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Abstract Collection

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7-P03	Rajesh Janardanan (NIES, Japan)	Observations of atmospheric CH_4 enhancements due to anthropogenic emissions by the GOSAT-2 satellite

The OCO-2 and OCO-3 Missions: Status, results and plans

Vivienne Payne*[1], Abhishek Chatterjee[1], Junjie Liu[1] and the OCO-2 & OCO-3 teams

[1]Jet Propulsion Laboratory, California Institute of Technology, USA

The Orbiting Carbon Observatory 2 (OCO-2) was successfully launched into a polar orbit in July 2014, joined the Afternoon Constellation in August 2014 and has been providing science measurements since September 2014. In May 2019, the OCO-3 instrument was installed on the International Space Station (ISS) and has been providing science measurements from that precessing orbit since August 2019. Together, these instruments have collected millions of observations globally. Here, we present a high-level overview of these missions to date. We will discuss the coverage and scientific opportunities offered by the XCO2 and SIF products from the nadir, glint and target observations from OCO-2 and OCO-3, as well as the “Snapshot Area Map” capability unique to OCO-3, that can be used to sample emission sources and gradients over selected ~80 by 80 km areas. We will describe instrument status, calibration and Level 2 algorithm updates, including the release of the v11 products, and plans for the future.

Keywords: OCO-2, OCO-3, CO2

Progress in understanding the natural carbon cycle with remote sensing CO_2 observations

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3. University of Maryland, United States of America
4. LSCE, France
5. University of Wollongong, Australia
6. University of Oklahoma, United States of America
7. AMES, NASA, United States of America
8. Johns Hopkins University, United States of America

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 provides a vantage point to quantify CO_2 sources and sinks and to understand 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 carbon-climate interactions since the launch of GOSAT in January 2009 using in situ and remote sensing CO_2 observations. Our focus is on the robust signals inferred from the six-year top-down flux inversion results generated by the OCO-2 MIP project. We will conclude by discussing the remaining sources of uncertainty in flux estimates from assimilation of atmospheric CO_2 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 remote sensing CO_2 observations.

Keywords: carbon-climate interactions, GOSAT, OCO-2 MIP, top-down inversions

Gridded Level 3 TROPOMI Methane Data Products

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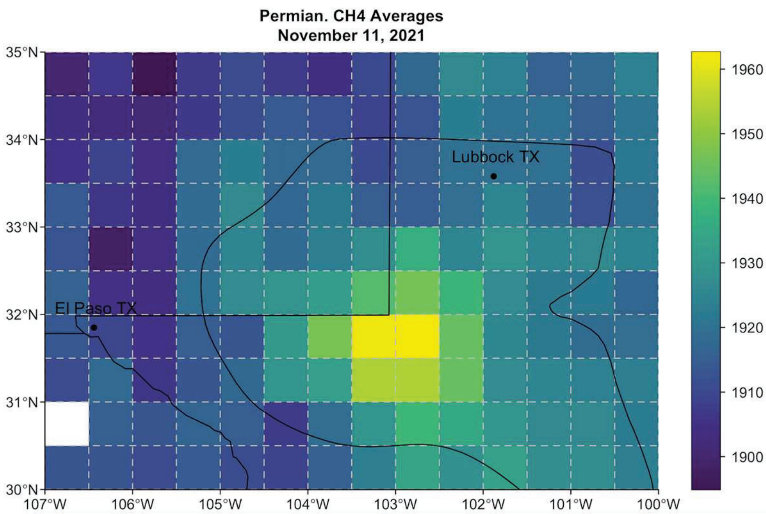
The Global Methane Pledge, an initiative introduced at the 2021 UN Climate Change Conference, is a major commitment signed by over 100 countries to reduce methane emissions by 30% by 2030. As of 2020, the oil and gas industry accounts for 32% of anthropogenic methane emissions in the US, making it a promising avenue for reducing anthropogenic emissions. Satellite data is a useful tool for monitoring methane emissions due to its global coverage and, in many cases, open access. The TROPOspheric Monitoring Instrument (TROPOMI) onboard the Copernicus Sentinel-5 Precursor satellite measures methane at a 7x5.5 km^2 resolution and provides a geolocated Level 2 product. The Level 2 products can be challenging to use for non-experts and to the best of our knowledge, there is no official Level 3 product publicly available. We processed TROPOMI Level 2 orbit files to create two versions of a gridded 0.5°x0.5° Level 3 methane product. The first product is created by taking averages of the Level 2 data that fall with latitude- and longitude-based grid cells. We create this product for two major US oil and gas producing basins, the Bakken and Permian, at daily and monthly temporal resolutions. Data are available starting from May 1, 2018. We give an example use-case for the average-based Level 3 product in economic analysis for the management of flaring and methane emissions. The second product is based on spatial modeling and attempts to leverage the spatial correlation structure of the Level 2 methane observations. We use the multi-resolution approximation (M-RA) spatial model to make predictions of the methane field and provide an alternative Level 3 product on a regular grid along with uncertainties. We show initial results from this more sophisticated product and compare it to the simple averaged product.

Keywords: TROPOMI, satellite data, methane, Level 3 product, M-RA



Results from GHGSat Constellation's First Full Year of Operation and Latest Phase of Expansion

Dylan Jervis*[1], Marianne Girard[1], Jean-Philippe MacLean[1], Jason McKeever[1], Antoine Ramier[1], Mathias Strupler[1], Ewan Tarrant[1], and David Young[1]

1. GHGSat Inc., Canada

It has been more than a year since the inception of GHGSat's commercial constellation for high spatial resolution (~25 m) methane sensing and quantification. We report on the emissions that we have detected and quantified with GHGSat-C1 and C2 - broken down by geographical location, source sector, as well as temporal trends in the emission rates that we have measured.

We also present an analysis of GHGSat methane measurement performance. In particular, we quantify how the column density precision compares to both the shot-noise prediction and estimated error, as well as correlations with environmental variables such as the solar zenith angle, albedo, and albedo heterogeneity.

We show results from an independently organized single-blind controlled release study where we successfully detected and quantified plumes over a wide range of emission rates.

Methane emissions may be mitigated in a cost-effective way if emission sources can be readily identified. With the launch of GHGSat-C3, C4 and C5 in May 2022, we anticipate successful commissioning of all three systems – including controlled release validation – that will more than double the coverage of the existing GHGSat constellation, all with emission rate detection sensitivities down to 100 kg/hr. The GHGSat constellation successfully bridges the spatial and detection sensitivity scales between aircraft and global-mapper satellite measurements and has been shown to be an effective tool for detecting and attributing methane emissions.

Keywords: Remote Sensing, Methane, High-resolution

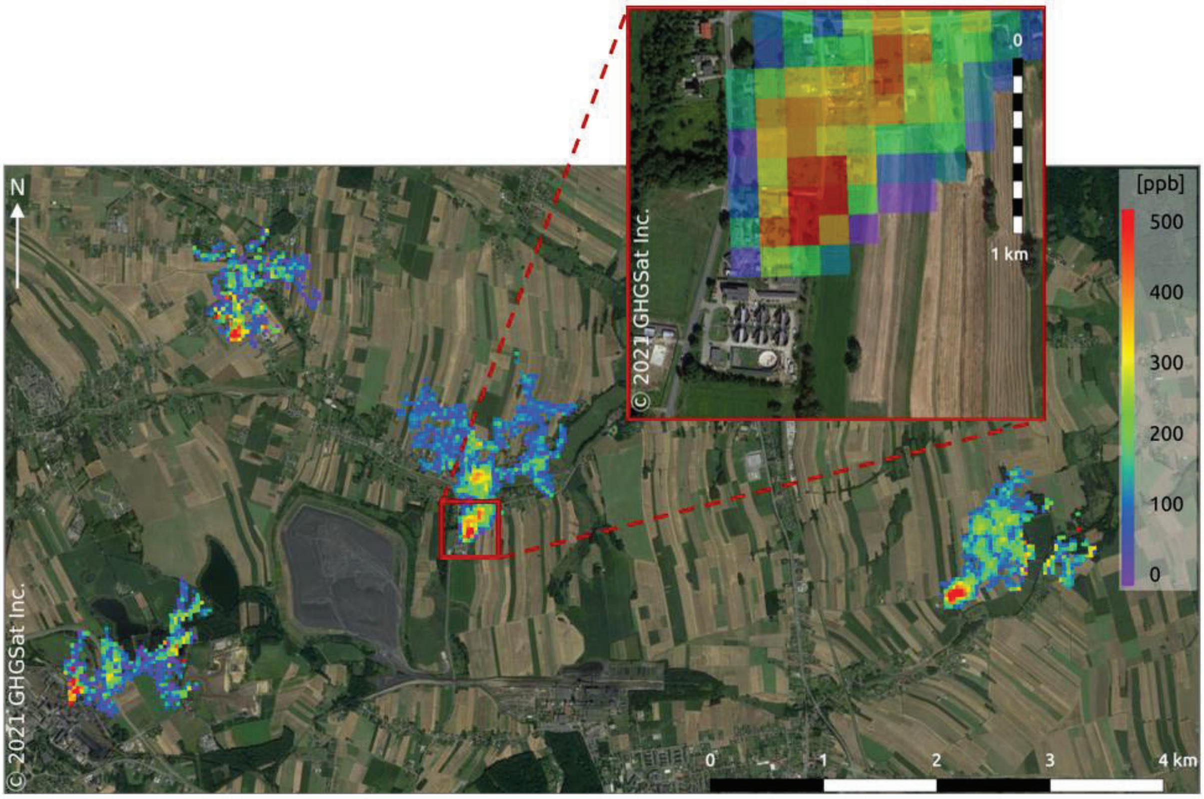


Figure 1: An example of a single GHGSat measurement of underground coal mining facilities in Europe showing the retrieved methane enhancement above background (colour scale) overlaid on 3rd-party reflectance imagery.

More than a decade of GOSAT and GOSAT-2 operations and data products using their unique capabilities of FTS multiplex advantage and target observations

Akihiko Kuze[*1], Hiroshi Suto[1], Kei Shiomi[1],
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JAXA has been operating the GOSAT and GOSAT-2 satellites, which have been measuring two greenhouse gases for more than a decade. Over this period, we have accumulated data on radiance spectra of reflected sunlight with two linear polarizations and thermal emissions, thank to updated Level 1 products with radiance degradation correction and the new solar irradiance data set of the Total and Spectral Solar Irradiance Sensor-1 (TSIS-1) Hybrid Solar Reference Spectrum (HSRS). The release plans for the next versions of GOSAT V300 and GOSAT-2 V220 follow.

Utilizing the multiplex advantages of the FTS, the EORC L2 algorithm retrieves the partial column densities of lower- and upper- tropospheric carbon dioxide (CO_2) and methane (CH_4), at roughly 0- 4 km and 4- 12 km, respectively. Thirteen years of total and partial columns data on 2, 2, and 11 vertical layers of CO_2, CH_4 and water vapor (H_2O), respectively, and solar-induced chlorophyll fluorescence (SIF) are available at https://www.eorc.jaxa.jp/GOSAT/GPCG/download_v2/. We have examined the lower-tropospheric CO_2 products from GOSAT target observations to estimate emissions over global megacities.

We started the joint ESA-NASA-JAXA #2 dashboard program to relate the stories about the air we breathe and greenhouse gases as a product of combustion. We apply CO_2 data from multiple instruments on GOSAT, GOSAT-2, and OCO-3, using nitrogen dioxide (NO_2) as a proxy for anthropogenic CO_2 emissions and SIF from TROPOMI over target megacities such as Cairo, Shanghai, New York City and Tokyo. The Committee on Earth Observation Satellites (CEOS) working group calibration and validation (WGCV) has opened the Vicarious Calibration Portal for Space-borne GHGs Sensors at https://www.eorc.jaxa.jp/GOSAT/GHGs_Vical/index.html. Using a seamless dataset from multiple sensors, we provide satellite data and calibration and validation dataset of the ground, radiosondes, airplanes, methodology, and analysis results to contribute to flux estimation, and data assimilation.

Key words: GOSAT, GOSAT-2, CEOS WGCV, TSIS, EO-Dashboard

Current Status and Recent Topics on

GOSAT and GOSAT-2 Standard Products and Other Data

Tsuneo Matsunaga [*1], Isamu Morino[1], Yukio Yoshida[1], Makoto Saito[1], Hibiki Noda[1], Hirofumi Ohyama[1], Hisashi Yashiro[1], Yu Someya[1], Tazu Saeki[1], Yosuke Niwa[1], Akihide Kamei[1], Fumie Kawazoe[1], Jiye Zeng[1], Ryoichi Imasu[2], Teruyuki Nakajima[2], Takashi Nakajima[3], Naoko Saitoh[4], and Makiko Hashimoto[5]

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3. Tokai University
4. Chiba University
5. Japan Aerospace Exploration Agency, Japan

GOSAT Series is a Japanese Earth observation satellite project jointly promoted by the Ministry of the Environment, the Japan Aerospace Exploration Agency (JAXA), and the National Institute for Environmental Studies (NIES) to monitor global distribution of greenhouse gases from space. It consists of three satellites, GOSAT launched in 2009, GOSAT-2 launched in 2018, and GOSAT-GW to be launched in FY2023. GOSAT data for 13 years since April 2009 and GOSAT-2 data for 3 years since March 2019 are being distributed from respective NIES websites.

In this presentation, the current status of various standard products derived from GOSAT and GOSAT-2 observations, such as column-average concentrations and regional fluxes of carbon dioxide and methane, will be introduced. In addition, recent topics such as contributions to UN's 1st Global Stocktake and the rapid increase of methane concentration in recent years (Figure 1) will be discussed.

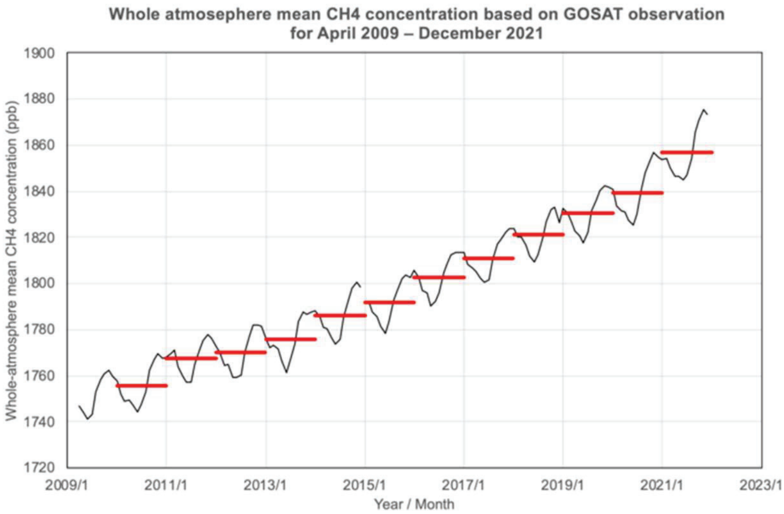

Figure 1. GOSAT whole-atmosphere monthly (black) and yearly (red) mean concentrations of methane.

https://www.eurekalert.org/news-releases/946874

Keywords: Global Stocktake, carbon dioxide, methane, whole-atmosphere

Towards near-real-time XCO_2 retrieval from OCO-2 observations using Neural Network techniques

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Column-averaged dry air mole fractions of CO_2 (XCO_2) retrieved from OCO-2 observations are increasingly used to infer the space-time distribution of natural and even anthropogenic CO_2 fluxes. Processing the large data volume of OCO-2 radiance measurements, while ensuring an exceptional retrieval accuracy, represents a major technical challenge. This has taken up considerable computing resources and has so far hampered near-real-time (NRT) applications, such as day-to-day monitoring of the distribution of CO_2 in the atmosphere by operational data assimilation centres.

We have shown earlier that a neural network (NNET) approach can estimate XCO_2 from OCO-2 spectra with negligible computing time and with accuracy and precision similar or better than that of the official retrieval algorithm (ACOS, based on a full-physics radiative transfer model inversion and a subsequent empirical bias correction). However, in this preliminary study, NNET retrievals were applied to the clear sky soundings identified by the ACOS processing chain, and therefore remained dependent of the delivery agenda of the L2-Standard product. In order to enable a NRT processing of XCO_2-NNET within the frame of the European Copernicus Atmosphere Monitoring Service, we have developed the capability to identify clear sky soundings from the OCO-2 L1b data only. It is based on a dual estimation of 1) the surface pressure (and removing soundings for which the surface pressure estimate departs from meteorological data) and 2) a cloud flag trained over corresponding information derived from the ACOS processing chain.

We will present 1) the performance of the XCO_2-NNET estimates when using either the ACOS cloud flag or that based on this innovative approach, and 2) the ability of the NNET to reproduce both large-scale features of XCO_2 and small scale features (plumes) that are generated by strong localized emissions, thus enabling a large range of applications for its product.

Keywords: XCO_2, OCO-2, neural network, machine learning, surface pressure

On-orbit characterization of the TanSat instrument line shape using observed solar spectra

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The Chinese carbon dioxide measurement satellite (TanSat) had collected a large number of measurements in the solar calibration mode. In order to improve the accuracy of XCO_2 retrieval, the Instrument Line Shape (ILS, also known as the slit function) must be determined accurately. In this study, we characterize on-orbit ILS of TanSat by fitting measured solar irradiance from 2017 to 2018 with a well-calibrated high spectral resolution solar reference spectrum. Various advanced analytical functions and stretch/sharpen of the tabulated preflight ILS are used to represent the ILS for each wavelength window, footprint, and band. Using supper Gaussian+P7 and stretch/sharpen functions significantly reduces the fitting residual in O_2 A-band and weak CO_2 band comparing to using the preflight ILS. Difference between the derived ILS width and on-ground preflight ILS can be up to -3.5% in weak CO_2 band, depending on footprint and wavelength. Large amplitude of the ILS wings depending on the wavelength, footprint and bands indicates possible uncorrected stray light. Broadening ILS wings will cause filling-in of deep absorption lines of the spectra, which is confirmed using offline bias correction of the solar-induced fluorescence retrieval. Errors due to the imperfect ILS are estimated using simulated TanSat spectra. Simulations shows that XCO_2 retrieval is sensitive to errors in the ILS, and 4% uncertainty in the full width of half maximum (FWHM) or 20% uncertainty in the ILS wings could induce an error of up to 1 ppm in the XCO_2 retrieval.

Assessment of the optimal operating point for a high resolution XCO_2 imager dedicated to the monitoring of 0.1 to 15.0 $MtC.yr^{-1}$ sources.

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The CO2M constellation planned for launch in 2025 or 2026 should become the main mission for the satellite monitoring of the CO_2 anthropogenic emissions on the short-term. Recent studies indicate that it could support the detection and inversion of plumes from cities and plants emitting more than 1-2 MtC/year. However, the spatial resolution and precision of its XCO_2 images should not be fine enough to support the monitoring of smaller size sources. Cities and plants emitting more than 1 MtC/year represent ~40 % of the global emissions. High resolution satellite imagery could thus play an important role by opening the opportunity to monitor smaller sources. Indeed, new instrumental concepts, like Compact Gas Imager acquiring signal with very high XCO_2 gain in one mega pixels image of XCO_2, could support the imagery of XCO_2 at sub-kilometric resolutions, with similar levels of precision but with swaths narrower than 100 km (while CO2M will have a swath > 200 km). In that regard, we use academic inversions with pseudo-images to study the coverage of sources in terms of extent and emission rate and the corresponding share of the global emissions that could be ensured by new high resolution XCO_2 imagery concepts, depending on the spatial resolution, precision and swath of the instrumental scenarios. Our study assesses the different satellite configurations in terms of complementarity with the coverage by CO2M. Our results indicate that the 50 km swaths and 100-200 m spatial resolution scenarios can provide < 20% precision estimates of instant emissions for a set of sources representing a larger percentage of global emissions compared to the scenarios with larger swaths (up to 240 km) but coarser sampling resolutions (up to 2 km). The narrow swath scenarios can provide good instant estimates for sources not covered by CO2M configuration that represent more than 30 % of the global emissions.

The MicroCarb CO2 mission : status and technical insight

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Decision by the French government of the MicroCarb program development by CNES occurred in December 2015, in the frame of the COP-21. Since then, partnerships for major contributions in the program have been developed with UKSA, EUMETSAT and EU through H2020 IOD-IOV program operated by ESA. MicroCarb will be the first European mission dedicated to CO2 fluxes monitoring from space, with a target launch for early 2024.
MicroCarb will make accurate measurements of the atmospheric CO2 column integrated concentrations (random error <1ppm, regional bias <0.2ppm) from an affordable micro satellite .The main objective is the study of natural fluxes for a better understanding of their mechanisms. An imagery mode is also implemented as a demonstrator for local emission estimations. The MicroCarb instrument is a grating spectrometer that acquires high-resolution spectra in four spectral bands: CO2 at 1.61 and 2.03 µm, O2 at 0.76 and 1.27 µm, this latter being specific to the MicroCarb mission. An imager is also embedded for cloud detection.
The presentation will introduce the mission, its objectives and the main technical characteristics and partnership organization. The current status of the program development will be highlighted.
Then, a technical insight of the mission will be given, with the following items : scientific algorithms developed to retrieve the CO2 contents from the raw measurements; current estimated performances of MicroCarb L1 & L2 orbital simulated products (including the impact of the instrument, satellite and algorithms); application of the L2 processor on real OCO-2 L1b data and comparison to TCCON and EM27; quick overview of the cal/val planned activities.

Key words: MicroCarb, CO2, retrieval, performances, cal/val

Quantifying localized carbon dioxide emissions from space: the CO2Image demonstrator

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Space-based measurements of carbon dioxide (CO_2) are the backbone of the global and national-scale carbon monitoring systems currently being developed to support and verify greenhouse gas emission reduction measures. Current and planned satellite missions such as JAXA's GOSAT and NASA's OCO series and the upcoming Copernicus Carbon Dioxide Monitoring (CO2M) mission aim to constrain national and regional-scale emissions down to scales of urban agglomerations and large point sources with emissions in excess of ~10 $MtCO_2$/year.

We report on the demonstrator mission "CO2Image", now in Phase B, which is planned for launch in 2026. The mission will complement the suite of planned CO_2 sensors by zooming in on facility-scale emissions, detecting and quantifying emissions from point sources as small as 1 $MtCO_2$/year. A fleet of CO2Image sensors would be able to monitor almost 90% of the CO_2 emissions from coal-fired power plants worldwide. The key feature of the mission is a target region approach, able to observe up to five scenes of 50 km x 50 km per orbit, with a spatial resolution of 50 m x 50 m. This will enable CO2Image to resolve plumes from individual localized sources, essentially providing super-resolution nests for survey missions such as CO2M.

We present the instrument concept, which is based on a spaceborne push-broom imaging grating spectrometer measuring spectra of reflected solar radiation in the SWIR-2 spectral window. It relies on a comparatively simple spectral setup, with a single spectral window and a moderate spectral resolution of approximately ~ 1.3 nm. The instrument is designed to fly in a sun-synchronous orbit at an altitude of 500 to 600 km. We report on ongoing work in developing the sampling strategy and robust methods to estimate emission strengths based on retrieved scenes.

The Copernicus Anthropogenic CO_2 Monitoring (CO2M) Mission – Recent Progress

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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 to include measurements for anthropogenic CO_2 emission monitoring. The greatest contribution to the increase in atmospheric CO_2 comes from emissions from the combustion of fossil fuels and cement production. In support of well-informed policy decisions and for assessing the effectiveness of strategies for CO_2 emission reduction, uncertainties associated with current anthropogenic emission estimates at national and regional scales need to be improved. Satellite measurements of atmospheric CO_2, complemented by in-situ measurements and bottom-up inventories, will enable, by using advanced (inverse) modelling capabilities, the transparent and consistent quantitative assessment of CO_2 emissions and their trends at the scale of megacities, regions, countries, and at global scale.

Operational monitoring of anthropogenic emissions requires high precision CO_2 observations (0.7 ppm) with, on average, weekly effective coverage at mid-latitudes. These observations will be obtained from NIR and SWIR radiance spectra at moderate spectral resolution. The measurements will be complemented by (1) aerosol observations, to minimise biases due to incorrect light path corrections, and (2) NO_2 observations as tracer for high temperature combustion. Retrieval of CO_2 is further facilitated by a cloud imager, to identify measurements contaminated by low clouds and high-altitude cirrus. In order to support the CO2M Mission implementation, several scientific support activities are currently undertaken and selected results will be presented. One study has a focus on better observations over snow-covered areas, which can be best observed in a measurement configuration similar to glint over water. Another study confirms the results obtained earlier in another study that observations significantly improve by adding multi-angle polarimeter observations of aerosol. Two new studies will start soon. One study will focus on directly supporting the project implementation and tackling any potential issues arising regarding requirements. The other study will support the Mission Operational Planning Concept by deriving an optimal sequencing of glint and nadir mode with focus on including good coverage over snow-covered regions and coastal areas. This presentation will provide first outcomes of the studies. It will also give the opportunity to present a status overview of implementing the space segment of the Copernicus CO_2 Monitoring (CO2M) mission, as keystone of the future global CO2 stocktake.

Keywords: Copernicus, anthropogenic, CO_2, CH_4, NO_2

The GeoCarb Mission: Progress and Future Plans

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Abstract: Since selection in 2016, the OU/NASA-led GeoCarb Mission has navigated successfully through numerous challenges towards building the first ever geostationary greenhouse gas observatory. The flight instrument is currently being integrated at the Lockheed Martin Advanced Technology Center in preparation for calibration and testing later this year in order to begin integration with a dedicated spacecraft in fall 2023 and launch in late 2024. In this presentation, we will share the major developments in the past year in hardware development, algorithms, and expected mission operations as we prepare for instrument testing and eventual launch. This will include some first testing results and performance characterization of subsystems as well as science algorithm simulations with expected instrument performance and mission ops strategies. We will also solicit feedback from the community on potential synergies with the objectives of other missions like CO2M, GOSAT-GW, and Sentinel-5 as well as future field campaigns.

The GOSAT-GW greenhouse gases observing mission: Updates

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3. National Institute of Information and Communications Technology, Japan

Emissions inventories are one of key research elements in tackling the climate change issues. The bottom-up inventories provide, for example, accurate estimates of greenhouse gases (GHG) emissions from fossil fuel use, but can have large uncertainties in other sectors and are restricted to managed lands. Inventories can also be derived by the top-down approach using atmospheric inverse models, complementing the bottom-up methods by providing an integrated constraint on surface fluxes from all sectors/processes on spatial scales. For these models a variety of observations are used, including those from ground-based, ship, aircraft and satellite platforms. In particular, recent improvements in the capability of satellite observations of atmospheric composition are driving great advances in the modeling. There are several plans to launch additional GHG and air quality (AQ) observing satellites in near future. In Japan a plan is in progress to launch the third satellite in the GOSAT series, named “Global Observing SATellite for Greenhouse gases and Water cycle (GOSAT-GW)”, that will make observations of carbon dioxide (CO_2), methane (CH_4), and nitrogen dioxide (NO_2) at a horizontal resolution of 3 km or less. The missions of GOSAT-GW include (1) monitoring of whole atmosphere-mean concentrations of GHGs, (2) validation of nationwide anthropogenic emissions of GHGs, and (3) detection of GHGs emissions from large sources, such as megacities and power plants. In parallel, the National Institute for Environmental Studies (NIES) has been operating a long-term program for monitoring trace gases of atmospheric importance in Asia and the Pacific. Both long-lived GHGs and short-lived climate forcers (SLCFs) are observed with commercial cargo vessels and passenger aircraft that are in regular operation in constant routes for long periods over a wide area between various ports/airports. These routine platforms offer the advantage of systematic measurements of trace gases and aerosols, providing long-term datasets. Hence, the challenge imposed to us is how to combine these multiple observing platforms into one integrated system that can be best used for better understanding of the changing emissions and resulting impacts on the atmospheric composition. We will provide an overview of the projects and some recent highlights and discuss future perspectives in supporting the Global Stocktake (GST) mechanism, a key element in the Paris Agreement.

Keywords: greenhouse gas, air pollutant, carbon dioxide, nitrogen oxides, Global Stocktake

The future China’s greenhouse gas monitoring satellite missions

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The greenhouse gas mainly includes Carbon dioxide (CO_2) and Methane (CH_4) play a very important role in global warming. Our understanding of global sources and sinks of CO_2 and CH_4 and the coupling with climate change is still insufficient due to limitations in the surface monitoring network. Satellite remote sensing can provide global and densely sampled observations of CO_2 and CH_4 which fill the gaps in surface networks, and which can help to develop reliable estimates of regional surface fluxes.

Since the first Chinese greenhouse gas monitoring satellite mission (TanSat) launched in 2016, global XCO_2 and optimized CO_2 surface flux over land has been provide from TanSat monitoring. The FY-3 and GF-5(02) tried different way on CO_2 and CH_4 measurement implementation, based on Fourier transform technics comparing to grading spectrum that onboard TanSat.

After TanSat, the next generation of GHGs satellite, DQ-1, DQ-2, TanSat-2 and future FY series satellite mission that aiming to Global Stocktake service. The TanSat-2 mission will be a 3-6 satellites constellation. In order to improve the measurement coverage and repeat frequency, the satellite has a option to be built as a middle earth orbit, and hence each satellite observe earth in a large than 800 km width across track with 2x2 km pixel. The NIR/SWIR hyperspectral measurement on backscattered sunlight from spectrometer onboard TanSat-2 includes 0.76 um (O_2A), 1.61 um (CO_2), 2.06 um (CO_2) and 2.3 um (CH_4 and CO) band, the O_2B band and O_2 1.27 um band is also in consideration. There will be air pollution instruments onboard TanSat-2 to monitoring NO_2 and aerosol optical properties. TanSat-2 aims to measured atmospheric CO_2, as well as CH_4 in global coverage, at least twice per day, which will be helpful to investigate the daily variation of greenhouse gas and the emission that related to anthropogenic activities.

To improve the nighttime measurement, the DQ-1 and DQ-2 will carry greenhouse gas lidar, and coordinate measurement with passive instrument will provide more accurate result in aerosol highly polluted area. DQ-1 had been launched on April 2022.

Radiance Comparison from OCO-3 and OCO-2 Simultaneous Nadir Observations

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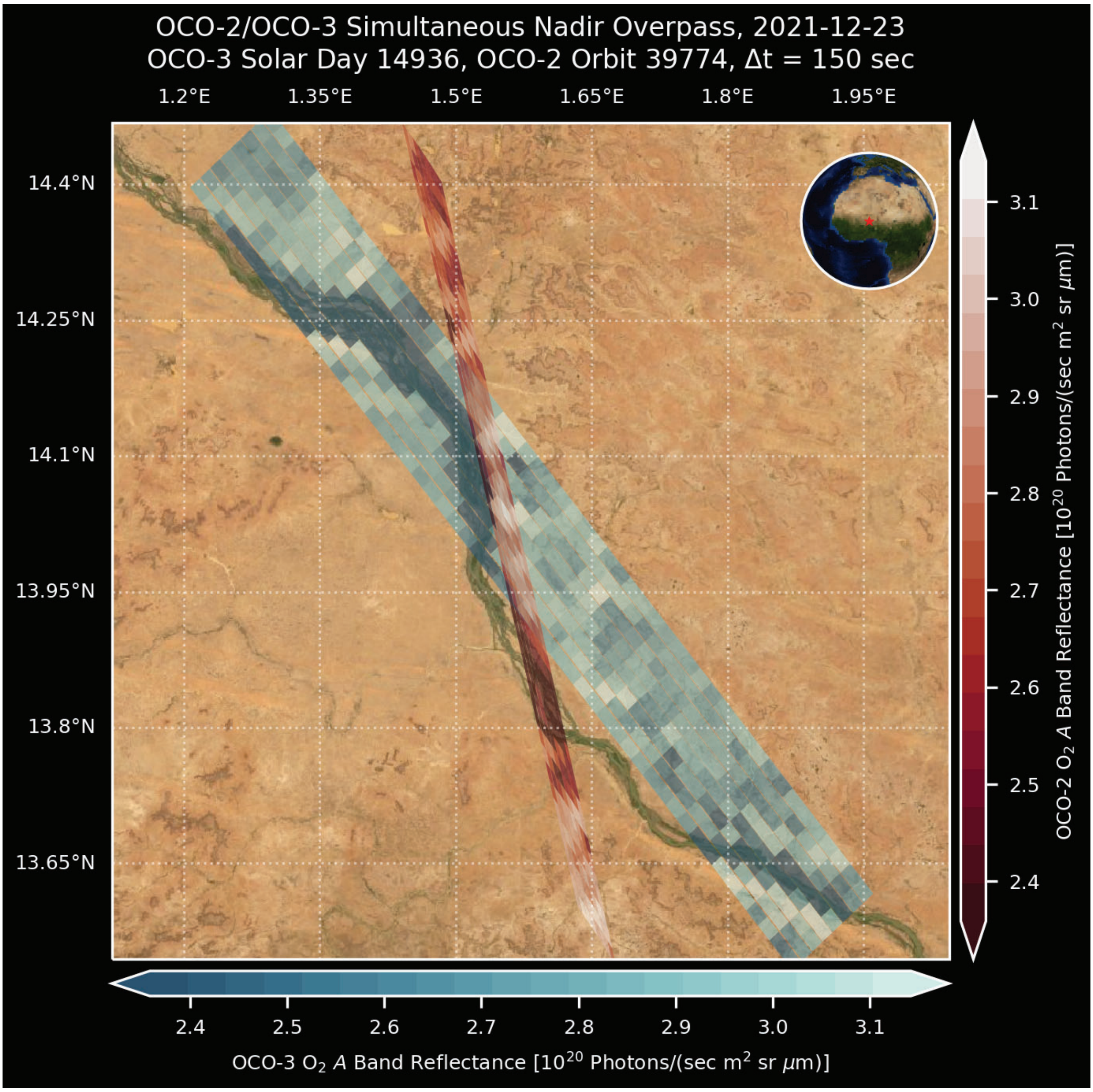
The Orbiting Carbon Observatory 3 (OCO-3) was launched to the International Space Station (ISS) in May 2019 and has been making routine measurements since August 2019. OCO-3 records reflected sunlight in the near-InfraRed spectral region to estimate the column average CO_2 dry air mole fraction (XCO_2) and solar-induced chlorophyll fluorescence (SIF). Originally built as the spare copy of the OCO-2 flight instrument, OCO-3 has several hardware differences from the OCO-2 spectrometer. Aside from an added polarizer and a telescope with a smaller blur spot, major differences are limited to external modifications like the pointing mirror assembly that was added to OCO-3 to accommodate operation on the ISS.

An important difference between OCO-2 and OCO-3 instrument operations is that OCO-3 is unable to perform direct solar observations, a limitation imposed by OCO-3's installation location on the ISS. This has consequences for OCO-3 in-flight radiometric calibration, which at present relies on on-board calibration lamps. To constrain lamp aging, supplementary calibration approaches like lunar measurements, vicarious calibration targets, and cross-calibration with independent satellite sensors are currently being considered.

The similarity of the OCO-2 and OCO-3 spectrometers makes OCO-2 the ideal candidate for cross-comparison of continuum radiances to establish radiometric accuracy. By early 2022, close to 500 incidences of OCO-2/3 near-Simultaneous Nadir Observations (SNOs) – i.e., both instruments recording measurements in nadir mode over the same position on the Earth within 10 minutes of each other – have been identified, which increases to about 1150 cases for a relaxed time window of 30 minutes. SNOs occur at all latitudes within the ISS spatial coverage region but tend to be concentrated around 50º N/S, where the ISS ground track changes between ascending and descending node and the OCO-2 and OCO-3 ground tracks are thus at their largest relative angle. We report on how we determine and select SNO incidents, present results from radiometric comparisons of co-located OCO-2/3 observations for different surface conditions and scene inhomogeneity, and show how SNOs may help us in optimizing radiometric calibration for the OCO-3 instrument. Our approach includes tessellation-based averaging that allows us to limit radiance comparisons to the geographic area of the actual OCO-2/3 footprint spatial overlap, thus compensating for the different footprint sizes of the two sensors.

The image shows continuum O_2 *A* band reflectances from OCO-2 (B11, red) and OCO-3 (B10, teal) for a Simultaneous Nadir Overpass over the Niger river. The significantly narrower swath of OCO-2 is due to the orientation of the OCO-2 spacecraft at the time the measurement was taken.

Keywords: OCO-2, OCO-3, Radiance Calibration


OCO-2/OCO-3 Simultaneous Nadir Overpass, 2021-12-23
OCO-3 Solar Day 14936, OCO-2 Orbit 39774, Δt = 150 sec
1.2°E
1.35°E
1.5°E
1.65°E
1.8°E
1.95°E
14.4°N
14.25°N
14.1°N
13.95°N
13.8°N
13.65°N
3.1
3.0
2.9
2.8
2.7
2.6
2.5
2.4
OCO-2 O2 A Band Reflectance [10^20 Photons/(sec m^2 sr μm)]
2.4
2.5
2.6
2.7
2.8
2.9
3.0
3.1
OCO-3 O2 A Band Reflectance [10^20 Photons/(sec m^2 sr μm)]

Using Clear Ocean Scenes to Constrain Changes in Instrument Response in OCO-3

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NASA's OCO-3 instrument, launched in 2019, measures atmospheric carbon dioxide and solar induced fluorescence (SIF) from the International Space Station (ISS). It consists of three long slit imaging spectrometers observing reflected solar light in three infrared spectral channels centered at 0.765 (ABO2), 1.61 (WCO2), and 2.06 µm (SCO2). As the band names suggest, the shortest wavelength channel is characterized by the presence of absorption lines from molecular oxygen and the other two channels show numerous carbon dioxide absorption lines. Due to its physical position onboard the ISS, OCO-3 cannot perform solar calibrations and relies on three on-board calibration lamps to track changes in instrument response. Throughout the mission, OCO-3 has experienced both gradual and abrupt changes in instrument response, which show wavelength dependence within the bands. These changes have two separate causes, depending on the band. The ABO2 is affected by gradual accumulation of contaminants and by their abrupt removal during planned decontamination events. The CO_2 bands, while not as impacted by contaminants, show sudden changes in overall instrument response related to instrument resets. In order to mitigate the changes in instrument response, OCO-3's radiometric calibration is frequently updated inflight. Analysis of thousands of clear ocean soundings has shown that during periods of high contamination, more accentuated starting in June 2020 and reaching a maximum in January 2021, the inflight correction for the ABO2, in data version 10, was less than ideal, with relative in-band calibration errors reaching 3 percent. This is caused by contaminants impacting the data from each lamp and from science observations differently. Here, we present the results obtained using clear ocean scenes to track the quality of the inflight relative calibration within the ABO2 and WCO2 and to further constrain the spectral shape of gain degradation in the ABO2 as viewed on Earth scenes.

Keywords: OCO-3, Radiometric Calibration, Lamps

UPlume: Automated algorithm for methane plume detection and source quantification by satellite point source imagers

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Methane is a potent greenhouse gas. Identification and quantification of methane point sources is a crucial step in understanding primary contributors to regional emissions and identifying targets for high impact mitigation. Point source imaging satellites like GHGSat-C1 are powerful tools for detection of point sources globally. Current methods for plume identification and source rate estimation are often error prone and labor intensive. They are not scalable to the quantity of high spatial resolution methane data that is presently becoming available from point source imagers. We have developed a hybridized method, UPlume, combining machine learning with a U-Net architecture for plume detection with physics-based source rate estimation methods. The UPlume method is successful in producing accurate plume masks in GHGSat-C1 imagery and separating out artifacts. Source rate estimations from the UPlume method support the viability of this method for automated detection and quantification over large datasets. The separation of masking and source rate estimation within UPlume allows visualization of the plume mask, identification of the point source, and quality control on the accuracy of image segmentation.

Keywords: Methane, Machine Learning, Image Segmentation

Understanding causes of differences between the GGG2014 and GGG2020 data products

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The Total Carbon Column Observing Network (TCCON) provides column-average measurements of greenhouse gases from sites around the world. A new version of the TCCON data products, produced using the latest version of GGG (GGG2020) was released at the end of April 2022. In this presentation, we will summarize the overall changes to column average CO_2 and CH_4 products in the new GGG2020 release, and examine several sites' data in detail to understand the factors driving the differences between the previous GGG2014 and new GGG2020 data product.

Keywords: TCCON, CO_2, CH_4, GGG2020

Characterization of TANSO-FTS-2 onboard GOSAT-2 and the Level-1 algorithm updates

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Greenhouse gases Observing SATellite-2 (GOSAT-2) launched on 29 October 2018, as the follow-up to Japanese Greenhouse gases Observing SATellite (GOSAT), aiming to improve CO2 and CH4 flux estimation globally and locally by adding CO channel and optimizing sampling patterns with wider pointing angles and improved target observation capability.

TANSO-FTS-2, a high-performance thermal near-infrared sensor for carbon observation, is installed in GOSAT-2. It uses Fourier-transform spectrometer technology inherited from GOSAT to acquire solar reflected lights with orthogonal linear polarizations and thermal radiation simultaneously. A key feature of TANSO-FTS-2 is that it allows to set a large AT/CT angle, which enables fully customized observation patterns to observe emission sources such as large cities, power plants, and waste disposal plants. TANSO-FTS-2 is equipped with multiple calibration sources and modes for instrument calibration: solar diffuser target observation, monochromatic laser observation, blackbody observation, deep space observation, and Lunar observation. The Level 1 products are observation results corrected for the effects of instrument characteristics.

The latest version is V210, which applies an algorithm that corrects for changes in sensitivity that depend on the orbit time and matches the NADIR radiance with that of other satellites. We are in the process of analyzing the V210 products in detail and preparing it for the next update. In particular, the laser calibration was performed at two wavelengths in GOSAT-2, enabling a more detailed evaluation. We obtained laser calibration continuously for 90 minutes (one orbit around the Earth) and confirmed that the SWIR sensitivity variation with orbital position. The SWIR brightness accuracy can be improved by updating to optimized brightness conversion coefficients that minimize the wavelength-dependent difference from TSIS. For the calibration of the high AT angles data, we plan to perform a calibration to minimize the difference by match-up IASI and GOSAT-2 observations with off-NADIR observations over Antarctica. In addition, AT angle-dependent characteristics are calibrated by observing the satellite calibration site RRV, US under multiple AT angle conditions.

Keywords: GOSAT-2, TANSO-FTS-2, Level-1 algorithm

Towards Arctic and boreal methane flux estimates: systematic evaluation of TROPOMI XCH_4 observations at high latitudes

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The Arctic and boreal regions are experiencing a rapid increase in temperature, resulting in a changing cryosphere, increasing human activity and a potential increase in the high-latitude methane emissions. Sentinel 5P TROPOMI observations provide an unprecedented coverage of XCH_4 in this region, compared to previous missions or in situ measurements. We present a systematic comparison of three TROPOMI methane products – operational and the scientific SRON and WFMD products – focusing exclusively on high Northern latitudes. We evaluate the seasonal coverage and regional XCH_4 features over the continuous and discontinuous permafrost regions, reflecting the potential of TROPOMI to inform inversion models on changing emissions in these regions. We also evaluate biases by carrying out comparisons to high-latitude TCCON, using the newest GGG2020 retrievals. TCCON analysis is further complemented by comparisons to atmospheric profile measurements with AirCore carried out in Northern Finland.

We find that TROPOMI observations enable seasonal analyses at high latitudes, even over permafrost regions. The operational, scientific SRON and WFMD products show a generally good agreement but also systematic seasonal and latitudinal differences. As presented by Tsuruta et al. (IWGGMS-18), seasonal biases may have a significant impact on the fluxes solved using inverse modelling (up to 0.5 $TgCH_4$/month in the fall over high Northern latitudes). All products have biases smaller than 27 ppb against the TCCON. TCCON/GGG2020 does not systematically improve the agreement. We make an effort to distinguish and analyse the albedo effects from snow cover and the changes in the CH4 profile shape caused by high-altitude depletion of methane in the polar vortex in order to identify potential, collective improvements. Collaboration in high-latitude algorithm, validation, and flux analysis developments will continue in the new ESA MethaneCAMP project that participates the ESA-NASA Arctic Methane and Permafrost Challenge (AMPAC).

Keywords: Arctic methane, TROPOMI, validation, permafrost, AMPAC

Comparison of IASI CH_4 retrievals based on ASIMUT and RTTOV

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Atmospheric methane (CH_4) is measured continuously from space, providing valuable information at global scales for atmospheric monitoring. Although most CH_4 measurements from space are based on observations in the shortwave infrared (SWIR) leading to a more uniform sensitivity to the atmospheric column, thermal infrared observations (TIR) also provide valuable information about the CH_4 atmospheric content, especially in the upper troposphere and lower stratosphere.

Among the various instruments performing measurements in the TIR, the Infrared Atmospheric Sounding Interferometer (IASI) instruments onboard the METOP satellites have been observing the Earth's atmosphere for nearly 15 years. Its low radiometric noise, large spectral coverage and good spectral resolution have led to the retrieval of several atmospheric species of interest. The Royal Belgian Institute for Space Aeronomy (BIRA-IASB) has been involved in the retrieval of several species based on IASI observations such as mineral dust, volcanic ash, CH_4 and N_2O.

In this work, we present recent developments of the IASI-derived CH4 dataset from BIRA-IASB. The official BIRA-IASB CH_4 product is retrieved based on the ASIMUT radiative transfer software, which models the radiance using a full line-by-line calculation of the absorption cross-section of atmospheric species and performs a retrieval based on the Optimal Estimation Method (OEM). It allows great flexibility, for instance in terms of spectroscopic databases and species included in the modelling, at the cost of computational efficiency.

RTTOV is another RTM which is less flexible since it is based on fixed spectroscopic data and allows only a subset of species to be explicitly modelled and varied for the purpose atmospheric retrievals, but is very fast and shows good accuracy. RTTOV has recently been used for the retrieval of the N_2O product at BIRA-IASB and has been adapted to also retrieve CH_4 with IASI as an alternative product.

In this work, we compare the results of using these two RTM on IASI observations in the TIR and highlight the differences in the CH_4 retrievals and spectral residuals. We will also look at the impact of using different spectroscopic databases and the implementation of the Tikhonov regularization.

Keywords: methane, IASI, ASIMUT, RTTOV, RTM

Commercial ship and aircraft-based evaluation of satellite derived XCO_2 and XCH_4 over oceans - updates and prospective

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Carbon dioxide (CO_2) and methane (CH_4) are the most important greenhouse gases (GHGs) whose atmospheric concentrations continue to increase. The global trends and variability of these GHGs can be monitored by satellite observations of the column-averaged mixing ratios of CO_2 (XCO_2) and CH_4 (XCH_4). The accuracy of satellite derived products is validated against reliable standards in some areas. But over oceans, limited reference data hinders successful uncertainty quantification or bias correction efforts and precludes reliable conclusions about changes in the carbon cycle.

In the initial study, we obtained an "observation-based column-averaged CO_2" (obs. XCO_2) dataset by integrating cargo-ship (Ship Of Opportunity, SOOP) and commercial aircraft (Comprehensive Observation Network for Trace gases by Airliner, CONTRAIL) observations with the aid of state-of-the art atmospheric chemistry-transport model calculations. With the new dataset, we successfully identified and evaluated improvements in the GOSAT (Greenhouse gases observing satellite) and OCO-2 (Orbiting Carbon Observatory) retrieval algorithms between 2014 and 2017 over the Western Pacific.

In the follow-up study, we made a temporal extension of the obs. XCO_2 dataset using data of the Copernicus Atmosphere Monitoring Service (CAMS) for the stratosphere this time. The same methodology was applied to CH_4 to obtain obs. XCH_4. To cross-check the observation-based datasets, and as a complimentary approach to validate satellite and model derived data over oceans, a customized EM27/SUN Fourier Transform infrared spectrometer was deployed on two research cruises in spring 2021 and winter 2021/2022. The semi-automatic setup was developed by the Heidelberg University. With the aim of continuous ground-based measurements of XCO_2, XCH_4, and XCO in coastal zones, this setup will be deployed on a cargo ship between Tokyo and Fukuoka, Japan, in June 2022 for the first time. We will present first results and challenges, and give an outlook on future applications.

Keywords: observation-based XCO_2/XCH_4, mobile EM27/SUN, validation

Analysis of Biases in XCO_2 measured by a pulsed multiwavelength airborne lidar during the 2017 ASCENDS/ABoVE Campaign

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May 25, 2022

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Abstract:

Since fluxes of CO2 from the surface cause only small changes in XCO_2, biases in measuring XCO_2 are a major concern. Because pulsed lidar measurements of XCO_2 are independent of solar illumination and insensitive to atmospheric scatter they allow low-bias measurements to be made under a wide variety of conditions, including in darkness. We have performed an analysis of the bias of XCO_2 (difference between an airborne lidar and in situ measured columns) in 37 locations during an airborne campaign flown in 2017.

The CO_2 Sounder lidar is a pulsed, multiple-wavelength IPDA lidar that measures XCO_2 in a nadir path from the aircraft. The lidar measures the range resolved shape of the 1572.33 nm CO_2 absorption line to the ground. The airborne lidar used 30 fixed-wavelength samples distributed across the line. The retrievals solve for the CO_2 absorption line shape and XCO_2 by using the atmospheric state, radiative transfer calculations, the aircraft altitude and range to the surface.

Eight flights were conducted during the ASCENDS/ABoVE airborne campaign which was flown in July and August 2017. XCO_2 measurements were made using the CO_2 Sounder lidar along with measurements of CO_2 made at the aircraft using AVOCET and Picarro in situ instruments. Forty-seven spiral-down maneuvers were conducted over locations in California, the Northwest Territories Canada, the Arctic Ocean and over Alaska, along with the transit flights from California to Alaska and return. Each spiral allowed comparing the retrievals of XCO_2 from the lidar measurements against those computed from the CO_2 measured in situ at the aircraft. This campaign allowed an unprecedented opportunity to assess the bias of lidar measurements of XCO_2 made over a wide variety of conditions.

We have performed an analysis of bias of XCO_2 (difference between the lidar and in situ measured columns) in 37 of these spirals. The bias values and their statistics were found to depend on the approach used to correct for the non-uniform spectral transmission of the lidar receiver. Using a quadratic line fit correction yielded the lowest average bias for the campaign. Using this approach for the 37 spirals the mean value of bias for the campaign was -0.15 ppm and the standard deviation was 0.44 ppm. The results from this airborne campaign also show there are several practical approaches to further reduce measurement bias that can be made in future updates to the airborne lidar, and in a space-based version. Details of the campaign, lidar measurements and bias analysis will be presented.

Keywords: XCO_2, Remote Sensing, Measurement bias, Lidar

Monitoring facility-scale CO_2 emission changes from space

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The central objective of the United Nations Paris Agreement is for countries to reduce their greenhouse gas emissions in order to limit future climate change. Transparent monitoring of CO_2 emission reductions is desirable at multiple spatial scales, including the scale of individual facilities such as fossil fuel burning power plants. Here, we present a case study on monitoring CO_2 emissions from Poland's Bełchatów coal-burning power plant (the highest CO_2 emitting power plant in Europe), using space-based observations from NASA's Orbiting Carbon Observatory-2 and -3 (OCO-2 and OCO-3) missions, including multiple 'Snapshot Area Mapping' (SAM) mode observations with OCO-3. The emission estimates are compared with reported power generation, demonstrating the ability to detect emission changes over time at the facility scale. This research gives us a glimpse of the potential capabilities of future CO_2 imaging missions like the Copernicus Anthropogenic CO_2 Monitoring Mission (CO_2M) and reinforces the value of future space-based CO_2 data for verifying local-scale CO_2 emission reductions with the potential to support the transparency framework under the Paris Agreement.

Keywords: power plant, plume, OCO-2, OCO-3, transparency

Monitoring anthropogenic emissions from space: insights from OCO-3's Snapshot Area Mapping (SAM) mode

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As the world embarks on ambitious efforts to verify emission reduction goals, accurate and precise monitoring of CO_2 emissions from anthropogenic activities is essential. Over the last decade, space-based retrievals of the dry-air mole fraction of column-mean carbon dioxide (X_{CO2}) from GOSAT and OCO-2 have provided significant new insights into our understanding of the anthropogenic and natural carbon cycles. However, neither of these missions were designed to monitor emissions from anthropogenic "hot spots", like large urban areas and megacities. GOSAT and OCO-2 observations are often limited to a single overpass over a large urban area/megacity, thus restricting their monitoring and detection capabilities to only a small portion of the domain. The OCO-3 mission, on board the International Space Station, specifically includes an observation strategy that is designed to monitor and quantify anthropogenic emissions. This viewing mode, called the Snapshot Area Mapping (SAM) mode, collects several adjacent swaths of X_{CO2} observations in a two-dimensional sweeping pattern over a spatial area of approximately 80 km by 80 km. This unique capability to map a given region of interest with the SAM mode results in a rich dataset for urban- and local-scale carbon cycle studies. In this presentation, we will go over this multi-swath measurement approach, technical challenges faced during the early days of operations, and the current data products available for scientific use. We will also highlight scientific findings from studies that are exploiting the information content in these dense, fine-scale maps. These studies are clearly demonstrating potential improvements in constraining urban emissions by using the OCO-3 SAM mode observations. The presentation will conclude with a discussion of proposed plans for terminating OCO-3 operations early next year, the resulting data gap between OCO-3 and future wide-swath missions with similar global anthropogenic emission monitoring capabilities (ESA CO2M), and implications for tracking city- and country-level progress towards meeting proposed CO_2 emission reduction goals.

Keywords: CO2 emissions, megacities, emission monitoring, NASA OCO-3, SAM mode

Satellite monitoring of urban CO2 emissions: optimizing the selection of cities and meteorological conditions

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Several concepts of spaceborne instruments providing high resolution 2D view of CO2 total column concentrations (XCO2) have been developed to monitor the CO2 anthropogenic emissions. Those images target mainly the CO2 atmospheric plumes from cities and large power plants, expecting that their study may quantify the emissions of those sources. However, there is still a need to assess the sensitivity of the precision of the emission estimates to the targeted cities and the meteorological conditions.

This presentation details the application of a plume inversion method based on a gaussian plume model to synthetic images over 31 cities across the world. These images are simulated with Ocean Land Atmosphere Model (OLAM), a variable-resolution general circulation model. We diagnose the main drivers of the level of error in the emissions estimates by classifying the errors as a function of the atmospheric conditions and of the general patterns of the emissions from the different cities. This classification is supported by a Decision Tree Regressor. The distribution of the variables used in the decision tree are studied for the most populated cities in the world.

The main separation criteria of the decision tree are the spatial variability of the wind direction in the PBL and the city emissions, but these parameters do not entirely explain the variability of the error statistics depending on the cities. The bias and IQR of the error on the estimate are of 4% and 25% of the emissions for Moscow and 25% and 95% for Chennai. The extension of the study of the criteria for the most populated cities allows us to give a list of cities to be privileged as targets for the current and future missions.

Keywords: CO2, city emissions, imagery, plume inversion

Carbon Mapper: on-orbit performance predictions and airborne prototyping

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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, often 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.

We present the predicted on-orbit performance of the Carbon Mapper program, a constellation of small satellites designed to track individual CH_4 and CO_2 point-source emitters in priority regions globally. Carbon Mapper is implemented as a public-private partnership with an open data policy for CH_4 and CO_2. The first two satellites are funded for launch in 2023 and will characterize the global distribution of point-sources in priority regions at 30m spatial resolution with visible-infrared imaging spectrometers. The system is designed for expansion to a larger satellite constellation in 2025 offering sub-daily to weekly sampling. We also present findings from prototype airborne surveys of diverse regions and emissions sectors including lessons learned from follow-up site-level measurements and mitigation by facility operators and regulators with implications on the emerging global, multi-scale (tiered) observing system of systems.

Estimating urban methane emissions from space

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Recent studies have shown that urban methane emissions often exceed inventory estimates; however, these studies are limited to a handful of cities and regions and the representativeness on a larger scale is unknown. As a result, anthropogenic methane from cities, which represents an important and addressable emission source, remain poorly characterized. A satellite-based approach provides a pathway to tackle this challenge on a national or global scale. We will present a space-based method that uses the simultaneous, daily observation of methane and carbon monoxide from the TROPOMI satellite to estimate urban methane emissions. We assess and validate the method and demonstrate that using these simultaneous observations enables robust assessment of methane emissions from urban centers without relying on atmospheric transport models. Initial assessments with this approach in eight United States cities suggest emission inventory underestimates previously discovered in older East Coast cities are more broadly representative. We further extend the method to consider urban emissions from different cities around the globe, and interrogate whether seasonal or annual signals can be extracted. We show this data driven approach provides a pathway to study urban methane emissions across the globe and track how emissions respond if urban mitigation measures are implemented.

Keywords: methane, urban, tropomi

Strong methane point sources contribute a disproportionate fraction of total emissions across multiple basins in the U.S.

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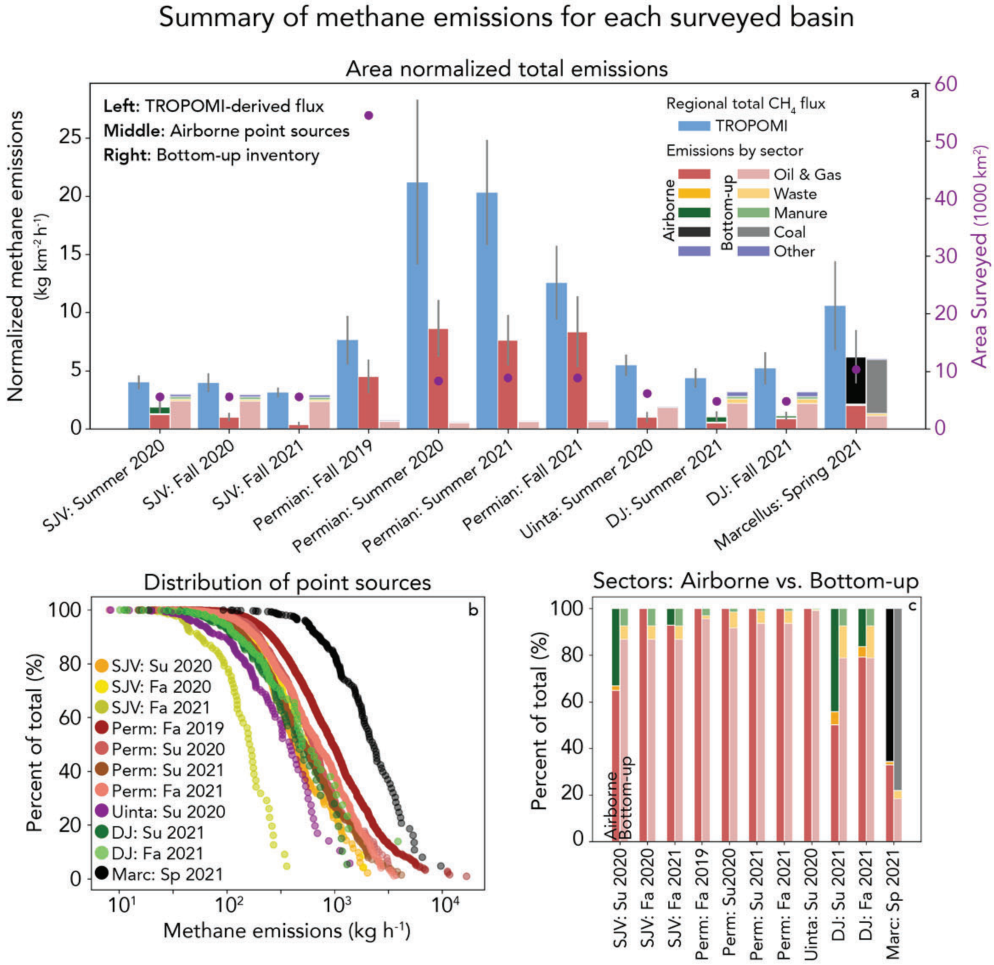
Understanding, prioritizing, and mitigating methane (CH_4) emissions requires quantifying methane budgets from facility scales to regional scales with the ability to differentiate between source sectors. We deployed a tiered observing system for multiple basins in the United States (San Joaquin Valley, Uintah, Denver-Julesberg, Permian, Marcellus). We quantify strong point source emissions (>10 kg CH_4 h^{-1}) using airborne high spatial resolution imaging spectrometers, then attribute them to sectors, and assess their intermittency with multiple revisits. We compare these point source emissions to total basin CH_4 fluxes derived from inversion of Sentinel-5p satellite observations. Across basins, point sources make up on average 40% of the regional flux. We sampled some basins several times across multiple months and years and find a distinct bimodal structure to emission timescales: the total point source budget is split nearly in half by short-lasting and long-lasting emission events. With the increasing airborne and satellite observing capabilities planned for the near future, tiered observing systems will more fully quantify CH_4 emissions from facility to regional scales, which is needed to effectively and efficiently reduce methane emissions.



Summary statistics for each basin surveyed between 2019-2021 (Figure 1). Panel (a) shows a comparison between aggregated point source emissions for each campaign with a top-down spatially/temporally synchronous TROPOMI flux inversion and bottom-up emission from the 2012 EPA gridded inventory. Panel (b) shows the cumulative distribution of airborne plume emissions quantified for each campaign. Panel (c) shows the relative sector breakdown between airborne plume emissions and the bottom-up inventory for the following emission sectors: oil & gas (dark/light red), waste management (dark/light yellow), manure management (dark/light green), and coal (dark/light black).

Detectable Weekly Cycle of Urban CO_2 Emissions from Satellite Observations: A Case Study in Los Angeles

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Abstract:
The weekday-weekend effect of anthropogenic emissions in cities, driven by the associated weekly changes in human activities, provides a unique opportunity to assess the sensitivity of observation networks (e.g., ground-based and space-borne instruments) on urban emissions. In this study, we focus on the weekly cycle amplitudes of carbon dioxide (CO_2), nitrogen dioxide (NO_2), and carbon monoxide (CO) in the Los Angeles (LA) megacity, where significant weekly cycle of human activities exists. In addition, abundant observations are being collected continuously from existing ground-based, mountaintop, and satellite platforms to monitor carbon emissions and air quality in LA.

From our analysis, significant agreement can be found in observations from different platforms. For CO_2, we show that the weekly cycle from OCO-2 observations has a Sunday decline (15%~20 %), relative to weekday values, consistent with ground-based observations and TCCON. This weekly pattern of CO_2 in a megacity detected directly by OCO-2 is reported for the first time. For NO_2, a 30%~35% Sunday decline can be observed from both ground-based and satellite observations. For CO, the Sunday drops from ground-based, mountain-top and satellite observations are 13%~20%. The TROPOMI instrument, with its high spatial resolution, provides detailed spatial information on the reduction of tropospheric column NO_2 and CO on Sundays. The spatial pattern is in good agreement with traffic density in LA. Impact due to the prevailing winds from the coast in the afternoon can also be observed. In addition, we also investigate the weekly cycles from stable carbon isotopologue of $\delta^{13}C$ from ground-based observations, which reflect the weekly variation in fossil fuel usage in LA. This study highlights the consistencies and effectiveness of existing observing platforms in monitoring the anthropogenic emissions of the LA megacity.

Keywords: CO_2 emissions, air pollutants, weekly cycle, satellite observations, Los Angeles

Associated Publication:

Huidong Wang, Fang-Ying Gong, Sally Newman, & Zhao-Cheng Zeng, 2022. Consistent weekly cycles of atmospheric NO_2, CO, and CO_2 in a North American megacity from ground-based, mountaintop, and satellite measurements, *Atmospheric Environment*, Vol. 268, https://doi.org/10.1016/j.atmosenv.2021.118809

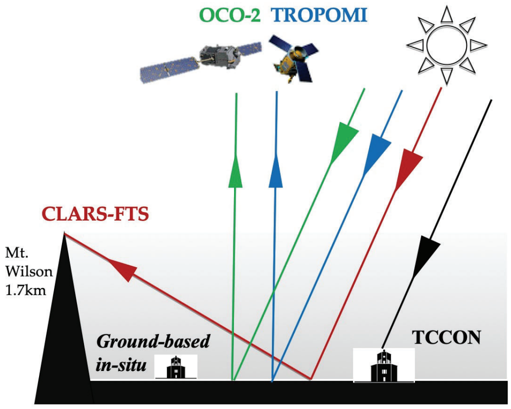

Figure 1. Observation geometries for satellites (including OCO-2 and TROPOMI), CLARS-FTS, and ground-based remote sensing TCCON observatory.

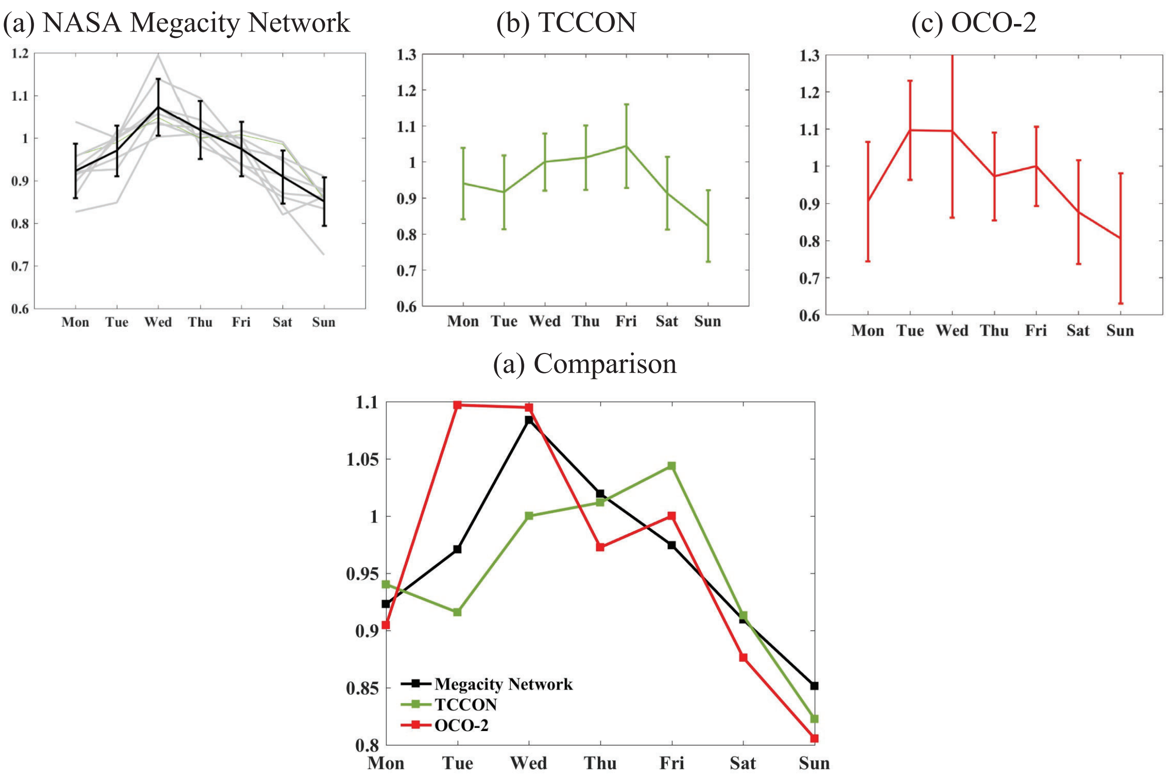

Figure 2. The CO_2 weekly change that has been normalized by the weekday median observed from (a) NASA megacity network ground-based in-situ stations (from 9:00am to 6:00pm, 2015-2016); (b) TCCON data at Caltech (2013-2019); (c) OCO-2 observations (2014-2019), and (d) their comparisons of weekly cycle. Error bars in (a) is the standard errors of the measurements. Error bars in (b) and (c) are one standard deviation of the measurements.

The impact of viewing geometry on the interpretation of high-resolution measurements of CO_2 plumes

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The CO2Image mission being developed at DLR will be measuring column-integrated atmospheric carbon dioxide abundance at a spatial resolution of 50 m x 50 m. The aim of the mission is to quantify emissions from anthropogenic point sources, providing information relevant for national emissions reporting under the Paris Agreement. By targeting a high spatial resolution, smaller emission plumes can be detected, and sensitivity to point source emissions as small as 1 $MtCO_2$/year is foreseen. The increasing resolution of the ground pixels also leads to some additional complications in the interpretation of the measurements. This study focuses on the assumption of nadir viewing that is often made when interpreting the retrieved column-integrated values. In reality, this column-integrated value usually represents two slant columns, depending on the solar and viewer angles. This can result in a slight shift in the location of plume, and a broadening of the width of the plume. The problem is exacerbated for plumes aloft, such as those from high chimneys. If this effect is not considered, it can lead to errors in the retrieved emission rates. By using both Gaussian plume and large eddy simulations, this study quantifies differences in the retrieved plume as a function of solar and viewer angles, pixel size, and emission height. Furthermore, we assess the difference in the resultant retrieved fluxes using common methods for emission estimation, such as the integrated mass enhancement (IME) approach.

Urban XCO_2 gradients from space: results from OCO-3 SAM's and a dense network of EM27/SUN over Mexico City

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Large metropolitan regions across the world represent a significant fraction of fossil fuel CO_2 emissions at the global scale, but recent studies have shown that large uncertainties might affect their official Self-Reported Inventories, most often leading to under-estimation of urban direct emissions. The metropolitan area of Mexico City, a densely populated region of about 20 million inhabitants, has pledged for carbon neutrality by 2050, an ambitious target that can be supported by atmospheric measurements. Mexico City has been selected for frequent Snapshot Area Mode (SAM) by the NASA Orbiting Carbon Observatory-3 (OCO-3) . In parallel, a French-Mexican research collaboration, called Mexico City's Regional Carbon Impacts (MERCI-CO_2), used a dense network of 7 ground-based column sensors located in the Mexico City metropolitan area (MCMA), offering a unique opportunity to compare and evaluate the quantification of urban XCO_2 gradients, and possibly the monitoring of XCO_2 emissions over the coming decades. The network included 1 permanent high resolution IFS 125 HR spectrometer at the high altitude Altzomoni observatory (4000 m a.s.l), and contributing to the NDACC network since 2014, 2 permanent EM27-SUNs stations located in Mexico City and measuring since 2016 and 2019, and four additional EM27-SUNs instruments deployed across the urban basin during a 7-month (October 2020 to May 2021) intensive field campaign.

During October 2020 to May 2021, an intensive 7-month field campaign included 7 solar-viewing Fourier transform infrared (FTIR) spectrometers (6 portable Bruker EM27/SUN and 1 IFS 125 HR). Two FTIRs were deployed in rural areas, in the basin and near mountain tops, while the other instruments were located across the urban basin of Mexico City. Thanks to NASA's Orbiting Carbon Observatory-3 (OCO-3) collecting urban-focused XCO_2 measurements at high-resolution (SAM and targets), a total of 20 partial XCO_2 maps are available over the same time period. After removing the background concentrations, we attempt to reconcile the observed intra-urban gradients and urban-rural gradients (ΔXCO_2) from FTIRs and OCO-3. The analysis is supported by column footprints, generated by X-Stochastic Time-Inverted Lagrangian Transport (X-STILT) driven by the Weather Research and Forecasting (WRF) model, to determine the observations less influenced by urban emissions (optimal background). Urban gradients are of great importance in inverse modeling; lower gradients would directly lead to lower estimation of the emissions over the city. This study identifies potential differences in observed XCO_2 gradients thanks to an unprecedented density of column sensors over a single metropolitan area. We evaluate satellite urban gradients and quantify the potential to constrain urban CO_2 emissions from different observing strategies over Mexico City.

The Greenhouse gas Observations of Biospheric and Local Emissions from the Upper sky (GOBLEU): New multi-species observations from passenger aircrafts in support of monitoring of Japan's anthropogenic carbon emissions

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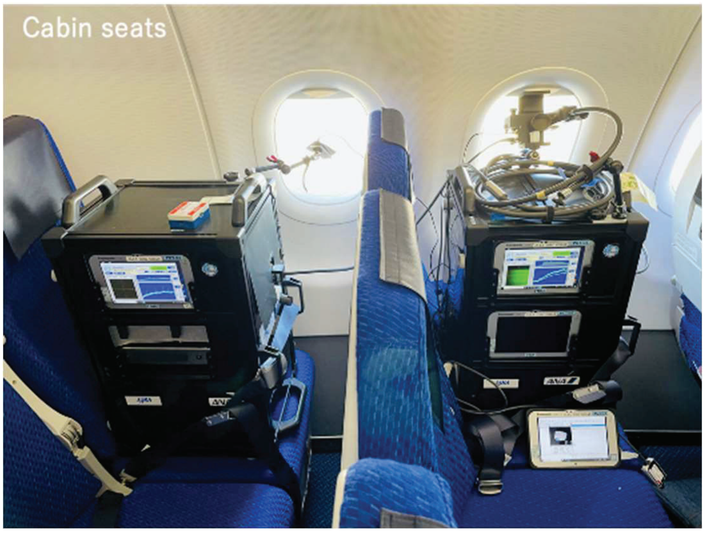
Japan Aerospace Exploration Agency (JAXA) and ANA HOLDINGS INC. (ANAHD) launched a new observation program, the Greenhouse gas Observations of Biospheric and Local Emissions from the Upper sky (GOBLEU). We introduced a "new passenger", a carry-on luggage sized imaging spectrometer suites we newly developed, to ANA's domestic passenger flights, and have started collected high-resolution (~sub km along track spatial resolution) spectra of nitrous dioxide (NO_2), carbon dioxide (CO_2) and solar induced fluorescence (SIF), with moderated spectral resolution. Our "passenger" instrument can be mounted on a passenger seat without any modification to the aircraft, and collects data routinely and frequently as regular flights go. The aim of our program is to quantify Japan's subnational carbon emissions, especially from cities and individual sources with emission sectoral attribution in order to provide actionable information towards Japan's 46% 2030 greenhouse gas (GHG) reduction goal. Based on the same remote sensing technique as ones used by GHG satellites, our program also prototypes the synergic use of CO_2 and NO_2 for enhancing the emission monitoring capability.

We will show data from early GOBLEU flights and present data analyses that examine the utility of the new data we collect. We will also discuss the unique utility of our new aircraft observation and its potential contribution to GHG emission monitoring and the upcoming Global Stocktakes (GST) with an expanded observation coverage and frequency.



Monitoring instruments onboard Japanese passenger flights.

Keywords:
Global Stocktakes, Anthropogenic carbon emissions, passenger aircrafts

Using OCO-2 column CO_2 retrievals to rapidly detect and estimate extreme terrestrial biosphere carbon anomalies

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Abstract

The global carbon cycle is experiencing continued increases in atmospheric carbon concentrations that are largely driving climatic change. Greenhouse gas satellites are designed to primarily observe seasonal to interannual variations of these atmospheric carbon concentrations to assess their anthropogenic and natural drivers. Recent work has shown that these satellites are further applicable to quantify surface emissions at smaller spatiotemporal scales. For example, simple mass balance approaches have been used to rapidly estimate surface methane fluxes from satellite atmospheric column methane measurements. However, less attention has been placed on using these satellite observations and mass balance methods to evaluate surface CO_2 fluxes from the terrestrial biosphere at shorter timescales. Such applications could be useful to monitor, in real time, extreme biosphere carbon fluxes. Here, we assess the ability of Orbiting Carbon Observatory-2 (OCO-2) column-averaged dry air CO_2 (XCO_2) retrievals to rapidly detect and estimate terrestrial biosphere CO_2 emissions. Using CarbonTracker model reanalysis as a testbed, we first demonstrate that a mass balance approach, previously used to estimate methane fluxes, can estimate monthly surface CO_2 flux anomalies in the Western United States. The method is optimal when the chosen target region is spatially extensive enough to account for atmospheric mixing and has consistent advection conditions with contributions primarily from one background region. While errors in individual soundings partially reduce the ability of OCO-2 XCO_2 to estimate more frequent, weaker surface CO_2 flux anomalies, we found that OCO-2 XCO_2 can often detect and estimate larger surface flux anomalies. Greenhouse gas satellites are therefore more useful for rapidly evaluating widespread terrestrial biosphere carbon anomalies due to extreme climatic events than currently appreciated. Any noise reduction in forthcoming greenhouse gas satellites and/or the existence of large surface carbon anomalies will increase the ability to rapidly estimate surface fluxes at smaller spatiotemporal scales.

Key Words:
OCO-2, XCO_2, biosphere, flux, satellite

Is GOSAT XCO2 useful in the OCO era?

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GOSAT launched in 2009 as the first dedicated greenhouse gas monitoring instrument, followed by OCO-2 in 2014 and OCO-3 in 2019. Among other quantities, these satellites observe the column-average dry air mole fraction of CO_2 (XCO_2). They hold a significant advantage over the existing in-situ network of CO_2 measurements in terms of spatial coverage, sampling most of the global on timescales of 3-14 days. However, satellite-based CO_2 flux products have been slow to be adopted by the larger science community, mainly because the requirements for systematic errors in the retrievals have been exceptionally challenging to address. Recently though, after incremental improvements to the ACOS retrieval algorithm, OCO-2 based flux products have gained more acceptance, with mainstream publications on fluxes inferred from satellite products becoming more common. However, GOSAT CO_2 flux products have generally not received the same attention.

In this work, we attempt to show that the quality of GOSAT flux products can approach that using OCO-2 and is not overly dominated by systematic errors in the retrievals. We first discuss the error statistics of several widely available GOSAT XCO_2 products. One of these, the ACOS version 9 GOSAT retrieval, was then assimilated into two global inversion systems: a 4DVarbased system from the University of Oklahoma, and the CAMS variational system from LSCE. We compare the results of these flux inversions with corresponding results from OCO-2 over the overlap period 2015-2019 and show that they are generally comparable. This preliminary result implies that GOSAT-based CO_2 flux inversions may be used to complement OCO-2 and other more recent satellites both spatially and temporally, providing potentially valuable information on terrestrial fluxes back to 2009.

MethaneAIR Point Source Quantification:

Method Exploration and Control Release Experiments

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The MethaneSAT satellite (launch in mid-2023) and its airborne precursor, MethaneAIR, measure concentrations of methane with high resolution, high sensitivity, and wide spatial coverage compared to currently deployed remote sensing instruments. We deployed MethaneAIR in August 2021 to measure area and point sources of methane. The NCAR GV overflew the Permian Basin and other regions at 12 – 13 km altitude, 450 kts, covering 90,000 km^2 with 4.5 km swaths of 5mx25m pixels, in 2.2 hrs. We developed two methods to estimate emissions from point sources from the resulting map of methane column-averaged dry-air mole fraction (XCH_4). The first method, the modified Integrated Mass Enhancement (mIME), estimates emissions (kg CH_4/hr) based on the total excess mass in detected plumes and winds from Weather Research Forecast's Large Eddy Simulations (WRF-LES), driven by High-Resolution Rapid Refresh (HRRR) meteorology. The second method, the Divergence Integral (DI), applies the Divergence (a.k.a. Gauss' theorem) to estimate the flux divergence within closed surfaces surrounding the sources. We did a blind comparison of mIME and DI emissions estimates with controlled releases, finding excellent agreement (slope 1.04 (+0.48/-0.34)). The detection limits were approximately 200 kg/hr for the mIME and 500 kg/hr for the DI. We also applied the two methods to estimate emissions from miscellaneous sources, finding a slope of 0.95 (+0.21/-0.17) when comparing the two. Although the mIME method has a lower detection limit than the DI, the mIME is more computationally expensive and dependent on plume identification and morphology. The DI does not require thresholds or plume identification. Our study validates the accuracy of these methods for quantifying methane emissions by MethaneAIR. In addition to its utility in advancing MethaneSAT, which has the same spectroscopy, MethaneAIR itself is a powerful new airborne platform for remotely quantifying and attributing methane emissions from point sources to regional scale.

Keywords: Methane, Point Source, LES, Divergence Integral, IME

Predictability of fossil fuel CO2 from air quality emissions

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Anthropogenic emissions of long-lived greenhouse gases (GHG) and short-lived air quality (AQ) pollutants drive climate change and human health. The trajectory of these emissions is controlled by common economic imperatives, technological development, and environmental policy. Quantifying the coevolution of these pollutants has the potential to provide insight into underlying processes and the predictability of their emission trajectories. To that end, we classify the dynamics of historic emissions in terms of a modified Environmental Kuznets Curve (MEKC), which postulates the coevolution of fossil fuel (FFCO2) and NOx emissions as a function of macroeconomic development, and assess the predictability of FFCO2 given top-down NOx emissions based upon a novel Kalman filter. For the last two decades, the MEKC broadly captures the distinct FFCO2/AQ dynamical regimes for countries including the US, China, and India. The US trajectory has plateaued while developing countries have taken advantage of technological and regulatory advances to transition more rapidly between these regimes. Because the underlying sectoral structure changes more slowly than activity in these sectors, the predictive skill of FFCO2 given NOx emissions constrained by satellite data is less than 2% error for many countries including China at one-year lags and less than 7 % for 4-year lags. These results point to the important interplay between AQ and GHG emission processes and how they may impact FFCO2 emissions at time scales relevant to international assessments, e.g., Global Stocktake. The proposed framework in conjunction with increasing air quality and carbon satellite constellation could provide valuable insight into near-term emission scenario development and evaluation.

Keywords: fossil fuel CO2, satellite, NO2, top-down, bottom-up

GOSAT and GOSAT-2 Level 4 global surface flux estimates

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We describe overviews of global surface carbon dioxide (CO_2) and methane (CH_4) flux estimates based on respective TANSO-FTS and TANSO-FTS-2 Column-averaged Dry-air Mole Fraction Products (GOSAT and GOSAT-2 SWIR Level 2 Products). The flux estimates derived from GOSAT SWIR Level 2 Products have been released as GOSAT Level 4 Products, whose latest versions (V02.07 for CO_2; V01.06 for CH_4) cover variability of global CO_2 and CH_4 fluxes for 2009 and 2019. We show that the GOSAT Level 4 Products using a fixed-lag Kalman smoother built on an atmospheric tracer transport model NIES-TM can provide an information to infer carbon cycle over regional scale. Preparation of new global surface flux estimates derived from GOSAT-2 SWIR Level 2 Products are underway using an atmospheric tracer transport model NICAM-TM with a four-dimensional variational assimilation (NICAM-TM 4D-Var). In the estimate large gradients of atmospheric concentrations at local scale being inherent in the GOSAT-2 SWIR Level 2 Products results in erroneous distributions of flux estimates, especially over the African continent. We demonstrate preliminary comparison of GOSAT-2 SWIR Level 2 products with ground-based observations and test an approach to evaluate observational errors of individual points in the GOSAT-2 SWIR Level 2 products based on the comparison. Our results show this approach improves global surface flux estimates and agreement of simulated variability in atmospheric concentrations using a posterior flux with atmospheric observations.

Keywords: GOSAT/GOSAT-2, greenhouse gases, surface flux estimates, atmospheric inverse model

Estimating the trend, seasonality, and variability of global and regional CO_2 fluxes with a Bayesian flux-inversion framework

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Natural CO_2 fluxes can be difficult to quantify because they arise as imbalances between the natural source and sink processes of the carbon cycle. Furthermore, climate change and land-usage change may be causing changes in the carbon cycle itself; that is, the climatology of natural CO_2 fluxes may be shifting. At each location on Earth's surface, these changes in the climatology can appear in the sign and magnitude of the average annual flux, as well as in the amplitude and phase of the location's seasonal cycle. To identify shifts in the carbon cycle over the entire surface of Earth requires the synthesis of bottom-up estimates of carbon fluxes, top-down inversion, and the high spatial coverage of remotely sensed, column-integrated CO_2 mole-fraction data.

We address this synthesis problem through the Wollongong Methodology for Bayesian Assimilation of Trace-gases (WOMBAT, Zammit-Mangion et al., 2022, *Geosci. Model Dev.*). WOMBAT is a fully Bayesian hierarchical framework for estimating trace-gas fluxes using data on atmospheric mole fractions. We extend WOMBAT to estimate a spatially varying time-series decomposition of the natural CO_2 fluxes. This extension separates the fluxes at each location into trend, periodic (i.e., seasonal), and residual components, the first two of which can be examined to identify changes in the natural CO_2 flux climatology. Bottom-up estimates of biosphere fluxes are taken from the Simple Biosphere Model, version 4. The data we use cover the six-year period from 2015 to 2020, and include in situ/flask CO_2 measurements and column-integrated CO_2 retrievals from NASA's Orbiting Carbon Observatory-2 satellite. The resulting estimates suggest that, overall, the amplitude of the global CO_2 seasonal cycle is increasing. This is driven by regional changes in seasonal cycle amplitudes, and some regions show evidence of changes in phase as well.

Keywords: flux inversion, carbon cycle, Bayesian hierarchical model, climatology

Interannual variability of anthropogenic methane emission estimated by an inverse model using GOSAT and surface observations

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Abstract

We report the country level analysis of anthropogenic methane emissions estimated with a high-resolution inverse model using observational data from global surface observation network and Greenhouse gases Observing SATellite (GOSAT; NIES Level 2, v02.95) for the period 2009-2020. The high-resolution inverse model is implemented by coupling a Lagrangian particle dispersion model FLEXPART to the global Eulerian transport model NIES-TM. The surface observational data include Obspack CH_4 (v4.0) and observations from ICOS network. For the anthropogenic prior emissions in the inversion, we used monthly data from Emissions Database for Global Atmospheric Research (EDGAR v6.0). For emission from biomass burning, Global Fire Emissions Database (GFED v4.1s) was used. Emissions from wetland and soil sink were taken from Saunois et al (2020). Other flux categories include emission from termites, geological and ocean sources, all fluxes provided at 0.1° spatial resolution. Flux corrections were estimated for six categories such as agriculture, biomass burning, waste, oil and gas sector, coal and wetlands on a bi-weekly time step. Variational optimization was applied to obtain flux corrections for the six categories as scaling factors of monthly varying prior uncertainty fields. For the GOSAT-based inversion, potential biases were removed from satellite retrievals using a surface-data optimized forward simulation, on monthly basis, for 5° latitude bands. The interannual variability and the trend of the estimated anthropogenic emissions were analyzed for the major emitting countries. The trend of anthropogenic methane emissions inferred from GOSAT observations for these countries were, China 0.38±0.17 Tg CH_4 yr^{-2} (p=0.045), USA -0.23±0.05 (p=0.001), India 0.15±0.1 (p=0.18), Brazil 0.12±0.14 (p=0.39), Russia 0.11±0.03 (p=0.005), Indonesia 0.35±0.05 (p<<0.0). These results are in conformity with recent country-specific studies on anthropogenic methane emission trends. Similar estimates were arrived by inversion using surface observations, with China having 0.49±0.19, USA -0.13±0.1, India 0.03±0.18, Brazil 0.46±0.1, Russia 0.17±0.04 and Indonesia 0.38±0.04 Tg CH_4 yr^{-2}.

Keywords: Anthropogenic emissions, inverse modeling, GOSAT, methane trend

Towards assimilation of GOSAT partial column retrievals in CTE-CH_4 atmospheric inverse model for estimation of global and regional CH_4 budgets

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It has been shown that atmospheric inverse models benefit from satellite retrievals for constraining global and regional greenhouse gas (GHG) budgets. Due to their spatial coverage, they have advantage over surface in-situ observations for the estimation of GHG fluxes in regions with a limited in-situ observation network, such as Tropics. However, assimilation of the satellite data has been challenging as both transport model and retrieval errors need to be taken into account. For methane (CH_4), several studies showed large discrepancies between modelled and retrieved values, even after the flux estimates are optimised based on surface observations. Possible explanations lay in the upper atmosphere. Model may not be able to estimate stratospheric profiles well due to e.g. limited number of model layers, incorrect distribution of the stratospheric sinks, and insufficient parameterization of troposphere-stratosphere exchange. For the satellite data, it is challenging to accurately retrieve the shape of the prior profiles over the stratosphere, especially at high latitudes.

In this study, we use the newly published JAXA/EORC's GOSAT partial column retrievals of CH_4 in CTE-CH_4 atmospheric inverse model for estimation of global and regional CH_4 budgets. First comparison with forward modelling showed a good agreement with the retrievals in the lower troposphere. Unlike the comparison to total column values (XCH_4), no strong systematic biases such as latitudinal dependencies were found. This confirms that the discrepancies in XCH_4 is mainly due to the upper atmosphere. However, the seasonal cycle of the partial column values did not agree entirely. At high northern latitudes, the seasonal cycle amplitude was generally overestimated by the model in the lower troposphere, and underestimated in the upper troposphere. The results show potential advantages in using the tropospheric partial column data in atmospheric inverse models, and increasing understanding of CH_4 budgets.

Keywords: GOSAT, partial column retrievals, methane, atmospheric inversion

Increasing Natural Gas Demand Threatens China's Carbon Reduction

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Natural gas is a popular choice as an alternative to coal for most countries to reduce air pollution. China promotes a coal-to-gas energy strategy since 2012 and achieves evident air pollution reduction. While methane leakage to the atmosphere from dramatic increase of natural gas production and consumption to the atmosphere cause serious climate warming issues. In this study, we analyze GOSAT satellite and surface-based methane observations with a high-resolution inverse model, and provide evidence of emission source changes, with implications for designing efforts for climate change mitigation at a regional level in China. we find that the methane emissions in China increase during 2010-2018 with the growth of natural gas use especially in Northern China. Those findings highlight the side effect of natural gas use and serve to awake the attention towards proper strategies facing the spread of natural gas use and pipeline expansion in China. Fugitive emissions of methane from natural gas can be reduced to the economic and environmental benefit of by the increasing natural gas use in China and call for methane emission reductions throughout the gas supply chain and promotion of low emission end-use facilities.

Keywords: methane emission inversion, natural gas leakage, GOSAT

Evaluation of GOSAT-2 SIF with ground-based SIF in three common vegetation types

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The importance of terrestrial ecosystem monitoring is increasing as to be facing to impact of climate change. Sun-induced chlorophyll fluorescence (SIF) is the radiation emitted from the photosynthetic process in plants. Thus, remote sensing of SIF is used as an indicator to detect photosynthetic activity. SIF has been measured with various platforms, including towers, UAVs, airborne, and satellites. However, these values are not comparable. In general, the footprint of satellite SIF is much larger than those of ground-based SIF capturing a single vegetation type. In addition, satellites can provide SIF data for overpassing time. As it is lacking hourly variations within a day, the daily cumulative amount will be an approximate extrapolation. Therefore, it is necessary to validate the satellite SIF with the ground-based SIF which is measured continuously in common ecosystem types. The present study aimed to evaluate the GOSAT-2 satellite SIF (FTS-2 SWIR L2 Ver.01.07) with the ground-based SIF. We have installed fine resolution spectrometers at three sites (deciduous broadleaved forest in Japan TKY: 36°N, 137°E, evergreen coniferous forest in Alaska PFA: 65°N,147°W, and paddy field in Japan MSE: 36°N 140°E) and measured SIF continuously. Although the ground-based and GOSAT-2 SIF were different from each other, those differences could be derived from the footprint land cover and the target-to-viewer geometry such as field-of-view and view zenith. If carefully considering those factors, the values were almost consistent with each other. We also demonstrate the uncertainty of each vegetation type.

Keywords: SIF, ground-based observation, vegetation types, forest, cropland

The US Plan for Measuring, Monitoring, Reporting, and Verifying (MMRV) GHG Emissions

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In January 2022, the current Government of the US announced a sweeping plan for reducing GHG emissions and monitoring and reporting these reductions. Some of these new activities are currently funded through the recently enacted Infrastructure law. In particular, the law includes funding for land reclamation for abandoned coal mines, modernization of the natural gas pipeline system, identification of orphaned wells, and the launch of a methane reduction infrastructure initiative. This announcement also called for the initiation of a Greenhouse Gas MMRV Working Group 'to help identify and deploy the best available tools and data systems to measure, monitor, report, and verify (MMRV) carbon dioxide, methane, and other GHG emissions and removals". This new working group is split into two Technical Working Groups (TWG), one focusing on emissions from Agriculture and Forestry and one focusing on GHG measurements and reporting. This presentation will focus on the latter. The US agencies that provide most of the observations of GHG observations are NASA (from space and aircraft remote sensing), NOAA (in situ), and NIST (focused urban intensives). These are the agencies providing the leadership within the TWG. The initial goals of this effort are to better coordinate the activities of these agencies and to focus initially on use cases where the existing observation programs can make substantial contribution. The intent is to start with a domestic focus, and then see where it makes sense to advance the system more globally. To do that, this activity will attempt to provide consistency with other international efforts for MMRV.

Mapping Emissions Over Offshore Oil and Gas platforms Using Sun Glint with Carbon Mapper

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Offshore oil and natural gas platforms are responsible for about 30% of global oil and natural gas production. Despite the large share of global production few studies have directly measured emissions from these facilities. Offshore platforms are typically understudied due to their remote location. Satellites offer the ability to regularly measure atmospheric methane and potentially carbon dioxide emitted from these facilities. However, passive satellites that rely on reflected radiance cannot always make measurements due to a lack of reflected radiance over water. To compensate satellite must rely on special sun glint acquisitions to capture a target with enough illumination. Few current satellites have a specific glint mode and none with fine enough spatial resolution to map point source emissions.

The upcoming Carbon Mapper satellite system intends to have a glint mode to map point sources emissions from offshore facilities. Carbon Mapper is scheduled to launch in 2023. In anticipation of the upcoming satellite mission, a pre-cursors airborne campaign was conducted in May and October of 2021 with the Global Airborne Observatory (GAO) platform, which is an aircraft equipped with a 432 band Visible Short-Wave InfraRed (VSWIR) imaging spectrometer, similar to the future Carbon Mapper instrument. In 2021, GAO used glint mode to survey over 150 offshore platforms and surrounding infrastructure in US federal and state waters in the Gulf of Mexico. This represents ~ 8% of active shallow water infrastructure in the US Gulf of Mexico and one of the largest surveys of offshore facilities to date. Here we present the methods and results from the airborne imaging spectrometer campaign, new insights learned about methane emissions from offshore oil and gas facilities, and plans for the Carbon Mapper satellite glint mode.

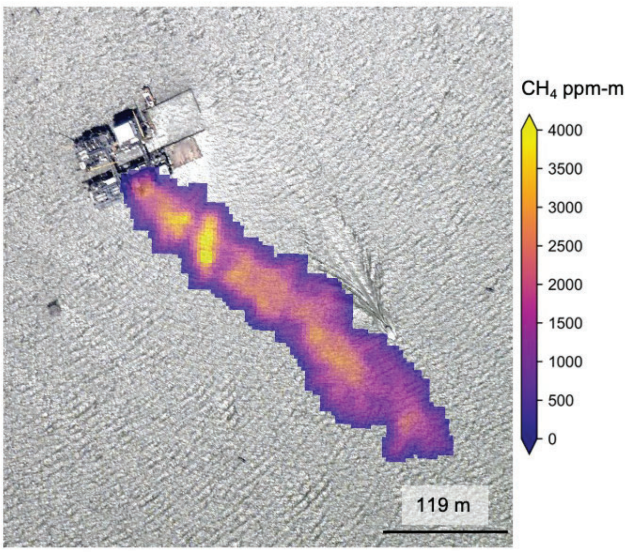

Figure 1: Methane plume observed from GAO with an estimated emission rate of 2510.4 ± 374.5 kg hr^{-1}. The plume is overlaid on the GAO high resolution true color camera image.

Building a validation support service for CO2M and other GHG satellite missions

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The success of a satellite mission is critically dependent on its ability to reach the targeted accuracy and precision requirements set for the mission. A well-developed calibration and validation concept for the mission is key to ensure verification and traceability to in-situ reference measurements. In the framework of the Copernicus CO2M mission, we are developing a service to support the cal/val concept. As a first task, we are doing an assessment of existing ground-based datasets relevant for continuous cal/val and monitoring of CO2M products, and the availability of complementary parameters, which influence the target measurand. We created a modular dynamic database describing the station characteristics, key instrument parameters, available data products and their quality, and network characteristics. The database is stored as a NetCDF file and can be accessed using an oPeNDAP interface with the possibility to request the parameters, filter and select variables via a web-based interface in json or ascii output. We created a web-based interface to project on a global map, level-3 files (gridded level-2 files) of target gases from satellites (e.g., S5P CH4, S5P NO2, OCO-2 CO2), emission inventory databases, make comparisons with each other, and over-plot the station list with parameters from the database. The service will facilitate the users to get an overview of the available measurements with respect to emission hot-spots, suitability of adding additional measurements at certain locations considering the criticality of emission, co-emitted species and pollution levels, and assist in identifying locations to fill observational gaps in the currently existing measurements networks. In this presentation, we will provide an overview of the service implemented on behalf of EUMETSAT for the CO2M mission, which is also useful for other satellite missions and for the scientific community.

Keywords: Greenhouse gases, station database, satellite validation, emission inventories, CO2M

Non-local metrics applied to the comparison of CO_2 plumes and their sensitivities to mesoscale meteorology.

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The next spectral image monitoring instruments from ESA missions like CO2M will provide spatial observations of CO_2 plumes. These new instruments have a large swath and 4 km^2 resolution allowing the monitoring of city plumes. Local metrics are, however, prone to heavily penalising small offsets between images which is known as the double penalty issue. This makes local metrics not always well suited for plume comparison within an emission inversion framework.

Therefore, we propose to use non-local metrics inspired by optimal transport and the Wasserstein distance. Such metrics have the advantage to treat plumes as coherent objects and hence to avoid the double penalty issue. Furthermore, these new metrics developed here are split into several terms that can be related to errors in source location, wind field, emission rate, and whose respective contributions to the global metric can be evaluated.

A sensitivity study with respect to these error sources is carried out for each metric. To this end, a large catalogue of realistic CO_2 plumes is built. The ultimate goal here is to discuss which metrics is the best suited to reduce the sensitivity of the comparison with respect to errors in the mesoscale wind field.

Keywords: inverse problem, optimal transport, pollutant plume

CO2 plume detection using deep neural networks: application to synthetic images of the XCO2 field over the Paris area

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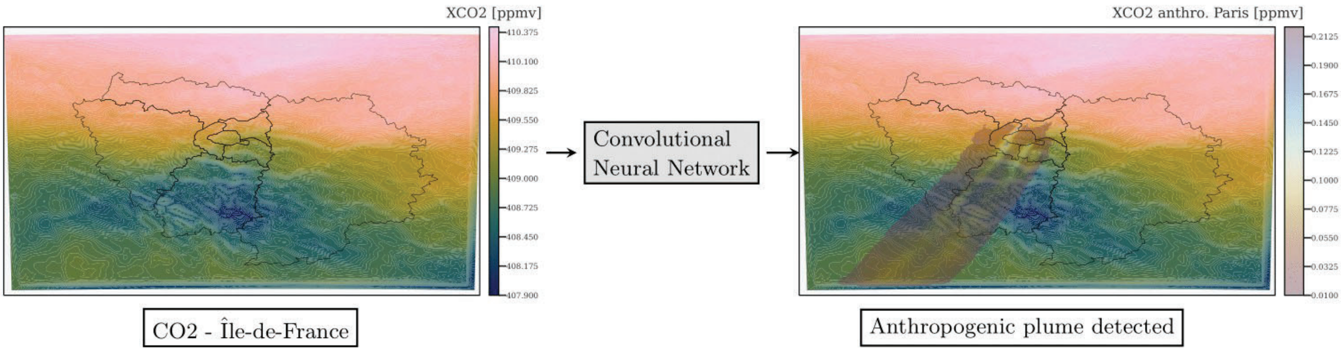
Carbon dioxide emissions are the main driver of climate change. Current estimates, which are needed to guide reduction policies, rely on statistical data of energy consumption and are subject to important uncertainties.

In order to assess these emissions in an independent, timely and accurate manner, the Copernicus CoCO2 project aims to build a prototype system for a CO2 emission monitoring service exploiting atmospheric CO2 measurements. As part of this project, our goal is to build a inverse modelling system to improve the quantification of CO2 sources of large magnitude at urban scale based on the spaceborne imagery of the CO2 atmospheric plumes from these sources.

The reconstruction of such sources depends on the detection of the associated plumes in the satellite images of the CO2 average column concentrations (XCO2), which represents a significant challenge. Indeed, the signal of CO2 plumes induced by cities emissions is intrinsically difficult to detect since it rarely exceeds values of a few ppm and is perturbed by variable regional CO2 background signals.

To tackle the problem of CO2 plume detection, we investigate the potential of deep learning methods. Neural networks are trained on hourly simulated XCO2 fields in the region of Paris, tracing the plume from Paris and other biogenic and anthropogenic fluxes and are applied on two problems.

In a first step, convolutional neural networks are trained to predict the presence of the CO2 plume from Paris in an image. The impact of using additional input information such as meteorological conditions or temporal variations is studied and the performance of the networks is evaluated. We show that plumes are almost always detected, with an accuracy greater than 95%. In a second step, we examine the possibilities of using neural networks specialised in semantic segmentation to the more ambitious problem of defining the plume contour.



Keywords: CO2, Convolutions, Neural Networks, Detection, Plume

CO2 Budget (2015-2020) constrained by space-based and ground-based atmospheric CO2 data in support of the Global Stocktake

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Accurate accounting of carbon stock changes is critical for the planning and verification of emission reduction targets in support of the Paris Agreement. Here, we present a pilot top-down dataset of net carbon exchange (NCE) and terrestrial carbon stock changes (driven by a combination of anthropogenic and natural drivers) aimed at informing country carbon budgets. These data are based on top-down NCE estimates from version 10 of the Orbiting Carbon Observatory (OCO-2) modeling intercomparison project (MIP), which includes flux estimates from an ensemble of inverse modeling systems that conduct standardized experiments assimilating OCO-2 column-averaged dry-air mole fraction (X_{CO2}) retrievals, in situ CO_2 measurements, or combinations of these data. The OCO-2 MIP NCE estimates are combined with bottom-up estimates of fossil fuel emissions and lateral carbon fluxes to estimate changes in terrestrial carbon stocks. These data are reported as annual fluxes over 2015-2020 and are provided as both a global 1°x1° gridded dataset and as country-level datasets. We discuss the state of the science for

tracking changes in carbon stocks using top-down methods, including current limitations and future developments towards top-down monitoring and verification systems.

Keywords: maximum OCO-2, Model Intercomparison, Global Stocktake

Using Remote Sensing to Detect and Mitigate Methane Plumes in California

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Satellite data has been used by the academic community to quantify the presence of greenhouse gases and other air pollutants over large areas. New satellites are starting to have sufficient spatial resolution to where individual emissions sources can be identified. This is less useful for overall stock take but can play a critical role in identifying and mitigating individual leaks. Specifically, these remote sensing technologies hold promise to enable the detection of methane plumes at a frequency and scale not considered feasible with traditional boots-on-the-ground methods, thus making these new satellites an attractive tool for regulatory agencies. In California, pilot studies (airborne campaigns) with a hyperspectral imager, which can image and locate individual plumes, have shown that these plumes exist in our infrastructure, and that often the emissions are unintentional and can be easily fixed if operators are made aware of them. In California this concept has been demonstrated with several airborne campaigns whereby California Air Resources Board staff worked closely with partners in industry. In this presentation we will describe the specifics of the mitigation efforts, show results from the airborne campaigns, and discuss the work being done to prepare for the launch of two satellites that will deliver this type of data regularly.

Keywords: methane, plumes, mitigation

Linking regional to global greenhouse gas budgets in RECCAP2

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Keeping global warming below 2°C by the end of the century, in line with the Paris Agreement, requires rapid reductions in greenhouse gas (GHG) emissions to reach net-zero emissions in the coming decades. The remote sensing measurements from space are leading to swift progress on GHG monitoring capabilities in order to link global growth rates of key GHGs to their sources/sinks at regional and national scales. Some of the regions in the tropics and nations in economic transition are typically devoid of high accuracy in situ measurements. Joint use of atmospheric measurements and models, in addition to the inventory accounting systems are moving toward robustly separate anthropogenic from natural fluxes and to provide low latency information about the progress towards climate change mitigation targets.

The second REgional Carbon Cycle Assessment and Processes (RECCAP2) activity of the Global Carbon Project aims to provide accurate information on regional sources and sinks of the three main greenhouse gases (CO_2, CH_4 and N_2O) for the decade 2010-2019. Activities target: Regional budgets for ten large land regions and six ocean regions that together cover the entire globe; several 'special focus' areas such as rapidly changing regions (permafrost and polar regions); the Land-Ocean Aquatic Continuum and lateral trade fluxes; the ocean's biological carbon pump; and future trends in regional GHG budgets. This effort is fueled by an ever-expanding constellation of in-situ and satellite-based GHG observations, and by increased process-based and data-driven modelling capabilities.

In RECCAP2, state-of-the-art datasets and modelling tools are being used to provide robust estimates of regional GHG budgets and constrain their uncertainties. Here, we will provide an overview of ongoing RECCAP2 activities, including progress regarding the harmonization of different approaches to estimate GHG budgets and showcase recent results for key regions.

Keywords: RECCAP2, regional CO_2, CH_4 and N_2O budget, top-down estimation, bottom-up estimation

A Role for Space-based CO_2 and CH_4 observations in Greenhouse Gas Emissions Monitoring

David Crisp

Crisp Spectra LLC

Over the past decade, space-based remote sensing of CO_2 and CH_4 have come of age with Japan's GOSAT and GOSAT-2, NASA's OCO-2 and OCO-3, China's TanSat and Europe's Sentinel 5 Precursor. Their data are now yielding estimates of XCO_2 with accuracies near 1 ppm and XCH_4 with accuracies near 15 ppb on regional scales. These data are not as accurate as those from surface and airborne sensors, but complement their measurements with increased resolution and coverage. Top-down atmospheric models, including global and regional-scale inverse models and discrete plume models have also advanced rapidly to better exploit the denser, but less accurate space-based products.

These data and models are now providing useful tools for monitoring atmospheric CO_2 and CH_4 sources and sinks. They are also attracting the attention of policy makers seeking ways to manage their greenhouse gas (GHG) emissions to mitigate the impacts of climate change and meet their UNFCCC reporting requirements. Those reports employ bottom-up inventories of emissions and removals GHGs from specific economic categories and sectors. These inventories provide accurate, actionable data in categories such as fossil fuel use for energy, where activity data and emission factors are well understood, but are less reliable in the Agriculture, Forestry, and Other Land Use (AFOLU) sector, where activity data and emission factors are more difficult to quantify. They also neglect emissions changes on unmanaged (natural) land and oceans. For these reasons, policy makers and other stakeholders and asking how atmospheric GHG data can be combined with bottom-up inventories to produce more complete and accurate global stocktakes. As we started to address this question, we identified additional capabilities needed by existing GHG missions and models. Some of these are addressed by future missions (GOSAT-GW, GeoCarb, CO2M), while others are not. This presentation will assess our progress and identify gaps needing attention.

Advancing Arctic-Boreal carbon cycle science using OCO-2 retrievals

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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, especially in the northern high latitudes (i.e., circumpolar Arctic and Boreal region North of approximately 50° latitude). This lack of understanding of Arctic-Boreal carbon cycle dynamics can be directly attributed to the limited constraint provided by atmospheric CO_2 measurements, both in terms of quantity (only a limited number of in situ observations are available) and quality (large biases in retrievals from space-based sensors such as GOSAT and OCO-2). In this presentation, we will discuss recent progress made in improving the quantity and the quality of retrievals over the Arctic-Boreal region from NASA's OCO-2 mission. These retrieval improvements relate to both refinement of the filtering and bias correction approach, and modification to the core Atmospheric CO_2 Observations from Space (ACOS) retrieval algorithm by incorporating a new BRDF model that captures snow surface reflection, polarization and spectral dependence at different wavelengths for snow & ice-covered surfaces. Validation against measurements from high latitude TCCON sites and EM27/Sun sites will be presented. In our talk, we will also highlight the potential value of these high-density satellite retrievals for constraining the magnitude and spatiotemporal distribution of carbon flux patterns during the shoulder seasons (Mar – May, Sep – Nov). Our results clearly illustrate that space-based observations have the potential to provide better insight into the most sensitive parts of the Arctic-Boreal carbon cycle system, i.e., parts of the system in which carbon cycle responses will lead to substantial positive, or modifications of negative feedbacks, to the climate system. We will finally conclude with how knowledge gained from our retrieval developments will be valuable beyond a single mission (i.e., OCO-2) and aid retrievals from future missions with similar aspirations (JAXA GOSAT-GW and ESA CO2M).

Keywords: NASA OCO-2, Arctic-Boreal carbon flux, snow/ice retrievals, snow BRDF

XCH4 retrieval from MethaneAIR using the CO2-Proxy Approach: First results over major US oil and gas basins

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MethaneAIR is the airborne precursor to MethaneSAT, an upcoming satellite mission commissioned to quantify methane emissions from the global oil and gas (O&G) sector. With near identical instrument specifications to MethaneSAT, it has been designed as a testbed for the satellite's data processing algorithms prior to launch, which is expected to be mid next year. MethaneAIR also serves as a unique observing mission in itself, capable of mapping accurate column averaged dry air methane mole fractions (XCH4) over a typical O&G basin at 5x25 m^2 spatial resolution using just a few hours of flight time.

Here we present XCH4 retrieval results from the second campaign of MethaneAIR, conducted onboard the NSF/NCAR HIAPER GV aircraft. The campaign concluded in August 2021, and surveyed the Bakken, Uintah, and Permian O&G production regions. The retrieval is based on the CO2-proxy approach, targeting the CO2 and CH4 absorption bands at 1.61 and 1.65 microns respectively, and will be the primary approach used for the satellite mission. We show validation of the MethaneAIR XCH4 retrievals using comparisons of aircraft overpasses of ground based EM27 observations, and colocated TROPOMI XCH4 data. We then estimate MethaneAIR's point source detection limit based on its observed precision and a set of WRF large-eddy simulations. Finally we show methane emission source attribution and quantification highlights from the first basin-scale surveys, and discuss implications for the upcoming satellite mission.

An analysis of GOSAT-TIR observation sensitivity to the near-surface CH_4

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The Thermal and Near Infrared Sensor for Carbon Observation Fourier-Transform Spectrometer (TANSO-FTS) onboard the Greenhouse gases Observation SATellite (GOSAT) detects CH_4 absorption spectra in the solar short wave infrared (SWIR) and the thermal infrared (TIR) bands. The SWIR observations provide information on column-averaged CH_4 (XCH_4) in cloud-free conditions during the daytime satellite overpass. The TIR observations are also carried out at night and in cloudy conditions providing much greater geographical and temporal coverage and resolving the vertical profiles of CH_4 at 22 retrieval levels. The sensitivity of TIR CH_4 observations is stronger in the mid to upper troposphere and relatively low near the surface because its spectral signatures depend on thermal contrast between the atmosphere and surface. Nevertheless, the TIR instrument has sufficient sensitivity to provide critical information about the CH_4 distribution at the top of the boundary layer.

In this work, we examined the TIR CH_4 variability in comparison with ground-based observations from the World Data Centre for Greenhouse Gases (WDCGG), and simulations by MIROC4.0-based Atmospheric Chemistry Tracer Model (MIROC4-ACTM) for the period 2009–2014. We studied the sensitivity of the TIR retrievals at the near-surface layers (950-850 hPa) of the atmosphere on the basis of the prior assumptions. Comparison with the monthly, daily, and hourly measurements showed that GOSAT TIR observations have a sufficiently high density of observations to detect the variability of CH_4 at different time scales. A good improvement has been achieved with respect to the GOSAT prior CH_4 for remote and coastal sites located mainly in East Asia, North America, and Europe. These achievements increase the reliability and confidence of the global distribution of GOSAT TIR CH_4 and the possibility of its application for the validation of three-dimensional methane products.

Keywords: GOSAT, thermal infrared band, CH_4, WDCGG, MIROC4-ACTM

Satellite-based detection of methane plumes from offshore platforms

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Mitigation of methane emissions from fossil fuel extraction, processing and transport is one of the most effective ways to slow global warming. Satellite methods are being instrumental for the detection, characterization, and quantification of methane plumes from fossil fuel sources. However, despite the rapid development of satellite-based methane plume detection methods for terrestrial surfaces, there is still an important observational gap with respect to offshore oil and gas infrastructure, which accounts for roughly 30% of global production. In this contribution, we will show results from recent work on the use of satellites for the detection of methane plumes from offshore oil and gas extraction platforms. We use data from high-resolution satellites sensitive to methane, including WorldView-3, Sentinel-2, Landsat and PRISMA (3.7-30 m/pixel). The satellite data are acquired in the shortwave infrared under a close-to-sunglint observation configuration, which is needed to enhance the amount of solar-reflected radiation reaching the sensor. We will show plume detections at a number of offshore platform areas around the world, including the Gulf of Mexico, the Gulf of Guinea, the Caspian Sea and Malaysia. In particular, we will show how data from WorldView-3 and Landsat have been used to investigate a 17-day ultra-emission event happened in December 2021 at an offshore platform in the Gulf of Mexico. These results pave the way for the systematic detection and attribution of methane emissions from offshore platforms.

Keywords: methane emissions, offshore platforms, high-resolution satellite data, plume detection

Evaluating OCO-2 & OCO-3 Retrospective Calibration Using Dark, Lamp, and Science Spectra

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The Orbiting Carbon Observatory 2 and 3 (OCO-2, OCO-3) instruments, launched in 2014 and 2019 respectively, have the primary objective to measure the column-average dry air mole fraction of carbon dioxide. Each instrument consists of three long-slit imaging grating spectrometers that share a common entrance telescope. The three spectral channels are centered near 765, 1607, and 2063 nm. Many radiometric and spectral calibration coefficients were determined preflight and do not change. Dark correction, gain degradation, and spectral dispersion are regularly adjusted using on-orbit calibration and science measurements. These updates are delivered frequently in two different data streams. Forward calibration, delivered weekly, extrapolates training data from the previous week, while retrospective calibration interpolates within slightly shorter periods. As it can be difficult to assess the quality of calibration coefficients in isolation, a series of test products is generated and reviewed before they are accepted for production. First, dark measurements, after applying calibration, should have radiances near zero and be spectrally smooth. Second, lamp measurements should be spectrally smooth and should change continuously with time. Third, science data is are analyzed with the Atmospheric CO_2 Observations from Space (ACOS) Level 2 Full Physics retrieval algorithm, ideally one orbit each in both Nadir and Glint modes. At all steps, spectrally dependent artifacts are of particular concern. This presentation will describe how this process helped identify refinements to increase the accuracy and goodness of fit of the retrieval. The most common improvement was to mark bad spectral samples to be ignored, especially for OCO-2.

Keywords: calibration, retrieval, bad pixels, OCO-2

Retrieval of solar-induced chlorophyll fluorescence (SIF) from satellite measurements: comparison of SIF between TanSat and OCO-2

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Solar-induced chlorophyll fluorescence (SIF) is emitted during photosynthesis in plant leaves. It constitutes a small additional offset to reflected radiance and can be observed by sensitive instruments with high signal to-noise ratio and spectral resolution. The Chinese global carbon dioxide monitoring satellite (TanSat) acquires measurements of greenhouse gas column densities. The advanced technical characteristics of the Atmospheric Carbon dioxide Grating Spectrometer (ACGS) onboard TanSat enable SIF retrievals from observations in the O2-A band. In this study, 1-year of SIF data was retrieved from Orbiting Carbon Observatory-2 (OCO-2) and TanSat measurements using the Institute of Atmospheric Physics Carbon Dioxide Retrieval Algorithm for Satellite Remote Sensing (IAPCAS)/SIF algorithm. A comparison between the IAPCAS/SIF results retrieved from OCO-2 spectra and the official OCO-2 SIF product (OCO2_Level 2_Lite_SIF.8r) shows a strong linear relationship ($R^2 > 0.85$) and suggests good reliability of the IAPCAS/SIF retrieval algorithm. Comparing global distributions of SIF retrieved by the IAPCAS/SIF from TanSat and OCO-2 shows the same spatial pattern for all seasons with a gridded SIF difference of less than 0.3 W m^{-2} μm^{-1} sr^{-1} . The global distributions also agree well with the official OCO-2 SIF product with a difference of less than 0.2 W m^{-2} μm^{-1} sr^{-1}. The retrieval uncertainty of seasonally gridded TanSat IAPCAS/SIF is less than 0.03 W m^{-2} μm^{-1} sr^{-1}, whereas the uncertainty of each sounding ranges from 0.1 to 0.6 W m^{-2} μm^{-1} sr^{-1} . The relationship between annually averaged SIF products and FLUXCOM gross primary productivity (GPP) was also estimated for six vegetation types in a $1^\circ \times 1^\circ$ grid over the globe, indicating that the SIF data from the two satellites have the same potential in quantitatively characterizing ecosystem productivity. The spatiotemporal consistency between TanSat and OCO-2 and their comparable data quality enable joint usage of the two mission products. Data supplemented by TanSat observations are expected to contribute to the development of global SIF maps with more spatiotemporal detail, which will advance global research on vegetation photosynthesis.

Keywords: SIF, TanSat, OCO-2, retrieval algorithm, comparison

An overview of the new and improved OCO-3 ACOS v10 XCO_2 data product

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Since its launch on May 4, 2019, the OCO-3 instrument has collected millions of CO_2 observations globally, including dense, fine-scale XCO_2 Snapshot Area Mapping mode (SAMs) observations of emission hotspots like cities, power plants, and volcanoes. Evaluating these space-based measurements against independent data sets provides information about the quality, potential biases, and errors in the OCO-3 data. Here, we present comparisons of the new and improved OCO-3 v10.4 data version against groundbased measurements from the Total Carbon Column Observing Network (TCCON). We focus on comparisons over land in nadir, target, and SAM mode and discuss sitedependent biases between OCO-3 and TCCON (GGG2020). The improved v10.4 data version reduces an XCO_2 time-dependent bias that was present in the previous data version. Further, we evaluate differences between OCO-3 and TCCON related to different local overpass times which informs about potential airmass and viewing geometry related biases. Finally, we analyze how well OCO-3 captures the mean seasonal cycle amplitudes and growth rates over selected TCCON sites. The OCO-3 v10.4 data product is a vast improvement over earlier OCO-3 data versions and is of comparable quality to the OCO-2 v10 data.

Using the O_2 column from the O_2 singlet delta band to derive proxy XCH_4 from MethaneAIR observations

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The area-mapping MethaneSAT satellite will aim to estimate CH_4 oil & gas emissions from over 80% of emitters. It will use one spectrometer to retrieve CH_4 from a window centered at 1.66 μm, and CO_2 from a window centered at 1.61 μm, and a second spectrometer to retrieve O_2 and surface pressure in a window centered at 1.27 μm. MethaneAIR is the airborne simulator for the MethaneSAT satellite, its observations are used to test the retrieval algorithms that will be used to process MethaneSAT data. We will present MethaneAIR Level 2 results (trace gas concentrations derived from observed spectra) obtained with the "proxy" method.

A "proxy" retrieval does not include the effect of aerosols on the light path in the forward model, it instead uses the column of another gas retrieved from a band spectrally close to the target gas as proxy for the aerosol-induced light path changes, assuming that they are similar in the two neighboring spectral regions. Typically, CO_2 has been used as the proxy species for XCH_4, but the variability in the modelled XCO_2 can introduce biases, especially over targets with sources of both CH_4 and CO_2. We investigate the use of the O_2 column from the O_2 singlet delta band to derive proxy XCH_4. XO_2 (~0.2095) is much less variable than XCO_2. However, the O_2 window is more spectrally distant from the CH_4 window than the CO_2 window, making the O_2 proxy more sensitive to aerosols. Unlike MethaneAIR, MethaneSAT observations in the O_2 window will be affected by airglow. We will investigate the effect of aerosols and airglow on the variability of the retrieved O_2 column.

Validation of TROPOMI Methane in the GeoCarb Domain

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The GeoCarb mission will make geostationary observations of CO2, CH4, CO, and SIF over Western Hemisphere land (50S-50N, 20W-125W), launching in 2024. In preparation for validation of GeoCarb, we compare validation of TROPOMI CH4 within the GeoCarb domain to the global validation of TROPOMI. We use the bias corrected v1 RemoTeC CH_4 product downloaded from GES DISC, described in Lorente et al. (2021). To estimate systematic error, both correlated error and regional bias error are added in quadrature, and co-location error (model at satellite vs. model at validation) and validation error (systematic error of validation estimates) are subtracted in quadrature. We compare validation versus GGG2020 global TCCON ("the gold standard"), TCCON within the GeoCarb domain (4 sites), and NOAA Global Monitoring Laboratory and DOE aircraft observations extended by the CAMS CH4 model in the GeoCarb domain (8 sites). We find systematic error estimates versus global TCCON, North American TCCON, and aircraft give consistent results with error estimates differing by less than 2 ppb.

Keywords: TROPOMI, Methane, GeoCarb, TCCON, Aircraft

Evaluation of XCO_2 estimates from OCO-2 and OCO-3 observations using the NASA ACOS version 10 retrieval algorithm

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Keywords: ACOS, retrieval, XCO_2, OCO-2, OCO-3

The version 10 (v10) Atmospheric Carbon Observations from Space (ACOS) Level 2 Full Physics (L2FP) retrieval algorithm has been applied to multi-year records of observations from NASA's Orbiting Carbon Observatory -2 and -3 sensors (OCO-2 and OCO-3, respectively) to produce estimates of the column-averge dry-air mole fraction of carbon dioxide (XCO_2). OCO-2 has been providing science measurements from a sun-synchronous polar orbit with an approximately 13:30 local overpass time since September of 2014, while OCO-3 has been operating in a precessing orbit from the International Space Station (ISS) since August of 2019, providing varying time-of-day sampling.

Although there are significant differences between OCO-2 and OCO-3 geolocation methodologies, and spectral and radiometric calibration techniques, the XCO_2 estimates are produced from Level 1b measurements using similar pre- and post-processing, i.e., cloud screening, quality filtering (QF) and bias correction (BC), as well as the same version (v10) of the L2FP retrieval algorithm. The shared heritage of the two sensors and the processing pipeline provides an ideal case for intercomparisons of the XCO_2 estimates.

Spatiotemporal analysis of the global XCO_2 products for the overlapping time period highlights both similarities, a reflection of shared heritage, and differences, driven mainly by differing orbit and sampling characteristics. A subset of several hundred clusters of soundings, tightly collocated in time and space was used to assess agreement in the XCO_2 estimates. Initial results showed a time-dependent divergence, which was found to be highly correlated against OCO-3 zero-level-offset in the weak CO_2 spectral band (First 4 panels of Figure 1). After application of a post-hoc correction to the OCO-3 v10 bias corrected XCO_2 (now L2Lite v10.4), the products show good agreement with no detectable time trend (Panel 5 of Figure 1). Comparisons of the satellite XCO_2 estimates (v10 for OCO-2, and v10.4 for OCO-3) to those derived from atmospheric inversion systems show qualitatively similar results (Figure 2).

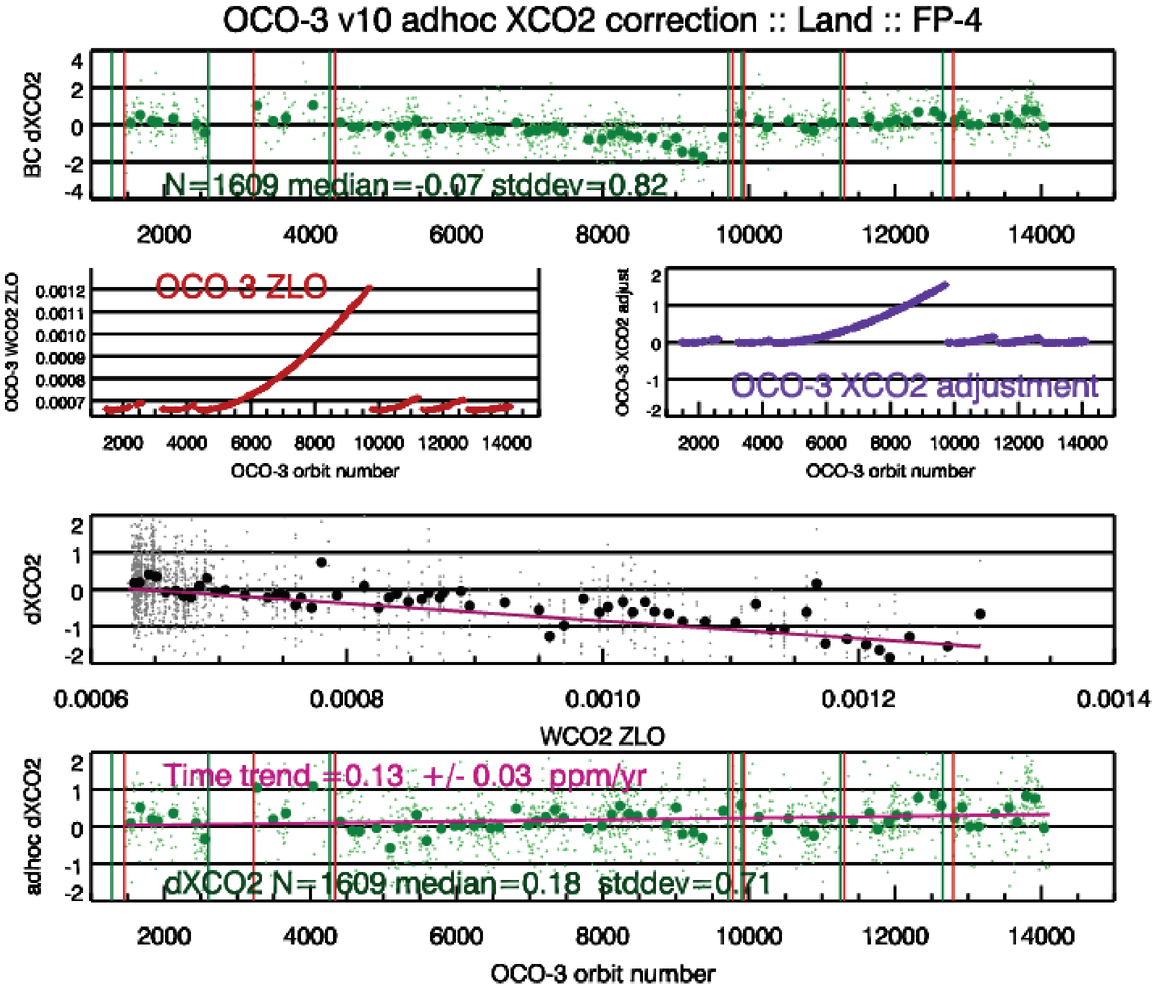

Figure 1. Correction of OCO-3 v10 XCO_2 estimates using the correlation between ΔXCO_2 (OCO-3 minus OCO-2 for tightly collected clusters of soundings) and the zero-level-offset in the weak CO_2 spectral band. Results shown for footprint 4 (of 8) and Land soundings.

2

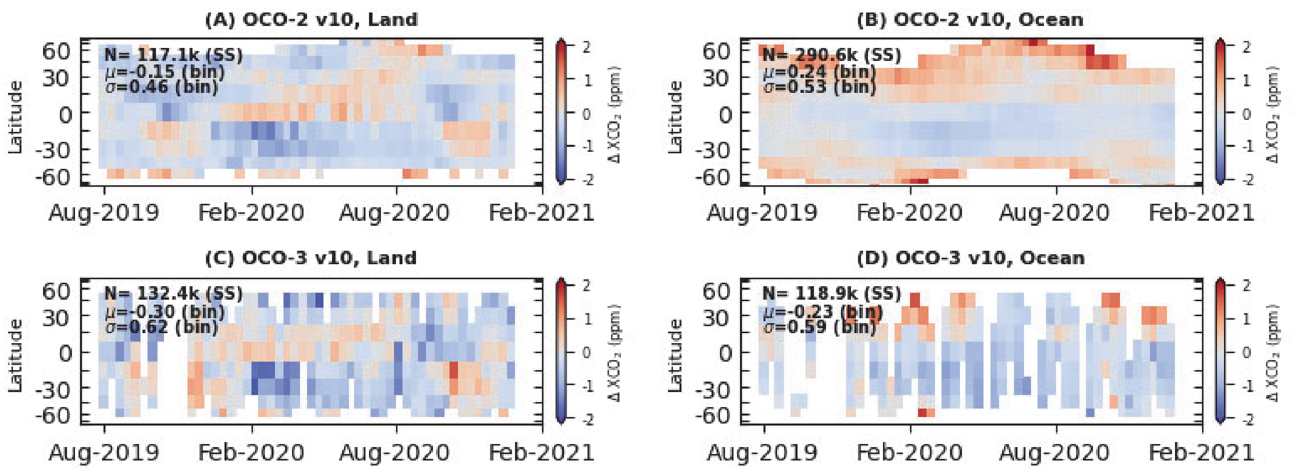

Figure 2. Comparison of v10 XCO_2 from OCO-2 (top) and OCO-3 (bottom) against model-derived XCO_2 for Land (left) and Ocean (right).

3

Overview of GOSAT-GW TANSO-3 data processing and product distribution in NIES

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Global Observing SATellite for Greenhouse gases and Water cycle (GOSAT-GW) is a polar-orbiting satellite, which is the 3rd flight unit of the GOSAT series. One of the mission instruments is named Total Anthropogenic and Natural emissions mapping SpectrOmeter-3 (TANSO-3) and aims to observe greenhouse gases (GHGs) such as carbon dioxide (CO_2) and methane (CH_4), nitrogen dioxide (NO_2), solar-induced fluorescence (SIF), and so on. The TANSO-3 instrument data received by ground stations is transmitted to and processed by Japan Aerospace Exploration Agency (JAXA) to create Level 1 products. NIES is responsible for processing TANSO-3 Level 2 products from JAXA's L1 products and storing and delivering all products of the TANSO-3 mission. Currently, three ground data processing systems are being developed by NIES according to the satellite launch schedule in the Japanese Fiscal Year of 2023: 1) GOSAT 3rd generation Data Processing/operating System (G3DPS) for product handling, storage, and publishing, 2) GOSAT-GW NO2 Data Processing System (GNDPS) for processing NO_2-related L2 products on cloud infrastructure service, and 3) GOSAT operational and research Computing Facility (GOCF) as large-scale computing resources for GHG-related L2 product processing. Because the TANSO-3 instrument provides GHG observation results with 100 times more observation points than those from the first two GOSAT-series satellites, a significant speedup of GHG retrieval processing is required as part of the system development. We are also in the process of formulating data policies and user policies for the release of TANSO-3 products. Observations by TANSO-3 are performed by switching between two imaging modes: Wide Mode at 10 km resolution and Focus Mode at resolutions of 3 km or less. Optimizing the exclusive use of the two modes in the TANSO-3 observation sequence is one of the considerations.

Keywords: GOSAT-GW, satellite data products, ground system, high performance computing, cloud computing

MethaneSAT: A new approach to quantifying area and point source methane emissions

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The MethaneSAT mission (launch ready in Q2 2023) intends to revolutionize the measurements and modeling of CH_4 emissions across the globe. Commissioned by MethaneSAT LLC, a subsidiary of the Environmental Defense Fund, MethaneSAT has been designed to systematically map and quantify CH_4 emissions from regions accounting for over 80% of global oil and gas production. The primary objective is motivating and enabling rapid emission reductions. Secondary objectives include observations of agricultural and urban areas.

The mission aims to fill the critical data gap between global mapping satellites (low spatial resolution, moderately high precision), and point-source missions (high spatial resolution, but small field of view and low precision). MethaneSAT's target observations will consist of a wide observing swath (~220 km @ nadir), a high spatial resolution (~100 m x 400 m), and a low detection threshold (~2 – 4 ppb precision @ 1.5 km^2) which will enable quantification of both concentrated as well as diffuse area-aggregate emissions associated with oil and gas production regions.

Over the past year substantial progress has been made in assembly, integration, and testing of MethaneSAT's two imaging spectrometers built by Ball Aerospace. Integration with the platform bus supplied by Blue Canyon Technologies will commence in Q3 2022 followed by flight-system level characterization and calibration activities. An airborne precursor instrument, MethaneAIR, was successfully deployed in July/August 2021 aboard the NSF/NCAR Gulfstream V and produced nearly 50 hours of atmospheric observations. These measurements have been used to develop and challenge the trace gas retrievals and flux algorithms needed to complete the MethaneSAT mission. Future flights of MethaneAIR are planned to map additional US oil and gas production regions, measure emissions from a large selection of landfills, and, post-launch, participate in MethaneSAT validation activities.

Keywords: MethaneSAT, methane

Operational product processing developments for the Copernicus anthropogenic CO_2 Monitoring (CO2M) mission

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As part of the Copernicus Programme of the European Commission, the European Space Agency (ESA) and the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) are expanding the Copernicus Space Component to include measurements for anthropogenic CO_2 emission monitoring. The greatest contribution to the increase in atmospheric CO_2 comes from emissions from the combustion of fossil fuels and cement production. In support of well-informed policy decisions and for assessing the effectiveness of strategies for CO2 emission reduction, uncertainties associated with current anthropogenic emission estimates at national and regional scales need to be improved. Satellite measurements of atmospheric CO_2, complemented by in-situ measurements and bottom-up inventories, will enable, by using advanced (inverse) modelling capabilities, the transparent and consistent quantitative assessment of CO_2 emissions and their trends at the scale of megacities, countries, and at global scale.

This presentation provides an overview of the status of the CO_2M operational mission data processing sub-segment (MDPS) developments ongoing at EUMETSAT. We will describe the milestones for implementing the full operational processing chain, which aims at maximising the available information content for the CO_2, Methane and NO_2 retrievals by combining the measurements from all three instruments on-board CO2M (the CO2/NO2 push-broom grating spectrometer (CO2I/NO2I), the Multi Angle Polarimeter (MAP), and the Cloud Imager (CLIM)). Key characteristics of top-of-atmosphere test data for all three instruments will be using realistic orbit scenarios based on a common atmosphere and common surface modelling.

In addition, we present the latest status on the centralised processing approach of MAP, CLIM and auxiliary data, co-located, co-registrated, and/or aggregated to the main CO2I/NO2I instrument footprint, and by this facilitating the creation of a three-sensor hyper-instrument for use in the downstream operational retrieval of GHG and NO_2 total column concentrations.

Keywords: CO2M, CO2, monitoring, products, processing

Overview on the proposed Arctic Observing Mission (AOM)

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The Arctic Observing Mission (AOM) is a satellite mission concept that would use a highly elliptical orbit (HEO) to enable frequent observations of greenhouse gases (GHGs), air quality, meteorological variables and space weather north of the usable viewing range of geostationary (GEO) satellites. AOM evolved from the Atmospheric Imaging Mission for Northern Regions (AIM-North) with and expansion of scope. AOM is envisioned as a Canadian-led mission to be implemented with international partners. AOM is currently undergoing a pre-formulation study to refine options for the mission architecture and advance other technical and design aspects, investigate socio-economic benefits of the mission and better establish the roles and contributions of partners. AOM would use an Imaging Fourier Transform Spectrometer (IFTS) with 4 near-infrared/shortwave infrared (NIR/SWIR) bands to observe hourly CO_2, CH_4, CO and Solar Induced Fluorescence spanning cloud-free land from ~40-80°N. The rapid revisit is only possible due to cloud avoidance using 'intelligent pointing', which is facilitated by the availability of real-time cloud data from the meteorological imager and the IFTS scanning approach. Simulations suggest that these observations would improve our ability to detect and monitor changes in the Arctic and boreal carbon cycle, including CO_2 and CH_4 emissions from permafrost thaw, or changes to northern vegetation carbon fluxes under a changing climate. This presentation will give an overview of AOM with a focus on the GHG instrument, its expected capabilities and its potential for carbon cycle science and monitoring.

Keywords: Arctic, boreal, imaging Fourier transform spectrometer, permafrost

MethaneSAT OSSE Simulation to Assess Errors in XCH_4 Derived From the CO_2 and O_2 Proxy Methods

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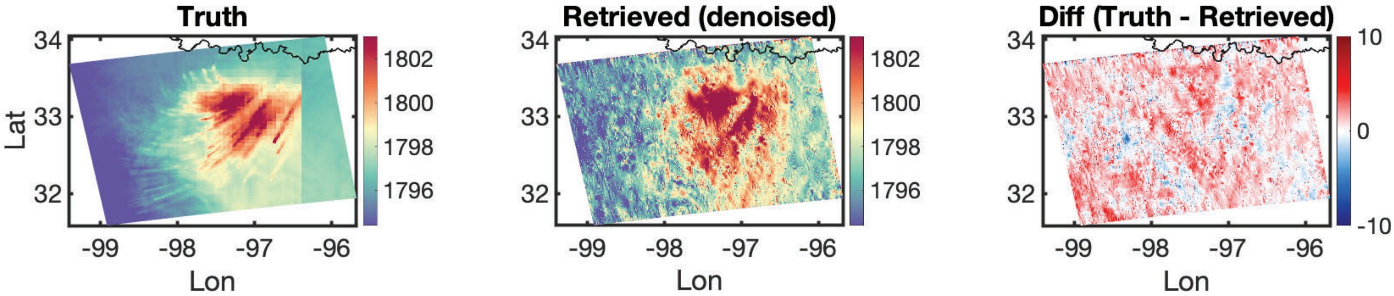
Abstract. An Observing System Simulation Experiment (OSSE) has been designed to systematically analyze and estimate the retrieval errors in XCH_4 for the upcoming MethaneSAT mission – a new earth-observing satellite under development by MethaneSAT, LLC, a subsidiary of the Environmental Defense Fund. Several case studies are generated at both regional and global scales. To account for a wide range of atmospheric conditions and surface properties, we incorporate dynamical inputs into the Smithsonian PLanetary ATmosphere interface to VLIDORT (SPLAT-VLIDORT) radiative transfer model to simulate radiances at MethaneSAT O_2 (1249–1305 nm) and CH_4 (1598–1676 nm) channels. These inputs include particle size distributions observed by AERONET, high-resolution anisotropic MODIS BRDFs, GEOS-FP reanalyses, and high-resolution CH_4 fields derived from a Lagrangian inverse modeling. We retrieve the total concentrations of CH_4, O_2, H_2O, and CO_2 without the consideration of multi-scattering (i.e., transmission only) from the simulated radiance with expected SNR levels. We then leverage the retrieved CO_2 and O_2 as light-path proxies to calculate XCH_4 and compare it to the true state of XCH_4 defined in the forward simulation. A primary advantage of the CO_2 proxy is the close proximity of the spectral absorption bands of CH_4 and CO_2 permitting non-scattering retrievals of XCH_4 in the presence of aerosols. The robustness in the retrieval O_2 proxy is inhibited by the presence of dust particles. Nonetheless, the O_2 proxy reveals a higher precision (18 ppbv at 100×400 m^2) and a lower bias (<1%) under specific aerosol conditions relative to the CO_2 proxy (26 ppbv at 100×400 m^2, 3%). Results encourage a development of a combined product that should provide more high-fidelity information than is possible when the proxy products are used individually.



Keywords: MethaneSAT, methane, OSSEs, errors

IAPCAS supports TanSat (-2) missions

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Since the first Chinese greenhouse gas monitoring satellite mission (TanSat) launched in 2016, the XCO_2, SIF and Carbon flux data has been produced and released to public. The next generation of TanSat mission has kicked off in early 2022 and will continued the name of Chinese global carbon dioxide monitoring satellite mission (TanSat-2). The aim of TanSat-2 mission will provide global coverage and fast repeat CO_2 and CH_4 measurement in a 2x2 footprint as well as pollution gas and contribute to Measurement, Verification Support (MVS) to Global Stocktake. Institute of Atmospheric Physics Carbon retrieval and inversion Algorithm System (IAPCAS) has been developed and obtain a series outcome such as XCO2 and SIF retrieval of TanSat mission. The IAPCAS is now developing toward a new evolution and servicing on TanSat-2 mission design (OSSE), and further application on retrieval and inversion.

Keywords: TanSat, retrieval, inversion, Greenhouse Gas, Carbon flux

Development of the MethaneSAT cloud and aerosol filter

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The MethaneSAT satellite mission aims at quantifying anthropogenic methane emissions by measuring reflected solar radiation in two spectral windows in the short wave infrared range. In the 1,249 nm - 1,305 nm spectral range the sensor will measure the oxygen (O2) singlet Delta band with a full width at half maximum (FWHM) of 0.17 nm. Additionally, the instrument will observe most of the 2v3 absorption band of methane (CH4) and a 3v1+v3 carbon dioxide (CO2) band in the spectral range 1,598 nm - 1,676 nm at a spectral resolution of 0.23 nm at FWHM. Clouds and aerosols can introduce biases into the inversion of methane column concentrations from solar backscatter measurements and we therefore develop retrieval processors to filter out contaminated scenes.

One processor makes use of surface pressure retrievals to infer the presence of scattering particles in the field of view of the sensor. These retrievals specifically take into account O2 airglow emission (see Sun et al. 2018). Surface pressure is retrieved by fitting spectra in the O2 band, assuming a non-scattering atmosphere. A complementary algorithm takes advantage of differences in the atmospheric light path between the two spectral windows of MethaneSAT in the presence of aerosols and clouds. Here, we retrieve water vapor (H2O) column concentrations from the 1.3 μm and 1.6 μm windows under the assumption of the geometric lightpath. We construct thresholds for both filters to identify aerosol and cloud contaminated scenes.

Both filtering approaches are applied to measurements of the MethaneAIR instrument (Staebell et al. 2021) to demonstrate their capacity in screening for clear scenes. In addition, we apply the cloud and aerosol processors to an ensemble of synthetic MethaneSAT scenes at realistic noise levels to evaluate their performance. Finally, we discuss our on-going efforts in developing a filter for observations affected by cloud shadows.

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The potential and feasibility of improved glint observations over snow for CO2M

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High latitudes pose significant challenges to reliable space-based observations of carbon dioxide. In addition to large solar zenith angles and frequent cloud coverage, snow-covered surfaces absorb strongly in the near-infrared wavelengths. Because of the resulting low radiances of the reflection measured by the satellite, the retrievals over snow may be less reliable and are typically filtered or flagged for potentially poor quality. Snow surfaces are highly forward-scattering and therefore the traditional nadir-viewing geometries over land might not be optimal and instead the strongest signal could be attainable in glint-like geometries. In addition, the contributions from the SWIR-1 (1.6 um) and SWIR-2 (2.0 um) CO2 absorption bands need to be evaluated over snow.

In this presentation, we will focus on the examination of the effects of a realistic, non-Lambertian surface reflection model of snow based on snow reflectance measurements on simulated top-of-atmosphere radiances in the wavelength bands of interest. The radiance simulations were carried out with various different viewing geometries, solar angles and snow surfaces. The effect of an optically thin cloud of ice crystals over snow is also investigated.

There are three main findings of the simulation study. Firstly, snow reflectivity varies greatly by snow type, but the forward reflection peak is present in all examined types and wavelength bands. Secondly, glint observation mode was found to be more reflective than nadir observation mode over snow surfaces across all the examined wavelengths bands and geometries. Thirdly, a simple information content analysis shows that glint-viewing geometries are significantly more informative than nadir-viewing geometries and that the SWIR-2 band is more informative than the SWIR-1 band over snow surfaces.

The study presented is part of the ESA SNOWITE project. The primary aim of the project is to support the development of the upcoming Copernicus CO2 Monitoring Mission (CO2M).

Keywords: Radiative transfer, high latitudes, CO2M, snow, BRDF

Solving scene inhomogeneity-induced errors without a slit homogenizer: application to GeoCarb

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A well-known cause of systematic errors in satellite-based measurements of trace gases is variations in brightness within a given scene. In particular, inhomogeneous illumination of a spectrometer slit can lead to distortions in the instrument spectral response function (ISRF). Because the ISRF is typically characterized pre-launch with detailed ground testing using an idealized setup with a fully illuminated slit, ISRF distortions caused by inhomogeneous slit illumination can lead to potentially large errors in trace gas retrievals from these instruments that assume the ISRF as part of the retrieval machinery. Scene inhomogeneity is typically caused by sub-scene variability in surface albedo and/or cloud features. Instruments like OCO-2 that are purposefully defocused can be insensitive to this effect. This effect was first widely studied for OMI retrievals of ozone and NO_2 and is also being studied for Sentinel-5P for methane and CO2M for multiple trace gases.

For instruments subject to this error source, one solution is to fly a so-called "slit homogenizer" that effectively scrambles the radiance pattern across the spectrometer slit. However, slit homogenizers have not yet been widely adopted and none have yet flown in space, though Sentinel 5 has installed a one-dimensional slit homogenizer and CO2M includes a two-dimensional homogenizer in its design. GeoCarb, a NASA geostationary greenhouse gas grating spectrometer planned for launch in late 2024, is also subject to these inhomogeneity-induced errors. The GeoCarb team recently decided to not fly a slit homogenizer, primarily due to a lack of sufficient technical maturity. In this presentation, we use detailed simulations of GeoCarb spectra including scene inhomogeneity to study this effect. We evaluate inhomogeneity-induced errors in the primary GeoCarb retrieval products of CO_2, CH_4, CO, and solar-induced fluorescence (SIF) using our standard retrieval and show how these errors can be significantly reduced with simple modifications to the retrieval algorithm. We also evaluate how prior information on the underlying scene inhomogeneity could be used to further reduce these errors.

Satellite (GOSAT-2 CAI-2) and surface (ARFINET) observations of Aerosol Black Carbon over India: Regional and Global Inferences

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The light-absorbing Black Carbon (BC) aerosols have very sensitive role in affecting the Earth's radiation budget and climate. In this study, we present the regional distribution of BC over India based on simultaneous observations of aerosol and surface properties by Cloud and Aerosol-Imager-2 (CAI-2) on-board Greenhouse gases Observing Satellite-2 (GOSAT-2). To evaluate and validate the spatio-temporal distribution of BC from satellite (CAI-2) retrieval, near surface BC mass concentrations measured across a network of aerosol observatories (ARFINET) over India are used and the findings are extended to understand the global BC features. Considering the limited spatial coverage of ground-based point-measurements as well as the biases in model simulated BC due to the inaccurate model inventories and meteorological input available for the simulations, the satellite-based observations synchronizing with surface measurements is a novel idea to quantify and classify the real BC environment across distinct geographic regions of the globe. The results indicate that, despite the seasonal biases, the overall regional distribution of BC is very well represented by the satellite retrieval, with close agreement with the ground-based measurements. The validation and closure studies between the two data sets show RMSE < 2, with absolute difference < 2 μg m^{-3} during winter (R = 0.79) and pre-monsoon (R = 0.74). Over the hotspot regions of India, the satellite retrievals show soot volume fraction of ~ 5%, columnar single scattering albedo of ~ 0.8 and BC column optical depth of ~ 0.1. In terms of global spatio-temporal variability, higher BC tends to occur mostly in areas where biomass burning is intense. Overall, this study highlights the effectiveness of first ever satellite retrieval of BC, which could be effectively used for the regular monitoring of BC load arising out of vehicular/ industrial/ biomass burning activities across the globe.

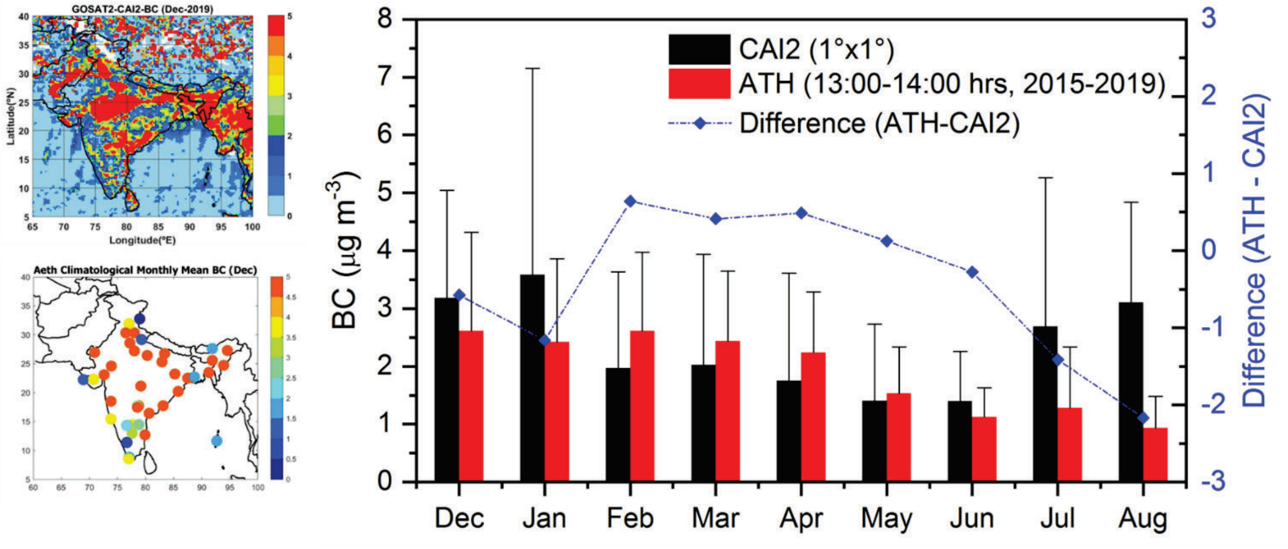

Figure: Regional distribution of monthly average BC from satellite (CAI2, 0.25 x 0.25 degree) and surface (climatological average) observations in the month of December (left panel). The surface BC is obtained from multi-wavelength aethalometer (ATH) measurements in the ARFINET. The right panel shows the monthly variation of regional average BC from satellite (CAI2) and surface (ATH) measurements (averaged over all the locations considered for inter-comparison), along with the absolute difference between the two data sets.

Biases in XCH_4 retrievals from the 2.3 µm spectral band

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The TROPOMI instrument (currently in-orbit) as well as the upcoming GeoCarb mission are both utilizing the methane absorption band at 2.3 µm. This band is convenient for greenhouse gas remote sensing, as it contains absorption features of methane (CH_4), carbon monoxide (CO) as well as water vapor (H_2O) allowing for the retrieval of those gas species.

As part of GeoCarb algorithm development activities, we have investigated the feasibility of single-band CH_4/CO/H_2O retrievals. Using an established radiative transfer and instrument model simulator framework, we conduct retrieval experiments with a focus on systematic errors and analyze the driving mechanisms that cause these errors.

We find that weak aerosol scattering, with total column optical depths of less than 0.05, is sufficient to cause a statistically significant surface albedo bias. This particular bias is qualitatively similar to one observed in real TROPOMI XCH_4 data and described in the work by Lorente et al. 2021. We further attempt an approach to prevent the bias from occurring by informing the retrieval algorithm with sufficient data regarding the true aerosol scattering profiles.

Surface-related biases can be prohibitive in the use of space based XCH_4 observations. This effect is amplified in the vicinity of darker surfaces such as wetlands, which are of special interest to the methane science community. Given the importance of space-based methane observations, we emphasize the need to better understand the limits of state-of-the-art retrieval algorithms.

Keywords: XCH_4, retrieval algorithm, systematic biases

Development of the MethaneSAT L0-1B processor

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MethaneSAT is an Environmental Defense Fund (EDF) satellite mission set to launch in mid-2023 to monitor methane emission from over 80% of the oil and gas industry and other sources with high precision and fine spatial resolution. The MethaneSAT instrument consists of two push-broom imaging spectrometers: the CH4 spectrometer (1.598-1.676 µm) to detect CH4 and CO2 absorption near 1.65 and 1.61 µm, and the O2 spectrometer (1.249-1.305µm) to detect O2 absorption near 1.27 µm. It is currently being built by Ball Aerospace and under sensor-level testing. Integration with the spacecraft bus by Blue Canyon Technologies will occur in Q3 2022 followed by flight-system level testing. MethaneAIR is the airborne simulator for MethaneSAT. It was successfully deployed in July/August 2021 aboard the NSF/NCAR Gulfstream V and produced ~50 hours of observations. A L0-1b processor has been developed for MethaneAIR to convert digital counts to radiometrically, spectrally, and geometrically calibrated L1b radiance spectra. The MethaneSAT L0-1b processor is being developed leveraging that the MethaneAIR L0-1b processor and analysis of MethaneSAT instrument calibration test data.

We will present the details of the L0-1b processor to process nominal radiance measurements as well as on-orbit dark, LED, lunar, and airglow measurements. First, image processing steps including various corrections (e.g., gain, nonlinearity, residual image, Pixel Response Non-Uniform (PRNU), Bezel, dark current and straylight), radiometric calibration and noise calculation will be performed to derive radiometrically calibrated data and measurement precision. Then, a wavelength calibration will be conducted to correct wavelength shifts and monitor the changes in Instrument Spectral Response Functions (ISRFs). An orthorectification procedure will be used to geolocate the measurements and calculate viewing geometry with optional GEO-AKAZE to verify geolocation accuracy again reference images and correct for potential errors. Finally, several geolocation related information such as snow/ice and surface types, sun glint will be added. Pixel flagging will be done at various steps. We will also present on-orbit utilities and methods to monitor bad and RTS pixels from dark current measurements, measure detector gains and nonlinearity from LED measurements, trend radiometric calibration and degradation from vicarious calibrations and lunar measurements.

Presentation Type: Poster

Session: 3 Retrieval algorithms and methods for inter-instrument and product Cal/Val

Updates to the Spectroscopic Model for the OCO-2 Retrieval Algorithm: ABSCO v5.2 for Level 2 v11

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Keywords: OCO-2, remote sensing, spectroscopy, ABSCO, cross sections

Accurate retrievals of absorbing gases in remote sensing missions such as the Orbiting Carbon Observatory 2 (OCO-2) require an accurate characterization of absorption cross sections. Systematic errors in the spectroscopic model can lead to both spatial and temporal errors in retrieved atmospheric composition and consequently to biases in derived flux estimates. The exacting error budget demanded by OCO-2 necessitates a degree of accuracy in the spectroscopy that has not yet been attained. Nevertheless, continual improvements are being made. This work highlights the latest update to the spectroscopy models used in version 11 of the OCO-2 algorithm. These models are ingested by the algorithm in the form of absorption cross section (ABSCO) tables covering two CO_2 bands (1.61 μm and 2.06 μm) and the O_2 A-band (0.76 μm). This latest update (v5.2) comprises two main changes: the adoption of a HITRAN-based H_2O line list developed by Geoff Toon[1] and a new parameterization of the CO_2 cross sections in the 2.06 μm ("strong") band which utilizes a full relaxation matrix representation of line mixing developed by Lamouroux[2]. Previous ABSCO versions for this band assumed a nearest neighbor line mixing formulation that required an ad hoc correction to account for "missing" absorption between the P and R branches.

This work compares retrieval results using ABSCO v5.2 with other models, including the previous version, v5.1, using both ground-based TCCON spectra as well as satellite OCO-2 data. We demonstrate that the revised water tables significantly reduce residuals, particularly in the TCCON retrievals, and show that the updated

[1] https://mark4sun.jpl.nasa.gov/toon/atm18/atm18.html

[2] J Lamouroux, L. Régalia b, X. Thomas b, J. Vander Auwera c, R.R. Gamache d, J.-M. Hartmann, "CO2 line-mixing database and software update and its tests in the 2.1 μm and 4.3 μm regions", JQSRT, 151, 88-96 (2015), http://dx.doi.org/10.1016/j.jqsrt.2014.09.017

CO_2 cross sections yield residuals comparable to those obtained previously but without the need for an ad hoc correction. We also discuss ongoing efforts currently underway to further improve existing tables.

A Neural Network Approach to Filtering OCO-2 Retrievals Over Snow

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Satellite retrievals of XCO_2 at northern high latitudes currently have sparser coverage and lower data quality than most other regions of the world. The OCO-2 B10 quality control filters out all retrievals made over scenes with snow, despite some of these retrievals providing reasonably accurate results. In order to recover some of these retrievals we have designed a new filtering scheme for the OCO-2 B10 bias-corrected XCO_2 retrievals made over snow using a neural network (NN). We tested two different truth proxies when training the NN: 1) the mean XCO_2 from several models, and 2) the small area approximation. To assess the performance of the NN filters we use Total Carbon Column Observing Network (TCCON) data at selected northern high latitude sites as an independent data set for validation. We found that the NN trained with the model mean data performed better compared to the NN trained with the small area data. In both cases we find that the throughput was much lower and the bias and precision were slightly worse compared to non-snow retrievals.

Key words: OCO-2, snow, filtering, machine learning, neural network

Recent status of GOSAT calibration and validation activities in 2022

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JAXA's GOSAT has been operating since 2009 and GOSAT-2 since 2018 to monitor the greenhouse gases (GHGs) carbon dioxide (CO_2) and methane (CH_4) by a Fourier Transform Spectrometer. The total column-average dry air mole fractions of CO_2 (XCO_2), and CH_4 (XCH_4) are measured from space using surface-reflected sunlight at near-IR wavelengths. The GOSAT-1/-2 and the other GHG missions, NASA OCO-2/-3 and ESA TROPOMI are collaborated in calibration and validation activities to maintain and improve GHG observation accuracy.

JAXA has deployed the TCCON station at Saga University and started ground-based XCO_2 and XCH_4 observations since 2011. Long-term dataset of the Saga TCCON has been newly released in April 2022, processed by the latest software GGG2020. GOSAT targets at Saga regularly every 3 days, GOSAT-2 in 2 days of a 6-day revisit. OCO-2 and OCO-3 observe Saga after target selection process.

GOSAT team has conducted vicarious calibration campaign at the Railroad Valley every June - July since 2009 in collaboration with NASA OCO team to ensure the radiometric accuracy. We have also deployed a portable EM27/SUN to measure XCO_2 and XCH_4 for validation since 2014. JAXA has released a website for the Vicarious Calibration Portal for Space-borne GHGs Sensors to archive the vicarious calibration techniques and datasets as part of the CEOS activity. GOSAT team will visit to join the Railroad Valley for the OCO-TROPOMI-GOSAT joint calibration campaign in June 2022 after the last visit of 2019.

We will present the recent status of JAXA's GOSAT calibration and validation activities of Saga TCCON and Railroad Valley campaign.

Keywords: GOSAT, OCO-2, TCCON, EM27

An overview of the tests and evaluations of the OCO-2 version 11 retrieval algorithm

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The OCO-2 Atmospheric Carbon Observations from Space (ACOS) column-averaged dry-air mole-fraction of carbon dioxide (XCO_2) product has been widely used to improve our understanding of regional- and global-scale carbon fluxes. However, known outstanding issues remain with the existing v10 product. These include spectral residuals above the instrument noise and regionally-dependent biases in retrieved surface pressure, which propagate into errors in the bias corrected XCO_2.

Here, we show results of testing for the new version 11. The updates accepted for v11 include 1) updating the spectroscopy to ABSCO v5.2, 2) instrument line shape improvements, 3) South Atlantic Anomaly screening modifications, 4) an updated CO_2 prior and 5) new ABSCO scaling coefficients. For example, ABSCO v5.2 includes improvements to the water vapor absorption lines and an updated strong CO_2 table and scale factor. The initial v11 test retrievals are found to better estimate the H_2O column and improve the reduced $\chi 2$, a metric of how well the residuals are being fit by the retrieval. New CO_2 prior profiles and new CO_2 ABSCO scale factor resulted in a less biased XCO_2 by reducing "co2_grad_del", which is a metric that describes the difference between the retrieved and prior CO_2 profiles and is often highly correlated with XCO_2 bias. We will also show the impacts of other tests on the v11 products by comparing to v10.

Keywords: OCO-2, retrieval algorithm, version 11

Comparison of aerosol properties between GOSAT-2/TANSO-CAI-2 and ground-based observations and other satellites

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Greenhouse gases Observing Satellite-2 (GOSAT-2) has two sensors, TANSO-FTS-2 (FTS-2) and TANSO-CAI-2 (CAI-2). CAI-2 is a cloud and aerosol imager and makes observations at ten bands composed of seven wavelengths from ultraviolet (UV) to near-infrared (NIR) region, performing two-directional observation in forward and backward directions. The spatial resolution (IFOV) is 460m other than a NIR band at 1630nm. CAI-2 is characterized by having two UV bands, 340 and 380nm that have sensitivity to light absorption by aerosol particles.

We have developed aerosol retrieval algorithm called MWPM (Multiple wavelengths and pixels method) (Hashimoto and Nakajima, 2017). The method simultaneously retrieves fine and coarse mode AOT and single scattering albedo (SSA) by using several wavelengths and spatial difference of surface reflectance. The method is useful for aerosol retrieval over spatially inhomogeneous surface region like an urban area.

We applied the algorithm to CAI-2 data and deriving and calculating aerosol properties such as fine and coarse mode of AOT, soot volume fraction in fine mode particles, SSA, Angstrom exponent (AE). The results were compared with ground-based observation, SKYNET and AERONET. In the case that Ag is less than 0.1, AOT at 550nm (AOT550) is in good agreement with ground-based observations. CAI-2 SSAs at 340 and 380nm and AE are likely to correlate with those of SKYNET and AERONET when AOT550 > 0.3. However, CAI-2 AE is basically underestimated compared with AERONET and SKYENT. We also compared the results with other satellite data such as VIIRS, MODIS and Himawari-8/AHI aerosol products. CAI-2 AOT is a little overestimate, but in good agreement with those of other satellites with correlation coefficient over 0.8. However, CAI-2 AOT looks underestimate over bright surface region like desert area. We will show the comparison results and discuss the results for modification of the algorithm in the future.

Keywords: Aerosol, GOSAT-2, CAI-2, Remote sensing

Exploring the sensitivity of northern high latitude retrievals from OCO-2 to the referenced digital elevation model

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Carbon exchange in the northern high latitude regions plays an important role in completing our understanding of global carbon dynamics, and a paucity of atmospheric observations of CO_2 in these regions hinders further investigation. Polar orbiting satellites such as the NASA Orbiting Carbon Observatory 2 (OCO-2) have great potential for providing an abundance of observations over northern high latitude regions if issues of retrieval quality can be addressed. One reason satellite-based observations of high latitude regions are challenging is that supporting information and observations necessary for trace gas retrievals are sparser, outdated, or of lower quality in these regions than at mid-latitudes. Observations of atmospheric column average dry air mole fractions of CO_2 (X_{CO2}) depend on accurate knowledge of the number density of dry air in the atmospheric column, which requires accurate knowledge of surface pressure. For X_{CO2} retrievals from OCO-2, prior estimates of surface pressure are used that are adjusted for to the average elevation in the satellite footprint based on a Digital Elevation Model (DEM). A global empirical bias correction is applied to the retrieved X_{CO2}, after the fact, that has the effect of moving the density of dry air in the column closer to that implied by the prior surface pressure and away from that implied by the retrieved surface pressure. As a result, an accurate DEM is essential for defining an appropriate bias correction for northern high latitude retrievals from OCO-2. Different DEMs for the northern high latitude regions (north of ~50°N or ~60°N) can differ by as much as 50 m, implying differences in surface pressure of ~5-6 hPa, which can produce differences in retrieved, bias corrected X_{CO2} up to or more than 1 ppm. We will present an exploration of the impact of changing the DEM on OCO-2 retrieved X_{CO2} in northern high latitude regions.

Carbon dioxide and methane measurements at Sodankylä, Finland and comparisons with satellite borne observations

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Ground based observations by Fourier Transform Spectrometers (FTS) are frequently used for comparisons with satellite born sensors. At Sodankylä (67.4° N, 26.6° E) we installed an FTS instrument in early 2009. The spectrometer is recording direct solar spectra in the near-infrared spectral region in the spectral range between 0.7 and 2,5 μm. From the spectra column-averaged abundance of CO_2, CH_4, N_2O, HF, CO, H_2O, and HDO are retrieved. The FTS instrument (based on Bruker 125 HR) has been optimized for greenhouse gas measurements and participates in the Total Carbon Column Observing Network (TCCON).
Here we present comparisons with the Greenhouse gases Observing SATellite (GOSAT) observations. We find a good agreement between GOSAT and ground-based observations. In case of CO2 the relative difference between the two instruments has been -0.04 +/- 0.01 % and in case of CH4 the relative difference has been calculated to be -0.04+/-0.02 %.
Secondly, we present results of AirCore profile measurements at Sodankylä. AirCore is a sampling system, which is directly related to the World Meteorological Organization in situ trace gas measurement scales. AirCore sampling is possible for both stratosphere and troposphere, which is a benefit, compared to the aircraft in situ measurements. Therefore, the AirCore sampling system can provide a ground-truth standard for comparison with total column measurements from either ground-based FTS or satellites. We have used AirCore profiles to compare with TCCON measurements. At Sodankylä we have made AirCore measurements during all seasons, including springtime flights under polar stratospheric vortex conditions.

Keywords: TCCON, GOSAT, AirCore, carbon dioxide, methane

Water and Temperature SVD Estimates to Improve OCO-2 XCO_2 Errors

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The NASA Orbiting Carbon Observatory-2 (OCO-2) was launched in 2014 with the goal of accurately and precisely measuring column-mean carbon dioxide. In order to fit the measured near infrared radiances properly, many physical parameters besides CO_2 must be included in the optimal estimation state vector. Atmospheric water vapor and temperature are two such parameters. Up until now, the NASA Atmospheric Carbon Observations from Space (ACOS) retrieval simply solved for a multiplicative scaling factor on an a priori water vapor profile and an additive offset on an a priori temperature profile. However, preliminary synthetic studies have indicated that both water vapor and temperature have 2-3 degrees of freedom in the vertical atmospheric column and that solving for full profiles can lead to improved CO_2 retrievals. In this work, we use singular value decomposition (SVD) to determine the most common "patterns" of atmospheric water vapor and temperature, then solve for scaling factors on these patterns. We assess retrieval errors statistics by comparing against TCCON and other validation sources.

Keywords: OCO-2, XCO2, water vapor, temperature, singular value decomposition

Update on the retrieval algorithm for the NIES TANSO-FTS/GOSAT SWIR L2 product

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National Institute for Environmental Studies (NIES) has provided the TANSO-FTS/GOSAT SWIR L2 product for more than a decade. The latest versions of the L2 product are V02.90/91 and the related bias-corrected ones based on the retrieval algorithm described in Yoshida et al. (2013). We recently updated the retrieval algorithm by focusing on the increase of available scans and improvement of the spectral fitting accuracies to produce the next version of the L2 product, V03.00. The main updates of the retrieval algorithm are:

1. estimate cirrus optical thickness and top pressure simultaneously with gases instead of the 2 μm band cloud screening
2. replace the TANSO-FTS degradation model with that of Someya and Yoshida (2020)
3. replace the solar irradiance spectra to that based on TSIS-HSRS
4. update the gas absorption coefficient tables

The retrieval results show that the spectral residuals are decreased except for those in the strong CO_2 sub-band over ocean. Available scans are increased by 14% over land although that is decreased by 20% over ocean. The data over ocean is decreased because of the residuals of the strong CO_2 sub-band and the stricter thresholds of the residuals in the post-screening. The validation result of XCO_2 from V03.00 against TCCON with the version of GGG2020 revealed almost the same quality as that from V02.90/91 over land and increased negative bias over ocean. Therefore, bias correction is necessary for XCO_2 over ocean. The XCH_4 from V03.00 has a negative bias with several ppb opposite to the positive bias of that from V02.90/91. In addition, the inconsistency in the decadal CO_2 growth rate with the field measurements over ocean which is recently founded in V02.90/91 (NIES GOSAT project, 2021) is resolved in the V03.00 product.

Keywords: GOSAT, retrieval algorithm, Full Physics, CO_2, CH_4

Design of the retrieval algorithm and level 2 product for greenhouse gases from GOSAT-GW

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Global Observing SATellite for Greenhouse gases and Water cycle (GOSAT-GW) is planned to launch at the end of Japanese FY2023. The instrument for monitoring greenhouse gases (GHGs) onboard GOSAT-GW is named Total Anthropogenic and Natural emissions mapping SpectrOmeter-3 (TANSO-3). TANSO-3 has the three spectral bands covering 420 – 490, 747 – 783, and 1590 – 1654 nm with the full-width half-maximum of 0.75, 0.075, and 0.3 nm respectively. The GHG retrieval algorithm is based on that for GOSAT-2 SWIR level 2 (L2) using the 760 and 1600 nm bands. The full physics algorithm estimates column-averaged dry-air mole fractions of CO_2 and CH_4 (XCO_2 and XCH_4) with the ancillary parameters such as water vapor, aerosol effective height, total aerosol optical thickness, surface pressure, temperature shift, and surface albedo. A priori values are taken from the calculations by Nonhydrostatic ICosahedral Atmospheric Model (NICAM) for greenhouse gases and aerosols, and the Japanese reanalysis dataset, JRA-3Q for the other atmospheric conditions. In addition to the full physics retrieval, proxy and solar-induced fluorescence (SIF) retrievals are processed. Because no imaging sensors are onboard GOSAT-GW, cloud screening with two procedures is conducted by using the TANSO-3 spectra itself. One is the reflectance test which discriminates the bright surfaces as clouds. The other one utilizes the estimated surface pressure from O_2 A band same as the ACOS retrieval algorithm. The GHG L2 product is planned to be provided as the combined one with the results of all the above processing including main outputs, XCO_2 and XCH_4 from full physics retrieval, XCH_4 from proxy retrieval, and SIF.

Keywords: GOSAT-GW, retrieval algorithm, CO_2, CH_4

GOSAT-2 TANSO-FTS-2 SWIR L2 Version 02 Products

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The Greenhouse gases Observing SATellite-2 (GOSAT-2), the successor to the GOSAT (2009 - current), was launched on 29 October 2018, and its operational observation has started from February 2019. 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), retrieved from Short-Wavelength InfraRed (SWIR) spectral data (Bands 1, 2, and 3 at 0.75–0.77, 1.56–1.69, and 1.92–2.33 μm, respectively) using a so-called full-physics retrieval method, are released as the "GOSAT-2 TANSO-FTS-2 SWIR L2 Column-averaged Dry-air Mole Faction Product" (hereinafter called SWFP). Retrieval uncertainties of Xgas are evaluated primarily by comparing with the Total Carbon Column Observing Network (TCCON) data. As for the SWFP V01.07 land data, the single-sounding precision values evaluated by TCCON GGG2014 data are 3.72 ppm, 16.3 ppb, 7.3 ppb, and 130.4 ppm for XCO_2, XCH_4, XCO, and XH_2O, respectively. Relatively lower precision of Xgas seems to come from a small fluctuation in full-width at half maximum (FWHM) of the TANSO-FTS-2 instrumental line shape functions (ILSF), which depends on the on-orbit instrument temperature environment, and a radiance offset, which depends on the incident signal level. To suppress the retrieval error due to the change of the FWHM of ILSF and the radiance offset, several parameters will be added to the state vector in the SWIR L2 V02 retrieval algorithm. A tentative result shows the single-sounding precision of 2.01 ppm, 10.0 ppb, 7.1 ppb, and 124.2 ppm for XCO_2, XCH_4, XCO, and XH_2O, respectively. The error characteristics and remaining issues of SWIR L2 V02 products will be shown in the session.

Keywords: GOSAT-2, retrieval algorithm, column-averaged dry air mole fraction of gases

Oxygen Airglow Studies in Support of the MethaneSAT Mission

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The main topic of this work is an optimal estimation-based algorithm to retrieve number density of excited oxygen (O_2) molecules that generate airglow emissions near 0.76 μm ($b^1\Sigma_g^+$ or *A* band) and 1.27 μm ($a^1\Delta_g$ or $^1\Delta$ band) in the upper atmosphere. Both oxygen bands are important for the remote sensing of greenhouse gases. The algorithm is applied to the limb spectra observed by the SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY (SCIAMACHY) instrument in both nominal (tangent heights below ~90 km) and mesosphere-lower thermosphere (MLT) modes (tangent heights spanning 50-150 km). The number densities of emitting O_2 in the $a^1\Delta_g$ band are retrieved in an altitude range of 25-100 km near daily in 2010, providing a climatology of O_2 $a^1\Delta_g$ band airglow emission. This climatology will help disentangle airglow from backscattered light in nadir remote sensing of the $a^1\Delta_g$ band. The global monthly distributions of the vertical column density of emitting O_2 in $a^1\Delta_g$ state show mainly latitudinal dependence without other discernible geographical patterns. Temperature profiles are retrieved simultaneously from the spectral shapes of the $a^1\Delta_g$ band airglow emission in the nominal limb mode (valid altitude range 40-100 km) and from both $a^1\Delta_g$ and $b^1\Sigma_g^+$ band airglow emissions in the MLT mode (valid range 60-105 km). The temperature retrievals from both airglow bands are consistent internally and in agreement with independent observations from ACE-FTS and MIPAS with absolute mean bias near or below 5 K and root mean squared error (RMSE) near or below 10 K. Besides, the zenith airglow for the $a^1\Delta_g$ band observed by the MethaneAIR instrument on board of the NSF/NCAR Gulfstream V aircraft in August 2021 will be discussed.

Keywords: oxygen, airglow, SCIAMACHY, MethaneSAT, MethaneAIR

XCO_2 observation network for verification of Kanto intensive observations and sun-glint observations by GOSAT and GOSAT-2

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Solar-tracking spectrometers developed by a group of the Nagoya University have been installed at four observation sites in the Kanto Plain for validating columnar dry-air mixing ration of carbon dioxide (XCO_2) observed by GOSAT and GOSAT-2 during the Kanto intensive observations. The system was named " Compact Array Spectrometer Targeting Local Emissions of CO_2 (CASTLE-CO_2)". It consists of a sun tracker and a grating spectrometer (Ocean Optics NIRQuest 512-1.7). One of CASTLE-CO_2 was placed at a Total Carbon Column Observing Network (TCCON) site in Tsukuba city (Ibaraki) for its calibration. On the other hand, The University of Tokyo (UTokyo) and the National Institute for Environmental Studies (NIES) have been carrying out simultaneous observations of GOSAT/ GOSAT-2 and onboard observations using a CASTLE-CO_2 on a meteorological observation ship of the Japan Meteorological Agency (JMA) as part of the joint observation of greenhouse gases based on the agreement between the JMA and the Ministry of the Environment (MOE). Within this framework, XCO_2 obtained through the sun-glint observations by GOSAT and GOSAT-2 have been compared with the data observed by a CASTLE-CO_2. For the same purpose, CASTLE-CO_2 was installed on a Pacific island, Minamitorishima (24.28N, 153.98E) and XCO_2 observation was started in 2019. Currently, we are preparing to install CASTLE-CO_2 on another Pacific island, Amamioshima (28.32N, 129.37E) as a joint research with Atmosphere and Ocean Research Institute (AORI) and The institute of Medical Science (IMS) of UTokyo.

Keywords: ground-based remote sensing, XCO2, CASTLE-CO2, validation, remote island

Improvements of S5P methane retrievals by using updated digital elevation models

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The Sentinel-5 Precursor (S5P) mission was launched on October 2017 and has since provided data with high spatio-temporal resolution using its remote sensing instrument, the TROPOspheric Monitoring Instrument (TROPOMI). The latter is a nadir viewing passive grating imaging spectrometer. The retrieval of trace gases of TROPOMI spectra yields e.g. column-averaged dry air mole fractions of methane (XCH_4) which is the product of interest to this study. The daily global coverage of the atmospheric methane mole fraction data enables the analysis of the methane distribution and variation on large scales and also to estimate surface emissions. The spatio-temporal high-resolution satellite data are potentially particularly valuable in remote regions, such as the Arctic, where few ground stations and in-situ measurements are available. In addition to the operational Copernicus S5P total-column averaged dry air mole fraction methane data product developed by SRON, the scientific TROPOMI/WFMD algorithm data product v1.5 (WFMD product) was generated at the Institute of Environmental Physics at the University of Bremen. In a recent study (Hachmeister et al. 2022, in review) we showed that noticeable features in the maps of retrieved XCH_4 over Greenland can be explained by inaccuracies in the underlying digital elevation model (DEM). In follow-up research we identified further regions with inaccuracies in the Global Multi-resolution Terrain Elevation Data (GMTED2010) and show that the use of the GLO90 Copernicus DEM can solve these issues.
This study shows the importance of the chosen topography data on retrieved dry air mole fractions. Use of a precise and up-to-date as possible DEM is advised for all S5P data products as well as for future missions which rely on DEM as input data. A modification based on this study is planned to be introduced to the next version of the WFMD data product.

Keywords: methane, TROPOMI, topography

Comparison of GOSAT-2 XCO_2 and an independent inversion analysis

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GOSAT-2, designed to monitor the carbon budget, was launched in 2018 and has been accumulating observation data continuously. Compared to the previous satellite GOSAT, this satellite increases the number of observation data by expanding the observable area using intelligent pointing, etc. We compared the latest XCO_2 version 0107 observed by GOSAT-2 with the JMA CO_2 distribution, which is an independent inversion analysis using only in-situ observations. The satellite observation data and the JMA CO_2 distribution were compared after taking monthly averages at 5-degree horizontal grid points. The comparison period is 2019-2020. The GOSAT-2 observable area has expanded compared to GOSAT, and the number of observation data per unit area has also increased. On the other hand, the differences from the independent analysis results, which were small in GOSAT (NIES SWIRL2Ver. 2.9X), became larger overall, and in many areas, there was a tendency toward overestimation compared to the analysis. More detailed comparison results will be reported at the workshop.

Keywords: GOSAT-2, XCO_2 Bias estimation, Inverse model

Validation of recent results of the GOSAT-2 FTS-2 SWIR L2 products

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The validation is made using the recent products of GOSAT-2 FTS-2 SWIR L2 Full Physics products (Ver. 01.04 & 01.07). The validation period of these products is March 1, 2019 ~ November 30, 2021 (not overlapped). The area definitions are “Land” (≧ 10% of land fraction) and “Ocean” (< 10% of land fraction). Only data with the quality flag “good” are used. No distinction is made by gain in these analyses.

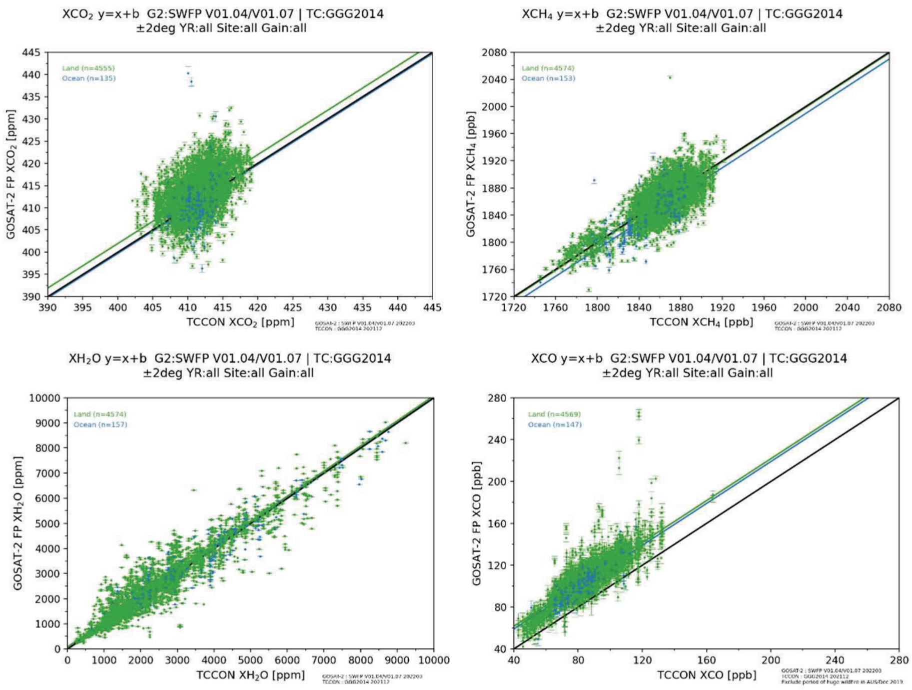

Figure 1 Scatter Plot of GOSAT-2 SWIR L2 Full Physics product against TCCON observations for XCO_2, XCH_4, XH_2O, and XCO.

The results of validation on GOSAT-2 Full Physics product (Ver.01.04 & Ver.1.07) for XCO_2, XCH_4, XH_2O in the comparison area of ± 2º are as follows.

- The mean biases and their standard deviations of XCO_2 over Land and Ocean are 1.93 ± 4.12 ppm (0.47 ± 1.00%) and -0.31 ± 5.60 ppm (-0.08 ± 1.36%), respectively.
- The mean biases and their standard deviations of XCH_4 over Land and Ocean are -1.43 ± 19.76 ppb (-0.07 ± 1.06%) and -10.28 ± 23.92 ppb (-0.56 ± 1.30%), respectively.
- The mean relative biases and their standard deviations of XH_2O over Land and Ocean are 5.6 ± 23.2% and 3.0 ± 19.9%, respectively. Their standard deviations are relatively large.
- The mean biases and their standard deviations of XCO over Land and Ocean are 21.75 ± 9.76 ppb (25.92 ± 11.69%) and 19.01 ± 7.63 ppb (23.42 ± 9.36%), respectively.
- The trends of bias for XCO_2 and XCH_4 show some variations during the observation term, the term is not so long though.

The influences of aerosols and the validation results of GOSAT FTS SWIR L2 Ver 03.00 will be also presented.

Keywords: GOSAT-2, Full Physics product (Ver. 01.04 & 01.07), GOSAT, validation, mean bias against TCCON

The Information Content of Dense Carbon Dioxide Measurements from Space: A Case Study with OCO-3

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Abstract
While bottom-up inventories of carbon dioxide (CO_2) emissions can provide high-resolution estimates at a global scale, the in-situ CO_2 measurements necessary to verify these estimates are sparse. The use of space-based instrumentation has increased the coverage of CO_2 observations to a near-global-scale, increasing the potential to inform both science and policy. The first part of this work applied an observing system simulation experiment (OSSE) to characterize the flux information contained in the "Snapshot Area Map" (SAM) observations from NASA's OCO-3 instrument. A Bayesian inversion scheme was applied to model-generated, "synthetic" SAM observations with known "true" emissions to assess how much prior CO_2 emission estimates can be corrected towards true values in the Los Angeles Basin. Results from this work indicated that individual SAM observations can provide modest hourly flux corrections for 1-3 hours prior to the observation in question. Additionally, aggregated SAM observations can remove significant systematic biases in sector-specific emissions, namely the Transportation and Manufacturing sectors. Results from this OSSE informed follow-up analyses where annual sector-specific scaling factors were generated from OCO-3 SAMs observations collected in 2019, 2020, and 2021. These scaling factors were generated in relation to the latest flux estimates from the Vulcan 3.0 emissions inventory (2015). To quantify the accuracy of these scaling factors, their magnitudes were compared to hourly traffic and power plant emissions data. This system's ability to produce accurate scaling factors provides a pathway to further synthesize near-real-time observations of CO_2 with the generation of accurate, spatially-distributed flux estimates. Preliminary results from this work are presented.

Keywords: Urban carbon cycle, CO_2 emissions, OCO-3, Bayesian inversion, emissions inventory

Accurately Measuring Atmospheric CO_2 Enhancements and Quantifying CO_2 Emissions from Wildfires – an Airborne Demonstration

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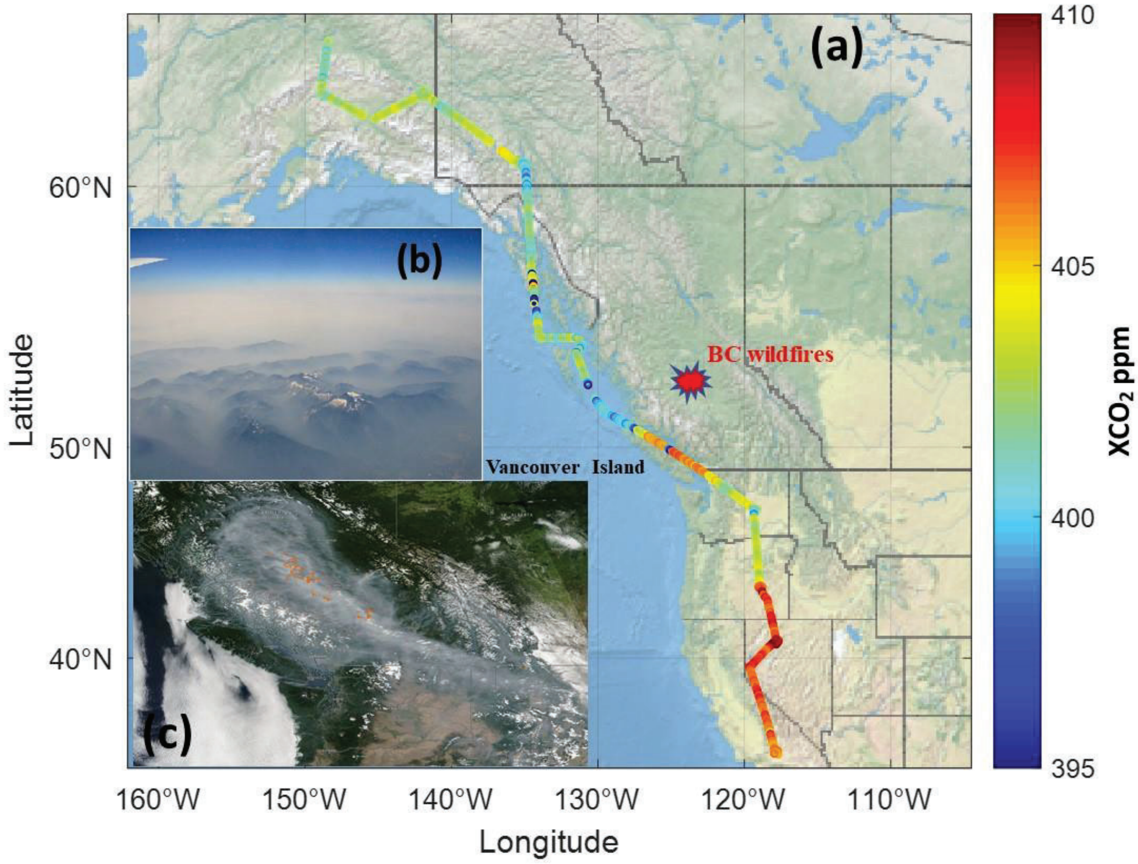
Vegetation fires are a major source of greenhouse gases. Recent wildfires in the Western United States have had profound impacts on air quality and have emitted a record amount of CO_2. The CO_2 emissions from fires estimated with fire emission models or databases have large discrepancies and uncertainties. Ground-based and airborne measurements of fire emissions are few and difficulty to obtain, and CO_2 retrievals from satellite measurements using passive remote sensing are significantly degraded by scattering effects of smoke in the scene.

NASA Goddard Space Flight Center has developed the CO_2 Sounder lidar, an integrated-path, differential absorption lidar approach to measure global atmospheric column-averaged CO_2 (XCO_2) from space as a candidate for NASA's Planned ASCENDS mission. This pulsed laser approach measures CO_2 absorption at multiple wavelengths across a CO_2 line centered at 1572.335 nm. Measurements of height-resolved laser backscatter profiles allow this technique to accurately estimate XCO_2 through fire smoke plumes.

We demonstrate this measurement capability over wildfires using lidar measurements from the summer 2017 ASCENDS/ABoVE airborne science campaign. During the August 8 flight over Vancouver Island, there were dense smoke plumes from the record-breaking wildfires in the Canadian Rockies. The aircraft overflow this region at a 9-km altitude, the lidar XCO_2 retrievals showed an average enhancement of 4 ppm from the wildfires. A spiral-down validation performed at Moses Lake airport, Washington, showed a bias of 0.1 ppm relative to in situ measurements and a standard deviation of 1 ppm in lidar XCO_2 retrievals. We compared these enhancements with those from the Goddard chemistry transport models using the Global Fire Emission Database (GFED) and the Quick Fire Emissions Dataset (QFED). The comparison results suggest that the CO_2 emissions from GFED and QFED for these wildfires were underestimated by more than a factor of 2. To our knowledge this is the first use of lidar to remotely sense CO_2 enhancements from large wildfires.

The results show that future airborne campaigns and spaceborne missions with this capability will significantly reduce the uncertainty in emission modeling and improve estimates of the impact of wildfires on air quality and ecosystem. This capability will further benefit atmospheric transport process studies and estimates of carbon fluxes.

Keywords: CO_2, wildfires, lidar, emissions, airborne



(a) the cloud-free XCO2 retrievals from the CO2 Sounder lidar for the flight on August 8, 2017. Significant XCO2 enhancements were seen in the flight segment cross Vancouver Island. The British Columbia wildfires are marked in the north of these enhancements. (b) image of the smoke plumes from the wildfires in Canadian Rockies as seen from DC-8 over Vancouver Island (Photo by Graham Allan). (c) true color image from Aqua/MODIS showing the smoke and fires on the same day.

Mao, J., Abshire, J. B., Kawa, S. R., Riris, H., Sun, X., Andela, N., & Kolbeck, P. T. (2021). Measuring atmospheric CO_2 enhancements from the 2017 British Columbia wildfires using a lidar. Geophysical Research Letters, 48, e2021GL093805. https://doi.org/10.1029/2021GL093805

Urban Greenhouse Gas Emission Monitoring in Seoul and Tokyo

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Greenhouse gases (GHGs) are the main driver of anthropogenic excess radiative forcing and thereby largely contribute to the current increase of global mean temperature. Out of the GHGs, carbon dioxide (CO_2) and methane (CH_4) are the most important species with respect to radiative forcing. The importance of reducing GHGs and achieve carbon neutrality has been acknowledged by international parties, leading to the Kyoto protocol and subsequent Paris COP21 agreement. For the successful implementation of the mitigation goals cities are of special importance, as over 50 % of the human population lives in urban areas and the population growth is predicted to occur predominantly in urban centers. At present, cities are estimated to be responsible for 53 % - 87 % of fossil fuel CO_2 emissions. While emissions of CO_2 can be estimated rather precisely on the national scale, higher uncertainties are reported for urban GHG emissions, especially CH_4. The large uncertainty of the global contribution of urban areas to GHG emissions is why a new generation of city-scale observing and modelling systems are needed. Here, mobile Fourier Transform spectrometers (EM27/SUN) measuring column-averaged dry air mole fractions of trace gases (X_{gas}) are utilized together with additional instrumentation to simultaneously measure city scale emissions of CO_2 and CH_4 in Seoul and Tokyo, two of the most populous metropolises in the world. We present first results from observations carried out in February 2022 with a focus on the measurements in the Tokyo metropolitan area.

Keywords: Urban emission monitoring, GHG, EM27/SUN

Development of an Integrated Lightweight Multi-Rotor UAV Payload for Atmospheric Carbon Dioxide Mole Fraction Measurements

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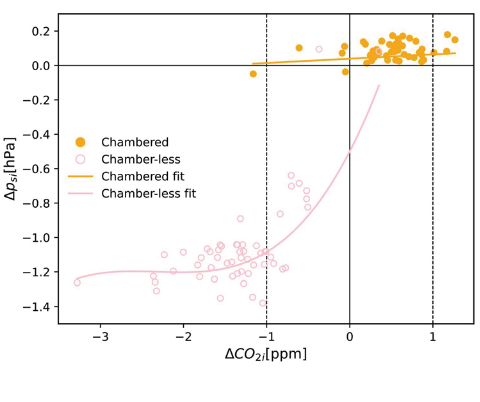
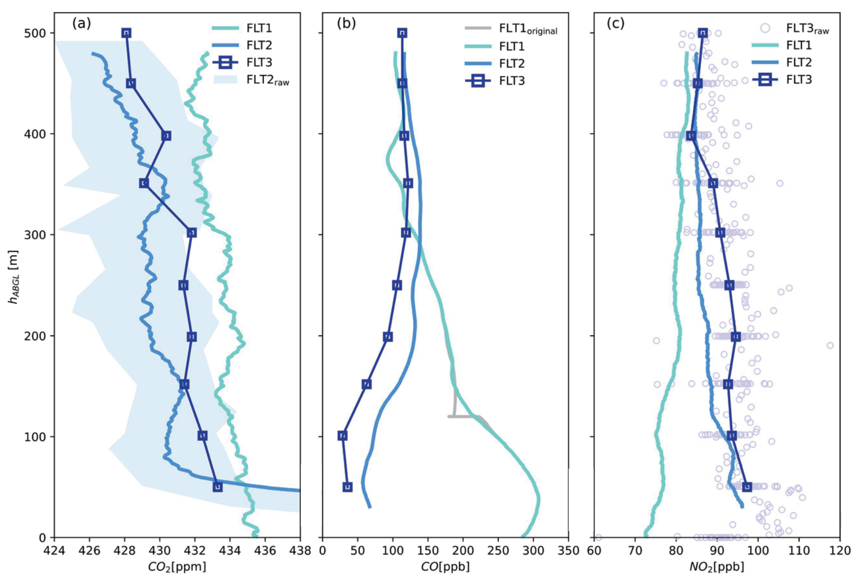
Records and projections of increasing global average temperature call for improvements of global stocktake inputs, which are vital to achieving targets of intergovernmental agreements on climate change. Unmanned Aerial Vehicle (UAV)-based atmospheric observation of greenhouse gas (GHG) concentrations is an upcoming addition to the top-down measurement methods due to its advantageous spatial-temporal resolutions, greater coverage area and lower costs. Hence, we developed and tested a lightweight UAV payload enclosure integrating a non-dispersive diffusion infrared (NDIR) spectrometer and two electrochemical sensors for measurements of carbon dioxide (CO_2), carbon monoxide (CO) and nitrogen dioxide (NO_2). To achieve higher response times and maintain measurement qualities, we designed a custom air inlet on the rotor-facing side of the enclosure to reduce measurement fluctuations caused by rotor downwash airflow. To validate the payload design, we conducted a controlled test for comparing chambered and chamber-less NDIR spectrometer measurements. From the test we observed a reduction of 0.48 hPa in terms of standard deviation of pressure measurements and minimised downwash-flow-induced anomalous biases (+0.49 ppm and +0.08 hpa for chambered compared to −1.33 ppm and −1.05 hpa for chamber-less as shown in the bottom left figure). We also conducted an outdoor in-situ measurement test with multiple flights reaching 500 m above ground level (ABGL). The test yielded high resolution results representing vertical distributions of mole fraction concentrations of three types of gases via two types of flight trajectory planning methods (bottom right figure). Therefore, we provide an alternative UAV payload integration method for NDIR spectrometer CO_2 measurements that complement existing airborne GHG observation methodologies. Additionally, we also introduced an aerodynamic approach in reducing measurement noises and biases for a low response time sensor configuration.

Keywords: drone-based, NDIR, CO_2, emission monitoring, lower atmosphere





Publication: Zhao, T.; Yang, D.; Liu, Y.; Cai, Z.; Yao, L.; Che, K.; Ren, X.; Bi, Y.; Yi, Y.; Wang, J.; et al. Development of an Integrated Lightweight Multi-Rotor UAV Payload for Atmospheric Carbon Dioxide Mole Fraction Measurements. *Atmosphere* **2022**, *13*, 855. https://doi.org/10.3390/atmos13060855

Deriving CO_2 emissions of localized sources from OCO-3 XCO_2 and TROPOMI NO_2 data

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Most of the anthropogenic CO_2 emissions result from the combustion of fossil fuels by localized sources. Monitoring these emissions is key to track the reduction efforts to comply with the objectives of the Paris Agreement, under which bottom-up estimates are regularly reported. Top-down observation-based estimates can complement and verify these inventories. Satellite observations play an important role in this context, since they can provide global information.

The detection of CO_2 emission plumes is challenging due to the small enhancements resulting from anthropogenic emissions from individual point sources compared to the background concentrations and the satellite's instrument noise. NO is produced in the combustion of fossil fuels and it rapidly reacts with O_3 to make NO_2, which has a short lifetime. Therefore, its vertical column densities can exceed background values and sensor noise by orders of magnitude in emission plumes. This makes NO_2 it a suitable tracer for recently emitted CO_2.

The goal of this study is to quantify CO_2 emissions from localized sources such as power plants by using XCO_2 (the column-averaged dry air mole fraction of CO_2) retrievals from the Orbiting Carbon Observatory 3 (OCO-3) in its snapshot area mode. Our inversion technique uses TROPOMI NO_2 data which is co-located with the XCO_2 snapshot to detect the emission plume, and a cross-sectional flux method to quantify the CO_2 emissions, so that our source rate estimate is obtained from the flux through a number of cross-sections downwind of the source.

We present the results obtained for the top-down estimates of the emissions together with bottom-up estimates for comparison, showing that we can repeatedly monitor power plant CO_2 emissions.

Keywords: CO_2 emissions, power plant, OCO-3 satellite

Quantification of CO_2 emissions over the Greater Toronto Area: Comparison of model simulations with OCO and EM27/SUN measurements

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Atmospheric carbon dioxide (CO2) is the most important greenhouse gas. Urban areas are estimated to be responsible for more than 70% of global fossil fuel CO2 emissions. While many cities now have emission reduction policies, the observation methods to verify their outcomes are limited. Satellite measurements and high resolution modelling are effective ways to monitor and quantify CO2 in the atmosphere. In this study, we present and analyze the XCO2 (column averaged dry-air CO2 mole fraction) distributions over the Greater Toronto Area (GTA) using the results of the GEM-MACH model (Global Environmental Multiscale model - Modelling Air quality and Chemistry) with 2.5 km resolution for the period of April to August 2020. The simulated values are compared with multiple OCO-3 SAM (Snapshot Area Map) and OCO-2 Target mode observations collected over the GTA. The comparison between the XCO2 measurements by two EM27/SUN instruments located in the GTA with the simulated values and the OCO observations are discussed as a step toward combining these datasets to improve our understanding of GTA emissions.

Keywords: CO2, XCO2, GEM-MACH, OCO-3, GTA

Analysis of methane mitigation actions in the Permian basin using TROPOMI: drastic reduction of oil and gas activity scenario

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The last IPCC report highlights the imperative of promptly reducing methane emissions to mitigate anthropogenic climate change. Continuous monitoring of oil and gas basins using satellite data is essential to reveal unexpected methane emissions and to monitor the effectivity of emission reduction measures.

The TROPOMI satellite instrument has daily monitored the Permian basin, the largest unconventional oil and gas production region on Earth, since 2018. Observations show a continuous growth of methane concentration background in the area, persistent even during and after the production decline due to the COVID-19. In the case of methane enhancements, the impact of the drastically reduction of oil and gas activities reveal a decline below of previous years especially during the lockdown period.

The successful application of the divergence method to derive NO_2 emissions, encouraged the implementation of the method also for methane emissions. Comparisons between plumes from aerial surveys and emissions maps derived using the divergence method, show a good agreement in the location of emissions “hot spots”. Furthermore, the results indicate that for the Permian basin emissions both large leakages and many small continuous are significant.

This work highlights how TROPOMI is crucial for monitoring the methane emissions and for evaluating the impact of a drastic reduction of the oil and gas activity in the Permian basin during the COVID-19. This mitigation action can help to achieve the 33% reduction of global methane emissions by 2030, as the IPCC recommends in the last report to stay below the 1.5º global temperature increase.

Keywords: TROPOMI, methane, Permian basin, Oil and Gas

Detection of locally elevated methane concentrations by analyzing Sentinel-5 Precursor satellite data

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Methane CH_4 is an important anthropogenic greenhouse gas and its rising concentration in the atmosphere contributes significantly to global warming. Satellite measurements of the column-averaged dry-air mole fraction of atmospheric methane, denoted as XCH_4, can be used to provide information on emission trends of emission sources, which can help to improve emission inventories and review policies to mitigate climate change.

The Sentinel-5 Precursor (S5P) satellite with the TROPOspheric Monitoring Instrument (TROPOMI) onboard was launched in October 2017 into a sun-synchronous orbit with an equator crossing time of 13:30. TROPOMI measures reflected solar radiation in different wavelength bands to generate various data products and combines daily global coverage with high spatial resolution. TROPOMI's observations in the shortwave infrared (SWIR) spectral range yield methane with a horizontal resolution of typically 7×7 km^2.

We used a monthly XCH_4 data set (2018-2020) generated with the WFM-DOAS retrieval algorithm, developed at the University of Bremen, to detect temporally stable, locally enhanced methane concentrations originating from potential emission sources. At first, we applied a spatial high-pass filter to the XCH_4 data set to filter out the large-scale methane fluctuations. The resulting anomaly ΔXCH_4 maps show the difference of the local XCH_4 values compared to its surroundings. We then analyzed the monthly anomaly maps to identify hot spot regions by utilizing different filter criteria, such as the number of months in which the local methane anomalies ΔXCH_4 must exceed certain threshold values. In the last step, we calculated some properties of the detected hot spots like the mean monthly methane enhancement and attributed them to emission sources by comparing them with inventories of anthropogenic methane emissions.

In this presentation, the algorithm and initial results concerning the detection of local methane enhancements by spatially localized methane sources (e.g., wetlands, coal mining areas, oil and gas fields) are presented.

Keywords: detection algorithm, hot spots, methane, Sentinel-5 Precursor

NO_x and CO inversions for the derivation of $FFCO_2$ emissions in Europe

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We have developed an atmospheric inversion configuration to quantify monthly to annual budgets of the national emissions of $FFCO_2$ in Europe. These $FFCO_2$ emission estimates are based on the assimilation of the long-term series of NO_2 OMI and of CO MOPITT space-borne observations, with the Community Inversion Framework (CIF) and the CHIMERE regional chemistry-transport model.

In a first step, variational regional inversions are performed to estimate monthly European NO_x or CO emissions at 0.5° horizontal resolution, using the TNO-GHGco-v3 inventory as a prior estimate of these emissions. In a second step, these maps are converted into estimates of the rescaling to be applied to monthly budget of sectoral anthropogenic NO_x, CO and then $FFCO_2$ emissions per country.

The estimates of anthropogenic NO_x emissions are increased by the inversion compared to the TNO-GHGco-v3 inventory. As a natural consequence of the increase of the NO_x emissions and of the indirect use of the emission ratios from the inventory, the inverted $FFCO_2$ emissions from the NO_x inversions are larger than those from the TNO-GHGco-v3 inventory, and the differences between these inverted emissions and the inventory are relatively low (below 5% for all annual budgets at European scale). However, when the CO inversion is used to rescale jointly the monthly budgets of sectoral CO and $FFCO_2$ emissions from the inventory, it yields $FFCO_2$ emissions that are smaller than those from the TNO-GHGco-v3 inventory. The emissions derived from the CO inversion are quite consistent with the inventory. However, their sign is opposed to those obtained when assimilating NO_2 data. This demonstrates the need for a better understanding of the uncertainties, and in particular the potential sources of biases in the datasets and in the two inversion processes before attempting at synthesizing the CO and NO_2-based estimates of the $FFCO_2$ emissions.

Keywords: atmospheric inversion, NO_x, CO, $FFCO_2$

Spatial distribution and Seasonal cycle of northern high latitudes CH_4 fluxes inferred from an atmospheric inverse model using TROPOMI XCH_4

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Methane (CH_4) is an important anthropogenic greenhouse gas (GHG) with a global warming potential 28 times that of carbon dioxide on a 100-year time horizon. Recently, the number of atmospheric measurements from satellites is rapidly increasing and their retrieval quality is improving continuously. As those measurements have much higher spatial coverage compared to the ground-based observations, the potential to better constrain GHG budgets is expected to be high. However, the availability of the satellite data depends highly on the sunlight and clouds, and therefore, seasonality may not be as well constrained in regions such as northern high latitudes (NHL).

In this study, we examine the potential of the ESA Sentinel-5 Precursor TROPOMI XCH_4 retrievals to constrain CH_4 budgets at northern high latitudes (NHL), using the CarbonTracker-Europe CH_4 atmospheric inverse model. Fluxes are estimated by constraining the model using three sets of observations: 1) TROPOMI XCH_4 retrievals of SRON operational data, 2) TROPOMI XCH_4 retrieved based on WFM-DOAS algorism, and 3) ground-based observations of surface CH_4 from global and regional networks, e.g. ICOS and NOAA. The fluxes are estimated for 2018, and analysed by comparing between the three setups, and to the ground-based non-assimilated data such as TCCON retrievals. The estimated NHL wetland CH_4 emissions are decreased from the prior when TROPOMI data are assimilated, especially in summer. The anthropogenic CH_4 emissions also showed decrease from the prior in the TROPOMI inversions during spring and autumn. The evaluation against non-assimilated data showed that the seasonality driven by the TROPOMI inversions may be associated with the seasonal bias in the retrievals (Lindqvist et al., IWGGMS-18). For the spatial distributions, little differences were found in the location of emission hot-spots. The results indicated both potential and complication of using the TROPOMI data for estimation of NHL CH_4 budgets.

Keywords: TROPOMI, methane, atmospheric inversion, northern high latitudes

How does the ability to recover CO2 flux anomalies scale with observational coverage?

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Predicting future carbon-climate feedbacks will be critical for predicting the future airborne fraction of CO_2 and emission pathways needed to reach warming targets. Insights into carbon-climate feedbacks can be gained by understanding how ecosystems respond to climate variability. Here, we investigate how well climate-anomaly-driven CO_2 flux anomalies can be recovered by inversion analyses in a series of Observing System Simulation Experiments (OSSEs). In particular, we examine how the ability to recover CO2 flux anomalies scales with observational coverage.

Keywords: OSSE, flux inversion, carbon-climate feedbacks

Informing sector characteristics of urban CO_2 emissions using co-emitted trace gases

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Air pollutants (CO, NO_x) are co-emitted with CO_2 from many sources of combustion; their column abundances can be retrieved from space-based sensors. While the joint use of satellite-based CO_2 and co-emitted species columns have been advocated to better understand anthropogenic CO_2 emissions, few have demonstrated how those measurements may facilitate the spatial allocation and sector attribution of CO_2 emissions. Technical challenges including meteorological, chemical, biogenic, and retrieval influences, were less addressed when combining multiple species/sensors.

Our goal is to inform sector characteristics of CO_2 emissions by combining spatially-resolved column CO_2 from OCO-3 with column CO and tropospheric NO_2 (tNO_2) data from TROPOMI. Instead of relying on CO_2 emission inventories, intra-city anthropogenic activities were informed from 1) a high-resolution urban climate zone dataset or 2) retrieved tNO_2. To interpret tNO_2 more effectively we modified a Lagrangian atmospheric transport model to incorporate a simplified representation of the nonlinear NO_x chemistry and evaluated it over a few large US power plants with EPA-based emissions. The model identified a slight reduction in NO_x emission in 2020 compared to those in 2019 and 2021 over Phoenix, USA, possibly related to the COVID lockdown.

We also present results that analyze multiple species. Combustion efficiencies associated with heavy industrial activities in Shanghai are distinguishable from those in Los Angeles, as inferred from CO:CO_2 enhancement ratios. When the model is coupled with a chemical inversion system (LETKF), spatial distributions of urban NO_x emissions within Baotou, China and Phoenix were substantially improved. We plan to further constrain and investigate spatially-resolved NO_x:CO_2 emission ratios at source locations, when observed XCO_2 is ingested into our framework. We argue that our analysis has the potential to provide independent information about the spatial allocation and sector characteristics of urban CO_2 emissions according to either enhancement ratios or optimized emission ratios at emission sources.

Keywords: urban CO_2 emission, sector characteristics, CO and NO_x, inverse modeling

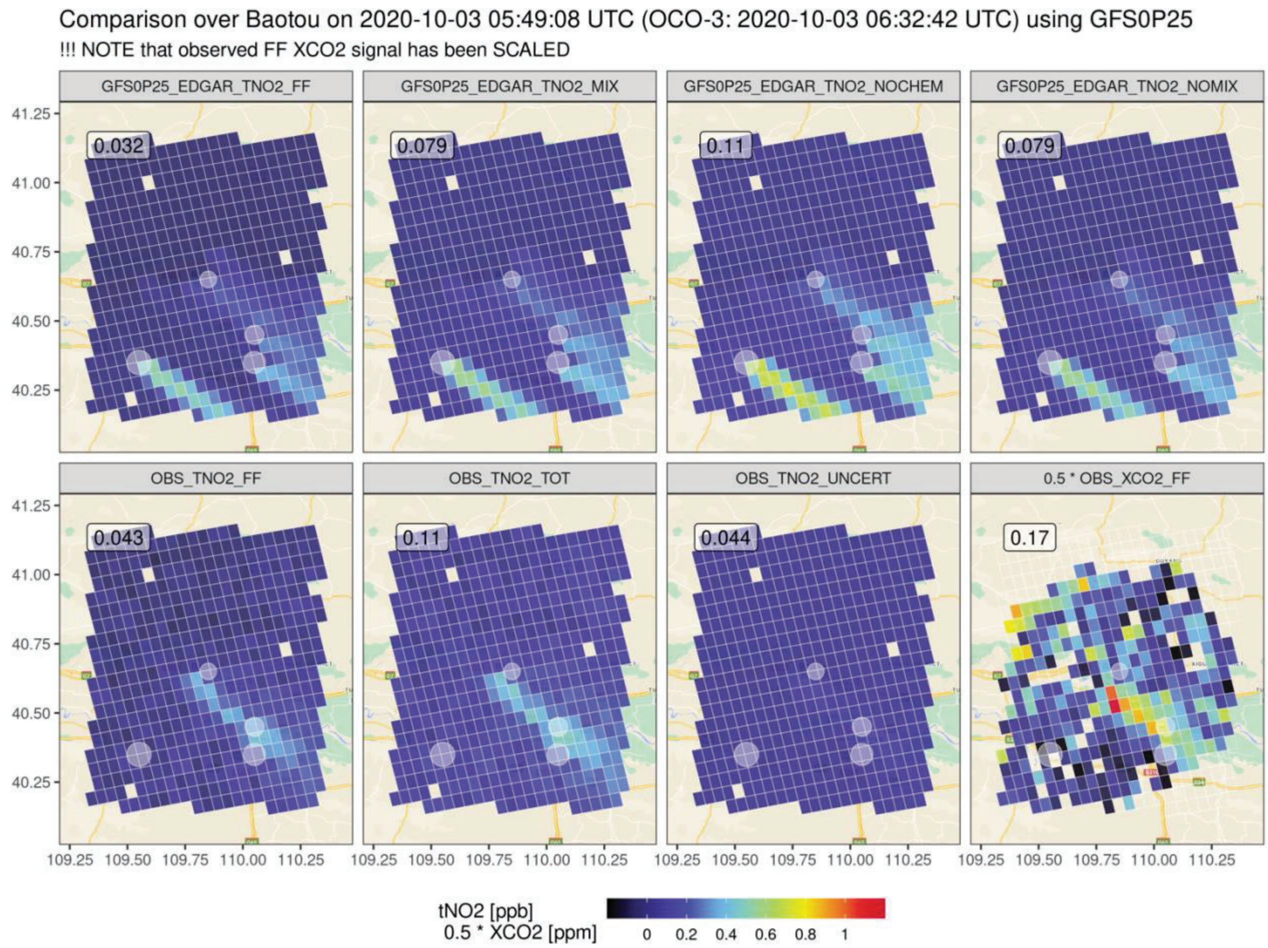

Figure. An example of the GFS-based modeled tNO_2 plumes using X-STILT-NO_x (upper row) vs. observed tNO2 plumes from TROPOMI and XCO_2 enhancements from OCO-3 (lower row) over Baotou on Oct 3rd, 2020. The modeled plumes are generated using annual mean ENO_x from EDGAR with top emitters highlighted in light-grey circles. Note that the observed XCO_2 signals are scaled to fit in the color bar, meaning the maximum XCO_2 signal aggregated to the TROPOMI scale within the scene is about 2.66 ppm.

Seasonal and Interannual Variability of Australian Carbon Fluxes Seen by GOSAT

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The semi-arid Australian continent significantly influences the interannual variability of the global terrestrial carbon sink. Atmospheric inverse models and machine learning based extrapolations can be used to estimate land carbon fluxes from CO_2 measurements. However, the sparse spatial coverage of in-situ CO_2 measurements over Australia leads to large uncertainties in estimated carbon fluxes for the continent. Satellite measurements of CO_2 offer an independent and spatially extensive source of information about the Australian carbon cycle. Combined with climatic variables and process-based ecosystem models, satellite data can reveal the underlying processes leading to the Australian carbon flux variability.

Here, we examine the decadal data set (2009-2018) of atmospheric CO_2 mole fractions delivered by the Greenhouse Gases Observing Satellite (GOSAT) above Australia. We estimate monthly satellite based land CO_2 fluxes from those measurements via the TM5-4DVAR inverse model and discuss their seasonal and interannual variability. We find that the seasonality of GOSAT atmospheric CO_2 is different from that of in-situ based atmospheric inverse models (CarbonTracker, TM5-4DVar, and CAMS). The largest difference occurs at the end of the dry season, when GOSAT shows around 1.5 ppm higher CO_2 concentrations than the models. The CO_2 concentration enhancements are reflected in strong CO_2 pulses in the satellite based fluxes in this time. The CO_2 pulses lead to a greater seasonal and inter-annual variability compared to fluxes of in-situ based atmospheric inverse models, FLUXCOM and the ensemble mean of process-based dynamic global vegetation models from the TRENDYv9 ensemble. We discuss implications and potential mechanisms for explaining the differences found.

Keywords: Semi-arid carbon cycle, Australia's CO_2 balance, satellite inversions, ecosystem modelling

Estimation of GHG emission/absorption using GOSAT satellite data in Mongolia

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The Paris Agreement requires each country to report anthropogenic emissions of greenhouse gases (GHG). However, there is a gap between actual GHG emission/sink and reported emission/sink due to the data quality of national statistics and the limitation of the emission factor of the guideline. In addition, Biennial Update Report (BUR) and Biennial Transparency Report (BTR) are rather difficult for many countries due to human resource limitations and budget shortages. Therefore, to make this report more transparent but with limited resources, vital needs exist to compare and verify their national GHG emission inventory data in BUR, BTR, and the Global Stocktake using the satellite data observed by GOSAT and GOSAT-2. We jointly developed an inverse modeling system that employs the inverse analysis based on the Green function using GOSAT-series satellite observation and the WRF-Chem-based simulation results or WRF- Vegetation Photosynthesis Respiration Model (VPRM) and estimated a posterior CO_2 emission.

As a result of emissions, a posterior annual total CO_2 emissions of the energy sector in 2018 was approximately 1 to 5 % higher than the Mongolian national GHG emissions inventory (pre-announcement).

We compared the amount of CO_2 absorbed in forests and the model result in 2018 showed a relatively bigger absorption than the Mongolian national GHG emission inventory 2018. Since there is no significant difference between the flux observation result and the model result, it is in the process of further refinement.

The approach with this co-development is ideal for building BUR and BTR when Mongolia utilizes it in the Quality Check (QC) or Verification part. Furthermore, by jointly preparing GHG emissions using satellite observation with the above methodology for countries without sufficient inventory data, highly transparent emission reports can be realized in the BUR and BTR. This research has been supported by the Ministry of Environment, Japan.

Keywords: GOSAT, Inversion analysis, Greenhouse Gas (GHG) Emission/Absorption, WRF-Chem, Biennial Update Report(BUR)/Biennial Transparency Report (BTR)

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Plume detection and characterization from XCO2 imagery: Evaluation of Gaussian methods for quantifying plant and city fluxes

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A comprehensive approach for the estimation of CO_2 emissions of localized sources (power plants, cities) from satellite imagery XCO_2 has been implemented, based on an optimal estimation method (OEM) fitting the measured images with a Gaussian plume model dealing with multiple and/or extended sources. It provides a full analysis of the retrieval uncertainty and its dependence to OEM model hypotheses, source characteristics, atmospheric conditions, and observation specifications (spatial resolution and spatial coverage).

In this paper, this approach is first used in an OSSE mode for assessing the potential of simulated satellite measurements from MicroCarb city mode and GEOCarb concepts for quantifying emissions and for estimating the performances of the flux retrieval method.
A comprehensive analysis of the expected precision on the source emissions over a representative set of European, US and South America target sites, considering the impact of the configuration mode and of instrument/system defaults, of the complex behavior of the plume dynamics, and of realistic cloud coverage, is provided.

A specific case study is performed by using Large Eddy Simulation (LES) model for the generation of synthetic observations, to evaluate the impact of atmospheric turbulence on the resulting XCO_2 images and on flux inversions uncertainty budget.
Then the performances and added-value of the gaussian-OEM method is evaluated in real conditions on OCO-2 measurements.

Regional land carbon sink estimates with NIES inverse model using ground-based, GOSAT and OCO-2 data.

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Assimilating ground-based and satellite data from continental locations, especially in densely populated regions, is obstructed by strong anthropogenic sources. High resolution transport modeling should help reducing the source/sink signal “crosstalk” among various sources, such as anthropogenic/fossil, ecosystem sink/respiration, and biomass burning. We estimated global CO_2 fluxes with GOSAT and OCO-2 data using our high resolution (0.1 degree) CO_2 inverse modeling system, which includes several new developments, such as (a) meteorology by ERA-5 reanalysis for improved interhemispheric transport rate and vertical mixings in the troposphere, (b) observation-based upscaled fluxes by the terrestrial vegetation (Zeng et al 2020) and oceans (Landschutzer et al 2020), (c) the large transport matrixes stored on disk for running inversion of GOSAT and OCO-2 satellite observations on general purpose computer systems. The land and ocean fluxes were estimated from GOSAT data for 2009-2019 separately for four data cases: data from surface background sites, surface background and continental data, and the two kinds of surface data with GOSAT. The estimated tropical land sink appeared to be close to neutral, which agree with recent model estimates. The Boreal land flux estimated at country scale showed a stronger uptake in Boreal Eurasia than in Boreal North America as similarly seen in bottom-up estimates. Our inverse modeling setup with OCO-2 data followed the OCO-2 v10 MIP experiment protocol, while using a 1.3 sec satellite data averaging over land. The model-estimated regional CO_2 fluxes for 2015-2020 were within the range of the OCO-2 model ensemble and will be used in the intercomparison and mean flux estimates.

Keywords: land carbon sink, inverse modelling, GOSAT, OCO-2

Global (2°×2.5°) and regional (0.5°×0.625°) daily surface CO_2 flux inferred from in-situ and OCO-2 B10 observations based on the Carbon in Ocean-Land-Atmosphere (COLA) system

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Atmospheric inversion of carbon dioxide (CO_2) measurements to better understand carbon sources and sinks has made great progress over the last two decades. However, most of the studies, including four-dimensional variational, ensemble Kalman filter, and Bayesian synthesis approaches, directly obtain only fluxes, while CO_2 concentration is derived with the forward model as part of a post-analysis. Kang et al. (2012) used the local ensemble transform Kalman filter (LETKF), which updates the CO_2, surface carbon flux (SCF), and meteorology fields simultaneously. Following this track, a system with a short assimilation window and a long observation window was developed (Liu et al., 2019). However, this data assimilation system faces the challenge of maintaining carbon mass conservation. To overcome this shortcoming, here we apply a constrained ensemble Kalman filter (CEnKF) approach to ensure the conservation of global CO_2 mass. After a standard LETKF procedure, an additional assimilation is used to adjust CO_2 at each model grid point and to ensure the consistency between the analysis and the first guess of the global CO_2 mass. Compared to an observing system simulation experiment without mass conservation, the CEnKF significantly reduces the annual global SCF bias from ~0.2 gigaton to less than 0.06 gigaton and slightly improves the seasonal and annual performance over tropical and southern extratropical regions. We show that this system can accurately track the spatial distribution of annual mean SCF. And the system reduces the seasonal flux root-mean-square error from a priori to analysis by 48-90%, depending on the continental region. Moreover, the 2015-2016 El Niño impact is well captured with anomalies mainly in the tropics.

Based on this system, Carbon in Ocean-Land-Atmosphere (COLA), we present a global (2°×2.5°) to North America and Europe (0.5°×0.625°) daily surface CO_2 flux inferred from in-situ and OCO-2 B10 observations. COLA is one of the OCO2MIP-v10 model, and it is well consistent with the space-based and ground-based estimations. COLA fully takes the advantages of EnKF that significantly reduced the computational costs compared with traditional methods. For example, using 20 cores of CPU, the 5 years of 4°×5° global inversion takes only 3 days and the 5 years of 0.5°×0.625° North America inversion takes ~30 days. We believe that the native resolution global inversion could be possible on the HPC using the methods proposed in COLA.

Global carbonyl sulfide budgets constrained by NOAA surface network and MIPAS satellite

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Carbonyl sulfide (COS) is a trace gas and becomes a diagnostic tool to better trace CO_2 footprint and estimate gross primary production (GPP). It is also important for its contribution to the stratosphere sulfur aerosols. However, COS comes from various sources and absorbed by plants, soil, and oceans. Therefore, accurate quantification of COS global budgets is challenging. We implemented an inversion model within TM5-4DVAR to both assimilate NOAA surface observations and MIPAS satellite data from space, in order to improve the inversion studies of COS. The two major precursors of COS, CS_2 and DMS are also simulated in the TM5 model. A bias correction scheme is developed to MIPAS satellite to handle the bias amongst different observational data sources. A few inversion experiments are designed to evaluate the performance of inverse system, and it proves that the bias correction helps fitting model to observations from both ground and space. The inversions show that COS largest sink as biosphere gains reduction from a prior 1053 GgS/year in all scenarios. Consequently, the other sources, e.g., COS ocean and CS_2 ocean gains increased to balance the budgets of COS. In general, the optimized sources and sinks of COS are well balanced to maintain COS in the atmosphere at relative equilibrium, as expected from long-term observations. Our study improves the data utilization of COS from ground and space, and provide new insights to COS global budget estimations.

Using a portable FTIR spectrometer for intercalibration of TCCON stations: The COCCON travel standard

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The precise knowledge of the global atmospheric concentrations of green-house gases (GHG) are crucial for understanding and monitoring climate change. Satellites for measuring GHGs are offering a global coverage, however, they need precise ground-based reference data for validation. The Total Column Carbon Observing Network (TCCON) measures column averages of GHG abundances at about 25 stations around the globe using Fourier Transform Infrared (FTIR) spectrometer.
For achieving the high data quality needed for the validation of current and upcoming GHG measuring satellite missions the control of site-by-site biases across the network is of utmost importance. So far, the verification of the individual TCCON sites mainly depends on the collection of collocated in situ measurements of GHG profiles, using airplane overflights or balloon air-core measurements, the use of calibrated HCl gas cells and on the evaluation of XLUFT.

In this work we present a new supplemental approach by using the portable EM27/SUN FTIR spectrometer, which is the standard instrument of the Collaborative Carbon Column Observing Network (COCCON). This instrument type has proven its high stability in various field campaigns and long-term studies. In the framework of the ESA project "Fiducial Reference Measurements for Green-House Gases II" we are exploiting the staibility of then instrument to use it as a travel standard for TCCON. It is planned to visit sides in Japan, Canada, Germany and Australia to perform side-by-side measurements with the TCCON spectrometer. Between the visits, the stability of the travel standard will be monitored using the Karlsruhe TCCON site and the COCCON reference spectrometer.
By the comparison of the different TCCON stations to a common reference we will be able to verify the level of station-to-station consistency currently achieved by the TCCON and support further improvements. Here, we present the first results of the travel standard visit at the TCCON site Tsukuba, Japan.

Keywords: Remote Sensing, FTIR, Satellite validation, TCCON, COCCON

The 2019 Methane Budget And Uncertainties At 1 Degree Resolution And Each Country Through Bayesian Integration Of GOSAT Total Column Methane Data And A Priori Inventory Estimates

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We use Optimal Estimation (OE) to quantify methane fluxes based on total column CH_4 data from the Greenhouse Gases Observing Satellite (GOSAT) and the GEOS-Chem global chemistry transport model. We then project these fluxes to emissions by sector at 1 degree resolution and then to each country using a new Bayesian algorithm that accounts for prior and posterior uncertainties in the methane emissions. These estimates are intended as a pilot dataset for the Global Stock Take in support of the Paris Agreement. However, differences between the emissions reported here and widely-used bottom-up inventories should be used as a starting point for further research because of potential systematic errors of these satellite based emissions estimates. We find that agricultural and waste emissions are ~263 +/- 24 Tg CH_4/yr, anthropogenic fossil emissions are 82 +/- 12 Tg CH_4/yr, and natural wetland/aquatic emissions are 180 +/- 10 Tg CH_4/yr. These estimates are consistent with previous inversions based on GOSAT data and the GEOS-Chem model. In addition, anthropogenic fossil estimates are consistent with those reported to the United Nations Framework Convention on Climate Change [80.4 Tg CH_4/yr for 2019]. Alternative priors can be easily tested with our new Bayesian approach (also known as prior swapping) to determine their impact on posterior emissions estimates. We use this aproach by swapping to priors that include much larger aquatic emissions and fossil emissions (based on isotopic evidence) and find little impact on our posterior fluxes. This indicates that these alternative inventories are inconsistent with our remote-sensing estimates and also that the posteriors reported here are due to the observing and flux inversion system and not uncertainties in the prior inventories. We find that total emissions for approximately 57 countries can be resolved with this observing system based on the degrees-of-freedom for signal metric (DOFS > 1.0) that can be calculated with our Bayesian flux estimation approach. Below DOFS of 0.5, estimates for a countries total emissions are more weighted to our choice of prior inventories. The top five emitting countries (Brazil, China, India, Russia, USA) emit about half of the global anthropogenic budget, similar to our choice of prior emissions but with the posterior emissions shifted towards the agricultural sector and less towards fossil emissions, consistent with our global posterior results. Our results suggest remote sensing based estimates of methane emissions can be substantially different (although within uncertainty) than bottom-up inventories, isotopic evidence, or estimates based on sparse in situ data, indicating a need for further studies reconciling these different approaches for quantifying the methane budget. Higher resolution fluxes calculated from upcoming satellite or aircraft data such as the Tropospheric Monitoring Instrument (TROPOMI) and those in formulation such as the Copernicus CO_2M, MethaneSat, or Carbon Mapper can be incorporated in our Bayesian estimation framework for the purpose of reducing uncertainty and improving the spatial resolution and sectoral attribution of subsequent methane emissions estimates.

Keywords: methane

Observations of atmospheric CH_4 enhancements due to anthropogenic emissions by the GOSAT-2 satellite.

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Abstract

We report the preliminary results of using observational data by the Greenhouse gases Observing SATellite-2 (GOSAT-2) for estimating the signature of local anthropogenic methane emissions in the column-averaged concentrations of atmospheric methane (XCH_4) around the globe using high-resolution transport modeling. We use the XCH_4 observations data retrieved with NIES Level 2 algorithms v01.03 (proxy algorithm) and v01.04 (full physics algorithm). To estimate the observed anomaly from XCH_4 we use a high-resolution transport model FLEXPART which has spatial resolution comparable to the size of the satellite observation footprint with an anthropogenic methane emission inventory (Emission Database for Global Atmospheric Research, EDGAR v5) to simulate the enhancements at all observation points. With a threshold simulated value we delineate background observations and those with anthropogenic influence and estimate the anomalies from the mean background. To relate the observed anomalies to the inventory-based estimates by the model in various regions, we do weighted linear regression with observed anomaly as response variable. To reduce the impact of the observation error we aggregate the anomalies into model simulated enhancement bins over large region. We found that the local enhancements observed by GOSAT-2 retrieved with both the algorithms scale linearly with inventory-based simulations of XCH_4 for the globe, confirming the potential for using GOSAT-2 observations for quantification of the methane emissions.

Keywords: anthropogenic methane emissions, GOSAT-2, emission inventory.