Abstract Collection

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Topic 7. Status of Future Satellite Missions about GHG Monitoring

The Copernicus Sentinel-5 Precursor Mission: Status and Results about products relevant for the future planned CO_2 Sentinel Mission (Methane, Nitrogen Dioxide, Cloud & Aerosol Information)

Claus Zehner*[1], Pepijn Veefkind[2], Ilse Aben[3], and Diego Loyola[4]

1. European Space Agency (ESA), Italy
2. Royal Netherlands Meteorological Institute (KNMI), The Netherlands
3. Netherlands Institute for Space Research (SRON), The Netherlands
4. German Aerospace Center (DLR), Germany

The Copernicus Sentinel-5 Precursor mission, launched on Oct. 13 2017, is the first atmospheric Sentinel and will support Copernicus services in particular for atmospheric applications, including activities such as air quality, ozone and climate monitoring. The instrument TROPOMI (Tropospheric Monitoring Instrument) is the single payload of the Sentinel-5 Precursor satellite and was co-funded by ESA and The Netherlands. Sentinel-5 Precursor ensures on the one hand continuity of atmospheric satellite data provision from the ESA ERS (GOME), ENVISAT (SCIAMACHY), and the USA EOS-AURA (OMI) missions in the various application and scientific domains and prepares on the other hand for the future atmospheric Sentinel-4 and Sentinel-5 instruments hosted on EUMETSAT platforms. Key features of the TROPOMI instrument are to have global coverage within one day and providing a spatial resolution of 7x3.5 km.
The Sentinel-5 Precursor mission has successfully finalised the Commissioning Phase on April 24 2018 and has been in routine operations phase since March 05 2019. During Commissioning Phase only pre-operational sample data products have been provided to selected Cal/Val experts. The staggered data release to the public has started during July 2018. Currently Level 1B Radiance/Irradiance (Offline); Methane and trop. Ozone (Offline), Formaldehyde, Sulphur Dioxide, Carbon Monoxide, Total Ozone, Nitrogen Dioxide, Aerosol Index and Cloud products (Offline and NRT) are available to the public via the Copernicus Sentinel-5 Precursor Pre-Operations Data Hub–s5phub.copernicus.eu. This presentation provides an overview about the Sentinel-5 Precursor Mission status and results about the Methane, Nitrogen, Cloud & Aerosol information products that are relevant for the future planned CO_2 Sentinel mission.

Key words: Sentinel-5 Precursor, TROPOMI, Methane

TROPOMI methane, water vapor isotopologue and carbon monoxide total column measurements at unprecedented temporal and spatial resolution: Validation results and applications

Jochen Landgraf, Tobias Borsdorff, Alba Lorente1, Joost aan de Brugh, Andreas Schneider, Otto Hasekamp

SRON Netherlands Institute for Space Research, Utrecht, Netherlands

The TROPOspheric Monitoring Instrument (TROPOMI) aboard of the Sentinel 5 Precursor (S5P) satellite is the first of the ESA's Sentinel missions to monitor air quality and climate change as part of the Copernicus programme. Since November 2017, TROPOMI provides unique global measurements of atmospheric composition at an unprecedented spatial resolution of 7x7 km^2 with daily global coverage. Among the observed species is methane (CH_4), the second most important greenhouse gas, the water vapor isotopologues $H_2{}^{16}O$ and $HD^{16}O$, and the air pollutant carbon monoxide (CO). For the CH_4 and CO products, SRON Netherlands Institute for Space Research developed the operational algorithms for data processing, for the water vapor isotopologues a scientific data product will be released soon by SRON. In this work, we present results on these product from the first year of TROPOMI measurements. The validation of the TROPOMI CH_4, CO and $HD^{16}O/H_2{}^{16}O$ column observations with collocated ground-based measurements at different TCCON sites shows a very good agreement. Because of the high signal-to-noise ratio of individual measurements, CO pollution hot-spots can be detected from measurements of single orbit overpasses, which opens up new opportunities for emission monitoring of pollution point sources on daily scales. For a set of cases, we demonstrate this application in more detail discussing CO emission estimates from wild fires and industrial activities using TROPOMI observations. Moreover, for CH_4 we show first case studies where we analyse the temporal and spatial variability of methane over several regions on the US.

Monitoring Global Carbon Dioxide from space: the TanSat mission and carbon flux investigation study in China

Yi Liu*[,1], Zhaonan Cai[1], Lu Yao[1], Jing Wang[1], Ke Che[1], You Yi[1], Hartmut Boesch[2], Liang Feng[3], Palmer Paul[3], Andre Butz[4]

1. Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China
2. University of Leicester, Leicester, UK
3. University of Edinburgh, Edinburgh, UK
4. University of Heidelberg, Heidelberg, German

The first scientific experimental CO_2 satellite of China - Chinese carbon dioxide observation satellite (TanSat) was launched in 22 Dec, 2016. After on-broad test and calibration, TanSat has been measuring the backscattered sunlight in scientific earth observation mode and produces XCO_2 data for more than two years.

In this paper, we will introduce the recent improvement on TanSat retrieval and validation campaign in China. **I**nstitute of **A**tmospheric **P**hysics **C**arbon dioxide retrieval **A**lgorithm for **S**atellite remote sensing (**IAPCAS**) is an optimal estimation method (OEM) 'full physics' retrieval algorithm that developed for greenhouse gas satellite, especially for TanSat measurement. IAPCAS-TanSat product has been retrieved and validated against TCCON measurements. In additional, we compared the IAPCAS retrieval with other two well-known algorithms, the University of Leicester Full Physical (UoL-FP) and the RemoTeC. The retrieval differences among algorithms have been investigated by verifying them against TCCON measurement.

The solar induced chlorophyll fluorescence (SIF) can be approached from clear solar lines from TanSat O_2A band hyperspectral measurement. IAPCAS-TanSat-SIF product indicates the seasonal variations of vegetation growth. We will introduce the results and learning from comparison on the regional distribution and seasonal variation of SIF product against OCO-2 measurements.

The validation campaign in Beijing and Inner Mongolia with multiple instruments coordinate measurement, incl. EM27/SUN, AirCore show a preliminary result in Greenhouse satellite validations and will contribute more for TanSat validation as well as new generation of greenhouse gas satellite, e.g. GOSAT-2, S5P and OCO-3.

The ecosystem carbon flux distribution and trend in China have been investigated using PYOSSE associated with in-situ and satellite measurement. We found the changes on carbon flux in last 10 years and differences estimated result compared with and without satellite measurement involved.

Key words: TanSat, Retrieval, Validation, Carbon flux

In-Flight Performance of the TanSat Atmospheric Carbon Dioxide Grating Spectrometer

Zhong-Dong Yang, Yan-Meng Bi, Qian Wang, Cheng-Bao Liu, Song-Yan Gu,
Yu-Quan Zheng, Chao Lin, Zeng-Shan Yin, Long-Fei Tian

TanSat was successfully launched on 22 December 2016 and has been acquiring global measurements of CO_2 and O_2 spectral bands in reflected sunlight since early February 2017. The atmospheric carbon dioxide grating spectrometer (ACGS) is a spaceborne three-band grating hyperspectral spectrometer suite onboard TanSat. The ACGS is designed to measure high-spectral-resolution, co-boresighted spectra of reflected sunlight within the molecular oxygen (O_2) A-band range from 0.758 to 0.778 microns and the weak and strong absorption bands of carbon dioxide (WCO_2 and SCO_2) ranging from 1.594 to 1.624 microns and from 2.042 to 2.082 microns, respectively; the spectral resolving power ($\lambda/\Delta\lambda$) of the ACGS is 19000, 12800 and 12250 in the O_2 A-band, WCO_2 band and SCO_2 band, respectively. The in-flight radiometric calibration accuracy is better than 5%, which satisfies the required specification. The spectral calibration accuracy of the O_2 A-band is 0.19 pm, that of the WCO2 band is 0.27 pm, and that of the SCO_2 band is 4.75 pm, all of which meet the 0.05 full width at half maximum (FWHM) requirement. The spectroscopic performance of the ACGS surpasses mission requirements with a margin. The ACGS has noise levels that are comparable to or smaller than those observed during prelaunch testing, and the noise has remained extremely stable in the three bands during on-orbit operations. The SNR levels of the three bands meet the specified requirement. As expected, the ACGS radiometric performance in the O_2 A, WCO_2 and SCO_2 bands was fairly good during its first sixteen months on orbit.

Index Terms

Spectrometer, Sounding, Atmosphere, Carbon Dioxide.

Zhongdong Yang is a Senior Scientist with the National Satellite Meteorological Centre. He is chief scientist of the ground segment project for the FengYun-3 satellites and TanSat and takes a leading role in the data processing and algorithm development of products for the FengYun-3 meteorological satellites and TanSat. (e-mail: zhongdong.yang@icloud.com and yangzd@cma.cn)

Yanmeng Bi, Qian Wang, Cheng-Bao Liu, Lei Yang, Song-Yan Gu are with the National Satellite Meteorological Centre (NSMC), CMA, China.

Yuquan Zhen, Chao Lin are with the Changchun Institute of Optics, Fine Mechanics and Physics (CIOFMP), CAS, China.

Zenshan Yin, Longfei Tian are with the Shanghai Engineering Centre for Microsatellites (SECM), CAS, China.

High-Resolution CH4 observations with GHGSat:
Plume Detections with GHGSat-D and Next-Generation Satellite Characterization Results

Dylan Jervis*[1], Jason McKeever[1], David Gains[1], Mathias Strupler[1], Ewan Tarrant[1], Daniel Varon[1,2], Stephane Germain[1]

1. GHGSat, Montréal, Canada
2. Harvard University, Cambridge, U.S.A.

The GHGSat demonstration satellite, GHGSat-D, is the first and only satellite on orbit designed for single-site measurements of GHG emissions with high spatial resolution (< 50 m). We present previously unpublished single-pass measurements of point-source emission plumes from industrial sites in the San Juan and Permian basins, as well as from other industrial sites around the world. Our high-resolution observations reveal the turbulent structure of methane plumes – a first from space – as well as allowing attribution of leaks to single pieces of equipment within industrial sites whose infrastructure is often complex. Furthermore, we show that emission quantification estimates derived from GHGSat-D satellite observation are corroborated by third-party estimates.

GHGSat will launch its next satellite, GHGSat-C1, in August 2019. We update on instrument construction, present GHGSat-C1 characterization data that helps to illustrate our spectrometer concept, describe how our new retrievals algorithm takes advantage of this characterization data, and provide an updated estimate on the performance limits of GHGSat-C1. Finally, we show how the GHGSat-C1 characterization campaign informed a significant refinement in spectrometer design for our follow-on satellite, GHGSat-C2, scheduled for launch in Spring 2020.

Key Words: GHGSat, Methane, Plumes, High-resolution

Toward 20-year GHG monitoring from space by GOSAT: operation, calibration, level 1 dataset, research product, and analytical tools

Akihiko Kuze*[1], Shiomi Kei[1], Nobuhiro Kikuchi[1], Hiroshi Suto[1], Makiko Hashimoto[1], Fumie Ktaoka[2] and Takahiro Kawashima[2]

1. Japan Aerospace Exploration Agency
2. Remote Sensing Technology Center of Japan

Key words: GOSAT; calibration, GHG partial-column density of lower troposphere

Since 2009 Thermal And Near infrared Sensor for carbon Observation Fourier-Transform Spectrometer (TANSO-FTS) onboard the Greenhouse gases Observing SATellite (GOSAT) TANSO-FTS onboard GOSAT has been monitoring arbon dioxide (CO_2) and methane (CH_4) from space using solar-reflected light in shortwave infrared (SWIR) and thermal infrared (TIR) light simultaneously with an agile pointing system.　Even though several anomalies had occurred during the 10-year operation in orbit, TANSO-FTS has been providing uniform quality data by calibration and updating non-linearity correction.　In June, we are planning to release Level 1B version 220 decade-long dataset.

The multiplex advantage of TANSO-FTS can measure both the SWIR light that passes from the top of the atmosphere to the Earth's surface providing column-averaged dry air mole fractions of CO_2 and methane CH_4 and TIR light of the thermal emission from the Earth's atmosphere and surface.　On March 2018, we also released new research product of the partial column density of lower and upper troposphere of mega-city from https://www.eorc.jaxa.jp/GOSAT/CO2_monitor/index_Ver.K.html.

Lastly, we have provided new analytical tools: a map of GHG emission source sectors for optimizing sampling pattern, a decade-long radiance data of CEOS calibration sites, and GHG airplane observation campaign data over greater Nagoya from https://www.eorc.jaxa.jp/GOSAT/index.html.

The Status and the Future Plan of GOSAT / GOSAT-2 Level 2 and 4 Products

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

1. National Institute for Environmental Studies (NIES), Japan
2. The University of Tokyo, Japan
3. Japan Aerospace Exploration Agency (JAXA), Japan
4. Tokai University, Japan
5. Chiba University, Japan

GOSAT-2 (Greenhouse Gases Observing Satellite 2), launched in October 2018, is the second Japanese Earth observation satellite for greenhouse gas observation from space. It is a joint mission promoted by Ministry of the Environment, JAXA (Japan Aerospace Exploration Agency), and NIES (National Institute for Environmental Studies) as similar to the first satellite, GOSAT, launched in and operated since 2009. Both satellites are designed to measure atmospheric concentrations of carbon dioxide (CO_2) and methane (CH_4) using Fourier transform spectrometers, FTS and FTS-2, with a help of moderate resolution imagers, CAI and CAI-2, for aerosol and cloud observation. The design lifetime of GOSAT-2 is five years and the 15-year record of atmospheric CO_2 and CH_4 is now expected from these two satellites.

NIES is responsible for the generation of GOSAT-2's Level 2 and Level 4 standard products which are

1) GOSAT-2 TANSO-CAI-2 L2 Cloud Discrimination Product
2) GOSAT-2 TANSO-CAI-2 L2 Aerosol Property Product
3) GOSAT-2 TANSO-FTS-2 SWIR L2 Chlorophyll Fluorescence and Proxy-method Product
4) GOSAT-2 TANSO-FTS-2 SWIR L2 Column-averaged Dry-air Mole Fraction Product
5) GOSAT-2 TANSO-FTS-2 TIR L2 Cloud and Aerosol Property Product
6) GOSAT-2 TANSO-FTS-2 TIR L2 Temperature and Gas Profile Product
7) GOSAT-2 L4A Global CO_2 Flux Product
8) GOSAT-2 L4A Global CH_4 Flux Product
9) GOSAT-2 L4B Global CO_2 Distribution Product
10) GOSAT-2 L4B Global CH_4 Distribution Product

The public release of GOSAT-2 Level 2 and Level 4 products will start by the end of October 2019 and 2020, respectively.

In this presentation, the latest status and the future plan of GOSAT / GOSAT-2 Level 2 and Level 4 products will be introduced.

Key words: GOSAT; GOSAT-2; Standard Product; Research Product

The OCO-3 Mission: Measuring Carbon Dioxide from the International Space Station – Mission Goals and Instrument Status

Annmarie Eldering, Thomas P. Kurosu, Ryan P. Pavlick, Brendan. M. Fisher, and Gregory. B. Osterman

NASA Jet Propulsion Laboratory/California Institute of Technology
Pasadena, CA 91109 (USA)
annmarie.eldering@jpl.nasa.gov
Phone: +1-818-219-9485

The Orbiting Carbon Observatory 3 (OCO-3) continues global CO_2 and solar-induced chlorophyll fluorescence (SIF) using the flight spare instrument from OCO-2. The instrument has been through ground testing and thermal vacuum, and has been shipped for installation on the International Space Station (ISS), currently scheduled for launch on 25 April 2019. By early June, OCO-3 is expected to be completing the decontamination cycle and First Light operations are imminent. This talk introduces the OCO-3 mission and its science goals, presents the current instrument status, and provides updates on the public release of L1b and L2 data products.

The low-inclination ISS orbit lets OCO-3 sample the tropics and sub-tropics across the full range of daylight hours with dense observations at northern and southern mid-latitudes (+/-52º). The combination of these dense CO_2 and SIF measurements provides continuity of data for global flux estimates as well as a unique opportunity to address key deficiencies in our understanding of the global carbon cycle. The instrument utilizes an agile, 2-axis pointing mechanism (PMA), providing the capability to look towards the bright reflection from the ocean and validation targets. In addition to the nadir-, glint-, and target-mode geometries familiar from OCO-2, OCO-3 includes a new observation mode dedicated to mapping out larger spatial-scale emitters like cities. This Snapshot Area Map (SAM) mode will be used to map areas of up to 80x80 km^2 on the Earth surface with the standard OCO-3 ground footprints of 2x2 km^2, providing unprecedented high spatial resolution coverage of large-scale CO_2 emitters worldwide. Measurements over urban centers could aid in making estimates of fossil fuel CO_2 emissions. Similarly, the snapshot mapping mode can be used to sample regions of interest for the terrestrial carbon cycle.

This talk will focus on instrument status, mission design, science goals, and global operations, including overviews of SAM and Target observation selection, sampling locations, frequency of revisit over the year, hours of the day that are sampled, the strategy for making the data easily accessible to the community, and updates on the public release schedule of L1b and L2 data products.

Accelerated MCMC for OCO-2's CO_2 retrieval

Otto Lamminpää*[1], Jenny Brynjarsdottir[2], Jonathan Hobbs[3], Amy Braverman[3],
Marko Laine[1], Hannakaisa Lindqvist[1], Johanna Tamminen[1]

1. Finnish Meteorological Institute, Finland
2. Case Western Reserve University, USA
3. Jet Propulsion Laboratory, USA

The Bayesian formalism and, in particular, Optimal Estimation (OE) has become the standard tool for computing the posterior mean as the answer to retrieval problems in atmospheric remote sensing. It is also the go-to option for retrieving carbon dioxide columns in the Orbiting Carbon Observatory 2 (OCO-2) mission. While OE is a fast and simple-to-implement computational framework, it still only provides a simplification of the solution as a "most probable point" and corresponding error estimates via linear Gaussian approximations, i.e., the solution is characterized with posterior maximum and covariance matrix around it. However, the forward models in atmospheric retrievals are generally non-linear and thus the resulting posterior distribution is not guaranteed to be Gaussian. This can lead to unpredictable errors in the final solution introduced by wrong characterization of the uncertainties or, in the worst case, by converging to local maxima.

Markov Chain Monte Carlo (MCMC) sampling methodology can be used as a remedy to this situation, providing a means to calculate the actual posterior. To speed up the otherwise slow MCMC algorithm, we use the Likelihood Informed Subspace (LIS) dimension reduction to reduce the size of the problem and apply this framework to the OCO-2 mission's CO_2 retrieval. We utilize a simplified surrogate forward model and a set of measurements obtained from simulated atmospheric states to compare OE and MCMC solutions.

We further identify the nonlinearities of the corresponding posterior distributions and characterize significant error sources that are not seen by the OE method. Key findings of this work show strongly non-Gaussian behavior in the aerosol parameters of the OCO-2 state vector. This helps to explain the known irregularities in the retrieval caused by aerosol misspecification, since the elements of the CO_2 part of the state vector are strongly correlated with the aerosol part.

Keywords: OCO-2, MCMC, Dimension Reduction, Uncertainty Quantification, CO_2

Recent progress of GOSAT and GOSAT-2 SWIR L2 products

Yukio Yoshida*[1], Haruki Oshio[1], Yu Someya[1], Hirofumi Ohyama[1], Akihide Kamei[1], Isamu Morino[1], Osamu Uchino[1], Tazu Saeki[1], Yosuke Niwa[1], Makoto Saito[1], Hibiki Noda[1], Tsuneo Matsunaga[1] and TCCON partner[2]

1. National Institute for Environmental Studies (NIES), Japan
2. https://tccon-wiki.caltech.edu

The Greenhouse gases Observing SATellite (GOSAT) was launched on January 23, 2009, and has been being operated for more than ten years. GOSAT is equipped with two instruments: the Thermal And Near-infrared Sensor for carbon Observation Fourier Transform Spectrometer (TANSO-FTS) and the Cloud and Aerosol Imager (TANSO-CAI). TANSO-FTS has three bands in the short-wavelength infrared (SWIR) region (0.75-0.78, 1.56-1.72, and 1.92-2.08 μm) and a thermal infrared (TIR) band (5.5-14.3 μm) at a spectral sampling interval of about 0.2 cm^{-1}. TANSO-CAI can detect optically thick clouds within the TANSO-FTS IFOV. The column-averaged dry air mole fractions of carbon dioxide, methane, and water vapor (XCO_2, XCH_4, and XH_2O; hereafter called Xgas) have been retrieved globally from cloud-free SWIR spectral data of TANSO-FTS. Xgas are simultaneously retrieved using a so-called full-physics retrieval method, and its accuracy and precision are evaluated by comparing with the Total Carbon Column Observing Network (TCCON) data. TCCON data is also utilized for an empirical bias correction of Xgas.

As a successor to the GOSAT mission, GOSAT-2 was launched on October 29, 2018, and its operational observation was started from February 2019. GOSAT-2 is also equipped with two instruments: TANSO-FTS-2 and TANSO-CAI-2. TANSO-FTS-2 has three SWIR bands (0.75-0.77, 1.56-1.69, and 1.92-2.33 μm) and two TIR bands (5.5-8.4 and 8.4-14.3 μm) at a spectral sampling interval of about 0.2 cm^{-1}. The SWIR L2 retrieval algorithm for GOSAT-2 is being developed based on the latest retrieval algorithm for GOSAT. Since the spectral range of TANSO-FTS-2 is expanded to cover the carbon monoxide (CO) absorption band at 2.3 μm, XCO is also retrieved simultaneously with the other gases in the full-physics retrieval method. In addition to the full-physics-based XCO_2, XCH_4, XH_2O, and XCO products, we are planning to provide the proxy-based XCH_4 product as well as solar induced chlorophyll fluorescence (SIF) product.

Key words: GOSAT; GOSAT-2; TCCON

PPDF-based method to account for atmospheric light scattering in spectroscopic observations of green-house gases from space: basic principles, validation, and comparison with other algorisms.

S. Oshchepkov [1], R. Imasu [2], C. Iwasaki [2] A. Bril [3], Y. Yoshida [4].

[1] Centre for Climate Research, Institute for Nature Management, Minsk, Belarus

[2] Atmosphere and Ocean Research Institute, the University of Tokyo, Kashiwa-shi, Chiba, Japan

[3] Institute of Physics, Minsk, Belarus

[4] National Institute for Environmental Studies, Tsukuba, Ibaraki, Japan

We present a method to detect and simultaneously retrieve optical path modification due to atmospheric light scattering in space-based greenhouse gas spectroscopic sounding. This method, which was applied to the analysis of radiance spectra measured by the Greenhouse Gases Observing Satellite (GOSAT), is based on the consideration of the statistical properties of the Path length Probability Density Function (PPDF) and on retrieval of PPDF parameters mostly from radiance spectra in the oxygen A-band of absorption at 0.76 mm. We show that these parameters can be effectively used to characterize the impact of atmospheric light scattering on carbon dioxide retrieval in the atmospheric carbon dioxide (CO2) absorption bands at 1.6 mm and 2.0 mm. The threshold for PPDF parameters when filtering aerosol contaminated atmospheric scenes is set so that the optical-path modification is negligible, and these settings are recommended as a basic guideline for selecting the clearest atmospheric scenarios. We apply use the measurements from TCCON sites for validation study and compare PPDF-based method with other algorithms.

Keywords: green-house gases, atmospheric light scattering, validation

Errors in Retrieved Gases and Inferred Fluxes Arising from Non-uniform Scene Illumination: A Case Study for the GeoCarb Mission

Jeff Nivitanont[1], Sean Crowell[*1], Chris O'Dell[2], Greg McGarragh[2], Eric Burgh[3], Denis O'Brien[4], and Berrien Moore[1]

1. University of Oklahoma, 2. CIRA/Colorado State University, 3. Lockheed Martin Advanced Technology Center, 4. University of Melbourne

Previous work (e.g. Hu et al (2016), Landgraf et al (2016) for the TROPOMI mission) has shown that inhomogeneous illumination within the field of view (FOV) leads to retrieval bias due to distortions in the actual instrument spectral response function (ISRF) relative to the ISRF that is measured in pre-flight calibration and characterization. Laboratory studies have shown that this distortion grows with wavelength. Various techniques have been employed to ameliorate these issues, including continuously scanning across the slit and temporal oversampling, and more recently hardware solutions have been developed, referred to as "slit homogenizers".

In this work, we demonstrate the impacts of the scene brightness inhomogeneity on retrievals of XCO_2, XCH_4 and XCO using the case study of the GeoCarb instrument, which measures in the 0.76um, 1.6um, 2.05um, and 2.3um spectral bands. We find that the posterior scatter and bias grow linearly with the brightness coefficient of variation within a footprint, and that this effect is not significantly ameliorated through the use of a continuous scan approach to operations.
The introduction of a slit homogenizer dramatically reduces, though doesn't eliminate, the worst of these effects. Quality filtering removes the worst offenders, though it also reduces coverage in areas such as the Amazon.

In addition to retrieved gases, we examine the effect of the degraded coverage and scatter on inferred flux estimates, and demonstrate that as long as errors are pseudo-random on 50+ km length scales (as was seen in the TROPOMI papers), regional flux constraints are maintained over the GeoCarb field of regard due to the daily revisit time.

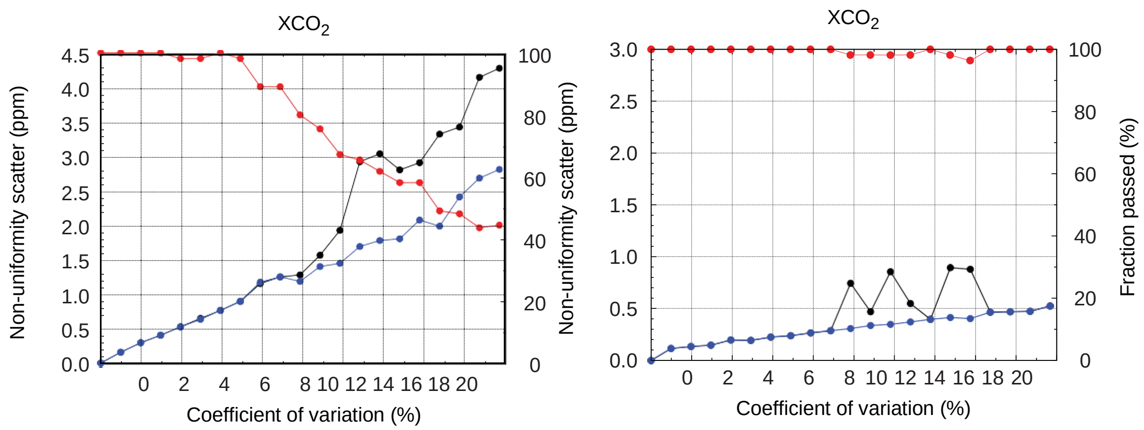


Figure 1 The results of the scene inhomogeneity retrieval study, where scene albedo coefficient of variation is plotted against the posterior error standard deviations both before (black line) and after (blue line) a quality filter is applied. The red line denotes the percentage of soundings that pass the quality filter. The left figure shows the results when a slit homogenizer is not employed, while the right figure shows the results when the slit homogenizer is included.

Generation of merged Level 2 and Level 3 XCO_2 data products from SCIAMACHY/ENVISAT, GOSAT and OCO-2 for the Copernicus Climate Change Service

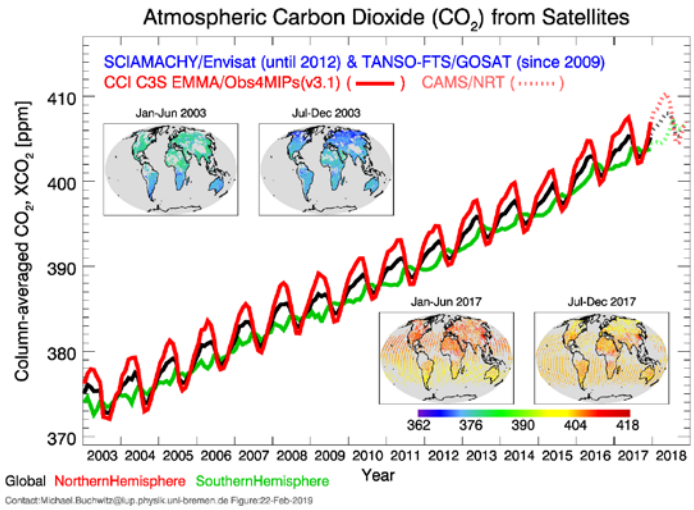
Michael Buchwitz*[1], Maximilian Reuter[1], Oliver Schneising[1], Stefan Noël[1], Heinrich Bovensmann[1] and John P. Burrows[1]

1. Institute of Environmental Physics (IUP), University of Bremen FB1, Otto Hahn Allee 1, 28334 Bremen, Germany

The generation of long-term merged multi-sensor multi-algorithm satellite-derived Essential Climate Variable (ECV) Greenhouse Gas (GHG) data sets started several years ago within the framework of the GHG-CCI project of ESA's Climate Change Initiative (CCI, http://www.esa-ghg-cci.org/). This activity is now continued operationally in the framework of the Copernicus Climate Change Service (C3S, https://climate.copernicus.eu/). The latest C3S GHG satellite data set is available from the Copernicus Climate Data Store (CDS, https://cds.climate.copernicus.eu/) and covers the time period 2003-2017. This data set contains merged Level 2 and Level 3 data products for XCO_2 and XCH_4 from SCIAMACHY/ENVISAT and GOSAT. For the next release, which will cover the time period 2003-2018, it is planned to also include OCO-2 XCO_2. The current status of this activity will be presented including a short description of the latest version of the Ensemble Median Algorithm (EMMA) used for merging the individual Level 2 data products and for quality assessment of the individual sensor and the merged products.

Key words: SCIAMACHY; GOSAT; OCO-2; C3S; TCCON

Latest version of the C3S merged XCO_2 data product (2003-2017) extended with preliminary GOSAT near-real-time retrievals (2018) as generated at Univ. Bremen for CAMS (https://atmosphere.copernicus.eu/):



Retrieval of aerosol optical properties using GOSAT/TANSO-CAI and GOSAT2/TANSO-CAI2 measurements over the ocean

Chong Shi*[1], Teruyuki Nakajima[1], Makiko Hashimoto[1], Hideaki Takenaka[1]

1. Japan Aerospace Exploration Agency (JAXA), Japan

A flexible inversion algorithm is proposed for the retrieval of aerosol optical properties over the ocean. To account for the effect of the oceanic substances on the retrieval, the forward radiation calculation is performed by a coupled atmosphere-ocean radiative transfer model combined with a comprehensive bio-optical ocean module. A combined multi-wavelength and multi-pixel constraint approach is used to estimate aerosol and oceanic substances simultaneously. This sort of simultaneous inversion helps to correct the biases induced by the neglect of water-leaving radiance in the traditional aerosol retrieval algorithms, particularly over the turbid waters; in addition, it can provide more aerosol information than the standard ocean color approach. To investigate the availability of current scheme, we conduct the retrieval using the synthetic and real measurements from the GOSAT/TANSO-CAI (hereafter, CAI). Inter-comparisons between CAI-retrieved and counterpart satellite products, i.e., MODIS, as well as the ground-based observed aerosol data, i.e., AERONET, are also performed. Generally, good agreement between CAI-AOT of fine and coarse aerosols and those of MODIS/AERONET are identified. There are also promising retrieval over the sun glint and high turbid water using current scheme. Finally, a preliminary result of the retrieved AOT based on the GOSAT2/TANSO-CAI2 is shown over the global ocean.

Key words: GOSAT; GOSAT-2; Aerosol; Remote sensing

Efficient Multiscale Gaussian Process Regression for Remote Sensing Data

Jouni Susiluoto*[1,2], Alessio Spantini[1], Heikki Haario[2], and Youssef Marzouk[1]

1. Massachusetts Institute of Technology, USA
2. Lappeenranta University of Technology, Finland

Observing greenhouse gas concentrations from space provides a global view to processes on Earth that has unique benefits compared to measurements made on the ground. The global coverage comes, however, with the price of spatial and temporal irregularities when the retrievals are sometimes spoiled by external factors such as dust particles or prevailing weather conditions. In some applications, if the satellite does not make a measurement exactly when and where information of the quantity of interest is needed, modeling to extract the distributions of this quantity of interest can be performed.

We tackle these modeling and uncertainty quantification problems by designing and implementing a computationally effective multi-scale Gaussian Process algorithm, which is able to compute expected values and uncertainties with arbitrary spatio-temporal resolution and also draw samples from the random process, conditioning on even enormous amounts of data. We utilize multi-scale kernels, which are able to resolve the spatial heterogeneity present in the data.

We learn the covariance kernel parameters with adaptive Markov Chain Monte Carlo and present a way of prescribing the mean function of the Gaussian Process by calculating marginals of a Markov Random Field, also computing the associated uncertainties. The validity of the multi-scale approach is presented and its limits discussed. The results are presented in an OCO-2 v9 context.

Key words: Gaussian Process, OCO-2, Uncertainty Quantification, MCMC

Detecting methane point sources from space using hyperspectral surface imagers

Daniel H. Cusworth*[1,3], Daniel J. Jacob[1], Daniel Varon[1], Christopher Chan Miller[2], Xiong Lu[2], Kelly Chance[2], Andrew Thorpe[3], Riley Duren[3], Charles Miller[3], and Christian Frankenberg[3,4]

1. School of Engineering and Applied Sciences, Harvard University, Cambridge, MA, USA
2. Atomic and Molecular Physics Division, Harvard Smithsonian Center for Astrophysics, Cambridge, MA, USA
3. Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA
4. Division of Geology and Planetary Sciences, California Institute of Technology, Pasadena, CA, USA

Several new surface imaging satellites are set to be launched in the near future. These imagers observe radiances in the shortwave infrared (SWIR), which is a spectral region with strong methane absorption. Methane observing satellites typically have much finer spectral resolution than surface imagers. For example, the TROPOMI full-width at half-maximum (FWHM) SWIR resolution is 0.25 nm whereas the EnMAP instrument's FWHM is 10 nm. However, surface imagers have the benefit of much finer spatial resolution than methane satellites, with pixels on the scale of 30 m compared to several kilometers. We test if the coarser spectral resolution of the soon to be launched instruments can identify methane absorption features in an atmospheric retrieval. We simulate EnMAP-like scenes using the EnMAP End-to-End Simulation Tool (EeteS) with WRF-LES generated methane plumes. We find that EnMAP should be able to capture methane enhancements within a methane plume with about 5.5% error, depending on the underlying surface. Previous work found that an instrument with 5% error should be capable of constraining plumes of 170 kg h^{-1}, which would account for a major fraction of point source emissions. Reducing the spectral resolution to 5 nm and 1 nm in simulated retrievals further reduces the error to 3.6% and 2.3%, respectively. We spectrally and spatially downsample AVIRIS-NG images taken during the California Baseline Methane Survey to match EnMAP instrument specification and perform retrievals over methane emitting facilities. We find that these EnMAP-like retrievals still detect methane hotspots. The results from this study show that satellite imagers could play a transformative role in detecting and quantifying global methane point source emitters.

Key words: Hyperspectral, EnMAP, AVIRIS-NG, WRF-LES

Information Content Of Methane Flux Estimates From Joint AIRS and GOSAT Lower-Troposphere Methane Retrievals

John Worden, Yi Yin, and Anthony Bloom

Evaluating surface fluxes of CH4 using total column data requires models to accurately account for the transport and chemistry of methane in the free-troposphere and stratosphere, thus reducing sensitivity to the underlying fluxes. Here we demonstrate the potential for estimating lower tropospheric CH4 concentrations through the combination of free-tropospheric methane measurements from the Atmospheric Infrared Sounder (AIRS) and XCH4 (dry-mole air fraction of methane) from the Greenhouse Gases Observing Satellite Thermal And Near Infrared for Carbon Observations (GOSAT TANSO, herein GOSAT for brevity). These retrievals, currently provided on a 5x4 (lon/lat) grid, have an uncertainty that ranges from 15 to 35 ppb but with peak sensitivity at 908 hPa and little sensitivity to the upper troposphere and stratosphere. These lower-tropospheric estimates can be compared to the surface network, and these comparisons show a similar error structure as the calculated uncertainties. The accuracy degrades with latitude such that we only use the initial version of these data for evaluating tropical methane fluxes. Using an analytical (Bayesian-based) flux estimation approach, We find these lower-tropospheric retrievals are almost directly sensitive to methane fluxes in S. America, Africa, and Asia, with degrees-of-freedom-for signal (DOFS) of these methane fluxes ranging from 0.7 to 0.9. Theoretical error reduction ranges from 30 to 70% for tropical wetland fluxes.

Updates on AIRS CH_4 and N_2O Retrievals

Juying Warner[*1], Zigang Wei[1], Xiaozhen Xiong[2] and others to be added[2]

1. University of Maryland, Dept. of Atmospheric and Oceanic Science, Maryland, U.S.A.
2. NOAA/NESDIS/STAR, U.S.A.

The concentrations of methane (CH_4) and nitrous oxide (N_2O) in the atmosphere have been gradually increasing and may continue, which plays a significant role in climate change. CH_4 and N_2O are two of major greenhouse gases besides carbon dioxide (CO_2). This study will ultimately make use of the high-quality global measurements of N_2O and CH_4 in the thermal infrared domain of the TANSO-FTS-2 instrument to inter-calibrate with other similar hyperspectral space-borne observations (e.g., GOSAT CH_4, AIRS/CrIS CH_4 and N_2O, IASI N_2O, and HIRAS CH_4), to establish longterm climate records. The concentrations derived from different space sensors may differ significantly due to sensor and algorithm choices, and therefore, knowing these differences will improve our understanding of the variabilities in CH_4 and N_2O. We will present the updates of the retrievals and data distributions of CH_4 and N_2O from AIRS and CrIS sensors at the IWGGMS-15. We will also discuss the short-term trends of CH_4 and N_2O starting in 2002 until present, as well as comparisons with in situ ground and aircraft measurements.

Key words: AIRS; CH_4; N_2O

Detection of XCO_2 anomaly changes in space and time at a global

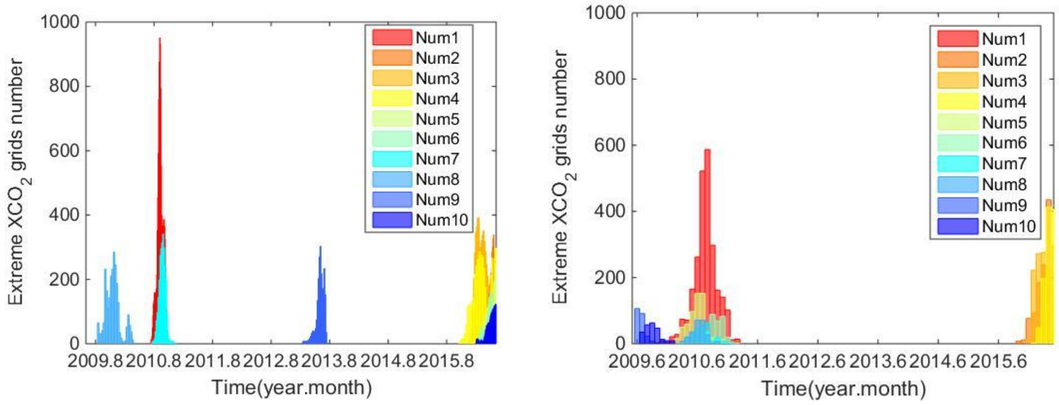
Shaoqing Zhang[12], Liping Lei*[1], Zhonghua He[12], Mengya Sheng*[12], Shaoyuan Yang[12], Hui Zhong[12], Zhaocheng Zeng[3] and Bing Zhang[12]

1. Key Laboratory of Digital Earth Science, Institute of Remote Sensing and Digital Earth, China
2. College of Resources and Environment, University of Chinese Academy of Sciences, China
3. Division of Geological and Planetary Sciences, California Institute of Technology, USA

It has been known that the anomaly change of atmospheric carbon dioxide (CO_2) concentration is closely related to the extreme climate. Detecting where and when the anomaly change of CO_2 exactly occur can help us better to understand how the change of atmospheric CO_2 concentration respond to the regional release and uptake of CO_2 in the terrestrial biosphere which could be significantly impacted by the extreme climate. Zhonghua He et al. propose a method for detecting the abnormal changes of atmospheric CO_2 concentration by using mapping GOSAT XCO_2 data. This method makes use of the residual error value after fitting seasonal variation of yearly detrended XCO_2 for anomaly detection (hereafter referred to RE method). However this RE should be evaluated as the fitting approach of seasonal variation is also applied in mapping XCO_2 data. On the other hand, R. G. Detmers et al. applied the monthly averaged XCO_2 after detrended yearly (hereafter referred to as MA method) to analyze the abnormal changes of atmospheric CO_2 concentration.

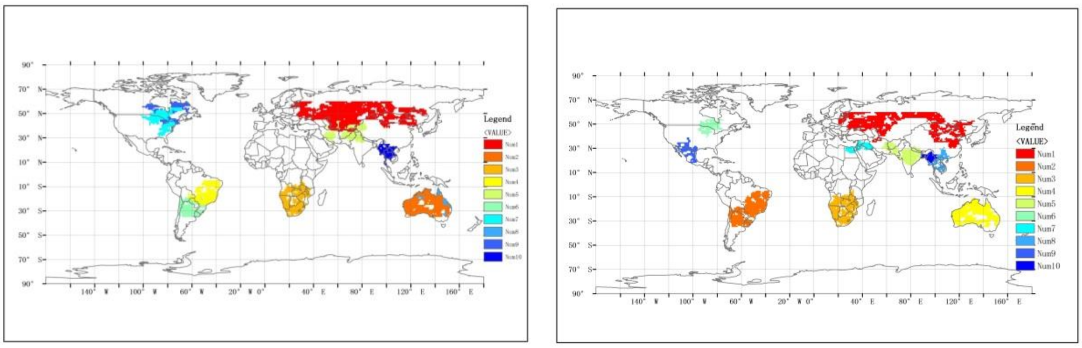
We compare this two method using mapping GOSAT-XCO_2 from Zhonghua He's paper. As a result, we find that the anomaly change of XCO_2 detected by two method generally show consistent anomaly period (see Fig.1) where both of methods detected abnormal units that occurred in 2010 and 2015 when is same as the period of ENSO event. MA method, however, did not detect the anomaly change in 2013 in North America (Num 9 in Fig.1 (a)) which is detected by RE method. It is likely because the anomaly change in 2013 is a short-time while the detecting time unit is month in MA method. The spatial distribution of detected anomaly change show some differences between two methods (see Fig.2). MA method detected the anomalies in North America (Num 9 in Fig.2 (b)), Arabia (Num 7 in Fig.2 (b)) and India (Num 5 in Fig.2 (b)) around 2010 that RE method did not display because these areas in RE method were not ranked in the top ten. Moreover, the spatial distribution range of anomalies detected in the Eurasian continent (Num 1 in Fig.2) and North America (Num 6 in Fig.2) is smaller by MA method than by RE method. In the next step, we will use auxiliary data for further comparative analysis and verification for the results of two methods.

Key words: XCO_2, GOSAT, anomaly change, monthly mean of XCO_2, fitting residuals for XCO_2



（a） RE method （b） MA method

Figure.1 The time of anomaly changes of XCO_2 detected by two methods using mapping GOSAT XCO_2 data respectively.



（a） RE method （b） MA method

Figure.2 The spatial distribution of anomaly changes of XCO_2 detected by two methods using mapping GOSAT XCO_2 data respectively.

A spectral-sorting approach for constraining coastal aerosol profile using OCO-2 O_2A measurements

Zhao C. Zeng[1], Vijay Natraj[2], Feng Xu[2], and Yuk Yung*[1]

(Correspondences: zcz@gps.caltech.edu or yly@gps.caltech.edu)

1. California Institute of Technology, USA
2. Jet Propulsion Lab, California Institute of Technology, USA

Aerosols scattering effect is one of the largest sources of uncertainty in greenhouse gas retrievals from space by influencing the path of atmospheric radiation. Especially, the vertical distribution of aerosols has a substantial impact on the radiative transfer from aerosol scattering when trying to reduce the retrieval uncertainty. Satellite and ground-based measurements have enabled accurate and continuous monitoring of total aerosol loading. However, these measurements provide little or no information on the vertical distribution of aerosols. It has long been recognized that passive remote sensing using absorption spectroscopy of molecular oxygen has the potential for aerosol vertical profiling. Absorption in the center of strong O_2 lines is saturated, such that any radiance measured in these regions must originate from scattering in the upper part of the atmosphere. In weak lines light can penetrate to lower atmospheric layers, allowing for the quantification of aerosols and other scatterers near the surface.

In this study, we applied a developed spectral-sorting algorithm (Zeng et al., 2018, GRL) to retrieve the vertical structure of aerosols in the coastal regions using hyperspectral O2A measurements from OCO-2. The algorithm is applied to infer the total aerosol optical depth (AOD) and the aerosol layer height (ALH) of the pollutant plumes over the coastal regions of Sahara Desert and Northern China. The spectral sorting technique provides two advantages over a conventional fitting scheme: (1) information related to aerosol loading and its vertical structure can be extracted in a straightforward manner from the observed radiance; (2) the spectral region(s) with the largest sensitivity to arbitrary geophysical retrieval parameters (total AOD and ALH in this study) can be identified. The proposed retrieval algorithm to constrain aerosol vertical distribution will potentially help quantify the aerosol direct radiative forcing and reduce bias in greenhouse gas retrievals from space due to uncertainty caused by aerosol scattering.

Key words: OCO-2 ; O2A; Aerosols

First validation results of the Sentinel-5P methane using global TCCON and NDACC-IRWG data

Mahesh Kumar Sha*[1], Bavo Langerock[1], Martine De Mazière[1], Dietrich G. Feist[2], Ralf Sussmann[3], Frank Hase[4], Matthias Schneider[4], Thomas Blumenstock[4], Justus Notholt[5], Thorsten Warneke[5], Rigel Kivi[6], Yao Té[7], Paul O. Wennberg[8], Debra Wunch[9], Laura Iraci[10], Kimberly Strong[9], David W. T. Griffith[11], Nicholas M. Deutscher[11], Voltaire Velazco[11], Isamu Morino[12], Hirofumi Ohyama[12], Osamu Uchino[12], Kei Shiomi[13], Tae-Young Goo[14], David F. Pollard[15], Alba Lorente[16], Haili Hu[16], Tobias Borsdorff[16], Otto Hasekamp[16], Jochen Landgraf[16], Coleen Roehl[8], Matthäus Kiel[8], Geoffrey Toon[17] and TCCON and NDACC-IRWG team

1. Royal Belgian Institute for Space Aeronomy, Belgium
2. German Aerospace Center (DLR), Germany
3. Karlsruhe Institute of Technology, IMK-IFU, Germany
4. Karlsruhe Institute of Technology, IMK-ASF, Germany
5. University of Bremen, Germany
6. Finnish Meteorological Institute, Finland
7. LERMA-IPSL, Sorbonne Université, CNRS, PSL Research University, Paris
8. California Institute of Technology, USA
9. University of Toronto, Canada
10. NASA Ames Research Center, USA
11. University of Wollongong, Australia
12. National Institute for Environmental Studies, Japan
13. Japan Aerospace Exploration Agency, Japan
14. National Institute of Meteorological Research, Republic of Korea
15. National Institute of Water & Atmospheric Research Ltd, New Zealand
16. SRON Netherlands Institute for Space Research, Netherlands
17. NASA Jet Propulsion Laboratory, USA

The Sentinel-5 Precursor (S-5P) mission with the Tropospheric Monitoring Instrument (TROPOMI) onboard was launched on 13 October 2017. The S-5P provides daily global coverage of methane (CH_4) with high spatial resolution of 7 x 7 km^2. The S-5P CH_4 standard and bias-corrected products are available over land surface. The ongoing TCCON4S5P project led by the Royal Belgian Institute for Space Aeronomy (BIRA-IASB) focuses on the validation of the S-5P CH_4 and carbon monoxide (CO) products using the ground-based Total Carbon Column Observing Network (TCCON) data from the whole network, which includes currently about 26 globally distributed stations. The early validation of the S-5P CH_4 data using the standard and rapid delivery TCCON and the Infrared Working Group of the Network for the Detection of Atmospheric Composition Change (NDACC-IRWG) data was performed. The

NDACC-IRWG validation work is done as part of the S-5P mission performance centre (MPC). The validation results contributed significantly to the quantification of the S-5P CH_4 bias and precision (~0.3% bias and ~0.6% precision for the bias corrected CH_4 product), thereby leading to an official release of the S-5P CH_4 data being recommended to the European Space Agency (ESA).
The first validation results will be presented focusing on the identification and quantification of the bias and the precision of S-5P CH_4 products.

Keywords: methane-validation; S-5P; TROPOMI; TCCON; NDACC-IRWG

Evaluation of greenhouse gas satellite observations at high Northern latitudes

Hannakaisa Lindqvist*[1], Rigel Kivi[2], Ella Kivimäki[1], Tomi Karppinen[2], Pauli Heikkinen[2], Lena Schreiner[1], Janne Hakkarainen[1], Iolanda Ialongo[1], Otto Lamminpää[1], Antti Mikkonen[1], and Johanna Tamminen[1]

1. Finnish Meteorological Institute, Helsinki, Finland
2. Finnish Meteorological Institute, Sodankylä, Finland

Satellite observations have tremendously increased the coverage of greenhouse gas measurements in the remote Arctic and boreal regions. Monitoring these rapidly changing regions is vital for quantifying their contributions to the carbon cycle. However, high Northern latitudes pose various challenges to the space-based retrievals of greenhouse gases, including large solar zenith angles, frequent cloud coverage, and a seasonally snow-covered ground. These factors affect the passive space-based observations and potentially the quality of the retrievals through biases in the retrieved products. To help quantify these biases, we present results for high-latitude evaluation of XCO_2 and XCH_4 retrievals from the Greenhouse Gases Observing Satellite (GOSAT), the Orbiting Carbon Observatory -2 (OCO-2) and Sentinel 5 Precursor TROPOMI (S5P-TROPOMI). We will primarily address comparisons against the high-resolution Fourier Transform Spectrometer at the Sodankylä TCCON site operated by the Finnish Meteorological Institute (FMI). In addition to single-sounding differences, we evaluate also seasonally varying biases and quantify the seasonal cycle. The prior atmospheric profiles used by the retrievals are evaluated against AirCore profile measurements. We will also introduce novel measurements at Sodankylä that complement the existing measurements. In the coming years, FMI is investing a lot for expanding the cryospheric, biospheric and atmospheric observations in Sodankylä to study the carbon and water cycles at high Northern latitudes and thus provide valuable information also for GHG satellite validation activities. Finally, we plan to evaluate the satellite retrievals against model results in Northern Finland but also throughout high Northern latitudes.

Keywords: CO_2, CH_4, Arctic, Boreal, GOSAT, OCO-2, TROPOMI, AirCore, TCCON, CTE-CH4, CAMS

GOSAT observations of tropospheric CO_2 and CH_4 concentrations over permafrost regions and comparison with in situ measurements of the ASCENDS/ABoVE 2017 airborne science campaign

Nobuhiro Kikuchi*[1], Akihiko Kuze[1], Fumie Kataoka[2], Kei Shiomi[1], Makiko Hashimoto[1], Hiroshi Suto[1], Joshua P. DiGangi[3], Stephan R. Kawa[4], and Jianping Mao[4]

1. Japan Aerospace Exploration Agency, Japan
2. Remote Sensing Technology Center of Japan, Japan
3. NASA Langley Research Center, USA
4. NASA Goddard Space Flight Center, USA

TANSO-FTS onboard GOSAT has spectral windows in both SWIR and TIR, which enable us to simultaneously observe the Earth's surface reflected sunlight and the thermal emission at the exact same footprint. SWIR spectra have information on the total column amount of CO_2 and CH_4, while TIR spectra are sensitive to these gases mainly in the upper troposphere. Combining these two windows, GOSAT is capable of retrieving concentrations of CO_2 and CH_4 in the lower troposphere, which helps the surface flux estimate of these greenhouse gases.

It is widely accepted that a large amount of organic carbon is stored in permafrost, which can be released as a result of warming in high-latitude regions (Schuur et al., 2015, Nature). This additional emission of greenhouse gases may accelerate global warming. Therefore, monitoring of the greenhouse gas emissions in permafrost regions is one of the important roles of satellite observations. In this study, we applied our JAXA/EORC experimental retrieval algorithm to derive CO_2 and CH_4 concentrations in the troposphere over the permafrost regions of North America, using both GOSAT SWIR and TIR spectra. In our retrieval algorithm, the entire atmosphere is divided into 5 vertical layers, 2 of which are assigned to the lower and upper troposphere.

To validate our retrieval algorithm, we compared CO_2 and CH_4 concentrations in the troposphere to the in situ measurements of the ASCENDS/ABoVE airborne science campaign conducted in the summer of 2017 in Alaska. There are a total of 47 vertical profiles of CO_2 and CH_4 concentrations from the campaign, some of which can be directly compared with co-located GOSAT observations. We found that the CO_2 concentrations of the co-located GOSAT observations were comparable to these in situ measurements. The co-located CH_4 concentrations observed by GOSAT seem to be a little underestimated, though monthly mean concentrations in North America is reasonable.

Key words: GOSAT; retrieval algorithm; validation, ASCENDS, ABoVE

Real or spurious? An examination of the OCO-2 version 9 XCO_2 data set, and curious features therein

Christopher O'Dell [1], Annmarie Eldering [2], Aronne Merrelli [3], Emily Bell [1], David Crisp [2], Kenneth Davis [4], Brendan Fisher [2], Matt Kiel [5], Thomas Lauvaux [6], Robert Nelson [2], Maximilian Reuter [7], Paul Wennberg [5]

1 CIRA, Colorado State University
2 NASA Jet Propulsion Laboratory
3 SSEC, University of Wisconsin-Madison
4 Penn State University
5 California Institute of Technology
6 Laboratoire des Sciences du Climat et l'Environnement
7 Institute for Environmental Physics, University of Bremen

It has long been recognized that space-based measurements of the column-mean dry air mole fraction of carbon dioxide (XCO_2), if made with sufficient accuracy and precision, offer a potential goldmine of information on CO_2 surface fluxes at both small and large spatial scales. However, possible biases in satellite XCO_2 will create spurious fluxes and are a limiting factor in utilizing these data. The current OCO-2 XCO_2 data set, version 9, generally agrees well with truth metrics, such as model data and collocated measurements from the TCCON network. After post-retrieval filtering and bias correction, there are no obvious correlations of the XCO_2 error versus any retrieved or auxiliary variable that is globally consistent across either all land or all ocean measurements. However, the bias correction is ad-hoc and largely empirical, and is of the same order of magnitude as the change from the prior induced by the ACOS retrieval algorithm itself. This calls into question whether unexpected features in the data are real or spurious, in the absence of independent validation data.

In this presentation, we give an overview of the V9 XCO_2 data set and its general features when compared against both models and TCCON validation measurements. We then explore some individual features found in the data at both small and large scales, including an apparently false CO_2 plume in the middle of the Arabian desert, apparent “XCO_2 waves” from an orbit track in northern Virginia, USA, and apparent large-scale biases with respect to models over the oceans. These features are typically between 1 and several ppm. We will discuss how to create tests to determine if these features are likely spurious or not, and show the results of these tests as applied to these particular features. We will conclude with a general discussion on how to use this knowledge to improve the ACOS algorithm in order to minimize spurious data features at all scales.

A first step toward the validation of the Merlin satellite mission: Magic campaigns and spatiotemporal variability of methane.

Caroline Bès[1] Cyril Crevoisier[2], François Danis[2], Morgan Lopez[3], Michel Ramonet[3], Pascal Jeseck[4], Yao Té[4], Lilian Joly[5], Hervé Herbin[6], Aurélien Bourdon[7], Jean-Claude Rubio[1], Jordi Chinaud[1], Denis Jouglet[1], Véronique Tyrou[1], Andreas Fix[8], Bruno Millet[1], Gerhard Ehret[8], Philippe Bousquet[3]

1. Centre National d'Etudes Spatiales, 31401 Toulouse, France
2. Laboratoire de Météorologie Dynamique, LMD/IPSL, CNRS, Ecole polytechnique, 91128 Palaiseau, France
3. Laboratoire des Sciences du Climat et de l'Environnement, LSCE/IPSL, CEA-CNRS-UVSQ, Université Paris Saclay, 91191 Gif sur Yvette, France
4. LERMA-IPSL,Sorbonne Université, Observatoire de Paris, Université PSL, CNRS, 75005 Paris, France
5. Groupe de Spectrométrie Moléculaire et Atmosphérique
GSMA, CNRS, Université de Reims-Champagne Ardenne, 51687 Reims, France
6. Laboratoire d'Optique de Lille, LOA, Université de Lille, Villeneuve d'Ascq, France
7. Service des avions français instrumentés pour la recherche en environnement, SAFIRE, Météo-France/CNRS/CNES, 31270 Cugnaux, France
8. German Aerospace Center, Institute of Atmospheric Physics (DLR-IPA), Oberpfaffenhofen-Wessling

The MEthane Remote sensing Lidar missioN (MERLIN) will measure concentrations of atmospheric methane with a high accuracy, in order to quantify and locate emission sources and to improve surface CH4 flux estimates. MERLIN, set up by CNES (French Space Agency) and DLR (German Space Agency) is scheduled to be launched in 2024.

MERLIN IPDA lidar measurements will enable to estimate the methane dry-air mixing ratio columns (XCH4). This main level 2 product is expected to be provided to end users with a very low error: 1% relative random error and 0.2% relative systematic error for a typical value of 1780 ppb. The Science Products Expertise (SPEX) entity is responsible for the calibration, validation and quality control along the duration of the mission, in order to verify these binding requirements. Long term and specific calibration and validation activities have to be carefully anticipated and planned to supply the SPEX entity.

The first step of the validation activities is carried out through the MAGIC (Monitoring of Atmospheric composition and Greenhouse gases through multi-Instruments Campaign) campaigns. One of its goals is to evaluate the merits of several instruments and their complementarity for comparison with Merlin XCH4 columns. MAGIC means will also be used for the validation of XCO2 measured by the MicroCarb-CNES mission.
The first issue of MAGIC was set up in January and May 2018. It involves several laboratories, several instruments which perform surface, in-situ and remote sensing total column simultaneous measurements, hold by different platforms: aircraft, balloons, tower or ground.

An important issue for satellite mission validation is also the difficulty to perform simultaneous satellite and on-Earth measurements for comparison. CH4 spatiotemporal variability has been investigated through CH4 CAMS profiles data analysis, in order to evaluate the impact of the imperfect colocalisations of measurements made by different instruments.

Ongoing Efforts to Develop Top-Down Atmospheric Flux Inventories for CO_2 and CH_4

David Crisp* (Jet Propulsion Laboratory, California Institute of Technology)

for the CEOS AC-VC Greenhouse Gas Team

Keywords: Remote Sensing, Greenhouse Gases, CO_2, CH_4, Fluxes

Advances in remote sensing instruments and analysis techniques are beginning to yield substantial improvements in the precision, accuracy, resolution and coverage of space-based estimates of atmospheric CO_2 and CH_4. Preliminary efforts are under way to integrate XCO_2 and XCH_4 estimates from GOSAT and OCO-2 with measurements from ground-based and airborne instruments and assimilate these data into atmospheric inverse models to estimate CO_2 and CH_4 fluxes.

To coordinate ongoing efforts across the growing fleet of space-based greenhouse gas monitoring satellites, the Committee on Earth Observation Satellites (CEOS) has endorsed an ambitious plan to promote the development of a prototype atmospheric flux product. The long-term objectives of this product are to: (i) reduce uncertainty of national emission inventory reporting, (ii) identify additional emission reduction opportunities and provide nations with timely and quantified guidance on progress towards their emission reduction strategies, and (iii) track changes in the natural carbon cycle caused by human activities and climate change. CEOS has started to work with stakeholders in the policy and GHG inventory community to refine these requirements. The initial effort will target the delivery of a prototype global atmospheric CO_2 and CH_4 flux product by 2021, so that it is available in time to support the 2023 global stocktake mandated by the Paris Agreement. This product may not meet the above objectives in the developed world, but should provide useful insights into CO_2 and CH_4 emissions in the rapidly developing world, where the bottom-up inventories are less mature. The lessons learned from this prototype development effort are expected to play a key role in the plans for future, operational constellations of space-based CO_2 and CH_4 sensors that will be deployed before the 2028 global stocktake. This presentation summarizes these objectives and describes the rapidly evolving implementation approach and near-term plans.

CO_2 inverse modeling with satellite X_{CO2} retrievals, ground-based observations and a high-resolution tracer transport.

Shamil Maksyutov*[1], Rajesh Janardanan[1], Tomohiro Oda[2], Makoto Saito[1], Yukio Yoshida[1], Vinu Valsala[3], Johannes W. Kaiser[4], Annmarie Eldering[5], David Crisp[5], Tsuneo Matsunaga[1]

1. National Institute for Environmental Studies, Japan,
2. USRA/NASA GSFC, USA
3. Indian Institute of Tropical Meteorology, India,
4. Deutscher Wetterdienst, Germany,
5. Jet Propulsion Laboratory, California Institute of Technology, USA

We apply a CO_2 flux inversion system based on the high-resolution Lagrangian-Eulerian coupled tracer transport model to estimate surface fluxes from atmospheric CO_2 data observed at surface stations and X_{CO2} by NASA's OCO-2 satellite and GOSAT. We use the Lagrangian particle dispersion model (LPDM) FLEXPART to estimate surface flux footprints at a 0.1-degree resolution for the OCO-2 observations (version V9r, over land) aggregated into 1 second averages and GOSAT (v02.72) single shot data. The LPDM is coupled to a global atmospheric transport model (NIES-TM). The adjoint of the coupled model is used in an iterative optimization procedure to derive surface flux corrections for the terrestrial biosphere and oceans. High-resolution prior fluxes were prepared for anthropogenic emissions (ODIAC), biomass burning (GFAS), and the terrestrial biosphere (VISIT model). The prior flux uncertainty is based on monthly mean MODIS GPP for land, and flux variability by the OTTM (Ocean Tracer Transport model) for ocean. The high-resolution transport improves simulations of the anthropogenic plumes observed at continental continuous observation sites. Before including satellite observations in the inversion, the monthly varying, latitude-dependent satellite data bias is estimated by comparing satellite observations with the X_{CO2} with surface fluxes optimized using data from surface stations for the year 2015. Monthly mean differences between the model and OCO-2 XCO_2 estimates in 5-degree latitudinal bands are below 1 ppm between 30° South and 50° North. The bias correction of satellite data improves consistency between the flux estimates based on ground-based and satellite observations. Inverse modeling reduces the monthly mean mismatch between OCO-2 and model to below 0.5 ppm for each latitudinal band, and to below 0.2 ppm in mid latitudes. Low bias of the model simulation made with optimized natural fluxes ensures it can be used as a reliable background for studying the anthropogenic emissions with OCO-2 and GOSAT data.

Key words: OCO-2; GOSAT; inverse modeling; carbon cycle

Constructing a carbon flux estimation system with bias corrected satellite data

Takashi Maki*[1], Tsuyoshi Thomas Sekiyama[1], Keiihi Kondo[1] and Takashi Nakamura[2]

1. Meteorological Researhc Institute (MRI), Japan
2. Japan Meteorological Agency (JMA), Japan

In recent years, many greenhouse gas observation satellites have been launched and operated (GOSAT, OCO-2, TanSat, GOSAT-2, etc.). The satellite observation has advantages such as its wide observable area and spatial representation close to the model horizontal resolution. On the other hand, satellite observation has a critical issue of bias. This bias varies spatiotemporally. We need to properly evaluate and correct this bias in carbon cycle analysis. Many researchers have attempted to verify the bias of satellite observation data by direct observations. However, ground observation sites are limited and it is insufficient to evaluate the bias of satellite observation with a vast observable area in detail. We constructed a method to evaluate bias of satellite observation data with independent inverse analysis data (JMA CO2 distributions) without using satellite observation data. As we can obtain long-term observation data from 2009 to 2017 from GOSAT, we calculated average bias data of satellite observation data by averaging differences from monthly satellite observation data and independent analysis values in order to extract signal and remove noise. The global average bias of GOSAT observation data (NIES SWIR L2 Ver. 2.8) throughout the whole period was -1.17 ppm (at 2.8 degrees grid) and -1.26ppm (at 5 degrees grid), almost consistent with verification results by ground observation. Looking at the geographical distribution, the bias of the GOSAT observation data showed relatively large seasonal fluctuation at the land area. By using this satellite observation data after this bias correction method for inverse analysis, we can obtain CO2 flux analysis consistent with the existing inverse analysis. We have a plan to show inverse model results using in-situ and bias corrected satellite data.

Keywords: GOSAT, Bias correction, Inverse modeling, carbon flux estimation

Global and regional methane budgets derived from GOSAT retrievals and ground-based observations using CTE-CH_4 atmospheric inverse model

Aki Tsuruta*[1], Janne Hakkarainen[1], Leif Backman[1], Yukio Yoshida[2], Dietrich G. Feist[4,3], Toshinobu Machida[2], Jost V. Lavric[3], Ed Dlugokencky[5], Juha Hatakka[1], Petri Keronen[6], Elena Kozlova[7], Paul Krummel[8], Tuomas Laurila[1], Zoe Loh[8], Nikos Mihalopoulos[9], Simon O'Doherty[9], Michel Ramonet[11], Yasunori Tohjima[3], Ray Wang[12], Doug Worthy[13],and Tuula Aalto[1]

1. Finnish Meteorological Institute, Finland
2. National Institute for Environmental Studies (NIES), Japan
3. Max Planck Institute for Biogeochemistry, Department Biogeochemical Systems, Germany
4. Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Physik der Atmosphäre, Germany
5. National Oceanic and Atmospheric Administration, Global Monitoring Division, USA
6. University of Helsinki, Institute for Atmospheric and Earth System Research / Physics, Finland
7. University of Exeter, College of Life and Environmental Sciences, UK
8. CSIRO Oceans and Atmosphere, Australia
9. Department of Chemistry, University of Crete, Greece
10. University of Bristol, School of Chemistry, UK
11. Laboratoire des Sciences du Climat et de l'Environnement, France
12. Georgia Institute of Technology, School of Earth and Atmospheric Sciences, Georgia
13. Environment and Climate Change Canada, Canada

Atmospheric methane (CH_4) has in recent years increased as rapidly as at the end of the 20th century. The cause of the rapid increase and its interannual variability are still under discussion due to lack of flux information and modelling complexity. Global CH_4 budgets are fairly well understood, but the regional estimates still vary between models. In order to obtain further understanding especially on the regional budgets, we present global and regional CH_4 emission estimates from CarbonTracker Europe-CH_4 (CTE-CH_4) atmospheric inverse model that assimilates 1) the global network of ground-based surface atmospheric CH_4 observations, and 2) column averaged dry-air mole fractions of CH_4 (XCH_4) retrieved from GOSAT TANSO-FTS. Emissions from anthropogenic and natural (wetlands and other soils, biofuel and biomass burning, termites, ocean and geological) sources are taken into account, and among those, emissions from anthropogenic and biospheric (wetlands and small sink to soils) sources are optimized simultaneously based on the ensemble Kalman filter. In the GOSAT inversion, XCH_4 zonal mean differences at 5° latitudinal bands between the GOSAT retrievals and 3D atmospheric CH_4 fields from an inversion assimilating surface observations were removed from GOSAT XCH_4 values before the inversion. The two inversions estimate similar global total CH_4 emissions for 2010-2017 (540-545 Tg CH_4 yr^{-1}), with increasing trends in emissions during 2004-2008 and 2013-2016. The seasonal cycle of the emission estimates were different in the two inversions in the Southern Hemisphere extratropics, and the summer emissions in Northern Hemisphere temperate regions were greater in the GOSAT inversion. The latitudinal gradient of the emissions were evaluated using non-assimilated observations from HIPPO aircraft campaigns and TCCON, which showed a positive bias in the Northern Hemisphere. In addition, the seasonal cycle and trend of the emissions, especially for the Tropics were evaluated using non-assimilated observations from CONTRAIL and ATTO observatory.

Key words: GOSAT; CH_4; atmospheric inversion

Constraining carbon fluxes in northern regions by combining constraints from multiple atmospheric CO_2 observing systems

Brendan Byrne[*1], Junjie, Liu[1], Meemong Lee[1], Ian Baker[2], Kevin W. Bowman[1], John S. Kimball[3], Charles E. Miller[1], Nicholas C. Parazoo[1]

[1]Jet Propulsion Laboratory, California Institute of Technology, CA, USA
2Atmospheric Science Department, Colorado State University, Fort Collins, CO, USA
[3]Numerical Terradynamic Simulation Group, W.A. Franke College of Forestry & Conservation, The University of Montana, Missoula, MT 59812, USA

Northern latitudes (> 50°N) are experiencing the most rapid warming on Earth, resulting in major ecological change and permafrost thaw. Yet many fundamental questions about the northern biosphere remain unanswered due to poor observational coverage of these northern regions. To fill in observational gaps, we combine atmospheric CO_2 measurements from the network of surface sites, GOSAT and TCCON in a single flux inversion analysis. We perform a six-year flux inversion, producing data-constrained net ecosystem exchange of CO_2 (NEE) in northern latitudes over 2010-2015. We further combine satellite observations of solar induced fluorescence (SIF) with NEE to disentangle fluxes of gross primary productivity (GPP) and ecosystem respiration (Re) for improved process attribution. These data-constrained estimates of GPP and Re are then applied to evaluate terrestrial biosphere model estimates of the seasonal cycle and interannual variability of NEE over northern ecosystems, giving insights into model deficiencies.

Key words: Flux inversion; GOSAT; TCCON; SIF

Resolving the information in large-scale inversions: application to CMS-Flux

K. Bowman*[1], N. Bousserez[2], J. Liu1, M. Lee[1], D. Henze[3]

1. Jet Propulsion Laboratory, California Institute of Technology, USA
2. European Centre for Medium Range Weather Forecasting, Reading, UK 3. Department of Mechanical Engineering, University of Colorado, Boulder, USA

Large-scale 4D variational (4D-var) assimilation techniques, which can efficiently incorporate large datasets (e.g. satellites), have migrated from numerical weather prediction to new areas in the Earth System including atmospheric chemistry and the carbon cycle. Of primary importance in these new applications is the inference of boundary conditions (e.g. fluxes), which need to be characterized in terms of uncertainty, resolution, and information content. However, these metrics have been difficult to compute because they implicitly require large matrices. However, recent advances in stochastic matrix decomposition and optimal dimension reduction techniques enable a new class of inversion methods that can resolve independent spatio-temporal patterns of geophysical states. We show that these patterns are a function of the observing system sampling and precision, the variability of the geophysical state itself, and the sensitivity of those states to observations. We then introduce the Fast Randomized Optimal approach for Diagnostic and Optimization (FRODO) algorithm that can practically compute these patterns along with critical information diagnostics, including the averaging kernel and the degrees of freedom for signal. We integrate FRODO into the NASA Carbon Monitoring Flux (CMS-Flux) carbon cycle data assimilation system to estimate optimal patterns of global CO_2 fluxes and compute associated diagnostics constrained by the NASA Orbital Carbon Observatory (OCO-2) sampling for the year 2015. Using an Observing System Simulation Experiment (OSSE), we show how the spatial resolution of the flux estimate can vary substantially even within a continent based upon the intersection of transport patterns and observations. The potential of FRODO to quantify the impact of an emerging virtual constellation of carbon measurements to advance both policy and scientific objectives is explored.

Exploring Constraints on a Wetland Methane Emission Ensemble with GOSAT

R. J. Parker[*1,2,3], H. Boesch[1,2,3], C. Wilson[3,4], A. Bloom[5], E. Comyn-Platt[6], J. McNorton[7], M. Chipperfield[3,4]

1) Earth Observation Science, Department of Physics and Astronomy, University of Leicester, Leicester, UK
2) Leicester Institute for Space and Earth Observation, University of Leicester, Leicester, UK
3) NERC National Centre for Earth Observation, UK
4) School of Earth and Environment, University of Leeds, UK
5) Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA
6) Centre for Ecology and Hydrology, Wallingford, UK
7) European Centre For Medium Range Weather Forecasts, Reading, UK

Methane (CH_4) is an important greenhouse gas and contributes significantly to the increase in radiative forcing responsible for the changing climate. Despite its importance in understanding the current and future Earth system, the past behaviour of atmospheric CH_4 and crucially, its response in future climate scenarios is still poorly understood.

Natural wetlands are the largest contributors to global CH_4 emissions but there remains a crucial lack of understanding on what drives the spatial and temporal variability of these emissions due to complex interactions between the hydrological and carbon cycles.

In this study we use an ensemble of CH_4 emission data from the WetCHARTs dataset which derives emissions from a combination of different wetland extent scenarios and temperature dependencies. This data is input into a global chemistry transport model to produce total column amounts which can be directly compared to GOSAT CH_4 observations.

Through comparison of these different ensemble members over different wetland regions, we are able to assess which constraints on wetland extent and temperature dependency provide the best agreement to observations and determine which processes will be key in driving wetland CH_4 emissions in the future climate.

Difference of detecting anthropogenic CO_2 emission by GOSAT and OCO-2 observations in China

Mengya Sheng*[12], Liping Lei*[1], Shaoyuan Yang[12], Zhonghua He[12], Hui Zhong[12], Shaoqing Zhang[12], Zhaocheng Zeng[3] and Bing Zhang[12]

1. Key Laboratory of Digital Earth Science, Institute of Remote Sensing and Digital Earth, China
2. College of Resources and Environment, University of Chinese Academy of Sciences, China
3. Division of Geological and Planetary Sciences, California Institute of Technology, USA

GOSAT takes measurements of reflected sunlight from Earth's surface with a circular footprint of approximately 10.5km diameter while OCO-2 observes with a parallelogram footprint of 1.29km×2.25km. The column-averaged CO_2 dry air mole fraction (XCO_2) retrieved from the two satellites observation could be different due to different sensors, viewing geometries, and repeat cycles for regional analysis of CO_2. In this studying, we investigate their performance for detecting anthropogenic emissions.

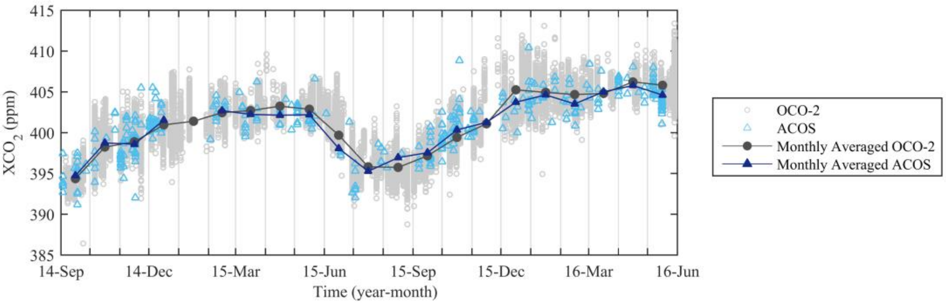
We collected GOSAT and OCO-2 XCO_2 datasets (ACOS v7.3, OCO-2 v9) with consistent retrieval algorithms. To evaluate the response differences between satellites to anthropogenic CO_2 emissions, we select an emission region (Beijing-Tianjin-Hebei, high-density urban area) and a background region (western area of Inner Mongolia, sparse vegetation and low-population area) as contrasting area. The difference of XCO_2 (ΔXCO_2) between emission area and background area are calculated as the contrast of emission to background during overlapping period of two satellites observation, from September 2014 to May 2016.

The results show that the differences of monthly averaged XCO_2 between GOSAT and OCO-2 change from -1.62 ppm to 1.20 ppm in the emission region, from -2.16 ppm to 1.30 ppm in the background region and the difference in emission region is lightly less than that in the background region. Both of maximum difference is in summer for GOSAT and OCO-2.

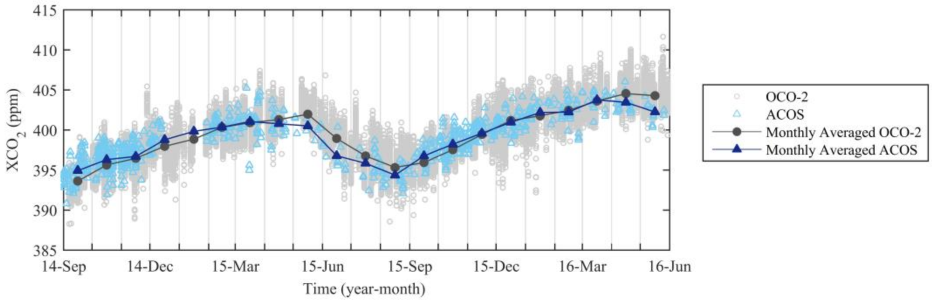
When comparing monthly ΔXCO_2 of GOSAT and OCO-2, the trends are approximately similar. Their differences are generally -1ppm to 1ppm excluding 2.16 ppm in August 2015 and -1.28 ppm in December 2015, which are mainly induced by the difference in the location where industrial heat sources and power plants are dense cluster and the amount of satellite observations, especially OCO-2 observations.

Our results indicate that regional CO_2 anthropogenic emission detected by contrast between emission region and background region with OCO-2 and GOSAT should consider about the distribution of satellite observations.

Key words: GOSAT; OCO-2; XCO_2; anthropogenic CO_2 emission



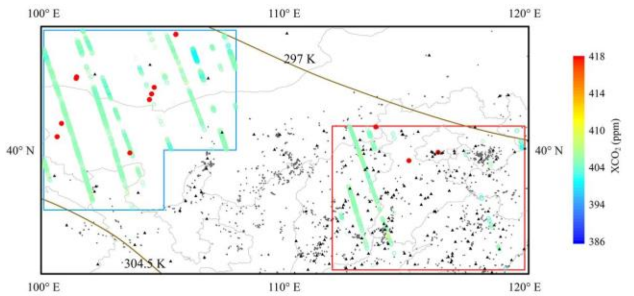
(a)



(b)

Fig1. Timely variations of XCO_2 footprints and Monthly averaged XCO_2 from September 2014 to May 2016.

(a) Emission-region; (b) Background-region.



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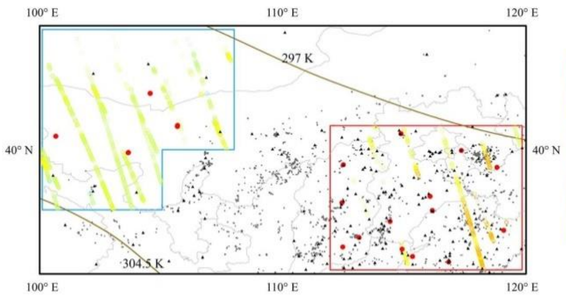


(b)

Fig2. CO_2 observations of GOSAT and OCO-2 in August 2015 (a) and December 2015 (b). The dots with different colors represent OCO-2 observations. The red dots represent GOSAT observations. The gray dots represent industrial heat sources derived from VIIRS Nightfire product (Yongxue Liu et al.,2017). The black triangles represent power plants from the database of Carbon Monitoring for Action (CARMA).

The potential of the XCO_2 high resolution imagery for the monitoring of CO_2 emissions from large cities and industrial plants: an overview of the studies at LSCE

Grégoire Broquet*[1], Diego Santaren[1], Yilong Wang[1], Anastasiia Prokaieva[1], Franck Lespinas[1], Elise Potier[1], François-Marie Bréon[1], Frédéric Chevallier[1], Philippe Ciais[1], Michael Buchwitz[2], Maximilian Reuter[2], Heinrich Bovensmann[2], Cyril Crevoisier[3], Vincent Cassé[3], Greet Janssens-Maenhout[4], Tomohiro Oda[5,6], Denis Simeoni[7], Armin Löscher[8] and Yasjka Meijer[8]

1. Laboratoire des sciences du climat et de l'environnement, CEA-CNRS-UVSQ, Université Paris Saclay, Orme des Merisiers, 91191 Gif sur Yvette, France
2. Institute of Environmental Physics (IUP), University of Bremen FB1, Otto Hahn Allee 1, 28334 Bremen, Germany
3. Laboratoire de Météorologie Dynamique, Centre National de la Recherche Scientifique, Institut Pierre-Simon Laplace, Palaiseau, France
4. Joint Research Center, Institute for Environment and Sustainability, Ispra (Va), Italy
5. Global Modeling and Assimilation Office, NASA Goddard Space Flight Center, Greenbelt, MD, USA
6. Goddard Earth Sciences Technology and Research, Universities Space Research Association, Columbia, Maryland, USA
7. Thales Alenia Space, Cannes, France
8. European Space Agency (ESA), ESTEC, Noordwijk, The Netherlands

The high-resolution spectro-imagery of vertically integrated CO_2 concentrations (XCO_2) from space may become a critical component of operational atmospheric inversion systems for the monitoring of CO_2 anthropogenic emissions, allowing the detection of CO_2 plumes downwind of large cities and industrial plants. Much remains to be understood and developed to ensure that the constellation of the Copernicus Anthropogenic Carbon Dioxide Monitoring mission (CO2M, to be deployed in 2025/2026), will feed a system quantifying the emissions with a coverage and accuracy that are relevant for policy makers. LSCE has led or contributed to various projects (including ESA-LOGOFLUX, ESA-PMIF, H2020-CHE, and TRACE in collaboration with Thales Alenia Space) for the preparation of XCO_2 imaging missions such as CarbonSat, CO2M, and the “city-mode” of MicroCarb. We present an overview of the high-resolution modeling systems and of the Observing System Simulation Experiments (OSSEs) developed at LSCE to assess the potential of such missions. These systems target all the large CO_2 sources potentially seen from space across a country or the globe. They are built on an automatic delimitation of the emission “clumps” corresponding to cities and large industrial plants in spatialized inventories. The ability to link information from successive images or from different cities has been assessed based on new analysis of the uncertainties in inventories. Results for cities and plants at the hourly to annual scale are analyzed as a function of the emission rate, of observation parameters (precision, spatial resolution and swath) of typical wind, cloud and sunlight conditions, and of the ability to disentangle neighbor diffuse and point sources and natural fluxes. A 2x2km^2 resolution and <1ppm precision imagery is required to achieve <10% uncertainty in estimates over few hours for megacities emitting ~10MtCy^{-1}. Results also show that cities and plants emitting <1MtCy^{-1}, can hardly be monitored.

Key words: CO_2 emissions; cities; XCO_2 imagery; atmospheric inversion; CO2M

Plume detection and characterization from XCO_2 imagery: potential of Gaussian methods for analyzing and estimating plant and city fluxes in the context of MicroCarb and GeoCarb

Claude Camy-Peyret
IPSL/SU-UVSQ, Paris, France

Pascal Prunet, Olivier Lezeaux
SPASCIA, Toulouse, France

François-Marie Bréon, Grégoire Broquet, Diego Santaren
LSCE/IPSL, Gif-sur-Yvette, France

We have used simulations over Western Europe of daily fields of column averaged dry air carbon dioxide mixing ratio (XCO_2) generated using kilometer scale emission inventories and an Eulerian transport model. Sixteen typical European sites covering power plants and cities in France, Belgium, Germany, Great-Britain and the Netherlands have been selected as targets for the inversion of emissions based on XCO_2 images of the corresponding areas. These simulated images have been used to assess the potential of satellite instruments able to acquire such images for emission estimates from LEO or GEO platforms. The simulated plumes have a realistic character and have been fitted (using an optimal estimation method) with a Gaussian-based plume model able to deal with multiple and/or extended sources. The number of retrieved parameters as well as the dependence of their *a posteriori* uncertainties on the input XCO_2 uncertainty (in ppmv) or on the assumed spatial resolution (size of the pixels) and spatial coverage (area of the measurement scene) are discussed. Systematic retrievals from MicroCarb and GeoCarb simulated images (with the presently known characteristics of these satellite sounders) have been performed. These results are used to identify suitable sites to be targeted by the MicroCarb "City Mode". A quantification of the expected precision on the derived source fluxes, considering the impact of the instrument characteristics, of the complexity of the plumes, and of realistic assumptions on cloud coverage, will be presented.

Quantifying Methane Emissions from Individual Coal Mine Vents with GHGSat-D Satellite Observations

Daniel J. Varon*[1,2], Daniel J. Jacob[1], Dylan Jervis[2], Jason McKeever[2]

1. Harvard University, 2. GHGSat, Inc.

GHGSat-D was launched in June 2016 as a demonstration instrument for the planned GHGSat satellite constellation, which aims to quantify emissions from individual methane point sources using fine-resolution (< 50 m) observations of methane plumes. GHGSat-D has coarser precision (13%) than is planned for the constellation (1%-5%), but we show that it can still detect plumes from individual coal mine vents after time averaging of wind-rotated observations on successive overpasses. We present observations for the San Juan (USA), Appin (Australia), and Bulianta (China) coal mines and deduce the corresponding emissions with error estimates using integrated methane enhancement (IME) and cross-sectional flux methods.

Trends and interannual variation of African CH_4 fluxes inferred from GOSAT XCH_4 retrievals

Liang Feng[1], Mark Lunt[1], Paul Palmer[1], Robert Parker[2], Hartmut Boesch[2]

1. National Centre for Earth Observation (NCEO), University of Edinburgh, UK
2. National Centre for Earth Observation (NCEO), University of Leicester, UK

We infer global CH_4 fluxes by using an Ensemble-Kalman filter (EnKF) to assimilate proxy GOSAT XCH_4 retrievals for 8 years from 2019 to 2016, based on a global 3D chemistry transport model GEOS-Chem. We focus on the interannual variation of the resulting fluxes and, find significant increases in CH_4 emissions from the Eurasia temperate and from the tropical Africa regions between 2010 and 2016. Subsequently a more detailed investigation has been made over Tropical Africa, which contains one of the largest river basins in the world and substantial wetlands which account for a significant part of global methane emissions. We used a novel approach, based on the high-resolution nested regional version of the GEOS-Chem model, to infer fluxes at much higher spatial and temporal resolution over Africa, which enables us to study possible causes for annual and seasonal variations of the resulting fluxes, such as changes of temperature, precipitation as well as the wetland area etc. We find that the robust positive trend in tropical Africa CH_4 emissions is largely due to increased emissions from the Sudd wetlands in South Sudan. Furthermore, we find a strong seasonality in emissions across Northern Hemisphere Africa, with the timing of the seasonal emissions peak occurring in the latter part of the northern hemisphere wet season.

Keywords: CH_4, GOSAT, Africa

Solar-induced chlorophyll fluorescence from the geostationary geoCARB instrument

Peter Somkuti*[1], Christopher O'Dell[1], Greg McGarragh[1]

1. Colorado State University, USA

The geoCARB mission, to be launched in 2023, is aimed at retrieving atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4) and carbon monoxide (CO) at a spatial resolution of 5.3x4.4 km^2 in order to investigate science questions related to the American carbon cycle as well as anthropogenic carbon emissions. Similar to other space-based missions like GOSAT and OCO-2, the geoCARB instrument will feature bands in the shortwave infrared wavelength range, including the O_2 A-band at 0.76 µm. This band can be utilized to retrieve solar-induced chlorophyll fluorescence (SIF), a byproduct of photosynthesis and a direct proxy for carbon uptake. Since GeoCARB will be placed in a geostationary orbit, situated at a longitude between 65°W and 105°W, it will be the first time that space-based measurements of SIF can be performed at a daily repeat cycle, covering most of the contiguous United States as well as the Amazon basin. Depending on the chosen scanning strategy, even multiple measurements per day of a certain region are possible.

To assess the quality and quantity of SIF retrievals that can be expected from geoCARB, we perform (observing system) simulation experiments based on realistic instrument specifications and observing geometries. Given the several millions of measurements per day, we estimate the number of SIF retrievals that pass quality filtering and analyze the biases for two different retrieval algorithms. This provides the SIF community with a first indication of the amount and the quality of SIF retrievals to expect from the geoCARB instrument.

Key words: Geocarb; SIF; Fluorescence

Seasonal trends of GOSAT-SIF in temperate vegetations

Hibiki M. Noda*[1], Haruki Oshio[1], Yukio Yoshida[1], Kouki Hikosaka[2] and Tsuneo Matsunaga[1]

1. National Institute for Environmental Studies (NIES), Japan
2. Tohoku University, Japan

In recent decades, global warming has progressed owing to increase of CO_2 emitted by human activities. Terrestrial ecosystem absorbs about 30 % of anthropogenic CO_2 through photosynthesis and the photosynthetic rate is quite sensitive to meteorological conditions0. Thus, to deal effectively with global warming, it is necessary to monitor photophoretic production with their underlying mechanisms including biogeochemical processes. Satellite remote sensing is a powerful tool to monitor spatial and temporal dynamics in the structure and function of terrestrial ecosystem those are responsible for such photosynthetic CO_2 absorption. Recently satellite-based SIF (solar-induced chlorophyll fluorescence) has been utilized as a new technique to estimate GPP (gross primary production) of terrestrial ecosystems. Although typical vegetation indices, e.g., NDVI and EVI are correlated to the amount of foliage, SIF is thought to be directly linked to photosynthetic activities because the chlorophyll fluorescence is a radiation emitted from chlorophylls in the photosynthetic process itself.

Since SIF is obtained by gas-measurement satellites, such as GOSAT, GOSAT-2, OCO-2 and GOME-2, special and/or temporal resolutions of those are too rough to monitor vegetation condition. So, several studies have used average SIF of large area, such as 2 x 2^{o} grid. However, because GOSAT measurements sparsely and spatial distribution of SIF data is highly heterogeneous, this approach is not suitable for the monitoring in regional scale. In present study, to examine how much single-shot data of GOSAT-SIF reflects the vegetation activities, we selected five sites in Japan including deciduous forest, evergreen forest, cropland and urban area and analyzed seasonal trend of SIF at those points observed by GOSAT from 2009 – 2018. SIF at deciduous forest in cool-temperate region showed clear seasonal trend, similar to leaf phenology of deciduous trees. In total, SIF of forest sites were two to four times higher than crop land.

Key words: GOSAT; GOSAT-2; SIF; phenology; vegetation monitoring

What can we learn about effectiveness of carbon reduction policies from interannual variability of carbon emissions? Applying ODIAC emission estimates from East Asia of the 2010s.

*Lev D. Labzovskii[1] , Hugo Wai Leung Mak[2] , Samuel Takele Kenea[1] , Jae-Sang Rhee[3], Azam Lashkari[4], Shanlan Li[1], Tae-Young Goo[1], Young-Suk Oh[1], and Young-Hwa Byun[1]

1. Climate Research Division, National Institute of Meteorological Sciences (NIMS), Seogwipo, Jeju-Do, 63568, Korea
2. Department of Mathematics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong
3. Department of Mechanical and Aerospace Engineering, Seoul National University, Seoul, Republic of Korea
4. School of Environmental Science and Engineering, Southern University of Science and Technology, Shenzhen, China

Most countries have submitted their Nationally Determined Contributions (NDC) but we still poorly understand what policies are effective in terms of reduction of carbon abatement under the announced pledges. We estimate the importance of national environmental policies of East Asia in terms of reduction in fossil fuel carbon emissions ($FFCO_2$) using ODIAC data. The national flagship policies in East Asia of the 2010s were generally beneficial in terms of slowing down $FFCO_2$ growth. When the polices were enacted, annual $FFCO_2$ growth rate has either slowed down by 1% (South Korea), 5% (Mongolia), 8% (China) or even resulted in a decline (Japan) comparing to prior periods. We find that the 12th Five-Year Plan (12th FYP) of China had the strongest footprint in $FFCO_2$ and the recent slowest rate of emission growth across East Asia (2011-2015) temporally corresponds to the 12th FYP. This rate is driven by decrements in annual growth of $FFCO_2$, coal use and cement production of China during the 12th FYP. We provide two baseline projections of emission distribution in East Asia, by assuming that all policies are enacted (policy-on) or not (policy-off) in the future. The projections approve that policies were beneficial since policy-on scenario results in 24%, 80%, 166% less $FFCO_2$ emissions than policy-off scenario in East Asia by 2020, 2025 and 2030 respectively. This progress is yet insufficient for reaching NDC goals by 2030. Even in policy-on scenario in 2030, East Asian countries would either experience insufficient decline of $FFCO_2$ like Japan (-13% of $FFCO_2$ comparing to pledged -17%) or increase of $FFCO_2$ like South Korea (11%) and Mongolia (4%) comparing to 2010 level. For China, due to lack of economy-independent goals, we were unable to assess NDC target compliance.

Key words: carbon emissions, carbon abatement, East Asia

The Collaborative Carbon Column Observing Network (COCCON): overview and current status

Matthias Frey*[1], Frank Hase[1], Darko Dubravica[1], Thomas Blumenstock[1], Mahesh K. Sha[2], Matthäus Kiel[3], Roland Harig[4], Gregor Surawicz[4], Nicholas M. Deutscher[5], Kei Shiomi[6], Jonathan E. Franklin[7], Hartmut Bösch[8], Jia Chen[9], Michel Grutter[10], Hirofumi Ohyama[11], Youwen Sun[12], Zhensong Cao[12], Andre Butz[13], Gizaw Mengistu Tsidu[14], Dragos Ene[15], Debra Wunch[16], Omaira Garcia[17], Michel Ramonet[18], Felix Vogel[19] and Johannes Orphal[1]

1. Karlsruhe Institute of Technology (KIT), IMK-ASF, Germany
2. Royal Belgian Institute for Space Aeronomy, Belgium
3. California Institute of Technology, USA
4. Bruker Optics GmbH, Germany
5. University of Wollongong, Australia
6. Japan Aerospace Exploration Agency, Japan
7. Harvard University, USA
8. University of Leicester, UK
9. Technische Universität München, Germany
10. Universidad National Autonoma de Mexico, Mexico
11. National Institute for Environmental Studies, Japan
12. Anhui Institute of Optics and Fine Mechanics, China
13. Universität Heidelberg, Germany
14. Botswana International University of Science and Technology, Botswana
15. National Institute for Research and Development in Optoelectronics, Romania
16. University of Toronto, Canada
17. Izana Atmospheric Research Centre, Spain
18. Laboratoire des sciences du climat et de l'environment, France
19. Environment and Climate Change Canada, Canada

Precise measurements of atmospheric abundances of greenhouse gases (GHGs), especially carbon dioxide (CO2) and methane (CH4), are of utmost importance for the estimation of emission strengths and flux changes. Furthermore, these measurements offer the prospect of being usable for the evaluation of emission reductions as specified by international treaties, e.g. the Paris COP21 agreement. The existing Total Carbon Column Observing Network (TCCON) measures column-averaged dry air mole fractions of CO2 and CH4 with reference quality. However, the instruments used by this network need large infrastructure to be set up as well as expert maintenance. Therefore TCCON stations have sparse global coverage. Current satellites like the Orbiting Carbon Observatory-2 and the Greenhouse Gases Observing Satellite offer global coverage. Nonetheless, they suffer from coarse temporal resolution. The Collaborative Carbon Column

Observing Network (COCCON) is intended to be a lasting framework for creating and maintaining a GHG observing network based on common instrumental standards and data analysis procedures. Currently, 20 working groups operating EM27/SUN Fourier Transform Infrared spectrometers are contributing. We expect that COCCON will increase the global density of column-averaged greenhouse gas observations and will especially contribute to the quantification of local sources. Therefore, the COCCON results can be used for the validation of satellite data. For achieving an optimal network performance, common standards for instrumental calibration, quality checks for new spectrometers before deployment, and finally a centralized processing and data storage facility is desirable. This framework will be provided by COCCON. Within the ongoing ESA supported project COCCON-PROCEEDS, a common preprocessing tool and a centralized data handling facility (CPDHF) demonstrator is under construction. We will present the already operational components of COCCON (quality checks of new spectrometers, instrumental calibration of all devices) and the current status of COCCON-PROCEEDS.

Key words: COCCON; TCCON; GHG

Airborne Demonstration of Atmospheric CO_2 Concentration Measurements with a Pulsed Multi-wavelength IPDA Lidar

Jianping Mao[*1], James B. Abshire[2], S. Randy Kawa[2], Haris Riris[2], Graham R. Allan[3], William E. Hasselbrack[3], Kenji Numata[2], Jeff Chen[2], Xiaoli Sun[2], Julie M. Nicely[1], Joshua P DiGangi[4] and Yonghoon Choi[4]

1. UMD; 2. NASA Goddard Space Flight Center; 3. Sigma Space Inc., Greenbelt, MD 20771; 4. NASA Langley Research Center, Hampton, VA 23681, USA

Globally distributed atmospheric CO_2 concentration measurements with high precision, low bias and full seasonal sampling are crucial to advance carbon cycle sciences. The passive remote sensing of column-averaged atmospheric CO_2 mixing ratio (XCO_2) from space using Earth's surface-reflected sunlight present significant local biases, which are likely related to atmospheric scattering effects and to the low measurement sensitivity due to insufficient sensor spectral resolution. NASA Goddard Space Flight Center has developed an integrated-path, differential absorption (IPDA) lidar approach to measure global XCO_2 from space as a candidate for NASA's Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) mission. This pulsed laser approach uses a step-locked laser diode source and a high-efficiency detector to measure atmospheric column CO_2 absorption at multiple wavelengths across a CO_2 line centered at 1572.335 nm at very high spectral resolution and high sensitivity to atmospheric CO_2 variation.
Measurements of time-resolved laser backscatter profiles from the atmosphere allow this technique to estimate XCO_2 and range to cloud tops in addition to those to the ground with precise knowledge of the photon path-length regardless of atmospheric scattering.

We demonstrate this measurement capability using airborne lidar measurements from summer 2017 ASCENDS airborne science campaign in Alaska. It is the first time our airborne lidar measurement was extended to the Arctic region where atmosphere is more dynamic and measurement conditions are more challenging. We have developed an "uninformative" retrieval algorithm that does not depend on a prior information and minimizes bias by taking advantage of the highly sensitive lidar measurements at multiple wavelengths. We show retrievals of XCO_2 to a variety of cloud tops in addition to the ground. We will also demonstrate how the partial column XCO_2 to cloud tops and cloud slicing approach help resolving vertical and horizontal gradient of CO_2 in cloudy conditions. The XCO_2 retrievals from the lidar are validated against on-board in situ measurements of CO_2 vertical profiles during flight spiral down maneuvers.

Adding this measurement capability to the future lidar mission for XCO_2 will provide full global and seasonal data coverage and some information about vertical structure of CO_2. This unique facility is expected to benefit atmospheric transport process studies, carbon data assimilation in models, and global and regional carbon flux estimation.

Characterization of aerosol absorption over south Asia based on multi-platform measurements and CAI-2 retrieval of AOD and soot volume fraction

Mukunda M Gogoi*[1], S Suresh Babu[1] and Ryoichi Imasu[2]

1. Space Physics Laboratory, Vikram Sarabhai Space Centre, ISRO, India
2. Atmospheric and Ocean Research Institute, University of Tokyo, Japan

Improved understanding of the large heterogeneity in the nature and sources of aerosols and their climate impact is of paramount importance over the south Asian region, because of the rapid changes in anthropogenic emissions associated with rapid urbanization and industrialization coupled with distinct topography, meteorology and land-use of the region. In this context, assessment and application of aerosol retrievals by cloud-aerosol imager-2 (CAI-2) onboard GOSAT-2 satellite, in conjunction with multi-platform measurements of aerosols over South-Asia is very important. Based on ground based estimates of aerosol physical and optical properties across a dense network of observatories (ARFINET) over India, it is revealed that the seasonal variation of near surface aerosol concentration is different from the columnar aerosol loading over most of the Indian regions. The near surface Black Carbon (BC) mass concentrations show high values during winter and post-monsoon; while columnar Aerosol Optical Depth (AOD) peaks during pre-monsoon. This pattern changes at high altitudes where pre-monsoon enhancement is seen in both AOD and BC. Despite the seasonal and regional distinctiveness, the regions with high AOD coincide with the regions having high BC, occurring mainly over the Indo-Gangetic Plains (IGP), followed by northeast India and western India; while peninsular region and southern India show relatively lower values. Extensive aircraft measurements of the vertical distribution of aerosols revealed a definite enhancement in aerosol absorption in the lower free troposphere over the IGP during spring, along with a reduction near the surface. On the other hand, aerosol absorption depicted region specific absorption characteristics just prior to the onset of the Indian summer monsoon, leading to a west–east gradient in the vertical structure of single scattering albedo (SSA). Hence a synergistic approach of combining both ground based and space borne observations is necessary for the accurate characterizations of aerosols over south Asia. It is proposed to combine the CAI-2 retrievals of AOD and soot volume fraction with the ground based ARFINET data to retrieve a more accurate regional picture of aerosol absorption over the south Asian region.

Research Field: Data application/ related ground-based, ship-borne, and air-borne measurements;

Low-resolution FTIR spectrometers supplementing TCCON for the validation of space-borne observations of greenhouse gases (CO_2, CH_4) and CO

Mahesh Kumar Sha*[1], Bavo Langerock[1], Martine De Mazière[1], Christian Hermans[1], Justus Notholt[2], Christof Petri[2], Huilin Chen[3], David Griffith[4], Nicholas Jones[4], Frank Hase[5], Thomas Blumenstock[5], Qiansi Tu[5], Rigel Kivi[6], Pauli Heikkinen[6], Damien Weidmann[7], Neil Macleod[7], Angelika Dehn[8]

1. Royal Belgian Institute for Space Aeronomy, Belgium
2. University of Bremen, Germany
3. University of Groningen, Netherlands
4. University of Wollongong, Australia
5. Karlsruhe Institute of Technology, IMK-ASF, Germany
6. Finnish Meteorological Institute, Finland
7. Rutherford Appleton Laboratory, United Kingdom
8. European Space Agency (ESA)/ESRIN

Ground-based FTIR passive remote sensing networks like the TCCON and NDACC-IRWG have been the key facilities for the validation of satellites measuring greenhouse (CO_2, CH_4) and pollution (CO) gases. Even though TCCON is the baseline network for high-precision and accurate total column measurements of these gases, the number of stations (currently about 26) available worldwide is limited. The 20 NDACC-IRWG stations, add to the list of stations used for satellite validation. Even though, some of these stations are based on the same instruments as TCCON. Nadir viewing satellite instruments measure gas concentration globally. To improve on the satellite measurement validation a denser distribution of zenith-looking ground-based measurements covering different surface conditions (albedo), latitudinal and seasonal distribution, as well as stations in the southern hemisphere are needed. For this reason, several groups are investigating alternative portable low-cost instruments, which can complement the existing networks and enhance the validation of satellite measurements.

The ongoing campaign "Fiducial Reference Measurements for Ground-Based Infrared Greenhouse Gas Observations (FRM4GHG)" at the Sodankylä (Finland) TCCON site, funded by the European Space Agency (ESA), aims at characterizing the assessment of several low-cost portable spectrometers for precise solar absorption measurements of CO_2, CH_4 and CO. These measurements are performed simultaneously next to the TCCON instrument since 2017. In addition, regular AirCore launches are performed from the site to provide in-situ reference profiles of these gases; this is useful for the verification of the instrument calibration. The intercomparison results show that the low-resolution instruments tested provide high quality data comparable to that of TCCON. The data collected during 2 years were used for the validation of CO_2 measured by OCO-2 and CH_4, CO measured by Sentinel-5P satellite missions.

The results of the validation exercise will be presented and the added value of the portable FTIR remote-sensing

instruments will be discussed.

Keywords: S-5P; OCO-2; TCCON; FRM4GHG; validation

Development of MRV system of Methane emissions from rice paddies in the Mekong delta

Hironori Arai* (the University of Tokyo, RIKEN Center for Computational Science, Japan)
Wataru Takeuchi (Institute of Industrial Science, the University of Tokyo, Japan)
Kei Oyoshi (Earth Observation Research Center, Japan Aerospace Exploration Agency, Japan)
Lam Dao Nguyen (Ho Chi Minh City Space Technology Application Center, Vietnam)
Towa Tachibana (Faculty of Law, Politics and Economics, Chiba University, Japan)
Ryuta Uozumi (Uozumi sustainability research institute, Japan)
Koji Terasaki (RIKEN Center for Computational Science, Japan)
Takemasa Miyoshi (RIKEN Center for Computational Science, Japan)
Hisashi Yashiro (RIKEN Center for Computational Science, Japan)
Kazuyuki Inubushi (Graduate School of Horticulture, Chiba University, Japan)

Monitoring sustainability and implementation status of a water-saving irrigation in tropical rice paddies

Greenhouse gas (GHG) emission observation/reduction technologies are attracting greater deal of attention from policy makers to achieve Sustainable Development Goals. In terms of GHG accounting, Monitoring, Reporting and Verification (MRV) systems have become significantly important for the countries which ratified Paris Agreement by promising Intended Nationally Determined Contributions (INDC). Not only evaluation of the amount of GHG emitted from the countries, but also the mitigation's effect and its dissemination status need to be monitored by the policy makers. In this regard, the societies require the MRV systems with transparency and high cost-performance. To address such concern, the authors are building an efficient/transparent MRV system in a tropical rice cropping system based on satellite remote sensing data. We are developing a long-term consistent bottom-up approaching method with high spatio-temporal resolution, based on the Japanese earth observation technology (e.g., ALOS-2, AMSR-E/2, GCOM-C). In order to validate the outputs from the bottom-up approaching method, now we are also challenging to build an independent top-down approaching method based on the other satellites data (GOSAT, SCIAMACHY) using NICAM-LETKF with 1way-multivariate variable localization, which can estimate the surface fluxes without requiring any direct observation or a-priori information of the fluxes with K-computer.

Kewords: Methane, Synthetic Aperture Radar, GOSAT, data-assimilation,

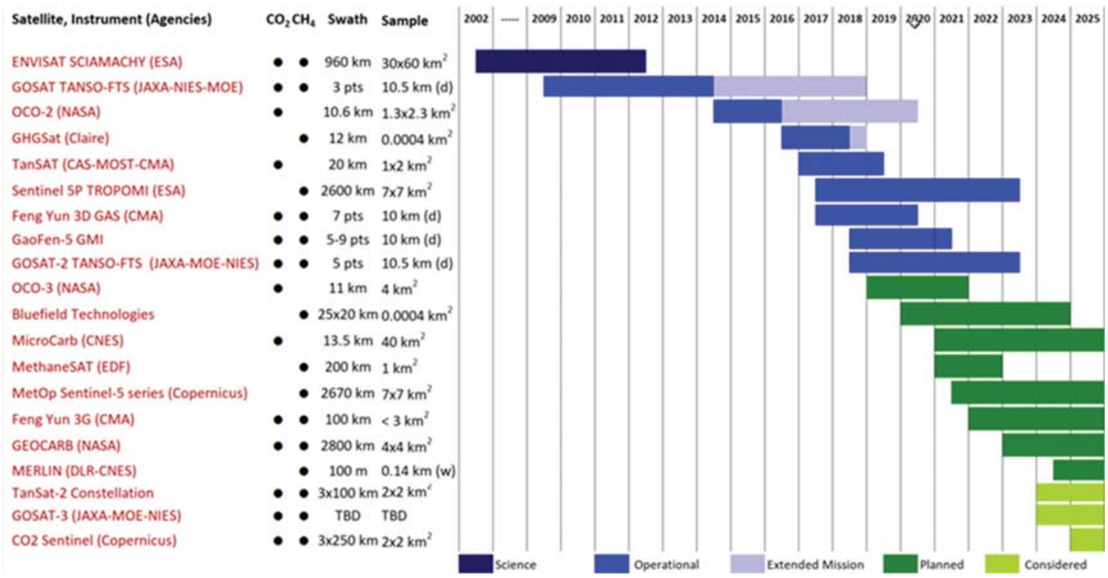
The Evolving Space-based Greenhouse Gas Measurement Fleet

David Crisp* for the OCO-2 and OCO-3 Teams

Jet Propulsion Laboratory, California Institute of Technology

Space agencies are deploying a growing fleet of space-based sensors designed to collect high-resolution spectra within CO_2 and CH_4 bands at shortwave infrared (SWIR) wavelengths. These sensors are well suited for monitoring surface CO_2 and CH_4 fluxes because estimates of their column averaged dry air mole fractions (XCO_2 and XCH_4) are most sensitive to changes in the concentration these gases in the lower troposphere. The first generation of sensors included the ESA ENVISAT SCIAMACHY, Japanese GOSAT TANSO-FTS, and NASA OCO-2 instruments. These pioneering instruments were recently joined by the Chinese TanSat ACGS, Feng Yun-3D GAS and Gaofen-5 GMI, European Copernicus Sentinel 5 Precursor TROPOMI, and Japanese GOSAT-2 TANSO-FTS-2. NASA expects to launch OCO-3 to the International Space Station in late April, and it will followed by another half dozen missions by 2025, when the European Commission hopes to deploy the first, operational CO_2 monitoring constellation (Figure 1).

Recent efforts to analyze the data from these sensors have demonstrated the precision (~0.125%) and accuracy (~0.25%) needed to resolve both anthropogenic and natural fluxes of CO_2 and CH_4 on spatial scales spanning individual power plants to regional scales. However, these systems still do not have the spatial or temporal resolution and coverage needed to provide timely, quantified guidance on natural and anthropogenic fluxes at urban to national scales. One way to address this challenge would be to would be to integrate the available space-based sensors into a virtual constellation, and harmonize their data products so that their XCO_2 and XCH_4 estimates can be combined and assimilated into atmospheric inversion models. This would require that their measurements be cross calibrated and their XCO_2 and XCH_4 estimates be cross validated against internationally-accepted standards. This presentation will summarize the status of the evolving fleet and the progress toward the harmonization of their XCO_2 and XCH_4 products.



The Figure 1: CO2 and CH4 satellite time line.

NASA's plans for Greenhouse Gas Observations from space.

Ken Jucks
NASA Headquarters

NASA has a robust set of observations for Greenhouse gas observations currently in orbit and in the plans for the near future. OCO-2 has been in operation for 5 years now and still producing high quality spectra that are used for retrievals of CO2. As long as OCO-2 is still producing high quality data, NASA intends to maintain continues operation of the satellite. OCO-3 recently launched and was deployed to the International Space Station. The instrument is still in on orbit checkout, though the expectation will be data that are of similar quality to OCO-2. In the future, the GeoCARB mission will launch to Geostationary orbit and observe the Americas completely (south of ~50 degrees latitude) on a daily basis or multiple times of day. The current expected launch date is 2023. The mission was selected under the Earth Venture Mission solicitation, which is part of the regularly solicitated calls for new space assets for NASA and are highly cost and schedule constrained. It is expected that the Earth Venture series of solicitations will continue in the future.

The recently released Decadal Survey called for prioritized science observations for NASA to pursue over the next decade or more. There were five observables that came out as the Highest priority for NASA to attempt to develop missions within an appropriate cost framework. Also called out for were six areas of high science priority observations for NASA to consider and make available for competed science missions, with the expectation that NASA would be able to afford three of them. Greenhouse gas observations fell within that category. I will discuss that the implications are for greenhouse gas observations now that NASA has the Decadal Survey guidance to consider.

The GeoCarb Mission

Berrien Moore III (University of Oklahoma) and Sean Crowell (University of Oklahoma)

This paper presents an update on the NASA Earth Venture-2 Mission, Geostationary Carbon Cycle Observatory (GeoCarb), which would provide measurements of atmospheric carbon dioxide (CO_2), methane (CH_4), and carbon monoxide (CO) from geostationary orbit. The GeoCarb mission would deliver daily maps of column integrated mixing ratios of CO_2, CH_4, and CO over the observed landmasses at a spatial resolution of roughly 5 x 10 km, which will establish the scientific basis for CO_2 and CH_4 flux determination at ecosystem/weather relevant time and space scale.

The instrument would exploit the four spectral regions: The Oxygen A-band for pressure and aerosols, the weak and strong bands of CO_2 near 1.61 and 2.06 microns, and a region near 2.32 microns for CO and CH_4. The O_2 and CO_2 bands are very similar to the instruments aboard OCO-2, and so we envision OCO-2 in geostationary orbit with the addition of a fourth channel to measure CO and CH_4, but without an oceanic capability. The O_2 A-band also provides for retrieval of Solar Induced Fluorescence (SIF).

The GeoCarb Mission persistent fine-scale daily mapping measurements, under changing conditions also enable significant advances on an important range of CO_2 biotic issues, including: CO_2 fertilization, change in primary production because of nitrogen deposition, and the influence of broad climatic patterns on terrestrial sources and sinks. This probes the mechanisms of the observed inter-annual variability in the atmospheric concentration of CO_2. In sum, GeoCarb attacks the primary question of the nature of the net terrestrial sink of CO_2.

Wetland ecosystems, rice paddies and livestock are major, and highly uncertain, sources of CH_4. Several approaches have been used to scale up from measurements at individual plots to estimations of CH_4 emissions at the landscape scale. However, there has been little large-scale top-down validation. Industrial sources are also poorly quantified. The GeoCarb Mission’s high space- and time-measurements of CH_4 enable important analyses of human impacts via agriculture and industry vs. natural phenomena on methane sources.

The MicroCarb project: recent achievements and review of the project status.

Francois Buisson (*)(1), Didier Pradines(1), Pascal Prieur(1), Véronique Pascal(1), Denis Jouglet(1), Arnaud Varinois(1), Emilie Limasset(1), Carole Deniel(1), Francois Marie Breon(2)

(1) Centre National d'Etudes Spatiales – Toulouse - France
(2) Laboratoire des Sciences du Climat et de l'Environnement – Gif sur Yvette - France

The MicroCarb satellite is fully dedicated to the monitoring of the atmospheric CO2 fluxes, thanks to a passive grating spectrometer with high spectral resolution in 4 narrow bands (0.76µ and 1.27 µ for O2, 1.6µ and 2.06 µ for CO2)

The MicroCarb project development is conducted by the CNES in partnership with several European agencies and organisms and in close cooperation with national research laboratories.

A major milestone has been recently passed with the successful completion of the detailed design phase resulting into an authorization to proceed with the realization phase heading for a launch in 2021.

Besides, the definition of the algorithms for processing the data and the different methods for calibrating the instrument on ground and in orbit and also for validating the data have significantly progressed.

The presentation will give an overview of the progress and the organization of the project.

It will highlight the original features of the design and the way they will be validated.

It will conclude with the provisions taken for the next phases of the project.

Keywords: greenhouse gas, satellite, CO2.

The MicroCarb L1 & L2 products

Denis Jouglet*[1], Pierre Lafrique[1], Christelle Pittet[1], Charlotte Revel[1], Bruno Vidal[1], Leslie David[2], François-Marie Bréon[2], Simon Prady[3], François Buisson[1], Didier Pradines[1]

1. Centre National d'Etudes Spatiales – Toulouse - France
2. Laboratoire des Sciences du Climat et de l'Environnement – Gif sur Yvette - France
3. Magellium – Toulouse – France

MicroCarb is a European initiative for the monitoring of global CO2 fluxes and a better understanding of the mechanisms that control these fluxes. It will provide atmospheric CO2 column integrated concentrations data to the scientific community, in the continuation or in parallel to the on-going operational programs. 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. The aimed random error precision is <1ppm for a regional bias <0.2ppm. After a first talk (F. Buisson) dedicated to a status of the project, we here focus on the L1 and L2 products.

We present an overview of the MicroCarb L1 and L2 scientific algorithms. The ATBDs are defined and are prototyped or close to be. L1 is decomposed in L1A (calibrated for radiometry and spectrometry at pixel detector level), L1B (calibrated for radiometry, spectrometry and geometry at footprint level) and L1C (corrected calibrated spectra using geophysical data). L1C includes the cloud detection, based on intra-FOV information resulting from the temporal intermediate readings of the detector. L2 is based on the 4ARTIC retrieval tool, based on optimal estimation. The prior knowledge will be obtained from ECMWF, CAMS for CO2 and aerosols, Sentinel 2 for surface albedo and SRTM for the Digital Elevation Model. The 4ARTIC performances are under estimation using the OCO-2 data and TCCON.

A quick overview of the cal/val methodology will also be presented.

Key words: MicroCarb, algorithms, performances, CO2

Anthropogenic CO_2 monitoring with the European candidate Copernicus mission

Yasjka Meijer*[1], Jean-Loup Bezy[1], Mark Drinkwater[1], Thorsten Fehr[1], Valerie Fernandez[1], Armin Loescher[1], Herbert Nett[1], Bernd Sierk[1], Bernard Pinty[2], Hugo Zunker[2], Hartmut Boesch[3], Michael Buchwitz[3], Philippe Ciais[3], David Crisp[3], Oleg Dubovik[3], Richard Engelen[3], Sander Houweling[3], Greet Janssens-Maenhout[3], Jochen Landgraf[3], Ruediger Lang[3], Hannakaisa Lindqvist[3], Masakatsu Nakajima[3], Pepijn Veefkind[3]

1. European Space Agency (ESA), The Netherlands
2. European Commission, DG-GROW, Belgium
3. Copernicus CO_2 Monitoring Mission Advisory Group, ESA

As part of the European Copernicus Programme, the European Commission and the European Space Agency (ESA) together with the support of EUMETSAT and ECMWF are considering the further development of the first generation Copernicus Space Component to include measurements for fossil 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 CO_2 emission strategies, uncertainties associated with current anthropogenic emission estimates at national and regional scales need to be improved.

Satellite atmospheric measurements, in addition to in-situ measurements and bottom-up inventories, would enable the transparent and consistent quantitative assessment of CO_2 emissions and their trends at the scale of megacities, regions, countries, and the globe as well. Such a capacity would provide the European Union with a unique and independent source of information, which can be used to assess the effectiveness of policy measures, and to track their impact towards decarbonizing Europe and meeting national emission reduction targets.

This presentation will provide an overview of the candidate Copernicus CO_2 monitoring mission objectives, the consolidated observational requirements on CO_2 and auxiliary measurement capabilities. Operational monitoring of anthropogenic emissions requires high precision CO_2 observations (0.5–0.7 ppm) with 2–3 days geometrical revisit time at mid latitudes. These observations will be obtained from NIR and SWIR spectra, and will be supported by (1) multi-angle polarimeter observations, to minimize 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 with a cloud imager to identify measurements contaminated by low clouds and high altitude cirrus. In addition, an update will be presented of activities and studies currently undertaken to prepare for the implementation of the space component.

Keywords: CO_2, CH_4, NO_2, aerosol, Copernicus

EUMETSAT's contribution to the CO_2M mission – continuous operations, processing, monitoring, and Cal/Val

Ruediger Lang*[1], Vincenzo Santacesaria[1], and Bojan Bojkov[1]

1. EUMETSAT , Germany

The European Commission (EC) has identified a set of new missions, including one dedicated to CO_2 Monitoring (CO_2M), as part of the possible evolution of the Copernicus program. The CO_2M mission will be the space component of a European integrated anthropogenic CO_2 emission monitoring system, which will also include in-situ observations and inversion modelling. The European partners involved in this project (EC, ECMWF, ESA, EUMETSAT and ICOS) have agreed on a CO_2 monitoring roadmap, with the objective to have this system in place to support the 2nd stock-taking in 2028 as planned by the Paris Agreement.

In a cooperation's agreement between EUMETSAT, the EC and ESA, EUMETSAT will take on the responsibility for developing the Payload Data Ground Segment (PDGS) which facilitates the continuous processing, monitoring, validation and, where needed, vicarious calibration of the payload data-products and their operational dissemination to users. EUMETSAT will also be responsible for the routine operations of the CO_2M platforms, while ESA will be responsible for developing the space-component and its instrument payload, together with an end-to-end testing and in-orbit verification system activities and the operations of the platforms before starting the routine activities.

For CO_2M the availability of robust and well maintained ground based and in-situ networks, complemented by relevant and ideally operational satellite data from other missions, as well as the usage of model data for continuous verification and Cal/Val will be of vital importance for monitoring and maintaining the stringent long-term performance requirements of the mission. We will outline how such a monitoring, verification and validation system, relying on robust data-streams from many different sources, might be established in close collaboration with our European partner agencies, the EC and ICOS, and what its key-elements will be in the context of an operational Cal/Val and monitoring environment to be established as part of a future PDGS at EUMETSAT. We will also address some key-challenges for such a continuous monitoring and Cal/Val environment for a future operational European CO_2M mission.

This paper provides an overview of the key elements of the CO_2M operational processing system for starting the CO_2M-PDGS Phase A activities at EUMETSAT. In particular we provide an overview of the key elements for a future continuous monitoring, verification, validation, and calibration system, which will be established using and/or expanding on existing multi-mission monitoring and Cal/Val elements at EUMETSAT.

Key words: CO_2M; OPERATIONS; CAL/VAL

AIM-North: The Atmospheric Imaging Mission for Northern Regions

Ray Nassar[1], Chris McLinden[1], Chris Sioris[1], Joseph Mendonca*[1], Ryan Cooney[2], Helena van Mierlo[2], Natasha Jackson[2], Louis M. Moreau[3], Sebastien Roche[4], Debra Wunch[4], Kim Strong[4], Dylan B.A. Jones[4], Feng Deng[4], Saroja Polavarapu[1], Michael Neish[1], Cameron MacDonald[5], Bruce Kuwahara[5], Charles E. Miller[6], Stanley J. Sander[6], Jean-Francois Blavier[6]
and the rest of the AIM-North Team

1. Environment and Climate Change Canada
2. Canadian Space Agency
3. ABB
4. University of Toronto
5. University of Waterloo
6. NASA Jet Propulsion Laboratory, California Institute of Technology

The Atmospheric Imaging Mission for Northern Regions (AIM-North, www.aim-north.ca) is satellite mission concept that began Phase 0 study for the Canadian Space Agency (CSA) in 2019. AIM-North would observe greenhouse gases (GHGs), air quality (AQ) species and solar induced fluorescence (SIF) using a pair of satellites in a highly elliptical orbit (HEO) formation to give quasi-geostationary coverage over northern land (~40-80°N) multiple times per day. This presentation gives an update on mission status and describes new instrument and science studies. In Phase 0, both an Imaging Fourier Transform Spectrometer (IFTS) and a dispersive spectrometer have been considered as options to record spectra of reflected near infrared (NIR) and shortwave infrared (SWIR) solar radiation to image XCO_2, XCH_4, XCO and SIF, while a dispersive ultraviolet-visible spectrometer (UVS) would image NO_2, O_3, aerosols and other species. Recent retrieval studies have determined signal-to-noise ratio (SNR) and other instrument requirements to meet the Level 2 precision and accuracy targets for different instrument designs. Simulations on the use of a cloud imager to locate clear-sky areas to facilitate an intelligent pointing approach have shown significant improvements to the yield of cloud-free observations relative to standard pointing. Simulated AIM-North XCO_2 observations are being used in Observing System Simulation Experiments (OSSEs) to assess their ability to quantify northern CO_2 fluxes from regions of permafrost, boreal forests and other northern vegetation.

Development and Field Validation of the PanFTS Instrument for Geostationary Measurements of GHGs, Trace Gases and SIF

Stanley Sander[*1], Jean-Francois Blavier[1], Yen-Hung Wu[1], Maxwell Bryk[1], Thomas Pongetti[1], Zhao-Cheng Zeng[2], Liyin He[2] and Yuk L. Yung[2]

1. Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California USA
2. Geological and Planetary Sciences, California Institute of Technology, Pasadena, California USA

The most recent Earth Science Decadal Survey from the U.S. National Research Council identified several key science questions and observables related to atmospheric composition. These include questions related to vertical profiling of aerosols; emission, transformation and long-range transport of tropospheric pollutants and greenhouse gases that drive radiative forcing. The next generation of instruments and platforms must address the specific requirements that flow from the measurement requirements articulated in the Decadal Survey.

The Panchromatic Fourier Transform Spectrometer (PanFTS) is a NASA Earth Science Technology Program-funded development to demonstrate a geostationary instrument capable of meeting or exceeding measurement requirements posed by the Decadal Survey. The PanFTS flight instrument design combines measurement capabilities for the 0.26-15 micron spectral range in a single package. The wide spectral coverage is important for retrieving the entire suite of target molecules, including several in widely different wavebands. Measurement of the same species in different spectral regions significantly enhances the information content of the vertical profile retrievals.

PanFTS combines an imaging Michelson interferometer design with several unique features. The PanFTS instrument is a hybrid based on spectrometers like TES (Tropospheric Emission Spectrometer) that measures thermal emission, and those like OCO (Orbiting Carbon Observatory) and OMI (Ozone Monitoring Instrument) that measure scattered solar radiation. As such the PanFTS design has two parallel optical trains, one for infrared wavelengths and one for UV-Vis. These channels incorporate imaging focal planes to meet requirements for high spatial resolution (few km) and large instantaneous field of regard from geostationary orbit.

This presentation will discuss the development status and future evolution of the PanFTS instrument. We will present results obtained from versions of the PanFTS instrument located at JPL's California Laboratory for Atmospheric Remote Sensing (CLARS) on Mt. Wilson, California, overlooking the Los Angeles Basin. These will include long-term measurements of greenhouse gas emissions and solar-induced fluorescence (SIF) from vegetation.

Keywords: PanFTS, geostationary, greenhouse gases, SIF, air quality, CLARS

Measuring Carbon Dioxide from Space Using Lidar: Status and Updates from the NASA ASCENDS Development Activity

S. R. Kawa*[1], J. B. Abshire[1], D. F. Baker[2], E. V. Browell[3], A. Chatterjee[1], D. Crisp[4], S. M. Crowell[5], J. J. Hyon[4], K. W. Jucks[6], B. Lin[3], L. E. Ott[1], T. S. Zaccheo[7]

1. NASA Goddard Space Flight Center, USA
2. Colorado State University, USA
3. NASA Langley Research Center, USA
4. NASA Jet Propulsion Laboratory, USA
5. University of Oklahoma, USA
6. NASA Headquarters, USA
7. Atmospheric and Environmental Research, Inc., USA

Measuring atmospheric carbon dioxide (CO2) from space using lidar sensing techniques has several significant, inherent advantages in comparison to ongoing and planned passive remote sensing missions. Accordingly, the 2007 US National Academy of Sciences (NAS) Decadal Survey for Earth Science and Applications from Space recommended the ASCENDS mission (Active Sensing of Carbon Emissions, Nights, Days, and Seasons) for NASA's next generation CO2 observing system. What followed was a decade of major progress in development of integrated path differential absorption lidar sensing methods. The instrument concepts, measurement approaches, and retrieval techniques have matured significantly, driven by advances in technology, experience with airborne simulators, and analysis of requirements in observing system simulation model experiments. The current results affirm the benefits of ASCENDS-like measurements for carbon cycle science and show that such a mission technologically is ready for implementation. However, the 2017 NAS Decadal Strategy for Earth Observation from Space, while maintaining high importance for greenhouse gas measurements from space, has left open their relative priority as well as the preferred implementation approach. Furthermore, it imposed a cost cap for Explorer-class missions that presents a challenge for a space lidar.

In this presentation, we will review the current status of lidar CO2 measurements highlighting updates from the recently released Final Report of the ASCENDS Ad Hoc Science Definition Team (2018). The new findings further substantiate that lidar measurements can provide high-quality, low bias CO2 data with full global and seasonal sampling that will contribute substantially to our knowledge of carbon flux distributions and their dependence on underlying physical processes in critical regions. The question that remains is: How best to make it happen?

Key words: ASCENDS, Lidar, Carbon Dioxide

Spectral-radiance inter-comparsion between GOSAT/FTS, GOSAT-2/FTS-2, and OCO-2

Fumie Kataoka[*1], Akihiko Kuze[2], Kei Shiomi[2], and Hiroshi Suto[2]

1. Remote Sensing Technology Center of Japan, 2-1-1 Sengen, Tsukuba-city, Ibaraki, JAPAN
2. Japan Aerospace Exploration Agency, 2-1-1 Sengen, Tsukuba-city, Ibaraki, JAPAN

The Greenhouse gases Observing SATellite-2 (GOSAT-2) was launched on 29 October 2018. GOSAT-2 is equipped with the Thermal and Near-infrared Sensor for carbon Observation Fourier Transform Spectrometer-2 (TANSO-FTS-2). FTS-2 observes sunlight reflected light and thermal infrared radiation from the Earth' surface and atmosphere with five spectral bands.

FTS-2, GOSAT/TANSO-FTS, and Orbiting Carbon Observatory 2 (OCO-2) have the common spectral bands at 0.76, 1.6 and 2.0 µm. The spectral radiances of these three spectrometers were compared at temporally coincident and spatially collocated points. GOSAT and GOSAT-2 have 2-axis agile pointing system. We planned to target the same observation points by uploading pointing angles in the GOSAT-2 initial calibration phase. The surface reflectance differences caused by observation geometries have been reduced by correcting with Suomi-NPP VIIRS surface bidirectional reflectance distribution function (BRDF) product.

The thermal infrared spectra of FTS and FTS-2 were also compared with Aqua/AIRS and Suomi-NPP/CrI with simulated spectra using a radiative transfer model.

Atmospheric Variations in Column Integrated CO_2 On Synoptic and Seasonal Time Scale Over the U.S.

Qingyu Wang, Sean Crowell*

* School of Meteorology, University of Oklahoma, Norman, OK 73072

Past studies have demonstrated that synoptic events play an important role in the spatial and temporal variations of carbon dioxide (CO_2). In this study, in order to investigate whether cold fronts have impact on synoptic CO_2 concentrations, we collect 83 cold frontal cases over United Sates, east Pacific Ocean and west Atlantic Ocean from 2015 to 2017 with data from Orbiting Carbon Observatory-2 (OCO-2), Version 8 (V8) and Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2), calculate the Column-averaged carbon dioxide dry air mole fraction (X_{CO2}) difference anomalies across the fronts, and apply significance test to decide whether cold fronts relate to CO_2 changes. The results show cold fronts in the summer in these three years do relate to synoptic CO_2 changes, spring may also, but other seasons are not apparently related to CO_2 changes though in our study. Frontal gradients from OCO-2 Version 9 (V9) data show the similar pattern, however spring cases are less significant than those with V8, which indicates frontal gradients in V9 data are only significant in summer.

Sensitivity evaluation of TANSO-FTS/GOSAT using principal component analysis

Yu Someya*[1] and Yukio Yoshida[1]

1. National Institute for Environmental Studies (NIES), Japan

Reportedly, the sensitivities of the short-wavelength infrared (SWIR) band of Thermal And Near-infrared Sensor for carbon Observation - Fourier Transform Spectrometer (TANSO-FTS) have been degraded (Kuze et al., 2012) with wavenumber dependencies (Yoshida et al., 2012). In the current retrieval system for the SWIR level 2 product provided by National Institute for Environmental Studies (NIES), the degradations are evaluated according to Yoshida et al. (2012). Although this paper assumes that wavenumber dependency is slightly changed with time, we found that there are time-independent variations. In this work, we developed a new algorithm to evaluate these degradations from on-orbit solar calibration spectra using principal component analysis (PCA). The effectiveness of this algorithm is to be able to distinguish the time-dependent components of the spectral variability from the independent ones. This possibly enables us to evaluate the temporal change of sensitivity more precisely. The degradation models were constructed with the following sequence.

1. Normalizing observed spectra with calculated spectra
2. Decomposing the dataset defined as a set of the differences of the normalized spectra from the referenced spectrum into eigenvectors and principal component (PC) scores by singular vector decomposition for each band
3. Correcting the incident angle and outgoing angle dependencies of PC scores
4. Fitting the temporal variations of the corrected PC scores
5. Reconstructing the temporal variations of the normalized spectra from the eigenvectors and the fitting functions of PC scores accounting for exceeding 0.95 of cumulative proportions

This PCA-based degradation model is planned to be applied to the next version of the SWIR L2 retrieval system.

Key words: GOSAT; on-orbit calibration; PCA; retrieval algorithm

GOSAT-2 cal/val phase operation plan for ensuring the consistency with GOSAT

Kei Shiomi*[1], Hiroshi Suto[1], Makiko Hashimoto[1], Shin Ishida[1], Hiroko Imai[1], Fumie Kataoka[2], Akihiko Kuze[1] and Masakatsu Nakajima[1]

1. Japan Aerospace Exploration Agency (JAXA), Japan
2. Remote Sensing Technology Center of Japan (RESTEC), Japan

GOSAT has been operating since 2009 to monitor greenhouse gases carbon dioxide (CO_2) and methane (CH_4) by a Fourier Transform Spectrometer (FTS) and cloud and aerosol information by a fine-resolved imager (CAI) in 3-day revisit. The 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 and the profiled densities of CO_2 and CH_4 using surface and atmospheric radiation with ten-kilometer resolution by pointing system of wide swath. GOSAT-2 has been operating since October 2018 with upgraded FTS-2 and CAI-2 in 6-day revisit. The FTS-2 observes XCO_2, XCH_4 and an additional XCO by an upgraded detector to enhance the combustion sources discrimination than the FTS. The CAI-2 has two slant views of forward and backward directions with UV bands to avoid overlapping sunglint area for aerosol application by the FTS-2.

GOSAT-2 initial commissioning phase has finished by the end of January 2019 and the following calibration and validation phase has started since February. The FTS-2 observation was optimized to regular 5-grid observation points in swath, target observations at over 50 large cities, CEOS calibration sites over desert, and ground-based TCCON, CONTRAIL / NOAA aircraft validation sites. All the observation points of the FTS-2 can be selected within the rotating angle range of along-track (AT) and cross-track directions by the upgraded pointing system. The FTS-2 AT pointing expands +/-40 degrees twice the AT range of the FTS. Hence, the FTS-2 can be allocated about 32 observation points for one target location. GOSAT and GOSAT-2 observations almost synchronize every 6 days. The FTS-2 is targeted the same locations as the FTS in 2 days out of 6 days for calibration and validation of inter-comparison opportunities. The GOSAT-2 observation will be further optimized by users' feedback to improve the observation plan for better measurements.

Key words: GOSAT; GOSAT-2; operation

The ability of GeoCarb to constrain the interannual variability of carbon gases over the Amazon

Brad Weir*[1,2], Sean Crowell[3], S. Randolph Kawa[2], Lesley Ott[2], Abshishek Chatterjee[1,2], Steven Pawson[2] and Berrien Moore[3]

1. Universities Space Research Association (USRA), Maryland, USA
2. NASA Goddard Space Flight Center, Maryland, USA
3. University of Oklahoma, Oklahoma, USA

We perform a number of idealized assimilation experiments with the GEOS constituent data assimilation system to test the ability of GeoCarb retrievals of CO, CO2, and CH4 to constrain the interannual variability of these gases over the Amazon. Retrievals for instruments on other satellites which observe in similar channels (e.g. MOPITT, GOSAT, and OCO-2) are limited due to persistent cloud coverage. Given its ability to sample the same location multiple times in one day, the expectation is that GeoCarb retrievals will return more soundings than those from previous missions. The goal of the assimilation experiments is to understand which scanning strategies lead to the best sounding densities and thus have the best chance of constraining interannual variability in the carbon species. The experiments each begin by picking a given year at random from a nature run (i.e., a model simulation meant to represent the truth). The model fields are sampled according to a given strategy and then screened to account for cloud coverage. Next, we pick another year at random and assimilate the synthetic GeoCarb samples into the GEOS model for that year. The output of the assimilation, 6-hourly, 3D fields of each constituent, is then directly comparable to the nature run. This comparison allows us to evaluate the ability of GeoCarb measurements to constrain the interannual variability of each gas.

Key words: GeoCarb; GEOS; Amazon

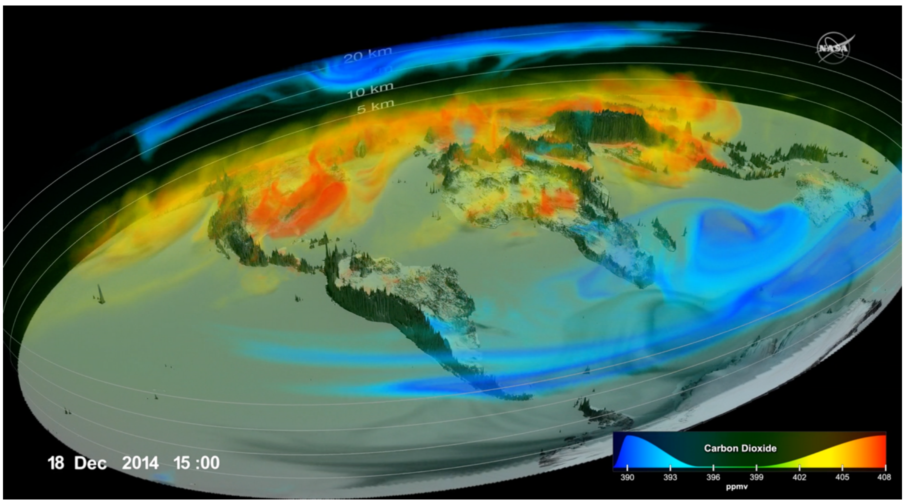
Progress in atmospheric carbon monitoring using NASA's Goddard Earth Observing System (GEOS) model and data from the OCO and GOSAT missions

Brad Weir*[1,2], Lesley Ott[2], Abshishek Chatterjee[1,2], Tomohiro Oda[1,2] and Steven Pawson[2]

1. Universities Space Research Association (USRA), Maryland, USA
2. NASA Goddard Space Flight Center, Maryland, USA

NASA's Global Modeling and Assimilation Office (GMAO) produces a variety of carbon products based the synthesis of satellite remote sensing data and outputs of the Goddard Earth Observing System (GEOS). This includes bottom-up surface fluxes due to fossil fuel emissions, biomass burning, terrestrial biospheric exchange, and ocean exchange constrained by measurements of nighttime lights, fire radiative power, normalized difference vegetation index, and ocean color. These fluxes are the basis of top-down estimates of carbon concentrations and fluxes. In particular, the GMAO system processes retrievals of column carbon dioxide (XCO2) from GOSAT and OCO-2 to produce a high-resolution, long-term global analysis of CO2 in three dimensions every 6 hours. Here, we discuss the potential applications of such products for satellite intercomparison and evaluation against independent, non-coincident data. We also highlight the ability to provide monthly global atmospheric growth rates inferred from the assimilated CO2 concentration product. Finally, we discuss the challenges facing such products including bias correction and the estimation and analysis of model transport errors.

Key words: GOSAT; OCO; GEOS



Snapshot of the CO2 field produced by the GEOS analysis of OCO-2 retrievals.

The OCO-3 Mission: Global Observations of CO_2 and Solar-Induced Fluorescence from the International Space Station – Snapshot Area Map and Target Mode Observations

thomas p. kurosu, annmarie eldering, ryan p. pavlick, brendan. m. fisher, gregory. b. osterman, and The OCO Teams

NASA Jet Propulsion Laboratory/California Institute of Technology
Pasadena, CA 91109 (USA)
thomas.kurosu@jpl.nasa.gov
phone: +1-818-354-2432

The Orbiting Carbon Observatory 3 (OCO-3) continues and extends global CO_2 and solar-induced chlorophyll fluorescence (SIF) using the flight spare instrument from OCO-2. The instrument has been through ground testing and thermal vacuum, and has been shipped for installation on the International Space Station, currently scheduled for launch on 25 April 2019. By early June, OCO-3 is expected tobe completing the decontamination cycle and First Light operations are imminent. This talk focuses on the new Snapshot Area Mode (SAM) as well as Target Mode observations, including observation selection, sampling locations, spatial coverage, frequency of revisit over the year, and hours of the day that are sampled.

The low-inclination ISS orbit lets OCO-3 sample the tropics and sub-tropics across the full range of daylight hours with dense observations at northern and southern mid-latitudes (+/- 52º). The combination of these dense CO_2 and SIF measurements provides continuity of data for global flux estimates as well as a unique opportunity to address key deficiencies in our understanding of the global carbon cycle.The instrument utilizes an agile, 2-axis pointing mechanism, providing the capability to look towards the bright reflection from the ocean and validation targets. In addition to the nadir-, glint-, and target-mode geometries familiar from OCO-2, OCO-3 includes a new observation mode dedicated to mapping out larger spatial-scale emitters like cities. This *Snapshot Area Map* (SAM) mode will be used to map areas of up to 80x80 km^2 on the Earth surface with the standard OCO-3 ground footprints of 3.5 km^2, providing unprecedented high spatial resolution coverage of large-scale CO_2 emitters worldwide. Measurements over urban centers could aid in making estimates of fossil fuel CO_2 emissions. Similarly, the snapshot mapping mode can be used to sample regions of interest for the terrestrial carbon cycle. In addition, there is potential to utilize data from the currently operating ISS instruments ECOSTRESS (ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station) and GEDI (Global Ecosystem Dynamics Investigation), which measure other key variables of the control of carbon uptake by plants, to complement OCO-3 data in science analysis.

In early June 2019, OCO-3 will be completing the decontamination phase and First Light operationsare imminent. This talk focuses on the planned observation strategies for SAM and Target measurement modes, including statistics of spatial coverage, sampling locations, sampling times of year and hours of the day, and the expected performance of the SAM and Target selection and coverage algorithm. We also present updates on the public data release schedule for L1b and L2 data products.

Exploring Improvements to the Aerosol Parameterization in the OCO-2 XCO_2 Retrieval Algorithm

Robert R. Nelson*[1], Christopher W. O'Dell[2], Annmarie Eldering[1],

1. Jet Propulsion Laboratory, California Institute of Technology, USA
2. Cooperative Institute for Research in the Atmosphere, USA

The scattering effects of clouds and aerosols are one of the primary sources of error when making space-based measurements of carbon dioxide. This work describes multiple investigations into optimizing how aerosols are parameterized in retrievals of the column-averaged dry-air mole fraction of carbon dioxide (XCO_2) performed on near-infrared measurements of reflected sunlight from the Orbiting Carbon Observatory-2 (OCO-2). The primary goal is to enhance both the precision and accuracy of the XCO_2 measurements by improving the way aerosols are handled in the NASA Atmospheric CO2 Observations from Space (ACOS) retrieval algorithm. Two studies were performed: one on ingesting more intelligent aerosol priors into the retrieval and another on reducing the complexity of the aerosol parameterization. It was found that using co-located, instantaneous aerosol information from the Goddard Earth Observing System Model, Version 5 (GEOS-5) resulted in a small improvement against multiple validation sources but that the improvements were restricted by the accuracy and limitations of the model. Implementing simplified aerosol parameterizations that solved for fewer parameters sometimes resulted in small improvements in the retrieved XCO_2, but further work is needed to determine the optimal way to handle the scattering effects of clouds and aerosols in near-infrared measurements of XCO_2. Finally, we present work on investigating the characteristics and physical causes of multiple sources of bias within the XCO_2 retrieval algorithm. With several multi-million dollar space-based greenhouse gas measurement missions scheduled and in development, the massive amount of measurements will be an incredible boon to the global scientific community, but only if the precision and accuracy of the data are sufficient.

Key words: OCO-2; retrieval; aerosol

Validation of cloud judgements in TANSO-FTS FOVs by using Himawari-8/AHI data

Katsuki Kitamura[1] and Naoko Saitoh*[1]

1. Center for Environmental Remote Sensing (CEReS), Chiba University, Japan

In the retrieval processing of greenhouse gases from the Thermal and Near Infrared Sensor for Carbon Observation (TANSO)-Fourier Transform Spectrometer (FTS) on board Greenhouse Gases Observing Satellite (GOSAT), cloud contamination in the field of views (FOVs) of TANSO-FTS has been judged by TANSO-Cloud and Aerosol Imager (CAI) in the daytime and by the thermal infrared (TIR) band of TANSO-FTS in the nighttime. We compared the cloud judgements in the TANSO-FTS FOVs by TANSO-CAI or TANSO-FTS TIR band with cloud judgements by the Advanced Himawari Imager (AHI) on board a Japanese geostationary satellite, Himawari-8. The AHI on board Himawari-8 has 16 bands from visible through thermal infrared regions, which is of great advantage to detect clouds in the FOVs of TANSO-FTS.

About 90% of cloud judgements by TANSO-CAI and Himawari-8 agreed with each other over the ocean. TANSO-CAI used only reflectance data in its visible bands for the cloud detections, whereas Himawari-8 used both reflectance and brightness temperature data in its visible and infrared bands, respectively, which may cause their ~10% disagreements. In contrast, agreements in cloud judgements between TANSO-FTS TIR band and Himawari-8 became worse by more than 10% compared to the TANSO-CAI and Himawari-8 cloud judgements. This is because that the FOVs of TANSO-FTS (10.5 km) is larger than those of TANSO-CAI and Himawari-8 (0.5-2 km), and TANSO-FTS TIR band uses only brightness temperature values for the cloud detections. In the case of TANSO-FTS FOVs judged as "clear" by TANSO-FTS TIR band and "cloud" by Himawari-8, small-scale clouds partly existed there judging from relatively low brightness temperature values of the coincident Himawari-8 data. This suggests the possibility that TANSO-FTS TIR band cannot detect such small-scale clouds, which may degrade the accuracy of CO_2 and CH_4 retrieval from the TANSO-FTS TIR band.

Key words: GOSAT/TANSO-FTS, Himawar-8/AHI, cloud detection

Carbon dioxide enhancement over Seoul from space and surface measurements

Chaerin Park*, Su-Jong Jeong

Department of Environmental Planning, Graduate School of Environmental Studies, Seoul National University, Seoul, Korea

Assessment of urban carbon emission is a critical issue to understand the global carbon cycle. In this research, we evaluate the spatial and temporal variations in atmospheric carbon dioxide concentrations over the Seoul Capital Area, where is one of apparent Megacities across the world. This study analyzed urban CO2 variations using column integrated XCO2 from Orbiting Carbon Observatory-2 from 2014 to 2018 and ground-based measurements over Seoul capital area. Results show that Seoul has higher values of carbon dioxide concentration than its neighbor background value. From XCO2, Seoul's carbon dioxide concentration is increasing from 398.622ppm to 409.233ppm during the research period. XCO2 concentration of Seoul is 1.387 ppm to 2.851 ppm higher compared to the nearby background area of Mt. Jiri. A comparison of ground-based CO2 concentrations between Seoul and Anmyeond-do (GAW site) shows that concentrations in Seoul is on average 30.3 ppm higher than that of Anmyeond-do. More details in our study will be presented in the workshop. Our Carbon dioxide anomaly statistics and distribution of Seoul can provide valuable insight for comprehending carbon dioxide emissions over the megacity across the world.

Key words: OCO- comparison of2; GOSAT; CT; Surfaced based measurements; Seoul

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Regeneration of CO_2 Satellite Column Data tailored to an Atmospheric inversion Scheme

A.Webb. H. Boesch, F. Chevallier, C. ODell

Current atmospheric inversion schemes assume rather realistic prior information (to the first order) when projected in concentration space while satellite retrieval schemes try to maximize the measurement contribution in the retrievals by giving a very weak weight to prior information. Such inconsistent statistical hypotheses between XCO2 retrieval and atmospheric inversion schemes may be a significant cause of error in atmospheric inversions assimilating satellite data.

By using sounding-specific covariances from model covariances representing the prior flux uncertainties of the CAMS model projected in space and time, we can derive satellite CO2 columns tailored towards and consistent with the specific assumptions of the CAMS atmospheric inversion scheme. Using global level-2 CO2 column data from the NASA OCO-2 v9, we reconstruct CO2 columns with prior information from the CAMS model using linear approximations thus avoiding the need for time-consuming re-retrieval of the satellite observations.

In this presentation, we will describe the approach that is used for re-constructing the satellite CO2 columns and we will evaluate the re-constructed CO2 columns from OCO-2 against the CAMS model and ground-based TCCON data before using them for a formal atmospheric inversion with the CAMS model.

Characterization of OCO-2 and ACOS-GOSAT biases and errors for flux estimates

*Susan S. Kulawik[1], Sean Crowell[2], David Baker[3], Junjie Liu[4], Kathryn McKain[5], Colm Sweeney[5,6], Sebastien C. Biraud[7], Steve Wofsy[8], Christopher W. O'Dell[3], Gregory B. Osterman[4], Paul O. Wennberg[9], Debra Wunch[10], Coleen M. Roehl[9], Nicholas M. Deutscher[11],[12], Matthäus Kiel[9], David W.T. Griffith[13], Voltaire A. Velazco[11], Justus Notholt[12], Thorsten Warneke[12], Christof Petri[12], Martine De Maziere[14], Mahesh K. Sha[14], Ralf Sussmann[15], Markus Rettinger[15], Dave Pollard[16], Isamu Morino[17], Osamu Uchino[17], Frank Hase[18], Dietrich G. Feist, Kimberly Strong[19], Rigel Kivi[20], Laura Iraci[21], Kawakami Shuji[22], Manvendra K. Dubey[23], Eliezer Sepulveda[24], Omaira Elena Garcia Rodriguez[24], Yao Te[25], Pascal Jeseck[25], Pauli Heikkinen[20], Edward J. Dlugokencky[5], Michael R. Gunson[4], Annmarie Eldering[4], David Crisp[4], Brendan Fisher[4]

1 BAER Institute: 625 2nd St, Ste 209, Petaluma, CA, USA
2 College of Atmospheric and Geographic Sciences, University of Oklahoma, Norman, OK, USA
3 Cooperative Institute for Research in the Atmosphere, Colorado State University, Fort Collins, CO, USA
4 Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA
5 National Oceanic and Atmospheric Administration, Earth System Research Laboratory, Boulder, CO, USA
6 University of Colorado, Cooperative Institute for Research in Environmental Sciences, Boulder, CO, USA
7 Lawrence Berkeley National Laboratory, Earth Science Division, Berkeley, CA, USA
8 Harvard University, Cambridge, MA, USA
9 Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA, USA
10 Department of Physics, University of Toronto, Toronto, Canada
11 University of Wollongong, Wollongong, Australia
12 University of Bremen, Bremen, Germany
13 Centre for Atmospheric Chemistry, University of Wollongong, Wollongong, Australia
14 Royal Belgian Institute for Space Aeronomy, Brussels, Belgium
15 Karlsruhe Institute of Technology (KIT), Institute of Meteorology and Climate Research (IMK-IFU), Garmisch-Partenkirchen, Germany
16 National Institute of Water and Atmospheric Research, Lauder, New Zealand
17 National Institute for Environmental Studies (NIES), Tsukuba, Japan
18 Karlsruhe Institute of Technology, IMK-ASF, Karlsruhe, Germany
19 University of Toronto, Toronto, Canada

20 Finnish Meteorological Institute, Sodankylä, Finland
21 NASA Ames Research Center, Moffett Field, CA, USA
22 Japan Aerospace Exploration Agency (JAXA), Tsukuba, Japan
23 Los Alamos National Laboratory, Los Alamos, NM, USA
24 Izaña Atmospheric Research Center, Meteorological State Agency of Spain (AEMet), Tenerife, Spain
25 ERMA-IPSL, Sorbonne Universités, UPMC Univ Paris 06, CNRS, Observatoire de Paris, PSL Research University, 75005 Paris, France

We characterize the systematic errors for OCO-2 v8 and ACOS-GOSAT v7.3 by comparisons to TCCON, ATom, ESRL aircraft, and surface observations. Although ACOS-GOSAT has larger random errors than OCO-2 and land observations have larger random errors than ocean observations, the systematic errors are very similar across both satellites and surface types, 0.6 +- 0.1 ppm. We find consistent estimates of systematic error whether dynamic versus geometric coincidences or ESRL aircraft (land) versus TCCON are used for validation, once validation and co-location errors are accounted for. We also find areas with sparse throughput (due to quality flags and preprocessor selection) over land have ~double the error of high-throughput regions. We characterize both raw and bias-corrected results, finding that bias correction improves systematic errors by a factor of 2 for land observations and improves errors by ~0.2 ppm for ocean. Additionally, we validate the lowermost tropospheric (LMT) product for OCO-2 and ACOS-GOSAT by comparison to aircraft and surface sites, finding systematic errors of ~1.0 ppm, which is good considering LMT has 2-3 times the variability of XCO2. OCO-2 v9 has better throughput (up to 5x better in some areas) than v8 with similar systematic error; v9 restricted to v8 quality results in a 0.1 improvement in the v9 land systematic error over v8. We characterize the time and distance scales of correlations for XCO2 errors, and find that the scales are similar to the scale length of the bias correction term. Assimilation of the OCO-2v7 bias correction term is used to estimate flux errors resulting from OCO-2 seasonal biases, finding annual flux errors on the order of 0.3 PgC/yr for Transcom-3 regions.
Key words: GOSAT; OCO-2; TCCON; error estimates

Observing patterns of greenhouse gases and pollutants across cities using satellite data

Hayoung Park*, Su-Jong Jeong

Graduate School of Environmental Studies, Seoul National University, Seoul, Korea

Cities are home to half of the global population and, as a result, cities and urban areas are a major source of anthropogenic emissions of CO_2 as well as other pollutants and greenhouse gases which have a great impact on the environment, air quality, and climate change. Therefore, reducing emissions is one of the biggest concerns of major metropolitan cities. Studies have shown that reducing greenhouse gas emissions often reduce co-emitted air pollutants, bringing co-benefits for air quality and slowing climate change, yet there is still a need for more research to be done on the relationships between CO_2 and other air pollutants. In this study, we observe the concentrations of CO_2, CO, and aerosol optical depth (AOD) using satellite data from OCO-2, TROPOMI, and MODIS/Aqua across more than 30 different cities around the world. This study aims to see the relationships between different anthropogenic emissions and pollutants. We also observe the difference of emission characteristics across regions as well as the relations in chemistry of the pollutants.

Key words: Cities, OCO-2, TROPOMI, MODIS AOD, Greenhous Gases

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Preliminary results from the ESA CH4TIR project: Spectroscopy and forward model error improvement for CH4 retrieval in the TIR.

Charles E. Robert[1], Ann-Carine Vandaele[1], Justin Erwin[1], Nicolas Kumps[1], Séverine Robert[1], Martine de Mazière[1] and Claude Camy-Peyret[2]

1. Institute for Space Aeronomy (IASB-BIRA), Brussels, Belgium
2. Institut Pierre Simon Laplace (IPSL), Paris, France.

Atmospheric methane is measured continuously from space, providing valuable information at global/regional scales for atmospheric monitoring as well as for surface flux estimates. Instruments in the SWIR provide a total atmospheric column with rather uniform sensitivity up to the tropopause, while nadir instruments in the TIR provide profile information, with typically a few pieces of information in the middle to upper troposphere. The synergistic exploitation of these two types of measurements has a great potential for capturing CH_4 information in the lowest part of the atmosphere, for better understanding, quantifying and monitoring surface processes as well as sources and sinks of this target gas.

However, as shown by several recent studies and publications [e.g. Liuzzi, 2016; Siddans, 2017; De Wachter, 2017; de Lange, 2018], CH_4 atmospheric concentration retrievals from TIR nadir sensors exhibits significant biases compared to independent observations, or when intercompared between different TIR and SWIR/TIR sensors products. It is necessary to analyze the possible causes of biases and to investigate potential processing improvements and/or bias-correction for proper and consistent CH4 measurements in the TIR. Results from [Alvarado, 2015] and [De Wachter, 2017] highlighted that incomplete spectroscopic knowledge could be a major source for these biases. However, this should be consolidated and other sources of error, such as systematic forward modelling error or instrument biases, could also contribute.

The aim of the ESA CH4TIR project is to explore and consolidate the possible sources of CH4 biases in retrievals from TIR sensors, and to establish and perform necessary actions and work for their mitigation. This shall be done by first performing an exhaustive analysis of possible error sources: spectroscopic knowledge and input data of radiative transfer models (RTM), forward model errors, and instrument biases. Then, a sensitivity analysis investigating the impact of these three types of errors on the final CH_4 systematic error, using a state-of-the-art forward/inverse model and retrieval scheme applied to IASI/GOSAT observations. Identifying the main bias contributors and provide specifications in terms of accuracy requirements on these three potential contributors in order to mitigate the biases in CH4 TIR retrievals.

In this work, we will present preliminary results of error and sensitivity analysis for the CH_4 retrievals performed with TANSO-FTS and IASI [De Wachter, 2017] data in the TIR region using the ASIMUT-ALVL software [Vandaele, 2006]. We will assess the impact of the extension of the retrieval spectral range, the use of different spectroscopic databases and the inclusion of different species, notably CF4 and HNO3.

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Key words: CH4; TIR; IASI; GOSAT; ASIMUT

GOSAT-2/TANSO-CAI-2 and the aerosol product

Makiko Hashimoto*[1], Hideaki Takenaka[1], Akiko Higurashi[2] and Teruyuki Nakajima[1]

1. Japan Aerospace Exploration Agency (JAXA), Japan
2. National Institute for Environmental Studies (NIES), Japan

GOSAT-2 (Greenhouse Gases Observing Satellite 2) was launched on October 29th, 2018. GOSAT-2 has two sensors, Fourier Transform Spectrometer 2 (FTS-2) and Cloud and Aerosol Imager 2 (CAI-2). CAI-2 observes near UV to near infrared regions with ten bands and seven wavelengths, such as 340, 380, 443, 550, 674, 870 and 1630nm, and performing two-directional observation in forward and backward directions. The spatial resolution (IFOV) is 920 m at a wavelength of 1630 nm and 460 m at the other wavelengths. CAI-2 is characterized by a wavelength in ultraviolet (UV) region of 340 nm that is sensitive to aerosol light absorption, and it is expected to increase the retrieval accuracy of light absorbing aerosol particles, such as soot and dust. The goals for CAI-2 are monitoring PM2.5 and soot volume fraction (sf) from space, improving accuracy of CO2 from FTS-2 by providing AOT at a wavelength of 1600nm (AOT1600). CAI-2 also provides aerosol optical thickness at a wavelength of 550nm (AOT550) as amount of the atmospheric aerosols and aerosol Ångstrom exponent (AE) as particle size information. Accurate retrieval of fine mode AOT is necessary to derive PM2.5 in urban region from space. Therefore, an aerosol retrieval algorithm called MWPM (Multiple wavelengths and pixels method) (Hashimoto and Nakajima, 2017) was developed. The method simultaneously retrieves fine and coarse mode AOT and single scattering albedo by using several wavelengths and spatial difference of surface reflectance. The method is useful for aerosol retrieval over spatially inhomogeneous surface like an urban area. We will show the results of aerosol properties from CAI-2 by the algorithm, MWPM.

Key words: GOSAT-2; CAI-2; Aerosol

Assessing OCO-2 Northern High Latitude XCO_2 Retrievals Over Snow

Joseph Mendonca*[1], Ray Nassar[1], Debra Wunch[2]

1. Environment and Climate Change Canada, Toronto, Canada
2. University of Toronto, Department of Physics, Toronto, Canada

Measurements of CO_2 in the Arctic and Boreal regions can help us understand how climate change has impacted the carbon cycle in these regions. Satellites measurements of reflected sunlight (as made by OCO-2) can be used to retrieve column averaged dry air mole fractions of CO_2 (XCO_2) to provide insight into the carbon cycle in regions where ground-based atmospheric measurements of CO_2 are sparse (such as the Arctic and Boreal forest). However, retrievals of CO_2 from spectra that are acquired over snow-covered surfaces are challenging. The albedo of snow in the CO_2 bands (used by OCO-2) varies with snow grain size, thus varying the signal-to-noise ratio (SNR), which impacts the bias and precision of the retrieved XCO_2. In this study, we will examine the bias and precision of XCO_2 retrievals made over snow-covered surfaces by comparing OCO-2 XCO_2 to up-looking measurements from the Total Carbon Column Observing Network (TCCON). Then, we will investigate the OCO-2 filters in order to more optimally remove bad XCO_2 retrievals over snow-covered surfaces. Finally, we will modify the OCO-2 retrieval algorithm to attempt to improve the retrievals for selected cases of soundings over snow near high latitude TCCON sites.

Key words: OCO-2; TCCON; Retrievals

A journey of the OCO-2 XCO_2 data set from version 9 to version 10: the ACOS retrieval algorithm validation

Le Kuai[1], Brendan Fisher[1], Vivienne Payne[1], David Crisp[1], Chris O'Dell[2], Annmarie Eldering[1]

1. Jet Propulsion Laboratory, California Institute of Technology
2. Colorado State University

The OCO-2 version 9 column-mean carbon dioxide (CO_2) dry air mole fraction (XCO_2) product derived using the Atmospheric CO_2 Observations from Space (ACOS) retrieval algorithm has shown reduced uncertainties in regional and global carbon fluxes (Liu, 2017). The OCO-2 algorithm team continues to improve the ACOS algorithm to reduce data scatter and bias, and understand the land-ocean contrast. This comprehensive, "full physics" retrieval algorithm couples multiple physical processes, such as CO_2 and O_2 absorption, aerosol scattering, and surface reflectance, together with modeled meteorological a priori values. Because of this, changes in any one part of the algorithm can introduce unanticipated changes to the outputs. In this study, we review the tests of retrieval algorithm as one parameter is updated in each test. For example, we describe the impacts of changes in 1) the O_2 gas absorption cross section (ABSCO) tables specifying the O_2 A-band line and collision induced absorption, 2) scaling of the O_2 A-band ABSCO table to minimize bias, 3) relaxing the surface pressure constraint in the prior, and 4) the top-of-atmosphere solar flux for better agreement with recent measurements. The retrieval results for each test are compared to the baseline retrieval results in the earlier product (version 8). For each case, we try to understand the reason of the changes, and determine if the update helps to improve the XCO_2 output.

TanSat XCO_2 retrieval, Inter-comparison and validation

Dongxu Yang[1,2,*], Peter Somkuti[1,3,4], Boesch Hartmut[1,3], Yi Liu[2], A. Webb[1,3], Zhaonan Cai[2], R. Parker[1,3], Lu Yao[2], J. Anand[1,3], Xi Chen[2], A. Di Noia[1,3]

1. Earth Observation Science, Department of Physics and Astronomy, University of Leicester, UK
2. Institute of Atmospheric Physics, Chinese Academy of Sciences, China
3. National Centre for Earth Observation, University of Leicester, UK
4. Now at Colorado State University, Fort Collins, CO, USA

Atmospheric Carbon Dioxide (CO_2), which is a main anthropogenic greenhouse gas whose concentration increase leads to heating of the troposphere and subsequently to global warming. We need to characterize the distribution and trend globally and investigate human emission contributions to the atmospheric CO_2 growth. Following the ESA SCIAMACHY/ENVISAT, which is the first space-based instrument to provide SWIR CO_2 band hyperspectral detection, the next generation satellites GOSAT and OCO-2 have been launched in 2009 and 2014, respectively. On 22 Dec 2016, China launched a carbon dioxide observation satellite, TanSat, which is the first Chinese greenhouse gas monitoring satellite that has been supported by the Ministry of Science and Technology of China, the Chinese Academy of Sciences, and the China Meteorological Administration, and recently joined the ESA 3rd party mission program. In-orbit calibration tests were completed in the summer of 2017, and the performance of the instrument has since been evaluated in test sessions. The TanSat XCO_2 retrieval algorithm is the Institute of Atmospheric Physics Carbon dioxide retrieval Algorithm for Satellite remote sensing (IAPCAS), which has also been used for GOSAT (ATANGO) and OCO-2 retrieval studies. The University of Leicester (UoL) algorithm has been used for GOSAT retrieval and provide XCO_2 product to the ESA Climate Change Initiative and the Copernicus Climate Change Service. The retrieval accuracy and precision of both, the IAPCAS and UoL algorithm, has been well investigated by verifying them against TCCON measurement. We will introduce the application of the IAPCAS and UoL algorithms to TanSat XCO_2 retrievals. The fitting residual has been analyzed, and PCA based analysis method show an improvement on residual. Validation against TCCON measurement show a good agreement on both algorithms. The method used in this study and results can help to improve the XCO_2 retrieval from TanSat and subsequently the L2 products.

Key words: CO_2, TanSat, retrieval algorithm, validation

Observing Water Vapour in the Planetary Boundary Layer from the Short-Wave Infrared

Tim Trent[1,2], Hartmut Boesch*[1,2], Peter Somkuti[3] and Noëlle A. Scott[4]

1. Earth Observation Science, Department of Physics & Astronomy, University of Leicester, University Road, Leicester LE1 7RH,

2. National Centre for Earth Observation, Department of Physics & Astronomy, University of Leicester, University Road, Leicester LE1 7RH, UK

3. Department of Atmospheric Science, Colorado State University, CO, USA

4. Laboratoire de Météorologie Dynamique, Ecole Polytechnique–CNRS, 91128 Palaiseau, France;

Water vapour is a key greenhouse gas in the Earth climate system. In this golden age of satellite remote sensing, global observations of water vapour fields are measured from numerous instruments operating between the ultraviolet/visible, through the infrared bands, and into to the microwave regions of the electromagnetic spectrum. While these observations provide a wealth of information on columnar, free-tropospheric and upper troposphere/lower stratosphere water vapour amounts, there is still an observational gap regarding resolved bulk planetary boundary layer (PBL) concentrations. In this study, we demonstrate the ability of the Greenhouse Gases Observing SATellite (GOSAT), to bridge this gap from highly resolved measurements in the shortwave infrared (SWIR). These new measurements of near-surface columnar water vapour are free of topographic artefacts and cab be interpreted as a proxy for bulk PBL water vapour. Validation (over land surfaces only) of this new data set against global radiosondes show low biases that vary seasonally between -2% to 5%. Analysis of broad latitudinal bands show biases between -3% and 2% moving from high latitudes to the equatorial regions. Finally, with the extension of the GOSAT program out to at least 2027, we discuss the potential for a new GOSAT PBL water vapour Climate Data Record (CDR).

Keywords: GOSAT; boundary layer; water vapour; validation; radiosonde

Improvement and application of PPDF-S method for retrieving XCO_2 over aerosol dense areas

Chisa Iwasaki*[1], Ryoichi Imasu[1], Bril Andrey[2], Sergey Oshchepkov[2], Yukio Yoshida[3], Tatsuya Yokota[3, 4], Vyacheslav Zakharov[5,6], Konstantin Gribanov[5], Nikita Rokotyan[5]

1. Atmosphere and Ocean Research Institute (AORI), The University of Tokyo, Japan
2. Center for Optical Remote Sensing, Institute of Physics of National Academy of Sciences of Belarus (IPNASB), Belarus
3. National Institute for Environmental Studies (NIES), Japan
4. Department of Information Networking for Innovation and Design, Faculty of Information Networking for Innovation and Design, Toyo University, Japan
5. Laboratory of Climate and Environmental Physics, Ural Federal University, Russia
6. Institute of Mathematics and Mechanics, Russia

The photon path length probability density function-simultaneous (PPDF-S) algorithm is effective for retrieving column-averaged concentrations of carbon dioxide (XCO_2) and methane (XCH_4) from Greenhouse gases Observing Satellite (GOSAT) spectra in ShortWavelength InfraRed (SWIR). Using this method, light-path modification attributable to light reflection/scattering by atmospheric clouds/aerosols is represented by the modification of atmospheric transmittance according to PPDF parameters. We optimized PPDF parameters for a more accurate XCO_2 retrieval under aerosol dense conditions based on simulation studies for various aerosol types and surface albedos. The optimization was applied to retrieval analysis of the GOSAT data that was measured when biomass burning was active in Western Siberia. The results demonstrated that optimization enabled retrieval, even under smoky conditions, and that the total number of retrieved data increased by about 70%. Furthermore, the results showed that atmospheric aerosol types that affected CO_2 analysis were identifiable by the PPDF parameter value. We will compare the GOSAT data analysis results with aerosol characteristics detected by satellite images such as MODerate resolution Imaging Spectroradiometer (MODIS) over the target area, and will discuss the usage of the PPDF parameters for the identification.

Key words: GOSAT; retrieval; XCO_2; photon path length probability density function (PPDF), aerosol dense conditions

Variation of carbon dioxide at upper troposphere/lower stratosphere derived from GOSAT TANSO-FTS TIR

Akihiro Honda[1], Nawo Eguchi*[2], Naoko Saito[3] and Yousuke Niwa[4]

1. Interdisciplinary Graduate School of Engineering and Sciences, Kyushu University, Japan
2. Research Institute for Applied Mechanics, Kyushu University, Japan
3. Center for Environmental Remote Sensing, Chiba University, Japan
4. Center for Global Environmental Research, National Institute for Environmental Studies, Japan

Stratospheric cooling was reported, it could be caused by increasing the carbon dioxide (CO_2), which is a major greenhouse gas. While, the concentration of CO_2 in the stratosphere is not well understood, nor are the exchange processes between the upper troposphere and lower stratosphere (UT/LS ; 250-100hPa). The present study investigated the intra-seasonal, seasonal and inter-annual variations of CO_2 to understand the CO_2 concentration at UT/LS and the Stratosphere and Troposphere exchange process.

We used the vertical profile data (Level 2) of CO_2 derived from thermal infrared (TIR) region (Band 4: 5.5 - 14.3 μm) of the Thermal And Near-infrared Sensor for carbon Observation (TANSO) - Fourier Transform spectrometer (FTS) on board Greenhouse gas Observing SATellite (GOSAT). The analysis period is four years from January 2010 to December 2013. We adapted the bias correction values derived from Saitoh et al. [AMT, 2016] which validated the TIR CO_2 profiles at UT/LS region with the Comprehensive Observation Network for TRace gases by AIrLiner (CONTRAIL). For reference, the atmospheric transport model, NIES-TM (ver.5) and the Nonhydrostatic Icosahedral Atmospheric Model (NICAM)–based Transport Model (TM) were used [Niwa et al., 2011; 2017].

The growth rate of CO_2 concentration at UT/LS were approximately 2 ppmv/year, which one at southern hemisphere were relatively larger than one at northern hemisphere. The seasonal variation of CO_2 concentration, showed that the maximum peak existed after a few month with respect to the peak at the middle or lower troposphere. The inter-annual variations were affected by the ENSO cycle; the higher (lower) CO_2 concentration at UT were seen during La Nina (Normal / El Nino) period. Finally, the intra-seasonal variation CO_2 concentration at UT/LS were associated with both the vertical and horizontal transportation due to the deep convection and the Asian monsoon anticyclonic circulation, respectively.

Key words: GOSAT; carbon dioxide; Stratosphere-Troposphere Exchange

Validating ratio component XCH_4/XCO_2 of GOSAT proxy retrieval of methane

Haruki Oshio*[1], Yukio Yoshida[1], Tsuneo Matsunaga[1] and TCCON partners

1. National Institute for Environmental Studies (NIES), Japan

Monitoring methane concentration in the atmosphere from space is important to understand and predict the global carbon cycle and the climate change. Proxy method and physics-based method have been used to retrieve the column-averaged dry air mole fraction of methane (XCH_4) from satellite measurements while accounting for the light pass modification by atmospheric scattering. We have been providing the physics-based XCH_4 data as the Greenhouse gases Observing SATellite (GOSAT) product. In addition to that, for GOSAT-2, we are planning to provide the proxy XCH_4 product. A few studies validated the ratio component XCH_4/XCO_2 of the proxy retrieval using the Total Carbon Column Observing Network (TCCON) data; however, it has not fully been investigated that to what extent of cloud and aerosol load the scattering related errors is canceled in the ratio component. Here we compared the ratio component between GOSAT and TCCON while considering the cloud fraction, the existence of cirrus, and other associated factors. Cloud and cirrus screening was conducted by investigating the variation of difference between GOSAT and TCCON according to the cloud fraction and the normalized radiance with its noise level at the strong water vapor absorptive channels in the 2 μm band. Large bias and precision error were found for data whose footprint was partly covered by snow and ice. To exclude such data, it was required to adjust the threshold of blended albedo that has been used to screening the snow and ice cover or to use a snow index calculated by GOSAT O_2 A-band and weak CO_2 band similar to the Normalized Difference Snow Index (NDSI). Subsequently, negative correlation of the bias in the ratio component with the airmass and the difference in retrieved albedo between the CO_2 band and the CH_4 band was corrected.

Key words: GOSAT; GOSAT-2; TCCON; methane; proxy method

Simulation-retrieval experiments over the Western Hemisphere with the GeoCarb greenhouse gas retrieval algorithm

Gregory McGarragh, Christopher O'Dell, Denis O'Brien, Thomas Taylor, Eric Burgh, and Sean Crowell

The Geostationary Carbon Cycle Observatory (GeoCarb) mission aims to measure the spatial and temporal patterns of greenhouse gases with the ultimate goal of addressing fundamental questions in carbon cycle science, such as why and how the global carbon cycle is changing. GeoCARB will retrieve column integrated CO2, CH4, and CO concentrations over North and South America from shortwave-infrared measurements in four hyperspectral bands made from a geostationary satellite platform. The techniques used come from heritage algorithms developed for the polar-orbiting Orbital Carbon Observatories (OCO) 2 and 3 missions, but will include an additional band for CH4 and CO sensitivity. Other differences include spatial and temporal scan configurations. In our presentation we will discuss the modifications made to the OCO-2/3 heritage retrieval algorithm for application to GeoCARB, additional challenges that must be addressed, and the sensitivity of the retrievals to various sources of uncertainty. We will present results from synthetic scans over the Western Hemisphere that will shed some light on retrieved gas concentration errors expected by GeoCarb in both in space and in time.

Variations in CO_2 and CH_4 in upper atmosphere: the effects of biomass burning and Asian monsoon transport inferred from GOSAT/TANSO-FTS TIR data

Naoko Saitoh*[1], Shingo Kosaka[1], and Hinaoko Kobayashi[1]

1. Center for Environmental Remote Sensing (CEReS), Chiba University, Japan

Greenhouse Gases Observing Satellite (GOSAT) has continued its observations of greenhouse gases for more than 10 years since its launch on 23 January 2009. The thermal infrared (TIR) band of the Thermal and Near Infrared Sensor for Carbon Observation (TANSO)-Fourier Transform Spectrometer (FTS) on board the GOSAT has observed concentrations of CO_2, CH_4 and other greenhouse gases in several vertical layers. We have evaluated the data quality of the TANSO-FTS TIR Level 2 Version 1 (V1) CO_2 and CH_4 products (Saitoh et al., 2016, 2017; Holl et al., 2016; Zou et al., 2016; Olsen et al., 2017).

We applied the evaluated bias-correction values to the TANSO-FTS TIR V1 CO_2 data and then compared variations in concentrations of the TIR CO_2 data with those of Measurement Of Pollution In The Troposphere (MOPITT) CO data (Deeter et al., 2014) in upper troposphere over the northern Africa. The comparison result showed that both TANSO-FTS TIR CO_2 and MOPITT CO concentrations became larger there almost at the same time in March through May, which suggests air mass with high CO and CO_2 emitted due to biomass burning was transported to upper atmosphere.

As TANSO-FTS TIR V1 CH_4 profiles generally agreed with aircraft CH_4 profiles to within 10-15 ppb in the troposphere in low and middle latitudes, we analyzed seasonal variations in CH_4 concentrations in each of the five atmospheric layers over India by using the TIR V1 CH_4 data. Our results were similar to the results reported in Chandra et al. (2017), but showed larger impact of CH_4 variations in lower troposphere on seasonal variations in XCH_4 concentrations over India.

Key words: GOSAT/TANSO-FTS TIR band, CO_2, biomass burning, CH_4, Asian monsoon

Greenhouse gas measurements at the Sodankylä TCCON site and comparisons with the satellite borne observations

Rigel Kivi*[1], Pauli Heikkinen[1], Tuomas Laurila[1], Huilin Chen[2], Hannakaisa Lindqvist[1] and Johanna Tamminen[1]

1. Finnish Meteorological Institute, Finland
2. University of Groningen, the Netherlands

High-resolution FTS measurement program was established at Sodankylä in early 2009. Since then regular ground-based measurements of CO_2, CH_4 and other gases have been performed at the site. Sodankylä participates in the Total Carbon Column Observing Network (TCCON). The ground based measurements at the TCCON sites have been commonly used to validate satellite based retrievals. The relevant satellite missions include the Greenhouse Gases Observing SATellite (GOSAT) and the Greenhouse gases Observing SATellite-2 (GOSAT-2). GOSAT-2 was launched recently, on October 29, 2018, while GOSAT became operational in early 2009. Here we have used FTS SWIR level 2 CO_2/CH_4 column amount products provided by NIES (National Institute for Environmental Studies). We found good agreement between the GOSAT and collocated ground-based measurements at the Sodankylä TCCON site, based on ten years of measurements. The relative difference calculated as (satellite-ground based FTS)/ (ground based FTS) for XCO_2 was 0.09 +/- 0.02 percent and for XCH_4 the relative difference over the ten year period was 0.06 +/- 0.02 percent. In addition we also performed AirCore in situ observations using a balloon based platform during all seasons. The AirCore profiles were obtained by a cavity ring-down spectrometer, the mole fractions for the reference and fill gas were calibrated to World Meteorological Organization in situ trace gas measurement scales. The in situ AirCore measurements were used to confirm the accuracy of total column retrievals of the ground based FTS.

Key words: TCCON; GOSAT; GOSAT-2

Profiles of greenhouse gases measured in the 2018 STEAM field campaign

Zhaonan Cai, Yi Liu, Dongxu Yang, You Yi, Zhixuan Bai, KeChe, Sihong Zhu, Xiaoyu Ren, Jianchun Bian

Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China

The stratosphere and troposphere exchange experiment over Asian summer monsoon (STEAM) is a five-year field campaign project sponsored by Chinese Academy of Science (CAS) to improve the understanding of the chemical and dynamical processes in the upper troposphere and lower stratosphere (UTLS). During the field campaigns in June and November 2018, we launched four research soundings and AirCore, to measure the vertical distribution of aerosol, ozone, water vapor, CH_4, CO, CO_2 in Inner Mongolia, with coincident column measurements using EM27. For the aircore system, we use the zero pressure balloon as platform. When the ascent stops, and the balloon will hover at a constant altitude. The sounding will hover for tens of minutes in order to stabilize, then cutting information will be send to the cutter, the payload separates from the balloon and a suitable parachute opened to control the descent speed enough slow that makes the pressure inside and outside of tube equivalent. In order to maximize resolution, we constructed an entire mobile analyzing system to shorten the time cost before recovery. For June campaign, we released Aircore in Xilin Hot on 13 June and 14 June and retrieved the vertical distribution of CO and CO_2 from ground to ~25 km. Profiles of the two days shows severe changes in vertical gradient because of long-range airmass transport, the comparison with satellites and model indicate that the column-averaged mixing ratio of CO and CO_2 are identical but specific profile are different when a cold vortex passes Xilin Hot. The aircore system was further improved in the November campaign, we released Aircore in Urad Middle Banner on 12 November and 13 November, and derived profiles of CO_2, CO, CH_4 and N_2O.

Seasonal and Diurnal Opportunities for XCH_4, XCO_2, and XCO for the Amazonian Rainforest Region Allowing Sampling and Validation

Robert Chatfield*[1], Robert Esswein[1,2], Manvendra Dubey[3], Sajian Heerah[3]

1. NASA Ames Research Center, Moffett Field, California, USA
2. Bay Area Environmental Research Institute, Moffett Field, California, USA
3. Los Alamos National Laboratories, Los Alamos, New Mexico, USA

There is considerable interest in the aggregate methane emissions from the Amazon and similar moist tropical regions, and XCH_4 measurements are well suited to constrain sources to the global atmosphere. Similarly, XCO_2 measurements constrain CO_2 in the region. XCO helps to partition CO2 patterns among burning and respiration processes. GeoCarb may allow these column measurements over the Western Hemisphere, but satellite retrieval require exacting calibration and validation by sun-focused Fourier transform spectrometers (FTS). The rarity of sufficiently large gaps in the cloud cover over the Amazon and similar rainforests restricts the validation opportunities for useful FTS observations and even more the opportunities for accurate retrievals. TropOMI observational statistics are extremely poor for the region. We have used two data sources to evaluate FTS opportunities at Manaus, Brazil, an FTS operated for 8 months near Manaus by Mavendra Dubai, and also sun-photometer measurements at several stations. We report initial results on five questions: (1) how frequent are observing opportunities of FTS?, (2) What evidence is there that gaps in clouds are wide enough for satellite retrievals at an appropriate accuracy? (3) What is the diurnal and seasonal variability of cloud gaps? and (4) What limitations are currently suggested for unbiased FTS measurement of XCH4 due to diurnal effect? And (5) What evidence is there for incidence of problematic high aerosol extinction at higher layers of the troposphere (800 hPa to 120 hPa) which alter the XCH_4 light-paths?

Key words: GeoCarb, TropOMI; TCCON, AERONET, Validation, Observation Opportunity

Progress on validation of the GOSAT and GOSAT-2 FTS SWIR L2 products

Isamu Morino[*1], Osamu Uchino[1], Hirofumi Ohyama[1], Tran Thi Ngoc Trieu[1], Yukio Yoshida[1], Tsuneo Matsunaga[1], Akihide Kamei[1], Makoto Saito[1], Hibiki Noda[1] and TCCON partners[2]

1. National Institute for Environmental Studies (NIES), Japan
2. https://tccon-wiki.caltech.edu

The Greenhouse gases Observing SATellite (GOSAT), launched on 23 Jan. 2009, is the world's first satellite dedicated to measuring the concentrations of the two major anthropogenic greenhouse gases, carbon dioxide (CO_2) and methane (CH_4), from space. Column-averaged dry air mole fractions of CO_2 and CH_4, and water vapor (H_2O) (denoted as XCO_2, XCH_4 and XH_2O) are retrieved from the Short-Wavelength InfraRed (SWIR) spectral data observed with the Thermal And Near-infrared Sensor for carbon Observation - Fourier Transform Spectrometer (TANSO-FTS) onboard GOSAT. The present NIES full physics SWIR retrieval algorithm (Ver. 02.80) for land high-gain soundings showed small biases and standard deviations: −0.33 ppm and 2.17 ppm for XCO_2, −1.9 ppb and 13.4 ppb for XCH_4, and −0.78% and 33.4% for XH_2O, respectively. (The mean value of the Total Carbon Column Observing Network (TCCON) data measured at each site within ±30 min. of the corresponding GOSAT overpass time at around 1:00 pm local time in most of the sites is compared with GOSAT data measured within ±2-degree longitude/ latitude box centered on the TCCON site. The observation period of the GOSAT data used for comparison is April 23, 2009 through June 30, 2018. Their comparisons are not considering the difference in column averaging kernels) Retrievals from the GOSAT TANSO-FTS SWIR spectra for more than nine years are already being used for scientific research applications.

A successor of GOSAT, GOSAT-2 was launched on 29 Oct. 2018, and is now in operational. In addition to XCO_2, XCH_4, and XH_2O, XCO (column-averaged dry air mole fraction of carbon monoxide) is retrieved from GOSAT-2 TANSO-FTS-2 SWIR spectra. The main approach of acquiring validation data for GOSAT-2 is the same as those for GOSAT. Ground-based FTSs data from TCCON and NDACC IRWG (Network for the Detection of Atmospheric Composition Change-InfraRed Working Group) sites will be used, and some sites will be co-located with lidar and sky-radiometer systems for extensive validation data acquisition. In-situ measurements and/or sampling of CO_2, CH_4, and CO onboard commercial and charter aircraft by CONTRAIL (Comprehensive Observation Network for TRace gases by AIrLiner) and NOAA (National Oceanic and Atmospheric Administration) will also be employed.

In this presentation, we focus on the current status of the GOSAT product validation and an overview of the GOSAT-2 validation plan, as well as preliminary validation result of the GOSAT-2 products.

Key words: GOSAT; GOSAT-2; FTS-SWIR; Validation; TCCON

Comparison between MOPITT and OCO-2 flux inversions : analyze of CO-CO_2 correlation

Helene Peiro [1] and Sean Crowell [1]

[1] University of Oklahoma, Norman, United States

Carbon monoxide (CO) and carbon dioxide (CO_2) are both emitted from combustion. CO is a product of inefficient combustion often used as a tracer of CO_2 for combustion. Observed CO-CO_2 correlation slopes thus provide useful constraints to characterize emissions sources. According to the concentrations of CO and CO_2, we can determine the types of sources. Most of the previous studies used CO measurements to constrain and improve CO2 flux inversions. But the correlation between CO and CO_2 can also be used to improve and analyze the variability of both CO and CO_2 flux inversions. Satellites measuring CO and CO_2 by Infrared remote sensing allow to improve our ability to map CO and CO_2 and to understand their variability.

The goal of this study is to observe the correlation between two independent inversions of CO and CO_2 and to analyze CO and CO_2 variability with these two flux inversions over the tropics for 2015.
Two independent inversions are compared : a CO_2 inversion with the OCO-2 (Orbiting Carbon Observatory-2) measurements and a CO inversion with the MOPITT (Measurements Of Pollution in The Troposphere) data. We apply a four-dimensional variational (4D-VAR) data assimilation system to optimize CO and CO_2 emissions in the two separate inversions using the chemistry transport model TM5. The 6°x4° global version of TM5 with 25 vertical sigma hybrid levels is used.

We will observe the positive and strong correlation between CO and CO_2 with these two independent inversions using MOPITT and OCO-2 data for the Southern America, Indonesia and Africa. CO-CO_2 correlation slopes will be study to observe seasonal correlation. A stronger correlation will be particularly observe during the boreal and austral winter than during the growing season. A deeper analyze will be able to give information on the flux sources (determination of the type of sources between power plants, biomass burning or car traffic).

Keywords : inversions, CO, CO2 , MOPITT, OCO-2

What biogeochemical processes drive the large decrease of atmospheric CO_2 growth rate in 2017?

Junjie Liu[*1,2], Kevin Bowman[1], David Schimel[1], Nick Parazoo[1], Anthony Bloom[1], Meemong Lee[1], Tom Oda[3], Paul Wennberg[2], Annmarie Eldering[1]

1. Jet propulsion Lab, Caltech
2. California Institute of Technology
3. Goddard Space Flight Center

Atmospheric CO_2 growth rate has large interannual variability that is closely related to El Nino Southern Oscillation cycle (ENSO). In general, it is anomaly high during El Nino years when tropical temperature is high, and anomalously low during La Nina years when tropical temperature is low. Atmospheric CO_2 growth rate during 2015-2016 El Nino was ~3 ppm, the highest since the record started in 1958. Correspondingly, the land surface temperature was also the highest. In 2017, the atmospheric CO_2 growth rate quickly dropped to 2.2 ppm in 2017, ~ 0.2 ppm lower than the mean value between 2010 and 2017. However, the global land surface temperature was the third highest since 1880, only lower than 2015 and 2016. So what caused the low atmospheric CO_2 growth rate in spite of high land surface temperature in 2017?

To address this question, we will quantify air-sea net carbon fluxes, net biosphere production (NBP), and its component fluxes including biomass burning and gross primary production (GPP) for the period of 2010 to 2017 by assimilating column CO_2 observations from GOSAT and OCO-2, CO observations from MOPITT, and Solar Induced chlorophyll Fluorescence (SIF) observations from GOSAT into NASA Carbon Monitoring System (CMS) – Flux inversion and optimization framework. In this talk, we will present the dominant regions and biogeochemical processes that have contributed to the low atmospheric CO_2 growth rate in 2017, and further discuss the relationship between carbon cycle responses and climate driver anomalies to reconcile between the low atmospheric CO_2 growth rate and high land surface temperature in 2017. In the end, we will discuss implications for future carbon-climate projections.

Characteristics of Atmospheric Carbon Dioxide Concentrations Based on GOSAT and Its Relations to Biomass Burning in China

Yusheng Shi*[1], Zhenghan Lv[2]

1. Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, China
2. Harbin Normal University, China

Carbon dioxide (CO_2), the main greenhouse gas, has been increasing over the past few decades at a rate of ~2 ppm/a worldwide. China, the largest emitter of the CO_2 emission, poses an important impact on the increase in global atmospheric CO_2 concentrations. In order to explain the spatial and temporal variation of atmospheric XCO_2 concentration and its influencing factors in China. We selected the satellite-retrieved atmospheric carbon dioxide column average dry air mixing ratio (XCO_2) dataset from greenhouse gas observation satellite (GOSAT) and three types of ancillary data (NDVI, ODIAC and GFED). We emphasized the effects of biomass burning emissions on the change of XCO_2 in different terrestrial ecosystem. Based on these long-term series of satellite-retrieved datasets, we analyzed the spatial and temporal characteristics of XCO_2 in China during 2009-2016 growing season by using standard deviation ellipse and trend analyses. The results showed that the concentration of XCO_2 in China increased at an average rate of 2.28 ppm/a with significant seasonal variation of 6.78 ppm annually. South China presented higher incremental rate of XCO_2 than other regions across China with obvious differences in seasonality. Pixel-based analysis indicates a significant difference between eastern and western China: high XCO_2 values were generally observed in the Southeast China, while low XCO_2 concentration were found in high latitude area in China with the annual median center of XCO_2 concentration shifting to the northwest during 2009-2016. Then, we quantified the relative contribution of biomass burning to the change of atmospheric XCO2 concentration. The biomass burning emission had a great contribution and influence on the atmospheric CO_2 change in the low latitudes of South China in autumn and the Yunnan Province in spring, respectively.

Key words: Atmospheric Carbon Dioxide Concentration; Spatial and Temporal Variation; Biomass Burning Emissions

Mesoscale atmospheric inversion of the CO_2 natural fluxes in Amazonia using GeoCarb and MicroCarb data

Sarvesh Kumar Singh[1*], Grégoire Broquet[1], Luis Molina[1,2], Yilong Wang[1], Francois-Marie Bréon[1], Philippe Ciais[1], Diego Santaren[1], Carsten Standfuss[3], Pascal Prunet[3], Claude Camy-Peyret[4], Sean Crowell[5], Berrien Moore[5]

1: Laboratoire des sciences du climat et de l'environnement, CEA-CNRS-UVSQ, Université Paris Saclay, Orme des Merisier, 91191 Gif Sur Yvette, France
2: International Center for Tropical Agriculture - Regional Office Asia, Hanoï, Vietnam
3: SPASCIA, 10 Avenue de l'Europe, 31520 Ramonville Saint Agne, France
4: IPSL, Sorbonne université 4 place Jussieu, Paris, France
5: GeoCarb, University of Oklahoma, 301, David L. Boren Blvd., 4 Partners Place, Suite 1120, Norman, OK 73072 USA

Amazon forests contain nearly half of the tropical forest carbon stocks. and play a major but uncertain role in the global carbon budget. Flux estimates based on atmospheric inversions are hampered by the lack of surface and satellite observations of atmospheric CO_2 in this region, and can hardly resolve uncertainties in the seasonal and inter-annual variations of the Amazon carbon cycle. The second NASA Earth Venture Mission, Geostationary Carbon Cycle Observatory (GeoCarb) is expected to provide daily images of the column concentrations of atmospheric CO_2 (XCO_2) from Geostationary orbit over tropical and mid-latitude America. In particular, it should provide basin wide images over Amazonia at a spatial resolution of typically 20-30 km^2 and once to several times during days with relatively low cloud cover. Here, we investigate the potential of assimilating such images in a regional inverse modelling system to estimate the Net Ecosystem Exchange (NEE) of CO_2 in Amazonia based on Observing System Simulation Experiments (OSSEs). We use the CHIMERE transport model and the variational inversion system PYVAR-CHIMERE to conduct inversions at 35 km and 6-hour resolution. A particular attention is paid to the consistency between the statistical characterization of the uncertainties in the prior NEE estimate and in the transport model, and the actual errors imposed in the frame of the OSSEs. The use of different meteorological forcings or estimates of the NEE to define the true transport and NEE as an alternative to random perturbations that are perfectly consistent with the assumptions made by the inversion challenges this consistency and the traditional assumptions underlying the theoretical framework of the inversion. OSSEs with the assimilation of XCO_2 data from the CNES MicroCarb mission are also conducted to further investigate the requirement and potential in the next decade for spaceborne monitoring of the NEE in the region.

Key words: carbon dioxide; GeoCarb; MicroCarb, transport-model errors; variational inversion.

Assessing errors and uncertainties in a global, high-resolution, fossil-fuel CO_2 emission dataset

Tomohiro Oda*[1,2], Rostyslav Bun[3,4], Vitaliy Kinakh[3], Sha Feng[5], Thomas Lauvaux[6], James Wang[2,7], Randy Kawa[7], Shamil Maksyutov[8], Miguel Roman[9], Zhousen Wang[10,11], Gregg Marland[12], Lesley Ott[1] and Steven Pawson[1]

1. Global Modeling and Assimilation Office, NASA Goddard Space Flight Center, USA
2. Goddard Earth Sciences Technology and Research, Universities Space Research Association, USA
3. Lviv Polytechnic National University, Ukraine
4. WSB University, Poland
5. Department of Meteorology and Atmospheric Science, Penn State, USA
6. Laboratoire des Sciences du Climat et de l'Environnement, France
7. Atmospheric Chemistry and Dynamics Laboratory, NASA Goddard Space Flight Center, USA
8. Center for Global Environmental Research, National Institute for Environmental Studies (NIES), Japan
9. Earth from Space Institute, Universities Space Research Association, USA
10. Terrestrial Information Systems Laboratory, NASA Goddard Space Flight Center
11. Earth System Science Interdisciplinary Center, University of Maryland, USA
12. Appalachian State University, USA

The Open-source Data Inventory for Anthropogenic CO_2 (ODIAC) is a global, high-resolution, gridded emission product that provides CO_2 emission estimates from fossil fuel combustion, cement production and gas flaring. ODIAC is based on spatial disaggregation of country-level emission estimates made by the Carbon Dioxide Information Analysis Center (CDIAC) and provides a complete high-resolution picture of the global fossil-fuel CO_2 emission based on a multiplicity of geospatial information. While ODIAC was originally designed for atmospheric tracer transport simulations and inverse flux calculations using data collected from carbon observing satellites, such as the Japanese Greenhouse gas Observing SATellite (GOSAT) and NASA's Orbiting Carbon Observatory (OCO), ODIAC has played a key role in many carbon budget analyses across different spatial domains, from global, through regional, to city scales, using data collected from different observation platforms. It has also been used to guide observing system design studies for future carbon missions. Thus, the errors and uncertainties in ODIAC are now of great interest to the wide variety of the data users. This study attempts to assess errors and uncertainties in ODIAC and their impacts in studies associated with the use of ODIAC. The evaluation of the gridded emission data products like ODIAC is fundamentally challenging because of the lack of physical measurements. We started with comparing ODIAC to GESAPU, a multi-resolution emission data product for Poland, in order to characterize errors and biases in the ODIAC emission disaggregation. We also employed NASA's PCTM and Penn State's WRF to evaluate ODIAC at global and urban scales, in relation to other emission datasets, such as CDIAC's global gridded data and the Hestia urban emission product. Our analyses show a promise of the continued, significant utility of the updated ODIAC emissions for ongoing/future missions, such as GOSAT-2, OCO-3 and beyond.

Key words: ODIAC, fossil fuel CO2 emission, emission inventory, GOSAT, OCO

Solving Methane Fluxes at Northern Latitudes using Atmospheric and Soil Earth Observations Data

Hannakaisa Lindqvist*[1], Aki Tsuruta[1], Ella Kivimäki[1], Tuula Aalto[1], Vilma Kangasaho[1], Tomi Karppinen[2], Tuomo Smolander[1], Maria Tenkanen[1] and Kimmo Rautiainen[1]

1. Finnish Meteorological Institute, Helsinki, Finland
2. Finnish Meteorological Institute, Sodankylä, Finland

Combined Earth Observations of atmospheric greenhouse gases and the cryosphere have the potential to fundamentally increase our understanding of the carbon cycle specifically at high Northern latitudes. In this work, we investigate the connection of the fluxes to the soil freezing and thawing at boreal and Arctic latitudes. We combine methods for the quantification of CH_4 emissions by applying data from several Earth Observing (EO) satellites, ground-based retrievals, in-situ measurements, and global atmospheric methane inversion model estimates. The EO data consist of a global soil freeze/thaw estimate obtained from the ESA Soil Moisture and Ocean Salinity (SMOS) mission as well as retrievals of atmospheric column-averaged methane (XCH_4) obtained from the Greenhouse Gases Observing Satellite (GOSAT) and Sentinel 5 Precursor TROPOMI (S5P-TROPOMI) observations. These EO data will be used in global atmospheric methane inversion model, CarbonTracker Europe – CH4, simulations, focusing on the identification and quantification of CH_4 sources in the Northern Hemisphere and a trend analysis on the total methane emissions. EO data will be used to assess the spatial variability of the emissions and to better quantify the contributions from regions dominated by anthropogenic emissions and by natural emissions, especially those from wetlands. Further, EO data will be used to create proxies of the seasonality of the natural methane emissions, focusing on the timing and length of the autumn freezing period and springtime melting period. The combined use of several Earth Observation datasets together with inverse modeling will increase the accuracy of the methane flux estimates at the remote Arctic and boreal regions where in-situ measurements are still rare, and also lead to a better understanding of the longer-term link between the changes in the soil conditions and the resulting methane fluxes.

Keywords: CH_4, Arctic, Boreal, cryosphere, GOSAT, SMOS, TROPOMI, CTE-CH4

Relationship between methane enhancements observed by GOSAT and country scale anthropogenic emissions in Asia

Rajesh Janardanan[1]*, Shamil Maksyutov[1], Akihiko Ito[1], Yukio Yoshida[1], Tsuneo Matsunaga[1]

1 National Institute for Environmental Studies, Japan

Anthropogenic greenhouse gas emissions need to be better quantified to strengthen the efforts for climate change mitigation plans. Here we report the update result of our attempt to estimate anthropogenic signal from GOSAT XCH_4 observations for a period from 2009 to 2016 (NIES L2 v02.72) and to use their relation to the underlying emission on spatial scale of large countries over Asia for an independent verification purpose. We employ a global Eulerian transport model (NIES-TM) coupled to a Lagrangian particle dispersion model (FLEXPART) with high-resolution methane emission inventories to simulate GOSAT XCH_4 observations. The anthropogenic emissions were taken from EDGAR (v4.3.2), wetland emissions were calculated using VISIT model and biomass burning emissions taken from GFAS, all at 0.1° resolution and meteorological fields were from JCDAS at 1.25°. We used the Lagrangian simulations using anthropogenic emission alone at GOSAT observation locations to classify the observations into polluted or background scans using XCH_4 threshold. We then use observations and the coupled model simulations to calculate monthly regional background values and the XCH_4 anomalies as deviations from their respective backgrounds of model simulations and observations. The bin-averaged pair of anomalies were used for a weighted linear regression accounting both errors in simulated and observation bins, with simulated against GOSAT observed over various regions over Asia. The regression slope is a measure of how the observed anomalies relate to the model simulation based on inventory over the region and can be used to correct inventory towards fitting to GOSAT observed enhancements. Our results suggest that the anthropogenic methane emission in India and Middle East is possibly lower than EDGAR inventory, while in China it is close to inventory. Over Japan, GOSAT observed anomalies suggest slightly higher emissions than inventory though the uncertainty in this estimate is larger owing to the limited number of observations.

Key words: GOSAT; anthropogenic methane emissions; emission verification

Characterizing and mitigating the impact of model transport errors on CO_2 flux estimates in the assimilation of XCO_2 data from OCO-2

Dylan Jones*[1], Feng Deng[1], Tailong He[1], Ilya Stanevich[1], and Xuesong Zhang[1]

1. Department of Physics, University of Toronto, Toronto, Ontario, Canada

Inverse modeling of atmospheric CO_2 holds the promise of providing better estimates of regional sources and sinks of CO_2. However, discrepancies in the atmospheric transport models employed in these analyses have posed a challenge to obtaining robust estimates of the sources and sinks. Here we use a weak constraint four-dimensional variational (4D-Var) data assimilation scheme to assimilate atmospheric CO_2 data from the surface observing network and from the Orbiting Carbon Observatory (OCO-2) to optimize the distribution of atmospheric CO_2 in the GEOS-Chem chemical transport model. We investigate the adjustments to the CO_2 distribution produced by the weak constraint 4D-Var scheme to quantify transport errors in GEOS-Chem. In particular, we examine the inferred spatial and temporal variability in the optimized CO_2 distribution and compare the information provided by the surface and OCO-2 data on atmospheric CO_2 to characterize the model errors. We also quantify the impact of these errors on regional flux estimates of CO_2.

Key words: OCO-2, Flux Inversion

The seasonal and inter-annual variations of regional CO_2 and CH_4 fluxes estimated from GOSAT data

Hiroshi Takagi[1*], Heon-Sook Kim[2], Shamil Maksyutov[1], Makoto Saito[1], and Tsuneo Matsunaga[1]
[1] National Institute for Environmental Studies (NIES), Japan
2 Pusan National University, Busan, Republic of Korea

Determining in detail how the Earth's carbon cycle is being modified by human activities and changing climate is an urgent societal need, and this called for establishing a coordinated system of space-based GHG monitoring platforms that can augment the existing networks of ground-based GHG observation in spatial and temporal coverage. The Greenhouse gases Observing SATellite (GOSAT), launched in early 2009 from Japan, is one of the pioneering spacecrafts dedicated toward that purpose, and has been making global measurement of reflected light spectra from which column-averaged concentrations of CO_2 and CH_4 are retrieved. At NIES, these retrieved concentrations are combined with ground-based observations to estimate monthly CO_2 and CH_4 surface fluxes on a sub-continental scale. The results of the flux estimation are made public as GOSAT Level 4 data products.

We herein present the latest version of the Level 4 CH_4 product (coverage: Jun. 2009 – Sep. 2015) and a candidate for the next release of the Level 4 CO_2 product (Jun. 2009 – Oct. 2017). Notable findings in the CH_4 flux estimates include a large year-to-year increase in CH_4 global total flux found in 2013-2014, which is in line with a sharp rise in annual CH_4 growth trends monitored by NOAA base-line stations. The largest contribution to this global emission rise was found to come from middle South America, where anomalously high precipitations were observed in 2011 and 2014; the regional CH_4 flux was found to be highly correlated with the region's water balance indicators. The 101-month-long Level 4 CO_2 product candidate was produced using a bias-corrected version of GOSAT Level 2 column-averaged CO_2 distribution (v02.75) and climatological VISIT biospheric flux data as an a priori information, both of which are new to the Level 4 CO_2 data processing. The result of evaluation is presented.

Comparing national methane emissions inventories with estimates by the global high-resolution inverse model

Fenjuan Wang[1,2], Aki Tsuruta[1,3], Shamil Maksyutov[1], Rajesh Janardanan[1], Akihiko Ito[1], Motoki Sasakawa[1], Toshinobu Machida[1], Isamu Morino[1], Yukio Yoshida[1], Johannes W. Kaiser[4], Greet Janssens-Maenhout[5], Ed Dlugokencky[6], Tsuneo Matsunaga[1]

1. National Institute for Environmental Studies (NIES), Japan
2. National Climate Center, China
3. Finnish Meteorological Institute, Finland
4. Deutscher Wetterdienst, Germany
5. European Commission, Joint Research Centre (JRC), Italy
6. National Oceanic and Atmospheric Administration, USA

The global and regional methane emissions were evaluated using the newly developed global 0.1° × 0.1° high spatial resolution inverse model NIES-TM-FLEXPART-VAR (NTFVAR) and atmospheric methane observation data at global in-situ network archived at WDCGG and NIES. Prior fluxes at 0.1° resolution were prepared with two variants of anthropogenic emissions, one is EDGAR v4.3.2 and the other is EDGAR gridded emissions scaled to match country totals by national reports to UNFCCC for 15 top emitting countries, augmented by biomass burning (GFASv1.2) and wetlands (VISIT). We compared the national reports of anthropogenic methane emission to UNFCCC and EDGAR4.3.2. The ratio of global anthropogenic methane emission scaled to UNFCCC to that by EDGAR is 97.5%, but the ratio varies by region, from nearly 200% in Russia to 84% in China and 62% in India. We selected the year 2012 to compare the globally and regionally optimized methane emissions to both priors. Our inverse model yields a net methane source of 528 Tg in the year 2012 with pronounced regional corrections to the priors. With changing prior from EDGAR country totals to UNFCCCC totals emissions in India is reduced, but inversion corrects emissions upward. For Russia, increasing prior to match national report leads to lowering the emissions after correction by inversion. Estimated anthropogenic emissions over large regions (US, China, India and Russia) are comparable to GCP-CH_4 top-down estimates and inverse model estimates based on GOSAT data. As there are differences between country scale inventories and model estimates, biases of the inversion need to be understood and reduced, and further effort is needed to achieve robust separation of the natural (wetlands) and anthropogenic emissions on a global scale, in the tropical band and in the extra-tropics.

Key words: methane emissions; inverse model; GOSAT

lnverse modeling of anthropogenic methane emissions based on ground-based monitoring and GOSAT satellite retrievals

Aki Tsuruta*[1], Shamil Maksyutov[2], Rajesh Janardanan[2], Akihiko Ito[2], Johannes Kaiser[3], Greet Janssens-Maenhout[4], Ed Dlugokencky[5], Motoki Sasakawa[2], Toshinobu Machida[2], Yukio Yoshida[2], Tsuneo Matsunaga[2]

1. Finnish Meteorological Institute, Finland
2. National Institute for Environmental Studies, Japan
3. Deutscher Wetterdienst, Germany
4. European Commission, Joint Research Centre (JRC), Italy
5. National Oceanic and Atmospheric Administration, Global Monitoring Division, USA

We perform a global high-resolution methane flux inversion to estimate methane emissions using atmospheric methane data available from the WDCGG archive, ICOS and JR-STATION networks, and GOSAT satellite retrievals. For better accounting of anthropogenic emissions localized around large cities, we use the Lagrangian particle dispersion model FLEXPART to model local tracer transport at 0.1° spatial resolution. FLEXPART is coupled to a global atmospheric tracer transport model (NIES-TM). Prior fluxes at 0.1° resolution were prepared for anthropogenic emissions (EDGAR v4.3.2), biomass burning (GFAS), and wetlands (VISIT). The inverse model NIES-TM-FLEXPART-VAR (NTFVAR) applies variational optimization to two categories of fluxes: anthropogenic and natural (wetlands). Bi-weekly emissions are estimated for 2009 to 2017. The coupled transport model manages to better reproduce the ground-based continuous observations than using only NIES-TM, because it can resolve anthropogenic emission plumes. Monthly mean differences between the GOSAT data and the inversion-optimized forward simulation are estimated for each 5° latitude band and then subtracted from GOSAT retrievals before including them in the inversion. The bias correction is designed to remove large scale biases in GOSAT retrievals, while retaining local scale variability that contains most of the information on anthropogenic emissions. Estimated anthropogenic emission trends showed a slight increase in the US and India, and a significant increase in China during 2010-2017. The estimated emission trends and seasonal cycles are further evaluated by comparing with other available estimates.

Key words: GOSAT; CH_4; atmospheric inversion

Retrieval of solar-induced chlorophyll fluorescence from TanSat space measurements

Lu Yao*[1,2], Yi Liu[1], Dongxu Yang[1]

1. Institute of Atmospheric Physics, Chinese Academy of Sciences
2. University of Chinese Academy of Sciences, China

Solar-induced chlorophyll fluorescence (SIF), re-emitted during the conversion of sunlight to chemical energy in plant leaves, constitutes a very small additional offset to the reflected radiance, which can be observed by sensitive remote sensing detectors. The Chinese global carbon dioxide monitoring satellite (TanSat) is the third satellite aiming at acquiring greenhouse gas column density. The advanced technical characters of the hyper-spectrum grating spectrometer (ACGS) onboard TanSat enable the retrieval of SIF from the space observation with just the spectrum in near-infrared band. We retrieved one year of global SIF data from OCO-2 and TanSat measurements with a simple and robust method to make an inter-comparison of the two instruments performance. The global seasonal distribution shows that the SIF retrieved with the KI Fraunhofer lines around 771nm from two satellite missions share the same spatial pattern in all seasons, which agrees with the OCO-2 L2 SIF official product. With one year of data, the regional temporal variation of SIF varies from different kinds of vegetation types, as well as the surrounding climate conditions mainly dominated by the geographic location. The consistency of temporal variation between TanSat and OCO-2 makes the comprehensive usage of these two kinds of products possible. Overall, the preliminary SIF result from TanSat observation could help to make a more valuable global SIF map and that will promote the research on global vegetation photosynthesis from space measurement.

Key words: TanSat; SIF; Retrieval

Long-term evaluation of zero-level offset in GOSAT FTS O_2 A-band and consistency of the derived SIF with OCO-2 SIF

Haruki Oshio*[1], Yukio Yoshida[1] and Tsuneo Matsunaga[1]

1. National Institute for Environmental Studies (NIES), Japan

Satellite remote sensing of solar induced chlorophyll fluorescence (SIF) has attracted attention as a method for improving the estimation accuracy of photosynthesis activity of terrestrial vegetation in recent years. Evaluating the artifact signal (e.g., zero-level offset caused by non-linearity in the analogue circuit in case of Greenhouse gases Observing SATellite (GOSAT)) is effective to infer the instrument status and important to retrieve SIF from satellite measurements. Although the zero-level offset of GOSAT has been evaluated, the detailed spatiotemporal variation has not been investigated. Recently, SIF data have been provided by several satellites, and we are planning to provide SIF data as the GOSAT-2 product; therefore, the consistency among satellite SIFs is important to utilize those data. Agreement among SIF data derived from satellite sensors has partly been reported, but difficulty due to difference in the observation pattern remains. Here we investigate the criteria for identifying vegetation-free areas to evaluate the GOSAT zero-level offset and the offset correction method, while comparing the derived SIF with Orbiting Carbon Observatory-2 (OCO-2) SIF at multiple spatial scale (footprint to global). Criteria were determined as small variation in radiance within the GOSAT instantaneous field of view for cloudy ocean scenes and higher albedo in 2.0 μm band than in 1.6 μm band for bare soil scenes, which were slightly different from the previously used criteria. GOSAT SIF that was most consistent with OCO-2 SIF was obtained when the zero-level offset was evaluated from bare soil over the globe, with bias of about 0.1 mW m^{-2} nm^{-1} sr^{-1}. Our results support the consistency among the present satellite SIF data. Temporal variation of the zero-level offset for 9 years suggests that the radiometric sensitivity of the GOSAT spectrometer changed after switching the optics path selector in January 2015.

Key words: solar induced chlorophyll fluorescence (SIF); GOSAT; GOSAT-2; OCO-2

Assessing the temporal dynamics of satellite-derived photochemical reflectance index (PRI) and solar-induced fluorescence (SIF) in climate-changing Mongolia

Tomoki Kiyono*[1], Hibiki Noda[1], Kouki Hikosaka[2], Tomo'omi Kumagai[3], Yukio Yoshida[1], and Haruki Oshio[1]

1. National Institute for Environmental Studies (NIES), Japan
2. Tohoku University, Japan
3. The University of Tokyo, Japan

Photosynthetic production is a fundamental process of ecosystems and it is sensitive to hydrometeorological conditions. In several studies, the vegetation indices which correlate with foliage amount, e.g., NDVI have been used to monitor temporal changes in gross primary production (GPP) [e.g., Muraoka *et al*. 2012]. However, using only such indices has difficulties in arid region [Turner *et al*. 2005] and evergreen forest, where light use efficiency (LUE) become much important for GPP. The recent advent of satellite remote sensing enables us to obtain two optical indices, which are directly linked to LUE; photochemical reflectance index (PRI) and solar-induced fluorescence (SIF). In a photosynthetic process, a part of absorbed light energy is consumed as heat dissipation and some other part is emitted as fluorescence. PRI correlates with the state of the xanthophyll cycle which is related to heat dissipation [Gamon *et al*. 1992] and SIF is the fluorescence observed under solar-radiation. Thus, PRI and SIF may give us complementary information. However, previous studies have simply discussed the seasonality and/or trends in the correlations between satellite-PRI/SIF and GPP. To use PRI and SIF, we have to consider physiological processes more deeply.

In the present study, we examined temporal changes in satellite-PRI and SIF in and around Mongolia (100°E–120°E and 40°N–50°N), includes desert, grassland, and boreal forest. This region is under rapid warming and experienced historic drought events in the late 1990s and 2000s [Hessl *et al*. 2018]. To reveal the temporal changes in PRI and SIF under the drought event, we analyzed satellite data, metrological data, and ground-measured CO2 flux data. PRI was obtained from new MODIS surface product, version 6 [Vermote and Wolfe 2015] for both morning (Terra-MODIS) and afternoon (Aqua). SIF was retrieved from GOSAT, according to Frankenberg *et al*. (2011). In this presentation, we will discuss the drought effect on photosynthetic activity in grassland and boreal forest in this region.

Key words: PRI; SIF; Drought Response; MODIS; GOSAT

Solar induced Fluorescence (SIF) Mapping from the Copernicus Anthropogenic CO_2 Monitoring Mission

H. Boesch[*,1,2], A. Webb[1,2], P. Somkuti[1,5], D. Yang[1], A. Di Noia[1], R. Parker[1,2], M. Buchwitz[3], Y. Meijer[4]

[1] Earth Observation Science Group, University of Leicester, Leicester, UK
[2] National Centre for Earth Observation NCEO, University of Leicester, Leicester, UK
[3] IUP, University of Bremen, Bremen, Germany
[4] ESA, Noordwijk, The Netherlands
[5] Now at Colorado State University, Fort Collins, USA

Photosynthesis is the process by which plants harvest sunlight to produce sugars from carbon dioxide and water. Unused absorbed photosynthetically-active radiation is released by plants primarily as heat with a small fraction being re-emitted as fluorescence in the shortwave-infrared range. Thus, the fluorescence signal is related to the photosynthetic process and offers thereby a potential to constrain the gross primary production (GPP) and to gain a more mechanistic understanding of the ecosystem carbon exchange. Although this fluorescence signal is small (about 1% of the reflected sunlight), it can be well measured from space and global fluorescence dataset are now available from sevel satellite missions.

The Copernicus Anthropogenic CO_2 Monitoring Mission is the space segment of a proposed operational capacity to monitor fossil fuel CO_2 emissions by the European Commission (EC) and the European Space Agency (ESA) in the support of the Paris Agreement. The space system will measure images of total column CO_2 from a multiple (low Earth orbiting) satellite constellation each with an across-track swath width of ~200 km providing global coverage every 3-days with a ground pixel size of 4 km2. The satellite will also measure the vegetation fluorescence signal which is needed as a correction for the CO_2 retrieval procedure but which will also provide valuable carbon cycle information that can be used in synergy with the CO_2 observations.

In this this presentation, we will describe the expected performance of the fluorescence retrieval obtained from the Copernicus Anthropogenic CO_2 Monitoring Mission. We will discuss the implication of the improved coverage and resolution obtained from this mission compared to existing missions. We will also discuss different sources of potential biases in the fluorescence retrieval, in particular from instrument calibration uncertainties and we will investigate how well these biases can be corrected using soundings over non-vegetated areas.

Implementing SIF estimation process to the terrestrial ecosystem model VISIT and applying the radiation transfer model

Tatsuya Miyauchi*[1], Makoto Saito[1], Hibiki M. Noda[1], Yukio Yoshida[1], Haruki Oshio[1] and Akihiko Ito[1]

1. National Institute for Environmental Studies (NIES), Japan

Since the solar-induced chlorophyll fluorescence (SIF) was reported that it could be retrieved from spectrum data observed by Greenhouse Gases Observing Satellite (GOSAT), many studies using SIF for GPP estimation and model improvement are actively conducted. The estimation of CO_2 absorption and emission in the terrestrial vegetation is important to estimate global CO_2 fluxes. The Vegetation Integrative Simulator for Trace graces (VISIT) is used to compute the prior fluxes in terrestrial ecosystem to produce GOSAT L4 products. To improve VISIT using SIF can contribute to upgrade L4 products. To adjust the model and its parameters using GOSAT SIF, the model is required to compute the SIF as prior value. We implemented the SIF estimation based on the biochemical process about the energy balance between photochemistry, thermal deactivation, fluorescence and non-photochemical quenching (NPQ) to VISIT. To compare computed SIF to GOSAT SIF, SIF calculated by VISIT must be converted SIF of satellite-observed direction. Moreover, SIF emitted sunshade leaf is too complex to calculate by high temporal and spatial resolution. Therefore, we used look-up-table (LUT) created by pre-computation using the radiation transfer model. We used SCOPE model, which is used in many previous studies for radiation transfer calculation in canopy. By using LUT for two ratios (1: shade leaf SIF to sun leaf SIF, 2: SIF of observed direction to SIF of sun zenith direction), we converted SIF calculated by VISIT to satellite-observed SIF using the LUT and compared with GOSAT SIF. In our presentation, we will introduce the description of ongoing developing VISIT-SIF model and our future plan applicating satellite-observed SIF to the model.

Key words: SIF; VISIT; SCOPE; GOSAT; GOSAT-2

Methane isotopologue parameter assessment of multiple spectral databases using TCCON

Edward Malina*[1], Ben Veihelmann[1], Dietrich G. Feist[2,3] and Isamu Morino[4]

[1]Earth and Mission Science Division, ESA/ESTEC, the Netherlands

[2]German Aerospace Center (DLR), Institute of Atmospheric Physics, Germany

[3]Max Planck Institute for Biogeochemistry, Jena, Germany

[4]National Institute for Environmental Studies, Japan

Copernicus Sentinel-5P with TROPOMI, and the future Sentinel 5 with the UVNS (Ultra-violet, Visible, Near InfraRed, Shortwave Infrared) instrument will enable daily global measurements of methane (and other trace gases). Both instruments, as well as the recently launched GOSAT-2/TANSO-FTS-2 exploit the spectral range 2305-2385 nm in the Short Wave InfraRed (SWIR) to retrieve methane total column information.

In this study, we assess TCCON retrievals of the two main methane isotopologues $^{12}CH_4$ and $^{13}CH_4$ in the TROPOMI SWIR band, and the 1630-1700 nm spectral region using the TCCON GGG retrieval environment. Four separate spectroscopy databases are used for this study: the TCCON spectroscopy database, the HITRAN2016 database, the GEISA2015 database, and the ESA SEOM-IAS database. The latter supports advanced treatment of line shapes by including non-Voigt line shape parameters, which is not included in the other databases assessed here. In this study, we analyse high spectral resolution irradiance spectra measured in solar occultation from two TCCON sites, Ascension Island (for background variations) and Tsukuba, Japan (for variable seasons).

Retrieval experiments have been conducted for a variety of cases with different spectroscopic databases and spectral fit windows. We find notable differences in the retrieved volume mixing ratios of methane isotopologues for both TCCON sites. Fitted mixing ratios vary depending on the spectral band under investigation (in some cases up to 5% for $^{12}CH_4$). Differences are persistent throughout the day, and across different sites. In most cases, however, there is more bias between the spectral bands, rather than between the spectroscopy databases. The SEOM-IAS database typically shows the best-fit metrics, i.e. lowest fit residuals and lowest posteriori retrieval errors. $^{13}CH_4$ is particularly challenging, with large variations in fit results and retrieval quality both across the spectral bands and databases (up to 20% retrieval volume mixing ratio bias), and non-uniformity between the 2300 nm and the 1650 nm spectral ranges.

Keywords: Copernicus; TCCON; methane; spectroscopy; non-Voigt.

In situ measurement of vertical distribution of CO_2 and CH_4 in the troposphere by aircraft and tethered balloon

Xiaoyu Sun*[1], Minzheng Duana,[1], Xiangao Xia[1], Disong Fu[1] and Zhongdong Yang[2]

1. Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing
2. National Satellite Meteorological Center, CMA, Beijing

Several Satellites have been launched into space to monitoring the greenhouse gases concentration, by observing the back-scattered hyper-spectral radiance in the SWIR, in the atmosphere therefore the vertical profile of greenhouse gases, especially carbon dioxide, and aerosol could greatly modulate the retrievals. To investigate how the interplay process of the CO_2 and aerosol scattering in the atmosphere, which is blamed for the uncertainty of the retrieval results of satellite measurements. Therefore, knowledge of CO_2 vertical distribution is crucial for the development of satellite-borne retrieval methods and algorithm. Aircraft in situ measurements of carbon dioxide mixing ratio and methane over Jiansanjiang (46.77 ° N, 131.99 ° E) (August 2018) were conducted, and compared to the retrieval results of Orbiting Carbon Observatory 2 (OCO-2) and Chinese Carbon Dioxide Observation Satellite (TanSat). The aircraft measurements were carried out between altitudes of 0.6 to 7 km, and obtained vertical profile of CO_2 and CH_4 by an Ultra-Portable Greenhouse Gas Analyzer (Los Gatos Research, LGR). A constant increase of an averaged 15.26 ppm in CO_2 mixing ratio were observed between altitude 2 to 7 km during the flight period. The methane measurements show an averaged 0.5 ppm in CH_4 mixing ratio increased below 2.0 to 0.6 km caused by the large emission from wide range paddy field below, and the mixing ratio above 2 km varies between 1.951 to 1.976 ppm without large mutation.

Another vertical profile measurements of CO_2 and CH_4 on tether-balloon platform was conducted on Changshou (107.00° E, 29.84° N) (January 2019). In this study, vertical profiles of CO_2 mixing ratio measurements was made at low troposphere within altitude 0 to 1000 km. A strong vertical mixture of CO_2 was observed between 0 to 700 km, and most profiles presents declining trends of CO_2 and CH_4 mixing ratio with the increase of altitude, since the experiment site located in an industrial park with a large greenhouse gases emission source. The results would enhance the understanding of the spatial variation of CO_2 and CH_4.

Key words: Aircraft; tethered balloon; TanSat; OCO-2

Measuring in-situ CO_2 profile and comparison with satellites and model

You Yi[a, b], Yi Liu[a, b], Zhaonan Cai[a], Shuangxi Fang[c], Dongxu Yang[a], Yong Wang[a], Miao Liang[c], Bo Yao[c], Qianli Ma[d]

[a] Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China
[c] Meteorological Observation Centre(MOC), China Meteorological Administration (CMA), Beijing 100081, China
[d] Zhejiang Lin'an Regional Atmosphere Watch Station, Zhejiang 311307, China

corresponding to caizhaonan@mail.iap.ac.cn

The vertical distribution of carbon dioxide in the atmosphere is critical to validate the vertical columns measured by satellite and ground-based spectrometers and estimate the sinks and sources of carbon dioxide. This work describes the in-situ air-sampler system (Aircore). Two profiles of CO_2 and CO were retrieved from two soundings of this system in Xilin Hot on 13 and 14 June, 2018 and are compared with Orbiting Carbon Observatory-2 (OCO-2), Tropospheric Monitoring Instrument (TROPOMI) and Copernicus Atmosphere Monitoring Service model (CAMS) respectively. Results show that the column-averaged mixing ratio of CO_2 (XCO_2) of OCO-2 agrees well with XCO_2 calculated from the in-situ CO_2 profile, with a small mean differences of 5±1.89 ppb, TRPOMI XCO agrees well with XCO calculated from in-situ CO profile with a slight bias of 0.4±0.6 ppm. OCO-2 a posterior profile has an obvious bias against in-situ CO_2 profile on 13 June with an underestimation between 600 hPa and 250 hPa and an overestimation below 600 hPa. CAMS also has the same bias against in-situ CO profile, however, CAMS agrees well with in-situ CO profile on 14 June in the troposphere because a weak cold vortex passed Xilin Hot on 13 June and disappeared the other day. In the stratosphere, there are significant bias in the vertical degradation. The striking agreement of the column-averaged mixing ratio and the difference of vertical distribution indicate new exciting applications for the profile product.

Provision of GOSAT data from the WDCGG website

Atsuya Kinoshita*[1], Saki Ohkubo[1] and Seiji Miyauchi[1]

1. Japan Meteorological Agency (JMA), Japan

The World Data Centre for Greenhouse Gases (WDCGG; a World Data Centre (WDC) of the World Meteorological Organization (WMO)) has been operated since 1990 by the Japan Meteorological Agency (JMA). As the only WDC specializing greenhouse gases, it serves to collect, archive and distribute data on such gases (e.g., CO2, CH4, CFCs and N2O) and other related gases (such as CO) in the atmosphere.

On 19 March 2019, WDCGG began online provision of CO2 observation data* from Japan's Ibuki Greenhouse gases Observing SATellite (GOSAT) for the period from April 2009 (https://gaw.kishou.go.jp/satellite) in addition to existing surface-based data. Integration of remote sensing satellite data and existing surface-based in situ data is expected to promote the wider use of this information and facilitate long-term monitoring of global distribution and sub-continental CO2 emission/absorption estimates.

WDCGG plans to continue improving its services for the collection, archiving and distribution of satellite data worldwide, including for GOSAT-2 (the successor to GOSAT), to support the monitoring of climate change and assist policy making, thereby helping to reduce environmental risks to society. Overview and objective of the website are presented and discussed.

*The original GOSAT data products are distributed by the National Institute for Environmental Studies, Japan (NIES). GOSAT Data Archive Service (GDAS, https://data2.gosat.nies.go.jp/index_en.html)

Key words: GOSAT; GOSAT-2; WDCGG

Intercomparison of XCO_2、XCH_4、XCO measurements using EM27/SUN and IFS125HR in Xianghe

Ke Che*[1], Yi Liu[1], Dongxu Yang[1], Zhaonan Cai[1], Pucai Wang[2], Yang Yang[2], You Yi[2], Sihong Zhu[2]

Key Laboratory for Middle Atmosphere and Global Environment Observation
Institute of Atmospheric Physics, Chinese Academy of Scinces

We present work on use a compact solar-tracking Fourier Transform Spectrometer (Bruker EM27/SUN) to precisely derive total column averaged amount of Greenhouse gases.
In order to ensure the high quality of the retrieved data, the total column averaged XCO2 measured from Bruker EM27/SUN are compared to well calibrated IFS125HR in Xianghe (39.798˚N, 116.958˚E, 50m a.s.l.) as reference. We also processed the EM27/SUN data using PROFFAST and GGG2014 for further investigation the performance of the EM27/SUN. The comparison between EM27/SUN and IFS125HR shows a 0.24% bia with GGG2014+EGI, while a bias of 0.53% approached by PROFFAST. To further characteristics the differences between the two algorithms, Xgas has been measured by EM27/SUN in Beijing (IAPCAS) with coordinate weather record by WS500 weather station. The GGG2014 and PROFAST are involved in data processing, but found a bias of 0.20%, 1.23%, -1.0% for XCO2, XCH4 and XCO respectively. Xair calculated by the above two algorithms are approximately 1.0012、0.9831. The correlation coefficient is 0.9979 for daily median XCO2 between the result of these two retrieval algorithms. Reasons for these differences could be attributed to the difference in pre-processing method, instrument lines shape model, gas spectroscopy. Furthermore, field campaign collaborating EM27/SUN and aircore soundings will contribute to the greenhouse gases validation for TanSat, Sentinel-5P as well as other greenhouse gas satellites, GOSAT and OCO-2.

Key words: EM27/SUN; intercomparison; validation

Towards Tracking East Asian Transport of Pollution using the Burgos TCCON site and the GOSAT Series Satellites

Voltaire A. Velazco[*1,2], Isamu Morino[3], Osamu Uchino[3], Nicholas M. Deutscher[1] and David W. T. Griffith[1]

1. University of Wollongong, Australia
2. OML Center for Climate Change and Disaster Risk Management Foundation, Philippines
3. National Institute for Environmental Studies (NIES), Japan

The Burgos TCCON station, which started operations in March 2017, has been validated using aircraft profiles within the EMeRGe mission, providing the last step towards a "full TCCON" site status. In this new project, we plan to combine existing resources at the Burgos TCCON site in the Philippines and nearby sondes from Laoag airport with GOSAT and GOSAT-2 data to measure, monitor and understand the formation and transport of pollutants from Southeast Asia. As a first step, we aim to analyze measurements taken at the Burgos TCCON site and investigate the correlation of aerosols properties, water vapor and thin clouds on the column of trace gases measured from TCCON. We will combine this analysis with data from an aircraft campaign (NASA-CAMP^{2}Ex). As a second step, we plan to compare GOSAT-2 retrievals over Ocean of XH_2O, XCO, XCO_2, and XCH_4 with the ground based measurements. In the third step, we will utilize a model to analyze the transport and address the question of how anthropogenic emissions from East Asian countries are formed and transported to the tropical western Pacific.

Key words: GOSAT; GOSAT-2; Pollution, Validation; TCCON

Intercomparison between TCCON XCO_2 and XCH_4 data in Japan and Philippines via a portable Fourier transform spectrometer

Hirofumi Ohyama*[1], Isamu Morino[1], Akihiro Hori[1], Kei Shiomi[2], Nobuhiro Kikuchi[2], Voltaire A. Velazco[3] and David W. T. Griffth[3]

1. National Institute for Environmental Studies (NIES), Japan
2. Japan Aerospace Exploration Agency (JAXA), Japan
3. University of Wollongong, Australia

Accuracies and precisions of column-averaged dry-air mole fractions of CO_2 and CH_4 (XCO_2 and XCH_4) obtained from space-borne measurements become higher due mainly to an improvement of retrieval algorithm, and therefore requirements for the consistency between data from the Total Carbon Observing Network (TCCON), which are widely used for validating the space-borne XCO_2 and XCH_4 data, is growing. In the present study, site-by-site biases across the four TCCON sites in Japan and Philippines (Rikubetsu, Tsukuba, and Saga in Japan and Burgos in the Philippines) were evaluated by using a portable and robust Fourier transform spectrometer (EM27/SUN) as a reference. Both the TCCON and EM27/SUN data were analyzed with the GGG2014 software. The obtained XCO_2 and XCH_4 data for each instrument were averaged every 10 minutes and were directly compared (i.e., not considering the difference in averaging kernels). The mean differences in TCCON XCH_4 with respect to EM27/SUN XCH_4 were consistent across the four sites with negative biases of 10.0–14.2 ppb. To probe the causes of the negative biases, the effects of the difference in spectral resolution on the XCH_4 data were examined. For this purpose, the raw TCCON interferograms were truncated to the maximum optical path difference of the EM27/SUN and were analyzed in the same procedure as the original TCCON spectra. We found that the XCH_4 biases were reduced to a few ppb and most of the biases are attributed to the difference in the spectral resolution. As for XCO_2, the mean differences were 1.57, 0.03, 0.75, and 0.60 ppm for Rikubetsu, Tsukuba, Saga, and Burgos, respectively. Although the causes of the site-by-site XCO_2 biases are under discussion, the candidate may be a parameter related to a phase correction of spectra because a change in the parameter resulted in decreases in the site-by-site XCO_2 biases.

Key words: TCCON; EM27/SUN; CO_2; CH_4

Ground-based measurement of solar-induced chlorophyll fluorescence with high-resolution spectrum in paddy field ecosystem, Japan

Kanokrat Buareal*[1], Tomomichi Kato[2] and Keisuke Ono[3]

1. Graduate School of Global Food Resources, Hokkaido University, Japan
2. Research Faculty of Agriculture, Hokkaido University, Japan
3. National Institute for Agro-Environmental Sciences, Japan

The terrestrial ecosystem photosynthesis plays a crucial role in the global carbon cycling estimation. Accurate tracking of terrestrial gross primary productivity (GPP) can provide more important information about the CO_2 dynamics between land and atmosphere as ecosystem level. Recently, tracking changes in photosynthesis at a global scale could be investigated through Solar-Induced Chlorophyll fluorescence (SIF) by satellite. Although satellite-derived SIF showed a high correlation with GPP, the coarser spatial-temporal scale by satellite needs to be validated by performing a ground-based SIF assessment to better understand the dynamics of CO^2 uptake by plants. SIF was measured by the high-resolution spectrum at the Mase eddy flux site (36.05°N, 140.03°E), a rice paddy field (*Oryza sativa* L.; cultivar Koshihikari), Tsukuba, Japan. The measurement was conducted from April to December using five spectroradiometers; FLAME, HR4000 x2, QE Pro x2 (Ocean Optics, Dunedin, FL, USA), with 0.11-1.08 nm of the full-width at half maximum (FWHM). The spectroradiometers were connected via fiber switches (FSM1x8, Piezosystem Jena GmbH, Jena, Germany, and MOL-1x8-600-H, LEONI Fiber Optics GmbH, Föritztal, Germany) with to three optical fiber cables: the first one was set looking downward at a viewing zenith angle of 45° as bare fiber (FOV of 25°), the second one was vertically set looking downward (FOV of 180°), and the third one was vertically set looking upward to the sky (FOV of 180°). The multispectral methods derived from the Fraunhofer Line Depth (FLD) principle, 3FLD, iFLD and Spectral Fitting Method (SFM) were used to estimate SIF and then compare with other conventional vegetation indices such as the normalized difference vegetation index *(*NDVI*)* and Enhanced Vegetation Index (EVI*)*. This study illustrated the preliminary result of the ground-based measurement of SIF to verify that the SIF has the potential to be a promising proxy of photosynthesis tracking in the paddy field ecosystem.

Key words: Fraunhofer Line Depth; Gross primary productivity; Photosynthesis; Spectroradiometers

Quick look algorithm for GHG plume detection by using airborne imaging spectrometer suite

Takahiro Kawashima[1], Fumie Kataoka[1] , Akihiko Kuze[2] , Hiroshi Suto[2], Kei Shiomi[2] , Nobuhiro Kikuchi[2], Makiko Hashimoto[2] and Shigetaka Mori[3]

1. Remote Sensing Technology Center of Japan,
2. Japan Aerospace Exploration Agency
3. JASTECS Corporation

Key words: Airborne, imaging spectrometer, GHG, methane, plume

In almost Japanese megacities, various CO_2 and CH_4 emission source like industrial activity (power plant, landfills, gas factory, water processing plants), and agricultural activity (rice cultivation, pig farm) are concentrated within a few tens kilometers region. An air borne imaging-spectrometer suite oriented for such CO_2 and CH_4 emission source observation was newly developed by JAXA. The instrument consists of NIR spectrometer for O_2-A band measurement and SWIR spectrometer for CO_2/CH_4 measurement. NIR and SWIR spectrometers have wavelength coverage of 747–783 nm with 0.09nm resolution and, 1560-1670nm with 0.17nm resolution respectively. Ground sampling distance is about 50m with sampling time interval of 0.5 s.

We found enhancement of CO_2 column density looking like 'plume' above Hekinan coal power plant located in Aichi prefecture during a flight on February 16 2018. As a methodology for detection of the phenomenon, very simple band ratio approach was enough because its location was predictable because of its large emission rate and already found by satellite observation (e.g. GOSAT, OCO-2) in the past.

On the other hand, detection of methane source was difficult, because of its relatively small variation of column density to background (< 10%) as well as its un-known location with limited spatial extent (~ 100m). One of remarkable features of the imaging spectrometer suite is its high spectral resolution which can improve an error in determination of absorption depth caused by overlapping among lines as well as by spectral un-flatness of background radiance. We discuss various methodologies like Continuum Interpolated Band Ratio (CIBR), reference spectral fitting and matched filter for methane detection. We also discuss instrumental characterization and its correction like thermal variation, optical aberration and frequency response of analogue circuit chain.

A Multi-wavelength Integrated Path Differential Absorption Lidar to Measure XCO_2 from Space: Status

James B. Abshire, Xiaoli Sun, Jianping Mao, Mark Stephen, Haris Riris and Stephan R Kawa

NASA Goddard Space Flight Center, Greenbelt, MD, United States
Contact: james.b.abshire@nasa.gov

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Abstract:

A multi-wavelength integrated path differential (IPDA) CO_2 lidar has been developed for measuring atmosphere column CO_2 concentration from space. The laser transmitter steps a single frequency laser across the CO_2 absorption line at 1572.33 nm measure the transmission line shape in the nadir path from space to ground.

The laser uses a tunable master-oscillator power-amplifier approach. A tunable diode laser is used as the transmitter source, whose wavelength is repetitively stepped across the CO_2 absorption line in 16 wavelengths a pulse rate of 7.5 kHz. A series of fiber laser amplifier stages are used to increase the laser diode's pulse energy to ~ 2.4 mJ for transmission. An engineering model of the space laser has been built, is in final testing now, and nearly at TRL 6. The receiver uses 80 to 100 cm diameter telescope and an HgCdTe avalanche photodiode detector. The receiver measures the laser pulse energy reflected from the surface and time of flight at each wavelength. The pulsed signal allows isolating the surface reflected signal from those from clouds or aerosols that occur earlier. The retrieval algorithm uses the lidar-measured line shape and fits a CO_2 line shape function that is based on a layered atmospheric model. A least squares retrieval algorithm is used to simultaneously solve for XCO_2, Doppler shif, and water vapor abundance.

A lower power airborne version of this lidar has been used to validate the measurement and to demonstrate the measurement approach and technology. The airborne instrument has been used successfully in the NASA ASCENDS airborne campaigns during 2014, 2016 and 2017. The 2016 and 2017 results have shown <1 part per million (ppm) measurement precision and accuracy when using 1-second averaging.

A lidar measurement model has also been developed. It includes effects of solar background, photon detection shot noise, detector dark current, preamplifier noise, laser speckle noise, and the inherent errors from least squares fit in the retrieval. The airborne model's parameters are based on laboratory measurements and the airborne lidar parameters. The model's calculated measurement performance agrees with the airborne measurement data. The space version of the lidar has been designed to work at the assumed 400 km altitude by increasing the laser energy, the laser spot diameter and the receiver telescope diameter. Using the same lidar measurement model, the results show that for vegetation and desert surfaces the space-based lidar should achieve <1 ppm measurement error using 1-sec averaging. The paper will give an overview of the design, and simulations using the measurement model.

NASA's Carbon Cycle OSSE Initiative - Informing future space-based observing strategies through advanced modeling and data assimilation

Lesley Ott*[1], Sean Crowell[2], Dave Schimel[3], Chris O'Dell[4], David Baker[4], Andrew Schuh[4], Stephan R. Kawa[1], Abhishek Chatterjee[1,5], Kevin Bowman[3], Berrien Moore III[2], and Piers Sellers[1]

1. NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.
2. University of Oklahoma, Norman, Oklahoma, U.S.A.
3. Jet Propulsion Laboratory, Pasadena, California, U.S.A.
4. Colorado State University, Fort Collins, Colorado, U.S.A.
5. Universities Space Research Association, Columbia, Maryland, U.S.A.

Satellite observations of CO_2 and CH_4 are a critical constraint on the contemporary carbon budget, providing insights into carbon-climate coupling, and demonstrating the ability to observe human emissions under certain conditions. Despite these advances, substantial gaps in coverage exist that limit our ability to estimate fluxes at regional and global scales. Next generation satellites will improve coverage, either through active remote sensing, a geostationary vantage point, or a combination of increased swath width and revisit frequency. Observing system simulation experiments (OSSEs) can quantify the relative strengths and weaknesses of the current observing system, identify key gaps, and evaluate the impact that future satellites may have. As such, OSSEs are essential tools to guide implementation of future carbon-observing missions.

To address these needs, a significant subset of the US carbon modeling community has come together with support from NASA to conduct a series of OSSEs, with close collaboration in framing experiments and analyzing results. This effort has produced realistic, model-based synthetic CO_2 and CH_4 datasets for use in inversion and signal detection experiments by the international community. NASA's Goddard Earth Observing System Model (GEOS) has been used to create a library of simulations representing the current state of atmospheric carbon and dozens of expected flux change scenarios. Last year, we presented an introduction to this effort including the OSSE framework and synthetic datasets. Here, we present an overview of lessons learned. This will include preliminary results of coordinated inversion experiments that assess the ability of different systems to observe subtle changes in the strength of the land carbon sink at continental scales. We also discuss the need for new metrics to assess performance that are model independent, presenting suggestions that could be incorporated in future mission planning. Finally, we summarize the challenges facing current OSSEs and highlight advances that are needed.

Key words: OSSE, flux inversion, OCO-2, GeoCarb, ASCENDS, future missions