropogenic CO_2 emissions. However, quantifying and continuously monitoring these emissions remains challenging due to the complexity of urban carbon dynamics and the lack of emission information. In this study, we aim to establish a framework to monitor CO_2 emissions from the Greater Tokyo Area using atmospheric observations and a high-resolution atmospheric model. As a first step, we examine the model reproducibility of CO_2 variations observed from our high-precision ground-based observations using the Weather Research and Forecasting model coupled with Chemistry (WRF-Chem). We also examine the sensitivity of emission inventories that prescribe the WRF-Chem model using five global and local inventories.

We conducted a one-year simulation for 2018 using the WRF-Chem model at a high spatial resolution of 1 km over the Greater Tokyo Area. We prescribe the runs using five different anthropogenic CO_2 emission inventories, including four global datasets (ODIAC, EDGAR, CAMS-GLOB-ANT, and GridFED) and a high-resolution dataset for Japan (MOSAIC). Monthly emissions from each dataset are downscaled to hourly temporal resolution. The simulated CO_2 concentrations are compared with continuous CO_2 observations from four in-situ sites in the Tokyo metropolitan area (Tokyo Skytree (TST) and Yoyogi (YYG)) and in the Tokyo suburbs (Tsukuba (TKB) and Yokosuka (NDA)). The CO_2 concentrations were measured using the cavity ring-down spectrometer (CRDS) (Picarro G2401).

The results show that our simulations reproduce the temporal atmospheric CO_2 variations, demonstrating its ability to resolve CO_2 in the urban atmosphere. Among the four sites, TKB showed the highest agreement between simulated and observed CO_2 time series, with an average correlation coefficient (r) of 0.65 for the five emission inventories, successfully capturing both the temporal variability and the magnitude of high concentration peaks of CO_2. NDA also captured the temporal variations of CO_2 increases well, with an average r of 0.59, although peak concentrations were generally overestimated. The simulation also captured the patterns of CO_2 increases well at YYG (r = 0.54), but the simulated peaks were often high by more than 200 ppm. At TST, the correlation was lower than the other sites, but the magnitude of the CO_2 variations was similar to the observations. This lower r value is likely due to limitations in the model's representation of atmospheric transport processes at a higher level (about 250 m above the surface). Among the five inventories, simulations with EDGAR (r = 0.60) and ODIAC (r = 0.57) showed relatively high correlations with the observed CO_2 concentrations.

Diurnal analysis indicated that the model tended to overestimate nighttime CO_2 concentrations at TKB, YYG, and NDA. In contrast, simulated nighttime concentrations at TST were lower than the observations. These differences are likely related to uncertainties in the diurnal emission patterns, limitations in the near-surface vertical mixing processes in the WRF-Chem model, and CO_2 accumulation under weak wind conditions. During the daytime the model-observation agreement was much better. The model-observation differences showed seasonal variations, with relatively larger differences in spring and summer at TKB and in winter at NDA. The relationship between CO_2 concentrations and wind direction indicates that high CO_2 values at TKB (and TST) were associated with southerly winds (dominant in summer) transporting CO_2 emitted from central Tokyo, while those at NDA were associated with northerly winds (in winter) transporting CO_2 from central Tokyo to southern coastal areas.

The results demonstrate the importance of combining high-resolution simulations with observational networks to improve our knowledge of CO_2 distribution and variations in complex metropolitan environments such as Tokyo. It would also be useful for comparison with GOSAT-GW analysis results. The differences in the emissions datasets are discussed further in the presentation.

Column and Surface Concentration Observations of CO_2 and NO_2 at Yokosuka, Japan, in Support of GOSAT-GW/TANSO-3

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We aim to improve the characterization of CO_2 emissions from the upcoming GOSAT-GW/TANSO-3 observations providing spatially dense XCO_2 as well as co-located NO_2 column observations that can be used as a tracer from combustion sources. Pre-launch studies measuring column and surface concentrations of CO_2 and NO_2 from the ground would provide critical information to characterize their co-variation patterns and thereby support the theoretical/practical basis of the satellite mission. For the purposes, we conducted intensive observations using a Pandora, MAX-DOAS, EM27/SUN, surface precision monitor (LI-7810), and low-cost sensors in and around Yokosuka (35.32°N, 139.65°E) in the southern part of the Tokyo metropolitan area, from November 2024 to February 2025.

Our original algorithm used for the long-term MAX-DOAS NO_2 retrievals since 2007 has been improved in terms of the lowest vertical layer thickness and the a-priori profile information considered in the optimal estimation. The biases previously present in comparisons with the tropospheric NO_2 vertical column density ($TropNO_2VCD$) observations from Pandora146 (direct-sun based total column minus climatological stratospheric column) and with the surface NO_2 observations were almost eliminated, providing a solid basis for satellite validation of TANSO-3 in addition to TROPOMI and GEMS. The column-averaged dry-air mole fractions (XCO_2) from the EM27/SUN at a 10 min resolution preliminarily showed apparent positive correlations with the $TropNO_2VCD$ from Pandora over 40 days of the period.

From our initial results, the slopes of the daily regression lines, $\Delta XCO_2/\Delta TropNO_2VCD$, were on average 2.8 (1.5-3.6) $\times 10^3$ mol/mol (N=10, when R > 0.7 and with a reasonable XCO_2 intercept). The values were higher than those for surface $\Delta CO_2/\Delta NO_2$ on the same days, 1.9 (0.41-4.3) $\times 10^3$ mol/mol, which was in reasonable agreement with the bottom-up CO_2/NOx emission ratios ranging from 0.38-0.09 $\times 10^3$ (road and other transportation) to 1. 95 $\times 10^3$ (power plants, from REAS v3.2 for Kanto and the year 2015), considering that the observed surface NOx/NO_2 were typically ~1.16. The even higher $\Delta XCO_2/\Delta TropNO_2VCD$ could have been influenced by other unknown sources or by oxidation of NOx to NOz. Some caution may be warranted when analyzing the satellite-based ratios. The correlation analysis provides implications for aircraft campaigns planned over the region and future satellite observations, including those from geostationary orbits.

Towards Shipborne Emission Monitoring and Satellite Validation of CO_2, CH_4, CO, and NO_2 Through Simultaneous Columnar and In Situ Observations

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Precise observations of anthropogenic greenhouse gas (GHG) and air pollutant emissions are essential for improving emission inventories and evaluating the potential of their reduction, supporting the global stocktake. The global coverage of ship-, aircraft-, and ground-based observations by public and private networks, together with satellite observations of GHGs and other trace gases, is expanding. However, observations and reference data over ocean and coastal regions remain scarce.

We conduct continuous cargo ship-based observations with a novel semi-automatic Fourier transform infrared (FTIR) spectrometer combined with a VIS (visible spectral range) grating spectrometer to measure the column-averaged dry-air mole fractions of carbon dioxide (XCO_2), methane (XCH_4), carbon monoxide (XCO) and the vertical column densities of nitrogen dioxide (VCD_{NO2}). Combined with simultaneous in situ observations (CO_2, CH_4, CO, NO_2), we aim to constrain anthropogenic emissions and contribute to a satellite validation framework for upcoming satellite missions like the Global Observing SATellite for Greenhouse gases and Water cycle (GOSAT-GW) or the Copernicus Anthropogenic Carbon Dioxide Monitoring (CO2M) mission. These missions are designed to identify and monitor anthropogenic emissions by observing the GHG CO_2 and the short-lived combustion tracer NO_2 simultaneously. With our novel setup, we have the capability to validate these concurrent observations.
The cargo ship operates along major anthropogenic emission sources on Japan's coast between the Tokyo metropolitan area and the island of Kyushu in the southwest with a weekly round-trip schedule. We present the initial analysis results of the combined columnar and in situ observations for emission plume detection and inventory validation, and provide perspectives of the setup for satellite validation and anthropogenic emission monitoring.

Step change in boreal fire emissions? A Canadian case study

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Significant variations in emissions from global biomass burning have been reported by several studies, including increases in boreal fire emissions. Here we examine a region in Western Canada that comprises different land surface and vegetation types to study changes in fire emissions over the NASA/EOS Terra and Aqua data records. We find that the last 3 years have seen a dramatic increase in this region in the number of fires, as detected by MODIS and corresponding carbon monoxide (CO) as measured by MOPITT. We also show changes in soil moisture that likely contribute to the conditions for increasing fires. These preliminary results motivate a more comprehensive look at multiple ecological factors undergoing rapid change in boreal forests.

Predicting fossil fuel CO2 using air quality emissions and emerging CO2 satellite observations for global carbon cycle assessment

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Fossil fuel CO_2 ($FFCO_2$) emissions remain the largest driver of anthropogenic climate change, while co-emitted air pollutants constitute a major global morbidity. Although both emission types originate from common activities such as fuel combustion, they differ in their relative contributions, characterized by distinct emission factors. Accurate and timely $FFCO_2$ emission inventories are crucial for assessments of the global carbon cycle, climate targets, and carbon cycle data assimilation. However, regionally dependent uncertainties in emission inventories persist due to limitations in reporting, sectoral disaggregation, and spatiotemporal variability.

Characterizing the coevolution of greenhouse gases (GHG) and air quality pollutants provide insight into underlying anthropogenic processes and enables predictions of their emission trajectories. We classify the dynamics of historic emissions in terms of a modified Environmental Kuznets Curve (MEKC) (Miyazaki and Bowman, Nature Communications, 2023), which describe the coevolution of fossil fuel CO_2 ($FFCO_2$) and NOx emissions as a function of macroeconomic development and evaluate the predictability of $FFCO_2$ and NOx emissions using a novel Kalman filter. For the past two decades, the MEKC broadly captures the $FFCO_2$/NOx dynamical regimes across multiple countries including the US, China, and India. While the US trajectory plateaued, some developing countries exhibit rapid transitions across dynamical regimes, influenced by shifts in energy infrastructure and technological adoption. Given these emission patterns, our analysis demonstrated that $FFCO_2$ can be predicted with an error of less than 2% at one-year lag and 10% at four-year lags when constrained by satellite-derived NOx data. These finding point to the important interplay between AQ and GHG emission processes at time scales relevant to international assessments, e.g., Global Stocktake.

Meanwhile, the proposed framework, integrated with an expanding constellation of AQ and carbon monitoring satellites, offers a novel approach for evaluating emission scenarios and constraining bottom-up inventories. Specifically, this framework will be employed to develop a predictive model utilizing satellite-derived NO_2 measurements from GOSAT-GW, in conjunction with the Program of Record (PoR), while satellite-based CO_2 observations will be leveraged to evaluate $FFCO_2$ estimates in combination with atmospheric CO_2 inversion models. This methodology addresses key limitations of existing point-source and non-point-source estimation approaches, ultimately delivering a Level 4 data product for the GOSAT-GW mission. The resulting dataset will enable high-resolution assessments of global $FFCO_2$ emissions across multiple spatial scales, from urban and city levels to regional and national scales.

Monitoring the “atmospheric stock” of greenhouse gases from space

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Of all the stocks of carbon on and around Earth, the atmospheric stock is the most important. Growing atmospheric concentrations of greenhouse gases (GHGs) continue to drive increases in surface-level temperatures that threaten human existence if left unchecked. Thus far, those increases have been directly attributable to anthropogenic emissions, a relationship that could change rapidly in the future given several “tipping point” scenarios. It is thus essential to monitor and attribute changes in the atmospheric stocks of GHGs with the precision and accuracy needed to identify major emissions sources and natural responses with a minimal latency. The coverage needed to answer the most pressing scientific and policy-relevant questions about GHGs necessitates the use of space-based observing systems. Nevertheless, the precision and accuracy needed are only possible in coordination with a robust, continuous in situ calibration standard. The GHG monitoring system effort led by NASA’s Goddard Space Flight Center synthesizes observations of vegetation, burned area, night lights, carbon dioxide (CO2), and methane (CH4) to produce a best-guess estimate of the global atmospheric state of CO2 and CH4 every 3 hours on a 72-layer vertical grid at a 12km horizontal resolution. It is maintained in support of the multi-agency United States GHG Center, where it is available along with several other driver and evaluation datasets. This work supports several stakeholders by providing boundary and initial conditions for regional to local studies, a calibration transfer standard for public and private data providers, the ability to quantify effectiveness of mitigation actions, and coordination with international efforts like the World Meteorological Organization’s (WMO) Global Greenhouse Gas Watch (G3W). The system also allows for synergistic studies of air quality through its shared heritage with meteorological and chemical GEOS products, notably the real-time GEOS Constituent Forecast (CF).

Top-down emission estimates of CO_2 and co-emitted air pollutants through a sector-based inversion framework

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Accurate quantification of carbon dioxide (CO_2) and air pollutant emissions from each human activity is critical for the planning and verification of emission reduction efforts. CO_2 emissions from fossil fuel and industrial processes are the largest contributor to the global increase in greenhouse gases. These CO_2 are co-emitted with several air pollutants, including nitrogen oxides (NO_x), carbon monoxide (CO), and sulfur dioxide (SO_2). We apply a newly developed sector-based inversion method based on the GEOS-Chem adjoint model to quantify CO_2 and co-emitted NO_x, CO, and SO_2 emissions in CONUS from various human activities, including powerplants, residential activities, road transportation, industry, etc. The estimate leverages the different ratios between these gases to identify the source sectors and advances top-down estimates by rigorously adjusting the underlying activity rates and emission factors for each sector, therefore improving emission quantifications and resolving discrepancies with bottom-up estimates at the process level. We first performed sector-based inversion in 2023 at a 0.25°×0.3125° resolution using TEMPO NO_2, TROPOMI NO_2 and SO_2, and MOPITT CO observations. The inversion suggests underestimates of the EPA EQUATES inventory in the transportation and industry sectors. We adjusted CO_2 emissions in these sectors using the corresponding scaling factors and will evaluate the resulting CO_2 simulations with OCO-2 and OCO-3 observations. We will also evaluate the possibility of simultaneously adjusting anthropogenic sectoral CO_2 along with NO_x, CO, and SO_2 emissions using the sector-based inversion framework.

Estimation of CO_2 and NO_X emissions using the divergence method applied to pseudo satellite observations

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Emission controls of carbon dioxide (CO_2) and other greenhouse gases are urgently needed to mitigate global warming. Satellite observations would provide objective, real-time, top-down estimates of emissions. A method based on the divergence theorem was developed to estimate emissions from high frequency and high horizontal resolution pseudo satellite observations of atmospheric trace gases (NO_2 and CO_2). Pseudo observations are prepared as per the expected performance of the upcoming TANSO-3 / Global Observing SATellite for Greenhouse gases and Water cycle (GOSAT-GW) and by using atmospheric chemistry transport model simulations (WRF-Chem/GHG) over the Kanto region of Japan at 1-km horizontal resolution. Observational errors were then added as normal distributions with the standard deviations of 1.8 ppm for CO_2 total column dry-air mole fraction (XCO_2) and 3×10^{15} molecules/cm^2 for NO_2 tropospheric column density. The results showed that our central emission estimates for the Kashima Industrial Zone were within 10-24% of the true values for CO_2 and NO_X, confirming the performance of the method. Uncertainties in the emission estimates propagated by observational errors (noise) were evaluated to be ±32% and ±2% for CO_2 and NO_X emissions of 16.6 $MtCO_2$/year and 25 $ktNO_2$/year, respectively, after averaging over 31 ideal observations, expected to occur within a 3-month period at best for GOSAT-GW. We will also compare the derived relationship between CO_2 emissions and ΔXCO_2 with other studies.

The SMART–s NO_2 vertical profile products from Pandora for GOSAT-GW validation

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Global Observing SATellite for Greenhouse gases and Water cycle (GOSAT-GW) can observe the tropospheric and total column density of NO_2 in addition to the greenhouse gases. To provide reliable a priori information on NO_2, we present a NO_2 vertical profile algorithm based on the direct-fitting method (i.e., SMART–s algorithm) from Pandora measurements. The inversion is based on the optimal estimation method (Rodgers, 2000) and exploits aerosol optical depth (AOD) products derived from Pandora using the SMART-s algorithm (Jeong et al., 2020; 2022). The dataset consists of MAX-DOAS measurements from Pandora instruments in Seoul and Busan, South Korea, collected between October 2024 and March 2025. The retrieved surface concentrations at each site were compared with nearby in-situ measurements. Additionally, for Seoul, the algorithm was evaluated by comparing it with the NO_2 profile data provided by PGN. The retrieved results showed a similar trend and moderate agreement with in-situ measurements and PGN data. These results demonstrate the potential for stable NO_2 profile retrieval and efficient satellite validation. Further efforts include extending the study area to East Asia. This will allow for regional characterization of the NO_2 profiles and comparison with satellite observations over the wider Asian region.

High-precision monitoring of combustion-origin CO_2 concentrations in a megacity using simultaneous observations of CO_2 and other combustion-origin species

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Global warming, which has been causing extreme weather disasters and threatening human life in recent years, is primarily driven by anthropogenic carbon dioxide (CO_2) emissions from fossil fuel combustion. Effective mitigation of CO_2 emissions requires continuous monitoring of atmospheric CO_2 concentrations. However, globally, only a limited number of sites conduct continuous observations of long-lived greenhouse gases while ensuring spatial representativeness on a scale of several kilometers in megacities. To address this gap, we have been conducting year-round continuous observations at Chiba University (35.625°N, 140.104°E, 60 m above sea level), a key urban area of the Tokyo Megacity, as part of the International Air Quality and SKY Research Remote Sensing Network (A-SKY). Our observations utilize a combination of two ground-based remote sensing techniques: sky radiometers and Multi-Axis Differential Optical Absorption Spectroscopy (MAX-DOAS). Since both techniques employ remote sensing, the obtained aerosol optical properties and trace gas concentration data have high spatial representativeness, extending several kilometers in the horizontal direction. Recent studies have revealed a clear positive correlation between fAAOD (fine-mode aerosol absorption optical depth in the 0–1 km altitude range) derived from these observations and BC (black carbon) mass concentrations measured using a Black Carbon Monitor (BCM3130; Kanomax Japan, COSMOS). This correlation ensures the spatial representativeness of the measured BC mass concentrations. At this well-characterized observation site, a trace gas analyzer (LI-7810, LI-COR Biosciences) was installed on December 6, 2021, to conduct continuous measurements of CO_2 and CH_4 concentrations. Analysis of these simultaneous observations revealed that CO_2 concentrations were also low on days when BC and NO_2 concentrations were significantly low. Furthermore, estimating the CO_2 increase (ΔCO_2) from the baseline concentration determined on these low-concentration days showed that ΔCO_2 exhibited a positive correlation with BC and NO_2 concentrations. This finding indicates that ΔCO_2 captures the increase in combustion-origin CO_2 concentrations near the observation site. Meanwhile, the baseline concentration fluctuated over time to some extent. Additionally, we conducted simultaneous observations using another gas analyzer (G4301, Picarro), which was more precisely calibrated with standard gases. The results showed a strong agreement between the ΔCO_2 values estimated from LI-7810 and G4301, with an exceptionally high correlation coefficient of 0.99. These findings demonstrate that simultaneous observations of CO_2 and other combustion-origin species, such as BC and NO_2, enable accurate estimation of ΔCO_2 while minimizing unexpected influences such as the instrumental drift. By employing this method, CO_2 concentrations in megacities can be monitored with high precision, ultimately contributing to more effective emission mitigation strategies.

Retrieval algorithm development for TANSO-3 NO_2 product

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The GOSAT-GW (Global Observing SATellite for Greenhouse gases and Water cycle) is the third successor of GOSAT series (GOSAT, GOSAT-2) and is planned to be launched in the first half of Japan's fiscal year 2025. The TANSO-3 sensor on-board the GOSAT-GW measures Earth-shine radiance spectra in a push-broom configuration with three bands, i.e., 420-490 nm (Band1) for NO_2, 747-783 nm (Band2) for O2 A-band and 1594-1650 nm (Band3) for CO_2/CH_4, to retrieve not only column-averaged mole fraction concentrations of greenhouse gases (XCO_2, XCH_4), but also total and tropospheric vertical column densities (VCDs) of nitrogen dioxide (NO_2). The instrument has two observation modes: one is the 'Wide Mode' with a spatial resolution of 10 km and ~900 km swath, and the other is the 'Focus Mode' with less than 3 km resolution and ~90 km swath. Additionally, the TANSO-3 Level 2 NO_2 product ($T3L2NO_2$) has two product types, i.e., the 'Quick-Delivery' product and the Monthly product, both which are free and open to anyone on the request, and which are planned to be published within 48 hours and two weeks after observations with the best effort, respectively. The former includes total and tropospheric NO_2 VCDs as well as a product quality flag, total and tropospheric air mass factors (AMFs) and uncertainties of the retrieved NO_2 VCD such as root mean squared error of the spectral fitting. The latter includes not only parameters mentioned above but also aerosol/cloud optical information such as an aerosol/cloud optical depth and those layer height. A conventional DOAS (Differential Optical Absorption Spectroscopy) technique is employed to retrieve NO_2 slant column densities (SCDs) from observed radiance spectra with absorption cross-sections such as O_3 and O_2-O_2 which have spectral features in UV-vis region. DOAS parameters such as a polynomial order and a fitting window are optimized for the TANSO-3 through a feasibility study using a pseudo synthetic spectrum and TROPOMI data. Subsequently, total NO_2 SCDs is separated to tropospheric and stratospheric portion considering AMFs and NO_2 vertical profiles, calculated from the radiative transfer model (VLIDORT v2.8) and the chemical transport model (CTM; CHASER v4.0), respectively. Finally, we can obtain tropospheric NO_2 VCDs through a conversion of slant to vertical columns applying tropospheric box-AMF. The box-AMF is derived from pre-calculated look-up tables (LUTs) weighting with a NO_2 profile. A remarkable point in this algorithm is to simultaneously retrieve aerosol/cloud optical parameters which significantly affect an AMF accuracy in operation using a developed LUT-based method. In our presentation, we will explain the algorithm flow in more detail. For verification of developed retrieval algorithm, we compared TROPOMI standard NO_2 VCDs data observed in 16 March 2022 02:47:22 utc with the results using our retrieval algorithm and the TROPOMI L1B radiance data, which shows good agreement in the Japan's metropolitan area with 0.89 of correlation coefficient and 0.9 of slope. Overall, stratospheric NO_2 VCDs from the CTM were underestimated compared to TROPOMI standard NO_2 profiles, which means that CAMS reanalysis (EAC4) monthly averaged data that we used were underestimated in comparison with TM5-MP data in stratosphere, and thus tropospheric NO_2 VCDs were supposed to be overestimated. In fact, the calculated tropospheric NO2 SCDs were overestimated by 2.0×10^{15} molec. cm^{-2}, especially in the polluted region like Tokyo, by more than 5.0×10^{15} molec. cm^{-2}. On the other hand, the calculated tropospheric AMF values were also overestimated by up to 100% due to inconsistent treatment of

terrain heights and as a result, although the comparison between our results and TROPOMI standard NO_2 VCDs shows good agreement, we should carefully consider and discuss the intermediate data such as stratospheric NO_2 SCDs and box-AMF. For more detailed results, we will explain more in our presentation.

Estimation of Direct Aerosol Radiative Forcing in Urban Areas of South Korea Using GEMS AOD and a Radiative Transfer Model

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Solar radiation has both direct and indirect impacts on the Earth-atmosphere system and climate. To quantify these effects, the concept of radiative forcing (RF) has been introduced. RF is known to be significantly influenced by changes in clouds and aerosols, as well as specific atmospheric constituents. Among these, direct aerosol radiative forcing (DARF) is a key parameter for understanding aerosol-induced radiative effects. In this study, we utilized aerosol optical depth (AOD) data from the Geostationary Environment Monitoring Spectrometer (GEMS) onboard the Geostationary Korea Multi-Purpose Satellite 2B (GK2B) to estimate DARF. The radiative transfer model used for RF calculations was libRadtran 2.0.4, with input data from the GEMS AOD algorithm version 2.0. Additionally, supplementary data from GEMS, such as solar zenith angle, aerosol type, and ozone, were incorporated as input parameters. The analysis covered the period from December 2021 to December 2023, and DARF was calculated and validated using surface (SFC) and top-of-atmosphere (TOA) measurements from six AERONET sites across South Korea. This study contributes to a better understanding of air pollution issues in South Korea and provides insights into the spatial and temporal variations of radiative forcing. In particular, the high temporal resolution of geostationary satellite observations is expected to enhance our understanding of diurnal variations in aerosol radiative effects.

Comparison of morning-afternoon difference of AOD in Southeast Asia

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MODIS observes Aerosol Optical Depth (AOD) twice a day (morning by Terra, afternoon by Aqua), allowing an analysis of the morning-afternoon AOD differences in Southeast Asia. Since MODIS provides two observations per day, it enables the examination of morning-afternoon AOD differences over a broad area using satellite data. MODIS AOD at 550 nm was used for the analysis, with all satellite data regridded to a 0.25-degree resolution. The evaluation was conducted using ground-based AOD measurements from AERONET. The analysis reveals that AOD is generally higher in the afternoon, as indicated by AERONET data, and this pattern is also observed in MODIS satellite data. In particular, many Southeast Asian cities exhibit a negative AOD difference (morning minus afternoon), meaning that AOD is consistently higher in the afternoon. To explore potential socioeconomic influences on these variations, the Subnational Human Development Index (SHDI) was examined. SHDI, provided by UNDP, reflects factors such as economic power, education levels, and life expectancy, and its regional-level applicability makes it a useful metric for studying spatial variations. Unlike GDP, which is only available at the national level in Southeast Asia, SHDI allows for finer-scale analysis of regional disparities. The results indicate a consistent negative correlation between SHDI and the morning-afternoon AOD difference, suggesting that more developed regions tend to have higher AOD levels in the afternoon. This pattern holds across multiple years, with Thailand's evolving trend from 2004 to 2022 standing out as a particularly noteworthy observation.

Development of a simple NO_x emission estimation method using satellite observations and a chemistry-transport model

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The Paris Agreement requires to keep the rise in global surface temperature below 2/1.5 degC above pre-industrial levels and to report the national emission inventory to the UNFCCC. This national emission inventory is created with a bottom-up approach and has a high precision, however, there is a delay in reflecting unknown emission sources and unconfirmed emission changes that have occurred after database updates. In contrast, a top-down approach with satellite observations and a chemistry-transport model is useful in the rapid estimation of emissions. The emission of NO_x is used as a proxy of anthropogenic CO_2 emission for short time. In this study, we aim to develop a rapid emission estimation method with low computational cost by combining satellite observations of NO_2 with forward calculations of a chemistry-transport model to perform a simplified estimation of NO_x emissions. We use the NO_2 data from the TROPOMI satellite observation and the NICAM-based transport model, which has a horizontal resolution of about 56 km. To ensure the same horizontal/temporal resolution, the original data is converted to a 1deg x 1deg resolution with monthly mean. The same emission evolution of NO_x is inputted to the model in each year, then the emission difference between the truth and the model appears in the NO_2 concentration difference between the satellite observation and the model, under the assumption of correct chemical processes of the model. By using this NO_2 difference as an emission correction factor for each urban area (e.g. 138-142E, 34-38N mean is used for Tokyo), the NO_x emissions input into the model are adjusted to derive the monthly emissions. In the future, we plan to verify the validity of our assumptions by comparing with ground-based observations and conducting experiments with the NO_2 observation from the GOSAT-GW.

Evaluation of aerosol layer height using O2-O2 and O2-A band from TANSO-3/GOSAT-GW

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Aerosols have an important role in the Earth's climate system, influencing climate directly by scattering and absorbing radiation, and indirectly by acting as cloud condensation nuclei. They are also related to air pollution such as atmospheric particulate matter which can endanger human health. In addition, aerosols provide the dominant error source in retrieving tropospheric NO2 vertical column density (VCD) through air mass factor (AMF) calculation. Hence, it is necessary to accurately consider the aerosol optical properties (AOPs) with aerosol layer height (ALH), which are used in the radiative transfer calculation. To improve the NO2 VCD's accuracy from the observations by the Global Observing Satellite for Greenhouse Gases and Water Cycle (GOSAT-GW) satellite, which will be launched in mid-2025, we aim to retrieve the AOPs, cloud optical properties, ALH, and cloud layer height highly related to tropospheric NO2 AMF. The TANSO-3 onboard GOSAT-GW has three hyperspectral observations at around 450, 760, and 1600 nm. The GOSAT-GW aerosol/cloud retrieval algorithm was developed using the spectral matching method from band 1 (450 nm) and band 2 (760 nm) observations. This study was used the bi-directional distribution function (BRDF) surface reflectance of the Visible Infrared Imaging Radiometer Suite (VIIRS) onboard Suomi NPP over land and the Cox and Munk method over ocean. Two ALHs are retrieved through RTM simulation using the SCD derived from O2-O2 with DOAS-fitting and the strength of the O2A absorption line. Finally, both retrieved ALH products were evaluated using operational TROPOMI ALH products over the Canadian and Amazon regions.

Top-down estimates of European emissions of black carbon for 2022

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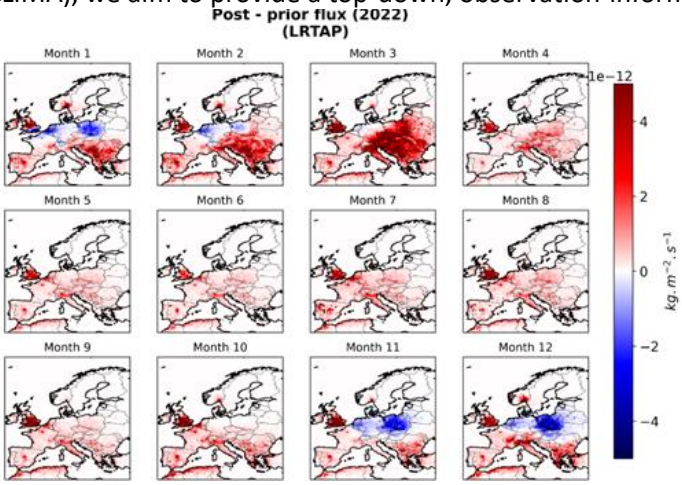
Black Carbon (BC) plays a key role in the earth's system, with a strong positive radiative forcing. Human exposure to BC is associated with adverse health effects. In the last decades, the enforcement of European air quality policies has reduced aerosol ambient levels and altered aerosol composition, with implications on aerosol-radiation interactions. Accurate bottom-up estimates of BC emissions are challenged by wildfire occurrence, changes in energy mix, and combustion technologies. Therefore, a comprehensive BC emission inventory is needed for a good understanding of the radiative forcing and associated climate feedback and to develop any successful mitigation strategies/policies. Under the Horizon Europe project Process Attribution of Regional Emissions (PARIS), in collaboration with the sister project Verifying Emissions of Climate Forcers (EYE-CLIMA), we aim to provide a top-down, observation-informed estimate of European BC emissions.



ission estimates of eBC using the FLEXPART (Bakels, ion framework. Here, we present our initial results European measurement sites operated under the ission inventories from ECLIPSE (Klimont, 2017), ons. The inversion results showed a pronounced likely driven by increased residential combustion mpared to other months, primarily originating from ed extreme droughts during the spring fire season, ıe Russia-Ukraine conflict resulted in sanctions on nce on biofuels. These unprecedented events were erscoring the importance of inverse modelling.

Figure 1. Difference between the posterior and the LRTAP prior emission fluxes for each month in 2022

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Engaging with stakeholders through the Greenhouse Gas Task Team

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The Committee on Earth Observation Satellites (CEOS) and the Coordination Group for Meteorological Satellites (CGMS) recognize that high-quality, systematic observations of atmospheric carbon dioxide (CO_2) and methane (CH_4) from space-based sensors can make critical contributions to an integrated global greenhouse gas (GHG) observing system. The joint CEOS-CGMS Working Group on Climate (WGClimate) was directed to establish a GHG Task Team to implement the roadmap for a constellation architecture for monitoring CO_2 and CH_4 from space. The primary objective of the GHG Roadmap is to coordinate efforts across CEOS and CGMS agencies to maximize the quality, utility, transparency and continuity of space-based GHG products for science and policy applications. Its goal is to facilitate the development of fit-for-purpose operational systems that integrate space-based GHG estimates with ground-based, airborne and shipborne observations of CO2 and CH4 to address the needs of a diverse range of stakeholders.

The first issue of the GHG Roadmap in 2020 focused on delivering space-based CO_2 and CH_4 products to support the Paris Agreement's Global Stocktake (GST) process. Issue 2 of the roadmap, published in 2024, continues to support that goal but has been updated to accommodate lessons learned from the first GST. Its scope has also been expanded to support the rapid evolution of the international GHG science, inventory, policy and regulatory communities. The issue 2 specifically includes collaboration with the new World Meteorological Organization Global Greenhouse Gas Watch (WMO G3W) and United Nations Environment Programme International Methane Emissions Observatory (UNEP IMEO).

In this presentation, we will outline the approach for delivering fit-for-purpose products to be co-developed with stakeholders providing actionable information for GHG monitoring policies, and provide an overview of the engagement with stakeholders.

UNEP's IMEO Methane Alert and Response System: Current status and new requirements to enhance the system

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UNEP's International Methane Emissions Observatory (IMEO) launched the Methane Alert and Response System (MARS) in 2023 to provide open, reliable, and actionable data to those individuals with the agency to act on them and ultimately reduce methane emissions. MARS uses satellite observations to detect and monitor large methane emissions and then notifies governments and companies worldwide. With the development of MARS, IMEO opened a new level of transparency that reveals dozens of large methane emissions around the world every week. Thanks to the synergistic use of more than a dozen different open-access satellite missions, combined with the development of Machine Learning models that support and optimize the work of the MARS analysis group, IMEO provides the largest open-access database of point source methane emissions detected with different satellites. At the same time, since its launch in January 2023, MARS has directly notified stakeholders of more than 2000 methane plumes linked to the oil and gas (O&G) sector in 30 countries. As a result of these notifications, IMEO has confirmed a number of mitigated emission sources following stakeholder action. Throughout the MARS process, we also learn new information and lessons about the accuracy of our measurements, the root causes behind the observed emissions, and the real feasibility of mitigating emission sources under different scenarios and geographic areas, among others.

While MARS notifications are currently sent for recent O&G point source emissions, it also has the capability to detect and monitor emissions from other sectors, such as coal and waste. Additionally, we have the ability to explore satellite archive data to conduct more in-depth analyses of the historical behaviour of the emitters. As a result, IMEO is currently expanding MARS' capacity to further support IMEO's scientific studies and its efforts towards increasing transparency in the metallurgical coal and waste sectors to drive emissions reduction.

However, the wide range of users that MARS and the IMEO remote sensing data has also creates a wide variety of requirements that must be fulfilled in order to maximize mitigation options, e.g., the data must be accurate but timely, detailed but easy to understand.

In this contribution, we will make a brief overview of IMEO's MARS, status, and next steps, and talk about the requirements we currently have to make more efficient use of the data, better communicate information on detections and satellite capabilities to the stakeholders, and the barriers we have encountered.

The U.S. GHG Center: improving the quality, transparency, and accessibility of GHG information for decision-making

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The U.S. Greenhouse Gas (GHG) Center is a collaborative, multi-agency effort to improve the quality, transparency, and accessibility of GHG information in support of decision-making and innovation. As the implementing partner of the GHG Center, NASA's activities include (1) coordination of its own internal GHG measurement and modeling contributions that are aligned with national priorities and (2) shared functions that NASA carries out on behalf of and/or with participation from partners including stakeholder engagement, user-friendly data delivery through services and tools, and coordination of interagency measurement and modeling activities. Collectively, these efforts increase the completeness and quality of information on emissions and removals, minimize overlap of efforts, and enable rapid innovation through private sector measurement and data service efforts.

Specific activities are designed to be responsive to feedback from a variety of stakeholders. Key constituencies include commercial satellite data providers, technology developers, data service providers, oil and gas facility owners/operators, and state/local governments. In this presentation, we provide an overview of the GHG Center structure and functions and introduce several pilot GHG Center activities:

- Expansion of ground-based remote sensing networks to support public and private sector satellite observations
- Coordination of U.S. based airborne and ground-based measurement campaigns to identify best practices for estimating emissions
- Development of quasi-operational modeling approaches that leverage decades of investment in weather and air quality prediction
- Provision of open source data, analysis tools, and training that support interoperability with a growing array of private sector data services
- Interagency coordination of stakeholder engagement to ensure that needs of private sector and non-federal actors are effectively communicated and prioritized

We conclude the presentation by discussing future directions and priorities including collaboration with international partners like Japan's GHG Center and other initiatives including CEOS and WMO's Global Greenhouse Gas Watch.

Development of the Japan Greenhouse Gas Center and its stakeholder engagement

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Japan has pledged to reduce greenhouse gas (GHG) emissions by 46% by 2030 (compared to 2013 levels). To achieve this, national efforts to reduce GHG emissions must be accelerated. Information on emissions, atmospheric and oceanic observations (from ground, aircraft, ship, satellite platforms), model simulations, etc. on GHGs provide the scientific basis necessary for policy decisions on global climate change. These data are generally acquired or created by research institutes, including National Institute for Environmental Studies (NIES), Meteorological Research Institute (MRI), Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Japan Aerospace Exploration Agency (JAXA), and universities, as well as operational agencies including Japan Meteorological Agency (JMA), but have been published by each organization in an independent manner. Therefore, the establishment of the Japanese GHG Center (exact name TBD) is under consideration, with the aim of accelerating climate change mitigation policy by consolidating scientific information on GHGs and spreading the information as “one voice” both domestically and internationally, so that it can be used for policy decisions and research aimed at reducing GHG emissions, and for the development of private businesses. In preparation for this, we have had scoping meetings to discuss what it should/could be. Although a final agreement as well as participating organizations has not yet been reached, discussions have progressed regarding the objectives and activities as follows.

Vision: Multi-organizations’ national initiative to accelerate global climate change mitigation policy and contribute to achieving carbon neutral society as early as possible

Mission: To advance integrated assessments of GHG emissions (or fluxes) (i.e. best practices on bottom-up vs. top-down inventory comparisons) and spread unified information and strong messages as “one voice” to help support climate change mitigation policies such as Global Stocktake, WMO’s GGGW, UNEP’s IMEO, and also business applications.

Highlight areas:

- Quantitative assessment of natural and anthropogenic GHG emissions and uptakes on a global scale
- Quantitative assessment of anthropogenic GHG emissions in Japan and its cities (prefectures)
- Quantitative assessment of anthropogenic GHG emissions in Asian countries and cities

Expected outcomes: The data will be used in policy-making and research aimed at reducing GHG emissions, as well as in the development of private services, accelerating climate change countermeasures

Possible future activities include capacity building for graduate students, inter-agency and international gas standards compatibility exercise, data sharing with international partners such as the US GHG Center and Copernicus, joint ground-based and airborne campaigns for satellite calibration/validation and emission estimates, outreach events such as COP, etc.
More information is available in “Future collaboration between the USA and Japan for possible development of a Japan GHG Center” (https://doi.org/10.1175/BAMS-D-24-0275.1).

The GOSAT series and its use in environmental policy and utilization concept

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The Ministry of the Environment, Japan, the National Institute for Environmental Studies, and JAXA have been observing global GHGs for about 16 years to date through the GOSAT series (GOSAT; launched in 2009, GOSAT-2; launched in 2018) and utilizing the data. The launch of GOSAT-GW is planned for the first half of this fiscal year starting from April.

There are three aspects to the utilization of observation data from the GOSAT series: (1) contribution to climate science, (2) utilization for environmental policy, and (3) utilization for private business. In this presentation, we will discuss the use of GOSAT series for environmental policy to date and future plans and initiatives for its use, including GOSAT-GW.

In 2019, the use of satellite data such as GOSAT, GOSAT-2, etc. to improve the accuracy of countries' emissions was first mentioned in the IPCC Inventory Guidelines, and 24 GOSAT-related papers were cited in WG1 of the IPCC AR6 (6th Assessment Report). Based on the Paris Agreement, countries are required to report GHG emissions by the end of 2024. In addition, at the G7 Turin Ministerial Meeting on Climate, Energy and Environment in 2024, its communiqué included the promotion of transparency through scientific data obtained from Earth Observation including existing and planned satellites, including OCO-3, GOSAT-GW, CO2M, MicroCarb, and enhancing coordination of activities by the Earth Observation community. Thus, there are high expectations for the GOSAT series and other GHG observation satellites to ensure transparency in the UN reporting of GHG absorption and emissions by each country and to track progress in reducing emissions.

Mongolia, with support from Chuo University funded by the Ministry of the Environment, validated their own annual amount of CO2 emission using GOSAT data in their BUR2 in 2023. India also published its NC3 that validated its annual CH4 emission estimation with GOSAT data in 2023. MOEJ is currently implementing such initiatives in Central Asian countries based on the MOU and plans to extend further to the Caucasus region, ASEAN, AZEC countries. In addition, we expect this estimation technique to be included in the IPCC Inventory Guidelines to ensure transparency through verification of inventory reported values by all countries and contribute to emission reductions.

The private sector, which has not utilized GOSAT series data, is also planning to make use of GOSAT-GW data. Examples include early detection of hot spots by linking the GOSAT series with private GHG observation satellites, which excel in local observations, use in carbon credit certification, and use in insurance business.

In addition, to promote the expansion of these data applications, we aim to expand the number of new users and provide concrete support for data utilization through the provision of data from Tellus, a Japan-originated satellite data platform, and the establishment of the Japan GHG Center.

The ESA-European Commission Earth System Science Initiative – A unique partnership and collaborative opportunity for advancing GHG knowledge

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The unique set of grand challenges that humankind is facing require more than ever that scientists advance their understanding of the planet, its processes and its interactions with human activities and translate that knowledge into novel solutions for society. To effectively respond to the major challenges in front of us, we need a major scientific and institutional collaboration effort.
The ESA-European Commission (EC) Earth System Science initiative (ESSI) is a partnership designed to jointly advance Earth system science and its contribution to respond to the global challenges that society is facing in the onset of this century.
The ESSI has three pillars:

1. Networking, bringing communities together and sharing knowledge.
2. Co-programming, linking aligned ESA and EC projects on methane research and other aspects of Earth system science.
3. Synergistic clusters, bringing teams together in order to develop collaborative actions.

Within the second pillar of the ESSI are the current methane initiative, a dedicated action towards better characterising observing and understanding CH4 sources and sinks. Jointly run by the ESA/ESRIN Atmospheric science cluster, with the core activity being the SMART-CH4 project (https://smart-ch4.lsce.ipsl.fr/), built on the heritage of many years of ESA methane studies; and the EC run IM^{4}CA project.
The aim of this presentation is twofold:

1) Give an overview of the methane cluster as a part of the ESSI, provide some context with other related methane focused projects currently being run by ESA, e.g. SMART-CH4 and EOWetMet (https://eo4society.esa.int/projects/eowetmet/).
2) To invite the IWGGMS participants to join the methane communities that we are building in order to propose new opportunities and actions for better collaborations between communities, and to advance methane science.

Meta-modeling for the Climate TRACE emissions inventory

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The Climate TRACE emissions inventory provides a comprehensive, bottom-up accounting of global emissions of greenhouse-gases and other pollutants, based primarily on remote sensing and satellite imagery. Emissions estimates for three greenhouse gases and eight other pollutants are attributed to 68 unique sub-sectors, delivered at monthly intervals with monthly resolution, and specified for over a million individual assets and for geographical regions like countries, states, and cities. Estimates include metadata such as asset-level activity, emissions factors, confidence indicators, and numerical uncertainties, which are important for developing emissions reductions strategies at arbitrary spatial or ownership domains. In this presentation, we describe methods for ensuring dataset completeness through data imputation and spatiotemporal (dis)-aggregation. We also explore Climate TRACE's application in atmospheric simulations and inversions, concluding with strategies to improve the inventory and use the inventory in reducing real-world emissions.

Enhancing the utility and adoption of space-based greenhouse gas observations by stakeholders in the inventory and policy communities

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Bottom-up greenhouse gas (GHG) inventories and top-down atmospheric GHG budgets provide complementary information about GHG emissions and removals from the atmosphere. For example, bottom-up inventories can provide reliable estimates of emissions by known sources with well-characterized activity data and emission factors, such as those associated with fossil fuel use. Top-down budgets derived from space-based GHG measurements can provide a more complete description of GHG sources and sinks associated with agriculture, forestry and other land use (AFOLU) on regional scales, especially across the developing world. If these bottom-up and top-down methods can be harmonized and combined, they could provide a more complete, accurate, and transparent description of GHG sources and sinks than either method alone. This information is critical for assessing collective progress toward the goals of the UNFCCC's Paris Agreement and for supporting national and sub-national efforts to reduce net GHG emissions.

To support these objectives and highlight progress on space-based GHG monitoring capabilities, the Greenhouse Gas Task Team of the Joint Working Group on Climate (WGClimate) of the Committee on Earth Observation Satellites (CEOS) and Coordination Group on Meteorological Satellites (CGMS) developed and delivered national-scale, top-down GHG budgets of CO_2 and CH_4 to the UNFCCC to support the first global stocktake. Unfortunately, these products were not widely adopted by the national inventory or policy communities. One reason for this is that most members of these communities do not understand the information content of top-down atmospheric GHG budgets or how to reconcile these products with their bottom-up inventories. In addition, while the guidelines for compiling national inventories from the IPCC Taskforce on Inventories (IPCC-TFI) encourage the use of top-down GHG budgets for inventory quality assessment & quality control (QA/QC), Parties to the Paris Agreement have not agreed to mandate their use.

To improve the utility and encourage the adoption of space-based data in the global stocktakes, CEOS and its partners are exploring new approaches for developing and delivering GHG and AFOLU products serving these stakeholders. Approaches currently under discussion include:

- Encouraging continuous interactions with the national inventory and policy communities to identify specific requirements for transparent, purpose-built space-based GHG and AFOLU products;
- Creating custom tools and products for harmonizing and combining top-down budgets with bottom-up inventories to address specific IPCC guidelines and meet UNFCCC requirements;
- Providing capacity building to encourage the use of these tools and data products;
- Identifying and nurturing champions for transparent, space-based products in these communities;
- Collaborating with UN agencies, including the WMO Global Greenhouse Watch (G3W) and UNEP International Methane Emission Observatory (IMEO) ,to deliver these products to their constituents;

- Working with IPCC-TFI to develop standards for combining AFOLU and GHG measurements to refine both activity data and emission factors used in bottom-up inventories;
- Working with the IPCC-TFI and UNFCCC to develop a protocol for using global, space-based GHG and AFOLU products for assessing the collective progress toward the goals of the Paris Agreement; and
- Working with the UNFCCC to expand the focus on systematic Earth observations beyond Earth Information Day at the annual Conferences of the Parties (COPs).

There are numerous opportunities for members of the IWGGMS community to work with the CEOS-CGMS WGClimate GHG Task Team to formulate and implement these efforts.

Special session

Session title: Measuring Greenhouse Gases from Space: Past, Present, and Future
Panelists: Dr. David Crisp (former OCO science lead, CEO of Crisp Spectra, LLC), Dr. Tatsuya Yokota (former GOSAT project leader, NIES), Dr. Akihiko Kuze (former GOSAT-2 project manager, GORadS CEO);
Date and time: June 9, 16:30 - 17:00
Moderators: Hiroshi Suto (JAXA), Tsuneo Matsunaga (NIES)

Twenty-one years ago, the very first International Workshop on Greenhouse Gas Measurement from Space (IWGGMS) was held at JAXA's Earth Observation Research Center (EORC) in Tokyo by a small group of pioneers, including Dr. David Crisp, former OCO science team lead, Dr. Tatsuya Yokota, former GOSAT leader, and Dr. Akihiko Kuze, the Developer of TANSO-FTS. The small group had a big ambition – measuring greenhouse gases (GHGs) from space and producing high-quality GHG data that enables science breakthrough. Fast forward to now, space-based GHG observation has become one of the key tools for studying GHGs globally, regionally, and locally. The world has witnessed a number of technological and science advancements that we as a community have made possible under the pioneers' leadership and close collaborations with the international community.

This short session invites the three pioneers of space-based GHG observation as distinguished guests/panelists. The session reviews the history of space-based GHG observation, recognizes the significant contributions of these three pioneers and their teams, and discusses the future of GHG remote sensing. In the session, we ask the panelists to provide a brief introduction and remarks regarding their work while addressing questions from the moderators (also from the audience if time allows). Questions will be customized to each panelist and will include (but not be limited to):

- What was the most challenging/difficult or joyful moment during your tenure? / What was the key to leading your mission to success?
- What do you see as the key challenges over the next 10 years? / What collaboration within the community do you want to propose to meet these challenges?
- What is the message for the members in the community, especially students and next generation career researchers/engineers?