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Abstract Booklet

Session 1: On-going and near-term satellite missions and calibration

1.1 Precision, Accuracy, Resolution, and Coverage: A few insights from GOSAT and OCO-2

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Early flux inversion studies indicated that space based remote sensing observations of XCO_2 with accuracies of 0.25% (1 ppm) on regional scales at monthly intervals could substantially improve our understanding of CO_2 sources and sinks (Rayner and O'Brien, 2001). Recent products from the OCO-2 mission are now meeting or exceeding this target (Eldering et al., 2017). In spite of this progress, and that anticipated from the growing fleet of greenhouse gas missions, substantial improvements in measurement accuracy, precision, resolution and coverage will be needed to deliver timely information about anthropogenic emission inventories on the scale of individual nations or to track subtle trends in the natural carbon cycle resulting from climate change. Spatially- and temporally-correlated XCO_2 biases must be reduced to vanishingly-small values (<< 1 ppm) to enable accurate local to regional scale CO_2 flux inversions that account for weak, but spatially-extensive natural sources and sinks as well as emission hot spots. Greater single-sounding precision is needed to quantify trends in emissions from localized sources such as mega cities and power plants. Higher spatial and temporal resolution is needed to locate discrete sources and sinks and to track their variations over diurnal to seasonal time scales. Improved coverage is needed, especially at high northern latitudes of the winter hemisphere and in tropical regions covered by persistent, optically-thick clouds. Some of these needs will require improved space based instruments, calibration techniques, XCO_2 retrieval algorithms, validation capabilities and flux inversion strategies. Others can be addressed by carefully coordinating the available space-based, aircraft, and ground-based sensors to produce a more effective greenhouse gas monitoring system. This presentation will summarize the progress and plans in both of these areas.

Rayner, P. J. and O'Brien, D. M.: The utility of remotely sensed CO_2 concentration data in surface source inversions, Geophys. Res. Lett., 28, 175-178, 2001.

Eldering, A., et al.: The Orbiting Carbon Observatory-2: first 18 months of science data products, Atmos. Meas. Tech., 10, 549 - 563, https://doi.org/10.5194/amt-10-549-2017, 2017.

1.2 Recent progress of GOSAT project and preparation for GOSAT-2 at National Institute for Environmental Studies (NIES)

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GOSAT (Greenhouse Gases Observing Satellite) and GOSAT-2 are Japanese Earth observation satellites for greenhouse gas observation from space and jointly promoted by Ministry of the

Environment, JAXA (Japan Aerospace Exploration Agency), and NIES (National Institute for Environmental Studies). GOSAT was launched in January 2009 and has been operating for more than nine years. GOSAT-2 will be launched in FY2018. NIES is responsible for generation, archiving, validation, and distribution of higher level standard and research products of GOSAT and GOSAT-2.

GOSAT's standard products such as FTS SWIR level 2 CO_2 / CH_4 / H_2O column amount products (V02.72, April 2009 - present), FTS TIR level 2 CO_2 / CH_4 profile products (V01.20, April 2009 - May 2014), and level 4A CO_2 / CH_4 flux products (CO_2: V02.05, June 2009 - October 2015, CH_4: V01.03, June 2009 - September 2013) are freely available from GDAS (GOSAT Data Archive Service). A new version of level 4A CH4 product (V01.04, June 2009 - September 2015) will be available soon.

GOSAT-2's standard and research products similar to those of GOSAT will be generated by G2DPS (GOSAT-2 Data Processing System) which is currently being developed and available from a dedicate website, GOSAT-2 Product Archive. For validation of GOSAT-2 products, several new ground-based measurement stations, such as a TCCON (Total Carbon Column Observing Network) station in Philippines, a SIF (Solar Induced Fluorescence) station in Shiga, Japan, and an urban air in-situ measurement and sampling station implemented in Tokyo Skytree, are established.

GOSAT RAs (Research Announcements) were issued eleven times in 2008 - 2017 to promote scientific researches using GOSAT data. GOSAT RA PIs (Principal Investigators) have several privileges such as access to GOSAT standard products earlier than general users, access to research products and other technical information, and a right to submit FTS observation requests. In total, more than 120 joint research contracts with scientists from more than twenty countries were concluded under GOSAT RA framework. GOSAT-2 RA is now being prepared and will be issued before GOSAT-2 launch.

1.3 TanSat Scientific Achievements and Future Plan

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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 one year. Validation against TCCON measurements and inter-comparison with OCO-2 measurements from near overlap footprints show the preliminary status and data quality of TanSat. On-orbit slit function and wavelength registration calibrations are evaluated using solar calibration data. The operational full-physical retrieval algorithm (IAPCAS) for TanSat has been developed and applied to process GOSAT and OCO-2 level 1b data. Further validation campions with EM-27 and AirCore system have been scheduled in 2018 and next few years in Inner Mongolia, Tibet plateau and megacity region aim to improve TanSat measurement. In this presentation, we are going to show the status and performance of TanSat CO_2 measurement in 2017, as well as the TanSat retrieval, validation, scientific application and international cooperation plans.

1.4 Status of the Sentinel-5 Precursor Mission and First Results on Methane

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Sentinel-5 Precursor (S-5P) is the first of a series of atmospheric chemistry missions to be launched within the European Commission's Copernicus (former GMES) Programme. Launched during Oct. 13 S-5P will provide continuity in the availability of global atmospheric data products between its predecessor missions SCIAMACHY (Envisat) and OMI (AURA) and the future Sentinel-4 and -5 series. S-5P will deliver unique data regarding the sources and sinks of trace gases with a focus on the lower Troposphere including the planet boundary layer due to its enhanced spatial, temporal and spectral sampling capabilities as compared to its predecessors. The S-5P satellite carries a single payload, namely TROPOMI (TROPOspheric Monitoring Instrument) which is jointly developed by The Netherlands and ESA. Covering spectral channels in the UV, visible, near- and short-wave infrared, it measures various key species including tropospheric/stratospheric ozone, NO_2, SO_2, CO, CH_4, CH_2O as well as cloud and aerosol parameters. The paper includes descriptions of the S-5P spacecraft, the TROPOMI instrument, data products, Ground Segment, in-orbit commissioning, planned data releases to the public, and first results on S5P Methane retrieval.

1.5 Measurements of Carbon Monoxide from Space using the MOPITT Instrument

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Carbon monoxide (CO) is not a greenhouse gas in the conventional sense. However, much of its passage on the planet is associated with burning of carbon fuels, measurements of CO can shed significant light on the carbon cycle. Fortunately, CO can be measured from space and that has been the task of the Measurements Of Pollution In the Troposphere (MOPITT) instrument for the last 18 years.

MOPITT is a Canadian instrument and was launched on NASA's Terra platform on 18th December 1999 and has operated fairly continuously since them providing a long-term record over the planet. This has enabled us to map sources and sinks of CO as well as transport and also allowed us to look at temporal variations on a decadal timescale with a single instrument.

In conjunction with models, MOPITT data have been able to shed light on source emissions and to tie these to greenhouse gas emissions.

After correction for instrument drift and similar factors a global trend of decreasing CO has been observed, but other phenomena have also been observed, both regular and sporadic. These are caused by a mix of changes in sources, transport and sinks, particularly with the increasing trend for the concentration of people in (mega)cities. This paper will consider some of these phenomena by way of case studies and statistics.

MOPITT was built in Canada by COMDEV of Cambridge, ON, data processing is performed at the National Center for Atmospheric Research (NCAR) in Boulder, CO. The Terra satellite is operated by NASA and the MOPITT instrument and operations are funded by the Canadian Space Agency.

1.6 Atmospheric Chemistry Experiment (ACE) Greenhouse Gas Measurements: CO2, CH4 and HFCs

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ACE (also known as SCISAT) is making a comprehensive set of simultaneous measurements of numerous trace gases, thin clouds, aerosols and temperatures by solar occultation from a satellite in low earth orbit. A high inclination orbit at 74 degrees gives ACE coverage of tropical, mid-latitude and polar regions. The primary instrument is a high-resolution (0.02 cm^{-1}) infrared Fourier Transform Spectrometer (FTS) operating in the 750-4400 cm-1 region, which provides the vertical distribution of trace gases, and the meteorological variables of temperature and pressure. After almost 15 years in orbit, the ACE-FTS is still operating exceptionally well. ACE measurements of CO_2 and CH_4 will be presented, as well as new HFC-134a and HFC-23 research products. These long-lived HFCs have large global warming potentials and their atmospheric concentrations are increasing rapidly. The Kigali Amendment to the Montreal Protocol will control HFC emissions starting in 2019.

1.7 GOSAT Calibration Updates and Operations toward an Optimized Observation Pattern

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Since 2009, the Thermal And Near infrared Sensor for carbon Observation Fourier-Transform Spectrometer (TANSO-FTS) onboard the Greenhouse Gases Observing SATellite (GOSAT) has been providing radiometrically and geometrically calibrated data. The recently released Level 1 V210 algorithm has been used to update the nonlinearity correction of the thermal-infrared band and quality flags. The new dataset exhibits seamless radiometric calibration before and after cryo-cooler anomalies in May 2014 and August 2015. In addition to the global grid observations, the number of target observations using an agile pointing system has been increased and the latitudinal range of the glint observation has been expanded. We have developed two tools from http://www.eorc.jaxa.jp/GOSAT/: the GOSAT trend viewer and the score map. The former provides long-term trend data of the selected targets, including the large point sources of methane (CH_4) and intensive observations of selected mega cites. The latter shows the maps of possible emission sources, vegetation, GOSAT observation results, and successful retrieval ratio together with GOSAT, GOSAT-2, and OCO-2 orbits. These global maps will help optimizing sampling patterns for better understanding the global and regional fluxes of carbon dioxide (CO_2) and/or CH_4 and identifying type of emission sources. They also show match-up locations of different greenhouse gases measurement satellites. We will present the recent topics in GOSAT operation, TANSO-FTS Level 1 V210 products, and analytical tools.

1.8 Characterization of OCO-2 biases and errors for flux estimates

Susan S. Kulawik*, Kathryn McKain, Colm Sweeney, Christopher W. O'Dell, Gregory B Osterman, Paul Wennberg, Debra Wunch, Coleen Roehl, Nicholas Deutscher, MatthÕ_us Kiel, David Griffith, Voltaire Velazco, Justus Notholt, Thorsten Warneke, Christof Petri, Martine De Maziere, Mahesh Kumar Sha, Ralf Sussmann, Markus Rettinger, Dave Pollard, Isamu Morino, Osamu Uchino, Frank Hase, Dietrich Feist, Kimberly Strong, Rigel Kivi, Laura Iraci, Kawakami Shuji, Manvendra Dubey, Eliezer Sepulveda, Omaira Elena Garcia Rodriguez, Yao Te, Pascal Jeseck, Matt Kiel, Pauli Heikkinen, Matthias Schneider

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Characterization of satellite CO_2 estimates is a prerequisite for using CO_2 measurements for flux inversion and establishing a long-term atmospheric CO_2 data record. We validate recent satellite observation of OCO-2 v8 using similar analysis as previous work through comparisons to the Atmospheric Tomogrophy (ATom) and the Total Carbon Column Observing Network (TCCON) to estimate regional biases and errors affecting carbon cycle science. CarbonTracker 2017 and NRT are also compared to the validation data to evaluate the mismatch between the validation and satellite observations. We also look at the correlation length of biases which can be used to estimate impact of biases on flux estimates.

1.9 The OCO-3 Mission: Science Objectives and Instrument Performance

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The Orbiting Carbon Observatory 3 (OCO-3) will continue global CO2 and solar-induced chlorophyll fluorescence (SIF) using the flight spare instrument from OCO-2. The instrument is currently being tested, and will be packaged for installation on the International Space Station (ISS). Thermal vacuum testing was completed in early 2018, and the current launch schedule is February 2019. This talk will focus on the science objectives, updated simulations of the science data products, and the outcome of recent instrument performance tests.

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 (+/- 52°). 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.

The PMA also allows for a snapshot mapping mode to collect dense datasets over 100 km by 100 km areas. 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. We will share updated simulations of the snapshot area maps, including details maps and frequency of measurements over the year.

The payload integration and testing was performed over 2018 and early 2019. Key characteristics, such as instrument ILS, spectral resolution, and radiometric performance will be described. Analysis of direct sun measurements taken during testing will also be discussed.

1.10 Upper tropospheric and stratospheric trends of greenhouse gases as derived from MIPAS observations

Gabriele P. Stiller*, Thomas von Clarmann, Maksym Chirkov, Ellen Eckert, Norbert Glatthor, Udo Grabowski, Florian Haenel, Sylvia Kellmann, Michael Kiefer, Alexandra Laeng, Andrea Linden, Stefan Lossow, Johannes Plieninger

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MIPAS on Envisat measured a large number of greenhouse gases (GHGs) in the upper troposphere and stratosphere during it mission lifetime from July 2002 to April 2012. Among these greenhouse gases measured are H_2O, O_3, N_2O, CH_4, CFC-11, CFC-12, HCFC-22, CCl_4, and SF_6. We have analysed the trends and shorter-scale variability of the GHGs as a function of altitude and latitude and have related their variations to the seasonal cycle, QBO impact and, in some cases, to solar variability and ENSO. We have also derived the linear trends over the 10-years mission lifetime. All GHGs show a similar trend pattern with a dipole structure in the two hemispheres. We trace this pattern back to a shift of the stratospheric mean circulation to the South that is demonstrated by the shift of the latitudinal positions of the subtropical mixing barriers. With this we demonstrate that a hitherto not recognised variability mode of the Brewer-Dobson circulation is important for the full understanding of the trends of greenhouse gases.

A1.1 Four years of IASI CO_2, CH_4, N_2O retrievals: validation with in situ observations from the Mauna Loa station

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IASI (Infrared Atmospheric Sounder Interferometer) soundings for the years 2014 to 2017 over sea surface for the Hawaii region have been used to retrieve column amount of CO_2, CH_4, N_2O. The analysis allowed us to derive CO_2 and CH_4 and N_2O growth rates, trend and seasonality, which have been compared to in situ observations from the Mauna Loa validation station. Day and night soundings have been used. During the day, for CO_2 and N_2O we make specifically use of the IASI SW band (2000 to 2250 cm^{-1}) which is sensitive to sun radiation. Our forward/inverse module deals with sun radiation

using a Cox-Munck model for the bidirectional reflectance distribution function. This makes it possible to exploit IASI soundings in sun-glint or close to sun-glint mode, which improves sensitivity of retrievals close to the surface. The analysis has been performed with our total IASI level 2 processor (tau2IP, e.g., doi:10.1364/AO.55.006576, doi:10.1016/j.jqsrt.2016.05.022, doi:10.1016/j.jqsrt.2017.07.006), which uses the whole IASI spectral coverage, therefore making it possible to exploit the whole information of data. tau2IP also uses a random projection approach to reduce the dimensionality of the data space. Random projections provide a) an unified and coherent treatment of systematic and random errors; b) a compression tool, which can reduce the dimensionality of the data space; c) a noise model which is truly Gaussian therefore, making it possible to apply rigorously Optimal Estimation and derive the correct retrieval error; d) a simplified treatment of the inverse algebra to get the final solution. Our analysis show that, although growth rates, trends and seasonality are extracted with high accuracy (for CO_2 and CH_4 we observe correlation with in situ data close to 0.90 and for N_2O close to 0.7), the column amount show a bias which is negative for CO_2 (about 3.5%) and N_2O (about 1.5%) and positive for CH_4 (about 1%). The nature and sign of this bias is also discussed in the light of the new HITRAN2016 release.

A1.2 Sentinel-5 Precursor: Early In-Flight Operation

Herbert Nett*, Herbert Nett, Sten Ekholm, Kevin McMullan, Pepijn Veefkind, Quintus Kleipool, Antje Ludewig

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The Sentinel-5 Precursor (S-5P) satellite was launched on 13 October ‘17. Carrying as single payload the TROPOspheric Monitoring Instrument (TROPOMI) S-5P is first in a series atmospheric missions in the European Commission’s Copernicus Programme.

The spacecraft was injected into its near-polar, sun-synchronous orbit by a Rockot launcher from Plesetsk (Russia). Following a flawless functional check-out of the satellite’s main components, and a 25 days initial outgassing period, the instrument’s radiant cooler was activated and TROPOMI started delivering Earth radiance, solar irradiance spectra as well as different types of Phase E1 specific calibration measurements. All observational data were immediately downlinked using two high latitude ground stations, Svalbard (N) and Inuvik (Ca), and transferred to the so-called Payload Data Ground Segment (PDGS), located at DLR-Munich (D). Depending on measurement type the acquired data were used to verify the instrument’s performance, to update calibration key data or in the functional testing of the Level 1B / 2 algorithms.

Various minor - though important - corrections to algorithms and configuration settings were identified shortly after instrument switch on, leading to the installation of enhanced processor versions in the PDGS mid December ‘17. The modified processors were used to generate a first set of sample products (Level 1B & 2) for use by expert teams worldwide taking part in the S-5P CalVal Announcement of Opportunity project.

During the first part of the 6 months commissioning phase excellent performance of the S-5P mission was demonstrated and key parameters regarding the payload’s radiometric sensitivity, spatial resolution and sampling capabilities could be fully verified. The Phase E1 specific measurement tasks will be completed in April '18 leading to the release of a second, overall update of L1B/2 processing chains and related calibration key data. The routine operations phase (Phase E2), with a nominal duration of 6.5 years, will commence immediately after the spacecraft In-Orbit Commissioning Review scheduled end April '18.

This presentation will summarize S-5P commissioning tasks and report on results of early in-flight calibration activities. An outlook will be given on the transition to the routine operations phase.

A1.3 Retrieved L2 products from the new version V205 of L1B spectra in the thermal infrared band of TANSO-FTS over the Arctic Ocean and comparison with retrievals from previous versions

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Among the instruments performing remote sensing from space, measurements using Fourier transform spectrometers operating in the thermal infrared (TIR) spectral domain are not hampered by the requirement of not too large solar zenith angles as in SWIR measurements. In this study we concentrate on the calibration/validation of the Thermal and Near Infrared Sensor for Carbon Observation (TANSO)–Fourier Transform Spectrometer (FTS) spectra in the TIR spectral region (B4 band) over the Arctic Ocean. We have previously performed inter-comparisons of the retrieved L2 products from four successive versions of L1B products (V150, V160, V201, V203) to check the differences and the improvement in the spectral and radiometric calibration of TANSO-FTS spectra in the narrow spectral domain of 940–980 cm^{-1} covering CO_2 lines of the so-called laser band in the rather clear 10.4 µm atmospheric window, allowing sounding down to the lowest atmospheric layers. To our knowledge, this was the first attempt to retrieve XCO_2 from this spectral region. A new L1B version (V205) is now available and we will present new retrievals using this data. The period covered is the summer months (July, August, September) and the years from 2009 to 2015. Internal comparisons of L1B TANSO-FTS spectra, as well as comparisons of our previously retrieved L2 products, i.e., T_{surf} (sea surface temperature or SST) and the retrieved column-averaged dry air volume mixing ratio XCO_2 derived with the same algorithm will be presented, as well as the overall trend in the XCO_2.

1.4 Characterization of the TanSat slit function using solar measurements

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TanSat, launched into orbit on 22 December, 2016, has collected a large number of measurements in the solar-mode. In order to improve the CO_2 retrieval accuracy, the slit function (i.e. Instrument Line Shape) must be determined accurately. The on-orbit behavior of slit function need to be characterize across the spectral pixels and the 9 ground pixels in the three spectrometers. On-orbit slit function and wavelength registration calibrations are performed by fitting the measured irradiance with a well-calibrated, high-resolution reference solar spectrum using a nonlinear least square fitting technique. Following the method proposed by Sun et al., 2017, several analytical functions such as Gaussian, hybrid Gaussian, Super Gaussian, and asymmetric Gaussian are used to parameterize the slit function, as well as fitting a homogeneous stretch of the preflight slit function.

A1.5 In-Flight Performance of TanSat Atmospheric Carbon Dioxide Grating Spectrometer

Zhong-Dong Yang[1], Yan-Meng Bi[1], Qian Wang[1], Cheng-Bao Liu[1], Lei Yang[1], Na Xu[1], Song-Yan Gu[1], Yu-Quan Zheng[2], Chao Lin[2], Zeng-Shan Yin[3], and Long-Fei Tian[3]

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The latest scientific assessment by the Intergovernmental Panel on Climate Change points out that climate warming is unequivocal. Many recent changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, snow and ice have diminished and sea level has risen. Changes such as these have resulted from positive radiative forcing caused by increased concentrations of atmospheric greenhouse gases. Carbon dioxide (CO_2) make the largest contributions to radiative forcing. TanSat is the first Chinese satellite mission designed dedicatedly to measure column-averaged carbon dioxide dry-air mole fraction, XCO_2, with the accuracy, resolution and coverage needed to study globe climate change and distinguish CO_2 sources and sinks on regional scales. Atmospheric Carbon dioxide Grating Spectrometer (ACGS) is a major spaceborne grating hyperspectral spectrometer suite on board the TanSat that was successfully launched into orbit from JiuQuan Base in Gansu Province of China on 22 December 2016 with an altitude of 700 km above the Earth surface, an inclination angle of 98.25° and a 13:45 local time ascending node. The ACGS is a three-band high spectral resolution spectroradiometer on the TanSat satellite, providing operational observations of top-of-atmosphere visible and near infrared radiance spectra for climate applications and into chemistry transport model for investigation of carbon source and sink in regional and global scale. It is a major step forward in the China scientific space based measuring capability of Atmospheric CO_2 previously provided by U.S. OCO-2 and Japanese GOSAT satellite. The ACGS high spectral resolution, large number of channels, high signal-to-noise ratio, high dynamic range combine to provide much improved resolution and accuracy in comparison to the GOSAT. The ACGS is the second grating spectrometer dedicated to measurement atmospheric CO_2 next to OCO-2. ACGS will continue the measurements provided by the OCO-2. It achieves a similar spectral resolution and spectral coverage on a similar afternoon orbit as the OCO-2. In this presentation, we present the ACGS in-flight performance during first year after TanSat has been launched, provides a more details on the ACGS design and on orbit calibration device, describes the in-flight spectroscopic, radiometric, and geolocation performance of the ACGS, describes a intercomparison results of product between ACGS and OCO-2 simultaneously observation.

A1.6 Using satellite observations to constrain the combined impacts of ecosystem memory and climate extremes on the tropical carbon balance

A. Anthony Bloom*, A. Anthony Bloom, Junjie Liu, Kevin Bowman, Alexandra G. Konings, Sassan Saatchi, John Worden, Helen Worden, Zhe Jiang, Nicholas Parazoo, Mathew Williams, David Schimel

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The trajectory of the tropical carbon balance is in part regulated by the size and frequency of extreme weather events. Specifically, understanding the cumulative impact of ENSO events remains challenging, largely due to uncertainties in the integrated response of carbon cycle processes to climate variability. Ultimately, an integrated understanding of both climate forcings and legacy effects ("ecosystem memory") on the terrestrial carbon balance is needed to understand the net impact of ENSO events on the tropical C balance. Here we use the CARbon DAta-MOdel fraMework (CARDAMOM) diagnostic model-data fusion approach - constrained by an array of C cycle satellite surface observations, including MODIS leaf area, biomass, OCO-2 and GOSAT solar-induced fluorescence, as well as "top-down" atmospheric inversion estimates of CO_2 and CO surface fluxes from the NASA Carbon Monitoring System Flux (CMS-Flux) - to constrain and predict spatially-explicit tropical carbon state variables during 2010-2016. The combined assimilation of land surface and atmospheric datasets places key constraints on the temperature sensitivity and first order carbon-water feedbacks throughout the tropics and combustion factors within biomass burning regions. We show that across all tropical biomes, memory effects account for roughly 50% of interannual flux variations; furthermore, we show that a quantitative disentanglement of direct forcing and memory effects is key for understanding the impact of individual ENSO events on the tropical C balance, and provides a critical constraint on the cumulative impact of ENSO events in future projections of the tropical C balance.

B1.1 The PFT results of the mission instruments of GOSAT-2

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The GOSAT-2 is the successor satellite to the GOSAT which is the first satellite dedicated to the measurements of the greenhouse gases such as carbon dioxide and methane. GOSAT was launched in January of 2009 and has been operated for about nine years.

The development of the GOSAT-2 started in April of 2014, and in early 2018, the manufacturing and the proto-flight test (PFT) of the mission instruments, TANSO-FTS-2 and TANSO-CAI-2, were completed. TANSO-FTS-2 is the Fourier Transform Spectrometer observing greenhouse gases and TANSO-CAI-2 is the imager observing the aerosols and clouds to compensate the TANSO-FTS-2 data and to grasp the movements of the aerosols such as PM2.5.

The results of the PFT had shown the excellent performances, and these results will promise that the observation from space will become more useful means than GOSAT. The large part of the

specifications of the TANSO-FTS-2 have exceeded the requirement, especially the signal to noise ration of the thermal infrared region bands have large margin to the requirement.

On the other hand, the development of the TANSO-CAI-2 had faced a lot of anomalies such as the polarization sensitivities, stray light and so on.

Unfortunately, it was difficult to get settled the stray light issue with the modification of the hardware, so we decided to resolve this issue by the processing the data on the ground.

In this presentation, the results of the PFT of the TANSO-FTS-2 and the TANSO-CAI-2, and the how to resolve the stray light issue.

B1.3 Methane Sensing by a Small Fabry-Perot Interferometer on the Space Station

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Our team composed mostly of personnel from NASA Goddard Space Flight Center have been operating a small Fabry-Perot based spectrometer on the Air Force STP-H5 platform attached to the International Space Station for a little more than a year. The instrument was damaged in preflight testing which caused its spectral range to move slightly away from the strong methane absorption line which was its target. This shift has complicated attempts to calibrate the instrument and retrieve methane columns. Nevertheless the instrument is generating spectra which show an atmospheric absorption that is almost certainly due to methane. We will present a brief outline of the instrument design and show partly analyzed data from selected orbits. The small size and low cost of this type of instrument recommends its use in future monitoring of methane and other atmospheric gases.

B1.4 GHGSat: Towards an Operational Constellation

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GHGSat's primary activity is measuring greenhouse gas emissions from individual industrial sites using small satellites in low earth orbit. Our demonstration satellite (GHGSat-D) has been active since June 2016, and the first satellite (GHGSat-C1) of our planned operational constellation will launch in early 2019.

In order to inform ongoing retrievals development and the GHGSat-C1 design phase, a series of detailed end-to-end simulations has been performed using an image simulation tool and the existing retrievals chain. This allowed us to quantify errors originating from various imperfections in GHGSat-D and tabulate an associated error budget. These simulations used models based on detailed analysis of ground calibration data as well as on-orbit images. Correspondence between the simulation results and retrieval

outputs from GHGSat-D allowed us to build confidence in the simulations and prioritize areas of improvement for GHGSat-C1. The same end-to-end simulation tools were then used to optimize the GHGSat-C1 design and ultimately produce performance projections. GHGSat-C1, currently being manufactured, will have GSD below 50 metres and quantify methane column density with an anticipated precision of ~2% of background for a nominal observation case. Design changes were selected to maximize performance improvements while avoiding major engineering changes with respect to GHGSat-D.

As a complement to the above, we have also developed a ground-based controlled release facility to conduct field trials with an engineering model of GHGSat-D. We are detecting methane plumes with this system using just a single adapter lens and minor parameter adjustments to the retrievals tools. This setup is being used for many purposes, including testing retrievals features, optimizing the instrument model and understanding and minimizing systematic retrievals artefacts. Furthermore, this setup can be used for additional validation of the end-to-end simulation tools and to test predictions of error levels and detection thresholds.

We will also discuss progress on GHGSat-D retrievals and plans for an aircraft variant instrument to be deployed commercially as a complement to the satellite system, and also used to support calibration and validation activities.

C1.1 MERLIN Level 0-1 Processing and Calibration Concept

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After water vapour and carbon dioxide, methane CH_4 is the most abundant greenhouse gas in the Earth's atmosphere. The new generation space borne Lidar mission MERLIN (Methane Remote Sensing Lidar Mission) will make very sensitive measurements of the CH_4 distribution with unprecedented quality, with an accuracy <2%. After its launch, MERLIN will track down sources and sinks of methane on a global scale. MERLIN is an active space-borne instrument using a IPDA (Integrated Path Differential Absorption) LIDAR that will measure the atmospheric column content of methane. The difference in atmospheric transmission between a laser emission with a wavelength placed around the center of a CH_4 absorption line (λ_on ≈ 1.6 μm) and a reference wavelength, λ_off, slightly shifted from λ on by a few tenths of a nm.

The Level 0-1 processing converts the raw signal coming from the satellite (essentially electronic counts as a function of time) to the differential absorption optical depth (DAOD). The main steps in the Level 0-1 processing are
- the removal of instrument effects and the calculation of the noise
- the calculation of the backscatter signal

- the calculation of the range
- the calculation of the DAOD.

Additionally, quality parameters for the measurements and cloud flags will be retrieved. Technically, the processor is based on the framework provided by GCAPS (Generic Calibration and Processing system), which is developed at DLR-IMF. We will give an overview of the processing steps, the mission requirements and the first design of the processor.

Session 2: Retrievals algorithms and uncertainty quantification

2.1 First Copernicus Climate Change Service (C3S) satellite-derived greenhouse gas (CO_2, CH_4) data set

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During recent years, satellite-derived Essential Climate Variable (ECV) Greenhouse Gas (GHG) data sets have been generated from SCIAMACHY/ENVISAT and TANSO-FTS/GOSAT within the framework of the GHG-CCI project of ESA's Climate Change Initiative (CCI). Additional climate variable GHG data sets have been generated from AIRS/Aqua and IASI/Metop. In parallel, data products from GOSAT and IASI have been and still are generated and delivered to ECMWF in quasi near-real-time for the Copernicus Atmosphere Monitoring Service (CAMS), e.g., XCO_2 by University of Bremen. The GHG-CCI activity is now continued operationally within the framework of the Copernicus Climate Change Service (C3S). The first C3S data set will be released in 2018 via the Copernicus Climate Data Store (CDS). An overview about this data set will be presented focusing on the underlying algorithms, the generated data products, their uncertainty quantification and initial use of these data products for scientific applications.

2.2 Carbon dioxide retrieval from OCO-2 satellite observations using the RemoTeC algorithm: application to single-view and multiple-angle modes

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In this study, we present the retrieval of the column averaged dry air mole fraction of carbon dioxide XCO_2 from the Orbiting Carbon Observatory-2 (OCO-2) satellite observations using the RemoTeC algorithm, previously successfully applied to retrieval of CH_4 and CO_2 concentrations from the Greenhouse Gases Observing Satellite (GOSAT). The XCO_2 product obtained from single-view observations has been validated with collocated ground based measurements from the Total Carbon Column Observing Network (TCCON) for almost 2 years of OCO-2 data from September 2014 to July 2016. We found that fitting an additive radiometric offset in all three spectral bands of OCO-2 significantly improved the retrieval. Based on a small correlation of the XCO_2 error over land with fit residuals, we applied an a posteriori bias correction to our OCO-2 retrievals. In daily averaged results,

XCO2 retrievals have a standard deviation ~1.30 ppm and a station-to-station variability of ~0.40 ppm among collocated TCCON sites. The seasonal relative accuracy (SRA) has a value of 0.52 ppm. The validation shows relatively larger difference with TCCON over high latitude areas and some specific regions like Japan.

Furthermore, we extended the RemoTeC algorithm to have the capability to take full advantage of the OCO-2 specific target observation mode, which contains soundings of certain ground sites observed from different viewing geometries. By using observations obtained under multiple angles simultaneously will allow for more accurate characterization of the most important error source, namely atmospheric scattering. We present a first investigation of this new feature with an ensemble of simulated multiple-angle observations for aerosol loaded scenes over land surfaces.

2.3 Plume detection and characterization from XCO2 imagery: methodology and expected uncertainties on derived point source fluxes

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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. Six typical European sites covering power plants in France, Belgium, Germany, Great-Britain and the Netherlands as well as one megacity (Paris) have been selected as targets for the inversion of emissions from point sources 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 such an emission estimate. The simulated plumes have a realistic character and have been fitted (using an optimal estimation method) with a Gaussian model (with various levels of a priori constraints). 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) will be discussed. A test on a few XCO_2 images from OCO-2 as well as retrievals from MicroCarb and GeoCarb simulated images (with the presently known characteristics of these satellite sounders) will be presented. The question of quantifying the expected precision on the source emissions will be discussed.

2.4 Correction of topography related biases in XCO2 measurements from OCO-2

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NASA's Orbiting Carbon Observatory 2 (OCO-2) has been successfully measuring column-averaged dry-air mole fractions of carbon dioxide (XCO_2) in the Earth's atmosphere for more than three years.

There are three key types of biases addressed by the OCO-2 Version 8 bias correction procedure: footprint-dependent biases; spurious correlations of the retrieved XCO_2 with other retrieval parameters; and a multiplicative factor to scale to the World Meteorological Organization (WMO). Moreover, the surface altitude is spatially correlated with changes in XCO_2. This topography related bias is caused by two factors: 1) an slight offset in the pointing of the instrument boresight and 2) a relative pointing mismatch between the O_2 A-Band and the weak and strong CO_2 bands. In this study we show that OCO-2 target mode data is well suited to determine the pointing offset and band mismatch. We present a method to correct for topography related biases in XCO_2 without re-running the L1B and L2 retrieval algorithm.

2.5 Vertical distribution of Arctic methane from ground-based FTS measurements

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In this work, we studied retrievals of vertical distribution of atmospheric methane (CH_4) using Fourier Transform Spectrometer (FTS) data measured in Sodankylä Northern Finland. Sodankylä often lies beneath the middle or on the edge of the stratospheric polar vortex resulting considerable variability in the vertical profile of methane. The CH_4 profiles were retrieved from the ground-based direct Sun FTS measurements using a method that utilizes a novel dimension reduction approach and Bayesian inference. The instrument belongs to Total Carbon Column Observing Network (TCCON), source for accurate and precise column-averaged abundance of several trace gases and the data are used for climatological studies and act as important reference for satellites such as OCO-2, GOSAT and S5P TROPOMI. The new profile data set covers years from 2009 to the present day (from February to November) and altitudes 0-40 km. The retrieved FTS profiles were validated against the ACE satellite measurements and AirCore balloon measurements. The total columns derived from the profiles were compared to the official TCCON XCH_4 data. Finally, we analyzed the altitude-dependent time series of CH_4 using a flexible method that allows smooth variations in the trend and seasonal cycle. These results provide valuable information on the CH_4 vertical distribution at a high-latitude site, and thus have a direct connection to further investigations of methane fluxes in the Arctic. The profile retrieval method developed in this work was proven particularly successful in the challenging conditions of a strong polar vortex and is directly applicable to other trace gases (e.g., CO_2) and, ultimately, to space-based retrievals.

2.6 IASI for Surveying Methane and Nitrous Oxide in the Troposphere: MUSICA products and its validation

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The large potential of the space-based instruments for observing global methane (CH_4) and nitrous oxide (N2O) distributions has extensively been reported in the literature. Among the current space-based remote sensing instruments, IASI (Infrared Atmospheric Sounding Interferometer) has special relevance, since it successfully combines the needed requirements for atmospheric trace gases retrievals (very good signal to noise ratio and a high spectral resolution), and a long-term data availability (between 2007-2022 on-board the EUMETSAT/Metop meteorological satellites). Within the European Research Council MUSICA project (MUlti-platform remote Sensing of Isotopologues for investigating the Cycle of Atmospheric water) an IASI processor has been developed for simultaneously retrieving tropospheric water vapour isotopologues and middle and upper tropospheric CH_4 and N_2O concentrations.

In this work the MUSICA IASI CH_4 and N_2O products are presented, characterised and comprehensively validated by using a multi-platform reference database. As validation references we consider: (1) aircraft CH_4 and N_2O profiles from the HIAPER Polo-to-Pole Observations (HIPPO) campaigns (missions 1-5), (2) continuous in-situ CH_4 and N_2O observations performed at the subtropical Izaña Atmospheric Observatory (Tenerife, Spain) in the framework of the WMO/GAW programme, and (3) continuous ground-based Fourier Transform Infrared (FTIR) measurements taken in the framework of the NDACC (Network for Detection of Atmospheric Composition Change) at the subtropical Izaña Atmospheric Observatory, mid-latitude Karlsruhe station and polar Kiruna site. This extensive validation exercise enables us to properly document the quality and long-term consistency of the MUSICA IASI CH_4 products as well as their geographical uniformity. Moreover, we will discuss the possibilities of using the co-retrieved N_2O estimates for reducing errors in the CH_4 product.

A2.1 The total IASI level 2 processor τ^2IP: Application to Seven-years of IASI sea surface temperature, CO_2, CH_4, N_2O retrievals for the Arctic Ocean during the summer season

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This paper will describe the level 2 processor we developed for IASI. The processor, we call τ^2IP (total level 2 processor for IASI, e.g., doi:10.1364/AO.55.006576, doi:10.1016/j.jqsrt.2016.05.022, doi:10.1016/j.jqsrt.2017.07.006), uses the whole IASI spectral coverage, therefore making it possible to exploit the whole information of data. τ^2IP also uses a random projection approach to reduce the dimensionality of the data space. Random projections provide a) an unified and coherent treatment of systematic and random errors; b) a compression tool, which can reduce the dimensionality of the data space; c) a noise model which is truly Gaussian therefore, making it possible to apply rigorously Optimal Estimation and derive the correct retrieval error; d) a simplified treatment of the inverse algebra to get the final solution.

IASI (Infrared Atmospheric Sounder Interferometer) observations for the years 2010 to 2016 over the Artic Sea during the summer season have been processed for the simultaneous retrieval of skin temperature, methane, nitrous oxide and carbon dioxide. The analysis allowed us to derive CO_2 and CH_4

growth rate for a region, where SWIR-based instrument operated in sun-glint mode cannot be operated. In fact, the satellite observations of greenhouse gases for the arctic region are rare. Comparison with in situ observations shows that IASI is capable to show the increase of greenhouse gases in the arctic atmosphere with a rate that in 2013 has reached the larger value on record of about 7 ppmv per year. The analysis has considered clear sky, sea water, IASI soundings for a latitude greater than 65°, which has allowed us to derive maps covering the whole Arctic sea.

Results have been rendered with maps of grid spacing of 1°×1°, which show a wealth of spatial structures. These findings are unexpected, mostly for CO_2, and could be used to tune and validate transport models.

A2.2 Reducing Biases in Greenhouse Retrievals by Quantifying Aerosol Scattering Effects: Case Study Using Measurements from the California Laboratory for Atmospheric Remote Sensing (CLARS)

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In addition to their impact on climate, air quality and human health, aerosols influence greenhouse gas retrievals from space by modifying the path of atmospheric radiation. For example, Orbiting Carbon Observatory-2 (OCO-2) retrievals of CO_2 abundances are showing biases up to 3 ppm at high southern latitudes over the ocean in the southern winter compared with measurements from the Total Carbon Column Observing Network. While spatially and temporally localized, this is significant considering that most sources and sinks of CO_2 produce 1 ppm or smaller changes in the background CO_2 distribution. A major portion of the residual error is attributed to the presence of aerosols in the atmospheric column. However, uncertainties about the origin and composition of aerosol particles, their size distribution, concentration, spatial and temporal variability make it challenging to mitigate these biases.

There are four ways to obtain aerosol information from passive remote sensing measurements — multi-angle, multi-wavelength, hyper-spectral and polarization measurements. Multi-angle measurements provide information on the aerosol single scattering albedo and phase function, while observations at multiple wavelengths provide extinction as a function of wavelength, and hence the loading and Angstrom exponent. Together, they provide information on the aerosol loading and composition. Polarization measurements provide aerosol particle size, optical depth, and some information on speciation. They can also distinguish between spherical and non-spherical particles. Further, they provide constraints to discriminate from the underlying surface. However, these measurements lack sensitivity to the vertical distribution of aerosols. On the other hand, hyper-spectral measurements in gaseous absorption bands (e.g. O_2 A-, B- and γ-bands and H_2O bands) can be used to characterize the vertical distribution of aerosol loading. This is because the large dynamic range of absorption in these bands allows different regions of the atmosphere to be probed at different absorption line strengths. Measurements in different bands also provide information on the wavelength dependence of aerosol extinction. Further, usage of O_2 absorption has the advantage that O_2 is well mixed with known concentration. H_2O, on the other hand, is variable, but has absorption features all across the electromagnetic spectrum.

We demonstrate this novel approach to describe the scattering effects of atmospheric aerosols using measurements from the California Laboratory for Atmospheric Remote Sensing Fourier Transform Spectrometer on top of Mt. Wilson, California, and a two-stream-exact single scattering radiative transfer (RT) model.

A2.3 Spectroscopy for the OCO-2 mission: Progress and plans for addressing remaining challenges

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The accuracy of remotely sensed quantities depends directly on the accuracy of the forward model used in the retrieval algorithm. Retrievals of well-mixed greenhouse gases place particularly stringent demands on the accuracy of the forward model, since the variations of these gases in the atmosphere are small compared to the background. Systematic errors in the forward model can lead to regional-scale and/or time-dependent biases in the retrieval products, which in turn can lead to biases in flux estimates derived from those products. Here we present recent and ongoing work on spectroscopy for the 0.76 micron O_2 A-band and the 1.61 and 2.06 micron CO_2 bands utilized by the NASA Orbiting Carbon Observatory (OCO-2) mission and discuss future directions relevant for OCO-2 and other greenhouse gas missions.

For the OCO-2 mission, efforts are underway to incorporate advanced line-shape formulations and to derive improved experimental line parameters. Advances in spectroscopy are included in the OCO-2 forward model by updating look-up tables for molecular absorption coefficients (ABSCO tables). The ABSCO v5.0 tables are utilized within the B8 version of the OCO-2 Level 2 algorithm. While the ABSCO v5.0 tables represent a significant improvement compared to previous versions, systematic features in spectral residuals remain for closure studies using new laboratory measurements as well as ground-based and spaceborne atmospheric measurements.

We show comparisons of ABSCO v5.0 against new, high signal-to-noise laboratory measurements in the O_2 A-band. These include spectra from both Photoacoustic Spectroscopy (PAS) and Cavity Ringdown Spectroscopy (CRDS) measurements. We show preliminary results from analysis of these new laboratory measurements to demonstrate potential improvements for the next ABSCO version. We also provide an update on status and plans for the 1.6 and 2.06 micron CO_2 bands. ABSCO v5.0 CO_2 tables have previously been validated using ground-based atmospheric spectra from the Lamont TCCON site. Here we quantify the impact updates to the water vapor line list (utilizing parameters from the HITRAN 2016 compilation) and continuum (utilizing the latest version of the MT_CKD continuum) on retrievals using these CO_2 bands. We also discuss progress and plans for testing of alternative CO_2 line mixing formulations.

A2.4 Aerosol properties in the atmosphere from GOSAT/CAI and GOSAT-2/CAI-2

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Aerosols continue to contribute the largest uncertainty to estimates and interpretations of the Earth's changing energy budget (IPCC, 2015) because of the strong temporal and spatial variability and a wide range of microphysical and optical properties of the aerosol particles.

The Greenhouse Gases Observing Satellite-2 (GOSAT-2), which is a satellite for monitoring the concentration of greenhouse gases such as carbon dioxide and methane from space, will launched in fiscal year 2018. The satellite has two sensors, TANSO-FTS-2 (Thermal And Near-infrared Sensor for carbon Observation; Fourier Transform Spectrometer-2, FTS-2) and TANSO-CAI-2 (Cloud and Aerosol Imager-2, CAI-2). CAI-2 is a supplement sensor of FTS-2 and measures cloud and aerosol properties.

CAI-2 observes ten bands of seven wavelength regions from two-directional viewing, forward and backward. Forward viewing. The forward viewing has 343, 442, 674, 869 and 1630 nm; backward, 380, 550, 674, 869 and 1630 nm. The spatial resolutions are 460 m for bands 1-4 and 6-9, 920 m for band 5 and 10.

We have developed a satellite remote sensing algorithm to retrieve the aerosol optical properties using multi-wavelength and multi-pixel information of satellite imagers (MWPM). The method simultaneously derives aerosol optical properties, such as aerosol optical thickness (AOT), single scattering albedo (SSA) and aerosol size information, by using spatial difference of wavelengths (multi-wavelength) and surface reflectance (multi-pixel). The method is useful for aerosol retrieval over spatially heterogeneous surface like an urban region.

In this algorithm, the inversion method is a combination of an optimal method and smoothing constraint for the state vector. Furthermore, this method has been combined with a radiation transfer calculation model (RTM) accelerated by neural network-based method, EXAM (Takenaka et al., 2011). We will apply the algorithm for CAI-2 Level 2 aerosol products.

We applied the MWPM combined with EXAM to GOSAT/TANSO-CAI (Cloud and Aerosol Imager, CAI). CAI has four bands, 380, 674, 870 and 1600 nm, and observes in 500 meters resolution for band1, band2 and band3, and 1.5 km for band4. Retrieved parameters are aerosol optical properties, such as aerosol optical thickness (AOT) of fine and coarse mode particles at a wavelength of 500nm, a volume soot fraction in fine mode particles, and ground surface albedo of each observed wavelength by combining a minimum reflectance method and Fukuda et al. (2013). We will show the results of global aerosol properties from CAI and discuss the accuracy of the algorithm for various surface types.

A2.5 What Can We Learn From Performing Simplified XCO2 Retrievals on Synthetic Near-Infrared Observations?

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The NASA OCO-2 retrieval algorithm for column-averaged dry-air mole fraction of carbon dioxide (XCO_2) has been significantly improved in terms of both precision and accuracy since its inception. However, one of the primary sources of uncertainty in the algorithm remains its cloud and aerosol parameterization. This is because near-infrared measurements are highly sensitive to even small levels of cloud or aerosol contamination. Thus, the retrieval algorithm must include clouds and aerosols as retrieved properties in its state vector. Information content analyses demonstrate that there are only 2-6 pieces of information about aerosols contained in the OCO-2 radiances. However, the current OCO-2 algorithm (B8) attempts to retrieve 9 aerosol parameters; this over-fitting can hinder convergence and has been shown to produce multiple solutions. In this work, we investigate several simplified cloud and aerosol parameterizations ranging from non-scattering algorithms to the operational NASA algorithm. We then use these algorithms to retrieve XCO_2 from synthetic, near-infrared radiances generated using the CSU OCO Simulator with the goal of learning how different levels of complexity in the algorithm impact both the precision and accuracy of the XCO_2 measurement. Expected benefits of reduced algorithm complexity include faster convergence, less nonlinearity, and greater throughput.

A2.6 Sensitivity test for PPDF-S retrieval method using atmospheric radiative transfer model

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Photon path length probability density function-Simultaneous (PPDF-S) method is one of effective algorithms for retrieving column-averaged concentrations of carbon dioxide (XCO_2) and methane (XCH_4) from Greenhouse gases Observing SATellite (GOSAT) spectra in Short Wavelength InfraRed (SWIR) [Oshchepkov et al., 2013]. In this study, we investigated accuracy of XCO_2 retrieved by the PPDF-S method through sensitivity tests using atmospheric radiative transfer models. One of the models are a multiple radiation transfer code based on Discrete Ordinate Method (DOM), Polarization System for Transfer of Atmospheric Radiation3 (Pstar3) [Ota et al., 2010], and sensitivity of surface albedos to gas concentrations was examined using the model. The accuracy of XCO_2 was defined by the difference between the retrieved XCO_2 and assumed values for Pstar3, and the values are described as "XCO_2 bias" hereafter. We calculated the biases for four types of the surface reflectance; "brown sandy loam", "green grasses", "ice" and "fine snow". The results showed that the accuracy of XCO_2 retrieved by the PPDF-S method depends on wavelength dependency of surface albedo as well as its absolute value.

A2.7 Single-band carbon dioxide retrievals from the OCO2-satellite using the 2 micron band

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Passive remote sensing of atmospheric carbon dioxide depends on spectroscopic measurements of sunlight backscattered by the Earth's surface and atmosphere. The current state-of-the-art retrieval methods use the oxygen A-band at 0.76 micron and the weak and strong CO_2 absorption bands at 1.61 and 2.06 micron respectively, to infer information on light scattering and the carbon dioxide column-averaged dry-air mole fraction XCO_2. In this study, we propose to retrieve XCO_2 by using solely the 2.06 micron band measurements from the OCO-2 satellite with RemoTeC in a new algorithm setup. We examine the validity and accuracy of our single band XCO_2 retrievals by comparing to multi-band retrievals and ground-based measurements from the Total Carbon Column Observing Network (TCCON).

A2.8 Toward improvement of the retrieval algorithm for GOSAT TANSO-FTS SWIR L2 products

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The column averaged dry-air mole fractions of CO_2, CH_4, and H_2O (XCO_2, XCH_4, and XH_2O) have been globally retrieved from the reflected sunlight spectra observed by TANSO-FTS onboard GOSAT. Although the latest NIES L2 products (V02.72) have generally high quality, there are several issues to address. Uchino et al. (2017) found negative bias in XCO2 in the southern hemisphere, especially at Lauder due to increased stratospheric aerosols after the volcanic eruption of Mt. Calbuco in April 2015. When integrated water vapor is large, most data are screened out due to large residuals caused by inaccurate spectroscopic line parameters of H_2O (Dupuy et al., 2016). We present significant changes in the retrieval products induced by taking into account stratospheric aerosol and by utilizing line parameter available recently.

In the operational L2 retrieval algorithm, fine and coarse mode aerosol profiles (logarithms of aerosol mass mixing ratio) are individually retrieved, simultaneously with partial columns of CO_2, CH_4, and H_2O and other ancillary parameters. We modified the algorithm such that an additional aerosol layer, which was assumed to be composed of small sulfate particles and to be distributed uniformly in the layer, was included in the stratosphere and optical thickness and top height of the aerosol layer were retrieved. The retrieved XCO_2 and XCH_4 data showed better agreement with the TCCON data at Lauder than V02.72 data, although the negative bias was not completely resolved.

The operational L2 retrieval algorithm uses HITRAN 2008 database as line parameters of CH_4 and H_2O. In this study, CH_4 line parameters were taken from Devi et al. (2015; 2016) for $^{12}CH_4$ lines in the 2ν3 band and the HITRAN 2016 (Gordon et al., 2017) for weak $^{12}CH_4$ lines and minor isotopologues. A speed-dependent Voigt line profile with line-mixing was used to calculate the absorption coefficient. As for H_2O line parameters, HITRAN 2016 database or atm line list (Toon, 2014) were used to evaluate impact of the differences in line parameters. The revised CH_4 line parameters slightly improved the spectral fits (residuals) and made latitude (airmass) dependent XCH_4 differences compared to those from the HITRAN 2008. We found that the atm line list could provide the smallest residuals for H_2O lines in the 1.6 and 2.0 μm regions and increase the number of available data by approximately 10%.

A2.9 Yonsei CArbon Retrieval Algorithm: Validation, Error Analysis, and Its Application to OCO-2 Satellite

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The Yonsei CArbon Retrieval (YCAR) algorithm, which retrieves the column-averaged dry air mole fraction of carbon dioxide (XCO_2) based on optimal estimation method, was developed to reduce the XCO_2 retrieval errors caused by uncertainty of aerosol information. Focused on East Asia, the YCAR algorithm uses a realistic aerosol information derived from the AERONET and the CAI measurements, and was also modified by simultaneously considering aerosol optical information to reduce aerosol-induced errors (Jung et al., 2016; Kim et al., 2016). Using short-wave infrared (SWIR) channels observed by the Thermal And Near-infrared Sensor for carbon Observation - Fourier Transform Spectrometer (TANSO-FTS) onboard the Greenhouse gases Observing SATellite (GOSAT), this algorithm was validated with ground-based FTS measurements (g-b FTS), showing higher correlation, lower biases, and improved data availability than operational algorithm.

In this study, we also applied the YCAR algorithm to Orbiting Carbon Observatory (OCO)-2 satellite considering polarization. In addition, the effects of Solar-Induced Fluorescence (SIF) are considered, and a real-time aerosol information from the MODerate-resolution Imaging Spectrometer (MODIS) and the Cloud-Aerosol LIdar with Orthogonal Polarization (CALIOP) measurements are used to reduce retrieval errors. The preliminary results were tested for validation with the g-b FTS. We expect to reduce apparent biases when proper pre- and post-screening procedures is added in the future.

A2.10 CO_2 Retrievals from OCO-2 using the UoL Retrieval: Validation against TCCON and evaluation of fast RT methods

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We have applied the UoL retrieval algorithm to spectra acquired by NASA's OCO-2 mission and evaluated the retrieval results against ground-based TCCON observations and the operational Level-2 v8 product. Such an intercomparison provides an independent assessment of the OCO-2 retrieval result and can help to identify regimes where retrieval uncertainties are large.

The UoL algorithm is an optical estimation retrieval algorithm based on a forward model that employs the LIDORT, TWOSTR, and 2OS radiative transfer (RT) solvers and makes use of the PCA-based (principal component analysis) method to speed up the calculations. Two scene-dependent aerosol mixture extinction profiles are informed by MACC/CAMS, where each mixture is sampled from five different tropospheric types with multiple size bins: sea salt, dust, organic matter, black carbon, and sulphate. For dust, the spherical shapes are replaced by non-spherical particle shapes from MISR. An additional ice cloud mixture is employed, where the peak height is varied with latitude.

Furthermore, current CO_2 algorithms employ different techniques to speed up the computationally very expensive multiple-scattering RT calculations. We have evaluated three established methods (LSI, linear-k and the PCA-based method) in a consistent framework and applied them to OCO-2 retrievals. For relatively low and modest aerosol loads ($\tau \leq 0.1$), all three methods yield consistent results. At larger aerosol optical thicknesses, however, we observe small, but significant differences between methods. This suggests that the fast RT methods can ultimately give rise to biases in XCO_2 in particular for regions with enhances aerosol loadings (e.g. urban areas).

A2.11 CO2 concentration in the boundary layer estimated from a synergy of SWIR and TIR of TANSO-FTS/GOSAT

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The objective of this study is to estimate the CO_2 concentration in the lower atmosphere, particularly in the boundary layer based on the synergetic usage of thermal infrared (TIR) and short wavelength infrared (SWIR) data, and applying this method to assess the budget of CO_2 emission from megacities.

CO_2 concentration near the surface is an important parameter for estimating the uptake speed of CO_2 into the forests and oceans, and/or emission strength over the urban areas. Generally, air is well mixed in the boundary layer (mixing layer) during the daytime keeping the columnar concentration of the gas, and the gas concentrations near the surface is almost same as the average concentration in the boundary layer. However, CO_2 mixing ration in the boundary layer is not directly determined only from the columnar concentration of the gas, i.e. the thickness of the boundary layer is necessary to determine it. The boundary layer height (or layer thickness) was estimated from temperature (or potential temperature) profiles retrieved from TIR band spectra as well as the tropopause height. By combining CO_2 columnar concentration retrieved from SWIR band spectra, upper air concentration retrieved from TIR spectra, and the tropopause height and boundary layer thickness, CO_2 concentration in the boundary layer was estimated assuming the concentration in the stratosphere based on the yearly trend. This method was applied to the dataset obtained over the Kanto Plain during the GOSAT specific observation periods were validated using in situ measurement data at the ground level. The results show that the difference between the estimated CO_2 concentrations in the boundary layer and those from in situ measurement was 2.9 ppmv (STD) and better than the value, 4.0 ppmv (STD), evaluated assuming a fixed layer height at 850 hPa.

A2.12 The improvement of using aerosol information from CAPI/TanSat nadir observation in CO_2 retrieval: Theoretical analysis

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Aerosols affect the radiative transfer in the absorption bands of carbon dioxide (CO_2), thereby contributing to the uncertainties in the retrieval of CO_2 from space. A Cloud and Aerosol Polarimetric Imager (CAPI) has been designed to fly on the Chinese Carbon Dioxide Observation Satellite (TanSat) and provide aerosol and cloud information to facilitate the measurements of CO_2. Based on previous study about aerosol retrieval ability of CAPI, this study aims to estimate the improvement of XCO_2 posterior error if aerosol information from CAPI measurements are used in TanSat CO_2 retrieval. We simulate TanSat hyperspectral observations using a forward model, from which the Jacobians of CO_2 concentration and aerosol properties could also be calculated to get the interference error of XCO_2 from the uncertainties of aerosol parameters, as well as posterior error according to optimal estimation theory. Five aerosol parameters in bimodal aerosol model with the largest information are selected based on CAPI simulation. All aerosol parameters are included in the state vector of CO_2 retrieval and the results of four types of aerosols with different properties from AERONET are compared. Both the interference error from aerosols and the improvement of XCO_2 error due to aerosol measurements are related to aerosol mixture described by fine mode fraction (fmfv) and highly depend on aerosol optical depth (AOD). When AOD changes from 0.1 to 1.0 with 0.1 to 0.9 fmfv, the total error in XCO_2 due to aerosols ranges from 0.05 ppm to 1.1 ppm. After the a priori uncertainties of aerosol properties are improved from CAPI measurements, XCO_2 posterior error could be reduced 0.1 ppm in average, depending on AOD, fmfv and solar zenith angle (SZA).

B2.1 MIPAS IMK/IAA carbon tetrachloride (CCl_4) retrieval and first comparison with other instruments

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MIPAS thermal limb emission measurements were used to derive vertically resolved profiles of carbon tetrachloride (CCl_4). MIPAS level-1b data were converted into volume mixing ratio profiles using the level-2 processor developed at Karlsruhe Institute of Technology (KIT) Institute of Meteorology and Climate Research (IMK) and Consejo Superior de Investigaciones Científicas (CSIC), Instituto de Astrofísica de Andalucía (IAA). Consideration of peroxyacetyl nitrate (PAN) as an interfering species, which is jointly retrieved, and CO_2 line mixing is crucial for reliable retrievals. Despite the inclusion of line mixing in the forward model, parts of the CO_2 Q-branch region overlapping with the CCl_4 signature were omitted because the spectral residuals were above the noise. Note, however, that without

accounting for line mixing the omitted spectral region would have been noticeably wider. A new CCl_4 spectroscopic dataset was introduced by Harrison et al., 2016, during the development of the MIPAS CCl_4 retrieval setup. Using it leads to slightly smaller volume mixing ratios. In general, latitude-altitude cross sections show the expected CCl_4 features with highest values of around 90 pptv at altitudes at and below the tropical tropopause and values decreasing with altitude and latitude due to stratospheric decomposition. Other patterns, such as subsidence in the polar vortex during winter and early spring, are also visible in the distributions. The decline in CCl_4 abundance during the MIPAS Envisat measurement period (July 2002 to April 2012) is clearly reflected in the altitude-latitude cross section of trends estimated from the entire time series. Comparisons with other instruments, such as ACE-FTS and MIPAS-B, show excellent agreement with the newly retrieved MIPAS CCl_4 dataset.

B2.2 Progress status of the GOSAT and GOSAT-2 SWIR L2 retrievals

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The Greenhouse gases Observing SATellite (GOSAT) has been operating for more than nine years, and the column-averaged dry air mole fractions of carbon dioxide, methane, and water vapor (XCO_2, XCH_4, and XH_2O; hereafter called X_{gas}) have been retrieved globally from the Short-Wavelength InfraRed (SWIR) spectral data (0.76 μm, 1.6 μm, and 2.0 μm bands) observed with Thermal And Near-infrared Sensor for carbon Observation Fourier Transform Spectrometer (TANSO-FTS) onboard GOSAT. Xgas are simultaneously retrieved using a so-called full-physics retrieval method. The retrieval results are released as the FTS SWIR L2 product and available via GOSAT Data Archive Service (GDAS; https://data2.gosat.nies.go.jp/). Recently, JAXA prepared FTS L1B sample product (V205.205) for upcoming version up. We have been re-evaluating the characteristics of the new spectral data, and results will be reflected to the next major version up of the SWIR L2 products (V03).

As a successor mission to the GOSAT, GOSAT-2 is planned to be launched in FY2018. According to the latest design of the TANSO-FTS-2 (FTS onboard the GOSAT-2), its SNR is higher than or almost equal to the TANSO-FTS, and its spectral range is expanded to cover the 2.3 μm carbon monoxide (CO) band. The SWIR L2 retrieval algorithm for GOSAT-2 is developing based on the latest retrieval algorithm for GOSAT. Our preliminary sensitivity test based on the designed specification shows that the SNR improvement in SWIR bands reduces the retrieval random error (precision) about 15% for XCO_2 and 35% for XCH_4 than those of GOSAT. 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.

B2.3 Evaluation of OCO-2 Small-Scale Variability Using Lidar and In Situ CO_2 Observations from the ACT-America Campaign

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NASA's Atmospheric Carbon and Transport – America (ACT-America) field campaign provides the unique opportunity to validate small-scale satellite column CO_2 measurements. The Orbiting Carbon Observatory 2 (OCO-2) satellite provides a robust XCO_2 dataset on a global scale, but the sparseness of ground-based networks makes validation on the finest OCO-2 resolutions, 1-10km, a challenge. After three complete ACT-America field campaigns, the Multi-functional Fiber Laser LIDAR (MFLL) instrument has completed nine underflights of OCO-2, allowing for direct spatial comparison of the two datasets over several North American regions. Comparisons show a respectable level of agreement between satellite- and LIDAR-observed XCO_2 gradients over the course of several hundred kilometers, but little agreement on smaller scales. Further comparisons to models and in situ column data, including two-dimensional CO_2 "curtains" constructed from in situ data along the flight track, show varying levels of spatial correlation and reveal idiosyncrasies in each dataset that must be considered in comparison evaluation. There is also evidence that the OCO-2 data remain contaminated to some degree by 3-D cloud effects, motivating current work by the science team on the identification and mitigation of such effects. In this work, we show key comparisons to date and attempt to draw conclusions on the fidelity of the remotely-sensed CO_2 gradients, including our ability to reconstruct these gradients using the curtain approach.

B2.4 Preliminary XCO_2 retrieval results of TanSat in Dunhuang

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TanSat is the first Chinese satellite to monitor the carbon dioxide (CO2) globally from space. It has been launched on December 22, 2016. Two instruments: A high-resolution Carbon Dioxide Spectrometer for measuring the near-infrared absorption by CO_2 and CAPI (Cloud and Aerosol Polarimetry Imager) to compensate the CO_2 measurement errors by high-resolution measurement of cloud and aerosol are accommodated on TanSAT. In order to fulfill the need of TanSat orbit test, a comprehensive ground experiments is conducted in Dunhuang calibration field during April 2017. Target mode of TanSat is used to cooperated with the ground experiments. WFM_DOAS algorithm is used to process the TanSat spectrum in weak CO_2 absorption band to retrieval XCO_2. The retrieval results are compared with ground measurements. Good spectrum fits and less than 1% bias from ground measurements show the good ability of TanSat in monitoring the greenhouse gas.

Session 3: Validation and supporting observations including ground-based and in-situ observations

3.1 First results of the ESA AO project TCCON4S5P focusing on the validation of the Sentinel-5P methane and carbon monoxide using TCCON data

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The ongoing TCCON4S5P, project led by the Royal Belgian Institute for Space Aeronomy (BIRA-IASB) and supported by the TCCON community, was submitted as an answer to the ESA-AO (announcement of opportunity) call for the calibration and validation of the Sentinel-5 Precursor (S5P) mission. This project is focused on the geophysical validation of S5P methane (CH_4) and carbon monoxide (CO) total column products using coinciding TCCON data from the whole network, which includes currently about 25 globally distributed stations. The S5P was successfully launched on 13 October 2017 with the TROPOspheric Monitoring Instrument (TROPOMI) as the single payload onboard. It measures the Earth's reflected radiances from the ultraviolet to the shortwave infrared spectral range with a spatial resolution down to 7x7 km^2 and has a daily global coverage. The S5P data will be made available to the S5PVT projects during the commissioning phase E1. The proposed validation activity in this project will be carried out using the TCCON rapid delivery data for the first twelve months of the satellite data followed by a second phase where the focus will be on the continuous long-term validation during the operational lifetime of the satellite. In this presentation we propose to show the first validation results of S5P CH_4 and CO products using TCCON data from the whole network provided there will be a sufficient number of satellite data available by that time. In addition, the presentation will give an overview and discuss the current status of the project.

3.2 Comparisons of MOPITT XCO with TCCON

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The Measurements of Pollutants in the Troposphere (MOPITT) instrument onboard the Terra satellite (launched December 1999) measures carbon monoxide (CO) globally. In Aug 2016, the latest data version was released (v7) which has a combined near-infrared and thermal infrared product to produce a total column dry-air mole fraction (XCO). Here we present comparisons of MOPITT v7 retrievals against observations from the ground-based Total Carbon Column Observing Network (TCCON). The focus of this work is to characterize the accuracy and precision of MOPITT retrievals against the TCCON measurements, which are tied to the World Meteorological Organization trace gas scale for CO through comparisons with coincident aircraft and in situ profile. We perform a small area analysis (SAA) to assess and quantify sources of bias in the MOPITT retrievals and find, in agreement with previous work, that pixel 1 is biased lower and produces noisier results compared with the other 3 pixels. We use the SAA, and comparisons with TCCON to derive a set of recommend data quality filters. Finally, we describe progress in using these comparisons to derive a set of empirical bias corrections.

3.3 Update on the Validation of OCO-2 XCO2 Data

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The first attempt to validate OCO-2 observations of column-averaged dry air mole fraction CO_2 (XCO_2) by comparing to data from the Total Carbon Column Observation Network (TCCON) was documented by Wunch et al. (2017). That work built on the methodology developed validating XCO_2 observations utilizing data from the Japanese GOSAT satellite and the OCO-2 retrieval algorithm Wunch et al. (2011). Recently, the OCO-2 team has released the Version 8 data set and work has been underway to update the validation analysis for this data set. We will present an update on the validation analysis including the latest comparisons to TCCON data. We will provide the latest information on OCO-2 target mode observations and the status of the Observatory as well as updates on the biases seen in the data and efforts to mitigate those biases. An update on the latest retrievals of GOSAT data using the OCO-2 retrieval algorithm (ACOS v8) will be also be presented.

Wunch et al., Atmos. Meas. Tech., 10, 2209-2238, 2017
Wunch et al. Atmos. Chem. Phys., 11, 12317-12337, 2011

3.4 Application of TanSat algorithm on GOSAT observation - ATANGO and OCO-2 XCO2 retrieval: validation, inter-comparison and new approach

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Chinese carbon dioxide observation satellite (TanSat) successfully launched in December 2016. A hyperspectral grating spectrometer onboard the TanSat is monitoring the column-averaged CO_2 dry-air mixing ratio (XCO_2) in global. The objective of TanSat retrieval algorithm is to approach the XCO_2 in a highly accuracy and precision as the scientific requirement. Application of TanSat algorithm on GOSAT observation (ATANGO), as well as TanSat algorithm, has been developed from Institute of Atmospheric

Physics Carbon Dioxide Retrieval Algorithm for Satellite Observation (IAPCAS). The XCO_2 is approached from satellite hyperspectral measurement of NIR/SWIR by the 'full physical' optimal estimation method. Recently, this algorithm is applied on OCO-2 retrieval. In this presentation, we are going to show the validation of XCO_2 approached from GOSAT and OCO-2 data retrieval experiments against TCCON measurement and inter-comparisons with NIES-FP, ACOS, UoL and RemoTeC products. The precision of XCO_2 will be reflected in the results, as well as the seasonality. Further studies on aerosol information and retrieval strategy is also a new approach of ATANGO.

3.5 Views from the 6 aircraft campaigns (ACT-America, HIPPO, CONTRAIL, ATom, ORCAS, and ABoVE): assimilation of airborne CO_2 measurements into GEOS and comparisons with satellite retrievals

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This presentation describes the assimilation of airborne measurements of carbon dioxide (CO_2) into the Goddard Earth Observing System (GEOS) general circulation model. The main goal is to construct observationally constrained fields of CO_2 starting from the bottom of the atmosphere and extending through the entire vertical column. These fields can then be compared directly to retrievals of column CO_2 (XCO_2) from the Greenhouse Gases Observing Satellite (GOSAT) and the Orbiting Carbon Observatory 2 (OCO-2) by using the averaging kernel and a priori profile. This approach does not require a direct satellite overpass, but rather an overpass of the much broader region impacted by the assimilation, which alleviates some of the jeopardy of coordinating flights with satellite tracks. Furthermore, checking if the story stays the same or if it changes when the unassimilated fields are compared to the satellite soundings allows us to separate model errors from retrieval errors. This work attempts to answer a number of questions including: What are the possible causes of systematic differences between model and satellite XCO_2 over the Pacific Ocean? What is the contribution of stratospheric uncertainty to XCO_2 errors? What is the impact of errors in boundary layer physics on modeled XCO_2?

3.6 Validation for Greenhouse Gases Measured by the Atmospheric Chemistry Experiment (ACE) Satellite Mission

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The Canadian-led Atmospheric Chemistry Experiment (ACE) satellite mission has completed fourteen years of measurements from orbit. It uses infrared and UV-visible spectroscopy to investigate the chemistry and dynamics of the Earth's atmosphere. The two instruments on-board are the ACE Fourier Transform Spectrometer (ACE-FTS), a high-resolution (0.02 cm-1) FTS operating between 750 and 4400 cm^{-1}, and a dual UV-visible-NIR spectrophotometer called ACE-MAESTRO (Measurements of Aerosol Extinction in the Stratosphere and Troposphere Retrieved by Occultation), which extends the ACE wavelength coverage to the 280-1030\,nm spectral region. The ACE instruments make solar occultation measurements from which altitude profiles of atmospheric trace gas species, temperature and pressure are retrieved. The 650 km altitude, 74 degree circular orbit provides global measurement coverage with a focus on the Arctic and Antarctic regions. This paper will describe validation results for the ACE-FTS and ACE-MAESTRO greenhouse gas data sets including CH_4, H_2O and N_2O.

A3.1 Philippines TCCON Project: Result on One-year Measurements and Future

Isamu Morino*, Voltaire A. Velazco, Akihiro Hori, Osamu Uchino, Hirofumi Ohyama, Tetsu Sakai, Toshiharu Izumi, Tomohiro Nagai, Gerry Bagtasa, Yukio Yoshida, MatthÕ_us Kiel, Beata Bukosa, Nicholas M. Deutscher, Jenny A. Fisher, David W. T. Griffith

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TCCON is dedicated to the precise measurements of total column-averaged abundances of greenhouse gases (GHGs) such as CO_2 and CH_4. TCCON measurements have been and are currently used extensively and globally for satellite validation, for comparison with atmospheric chemistry models and to study atmosphere-biosphere exchanges of carbon. With the global effort to cap GHG emissions, TCCON has taken on a vital role in validating satellite-based GHG data from past, current and future missions like Japanese GOSAT and GOSAT-2, NASA's OCO-2 and OCO-3, Chinese TanSat, TROPOMI, and others. The lack of reliable validation data for the satellite-based GHG observing missions in the tropical regions is a common limitation in global carbon-cycle modeling studies that have a tropical component. The international CO2 modeling community has specified a requirement for "expansion of the CO_2 observation network within the tropics" to reduce uncertainties in regional estimates of CO_2 sources and sinks using atmospheric transport models.

To address this challenge, we installed a newly-constructed TCCON FTS at a wind farm operated by the Energy Development Corporation in Burgos, Ilocos Norte, Philippines (18.5326°N, 120.6496°E), which followed rigorous site assessments and discussions at several TCCON and GOSAT-2 science team meetings. After installation and setup of the instruments in Mar. 2017, we started operations in the Philippines using TCCON protocols. Here, we will show result on one-year measurements, some interesting phenomena such as CO and CH_4 enhancements, comparisons with GOSAT and OCO-2 soundings, participation in aircraft observation campaigns such as EMeRGe-Asia and NASA CAMP2Ex.

A3.2 TCCON Updates and Improvements to Precision Requirements

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The Total Carbon Column Observing Network (or TCCON), which is currently made up of 26 sites, internationally, is a well established network of ground-based Fourier Transform Spectrometers that record direct solar spectra in the near-infrared. Accurate and precise column-averaged abundances of CO_2 (as well as of other atmospheric constituents - CH_4, N_2O, HF, CO, H_2O, and HDO) are retrieved from these spectra. Dating back to 2004, TCCON data have already proven to be valuable in providing ground truth for satellite measurements of CO_2 and CH_4 column abundances and in evaluating large-scale carbon models and improving global estimates of the sources and sinks of CO_2 and CH_4.

In this work, we will briefly describe developments to the TCCON network over the past year, including the most up to date CO_2 and CH_4 time series, the introduction of new network sites, and the extended measurement capabilities into the mid-IR at several sites. In addition, we will highlight ongoing efforts to reduce errors / improve precision of the TCCON results through a number of changes to the GGG retrieval software.

A3.3 Calibration of TCCON observations on Ascension Island with aircraft profiles from the NASA ATom campaigns

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The Total Carbon Column Observing Network (TCCON) provides the most precise column-averaged dry-air mole fraction observations of CO_2, CH_4, CO, N_2O and several other atmospheric trace gases. This is vital for satellite observations of greenhouse gases (GHGs) like CO_2 or CH_4 as the precision requirements for these GHGs are on the sub-percent level. Consequently, all current and (foreseeable) future satellite instruments for CO_2 and CH_4 rely on TCCON for calibration and validation.

However, to link TCCON (and thus satellite) observations to the established WMO GHG scale, TCCON itself must be calibrated with respect to in-situ GHG measurements. Otherwise, the accuracy of spectral parameters needed for the TCCON retrievals does not match the achievable precision. The standard procedure is to measure atmospheric profiles with aircraft in-situ instruments above the TCCON stations and compare these to the total column TCCON observations derived at the same time. Jet aircraft are needed for this to cover as much of the tropospheric column as possible. The results from many aircraft profiles derived over many TCCON stations are used to calculate network-wide calibration factors for all major TCCON target species.

Each TCCON station is required to have at least one aircraft calibration before it can become a full member of the network. However, the logistical constraints at some sites can be very limiting. It took more than four years of operation before the TCCON station on Ascension Island was visited by the NASA DC-8 aircraft during the Atmospheric Tomography (ATom) mission in August 2016 to receive its first aircraft calibration. Among many other species and parameters, altitude profiles of CO_2, CH_4, CO, and N_2O were measured by instruments from NOAA and Harvard University on board. Two more visits took place during ATom-2 in February 2017 and ATom-3 in October 2017. The results are now used to improve TCCON's in-situ calibration factors. The station itself was promoted to full TCCON status in mid-2017 as a result.

A3.4 Simultaneous Nadir Overpass Matchups of GOSAT/TANSO-FTS and AQUA/AIRS: TIR Band April 2009 - August 2017

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The Greenhouse Gases Observing Satellite (GOSAT) was launched in January 2009 to monitor global atmospheric concentration and flux of CO_2 and CH_4 from space. The TANSO-FTS sensor is an interferometer spectrometer measuring shortwave reflected solar radiation with high spectral resolution in three spectral bands. A bore-sighted Band 4 uses the same interferometer to measure thermal infrared radiation (TIR) at the top of the atmosphere. This paper presents a comparison of the TANSO-FTS TIR band with coincident measurements from the NASA Atmospheric InfraRed Sounder (AIRS) grating spectrometer. The time and space coincident matchups are at the Simultaneous Nadir Overpass (SNO) locations of the orbits of GOSAT and the NASA AQUA satellite. GOSAT/AQUA SNOs occur at about 40N and 40S latitude. A continuous set of SNO matchups has been found from the start of valid TANSO-FTS radiance data collection in April 2009 through August 2017. UW-SSEC has obtained the time, latitude, and longitude of the SNO locations using the ORBNAV software at http://sips.ssec.wisc.edu/orbnav. UW-SSEC obtained the matching AIRS v5 L1B radiances from the NASA archive. JAXA has reprocessed the entire TANSO-FTS TIR band dataset using the previous calibration version v161.161, and a new version v205.205 which includes parameter optimizations. The TANSO-FTS observations have been reduced to the AIRS spectral channels using the AIRS spectral response functions (SRFs). This paper shows the time series of observed brightness temperatures from AIRS and GOSAT TANSO-FTS TIR observations from the SNO matchups. Furthermore it validates the improvements in the GOSAT ground calibration software by providing an independent reference to the AIRS on-orbit calibration accuracy. Improvements in the ground calibration software are expected to lead to improvements in the TIR band Level 2 retrievals of CO_2 profiles.

A3.5 GOSAT and OCO-2 validation activities at Saga station and campaign sites

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GOSAT has been operating since 2009 to monitor the greenhouse gases carbon dioxide (CO_2) and methane (CH_4) by a Fourier Transform Spectrometer (TANSO-FTS). 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 with ten-kilometer resolution by pointing system of wide swath. OCO-2 has been operating since 2014, carries a grating spectrometer to make precise XCO_2 observations with a-few-kilometer resolution of narrow swath. GOSAT and OCO-2 target at particular calibration and validation sites.

Ground-based FTS with high spectral resolution has been operated at Saga University in the south-western part of Japan belonging to the Total Carbon Column Observing Network (TCCON) since July 2011. XCO_2 and XCH_4 are retrieved from direct sunlight spectra with high accuracy. TCCON dataset is utilized to make validation for the satellite observations such as GOSAT and OCO-2 with simultaneous measurements. The GOSAT observes at Saga every 3 days by pointing mirror orientation, while the OCO-2 has less opportunity because of satellite body pointing.

We measured XCO_2, XCH_4 and XCO using a portable FTS in western US and central Japan at different type emission areas. We targeted Pasadena as a large city near Los Angeles, and Railroad valley as a desert playa in Nevada. These measurements were conducted during the GOSAT/OCO-2 joint campaign in early summer. We also targeted Nagoya as one of the largest cities with industrial area in Japan for the airborne sensor model flight campaign. Before and after the campaigns, the portable FTS was compared with those from NIES, Caltech beside TCCON FTSs at NIES, Caltech, and JPL to ensure the accuracy.

We will present GOSAT and OCO-2 validation results at Saga station and campaign sites by the ground-based and the portable FTSs.

A3.6 Long-term Monitoring of Greenhouse Gases at the Izaña Atmospheric Observatory

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The Izaña Atmospheric Observatory (IZO), run by the Izaña Atmospheric Research Centre (IARC) belonging to the Spanish Meteorological Agency (AEMET), is a subtropical high-mountain observatory on Tenerife (Spain, 28.3°N, 16.5°W, and 2373 m a.s.l.). It is usually well above the level of a strong subtropical temperature inversion layer, which acts as a natural barrier for local pollution. This fact, together with the quasi-permanent subsidence regime typical of the subtropical region, makes the air surrounding the observatory representative of the background free troposphere. Hence, it offers excellent conditions for the in-situ and remote-sensing of the atmospheric composition.

The IZO has a long-term experience in monitoring and researching a large variety of atmospheric constituents, concentrating numerous measurement techniques and contributing to international networks and databases (WOUDC, NDACC, TCCON, WDCGG,…). This is fundamental since they allow for inter-comparing and documenting the quality and long-term consistency of the different observations. Regarding greenhouse gases monitoring, IZO has been a Global GAW (Global Atmospheric Watch) station since 1984, recording continuous in-situ concentrations of the main greenhouse gases (GHGs). In addition, since 1999 total column amounts and low-resolution vertical profiles of many different atmospheric trace gases, GHGs among them, are retrieved by using Fourier Transform Infrared Spectrometer (FTS) in the framework of NDACC and TCCON. In this context, this work will give an overview about the IZO capabilities and activities for monitoring of atmospheric trace gases, especially focusing on the validation of space-based greenhouse gases observations

A3.7 Comparison of N_2O and CH_4 retrievals from PARIS-IR and ACE-FTS.

Paul S. Jeffery*, Debora Griffin, Kaley A. Walker, Ellen Eckert, Pierre F. Fogal, Jim R. Drummond, Gloria L. Manney, Kimberly Strong, and Chris D. Boone

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The Atmospheric Chemistry Experiment satellite, also known as SCISAT-1, was launched into a low Earth polar sun-synchronous orbit in 2003 and began scientific operations in early 2004. Aboard the satellite are two instruments, the primary of which is a high resolution (0.02 cm^{-1}) Fourier Transform Spectrometer (ACE-FTS), operating in the spectral region of 750 - 4400 cm^{-1}. ACE-FTS operates in a solar occultation mode, recording absorption spectra at tangent heights spanning from the cloud tops to 150 km in altitude. The Portable Atmospheric Research Interferometric Spectrometer for the InfraRed (PARIS-IR) was designed as a ground-based version of ACE-FTS, with an identical spectral resolution and range. Between 2004 and 2017, PARIS-IR was a part of the annual Canadian Arctic ACE/OSIRIS Validation Campaign, which takes place at the Polar Environment Atmospheric Research Laboratory (PEARL; 80.05°N, 86.42°W) located in Eureka, Nunavut. For the six-week duration of this annual campaign, from just after polar sunrise in late February through to the beginning of April, PARIS-IR recorded a solar absorption spectra every seven minutes, weather permitting. Due to ACE-FTS's orbit and the timing of the validation campaign, a significant number of measurements coincident both spatially and temporally have been made by ACE-FTS and PARIS-IR for this period each year. The focus of this study is the comparison, for validation purposes, of retrieved quantities of atmospheric trace gases obtained from most recent coincident measurements made by PARIS-IR and ACE-FTS in the Canadian high Arctic over the period spanning 2014 to 2017. Analysis of two particular greenhouse gases, N_2O and CH_4, forms the focus of this effort in comparing the two data products.

A3.8 Ground based and satellite borne observations of greenhouse gases at Sodankylä, Finland

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Sodankylä is one of the sites participating in the Total Carbon Column Observing Network (TCCON). The retrievals include column-averaged, dry-air mole fractions of carbon dioxide (XCO_2) and methane (XCH_4), based on measured solar spectra. Here we provide results of the ground based FTS measurements since early 2009 and comparisons with the satellite based data. The relevant satellite missions include the Greenhouse gases Observing SATellite (GOSAT), the Orbiting Carbon Observatory-2, (OCO-2), TROPOMI on board ESA's Sentinel-5P satellite and the Chinese TanSat mission. Comparisons with the GOSAT observations show good agreement: the relative difference in XCH_4 has been -0.07 +/- 0.02 % and the relative difference in XCO_2 measurements has been 0.04 +/- 0.02%. In addition to the FTS measurements we have also performed a series of AirCore launches since September 2013 to obtain accurate in-situ profiles from lower stratosphere and troposphere. The AirCore measurements are calibrated to the World Meteorological Organization in situ trace gas measurement scales. The accuracy of AirCore measurements of CO_2 and CH_4 is 0.05 %.

A3.9 Development of a portable, low-cost XCO_2 observation system using a grating spectrometer and analysis of observation results

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The ground-based observation of CO_2 column concentration which is performed by near-infrared spectroscopy of solar light is very important. To obtain the CO_2 column concentration, The TCCON uses a large FTS (Bruker 125HR wavenumber resolution ~ 0.01 cm-1), some groups uses a small FTS (Bruker EM 27 resolution 0.5 cm-1). Both of them had highly cost. In previous research, we used OSA (Optical Spectrum Analyzer wavelength swept type spectrometer, resolution 0.2 cm-1) to obtain the CO_2 column concentration with lower cost. FTS and OSA take several seconds to several minutes to interferometer drive and wavelength sweep, and disturbance due to the passage of thin clouds there between may cause distortion of the spectrum.

In this study, we use a small size fiber spectrometer of a commercially available array type infrared sensor (Ocean Optics, NIR Quest, 1557-1625 nm resolution 1.0 cm-1) and an equatorial mount for amateur astronomy (Kenko Sky Memo S). This system uses an array type sensor, there is an advantage in that the entire area can be measured instantaneously. It can be observed even in cloudy weather. The sun tracking device is simple and easy to observe even in unstable places such as ships and automobiles. It was realized with a budget of about 1.8 million yen for the whole system such as spectrometer and automatic equatorial mount. Since it is sufficient for a budget of 1/50 or less of the large FTS and about 1/10 of the small FTS, this compact apparatus can be arranged in a large number. We used this instrument to conduct continuous solar spectrum observations at Nagoya University during one-month, calculated the XCO_2 column concentration and analyzed the results.

Finally, we are expecting it is possible to analyze the dynamics of CO_2 in urban areas from multipoint observations and not only in satellite verification at various places.

B3.1 Time Series Analysis for the ACE-FTS and MIPAS CFC-11 and CFC-12 Data Products

Jason Zou[1], Kaley A. Walker[1], Patrick E. Sheese[1], Chris D. Boone[2], Gabriele Stiller[3] and Thomas von Clarmann[3].

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To progress from monitoring atmospheric composition to investigating and quantifying atmospheric changes, well-characterized measurements over many years are required. The long lifetime of the Atmospheric Chemistry Experiment (ACE) has provided more than a decade of composition measurements that contribute to our understanding of ozone recovery, climate change and pollutant emissions. To enable the generation of climate data records using multiple data sets, characterization of the differences between data sets is required. This study analyzes and compares the time series of chlorofluorocarbon (CFC) measurements from two infrared satellite sensors, the ACE-Fourier Transform Spectrometer (ACE-FTS) and the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS). The long-term trend as well as annual, semi-annual and quasi-biennial oscillation terms derived from each data set will be compared for different altitude and latitude regions.

B3.2 Study on the first ground-based FTS measurements at Beijing, China and comparisons with GOSAT and OCO XCO_2 data

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In this study, the first observation of ground-based Fourier Transform Spectrometer (FTS) in Beijing (40.057N, 116.275E) was carried out. The FTS system and retrieval strategy are discussed. The spectrum has been recorded from March 2006 to December 2017 based on the FTS. The GGG2014 code was used to XCO2 retrieval, which is the standard software used in the total carbon column observing network (TCCON). The first validation of GOSAT and OCO XCO_2 data was explored by comparison with the FTS retrieved XCO_2 data in Beijing.

B3.3 Evaluation of the seasonal cycle and variability of the trend from GOSAT methane retrievals

Ella Kivimäki*, Hannakaisa Lindqvist, Janne Hakkarainen, Marko Laine, Aki Tsuruta, Johanna Tamminen, GOSAT partners and TCCON partners

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In this study, we evaluate the seasonal cycle and variability of the trend of XCH_4 from three GOSAT XCH_4 retrievals: National Institute for Environmental Studies retrieval algorithm version 02.72 (NIES), RemoTeC CH_4 Proxy retrieval algorithm version 2.3.8 (RemoTeC Proxy) and RemoTeC CH_4 Full Physics retrieval algorithm version 2.3.8 (RemoTeC Full Physics) retrievals. To study the cycle and the trend, we apply the dynamical linear model (DLM), which models the cycle with harmonic components and is able to consider nonlinear trends. The evaluation is done at 15 Total Carbon Column Observing Network (TCCON) sites, from which eleven are at the Northern Hemisphere and four at the Southern Hemisphere. The evaluation at the TCCON sites is done for the time period from 2009 to 2015. In addition, we study the latitudinal dependence of the seasonal cycle and growth rate by comparing the three retrievals against each other at latitude bands between 45 S and 54 N. We also compare the growth rates at latitude bands against NOAA's Marine Boundary Layer (MBL) reference data. [1]

Our results suggest that NIES, RemoTeC Proxy and RemoTeC Full Physics retrievals can present the seasonal cycle and variability of the trend accurately, if there are sufficiently co-located soundings available throughout the year. We show that if the number of co-located soundings is sufficient, GOSAT can capture the seasonal cycle amplitude to within 5 ppb. Generally, the day of maximum methane concentration is captured better than the day of minimum methane concentration. At most TCCON sites, both days are captured to within one month for the three retrievals. At the latitude bands, the three retrievals and the MBL reference are generally agreeing better in the growth rate of XCH_4 in the Southern Hemisphere. The seasonal cycle of XCH_4 is in agreement between the GOSAT retrievals at most of the latitude bands, except in the tropics. Reasons for the differences in the tropics might be explained by the lack of data but also by differences in the locations of soundings processed by the retrievals. [1]

[1] Kivimäki, E., Lindqvist, H., Hakkarainen, J., Laine, M., Tsuruta, A., Tamminen, J., Detmers, R., Deutscher, N., Hase, F., Hasekamp, O., Kivi, R., Notholt, J., Pollard, D. F., Roehl, C. M., Schneider, M., Sha, M. K., Sussmann, R., Velazco, V. A., Warneke, T., Wunch, D., Yoshida, Y.: Evaluation of the seasonal cycle and variability of the trend from GOSAT methane retrievals, in preparation, 2018.

B3.4 Improving OCO-2 Northern High Latitude Retrievals Over Snow

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The impact of a changing climate on the carbon cycle at high northern latitudes is not well understood. Satellite measurements of CO_2 in the Arctic and Boreal regions can help with this but retrievals over snow-covered surfaces are complex. Due to the high albedo of snow in the O_2 A band (used by OCO-2 to determine surface pressure and the presence of clouds) soundings over snow are typically removed by pre-processor cloud screening. This limits the amount of OCO-2 measurements available at high northern latitudes, during the winter, early spring, and late fall, obscuring the seasonal cycle of CO2. To complicate matters further, the albedo of snow in the CO_2 bands is low, decreasing the signal to noise ratio (SNR) and increasing the error on the XCO2 measurement. However, the albedo of snow in the CO_2 bands varies with snow grain size and other factors, which might provide enough signal to reduce the error on CO_2 measurements made over some snow covered surfaces. In this study, we will first determine the criteria in the OCO-2 cloud screening that are responsible for filtering out measurements made over snow. Secondly, we will report on preliminary modifications to the OCO-2 retrieval algorithm that show improved results for selected cases for soundings over snow near high latitude TCCON validation sites.

B3.5 A real-time retrieval of greenhouse gases from portable, ground-based Fourier-Transform Spectrometers

Kang Sun*, Jonathan Franklin, Matthaeus Kiel, Steven Wofsy, Taylor Jones, Xiong Liu, and Kelly Chance

*University at Buffalo

Both existing and proposed future spaceborne greenhouse gas measurements rely heavily on ground-based total column measurements for validation and bias correction. The TCCON network has served as the global standard, but the TCCON sites are sparse and immobile, making it impractical to cover the full ranges of surface and atmospheric conditions observed by the satellites. We present a clean, modern, open-source retrieval for the portable Fourier-Transform Spectrometers (EM27/SUN) that enables virtualization and decision-making for the field operators in real time. An absorption coefficient look-up table (ABSCO) approach is implemented to generate spectroscopic data before the field deployment, leveraging the HITRAN Application Programming Interface (HAPI) package. Temperature, pressure, water vapor profiles are fetched from operational forecasts (e.g., North American Mesoscale Forecast System, NAM). The retrieval algorithm performs real-time quality control, applies DC correction to the interferogram, and calculates spectrum with Fast Fourier Transform. A nonlinear least-square fitting is implemented to retrieve columns of Oxygen, Carbon Dioxide, and Methane. The processing time is < 3 s per sounding on a consumer-grade laptop with similar algorithm physics in offline retrievals.

B3.6 Validation of Satellite Measurements with Portable Fourier Transform Spectrometers (EM27/SUN)

Nasrin Mostafavi Pak*, Jacob Hedelius, Jonathan Franklin, Taylor Jones, Sajjan Heerah, Harrison Parker, Elaine Gottlieb, Debra Wunch, Steven Wofsy, Paul Wennberg

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On July 11th 2017, the Orbiting Carbon Observatory-2 (OCO-2) nadir ground track passed through the north end of the South Coast Air Basin (SoCAB) in Southern California, USA. On that day, we deployed three low-resolution portable spectrometers (EM27/SUN) across the north end of the SoCAB, near I-210 highway, and measured time-resolved column-averaged dry-air mole fractions of CO_2 (XCO_2). The three instruments were distributed evenly between the Pasadena TCCON station to the West, and the OCO-2 measurement track about 50 km to its east. Measurements of XCO2 with the EM27/SUNs are compared with the OCO-2 retrieved values at the time of the overpass, with a particular focus on the east-west gradients within the SoCAB. We use these gradients to investigate the contrast in XCO_2 between the urban central part of the SoCAB and the more rural East.

On January 26th 2018, both OCO-2 and the Greenhouse Gases Observing Satellite (GOSAT) made observations in Boston, MA, USA. We deployed four EM27/SUN instruments in the area on that day: one instrument was deployed in Harvard Forest approximately 20 km east of the OCO-2 measurement track, and the other three instruments were deployed downwind of the Harvard Forest on the east end of the Greater Boston Area. GOSAT collected target-mode measurements that were coincident with two of the EM27/SUN locations: Harvard Forest and Harvard University. The measurements are used to compare XCO_2 retrieved values from the satellites and the EM27/SUN spectrometers. In addition, we use the measured XCO_2 values from the upwind site and the three downwind sites to estimate CO_2 enhancements from the Boston area.

B3.7 Comparison of atmospheric CO_2 column measurements at high latitudes from ground-based and satellite-based methods

Nicole Jacobs*, William Simpson, Thomas Blumenstock, Manvendra Dubey, Frank Hase, Rigel Kivi, Greg Osterman, Harrison Parker, Qiansi Tu, Debra Wunch

*University of Alaska Fairbanks

Total column measurements of carbon-dioxide (CO_2) from the Orbiting Carbon Observatory-2 (OCO-2) satellite have been validated at mid-latitudes by comparison to the Total Carbon Column Observing Network (TCCON), but there are still a limited number of sites providing high-latitude validation data for satellite observations of CO_2, and no TCCON sites in Alaska. To understand the global distribution of CO_2 sources and sinks, it is essential that we increase the abundance of high-latitude satellite validation data. Total-column observations from ground-based infrared spectroscopy are highly comparable to OCO-2 satellite observations, which use infrared spectroscopy to measure the total atmospheric column from space. By comparing ground-based and satellite-based observations of CO_2 in central Alaska, we can determine whether significant disparities exist amongst these different observation methods and quantify biases. A careful comparative analysis may elucidate important characteristics of ground-based and satellite-based column measurements that would allow for improved methodologies in future measurements to enhance agreement amongst different types of high-latitude CO_2 measurements.

In August of 2016, we began the Arctic Mobile Infrared Greenhouse Gas Observations (AMIGGO) campaign in the Boreal Forest region around Fairbanks, Alaska with the goal of satellite validation and measurement of natural ecosystem fluxes across large transects at high-latitudes. In this campaign, we used the EM27/SUN mobile solar-viewing Fourier-transform infrared spectrometer (EM27/SUN FTS) then retrieved the total CO_2 column and column-averaged dry-air mole fraction of CO_2 (XCO_2) with the GGG2014 algorithm. The EM27/SUN FTS was designed by Bruker in collaboration with the Karlsruhe Institute of Technology (KIT) (Gisi et al., 2012, doi:10.5194/amt-5-2969-2012) and has been deployed in urban areas to measure anthropogenic fluxes of CO_2, CH_4, and CO. To evaluate the EM27/SUN performance, co-located observations were made with two EM27/SUN spectrometers, and we found that XCO_2 differed consistently by ~0.06% or ~0.24ppm. Five days of EM27/SUN observations coincident with OCO-2 targeted overpasses collected between May and July 2017 in central Alaska showed that after bias-corrections and recommended OCO-2 quality filters OCO-2 measured higher XCO_2 than the

EM27/SUN FTS by ~2 ppm on average. We will present an exploration of the distribution OCO-2 parameters for quality filtering of satellite-based measurements at high latitude Boreal forest sites including Fairbanks, Alaska, East Trout Lake, Saskatchewan, and Sodankyla, Finland that evaluates target, glint, and nadir soundings coincident to ground-based column measurements, as well as long term trends in CO2 observations at these sites.

B3.8 COCCON - a framework for operating the EM27/SUN spectrometer

Omaira García*, F. Hase, M. Frey, D. Dubravica, J. Groß, T. Blumenstock, Q. Tu, J. Orphal, A. Dehn, P. Castracane, A. Butz, R. Kleinschek, A. Luther, J. Chen, R. Harig, G. Surawicz, W.R. Simpson, N. Jacobs, M. Grutter, W. Stremme, N. Jones, D. W. Griffith, G. Mengistu Tsidu, K. Shiomi, I. Morino, H. Ohyama, S. Wofsy, O. Garcia, D. Pollard, M. Dubey, D. Wunch, P.O. Wennberg, M.K. Sha, H. Gadhavi, D. Ene, M. Ramonet, Y. Sun, and H. Boesch

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We will outline the development of a portable FTIR spectrometer for measuring column-averaged abundances of carbon dioxide and methane (commercially available from Bruker Optics today, type designation EM27/SUN). We will explore the performance of the novel device, which turns out to be adequate for supplementing the TCCON (Total Carbon Column Observing Network) by providing long-term measurements at remote locations. Moreover, the application of several spectrometers in an area of interest allows the quantification of local sources as cities, landfills, coal mine exhausts, etc., from differential upstream-downstream column observations. We will provide several application examples. We will introduce the concept of the COCCON (Collaborative Carbon Column Observing Network), which offers a framework for standardized, quality-controlled operation of the EM27/SUN spectrometer.

B3.9 Retrieving CO_2 profiles from TCCON near-infrared spectra

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The Total Carbon Column Observing Network (TCCON) is composed of high-resolution ground-based Fourier transform Infrared (FTIR) spectrometers that record solar absorption spectra. Column-averaged dry-air mole fractions of CO_2 (XCO_2) are retrieved from the recorded spectra and used to validate satellite observations of XCO_2 and to study the carbon cycle.

Even though TCCON XCO_2 observations are precise, they currently make no attempt to extract information about the vertical distribution of CO_2 in the atmosphere, which is of interest for the validation of satellite measurements and model simulations.

GFIT is a non-linear least-squares spectral fitting algorithm used for TCCON retrievals. Amongst other parameters, volume mixing ratio scale factors are retrieved for several gases. A single scale factor scales the a priori concentration profile of each fitted trace gas, thus it does not change the shape of the profile.

GFIT2 is a profile retrieval algorithm that allows the profile shape to vary during the retrieval process. The algorithm thus has more freedom to fit the observed spectra, but is also more sensitive to uncertainties in the forward model calculations such as spectroscopic errors and instrument misalignment, for example.

To exploit different sources of vertical information, CO_2 profiles were retrieved from spectral windows centered at 1.58, 1.61, 1.65, and 2.06 µm. Steps to improve the forward model of GFIT2 will be presented, as well as a method that attempts to account for remaining errors, and to combine the profiles retrieved from the different windows.

C3.1 Atmospheric CO_2 Concentration Measurements to Cloud Tops from an Airborne Lidar during 2017 ASCENDS Science Campaign in Alaska

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Globally distributed atmospheric CO_2 concentration measurements with high precision, low bias and full seasonal sampling are crucial to advance carbon cycle sciences. However, two thirds of the Earth's surface is typically covered by clouds, and passive remote sensing approaches from space are limited to cloud-free scenes and to the time when surface reflected sunlight is sufficient. NASA Goddard is developing a pulsed, integrated-path differential absorption (IPDA) lidar approach to measure atmospheric column CO_2 concentrations, XCO_2, from space as a candidate for NASA's ASCENDS mission. Measurements of time-resolved laser backscatter profiles from the atmosphere also allow this technique to estimate XCO2 and range to cloud tops in addition to those to the ground with precise knowledge of the photon path-length.

We demonstrate this measurement capability using airborne lidar measurements from summer 2017 ASCENDS airborne science campaign in Alaska. It is the first time that our airborne lidar measurement was extended to the Arctic region where atmosphere is more dynamic and measurement conditions are more challenging. We show retrievals of XCO_2 to a variety of cloud tops in addition to those to the ground. We 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.

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.

C3.2 Methane Monitor: An Airborne, Wide-Swath, Methane Mapping InstrumenT

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*Ball Aerospace & Technologies

Ball Aerospace flew its Methane Monitor system in the San Juan basin of Colorado and New Mexico in February 2018. The primary campaign objective was to map methane from compressor facilities in a joint effort with Colorado State University. Secondarily, the team took advantage of the opportunity to map a section of the Fruitland Outcrop, a region known for its natural methane seeps. Our presentation will cover some of our early findings from both industrial and natural sources in that region. The Methane Monitor is a differential absorption lidar system that measures the total column density of methane from an airplane flying 1,000 meters above the ground. The instrument can measure plumes with emission rates on the order of 50 Standard Cubic Feet per Hour (SCFH) while maintaining sufficient dynamic range to capture the largest plumes. The instrument can measure concentration path lengths up to 100,000 ppm-m before saturating. (The highest concentration path length measured to date is about 60,000 ppm-m.)

Session 4: Greenhouse gas observations and studies to quantify hot spots and local/urban emissions

4.1 Comparing carbon dioxide enhancement from anthropogenic emissions observed by GOSAT and OCO-2

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The increasing of atmospheric CO_2 abundances is primarily induced by the anthropogenic emissions including fossil fuel combustion, cement production and other human activities. To monitor CO2 levels in the atmospheric, independent measurement, reporting and verifying are required, especially emissions in urban areas.

The satellite observation of CO_2 gives us an important way to obtain accurate global and regional measures of CO_2 variations. Current orbiting satellites for greenhouse gas observation like Greenhouse gases Observing SATellite (GOSAT) and Orbit Carbon Observatory-2 (OCO-2) have been providing global measurement of column averaged dry air mole fraction (XCO_2). We collected XCO_2 data retrieved from GOSAT and OCO-2 observations in the study areas of urban intensive regions such as urban agglomerations around Beijing in northern China and around New York in eastern USA, aiming to quantify the enhancement from anthropogenic emission using the regional contrast method between emission and background. Our results indicate that OCO-2 observations show higher sensitivity to CO_2 emission variation due to its high spatial resolution and spectral resolving power compared with GOSAT observations. Regionally elevated CO_2 originating from urban intensive areas, about 3 ppm, is detected by comparing XCO_2 observations with nearby background areas. And the enhancements of CO_2 significantly present seasonal variations due to seasonal activities of CO_2 release and uptake from biosphere.

This study demonstrates the sensitivity to CO2 emission variation and differences in anthropogenic emissions detected from different satellite observations, GOSAT and OCO-2. The CO2 signals from biosphere flux and transport flux remained in the regional contrasts should be removed by a proper and valid way in the future work.

4.2 Global XCO_2 anomalies: Direct space-based observations of anthropogenic CO_2 emission areas from OCO-2 and comparison with inventory-based estimates

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Anthropogenic CO_2 emissions from fossil fuel combustion have large impacts on climate. In order to monitor the increasing CO_2 concentrations in the atmosphere, accurate spaceborne observations - as available from the Orbiting Carbon Observatory-2 (OCO-2) - are needed. In our recent work

[Hakkarainen et al., 2016] we provided a new approach to study anthropogenic CO_2 emission areas by deseasonalizing and detrending OCO-2 XCO_2 observations for deriving XCO_2 anomalies. The spatial distribution of the XCO_2 anomaly matches the features observed in the maps of the Ozone Monitoring Instrument NO_2 tropospheric columns, used as an indicator of atmospheric pollution, as well as the features observed in the ODIAC emission dataset. In addition, the results of a cluster analysis confirmed the correlation between CO_2 and NO_2 spatial patterns.

In this work, we study this idea further and provide the global XCO_2 anomaly maps for three full years 2015, 2016 and 2017. The patterns observed in these maps are compared with inventory-based estimates given by the Lagrangian particle dispersion model FLEXPART driven by the high-resolution ODIAC emission dataset. We also analyze the changes observed in XCO_2 anomaly maps and compare these changes to the inventory-based estimates, as well as to the changes observed in other trace gases (NO_2 and SO_2).

Hakkarainen, J., I. Ialongo, and J. Tamminen (2016), Direct space-based observations of anthropogenic CO_2 emission areas from OCO-2, Geophys. Res. Lett., 43, 11,400 -11,406, doi:10.1002/2016GL070885.

4.3 Advances in Quantifying Power Plant CO_2 Emissions from Space

Ray Nassar*, Cameron MacDonald, Tim G. Hill, Chris McLinden, Debra Wunch, Dylan B.A. Jones, and David Crisp

*Environment and Climate Change Canada

In our earlier work, we presented the first estimates of CO_2 emissions from individual coal power plants from space, using Orbiting Carbon Observatory 2 (OCO-2) version 7 XCO_2 data. With OCO-2's limited imaging capability, we fit observations to a vertically-integrated Gaussian plume model to derive emission and uncertainty estimates. The method was first demonstrated on US coal power plants, which have detailed emission data available from the Environmental Protection Agency (EPA), then it was applied to international power plants where CO_2 emissions have larger uncertainties. Here we extend our earlier work to present new estimates of power plant CO_2 emissions using the improved OCO-2 version 8 data, with a longer data record and the assistance of new prior emission information. We also discuss limitations, lessons learned and studies with simulated data that are relevant to the design of a future constellation for anthropogenic CO_2 emission monitoring.

4.4 Quantifying methane point sources from fine-scale (GHGSat) satellite observation of atmospheric plumes

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Anthropogenic methane emissions originate from a large number of relatively small point sources. There is considerable interest in developing the ability to quantify these sources from satellite observations of atmospheric methane columns. The 1-10 km pixel resolution of conventional methane observing satellites is too coarse to resolve individual methane point sources. GHGSat aims to fill this gap by measuring methane plumes over selected 12-km domains with an effective pixel resolution of 50x50 m^2 and 1-5% measurement precision. Our study develops an algorithm for retrieving point source emissions from such limited-domain, fine-resolution satellite observations of methane plumes. We conduct observing system simulation experiments using the Weather Research and Forecasting model (WRF) in large eddy simulation (LES) mode to simulate a large ensemble of plumes from point sources at GHGSat resolution and with representative noise. Several emission retrieval methods are evaluated, including Gaussian plume inversion, source pixel mass balance, cross-sectional flux estimates, and inference from the integrated mass enhancement (IME) of the plume. We show that the Gaussian plume method is unsuitable because the instantaneous plumes are too small to follow Gaussian statistics, and the source pixel method is unsuitable because winds across 50-m pixels are too variable. The IME method provides, by contrast, a robust approach to quantify point sources larger than ~0.5 tons h^{-1} based on knowledge of the 10-m wind speed from local measurements or meteorological databases. The cross-sectional flux method is similar to the IME method, but less robust.

4.5 First methane retrievals and hotspot identification with TROPOMI

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The Tropospheric Monitoring Instrument (TROPOMI) was successfully launched on October 13th, 2017 aboard ESA's Copernicus Sentinel-5 Precursor satellite. The spectrometer measures sunlight reflected by the Earth's surface and atmosphere in the ultraviolet, visible, near and short-wave infrared spectral range. From these measurements, concentrations of key atmospheric species are determined for monitoring air quality, climate and the ozone layer on a global daily basis with unprecedented combination of spatial resolution and spatial coverage. In this work, we present the first results on methane retrievals using TROPOMI measurements in the short-wave infrared band around 2.3 microns. We retrieve the column averaged dry air volume mixing ratio of methane while accounting for atmospheric scattering with the RemoTeC algorithm that employs the so-called full-physics approach. This algorithm was developed by SRON as the operational methane retrieval algorithm for TROPOMI. We compare our results with the proxy methane product from the Japanese GOSAT satellite that SRON delivers in the context of the Copernicus Atmospheric Monitoring Service (CAMS). Although different spectral ranges and retrieval methods are used, we find excellent agreement between the methane products obtained from the two satellites. Our results capture the latitudinal gradient and show expected regional and local enhancements. As a first case study, we focus on the US region where we have performed preliminary TCCON validation and show local methane enhancements and comparing them against emission databases.

4.6 Detection of local CH_4 sources using the WRF-CHEM model and TROPOMI XCH4

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The TROPOspheric Monitoring Instrument (TROPOMI) promises to greatly improve our capability to measure atmospheric constituents, such as O_3, CH_2O, NO_2, CO, CH_4 and SO_2, at an unprecedented combination of resolution, coverage and precision. One of the exciting prospects of TROPOMI is the detection of local CH_4 sources. Each pixel of TROPOMI is 7x7 km resolution which can allow detection of strong local sources of CH_4 of ~100kt/yr (in single overpass) to ~20kt/yr (after averaging).

Recent studies have shown that reducing CH_4 emissions from local sources can help to achieve short-term climate change mitigation targets. Many of these local sources are controlled or accidental releases from the natural gas industry which are also economically unfavorable. Hence, there is a substantial interest from the industry in the detection and quantification of their local CH_4 emission.

We show results from the first analysis of TROPOMI XCH_4 measurements to investigate its capability to detect local CH_4 sources. The observed CH_4 enhancements are further analyzed using WRF-CHEM model simulations of CH_4 to relate existing source estimates to TROPOMI observed signals, and to take into account the role of atmospheric transport.

4.7 CO_2 emissions from power plants derived from the Ozone Monitoring Instrument NO_2 dataset

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Environment and Climate Change Canada

With the Ozone Monitoring Instrument (OMI) annual NOx (NO_2+NO) emissions can be accurately estimated for individual, isolated power plants. NO_x is a good tracer for anthropogenic CO_2 emissions, as the largest part of tropospheric NO_x originates from the combustion of fossil fuel, it has a relatively short lifetime (of a few hours), and in areas near emission sources the vertical column densities exceed the background by as much as on order of magnitude.

Emission ratios of NO_x:CO_2 are derived from in-situ measurements at North American power plants, using the Continuous Emission Monitoring System (CEMS), Greenhouse Gas Emissions Reporting Program (GHGRP), and the National Pollutant Release Inventory (NPRI) datasets. This ratio was found to be between 0.001 and 0.003 for facilities emitting at least 5kt NO_x per year and linearly increasing with the NO_x emissions.

Annual CO_2 emissions can be estimated from the OMI NO_x emissions and the linear NO_x:CO_2 ratio. These estimates are in good agreement with CO_2 emissions using a site-specific ratio (from CEMS, GHGRP and NPRI), as well as OCO-2 derived emissions [Nassar et al., 2017], and the Open-source Data Inventory for Anthropogenic CO_2 (ODIAC) emission inventory for US plants.

To provide a better understanding of CO_2 emissions from power plants globally this NO_x:CO_2 ratio can also be applied to sources outside of North America, which especially proves to be valuable in areas that are not well monitored. As an example, we found that our estimates for power plants in Matimba (South Africa) and Sasan (India) are in good agreement with the CO_2 emissions derived from OCO-2 [Nassar et al., 2017].

Nassar, R., Hill, T. G., McLinden, C. A., Wunch, D., Jones, D. B. A., & Crisp, D. (2017). Quantifying CO_2 emissions from individual power plants from space. Geophysical Research Letters, 44, 10,045_Ñ_10,053. https://doi.org/10.1002/2017GL074702.

A4.1 Benchmarking chemistry-climate model top-of-atmosphere flux in the 9.6 micron infrared ozone absorption band with comparisons to satellite observations

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The 9.6 micron infrared absorption band of ozone is the primary contributor to long wave radiative forcing by tropospheric ozone, the 3rd most important greenhouse gas. Biases of present day top-of-atmosphere (TOA) flux for the 9.6 micron ozone band, which is predicted by IPCC chemistry-climate models, have never been evaluated with measurements and these biases impact estimates of ozone radiative forcing (RF) from pre-industrial to present day. Satellite measurements of TOA spectral radiances and ozone profiles allow evaluation of the performance of chemistry-climate models for both TOA flux and Instantaneous Radiative Kernels (IRK), which give the sensitivity of TOA flux to changes in the vertical distribution of atmospheric state, e.g. tropospheric ozone, water or temperature. Changes in the atmospheric state can then have a feedback effect on ozone radiative forcing by altering the sensitivity of TOA flux to ozone.

We compute the ozone band flux and the IRK, from Aura-TES and MetOP-IASI and SNPP-CrIS Fourier Transform spectrometer (FTS) measurements. The IRKs from spectrally resolved radiances explicitly account for more dominant radiative processes such as clouds and water vapor, due to the spectrally resolved absorption features, and allow attribution of changes in ozone RF to vertical changes in ozone and ozone precursor emissions. The continuation of the TES record of infrared ozone spectra and corresponding IRK with long-term IASI and CrIS data will allow accurate predictions of future ozone forcing and an assessment of the feedback from changes in the hydrological cycle on ozone RF. We use these IRK to evaluate the TOA flux bias in a suite of chemistry-climate models in terms of ozone, temperature, and water vapor. We show that the spatial pattern and the sign of these biases differs significantly between models. This evaluation suggests opportunities for model improvement in climate sensitive regions.

A4.2 First year results of the Fiducial Reference Measurements for GreenHouse Gases (FRM4GHG) intercomparison campaign performed at the Sodankylä TCCON site

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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 covering all seasons. In addition, regular AirCore launches are performed from that site which provide in-situ reference profiles of the target gases; this is useful for the verification of the instrument calibration. As the first year (2017) of the FRM4GHG campaign provided a significant dataset of CO_2, CH_4 and CO measurements from March to October 2017. It has been extended for performing another year of measurements in 2018. The campaign gave an important contribution for the assessment of small and mobile spectrometers for GHG measurements and demonstrated that small and mobile instruments can be used reliably. The extended campaign will also provide a significant dataset for validation of satellite and model data, and in particular for the validation of Sentinel-5P during its commissioning phase. The outcome of the campaign will then be a guideline for the further deployment of low-cost portable instruments at new observation sites to complement the TCCON network and better support the validation of the existing and future satellite missions and models.

This presentation will discuss the campaign objectives and its set-up, the results of the first year of measurements performed in 2017 and an overview of the extension of the campaign in 2018.

A4.3 The SACH4 project: Source Attribution of CH_4 using satellite observations, isotopic measurements and GEOS-Chem simulations

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The SACH4 project's main objective is to improve our current understanding of the balance between the sources and sinks that shape the CH_4 distribution. We use BIRA-IASB IASI CH_4 satellite observations together with GEOS-Chem tagged simulations to examine the contribution from different source regions to the total budget of CH_4. In addition, we investigate the possibility of retrieving the isotopic concentrations of CH_4 from ground-based FTIR measurements, to give additional information about the sources and reaction pathways.

For this symposium we will present first results of the comparison between IASI upper tropospheric CH_4 and GEOS-Chem tagged simulations on a global scale. These results will be complemented by ground-based FTIR measurements of methane. This study will allow us to quantify source region contributions to regional and global CH_4 concentrations and quantify unidentified source regions.

B4.2 The TROPOMI CO data product: Monitoring pollution with daily global coverage and high spatial resolution

Tobias Borsdorff*, Joost aan de Brugh, Haili Hu, Otto Hasekamp, Ralf Sussmann, Markus Rettinger, Frank Hase, Jochen Gross, Matthias Schneider, Omaira Garcia, Wolfgang Stremme, Michel Grutter, Dietrich G. Feist, Martine De Maziere, Mahesh Kumar Sha, David F. Pollard, Matthäus Kiel, Geoffrey C. Toon, Paul O. Wennberg, Jochen Landgraf

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ESA's Sentinel-5 Precursor mission with the Tropospheric Monitoring Instrument (TROPOMI) as its single payload was successfully launched on 13th October 2017. The spectrometer measures earthshine reflectance spectra from the ultraviolet (UV) to the shortwave infrared (SWIR) spectral region and one of the primary targets of the mission is to monitor the atmospheric trace gas carbon monoxide (CO) with unprecedented daily global coverage and a spatial high resolution of 5.5 7.5 km2. CO is emitted by incomplete combustion to the atmosphere. It is known as an indirect greenhouse gas because through its reaction with the atmospheric OH radical, it regulates the atmospheric lifetime of methane and other strong greenhouse gases. Furthermore, it is an important precursor of tropospheric ozone and so influences air quality. In this study, we present first results of the TROPOMI CO data product showing the ability of the instrument to detect weak pollution signals above mega cities with only single orbit overpasses. Moreover, due to its moderate lifetime CO can be used to track the transport of pollution from e.g. biomass burning in Africa and Madagascar with daily resolution on regional and global scales. We validate the TROPOMI CO total columns with independent observations at nine ground-based Fourier-transform spectroscopy stations operated by the TCCON network and compare the TROPOMI product with the ECMWF-IFS model results on a global scale.

B4.3 Greenhouse gas emission from megacities observed by GOSAT TANSO-FTS

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To meet an increasing demand for monitoring the anthropogenic emission of greenhouses gases from large cities, GOSAT has carried out extensive target mode observations since 2016. In this observation mode, GOSAT covers a target city with a dense matrix of sampling points, the number of which is up to 17, using the agile pointing mechanism of TANSO-FTS. Another advantage of TANSO-FTS is that it has spectral windows in both SWIR and TIR, making it sensitive not only to the column amount, but

also to the vertical profile of carbon dioxide and methane. Information on the vertical profile is useful especially for estimating the surface flux of the greenhouse gases from megacities.

For some selected megacities including New York City, Delhi, and Mumbai, we retrieved concentrations of carbon dioxide and methane from TANSO-FTS measurements in both SWIR and TIR. Our retrieval algorithm was developed by adding a TIR module to the existing SWIR algorithm of Kikuchi et al. (2016). To represent the vertical profile of gas concentrations, we used 5 layers in total, with 2 layers in the troposphere.

We estimated the surface flux of carbon dioxide and methane from the retrieved gas concentrations using a simple 1-dimensional steady state model. In this model, we assumed that the surface flux was uniform within a city, and that the wind blew with a constant velocity. Under these assumptions, the surface flux is proportional to the gradient of the gas concentrations along the wind direction.

From the gradient of the retrieved gas concentrations and the wind velocity of the NCEP data, we obtained the surface flux of carbon dioxide and methane from megacities. We found that in many cases the surface flux derived in this way is comparable to that of the emission inventory such as EDGAR. In addition to the 1-dimensional model, a time-dependent 2-dimensional model is now under investigation, which would further improve the estimates of the surface flux.

B4.4 Analysis on possible anomalous regional emission and absorption events of greenhouse gases with GOSAT and OCO-2

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Global observation of greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4) with high spatio-temporal resolution and accurate estimation of sources and sinks are important to understand greenhouse gases dynamics. Greenhouse Gases Observing Satellite (GOSAT) has observed column-averaged dry-air mole fractions of CO_2 (XCO_2) and CH_4 (XCH_4) over 9 years since January 2009 with wide swath but sparse pointing. The GOSAT conducts strategic target observations frequently as well as grid pattern observations every 3 days over megacities and possible emission sources. Orbiting Carbon Observatory-2 (OCO-2) has observed XCO2 jointly on orbit since July 2014 with narrow swath but high resolution. The OCO-2 is operated with a 16-day (233-revolution) repeat cycle, thus there also exist finer-resolved observations over megacities.

We use satellite observed XCO_2 and/or XCH_4 datasets with GOSAT and OCO-2, and TCCON ground-based observation dataset. Curve fitting method and harmonic analysis are applied to time series of XCO_2 and XCH_4. The smoothed curve, trend, detrended seasonal cycle, and growth rate are calculated and compared among datasets. The purpose of this study is to detect typical time series variation and anomalous emission and absorption events on a regional scale.

Possible cause estimations of extracted anomalous events are also performed in order to validate the change of anthropogenic or biogenic effects. Solar-induced chlorophyll fluorescence (SIF) from satellite observation and Open-source Data Inventory of Anthropogenic CO_2 emission (ODIAC) datasets are used in this study. Additionally, XCO (column-averaged dry-air mole fractions of carbon monoxide) observed by Terra/MOPITT dataset is utilized to conduct correlational analysis between XCO and XCO_2 to distinguish fossil fuel combustion. This analysis could be a preliminary analysis of GOSAT-2, which will observe XCO_2, XCH_4 and XCO.

B4.5 CO_2 emissions from anthropogenic and fire activity based on SCIAMACHY, GOSAT and OCO-2

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Anthropogenic CO_2 emissions from fossil fuel combustion and fire CO_2 emissions from biomass burning both have large impacts on climate. The spatial distributions and temporal variations of atmospheric CO_2 concentrations are significantly affected by the anthropogenic and fire activity worldwide. This study explored the correlations between the changes of CO_2 concentrations and anthropogenic CO_2 emissions and fire CO_2 emissions in human and fire-dominated regions in Asia. The used available spaceborne observations included the SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY (SCIAMACHY), The Greenhouse gases Observing SATellite (GOSAT) and Orbiting Carbon Observatory-2 (OCO-2). The seasonal cycle and interannual variations of column-averaged volume mixing ratios of atmospheric carbon dioxide (XCO_2) over the main pollution regions (North China) and fire-affected regions (Southeast Asia) were analyzed from 2003 to 2017. The XCO_2 anomaly in different regions from the three datasets were derived by detrending the SCIAMACHY, GOSAT and OCO-2 XCO_2 observations. Results showed the spatial distribution of the XCO_2 anomaly corresponded well with the features observed by the Ozone Monitoring Instrument NO_2 tropospheric columns, used as an indicator of atmospheric pollution. We found strong positive correlation between XCO_2 anomalies and emission inventories after cluster analysis in both North China and Southeast Asia. The results demonstrate the ability of spaceborne data for monitoring CO_2 emissions and provide an insight in information on the interannual variability of land-atmosphere exchange over anthropogenic and fire affected regions.

C4.1 Temporal and spatial variability of methane over Alberta as observed from space

Heba Marey*, Zaher Hashisho, Long Fu

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This study aims to assess the CH_4-levels in Alberta, based on total column data measured by the Atmospheric Infrared Sounder (AIRS) on the EOS/Aqua satellite from 2003 to 2013. Space-borne measurements by AIRS provide a global view of CH_4 distribution in the mid-upper troposphere. Land cover and meteorological data sets, were also used in this study. The results show that, the temporal variations of the CH_4 levels demonstrates a significant rise in the last ten years. This ascending trend is consistent with the increase of global CH_4 levels in the same time period. However, the abrupt CH_4

concentration increase in 2010 coincides with the significant change in economic activities during that time period. The monthly averaged variability of CH_4 over Alberta fluctuates, with a peak occurring in August, which is probably driven by enhanced convection. Spatial distributions of CH_4 reveal a strong west-east gradient with maximum levels in northern regions (55-65 N). The enhanced summer levels over northern and eastern regions suggest possible pathways for CH_4 emitted from natural sources (wetlands, lakes and permafrost) in high northern latitude regions and Canadian wetlands (e.g. Hudson Bay wetland). Since some of the wetland CH_4 fluxes are collocated with large anthropogenic sources, so it is difficult to disentangle various sources. Thus, further studies about CH_4 emission and transport over Alberta are recommended to reduce the uncertainties about the natural and anthropogenic contributions of Alberta to Canada's CH_4 emissions.

C4.2 Finding emission sources with lightweight data driven modeling

Jouni Susiluoto*, Alessio Spantini, Heikki Haario

Lappeenranta University of Technology / Massachusetts Institute of Technology

The OCO-2 satellite has provided valuable data now for three years with a global coverage of the planet. While this data is a valuable source of information regarding emission sources, it has also several limitations, such as temporal and spatial sparsity. We present ongoing work, where we attempt to extract information such as locations of major emission sources without the use of computationally expensive dynamical models.

C4.3 A methodology for characterizing methane emissions from urban and oil and gas producing regions using a methane column imaging satellite

Joshua Benmergui*, Steven C. Wofsy, Steven Hamburg, Ritesh Gautam, Kang Sun

*Harvard University

Emerging satellite technologies promise to provide high resolution images of total column methane. Such observations could be used to identify and quantify emissions with an unprecedented combination of detail and coverage. In this study, we designed and tested an algorithm that takes in a satellite image of total column methane and outputs a characterization of emissions. The algorithm uses image processing techniques to find the locations of large emissions sources. It then uses these locations as prior information in a geostatistical inverse modeling framework to simultaneously estimate the large emitters and the field of smaller emitters. The optimized emissions are attributed to sources, both directly and statistically, by linking the optimized emissions to infrastructure databases. We tested the algorithm using simulated scenes of the MethaneSAT concept in Dallas-Ft. Worth, San Francisco, Indianapolis, Prudhoe Bay, London, and the Gulf of Mexico.

C4.4 The ODIAC - A global monthly high-resolution fossil fuel CO_2 emissions data product for tracer transport simulations and surface flux inversions

Tomohiro Oda*, Shamil Maksyutov, Lesley Ott, Miguel Roman, Zhousen Wang, Thomas Lauvaux, Sha Feng, Sally Newman, Rostyslav Bun, Steven Pawson

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The Open-source Data Inventory for Anthropogenic CO_2 (ODIAC) is a global, monthly, high resolution gridded data product for fossil fuel carbon dioxide (CO_2) emissions. The ODIAC was primarily designed to prescribe high-resolution CO_2 transport model simulations for inverse flux calculations, especially using data collected by carbon observing satellites such as the Japanese Greenhouse gas Observation SATellite (GOSAT) and NASA's Orbiting Carbon Observatory 2 (OCO-2). Since its establishment in 2009, the ODIAC has been extensively used in global and regional flux inversions and also successfully applied to studies for localized emissions sources such power plants and cities. In this presentation, we will present the current status of the ODIAC project, highlighting the recent ODIAC emission data production, the application of NASA's Visible Infrared Imaging Spectrometer Suite (VIIRS) Nighttime Environmental Product (nightlight), as well as extensive data evaluations.

C4.5 Comparing potential of a satellite constellation to monitor fossil fuel CO_2 emissions from large cities and industrial sites

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*LSCE

Reducing the emissions of the greenhouse gases (GHG) is considered one of the most important environmental challenges of the 21st century to keep global warming below 2°C with respect to pre-industrial times. This objective implies use of independent observation systems to accurately monitor GHG emissions at spatial scales relevant to carbon policy. Low earth orbiting satellites can provide imagery of CO_2 concentrations at spatial scales as small as 2 x 2 km^2 ground pixel size at daily intervals over the globe, with a contiguous sampling over a 350 km-wide swath. Combining these data with inversion methods allows to give estimates of CO_2 emissions from large cities and industrial sites, and hence to evaluate the efficiency of CO_2 emissions reduction policies coming from fossil fuel combustion. This study compares the performance of 2 km resolution imagery of CO_2 concentrations from the shortwave-infrared measurements provided by various combination of low earth orbiting satellites to monitor the fossil fuel CO_2 emissions from main cities and large industrial sites throughout the globe. This comparison is based on Observing System Simulation Experiments (OSSEs) with an atmospheric inversion approach at local scale. The inversion system solves for hourly fossil fuel CO_2 emissions during the three hours before a given satellite overpass. These three hours correspond to the period during which emissions produce CO_2 plumes that can be identified on satellite imagery. The statistical framework of the inversion accounts for the existence of some prior knowledge about the hourly emissions from an inventory based on energy and carbon fuel consumption statistics. A Gaussian plume model is used to simulate the link between the hourly emissions and the vertically-integrated

columns of CO_2 concentrations observed by the satellites. Preliminary results indicate that the performance of the inversion system significantly increase as a function of the number of satellites.

Session 5: Flux inversions on regional and global scales

5.1 "Are we there yet?" A look at the status and prospects of inferring top-down carbon fluxes from CO_2 remote sensing

Christopher O'Dell*, Annmarie Eldering, David Crisp, David Schimel, Andrew Schuh, Sean Crowell, and Lesley Ott

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Over the past decade, satellite-based measurements of column-averaged carbon dioxide concentration, called XCO_2, have proliferated with sensors such as GOSAT, OCO-2, and TanSAT. Even more capable future systems are planned to launch both polar and geostationary orbits, in the hopes of using these measurements to answer fundamental questions about the carbon cycle and to possibly measure or even monitor anthropogenic emissions of CO_2. Previous work has shown that persistent spatiotemporal biases in satellite measurements of CO_2 can lead to spurious flux signals, when these measurements are assimilated into inverse carbon flux models. Coherent regional biases or transport errors of even 0.5 ppm out of the ~400 ppm background appear too large.

Such a tight requirement represents a daunting challenge for instrument calibration, retrieval algorithms, and tracer transport models alike. In general, rather than making either random errors or constant biases, these sources of error create patterns of uncertainty that can alias into the fluxes we are attempting to infer. In this talk I give a broad outline of the various challenges we face, focusing on the measurement of XCO_2 itself. It is found that while systematic errors have generally decreased over time because of improvements in spectroscopy, instrument characterization, and the retrieval algorithm itself, important systematic errors remain. I will close with an ambitious series of proposed OSSEs that may shed light on how far we have to go before we can infer regional and seasonal carbon fluxes of with confidence, based upon space-borne measurements of CO_2.

5.2 On the spatial scales informed by surface and GOSAT CO2 observations

Saroja Polavarapu*, Feng Deng, Brendan Byrne, Dylan B. A. Jones, Michael Neish

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In this work, we present a new way of assessing the spatial scales of CO_2 informed by posterior fluxes. Using the GEOS-Chem 4D-Var flux inversion system of Deng et al. (2014, 2016), we obtain two sets of posterior fluxes informed by either the surface in situ network, or by GOSAT observations. Then we compute the "flux signal" which is defined as the 3D CO_2 distribution obtained from posterior fluxes minus that obtained from prior fluxes. The flux signal reflects the impact of the observing system as manifested in the posterior fluxes convolved with a time history of atmospheric transport and is a function of the transport model as well as the prior fluxes. We use two different transport models (GEOS-Chem and GEM-MACH-GHG) to compute the flux signal in order to assess the sensitivity of results to transport model errors. Moreover, we are able to define a "minimum" transport error level as the change in CO_2 distributions arising from imperfect wind fields by repeating simulations with perturbed wind fields from the ECCC operational ensemble Kalman filter system. It is only when this minimum transport error level is exceeded that we trust the flux signal. For in situ-informed fluxes, we find that in the lower troposphere, zonal asymmetries in the flux signal exceed that arising from meteorological uncertainties only in boreal summer. However, GOSAT-informed fluxes produce zonally asymmetric structures that exceed this minimum error year-round in the tropics and in the northern extratropics in all seasons except boreal winter. GOSAT-informed fluxes also better capture the seasonal cycle of CO_2 in the northern extratropics, but using in situ data yields better a match to independent observations on the global, annual scale. Such complementarity of the observing systems can be exploited in greenhouse gas data assimilation systems.

5.3 GOSAT CO2 Inversion Inter-comparison Experiment Phase-II: intermediate progress report

Hiroshi Takagi[1], Sander Houweling[2], Shamil Maksyutov[1], David Baker[3], Frederic Chevallier[4], Feng Deng[5], Liang Feng[6], Fei Jiang[7], and Julia Marshal[8]

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Atmospheric inversion techniques have been utilized for estimating the space-time distribution of GHG surface fluxes in gaining insight into how anthropogenic activities modify the stocks and flows of carbon over the globe. To make further progress in the effort, it is essential to evaluate, quantify, and subsequently reduce the uncertainties in the flux estimation process. Inter-comparisons of existing atmospheric inversion systems as well as their components provide the opportunity to investigate the uncertainties. In the late 1990s, the TransCom model inter-comparison studies assessed the role of transport model uncertainties in flux estimation, and more recently, after the advent of satellites dedicated to GHG monitoring, the GOSAT inversion inter-comparison (Phase-I) evaluated the full uncertainty of GOSAT-based CO_2 flux estimation by allowing the study participants to use the inversion system, a priori flux dataset, surface CO_2 observation dataset, and GOSAT column-mean CO_2 (XCO_2) retrieval dataset of their choice.

Here, in the second phase of the GOSAT inversion inter-comparison, we explore differences among the existing inversion systems and evaluate their contribution to the uncertainties of flux estimates. For this, the participants used a common input dataset that consists of an a priori flux dataset, GOSAT XCO_2 retrieval dataset, and a surface CO_2 observation dataset. A common criterion for observation data filtering was also specified. The second phase study takes advantage of a 5-year-long analysis period (2009-2014) during which GOSAT XCO_2 retrievals are continually available, to assess the robustness of inversion-derived estimates of the impact of major weather anomalies on carbon fluxes. We contrast and characterize fluxes that are estimated from satellite and surface CO_2 data combined, satellite data only, and surface data only, respectively. Our latest results are presented.

5.4 The OCO-2 Level 4 Flux Product: The Global Carbon Cycle as Seen From Space

Sean Crowell*, Andrew Schuh, Sourish Basu, David Baker, Junjie Liu, FrÕ©dÕ©ric Chevallier, Liang Feng, Feng Deng, Andrew R Jacobson, Chris O'Dell, Annmarie Eldering, David Schimel, Michael Gunson, David Crisp

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With over three years on orbit, the OCO-2 mission is providing a mature, high precision data product consisting of column concentrations of CO_2. Numerous modeling teams have taken part in a large intercomparison project whose focus has been to assess the information content of OCO-2 data on regional flux estimates over and above obfuscating factors such as transport model uncertainty and instrument noise. Early results have shown that OCO-2 observations drive greater agreement between flux estimates than the global in situ network in regions such as the tropics.

In this presentation, we will introduce the official OCO-2 Level 4 Flux Product and show that OCO-2 detected an earlier ramp up in terrestrial emissions due to the 2015-2016 El Nino than that inferred by the global flask and in situ network. Additionally, we will show comparisons of posterior concentrations with measurements from the Total Column Concentration Observing Network (TCCON), observations from CONTRAIL, ACT America, and other aircraft campaigns, as well as surface measurements.

In addition to providing flux information in poorly constrained regions, comparisons between different observing modes of OCO-2 alongside in situ constrained inversions allow the science team to diagnose potential biases in the OCO-2 measurements. This feedback loop between the flux and retrieval communities has led to a quicker maturation of both processes than either on their own.

5.5 Role of Climate Variability and Land Use on Fire Emissions of Carbon Gasses in the 21st Century

John Worden*, Anthony Bloom, Yi Yin, Zhe Jiang, Helen Worden, Kevin Bowman, Junjie Liu, Sassan Saatchi, David Schimel

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Large scale reductions in biomass burning are observed across the globe from 2002 through the present through measurements of burnt area and carbon monoxide. These reductions are likely due to shifts in land-use changes as most declines are related to agricultural expansion. However, these reductions are in the context of environmental variability that can create dry conditions in Indonesia and the N. American Western states and possibly increased lightning in the Boreal forest that in turn can create large-scale fires. The changing character of fires has also altered the expected emissions. For example, emissions from fires in 2007 from South America were found to be larger than those in 2010 despite increased burnt area in 2010, likely because of changes in biomass density and combustion efficiency. Across the tropics, emissions in CO are decreasing faster than burnt area, also suggesting that the widespread shift in land-use is resulting in (not unexpectedly) changing fire combustion characteristics. Here we use data from the Terra MOPITT, Aura TES, OCO-2, and MODIS instruments as well as a state-of-the art land/atmosphere/ocean carbon cycle modeling data/model system to quantify emissions of carbon gasses using CO emissions and the range of emission factors up-scaled from vegetation type. We show that at least over the last two decades, until the 2015 El Nino, these changes in land-management practices has a substantial effect on the fire-component of global respiration that is larger in aggregate than environmental variability. We then examine how these constraints on fire emissions of carbon (CO_2, CH_4, and CO) affect our understanding of the other components of the carbon budget such as the global land sink of CO_2.

5.6 Evaluating GPP and respiration estimates over northern mid-latitude ecosystems using solar induced fluorescence and atmospheric CO_2 measurements

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On regional to global scales, few constraints exist on gross primary productivity (GPP) and ecosystem respiration (R_e) fluxes. Yet, constraints on these fluxes are critical for evaluating and improving terrestrial biosphere models. In this study, we evaluate the seasonal cycle of GPP and R_e produced by four terrestrial biosphere models and FLUXCOM (upscaled flux tower observations) over northern mid-latitude ecosystems. First, we evaluate the seasonal cycle of GPP using Solar Induced Fluoresence observations from GOME-2. We calculate an optimized R_e seasonal cycle by combining constraints on GPP with constraints on NEE from two flux inversions. Using this approach, we infer a seasonal cycle of R_e which has a systematically broader summer peak from early June through mid-August than R_e fluxes produced by FLUXCOM and the four terrestrial biosphere models. The results presented here show consistency between bottom up and top down estimates of GPP, but indicate systematic differences between bottom up and top-down (flux inversion based) estimates of R_e.

5.7 Detecting drought impact on terrestrial biosphere carbon cycle over US in the context of carbon-climate interannual variability

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Atmospheric inversion shows that North America (NA) terrestrial biosphere absorbs ~0.9±0.4 GtC/year from the atmosphere, offsetting ~25%-50% of the total NA fossil fuel emissions. However, the terrestrial biosphere carbon sink has large interannual variability that is closely related to the variability

of the physical climate system, especially drought and heat waves. With the projection of increasing drought and heat events in the future over NA, understanding how the natural carbon cycle responds to drought events is a prerequisite to predict the fate of land carbon sink and atmospheric CO_2 concentrations and climate. In this study, with satellite observations, we investigated the impact of 2011 and 2012 droughts on terrestrial biosphere carbon cycle over contiguous US (CONUS) in the context of carbon-climate interannual variability over 2010 and 2015. We quantified Net Biome productivity (NBP), and its components including Gross Primary Productivity (GPP), fire, and total ecosystem respiration (TER) with column CO_2 (XCO_2), Solar Induced Chlorophyll Fluorescence (SIF) from the Greenhouse Gases Observing Satellite (GOSAT), and CO observations from Measurements of Pollution in the Troposphere (MOPITT) using the NASA Carbon Monitoring System Flux (CMS-Flux) carbon cycle data assimilation system. We found that the anomaly of NBP and its component fluxes resulted from the 2011 and 2012 drought events showed similar spatial and temporal patterns as previous studies (Wolf et al., 2015), indicating the ability of satellite observations to detect drought impact on terrestrial biosphere carbon cycle. Over the drought-impacted region, the NBP decreased by 0.20±0.10 GtC and 0.23±0.16 GtC respectively in 2011 and 2012, with half the NBP reduction attributed to decrease of GPP and the other half attributed to increase of TER. We further showed that the drought impact on terrestrial biosphere carbon cycle occurred in the context of covariation between climate states (e.g., soil moisture and temperature) and carbon fluxes. On the interannual timescale, the soil moisture variability explains more than 80% of GPP variability while it explains 40% to 70% of NBP variability during summer, indicating the opposite effect of soil moisture on GPP and TER.

5.8 Anomalies in Chinese CO2 fluxes during 2015/2016 El Niño: Comparison between satellite and in-situ observation assimilation

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We report Chinese carbon dioxide (CO_2) flux estimates 2009-2016, inferred from GOSAT XCO_2 retrievals and newly available in-situ CO_2 mole fraction measurements using an ensemble Kalman filter. Our control in-situ inversion assimilates NOAA/ESRL data that is supplemented by additional data collected around mainland China, including Siberia, Japan and Hong Kong. We find the magnitude and distribution of the revised in-situ inversion are consistent with fluxes inferred from GOSAT (2009-2016) and OCO-2 (2014-2016) XCO_2 retrievals. During the 2015/2016 El Niño period, both the satellite and in-situ inversions show elevated uptake during the summer of 2015 (compared to previous summers), while being muted during summer months in 2016. This year-to-year variation is supported by GOSAT measurements of solar induced fluorescence. We use land-surface and correlative atmospheric remote sensing data to explore the relative importance of different processes associated with Chinese carbon cycle dynamics during the 2015/2016 El Niño period.

5.9 Reconciling satellite and in-situ estimates of North American methane emissions during the unconventional gas boom of 2007 - 2014

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There have been several studies of trends in methane emissions over North America over the recent period of rapid growth in unconventional gas production (2007 - 2014). Some studies that analyzed GOSAT observations have shown evidence of increasing emissions, while others called into question the ability of these studies to constrain the trends.

The effect of transport is a major source of the disagreement. To estimate emissions, one must distinguish local enhancements from background concentrations. Background methane concentrations are highly variable and sensitive to transport, because there is a sharp latitudinal gradient of methane concentrations. There is multi-year variability in mean transport due to teleconnections. If transport is not carefully considered in the calculation of background concentrations, then inter-annual variability in transport can alias the latitudinal methane gradient as a trend in emissions.

In this study, we estimated North American methane emissions for the period 2007 - 2014 using independent geostatistical inverse models of 1) GOSAT (for August 2009 - August 2014) and 2) surface and aircraft data (for January 2007 - August 2014). We used the WRF-STILT Lagrangian particle dispersion model to account for transport. For background concentrations for surface and aircraft data, we used the NOAA empirical boundary curtain. For background concentrations for GOSAT, we created a quantile regression model that incorporates the NOAA empirical boundary curtain and stratospheric methane concentrations from the CLAMS model. The optimized emissions agree well, and do not show a statistically significant trend on the continental or national scale.

5.10 Identifying leaky wells in oil/gas fields by satellite observation of atmospheric methane

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Oil/gas fields have thousands of wells. A small population of leaky wells can make up a large proportion of total emissions from the field. Here we examine the potential of recently launched or planned satellites to promptly identify leaky wells through monitoring of atmospheric methane, alone or supplemented by a surface observation network, in order to enable corrective action. We model atmospheric methane for a 1-week period (WRF-STILT simulation) with 1.3 x 1.3 km^2 resolution and for many random realizations of 100-500 oil/gas wells of different categories over a 70x70 km^2 field. Bimodal probability density functions (pdfs) for each well category are applied to simulate leaky wells. This atmospheric field is sampled with different satellite and surface observing configurations, and inverse modeling using either L-1 or L-2 norms as prior constraints is used to assess the ability of these different configurations for identifying the leaky wells. The L-1 norm performs consistently better for optimizing the bimodal distribution. We find that the recently launched TROPOMI instrument (low Earth orbit, 7x7 km^2 nadir pixels, daily return time) and the planned geoCARB instrument (geostationary orbit, 2.7x3.0 km^2 pixels, 2x or 4x/day return time) are unsuccessful at precisely locating the leaks, but are far more successful at locating them within a 5-km radius (24% false alarm ratio for TROPOMI, 6% for geoCARB). A next-generation geostationary satellite with 1.3x1.3 km^2 pixels, hourly return time, and 1 ppb precision would produce almost no false alarms. We compare satellite OSSEs to the detection capability of deploying 5-20 surface monitors in the same subdomain, and find that geoCARB is able to detect high mode emitters at almost nearly the same capacity as 5-10 surface monitors. Our results indicate that satellites can be a useful tool for interested parties to monitor the status of production sites and locate regions of anomalously high emissions.

B5.1 Broad-scale CO_2 fluxes given by inverting new (v8) retrievals of OCO-2 column CO2

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A new version (v8) of the Orbiting Carbon Observatory (OCO-2) column CO_2 retrievals has recent been released. The calibration, validation, and bias correction of the measurements have been improved, and the treatment of stratospheric aerosols that caused problems in ocean glint mode has been corrected. What do these new OCO-2 retrievals (especially those taken over the ocean) tell us about the broad-scale distribution of CO_2 flux? Here we estimate surface CO_2 fluxes with a variational data assimilation system based on the PCTM global off-line atmospheric transport model. Retrievals calculated over land and ocean with the old and new OCO-2 retrieval schemes (v7 & v8) are assimilated in separate experiments, with a set of four different ocean fluxes used as priors. The v7 and v8 land data give similar flux results for the large-scale seasonal and inter-annual variability. Both attribute the release of CO_2 seen globally across the 2015/2016 El Nino to the tropical land biosphere, as does the new v8 ocean glint data with the positive bias in the south corrected. However, the v8 ocean glint data also drive a shift in the annual mean fluxes towards a much stronger global ocean uptake, balanced by less land uptake, particularly in the tropics and south. The magnitude of the ocean uptake (~6 PgC/yr) as well as its location (much of it in the tropics) is implausible -- it is likely that substantial biases remain in the ocean glint data that must still be removed. One feature of the v8 ocean glint results that is intriguing, however, is an increase in the magnitude of the seasonal cycle of flux for the Southern Ocean, with greater uptake in the SH summer that agrees well with vertical gradients in the atmosphere found by the ORCAS campaign in early 2016. This greater SH summer uptake may be balanced by greater SH winter release of CO_2 there, as suggested by analysis of ocean data from the SOCCOM floats -- the little OCO-2 data at those latitudes in the SH winter cannot disprove this possibility when tested in the inversions. This balancing out-gassing, if it is real, would prevent the annual mean Southern Ocean uptake from growing much larger, which would in turn agree better with APO and ocean heat flux data, which suggest that there should be less CO_2 uptake by the SH oceans and more in the NH (Resplandy, et al, Climate Dynamics, 2016).

B5.2 A Comparison of Eddy Decompositions of TM5 and GEOS-Chem in CO2

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"Eddy decompositions of meridional tracer transport flow are useful tools to investigate the global mixing mechanisms at play in chemical transport model (CTMs). We compare two well-used CTMs, GEOS-Chem and TM5 by deriving the strength of meridional transport due to stationary and transient eddies, as well as mean meridional flux. A recently submitted paper documents large differences in column average CO_2 between the two transport models and we use these eddy decomposition derivations to help illuminate the mechanisms at play which result in those column differences.

B5.3 On what scales can GOSAT flux inversions constrain inter-annual variability in terrestrial ecosystems?

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We investigate the spatial scales over which inter-annual variability (IAV) in the terrestrial carbon cycle can be constrained using atmospheric CO2 observations from the Greenhouse Gases Observing Satellite (GOSAT). We estimate net ecosystem exchange (NEE) anomalies by performing a series of flux inversions assimilating GOSAT observations. We compare monthly NEE anomalies to "proxies", variables which are associated with IAV in the terrestrial carbon cycle. Strong correlations ($P<0.05$) are found between the flux inversions and proxies in the tropics on continental and larger scales, suggesting that GOSAT flux inversions can isolate IAV in NEE on these scales. We also find good agreement between the inversions and proxies in northern extratropics on sub-continental scales during the summer ($R2>0.6$). However, in both the tropics and northern extratropics, we find that agreement between the inversions and proxies is sensitive to the flux inversion set-up. In particular, we find that IAV in the prior fluxes significantly degrades agreement with the proxies.

B5.4 On the consistency of OCO-2 XCO_2 data from different observing modes and their application to atmospheric inversion analyses

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Satellite remote sensing of column-average concentrations of carbon dioxide (XCO_2) have been increasingly used to infer surface CO_2 fluxes through atmospheric inverse modeling. The accuracy of the XCO_2 data and the consistency between the different satellite observation modes are critical in determining the quality of the surface flux estimates inferred from the satellite measurements. Here, using the GEOS-Chem model we investigated the consistency in Version 8 XCO_2 between the different

observation modes from the Orbiting Carbon Observatory-2 (OCO-2). We then conducted a series of atmospheric inversions using various combinations OCO-2 XCO_2 data. We evaluated our inversion results using independent atmospheric CO_2 observations and assessed the impact of the consistency between the different subsets of the OCO-2 data on the inferred fluxes. We also examined the spatio-temporal distribution of the a posteriori fluxes with corresponding data that capture changing climatic conditions to further evaluate the added value of the different combinations of the OCO-2 data in the inversion analyses.

B5.5 The Impact of Accounting for 3-D CO_2 Production on Inversion for Natural Fluxes Using GOSAT and In Situ Observations

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Most atmospheric inversions for estimating natural carbon dioxide (CO_2) fluxes have placed CO_2 release from fossil fuel combustion and other sources entirely at the surface. However, a portion of fossil fuel and biospheric carbon emissions (~1 Pg C y-1) actually occurs in the form of reduced carbon species including carbon monoxide (CO) and volatile organic compounds (VOCs), which are eventually oxidized to CO_2 downwind of the emissions. As pointed out by a few previous studies, the typical assumption can result in a significant shift in the distribution of the posterior fluxes, e.g. a shift in the global sink from tropical land to the northern extratropics and from ocean to land. In this study, we estimate the effect of accounting for 3-D atmospheric CO_2 production on posterior natural fluxes during 2009-2010 using a global batch Bayesian synthesis inversion system based on the PCTM transport model, which has been applied previously to in situ and NASA ACOS GOSAT observations. We use the ODIAC high-resolution fossil fuel emission dataset as the baseline. We then apply period-specific 3-D CO loss rates archived from a state-of-the-art GEOS-5 chemistry and climate model simulation in a forward PCTM run to simulate the distribution of CO_2 originating from oxidation. To avoid double-counting, we subtract an amount from surface emissions equal to the CO_2 produced aloft. Inversions are then carried out using either the baseline atmospheric CO_2 distribution or the distribution that accounts for 3-D CO_2 production. We examine the differing regional impacts in the GOSAT and in situ inversions due to differences in the horizontal and vertical sampling of the two observation types.

B5.6 Opportunities and challenges of posterior CO_2 flux validation with aircraft CO_2 observations

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Validating posterior CO_2 fluxes from atmospheric inversion is challenging, since there are no direct flux observations that have comparable spatiotemporal resolution. Comparing CO_2 concentrations before and after atmospheric flux inversion against independent aircraft observations has been a standard practice to validate posterior fluxes. The utility of aircraft CO_2 observations to validate posterior fluxes has several

challenges, including representation errors in simulating aircraft observations with global transport model, and sparse aircraft CO_2 observations over most of the land region. In this study, we will validate posterior CO_2 fluxes constrained by OCO-2 with all the available aircraft observations in ObsPack. We will investigate the following questions: 1) What can the accuracy differences between posterior and prior CO_2 concentrations tell us about the accuracy of regional fluxes, and where? 2) What can the validation against aircraft observations tell us about the quality of assimilated satellite observations and which observations? 3) What are the observation gaps to validate fluxes over critical regions? In the end, we will discuss possible pathway forward.

B5.7 Satellite bias estimation by independent CO_2 inversion analysis

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In recent years, many greenhouse gas observation satellites have been launched and operated. 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 tried a method to evaluate bias of satellite observation data with independent inverse analysis data (JMA CO_2 distributions) without using satellite observation data. With regard to this satellite, since we can obtain long-term observation data from 2010 to 2016, 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 L2 Ver. 2.X) throughout the whole period was -1.2 ppm, 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 CO_2 flux analysis consistent with the conventional inverse analysis.

B5.8 Implications of Overestimated Anthropogenic CO_2 Emissions on East Asian and Global Land CO_2 Flux Inversions

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Measurement and modelling of regional or country-level carbon dioxide (CO_2) fluxes are critical for verification of the greenhouse gases emission control. One of the commonly adopted approaches is inverse modelling, where CO_2 fluxes from the terrestrial ecosystems are estimated by combining atmospheric CO_2 measurements with atmospheric transport models. The inverse models assume

anthropogenic emissions are known, and thus an uncertainty in the emissions would introduce systematic bias in estimated terrestrial (residual) fluxes by inverse modelling. Here we show that the CO_2 sink increase, estimated by inverse modellings, over East Asia (China, Japan, Korea and Mongolia) is likely an artifact of the a priori anthropogenic CO_2 emissions. The residual CO_2 sink increase by about 0.26 PgC yr-1 (1 Pg = 10^15 g) during 2001-2010 is calculated as the fossil fuel (anthropogenic) emissions increased too quickly in China by 1.41 PgC yr^{-1}. Independent results from methane (CH_4) inversion suggested about 41% lower rate of East Asian CH_4 emission increase during 2002-2012. We thus apply a scaling factor of 0.59, based on CH_4 inversion, to the rate of anthropogenic CO_2 emission increase. By doing that we find no systematic increase in land CO_2 uptake over East Asia during 1993-2010 or 2000-2009. High bias in anthropogenic CO_2 emissions also leads to stronger land sinks in global land-ocean flux partitioning in our inverse model. The corrected anthropogenic CO_2 emissions by CH_4 inversion results also produce measurable reductions in the rate of global land CO_2 sink increase post-2002, leading to a better agreement with the terrestrial biospheric model simulations that include CO_2-fertilization and climate effects.

B5.9 Radiance offset correction for observing SIF from GOSAT and inter-satellite comparison of the derived SIF

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In recent years, satellite observation of solar-induced chlorophyll fluorescence (SIF) has attracted attention as a method for estimating the photosynthetic capacity of plant canopies. Several studies retrieved SIF from high-resolution spectra in far-red domain obtained by the Greenhouse gases Observing SATellite (GOSAT). The retrieval principle was based on the filling-in of Fraunhofer line by SIF. Non-linearity of the analog circuit in GOSAT spectrometer adds zero-level offset to its spectra, having the same effect on the observed Fraunhofer line depth as SIF (retrieved signal = SIF + zero-level offset). Therefore, the zero-level offset correction becomes important to obtain the SIF accurately. We are planning to provide SIF as a new product for GOSAT-2. Although it is currently unknown that such correction is required for GOSAT-2 SIF retrieval, zero-level offset correction was tested using GOSAT data.

The zero-level offset can be evaluated from the retrieved signal over the areas where the value of SIF is expected to be zero. The filling-in signal was retrieved separately for P and S polarized components using the same method as the previous studies from GOSAT short-wavelength infrared spectra of L1B V201.202 product. We investigated the retrieved signal for clouds and bare soils and confirmed its applicability to evaluating the zero-level offset. The value and temporal-changing pattern of the zero-level offset differed between P and S polarized components. Therefore, zero-level offset correction was conducted separately for each component while considering offset's temporal change and dependence on the observed radiance. Evaluating the quality of satellite-derived SIF through comparison with SIF derived from ground observation, airborne observation, and other satellites is important to its usage in terrestrial carbon cycle study. Such evaluation is currently addressed by many research groups. We compared the derived SIF with Orbiting Carbon Observatory-2 (OCO-2) SIF product for local scale and global scale. For some specific locations, influence of difference in viewing angle between GOSAT and OCO-2 on the comparison was assessed using three-dimensional radiative transfer model of vegetation.

B5.10 Seasonal changes in SIF in a warm-temperate evergreen coniferous forest in Japan

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Chlorophyll fluorescence is weak radiation that emitted by chlorophyll in the photosynthetic process to release the extra energy, and the fluorescence under artificial light condition has been utilized to understand the status of photosynthetic systems in a laboratory. Advances in remote sensing have enabled us to observe the chlorophyll fluorescence under solar radiation in the field by using overlapping part of the fluorescence and the Fraunhofer lines (Meroni et al. 2009). In recent years, the solar-induced chlorophyll fluorescence (SIF) has been observed by GHG observation satellite such as GOSAT, OCO-2 and GOME-2 on MetOp-A and B. GOSAT-2, the successor of GOSAT, which will be launched in fiscal year 2018 will also provide SIF as one of standard products. Several studies have shown that SIF is strongly correlated with vegetation gross primary production (GPP) but the relationship is influenced by season, vegetation types, etc. To utilize SIF as an index to evaluate GPP, it is necessary to deeply understand the consequence between SIF and photosynthetic function of the vegetation.

We have conducted in-situ SIF measurement at the forest in Kiryu Experiment Watershed ("Kiryu site"), near Kyoto, Japan from the end of March 2017. The forest is a warm-temperate evergreen coniferous forest dominated by Japanese cypress, Hinoki (Chamaecyparis obtusa). Kiryu site belongs to AsiaFlux network and CO2 flux has been measured from 2001. The SIF measurement system automatically observes the spectral irradiance of the sky and forest canopy by two optical fibers connected to fiber switch and HR 4000 spectralradiometer (Ocean Optics, Dunedin, Florida, USA). In this presentation we will show the seasonal changes in SIF in Kiryu site.

C5.2 Monitoring Global OH Abundances using Satellite Observations of Atmospheric Methane

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The hydroxyl radical (OH) is the main tropospheric oxidant and serves as the largest sink for atmospheric methane. The global abundance of OH has been monitored for the past several decades with the methyl chloroform (CH_3CCl_3) proxy. However, this approach is becoming ineffective as atmospheric CH_3CCl_3 concentrations decline exponentially. Here we propose that satellite observations of atmospheric methane in the shortwave infrared (SWIR) and thermal infrared (TIR) spectra can provide an effective replacement method to infer global OH abundances. The central premise is that the atmospheric signatures of methane sink from OH oxidation and methane source from surface emissions are distinct. We evaluate this method with an observing system simulation experiment (OSSE) framework using synthetic TROPOMI (SWIR) and CrIS (TIR) methane retrievals, interpreted with a Bayesian inverse analysis optimizing both gridded methane emissions and global OH concentrations with full error characterization. The OSSE simulations use different meteorological fields, global OH distributions, and methane emission rates for the "true" atmosphere and for the inversion. The results show little aliasing in the inversion between corrections to methane emissions and corrections to OH concentrations. The satellite observations can constrain the global OH concentration (as measured by the atmospheric lifetime of methane) with a precision better than 1% and an accuracy of about 3% for SWIR and 6% for TIR. The main source of error limiting the accuracy is the spatial and seasonal OH distribution. We also show that the satellite methane observations can provide constraints on the hemispheric OH distribution.

C5.3 Development of ECCC's regional transport model to simulate high spatial and temporal variability of atmospheric greenhouse gases

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With the advent of space-based observations of greenhouse gases (GHG) such as CO_2 and CH_4, which provides greater coverage than surface networks of GHG measurements, it may now be possible to constrain surface GHG fluxes at regional scale by atmospheric inverse modelling. However, this requires the transport model to be able to accurately simulate GHG variability on synoptic and mesoscales that may be captured in the measurements. Also, high resolution anthropogenic and biosphere prior fluxes are required to provide detailed information associated with high-resolution topography. Prior to the development of a regional-scale inverse modelling framework, a high-resolution regional transport model is needed in order to capture the observed variability of atmospheric GHG concentrations at small scales not possible with coarse resolution of global transport model.

Here we present the development of a regional transport model for GHG, aiming at understanding high spatio-temporal resolution of surface GHG fluxes, mainly focusing on Canada and most of the United States. This is carried out as a part of the development of Environment and Climate Change Canada's (ECCC) Carbon Assimilation System (EC-CAS) that is based on a global version of operational ECCC weather and environmental prediction model for GHG forecast. Our regional model is run at a 10 km horizontal grid spacing with 80 vertical levels spanning the ground to 0.1 hPa. The added benefit of the regional model over our low resolution global model (0.9° horizontal grid spacing) is assessed in terms of modelled tracer concentration and meteorological forecast quality. We find that our regional model has the capability to simulate high spatial and temporal scales of atmospheric GHG concentrations both horizontally and vertically based on comparisons to observations from various GHG observing systems including surface network, aircraft and Orbiting Carbon Observatory-2 (OCO-2) satellite. In addition, several sensitivity tests are conducted to investigate the impact of different lateral boundary conditions on modelled concentrations.

C5.4 Tropical wetland methane emissions inferred from GOSAT XCH_4 retrievals

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Wetlands represent the largest individual contribution to natural methane emissions. Consequently, they play an important role in determining global-scale variations in atmospheric methane. Variability in tropical wetland emissions, in particular, may be linked to the El-Niño Southern Oscillation. Past work has shown the value of using satellite observations of column methane to infer tropical methane fluxes. We develop a simple model of wetland fluxes based on water table depth and temperature to explore the seasonal cycle and inter-annual variability of regional tropical wetland emissions. Using GOSAT XCH_4 retrievals and a Bayesian inversion approach we infer flux model parameters that describe the temporal and spatial variability of tropical wetland fluxes. We use the resulting model to evaluate the contribution of regional patterns in wetland fluxes to global trends of methane.

C5.5 Global CO emission estimates inferred from assimilation of MOPITT CO data, together with observations of O_3, NO_2, HNO_3, and HCHO

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Atmospheric carbon monoxide (CO) emissions estimated from inverse modeling analyses exhibit large uncertainties, due, in part, to discrepancies in the tropospheric chemistry in atmospheric models. We attempt to reduce the uncertainties in CO emission estimates by constraining the modeled abundance of ozone (O_3), nitrogen dioxide (NO_2), nitric acid (HNO_3), and formaldehyde (HCHO), which are constituents that play a key role in tropospheric chemistry. Using the GEOS-Chem four-dimensional variational (4D-Var) data assimilation system, we estimate CO emissions by assimilating observations of CO from the Measurement of Pollution In the Troposphere (MOPITT), together with observations of O_3 from the Optical Spectrograph and InfraRed Imager System (OSIRIS) and IASI, NO_2 and HCHO from the Ozone Monitoring Instrument (OMI), and HNO_3 from the Microwave Limb Sounder (MLS). Although our focus is on quantifying CO emission estimates, we also infer surface emissions of nitrogen oxides ($NO_x = NO + NO_2$) and isoprene. Our results reveal that this multiple species chemical data assimilation produces a chemical consistent state that effectively adjusts the CO-O_3-OH coupling in the model. The O_3-induced changes in OH are particularly large in the tropics. We show that the analysis results in a tropospheric chemical state that is better constrained. Our experiments also evaluate the inferred CO emission estimates from major anthropogenic, biomass burning and biogenic sources.

C5.6 How well do surface observations constrain the CO state? Assimilation experiments with EC-CAS in an OSSE framework

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The ECCC Carbon Assimilation System (EC-CAS) is being developed to study the global carbon cycle and to monitor greenhouse gas emissions over Canada. By assimilating atmospheric measurements of greenhouse gases, exchanges of carbon (CO_2, CH_4 and CO) between the surface and the atmosphere can be estimated. While the traditional approach to flux estimation is through inverse modelling using analysis winds, EC-CAS uses a coupled state-flux estimation with the low resolution configuration of our operational Ensemble Kalman Filter (EnKF) (Houtekamer et al. 2014) and our operational weather forecast model (GEM). GEM was adapted to simulate greenhouse gases and is run on a global 400x200 grid with 81 vertical levels (Polavarapu et al. 2016). In the EnKF approach the uncertainty in winds contributes to the uncertainty in the tracer field. In this work, we test and tune the EnKF for CO state estimation using OSSEs (Observation System Simulation Experiment). An ensemble of size 64 is used to represent the uncertainty in the meteorological and CO state. An IAU (Incremental Analysis Update) is used within the EnKF to supress high frequency oscillations. Simulated observations are assimilated every 6 hours and consist of radiosonde, scatterometer, satellite winds, gps, aircraft and surface observations of CO. Variable localization (Kang et al. 2011) is implemented which results in the CO observations updating the CO state only. Similarly the meteorological observations update the meteorological state only. The analysis RMSE for meteorological variables averaged over the 3d model domain tends to saturate in about 15 days. At saturation, the spread is under-dispersive (by 5%) for all the variables owing to the moderate ensemble size. Interestingly, without assimilating any CO observations, the RMSE in CO averaged over the bottom 3 km nevertheless decreases from about 6 ppb to about 3 ppb in 4 days simply due to the concurrent improvement in the wind fields. Results from the OSSEs used to tune the localization radius for the assimilation of surface observations of CO will be reported. We demonstrate that the surface CO observations are able to impact the CO state in the boundary layer. This impact is seen only in areas (North America and Europe) which has surface observation stations. The system will also be tested for the assimilation of MOPITT satellite retrieval data.

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C5.7 Towards global and regional methane budgets estimated by high spatial resolution atmospheric inverse model with GOSAT retrievals

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Atmospheric methane (CH_4) started to increase again since 2007, after a period with near-zero growth from 1999-2006. Various reasons for the increase have been discussed, but large uncertainty still remains, especially on regional scales. In this study, we estimate global and regional CH_4 fluxes for the 21st century by a high resolution variational inverse model, based on a Lagrangian-Eulerian coupled tracer transport model, constrained by in situ and GOSAT retrievals of column-averaged atmospheric CH_4. The high spatial resolution Lagrangian model FLEXPART, coupled with a global atmospheric tracer transport model (NIES-TM), will be run at 0.1°x0.1° horizontal resolution. For the prior emissions, the inventory and process model based estimates are used; EDGAR for anthropogenic sources, GFAS for biomass burning, VISIT for wetlands. The emissions from anthropogenic sources and wetlands will be optimized at bi-weekly resolution. The atmospheric burden estimated from a simulation assimilating only in situ observations will be compared to the GOSAT retrievals. Possible large scale biases between GOSAT retrievals and the model simulation will be considered when assimilating the GOSAT retrievals. The model simulated methane concentrations will be evaluated against surface in-situ and aircraft CH_4 observations. The model simulated methane concentration will be evaluated against surface in-situ and aircraft CH_4 observations. The flux estimates will be compared with those from a global ensemble filter based inverse model (CTDAS-CH_4).

C5.8 Impact of coarse model resolution on chemical transport modelling of methane

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Systematic errors in chemical transport models (CTMs) significantly impact CH_4 surface emission estimation due to relatively weak signature of emissions in the atmosphere. Numerical errors related to the CTM horizontal resolution are one of the major types of errors. We evaluated biases in the GEOS-Chem CTM CH_4 fields caused by coarsening the model resolution. The origin of resolution-induced errors was investigated in the experiments using ^{222}Rn, ^{7}Be and CH_4 tracers. Results of the experiments showed that a majority of the biases are caused by increased numerical diffusion at coarse resolution, which acts to smear tracer concentration gradients and weaken transport barriers in regions such as the tropopause layer, the tropical pipe, and the polar vortex in the stratosphere. This leads to enhanced stratosphere-troposphere exchange and enhanced mixing in the stratosphere. Results suggested that the 4 x 5 resolution model cannot maintain adequate mixing barriers. The tracer experiments also pointed to a weakening of the vertical transport at coarser resolution, mainly, in mid- to high latitudes. This was partly related to the specific implementation of the advection scheme in GEOS-Chem and was caused by the loss of the air mass fluxes at the grid box interfaces after remapping horizontal winds to coarse

resolution. The rest of the difference in the vertical transport was explained by the loss of the tracer eddy mass flux due to averaging of sub-grid model variability at coarse resolution. Doubling the model resolution from 4 x 5 to 2 x 2.5 significantly improved the simulation, however did not eliminate biases completely. Generally, the results showed that GEOS-Chem at 4 x 5 should not be used for CH_4 surface emissions estimation due to significant numerical errors.

C5.9 A city to national scale atmospheric inverse modeling system to assess the potential of new space borne measurement concepts for the monitoring of CO_2 anthropogenic emissions in Western Europe: a case study focused on Paris

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Comprehensive information about anthropogenic CO_2 emissions at the scale of power plants, cities, and countries up to the globe is essential for decision makers to track the effectiveness of emission reduction policies in the context of the Paris Agreement on Climate and other voluntary emission reduction efforts. To answer that need, the TRAcking Carbon Emissions (TRACE) research project aims to develop simulations of new observing systems for the monitoring of greenhouse gas (GHG) emissions from space based on atmospheric inversion methods. The TRACE project deals with abroad range of spatial scales across which GHG emissions are distributed: scales ranging from local intense point sources like industrial sites to regional and national scales.

In particular, TRACE studies the potential of new satellite measurements of atmospheric CO_2 to monitor anthropogenic emissions with an end-to-end performance simulation platform which will combine an advanced radiative transfer inverse modeling with an atmospheric inversion system based on a high-resolution atmospheric transport model. This atmospheric inversion system uses a zoomed configuration of the regional transport model CHIMERE which covers most of western Europe and with a 2km to 1km resolution grid over Northern France, Western Germany and Benelux. The inversion will control at high temporal resolution the emissions of 100-200 cities and power plants in this area and regional budgets in the lower resolution part of the domain. This will enable the analysis of results at the city to national scales, accounting in both cases for the more or less important overlapping of the plumes from the different point sources.

As a preliminary study, the inversion system is used to study the potential of CO_2 spaceborne spectro-imagers to constrain the hourly emissions of the Paris urban area. Extending the study of Broquet et al. (2018) for the ESA-Logoflux I and II projects, and using the 1 km zoom of the model configuration in the Paris area, this provides the analysis of the sensitivity of the results as a function of a wider and more detailed range of specifications on the spatial resolution, precision and swath of the satellite XCO_2 images. The curves of sensitivity appear to be smooth except when considering that to the swath when the wind blows across the satellite track. When targeting a large and isolated city such as Paris, increasing the spatial resolution of the imager by 2 does not appear to provide better results than if decreasing the measurement noise by 2. This indicates that the system does not really take advantage of the information on the fine scale patterns of the plume for such a city.

Session 6: Future missions and observing strategies

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

Lesley Ott*, David Schimel, Christopher O'Dell, Berrien Moore III, Sean Crowell, David Baker, Ian Baker, Kevin Bowman, Abhishek Chatterjee, Scott Denning, Kathy Haynes, Stephan Kawa, Charles Miller, Denis O'Brien, Steven Pawson, Benjamin Poulter, Andrew Schuh, Thomas Taylor

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Satellite observations of carbon dioxide (CO_2) and methane (CH_4) are critically needed to improve understanding of the contemporary carbon budget and carbon-climate feedbacks. New space-based observations have provided valuable data in regions not covered by traditional surface in situ measurements, showing examples of the coupling between carbon and climate, and of the ability to observe human emissions under certain circumstances. Next generation satellites will improve coverage in data sparse regions, either through use of active remote sensing, a geostationary vantage point, or a combination of increased swath width and revisit frequency. Observing system simulation experiments (OSSEs) can be used to quantify the relative strengths and weaknesses of the current observing system, identify key gaps, and evaluate the impact that next generation satellites may have. As such, OSSEs are essential tools to guide cost effective implementation of future carbon-observing satellite 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 coordinated OSSEs, with close collaboration in framing the experiments and in analyzing the results. Here, we report on advances in the creation of realistic, model-based synthetic CO_2 and CH_4 datasets for use in inversion and signal detection experiments. Datasets have been created using NASA's Goddard Earth Observing System Model (GEOS) at global resolutions ranging from 3 to 50 km. These simulations represent the current state of atmospheric carbon as well as best available estimates of expected flux changes. The library of 50-km simulations represents dozens of scenarios that include changes in urban emissions, release of permafrost soil carbon, changes in carbon uptake in tropical and mid-latitude forests, changes in the Southern Ocean sink, and changes in both anthropogenic and natural methane emissions. Global mesoscale CO_2 simulations provide an exciting new tool for mission planning, allowing the complex influence of clouds and aerosols on CO_2 observations to be examined in greater detail than ever before. Statistical analyses of these synthetic datasets provide a simple, objective method for evaluating mission design choices. These datasets will be made publicly available for use by the international carbon modeling community and in mission planning activities. We will also outline model developments that are needed to advance future carbon cycle OSSE efforts.

6.2 Assessing the potential of satellite spectro-imagery to monitor fossil fuel CO_2 emissions across the globe from the city and daily scales to the national and annual scales

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Cities and large industrial sites account for about 70% of the total CO_2 emission from fossil fuel. A growing number of cities and regions being engaged in climate change mitigation have disclosed their plans to reduce greenhouse gas emissions. Atmospheric inversions can use CO_2 measurements to provide an independent way of monitoring the fossil fuel CO_2 emissions and to evaluate effectiveness of the emission reduction pledges. Measurements of vertically integrated columns of dry air mole fractions of CO_2 (XCO_2) from satellites offer the advantage of a dense set of observations with global spatial coverage to monitor the fossil fuel CO_2 emissions at the scales of large cities, industrial sites, regions and countries that are relevant to the carbon policy. In this study, we first identified 8245 targets of emitting clumps (defined as clusters of adjacent emitting area) covering major cities and large point sources all over the globe and representing about 75% of total CO_2 emissions. These clumps were delineated from a high-resolution emission map and administrative information, and may cause atmospheric XCO_2 plumes detectable from space. This study assesses the potential of the XCO_2 imagery from one to multiple low earth orbiting satellites for monitoring the fossil fuel CO_2 emissions from these clumps. Such imagery could be provided by future space borne passive spectral-imagers in the short wave infrared spectrum, at a high spatial resolution of 2 km x 2 km with a swath width of 300 kilometers and with individual sounding precision of less than 1 ppm. This assessment was based on Observing System Simulation Experiments (OSSEs) with an atmospheric inversion approach. The inversion system solved for the average emissions before a given satellite overpass, using a Gaussian plume model to link the average emissions and the XCO_2. The inversion framework accounted for the existence of some prior knowledge about the average emissions before the satellite overpasses with 100% uncertainty. These OSSEs indicated that when assimilating the observations from one such XCO_2 imager, 1391 emission clumps, representing 13% of the global total emissions, can have more than 12 days when the uncertainty was reduced by more than 50%, assuming no correlations in the prior uncertainty. Some preliminary results showed that a constellation of such imagers could significantly increase the potential of such an inversion system to constrain fossil fuel CO_2 emissions. When aggregating the emissions at national and annual scales, the decrease of uncertainties largely relies on the spatial and temporal correlations in the prior uncertainty in the emissions. Tests were conducted for different simulations of these error structures.

6.3 An updated status of MicroCarb Project

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MicroCarb program was decided at the end of 2015 and is presently in its development phase and targeting a launch in 2021. MicroCarb takes its name from its capacity to perform accurate- that is in line with the requirements of the community- measurements of the atmospheric CO_2 concentration with a micro satellite weighing less than 200 kg. The project is conducted by the CNES in partnership with the UK Space Agency, and involves the scientific community from both France and UK. Aperture to other European organizations in order to re inforce the international participation to the program is under

way. The presentation will recall the main characteristics of the mission, give an highlight on the original features and present the technical challenges being addressed; it will introduce the organization and provide an update of the progress of the development.

6.4 State of play of the European Anthropogenic CO_2 Monitoring Mission

Yasjka Meijer*, Y.J. Meijer[1], M.R. Drinkwater[2], J.-L. Bezy[2], A. Loescher[2], B. Sierk[2], B. Pinty[3], H. Zunker[3], with contributions from many experts 4

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As part Europe's Copernicus Programme, the European Commission (EC) and the European Space Agency (ESA), together with the support of Eumetsat and the European Centre for Medium-range Weather Forecasts (ECMWF), are considering to expand the capabilities of the first generation Sentinel satellites for measurements of anthropogenic CO_2 emission as part of the Copernicus Space Component monitoring capabilities. The atmospheric measurements made by a combination of satellites and in-situ networks would be assimilated in the ECMWF operational system and combined with inventories. Inverse modelling techniques would then allow the transparent and consistent quantitative assessment of CO_2 emissions and their trends at the scale of megacities, regions, countries, and the globe. Such a capacity would provide the European Union with a unique and independent source of information, which can be used to inform on the effect of policy measures, and to track their impact en-route towards decarbonising Europe and meeting national emission reduction targets.

The space system activities have recently entered their feasibility phase and will study the implementation of a multiple (LEO) satellite constellation providing a 3-day revisit at mid-latitudes, at 4 km2 sampling and a precision better than 0.7 ppm in XCO_2. In order to limit the systematic error, the system activities consider inclusion of a multi-angle polarimeter enabling the CO_2 retrieval process to better account for cloud and aerosol scattering effects. In addition, the inclusion of measuring NO_2 is considered as proxy for anthropogenic CO_2 plumes from power plants and cities, which could significantly increase the accuracy of the emission estimates. This presentation focuses on the state of play of the space component development providing an overview of the scientific and technical activities.

6.5 The European Anthropogenic CO_2 Monitoring Mission: Instrument spectral sizing and the supporting aerosol instrument

Jochen Landgraf[1], Joost aan de Brugh[1], Lianghai Wu[1], Stephanie Rusli[1], Hein van Heck[1], Rob Detmers[1], Haili Hu[1], Otto Hasekamp[1], Andre Butz[2], Michael Buchwitz[3], Heinrich Bovensmann[3], Hartmut Bösch[4], Yasjka Meijer[5], Armin Löscher[5], Bernd Sierk[5]

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The European Space Agency is investigating the implementation of a future CO_2 mission to monitor anthropogenic CO_2 emission from space as part of the Copernicus programme of the European Commission. The mission scopes the relevance of policy-science questions, like localizing hot spots or high emitting areas to identify and monitor the impact of local measures for emission reduction. Therefore, a careful trade-off has to be made between feasible instrumentation, measurement requirements and heritage from CO_2 measuring instruments in space, like OCO-2 and GOSAT. In this contribution, we discuss the selected spectral sizing, i.e. the choice of spectral coverage, spectral resolution and signal-to-noise ratio, of current and planned space-borne instruments measuring XCO_2. In addition, we investigate the need of a facilitating multi-angle polarimeter reducing aerosol induced XCO_2 errors on one hand and achieving global coverage on the other hand.

To this end, we reduced the spectral resolution and coverage of OCO-2 and GOSAT measurements by an additional spectral smoothing of the measurements and performed a validation of the derived XCO_2 product with ground-based measurements at 18 TCCON sites. Moreover, the study is complemented with an extensive sensitivity study using simulated measurement ensembles on regional and global scales and considering key instrument and aerosol induced errors. To mitigate the aerosol induced XCO_2 errors as one of the key uncertainties of current CO_2 emissions, we discuss in detail the importance of a supporting multi-angle polarimeter. We conclude that this state-off-the-art sensing concept is well-suited to monitor aerosol properties from space and will be of great benefit to achieve the challenging mission objectives of the European future CO_2 monitoring mission.

6.6 The next generation of Chinese greenhouse gas monitoring satellite mission: TanSat-2

Dongxu Yang[1,2], Yi Liu, Maohua Wang, Zengshan Yin, Zhaonan Cai, Lin Qiu, Longfei Tian, TanSat-2 team

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The next generation of Chinese greenhouse gas monitoring satellite - TanSat-2, which continued the name of Chinese global carbon dioxide monitoring satellite (TanSat), is initiative the by Shanghai Advanced Research Institute Chinese Academy of Sciences (SARI), Shanghai Engineering Center for Microsatellites Chinese Academy of Sciences (MicroSat), ShanghaiTech University and TanSat team. The TanSat-2 mission will cover much wider swath and improve signal-to-noise and calibration. The tansat-2 mission, as a constellation, is consisted by six satellites that fly on sun-synchronous orbit, including three morning satellite and three afternoon satellites, in order to improve the measurement coverage and repeat. Each satellite observe earth in a 100 km width across track, and hence the measurement covers the global in 3-4 days. The NIR/SWIR hyperspectral measurement on backscattered sunlight from spectrometer onboard TanSat-2 includes 0.76 µm (O_2A), 1.61 µm (CO_2), 2.06 µm (CO_2) and 2.3 µm (CH_4 and CO) band. TanSat-2 aims to measured atmospheric CO_2, as well as

CH_4 and CO, twice per day, which will be helpful to investigate the daily variation of greenhouse gas and the emission that related to anthropogenic activities.

6.7 IASI-New Generation: program status, system overview and scientific objectives

Adrien DESCHAMPS*, François Bermudo, Eric Jurado, Frederic Bernard, Sarah Guibert

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The IASI instrument (Infrared Atmospheric Sounding Interferometer) has been flying on Europe's MetOp satellites since 2006, in the frame of the EPS program of EUMETSAT. As well as acquiring temperature and humidity data, IASI also measures more than 25 other atmospheric components with a high degree of precision. To ensure continuity of service, CNES is working on the IASI-NG next-generation instrument. The IASI-NG system aims at observing and measuring twice a day the spectrum of infrared radiation emitted by the Earth, in the 645-2750cm-1 spectral region at the resolution of 0.125 cm^{-1}, from a low altitude sun-synchronous orbit, over a swath of 2,000 km. IASI-NG is designed to provide invaluable information for numerical weather prediction as well as for climate monitoring and atmospheric chemistry.

Like its predecessor, IASI-NG will use a passive infrared sensor to determine temperature and water vapour profiles in the atmosphere, record ocean surface and land temperatures and monitor a vast range of chemical compounds and other key variables for climate research, including greenhouse gases, desert dust and cloud cover. With its innovative optical configuration, IASI-NG's spectral resolution and signal-to-noise ratio will be improved by a factor of two. Measurement precision will also be improved (1 K for temperature and 10% for humidity). More than just a continuation of IASI, the IASI-NG instrument will be a real asset for atmosphere sciences and a key element of Europe's three MetOp-SG-A series weather satellites, scheduled to launch in 2021, 2028 and 2035.

In this talk, we present the status of the IASI-NG program and the IASI-NG instrument, which is an Fourier Transform Spectrometer based on the Mertz concept. We will give also an overview of the Level 1 processing that aims at calibrating the spectrum, both radiometriccaly and spectrally, and present some examples of the estimated added-value of IASI-NG, compared to IASI, in terms of amtospheric components retrievals.

6.8 The GeoCarb Mission

Berrien Moore*, Sean Crowell, Chris O'Dell, David Crisp, David Schimel, Annmarie Eldering, Susan Kulawik, Bob Chatfield, Xiangming Xiao, Eric Burgh, Jim Lemen, and the GeoCarb Team

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GeoCarb was selected in December 2016 by NASA as the next Earth Venture Mission. Starting in 2022, GeoCarb will make observations of CO_2, CO, CH_4 and solar induced fluorescence from geostationary orbit over the Americas. The orbit will allow for daily observations of the land mass between 50°S and

50°N at high spatial resolution (5-10 km). In this presentation, we will present an overview of the GeoCarb mission as well as provide a description of the instrument and expected impact on important carbon cycle process level understanding.

6.9 ARRHENIUS: Exploring Carbon Regional Flux Dynamics in Africa, Europe and the Middle East from Geostationary Orbit

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Tropical and subtropical ecosystems play an important role in the global carbon cycle. The African tropics and subtropics is the most dynamic region of the world with respect to terrestrial carbon flux variability and population growth, which imposes direct carbon emissions and perturbations to the natural ecosystems. The underlying mechanisms such as photosynthesis, respiration, natural and man-made biomass burning, as well as fossil fuel related emissions vary on sub-daily timescales. The forcing by meteorological and climatic factors imposes a fingerprint being variable on the seasonal and inter-annual time-scale. Event-wise emissions such as caused by agricultural burning blend with episodic change in land-use practices and permanent ecosystem degradation. Thus, gaining insights into the functioning of African tropical and subtropical carbon cycling and into its sensitivity to environmental variability and perturbations needs observations from the sub-daily to the seasonal to the year-to-year time-scale. However, the African continent is poorly sampled by current and planned atmospheric observation systems. Establishing a dense and robust ground-based network is logistically challenging. Satellite observations from low-Earth-orbit (LEO) are limited to a single local overpass time per day and, they are frequently cloudy.

The Middle East and Europe are major global players in fossil fuel extraction and usage, respectively. Leakage of carbon gases has been reported throughout the extracting-processing-transportation-consumption chain. Satellite observations from LEO will become progressively available as part of envisioned surveillance concepts. These LEO sensors, however, do not capture characteristic diurnal variations of fluxes, potentially resulting in biased emission estimates and lacking the ability to discriminate between man-made and biospheric flux signals.

The AbsoRption spectRometric patHfindEr for carboN regIonal flUx dynamicS (ARRHENIUS) is a proposed mission concept that will overcome the sampling gaps in Africa, Europe and the Middle East and on the sub-daily time scale by adopting a process-focused sampling strategy from geostationary orbit (GEO). For selectable focus regions, ARRHENIUS will deliver quasi-contiguous maps of atmospheric carbon species concentrations (carbon dioxide (CO_2), methane (CH_4), and carbon monoxide (CO)) and a photosynthesis process marker (solar induced plant fluorescence (SIF)) with sub-daily, seasonal, and year-to-year coverage. These observations will be used by top-down inverse atmospheric models and by bottom-up biosphere and land-surface models to inform on regional carbon cycle processes. Being process focused instead of surveillance driven, ARRHENIUS will pioneer a flexible and intelligent sampling approach with short lead times for pointing adjustments. Sampling will be flexible with regard to focus region selection, region extent (typically 1300x2400 km^2), dwell times (typically 1h) and the number of revisits per day (up to 5 times per day), per season and per year. Sampling will be intelligent by actively avoiding regions which are expected cloudy based on observations of meteorological sounders (such as Meteosat Third Generation) from adjacent orbits. Small footprint sizes (2x2 km^2 at sub-satellite) and flexible day-time observation hours will further support cloud avoidance.

6.10 AIM-North: The Atmospheric Imaging Mission for Northern Regions

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Canada has studied Highly Elliptical Orbit (HEO) satellite mission possibilities for atmospheric composition for many years, since the HEO vantage point enables quasi-geostationary observations of northern regions like the Arctic. Early concepts for atmospheric composition assumed a microsatellite-scale instrument suite hosted on a larger weather and communications satellite. Here we present AIM-North (www.aim-north.ca), a new HEO mission concept under consideration by the Canadian Space Agency (CSA), that would provide observations of unprecedented frequency, density and quality for monitoring greenhouse gases (GHGs), air quality (AQ) and solar induced fluorescence (SIF) from vegetation in northern regions. AIM-North would use an imaging Fourier Transform Spectrometer (IFTS) to record spectra of reflected near infrared (NIR) and shortwave infrared (SWIR) solar radiation to image XCO_2, XCH_4, XCO and SIF, along with a dispersive ultraviolet-visible spectrometer (UVS) to image numerous other trace gas species, spanning ~40-80°N with 3x3 km^2 pixels. IFTS scanning patterns and methods times are being studies with potential revisit rates of ~60-90 minutes during daylight, giving multiple points in the diurnal cycle to assist in process understanding and source attribution. Precision and accuracy targets for GHGs are aligned with upcoming and proposed international GEO missions. We will present an overview of the proposed mission, instruments, spectral band selection, strategies for cloud avoidance, validation and outline synergies/complementarity with international missions.

6.11 CARBO: The Carbon Balance Observatory

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The 2017 Earth Science Decadal Survey highlighted the need for a wide-swath (mapping) low earth orbit (LEO) instrument delivering carbon dioxide (CO_2), methane (CH_4), and carbon monoxide (CO) measurements with global coverage. OCO-2 pioneered space-based CO_2 remote sensing, but lacks the CH_4, CO and mapping capabilities required for an improved understanding of the global carbon cycle. The Carbon Balance Observatory (CARBO) advances key technologies to enable high-performance, cost-effective solutions for a space-based carbon-climate observing system. CARBO is a compact, modular, 15-30° field of view spectrometer that delivers high-precision CO_2, CH_4, CO and solar induced chlorophyll fluorescence (SIF) data with weekly global coverage from LEO. CARBO employs innovative immersion grating technologies to achieve diffraction-limited performance with OCO-like spatial (2x2 km^2) and spectral ($\lambda/\Delta\lambda \approx 20{,}000$) resolution in a package that is smaller, lighter and more cost-effective, opening diverse new space-based platform opportunities.

6.12 Pulsed Lidar Measurements of CO2 Column Concentrations in the 2017 ASCENDS Airborne Campaign, and beyond

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NASA Goddard's CO_2 Sounder is a pulsed, multiple-wavelength IPDA lidar that measures XCO_2 in a nadir path from the aircraft. The lidar measures the range resolved shape of the 1572.33 nm CO_2 absorption line to the ground and cloud tops. The airborne lidar used 30 fixed-wavelength samples distributed across the line. Analysis estimates the lidar range and pulse energies. For each second the retrievals solve for the CO_2 absorption line shape and the column average CO_2 concentrations by using radiative transfer calculations, the aircraft altitude and range to the surface, and atmospheric conditions.

The CO_2 Sounder team participated in the 2017 ASCENDS airborne campaign, that was flown on the NASA DC-8 in late July and early August. The campaign objectives were to assess the accuracy of airborne IPDA lidar measurements of CO_2 column concentrations (XCO_2), and to extend these lidar measurements to the ABoVE study area in the Arctic. Eight flights were conducted with XCO_2 measurements from the CO_2 Sounder and the NASA Langley ACES lidar along with in-situ CO_2 measurements made at the aircraft with the AVOCET and Picarro instruments. Forty-seven spiral-down maneuvers were conducted over locations in California, Northwest Territories Canada and over Alaska, along with the transit flights from California to Alaska and return. Since each spiral maneuver allows comparing the retrievals of XCO_2 from the lidar against those computed from in-situ measured CO_2, this campaign allowed an unprecedented opportunity to assess the lidar measurements of XCO_2 over a diverse set of conditions, including in the Arctic.

The presentation will describe the flight, and will present the results from analyzing the retrieved XCO_2 from the CO_2 Sounder lidar over some of the campaign's regions. It will also discuss the approach and technology for a space lidar mission and its estimated measurement performance.

C6.1 GOSAT score map toward optimizing sampling pattern for global and regional flux estimation

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The Greenhouse gases Observing SATellite (GOSAT) was launched on January 23 2009 and continues its measurement of carbon dioxide (CO_2) and methane (CH_4) for more than 9 years. GOSAT-2 is scheduled to be launched in 2018.

Although the number of sampling points is smaller than other GHG observing satellites such as OCO-2, TanSat, and Sentinel-5P, the advantage of GOSAT and GOSAT-2 is their 2-axis agile pointing system to target area by uploading pointing command every day from the ground. The optimization of sampling pattern for global and regional flux estimation is challenging. At first, we have prepared global maps related to the satellite observation planning: (1) long term GOSAT observation results such as successful retrieval ratio and surface albedo, (2) related parameters acquired from other satellites such as carbon monoxide (CO), solar induced chlorophyll fluorescence (SIF), ODIAC database, population density, and EDGAR CO_2 and CH_4 emission inventories from their source sectors. These are monthly database with latitudinal and longitudinal grid of 0.1 deg.

We have released the "GOSAT Score Map for Sampling Optimization" tool from the JAXA EORC GOSAT website (http://www.eorc.jaxa.jp/GOSAT/GOSAT_Optimization/index.html). Users can weigh the above-mentioned parameters and calculate the weighted score global distribution. The tool also includes orbit information of GOSAT, GOSAT-2 and other GHG satellites. We are also planning to add the function to integrate the scores from selected target points in order to maximize the GOSAT and GOSAT-2 performance.

C6.2 The next generation of TanSat and space-air-ground monitoring system

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In December 22, 2016, China successfully launched the global CO_2 monitoring experiment satellite (TanSat) to monitor greenhouse gases through its own carbon satellite. The designed service life of TanSat is three years, in order to continue providing the world with abundant CO_2 monitoring data, it needs to start the next generation of TanSat programs as soon as possible. The next generation of TanSat will be a constellation, which consists of six sun-synchronous orbit micro-satellites distributed in two orbital planes with swath of 100 km. As a result, the constellation is capable to revisit any location in the world at two different local time in less than three days. Moreover, those six satellites will be equipped with three different types of payloads in order to observe CO_2, CH_4, CO, NO_2 and other air pollutants. Based on the next generation of TanSat, a space-air-ground monitoring system will be also build up, integrating carbon emission data from ground stations, mobile stations, flux towers, 1km-high captive balloons and 10km-high remote sensing air crafts, to provide robust scientific and technical support for addressing climate change and air pollution control in covered regions. The preliminary space-air-ground monitoring system will be build up in the region of the largest city in China, Shanghai, the system of which will become a typical model to be promoted to other cities and regions in China to provide policy makers with independent data to help achieve the global emission reduction goal as early as possible.

C6.3 The European Anthropogenic CO_2 Monitoring Mission: Instrument requirements for space-borne measurement of greenhouse gas point sources

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The European Commission (EC) is targeting the establishment of a global multi-technique observing system for monitoring anthropogenic CO_2 emission [European Commission, 2017]. The European Space Agency (ESA) will be responsible for the technical definition of the space component, aiming for implementation in the mid-2020s as part of the Copernicus programme. Current plans foresee a constellation of LEO satellites in Sun-synchronous orbit, providing complete global land coverage within five days. The ambitious objectives of this mission call for a definition of dedicated observational requirements, focusing on the primary goal of detecting and quantifying point-sources of greenhouse gas emission. In particular, the single-sounding precision has to be optimised in order to ensure the capability of identifying plumes of elevated CO_2 and CH_4 concentration from instantaneous image acquisitions without regional and temporal averaging. This optimisation requires a thorough analysis of random errors in XCO_2 and XCH_4 retrieval, originating from instrumental, as well as geophysical effects. The presentation will address both types of noise-error sources in the context of the future Copernicus mission. The predominant instrumental figure-of-merit affecting retrieval precision is the signal-to-noise ratio (SNR) of the measured radiance spectra. We present the methodology for deriving SNR requirements in the Shortwave Infrared spectral bands (centered at 1.6 µm and 2.0 µm), on the basis of simulated retrievals using the RemoteTec software [Butz et al., 2011]. The method allows for derivation of required SNR for any desired precision in XCO_2 and a given geophysical scenario. Another significant geophysical error source for push-broom imaging spectrometers is the pseudo-noise generated by radiometric non-uniformity of the ground scene, mainly due to albedo contrast within the instrument field-of-view. We demonstrate the impact of scene non-uniformity on mapping of greenhouse gas concentration, using retrieval simulations and albedo contrast derived from space-borne hyper-spectral measurements. We conclude with an overview of strategies for mitigating the impact of scene non-uniformity to enable greenhouse gas plume imaging.

C6.4 Optical Bench Breadboard Of An Imaging Fourier Transform Spectrometer (IFTS) For Climate Observations

Gurpreet Singh*, Tom McElroy, Zahra Vaziri, David Barton, Greg Blair, Rehan Siddiqui, and Frederic Grandmont

*York University

The fifth assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) states that the warming of zonal mean surface temperature at higher latitudes exceeds the global average temperature change. This poses a great problem as the warming leads to the thawing of the permafrost in the Arctic region that acts as an envelope to trap greenhouse gases such as carbon dioxide and methane. Therefore, there is an urgent need to develop scientific instruments that can be flown in space over the Arctic to provide atmospheric information to quantify the evolution and transport of these gases. The Laboratory for Atmospheric Remote Sounding from Space (LARSS) at York University is developing an imaging Fourier transform spectrometer (IFTS) for climate observations by atmospheric sounding. The spectrometer has two individual channels, one centred at 1650 nm to measure the atmospheric column of carbon dioxide and methane, and another centred at 762 nm to measure the temperature-pressure profile by making measurements of the O_2 A band. A Commercial-Off-The-Shelf (COTS) modulator has been purchased from ABB Inc. of Quebec City. Interferometers are widely used in many scientific laboratories to measure concentrations of different constituents in a given sample. The performance of these instruments is highly dependent on environmental effects and various properties of the input beam such as coherence, polarity, etc. Thus, the use of such instruments to measure atmospheric concentration is complicated and challenging. The immediate goal of this project is to develop an IFTS system which can measure backscattered radiation in a laboratory environment and develop design elements that will make it operable in the space environment. Progress on the project and information concerning some of the issues listed above will be discussed.

The developments which flow from this research project will support efforts by Environment and Climate Change Canada, the Canadian Space Agency and ABB, Inc. in developing a satellite instrument.

C6.5 An Imaging Fourier Transform Spectrometer for Remote Nadir Atmospheric Measurements of CO_2, CH_4 and the O_2 A-band

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The Arctic multi-year ice cover is disappearing more rapidly than climate models estimate and the arctic climate is also changing. With declining ice cover, the Arctic Ocean will be subject to increased shipping traffic and exploration activity for natural resources with a concomitant increase in air pollution. Thus, there is a multifaceted need to monitor greenhouse gases in the polar region. This requires the development of techniques and instrumentation as well as modelling and validation of the

measurements. Some of the more important atmospheric species that contribute significantly to climate change are methane (CH_4), carbon dioxide (CO_2) and water vapour, although the water vapour in the atmosphere is controlled by the radiative impact of the other gases. The effect of the changes in these species is more prominent in the Arctic region. The Arctic is a sensitive world were small changes in greenhouse gas amounts can have amplified effects through their impact on surface albedo, humidity, ocean currents and temperature. Part of this is simply the result of the Stefan-Boltzmann law which implies that a larger temperature change is needed at lower temperatures to account for a given amount of change in energy input.

This paper will focus on the development of a demonstrator Imaging Fourier Transform Spectrometer (IFTS) to be flown on a high-altitude balloon to demonstrate the capacity to measure atmospheric mixing ratios of CH_4 and CO_2 and the O_2 A-band in near space conditions. The spectrometer has two individual channels centered at 762 nm and 1650 nm. The Laboratory for Atmospheric Remote Sounding from Space (LARSS) at York University is developing the IFTS payload and ABB of Quebec City developed the core of the interferometer.

C6.6 Determining required signal-to-noise ratios for XCO_2 and XCH_4 precision targets: Application to AIM-North

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AIM-North (The Atmospheric Imaging Mission for Northern Regions) is a mission concept for remote sensing of air quality and greenhouse gases in northern regions, supported by the Canadian Space Agency. It builds off previous mission development under the PHEOS (Polar Highly Elliptical Orbital Science) program but sets stricter precision targets. XCO_2 and XCH_4 are to be measured with precision goals of 0.25% and 0.5%, respectively. We explore how the signal-to-noise ratio depends on instrument type (grating spectrometer versus Michelson interferometer), the spectral resolution (0.2 to 0.6 cm^{-1}), and the choice of absorption band(s). Greenhouse gases will be measured via the shortwave infrared to provide sensitivity to the entire column. We also compare the A band and singlet Delta band with regard to the SNR required to measure O_2 vertical column density (VCD) to 0.125%. We find a large advantage in using the strong 2.0 micron band of CO_2 relative to the weaker 1.6 micron bands and a similar conclusion for the stronger methane absorption at 2.3 micron relative to the 1.67 micron region. Much larger SNRs are required if using the singlet Delta band to determine the O_2 VCD, relative to the A band.

C6.7 Reevaluating the use of Oxygen band at 1.27 micron in spaceborne remote sensing of greenhouse gases

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Although the Oxygen "singlet Delta" band at 1.27 micron has long been used in ground-based greenhouse gas remote sensing to constrain the light path, it is challenging for nadir spaceborne sensors due to strong mesosphere/stratosphere airglow. Compared to SCIAMACHY limb observations, the airglow spectrum simulated using populations appropriate for the lower state gives relative residuals > 5%. Simulations using upper state populations successfully reconstruct the airglow spectra with excellent agreement with SCIAMACHY. The accurate knowledge of airglow spectrum enables retrieval of singlet Delta Oxygen concentration, volume emission rate, and temperature. At nadir, the airglow derived from SCIAMACHY observations will lead to a negative bias of ~10% to Oxygen column if not considered. However, when airglow is properly included, its spectral feature can be adequately separated from Oxygen absorption (mean bias < 0.1%) at the spectral resolution of modern spaceborne spectrometers.

C6.8 The MicroCarb L1 & L2 algorithms and performances

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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 (GOSAT, OCO-2, Tansat). The MicroCarb instrument is a grating spectrometer that acquires high-resolution spectra in four spectral bands: CO_2 at 1.61 and 2.03 µm, O_2 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 mission performances and processing tools.

We will present our L1 and L2 processing tools. We detail our L2 XCO_2 retrieval tool, which is based on the 4ARTIC optimal estimation and the 4AOP radiative transfer code. We will then present the mission performance budget for XCO_2, identifying all system, instrument and processing contributors at level 1 and level 2, including geolocation, spectral resolution, SNR, ISRF knowledge, polarization, non-linearity, spectroscopic parameters, radiative transfer unknowns, for the main ones. We will finally present the interest of the new 1.27 µm O_2 band, which should help to retrieve an accurate XCO_2 even in aerosol loaded conditions, provided the mesospheric airglow emitting in this band can be accounted for.

C6.9 High resolution methane tracking micro-satellites

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The accurate measurement of ground-level methane emissions from low-Earth orbit is a challenging but urgent task for efforts to mitigate climate change. Our solution starts with a remote sensing approach called Gas Filter Correlation Radiometry (GFCR), which differences images of the Earth's surface measured in a continuous push-frame configuration through a methane spectral filtering gas cell. The GFCR approach has been developed and improved over the last three decades through research projects and NASA missions, and demonstrated for methane detection on aircraft flights. The resulting data is then mastered with artificial intelligence (AI) algorithms for advanced image processing, enabling the automatic extraction of minute signals even against a high noise level. This combination creates an accurate differential image of methane column perturbation in near-real time.

Based on this technology, Bluefield is deploying a constellation of methane tracking microsatellites capable of locating and quantifying every methane emitting site on Earth at an unprecedented sensitivity level of 15 kg/hour with a spatial resolution of 20 meters. By using attitude determination and control subsystems (ADCS) in combination with fast frame image alignment to precisely lock onto specific 25 km by 20 km ground scenes, the noise on any specific 20 meter by 20 meter location in these images can be reduced by massive oversampling and our AI processing. This results in a modeled sensitivity corresponding to less than 1% natural abundance.

C6.10 The challenges of measuring Methane from orbit

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The global and regional quantification of methane fluxes and identification of its sources and sinks has been highlighted as one of the goals of the 2017 Earth Science Decadal Survey. Detecting methane from space with an active (laser) remote sensing instrument presents several unique technology and measurement challenges. The instrument must have a single frequency, narrow-linewidth light source, and photon-sensitive detector at the right spectral region to make continuous measurements from orbit, day and night, all seasons and at all latitudes. It must have a high signal to noise ratio and must be relatively immune to biases from aerosol/cloud scattering, spectroscopic and meteorological data uncertainties, and instrument systematic errors.

The technology needed for a spaceborne mission is currently being developed by NASA and industry. At Goddard Space Flight Center (GSFC), we have developed an airborne instrument to measure methane. Our instrument is a nadir-viewing lidar that uses Integrated Path Differential Absorption (IPDA), to measure a methane vibration-rotational line near 1.65 μm that is relatively free of interferences from other trace gases. We sample the absorption line using multiple wavelengths from a narrow linewidth laser source and a sensitive photodetector. This measurement approach provides maximum information content about the vertical distribution of CH_4, minimum bias, and sensitivity to atmospheric temperature uncertainty in XCH_4 retrieval.

However, technical and measurement challenges remain. In this paper, we will review our progress to date and discuss the technology challenges, options and tradeoffs to measure methane from space.

C6.11 A Cost Effective Laser-Based Enhancement of Passive Carbon Monitoring Approaches form GEO or LEO Orbits

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For the past decade significant advancements have been made toward understanding the global carbon budget using passive remote sensing techniques such as GOSAT and OCO-2. Japan is preparing to launch the follow-on instrument GOSAT-2 and NASA is planning a mission with OCO-3 hosted on the ISS. Although the advancement provided from these sensors has been game changing, there are limitations of these approaches in terms of temporal coverage and potential for location and surface dependent systematic bias from clouds, aerosols, and column-height uncertainties. Recently NASA announced the selection of the GeoCARB instrument that will enhance the current record by enabling high frequency coverage of land, atmosphere and ocean exchange of carbon, including vegetation health. However, GeoCARB will be affected by similar biases.

In this talk, we present a cost-effective laser based concept aimed at enhancing the GeoCARB mission, or other future passive remote sensing platforms from Leo or Geo. Originally developed by Harris in 2011, the Laser Atmospheric Transmitter and Receiver-Network (LAnTeRN) concept uses a single space-based laser transmitter to make total column measurements of CO_2 from GEO between the satellite and a network of ground-based receivers. Following initial concept development, we demonstrated the LAnTeRN feasibility through ground-based horizontal path testing. The horizontal testing then led to the Greenhouse-gas Laser Imaging Tomography Experiment, or GreenLITE_†¢, that enables spatial mapping of greenhouse gases including CO_2 and CH_4 over areas of 1 to 25 km^2 and estimates flux from a limited number of dominant sources within the footprint. The LAnTeRN concept is currently implementable using existing high TRL technologies. We will review the LAnTeRN concept and how it might be coupled with GeoCARB, or other similar observations in the future, to eliminate the bias uncertainty inherent in passive measurement systems. We will also discuss how a similar approach might be implemented along with future passive carbon monitoring instruments from LEO platforms as a calibration and validation tool to minimize potential sources of bias.

6.12 Combining cloud-top and total-column methane retrievals from an active sensor

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Active remote sensing of trace gases from aircraft or satellite brings with it the ability to retrieve meaningful data even under conditions of broken clouds, since lidars operate with small and defined footprints. Given sufficient optical thickness, retrieval of partial columns from cloud tops has also been shown to be possible for carbon dioxide (Ramanathan et al., 2015). The same has been demonstrated for the CHARM-F measurements from aircraft, using a differential absorption lidar measuring both methane and carbon dioxide (Amediek et al, 2017). This study examines the use of these partial columns for the interpretation of methane measurements, using both measurements from test flights as well as synthetic measurements to simulate what this would mean for the planned MERLIN mission, which will be measuring methane from space using the same technique. Cloud heights and optical depths measured by aerosol lidar CALIPSO provide information about when and where we expect to be able to make such measurements, but this has to be adjusted to take into account a different overpass time, given the planned dawn-dusk orbit of MERLIN. In addition to attempting to isolate the boundary signal from partial columns going down to low clouds, the possibility of mapping vertical distributions from different cloud heights is examined. For methane this proves to be particularly interesting, as it may provide an additional constraint on the vertical distribution brought about by both the distribution of the tropospheric chemical sink as well as the stratospheric component.

6.13 Airborne CO_2 Lidar Measurements for the Atmospheric Carbon and Transport - America (ACT-America) Project and the ASCENDS 2017 Field Campaign

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The Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) CarbonHawk Experiment Simulator (ACES) is a NASA Langley Research Center instrument funded by NASA's Science Mission Directorate that seeks to advance technologies critical to measuring atmospheric column carbon dioxide (CO_2) mixing ratios in support of the NASA ASCENDS mission. The ACES instrument, an Intensity-Modulated Continuous-Wave (IM-CW) lidar, was designed for high-altitude aircraft operations and can be directly applied to space instrumentation to meet the ASCENDS mission requirements. The ACES design demonstrates advanced technologies critical for developing an airborne simulator and spaceborne instrument with lower platform consumption of size, mass, and power, and with improved performance.

ACES recently flew on the NASA DC-8 aircraft during the 2017 NASA ASCENDS/Arctic-Boreal Vulnerability Experiment (ABoVE) airborne measurement campaign to test ASCENDS-related technologies in the challenging Arctic environment. Data were collected over a wide variety of surface reflectivities, terrain, and atmospheric conditions during the campaign's 8 research flights.

The Atmospheric Carbon and Transport - America (ACT-America) is an Earth Venture Suborbital -2 (EVS-2) mission sponsored by the Earth Science Division of NASA's Science Mission Directorate. A major objective is to enhance knowledge of the sources/sinks and transport of atmospheric CO2 through the application of remote and in situ airborne measurements of CO_2 and other atmospheric properties on spatial and temporal scales. ACT-America consists of five campaigns to measure regional carbon and evaluate transport under various meteorological conditions in three regional areas of the Continental United States. Regional CO_2 distributions of lower atmosphere were observed from the C-130 aircraft by the Harris Corp. Multi-Frequency Fiber Laser Lidar (MFLL) and the ACES lidar. The airborne lidars provide unique data that complement the more traditional in situ sensors. This presentation shows the applications of CO_2 lidars in support of these science needs.